Upcoming Parity Violation Experiments and the New RTP Pockels Cell

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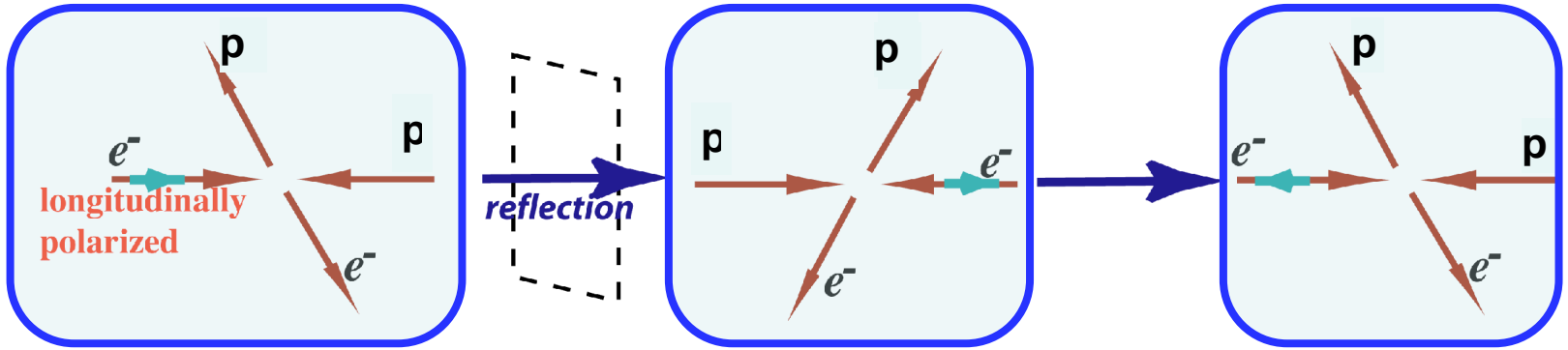
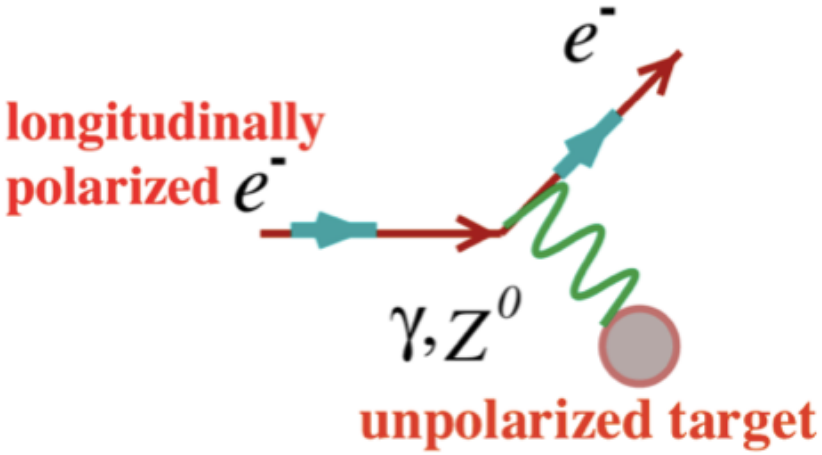
University of Virginia

JLab Feb 6, 2019

Electron Scattering and Parity-violation



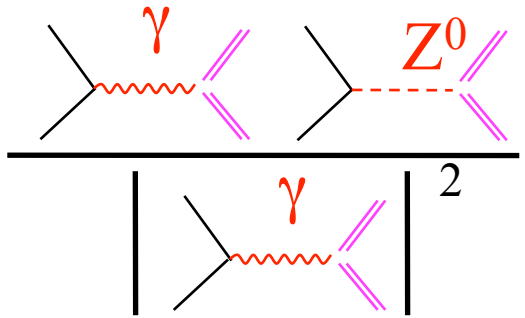
- Incident beam is longitudinally polarized
- Change sign of longitudinal polarization
- Measure fractional rate difference



$$\sigma \propto |M_\gamma + M_{weak}|^2$$

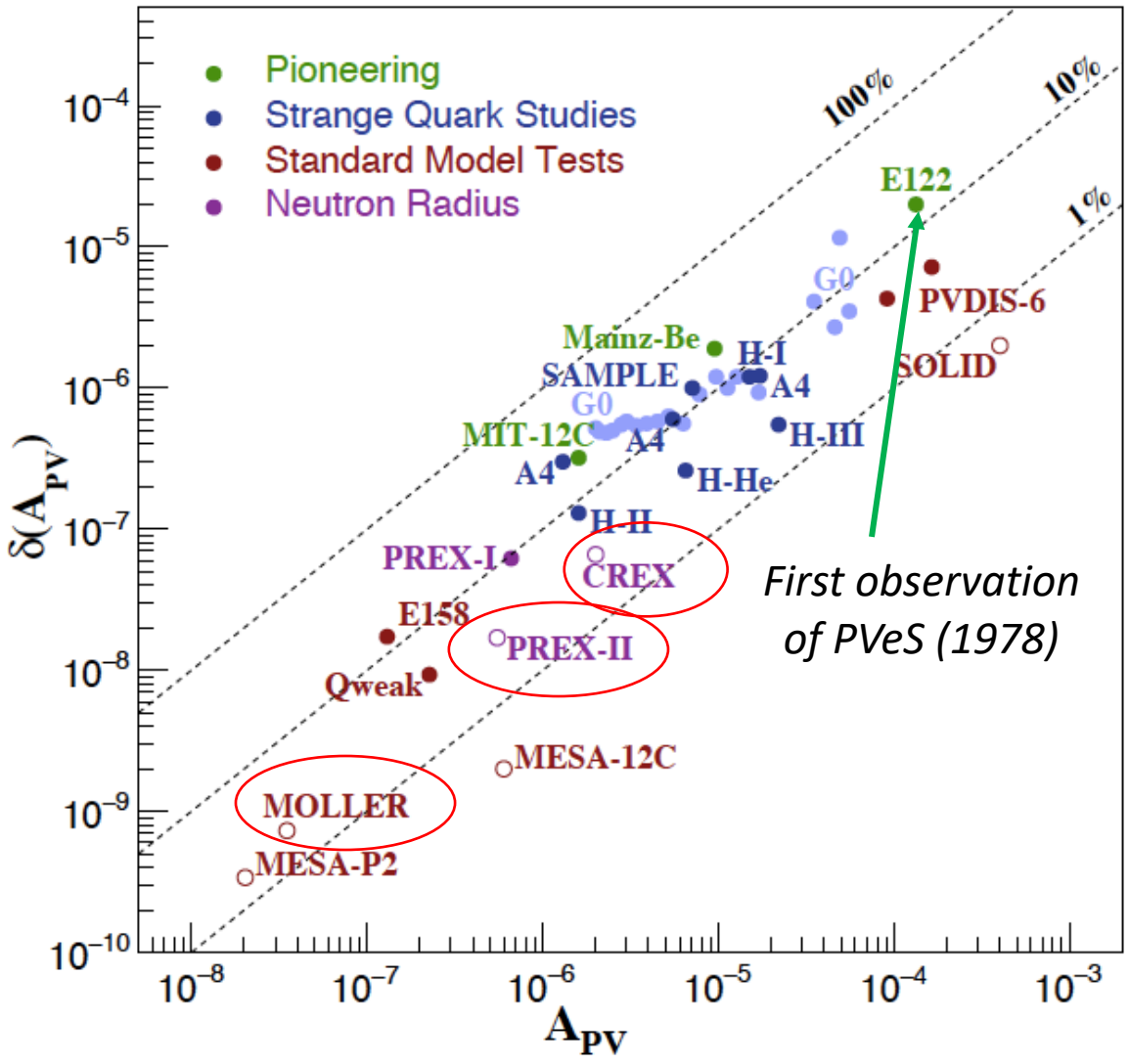
$$\sim |M_\gamma|^2 + 2M_\gamma (M_{weak})^* + \ldots$$

$$A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \sim \frac{\left|\ \right|^2}{\left|\ \right|^2} \propto \frac{|\mathcal{M}_Z|}{|\mathcal{M}_\gamma|}$$



"Electroweak" models predicted
- interference of electromagnetic and weak amplitudes
- values for electron & quark weak neutral current coupling

PVES has become a precision tool



First observation of PVeS (1978)

Broad program studying the structure of protons and nuclei, and searching for new (Beyond Standard Model) physics

Measurements of the Neutron Skin of ^{208}Pb and ^{48}Ca

PREX

^{208}Pb

CREX

^{48}Ca

Mapping Electric & Weak Charge Distributions

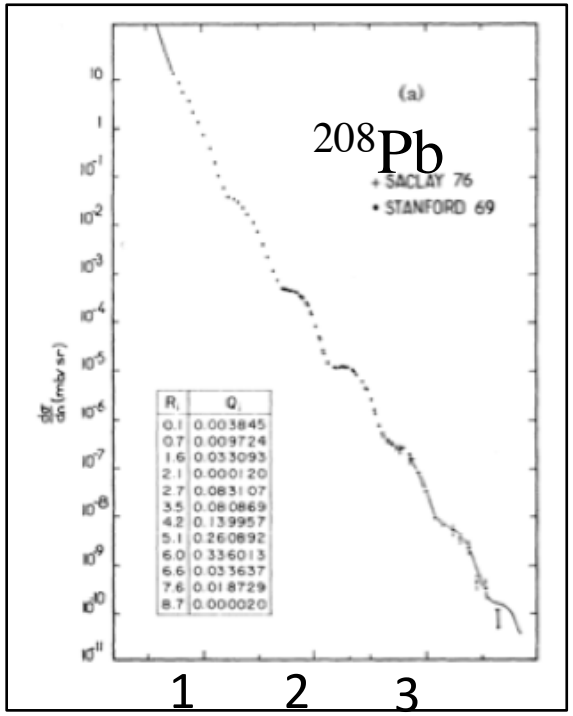
Our picture of nuclei is the electric charge distribution:

Differential cross-section

$$\left(\frac{d\sigma}{d\Omega}\right)_{\text{Mott}} = \frac{4Z^2\alpha^2E^2}{Q^4}$$

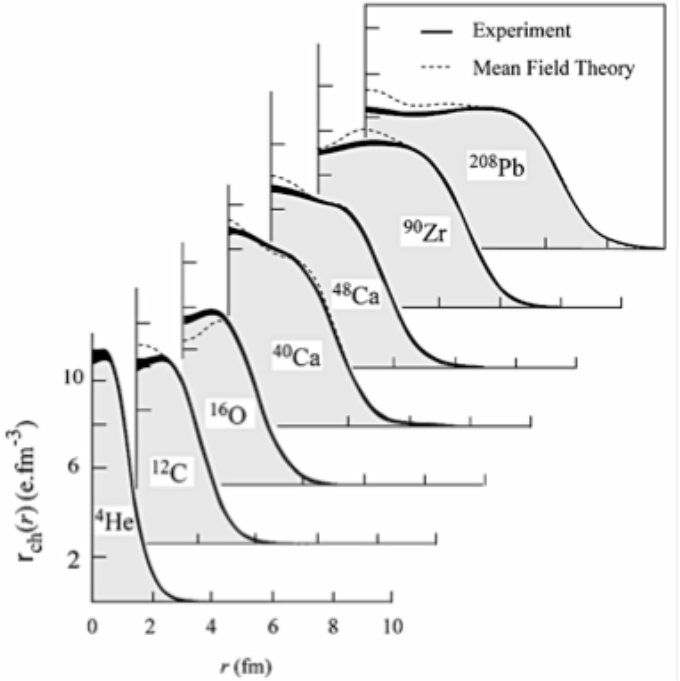
As Q increases, nuclear size becomes important correction

$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{\text{Mott}} |F(q)|^2$$



q (fm)$^{-1}$

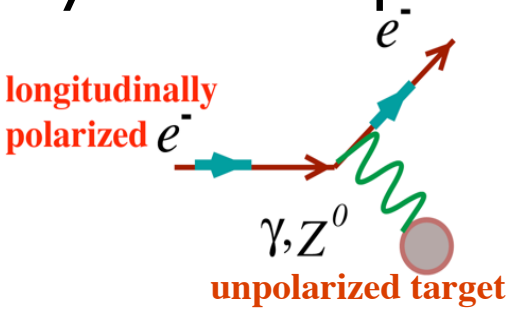
Neglecting relativistic recoil, the form-factor $F(q)$ is the Fourier Transform of charge density



One can map the weak charge using parity-violation

Introduction to PREX/CREX

Parity violation experiments map the weak charge distribution :



$$\sigma \propto |M_\gamma + M_{weak}|^2$$
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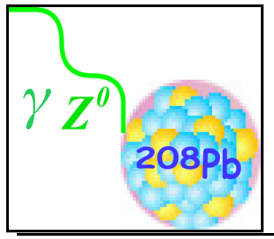
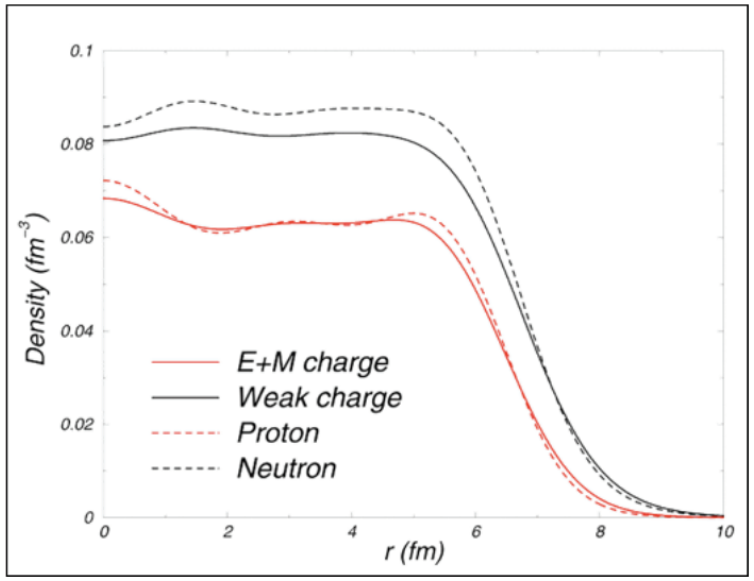
$$A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L}$$

$$A_{PV} \approx \frac{G_F Q^2}{4\pi\alpha\sqrt{2}} \frac{F_W}{F_{ch}}$$



	proton	neutron
Electric charge	1	0
Weak charge	~0.08	1

for spin-0 nucleus



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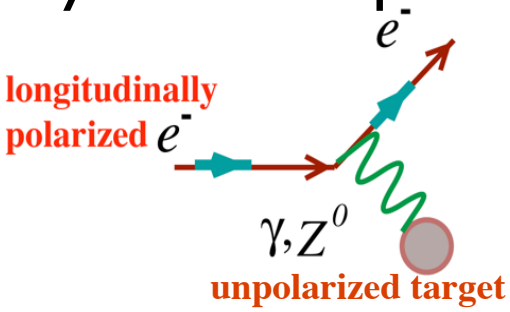

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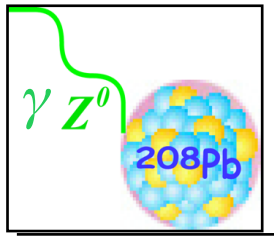
Weak interaction almost entirely couples to neutron distribution
& EM interaction entirely couples to proton distribution



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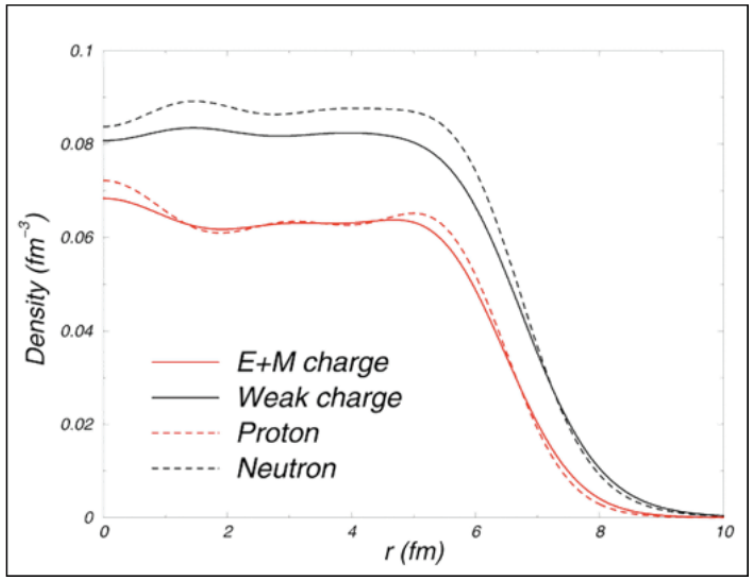

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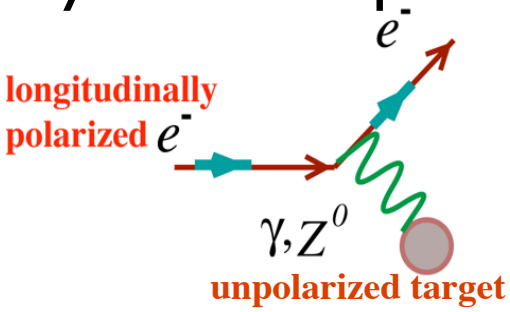

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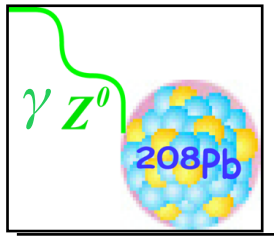

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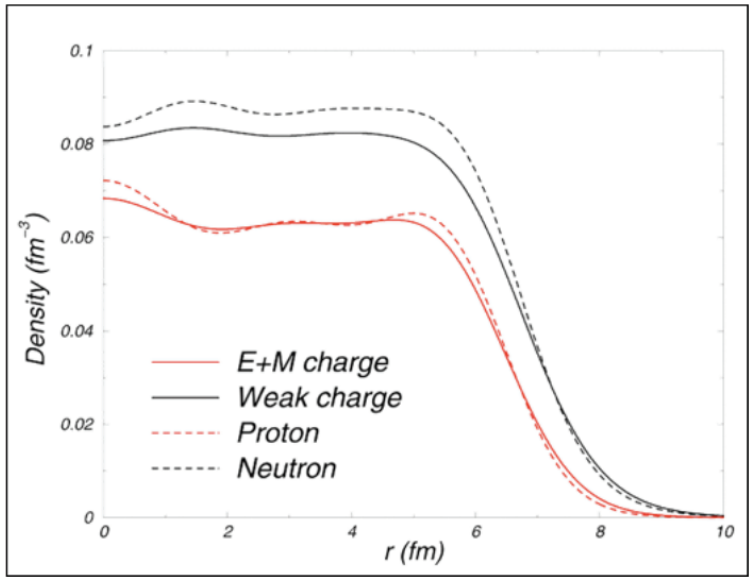

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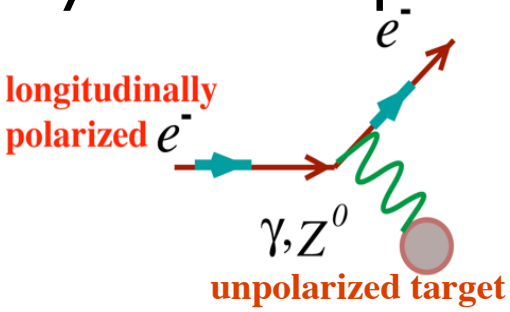

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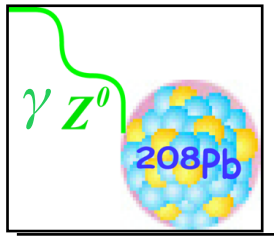

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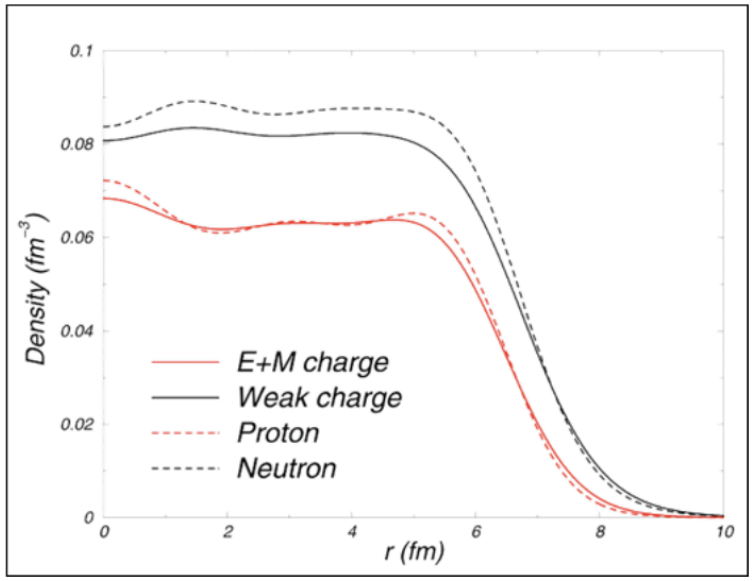
Ratio of weak to E&M FF is directly related to neutron skin thickness on heavy nuclei as predicted by nuclear theory



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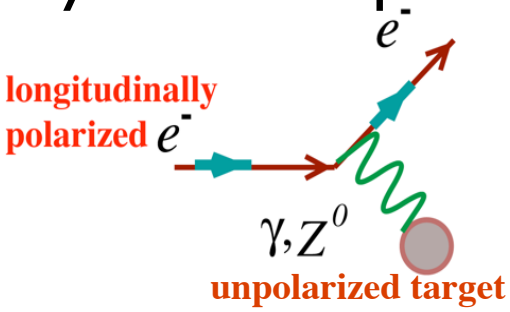

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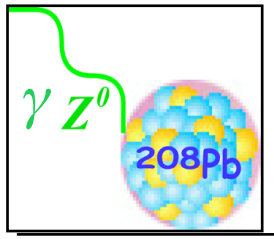

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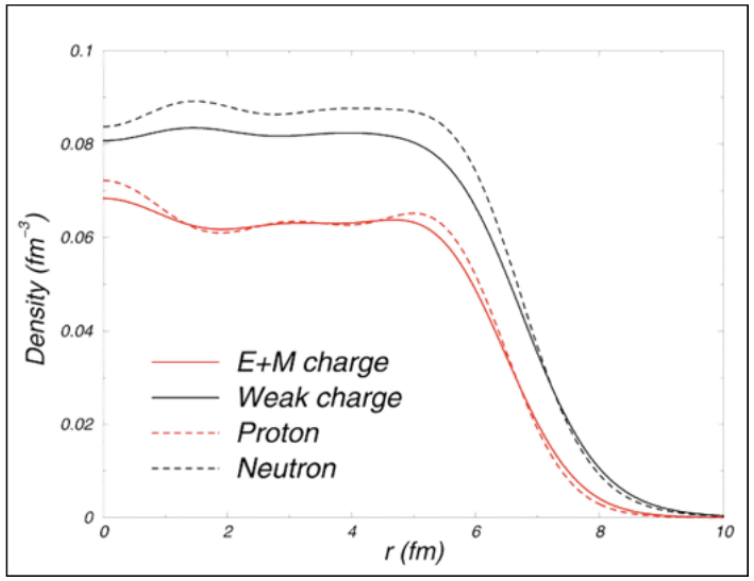

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Neutron skin thickness is highly sensitive to the pressure of pure neutron matter & EOS: the greater the pressure, the thicker the skin as neutrons are pushed out against surface tension.

A_{PV} provides clean measure of neutron skin thickness

Neutron skin measured by A_{PV}

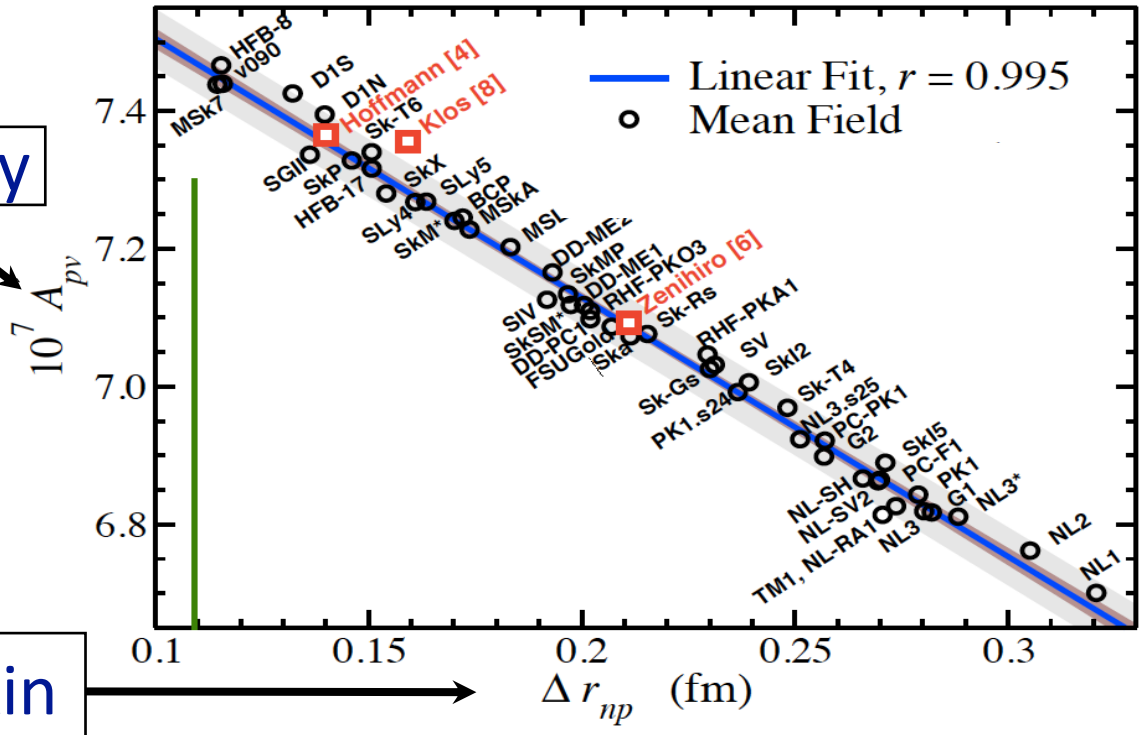
Models

Weak charge density

Solve Dirac Eq.

Predicted Asymmetry

Predicted Neutron Skin



X. Roca-Maza, M. Centelles, X. Vi˜nas, and M. Warda, Phys. Rev. Lett. 106 252501 (2011)

Models that predict a weak charge density demonstrate that neutron skin and Apv are not independent parameters

Robust correlation between ^{208}Pb A_{PV} and the neutron skin over existing nuclear structure models

Apv in PVES provides a clean probe of the neutron distribution

One is a direct measure of the other

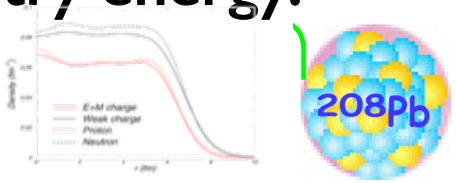
PREX: A_{PV} to 3% from ^{208}Pb -> r_n to 0.06 fm

CREX: A_{PV} to 4% from ^{48}Ca -> r_n to 0.022 fm

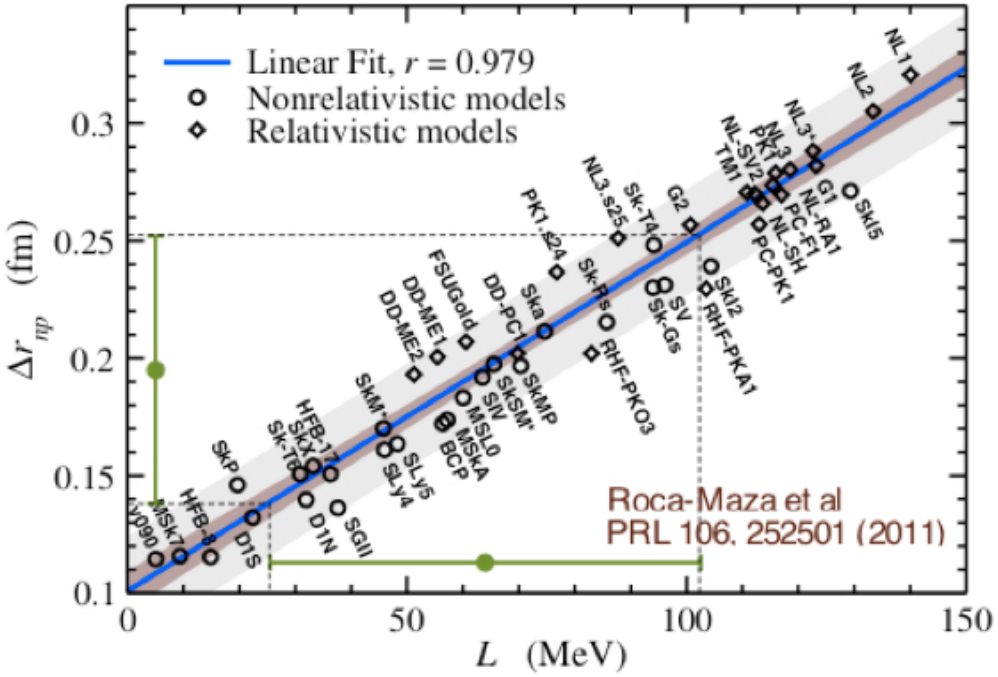
Neutron skin and Symmetry Energy

Mean-Field predictions show a clear correlation between neutron skin of a heavy nucleus and the density slope of the symmetry energy.

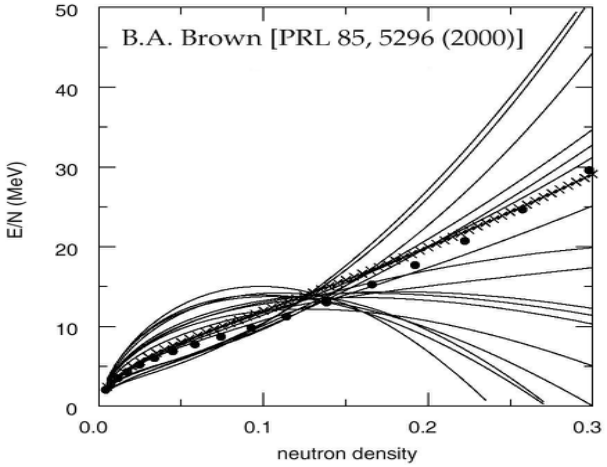
Energy penalty for breaking N=Z symmetry



Slope of symmetry energy at saturation density



$$L \propto \frac{\partial S(\rho)}{\partial \rho}\Big|_{\rho_0}$$



So far the probes for stable heavy nuclei have been strongly interacting, having a somewhat more complicated interpretation

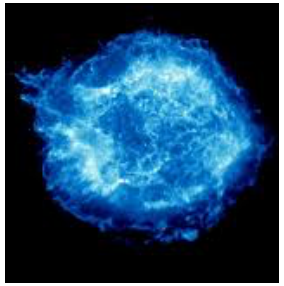
r_n calibrates the **Equation of State** of neutron rich matter directly, constrains and guides models needed for heavy nuclei via L

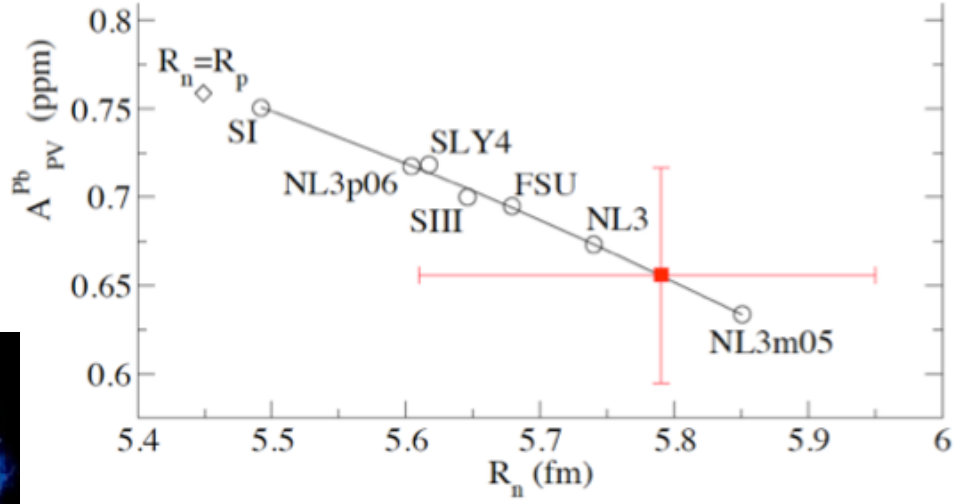
PREX-I Result

A_{PV} = 0.657 ± 0.060(stat) ± 0.014(sym) ppm

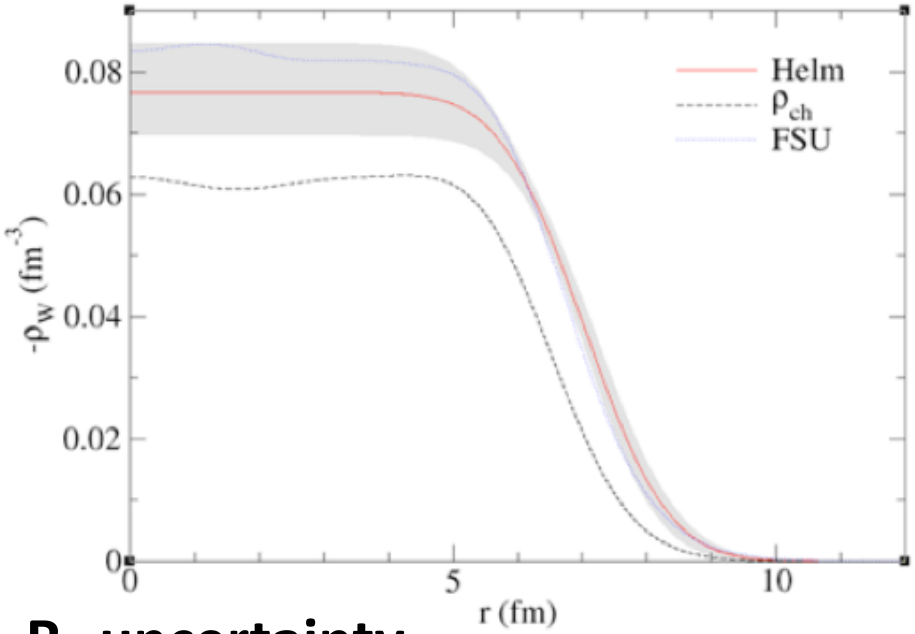
- First electroweak observation that weak charge density more extended than (E+M) charge density → first electroweak proof of neutron skin

- Interestingly, current PREX central value not consistent with measured <u>neutron star</u> properties and existing models.





Rn - Rp= 0.33 +0.16-0.18 fm

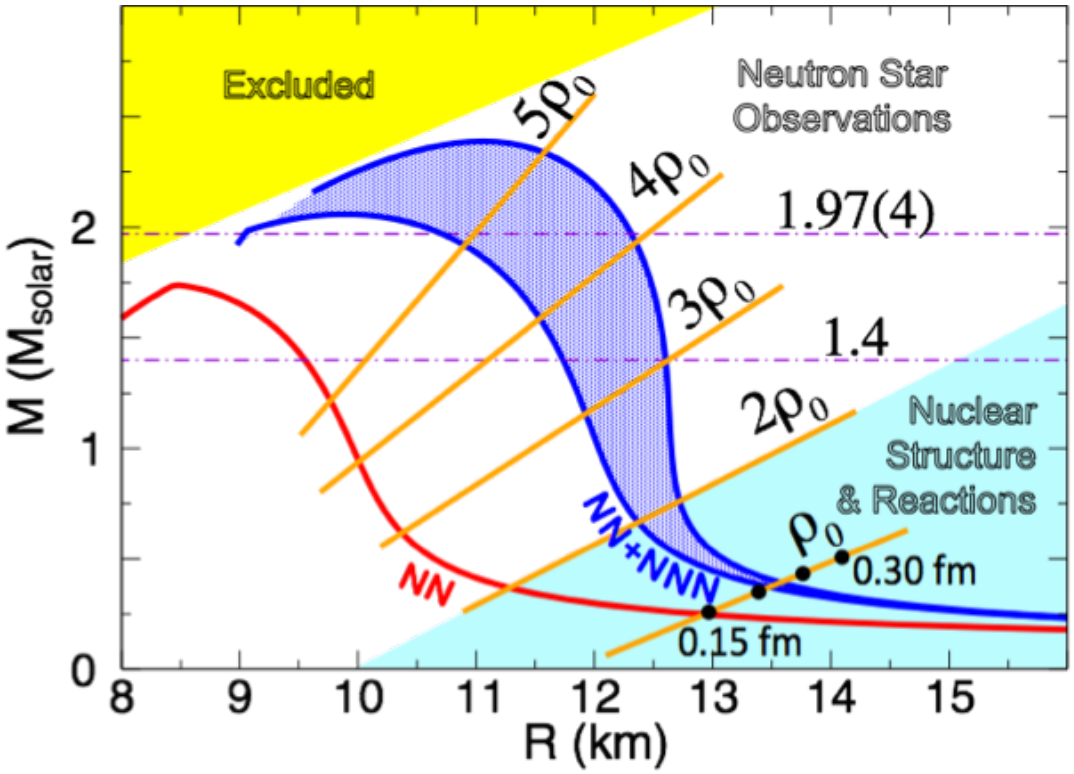


Phys Rev Let. 108, 112502 (2012),
Phys. Rev. C 85, 032501(R) (2012)
(250+ references on Inspire,
->full result eagerly anticipated)

PREX-II: achieve 3x improvement on R_n-R_p uncertainty

Neutron Star Mass vs. Radius

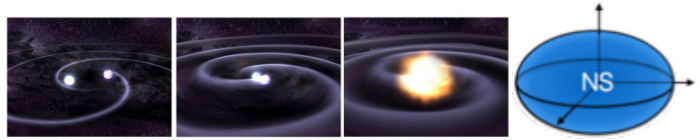
Strong analogy to nuclei: Symmetry pressure pushes against **gravity**



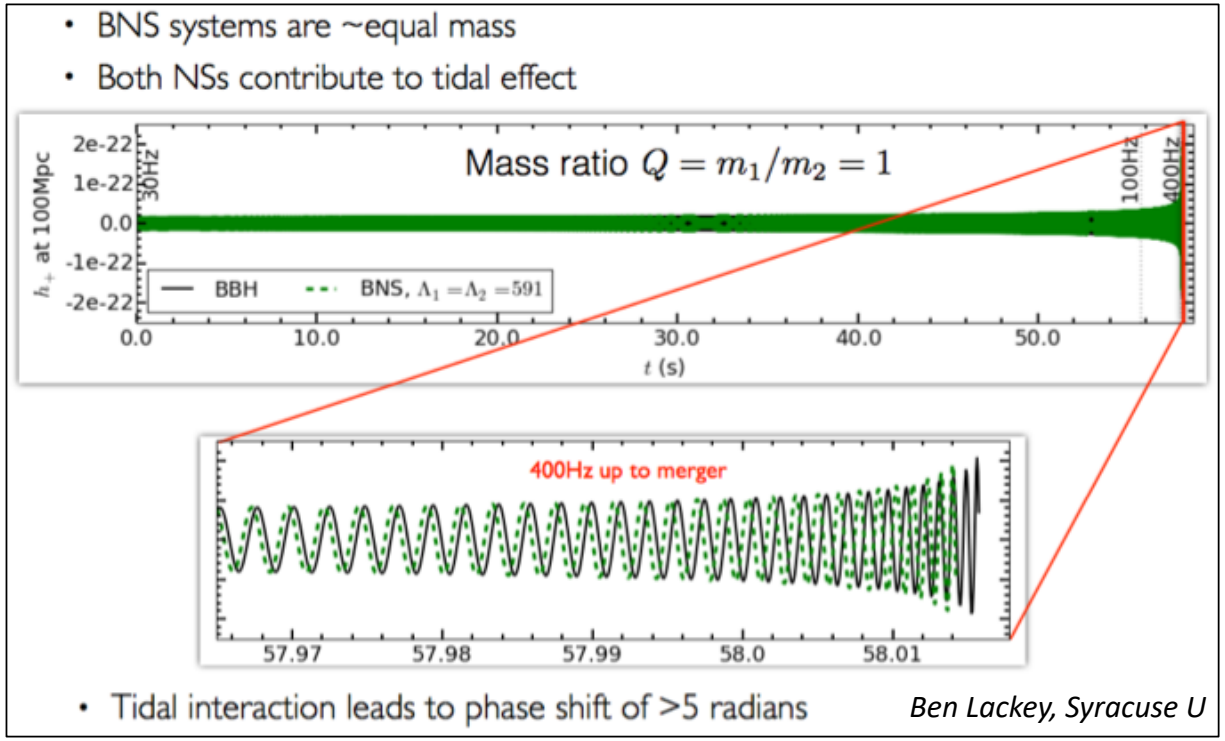
- All neutron star radii between 10.4 and 12.9 km
- Suggests $R_n(^{208}Pb) < 0.2$ fm
- **PREX informs neutron star size vs. mass**

Gravity Waves and EOS

- Tidal field created by companion induces a quadrupole moment in the NS
  - Tidal field: $\mathcal{E}_{ij}$
  - Quadrupole moment: Q_{ij}



- Amount of deformation depends on stiffness of EOS via the tidal deformability λ:



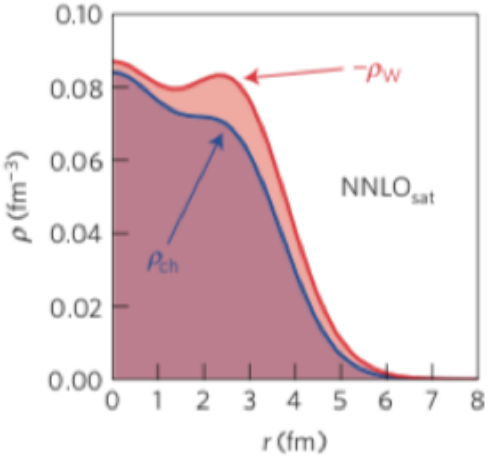
The waveform is sensitive to the nuclear EOS for neutron stars

^{48}Ca : CREX

link between *ab initio* models and Density Functional Theory

^{48}Ca: nuclear distribution

- influenced by finite size effects.
- Within reach of ab initio, microscopic calculations



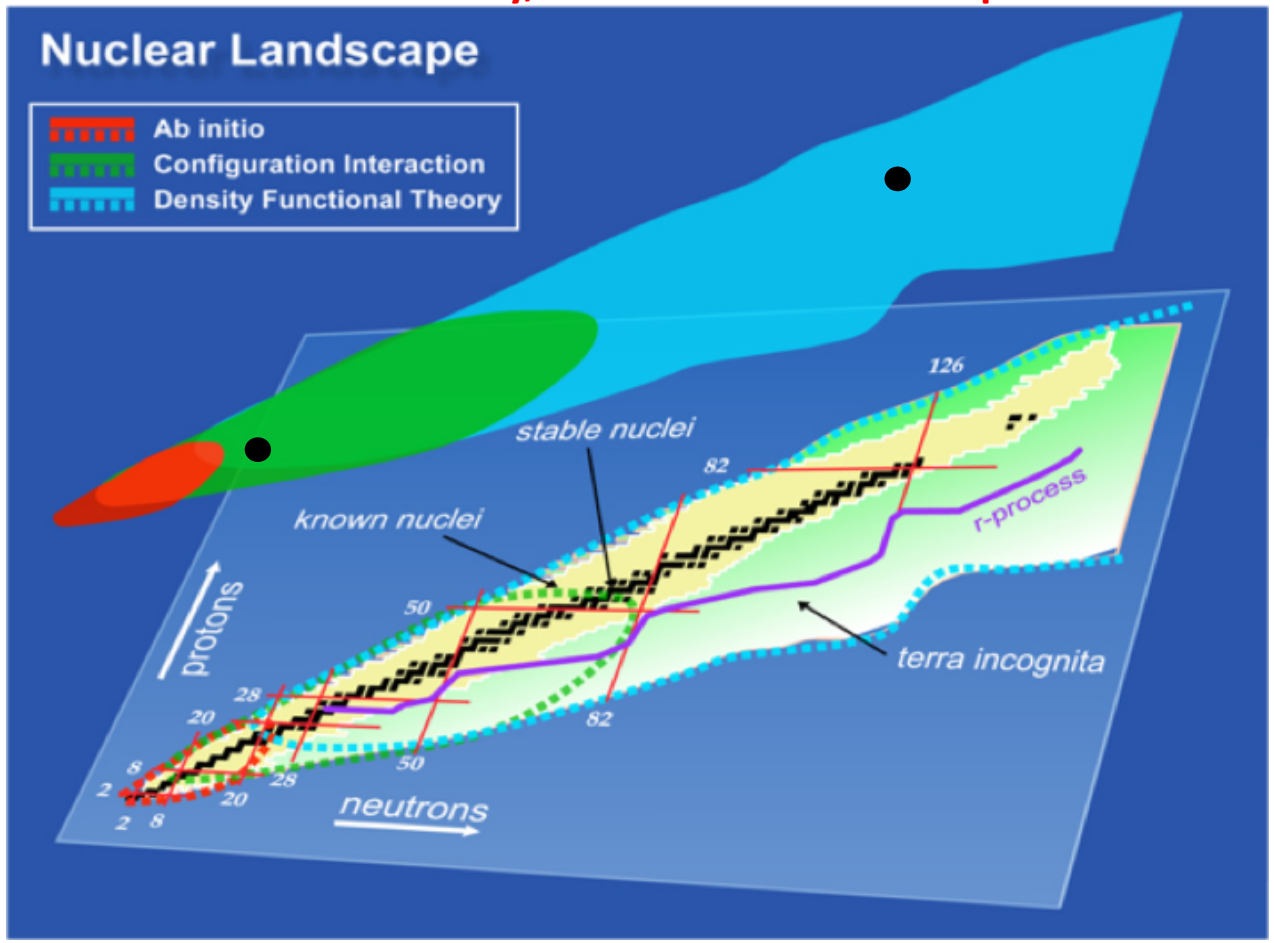
coupled-cluster model of ^{48}Ca: G. Hagen et al, Nature Physics 12, 186–190 (2016)

$$0.12 \lesssim R_{\rm skin} \lesssim 0.15\,\text{fm}.$$

^{208}Pb:

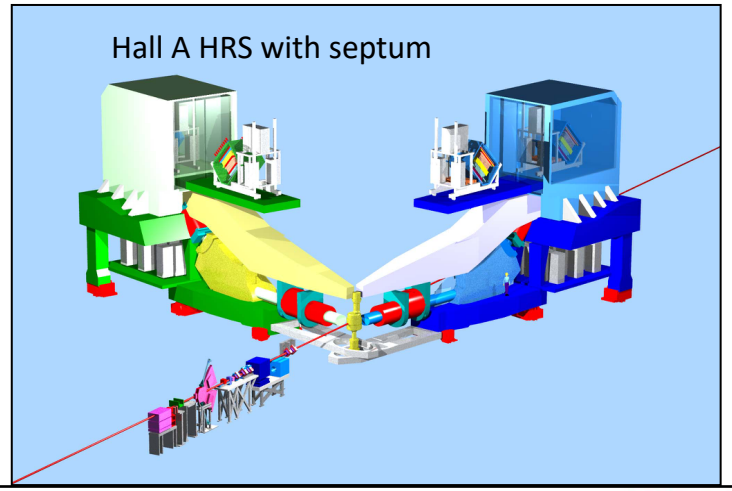
- lies further up in A
- in realm of uniform nuclear matter & DFT
- serves as terrestrial laboratory to test n-star structure

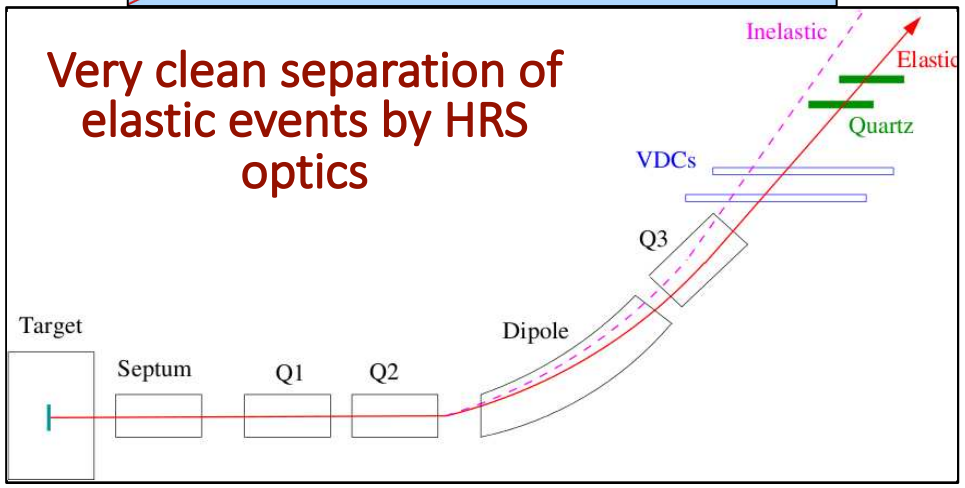
Chiral effective field theory, based on NN and NNN potentials



PREX and CREX together span the nuclear landscape of highly dense matter

PREX / CREX in Hall A





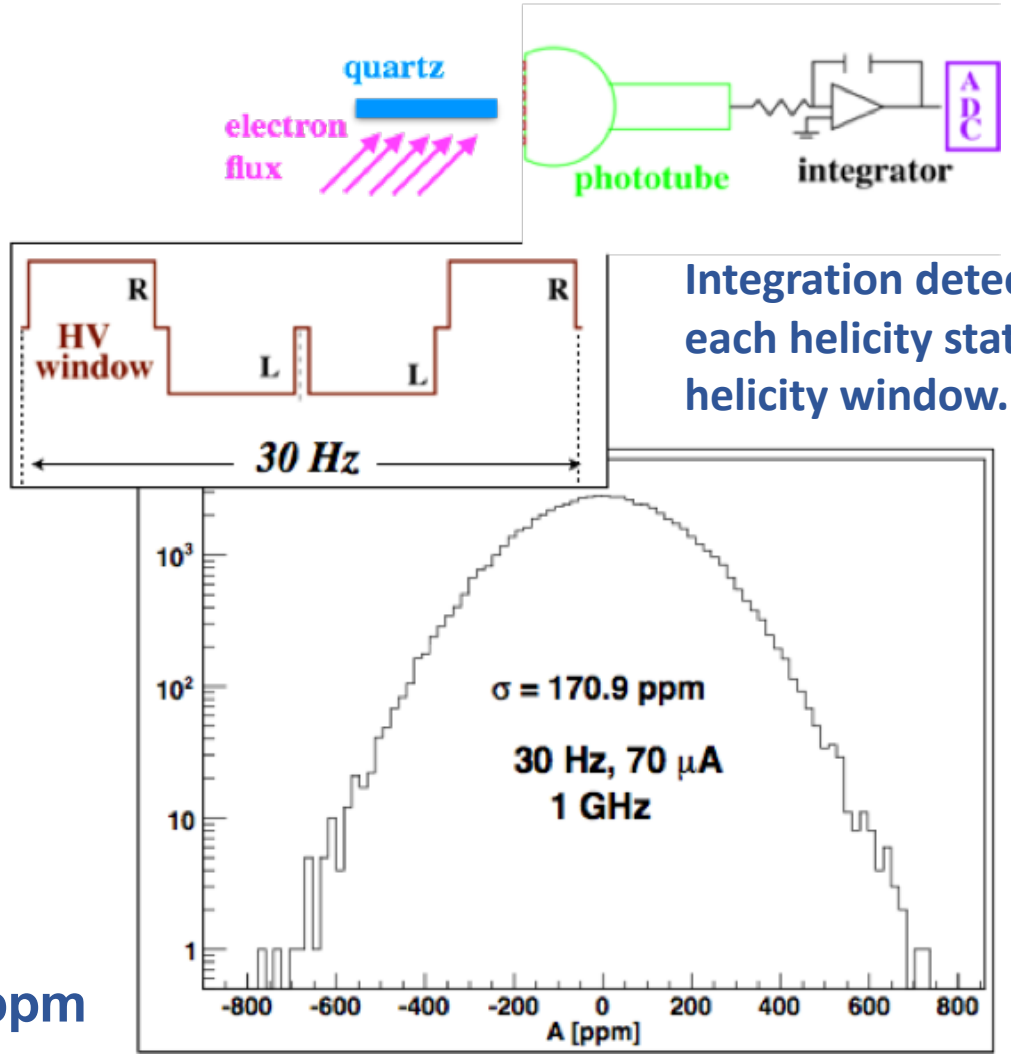
Analog integration of everything that hits the detector

$Q^2 \sim 0.009\ GeV^2$ ⇒ $A_{PV} \sim 0.6$ ppm +-0.02ppm

5° scattering angle

Rate ~1 GHz

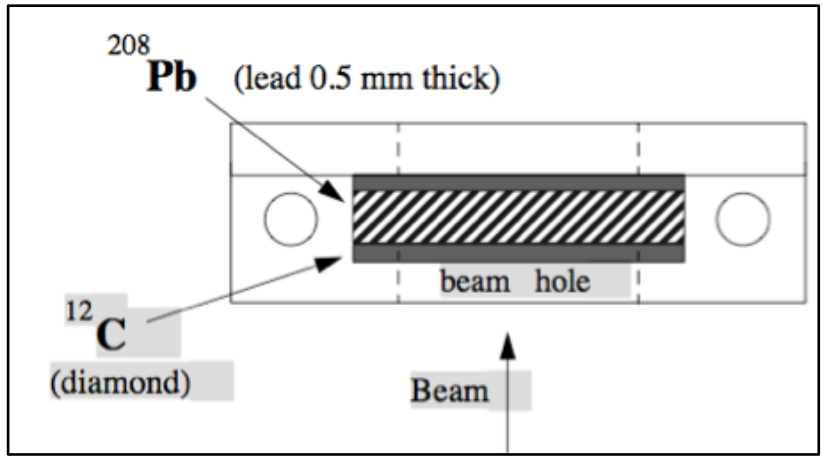
Flux integration Technique



Integration detection for each helicity state in a helicity window.

PREX targets

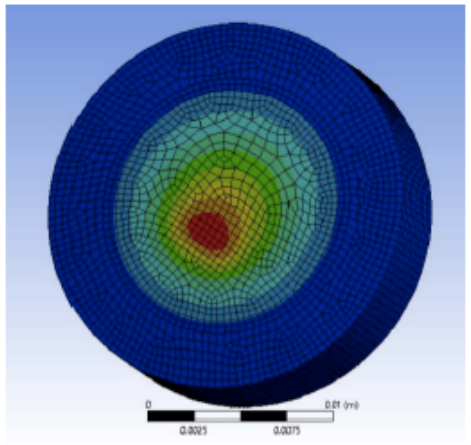
- Diamond foils - excellent thermal conductivity
- ^{12}C is isoscaler, spin-0, Apv is well-measured, so benign background! (dilution, not false asymmetry)
- 70uA limited in PREX because of target thermal properties

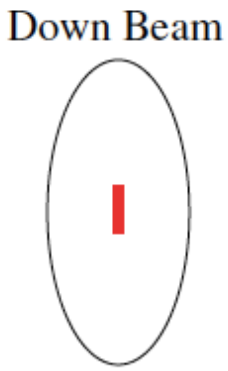


0.5mm lead,
0.25mm diamond, 1 sqin

Use synchronized 4x4mm raster to handle non-uniform lead thickness

CREX target

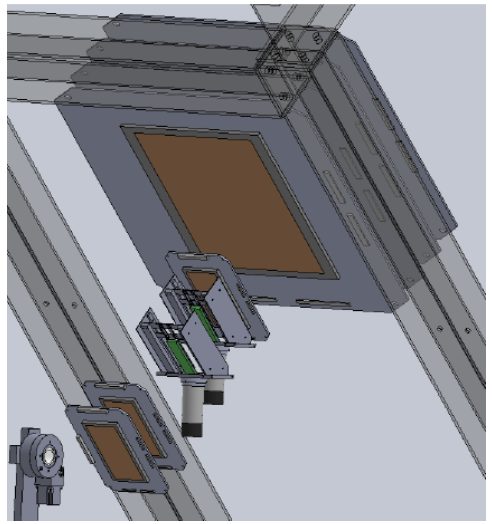




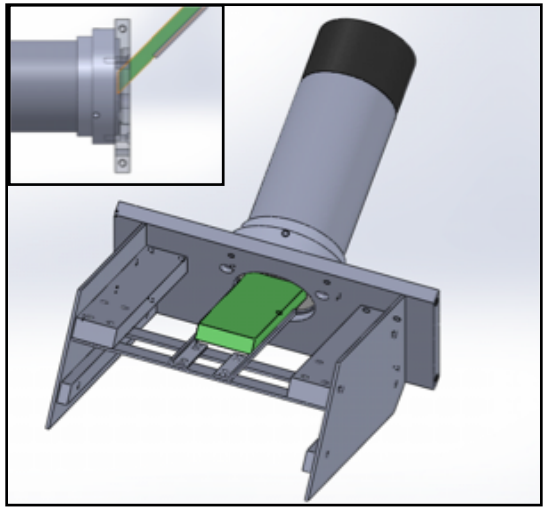
1.1g/cm2
~4x1mm raster (tbd)

- Target has good thermal conductivity, so can run at higher 150uA current
- New Target: 96% 48Ca, ~4% 40Ca (I think…)
- 40Ca isoscaler, spin-0, also benign

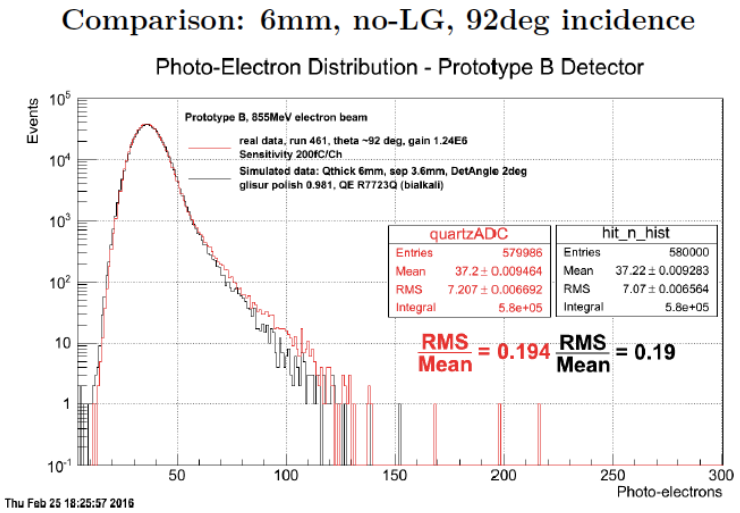
Integrating Detectors



ISU



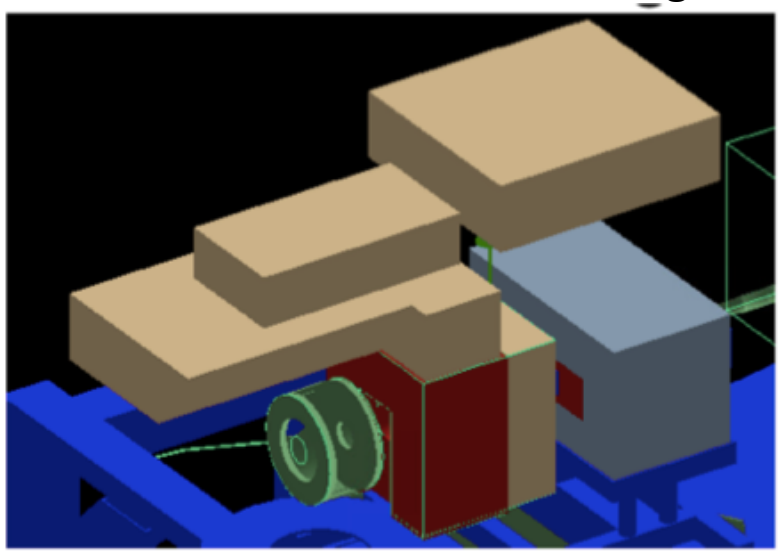
$$\sigma = \sigma_{stat}\sqrt{1+\sigma_{res}^2}$$

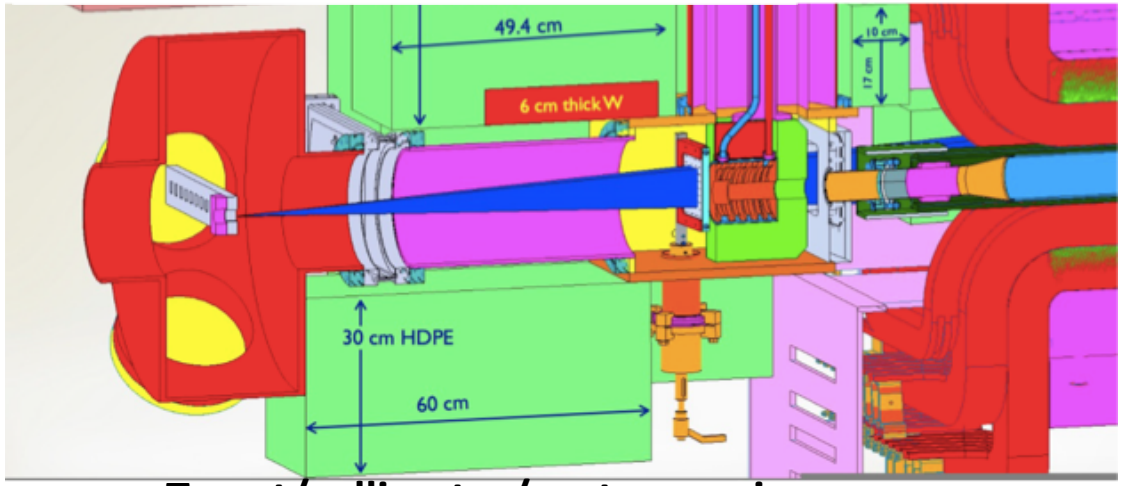


- Thin quartz integrating e- detectors with phototubes to detect Cherenkov radiation from particles traversing the quartz
- Balance shower fluctuations and photon statistics

Radiation Shielding + New Collimator

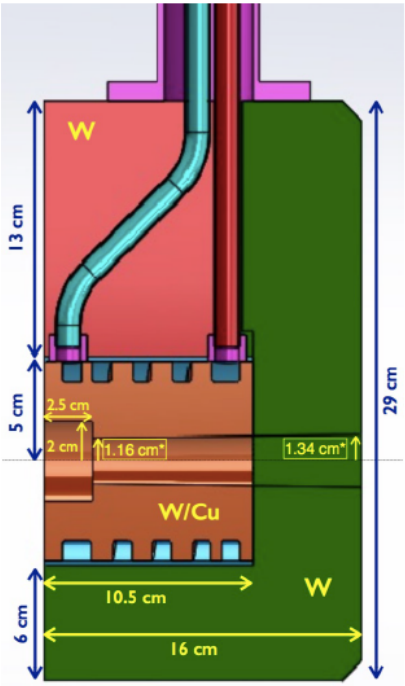
Concrete + HDPE Shielding





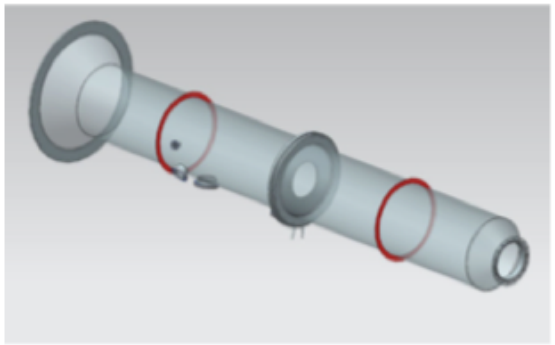
Target/collimator/septum region

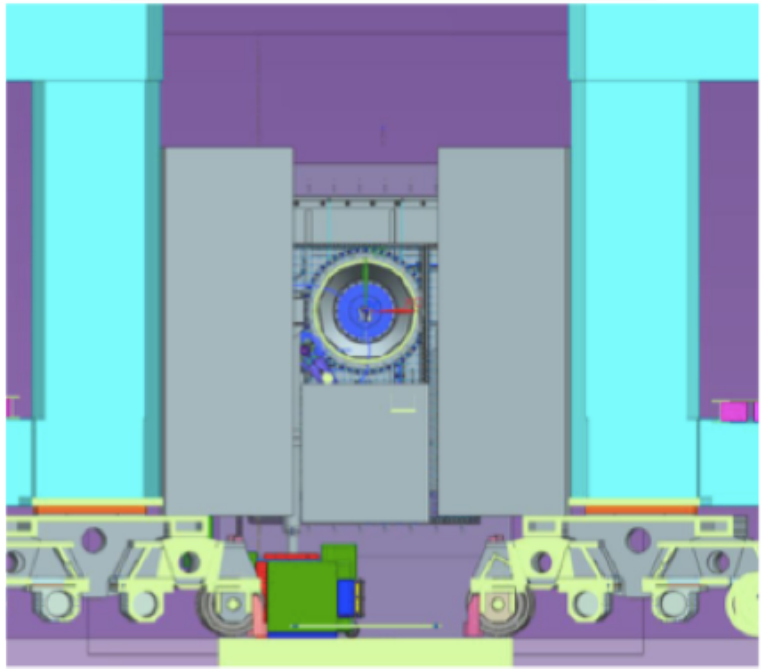
Tungsten shielding



Collimator

Beam Dump Shielding





Dump

PREX-I suffered from excessive radiation damage to electronics, so new shielding and collimation will be used.

PREX/CREX Experiments

PREX-2: 3% stat, 0.06 fm
CREX: 4% stat, 0.02fm

Achieved

PREX-I
E=1.1 GeV, 5°
A=0.6 ppm

Charge Normalization	0.2%
Beam Asymmetries	1.1%
Detector Non-linearity	1.2%
Transverse Asym	0.2%
Polarization	1.3%
Target Backing	0.4%
Inelastic Contribution	<0.1%
Effective Q^2	0.5%
Total Systematic	**2.1%**
Total Statistical	**9%**

PREX-II
E=0.95 GeV, 5°
A=0.6 ppm
70 μA, 25+10 days

Charge Normalization	0.1%
Beam Asymmetries*	1.1%
Detector Non-linearity*	1.0%
Transverse Asym	0.2%
Polarization*	1.1%
Target Backing	0.4%
Inelastic Contribution	<0.1%
Effective Q^2	0.4%
Total Systematic	**2%**
Total Statistical	**3%**

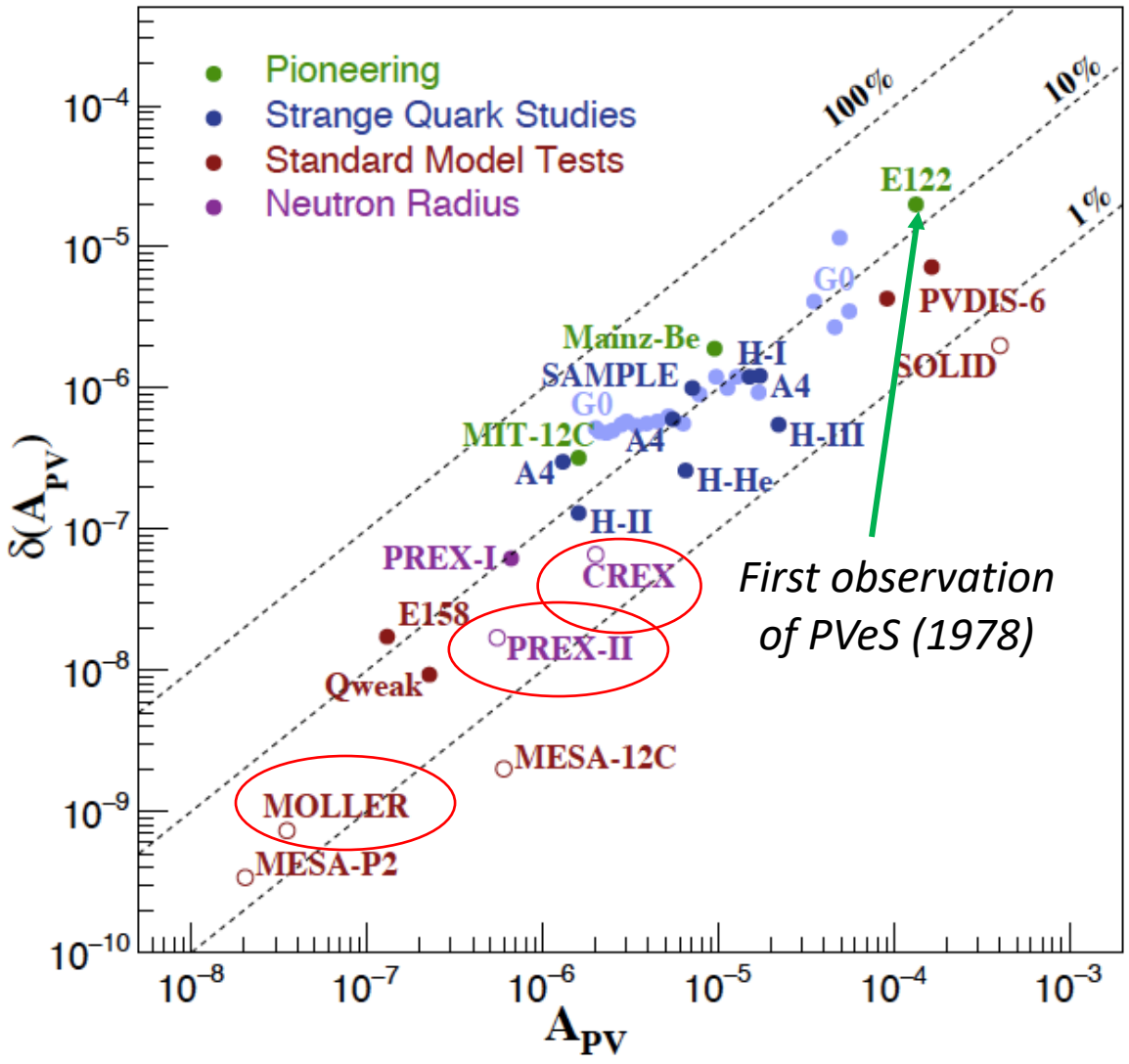
CREX
E=2.2 GeV, 5°
A = 2.3 ppm
150 μA, 35 + 10 days

Charge Normalization	0.1%
Beam Asymmetries	0.3%
Detector Non-linearity	0.3%
Transverse Asym	0.1%
Polarization	0.8%
Target Contamination	0.2%
Inelastic Contribution	0.2%
Effective Q^2	0.8%
Total Systematic	**1.2%**
Total Statistical	**4%**

statistics limited result,
Most systematics well under control

***Experience suggests that leading systematic errors such as beam asymmetries can be improved further**

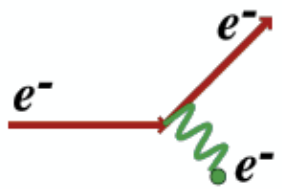
PVES has become a precision tool



Broad program studying the structure of protons and nuclei, and searching for new (beyond Standard Model) physics

Searches for New Neutral Currents

Møller (ee) scattering : Weak charge of the electron



SLAC-E158 1997-2004

MOLLER

Extend the reach of new physics beyond the Standard Model

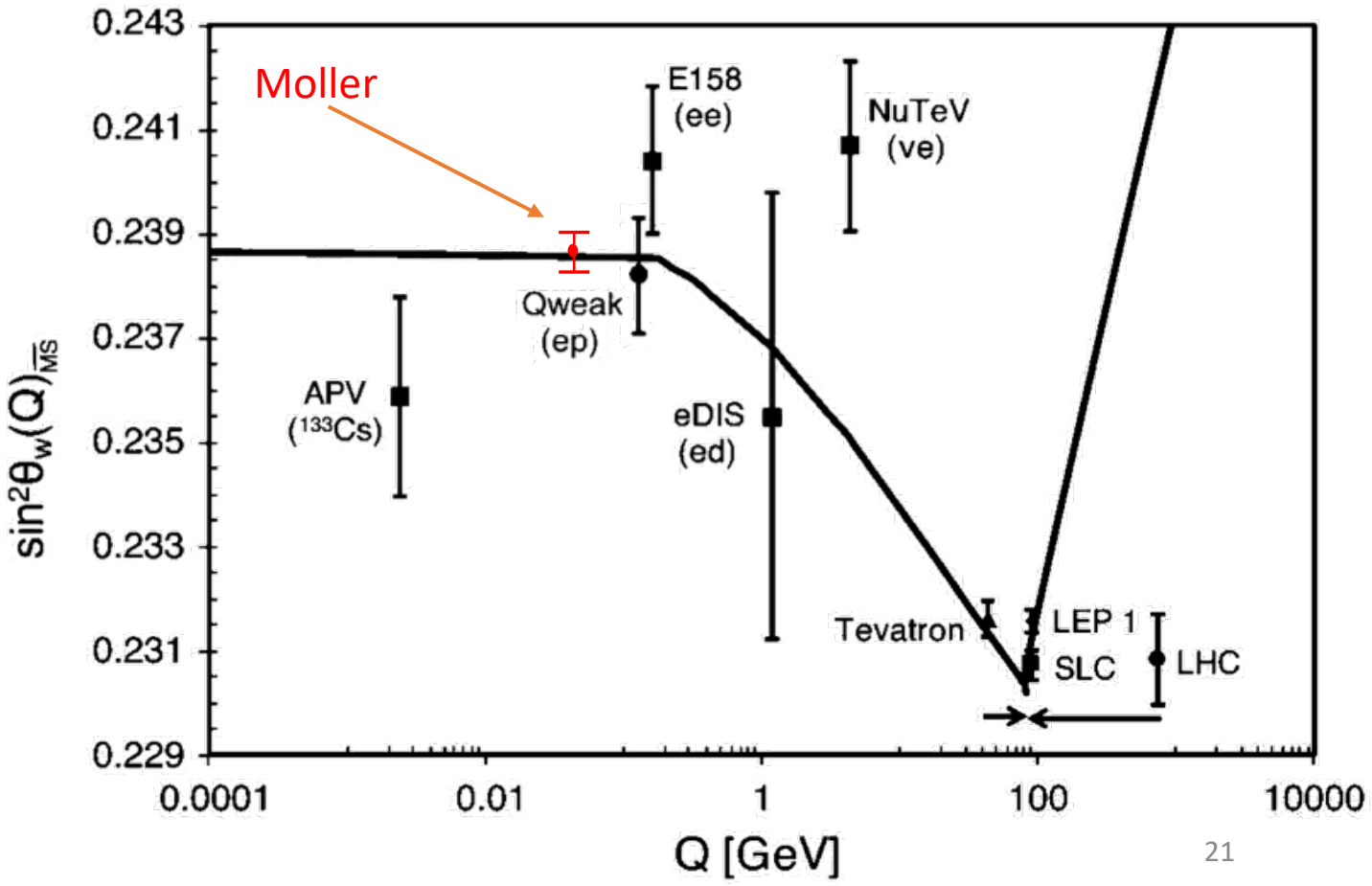
- Measure the **weak charge of the electron** to extremely high precision

Interference term between the electro-magnetic and weak amplitudes gives rise to parity-violating asymmetry,

$$A_{PV} \Rightarrow Q_W^e \Rightarrow \theta_W$$

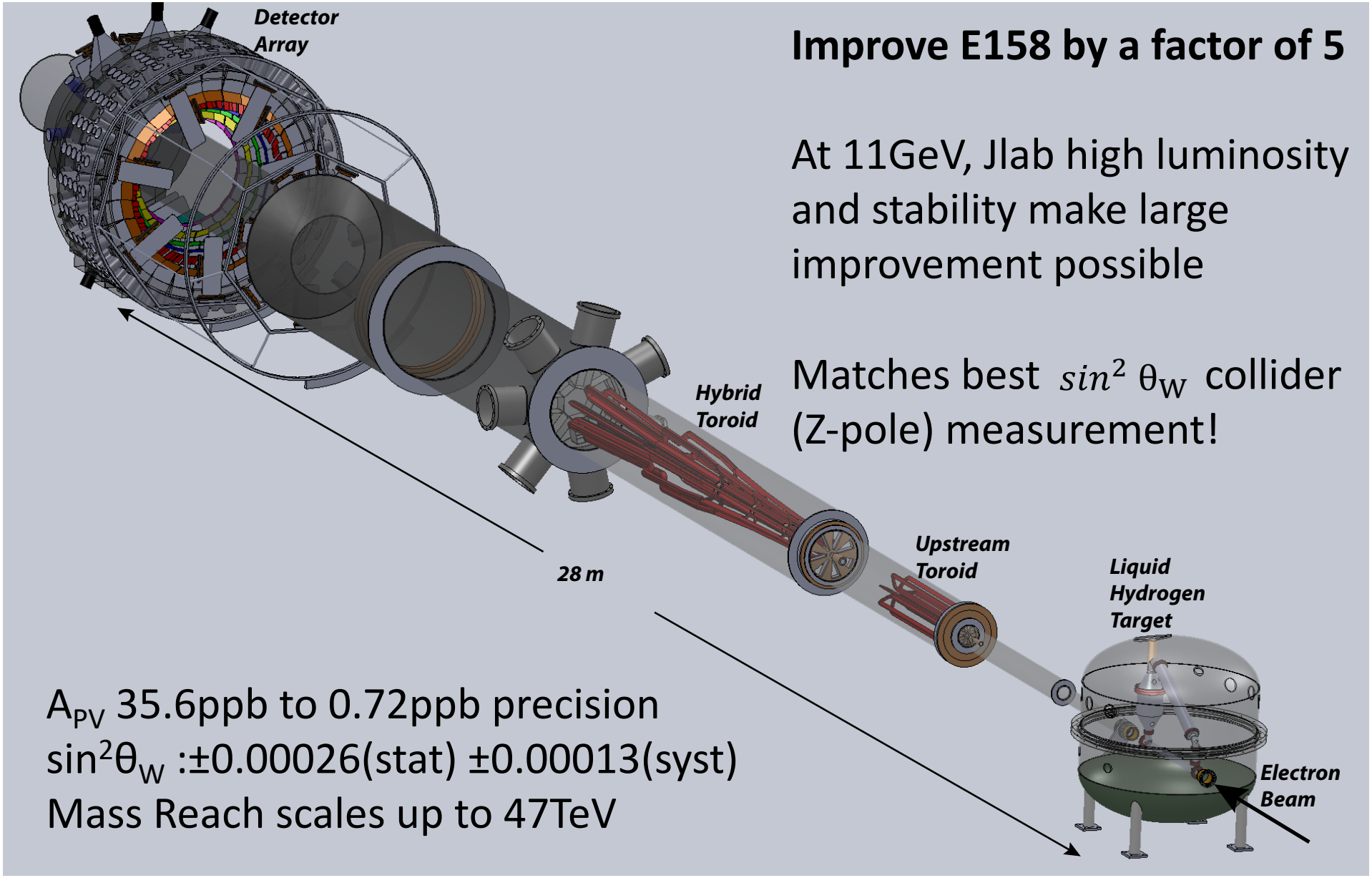
$$Q_W^e = 1 - 4sin^2\,\theta_W$$

Which relates directly to the electron weak charge and weak mixing angle



Ultra-precise measurement sensitive to new parity-violating interactions

Design for Moller experiment



Improve E158 by a factor of 5

At 11GeV, Jlab high luminosity and stability make large improvement possible

Matches best $sin^2\,\theta_W$ collider (Z-pole) measurement!

A_{PV} 35.6ppb to 0.72ppb precision
$\sin^2\theta_W$:±0.00026(stat) ±0.00013(syst)
Mass Reach scales up to 47TeV

Mass Reach is ~600X the mass of the W mediator, ~400X the Higgs Mass

Moller Uncertainty Requirements

60 μA, 90% polarization

2 kHz helicity flip rate with 10 μs settle time (past: 1 kHz, 60 μs T_{settle})

35ppb Apv

Error Source	Fractional Error (%)
Statistical	**2.1**
Absolute Normalization of the Kinematic Factor	0.5
Beam (second order)	0.4
Beam polarization	0.4
$e + p(+\gamma) \rightarrow e + X(+\gamma)$	0.4
Beam (position, angle, energy)	0.4
Beam (intensity)	0.3
$e + p(+\gamma) \rightarrow e + p(+\gamma)$	0.3
$\gamma^{(*)} + p \rightarrow (\pi, \mu, K) + X$	0.3
Transverse polarization	0.2
Neutral background (soft photons, neutrons)	0.1
Total systematic	**1.1**

	MOLLER	previously achieved
Intensity Asymmetry	10 ppb	~ 30 ppb (Qweak)
Energy Asymmetry	<0.7 ppb	0.2 ppb (H-II)
Position Difference	<1.2 nm	2 nm (H-II)
Angle Differences	<0.12 nrad	0.25 nrad (H-II)
Size Differences	< 1×10^{-5}	<1×10^{-4} (PREX-I, Qweak)

$$A_{raw} = A_{det} - A_Q + \alpha\Delta_E + \Sigma\beta_i\Delta x_i$$

Any change in the polarized beam, correlated to helicity reversal, can be a potential source for a false asymmetry

	Source
Intensity	**<20 ppm (injector)**
Position /angle	**~20 nm (injector)** (Past: 50-200 nm)
Spot Size	**(laser) $\Delta\sigma/\sigma$ <10^{-5}** (Past: $\Delta\sigma/\sigma$ <10^{-4})

Obtaining High Precision for Parity Experiments

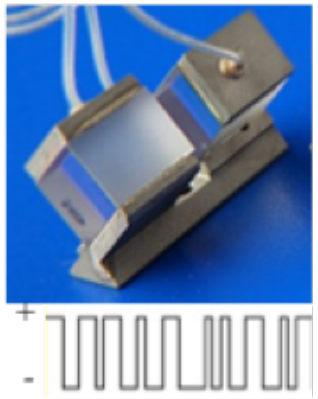
Polarized source:

(1) preparation of laser

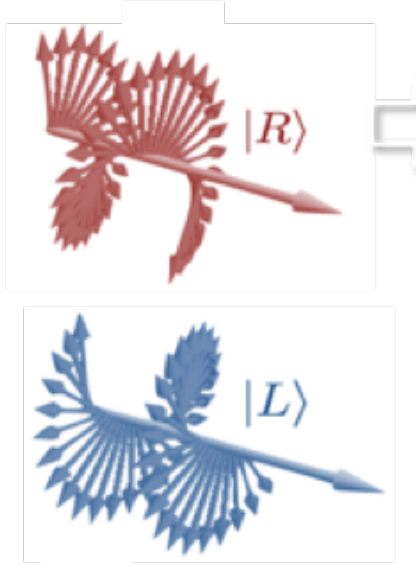
(2) e-beam treatment

Laser Beam

Pockels Cell (+- HV)

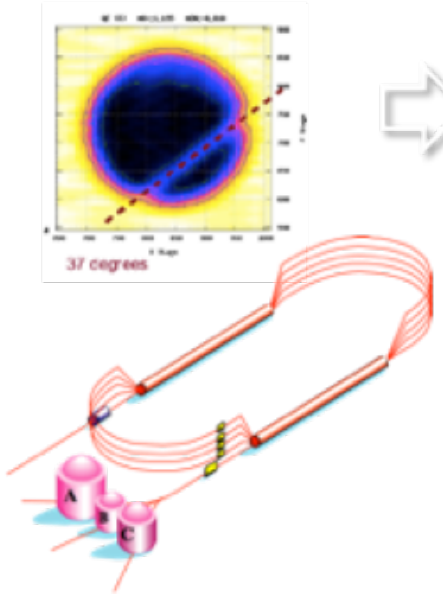


Circularly polarized light

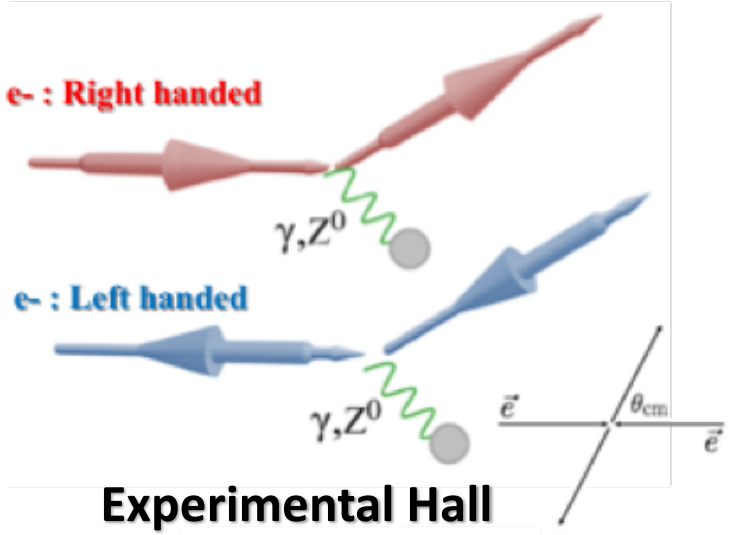


Electron Beam

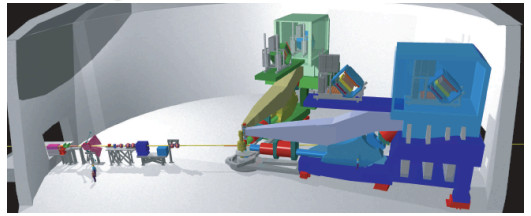
Photocathode (GaAs)



Polarized electrons

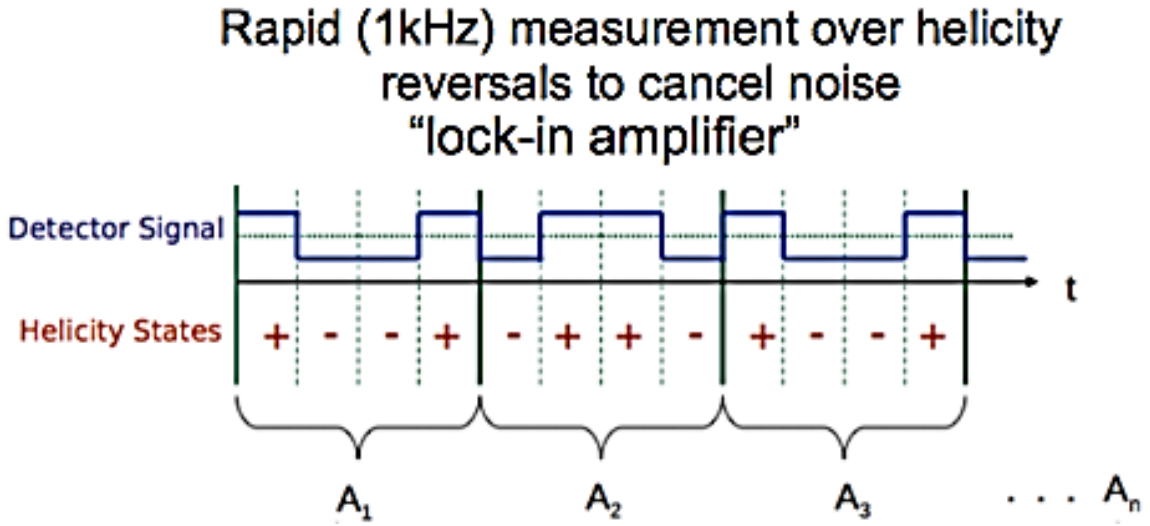


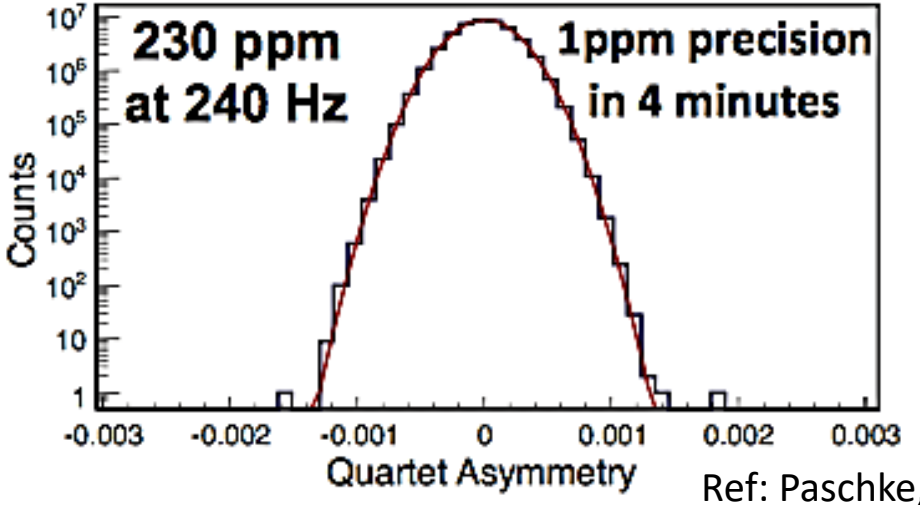
Experimental Hall



Statistical Error Goals & Helicity Flipping

- The electron beam must **switch** back and forth very **quickly** between helicity states so many comparisons can be made

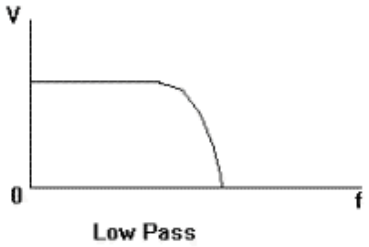




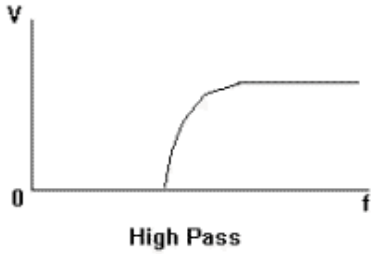
Ref: Paschke, Elba 2016

- Much of the frequency content in the beam is suppressed
- Cutting out slow drifts
- Filter High frequency content(via integration) and low frequency content(via forming pair differences)

Window Integration



Pair Difference

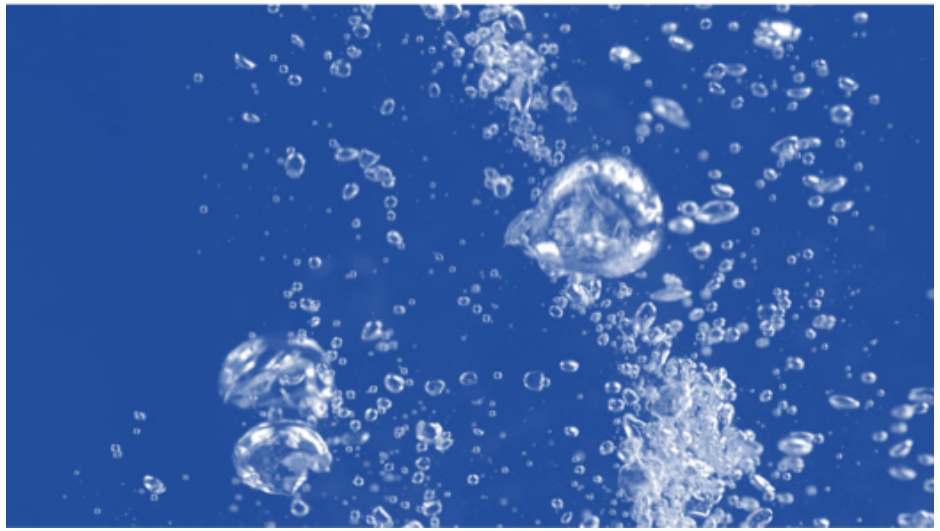


Moller is designed around a flip rate of at least 2 kHz

Target

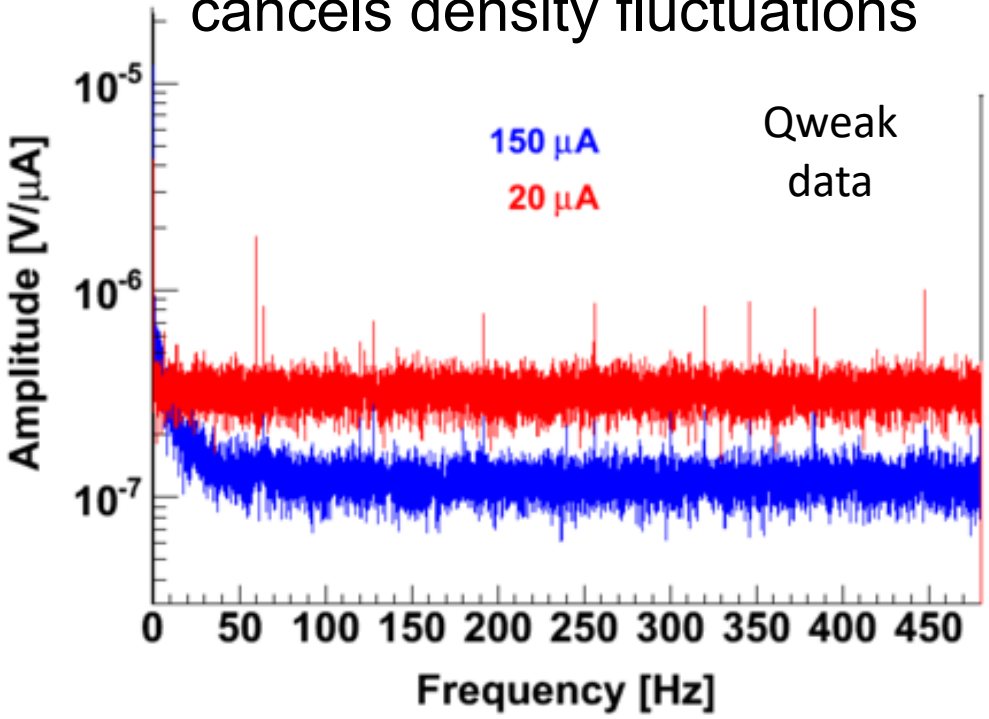
MOLLER goal: up to 85 A on 150 cm LHw - 5 kW power

Target Boiling



Fast helicity flipping = high speed camera

Fast helicity reversal (1 ms) cancels density fluctuations



Lesson from Qweak

Target boiling is a noise source that can't be filtered out using correlations with beam monitors, it must be suppressed by taking data faster than the bubbles form

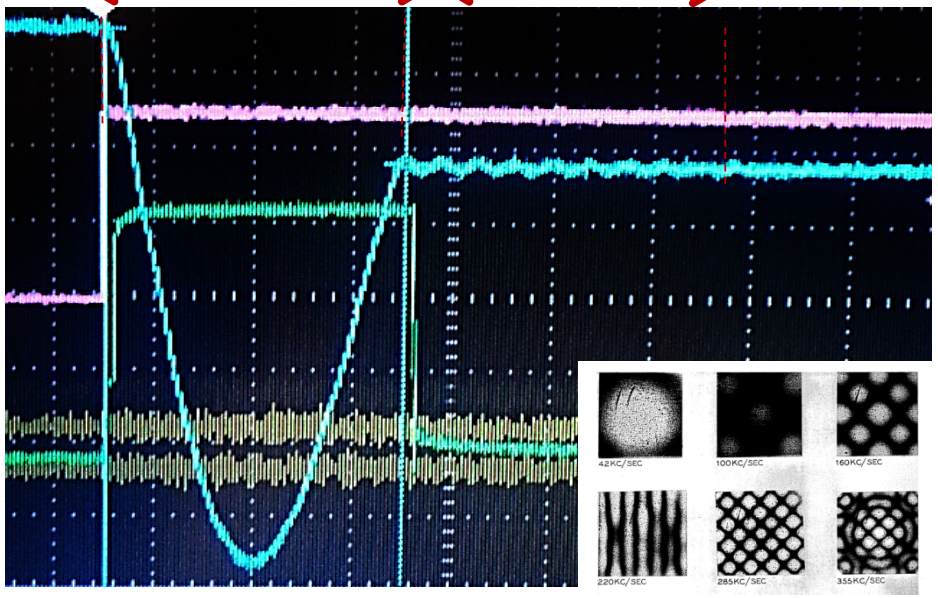
Moller is designed around a flip rate of at least 2 kHz

Switching faster – Use New Crystal

KD*P Cell

(Potassium Dideuterium Phosphate)

transition + ringing ~ 100µs



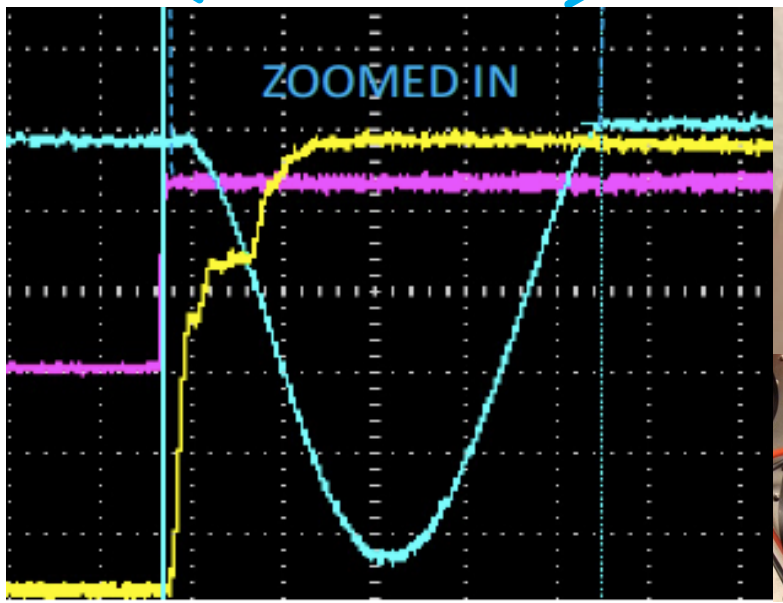
- Suffers from piezoelectric ringing
- At 2kHz helicity switching,

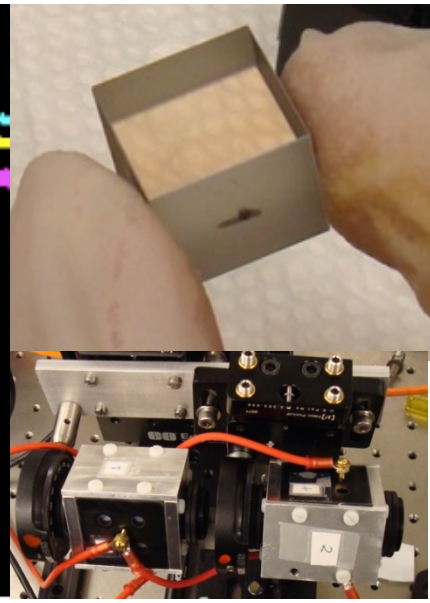
  70-100µs deadtime is <u>20% loss of data</u>

RTP Cell

(Rubidium Titanyle Phosphate)

transition ~ 12µs





- No piezoelectric ringing up to 100kHz
- At 2kHz helicity switching, 12µs transition,
- <u>Deadtime reduced by ~10x</u>

Precision & Systematic Error Goals

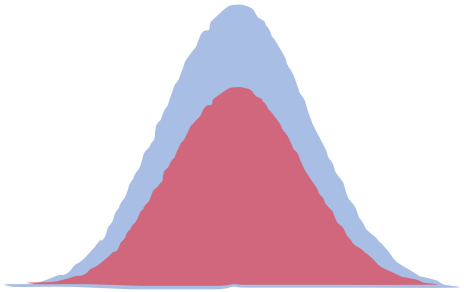
Any change in the polarized beam, correlated to helicity reversal, can be a potential source for a false asymmetry

$$A_{raw} = A_{det} - A_Q + \alpha\Delta_E + \Sigma\beta_i\Delta x_i$$

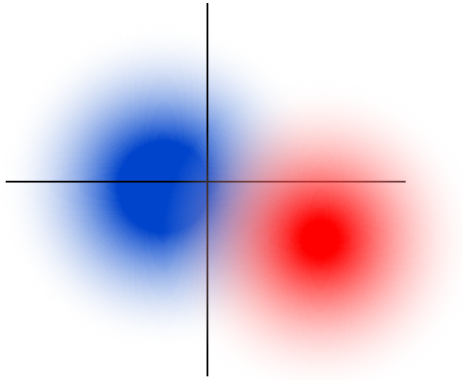
Goal: Helicity-correlated changes in the beam are expected to contribute *~0.14 ppb*

- The beam trajectory must remain unchanged with respect to the sign of the electron beam polarization at the sub-nanometer level (*0.5nm,0.05 nrad* in the experimental Hall)
- Electron beam **position differences** in the injector, before acceleration, must approach ~ *20nm*.
- Helicity-correlated laser **spot-size asymmetries** ~10^{-4}
- **Achieving these goals depends on the laser and Pockels Cell**

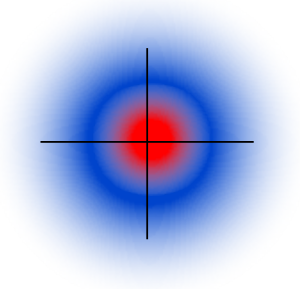
Intensity Asymmetry



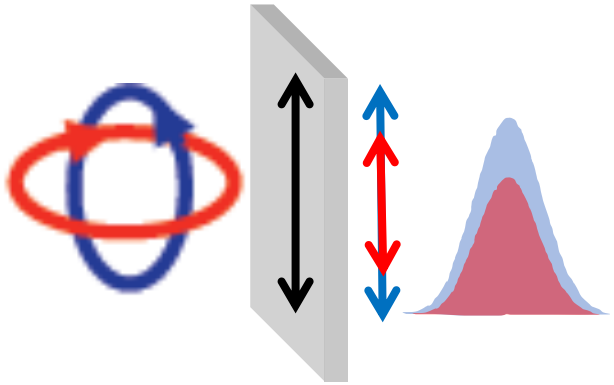
Position Difference



Spot-size *Asymmetry*

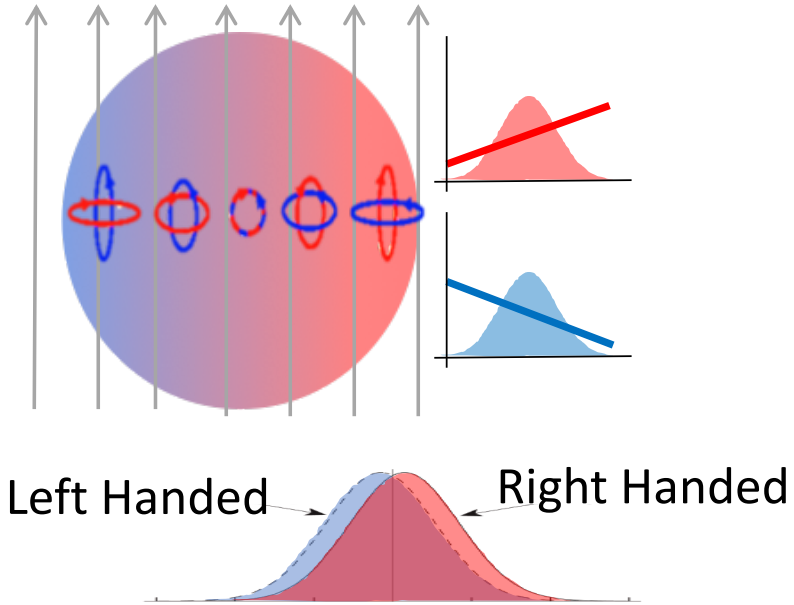


Intensity Asymmetry from Laser Polarization Asymmetry

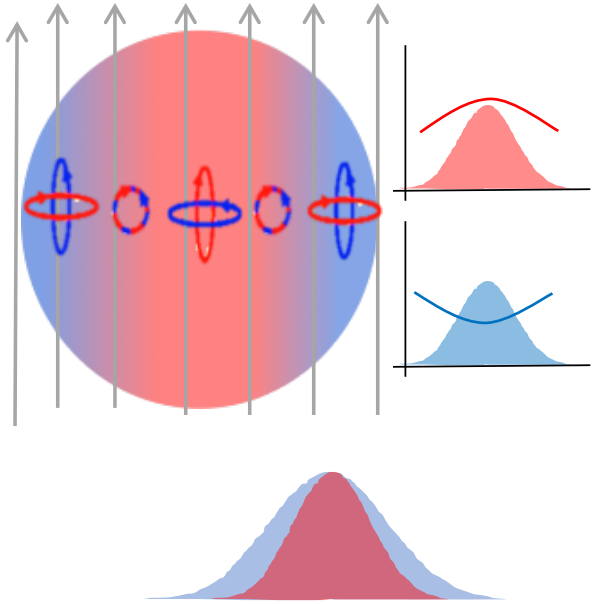


Analyzing element (i.e. photocathode)

Position Difference from 1st moment Polarization Gradient

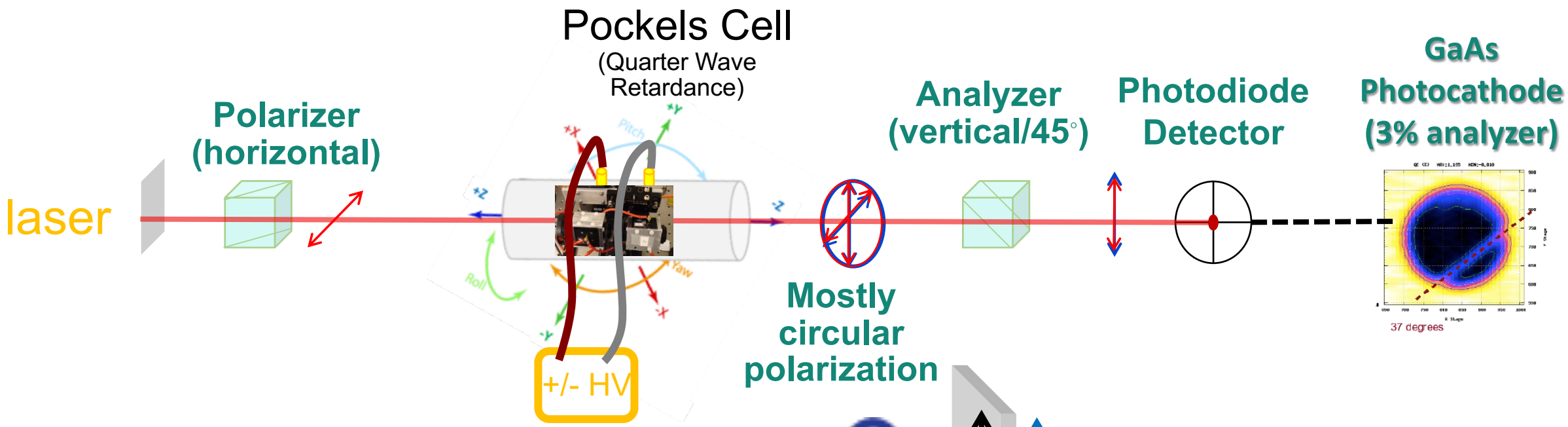


Spot-size Asymmetries from 2nd moment Polarization Gradient

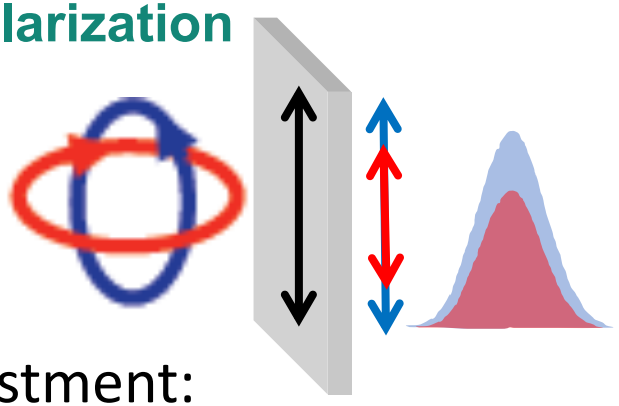


- The electron beam must be very **symmetric** to make this comparison, both helicity state electron beams must have the same intensity and the same direction, position, and spot-size.

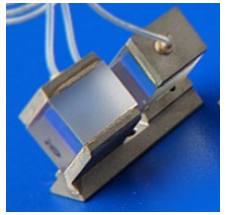
Minimize Intensity Asymmetries



Laser Polarization Asymmetry



Intensity Asymmetry

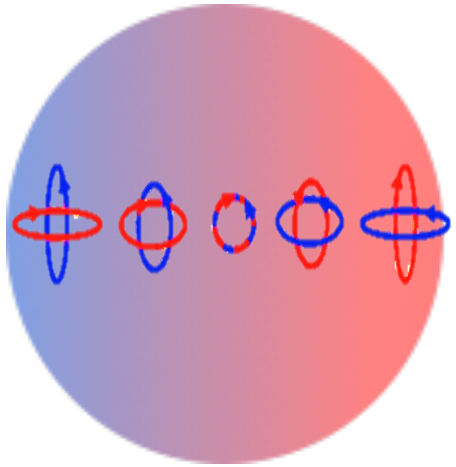


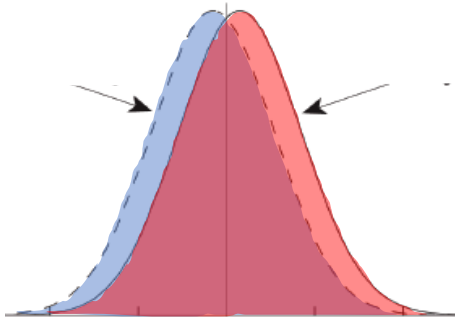
With angle, translation, and voltage adjustment:

- Minimized asymmetric degree of linear polarization – intensity asymmetry
- RTP – used relative roll between crystal pair to minimize asymmetry along 45°

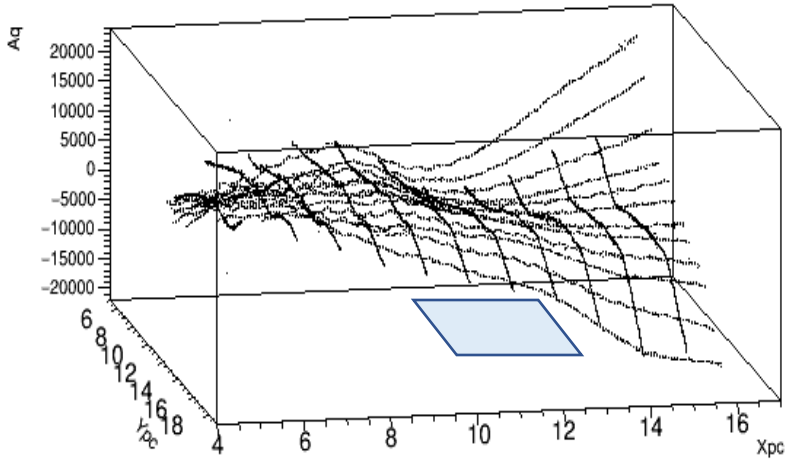
Greater Non-Uniformity than previously

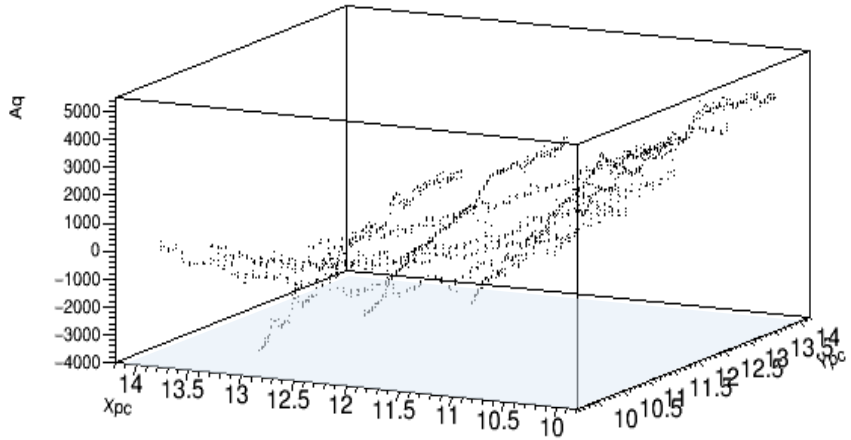
1st moment – Position Differences, Spot-Size Asymmetry





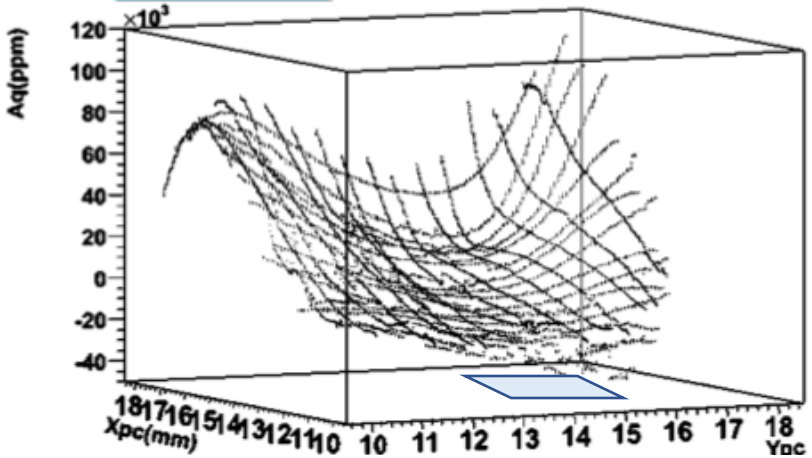
KD*P Cell

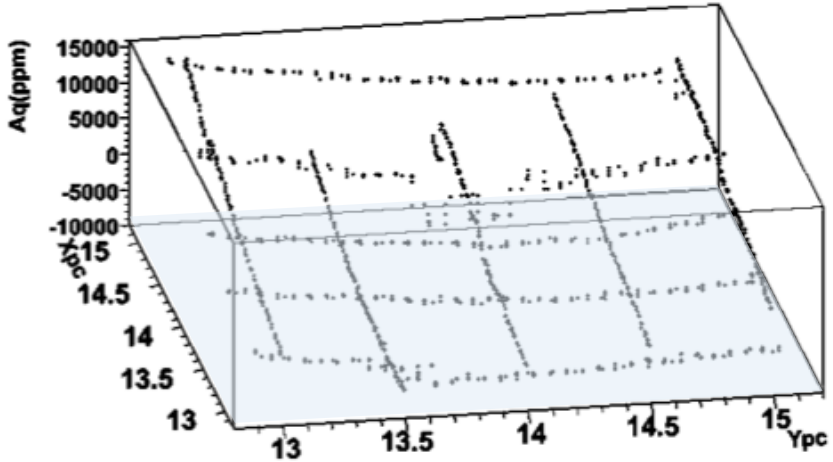




- 5k ppm over 2x2mm2

RTP Cell

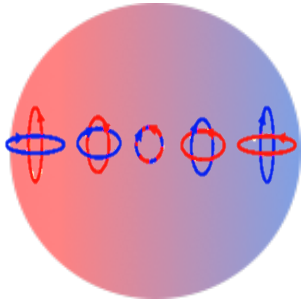




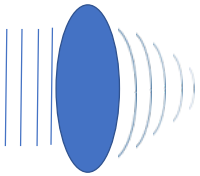
- 25k ppm over 2x2mm2
- 5X larger gradients in translation

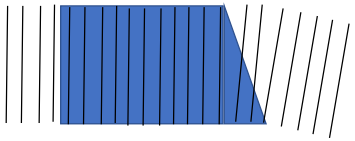
Building Our Own RTP-crystal Cell

Innovation: All crystal suffer from non-uniformity. We counteracted this non-uniformity by **controlling** electric field gradients with grounded side panels.

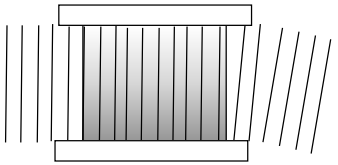


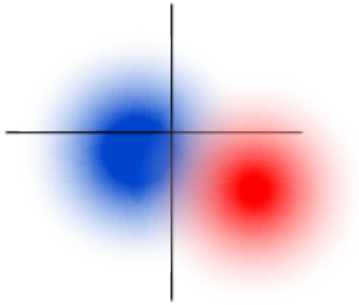
Position differences from asymmetry gradients



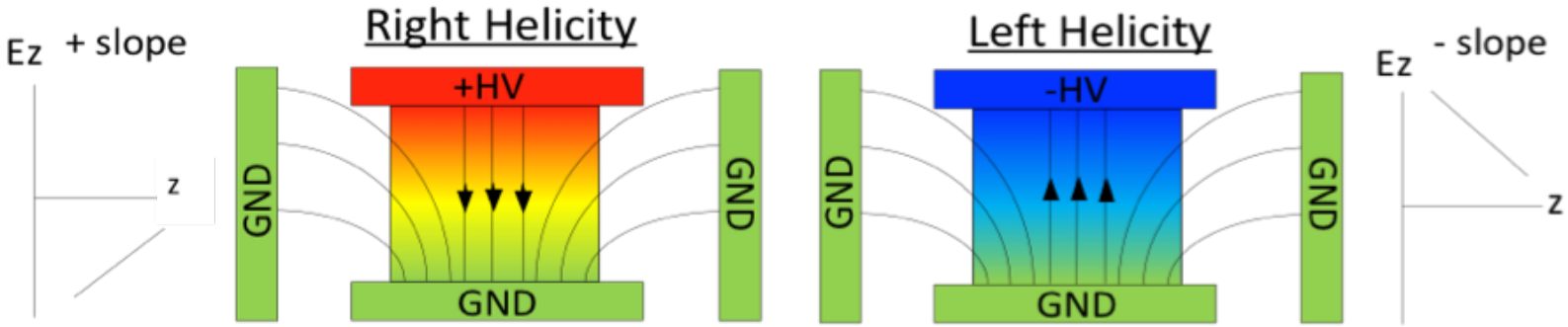


Steering Cancellation



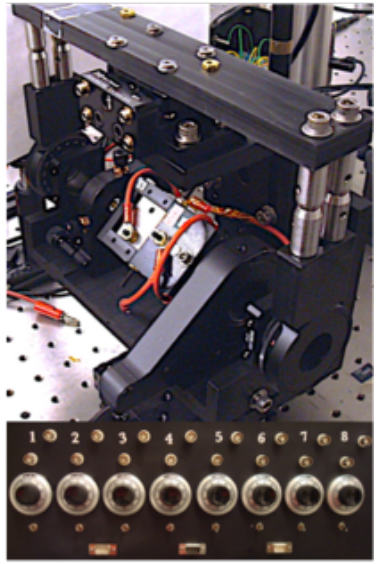


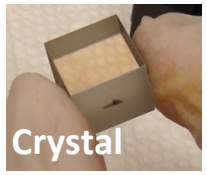
Efield gradient controllable because of transverse cell

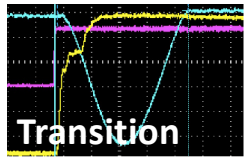


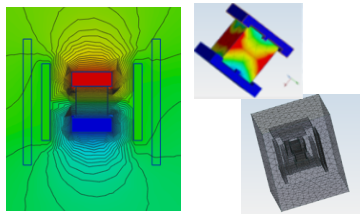
The RTP cell was fully characterized on the laser table

effective throw 2m, ~10nm/V

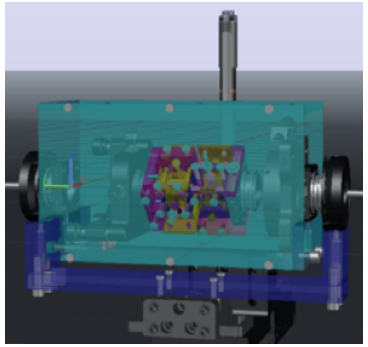




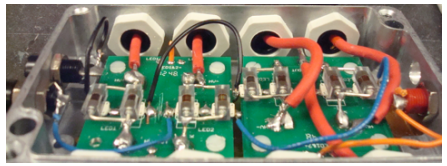


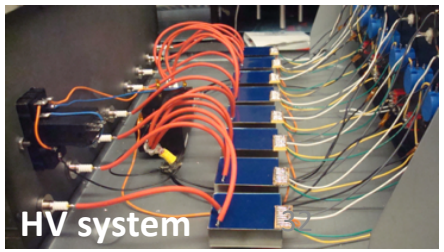


Field Modeling

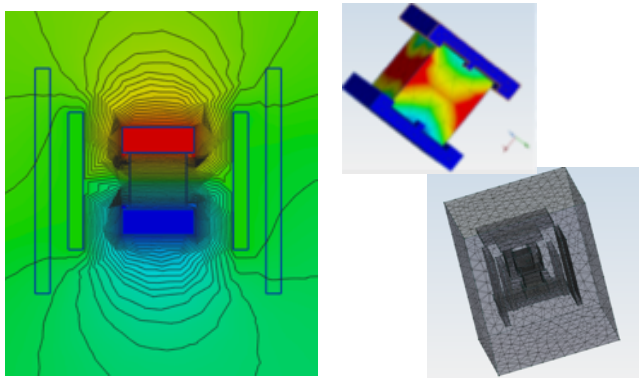


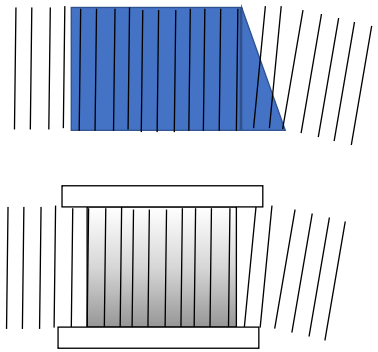
CAD design





Modeling E-field Gradients – Informed Cell Design





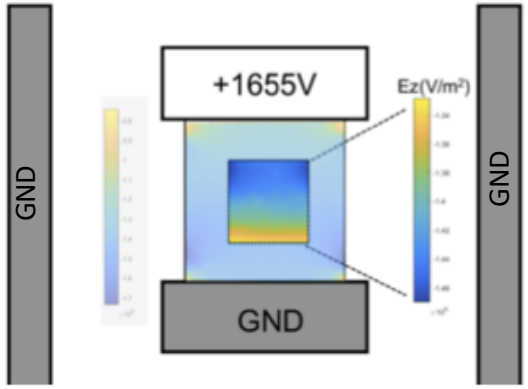
$$\phi_i^{R(L)} = 2\pi n_i^{R(L)} L^{R(L)}/\lambda$$

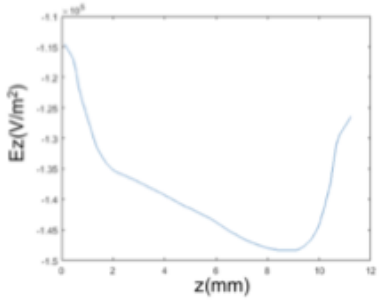
$$\Delta\theta = \theta^R - \theta^L = \theta_{wedge}\Delta n + L\frac{d\Delta n}{dx}$$

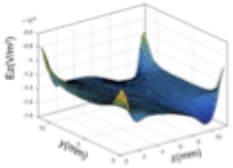
$$n_z^{R(L)} = n_{0,z} - \frac{1}{2}n_{0,z}^3 r_{33} E_z^{R(L)}$$

$$n_y^{R(L)} = n_{0,y} - \frac{1}{2}n_{0,y}^3 r_{23} E_z^{R(L)}$$

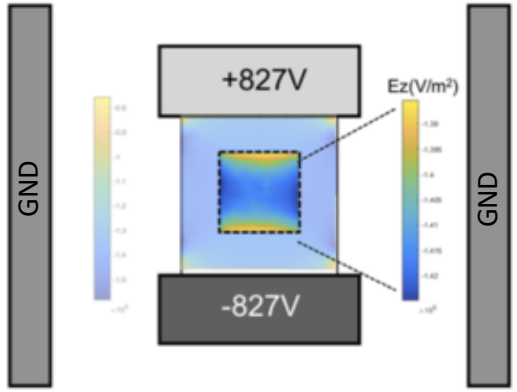
$$\Delta\theta_{z1} = D_{z1}/D = -(n_{y0}^3 r_{23} + n_{z0}^3 r_{33})L\frac{dE_{z1,0}}{dz1}$$

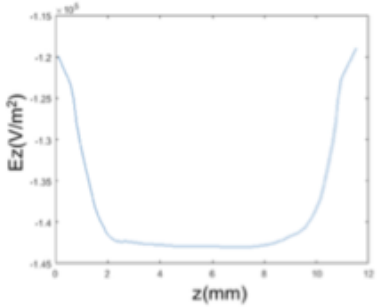




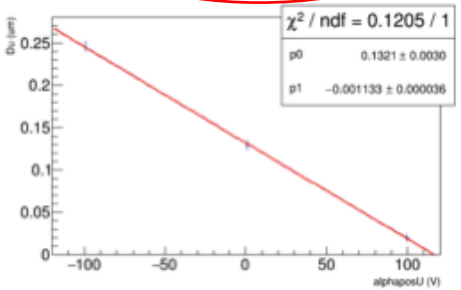


$$\frac{dE_{z1,0}}{dz1} = (3149.4V/m2/V_{\alpha pos})V_{\alpha pos}$$





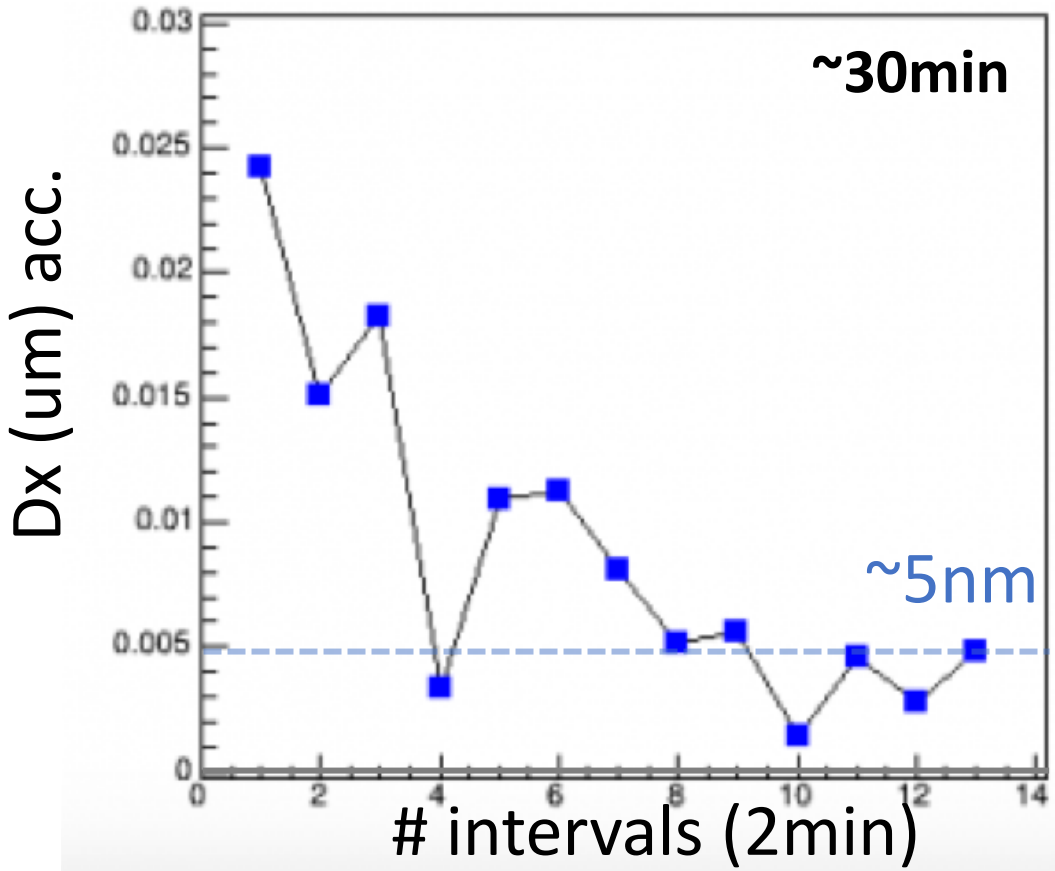
$$\frac{d\Delta\theta_{z1}}{dV_{\alpha pos}} = -(n_{y0}^3 r_{23} + n_{z0}^3 r_{33})L\frac{dE_{z1,0}}{dz1} = -9.4nrad/V$$

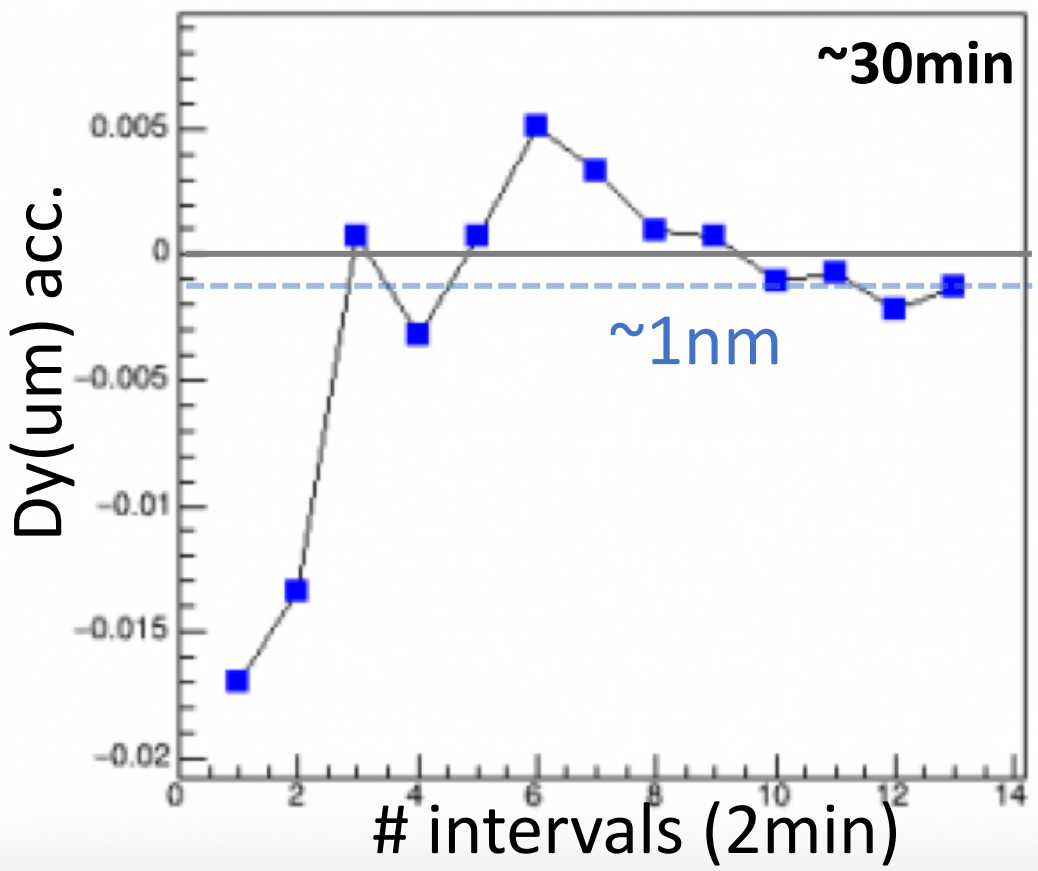


Position Difference Feedback: e-beam

The RTP Pockels Cell installed in polarized electron source at JLab

Using PC voltages, obtained 1-5nm convergence within 30min





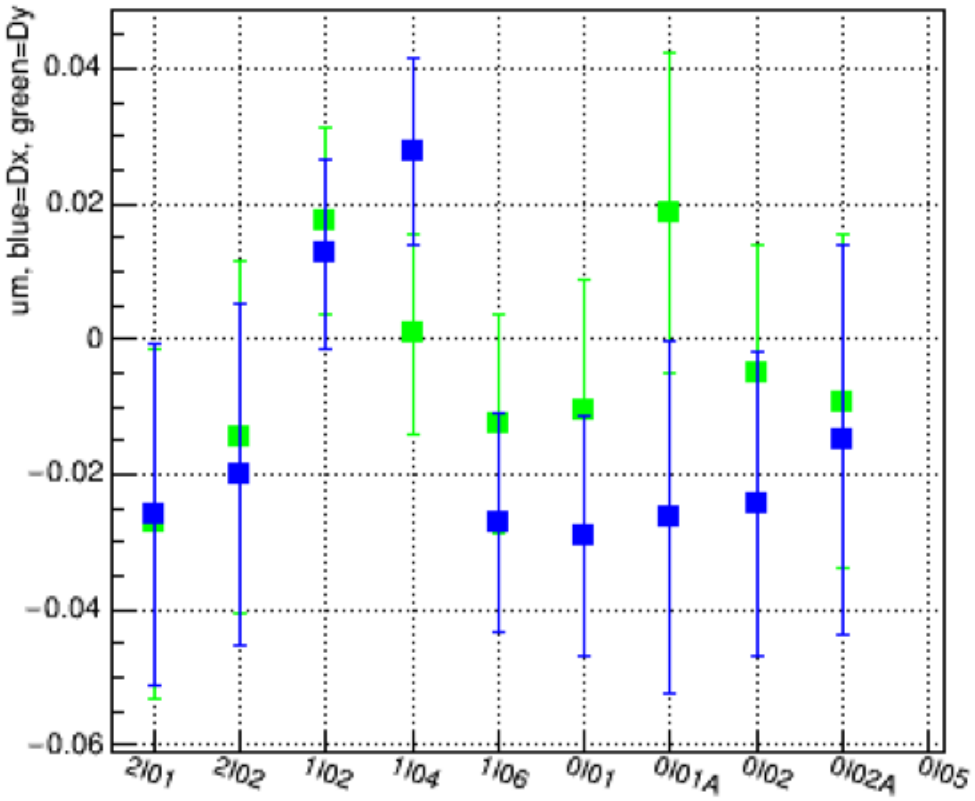
BPM1I04

Run4017_RHWP1000_IHWPout_1I04feedback_Dxconverge

Using the RTP-crystal Cell at JLab

The RTP Pockels Cell successfully produced e- beam which achieved **<30nm** position differences in the e- accelerator at JLab:

Dx,Dy<30nm



Run1141

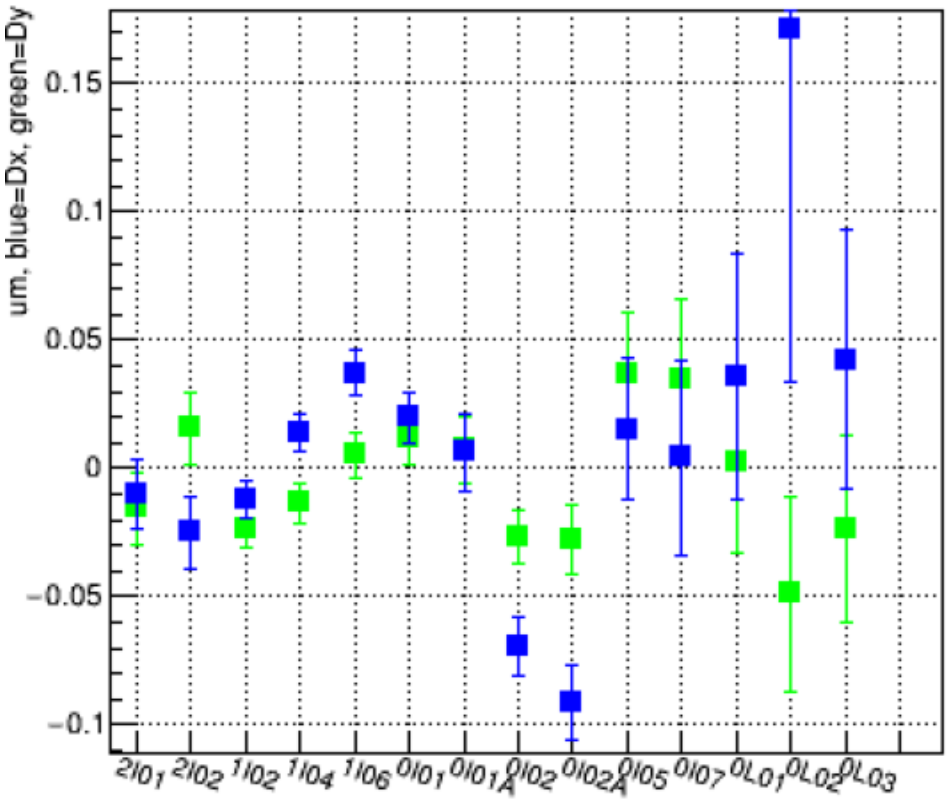
BEST EVER CONTROL IN POSITION DIFFERENCES IN THIS REGION

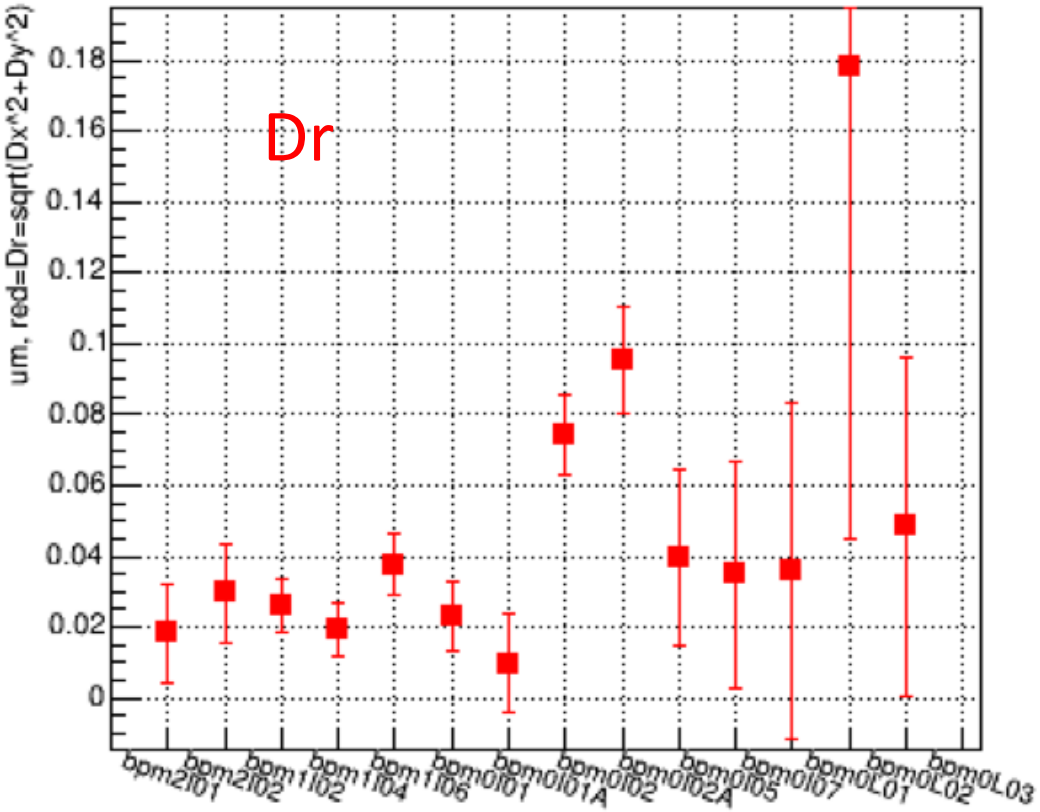
Using the RTP-crystal Cell at JLab

TRANSPORT: POSITION DIFFERENCES IN THE NEXT INJ. REGION

Bigger

Dx ,Dy~ 80nm

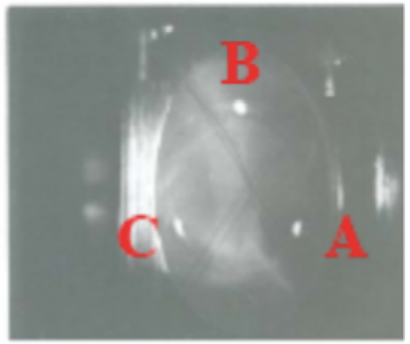


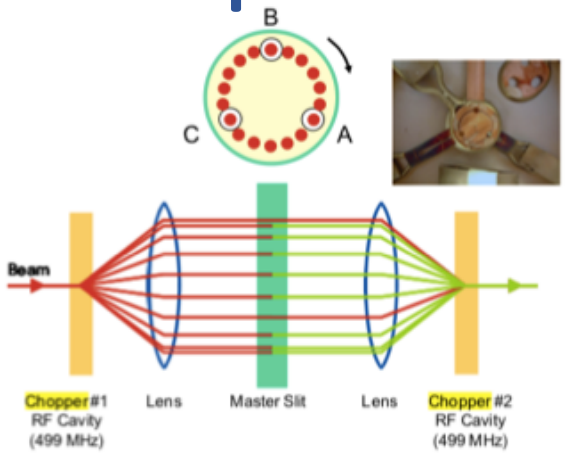


Further downstream, past apertures, prebucher, wein, chopper, position differences can become larger

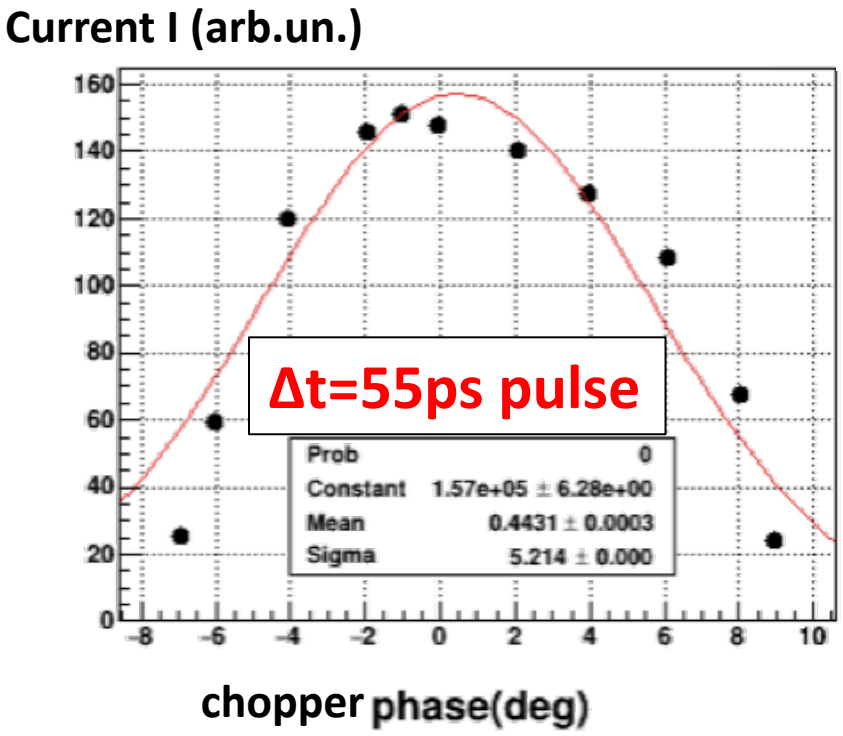
Run1146

Temporal RF Bunch Study

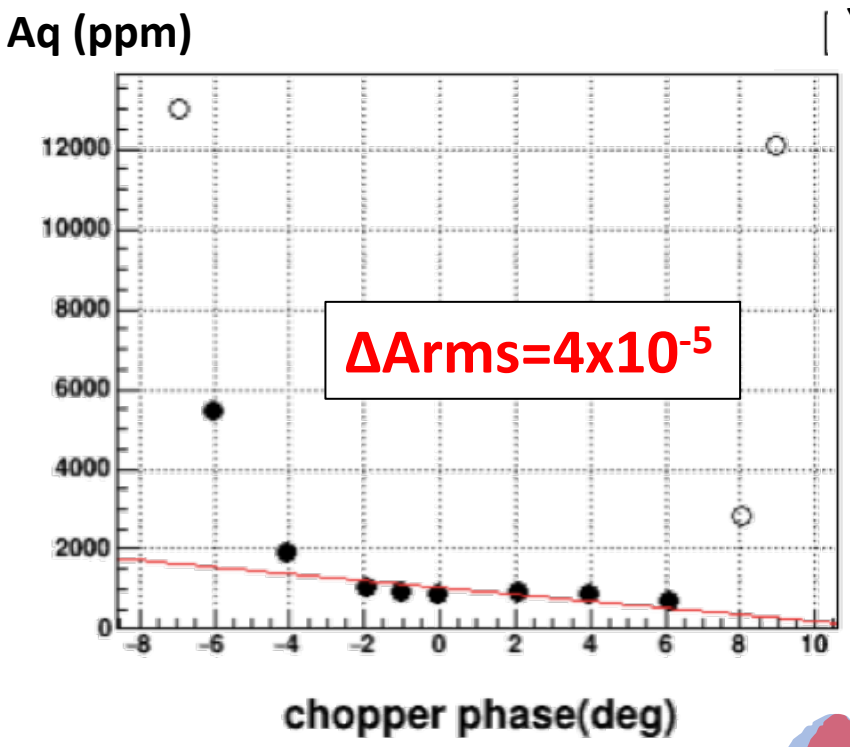


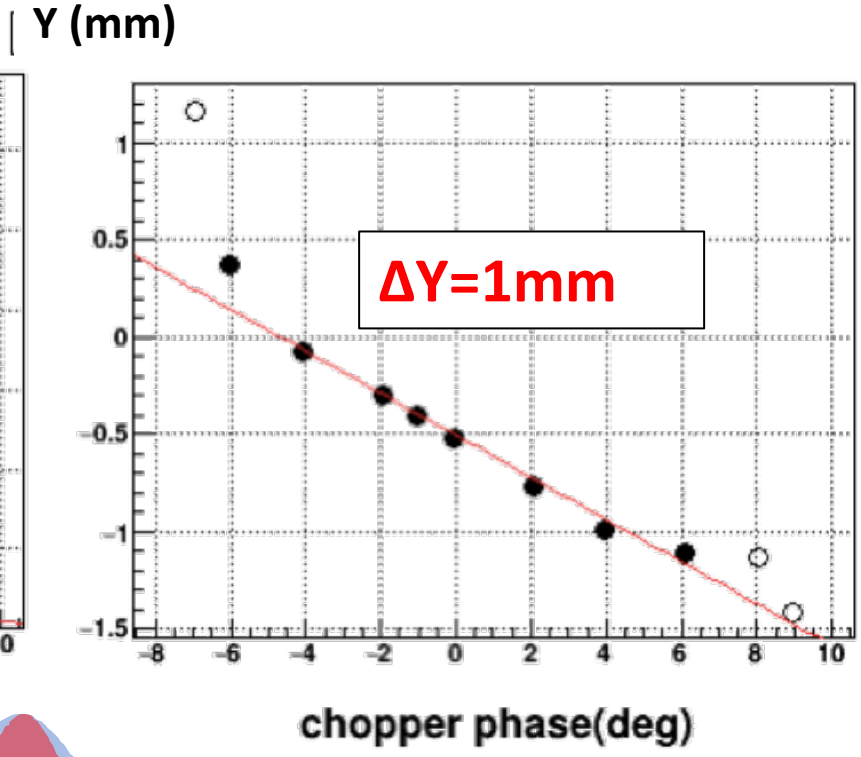


- Chopper: Stretches longitudinal pulse into an arc on circle
- Narrow slit = small time slice of RF bunch
- Scan RF phase and examine Aq as a function of time in 50ps e-bunch



500MHz





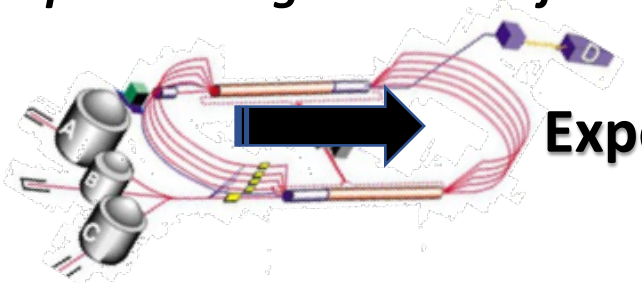
Longitudinal bunch length asymmetry

Run4198_IA503_Aq1513

Transport of Position Differences

Good optical transport throughout the injector and accelerator is crucial

Injector



Experimental Hall

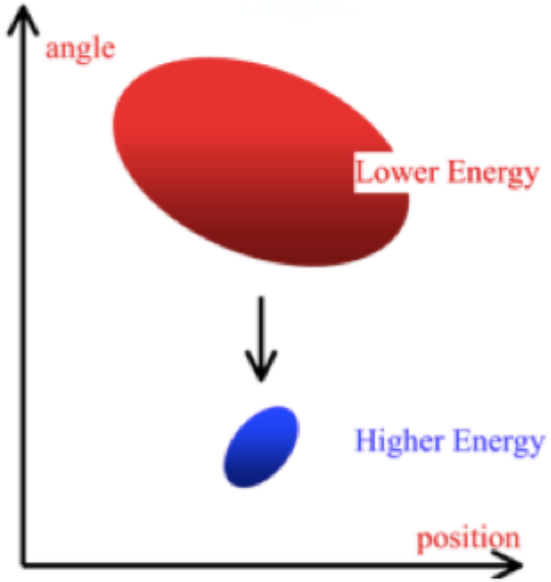
Adiabatic Damping From relativistic boost, transverse d.o.f. matter less

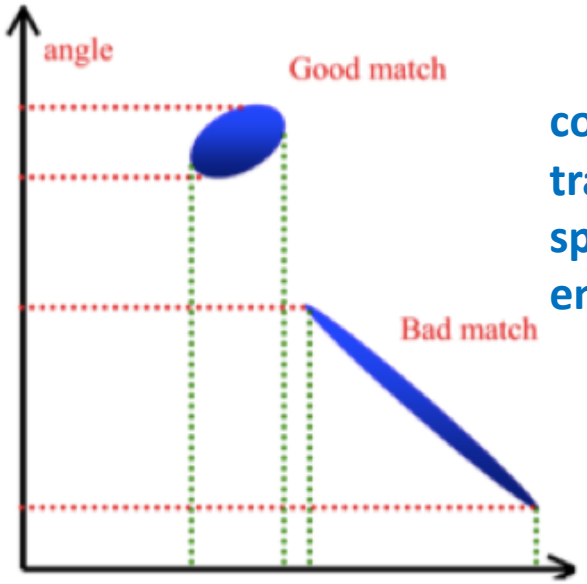
Area of beam distribution in the phase space (emittance) is inversely proportional to momentum.

~1/p , Theoretically up to 200X

i.e.from 100keV->3 GeV

$$\sqrt{\frac{3\,\text{GeV}}{335\,\text{keV}}} \approx 95$$



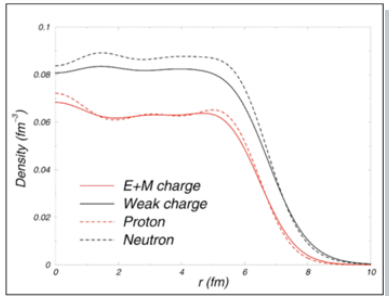


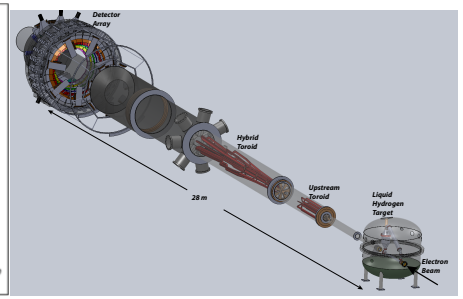
coupling in transverse phase space spreads the emittance out

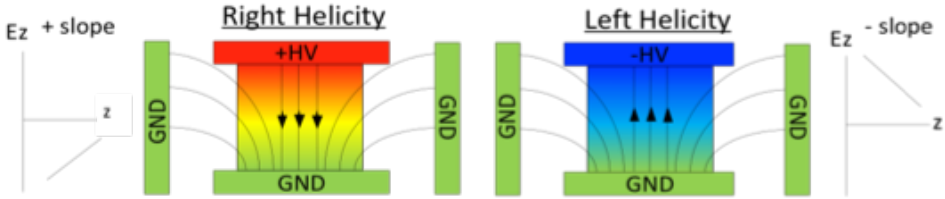
If beam optics deviate from design, significant correlations can develop
Now, more apparent need to think hard about and pay attention to longitudinal coupling

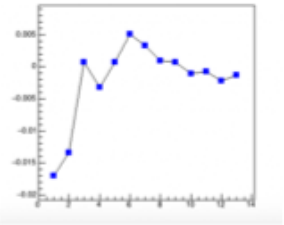
Summary

- Upcoming experiments:
  - PREX/CREX in 2019 will provide a clear, precision measurement of the neutron skin in 208Pb and 48Ca
  - The future MOLLER experiment will search for new BSM physics, providing an unprecedented precision on the electron weak charge and electroweak mixing angle
- New RTP Pockels cell system will provide fast flipping and suitable control of position differences and parity quality beam
- Interesting recent studies of temporal bunch properties show importance of accelerator beam transport in maintaining small HCBA

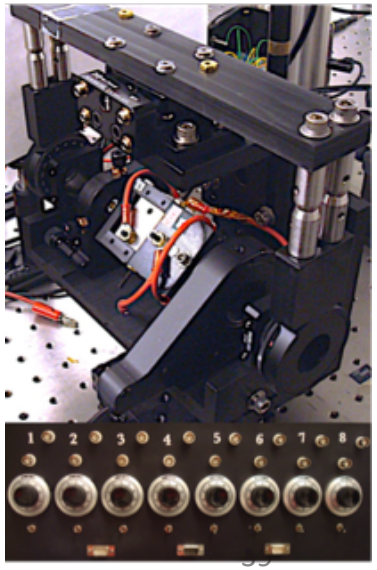








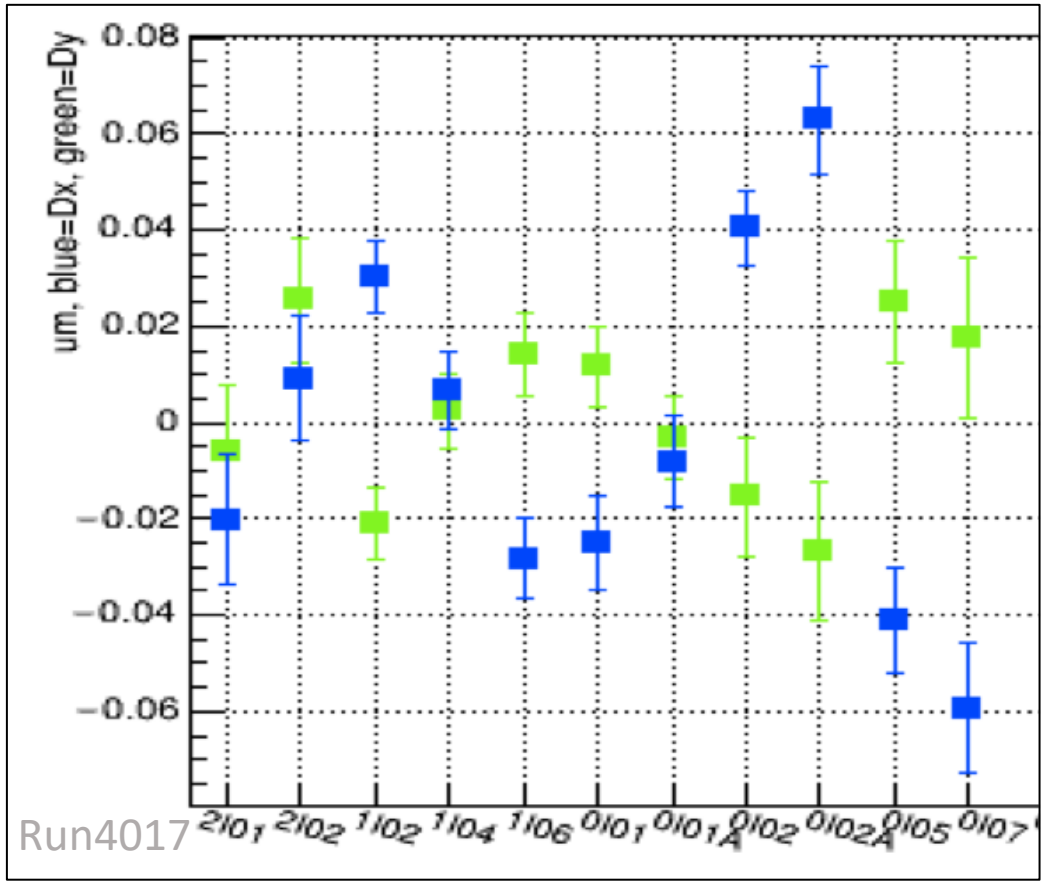
1nm!



EXTRAS

Using the RTP-crystal Cell at Nat'l Accelerator Facility

The RTP Pockels Cell successfully produced e- beam which achieved **<70nm** position differences in the e- accelerator at JLab:



Dx<70nm

Dy <40nm

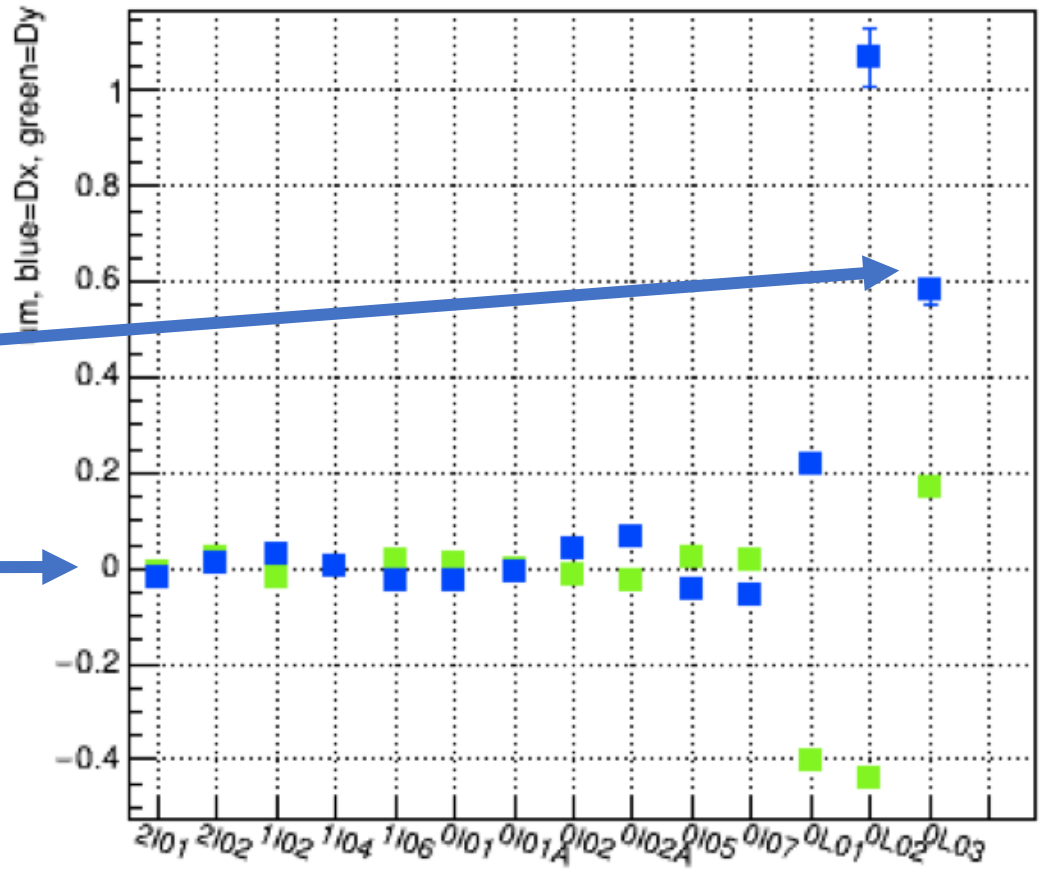
BEST EVER CONTROL IN POSITION DIFFERENCES IN THIS REGION

Using the RTP-crystal Cell at Nat'l Accelerator Facility

THE NOT, BEST EVER CONTROL IN POSITION DIFFERENCES IN THE NEXT REGION

Big
Dx ~ 0.6um
Dy ~0.4um

Tiny<70nm



Further downstream, past prebucher, wein, chopper, position differences became very large

Run4017_IHWPout_RHWP1000_FC2

https://www.youtube.com/watch?v=T44B9j3Vzxw

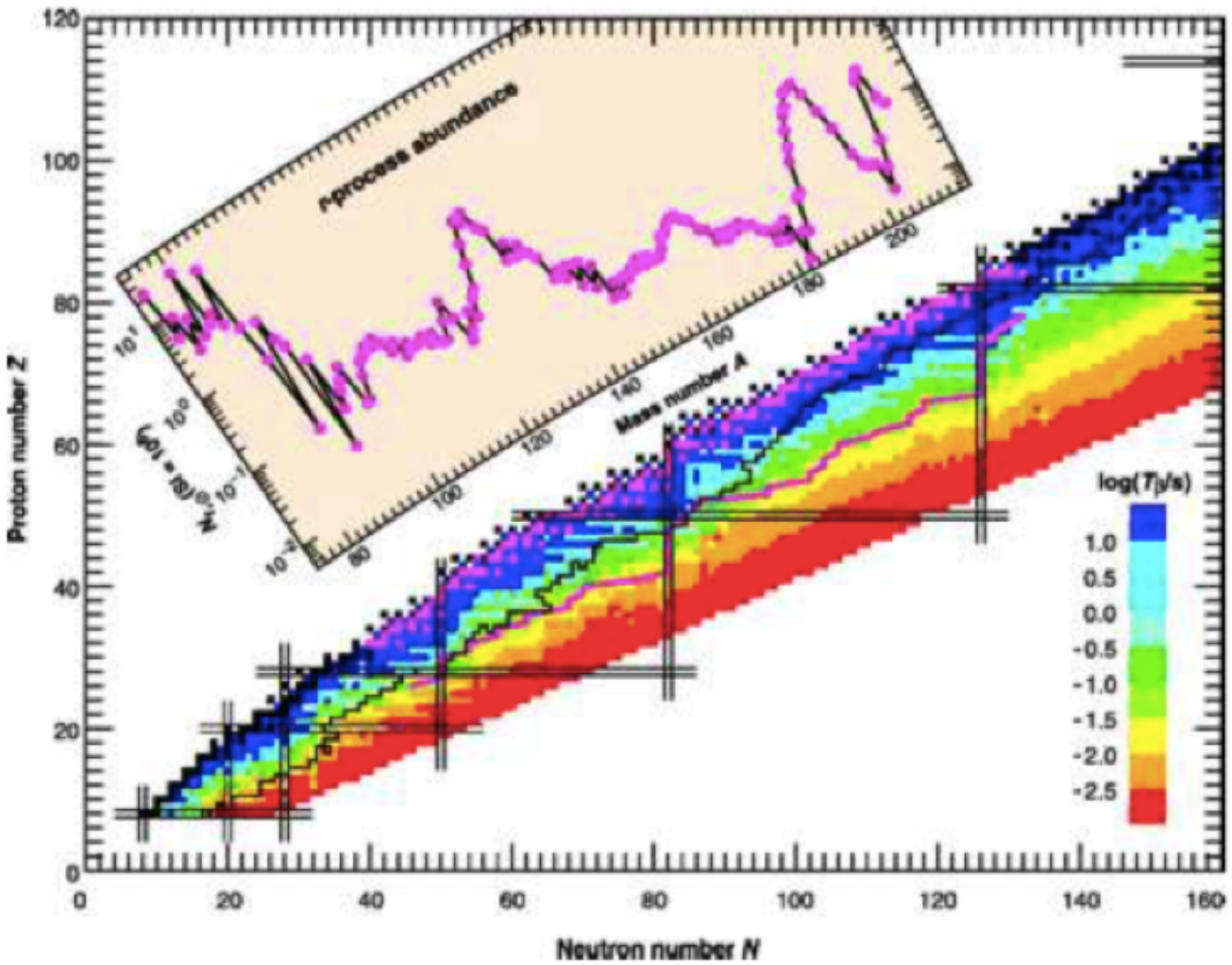
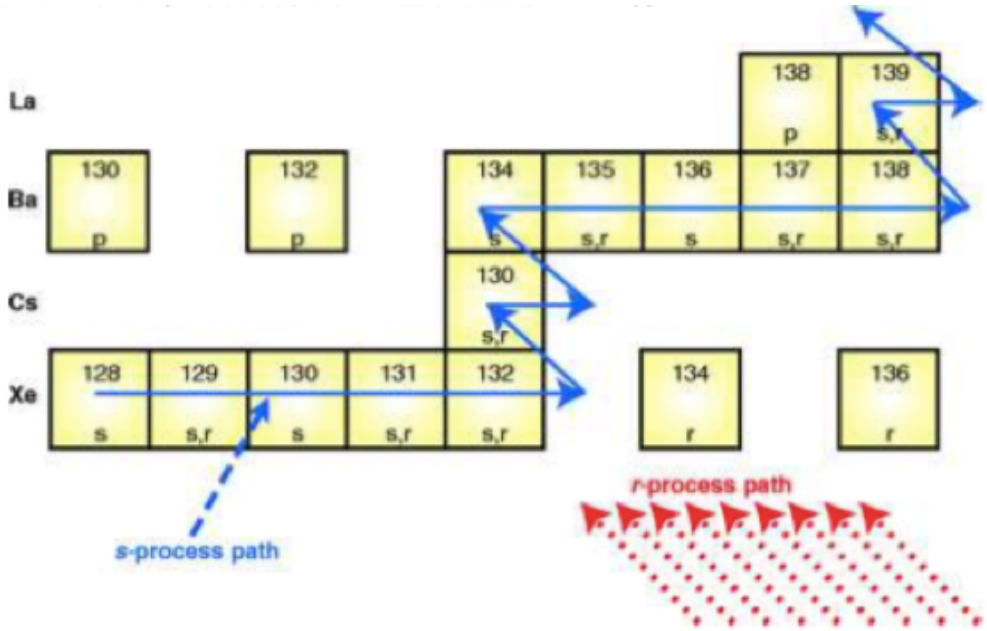


Figure 2: Chart of the nuclides illustrating beta decay timescales (color), stable isotopes (black squares), magic numbers (horizontal and vertical black lines), the limit of known nuclei (diagonal jagged black line), and the r-process path (purple line). Overlaid are the relative abundances of r-process nuclei, to illustrate the relation between magic numbers and abundances.

s-one proceeds to heavier nuclei ,stepping horizontally until an unstable nucleus is reached, then moving on a diagonal path increasing the proton number by 1 and decreasing the neutron number by 1



r- the beta-decay timescale is long compared to the neutron capture timescale. In this case, the capture chain continues at fixed Z until one goes so far from the path of beta stability, and the neutron binding energy becomes so low(practically zero), that further neutron captures are rejected.

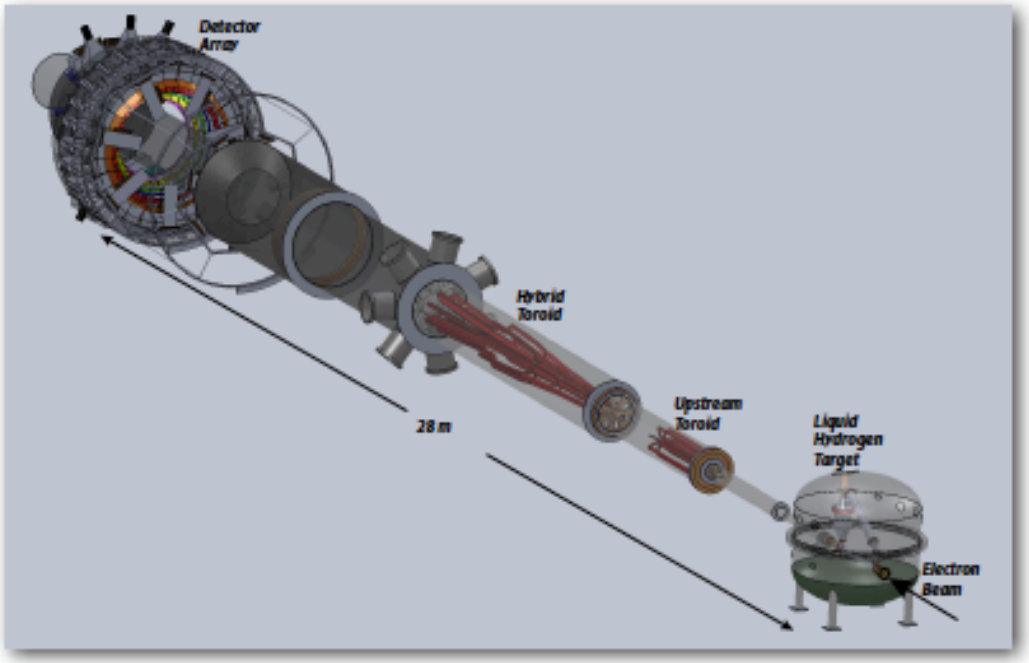
Moller experiment

Broad range of technical challenges

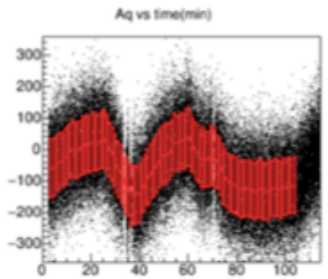
- Full Azimuthal coverage with to ~5° lab angle
  - Magnet construction and engineering
  - collimation
  - backgrounds
  - calibration procedures
- 1.5 m LH_2 target
  - up to 5 kW power
  - Boiling / density fluctuations <25ppm
- Polarized Source
  - Flip at 2 kHz, 10 µs deadtime
  - beam position stable (<1nm) with reversal
  - Improved slow reversal to cancel beam asymmetries
- Robust 0.4% beam polarimetry
  - Compton
  - Iron foil and atomic hydrogen target Møller
- Detector development
  - resolution, rad hard
  - Ancillary (background and tracking)

Collaboration:

~100 scientists, ~ 30 institutions, expertise from Qweak, E158, HAPPEX, PREX, A4, G0

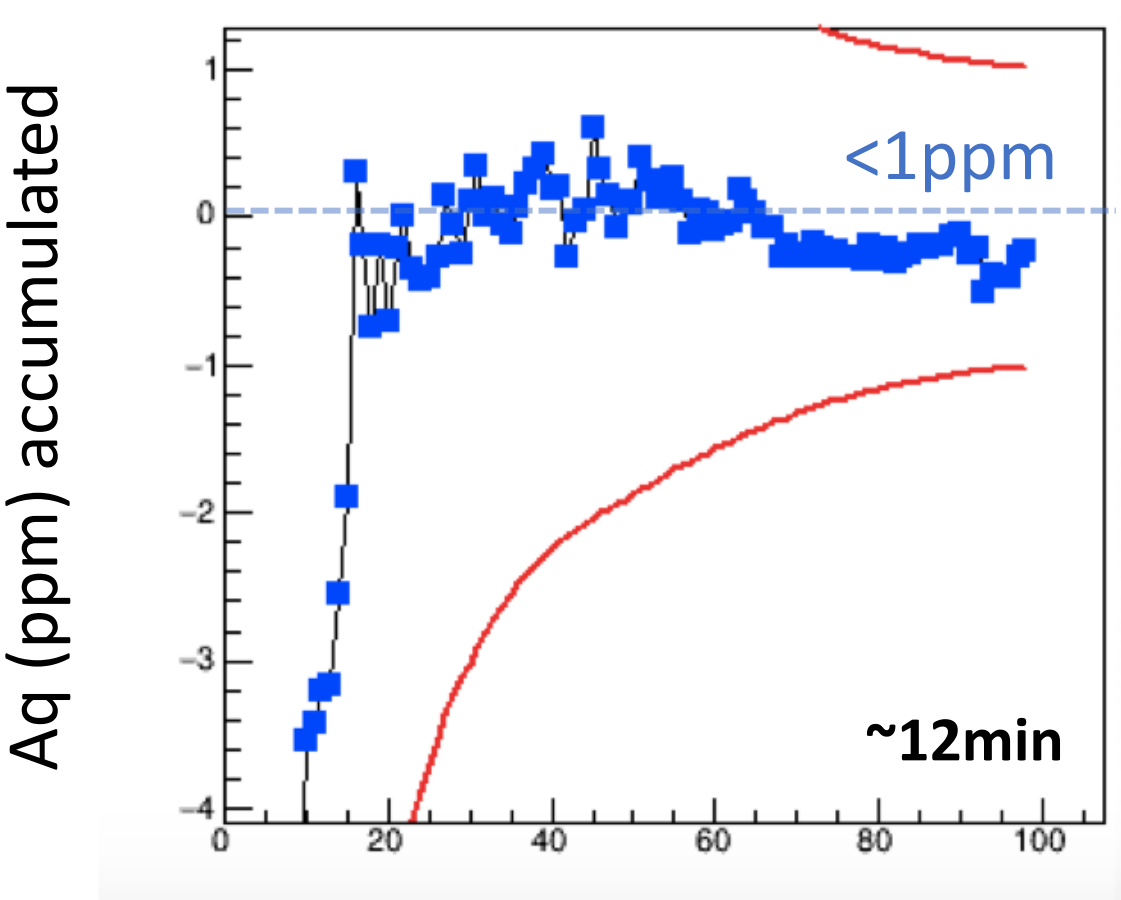


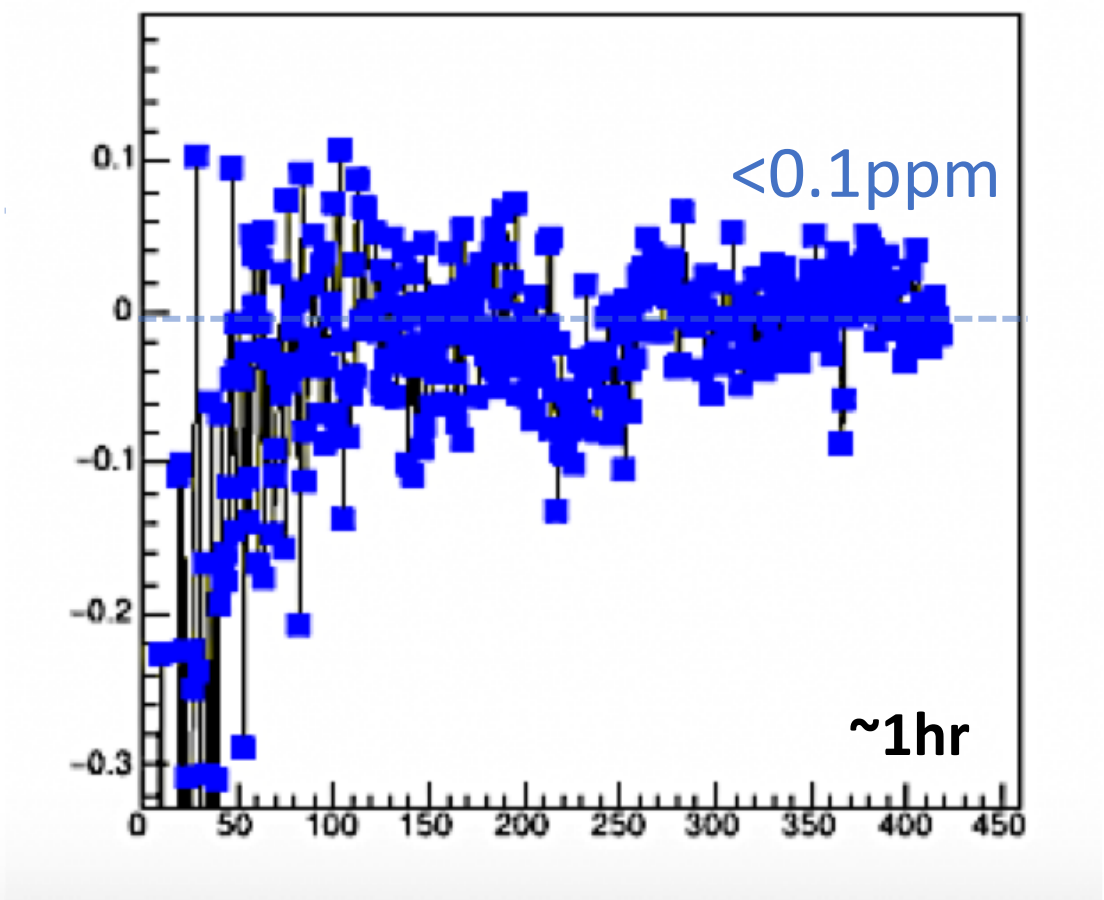
Charge Asymmetry Feedback



Fluctuation of ~50mKelvin T difference between crystal pair

Adjust PC voltages to keep intensity asymmetry minimized





Run4019 Run3972

History of Weak Interaction

Parity violation - signature of the weak force

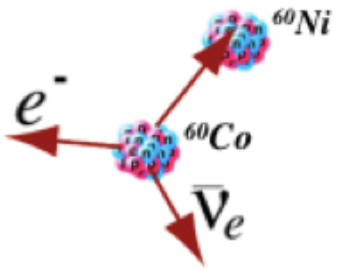
Parity transformation

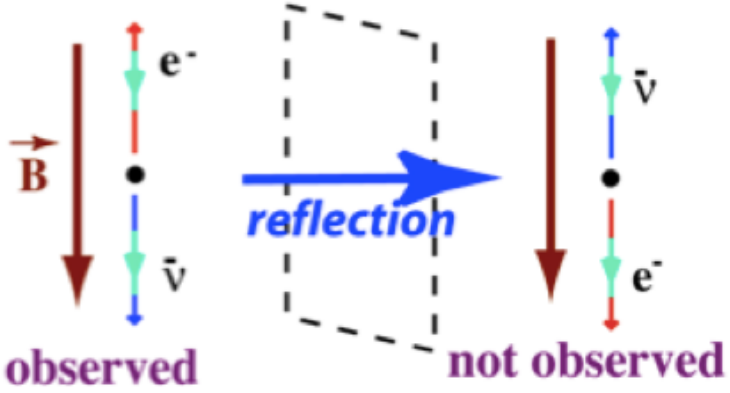
$$x, y, z \rightarrow -x, -y, -z$$

$$\vec{p} \rightarrow -\vec{p}, \quad \vec{L} \rightarrow \vec{L}, \quad \vec{S} \rightarrow \vec{S}$$

Mirror: reverses momentum, not ang. mom.

Weak decay of ^{60}Co Nucleus





1956- C.S. Wu carried out famous Co-60 experiment – test parity

- nuclei aligned, beta decay, recorded the direction of the emitted electrons.
- Observed: e- came out ***asymmetrically*** in the direction of the nuclear spin

PREX/CREX Collaborations

PREX

Kent Paschke *	UVa
Krishna Kumar	Stony Brook University
Robert Michaels	Jefferson Lab
Paul Souder	Syracuse University
Guido Urcioli	INFN Rome

* contact persons

CREX

Seamus Riordan*	Argonne Nat'l Lab
Robert Michaels	Jefferson Lab
Kent Paschke	UVa
Paul Souder	Syracuse Univeristy
Dustin McNulty	Idaho State University
Juliette Mammei	Manitoba University
Silviu Covrig	Jefferson Lab

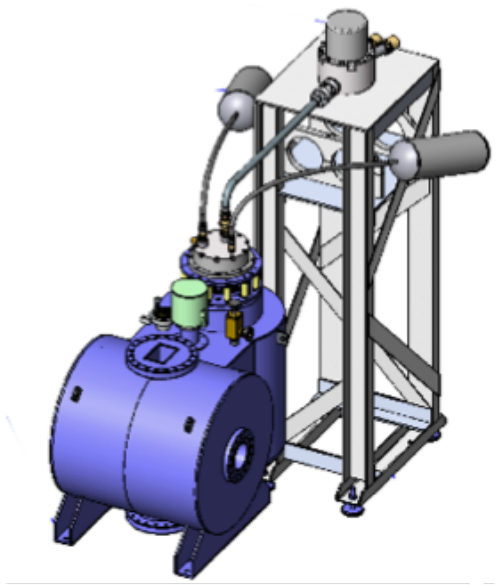
* contact persons

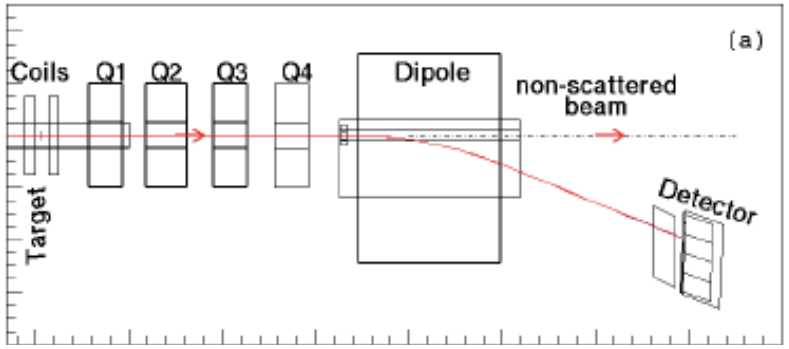
Polarimetry: Moller and Compton

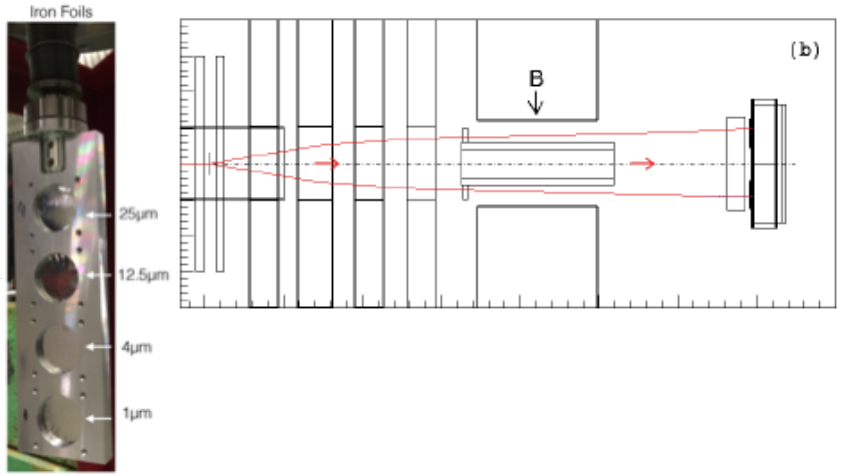
~0.5-1% precision on ~90% polarization

Moller

Moller: *ee* scattering off polarized iron foil
- 4T field, saturated iron
- experience with ~1% precision in Hall C
- modified spectrometer for 1 GeV
- invasive, low current only



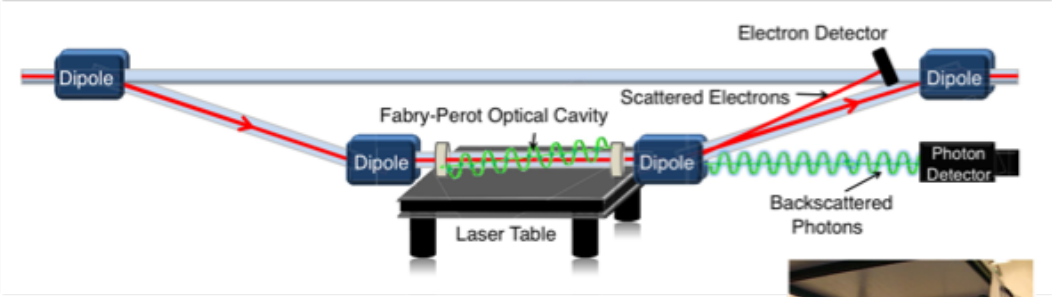


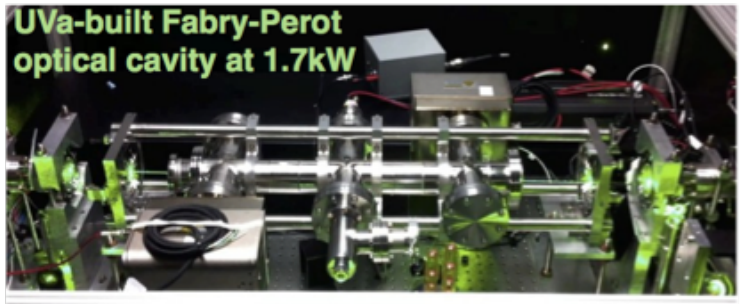


Four targets, in frame designed for rotation and Kerr monitoring

Compton

Compton: eγ scattering with polarized green laser light
- new polarimeter
- low Ebeam: low analyzing power, low scattering energies
- diamond microstrip detector
- per mille control of laser polarization inside cavity





- successful for PREX-I

Monitors:

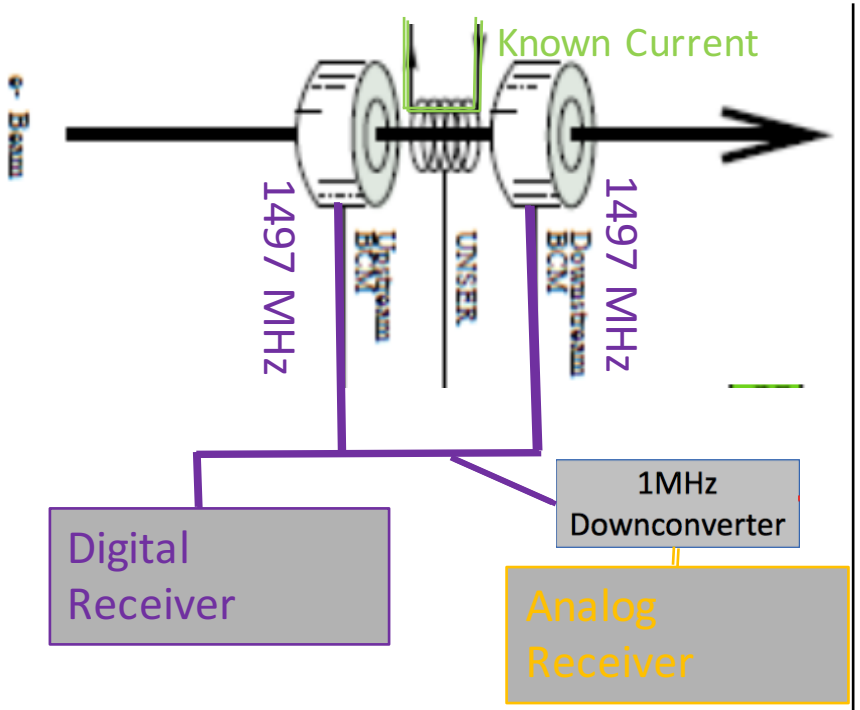
Once you have good beam, you still have to measure it

Beam Current Monitors (BCMs)

- Simgadsta< sigma Aq (Expect to have noise in beam intensity greater than monitor width)
- Stat. prec. -> fist remove beam noise

$$A_{raw} = A_{det} - A_Q + \alpha\Delta_E + \Sigma\beta_i\Delta x_i$$

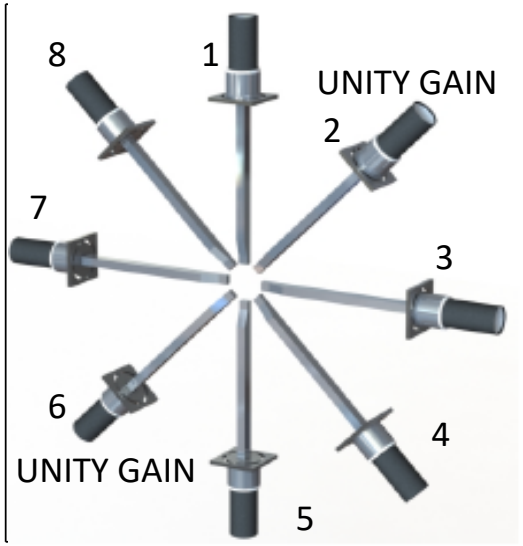
- Precision of corrected limited by beam curremtn monitor resolution
- In studying monitor noise (separate from beam noise), use high rate quartz detector to verify bcm inferred measurement noise

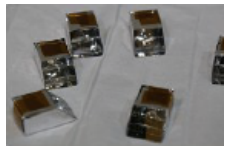


The two stainless steel pill-box cavities, tuned and critically coupled (Q~1500) to the 1497 MHz component of the beam

Small Angle Monitors (SAMs)

ISU



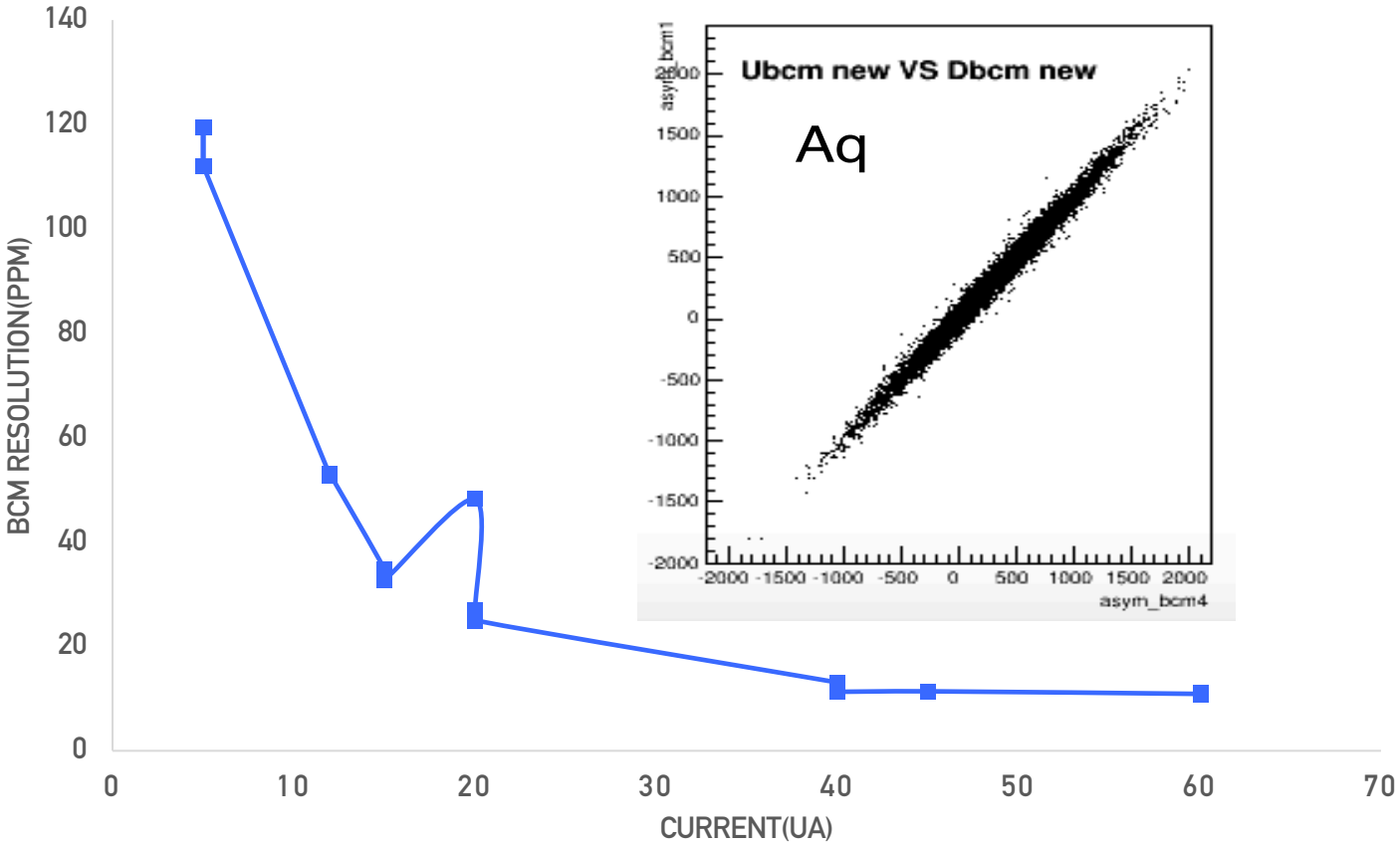


- 8 quartz detectors with light guides placed around beam line downstream of pivot
- Symmetric design helps disentangle beam position and angle HCBP's
- For large dynamic range, mix 'n matched

BCM resolution: from Double-Differences

$$\sigma_{bcm} \sim \sigma_{(Aubcm-Adbcm)}/\sqrt{2}$$

Resolution can be assessed from double difference widths of upstream and downstream BCMs



We need to know our bcm resolution

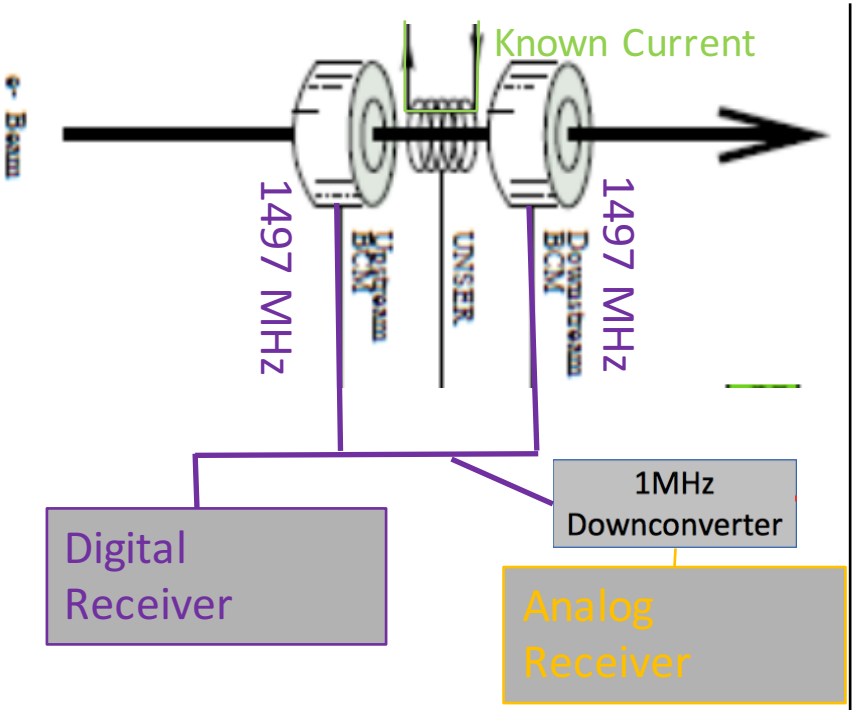
- Can compare 2 BCMS, take "Double Differences"
- But there's coherent electronics noise, Noise which is correlated between monitors, can give artificially narrow results
- So we use an independent monitor…to prove resolution using high rate detectors to verify BCM DD

Monitors:

Once you have good beam, you still have to measure it

Beam Current Monitors (BCMs)

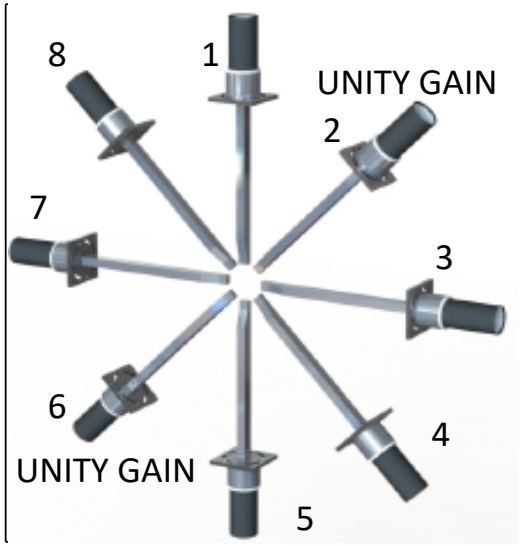
$$A_{raw} = A_{det} - A_Q + \alpha\Delta_E + \Sigma\beta_i\Delta x_i$$

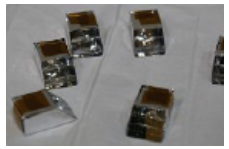


The two stainless steel pill-box cavities, tuned and critically coupled (Q~1500) to the 1497 MHz component of the beam

Small Angle Monitors (SAMs)

ISU





- 8 quartz detectors with light guides placed around beam line downstream of pivot
- Symmetric design helps disentangle beam position and angle HCBP's
- For large dynamic range, mix 'n matched

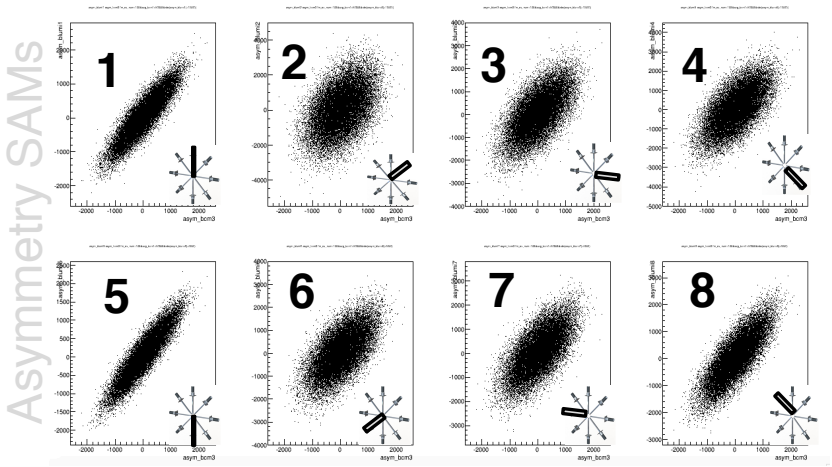
What's the resolution of the Analog BCMs?

Double check with the SAMs.

Independent confirmation of BCM resolution

NORMALIZE SAMS TO A BCM

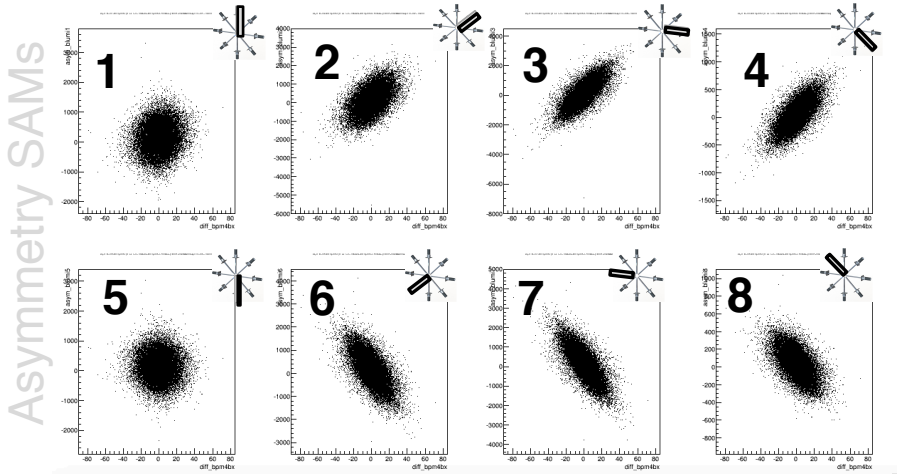
TO ELIMINATE BEAM CURRENT NOISE, include BCM electronics NOISE



$$S_{1n} = SAM_1 - S_{bcm}$$

TAKE SUM OF SAME PAIRS

TO ELIMINATE BPM CORRELATED NOISE

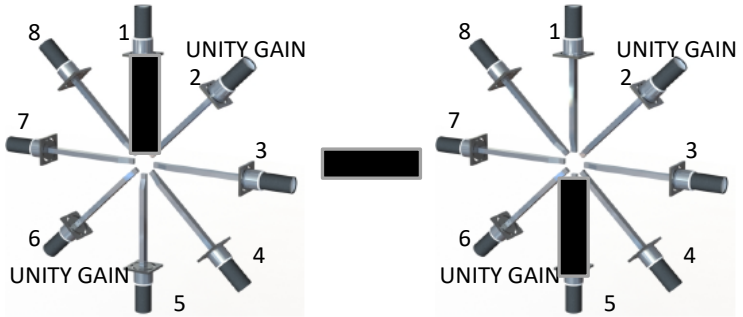


$$S_+ = SAM_1 + SAM_5 - 2S_{bcm}$$

$$\sigma_+^2 = \sigma_1^2 + \sigma_5^2 + 4\sigma_{bcm}^2$$

TAKE PAIR DIFFERENCES

TO ELIMINATE COMMON MODE NOISE(i.e BEAM CURRENT)



(REGRESS WRT BPM)

$$S_- = SAM_1 - SAM_5$$

$$\sigma_-^2 = \sigma_1^2 + \sigma_5^2$$

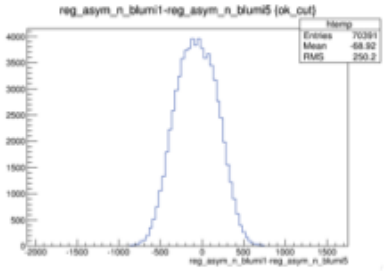
Asymmetry Width: w/ beam current noise vs w/o beam current noise (w/o beam position/angle noise)

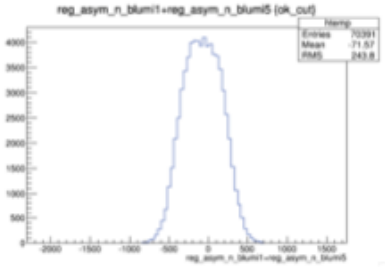
What's the resolution of the Analog BCMs?

Double check with the SAMs.

Independent confirmation of BCM resolution

$$S_+ = SAM_1 + SAM_5 - 2S_{bcm}$$
$$S_- = SAM_1 - SAM_5$$
$$\sigma_+^2 = \sigma_1^2 + \sigma_5^2 + 4\sigma_{bcm}^2$$
$$\sigma_-^2 = \sigma_1^2 + \sigma_5^2$$
$$\sigma_{bcm}^2 = (\sigma_+^2 - \sigma_-^2)/4$$
$$\sigma_{bcm} \sim (\sigma_{ubcm} - \sigma_{dbcm})/\sqrt{2}$$





Run 2503 – Al dummy 8.8GeV 45uA 30Hz, regress with all bpms

	RMS ppm
DOUBLE DIFFERENCE $\sigma_{bcm} \sim \sigma_{(Aubcm-Adcbm)}/\sqrt{2}$	13.1
PAIR SUM $\sigma_+^2 = \sqrt{\sigma_1^2 + \sigma_5^2 + 4\sigma_{bcm}^2}$	98.61
PAIR DIFFERENCE $\sigma_-^2 = \sqrt{\sigma_1^2 + \sigma_5^2}$	95.37
INDEP. RES. $\sigma_{bcm} = \sqrt{(\sigma_+^2 - \sigma_-^2)/4}$	12.5

Summary: So the precision is plenty good for PREX, but we need to test these up the reversal frequency (short integration time) that MOLLER will use.

Parity Quality Beam

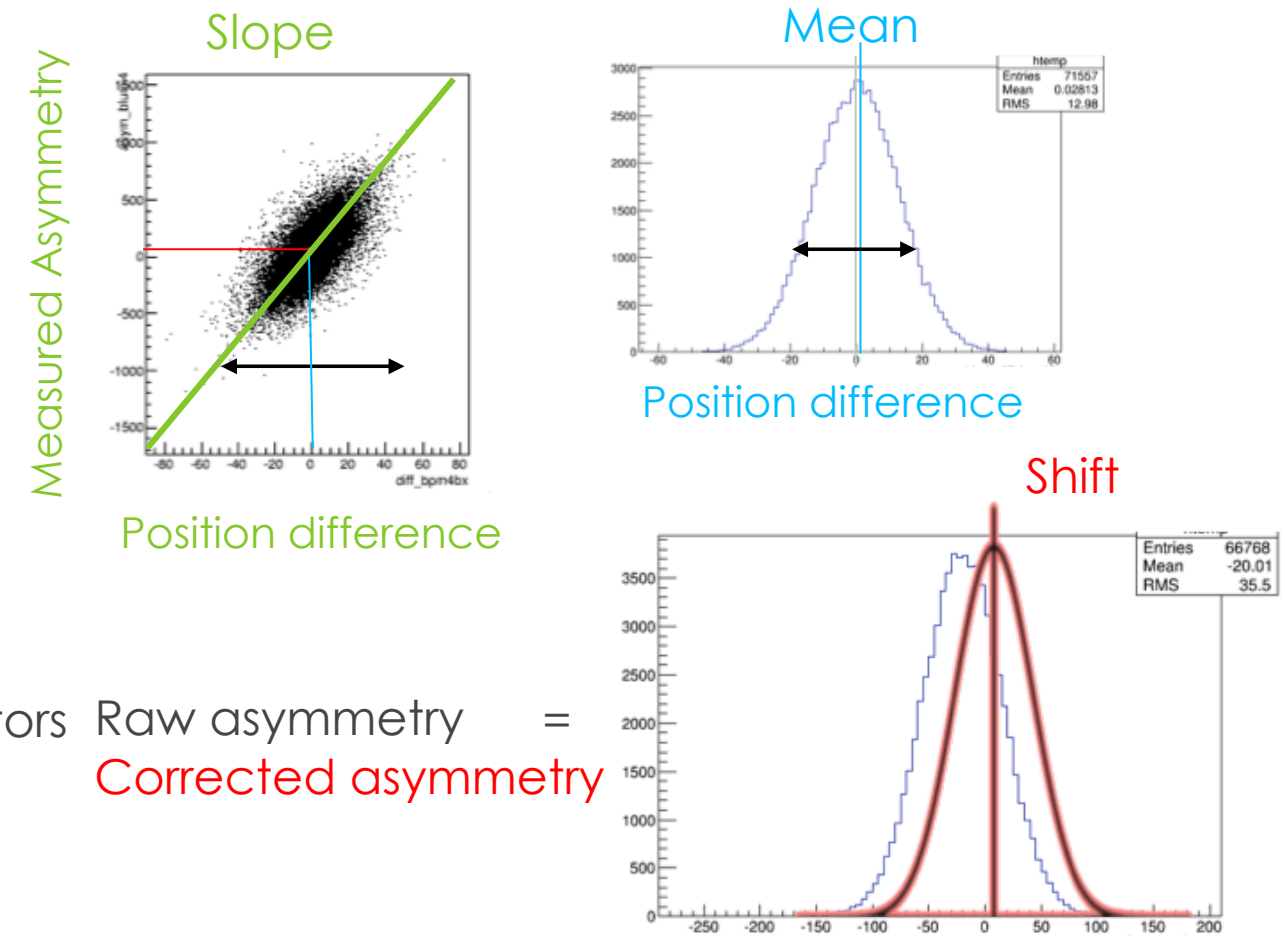
- People sometimes think of Parity Quality Beam as having low noise
- But what you really need are small helicity-correlated differences.
- Optimal = some noise, small helicity correlated differences
- NOT != low-noise.
- Can actually use beam noise for diagnosing various problems

MONITOR: I,E,X,Y

$$A_{raw} = A_{det} - A_Q + \alpha\Delta_E + \Sigma\beta_i\Delta x_i$$

- larger widths help establish correlations with monitors (ie slopes), which are then used to correct contributions from helicity correlated beam differences (ie. means)
- Subtract out the beam noise with the monitors anyway

Slope x Mean = Shift



Couplings in Transport

- Aq---(space charge)---> Arms ---(clipping)---> Dx,y
- Aq longitdudinal gradient --(beam rotations)--> Aq transverse grad -> Dx,y

Purpose of Beam Studies

Verify we are in position to get parity quality beam for PREXII/CREX

- Study the beam noise and verify widths look similar to the past
- *Study monitors and check we have sufficient monitors operational to perform a parity experiment*

Summary

Neutron skin studies at JLab will provide a crucial benchmark for the understanding of nuclear structure

^{208}Pb:

Uniform nuclear matter, DFT
The density dependence of symmetry energy
Tightly linked to neutron stars (radioactive nuclei, atomic PV, heavy ions)

^{48}Ca:

Extend studies over long lever arm of size and atomic number
Bridge microscopic models to DFT

Experimental Review (May 2016)

- confirmed radiation shielding concept & beam readiness. Septum conditions addressed by the design document.
- Second ERR in Spring 2017

Design Document completed and provides explicit requirements and rough design, for start of detailed design

- Collaboration is active with beam tests and reviving experimental systems; aims to be ready to run whenever scheduled
- Still on target for readiness in Summer/Fall 2018

- Note: PREX requires 1 GeV
- requires both HRS, so must run before SBS is on the floor

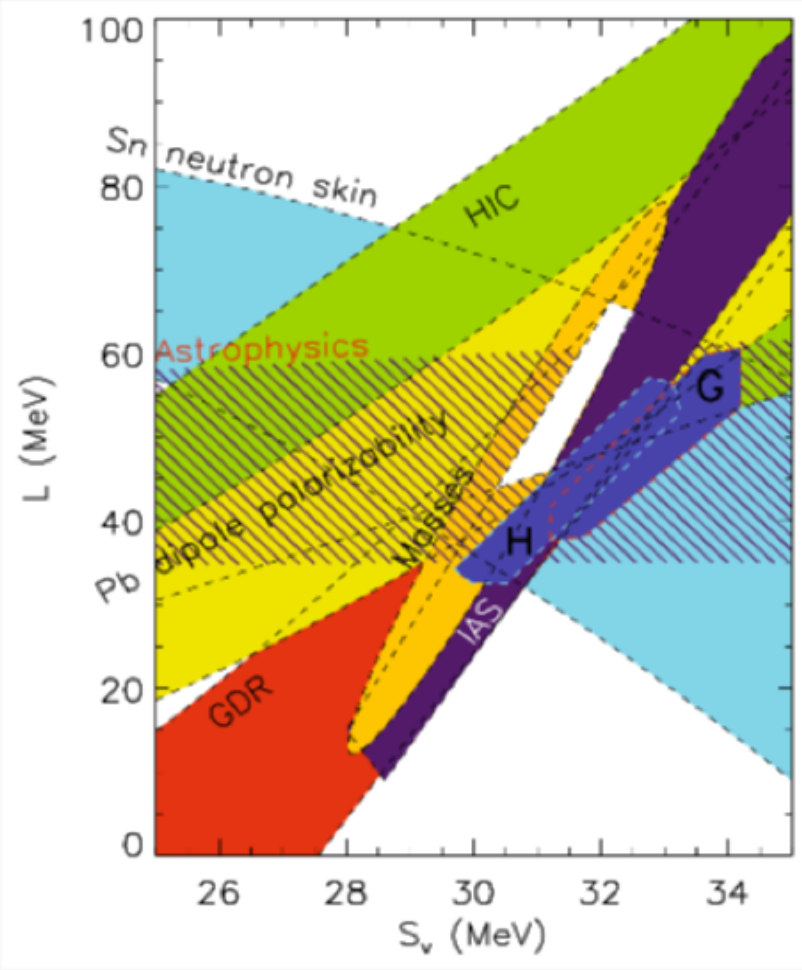
MITP NSkins workshop

Neutron Skins of Nuclei

17-27 May 2016
Mainz Institute for Theoretical Physics, Johannes Gutenberg University

Nuclear Symmetry Energy

4



From Lattimer and Steiner (2014)

- Most uncertain part of n-n interaction near saturation
- Combined progress in experiment, theory, and observation
- All of these constraints have uncontrolled systematics
- Need to go beyond the saturation density
- Wide astrophysical impact

[based on Shetty et al. (2007), Trippa et al. (2008), Tsang et al. (2009), Chen et al. (2010), Kortelainen et al. (2010), Tamii et al. (2011), Gandolfi et al. (2012), Hebeler et al. (2012), Steiner et al. (2012), Roca-Maza et al. (2013), Danielewicz et al. (2014)]

A.Steiner

EoS from GWs: an oversimplified picture

Two complementary approaches to infer EoS properties:

- GW inspiral:

  strong signal - weak EoS effect

  (e.g. Read et al. 2013 → ~1 km @ 100 Mpc; e.g. Flanagan & Hinderer 2008, Hinderer et al. 2010, Damour et al. 2012, Maselli et al. 2013, Del Pozzo et al 2013, Yagi & Yunes 2014, Wade et al. 2014, Agathos et al. 2015, Hinderer et al. 2016, ...) - accurate templates not yet available

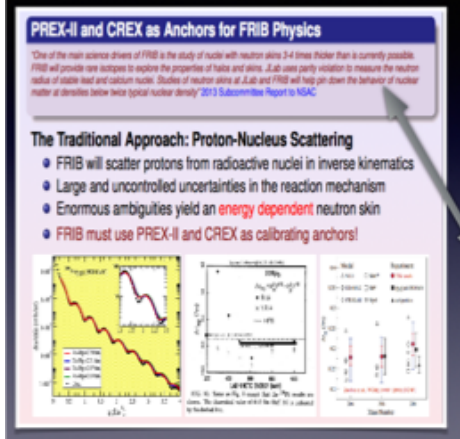
  Note: actually tidal deformability is measured (scales tightly with Ns radius, also "TOV-quantity")

- Postmerger oscillations:

  weak signal – robust strong EoS effect

A. Bauswein

Coherent Elastic Pion and Proton Scattering



Uncontrolled Uncertainties

- Impulse Approximation
- Off-shell Ambiguities
- Distortion Effects
- ...

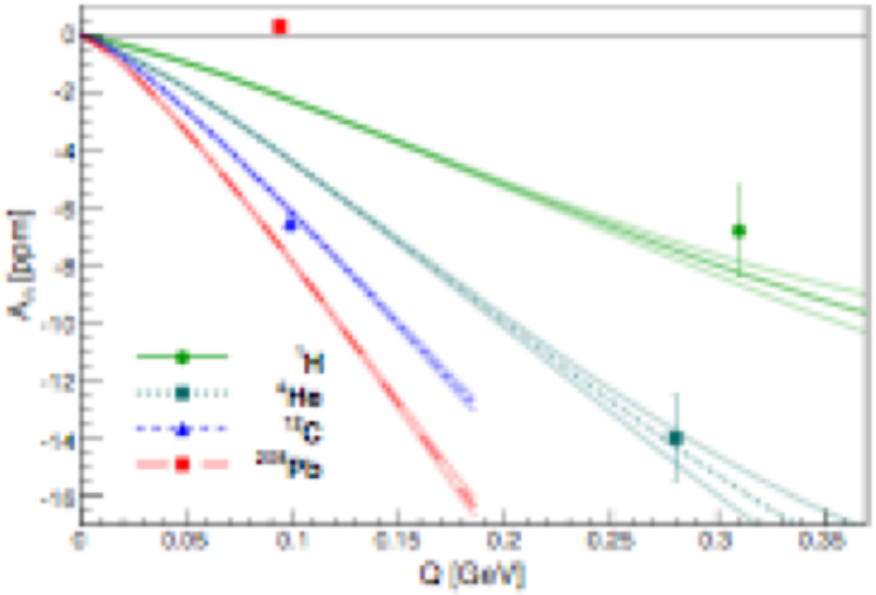
Potentially very useful observables
Difficult Experiment/Theory Homework.
Very large skins of unstable neutron-rich nuclei a critical new direction!

$\mathcal{M}_{PWIA} \sim A_1(s,t)\rho_T(Q)/Q \approx A_1(s,t)\rho_V(Q)$

J. Piekarew

Transverse Asymmetry

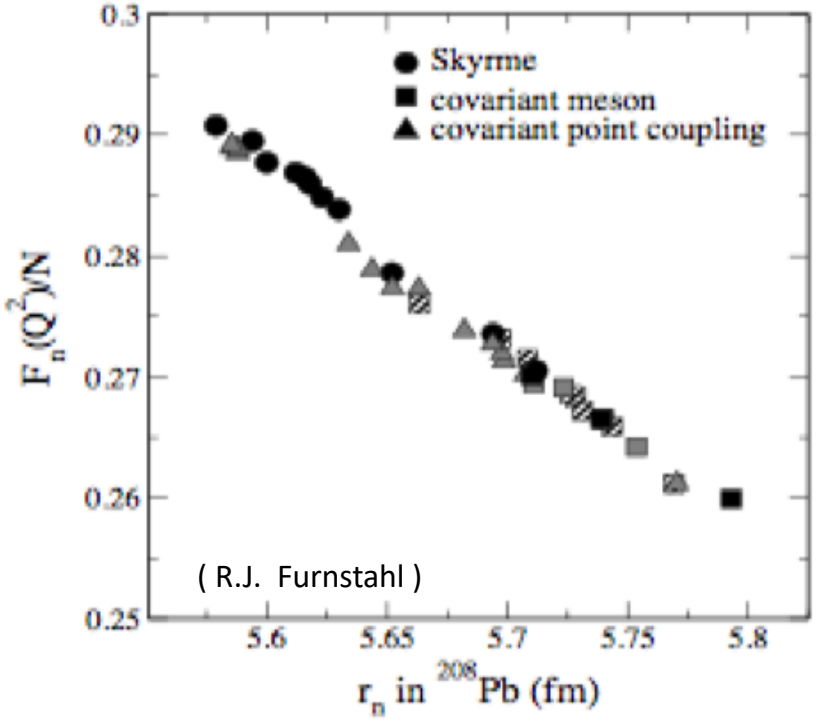
- Vertically transverse beam asymmetries sensitive to two photon effects
- Asymmetries are highly suppressed, few ppm for $Q^2 \sim 10^{-2}$ GeV^2

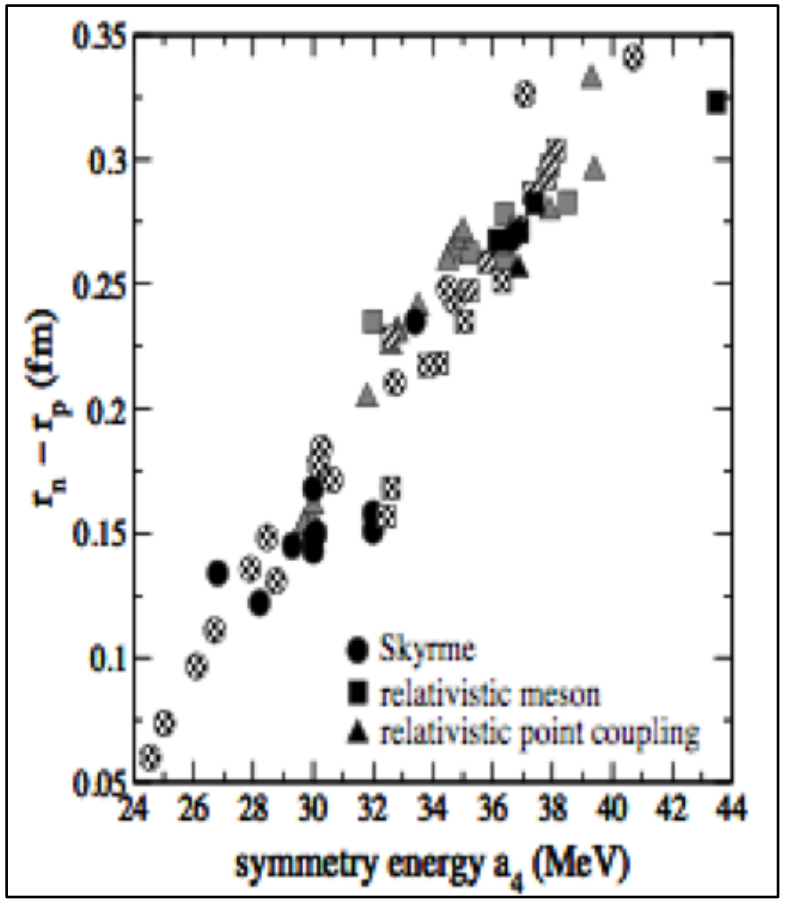


- Dispersion calculations: agreement with low Z nuclei
- ^{208}Pb is significantly off - Coulomb distortions?

Weak Charge Distribution and Symmetry Energy

The single measurement of F_n translates to a measurement of r_n (via mean-field nuclear models)





r_n in ^{208}Pb provides input to models to pin density dependence of symmetry energy

Neutron Skin at JLab

Q^2 ~ 0.01 GeV^2 ⇨ **A_{PV} ~ 0.6 ppm**

5° scattering angle

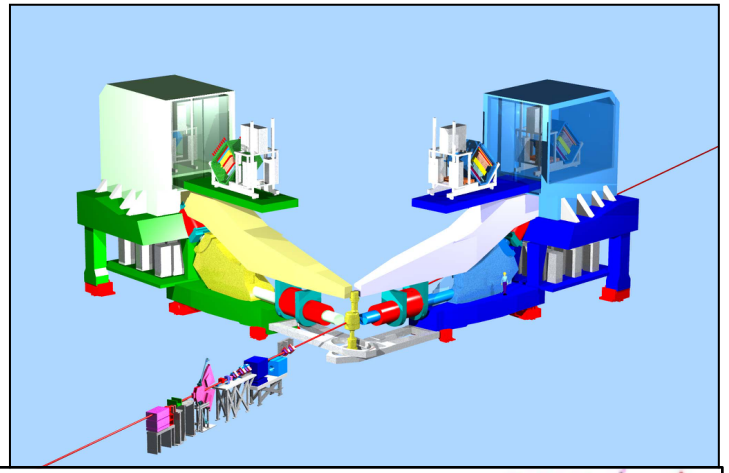
Rate ~1.5 GHz

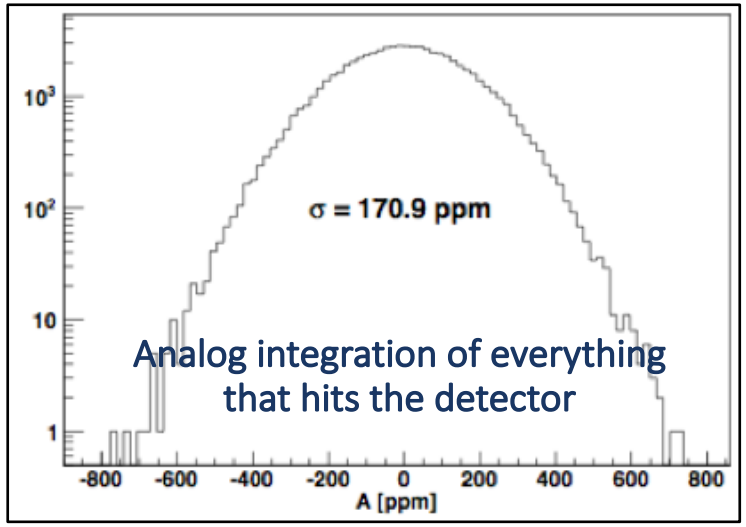
PREX-I (2012):

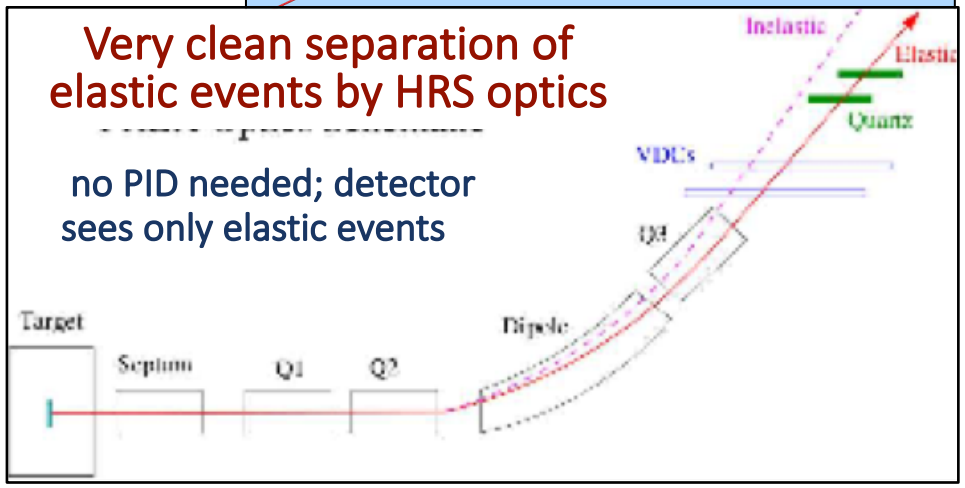
A_{PV} = 0.657 ± 0.060(stat) ± 0.014(sys) ppm

$r_n - r_p$ = 0.33+0.16-0.18 fm

- 0.5 mm ^{208}Pb foil, 70 μA
- 5° scattering
- P_b~ 90% +/- 1%







Summer 2017: PREX (3% A_{PV}, r_n to 0.06 fm), CREX (2.5% A_{PV}, r_n to 0.02 fm)

r_n and Nuclear Structure

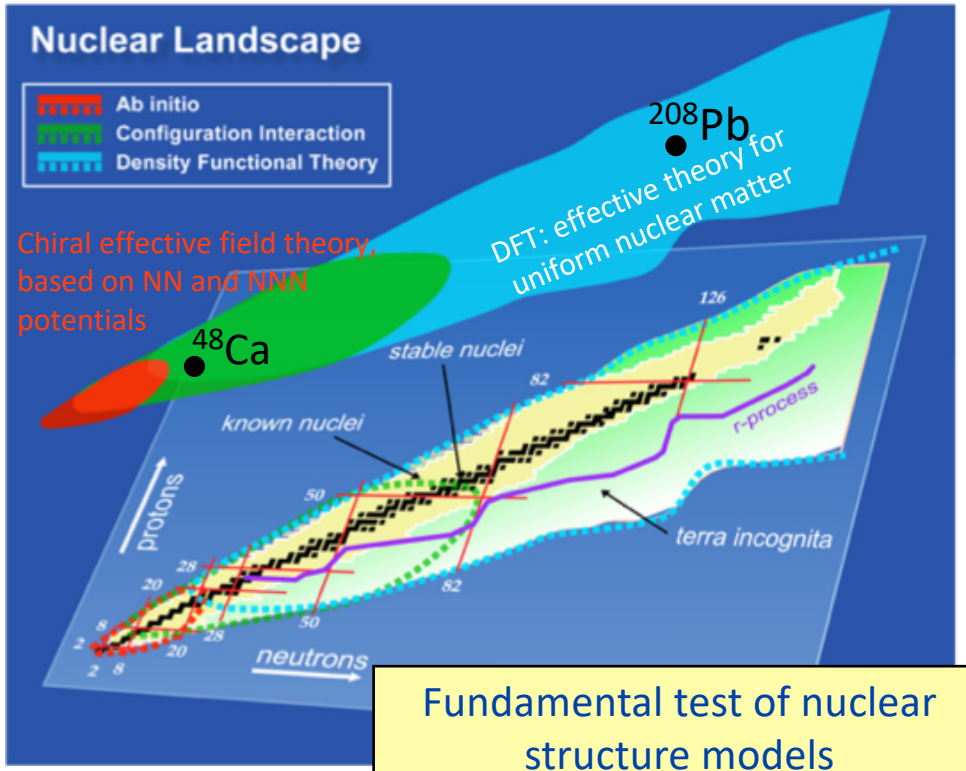
^{208}Pb:

- uniform nuclear matter
- terrestrial laboratory to test n-star structure

- Important calibration point for FRIB studies
- ρ(n) corrections to atomic PV

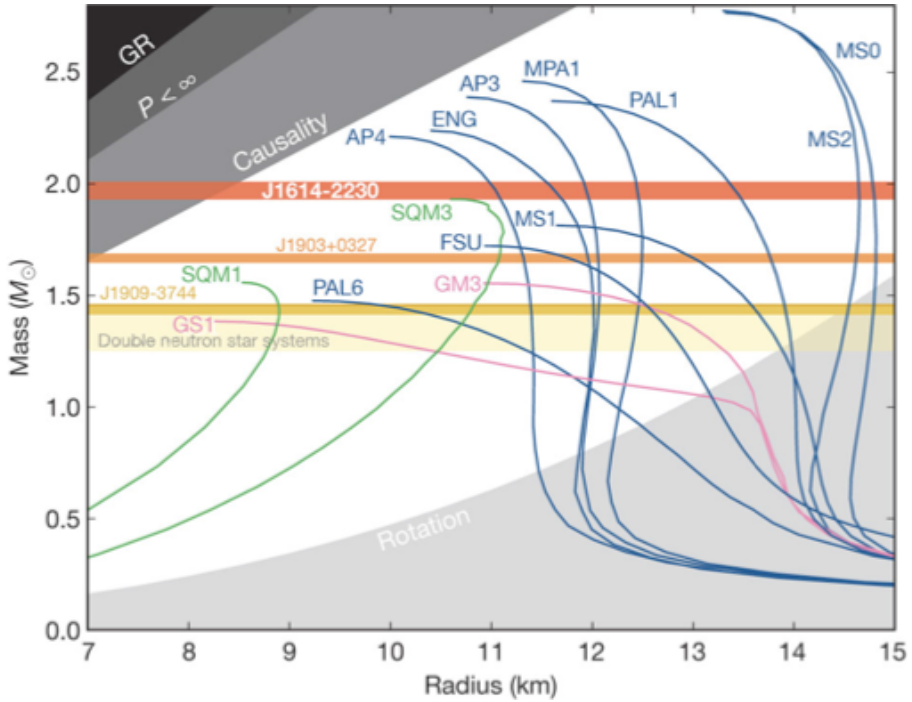
^{48}Ca:

- finite size effects.
- Within reach of microscopic calculations



Fundamental test of nuclear structure models

^{208}Pb r_n crucial information for neutron star E.o.S.



- Mass/radius ratio, compare to observation
- cooling mechanisms (URCA or not)

History of Weak Interaction: Parity Violation

1956- C.S. Wu carried out famous Co-60 experiment – test parity

- nuclei aligned, beta decay, recorded the direction of the emitted electrons.
- Observed: e- came out in the in the direction of the nuclear spin
- **Established Parity violation - signature of the weak force**.

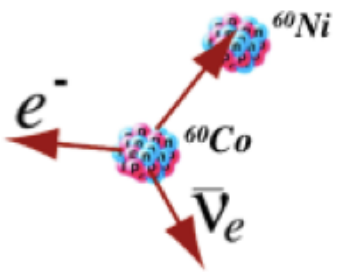
Parity transformation

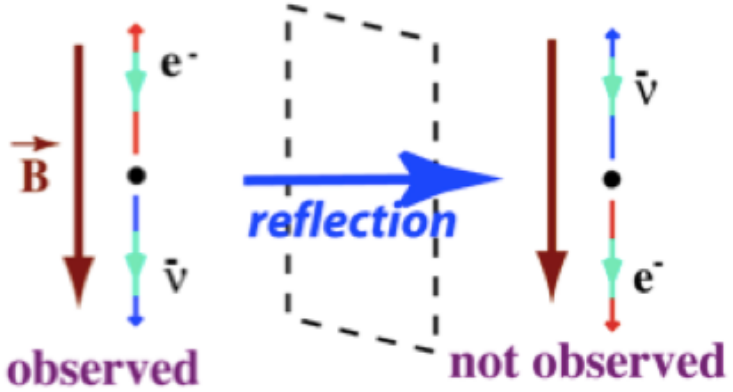
$$x, y, z \rightarrow -x, -y, -z$$

$$\vec{p} \rightarrow -\vec{p}, \quad \vec{L} \rightarrow \vec{L}, \quad \vec{S} \rightarrow \vec{S}$$

Mirror: reverses momentum, not ang. mom.

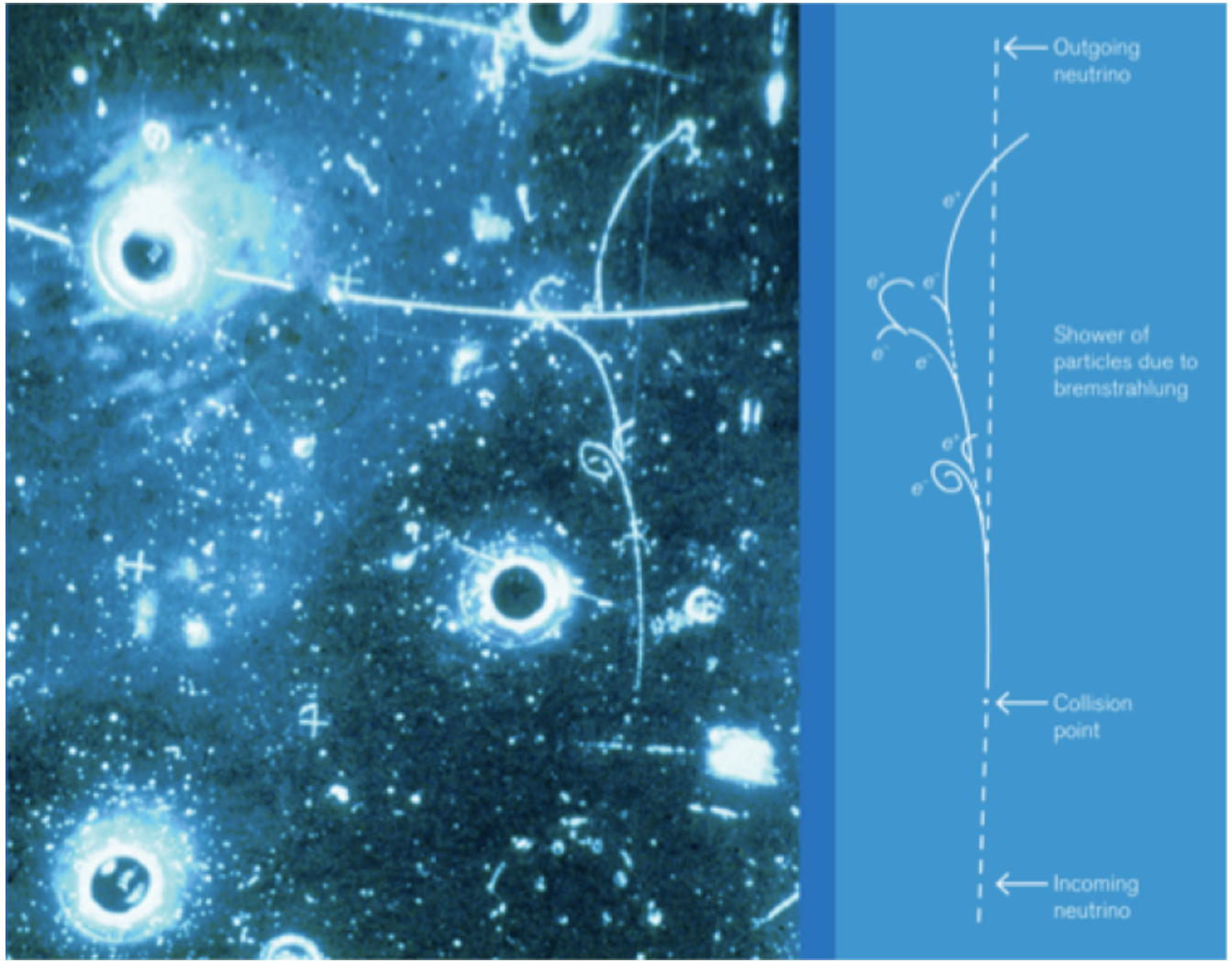
Weak decay of ^{60}Co Nucleus

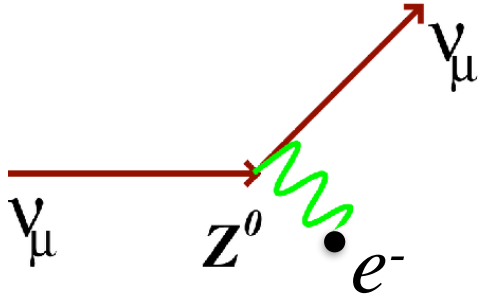




- 1960's – Glashow- Weinberg-Salam formulated theory unifying the weak and EM interaction – electroweak interaction – required W^{+-} and Z^0 - weak neutral currents
- 1973 – Gargamelle bubble chamber experiment at CERN - suggested existence of the Z^0 - the first observation of the neutrino reaction $\nu_\mu + e- \rightarrow \nu_\mu + e-$

History of Weak Interaction : Z^0 exists





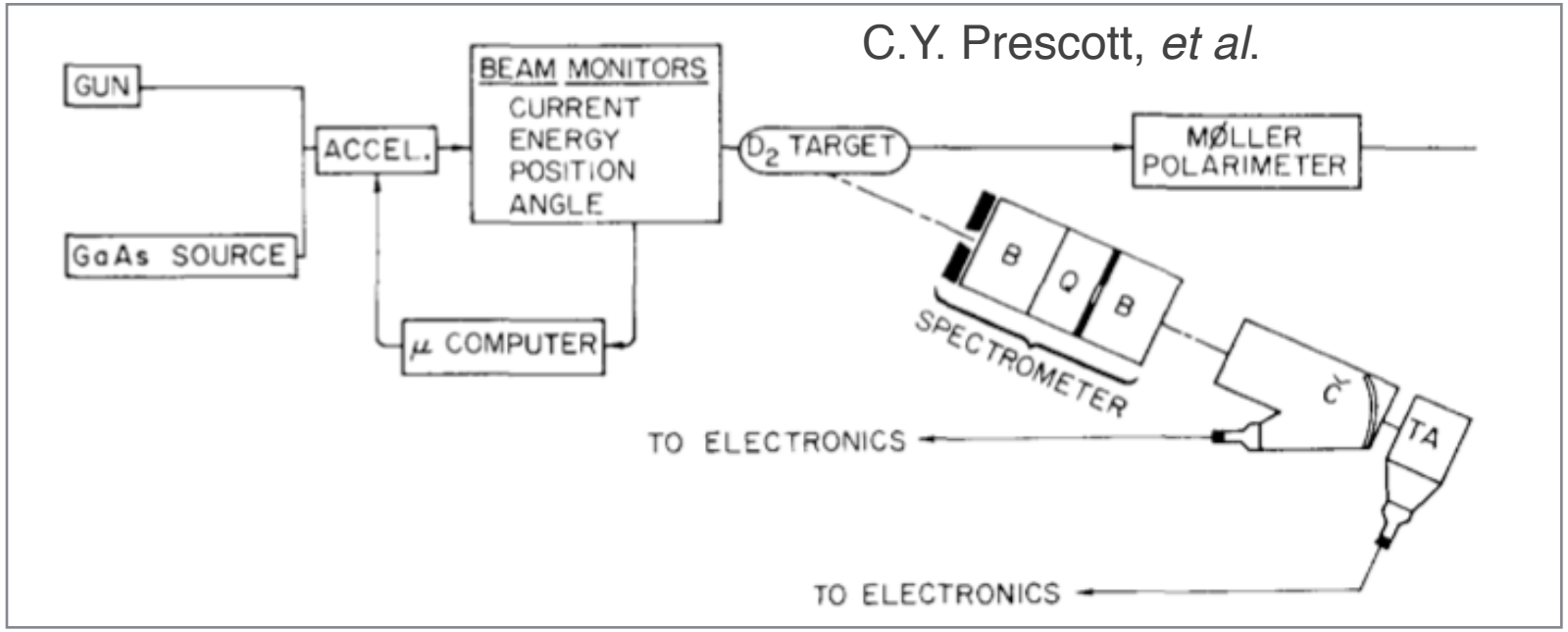
Gargamelle bubble chamber uncovers ν_μ e- events in 1973, more convincingly in 1976.

This demonstrated the existence of the neutral current (Z^0) but not it's nature

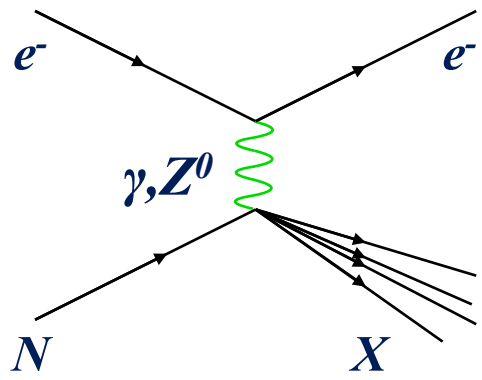
History of Weak Interaction: nature of Z^0

- GWS electroweak unification model – predictions of Z^0
  - Couplings determined by θ_w
  - Made possible firm prediction for mass of Z^0 - $M_w=M_z\cos\theta_w$
- In the early days it was hard to estimate θ_w - hence the Z^0 mass was quite uncertain
- 1978 – E122 at SLAC – Parity Violating Electron Scattering Experiment - verified parity non-conservation - $\sin^2\theta_w=0.2+-.03$
- Late seventies- experiments pointed to $\theta_w\sim29^o$,masses were calculated to be $M_w=82\pm2GeV/c^2$, $M_Z=92\pm2GeV/c^2$
- GWS awarded the Nobel prize in 1979
- 1983 – CERN observed the W($81\pm5GeV/c^2$) and Z(at $95\pm3GeV/c^2$).

E122 at SLAC (1978)

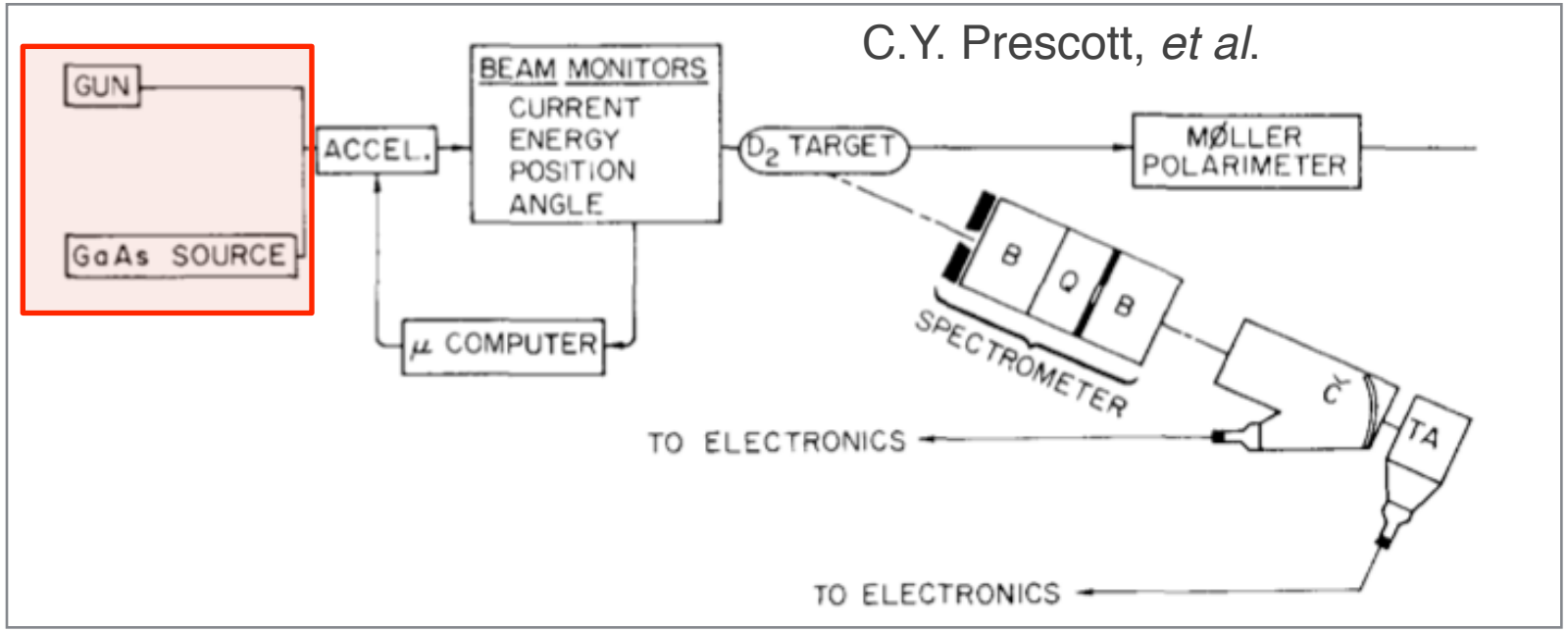


A_{PV} in Deep Inelastic Scattering from liquid Deuterium Q^2 ~1 GeV^2

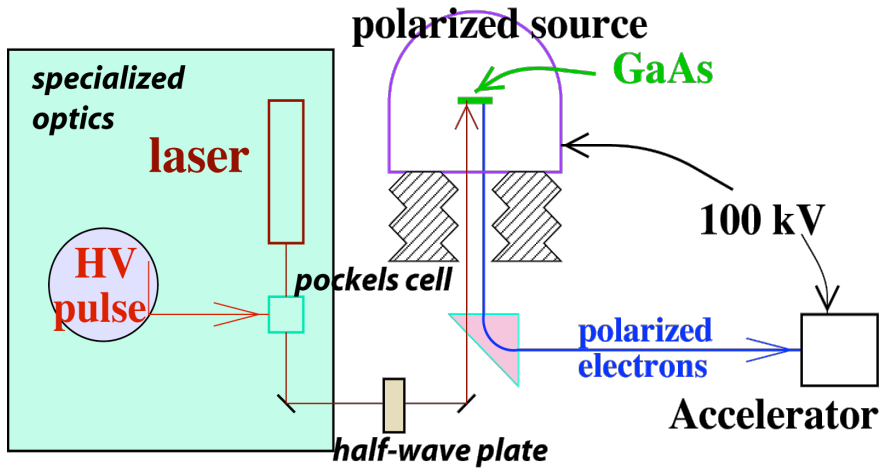


Inclusive measurement
detect scattered electron only

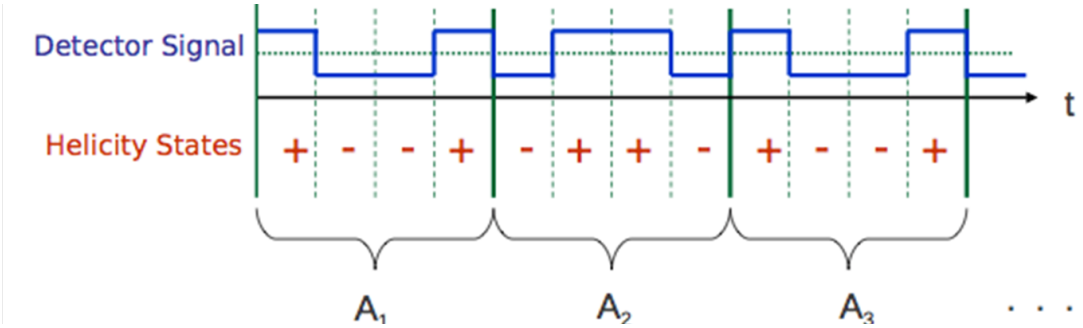
E122 at SLAC (1978)



- **High polarized luminosity laser-driven photoemission from GaAs cathode**
  - First developed for E122
  - NOW: superlattice cathodes for ~90% polarization, high QE and lifetime

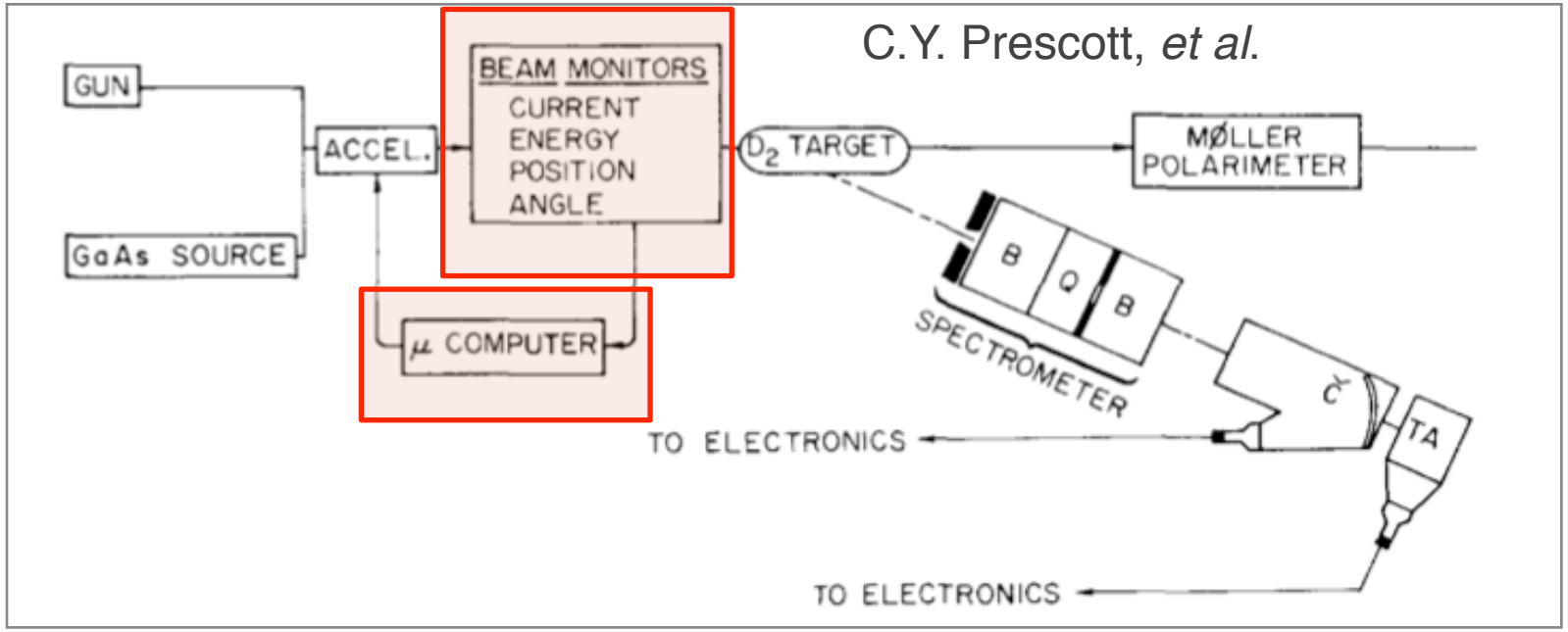


- **Rapid helicity-flip change sign of e^- polarization**
  - electro-optic Pockels cell in laser optics
  - NOW: up to 1kHz measurement over helicity reversal



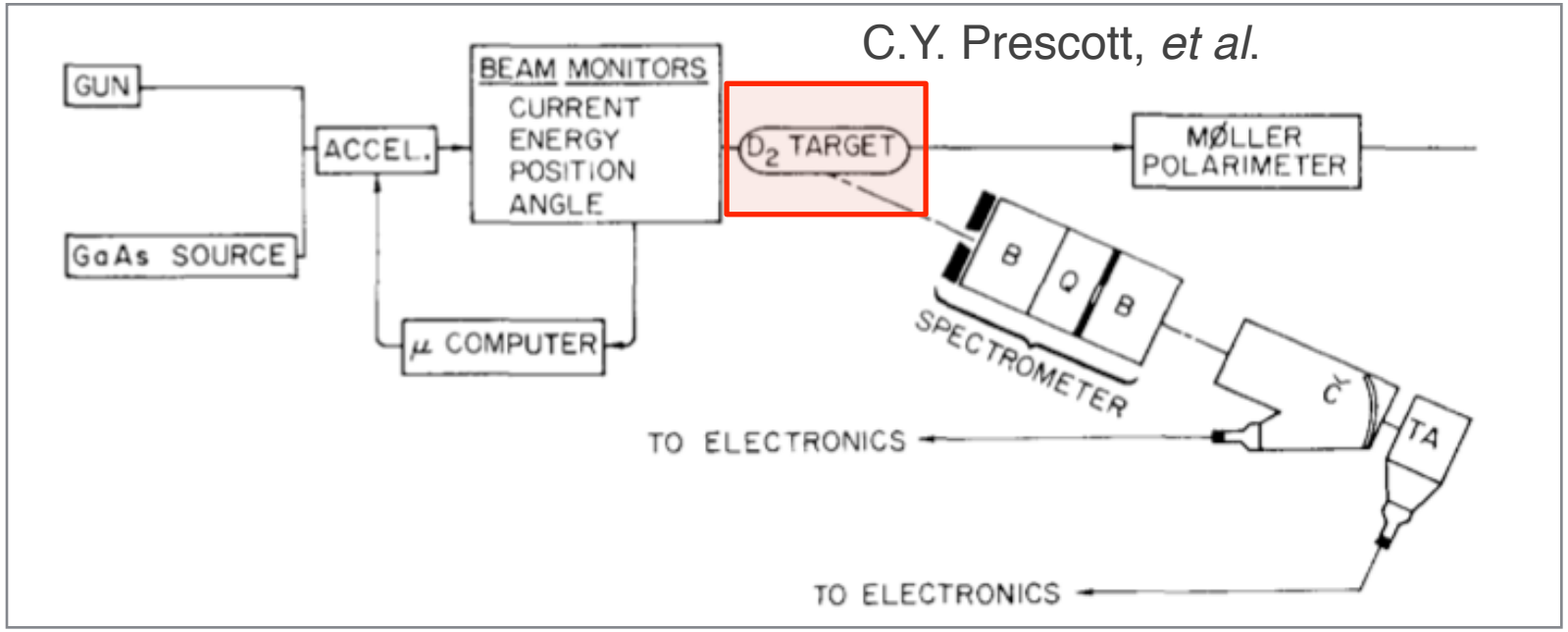
- **Helicity-correlated beam asymmetries**
  - NOW: A_Q ~ few ppb, Δx ~ 1nm
  - both precision configuration and feedback

E122 at SLAC (1978)



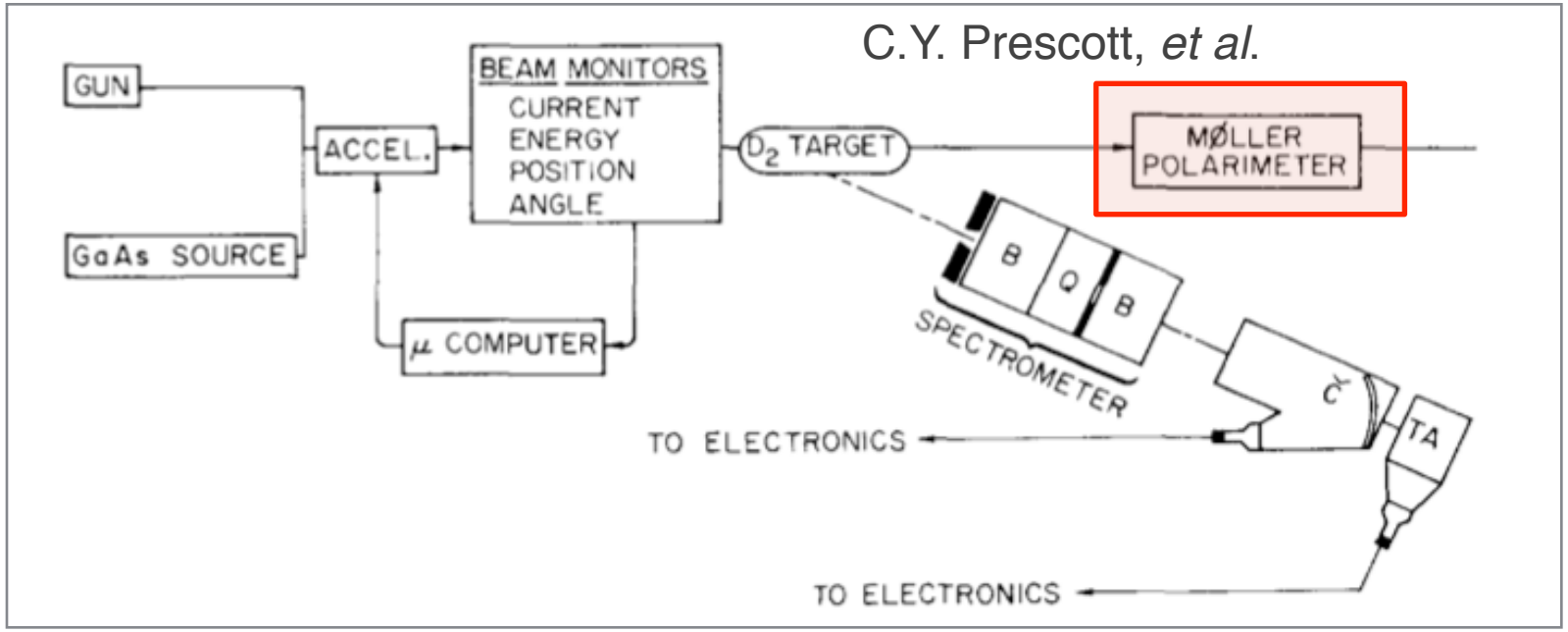
- **Beam Monitors**
  - Measure helicity-dependent changes in current and position
  - NOW: usually RF antenna or RF resonant cavity
  - Precision: Q ~ 30 ppm , x ~ 1 micron at 250 Hz
- **Fast Analysis**
  - Feedback to source to control beam asymmetries

E122 at SLAC (1978)



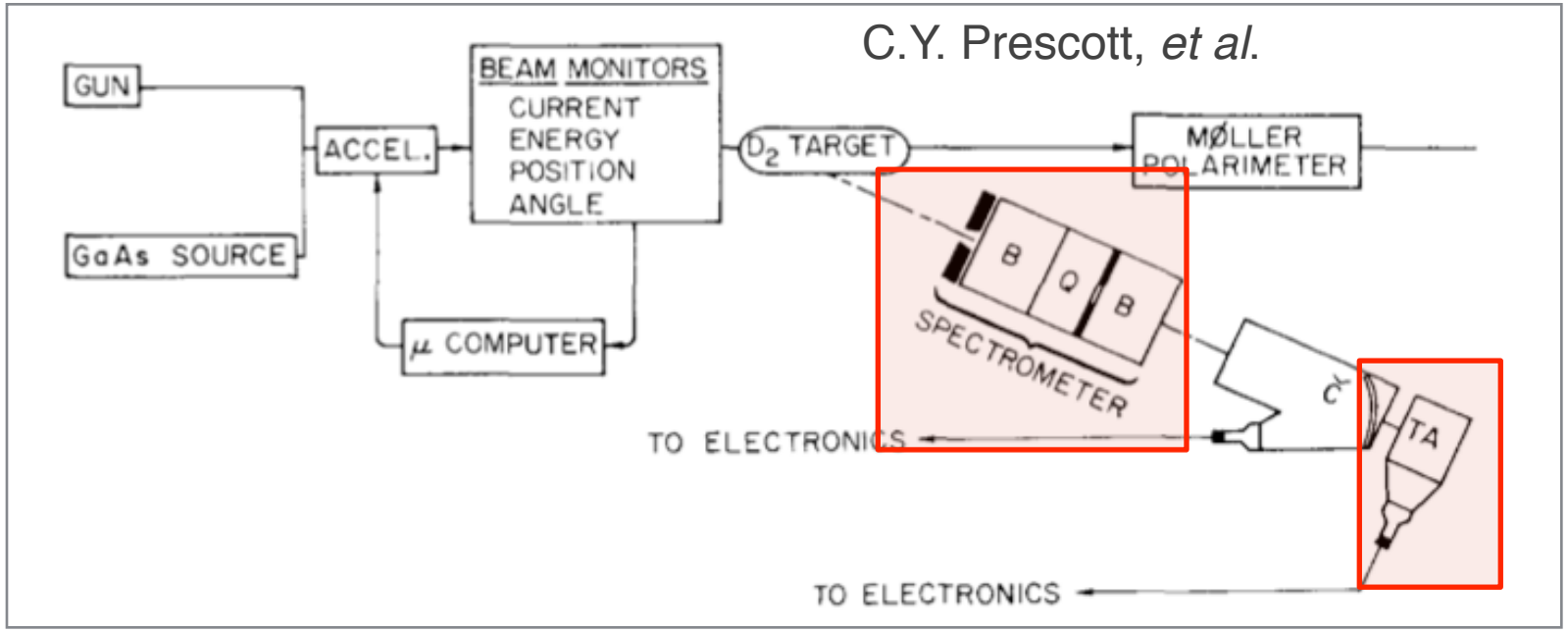
- **High-Power Cryogenic Target**
  - 30 cm long for high luminosity
  - NOW: power >2300 W, stability better than 40 ppm at 250 Hz
  - FUTURE: 1.5 meters, 4 kW, stability better than 25 ppm at 1kHz

E122 at SLAC (1978)

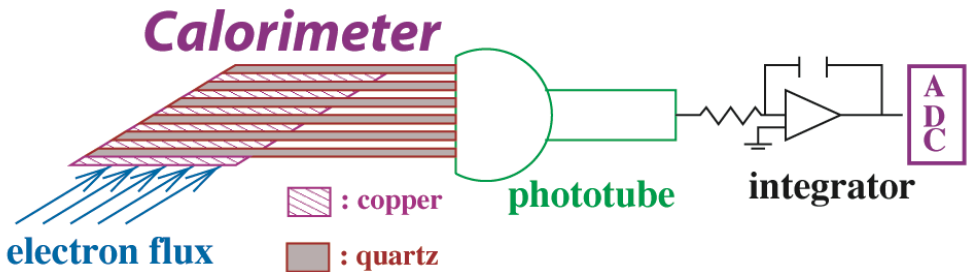


- **e-beam Polarimetry**
  - Møller polarimeter
  - NOW: Mott ~1%, Møller ~1%, Compton ~0.7% (continuous)
  - FUTURE: all three methods aim for 0.5%

E122 at SLAC (1978)



- **Magnetic Spectrometer**
  - directs scattered flux to background-free region
  - defines / calibrates kinematic acceptance



- **Integrating Detection**
  - integrate all signal during helicity window
  - measures high rate (>100 kHz) with no deadtime
  - NOW: ~6 GHz
  - FUTURE: ~500 GHz

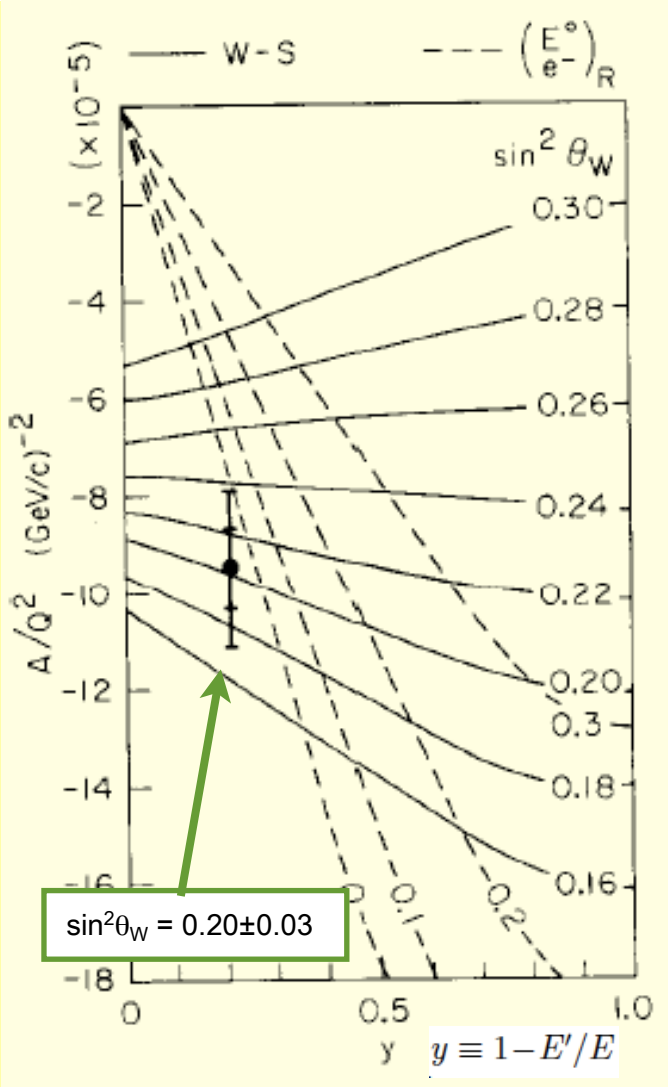
PVeS Verifies the "Standard Model" (1978)

Parity Non-Conservation in Inelastic Electron Scattering, ***C.Y. Prescott et. al, 1978***

A_{PV} ~ 100 ± 10 ppm

Definitive answer on gauge structure of electroweak interaction

	Left	Right
γ Charge	$q = 0, \pm 1, \pm\frac{1}{3}, \pm\frac{2}{3}$	$q = 0, \pm 1, \pm\frac{1}{3}, \pm\frac{2}{3}$
W Charge	$T = \pm\frac{1}{2}$	**zero**
Z Charge	$T - q\sin^2\theta_W$	$-q\sin^2\theta_W$

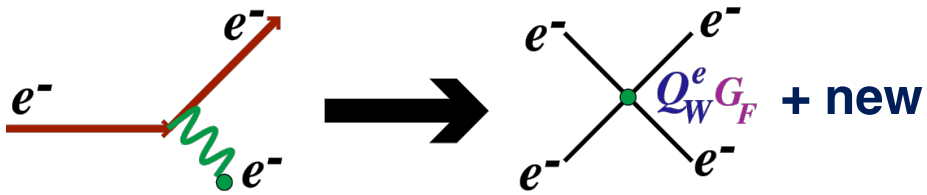


The Nobel Prize in Physics 1979 was awarded jointly to Sheldon Lee Glashow, Abdus Salam and Steven Weinberg *"for their contributions to the theory of the unified weak and electromagnetic interaction between elementary particles, including, inter alia, the prediction of the weak neutral current"*.

SLAC- E158: Weak charge of the electron

Møller (ee) scattering

1997-2004



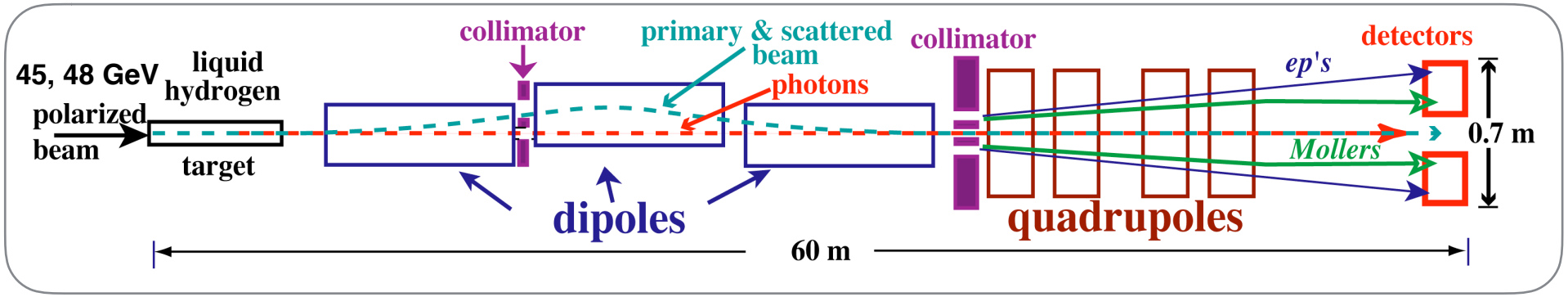
$$Q_W = 1 - 4\sin^2\theta_W$$

SM highly suppressed, so even a weakly-coupled or heavy new physics scenario can stand out

High-power (1kW) LH_2 target, 18% radiator

Dipole chicane + quadrupole spectrometer 45, 48 GeV, 4-7 mrad scattering angle

High beam polarization and current



First Measurement of the electron-electron weak interaction

A_{PV} = (-131 ± 14 ± 10) ppb

$$\frac{\delta(\sin^2\theta_W)}{\sin^2\theta_W} \sim 0.5\%$$

LEP200

$$\Lambda^{ee}_{VV} \sim 17.7 \text{ TeV}$$

E158 Reach

$$\Lambda^{ee}_{RR-LL} \sim 17 \text{ TeV}$$

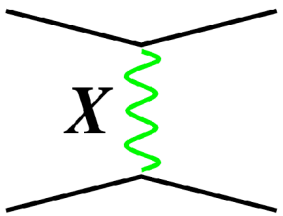
Defining Mass "Reach" of Precision Experiment

Need model independent way to:

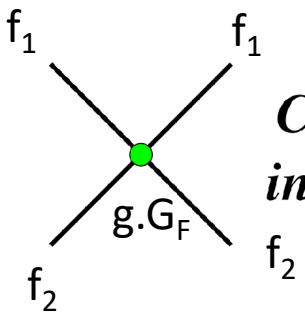
- Quantify the effects of new high energy dynamics in low E processes
- Translate high precision at low E into high energy regime
- Express the "reach" of precision experiment

Low energy new NC interactions ($Q^2 << M_x^2$)

Heavy mediators = contact interactions



$$A_X \propto \frac{1}{Q^2 - M_X^2} \sim \frac{4\pi}{\Lambda^2}$$



Contact interaction

For each fermion and handedness combination, reach characterized by mass scale Λ, coupling g

$$\mathcal{L}_{f_1 f_2} = \sum_{i,j=L,R} \frac{(g_{ij}^{12})^2}{\Lambda_{ij}^2} \bar{f}_{1i}\gamma_\mu f_{1i} \bar{f}_{2j}\gamma_\mu f_{2j}$$

Moller Experiment Example

Sensitivity: 2.3% uncertainty gives

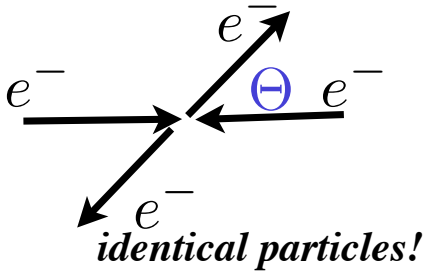
$$\frac{\Lambda}{\sqrt{|g_{RR}^2 - g_{LL}^2|}} = \frac{1}{\sqrt{\sqrt{2}G_F|\Delta Q_W^e|}} = 7.5\text{TeV}$$

Mass Reach:

Conventional "mass limits" for new contact interaction: assume coupling with compositeness scale $g^2=4\pi$

Gives mass reach scale of Λ=47TeV

High Luminosity, High Rate… ***High Acceptance***



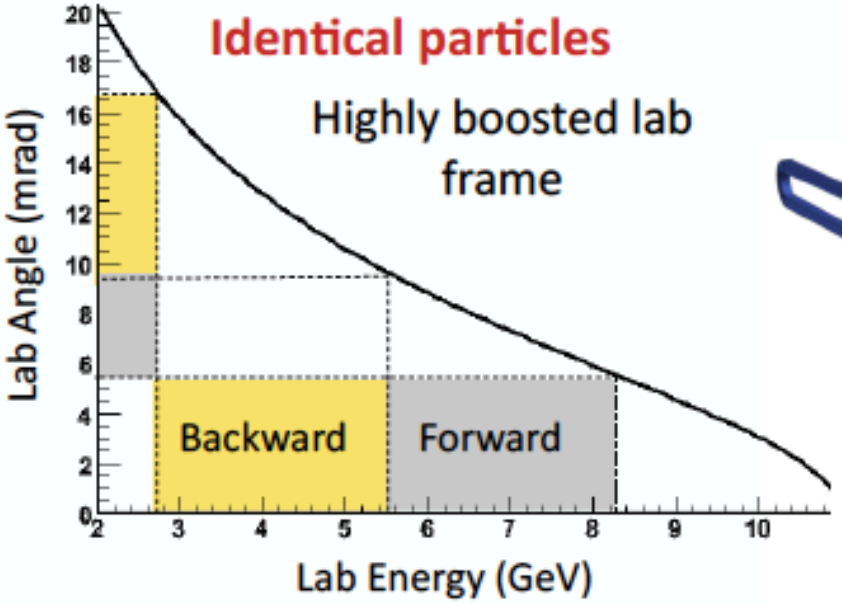
How do you maximize the azimuthal acceptance of the spectrometer?

Idea: 50% Azimuth, 100% Acceptance

Odd number of octants: accept CM[60°,120°] so you always get one of the electrons from each event

Figure of merit highest at θ_{CM} = 90°

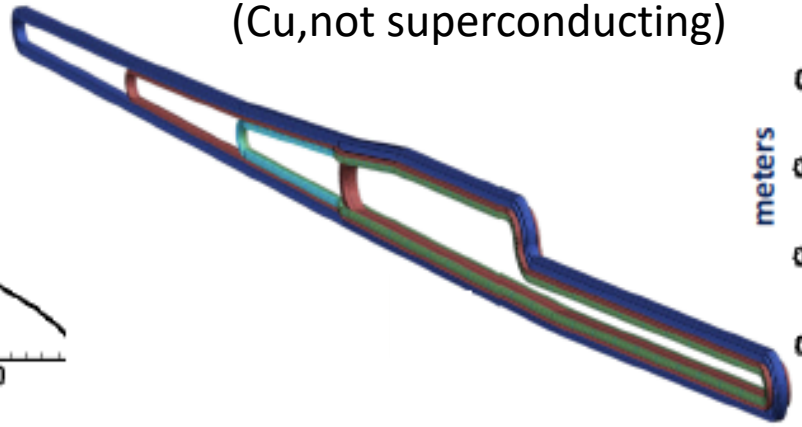
Optimum Acceptance [90°,120°]



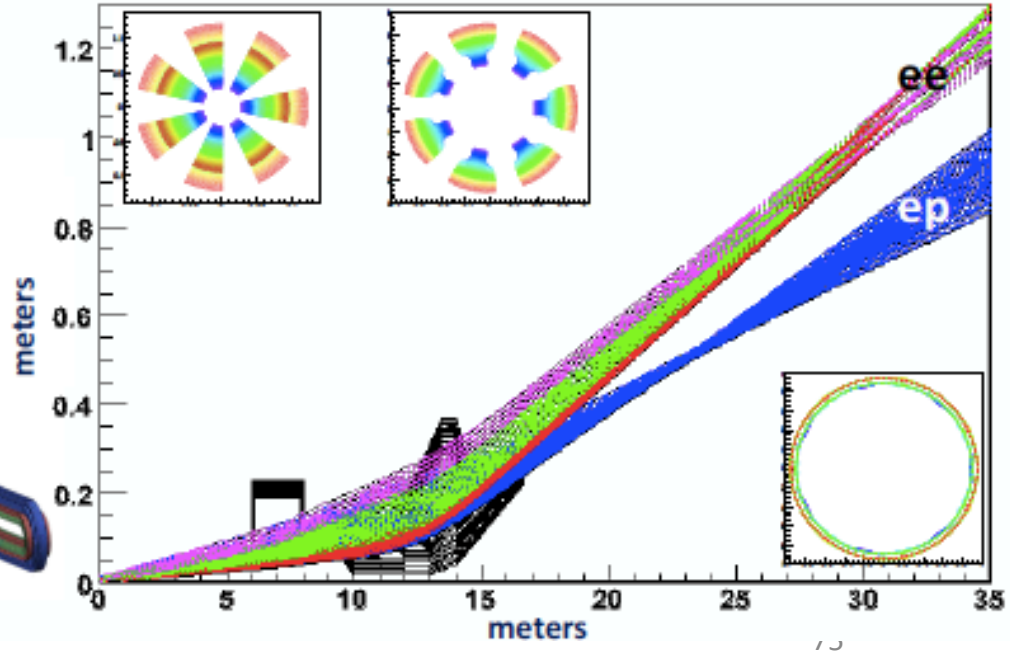
Toroid spectrometer

- E' = 2.5-8.5 GeV
- θ_{lab} = 0.3°-1.1°
- Two resistive torroids

(Cu,not superconducting)

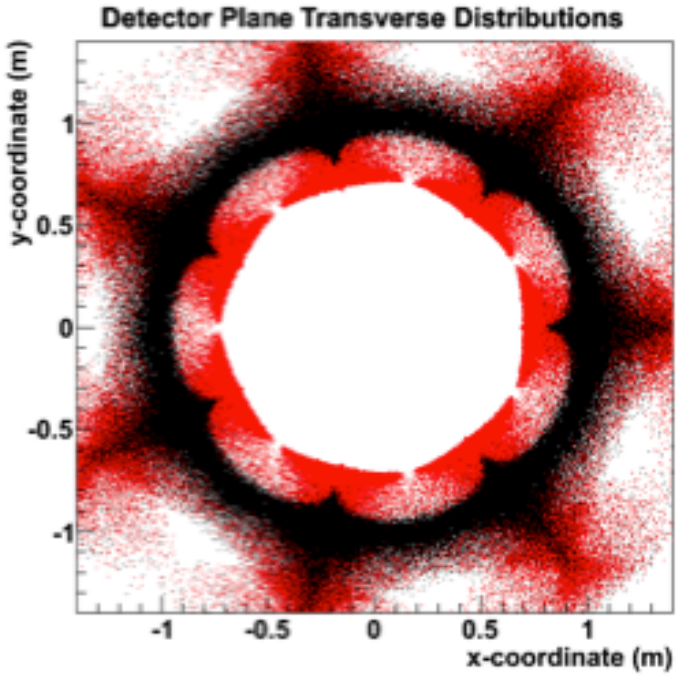


Radial Fields defocus azimuthally.
Full detector ring



Detector Plane Segmentation

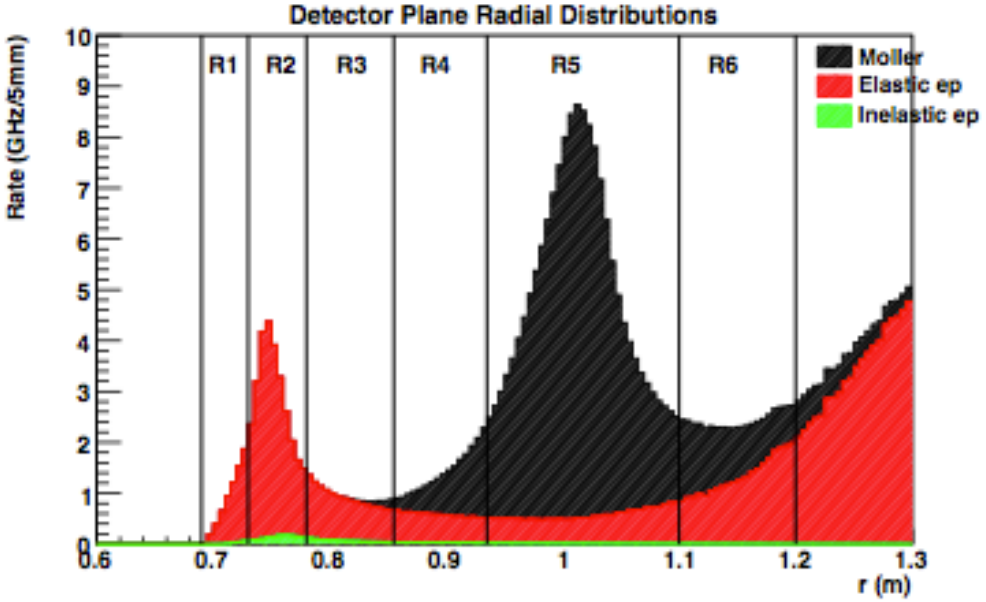
Cherenkov detectors will have radial and azimuthal segmentation



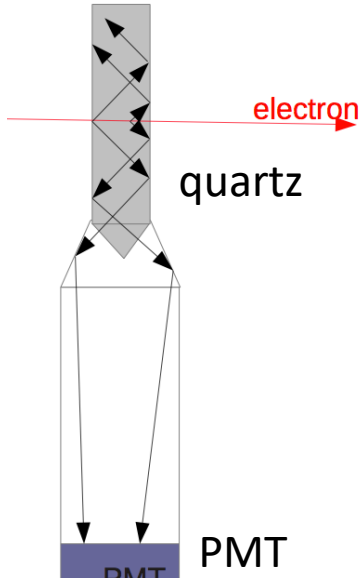
Azimuthal defocusing –

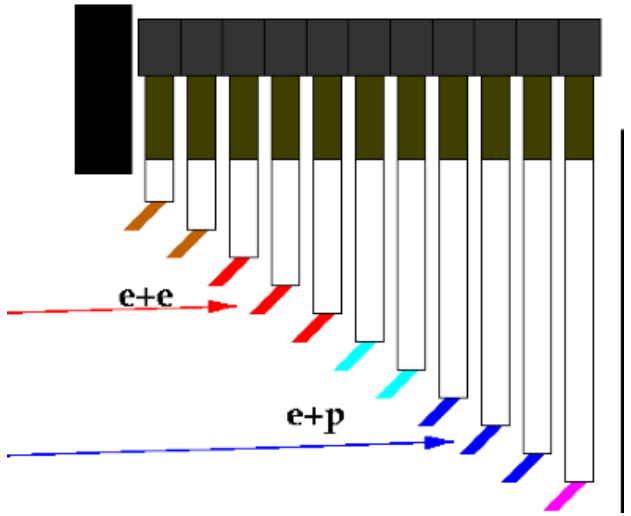
Different φ, different θ_{CM} bins

Detector Plane Radial Distribution



Main Moller peak in Region 5





Density Dependence of the Symmetry Energy

Energy penalty for breaking N=Z symmetry

$$S = \frac{E}{N}$$

$$L \propto \frac{\partial S(\rho)}{\partial \rho}|_{\rho_0}$$

Slope of symmetry energy at saturation density

Isovector properties are not well measured. Models informed mostly by measurements of properties sensitive to *p*+*n*.

Neutron properties in stable medium and heavy nuclei have been mainly measured by using strongly interacting probes.

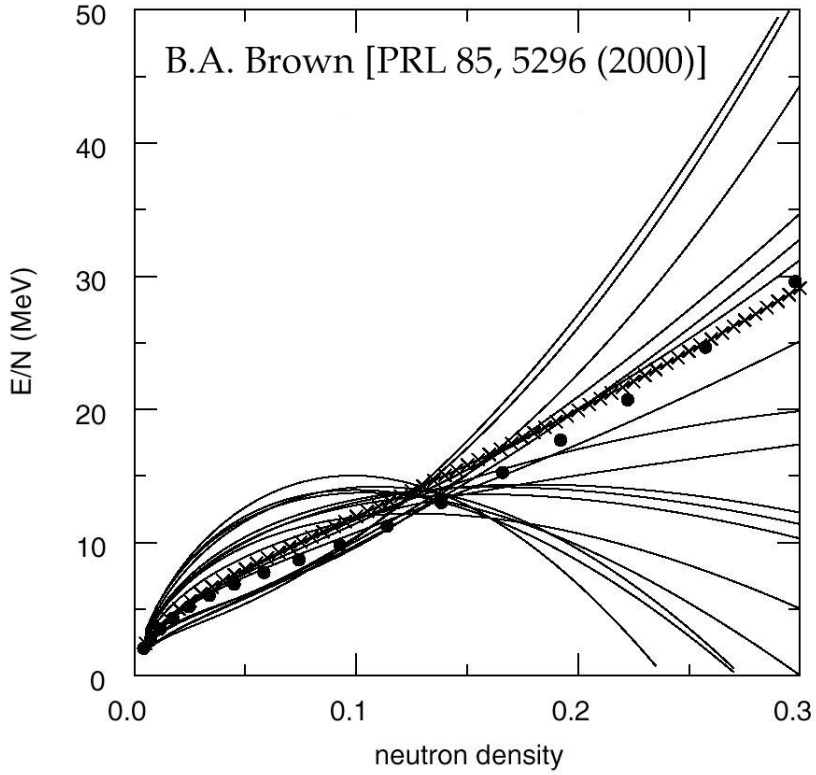


FIG. 2. The neutron EOS for 18 Skyrme parameter sets. The filled circles are the Friedman-Pandharipande (FP) variational calculations and the crosses are SkX. The neutron density is in units of neutron/fm^3.

PREXI demonstrated technologies for PREXII

What Worked:

New Septum
We now know how to tune it to optimize FOM

HRS Tune
We have a tune and good first-guess optics matrix for a tune optimized for the small detectors

Polarimetry at low energy
High-field Moller at 1.3%,
Integrating Compton at 1.2%

New Detectors
Suitable energy resolution achieved for 1 GeV electrons. <5% precision loss.

Lead Target
Established Min Survival lifetime >25 C exposure

Fast Helicity Flipping
We know how to control false asymmetries and monitor performance

Injector Spin Manipulation
Second Wein and solenoid are calibrated and used for helicity reversal. Important cancellation for systematic beam asymmetries from the polarized source.

Beam Modulation System
Fast beam kicks cancel low frequency noise and improve precision of beam position corrections

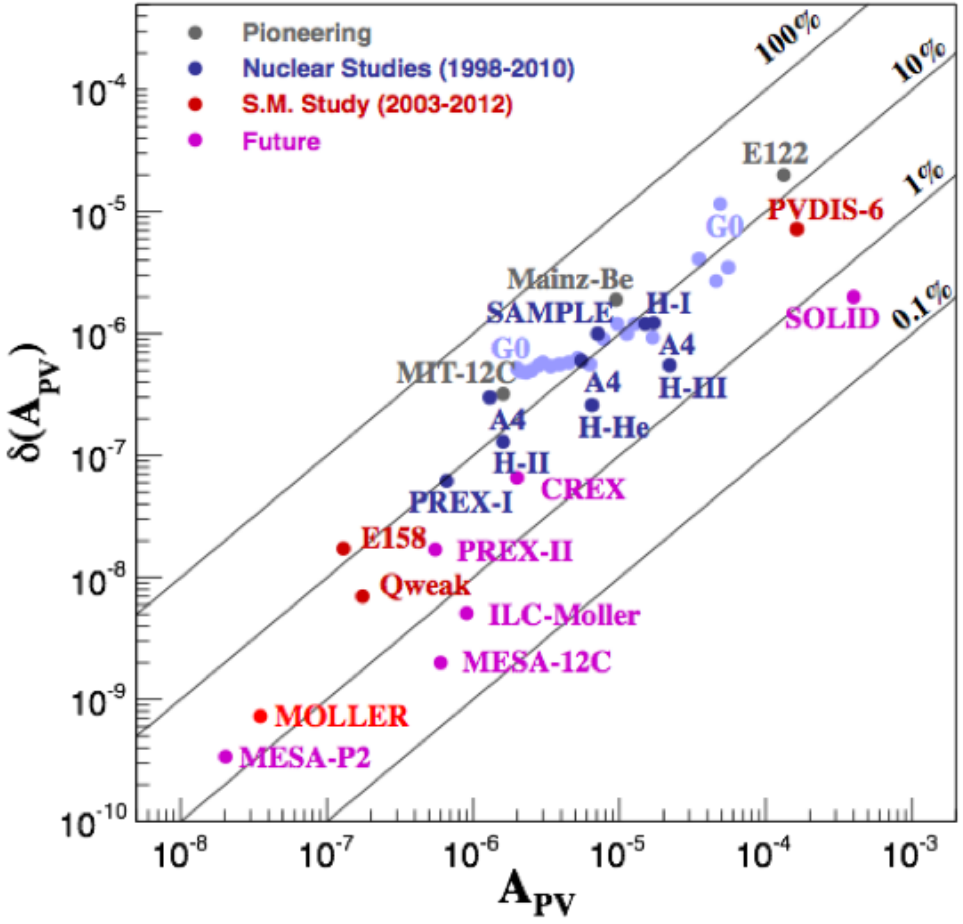
A_T false asymmetry
A_T is small (<1 ppm Pb, <10 ppm C) and A_{false} will be small if P_T is minimized

Needed to resolve:

- Target Vacuum system
- Radiation in Hall

Ready to meet PREX-II/CREX systematic and statistical goals

PVES has become a precision tool



Interplay between probing hadron structure and electroweak physics

- Beyond Standard Model Searches
- Strange quark form factors
- Neutron skin of a heavy nucleus
- QCD structure of the nucleon

For future program:

- sub-part per billion statistical reach and systematic control
- 0.5% normalization control

photocathodes, polarimetry, high power cryotargets, nanometer beam stability, precision beam diagnostics, low noise electronics, radiation hard detectors

Challenges: RTP Met 4+ out of 5 for Moller so far…

Switches Helicity States Faster

0th moment - Obtain Small Intensity Asymmetries

– Aligned RTP using 2-crystal relative degrees of freedom

1st moment - <u>Obtain Small Position Differences</u>

- Larger gradients in RTP
  - Apply compensating field gradient – CANCEL it out by steering the laser beam

- 2nd moment - Obtain Small Spot-Size Asymmetries ~10^-4
  - Have smaller angle dependencies in RTP
- Tested RTP cell with electron beam – 1/2

What the widths in pair differences are telling us

- We have <150nm means – helicity correlated position differences (HCPD)
- But the RMSs are comparable to the past – both upstream in the injector and downstream in the hall, for 1 pass, 2pass, 4pass, 5pass
- This is telling us the accelerator beam **noise (that parity daq sees)** isn't amplified in the new accelerator, it is not increased by doing more passes, it remains the same

  The beam **noise** in the hall **doesn't** suffer increased sensitivity to the beam **noise** in the injector
- Infer that likewise: **HCPD(helicity-correlated-position-differences)**

  The beam **HCPD** in the hall **don't** suffer increased sensitivity to the beam **HCPD** in the injector
- There is no reason to not think that:

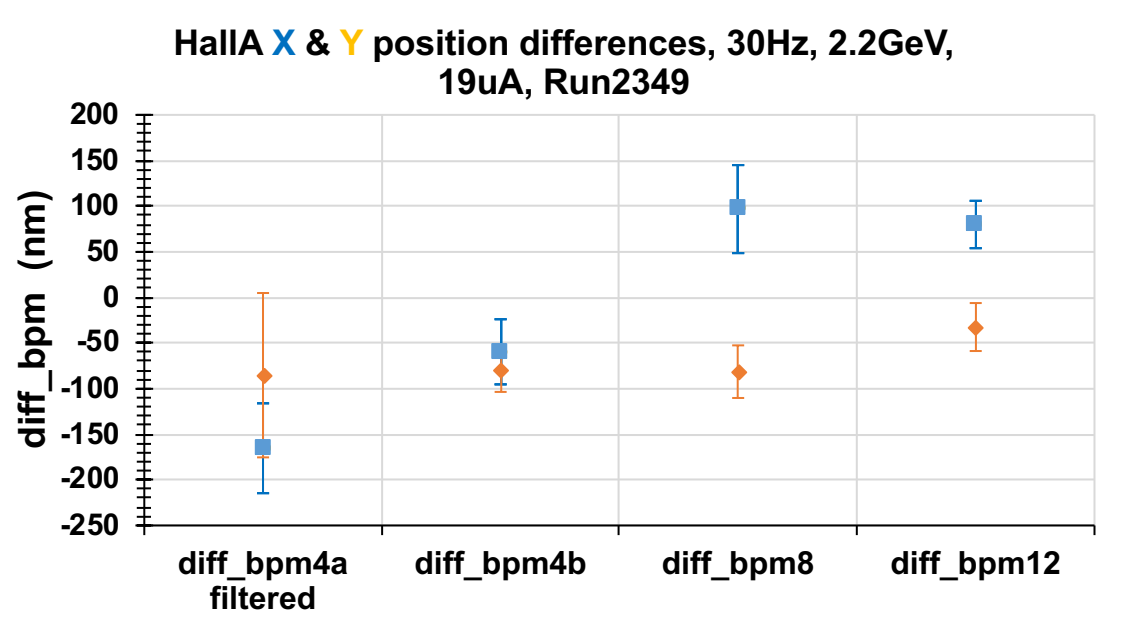
  If the injector HCPD means are minimized, the hall HCPD means are minimized
- The injector has the same components as previously, so

  the injector alignment procedure will be the same as previously (i.e. HAPPEX,PREXI)

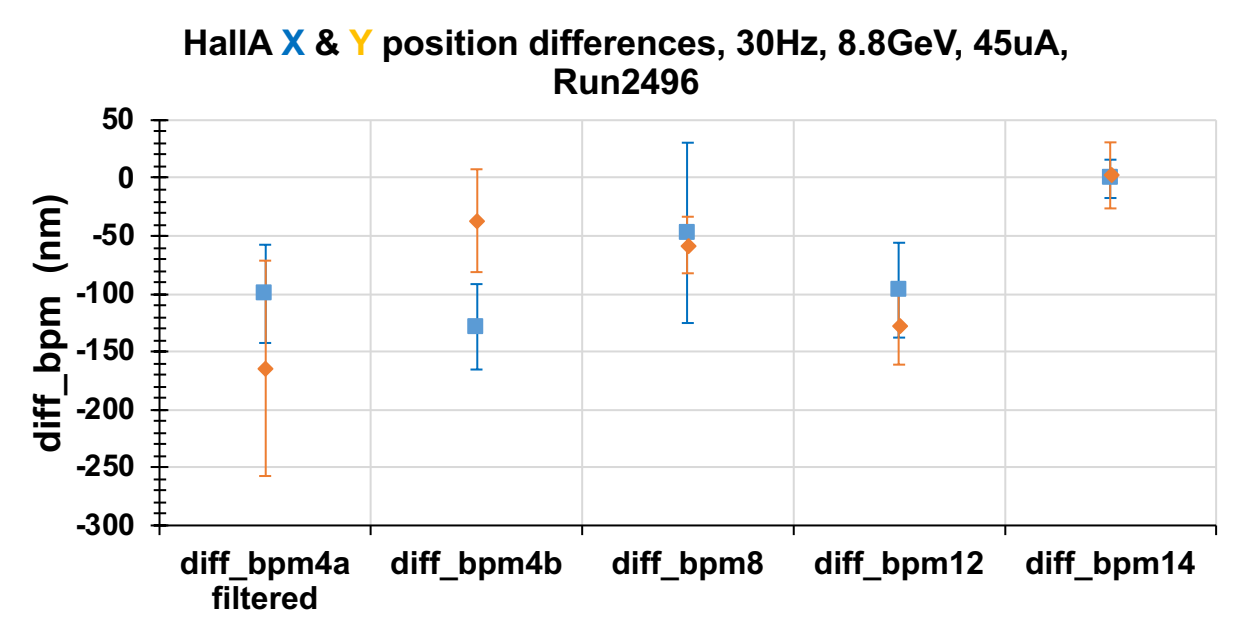
BEAM POSITION DIFFERENCES

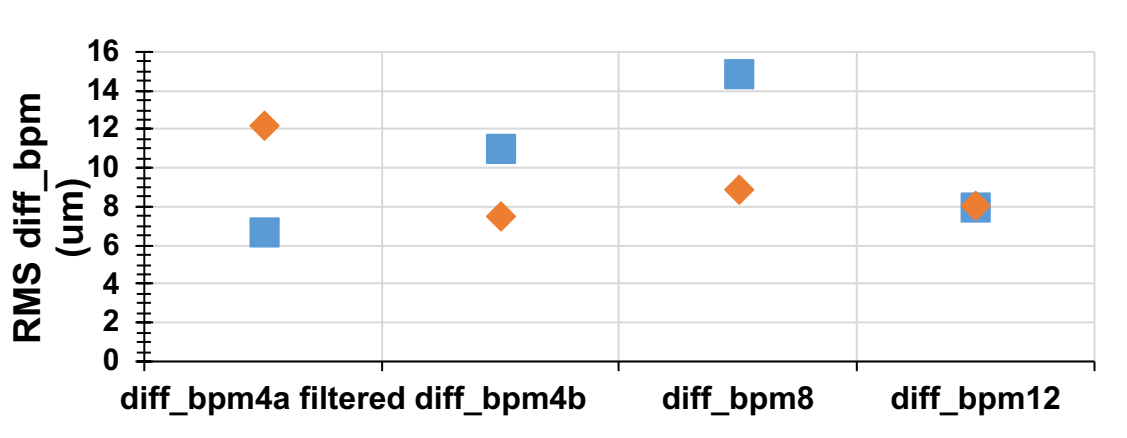
Not very dependent on number of passes

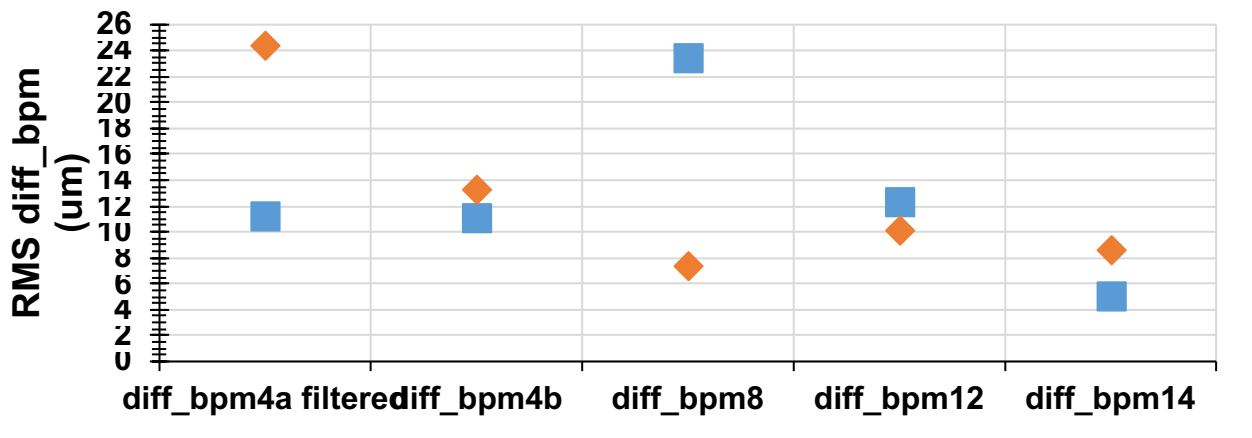
1 pass



4 pass

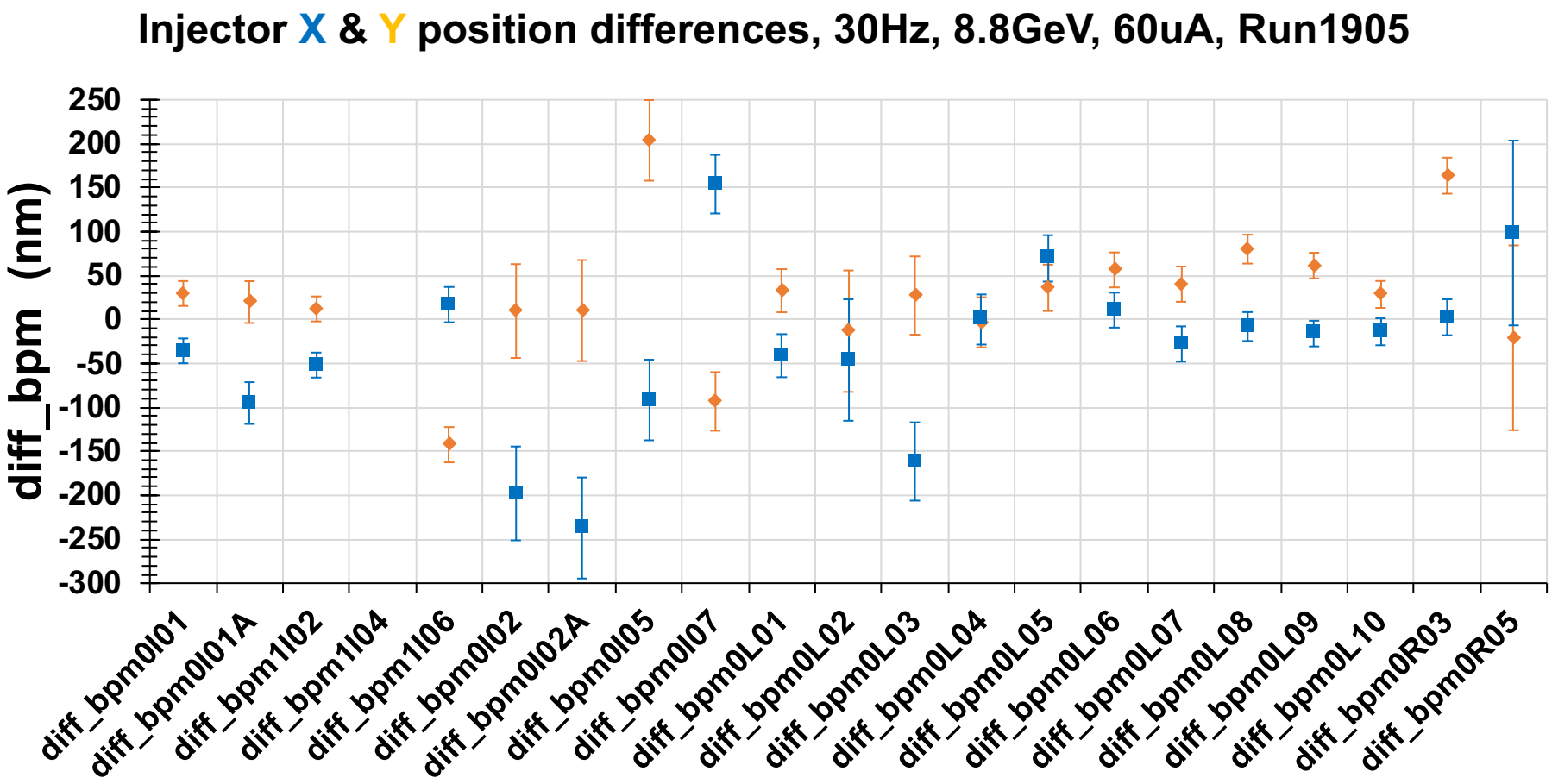






Beam position differences

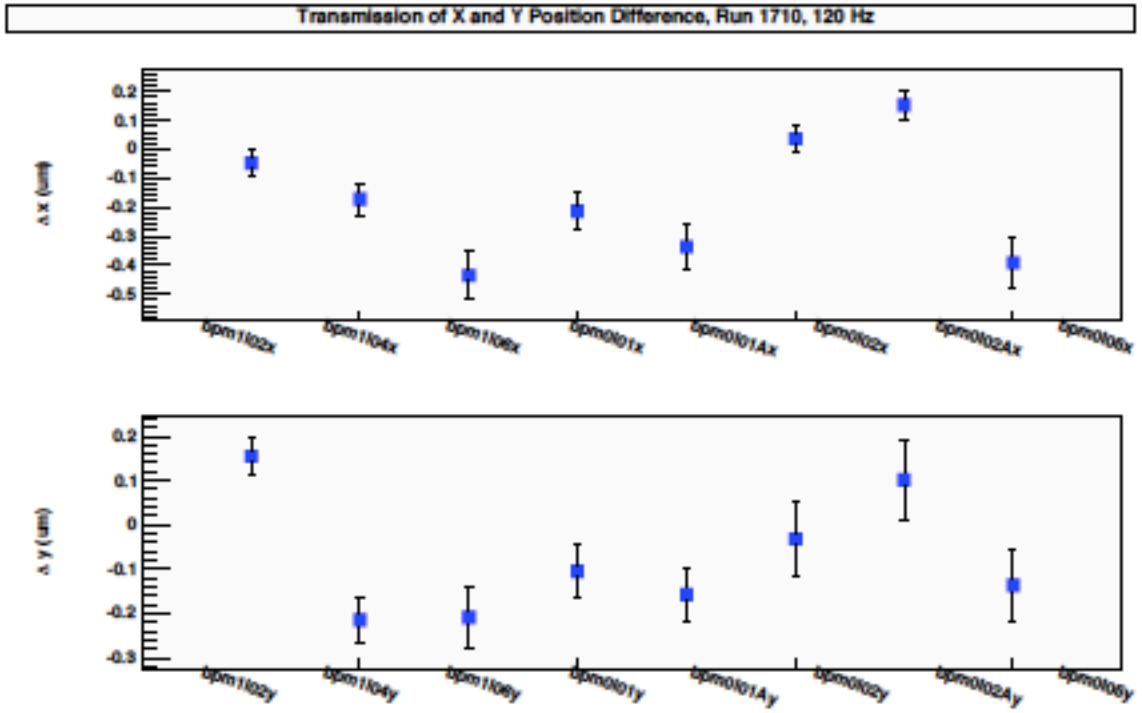
injector

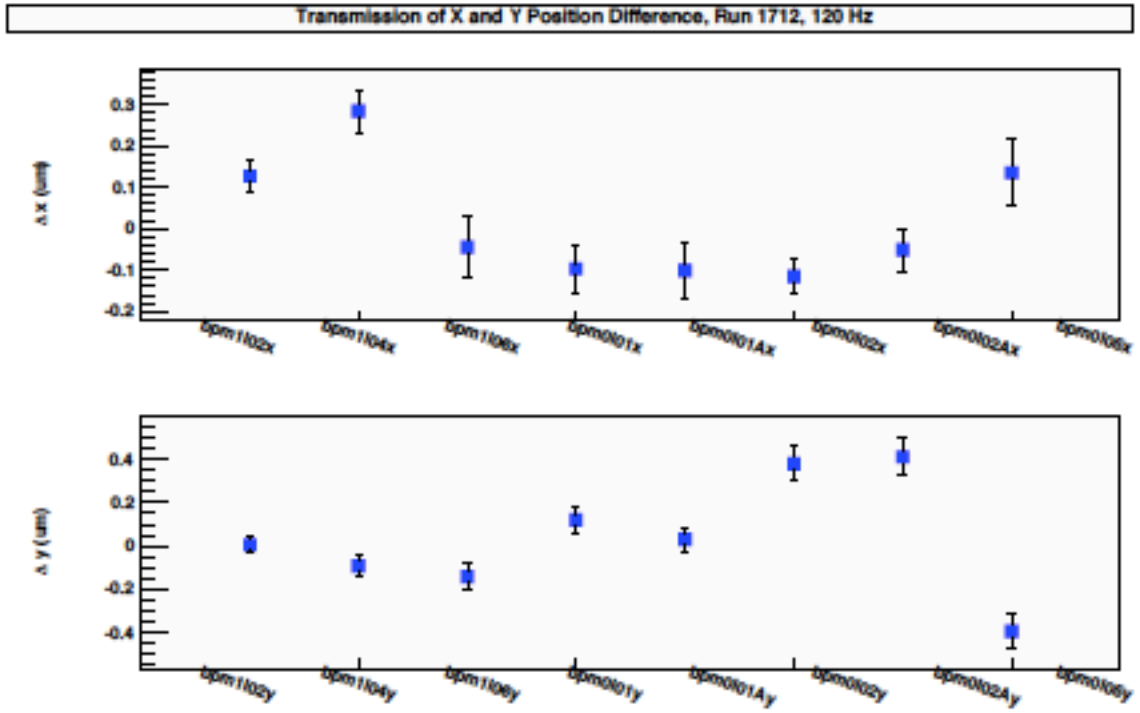


Beam position differences

injector

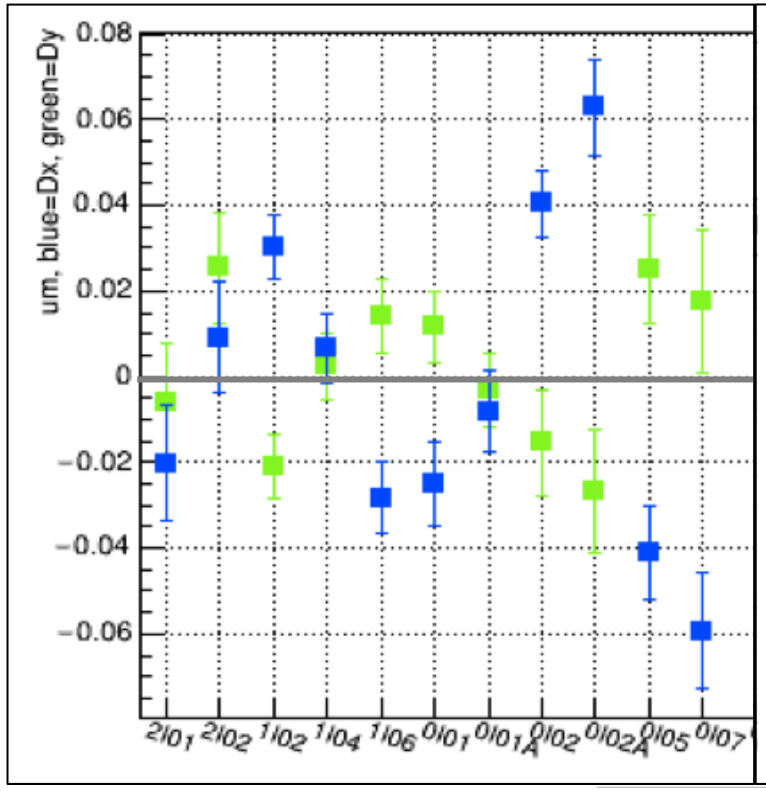
- **PREXI Ref: Silwal Thesis, Fig. 6.7.5**

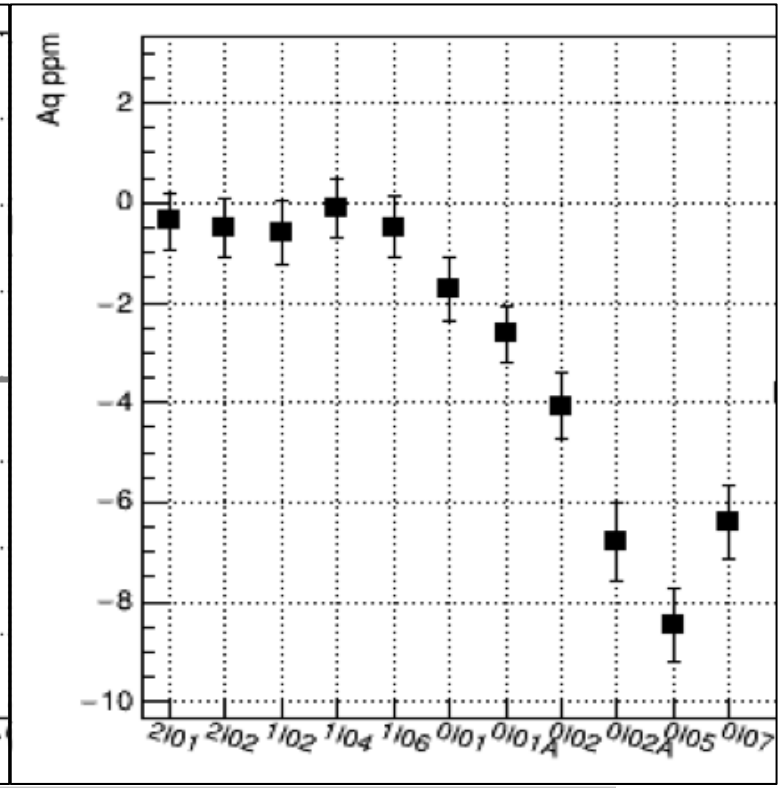




240Hz,Octet

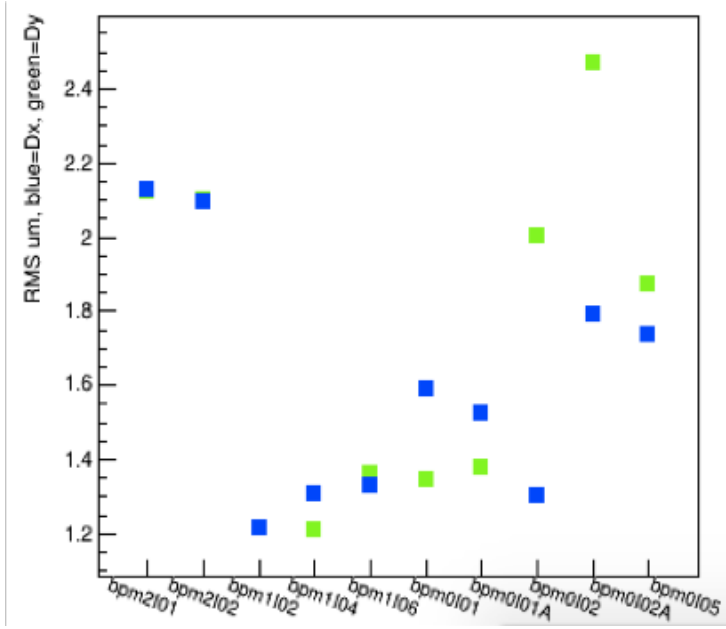
Dx<70nm
Dy <40nm

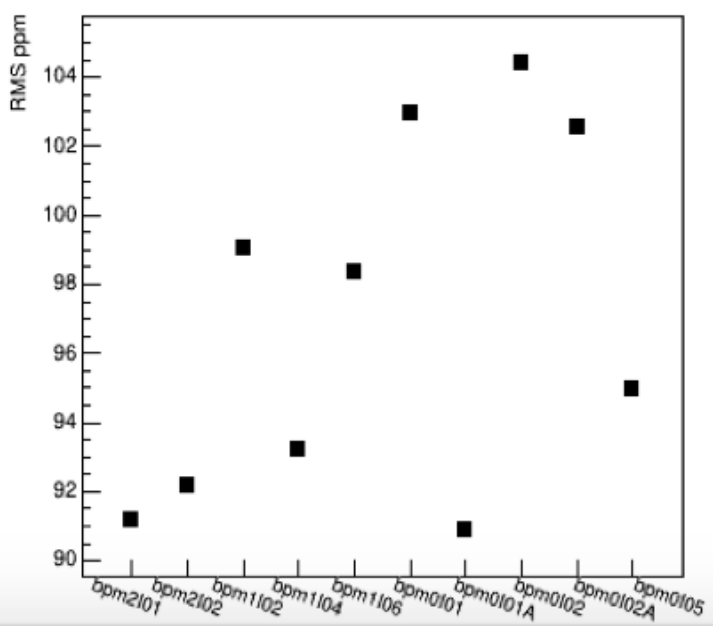




Aq 0-8ppm

RMS 1-3um





RMS
90-100ppm

Run4017IHWPoutRHWP1000

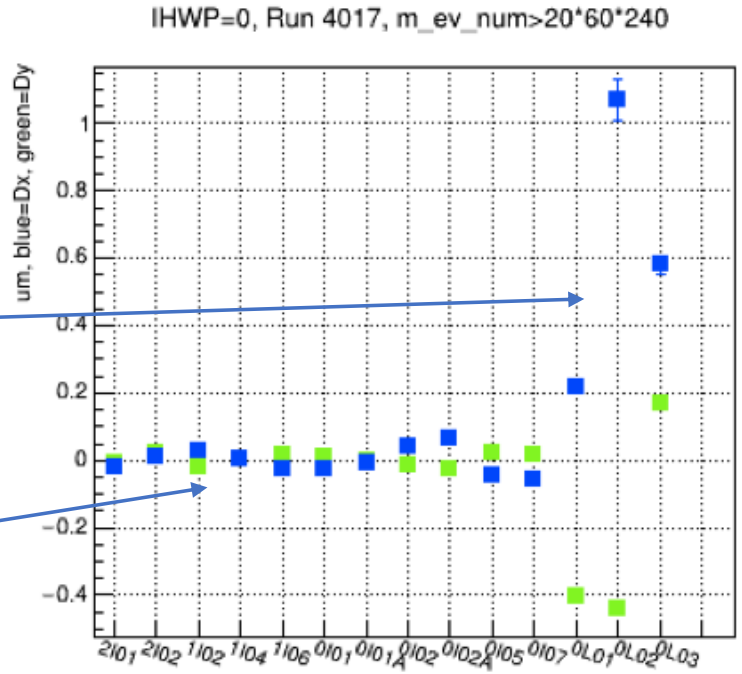
240Hz,Octet

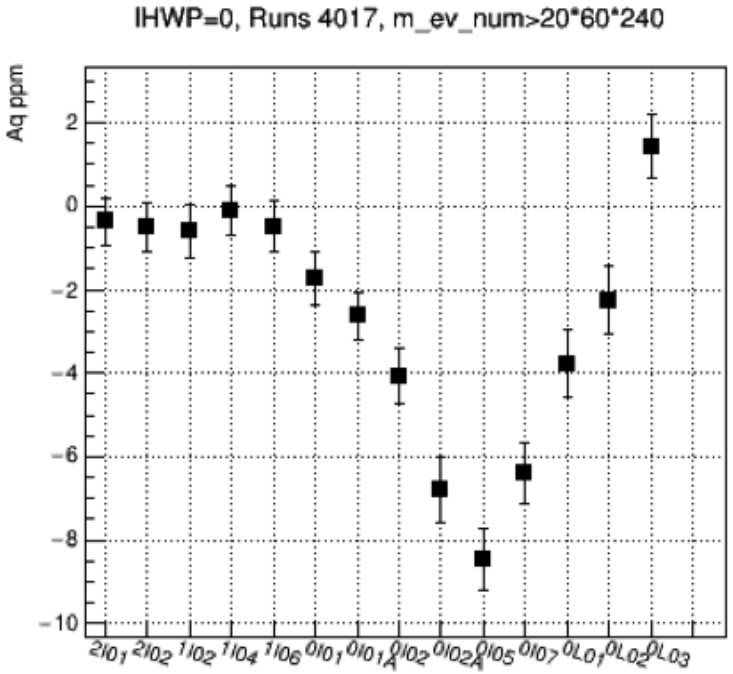
Big

Dx ~ 0.6um

Dy ~0.4um

Tiny<60nm



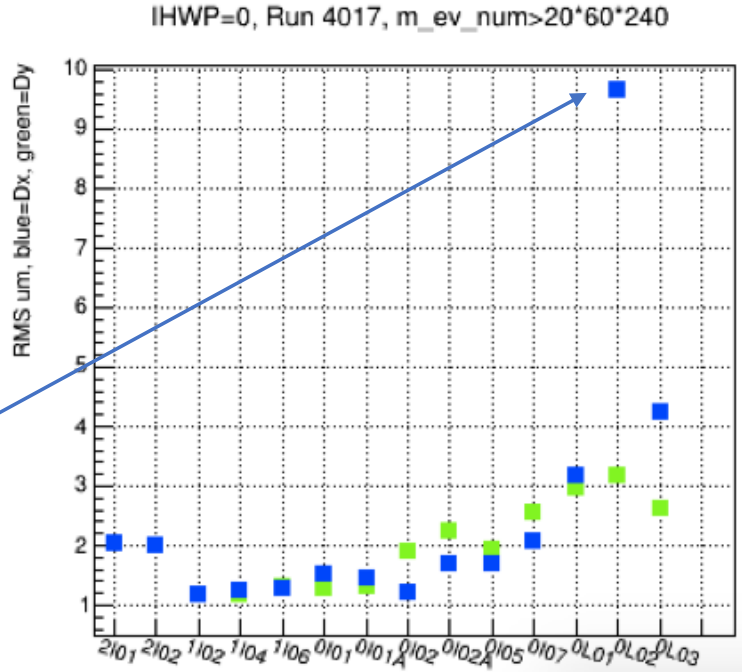


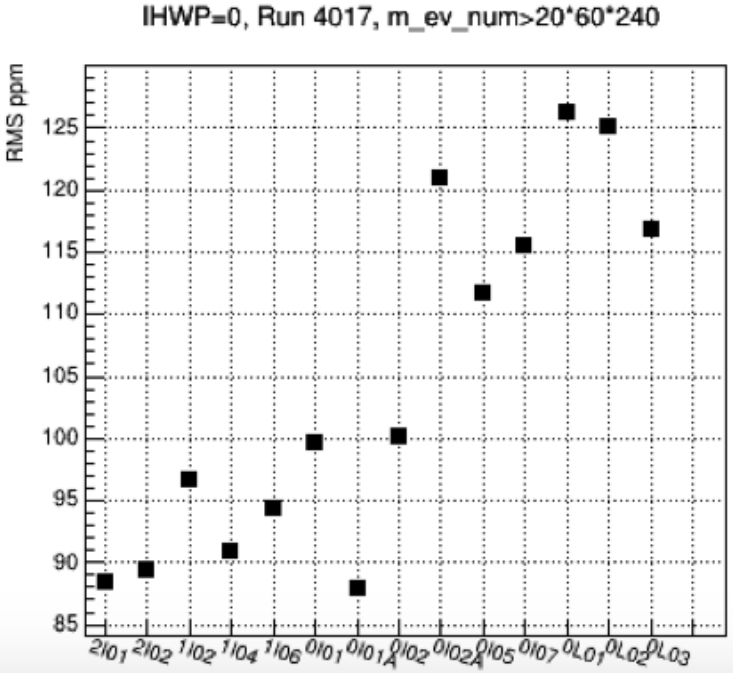
Aq 0-8ppm

Run4017_IHWPout_RHWP1000_FC2_REDO

RMS 1-3um

bpm0L02 may have an issue



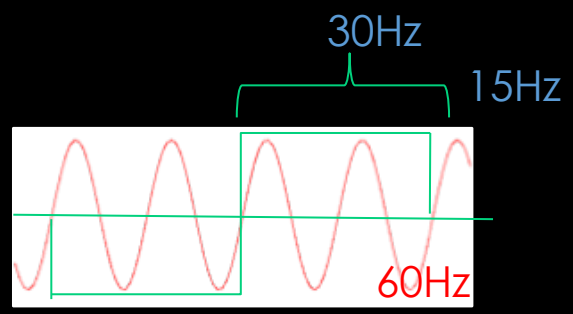


RMS 90-125ppm

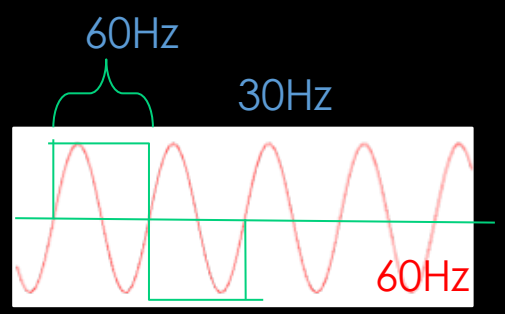
BEAM ASYMMETRY WIDTHS

- To analyze beam asymmetry widths for different frequencies
  - The parity DAQ ADCs oversamples by 4 times the helicity flip rate
  - By examining helicity window subblocks, can mimick ~60Hz and ~120Hz PC flip rates
  - FreeClock instead of Line synch mode during the run, so frequencies are not exact multiples of 60Hz and so 60Hz noise is not filtered out of data as it normally would be and manifests as a beat frequency in ~120Hz subblock analysis
  - By doing quad-like combination of sublocks, can mimick line-sync and filter out 60Hz
  - By decreasing integration time on ADC & examiingng subblocks, can access ~1kHz

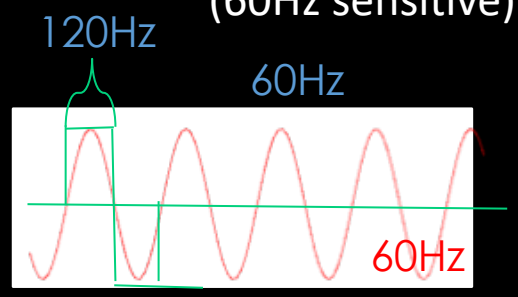
30Hz analysis:
(0-1)/(0+1)



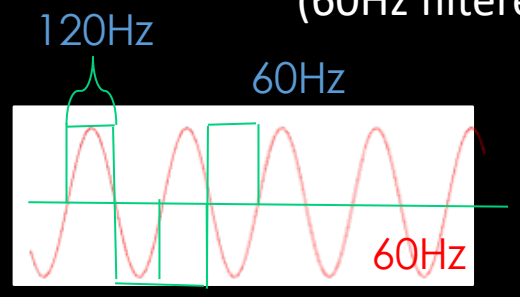
~60Hz analysis:
(b1+b2-b3-b4)/(b1+b2+b3+b4)



~120Hz analysis:
(b1-b2)/(b1+b2)
(60Hz sensitive)

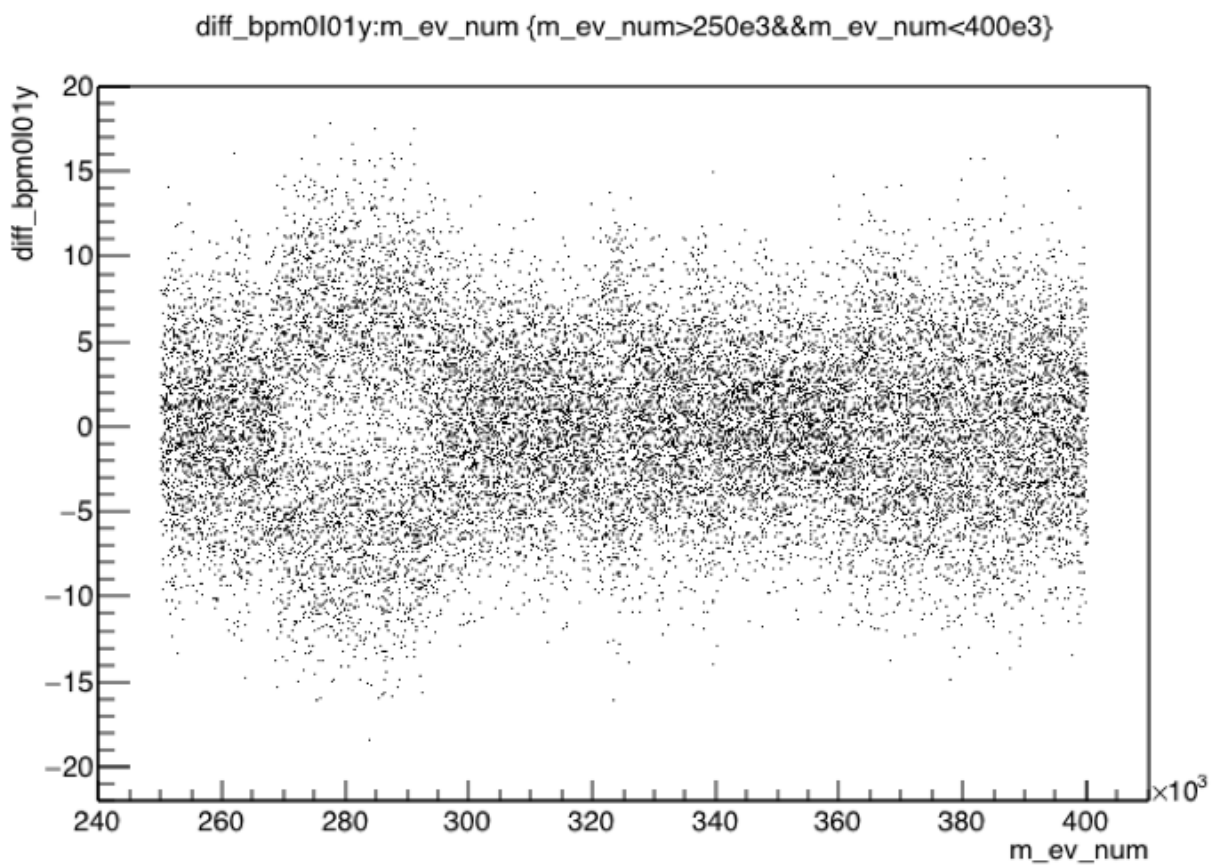


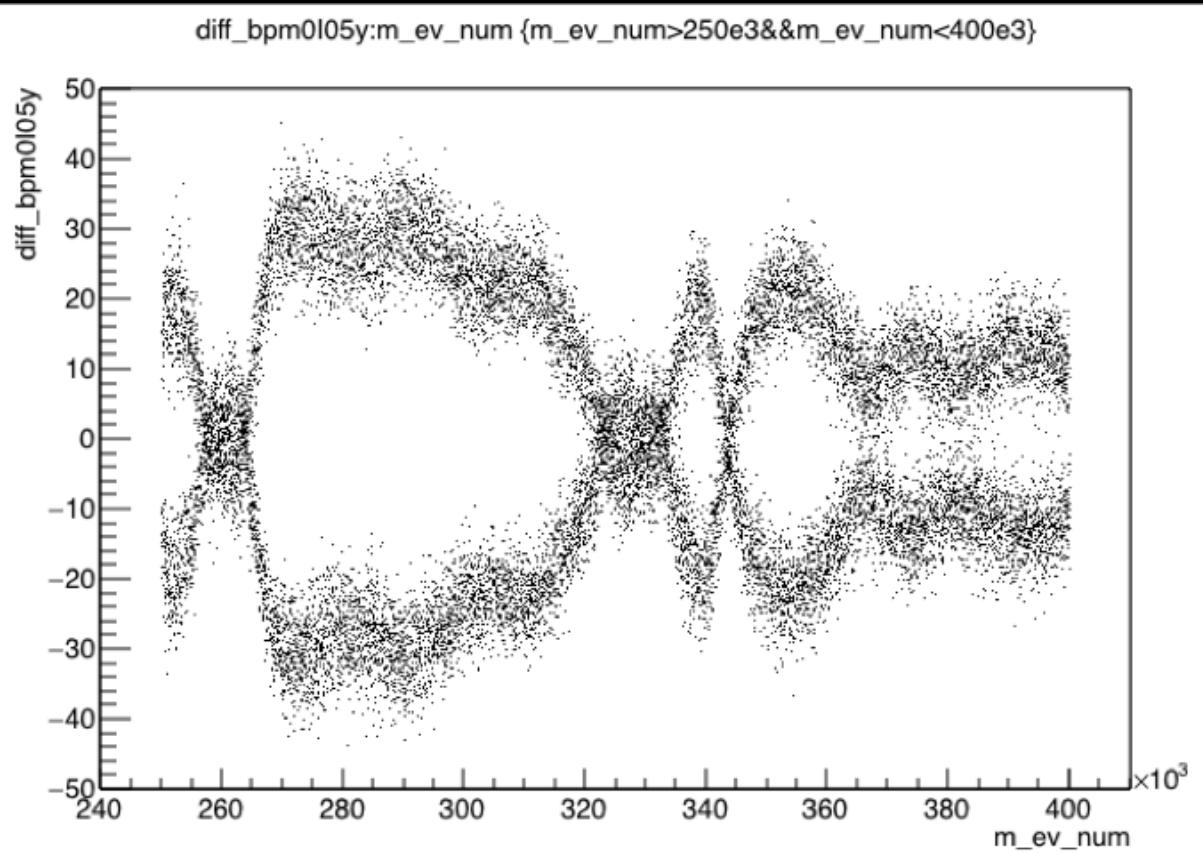
~120Hz line-synch-like analysis:
1/2((b1-b2)/(b1+b2)+ (b4-b3)/(b3+b4)
(60Hz filtered out)

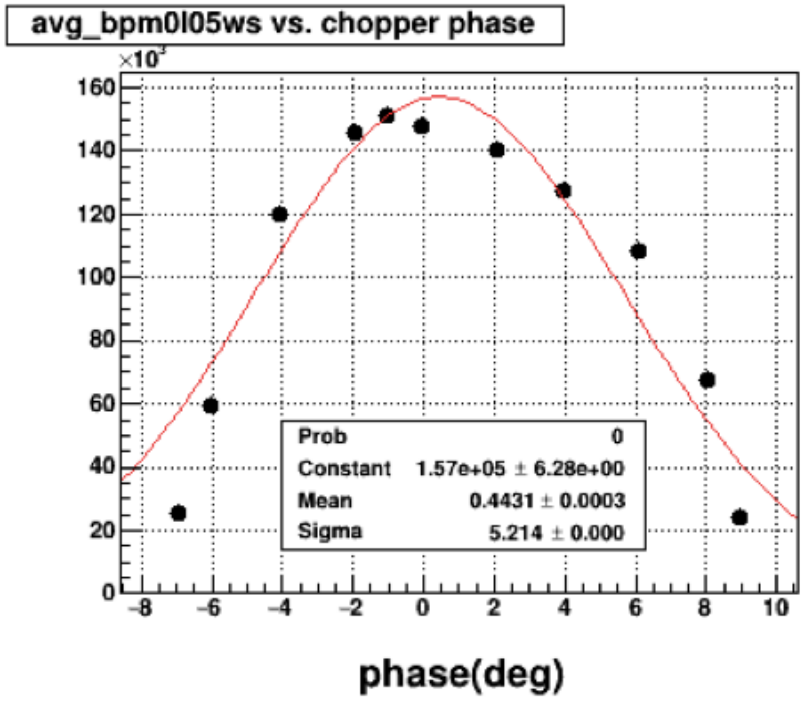


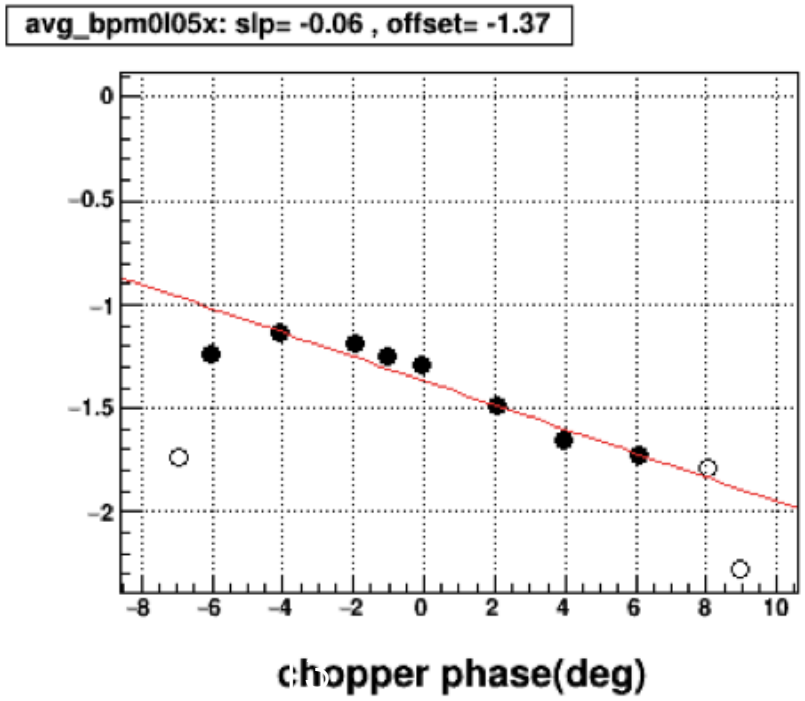
SOME OF THE RMS MAY NOT BE NORMAL NOISE

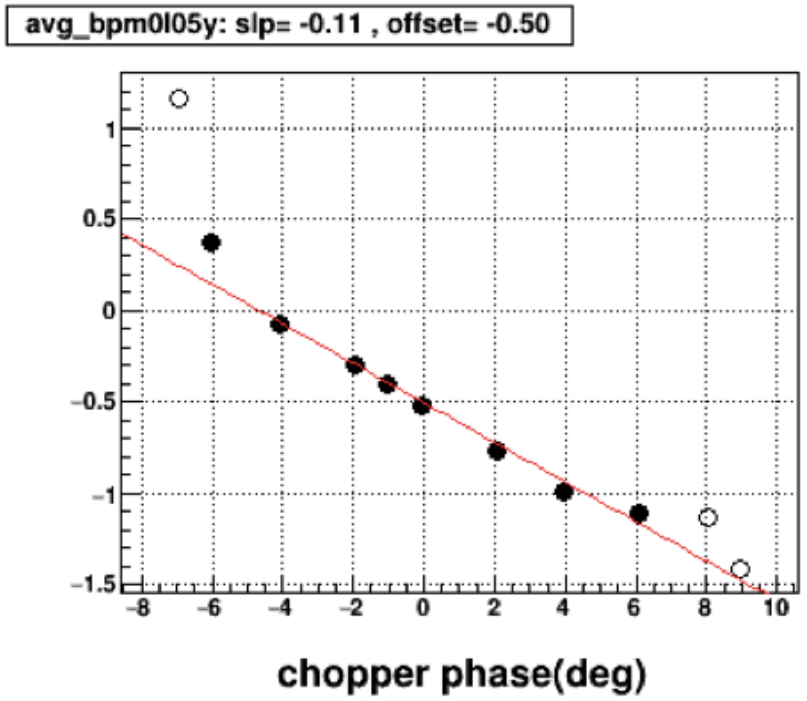
- Run3330 , 960Hz Mtree, Free clock, 40us Tsettle, 1001.65usec Tstable, Octet No Delay, 960.02Hz → periodicity >150e3 events, T >156s, <0.0064Hz beat and (960-960.02Hz)/8=0.0025Hz
- vqwk SamplesPerBlock=120, GateDelay=10, NumberofBlocks=4 (2us/sample)

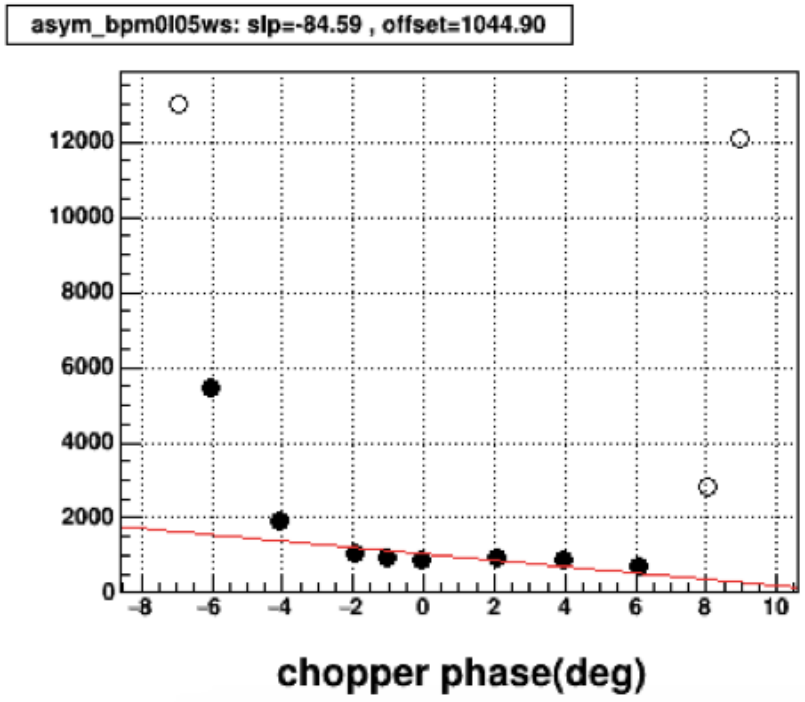


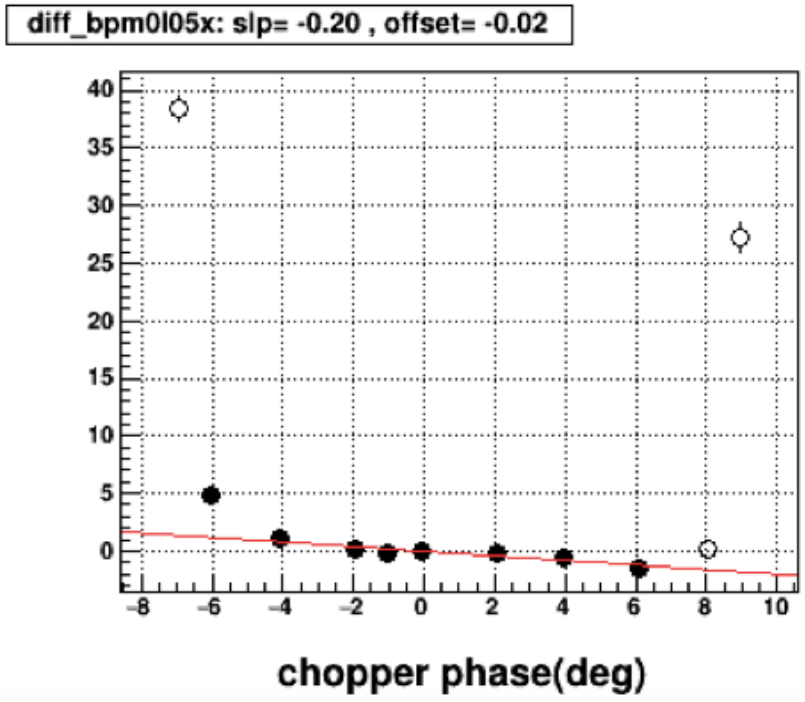


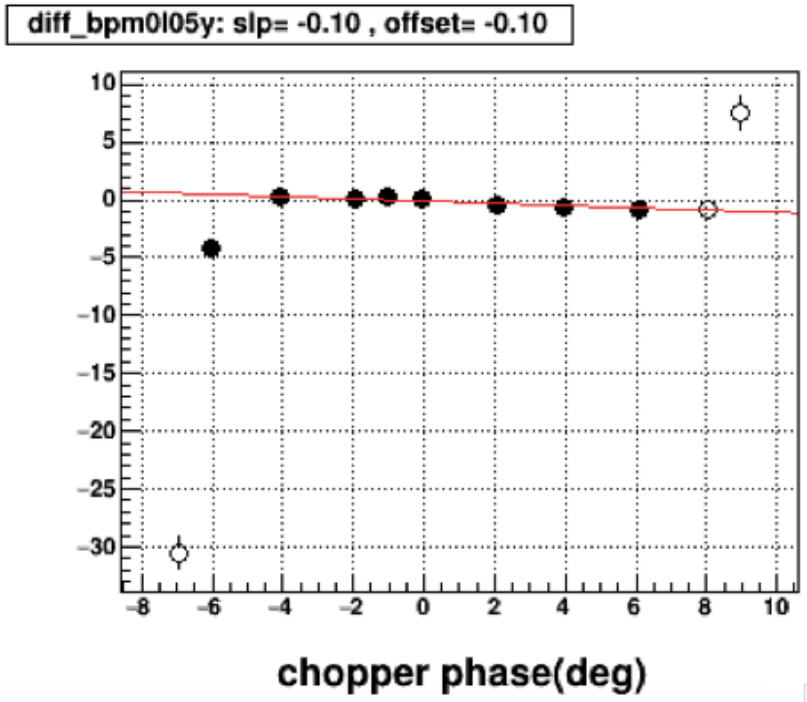

avg_bpm0l05ws vs. chopper phase
×10³
Prob 0
Constant 1.57e+05 ± 6.28e+00
Mean 0.4431 ± 0.0003
Sigma 5.214 ± 0.000
phase(deg)


avg_bpm0l05x: slp= -0.06 , offset= -1.37
chopper phase(deg)


avg_bpm0l05y: slp= -0.11 , offset= -0.50
chopper phase(deg)


asym_bpm0l05ws: slp=-84.59 , offset=1044.90
chopper phase(deg)


diff_bpm0l05x: slp= -0.20 , offset= -0.02
chopper phase(deg)


diff_bpm0l05y: slp= -0.10 , offset= -0.10
chopper phase(deg)

WHAT IS PARITY QUALITY?

- What does Parity Quality Beam mean? Small helicity correlated changes
- How is it achieved? Pockels Cell centering, RHWP & photocathode rotation,
- Do we have it? We are in position to get it as far as we can tell.
- Will we have it? Yes, with some small adjustments to the source alignment.
- Are the monitors working? We have sufficient monitors currently operational to perform a parity experiment. We want to optimize the additional monitors.
- Are the Parity DAQs running? Yes.
- Is the beam usable? Yes. If the beam can be delivered to the hall, it is usable for parity experiments.
- What about the noise? Widths look similar to the past (note Parity DAQ filters much of the beam noise out, so that frequency contributions not near the flip rate are suppressed)

PARITY QUALITY BEAM GOALS

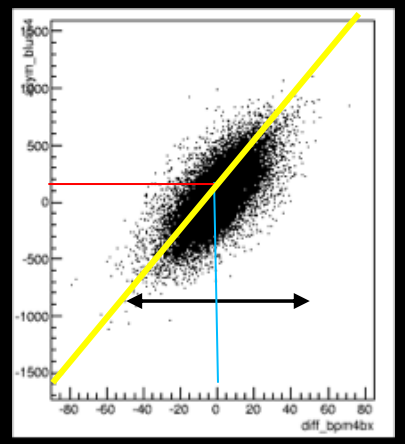
$$A_{raw} = A_{det} = A_0 + \alpha\Delta_E + \sum_i \beta_i \Delta x_i$$

MONITOR: I,E,X,Y

- Mean Values
  - Helicity correlated differences – Aq, Dx,Dy – Means of distributions
  - Want to minimize helicity correlated changes: Aq & position difference (*<100ppb , <1nm, spot size asym dSigma/sigma<10^-4)*
- Widths
  - RMS fluctuations after parity filtering (integration and pair difference, much frequency content is suppressed)
  - Want small widths to reduce statistical error on measurements of mean values
  - Want sufficient width to establish correlations with monitors (ie slopes) & perform regression to get corrections(ie shifts) to reduce systematic error contributions to asymmetry from helicity correlated beam differences (ie. means)

Slope

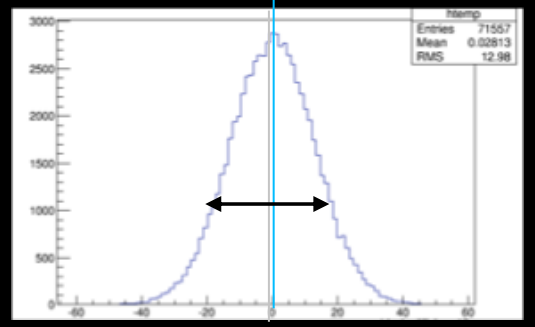
Measured Asymmetry



Position difference

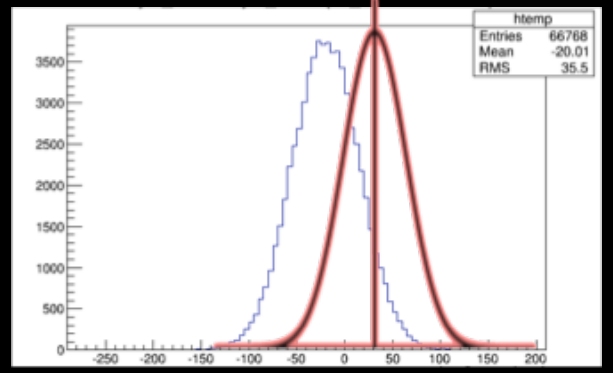
x

Mean



Position difference

Shift



=

Raw asymmetry

Corrected asymmetry

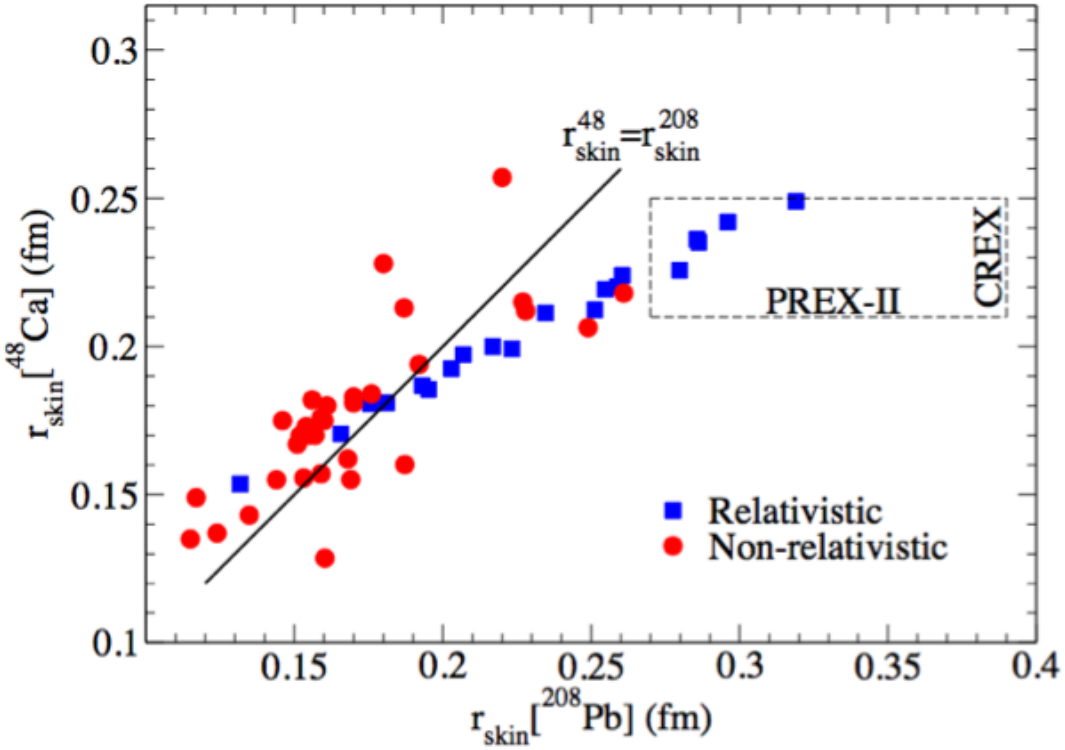
^{48}Ca

bridge between *ab initio* models and effective theory (DFT)

^{48}Ca:

- finite size effects.
- Within reach of microscopic calculations

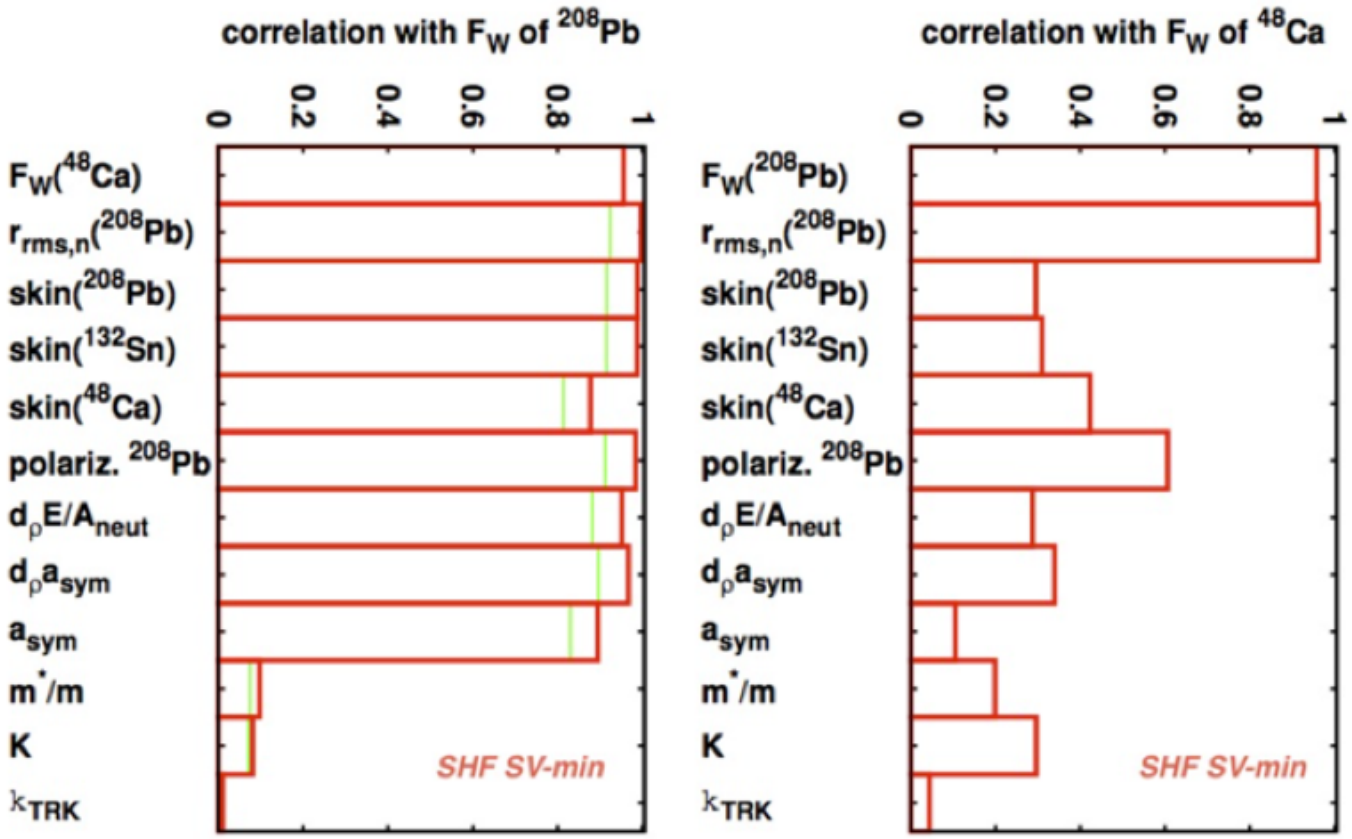
coupled-cluster model of ^{48}Ca:
G. Hagen *et al*, Nature Physics **12**, 186–190 (2016)



^{208}Pb:

- uniform nuclear matter
- terrestrial laboratory to test n-star structure

^{208}Pb & ^{48}Ca: Complementary sensitivity



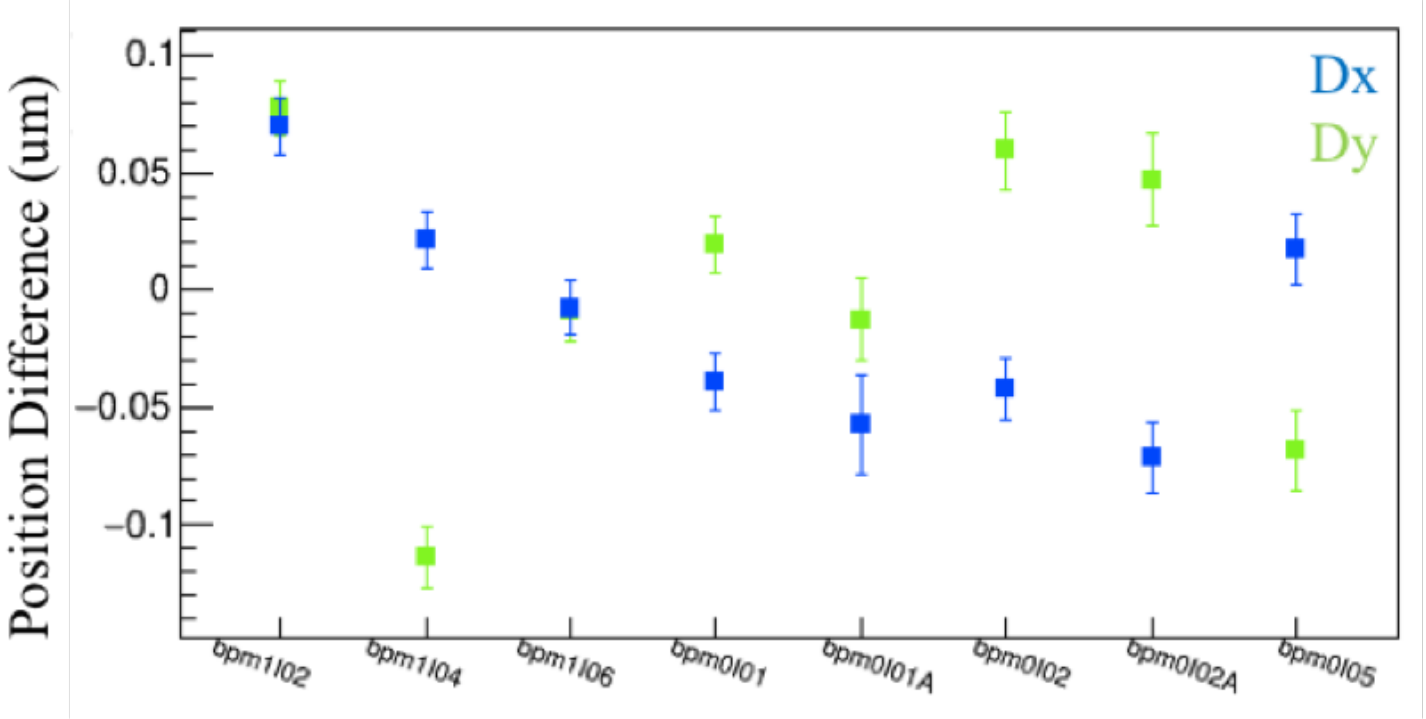
Jorge Piekarewicz

PARITY MEASUREMENTS CARE ABOUT

- Widths: Beam noise, Monitor Noise
  - RMS fluctuations after parity filtering (integration and pair difference)
  - Want sufficient width to establish correlations, obtain slopes, perform regression to reduce systematic error contributions to asymmetry
  - Want small widths to reduce statistical error on measurements of mean values
- Mean values: Charge asymmetry, Position differences, Spot-size Asymmetry
  - Helicity correlated differences – Aq, Dx,Dy – Means of distributions
  - Want to minimize these

Using the RTP-crystal Cell at Nat'l Accelerator Facility

The RTP Pockels Cell successfully produced e- beam which achieved <100nm position differences in the e- accelerator at JLab:

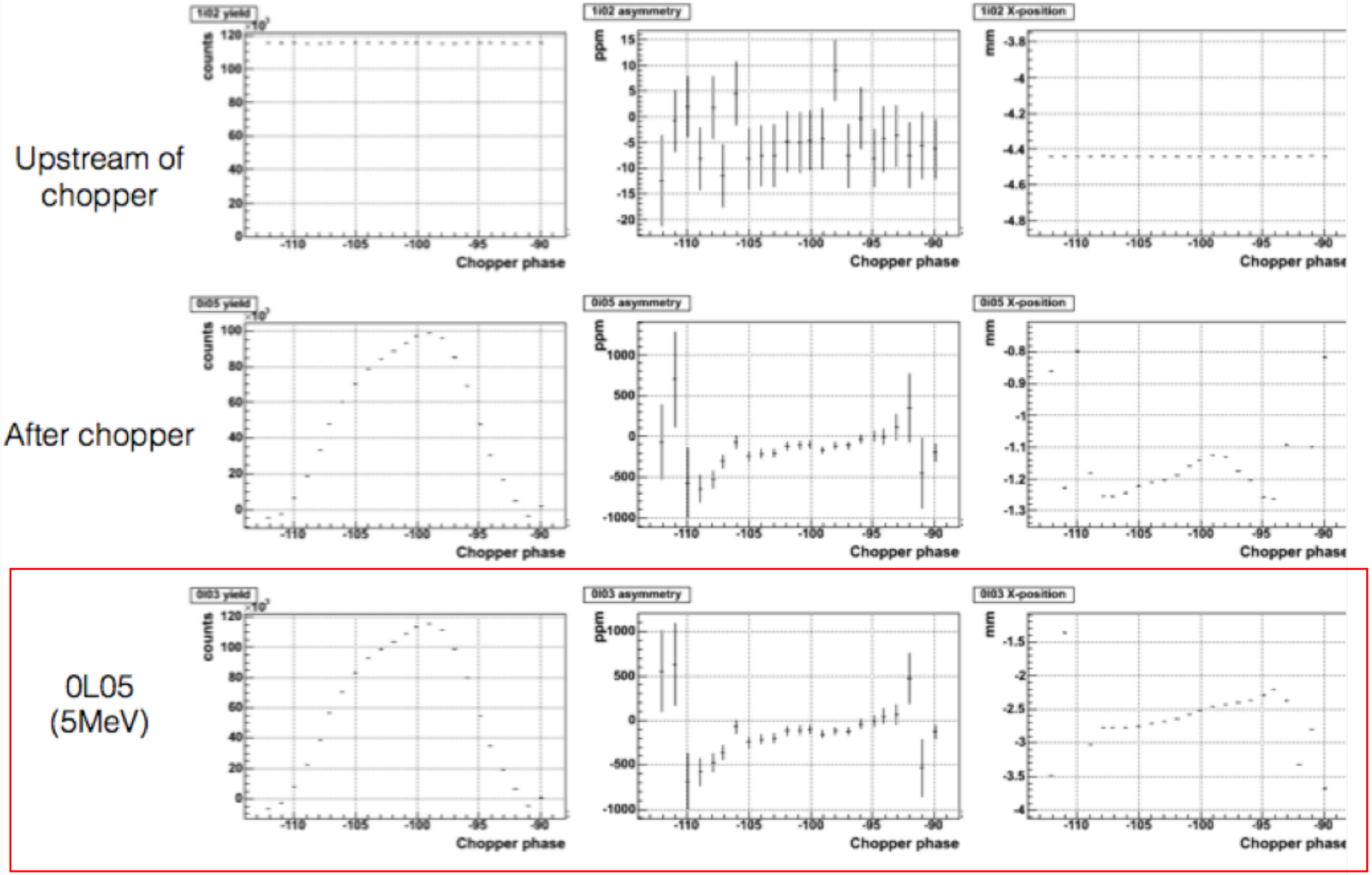


- Voltages were found to control steering position differences as predicted
- Position corrections ultimately used were small <100V (2000V range)

Asymmetry vs. bunch position

Narrow slit, scanning chopper phase to measure portions of each bunch

ELOG:Beam:259 [Manolis]



http://qweak.jlab.org/elog/Beam/259

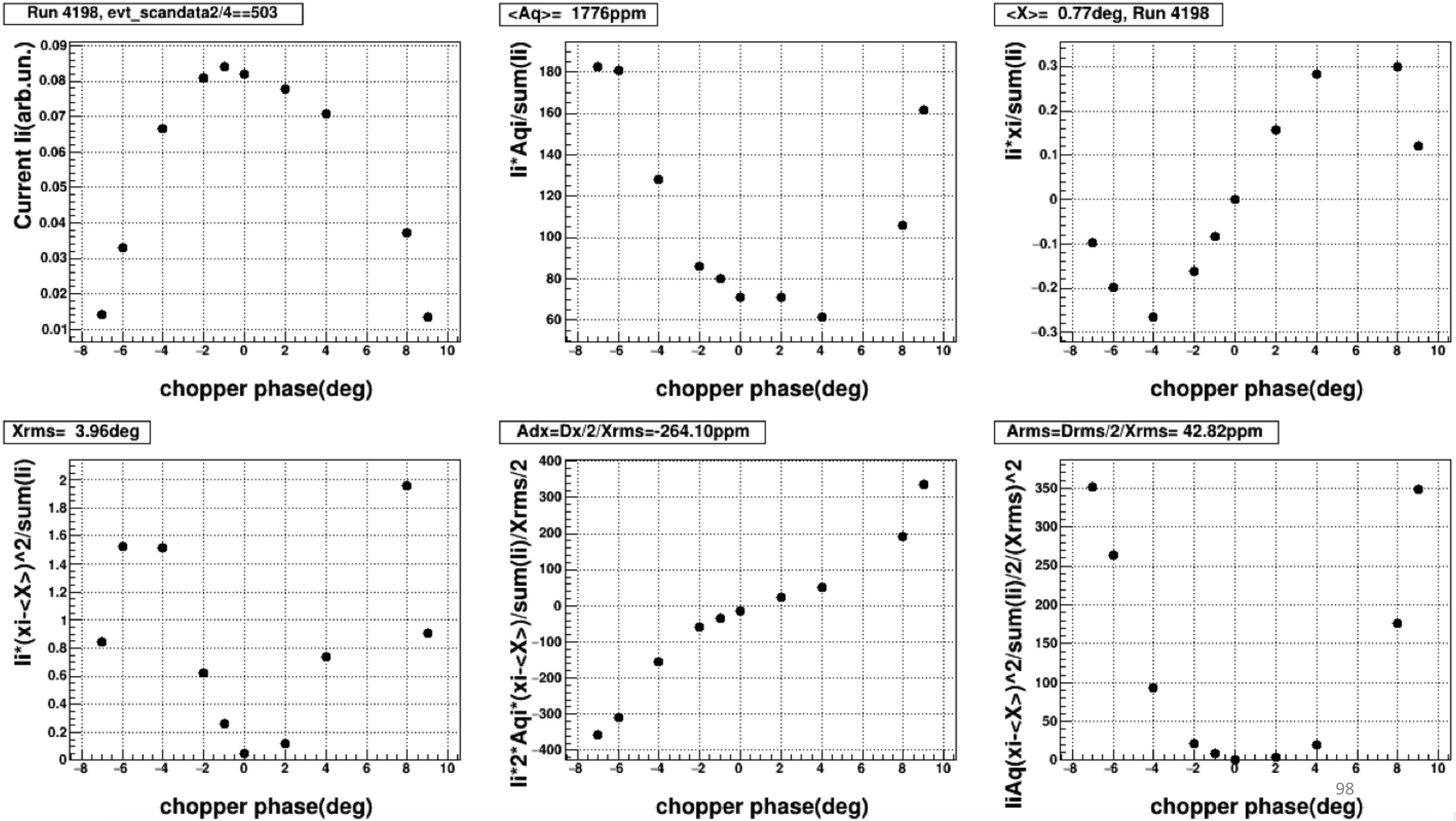
500MHz

Δt=55ps pulse

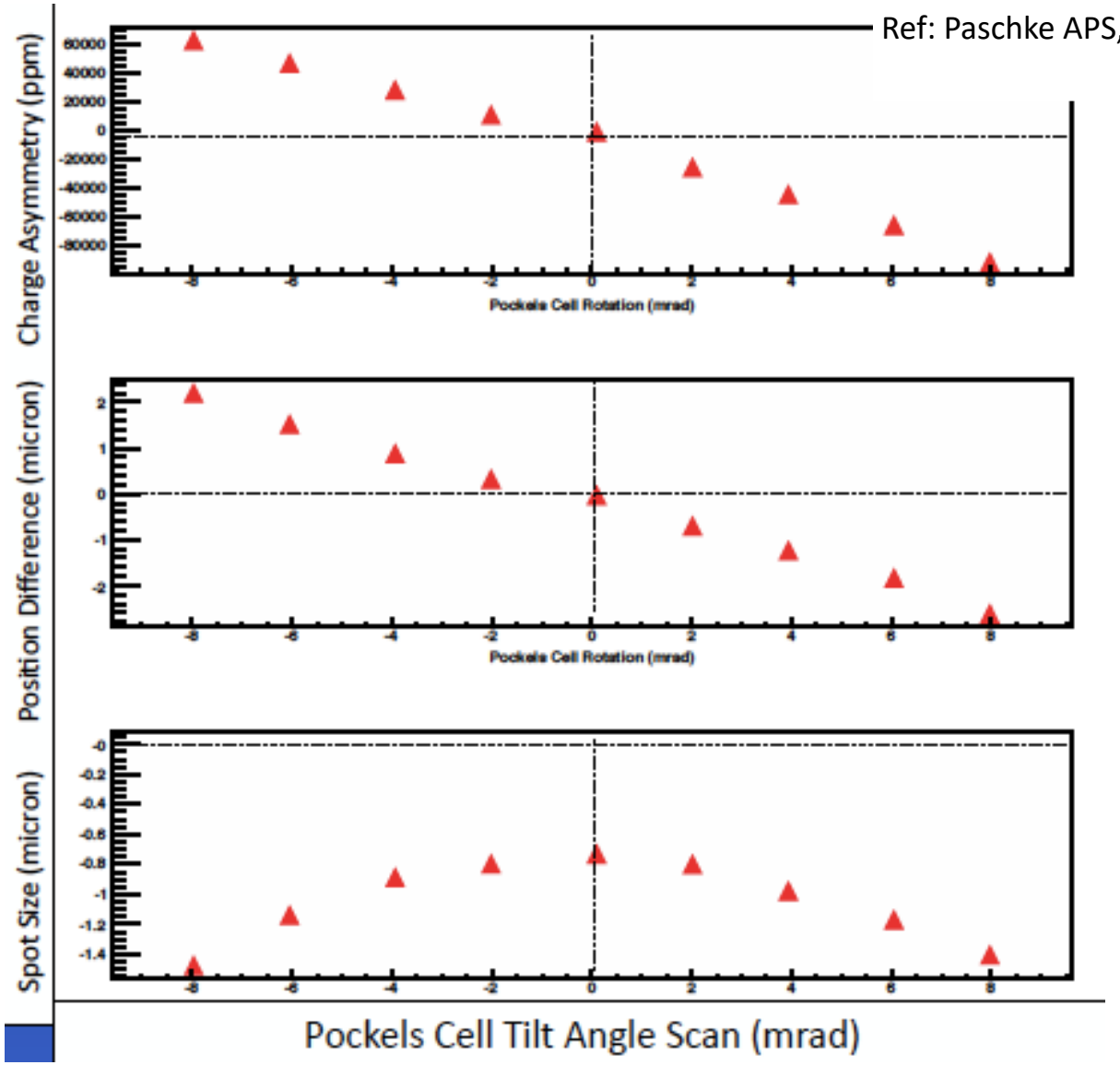
ΔAq=400ppm

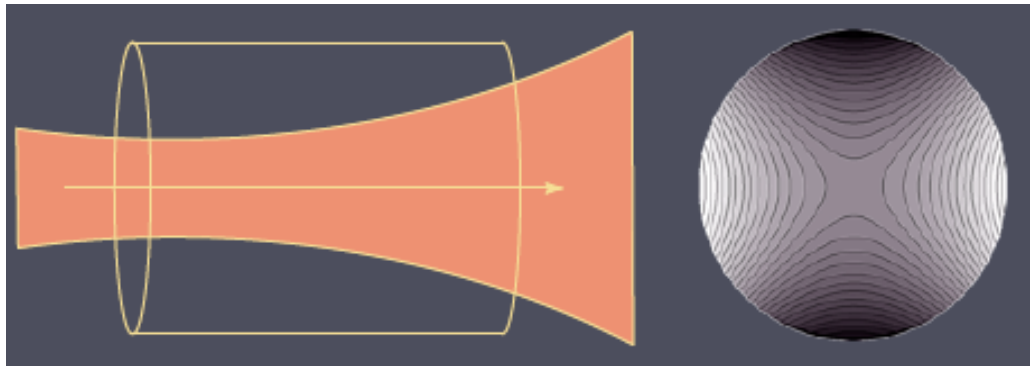
ΔX=0.5mm

- 50min+10min questions
- Cover PREX some
- Cover beamline studies showing we can do Moller statistically
- ¼ of work should be RTP injector stuff
- Showcase I know what it takes to do an experiment
- What do I want to showcase?


Run 4198, evt_scandata2/4==503
Current Ii(arb.un.)
chopper phase(deg)
<Aq>= 1776ppm
Ii*Aqi/sum(Ii)
chopper phase(deg)
<X>= 0.77deg, Run 4198
Ii*xi/sum(Ii)
chopper phase(deg)
Xrms= 3.96deg
Ii*(xi-<X>)^2/sum(Ii)
chopper phase(deg)
Adx=Dx/2/Xrms=-264.10ppm
Ii*2*Aqi*(xi-<X>)/sum(Ii)/Xrms/2
chopper phase(deg)
Arms=Drms/2/Xrms= 42.82ppm
IiAq(xi-<X>)^2/sum(Ii)/2/(Xrms)^2
chopper phase(deg)

Minimize Spot Size Asymmetry: Angle Dependence





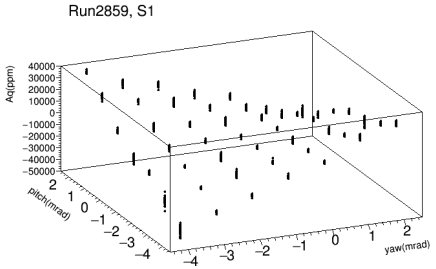
- Off-axis beam mixes index of refraction between ordinary and extraordinary axes
- Divergent beam couples to asymmetry
- Angle couples to position

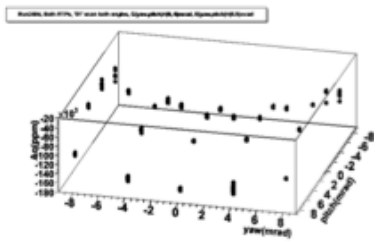
Result: a position-sensitive asymmetry

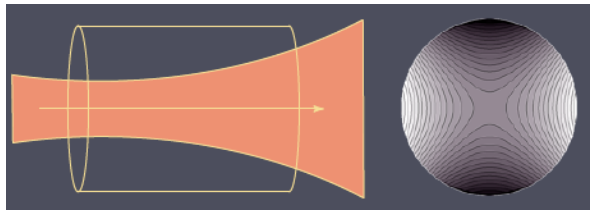
- this effect will lead to “quadrupole” breathing mode of beam spot.
- Hence a spot-size asymmetry

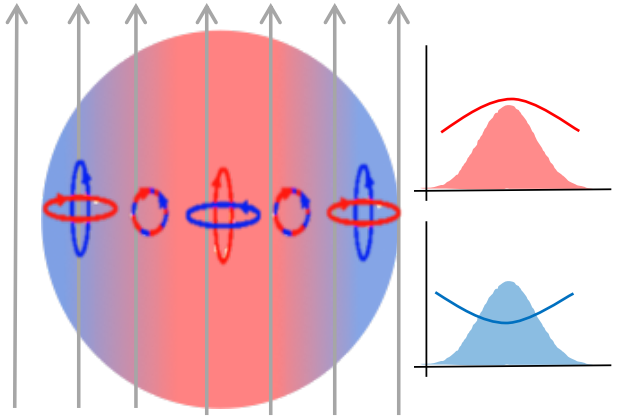
Spot Size Asymmetry

2nd moment – HCBA angle dependence

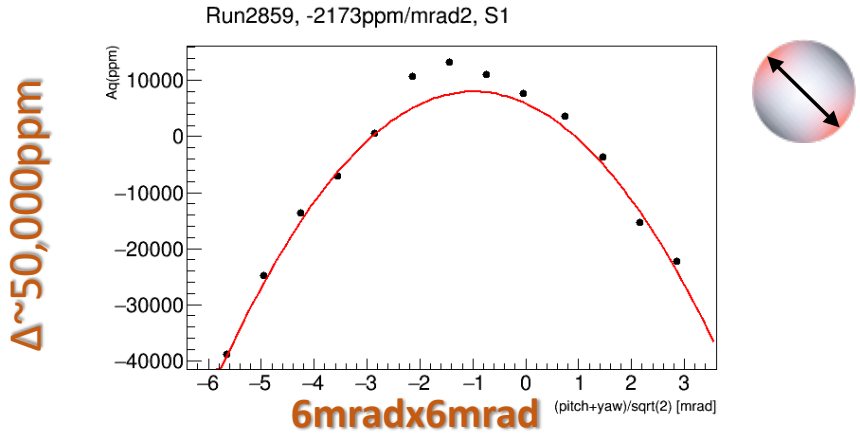


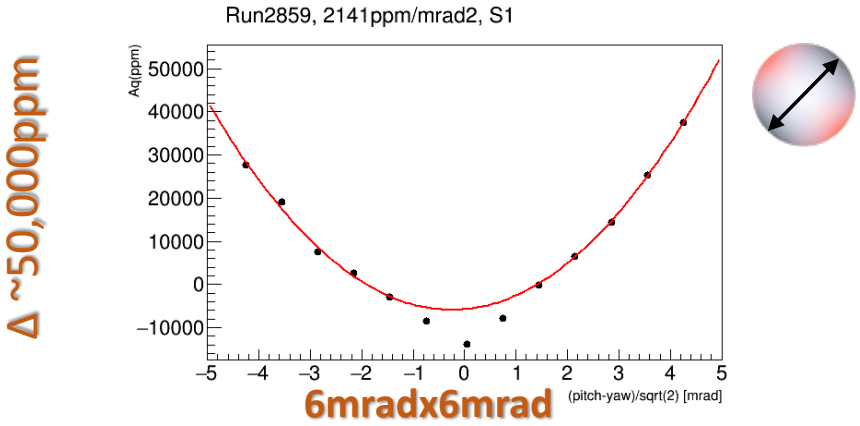






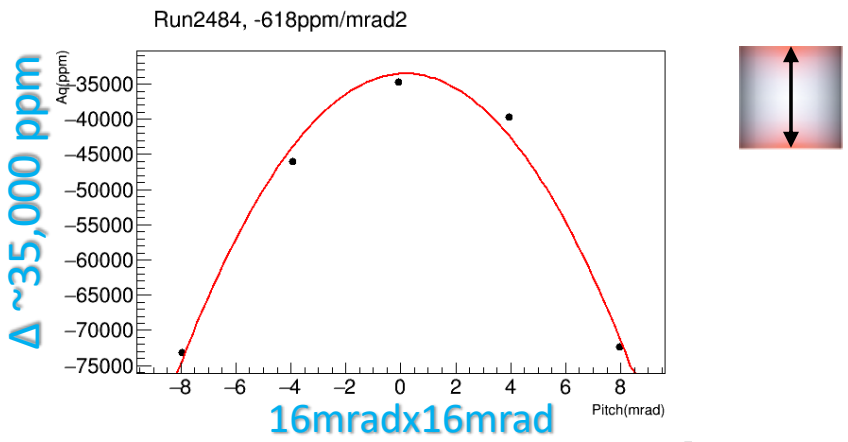
KD*P Cell

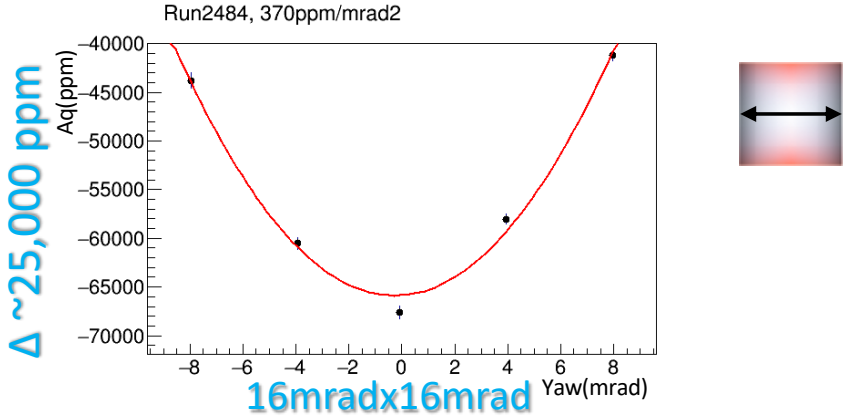




- ~2100ppm/mrad^2

RTP Cell

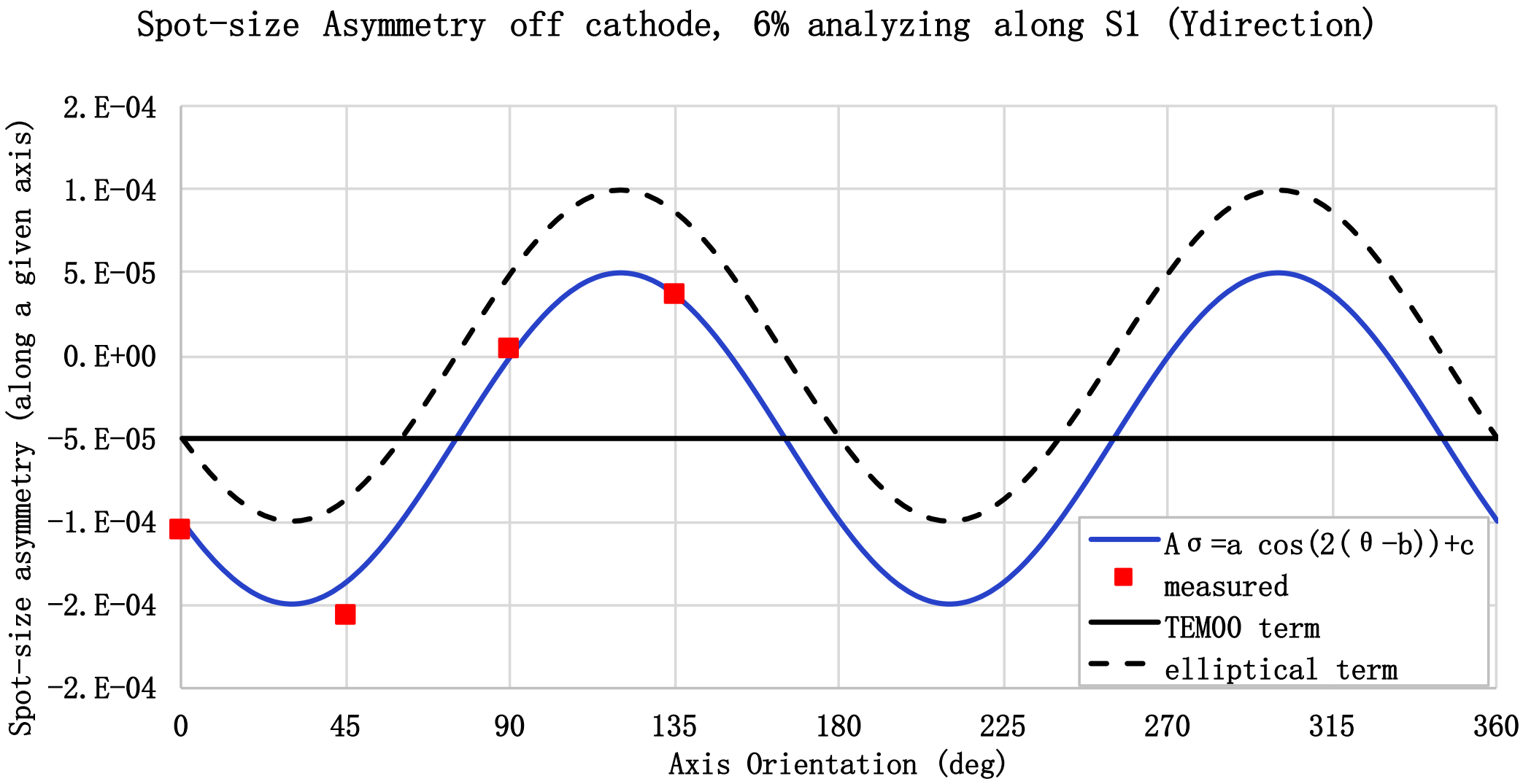




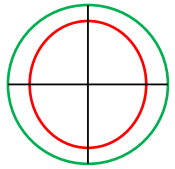
- ~600ppm/mrad^2
- <u>4-7x smaller depence on angle</u>

Spot Size Asymmetry

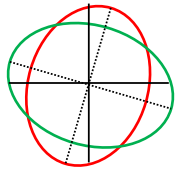
From laser table measurements: <2x10^{-4}



Circ. mode



Elliptical term



Aσ = a cos(2(θ-b)) + c

MODEL by-eye

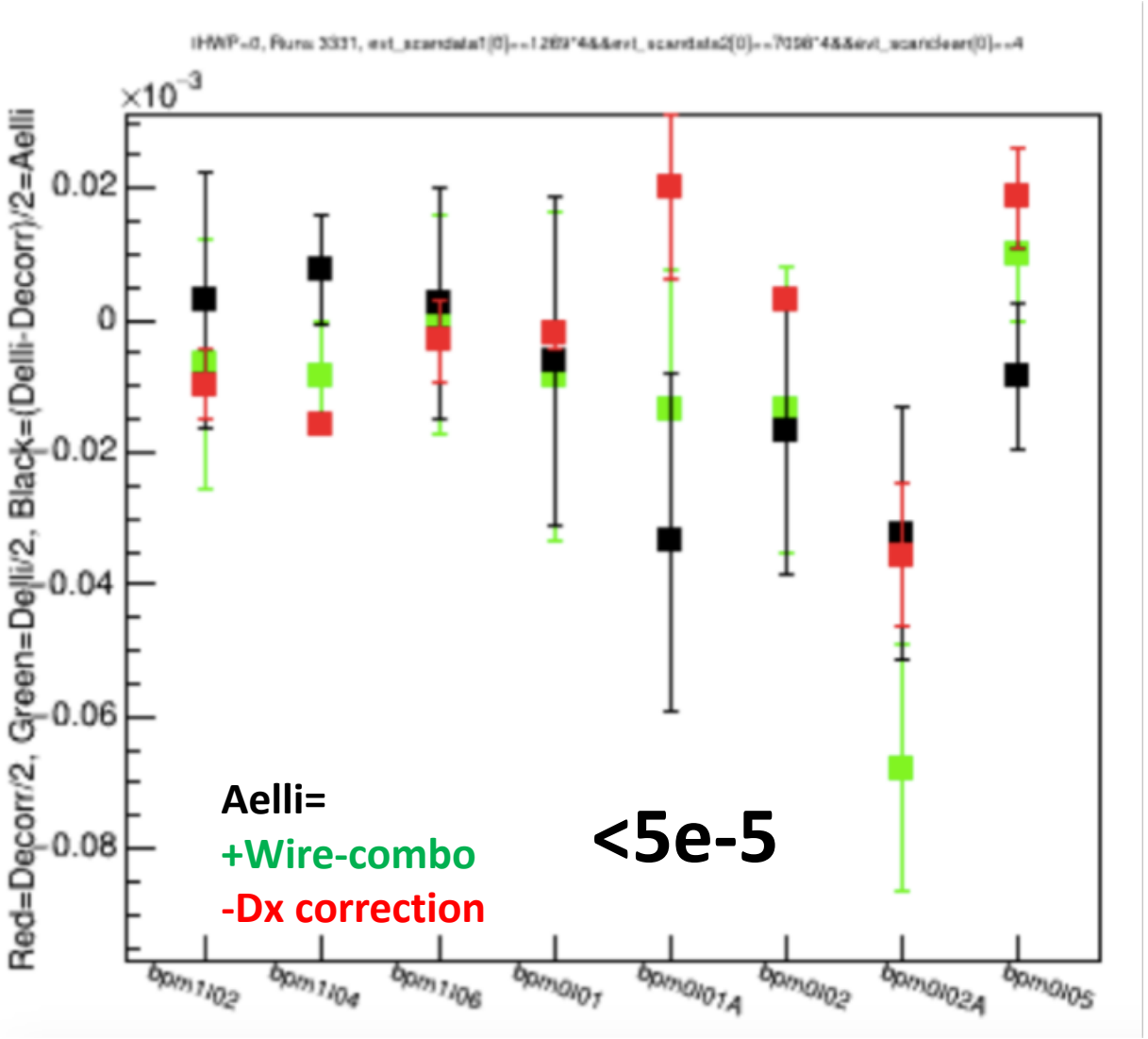
a	-1.00E-04
c	-5.00E-05
b	30

$$A_\sigma(\theta) = A_{circ} + A_{elli}\cos(2(\theta - \theta_0)),$$

Spot Size Asymmetry

From electron beam measurements: <5e-5 (elliptical term)

$$A_\sigma(\theta) = A_{circ} + A_{elli}\cos(2(\theta - \theta_0)),$$



RTP - 240Hz, octet, Run3331

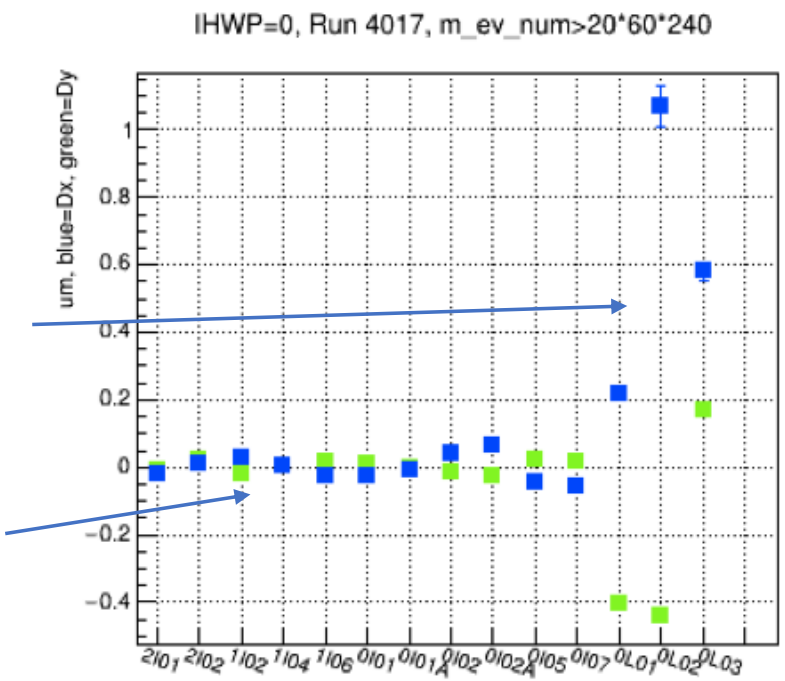
Using the RTP-crystal Cell at Nat'l Accelerator Facility

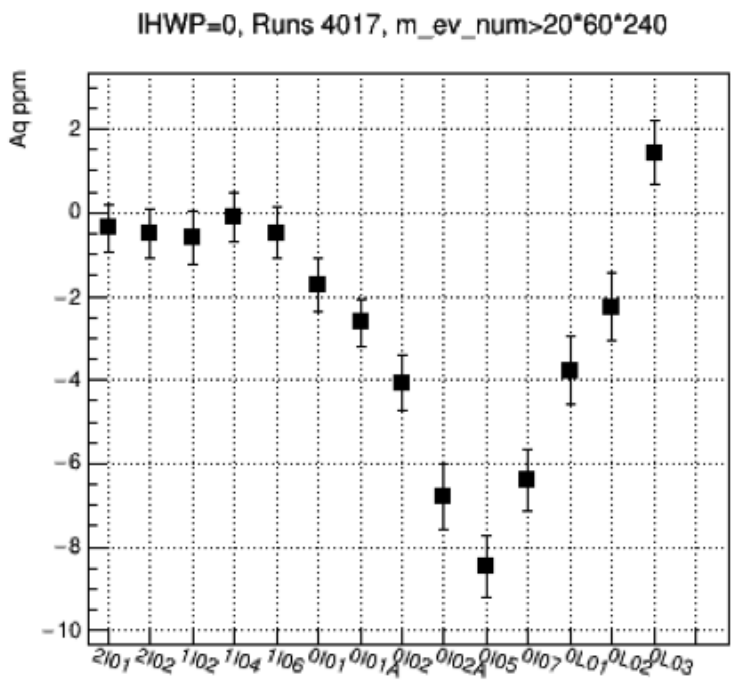
THE NOT, BEST EVER CONTROL IN POSITION DIFFERENCESIN THE NEXT REGION

240Hz,Octet

Big
Dx ~ 0.6um
Dy ~0.4um

Tiny<60nm





Aq 0-8ppm

Run4017_IHWPout_RHWP1000_FC2_REDO

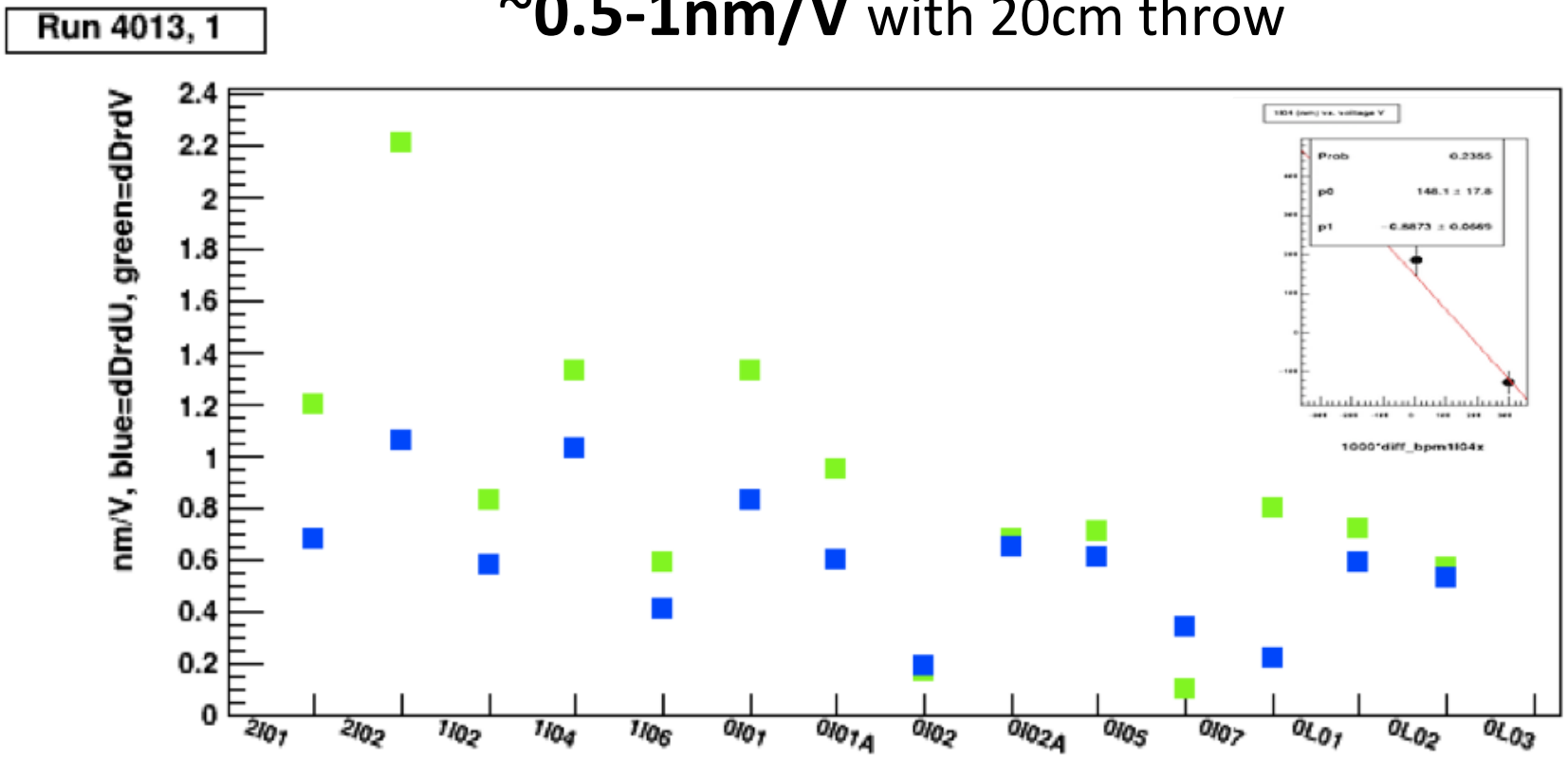
- Further downstream, past prebucher, wein, chopper, position differences became very large

Sensitivities: PITAposU/V control

- We changed the steering lens from 2m to 0.75m – making the beam smaller, but reducing the effective throw

~0.5-1nm/V with 20cm throw

~10nm/V with 2m throw



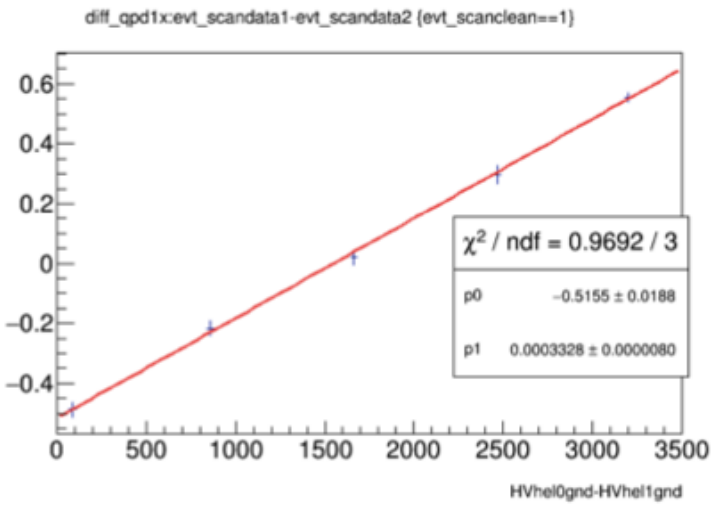
		Couplings before solenoid flip IHWP out, S1, Run3339	
		PITAposU	PITAposV
Dr ~ laser	nm/V	7.09	5.72
theta laser	deg	-47.96	32.97
Dr 1I02	nm/V	6.27	5.25
theta 1I02	deg	29.20	-58.56
Dr 1I04	nm/V	7.81	7.79
theta 1I04	deg	7.86	-85.67
Dr 1I06	nm/V	9.42	6.89
theta 1I06	deg	9.55	89.96
Dr 0I01	nm/V	5.01	1.84
theta 0I01	deg	8.44	77.63
Dr 0I01A	nm/V	1.54	2.10
theta 0I01A	deg	12.94	-70.08
Dr 0I02	nm/V	10.64	12.08
theta 0I02	deg	0.91	-83.86
Dr 0I02A	nm/V	17.62	17.26
theta 0I02A	deg	1.34	-80.78
Dr 0I05	nm/V	17.16	13.55
theta 0I05	deg	6.68	89.50

+-800V range → +- 0.4-0.8um (20cm) → +-80um range(2m)

Run4013_PITAPOSUVscan_coupling_REDO

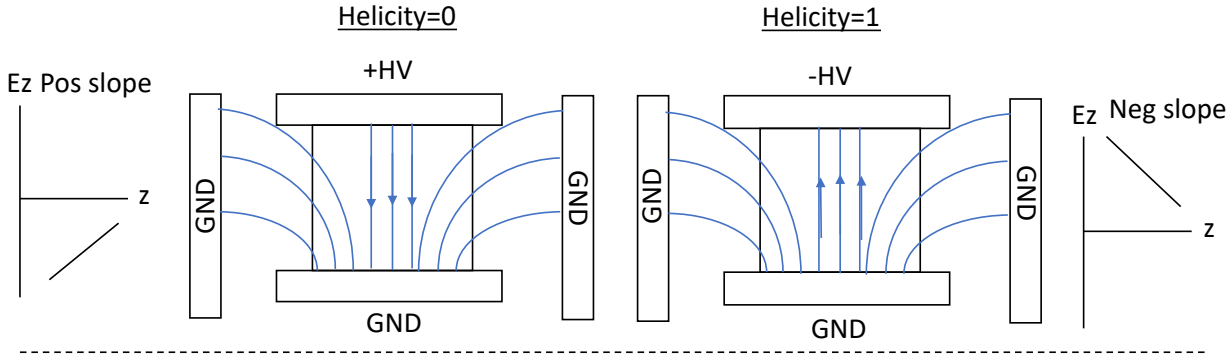
Position Difference Feedback Test

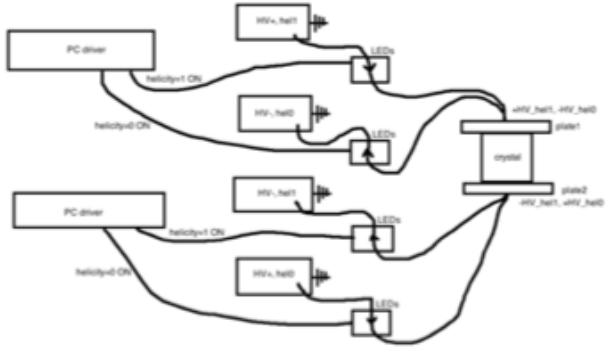
- Recall with RTP we also have the ability to control steering position differences with our 8HV system: “PITA-pos voltages”
- Reduced the spot size, but had smaller effective throw, so ~1nm/V
- Was able to run feedback on 1I04 and minimize it’s position differences

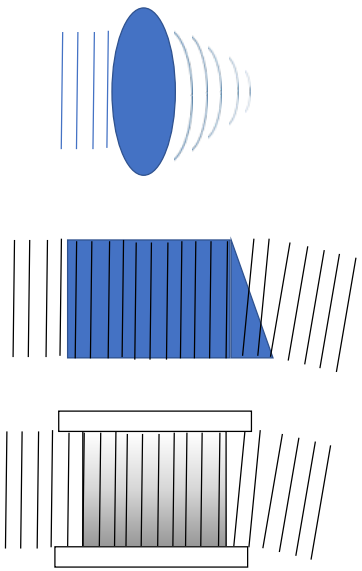


$$n_z = n_{z0} - 1/2 n_{z0}^3 r_{33} E_z$$

Run3143, qpd 70cm, Full metal jacket

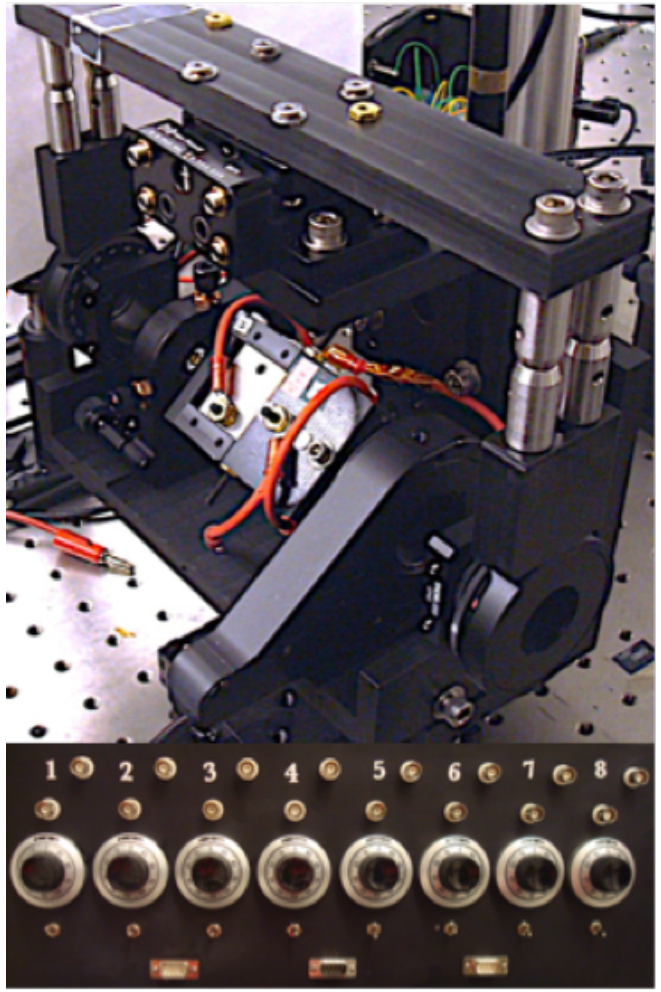


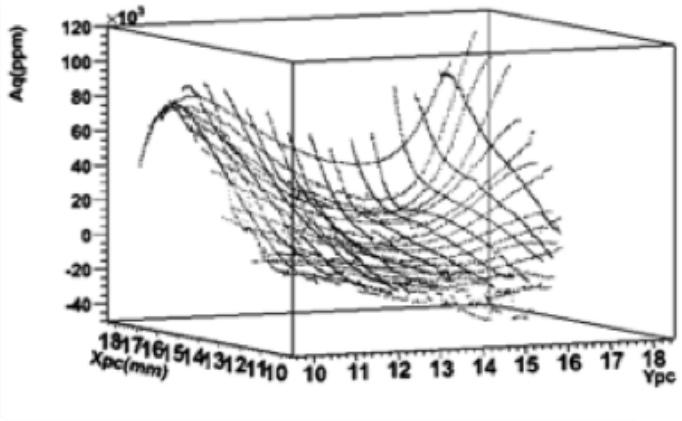


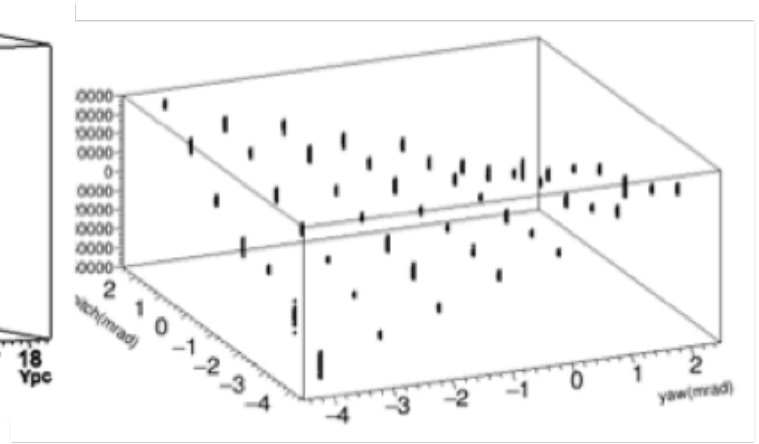


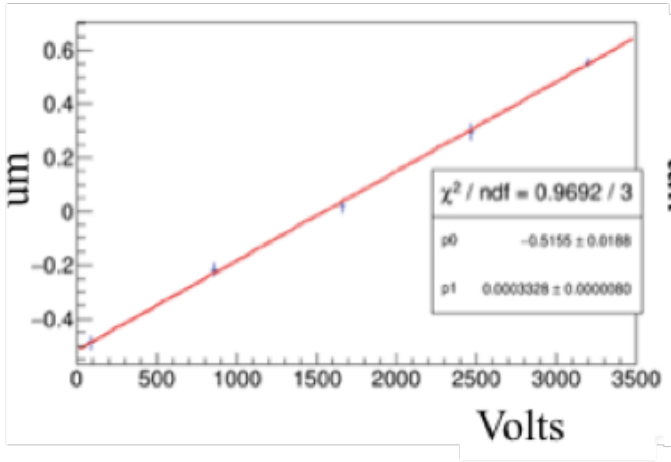
Testing RTP-crystal Cell

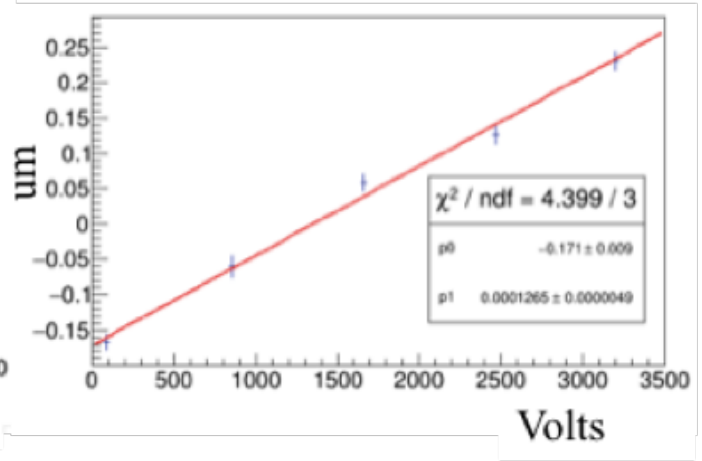
The RTP cell was fully characterized on the laser table







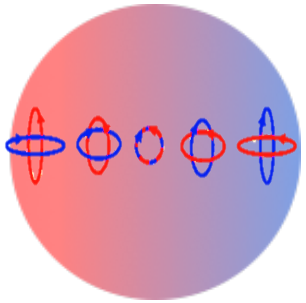


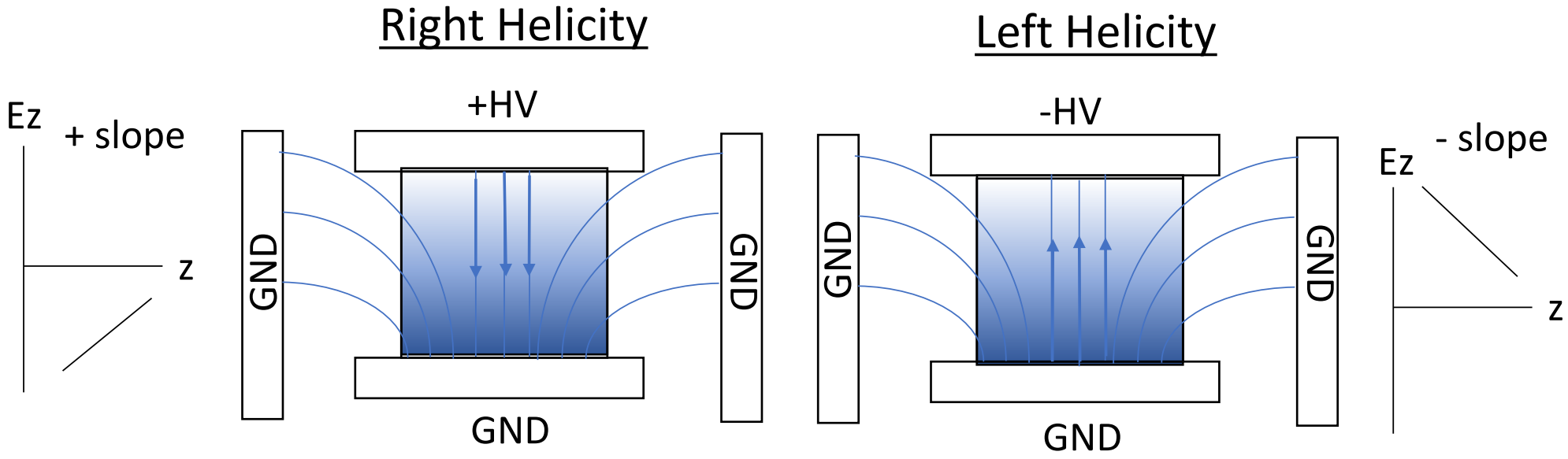


$$n_z = n_{z0} - 1/2 n_{z0}^3 r_{33} E_z \qquad n_y = n_{y0} - 1/2 n_{y0}^3 r_{23} E_z$$

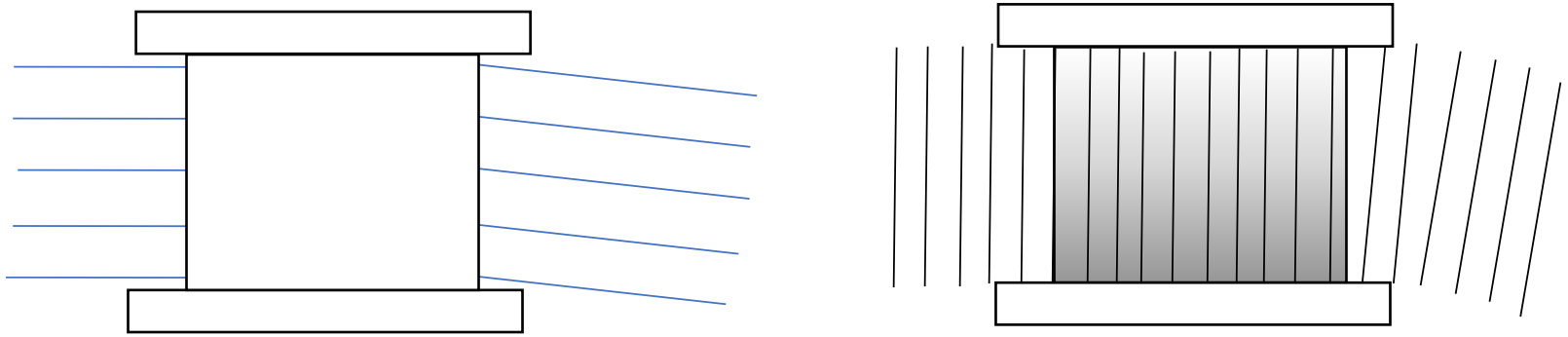
Cancel Position Differences by Applying Ambient Field

Position differences from asymmetry gradients

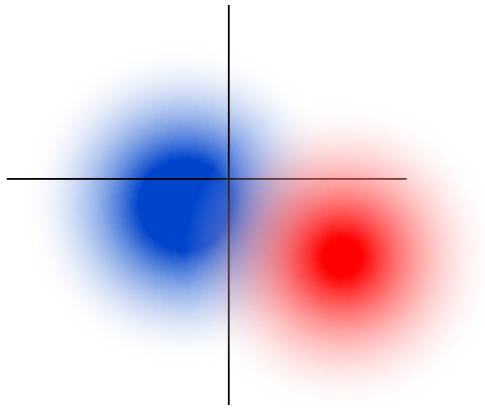




Steer Beam Direction

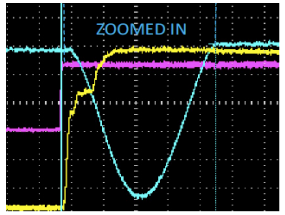


Steering Cancellation

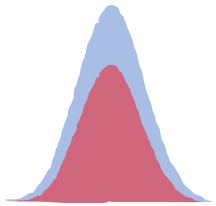


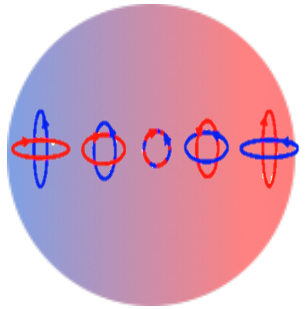
Pockels Cell Challenges

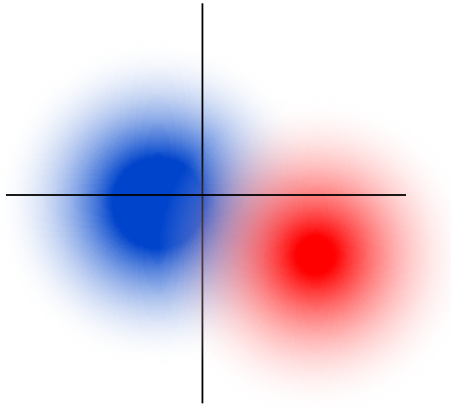
- Switch helicity states faster

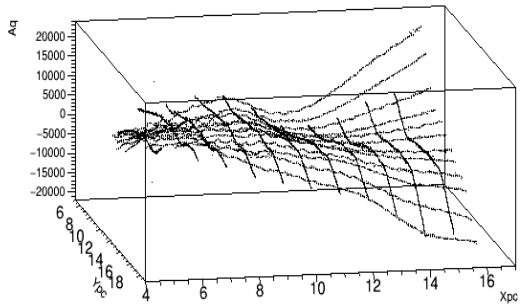


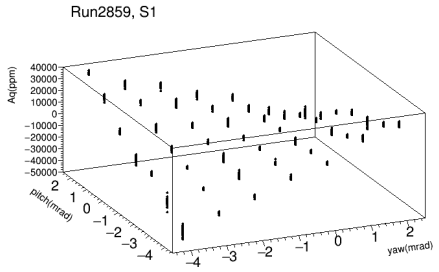
- 0th moment - Obtain small intensity asymmetries
- 1st moment - Obtain small position differences
- 2nd moment - Obtain small spot-size asymmetries



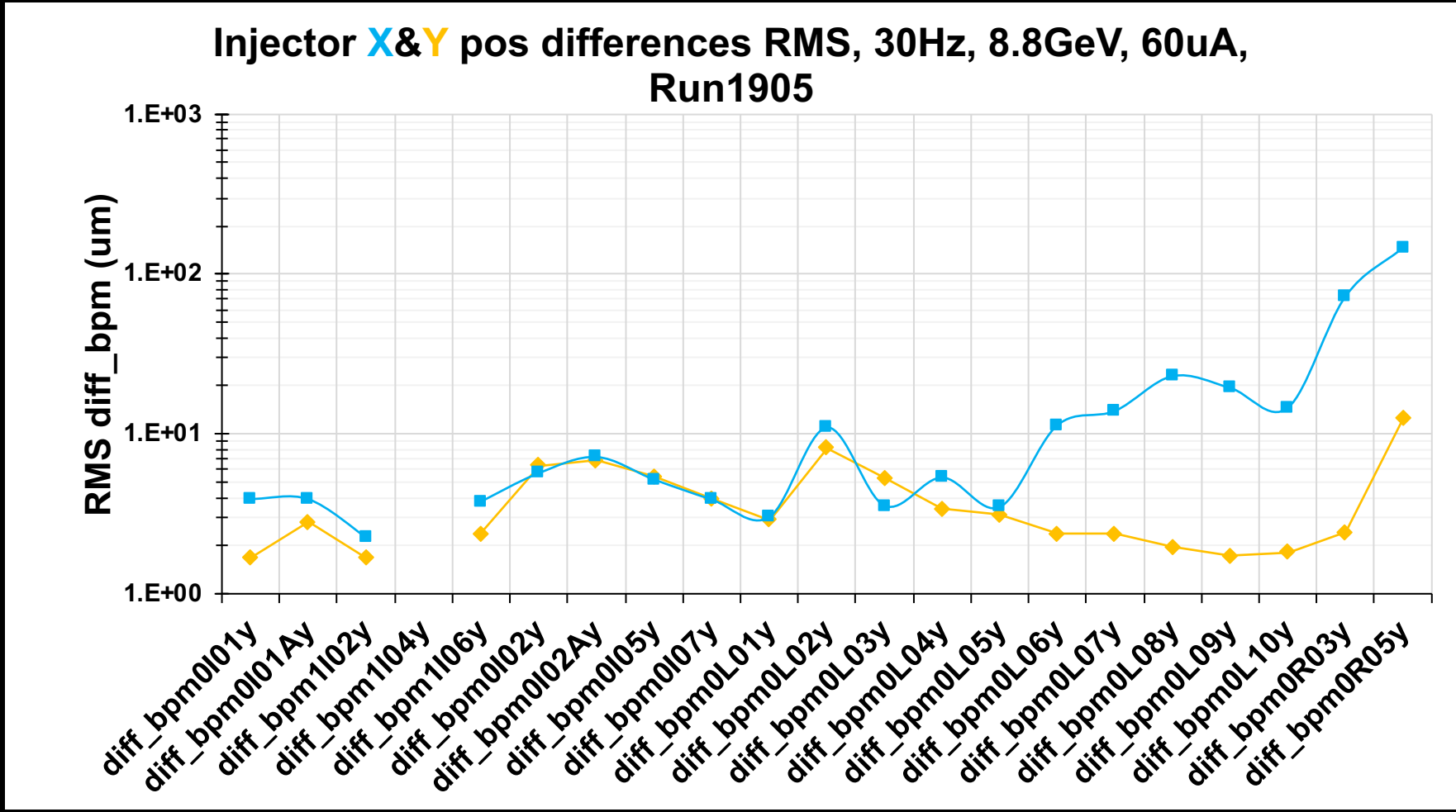








BEAM POSITION DIFFERENCE WIDTHS INJECTOR



Noise Table

S1 RHWP 2.25deg	Aq RMS (ppm) Mtree	Dx ,yRMS (um) Mtree	# samples per block , pattern	N	Aq RMS sqrt(N) (ppm) [RMS/sample]	Dx,y RMS sqrt(N) (um) [RMS/sample]	Time to get 10nm precision (min)
KD*P 30Hz RHWP 56.2	100-(170)	1.5-(8)	4141, quad	66256	25740-(43758)	386-(2059)	50-(1422)
KD*P 240Hz RHWP 59.4	185-(195)	2.2-(3.5)	495, octet	15840	23284-(24542)	277-(441)	27-(68)
RTP 240Hz RHWP 1	75-(95)	1.7-(2.9)	512, octet	16384	9600-(12160)	218-(371)	16-(47)
KD*P 960Hz RHWP 59.4	230-(285)	5-(17)	107, octet	3424	13458-(16677)	293-(995)	34-(401)
RTP 960HZ RHWP 1	140-(200)	4-(19)	120, octet	3840	8675-(12394)	248-(1177)	22-(501)

BEAM POSITION DIFFERENCE WIDTHS

Run	GeV energy	uA current	Hz frequency	conditions	RMS um bpm4ax	RMS um bpm4ay	RMS um bpm4bx	RMS um bpm4by	RMS um bpm8x	RMS um bpm8y	RMS um bpm12x	RMS um bpm12y	RMS um bpm14x	RMS um bpm14y
2347	2.2	18.6	30Hz		*6.395**	*14.23**	11.91	9.46	18.53	8.04	12.41	8.9	-	-
2349	2.2	18.7	30Hz		*6.644**	*12.15**	10.97	7.48	14.83	8.87	7.97	8.08	-	-
2333	4.4	12	30Hz	noisy run, ffb might not be on	*9.805**	*17.5**	15.87	8.95	48.84	9.73	27.14	14.55	-	-
2358	8.8	13.7	30Hz		*10.4**	*34.55**	10.4	13.27	30.96	13.34	15.47	43.87	-	-
2494	8.8	45	30Hz		*11.17**	*24.41**	11.05	13.31	23.34	7.32	12.27	10.15	4.96	8.55
2488	8.8	60	30Hz		*7.22**	*23.48**	*10.27**	*28.27**	21.06	7.12	11.26	10.41	6.51	9.82
2434	11	15	30Hz		-	-	12.91	10.03	21.27	9.76	13.39	21.99	6.55	6.97
2434	11	15	120Hz	1/2((b1-b2)/(b1+b2)+ (b4-b3)/(b3+b4)) (60Hz filtered out)	-	-	10.45	10.81	22.87	6.22	13.8	10.14	4.75	5.58
2437	11	15	2370Hz	(b1-b2)/(b1+b2), pairsynch=0	-	-	26.98	43.32	25.6	26.72	17.98	30.14	6.32	29.39
2434	11	15	120Hz	(b1-b2)/(b1+b2) , pairsynch=0, (60Hz sensitive)	-	-	18.66	16.34	34.27	36.33	19.4	66.9	10.34	15.07

*filtered: evt_bpm4ax[0]<a&&evt_bpm4ax[1]<a

Beam

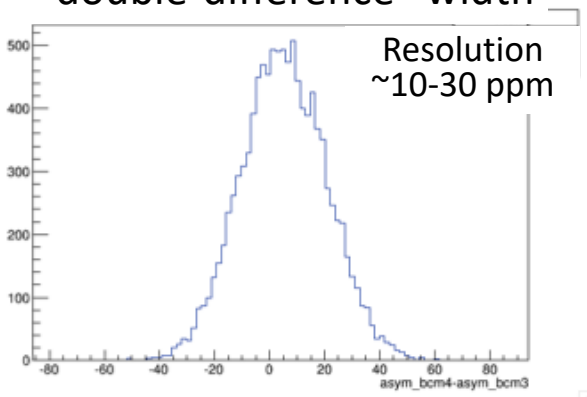
Tests during recent parasitic beam studies to check beam quality, monitors

BCM resolution exceeds PREX requirements

PREX-II statistical width ~ 120ppm @ 30Hz octet/quartet
BCM resolution of 40ppm would be 5% loss of resolution

1 MHz BCM electronics: ~25 ppm resolution @ 30 Hz, 20uA
Confirmed by excess noise with small-angle monitors
Similar to width measured in PREX-I

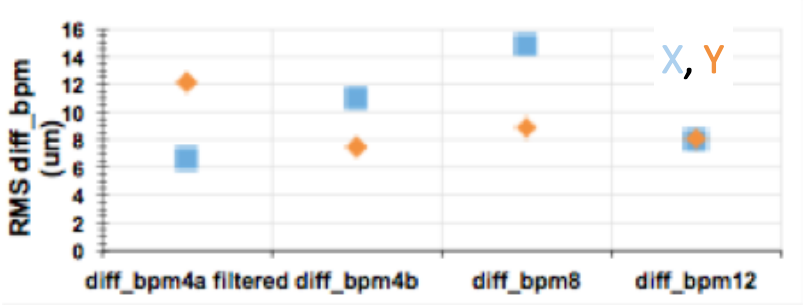
"double-difference" width



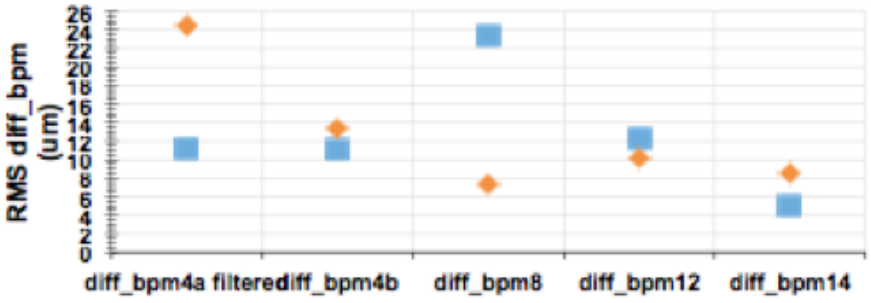
Charge and position jitter looks similar to 6 GeV era

A_Q: 100-300 ppm RMS. Δx: 5-25 um RMS. (20 μA, 30 Hz, 2.2 GeV)

1 pass beam



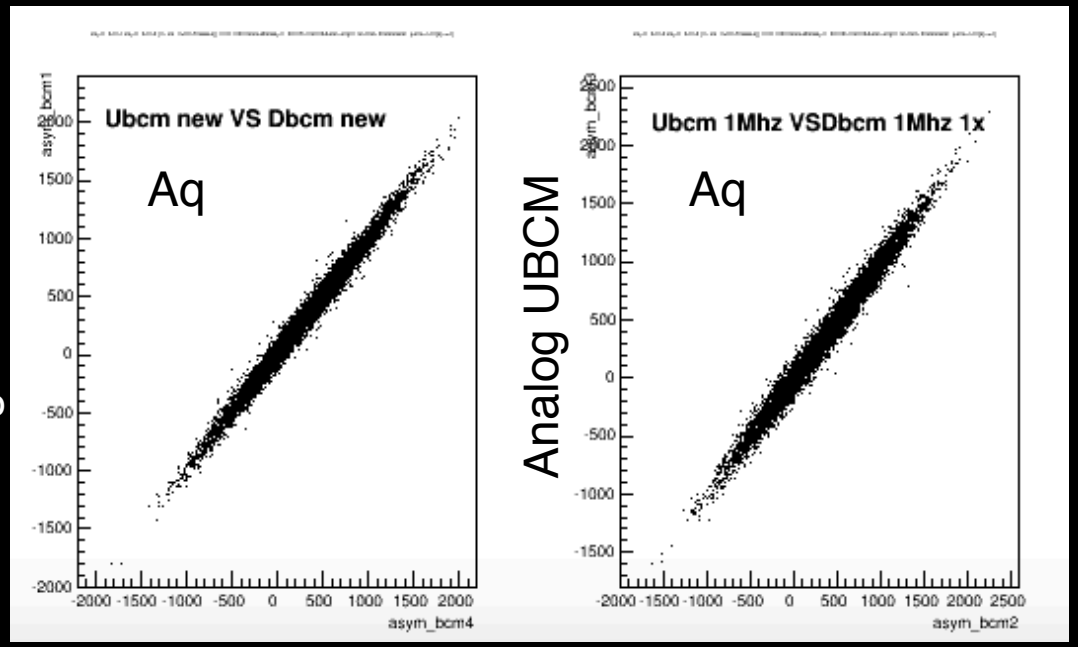
4 pass beam



Which BCMs are working well?

BCM correlations

Different Cavities, Same Receiver



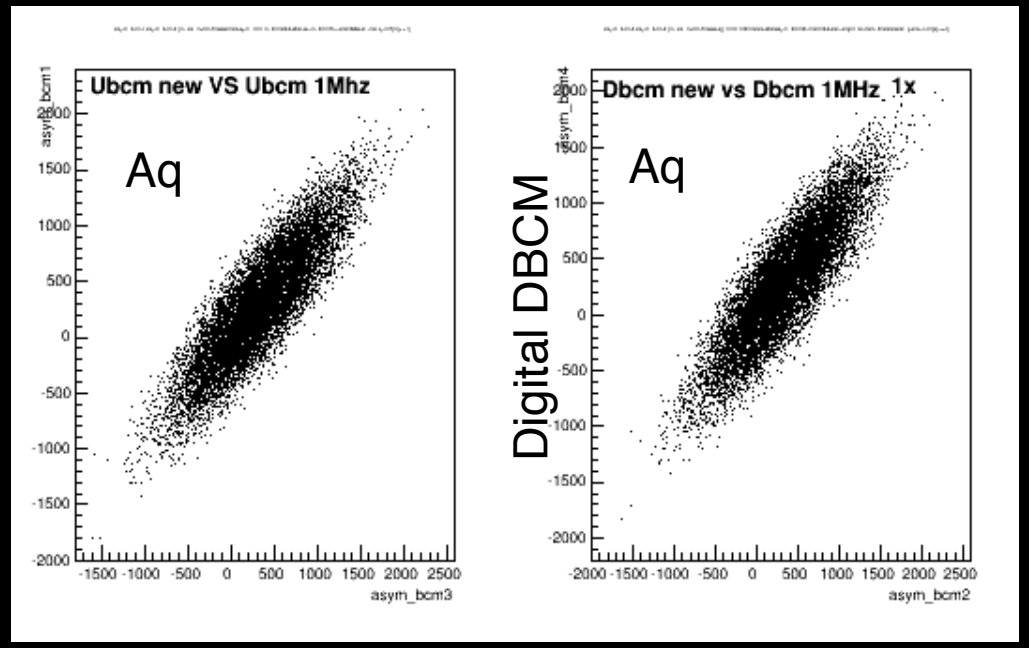
DigitalUBCM

Analog UBCM

Digital DBCM

Analog DBCM

Same Cavities, Different Receiver



DigitalUBCM

Digital DBCM

Analog UBCM

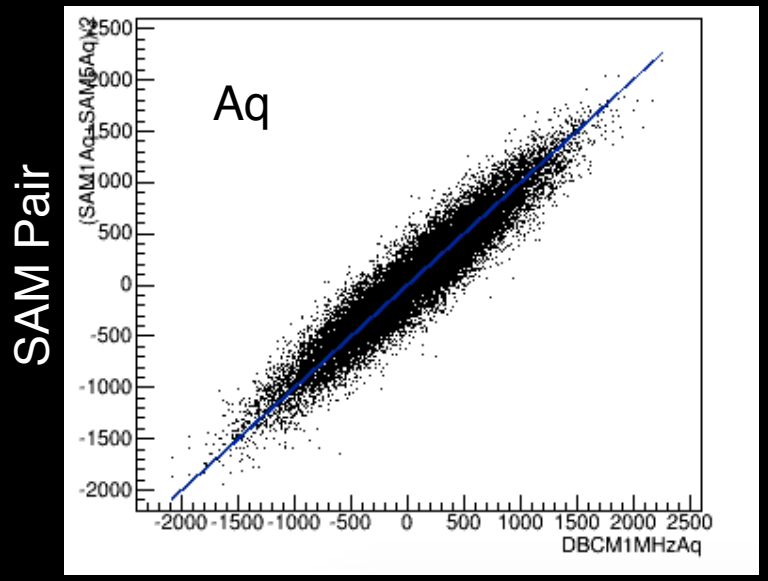
Analog DBCM

Run2333,4.4GeV 12uA, 15cm LH2 HV 1/5=-650V,2/6=-75V,3/7=-800V,4/8=-500V

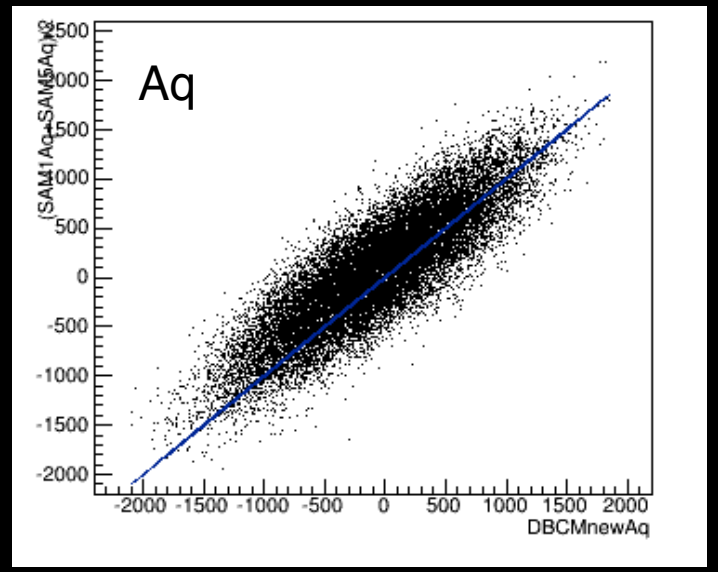
Which BCMs are working well?

Break degeneracy with the SAMs!

- Use SAM detectors as independent way to test the BCMs
- Analog BCMs are more correlated with SAMs than the Digital BCMs
- What's the resolution of the Analog BCMs?
  Double check with the SAMs.
- Can we rely on the SAMs?
  Must check.
- What's up with the digital BCMs?
  Must investigate.



Analog DBCM



Digital DBCM

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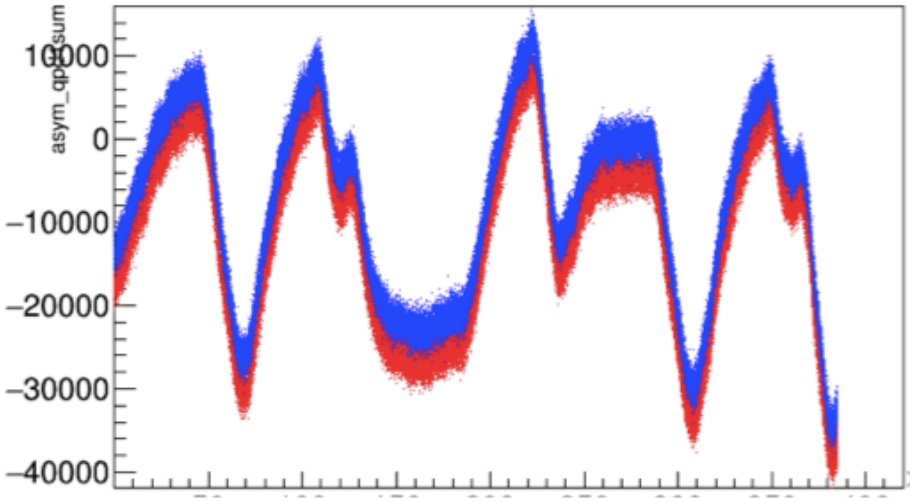
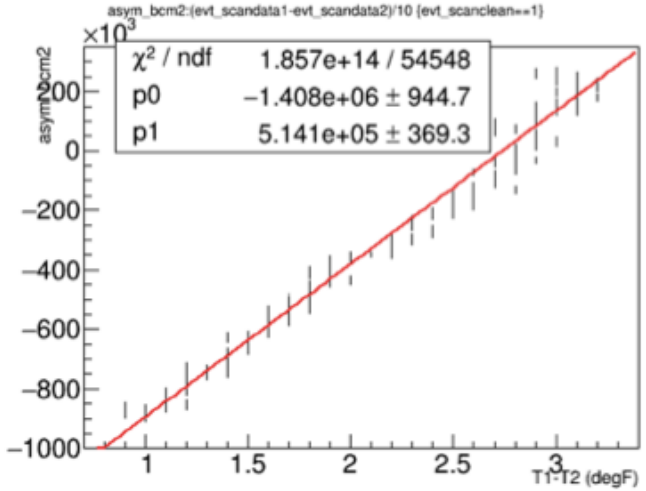
KD*P 960Hz RHWP 59.4	230-(285)	5-(17)	107, octet	3424	13458-(16677)	293-(995)	34-(401)
RTP 960HZ RHWP 1	140-(200)	4-(19)	120, octet	3840	8675-(12394)	248-(1177)	22-(501)

Temperature Sensitivity – correct with V

- Fluctuates +-30k ppm, which is ~30V PITA adjustment
- 30k ppm corresponds to fluctuation of ~45mKelvin T difference between crystal pair
- Temperature induced birefringence well within PITAV induced birefringence adjustment range
- <u>Intend to simply correct with voltage</u> rather than trying to force two crystals to have milli-Kelvin temperature differences



3hrs



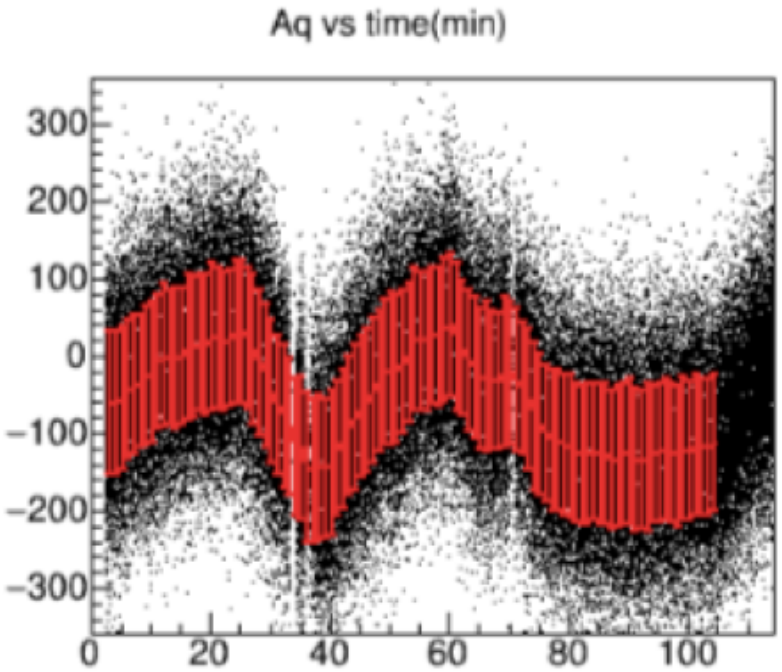
Modeling Feedback

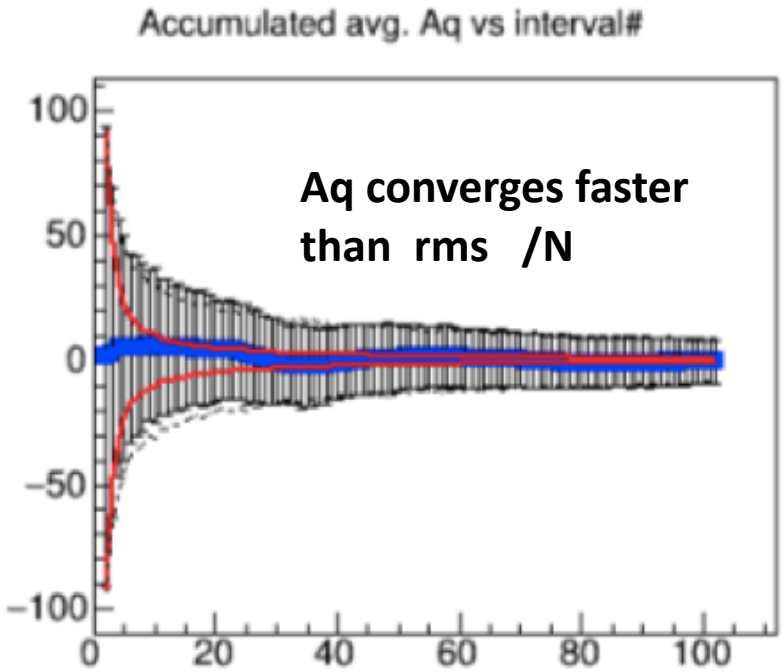
Intensity Feedback

Adjust PC voltages to keep intensity asymmetry minimized

Simple algorithm drives convergence of the mean as 1/N

Aq fluctuation +-150ppm





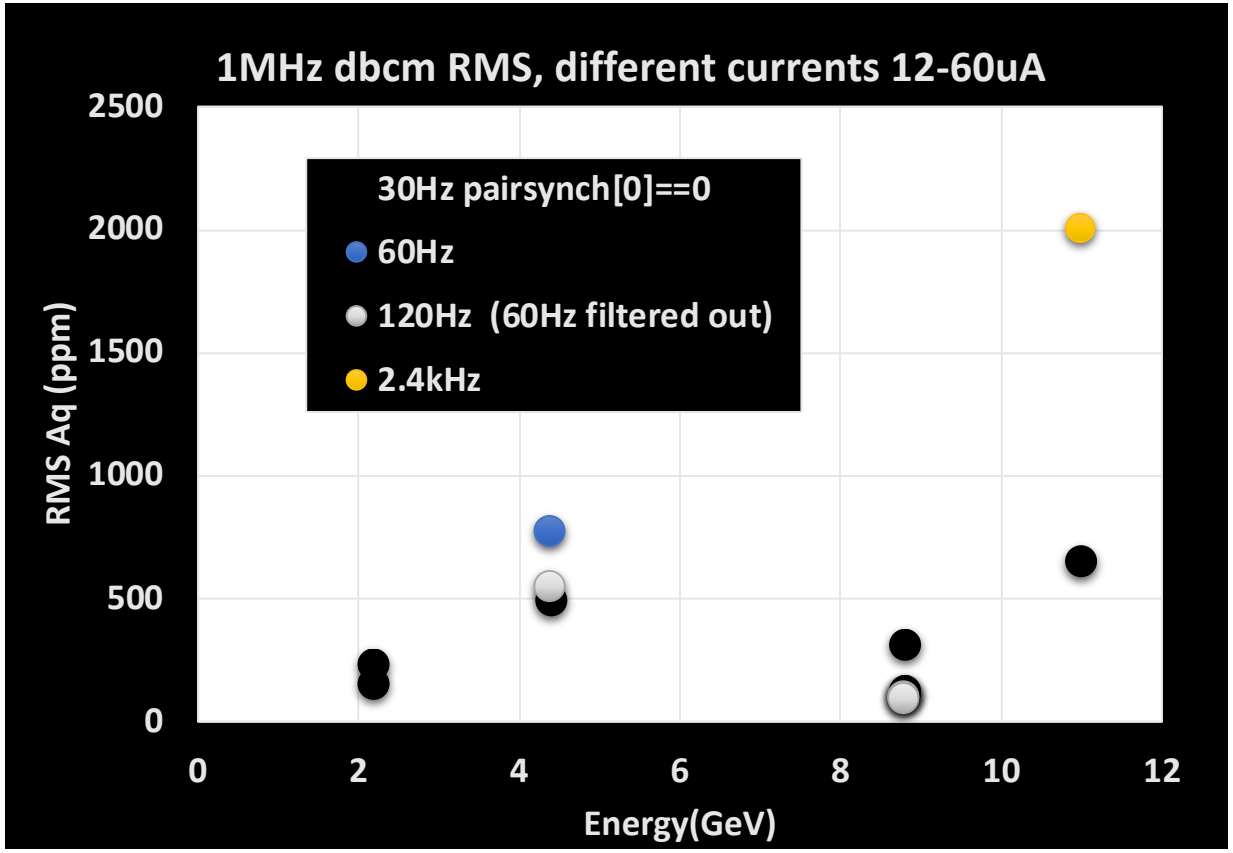
Position Feedback

- This can be done with voltage on the new home-built cell

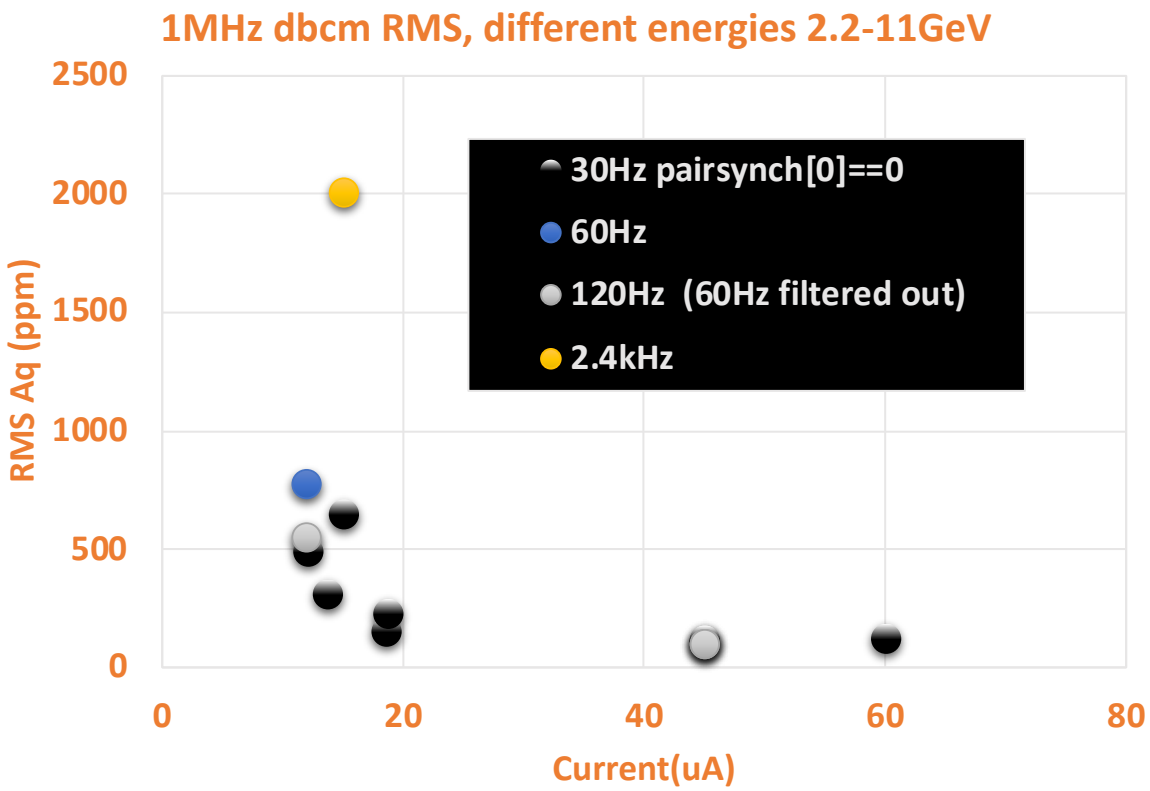
Beam Noise

Beam Asymmetry widths

- Higher energies don't appear to bear much relationship to widths observed



- Higher currents may generally tend to be associated with smaller widths



Beam Asymmetry widths

INjector

Injector

- Higher frequencies tend to result in smaller widths (scaled to counting statistics)

	Run	GeV energy	uA current	Hz frequency	bcm 0L02 RMS ps0=0	bcm RMS	Analysis with ADC subblocks of helicity window	ppm/sqrt(Hz) RMS/sqrt(f)
	1905	8.8	60	30	**208.1**		normal	**37.99**
	1905	8.8	60	60		**273.1**	(b1+b2-b3-b4)/(b1+b2+b3+b4)	**35.26**
Injector, multiple frequencies, 4pass	1905	8.8	60	120		**212.7**	1/2((b1-b2)/(b1+b2)+ (b4-b3)/(b3+b4)),(60Hz filtered out)	**19.42**
	1902	8.8	60	567		**653.6**	(b1+b2-b3-b4)/(b1+b2+b3+b4)	**27.45**
	1902	8.8	60	1134		**531.3**	(b1-b2)/(b1+b2)	**15.81**

DIFFERENCE BETWEEN PARITY BEAM AND 'OPTIMAL' BEAM

Stabilized Beam

- Minimize any changes
- All frequency content matters
- All noise is bad
- Narrower widths are better
- Optimal = no noise

Parity Quality Beam

- Minimize only helicity-correlated changes
- Much frequency content is suppressed
- Some noise is good
- Want widths to be small, but also want them to be larger than the means
- Optimal = some noise, no helicity correlated differences

$$A_{raw} = A_{det} - A_Q + \alpha\Delta_E + \Sigma\beta_i\Delta x_i$$

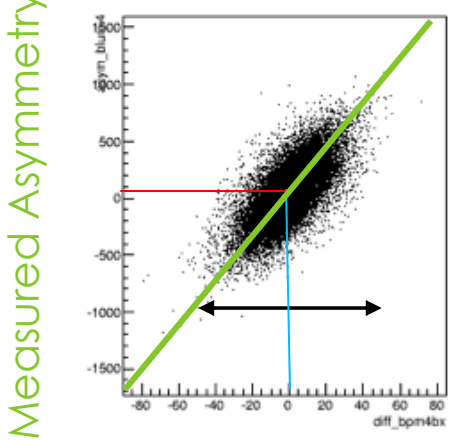
MONITOR: I,E,X,Y

WIDTHS AND MEANS

Slope x Mean = Shift

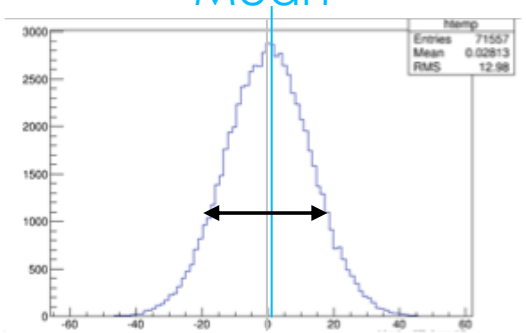
- Means: Charge asymmetry, Position differences, Spot-size Asymmetry
  - Small as possible
  - Minimize helicity correlated Aq
  - Minimize helicity correlated position differences
- Widths: Beam noise, Monitor Noise
  - smaller widths help statistically
  - larger widths help establish correlations with monitors (ie slopes), which are then used to correct contributions from helicity correlated beam differences (ie. means)
  - Help get corrections (ie shifts)

Slope



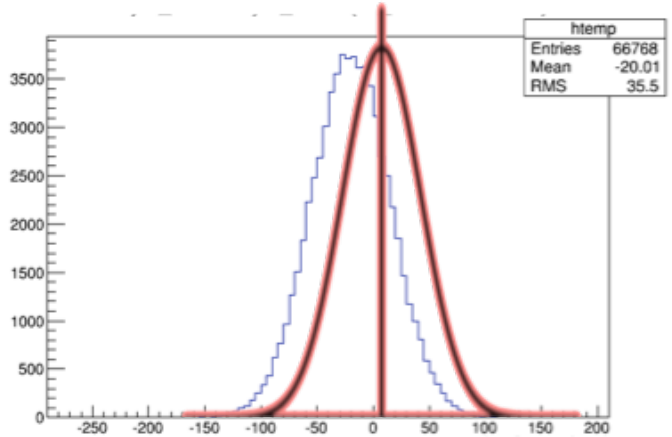
Position difference

Mean



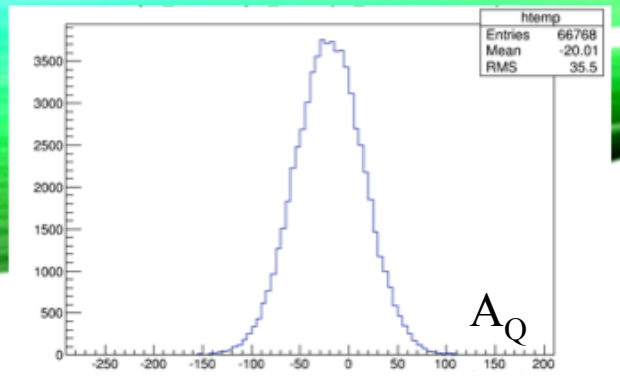
Position difference

Shift



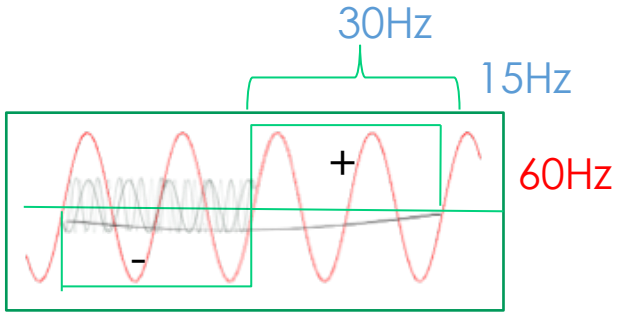
Raw asymmetry =

Corrected asymmetry

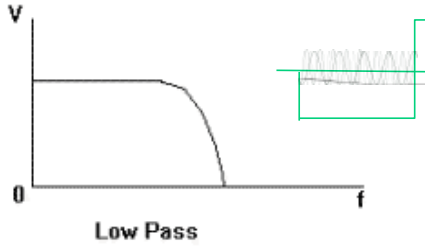


UNDERSTAND WHAT PARITY DAQ SEES

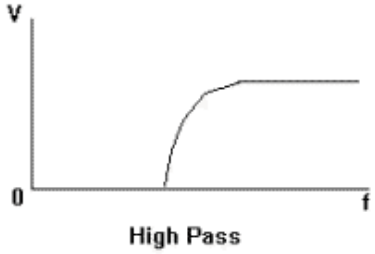
- Parity DAQ filters beam noise out, so much of the frequency content in the beam is suppressed
- Why filter? To see the helicity correlated differences more clearly
- What gets filtered? High frequency content(via integration) and low frequency content(via forming pair differences)
- Frequency content nearer the helicity flip-rate contributes to widths in helicity correlated differences

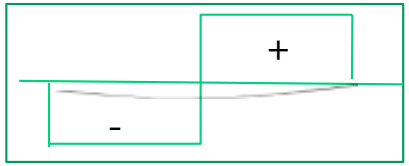


Window Integration



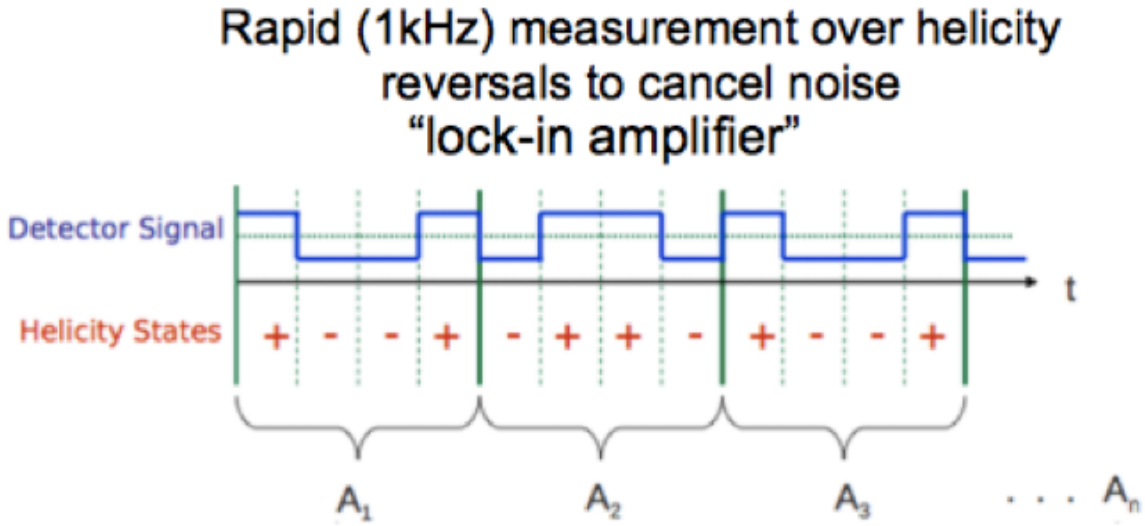
Pair Difference

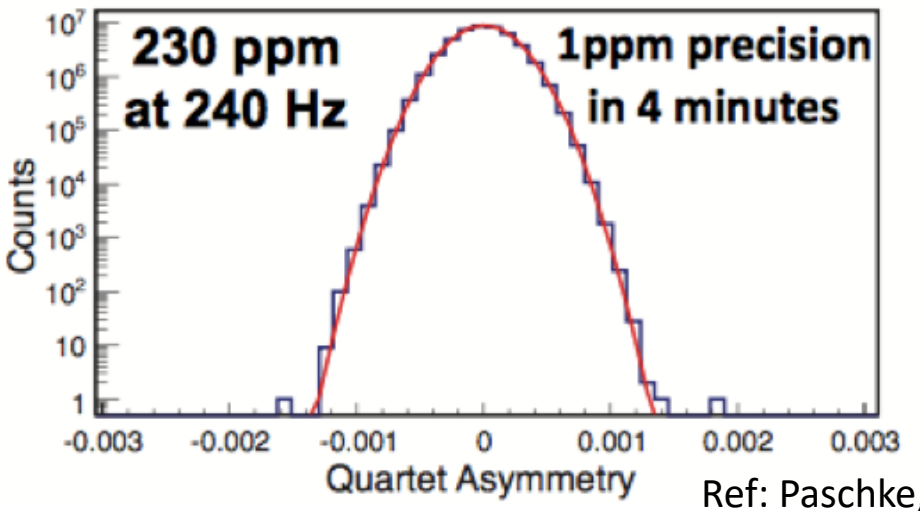




Statistical Error Goals & Helicity Flipping

- The electron beam must **switch** back and forth very **quickly** between spin facing forwards and backwards so many comparisons can be made





Ref: Paschke, Elba 2016

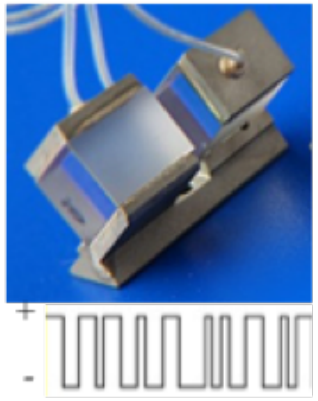
- Helicity switching: Time "windows" are generated in the electron bunch train at a selected flip rate, with the sign of the beam's longitudinal polarization in each window assigned on a pseudo-random basis.
- Frequency selection for helicity flipping – noise, widths, statistical errors
- Moller is designed around a flip rate of at least 2 kHz
- Goal: flip the Pockels cell within 10 μs, which implies a dead-time of 2%.

Obtaining High Precision for Parity Experiments

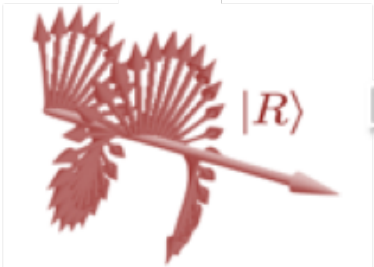
- **Beam from source to target:** An opto-electric device called a Pockels cell controls the spin of the electron beam by switching the polarization state of the laser beam generating it. There's a **new type of crystal**, RTP (Rubidium Titanyle Phosphate), which can switch states extremely quickly

Laser Beam

Pockels Cell (+- HV)

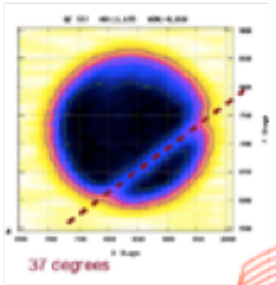


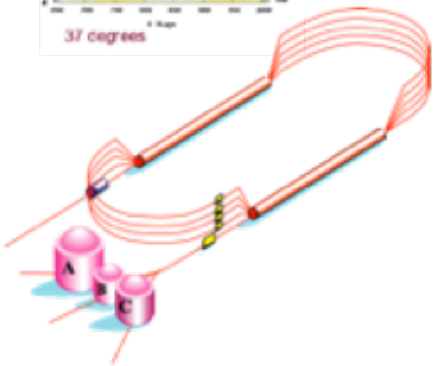
Circularly polarized light



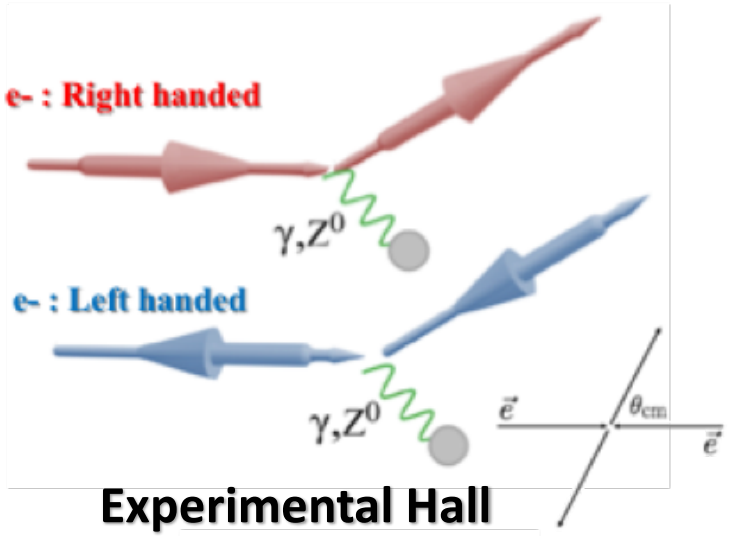
Electron Beam

Photocathode (GaAs)

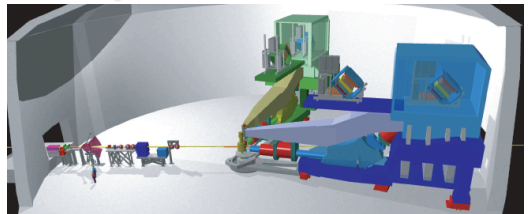




Polarized electrons



Experimental Hall



Statistics and Systematics: Summary

Error Source	Fractional Error (%)
Statistical	**2.1**
Absolute Normalization of the Kinematic Factor	0.5
Beam (second order)	0.4
Beam polarization	0.4
$e + p(+\gamma) \to e + X(+\gamma)$	0.4
Beam (position, angle, energy)	0.4
Beam (intensity)	0.3
$e + p(+\gamma) \to e + p(+\gamma)$	0.3
$\gamma^{(*)} + p \to (\pi, \mu, K) + X$	0.3
Transverse polarization	0.2
Neutral background (soft photons, neutrons)	0.1
Total systematic	**1.1**

Beam Property	Assumed Sensitivity	Accuracy of Correction	Required 2 kHz random fluctuations	Required cumulative helicity-correlation	Systematic contribution
Intensity	1 ppb / ppb	$\sim$1%	$<$ 1000 ppm	$<$ 10 ppb	$\sim$ 0.1 ppb
Energy	-1.4 ppb / ppb	$\sim$10%	$<$ 108 ppm	$<$ 0.7 ppb	$\sim$ 0.05 ppb
Position	0.85 ppb / nm	$\sim$10%	$<$ 47 μm	$<$ 1.2 nm	$\sim$ 0.05 ppb
Angle	8.5 ppb / nrad	$\sim$10%	$<$ 4.7 μrad	$<$ 0.12 nrad	$\sim$ 0.05 ppb

MOLLER Beam Requirements

75 μA, 80% polarization (or 60 μA, 90%) (past: 180 μA, 88%)

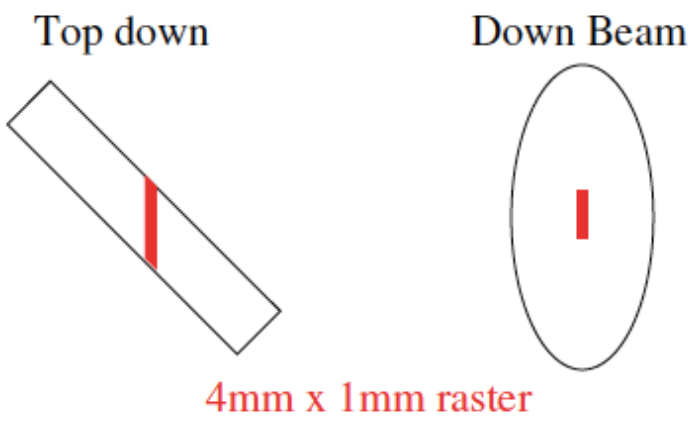
2 kHz helicity flip rate with 10 μs settle time (past: 1 kHz, 60 μs T_{settle})

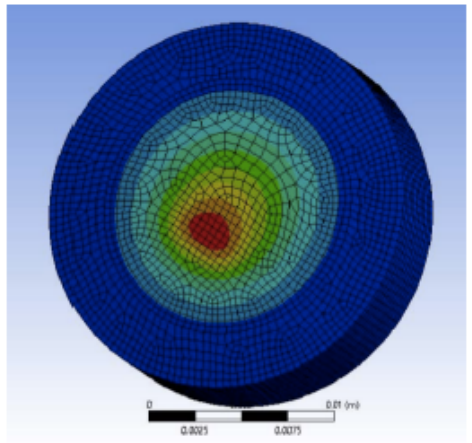
	MOLLER	previously achieved
Intensity Asymmetry	10 ppb	~ 30 ppb (Qweak)
Energy Asymmetry	<0.7 ppb	0.2 ppb (H-II)
Position Difference	<1.2 nm	2 nm (H-II)
Angle Differences	<0.12 nrad	0.25 nrad (H-II)
Size Differences	$< 1\times10^{-5}$	$<1\times10^{-4}$ (PREX-I, Qweak)

	Source	Adiabatic Damping	Slow Reversals	Feedback
Intensity	**<20 ppm (injector)**	-	**~10x**	**100x**
Position /angle	**~20 nm (injector)** (Past: 50-200 nm)	**~100x (150x max)** (Past: 10-30x, max 95x)	**~10x (IHWP, g-2, ISM)** (Past: ~10x IHWP, ISM)	**~10x, control jitter** (Past: ~10x, not often used)
Spot Size	**(laser) $\Delta\sigma/\sigma$ <10^{-5}** (Past: $\Delta\sigma/\sigma$ <10^{-4})	(synch light dilution)	**~10x (IHWP, g-2, ISM)** (Past: ~10x from ISM)	-

CREX target

- Run “tilted" at 45 to compensate for thinner target - 1.1g/cm2
- Windowless target at 45 provides best, simplest option for running
- Scraping of oxidized surface sufficient for decontamination
- Contamination tolerances are loose and shouldn't present a problem
  - *Relevant contaminant nuclei asymmetries are known, within 10% of 48Ca, and have rates suppressed by Z^2. Overall corrections are negligible (<0.16%)with very conservative residual contamination estimates (10%)*
- Narrow raster minimizes potential geometric-dependent systematics
- Transfer under oil should prevent oxidation under normal conditions
- Scattering chamber isolated with gate valves & gas purge in case of vacuum leaks
- Collaboration will have help of target group to finalize design





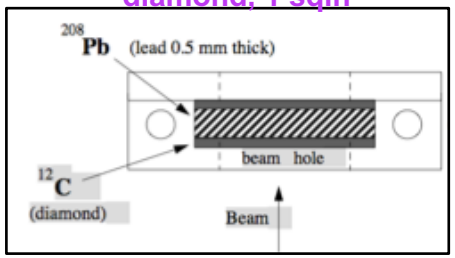
Lead / Diamond Target

Lead has low melting point, and low thermal conductivity

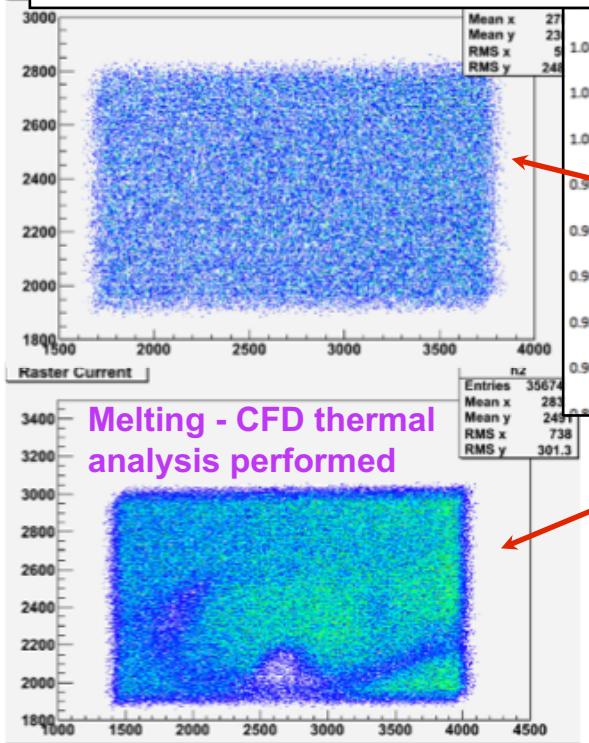
Diamond foils have excellent thermal conductivity, He cooled

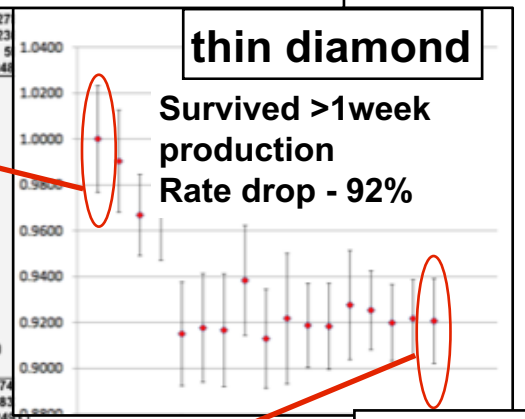
^{12}C is isoscaler, spin-0 (and well-measured) so benign background!

0.5mm lead, 0.25mm diamond, 1 sqin

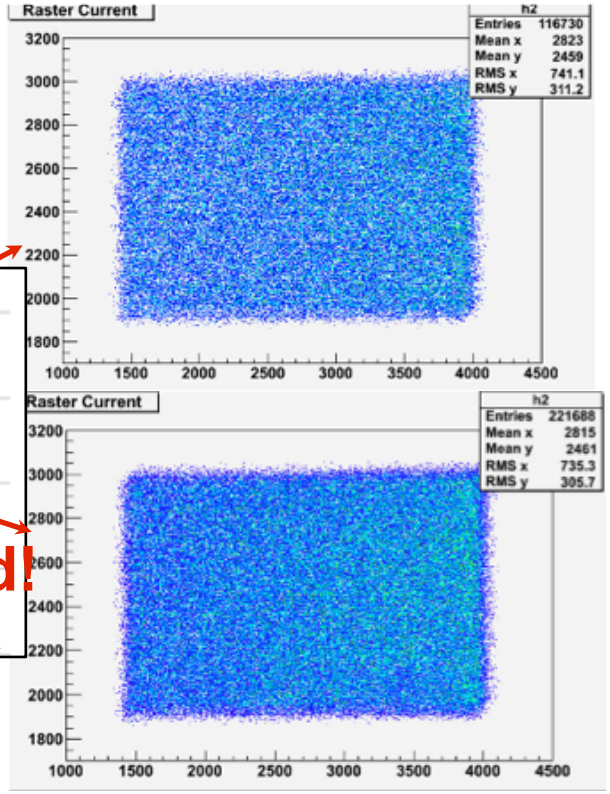


Raster Scan to measure density loss - PREX I test





Use synchronized 4x4mm raster to handle non-uniform lead thickness

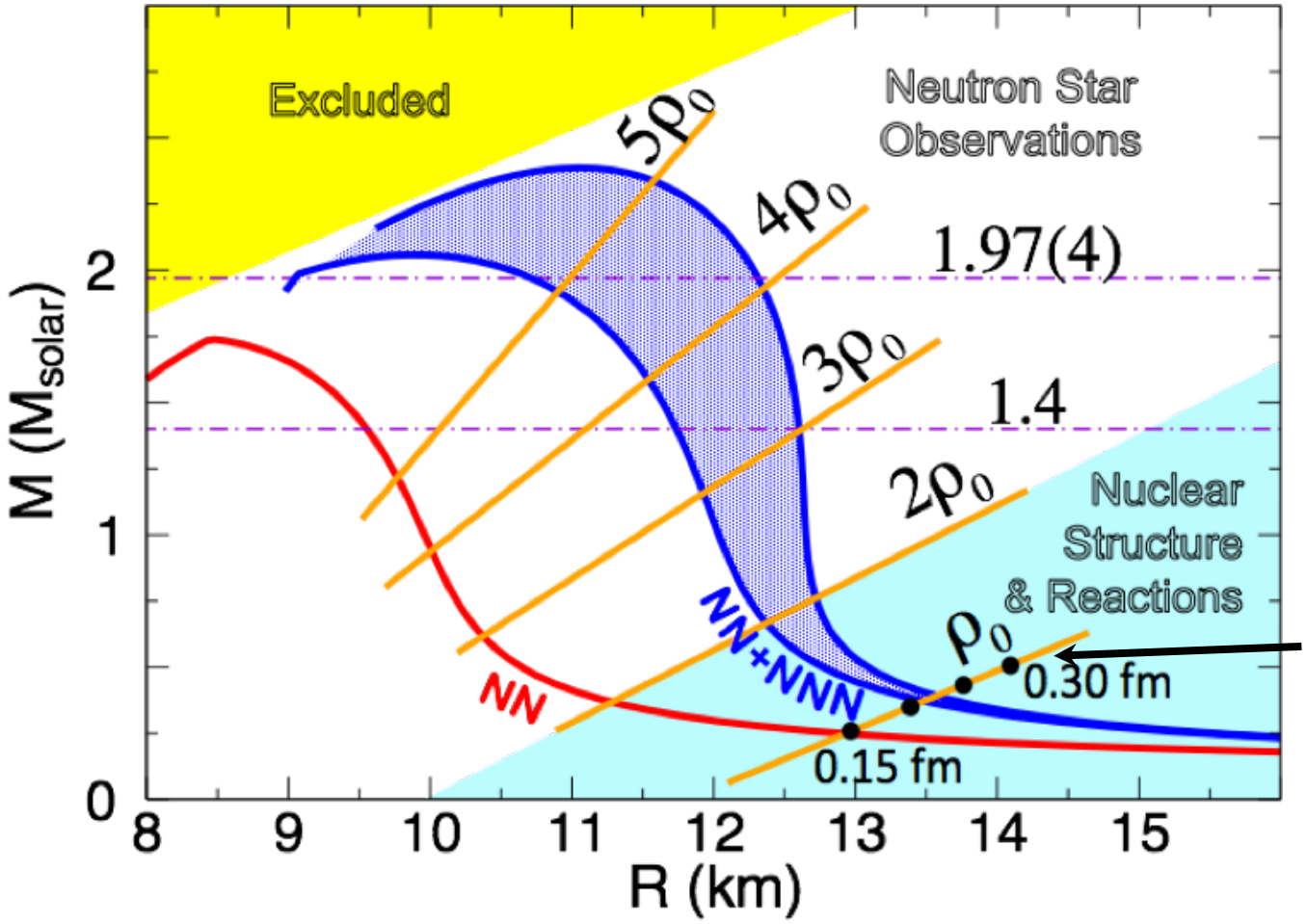


3 targets for PREX1 were used for 1/2 #C on target of PREXII, 6 enough

10 Production 'thick diamond' targets for PREX-2:
factor of ~2 (or more) margin based on PREX-I performance

Neutron Star Mass vs. Radius

Strong analogy to nuclei: Symmetry pressure pushes against **gravity**



Current PREX central value inconsistent with measured neutron star properties and existing models.

Potential phase changes(!) would disrupt this argument

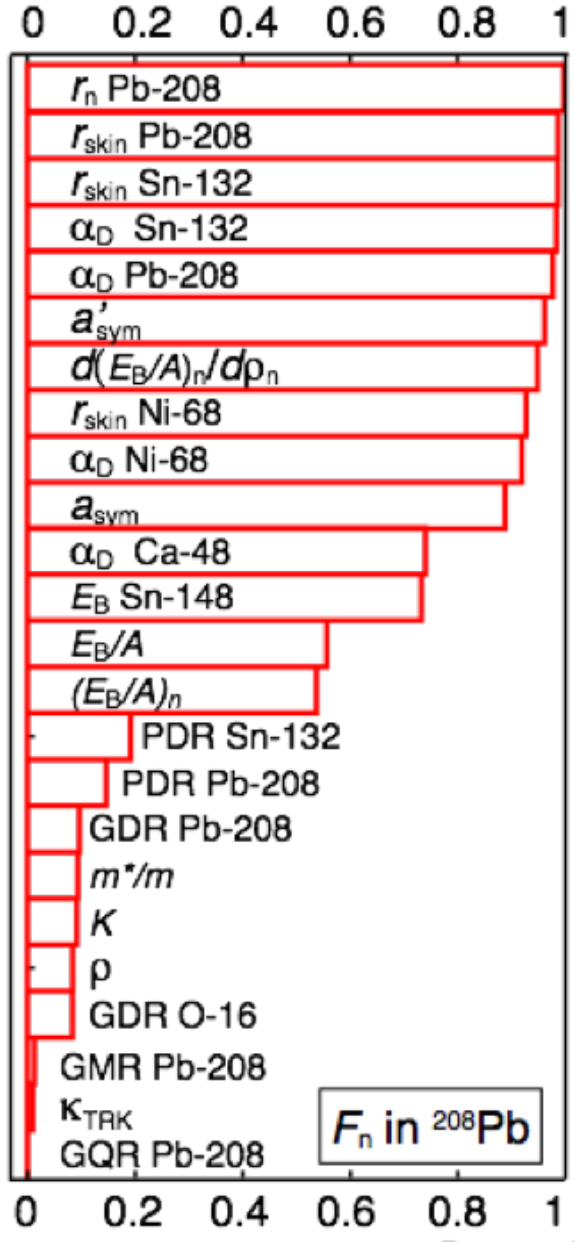
- All neutron star radii between 10.4 and 12.9 km
- Suggests $R_n(^{208}Pb) < 0.2$ fm

New information in a poorly measured sector

Within a specific model, correlation of prediction vs. changes to one empirical input

Good Isovector Indicators

Poor Isovector Indicators
(collective excitations, binding energies, etc.)
Relatively well measured

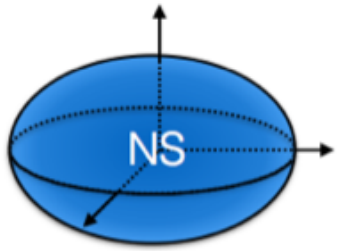


Jorge Piekarewicz

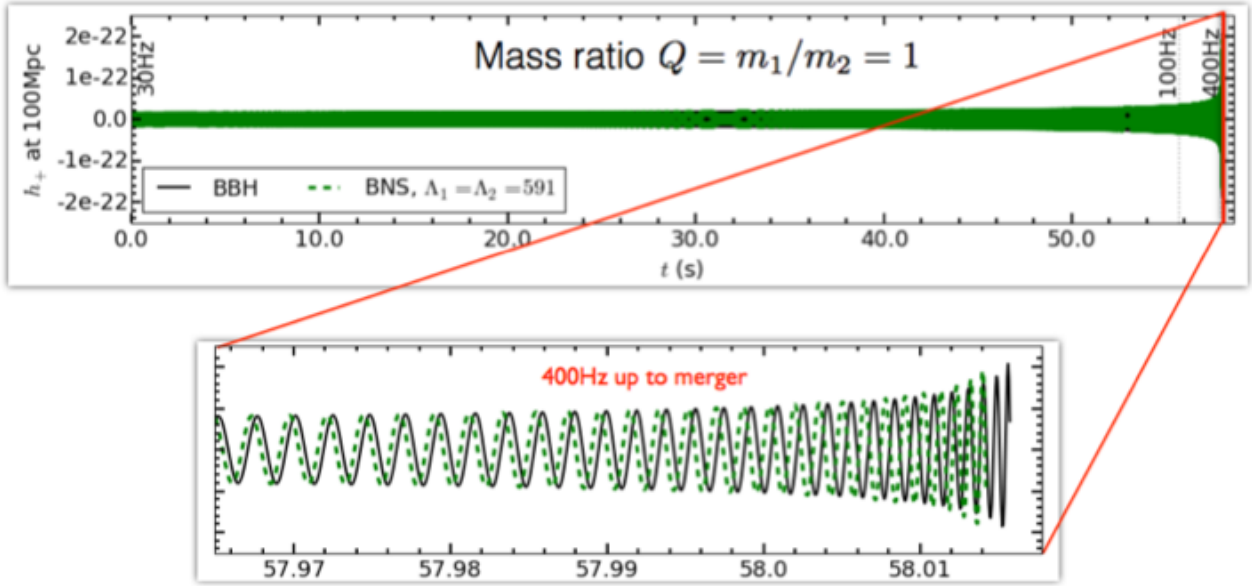
Gravity Waves and EOS

- Tidal field created by companion induces a quadrupole moment in the NS
  - Tidal field: $\mathcal{E}_{ij}$
  - Quadrupole moment: Q_{ij}
- Amount of deformation depends on stiffness of EOS via the tidal deformability λ:

Ben Lackey, Syracuse U

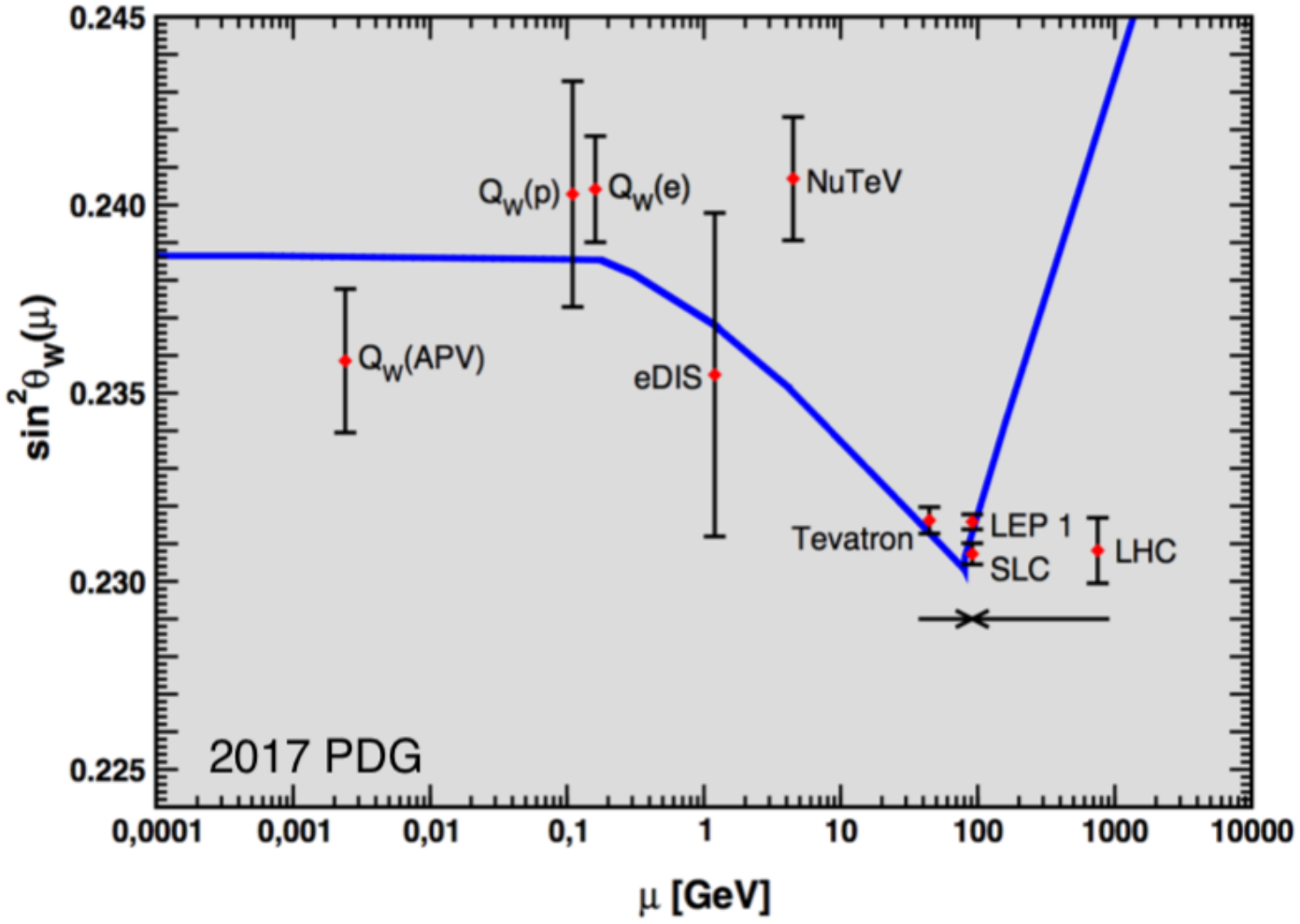


- BNS systems are ~equal mass
- Both NSs contribute to tidal effect

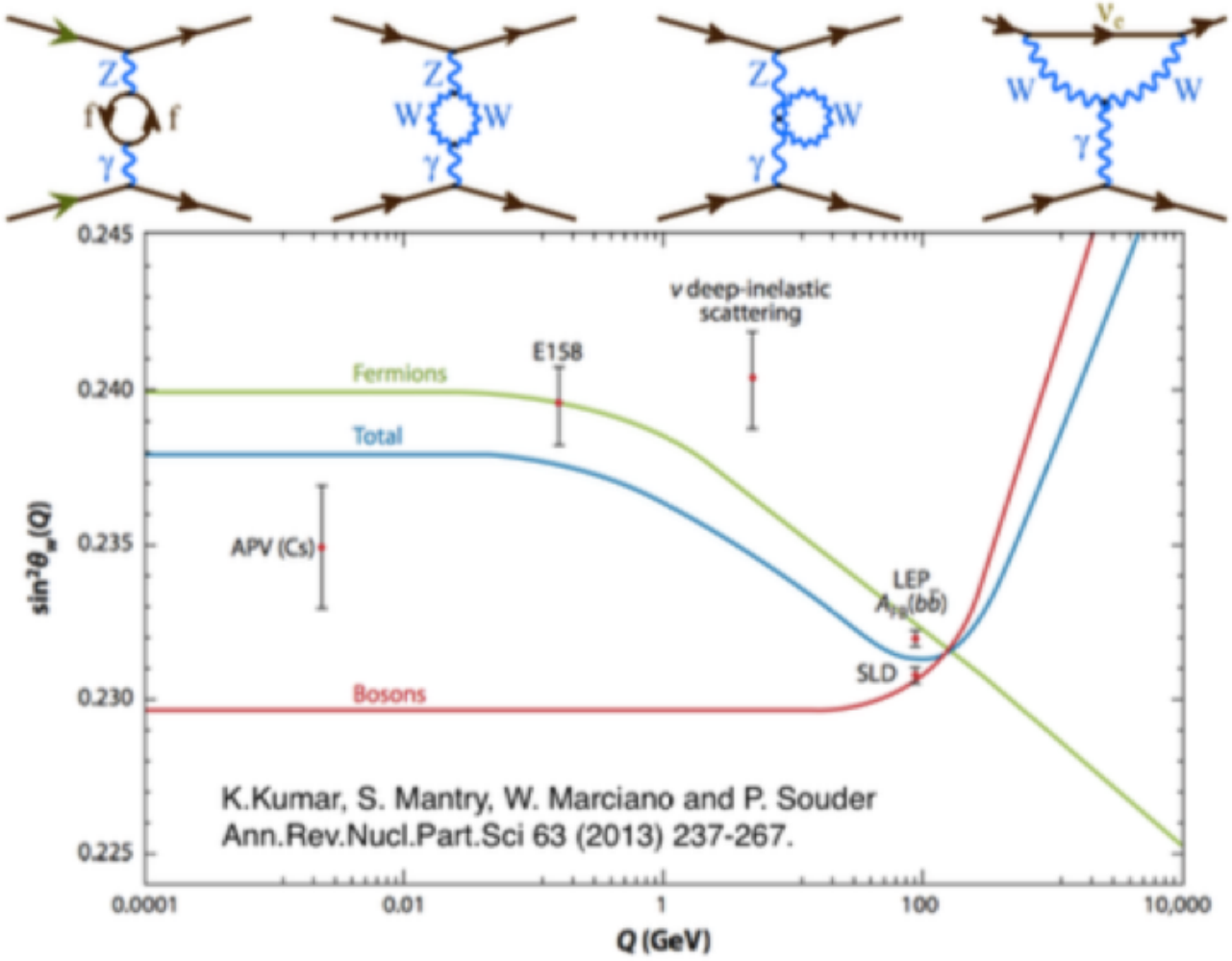


- Tidal interaction leads to phase shift of >5 radians

PREX informs neutron star size vs. mass, which is critical to matter effects in GW


0.245
0.240
0.235
0.230
0.225
$\sin^2\theta_W(\mu)$
$Q_W(p)$
$Q_W(e)$
NuTeV
$Q_W(APV)$
eDIS
Tevatron
LEP 1
SLC
LHC
2017 PDG
0,0001
0,001
0,01
0,1
1
10
100
1000
10000
μ [GeV]

The running of $\sin^2\theta_W$ from $Q^2=M_Z^2$ to 3% of its Z-pole value at $Q^2 \ll 1$ arises primarily from fermion vacuum polarization effects, whereas the running beyond the Z-pole is dominated by boson vacuum polarization effects



For low energies and under conditions where the electron does not penetrate the nucleus, the electron scattering can be described by the Rutherford formula. The Rutherford formula is an analytic expression for the differential scattering cross section, and for a projectile charge of 1, it is

$$\left(\frac{d\sigma}{d\ \cos\theta}\right)_R = \frac{\pi}{2} Z^2 \alpha^2 \left(\frac{\hbar c}{KE}\right)^2 \frac{1}{(1-\cos\theta)^2}$$

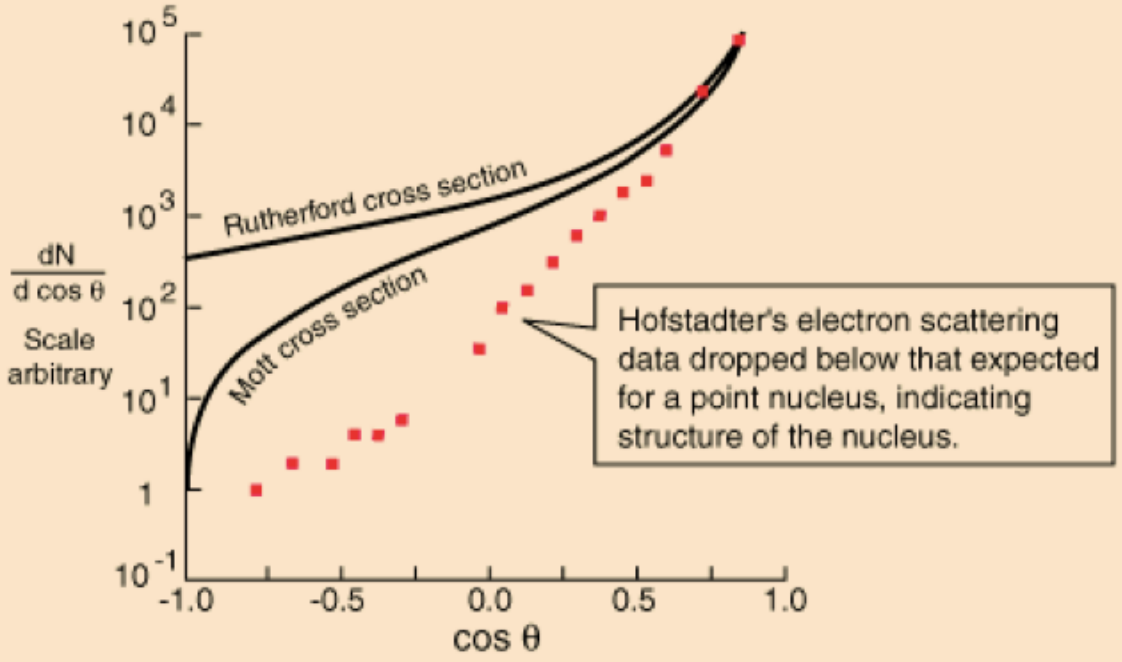
Mott cross section:

Electron Rutherford formula

Electron magnetic moment effect

$$\frac{d\sigma}{d\ \cos\theta} = \left(\frac{d\sigma}{d\ \cos\theta}\right)_R \frac{(1+\cos\theta)/2}{\left[1+\frac{(1-\cos\theta)KE}{Mc^2}\right]}$$

Nuclear recoil effect



$$r = r_0 A^{1/3} \quad where \quad r_0 = 1.2x10^{-15} m = 1.2\, fm$$

For elastic scattering from a spinless target, angular momentum cannot be absorbed by the nucleus, so backscattering is forbidden. The modifications to the cross section when it is calculated with a full relativistic theory do not change A_{PV}

lead208 - notable as the heaviest known stable isotope of any element.z=82, n=126, nuclear spin 0+

Ca 48 – 20=z, 28=n, "doubly magic" nucleus, nuclear spin 0+ simple doubly closed shell structure

(all nuclei with even Z and even N have nuclear spin I=0)

For the simplest case of elastic scattering from a heavy, spinless,isoscalar nucleus, the asymmetry and cross section are given by

$$A_{PV} = A_0 Q^2; \quad \frac{\mathrm{d}\sigma}{\mathrm{d}\Omega} = \frac{E^2 \cos^2(\theta/2)|F|^2}{Q^4}.$$

C12 – Apv measured : P. A. Souderet al.,Phys. Rev. Lett.65 (1990) 694

Z_i is atomic charge of i'th species

f_i is the fraction of counts from i'th species IN DETECTOR

g_i is the fraction of i'th species by atomic count in target

$f_i = (Z_i/20)^2 g_i$

A_{PV} ignoring structure is $G_F Q^2/(4 \text{ pi alpha sqrt}(2)) * [1 - 4 \sin^2 th_W - N/Z]$

A_{meas} = contaminants + signal = $(\text{sum}_i f_i A_i) + (1-\text{sum}_i f_i) A_{48}$

$A_{48} = (A_{meas} - \text{sum}_i f_i A_i)/ (1- \text{sum}_i f_i)$

$dA_{48}/df_i = (A_{48} - A_i)/(1 - \text{sum}_j f_j)$

Assumptions: A_48 = 2.2 ppm from proposal

A_48(r = n) ~= 0.8*2.2 ppm

A_40 = A_48(r=n)*20/28 = 1.3 ppm (Maybe this is too small, but it's conservative)

	^{48}Ca	^{40}Ca	^{16}O	^{14}N
A [ppm]	2.20	1.26	2.02	2.02
Z	20	20	8	7
g		0.1	0.01	0.01
f	0.897	0.1	0.0016	0.0012
dA_{48}/df		1.051	0.201	0.201
dg/g = df/f		0.1	35	45
dA_{48}/A_{48}		0.005	0.005	0.005