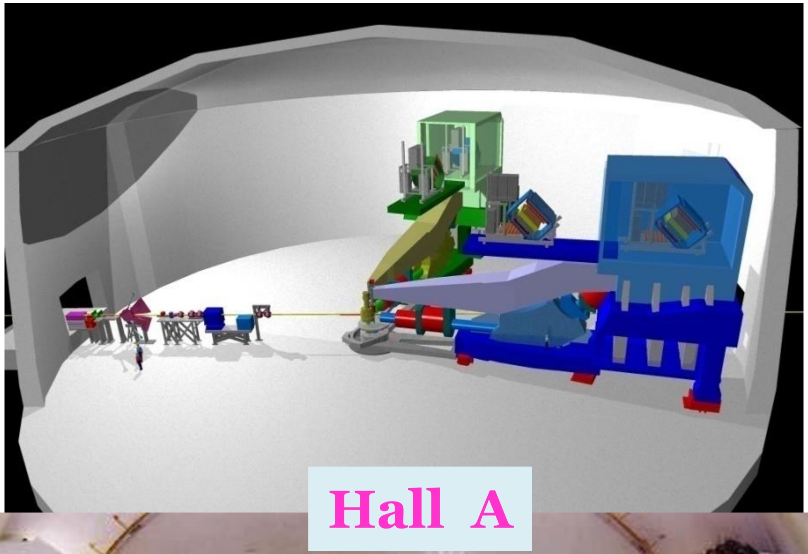
Using Weak Interaction to Probe Neutrons in Nuclei
the Why and How Experimentally

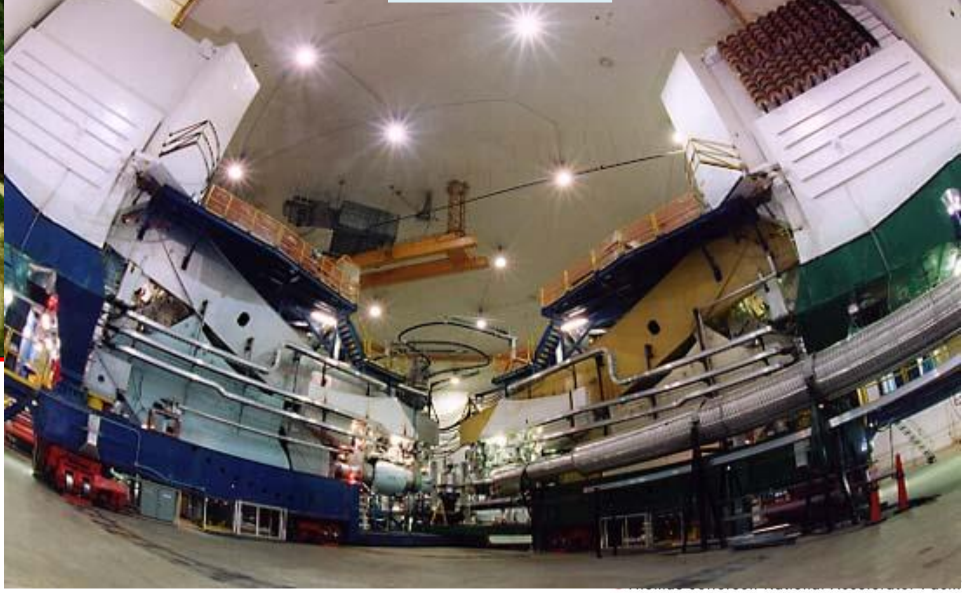
Robert Michaels

Jefferson Lab
(JLab)

Thomas Jefferson National Accelerator Facility

Hall A at Jefferson Lab





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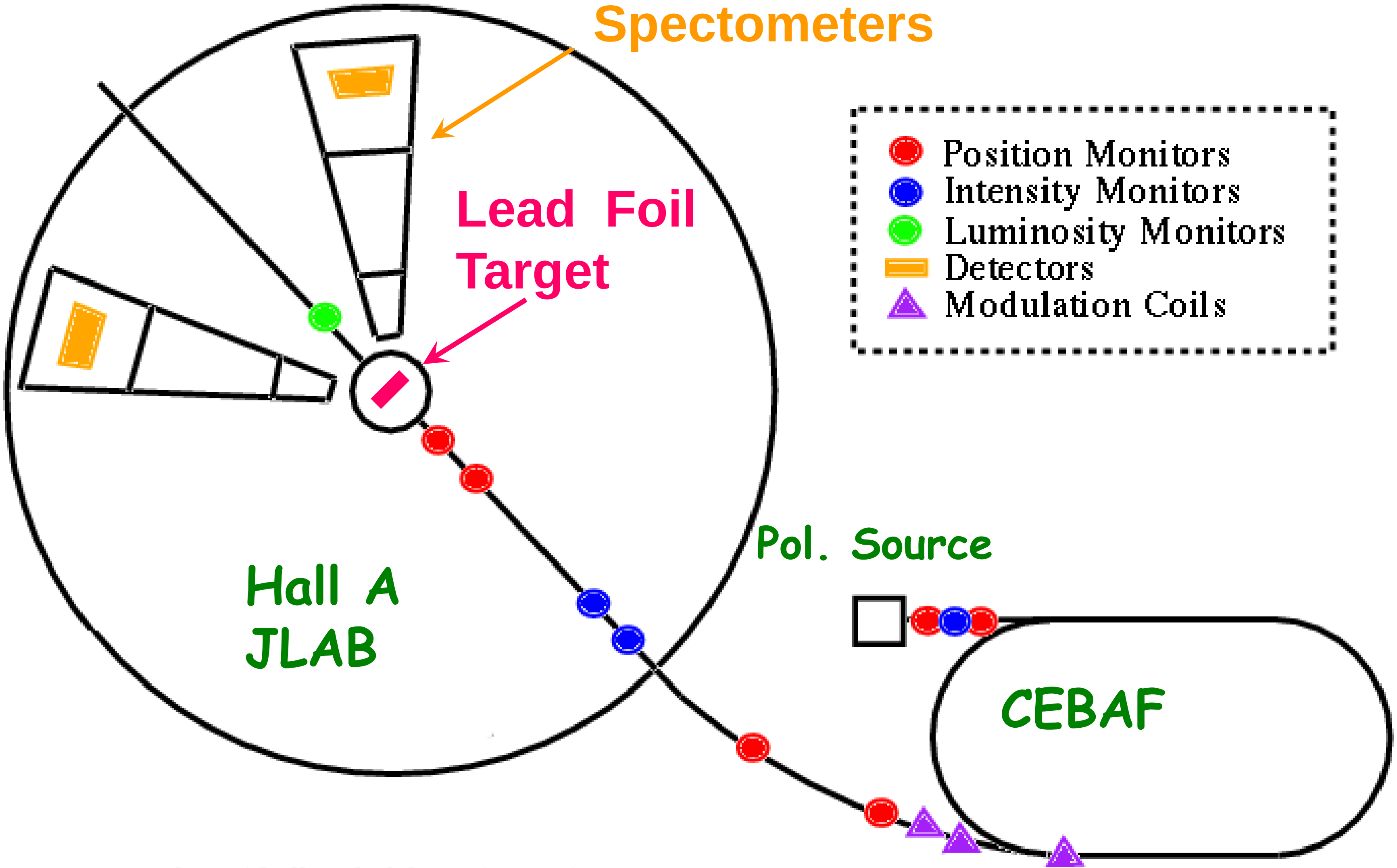
PREX Setup



Spectometers

Lead Foil Target

- 🔴 Position Monitors
- 🔵 Intensity Monitors
- 🟢 Luminosity Monitors
- 🟧 Detectors
- △ Modulation Coils

Pol. Source

Hall A JLAB

CEBAF

http://hallaweb.jlab.org/parity/prex

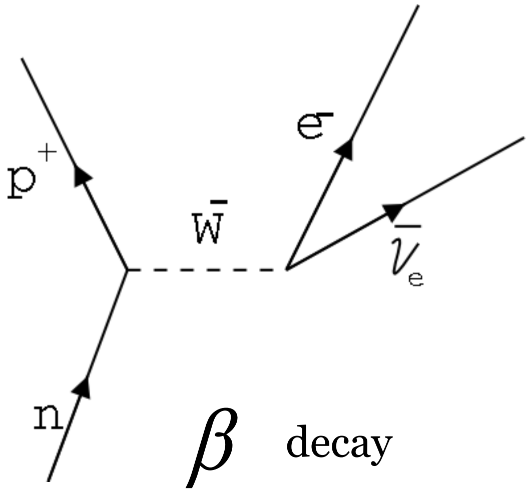
Weak Interactions

The **Glashow-Weinberg-Salam Theory** unifies the electromagnetic and weak interactions.

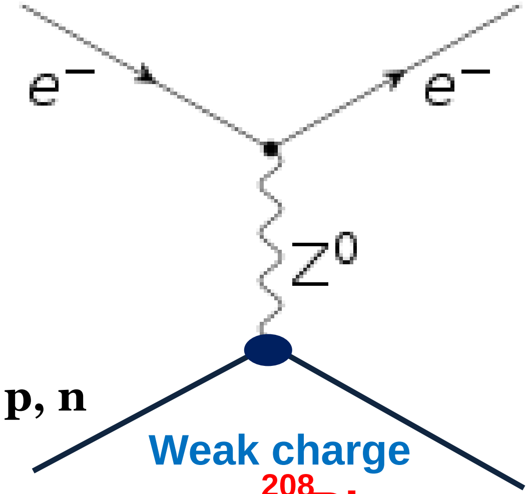
Left –handed fermion fields (quarks & leptons)
= doublets under SU(2)

Right-handed fields = singlets under SU(2)

Parity Violation



β decay



Weak charge
of ^{208}Pb

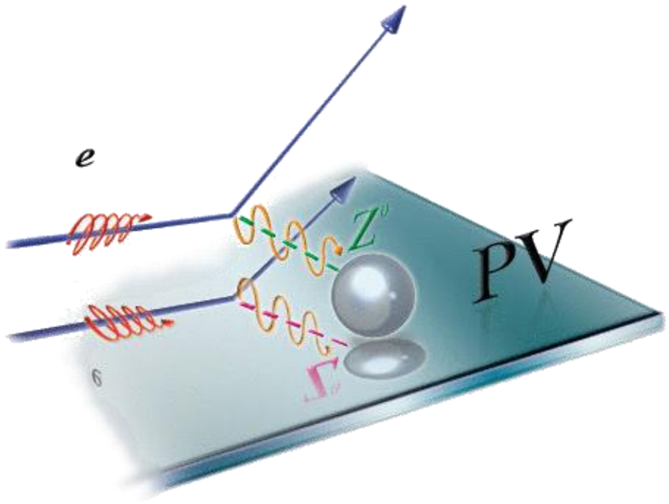
How to isolate the ***weak interaction***

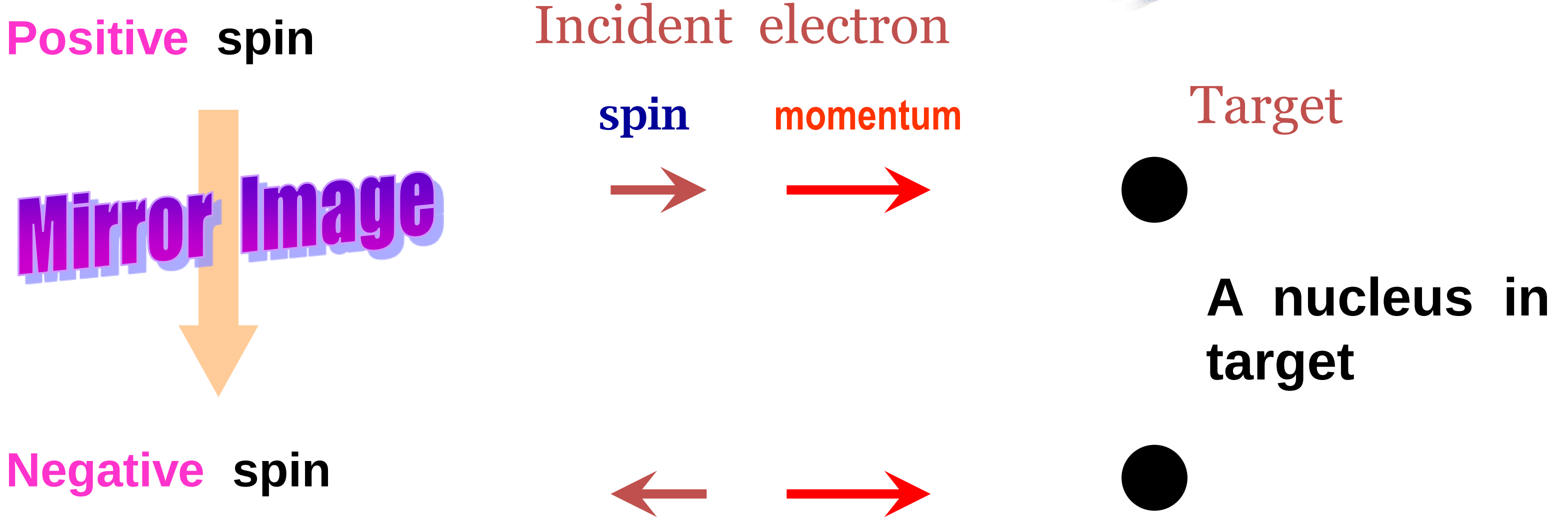
Do 2 experiments that are *mirror images* :

Weak interaction looks different.

EM interaction looks same.

The *weak interaction* changes with mirror imaging which allows to isolate it.





Positive **spin**

Incident electron

spin **momentum**

Target

→ →

Mirror Image

A nucleus in target

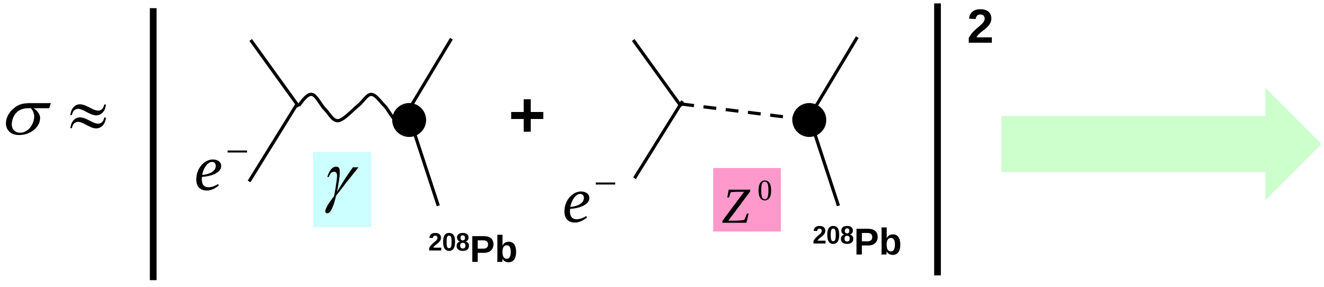
Negative **spin**

← →

Method: Flip spin of electrons and look for difference in scattering rate.

Parity Violating Asymmetry

$$A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \sim 10^{-4} \times Q^2 \sim 10^{-6}$$



A_{PV} from interference

Applications of A_{PV} at Jefferson Lab

- **Nucleon Structure**

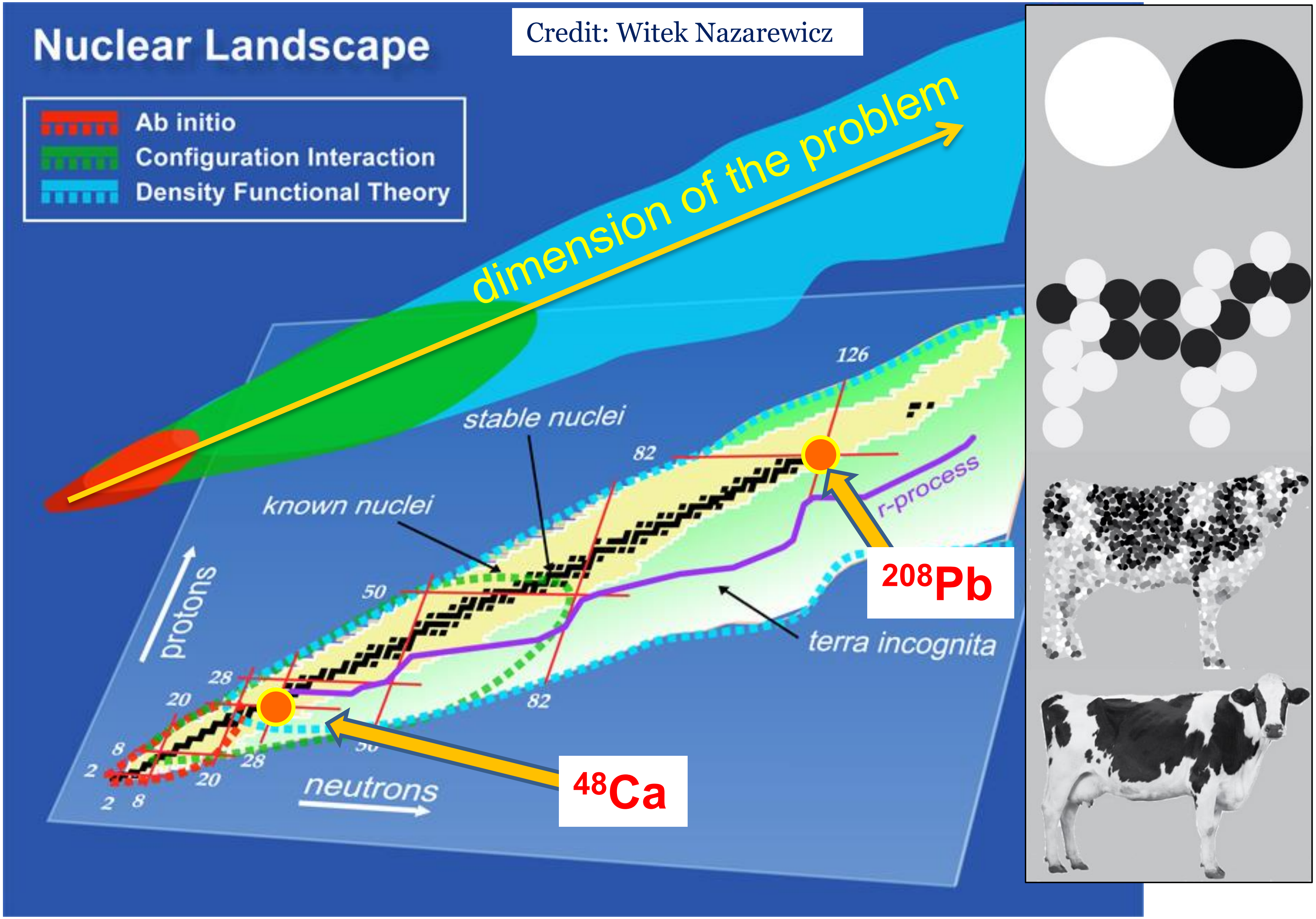
  Strangeness $s\bar{s}$ in proton (HAPPEX, G0 expts)

- **Test of Standard Model of Electroweak** $\sin^2\theta_W$

  e – e (MOLLER) or **e – q** (PVDIS)
  elastic e – p at low Q^2 (QWEAK)

- ***Nuclear Structure (neutron density)* : *PREX*** & ***CREX***

How to explain the nuclear landscape from the bottom up? **Theory roadmap**



Credit: Witek Nazarewicz

J. Phys. G 43, 044002 (2016)

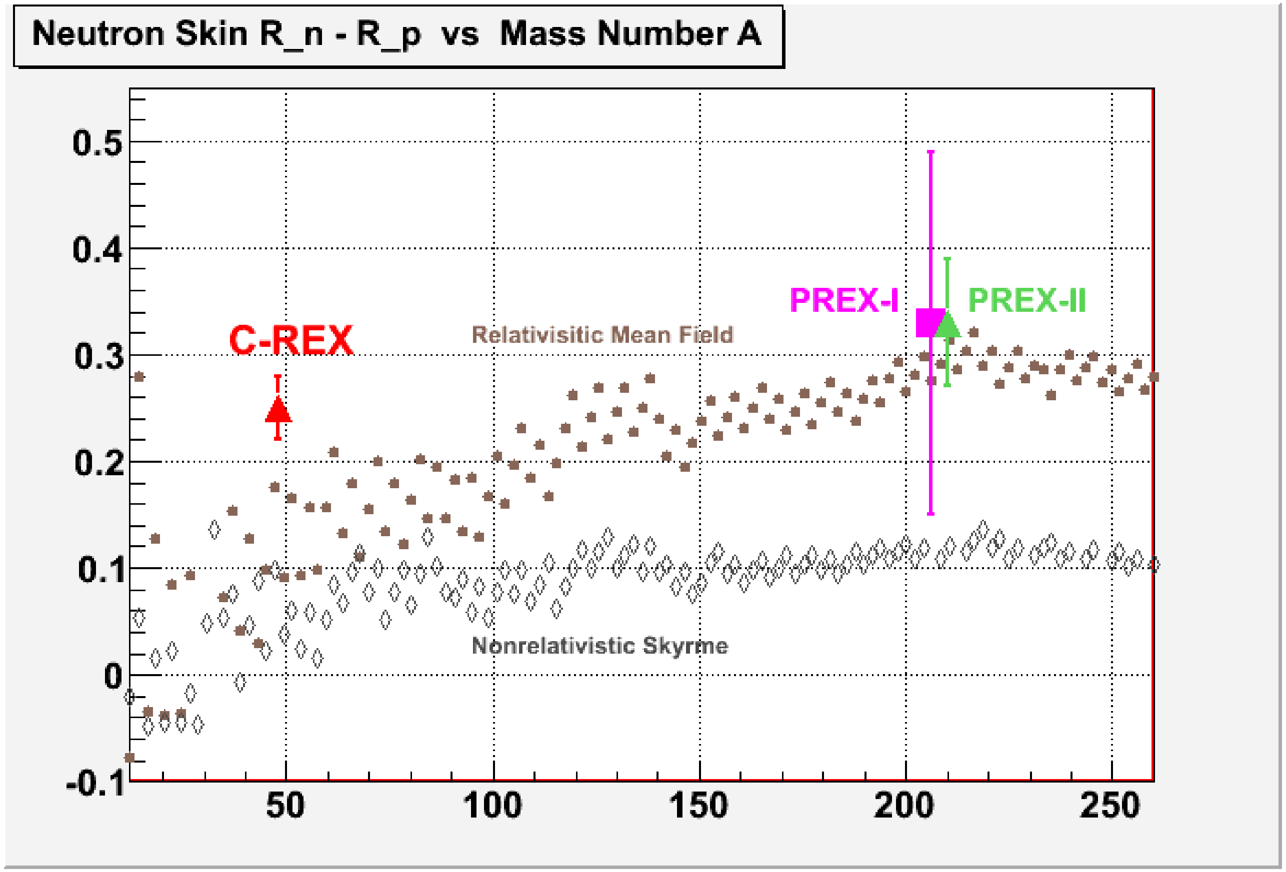
http://iopscience.iop.org/article/10.1088/0954-3899/43/4/044002

PREX (^{208}Pb) and CREX (^{48}Ca)

Measuring Neutron Skins $R_n - R_p$ provides new information and new constraints on nuclear structure theory

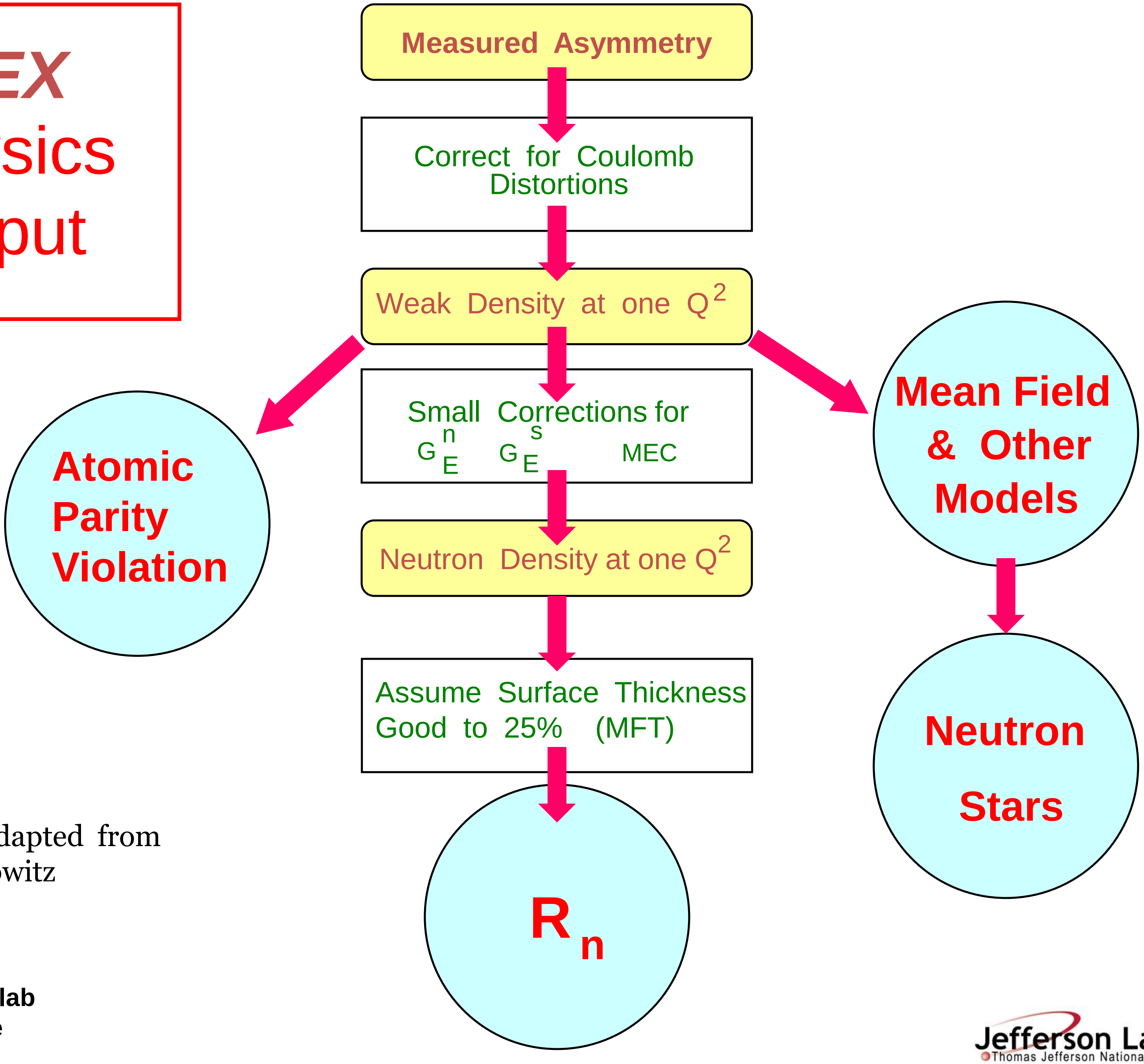
^{208}Pb more closely approximates infinite nuclear matter (and neutron stars)

The structure of **^{48}Ca** can, only recently, be addressed in detailed microscopic models.



Theory from P. Ring et al. Nucl. Phys. A 624 (1997) 349

PREX Physics Output



Measured Asymmetry

Correct for Coulomb Distortions

Weak Density at one Q^2

Small Corrections for G_E^n G_E^s MEC

Neutron Density at one Q^2

Assume Surface Thickness Good to 25% (MFT)

R_n

Atomic Parity Violation

Mean Field & Other Models

Neutron Stars

Slide adapted from
C. Horowitz

Fundamental Nuclear Physics :

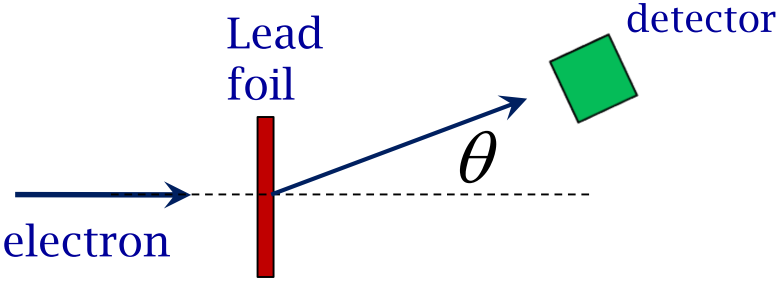
What is the size of a nucleus ?

Neutrons are thought to determine
the size of heavy nuclei like ^{208}Pb.

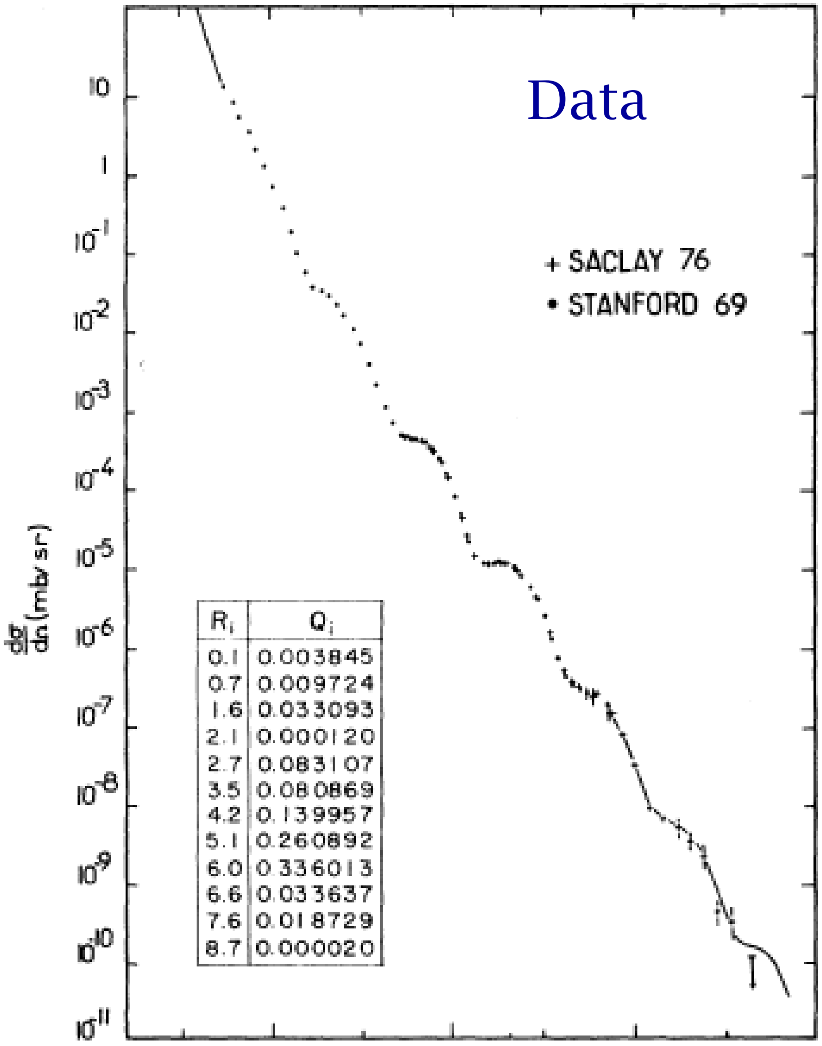
Can theory predict it ?

Scattering of High-Energy (here ~500 MeV) Electrons from Lead Nuclei.

The **nuclei** are the *“mysterious structures”* causing a pattern in the scattered electrons.



Scattering Rate vs Momentum Transfer

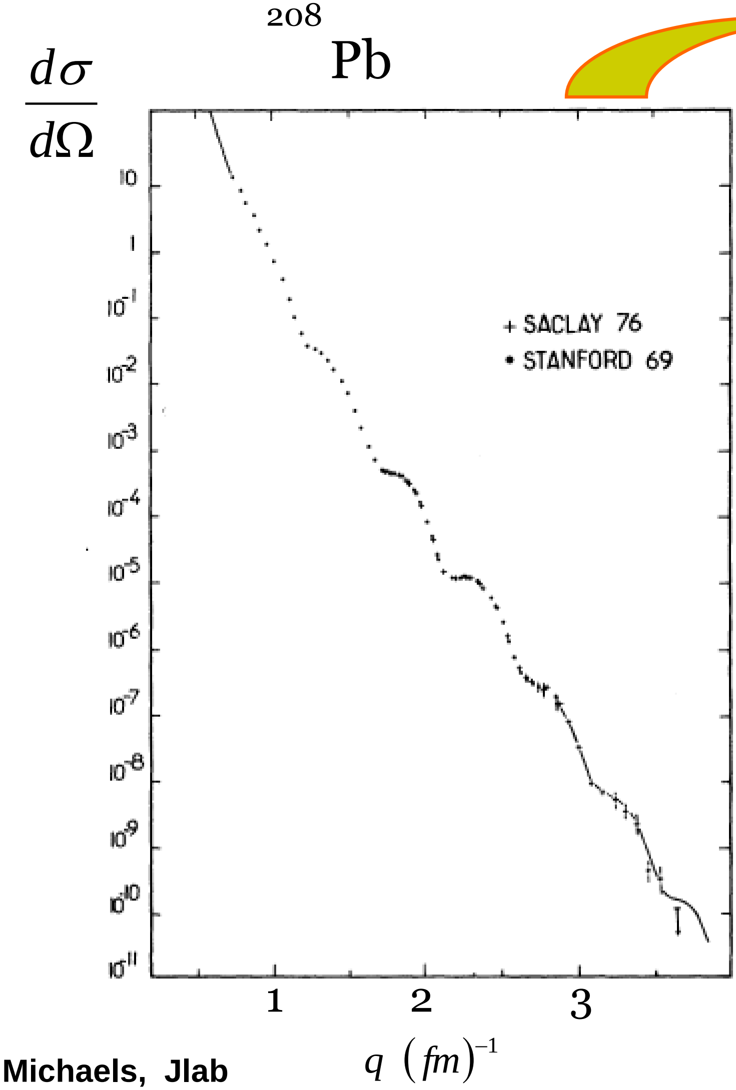


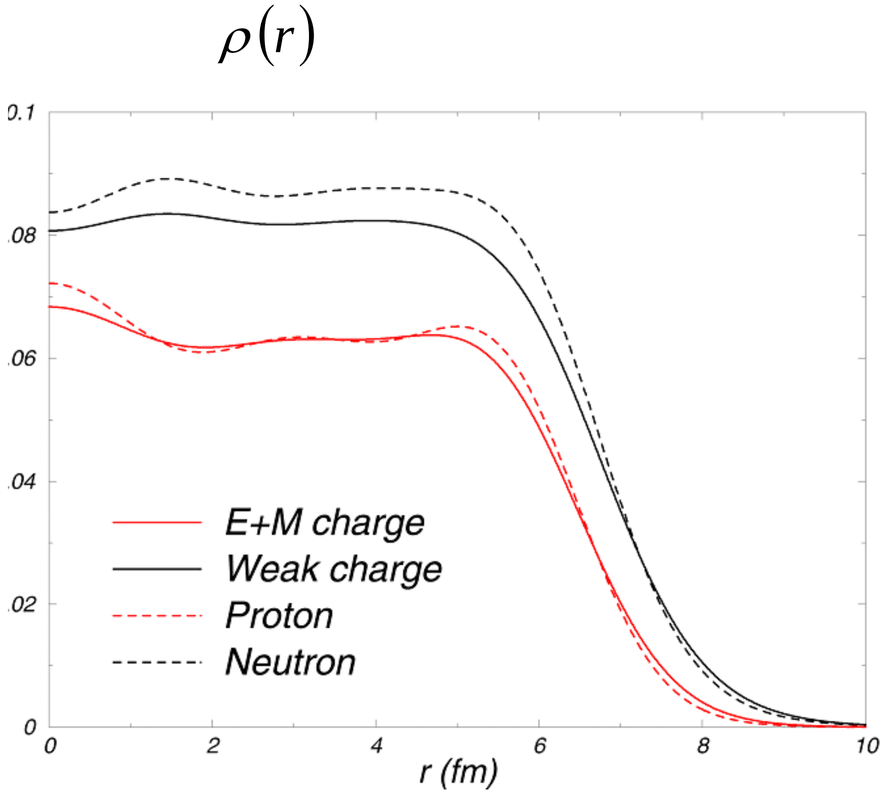
R_i	Q_i
0.1	0.003845
0.7	0.009724
1.6	0.033093
2.1	0.000120
2.7	0.083107
3.5	0.080869
4.2	0.139957
5.1	0.260892
6.0	0.336013
6.6	0.033637
7.6	0.018729
8.7	0.000020

$q \propto \theta$

Reminder: Electromagnetic Scattering determines $\rho(r)$

(charge distribution)





Z^0 of weak interaction : sees the neutrons

	proton	neutron
Electric charge	1	0
Weak charge	0.08	1

T.W. Donnelly, J. Dubach, I. Sick
Nucl. Phys. A 503, 589, 1989

C. J. Horowitz, S. J. Pollock,
P. A. Souder, R. Michaels
Phys. Rev. C 63, 025501, 2001

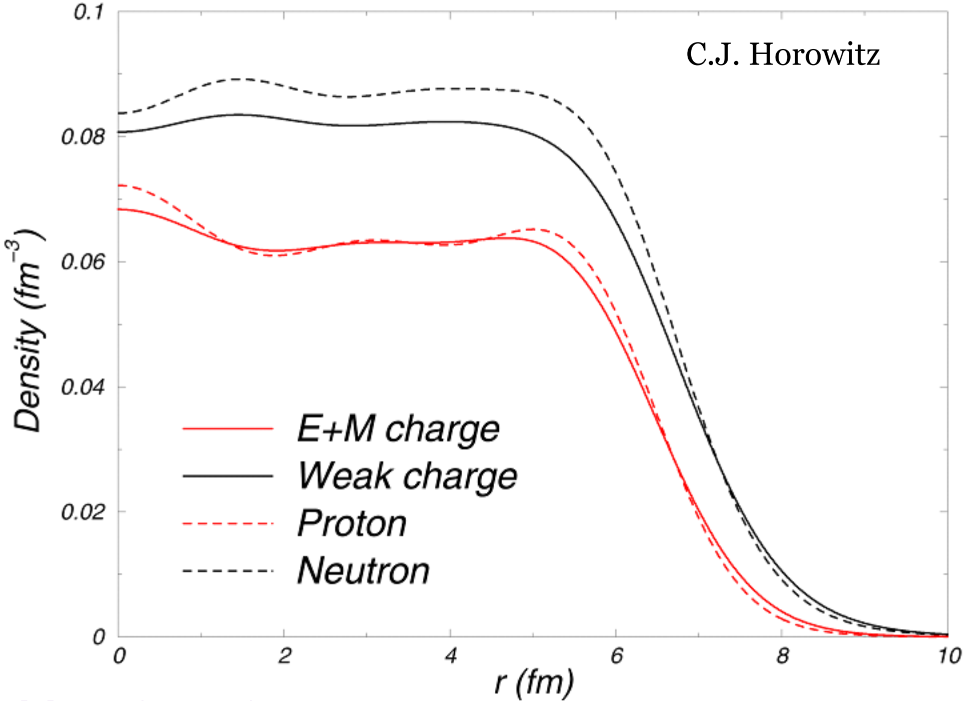
^{208}Pb

Neutron form factor

$$F_N(Q^2) = \frac{1}{4\pi}\int d^3r\; j_0(qr)\;\rho_N(r)$$

Parity Violating Asymmetry

$$A = \frac{G_F Q^2}{2\pi\alpha\sqrt{2}}\left[\underbrace{1-4\sin^2\theta_W}_{\approx 0} - \frac{F_N(Q^2)}{F_P(Q^2)}\right]$$



http://hallaweb.jlab.org/parity/prex

How to Measure

Neutron Distributions, Symmetry Energy

- Proton-Nucleus Elastic
- Pion, alpha, d Scattering
- Pion Photoproduction
- Heavy ion collisions
- Rare Isotopes (dripline)

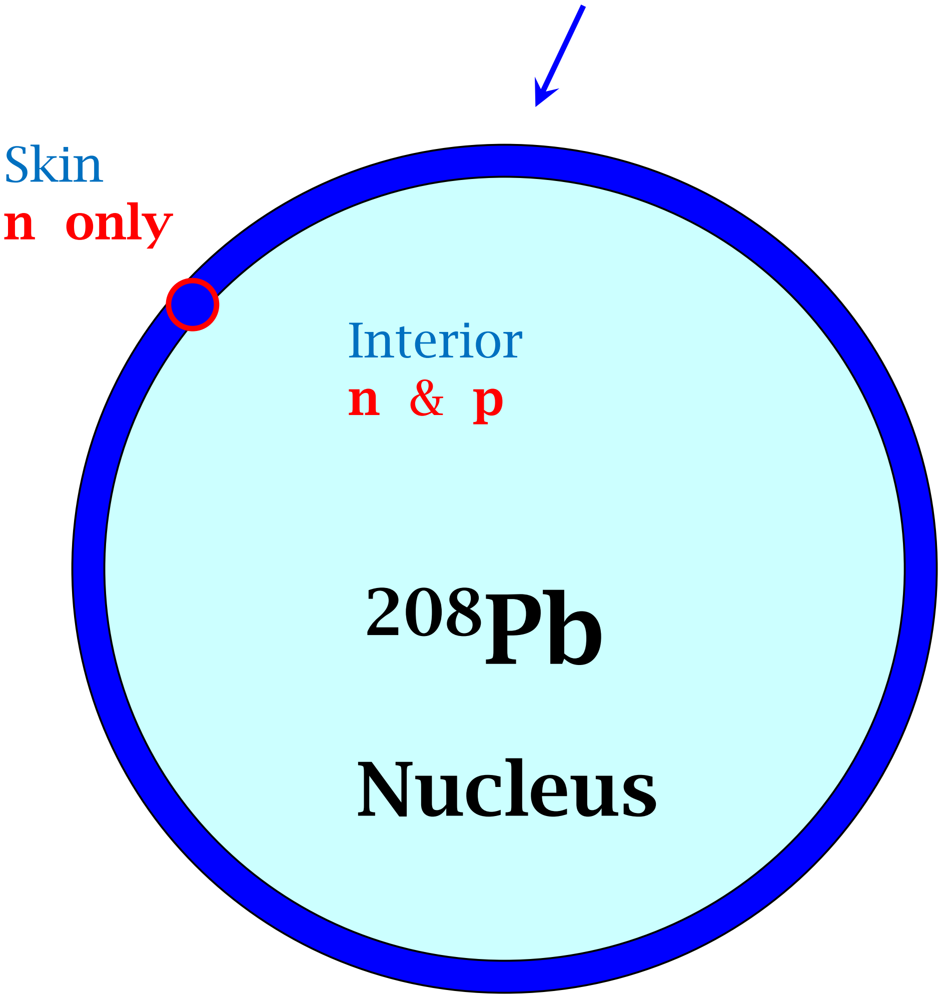
} Involve strong probes, the interpretation is clouded by understanding of the reaction mechanism

- Magnetic scattering → Most spins couple to zero.

- **PREX** / **C-REX** (weak interaction)

- Theory → MFT fit mostly by data *other than* neutron densities

PREX : Neutron Skin



Skin
n only

Interior
n & p

^{208}**Pb**

Nucleus

Was expected since more neutrons (n) than protons (p)

Observed by PREX-I
(95 % confidence)

Parity Violating electron scattering is "cleaner" than other probes
(e.g. proton scattering)

Fundamental check of nuclear theory

Using Parity Violation

Electron - Nucleus Potential $$\hat{V}(r) = V(r) + \gamma_5 A(r)$$

electromagnetic

$$\boxed{V(r) = \int d^3r' \; Z\, \rho(r') / |\vec{r} - \vec{r}'|}$$

axial

$$\boxed{A(r) = \frac{G_F}{2\sqrt{2}} \left[(1 - 4\sin^2\theta_W) Z \rho_P(r) - N \rho_N(r) \right]}$$

^{208}Pb is spin 0

$$\frac{d\sigma}{d\Omega} = \frac{d\sigma}{d\Omega}_{Mott} |F_P(Q^2)|^2$$

⇨ $A(r)$ is small, best observed by parity violation

⇨ $1 - 4\sin^2\theta_W << 1$ neutron weak charge >> proton weak charge

Proton form factor

$$F_P(Q^2) = \frac{1}{4\pi} \int d^3r \; j_0(qr)\, \rho_P(r)$$

Neutron form factor

$$F_N(Q^2) = \frac{1}{4\pi} \int d^3r \; j_0(qr)\, \rho_N(r)$$

Parity Violating Asymmetry

$$A = \frac{\left(\frac{d\sigma}{d\Omega}\right)_R - \left(\frac{d\sigma}{d\Omega}\right)_L}{\left(\frac{d\sigma}{d\Omega}\right)_R + \left(\frac{d\sigma}{d\Omega}\right)_L} = \frac{G_F Q^2}{2\pi\alpha\sqrt{2}} \left[\underbrace{1 - 4\sin^2\theta_W}_{\approx 0} - \frac{F_N(Q^2)}{F_P(Q^2)} \right]$$

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From low to medium to high density neutrons

Low density : nuclei

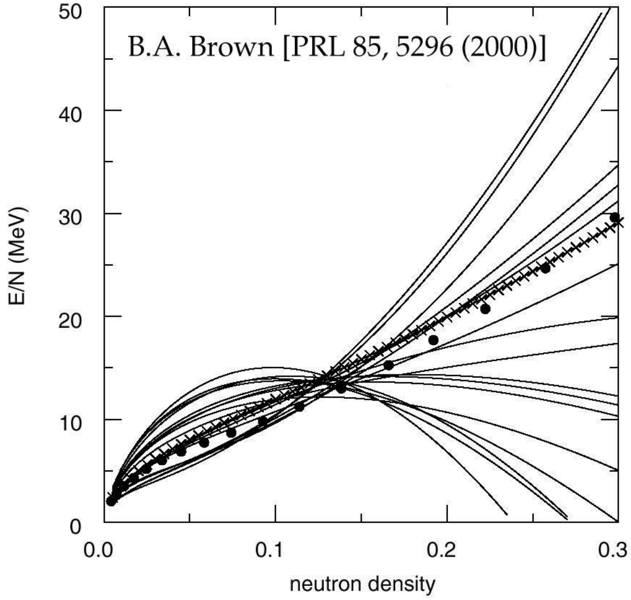
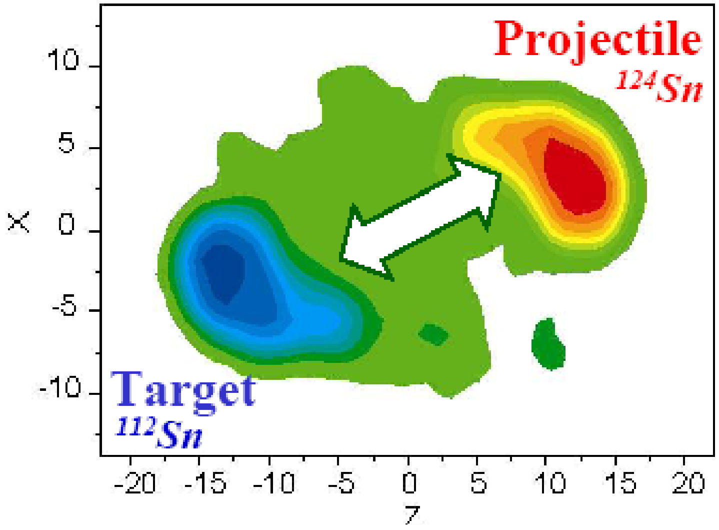


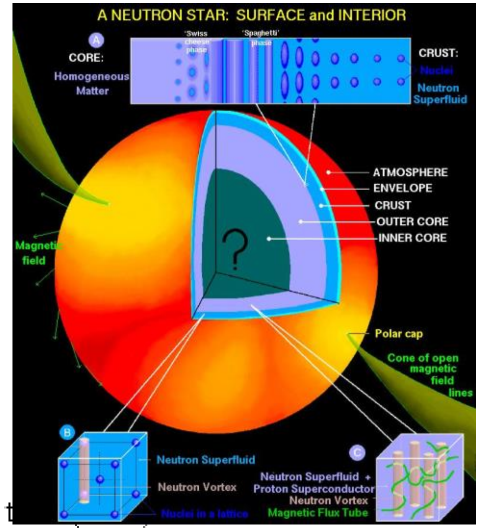
FIG. 2. The neutron EOS for 18 Skyrme parameter sets. The filled circles are the Friedman-Pandharipande (FP) variational calculations and the crosses are SkX. The neutron density is in units of neutron/fm^3.

Medium density :
Heavy Ion Collisions



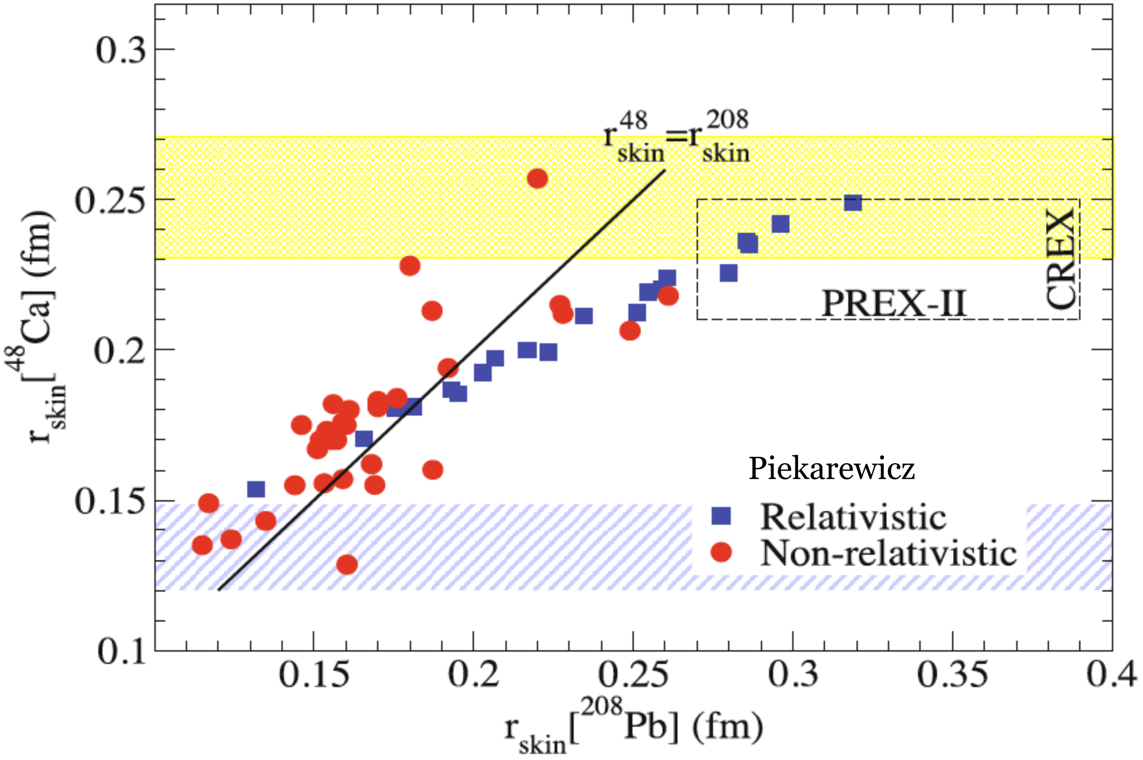
Danielewicz, Lacey, and Lynch,
Science 298 (2002) 1592.

Highest density :
Neutron Stars



"Ab Initio" (exact microscopic) calculations of R_{skin} for ^{48}Ca have recently been published. G. Hagen et al., Nature Physics 12, 186 (2016).

Can be compared to Density Functional Theory (the red and blue points) and Dispersive Optical Model (DOM).



DOM
W. Dickoff,
et al

ab initio

- "Ab initio":

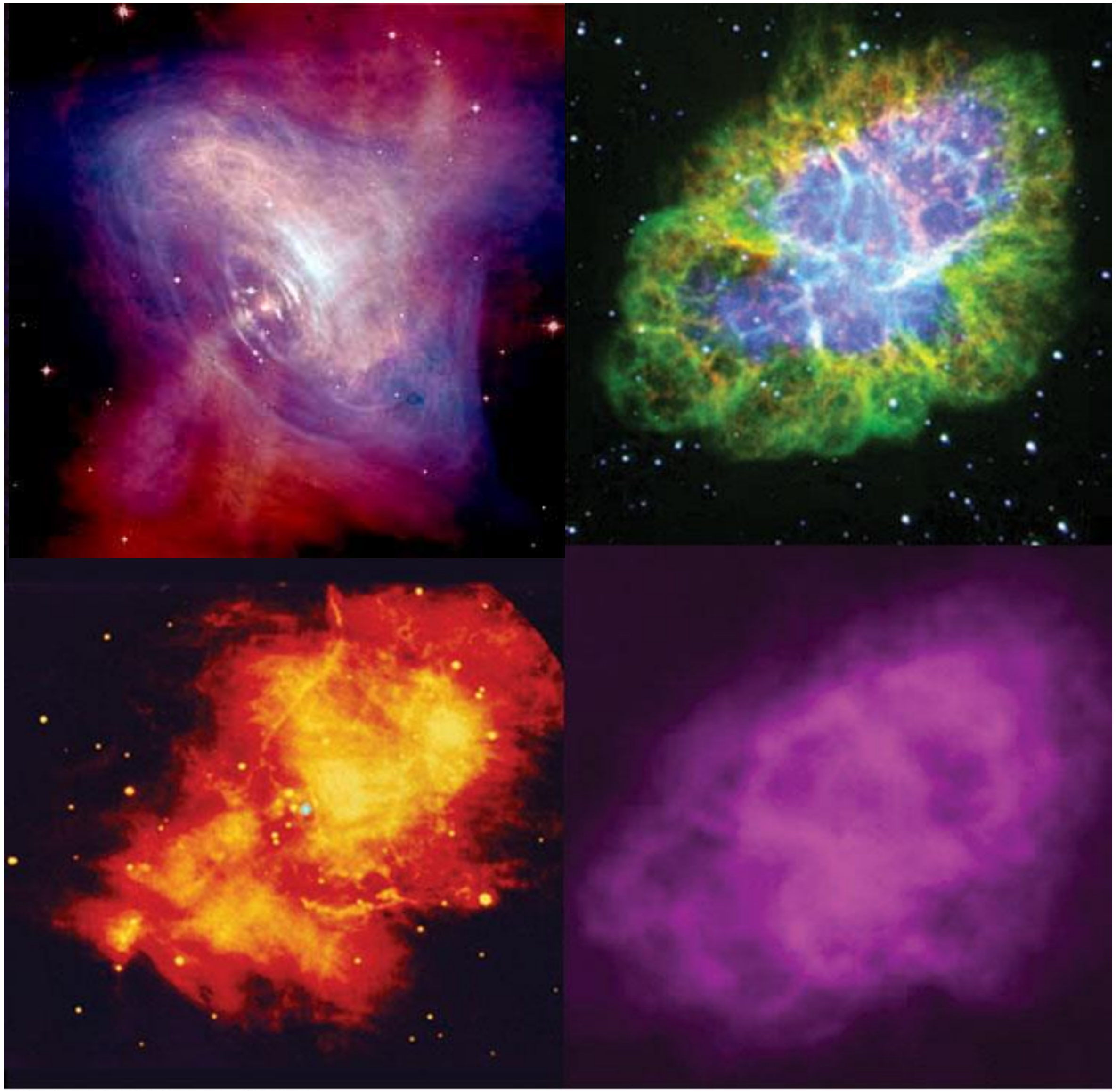
G. Hagen et al., Nature Phys. 12, 186 (2016)

Application :

Neutron Stars

What is the nature of extremely dense matter ?

Do collapsed stars form "exotic" phases of matter ? (strange stars, quark stars)



Crab Nebula (X-ray, visible, radio, infrared)

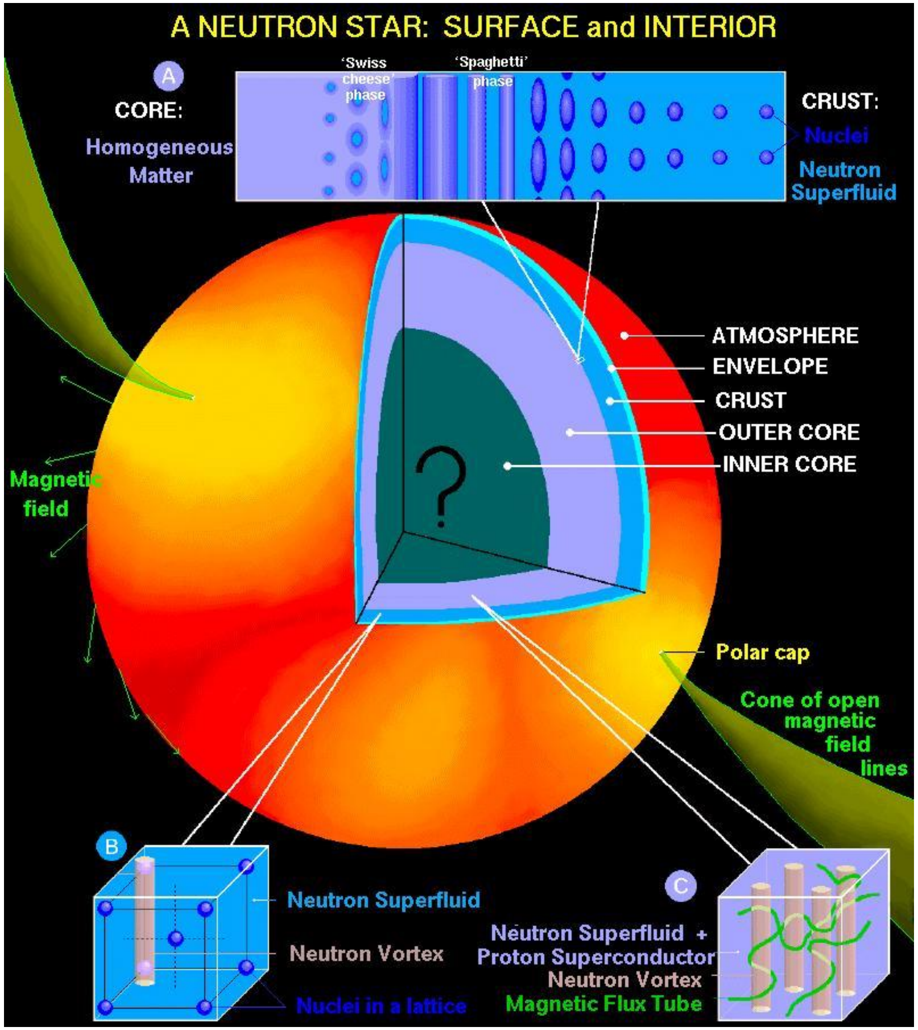


Fig from: Dany Page.

J.M. Lattimer & M. Prakash, Science 304 (2004) 536.

Inputs:

pressure

density

- Eq. of state (EOS) $\boxed{P(\rho)}$

PREX helps *here*

- Hydrostatics (Gen. Rel.)

- Astrophysics Observations

Luminosity L
Temp. T
Mass M from pulsar timing

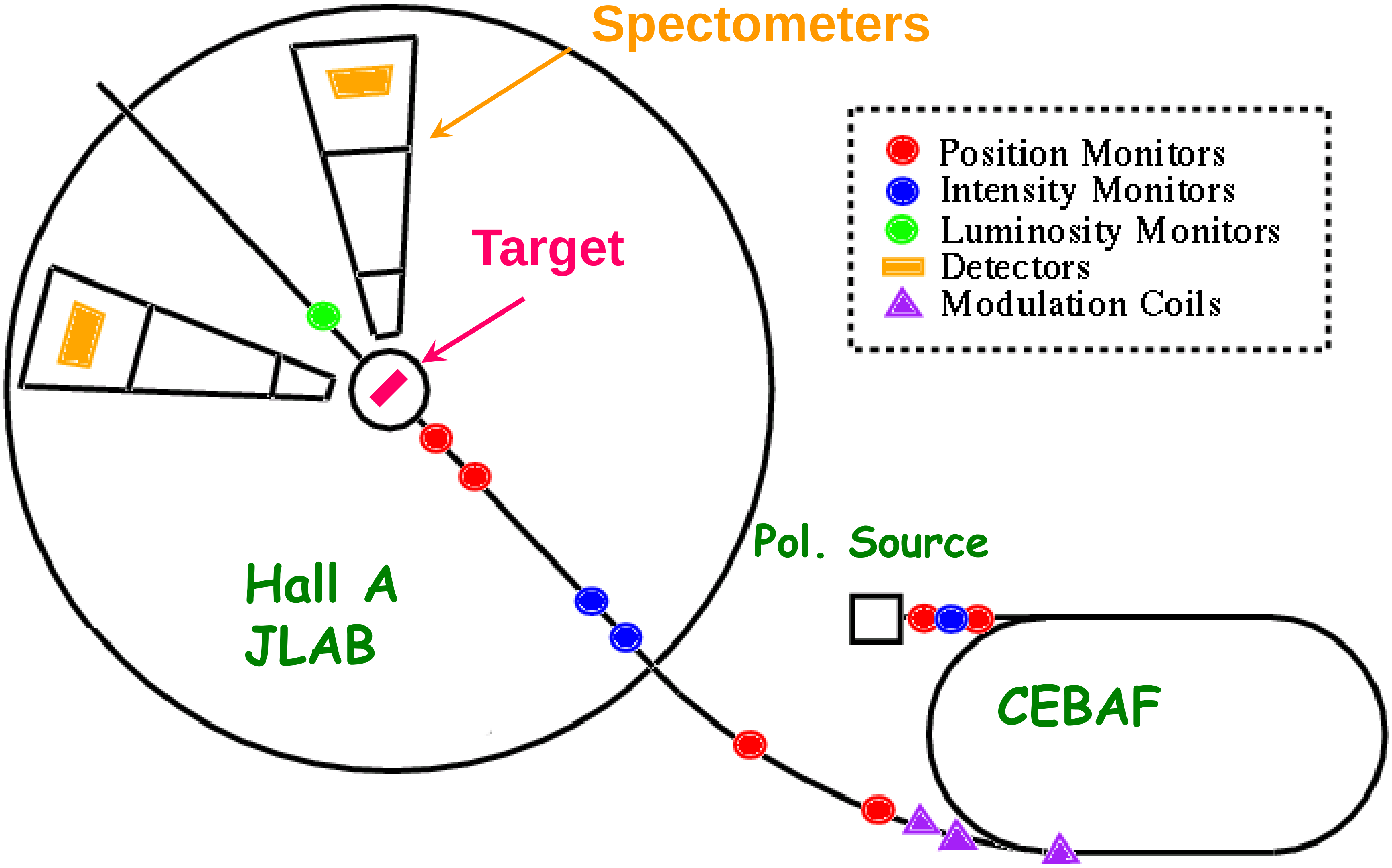
$$L = 4\pi\sigma_B R^2 T^4$$

(with corrections ...)

Mass - Radius relationship

Experiment Setup

Parity: “The entire lab is the experiment”



Spectometers

Target

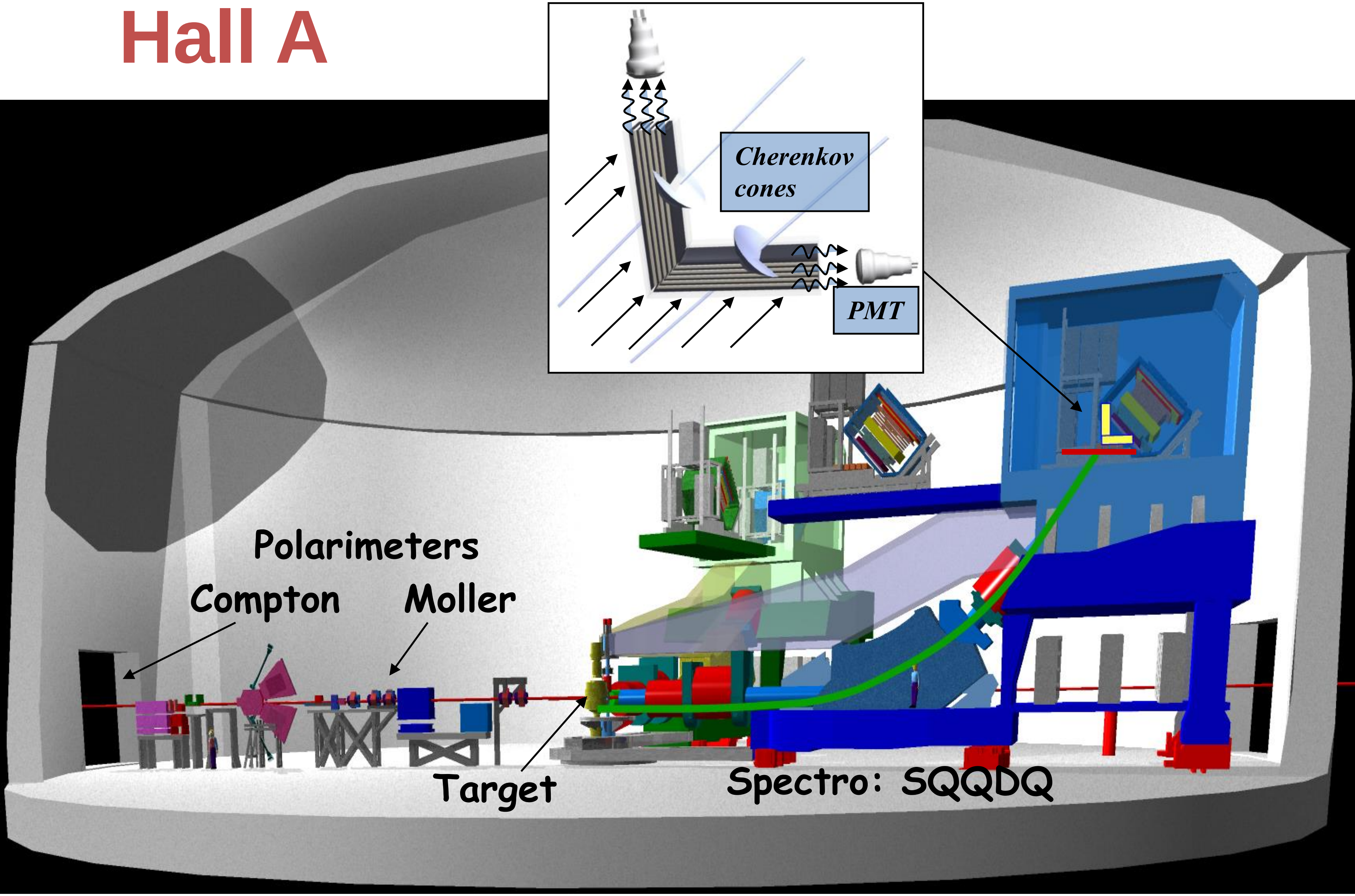
Hall A
JLAB

Pol. Source

CEBAF

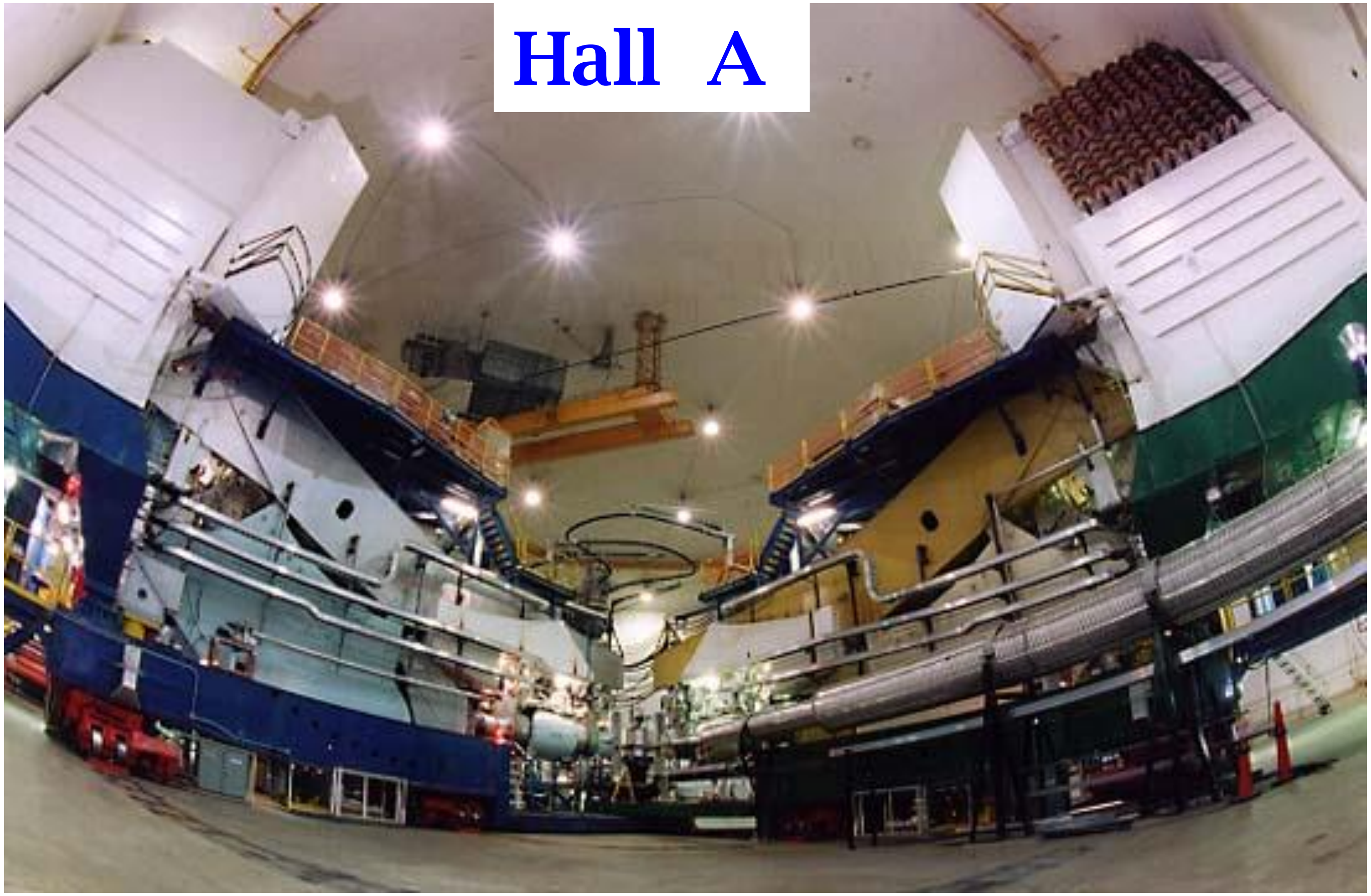
- 🔴 Position Monitors
- 🔵 Intensity Monitors
- 🟢 Luminosity Monitors
- 🟧 Detectors
- ▲ Modulation Coils

Hall A


Cherenkov cones
PMT
Polarimeters
Compton
Moller
Target
Spectro: SQQDQ

Spectrometers at Jefferson Lab

These machines are "microscopes" for looking at quarks.



Spectrometers at Jefferson Lab

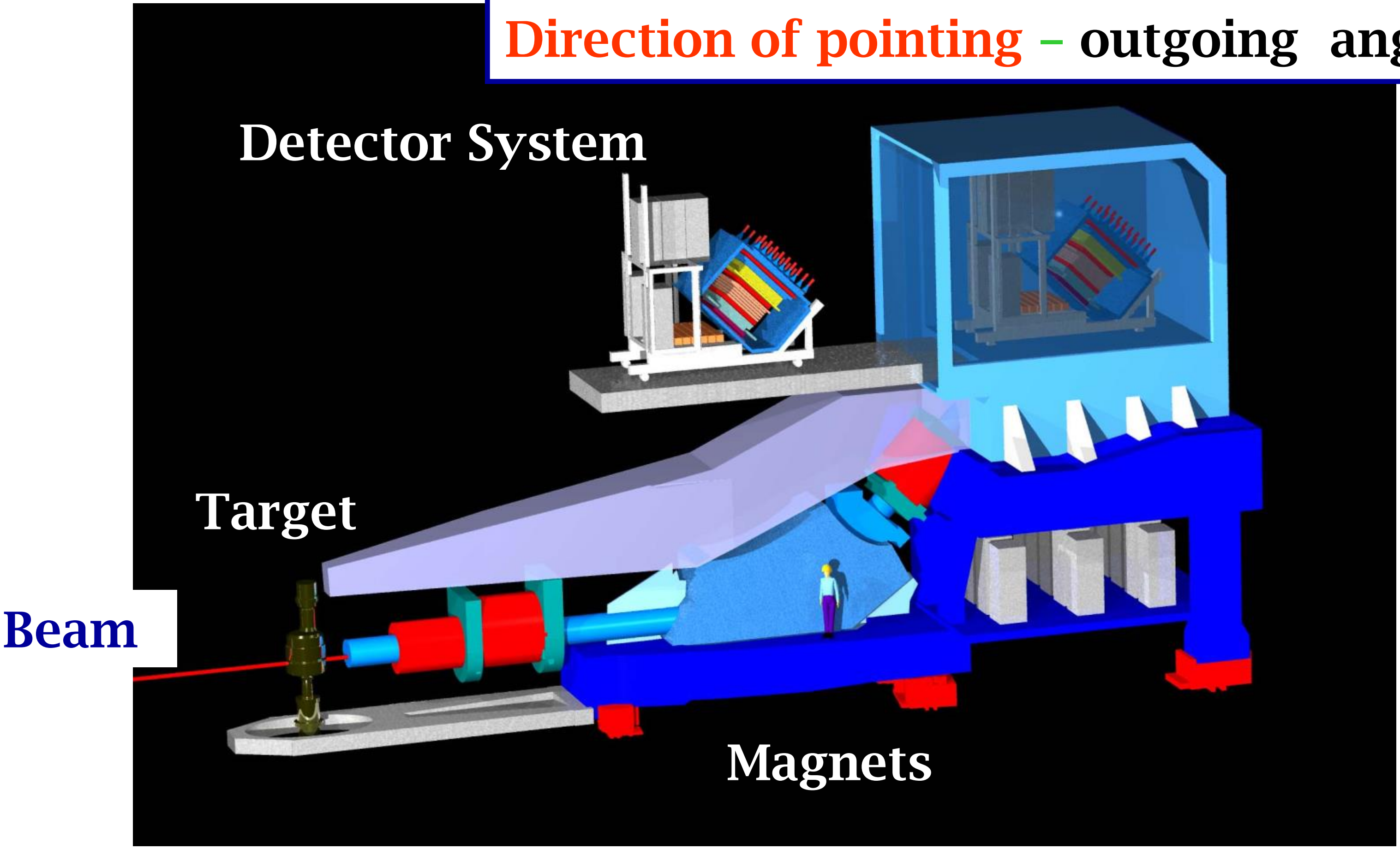
Hall A

Spectrometers Measure :

Magnets – measure momentum

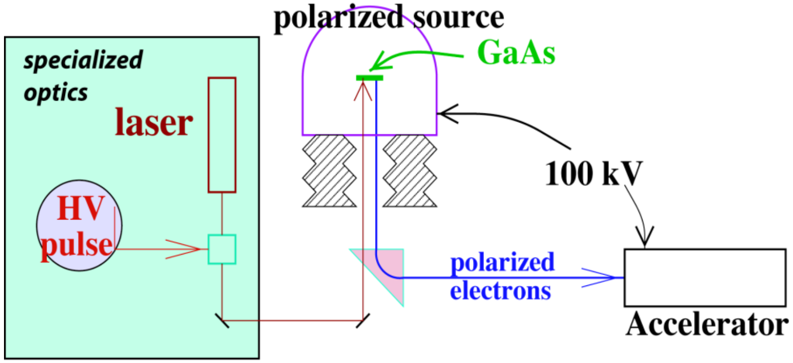
Detectors – identifies particles

Direction of pointing – outgoing angle



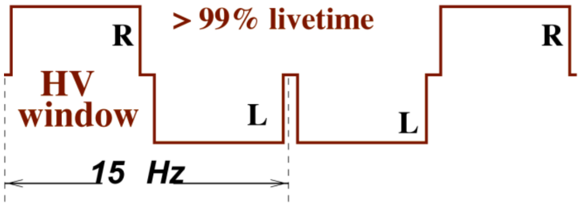
How to do a Parity Experiment

(integrating method)



rapid, random, helicity flipping

Rapid, Random Helicity Flips



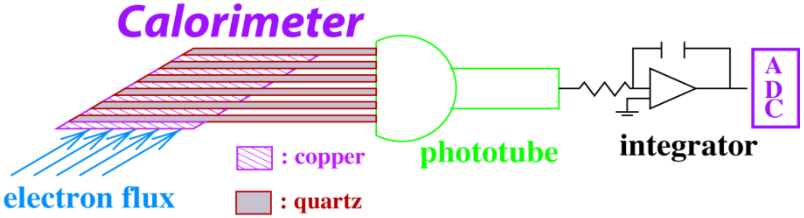
Measure flux F for each window

$$A_{\text{window pair}} = \frac{F_R - F_L}{F_R + F_L}$$

Flux Integration Technique:

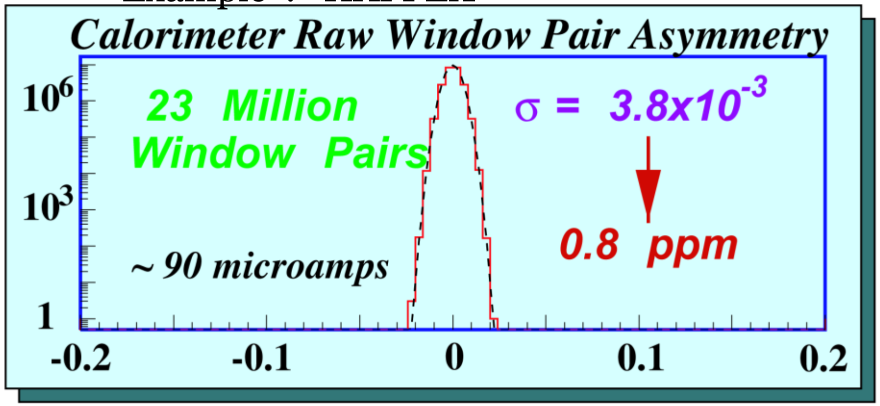
HAPPEX: 2 MHz

PREX: 500 MHz



Signal Average N Windows Pairs: $A \pm \frac{\sigma(A)}{\sqrt{N_{\text{windows}}}}$

Example : HAPPEX

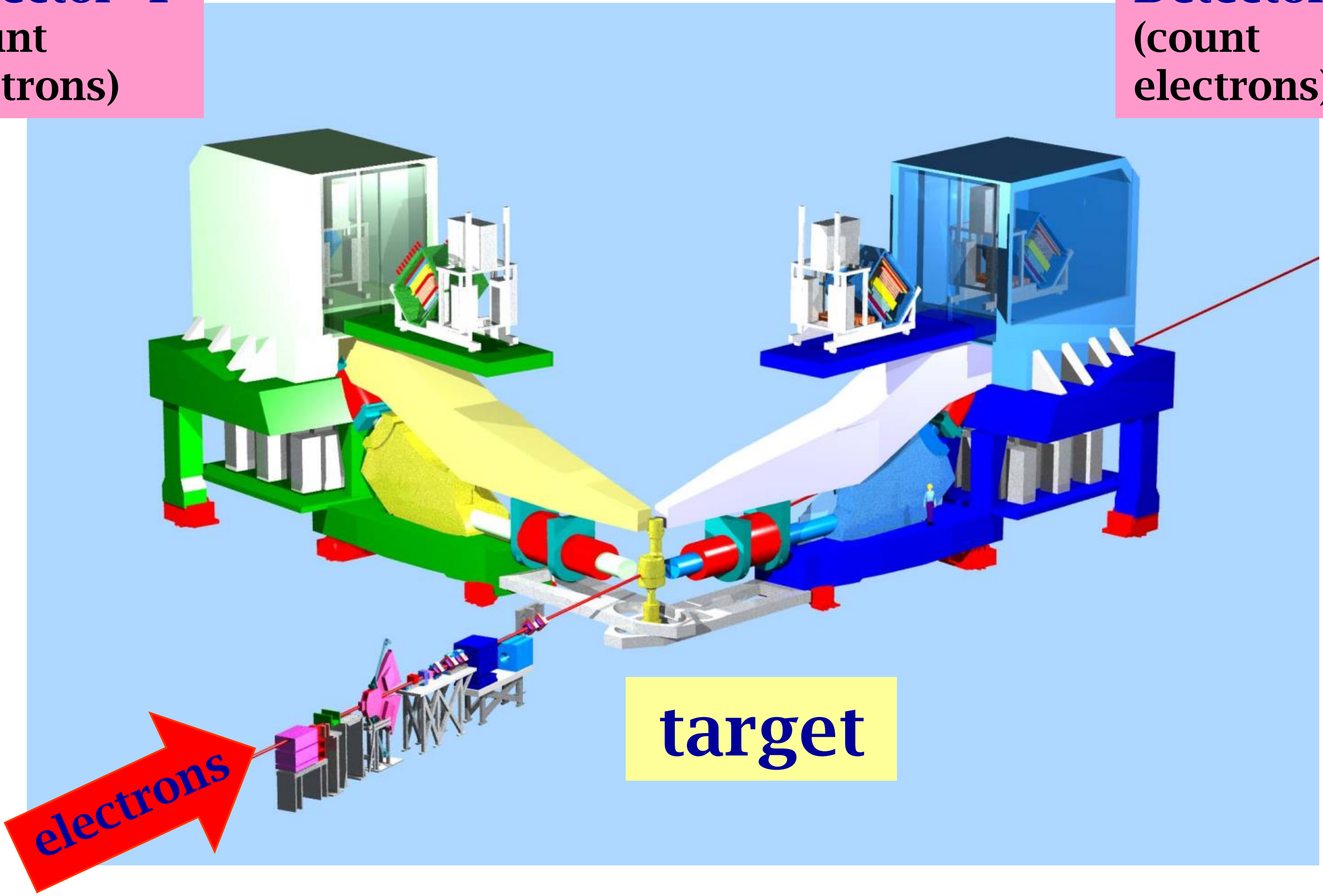


No non-gaussian tails to +/- 5σ

Experiment: Flip spin and count # scattered electrons in each spin state

Detector 1
(count
electrons)

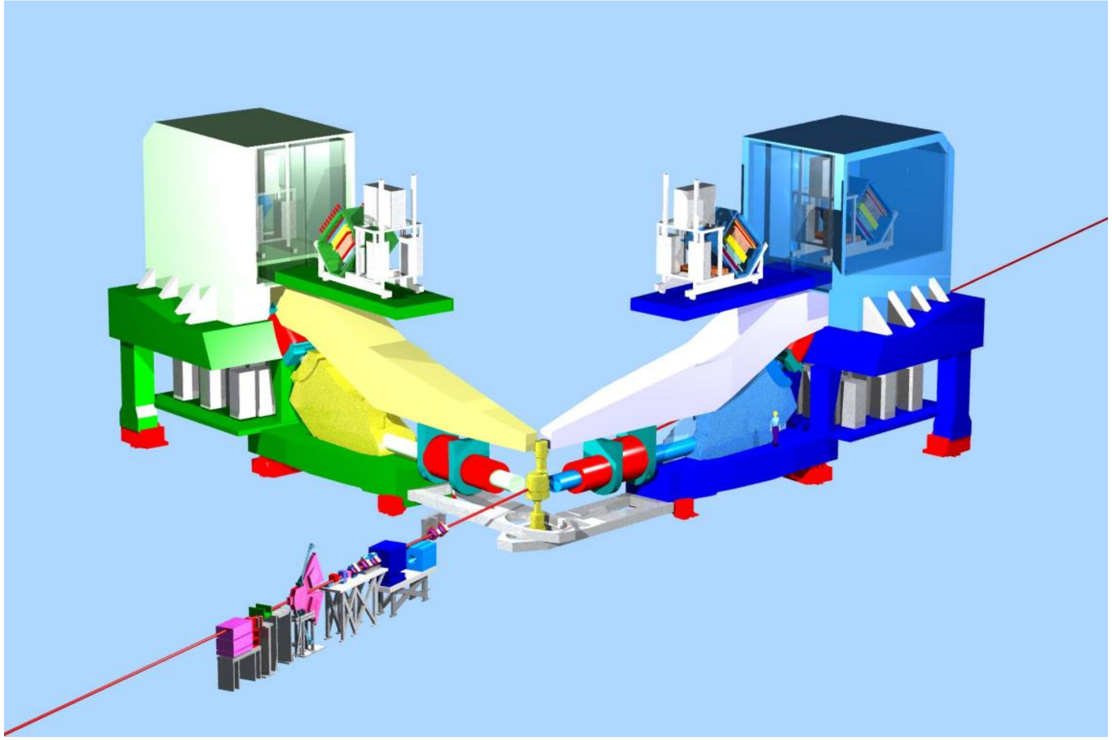
Detector 2
(count
electrons)



target

electrons

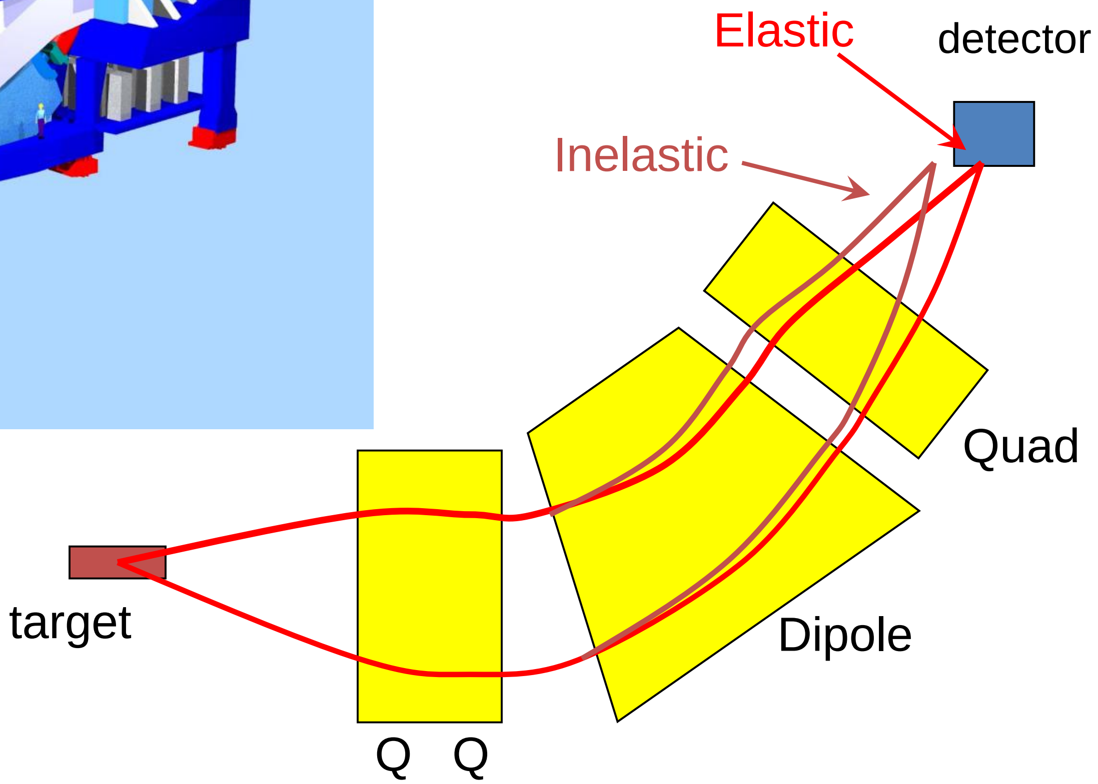
High Resolution Spectrometers



Left-Right symmetry to
control transverse
polarization systematic

Spectrometer Concept:
Resolve Elastic

1st excited state Pb 2.6 MeV



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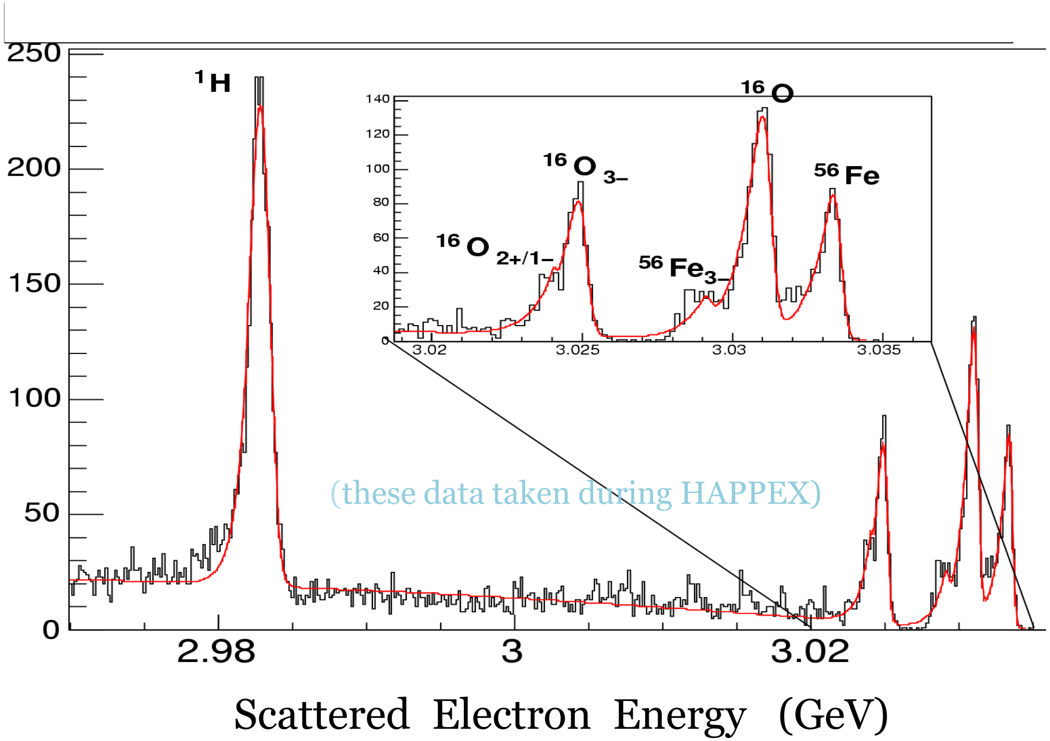
Measure θ from Nuclear Recoil



(these data taken during HAPPEX)

δE=Energy loss

E=Beam energy

M_A=Nuclear mass

θ=Scattering angle

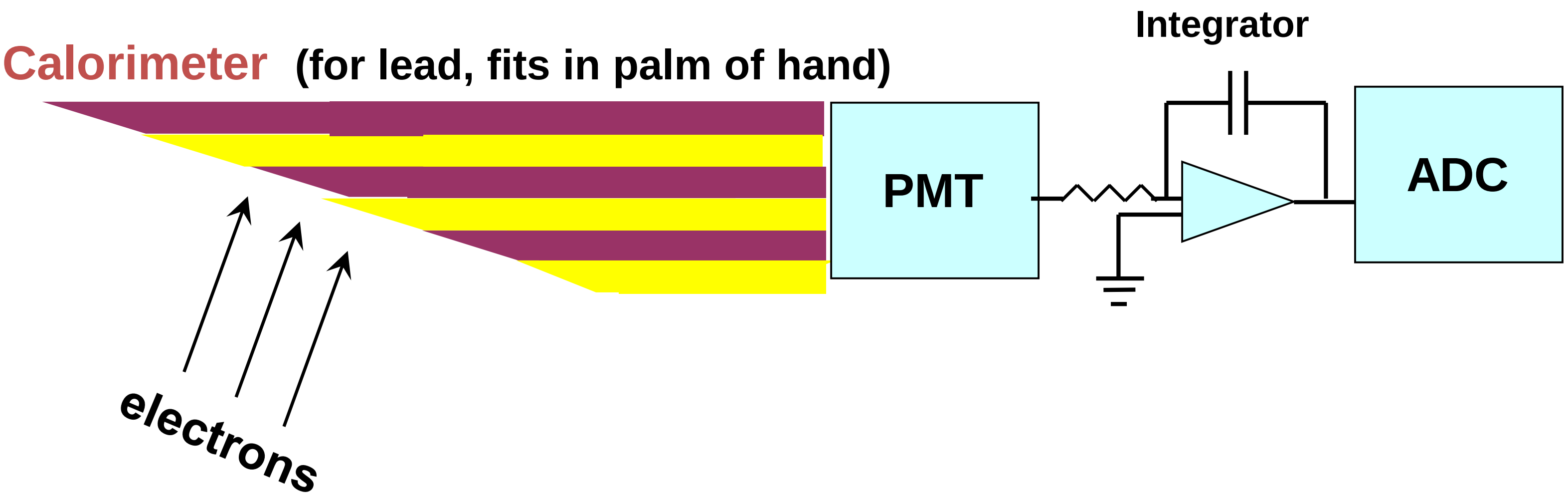
$$\frac{\delta E}{E} \approx \frac{\theta^2}{2} \frac{E}{M_A}$$

Recoil is large for H, small for nuclei

(3X better accuracy than survey)

Integrating Detection

- Integrate in 30 msec helicity period.
- Deadtime free.
- 18 bit ADC with $< 10^{-4}$ nonlinearity.
- But must separate backgrounds & inelastics (→ HRS).



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PREX-I
Physics Result

at $Q^2 = 0.00906\ \mathrm{GeV}^2$

$$A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} =$$

$$0.6571 \pm 0.0604\,(stat) \pm 0.0130\,(syst)$$

ppm 9.2 % 2.0 %

→ **Statistics limited (9%)**

→ **Followup expt, PREX-II to get to 3%**

→ **Systematic error goal achieved ! (2%)**

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A list of the **Systematic Errors** for **PREX**

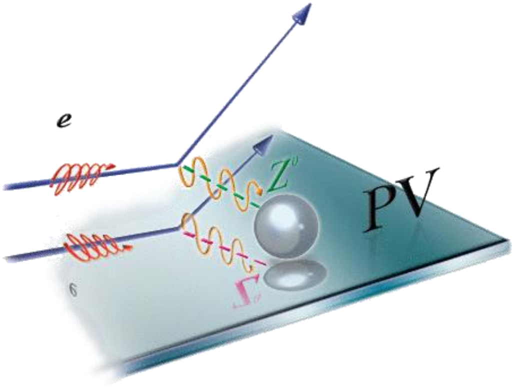
with explanations to follow for the first two …

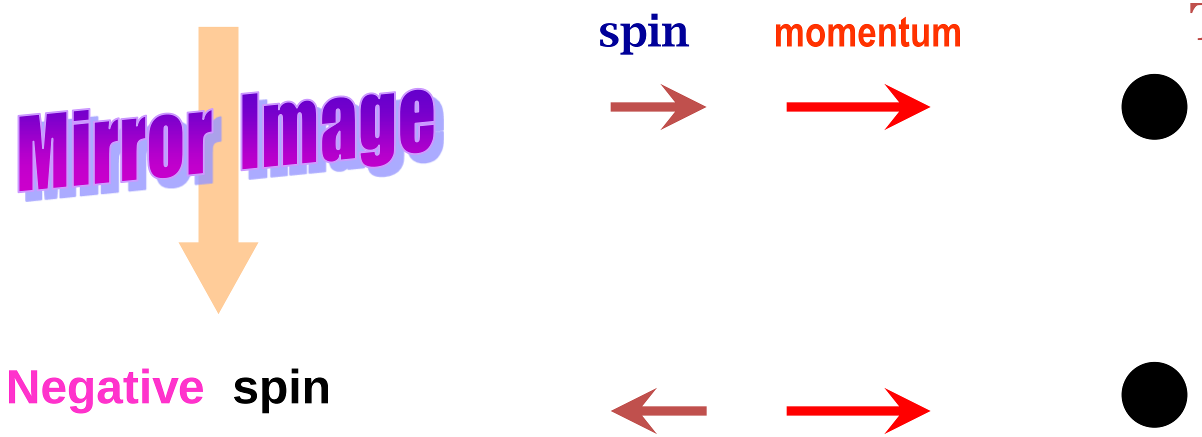
Error Source	Absolute (ppm)	Relative (%)
Beam Asymmetries **(1)**	0.0072	1.1
Polarization **(2)**	0.0083	1.3
Detector Linearity	0.0076	1.2
BCM Linearity	0.0010	0.2
Rescattering	0.0001	0
Transverse Polarization	0.0012	0.2
Q^2 **(2)**	0.0028	0.4
Target Thickness	0.0005	0.1
^{12}C Asymmetry **(1)**	0.0025	0.4
Inelastic States	0	0
TOTAL	**0.0140**	**2.1**

(1) Nonzero correction (the rest assumed zero)

(2) Normalization Correction applied

Isolating the *weak interaction* is not as easy as you think !





Positive spin

Incident electron

spin momentum

Target

Mirror Image

A nucleus in target

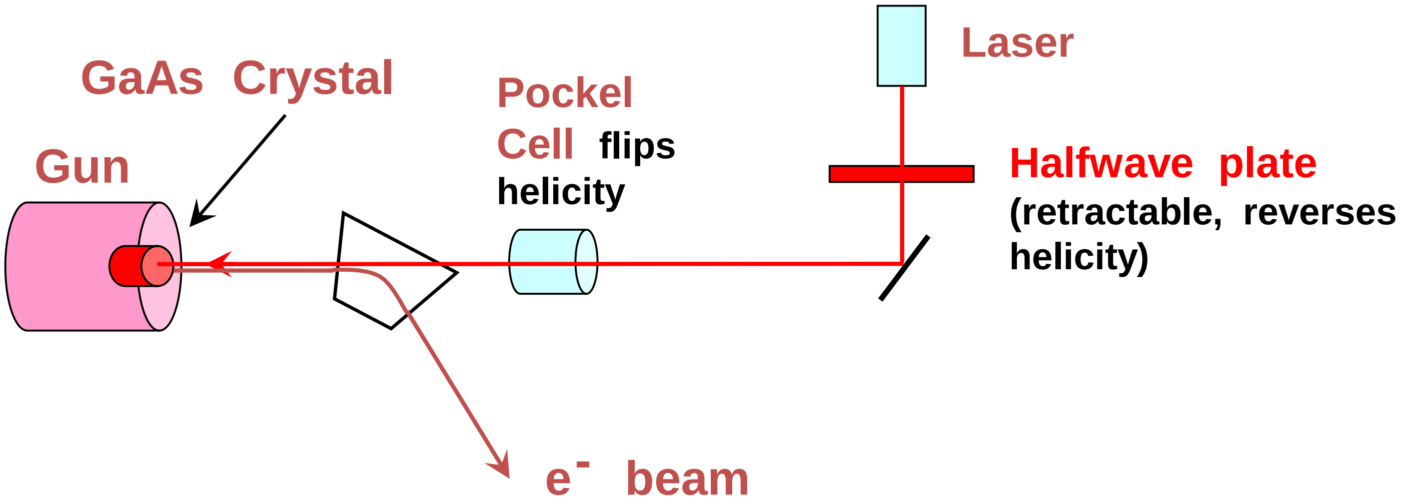
Negative spin

Want to flip spin of electrons and do not flip E, θ or anything else !

Beam Asymmetries

- Want to flip the helicity of the beam and nothing else.
- EM cross section depends on E, θ
- Residual helicity correlations will exist at some level. Need to measure them and correct for them.
- Systematic error = error in the correction.

Polarized Electron Source



- **Based on Photoemission from GaAs Crystal**
- **Polarized electrons from polarized laser**
- **Need :**
  - Rapid, random helicity reversal
  - Electrical isolation from the rest of the lab
  - Feedback on Intensity Asymmetry

Parity Quality Beam : *Unique Strength of JLab*

Helicity – Correlated Position Differences

$< X_R - X_L > \quad \textit{for helicity } L, R$

Plotted below

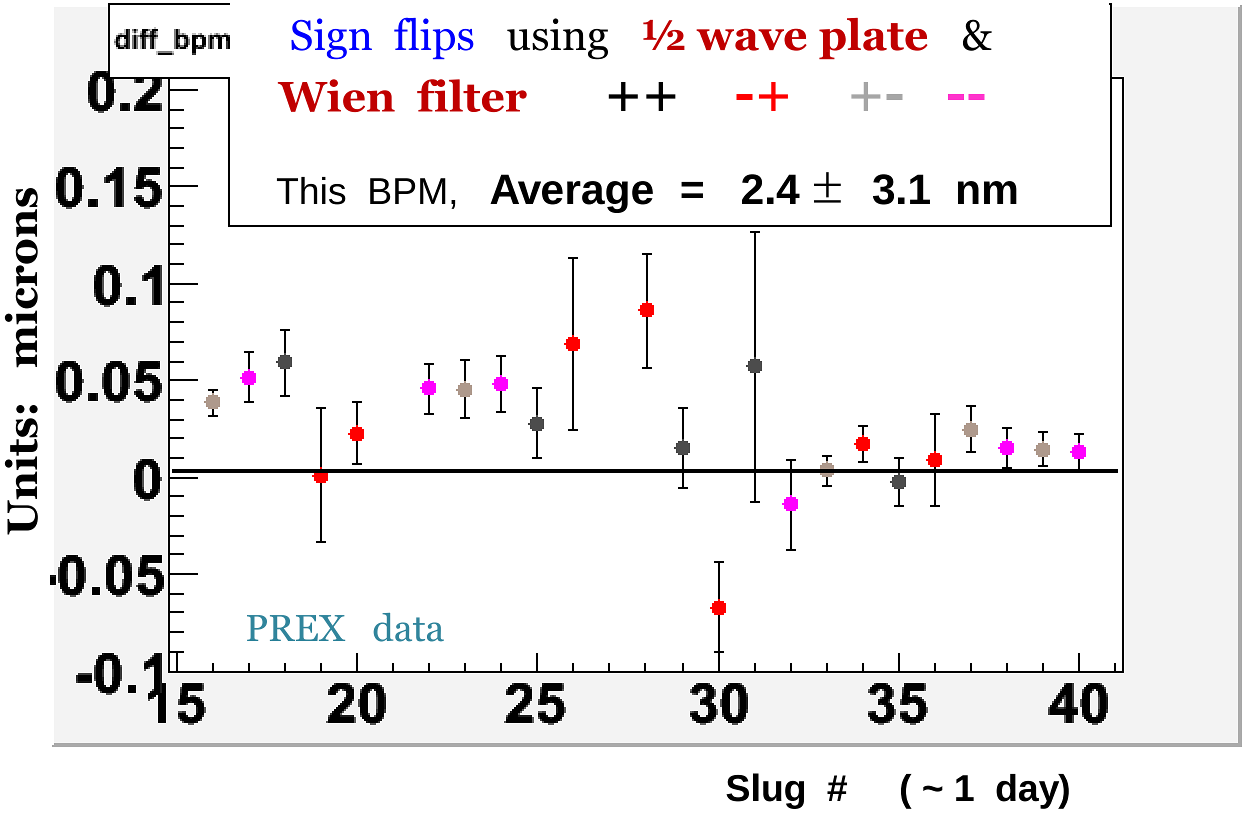
$$A_{raw} = A_{det} - A_Q + \alpha\, \Delta_E + \Sigma \beta_i\, \Delta x_i$$

Measured separately

Points: Not sign-corrected.
20-50 nm diffs. with pol.
source setup & feedback

Sign flips provide
further suppression :
Average with signs =
what experiment feels

achieved
< 5 nm



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Important Systematic : PITA Effect

Polarization Induced Transport Asymmetry

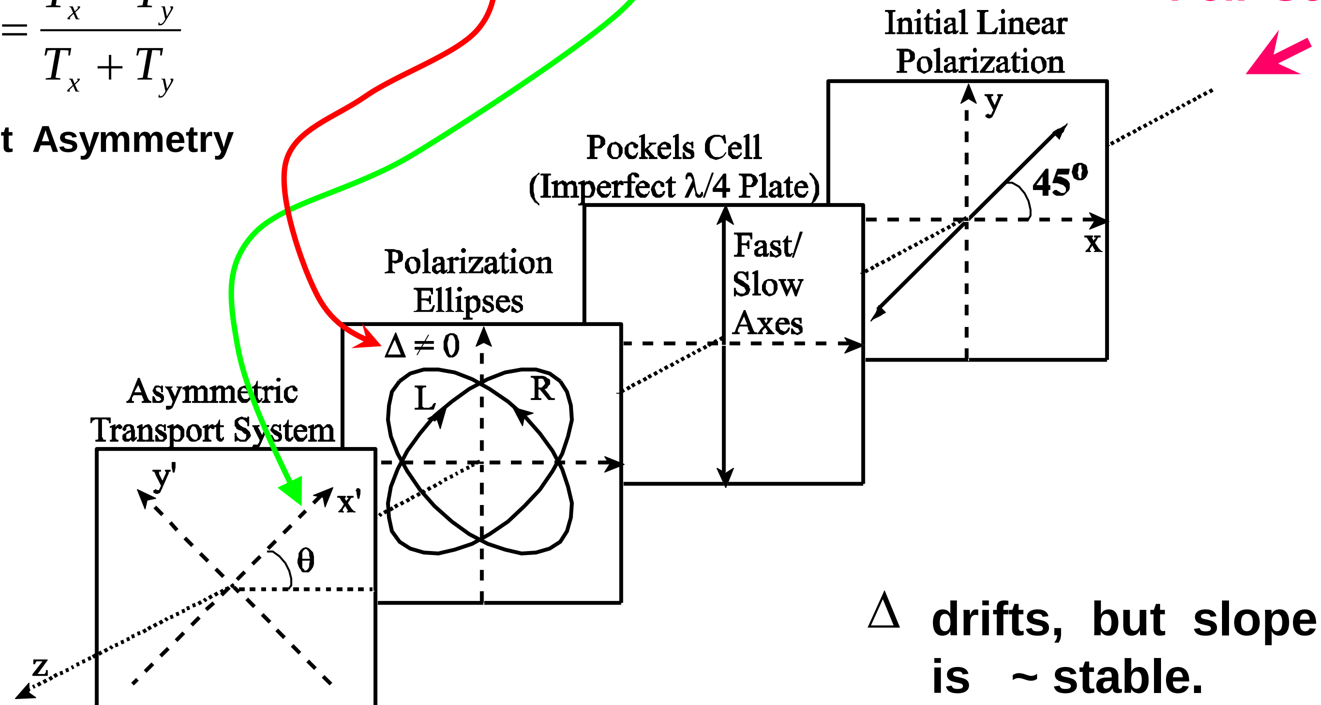
Intensity Asymmetry

$$A_I = \varepsilon \, \Delta \sin(\theta)$$

where $\varepsilon = \frac{T_x - T_y}{T_x + T_y}$

Transport Asymmetry

Laser at Pol. Source



Δ drifts, but slope is ~ stable.

⇨ Feedback on Δ

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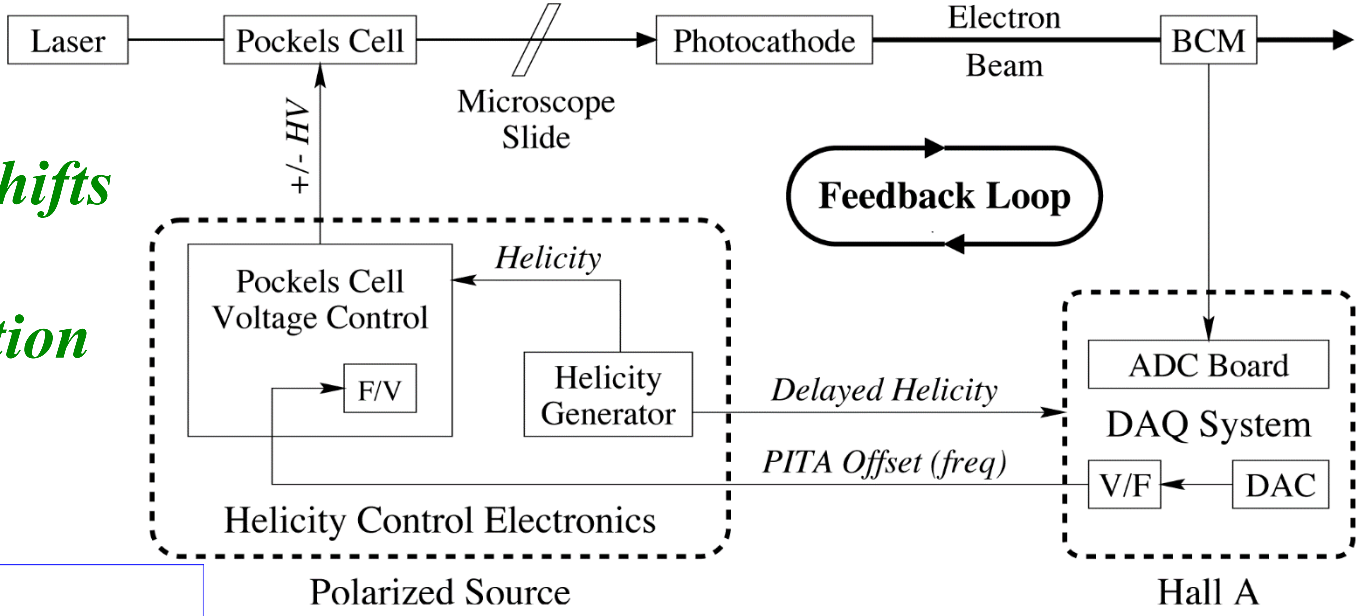
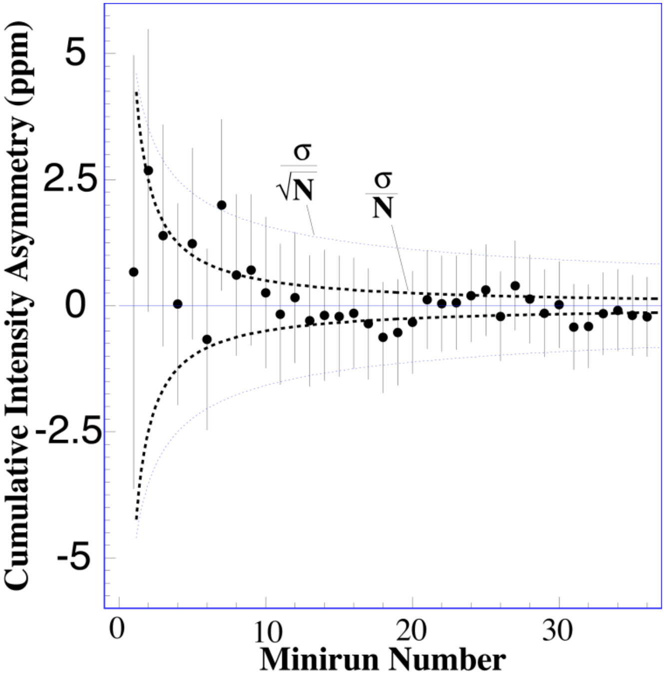
Intensity Feedback

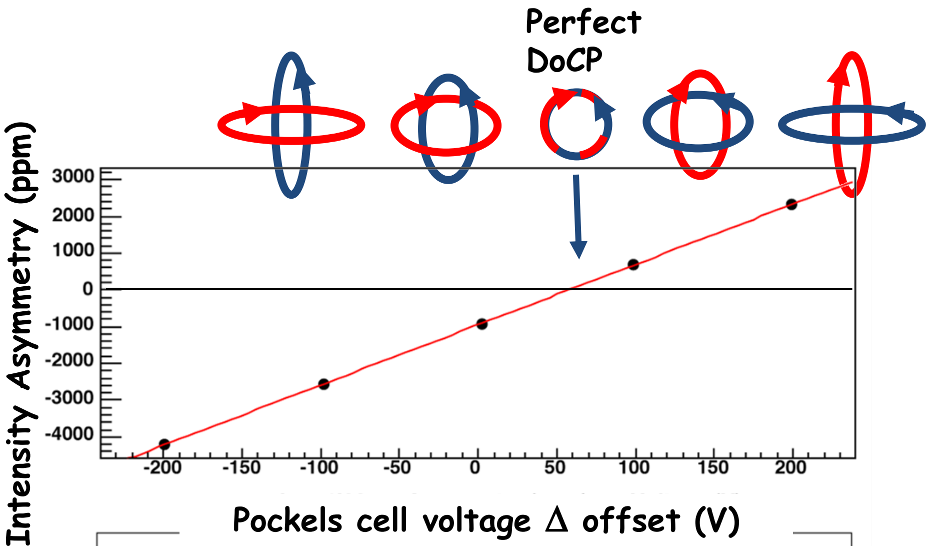
Adjustments
for small phase shifts
to make close to
circular polarization





Low jitter and high accuracy allows sub-ppm cumulative charge asymmetry in ~ 1 hour

Methods to Reduce Systematics

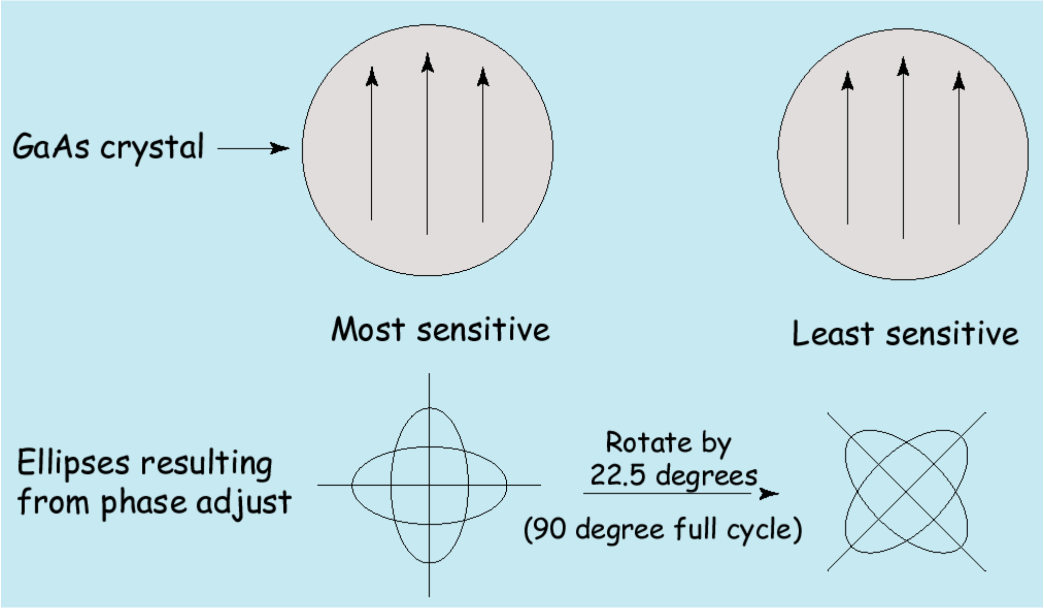


$$Aq = -947.06 + 16.39 * x$$

Scanning the Pockels Cell voltage = scanning the residual linear polarization (DoLP)

A simplified picture: asymmetry=0 corresponds to minimized DoLP at analyzer

A rotatable λ/2 waveplate downstream of the P.C. allows arbitrary orientation of the ellipse from DoLP



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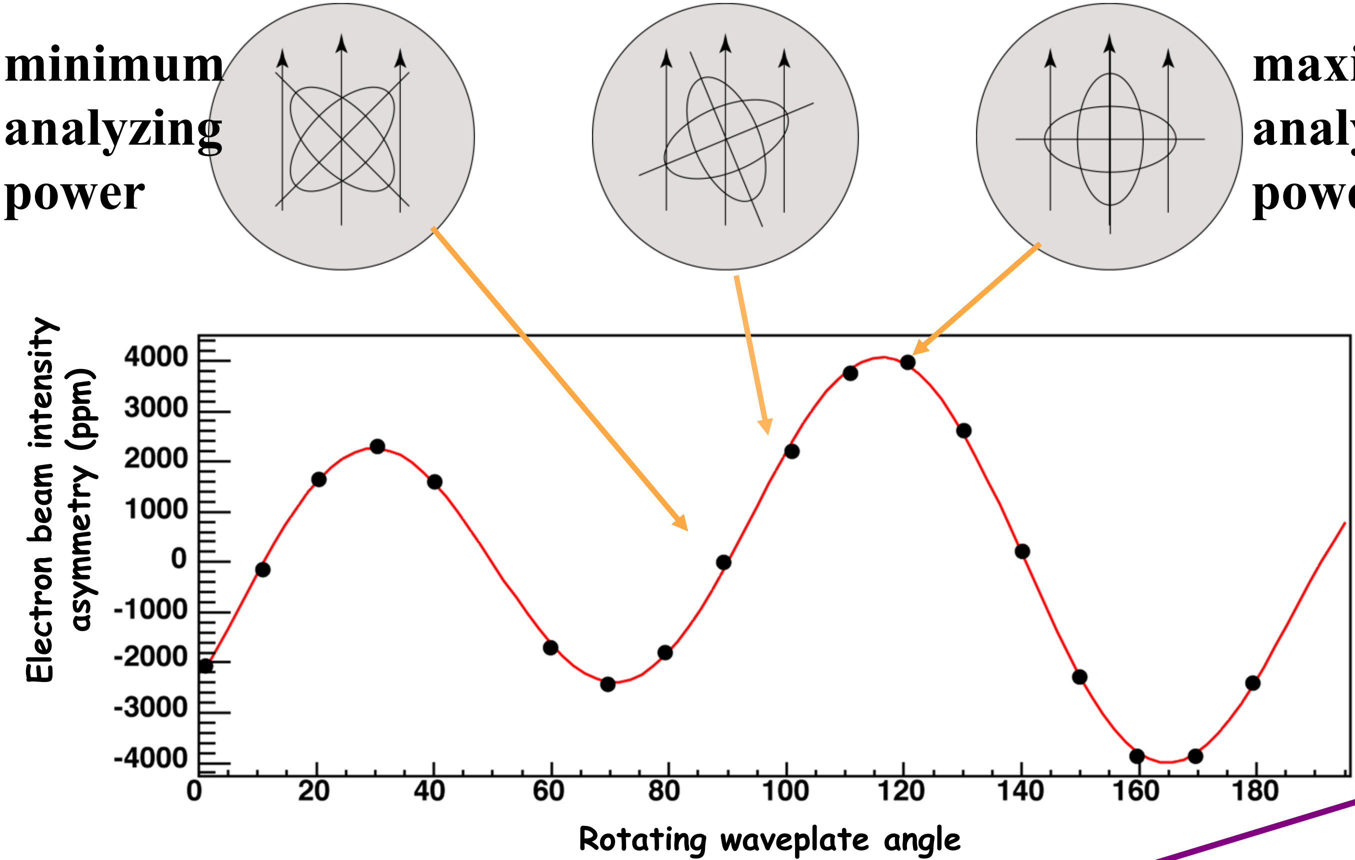
Rotatable Half-Wave Plate

minimum analyzing power

maximum analyzing power



Add λ/2 plate to minimize analyzing power

4θ term measures analyzing power*DoLP (from Pockels cell)

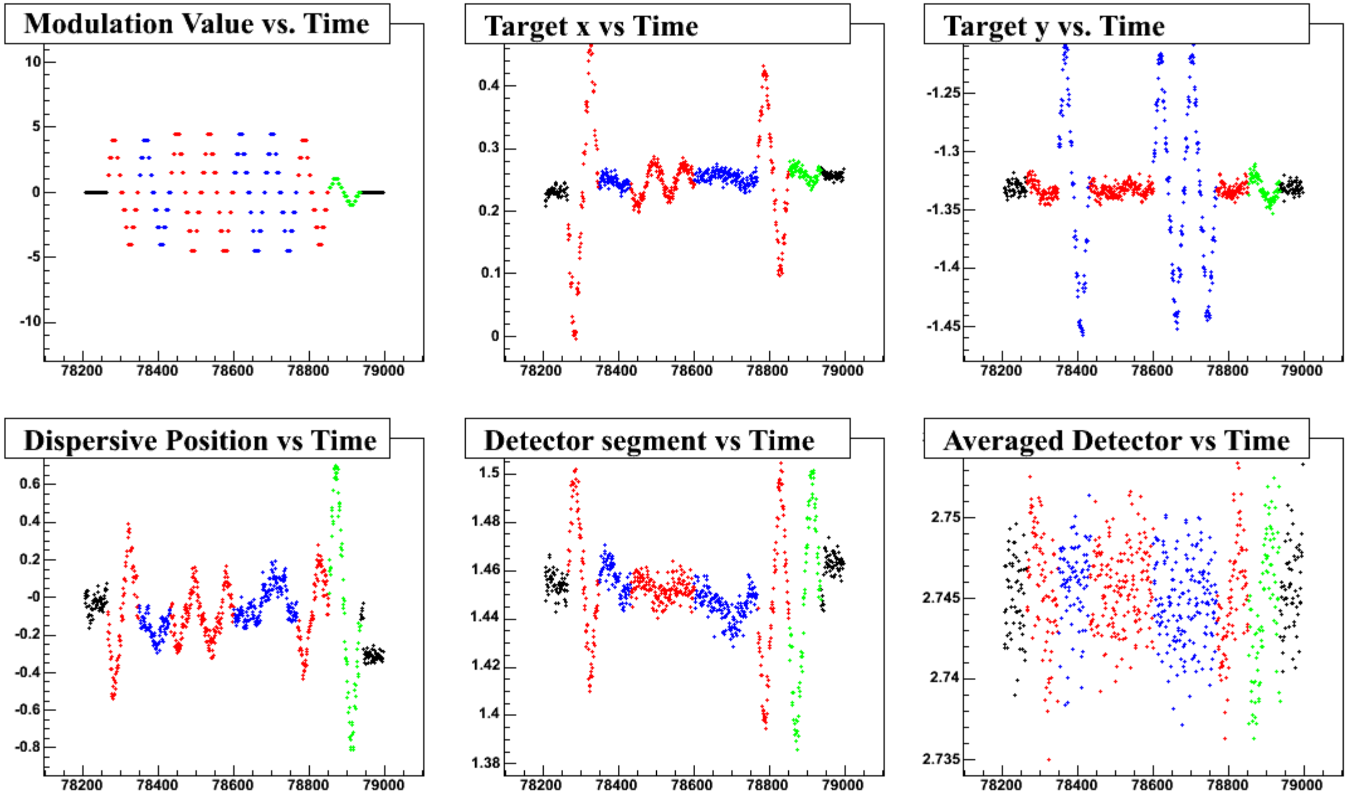
$$Aq = -7.98 + -1211.75 \sin(2x + 75.52) + -3151.04 \sin(4x + 158.47)$$

Beam Asymmetries

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

Slopes from

- natural beam jitter (regression)
- beam modulation (dithering)


Modulation Value vs. Time

Target x vs Time

Target y vs. Time

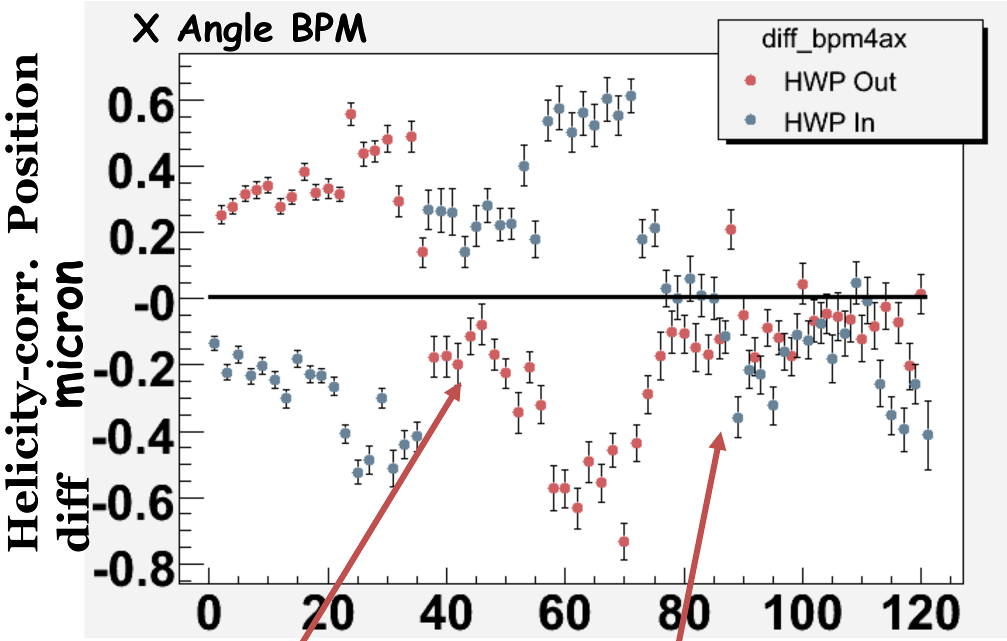
Dispersive Position vs Time

Detector segment vs Time

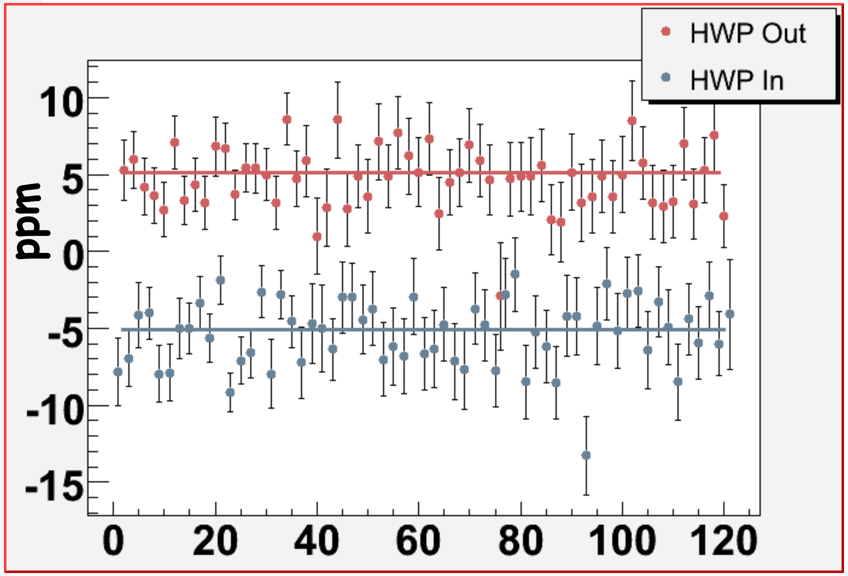
Averaged Detector vs Time

The Corrections Work !

Shown : period of data during HAPPEX (^{4}He) when beam had a helicity-correlated position due to a mistake * in electronics.



With corrections



Helicity signal to driver reversed

Helicity signal to driver removed

Raw ALL Asymetry

* The mistake: Helicity signal deflecting the beam through electronics “pickup”

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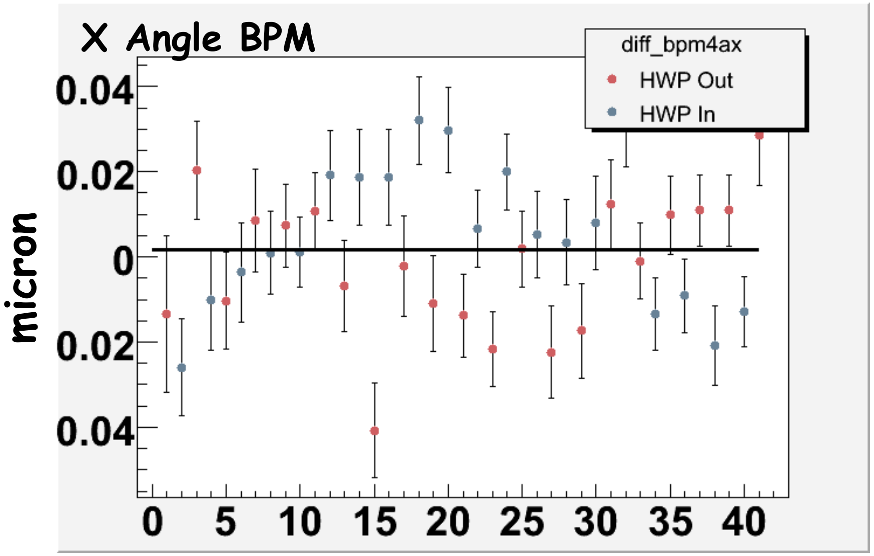
Final Beam Position Corrections (HAPPEX-H)



Beam Asymmetry Results

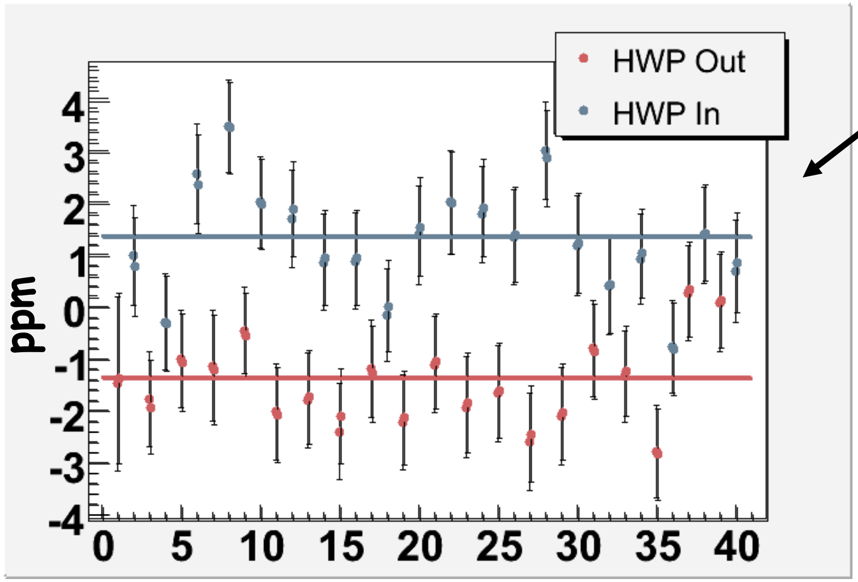
Energy: -0.25 ppb

X Target: 1 nm

X Angle: 2 nm

Y Target : 1 nm

Y Angle: <1 nm



Corrected and Raw, Left spectrometer arm alone, Superimposed!

Total correction for beam position asymmetry on Left, Right, or ALL detector: 10 ppb

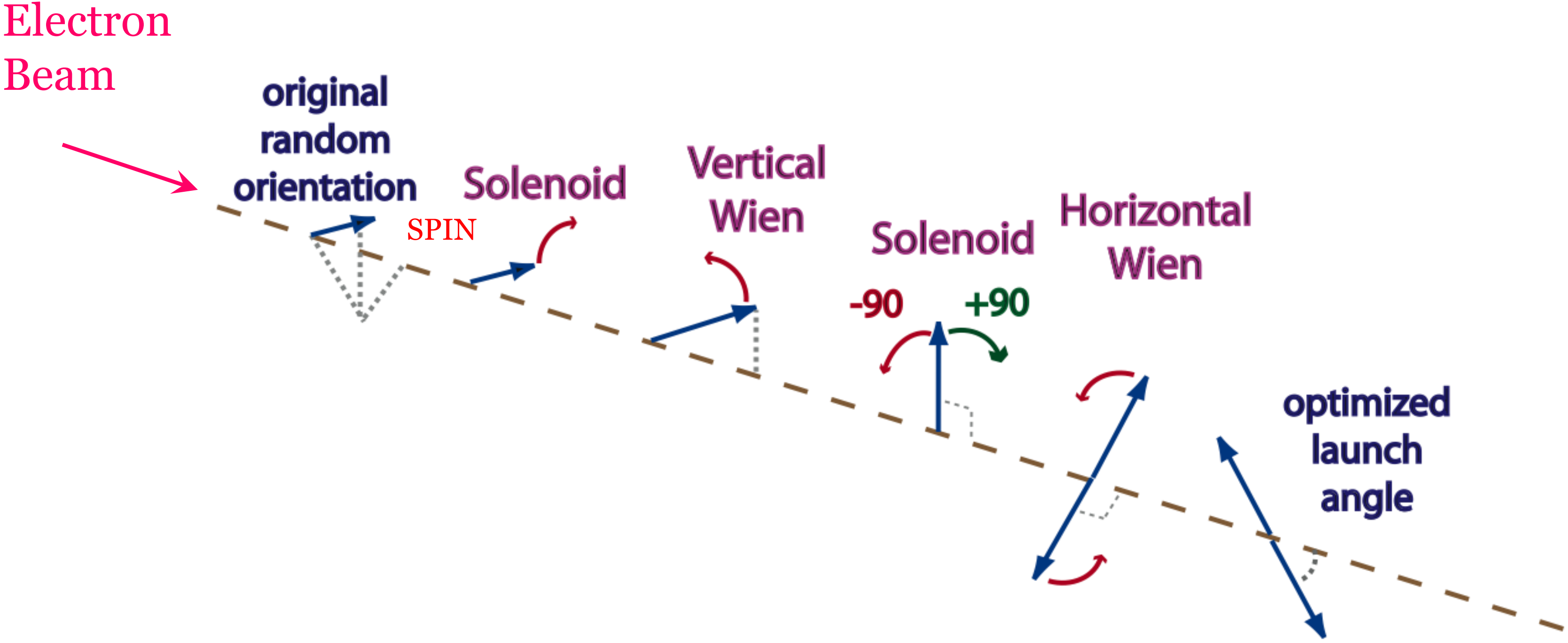
Spectacular results from HAPPEX-H showed we could do PREX.

Want multiple, redundant ways to flip the helicity. Here, we show the "Double Wien Filter"

Crossed E & B fields to rotate the spin

- Two Wien Spin Manipulators in series
- Solenoid rotates spin +/-90 degrees (spin rotation as B but focus as B^2).

Flips spin without moving the beam !



Electron Beam

original random orientation

SPIN

Solenoid

Vertical Wien

Solenoid

-90

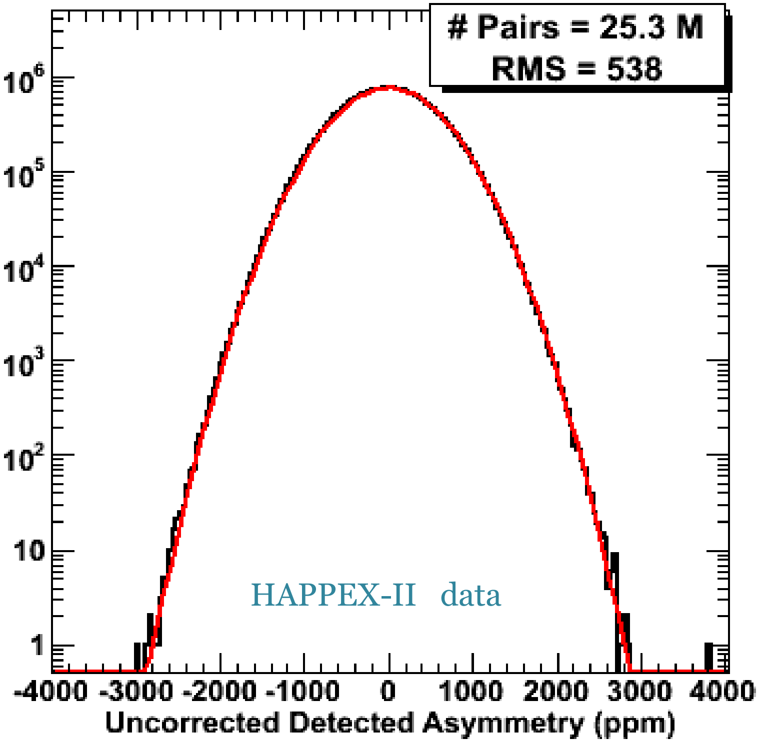
+90

Horizontal Wien

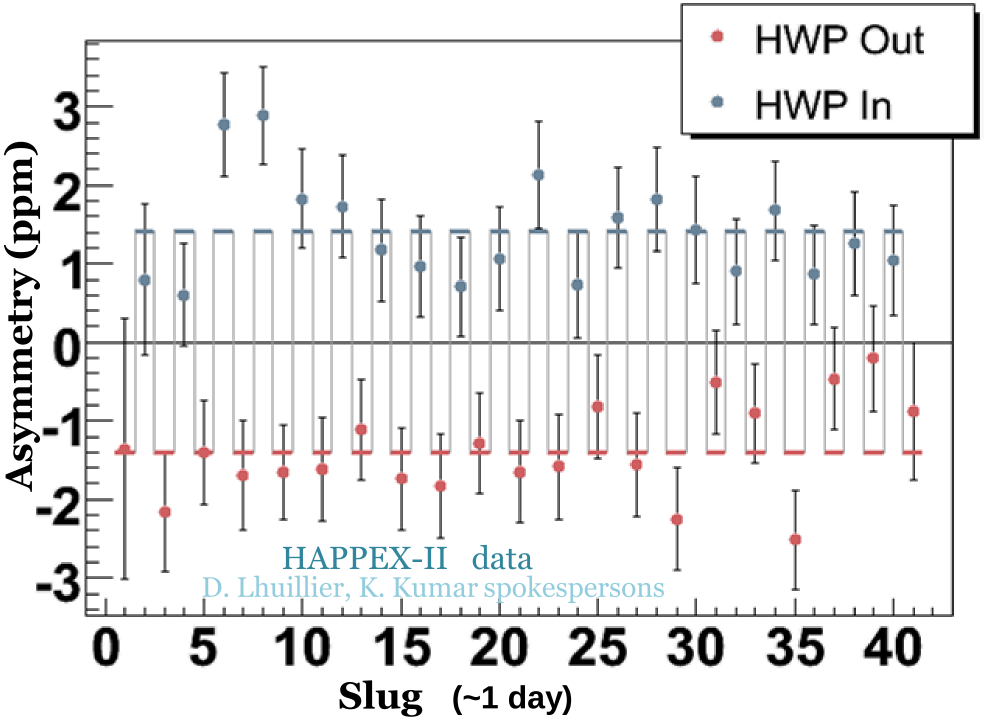
optimized launch angle

HAPPEX achieved 3 ppb Helicity Correlated Beam Systematics

- Corrections tiny (here, 3 ppb)
- Errors are statistical only



Parity Violating Asymmetry



A_{raw} = -1.58 ppm ± 0.12 (stat) ± 0.04 (syst)

(HWP = optical element used to flip beam helicity, helps suppress some systematics)

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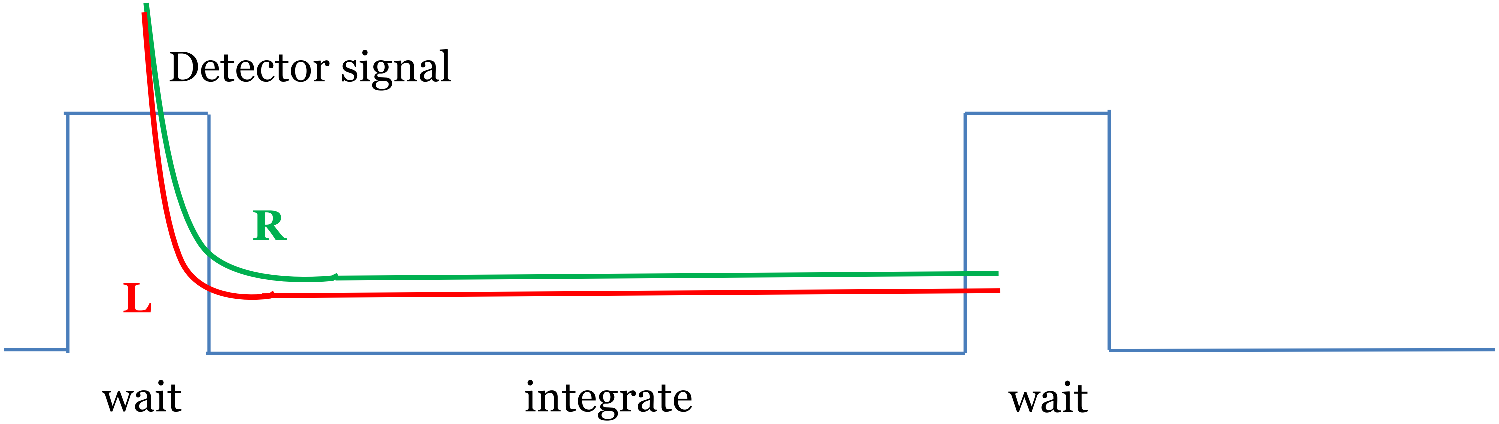
$$A = \frac{\left(\frac{D}{Q}\right)_R - \left(\frac{D}{Q}\right)_L}{\left(\frac{D}{Q}\right)_R + \left(\frac{D}{Q}\right)_L}$$

There may be helicity-correlated transients in the beam.

- D & Q may have different time constants in response to transients.
- D may be non-linear in Q.

$D =$ Detector signal

$Q =$ Charge in same time interval



Beam Polarization

$$A_{measured} = A_{physics} \times P_e$$

Want to
extract this

Polarization of electrons,
typically 0.9

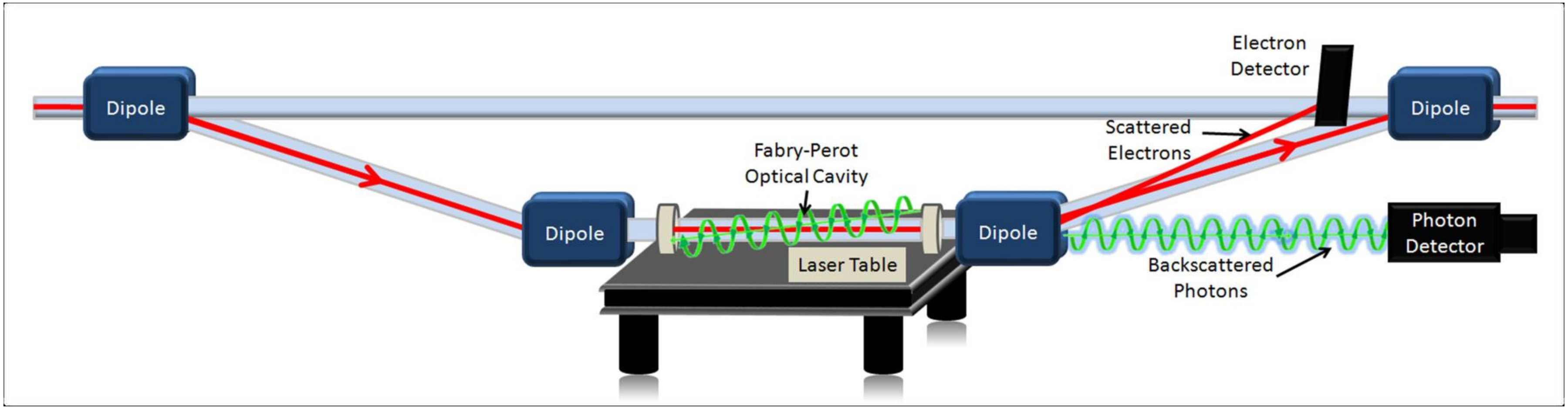
Measure P_e through

- Compton Scattering $\vec{e} - \vec{\gamma}$
- Moller Scattering $\vec{e} - \vec{e}$
- Mott Scattering (not discussed)

Compton Polarimetry

$\vec{e} - \vec{\gamma}$

beam laser



1. **Laser system: 1 W drive laser coupled to high gain Fabry-Perot cavity → several kW intracavity power**
2. **Photon detector: GSO crystal for low energies, or lead-tungstate for high energies.**
3. **Electron detector: silicon strip detector, 240 µm pitch, 192 strips/plane**

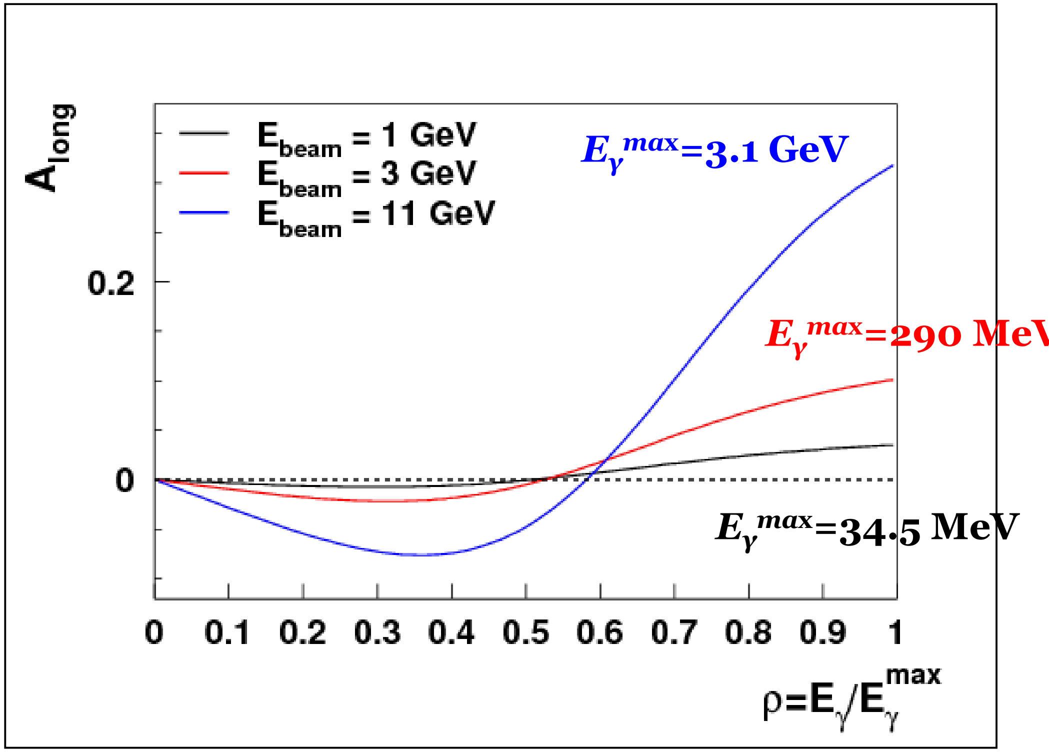
Compton Polarimetry

$$\frac{dP_e}{P_e} < 1\%$$

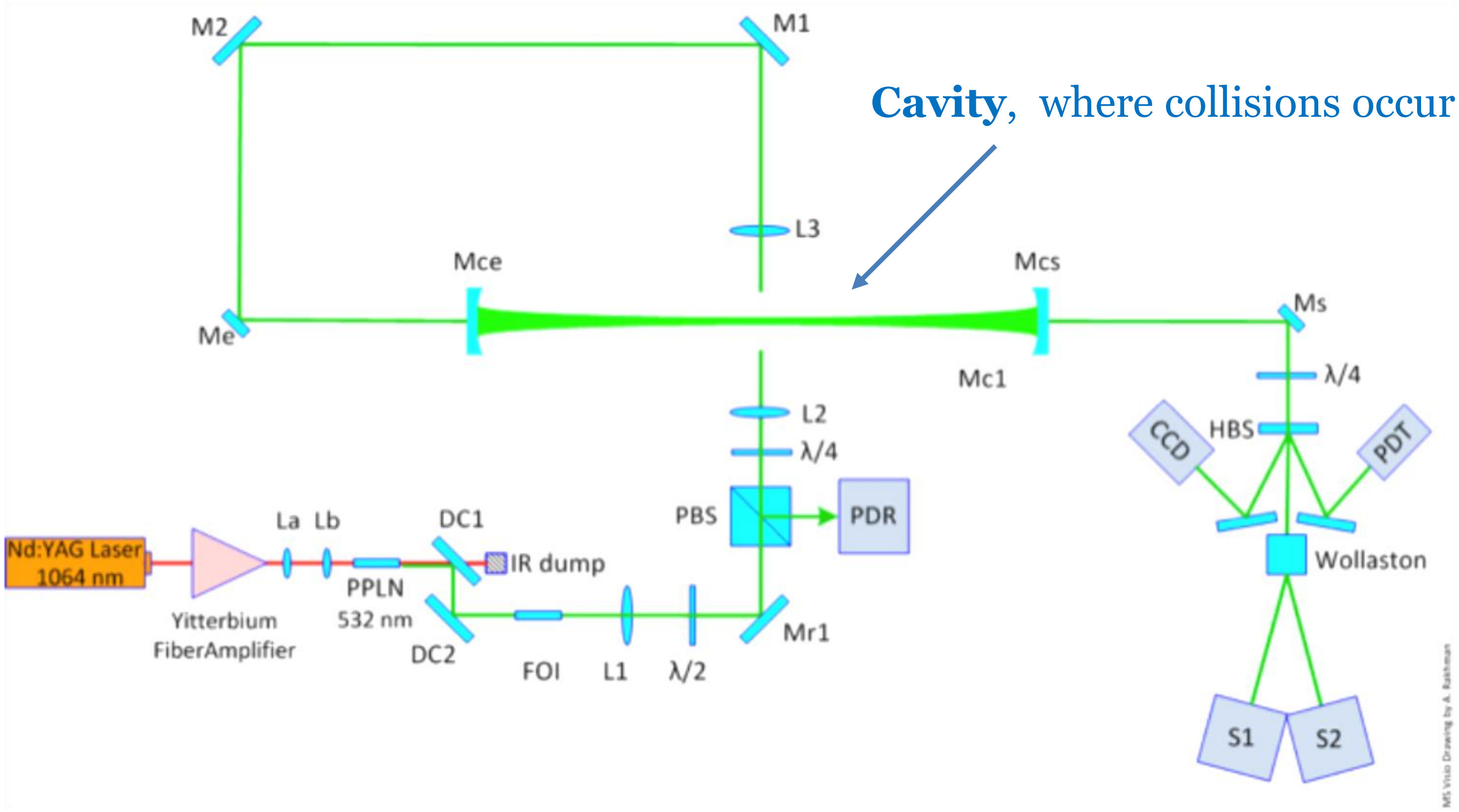
1%-level Compton polarimetry has been achieved with Hall A Compton at ~ 1 GeV (PREX) and ~ 3 GeV (HAPPEX-II)

$$A_{measured} = P_e \ P_\gamma \ A_{long}$$

Known exactly from QED



Compton Laser System



Cavity, where collisions occur

MS Visio Drawing by A. Rakhman

Measure P_γ

Recent Compton Data with 11 GeV Beam

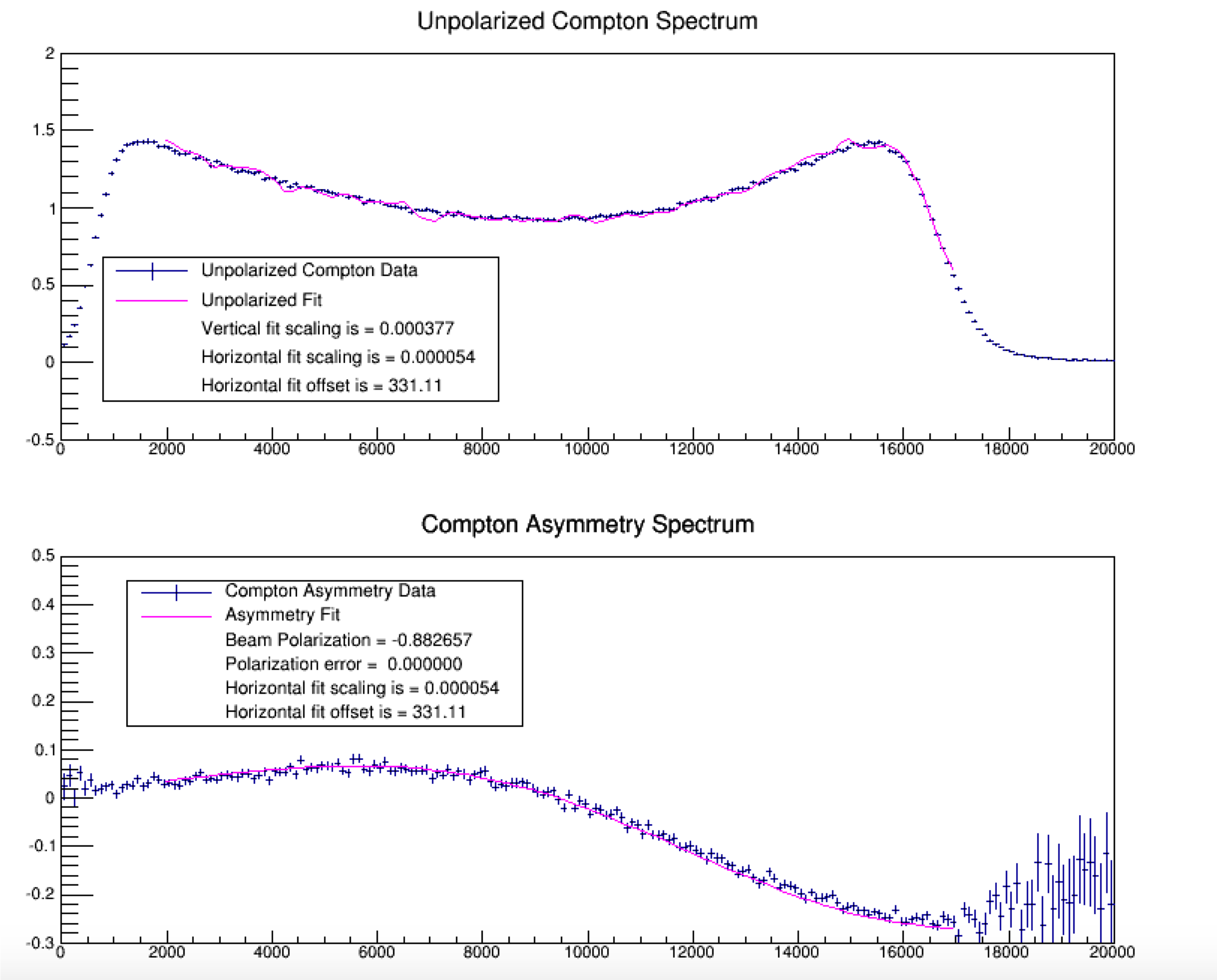
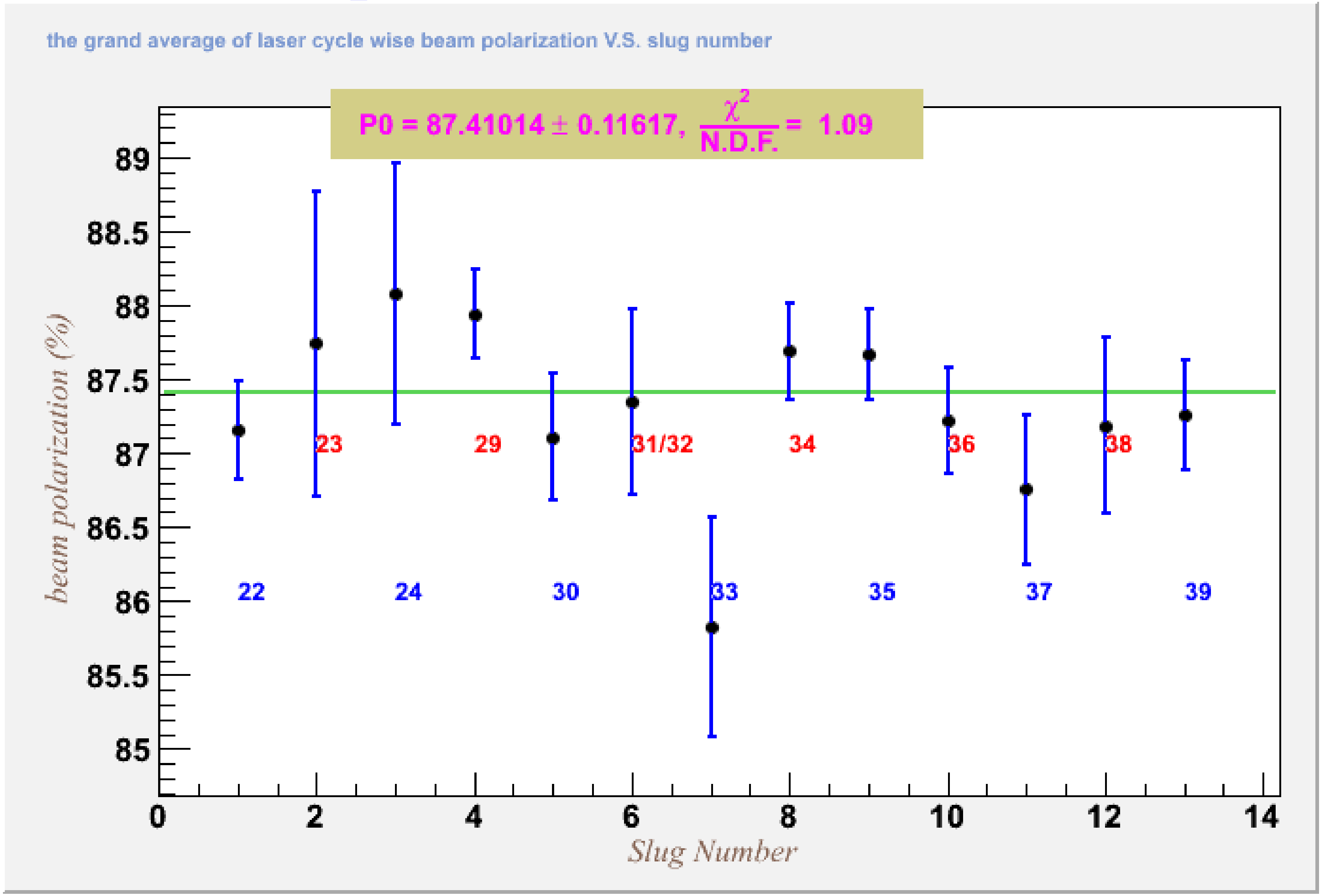


Figure courtesy Alexa Johnson

PREX data

Compton Polarimeter in PREX-I



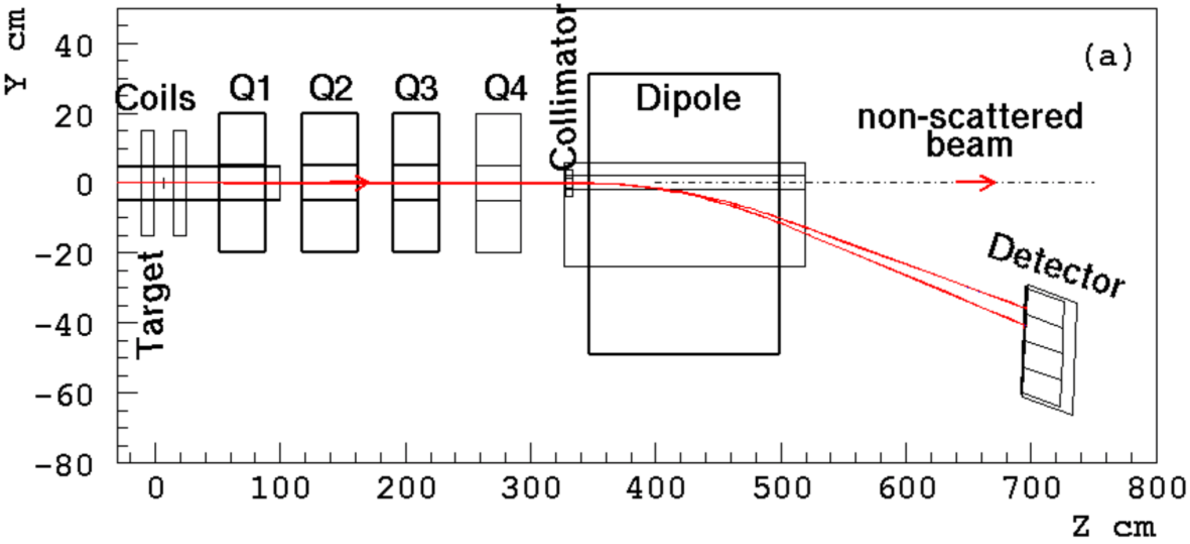
Moller Polarimeter

$\vec{e} - \vec{e}$

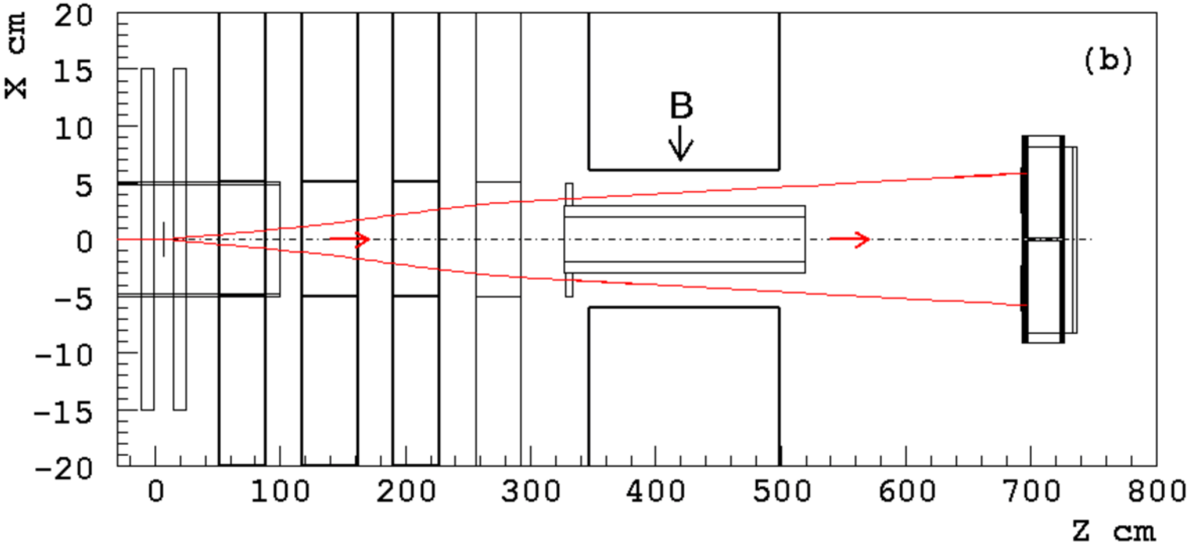
beam

Electrons in
an iron foil
in a strong
B field

Side View



Top View

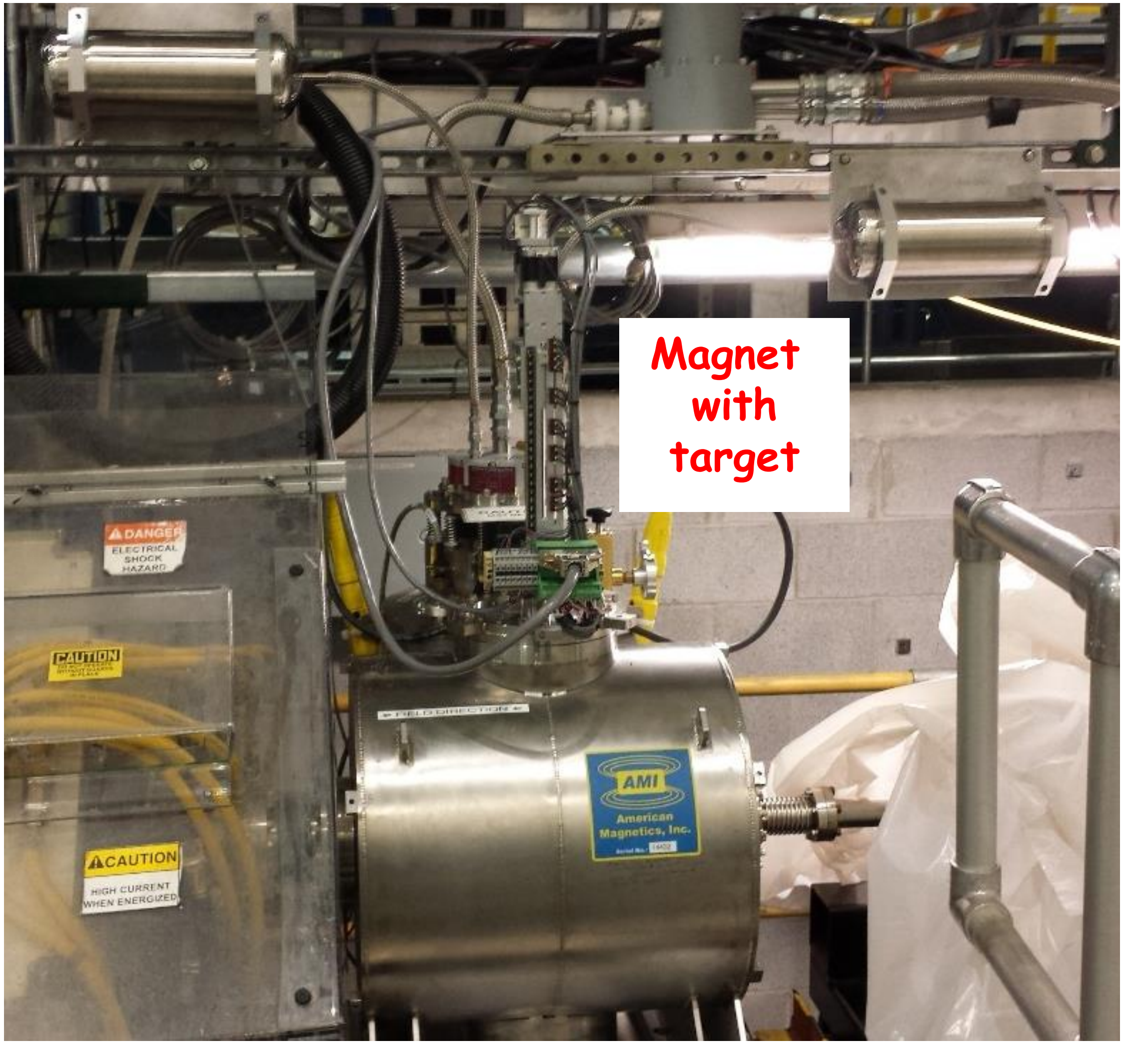


5 T   MAGNET

Power supply

Compressor

Water chiller

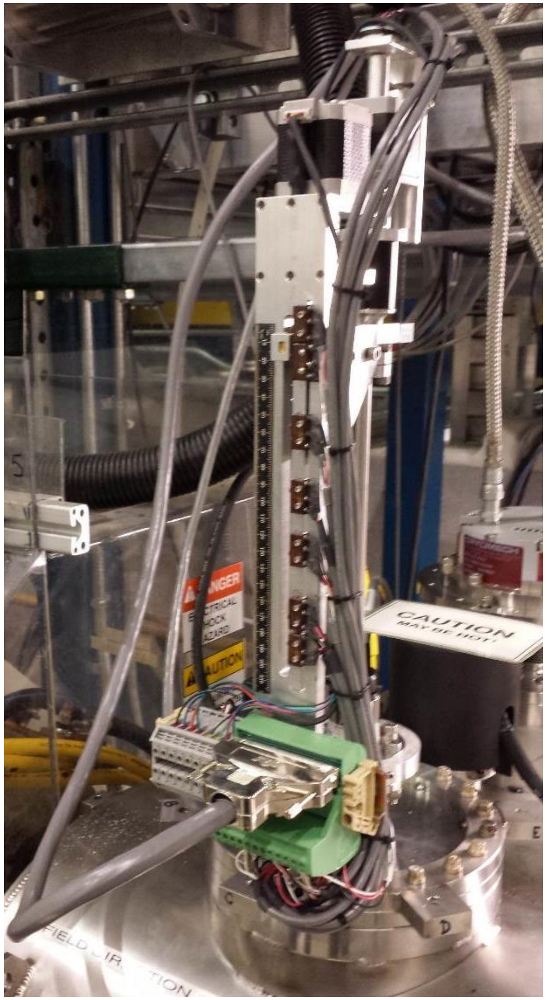


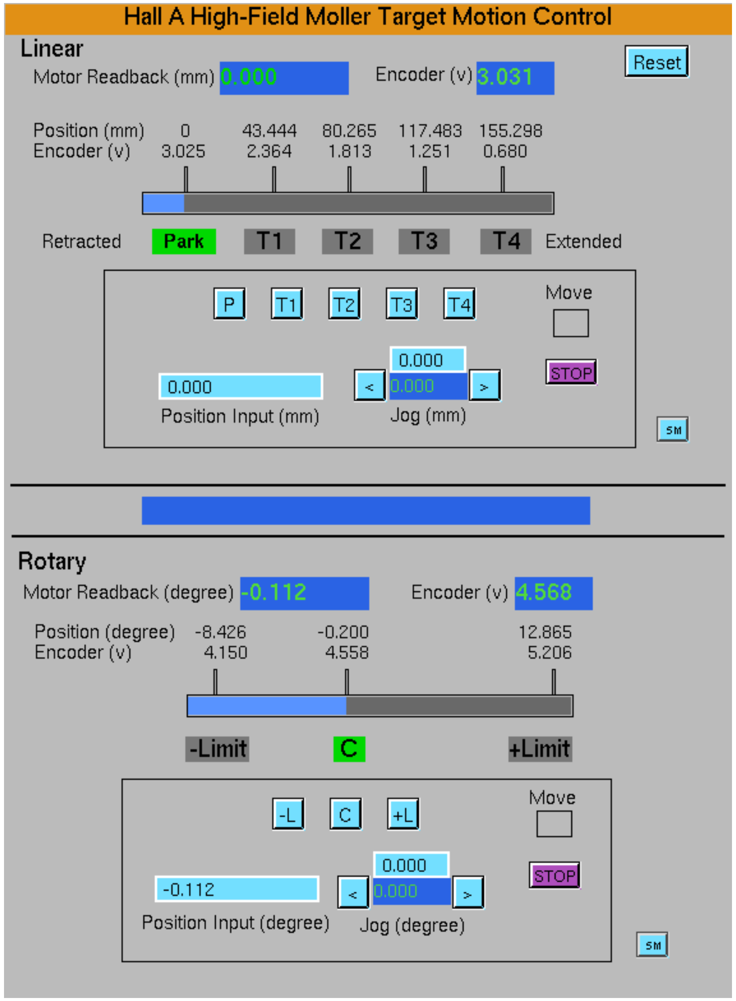
Magnet with target

Superconductive magnet:
Maximal field ±5T

The iron foil targets sit in this field and become sping-polarized.

NEW POLARIZED ELECTRON TARGET





Hall A High-Field Moller Target Motion Control

Linear

Motor Readback (mm) 0.000
Encoder (v) 3.031

Position (mm)	0	43.444	80.265	117.483	155.298
Encoder (v)	3.025	2.364	1.813	1.251	0.680

Retracted Park T1 T2 T3 T4 Extended

Position Input (mm) 0.000
Jog (mm) 0.000 / 0.000

Rotary

Motor Readback (degree) -0.112
Encoder (v) 4.568

Position (degree)	-8.426	-0.200	12.865
Encoder (v)	4.150	4.558	5.206

-Limit C +Limit

Position Input (degree) -0.112
Jog (degree) 0.000 / 0.000

Designed and made by Temple University
Rotation in horizontal plane ±10°
Vertical translation
Targets in holder: pure iron ~~1μm~~, 4μm, 12μm, 25μm

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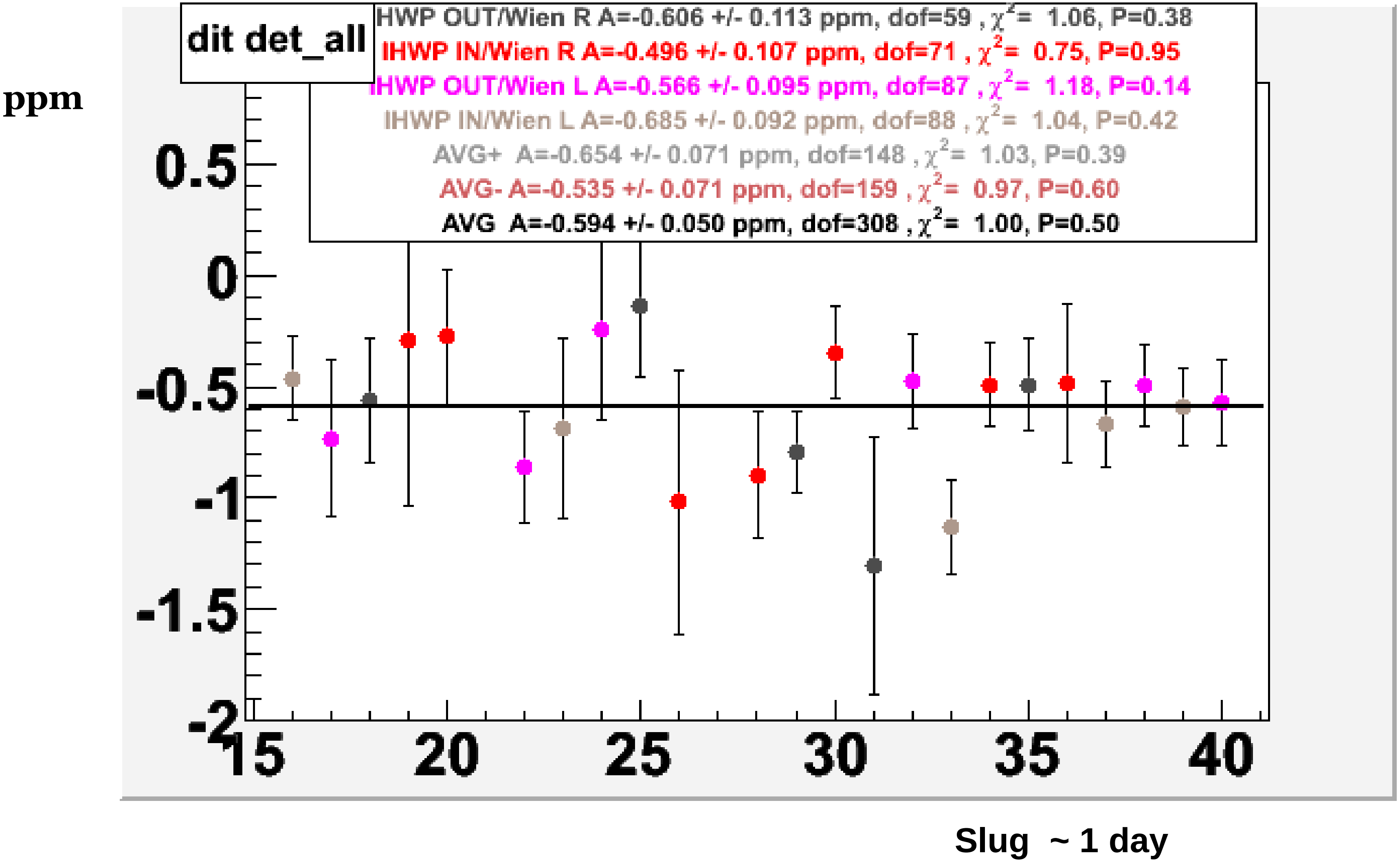
MØLLER SYSTEMATIC ERROR BUDGET

Variable	2010 (3.7T)	PREX (2017)
Target polarization	0.35%	0.25%
Analyzing power	0.3%	0.2%
Levchuk effect	0.3%	0.2%
Target temperature	0.02%	0.02%
Dead time	0.3%	0.05%
Background	0.3%	0.2%
*High beam current**	0.2%*	0.2%
Others	0.5%	0.3%
Total	0.87%	**0.53%**

Thanks, Sasha Glamazdin

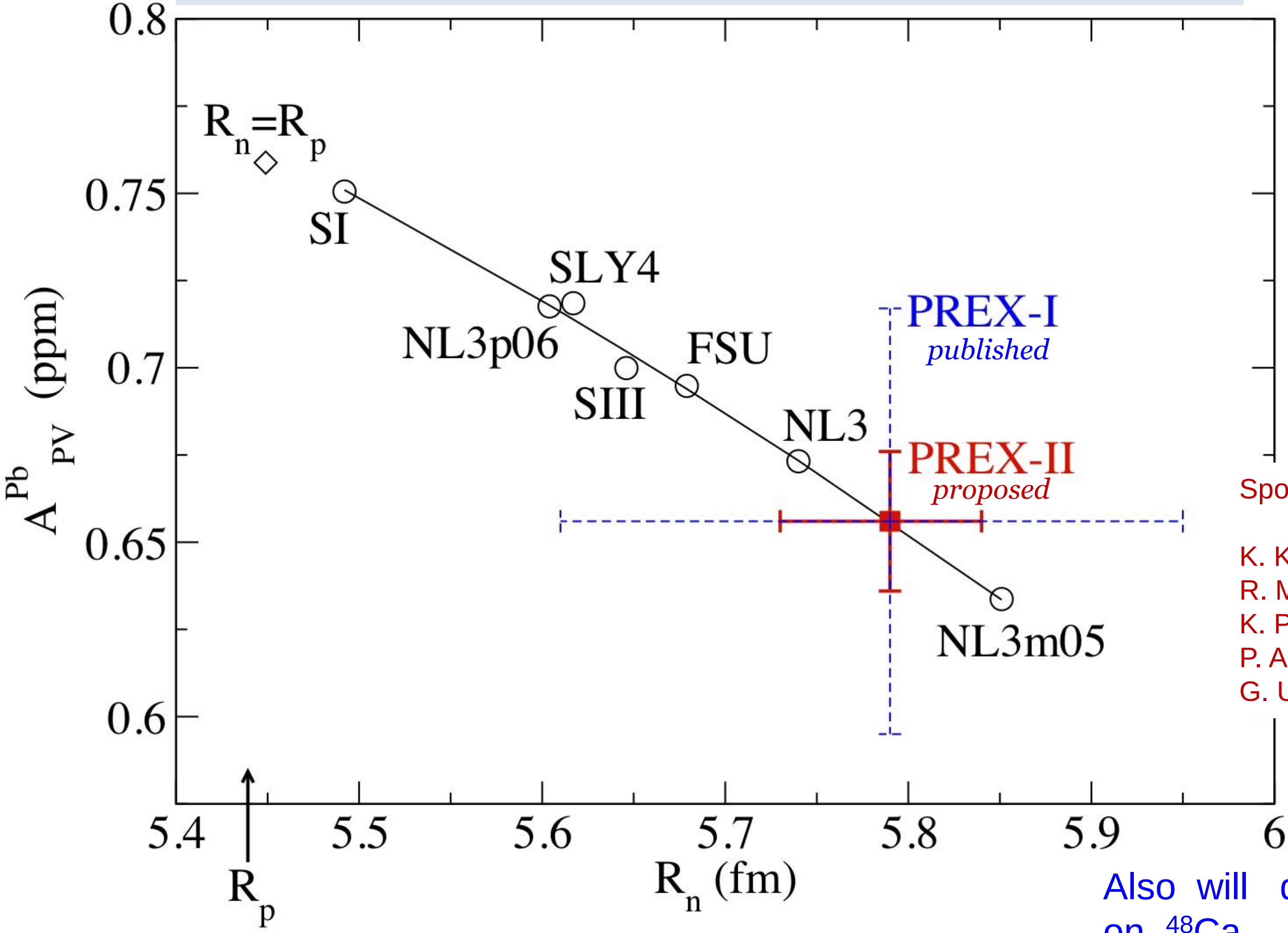
Returning to … PREX Asymmetry (P_e x A)



Asymmetry leads to R_N

Establishing a neutron skin at ~95 % CL

Neutron Skin = R_N - R_P = 0.33 + 0.16 - 0.18 fm



Spokespersons

K. Kumar
R. Michaels
K. Paschke
P. A. Souder
G. Urciuoli

Also will do C-REX on ^{48}Ca

http://hallaweb.jlab.org/parity/prex

PREX/CREX : Summary

- Fundamental Nuclear Physics with many applications

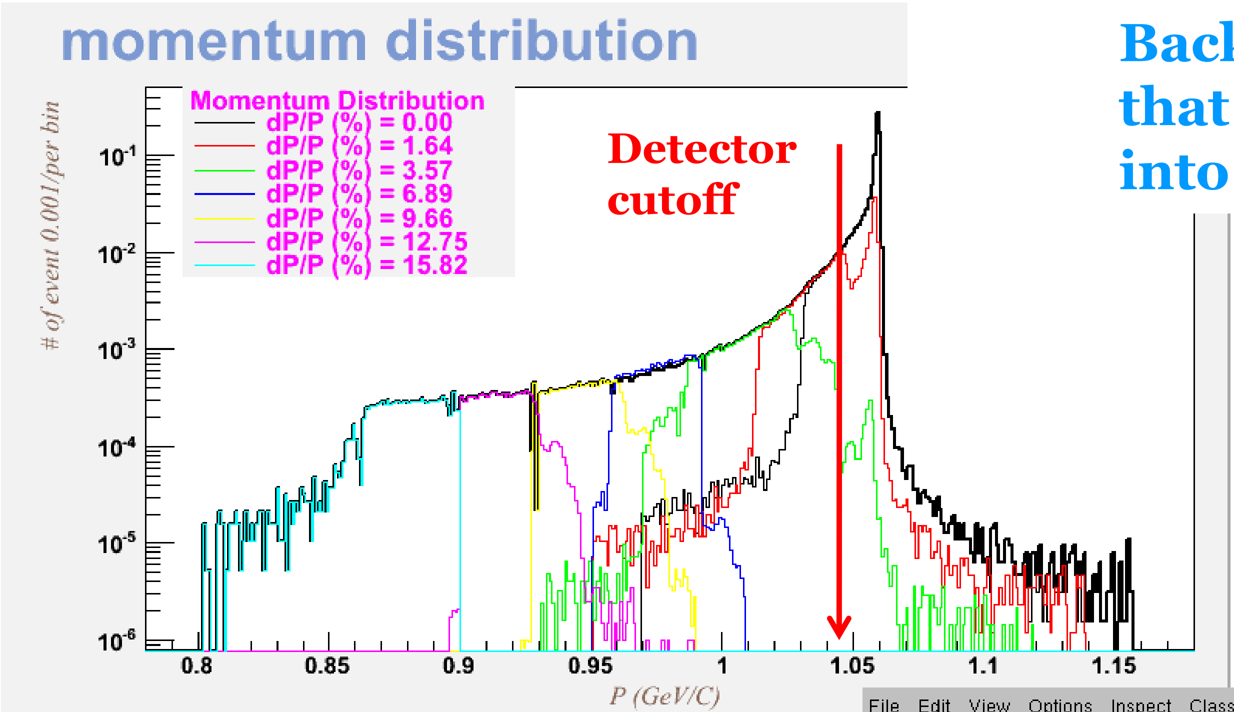
- PREX-I achieved a 9% stat. error in Asymmetry (original goal : 3 %)

- Systematic error goals already achieved.

- PREX-II and C-REX to run back-to-back, possibly in 2018 (being decided now)

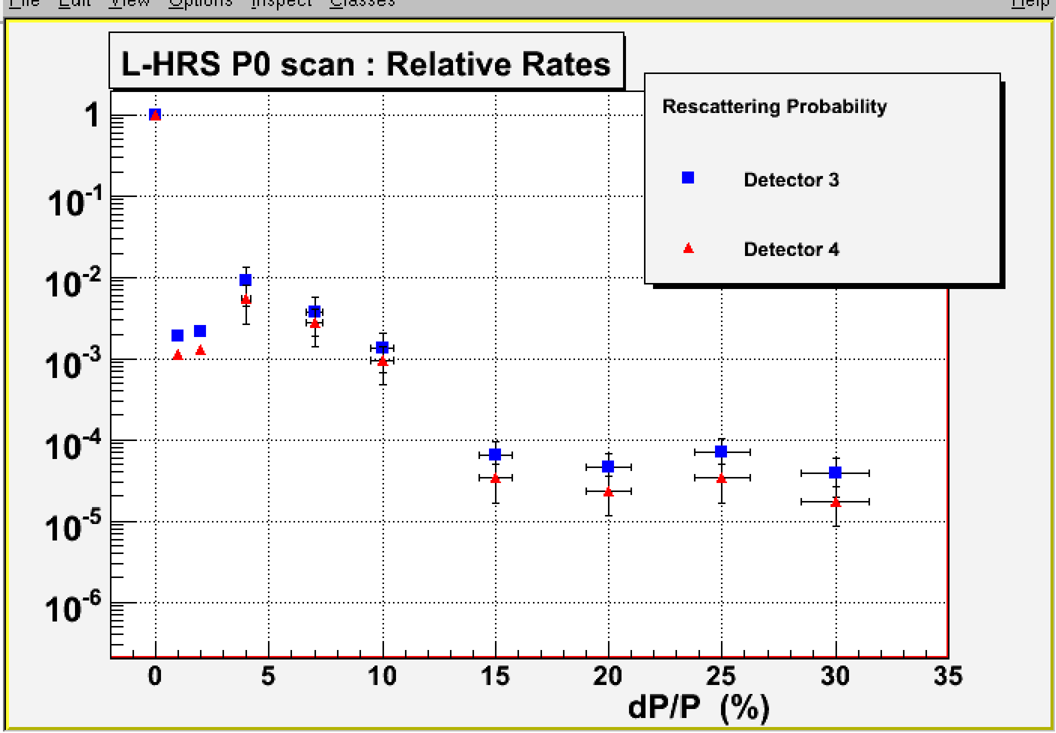
http://hallaweb.jlab.org/parity/prex

Extra Slides



Backgrounds that might re-scatter into the detector ?

Run magnets **down**: measure inelastic region



Run magnets **up** : measure probability to rescatter

No inelastics observed on top of radiative tail. Small systematic for tail.

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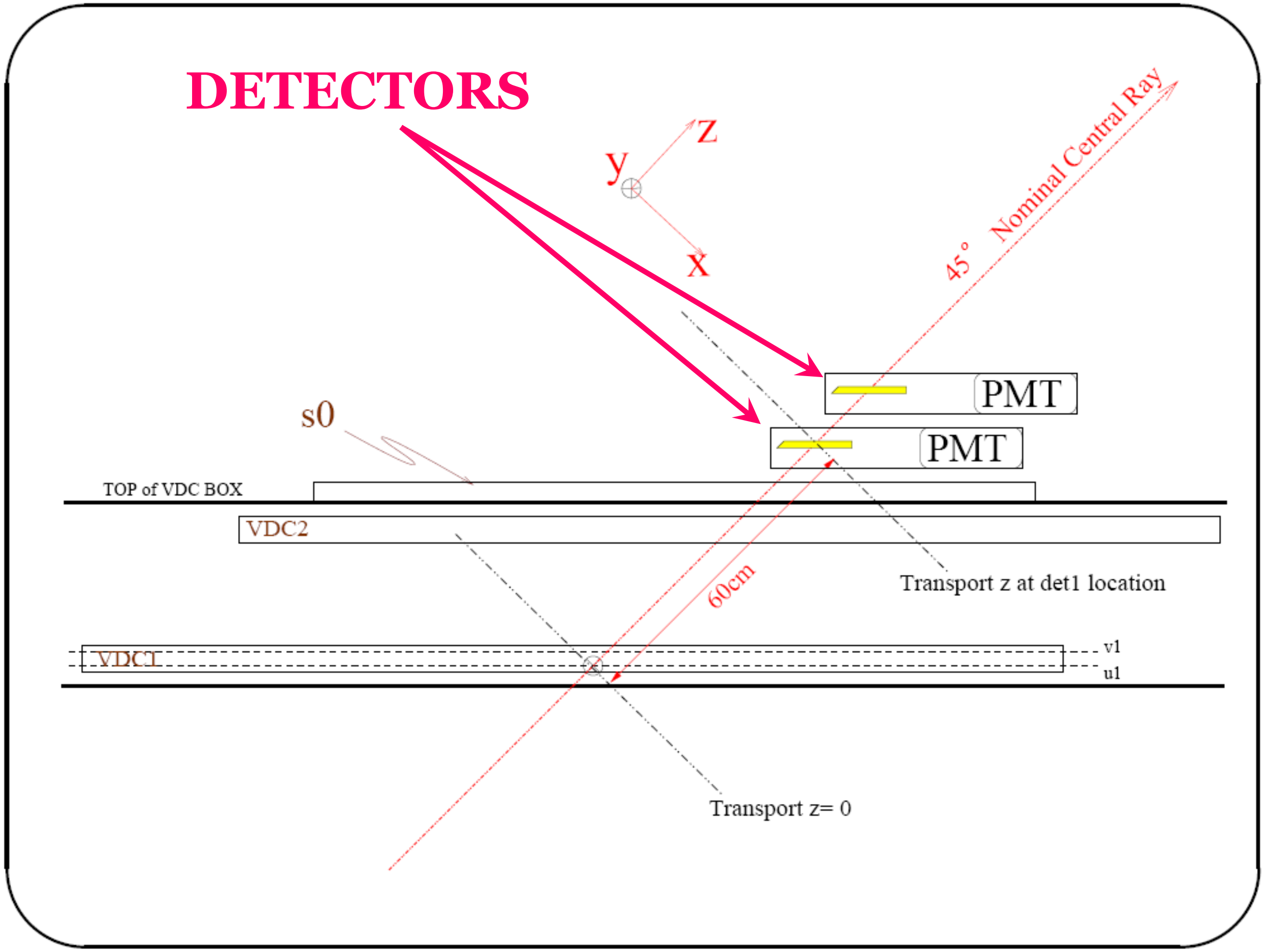
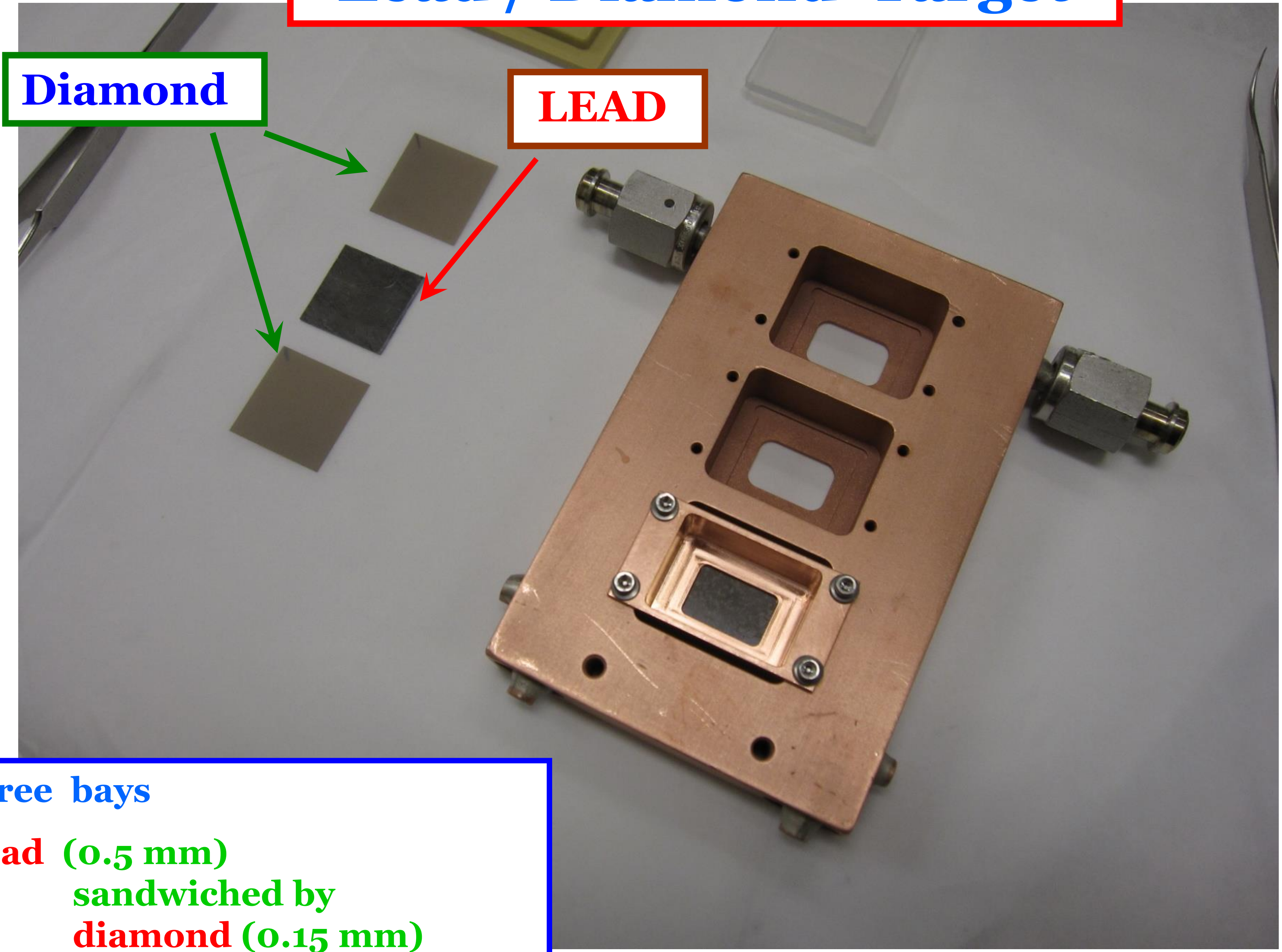
Detector Package in HRS

PREX Integrating Detectors

UMass / Smith

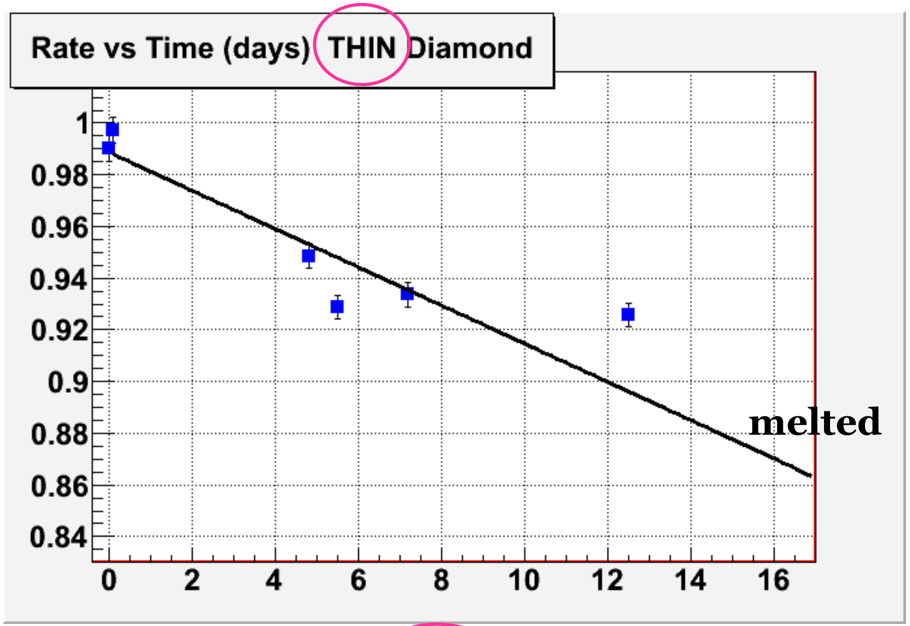


Lead / Diamond Target

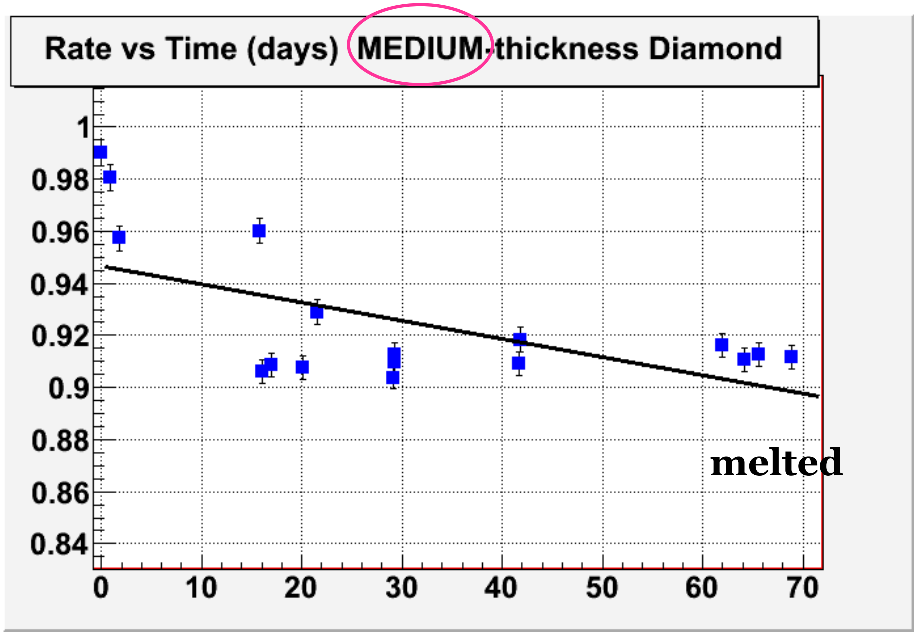


- Three bays
- Lead (0.5 mm)
  sandwiched by
  diamond (0.15 mm)
- Liquid He cooling (30 Watts)

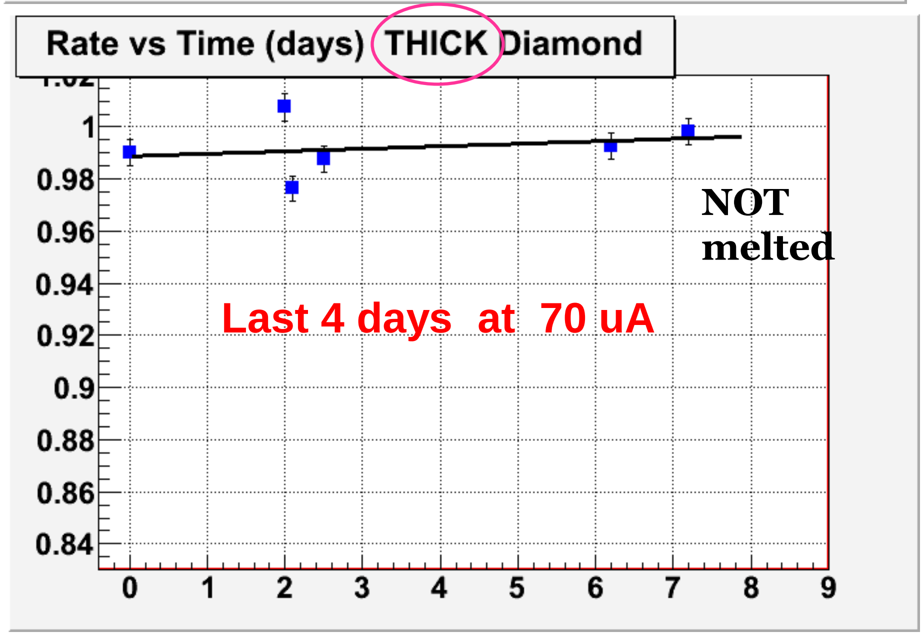
Performance of Lead / Diamond Targets


Rate vs Time (days) THIN Diamond

melted


Rate vs Time (days) MEDIUM-thickness Diamond

melted


Rate vs Time (days) THICK Diamond

NOT melted

Last 4 days at 70 uA

Targets with thin diamond backing (4.5 % background) degraded fastest.

Thick diamond (8%) ran well and did not melt at 70 uA.

→ Solution: Run with 10 targets.

PREX-I Result

Systematic Errors

Error Source	Absolute (ppm)	Relative (%)
Polarization (1)	0.0083	1.3
Beam Asymmetries (2)	0.0072	1.1
Detector Linearity	0.0076	1.2
BCM Linearity	0.0010	0.2
Rescattering	0.0001	0
Transverse Polarization	0.0012	0.2
Q^2 (1)	0.0028	0.4
Target Thickness	0.0005	0.1
^{12}C Asymmetry (2)	0.0025	0.4
Inelastic States	0	0
TOTAL	**0.0140**	**2.1**

(1) **Normalization Correction** applied

(2) **Nonzero correction** (the rest assumed zero)

Physics Asymmetry

$$A = 0.656\ ppm \pm 0.060(stat) \pm 0.014(syst)$$

→ **Statistics limited (9%)**

→ **Systematic error goal achieved ! (2%)**

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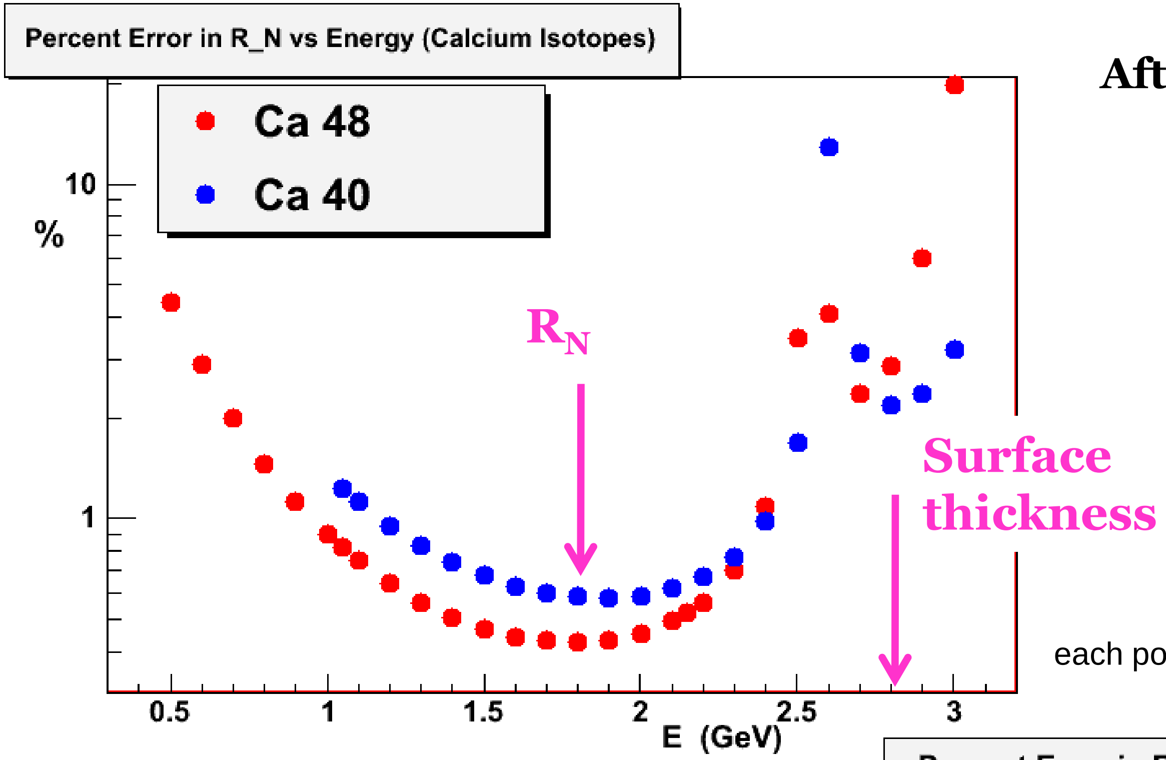
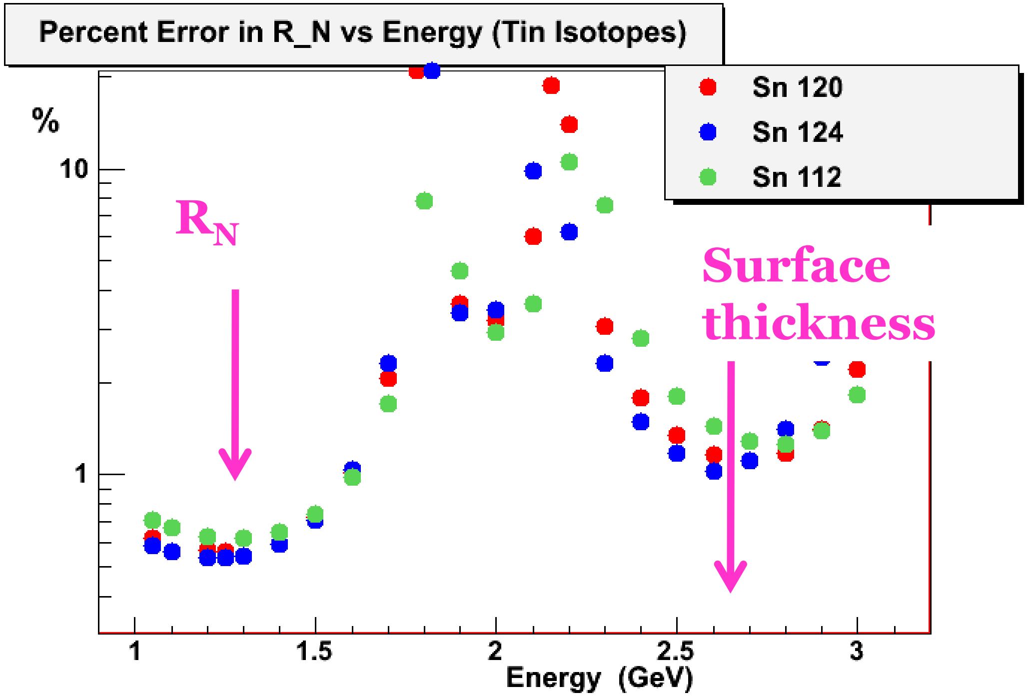


After PREX ...

Other Nuclei ?

and Shape Dependence ?

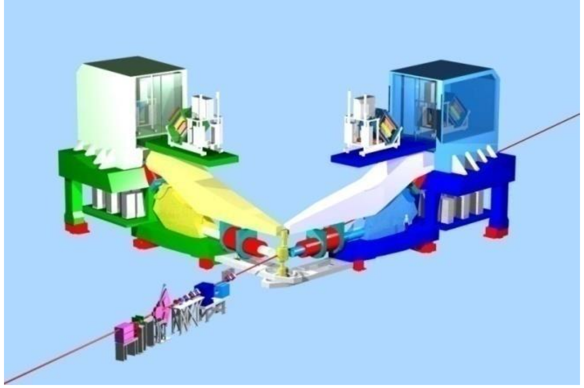
each point 30 days



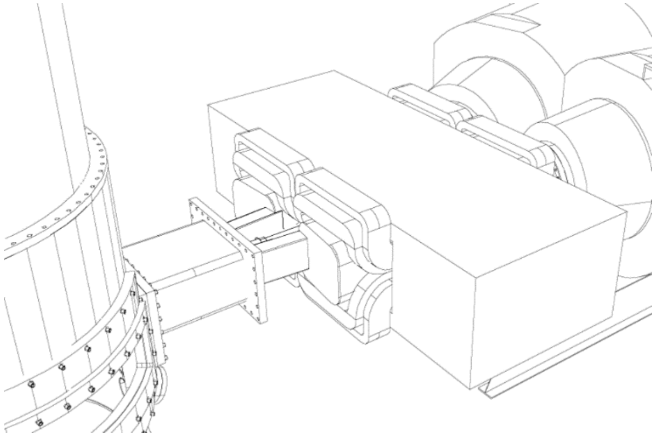
Parity Violating Electron Scattering
Measurements of Neutron Densities
Shufang Ban, C.J. Horowitz, R. Michaels

J. Phys. G39 014104 2012

R. Michaels, Jlab
HUGS Lecture



Possible Future PREX Program ?



Each point 30 days stat. error only

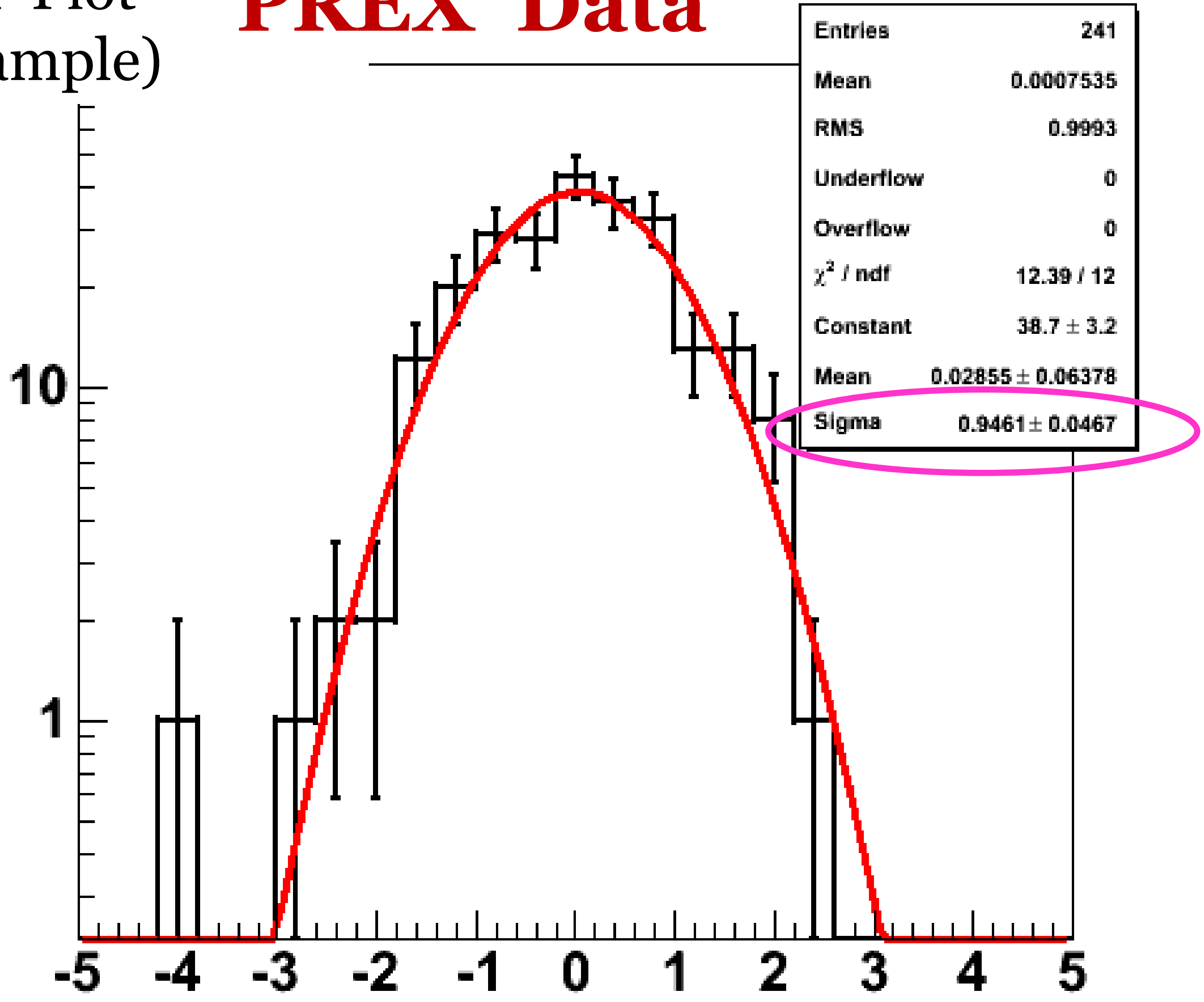
Nucleus	E (GeV)	dR_N / R_N	comment
^{208}Pb	1	1 %	**PREX-II** (approved by Jlab PAC, A rating)
^{48}Ca	2.2 (1-pass)	0.4 %	natural 12 GeV exp't will propose @ next PAC
^{48}Ca	2.6	2 %	surface thickness
^{40}Ca	2.2 (1-pass)	0.6 %	basic check of theory
tin isotope	1.8	0.6 %	apply to heavy ion
tin isotope	2.6	1.6 %	surface thickness

} Not proposed

Shufang Ban, C.J. Horowitz, R. Michaels **J. Phys. G39 014104 2012**

Pull Plot
(example)

PREX Data



$$(\,A - \bar{A}\,)\,/\,\sigma$$

Corrections to the Asymmetry are Mostly Negligible

- Coulomb Distortions ~20% = the biggest correction.
- Transverse Asymmetry (to be measured)
- Strangeness
- Electric Form Factor of Neutron
- Parity Admixtures
- Dispersion Corrections
- Meson Exchange Currents
- Shape Dependence
- Isospin Corrections
- Radiative Corrections
- Excited States
- Target Impurities

Horowitz, *et.al.* PRC 63 025501

Optimum Kinematics for Lead Parity: E = 1 GeV if $\theta = 5^\circ$

<A> = 0.5 ppm. Accuracy in Asy 3%

^{208}Pb

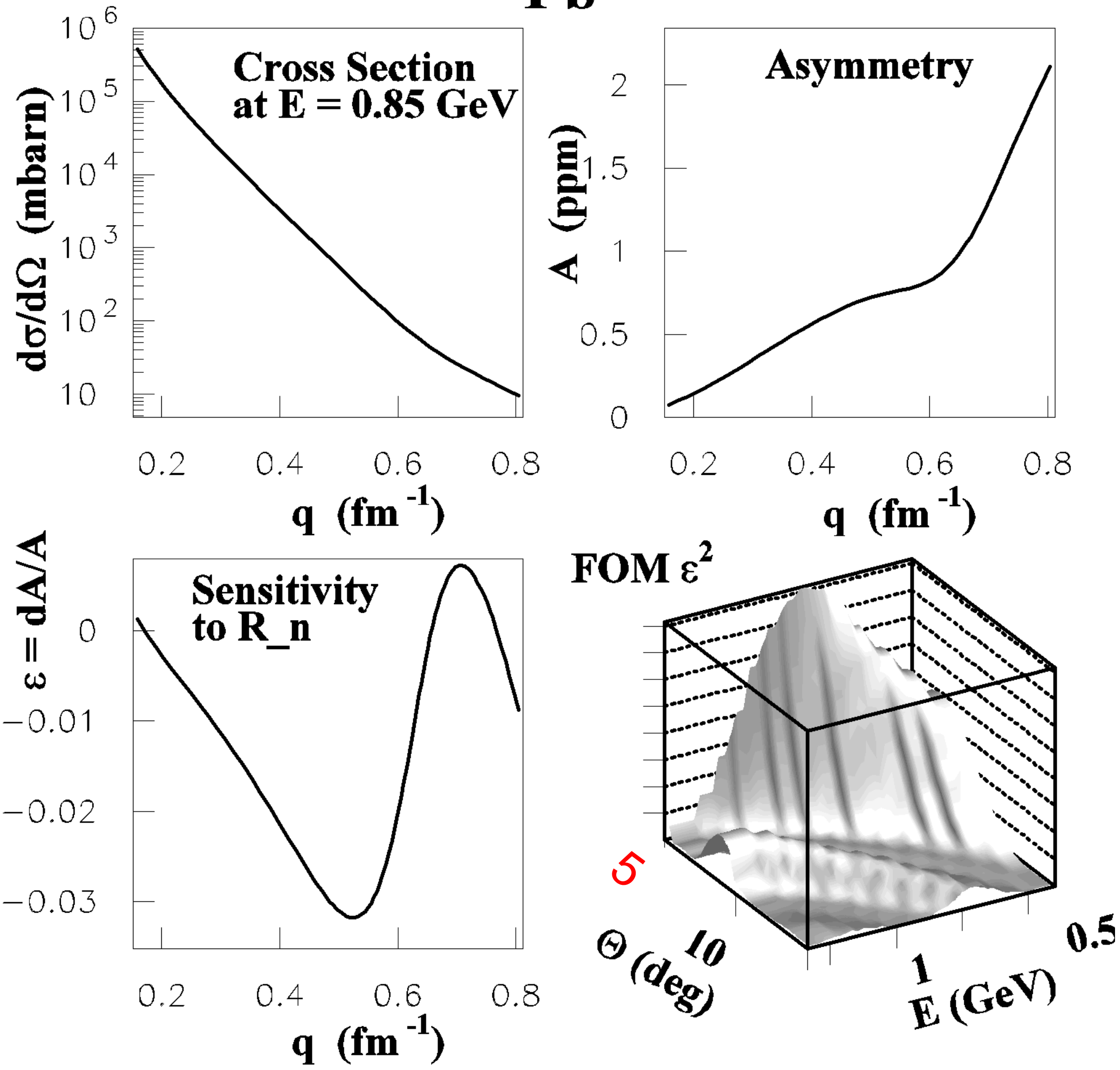


Fig. of merit

$$FOM = \frac{d\sigma}{d\Omega} \times A^2$$

Min. error in R_n

maximize:

→ $FOM \times \varepsilon^2$

1 month run

→ 1% in R_n

(2 months x 100 uA
→ 0.5% if no systematics)