New developments in beam properties for future Parity Violating Electron Scattering (PVES) experiments

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Acknowledgements to the QWeak and MOLLER collaborations.

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Outline

The Electroweak Physics available from PVES

The role of the beam properties

Current state of the art → QWeak experiment

Requirements for future experiments, particularly MOLLER

Possible technical improvements to realize these requirements

Electroweak parameters

To describe electroweak interactions, there are three parameters needed:

1. Scale of electromagnetism i.e. the fine structure constant
2. Scale of the weak interaction i.e. the W boson mass
3. Weak mixing angle i.e. the ratio of W and Z boson masses

The actual parameters are chosen from the three most precise EW experimental measurements:

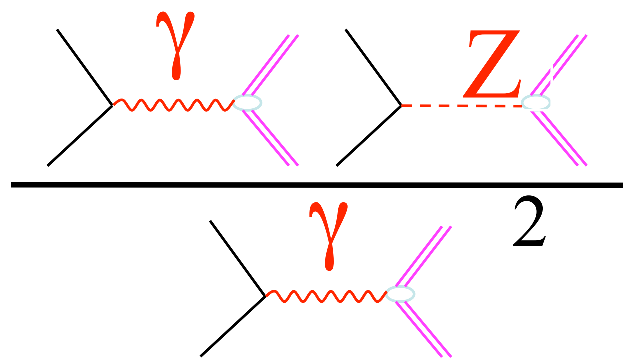
1. electron g-2
2. The muon lifetime
3. The Z line shape

4th and 5th measurements: M_W and $\sin^2\theta_W$ can then act as tests of the structure.

If measured values differ from tree level predictions: indirect access to "heavy" physics

Parity Violating Asymmetry

$$A = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \propto$$

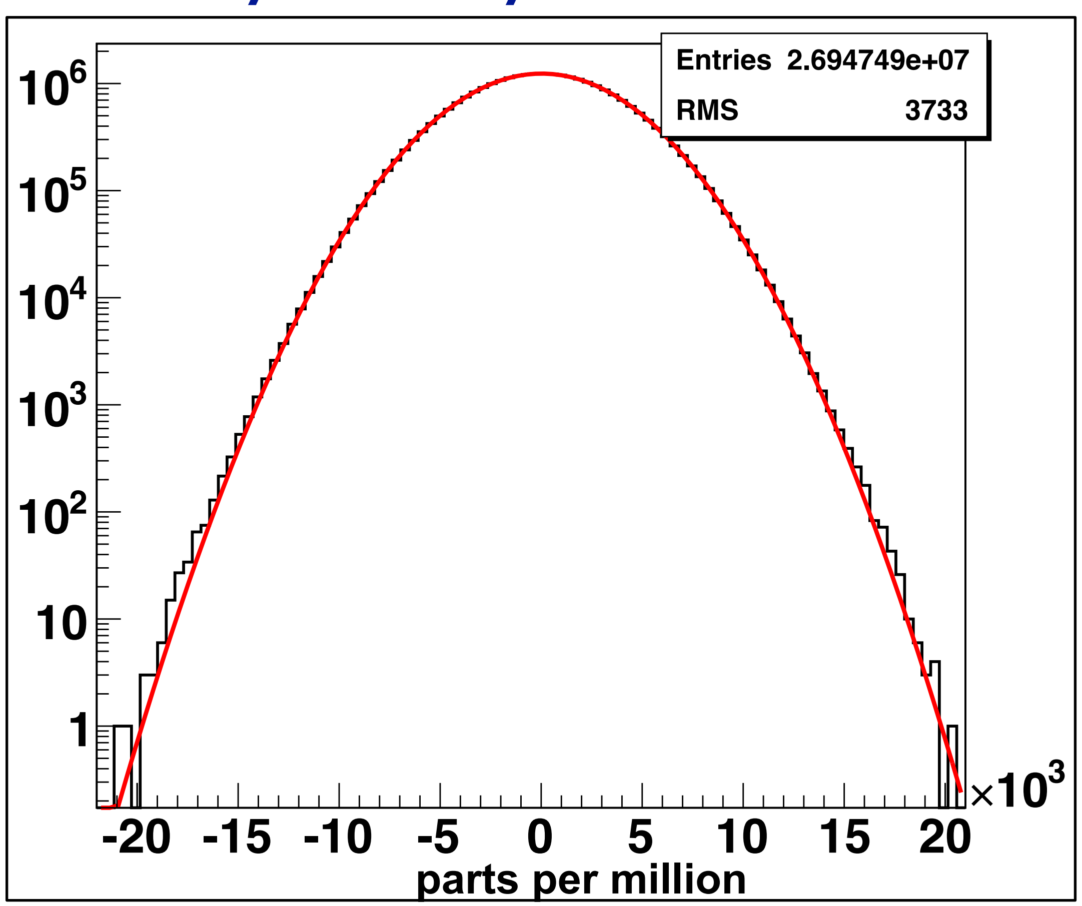


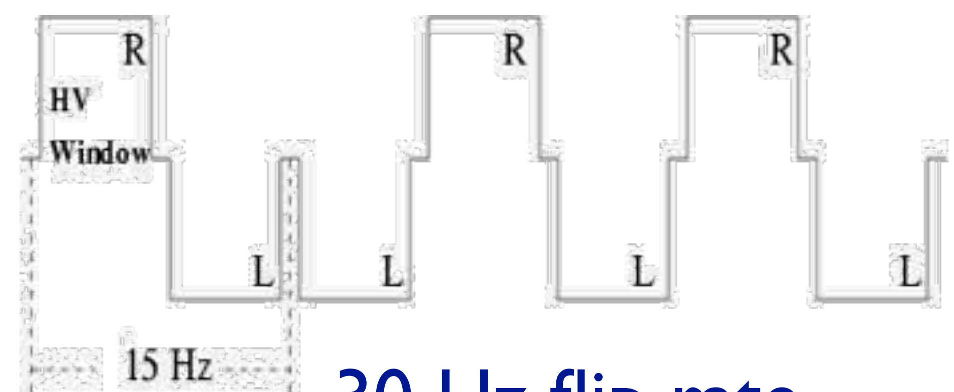
$$\sim \frac{10^{-4} Q^2}{\mathrm{GeV}^2}$$

sensitive to $1 - 4\sin^2\theta_W$

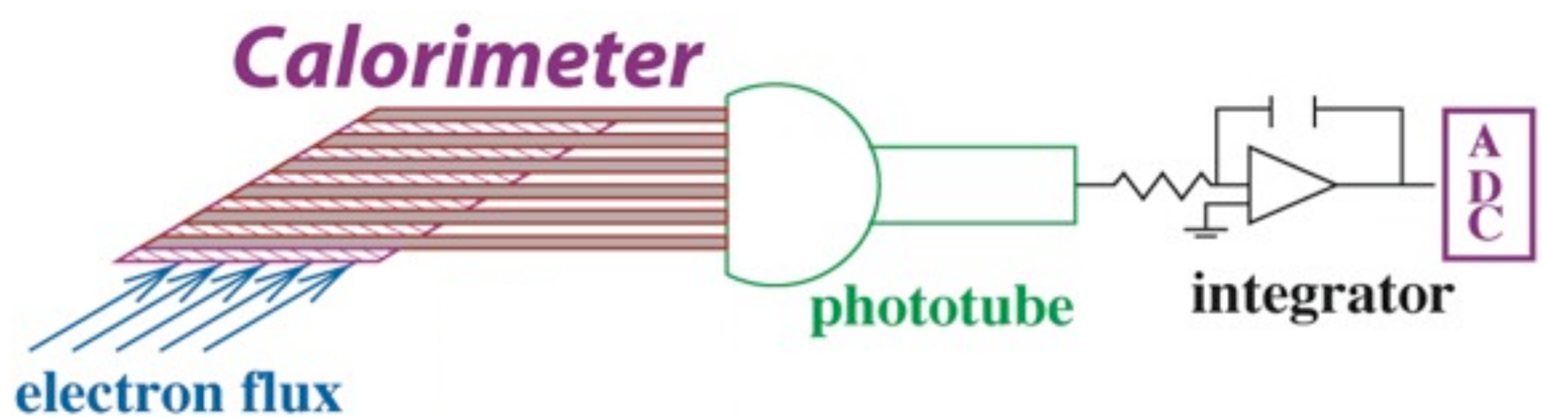
HAPPEx III example

Asymmetry distribution



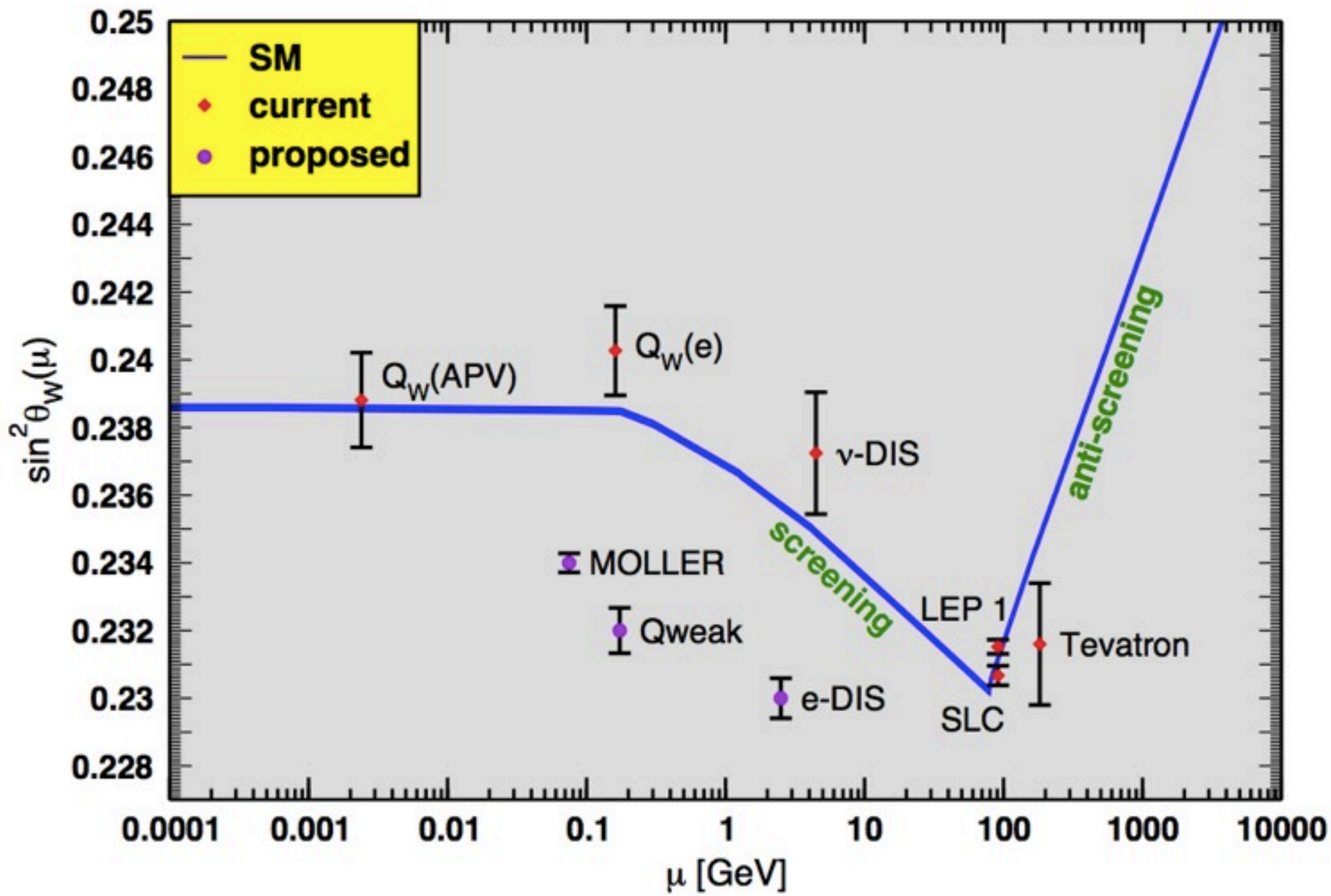


30 Hz flip rate



Testing of the Standard Model

Precision measurements at low energy can probe TeV scale physics through deviations from Standard Model predictions

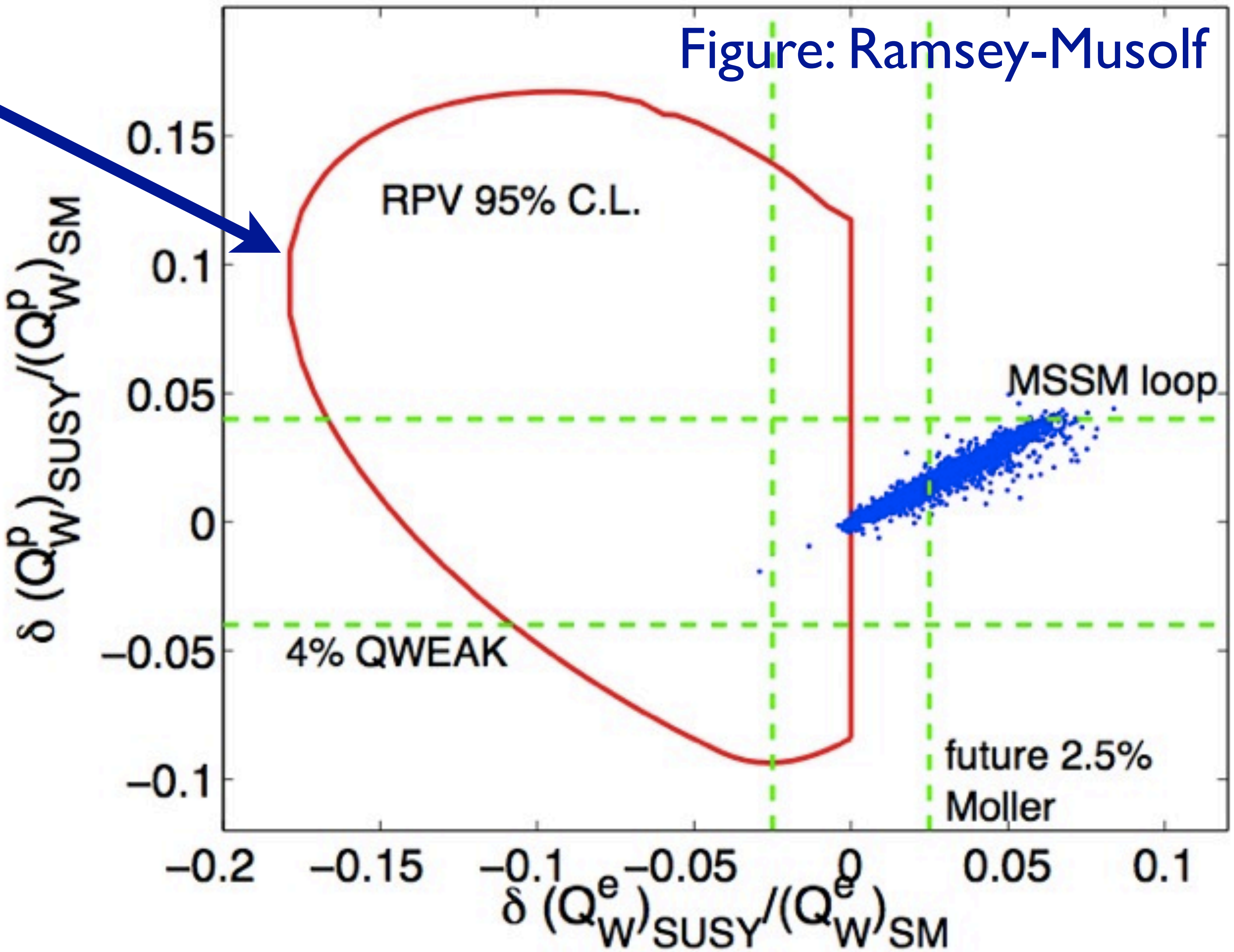


PVES access to New Physics

Including global fit constraints

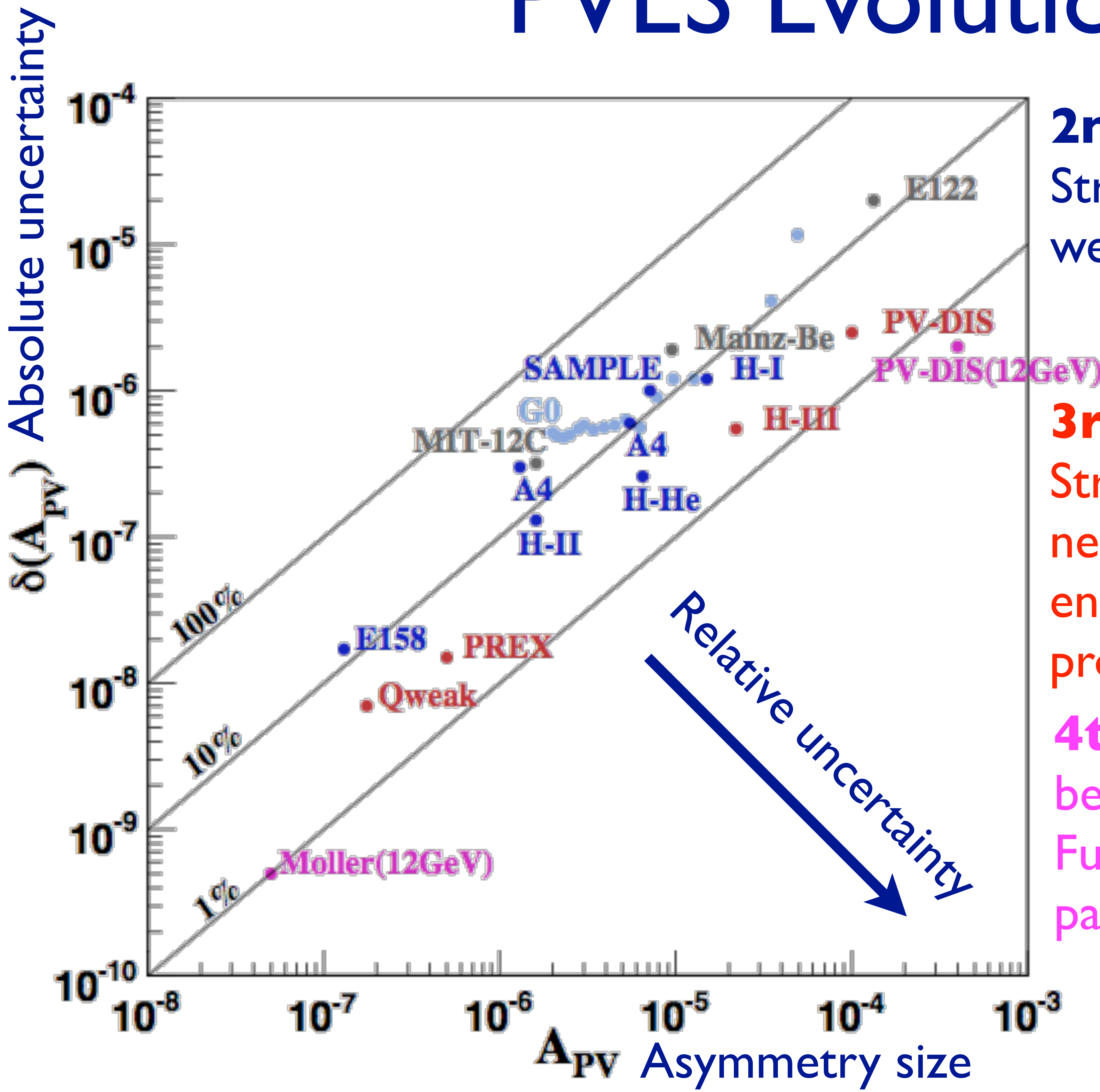
⇒ νs are Majorana

⇒ Lightest Supersymmetric Particle can't be Dark Matter



Tension between E158 and (g-2)μ ← (if interpreted in SS, favors large loop effects)

PVES Evolution



2nd generation: complete
Strange quarks in the nucleon, weak charge on electron.

3rd generation: in progress
Strange quarks swansong, neutron self interaction energy, weak charge on proton.

4th generation:
beginning 2016?
Fundamental Standard Model parameters.

Source of Polarized electrons

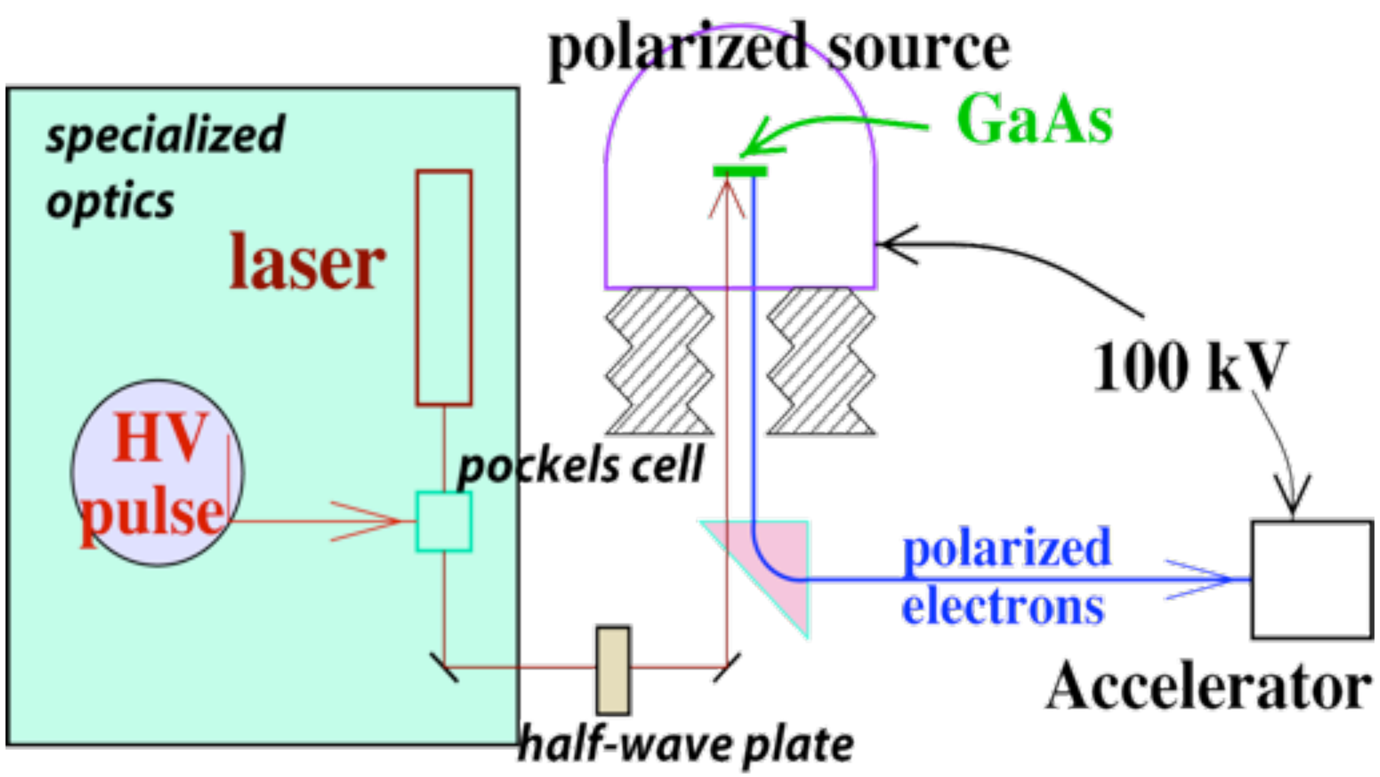
Goal: Provide **high current, high polarization** electrons in two helicity states.

Increase 'statistics'

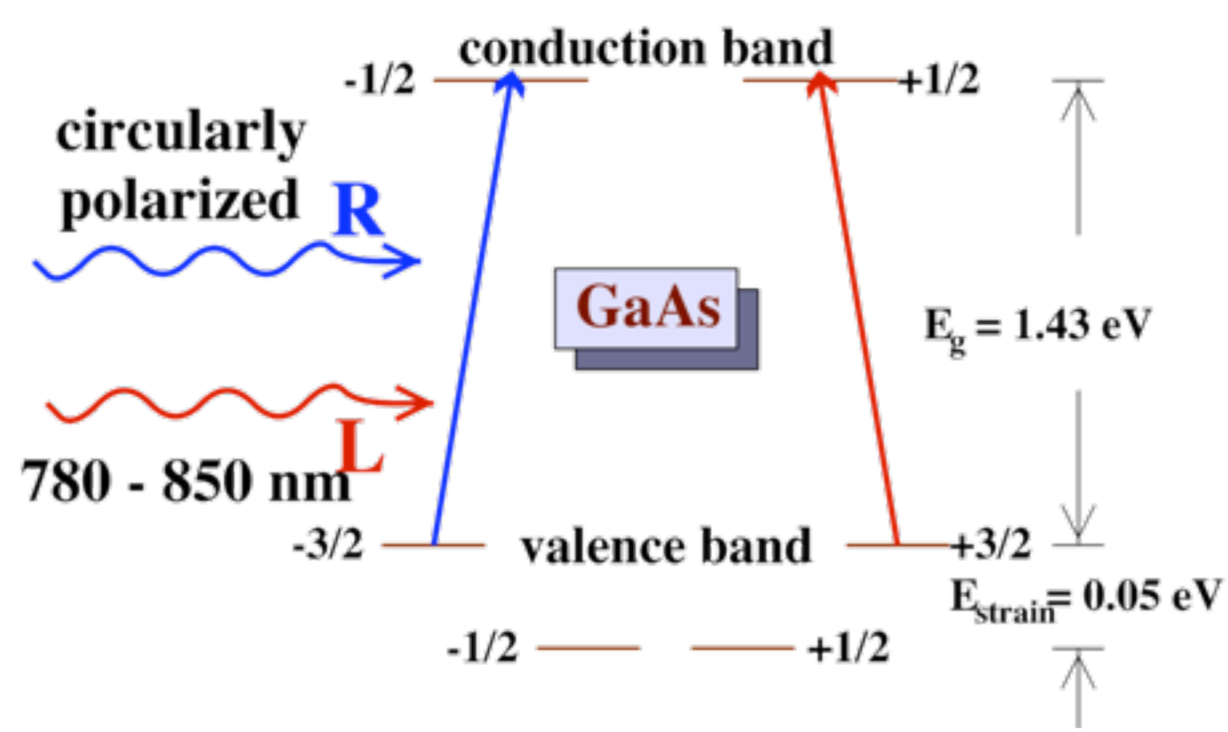
Identical in all other respects to:
Decrease systematic uncertainty

Step 1a: produce circularly polarized light

Step 1b: change helicity of light



Step 2: shine light on **strained** GaAs photocathode



Helicity Correlated Differences

charge asymmetry
Measure and feed back

zeroth moment

beam-position differences**, angle** differences and **energy** differences
Diminish as far as possible, measure and correct

1st moment

beam spot size differences, **beam "shape"** differences
Can't be directly measured, must be bounded

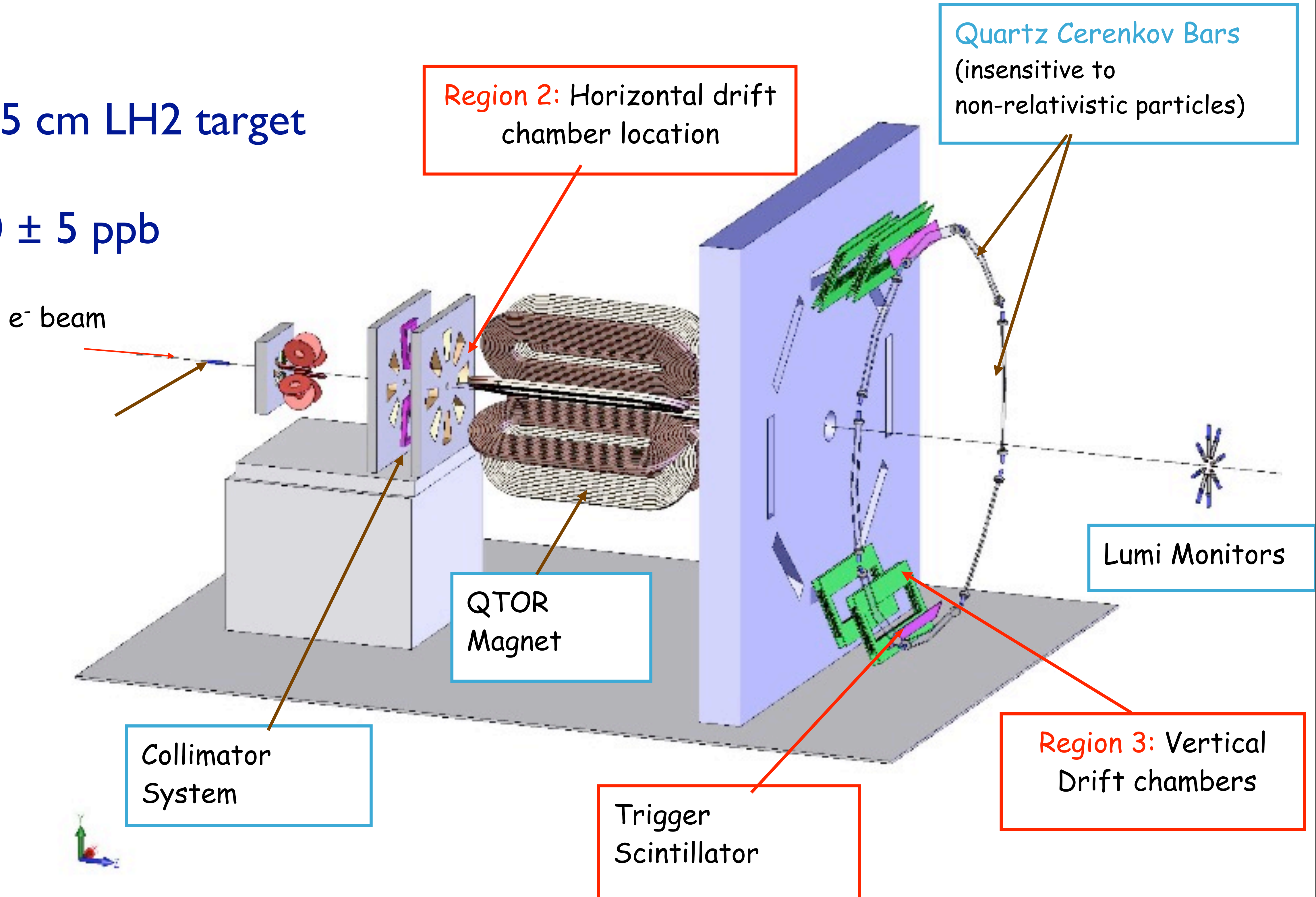
2nd moment

QWeak

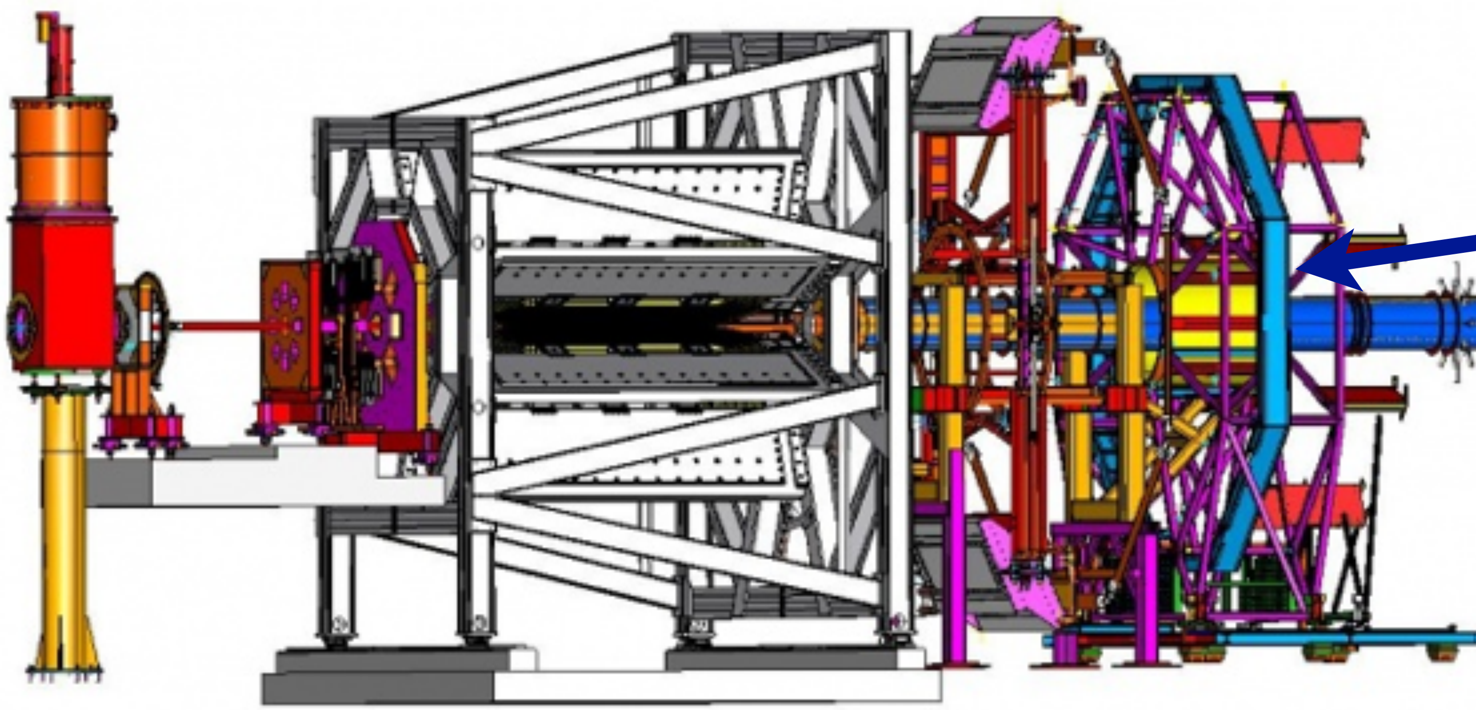
$Q^2 = 0.027\ (GeV/c)^2$
$E_{beam} = 1.16\ GeV$
$\theta_{lab} = 8°$

~165 µA, 35 cm LH2 target

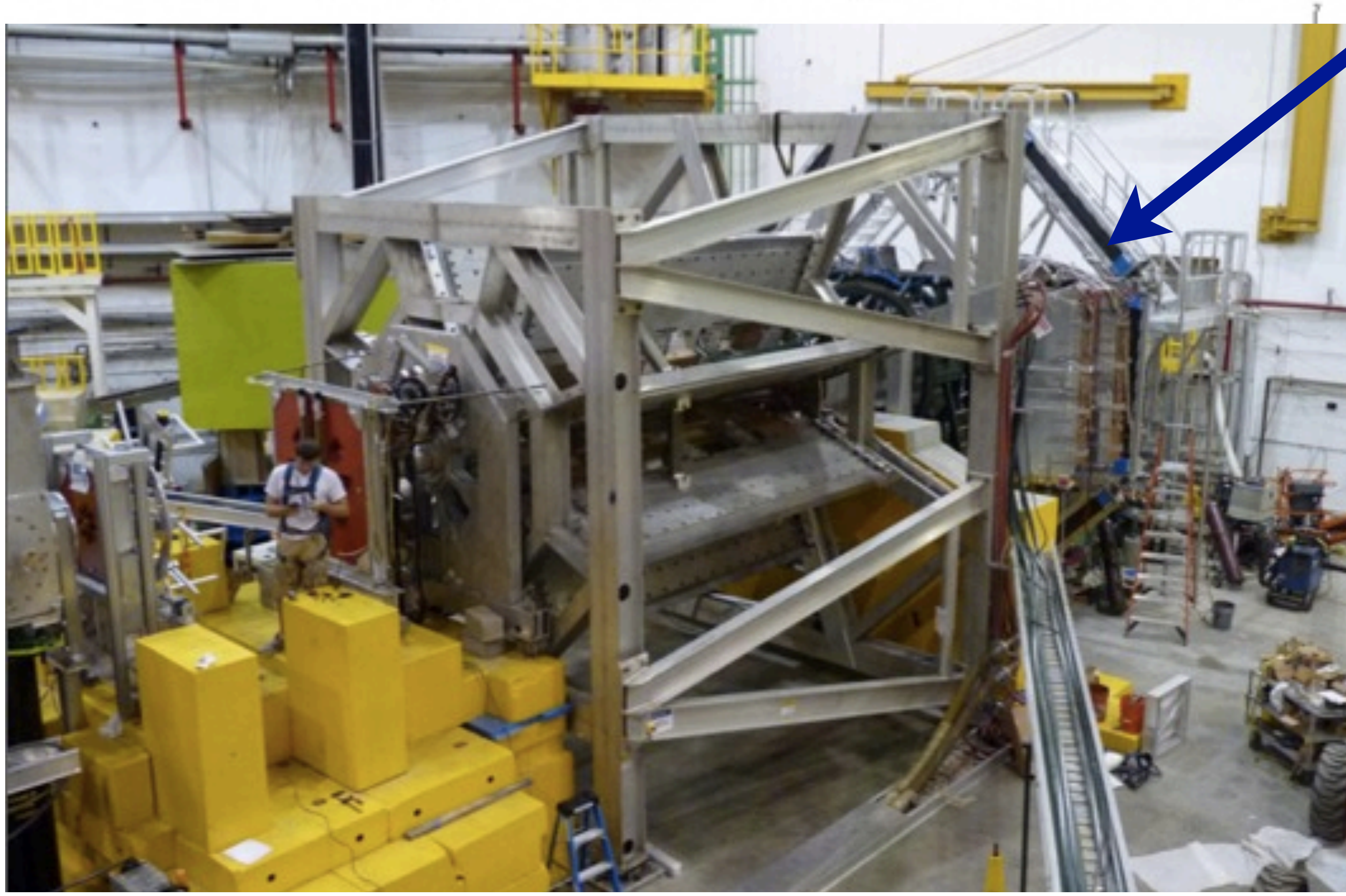
APV ≈ 200 ± 5 ppb

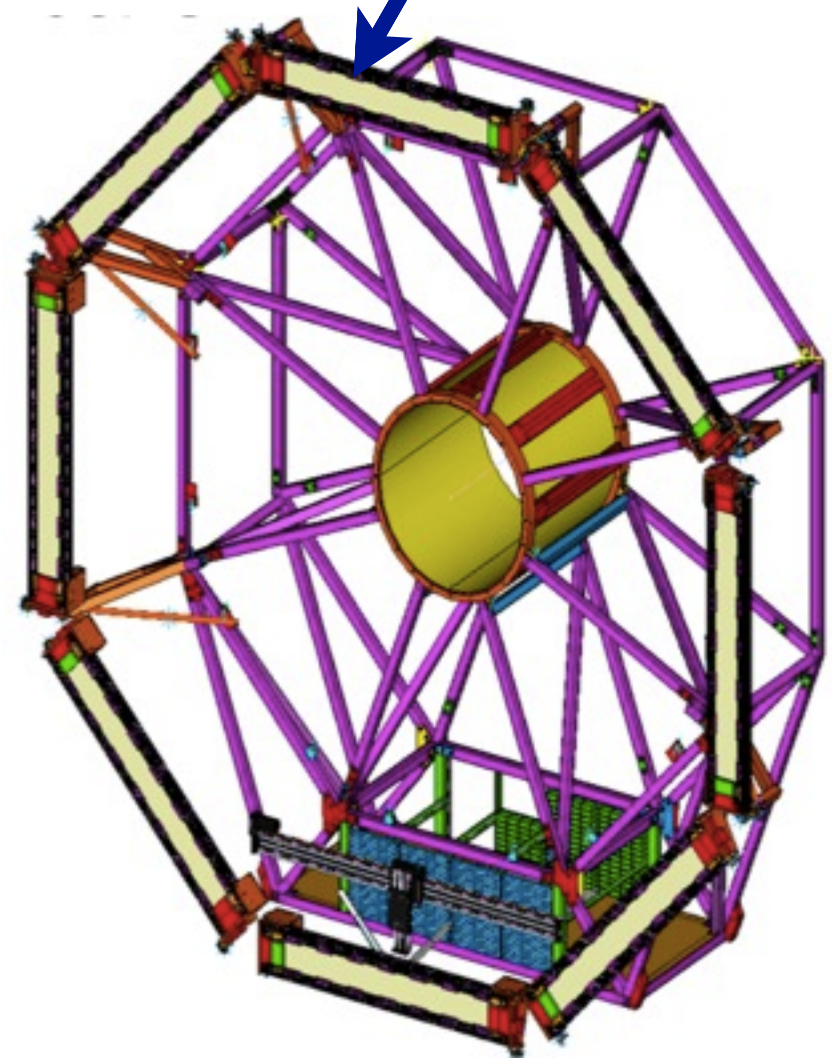


QWeak detector geometry

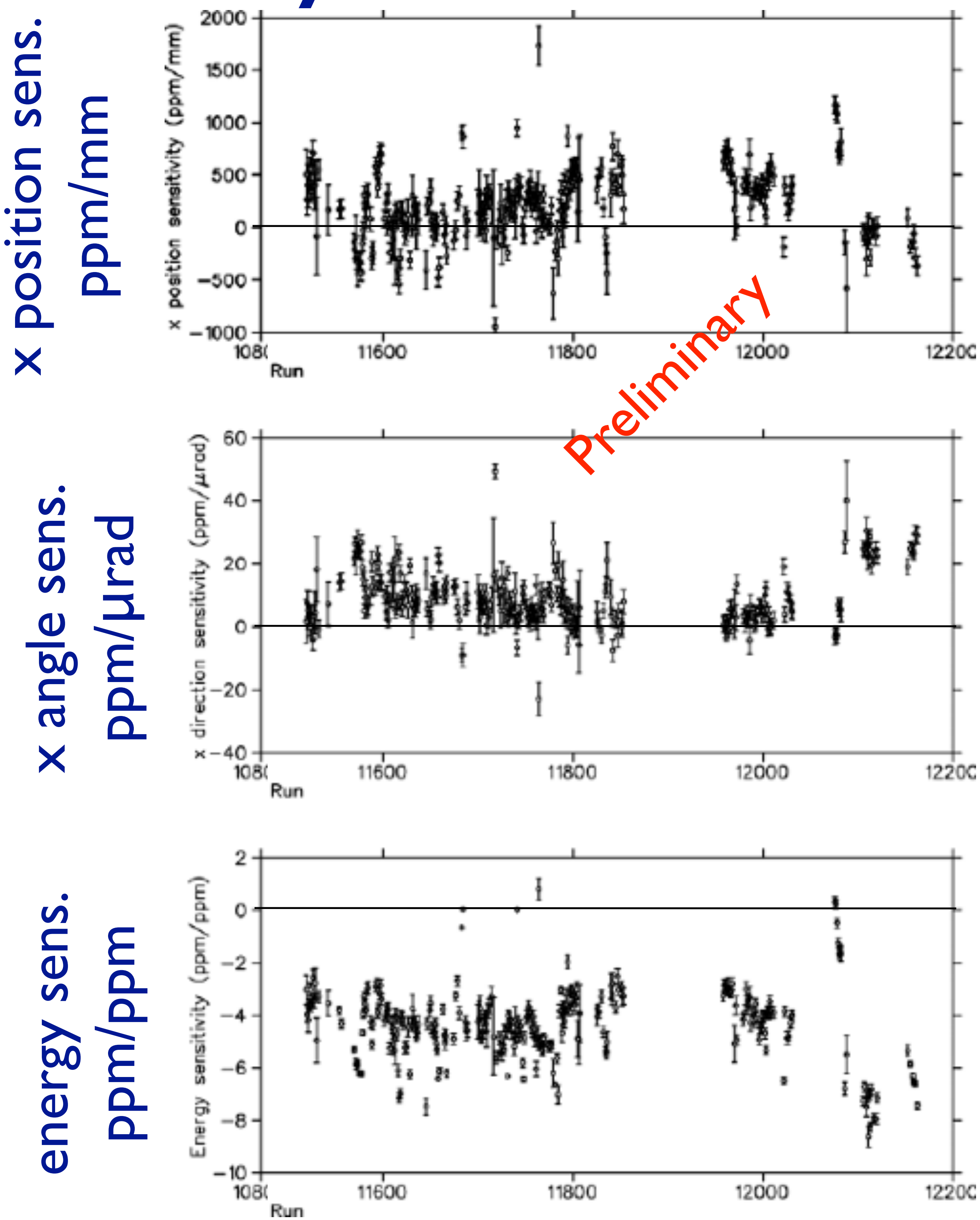


Azimuthally symmetric detectors decrease sensitivity to 1st moment HC beam motions.



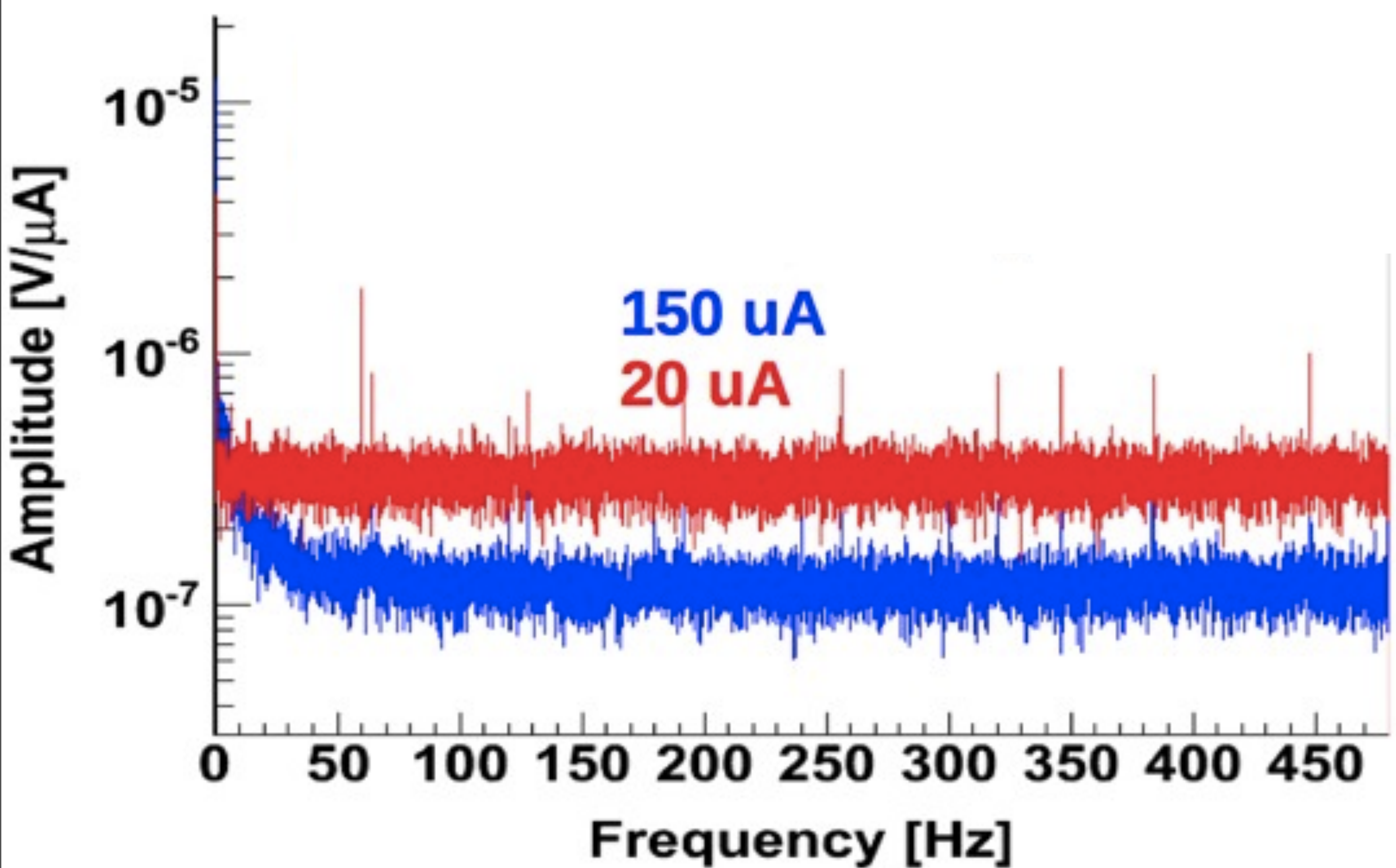


Helicity Correlated beam sensitivities

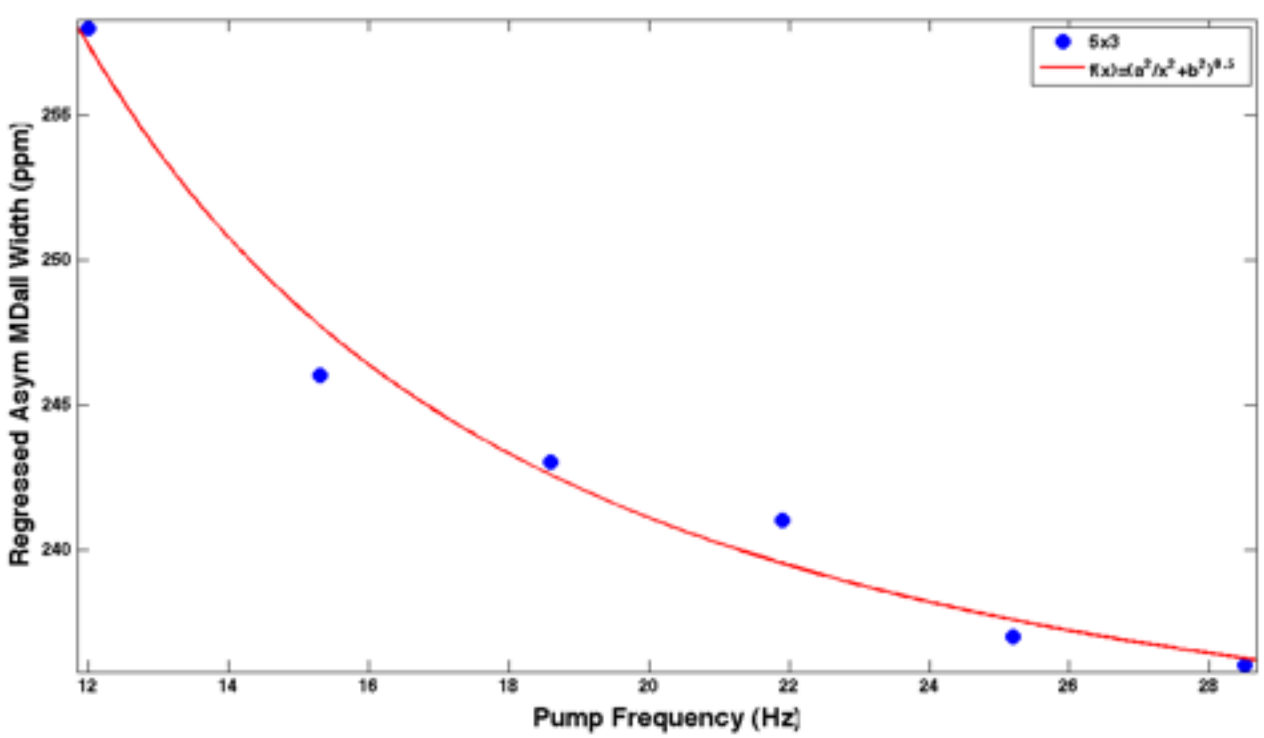


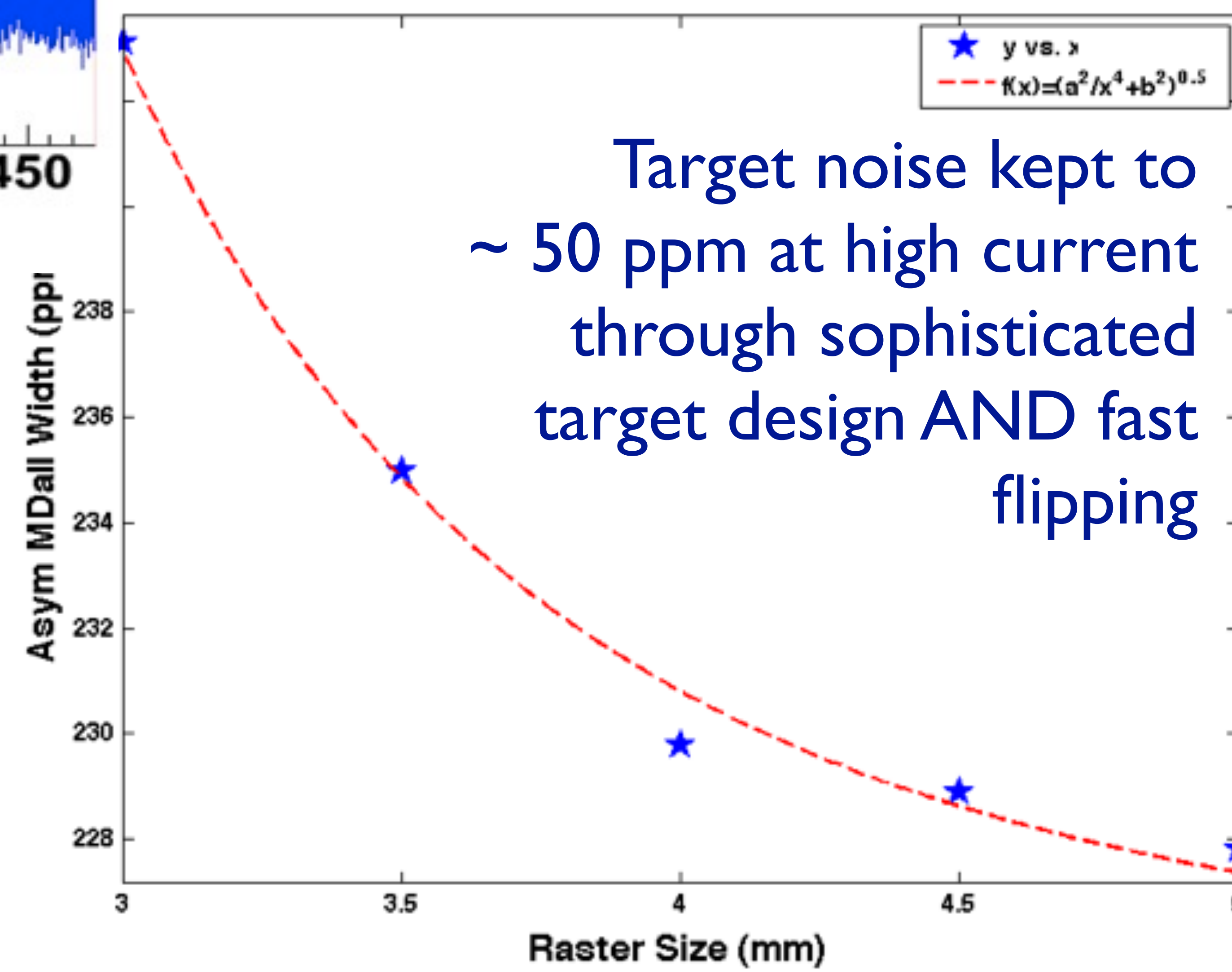
Despite the highly symmetrical detector QWeak is still sensitive to 1st moment HC beam properties

Target density fluctuations



High currents cause density fluctuations in target liquid which adds low frequency noise to the measurement





Target noise kept to ~ 50 ppm at high current through sophisticated target design AND fast flipping

Noise and Width: QWeak

Width calculation

Total detected rate = 5.83 GHz
Pure counting statistics = 215 ppm + detector energy resolution + beam current normalization + target fluctuations

Asymmetry distribution

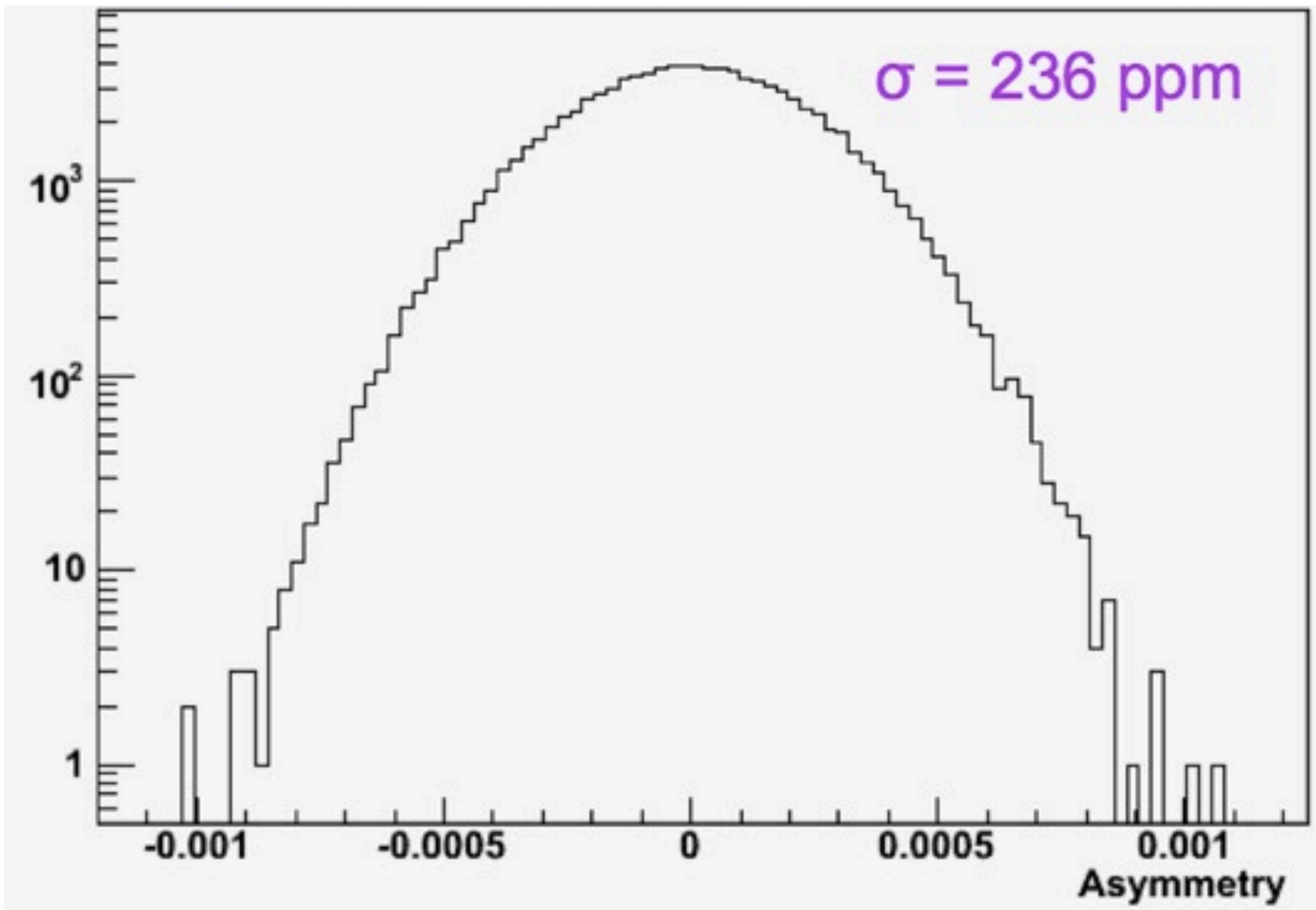
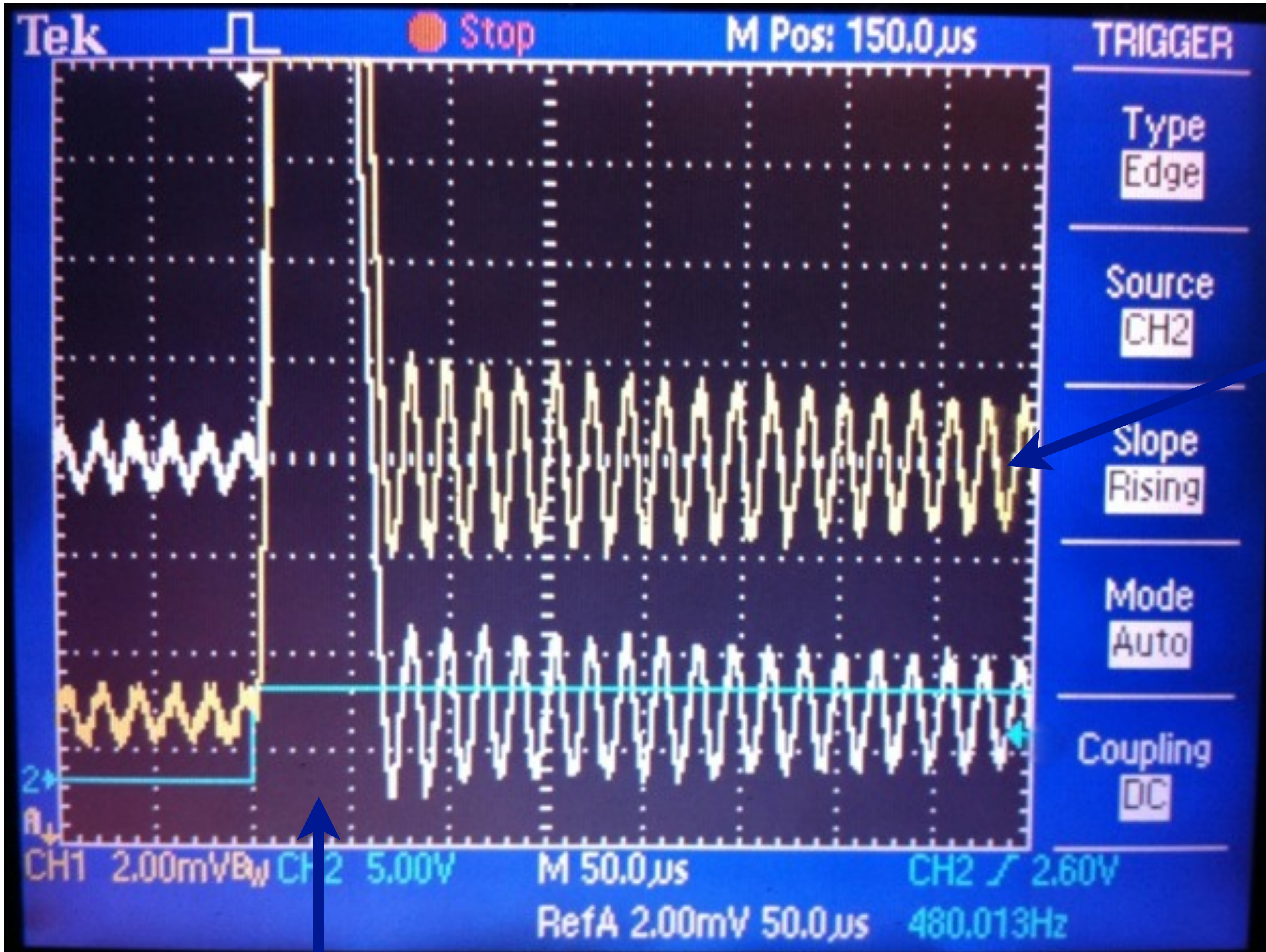


Figure: 6.5 minutes of data @ 165 μA (93K quartets)
0.8 ppm statistical error

Fast Flip Causes Pockels Cell 'Ringing'



QWeak experience

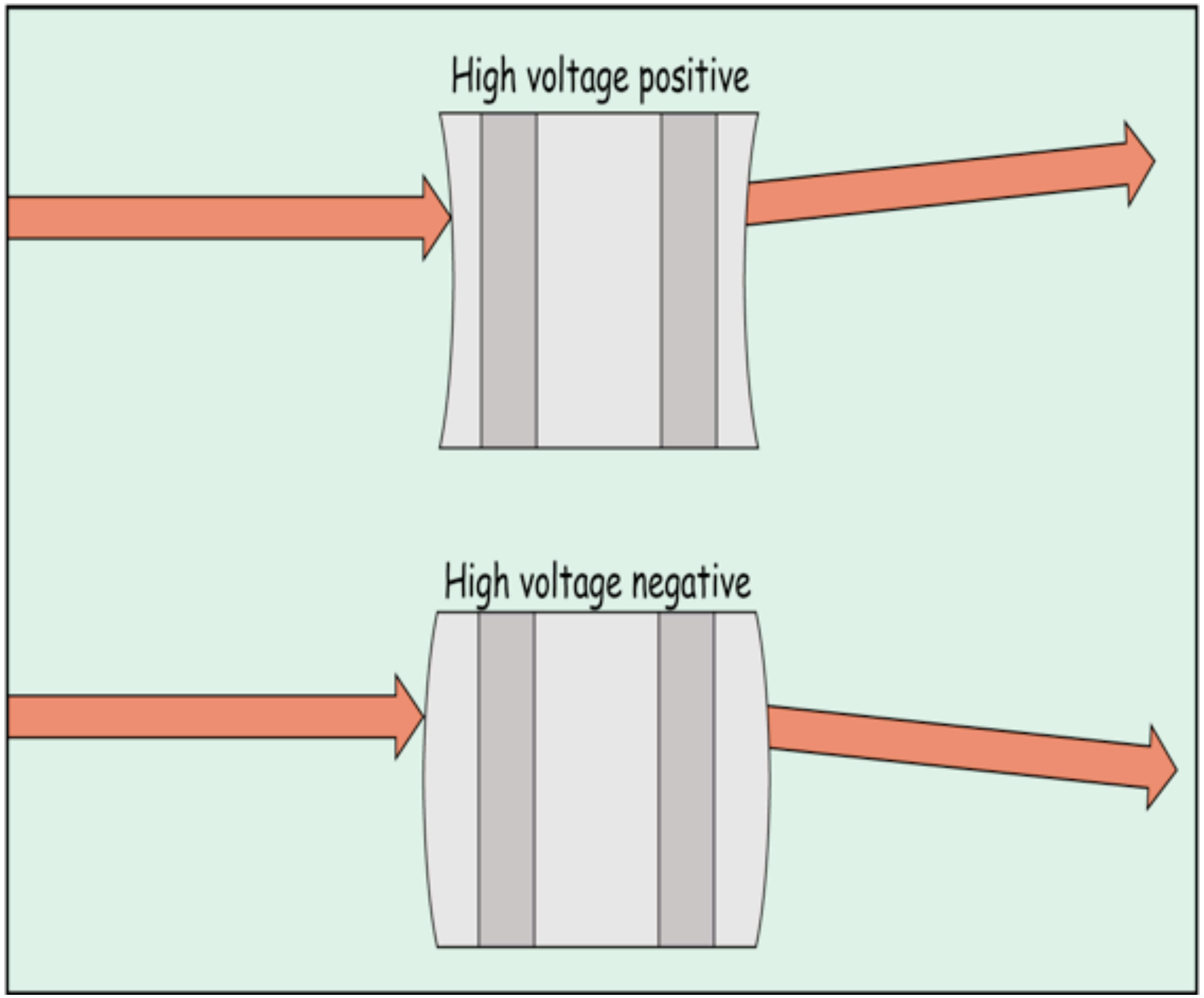
Potentially troublesome 'ringing' if coupled to other effects

Better Pockels Cells and high voltage switches exist but the setup is notoriously tricky.

70 µs switching time
For 960 Hz flip frequency ⇒ ~ 7 % dead time

Limitation of Pockels Cell

Crystal nature of Pockels medium leads to steering effects and vibrations after high voltage shocks which damp slowly.

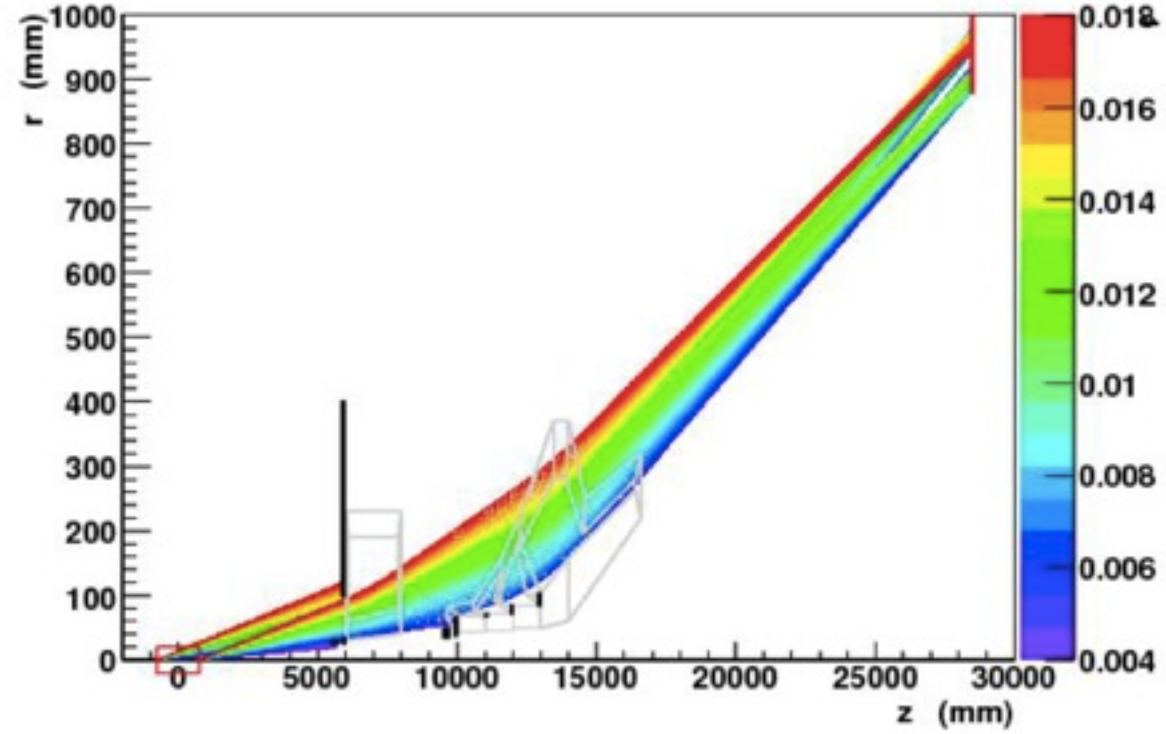


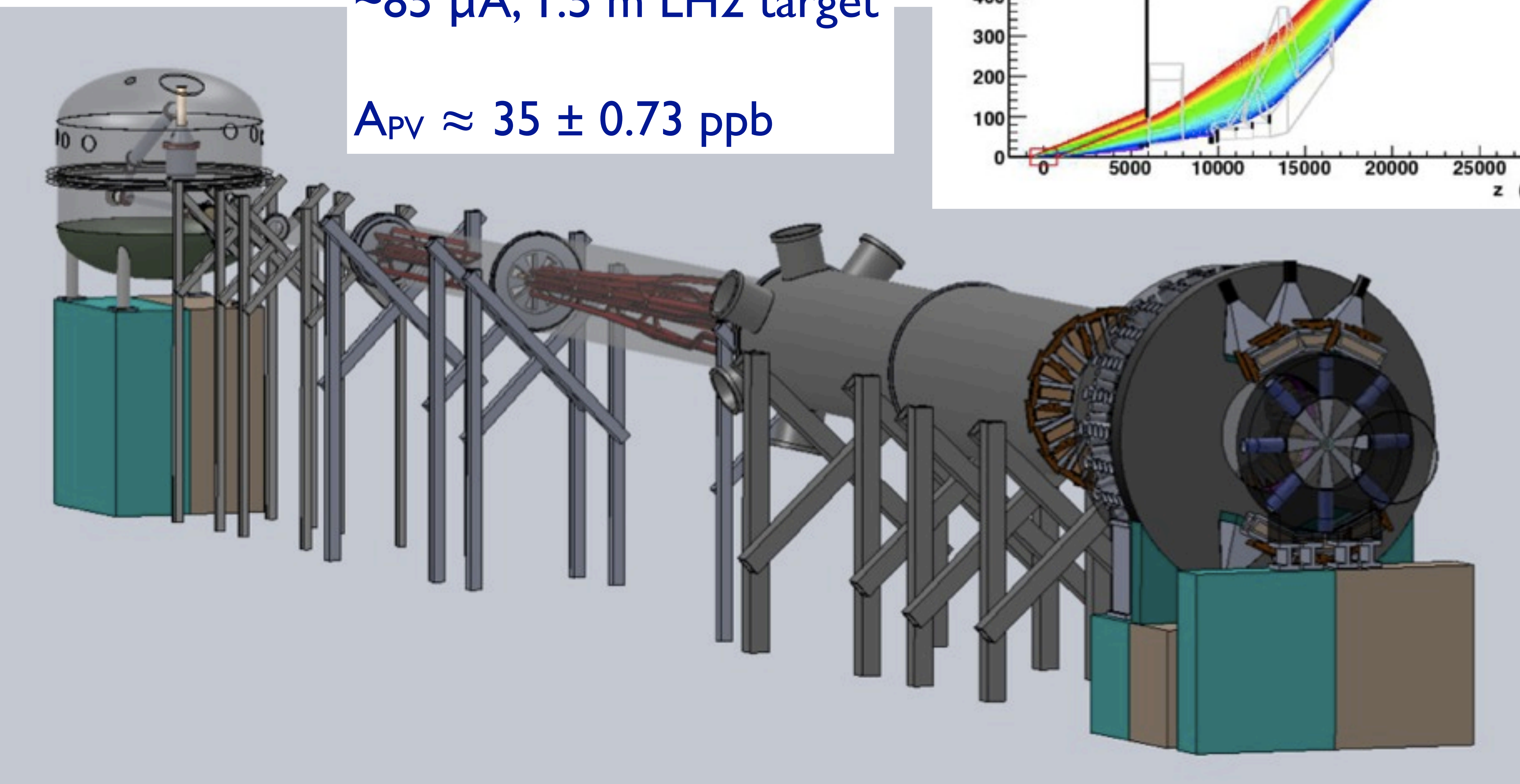
MOLLER Experiment

$Q^2 = 0.0056\ (\mathrm{GeV}/c)^2$
$E_{beam} = 11$ GeV
$0.29° < \theta_{lab} < 0.97°$

~85 μA, 1.5 m LH2 target

$A_{PV} \approx 35 \pm 0.73$ ppb





Statistics and Systematics Comparison

Accuracy goals for MOLLER are factors of 2 to 10 beyond those of E158 & Qweak

parameter	E158	Qweak	MOLLER
Rate	3 GHz	6 GHz	135 GHz
reversal rate	120 Hz	960 Hz	1920 Hz
pair stat. width	200 ppm	400 ppm	82.9 ppm
$\delta(A_{raw})$	11 ppb	4 ppb	0.544 ppb
$\delta(A_{stat})/A$	10%	3%	2.1%
$\delta(\sin^2\theta_W)_{stat}$	0.001	0.0007	0.00026

Extremely narrow width increases sensitivity to noise sources e.g. electronics noise

MOLLER apparatus

Enormous technical challenges: MOLLER is a IV Generation Expt at JLab

Polarized Beam
- unprecedented polarized luminosity
- unprecedented beam stability

Liquid Hydrogen Target
- 5 kW dissipated power (2 X QWeak)
- computational fluid dynamics

Toroidal Spectrometer
- Novel 7 “hybrid coil” design
- warm magnets, aggressive cooling

Integrating Detectors
- build on QWeak and PREX
- intricate support & shielding
- radiation hardness and low noise

MOLLER error budget

source of error	% error
absolute value of Q2	0.5
beam second order	0.4
longitudinal beam polarization	0.4
inelastic e-p scattering	0.4
elastic e-p scattering	0.3
beam first order	0.3
pions and muons	0.3
transverse polarization	0.2
photons and neutrons	0.1
Total	**1.0**

Very little room for uncertainties from HC beam properties

Demands from the beam

Small helicity correlated differences

Faster differential measurements

Decreased "dead" time

MOLLER limits
cumulative helicity-correlated :
position difference < 0.5 nm,
angle differences < 0.05 nrad,
laser spot size difference < 0.01 %

Flip rate: 960 Hz → 1920 kHz
Transition time: 70 μs → 10 μs

Can be achieved through:

significant improvements to existing technology:
- KD*P Pockels cell → RTP Pockels cell
- further improvements in alignment and setup methods

use of new technologies:
- Using a "Kerr" cell rather than a Pockels cell to reverse the helicity of the laser beam.

Speculative, R&D required

Kerr vs Pockels Effects

$\Delta n = \lambda K E^2$ birefringence that depends on the square of a transverse electric field

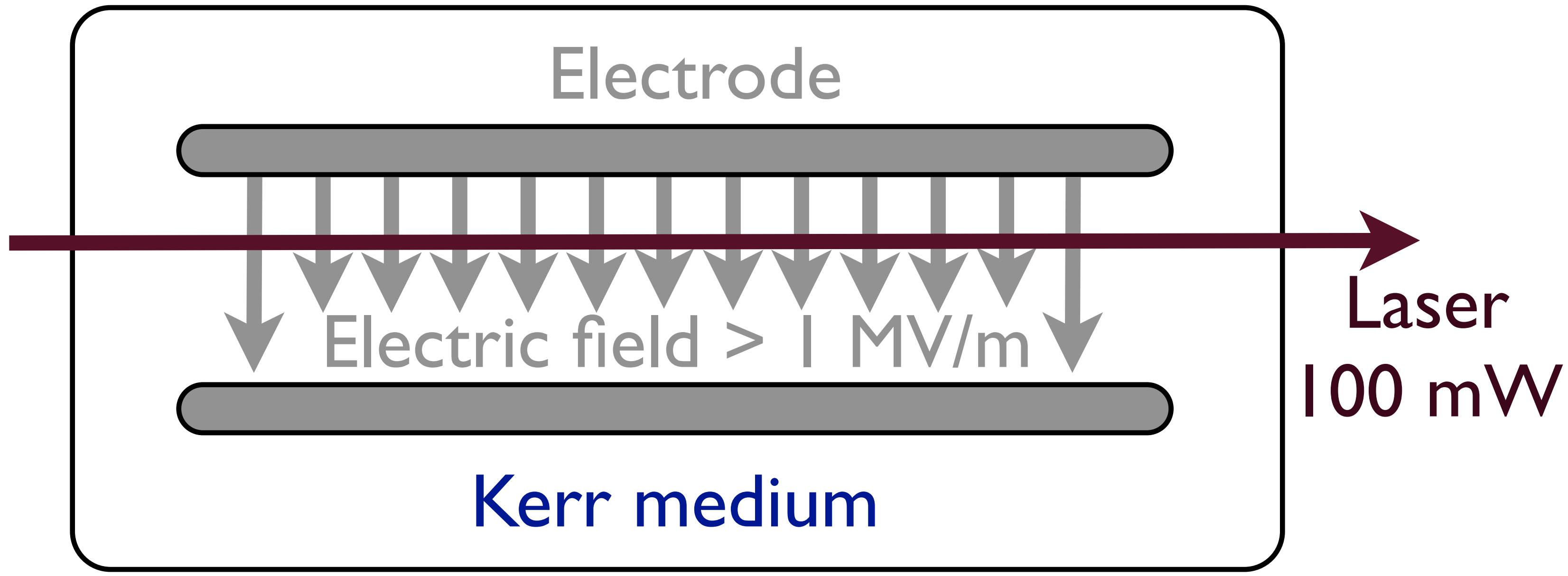
Pockels Cell	Kerr Cell
Crystal	Liquid or gas
Longitudinal Field	Transverse Field
Commercially available	Development required
Strong Effect ~3 kV (KD*P) Deuterated Potassium Dihydrogen Phosphate	Weak Effect ~ 30 kV (nitrobenzene, acetone)

Liquid or gas: mitigate steering effects, or physical oscillations following large potential changes.

Transverse Field: Self focussing, since laser is transverse E

Weak Effect: Even higher voltage

Geometry of a Kerr cell

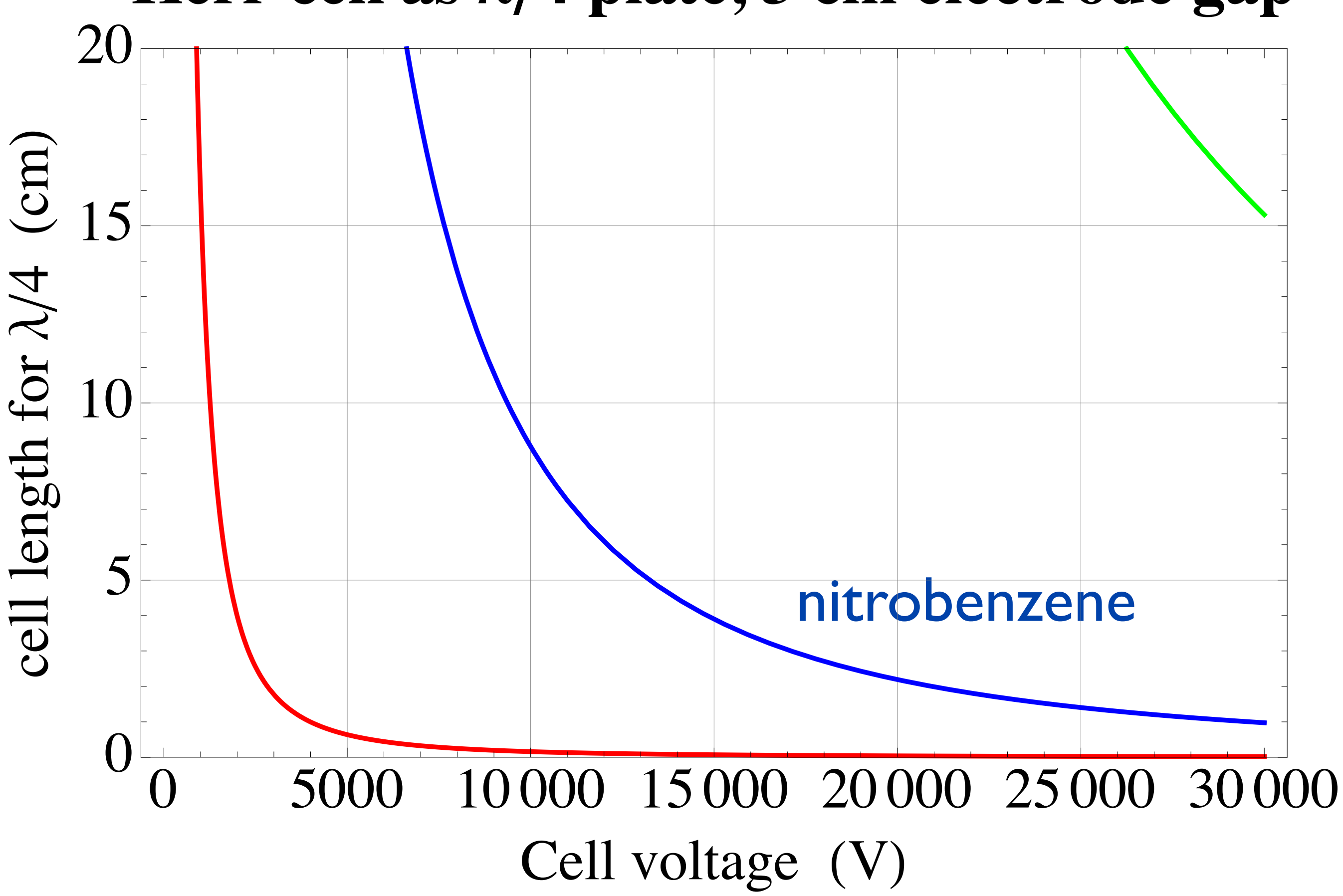


Self interaction: transverse electric field of the laser beam will itself cause a Kerr Effect.

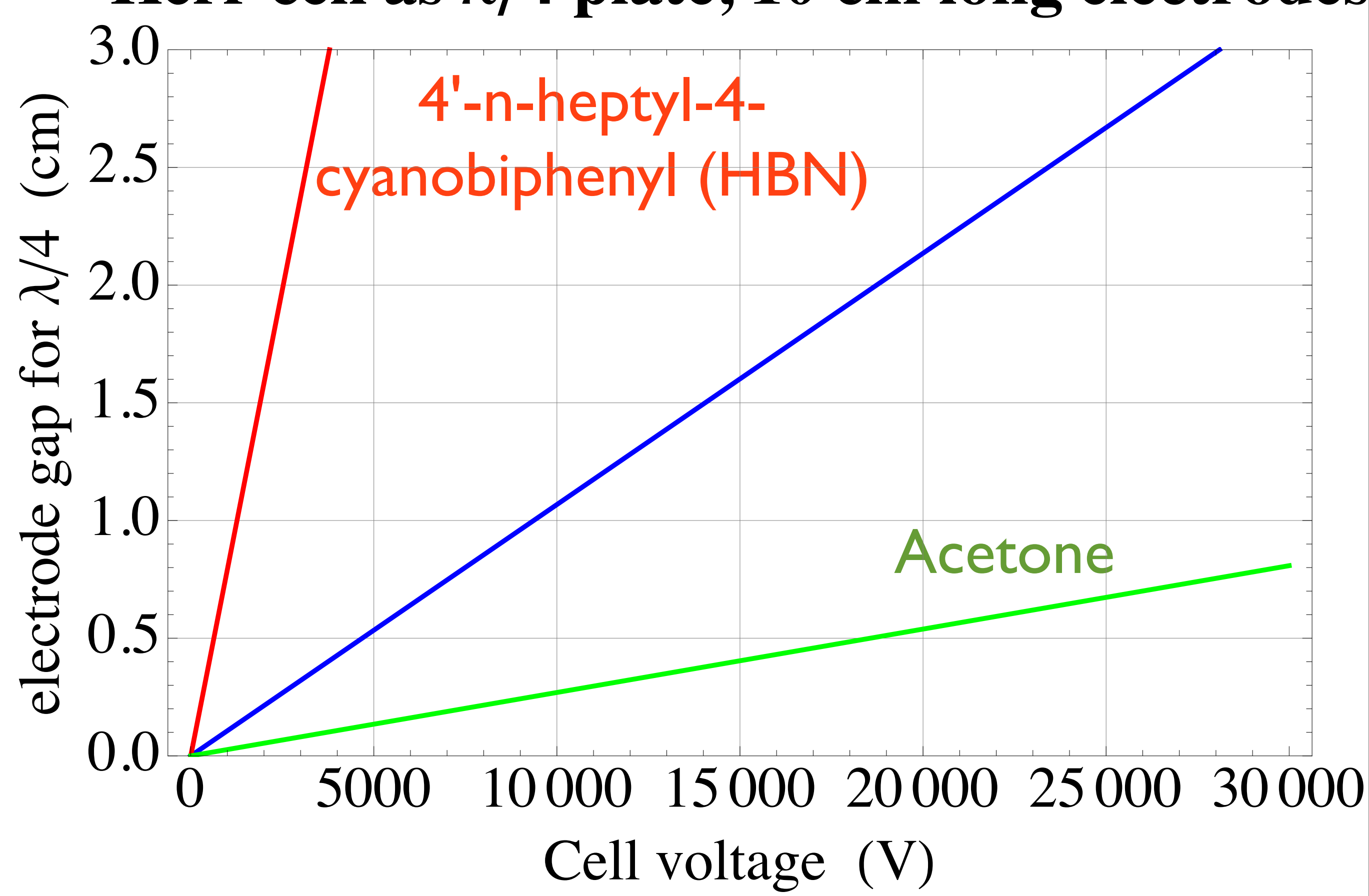
Can results in a "wave guide" or graded index focusing lens.

Mitigate by shortening the cell and increasing the high voltage.

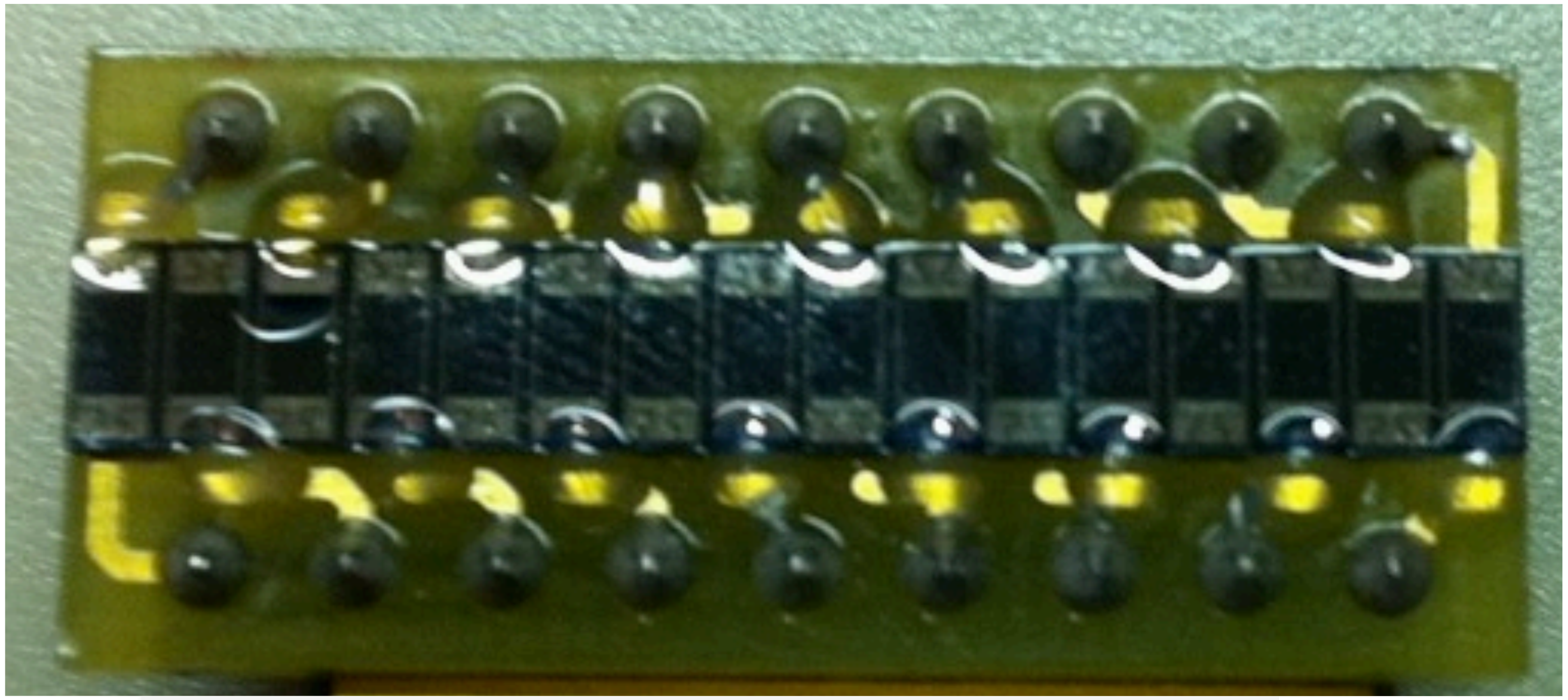
Kerr cell as $\lambda/4$ plate, 3 cm electrode gap



Kerr cell as $\lambda/4$ plate, 10 cm long electrodes

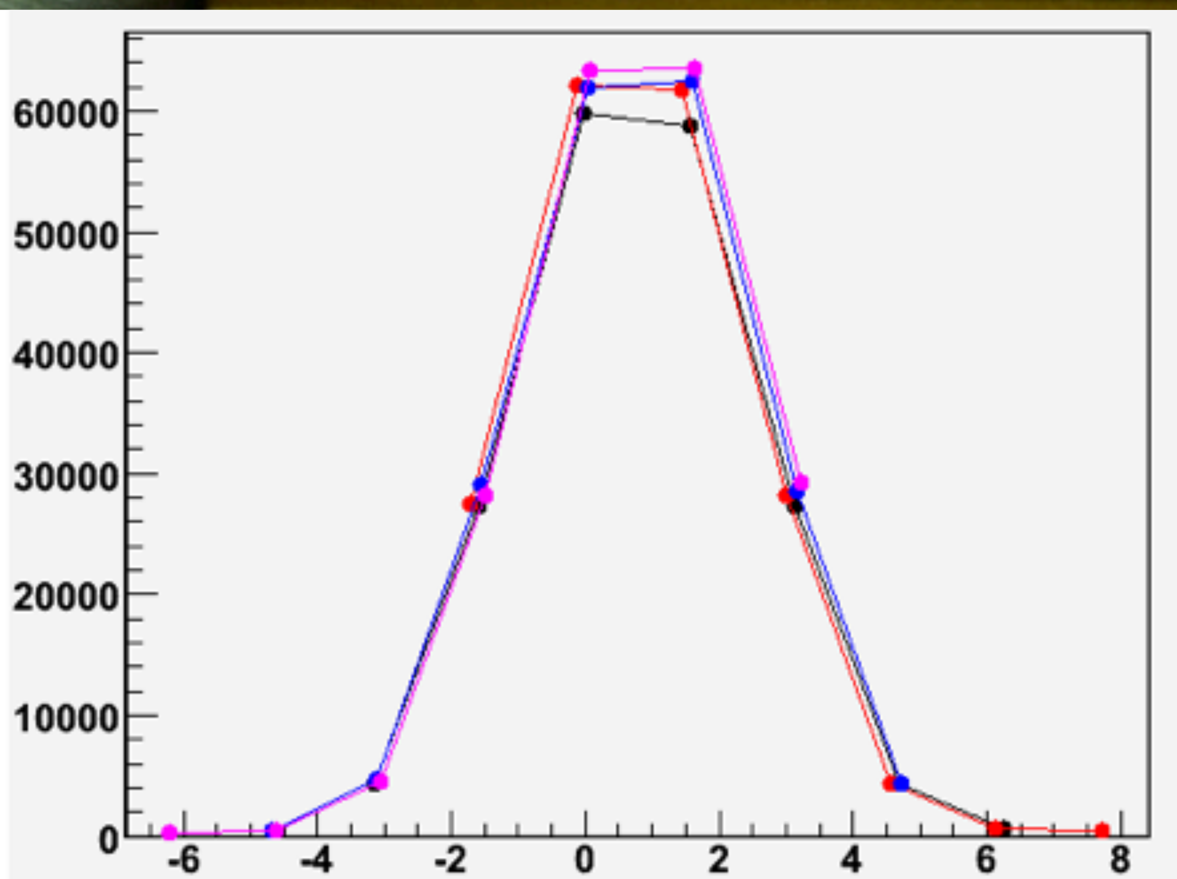


Spot Size Asymmetry Measurement



Linear Photodiode Array

Already used in PREx and QWeak to bound spot size differences to < 10e-4



Profile laser beam at high differential rate

Measure helicity correlated
spot size asymmetry
higher moment spot "shape" asymmetry

Summary

Future parity experiments provide indirect access to new physics at the multi-TeV energy scale.

Particularly the MOLLER experiment, will require significant improvements in helicity correlated differences and helicity state transition time, while also increasing the helicity reversal rate.

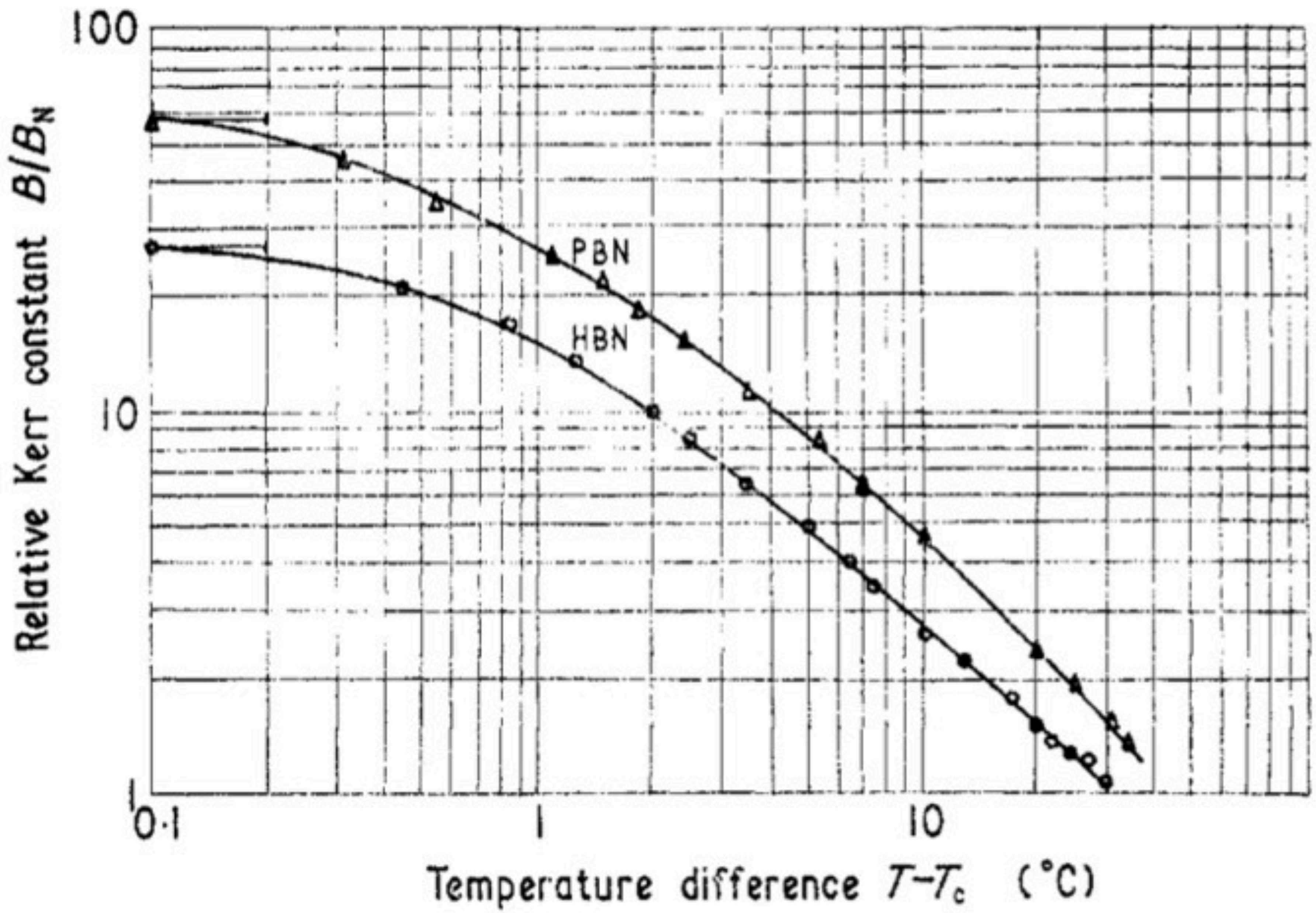
Kerr cells should offer significant advantages over Pockels cells:
helicity reversed quicker, less dead time;
reduced helicity correlated effects reduced

Bonus Slides

Liquid Crystals?

4'-n-pentyl-4-cyanobiphenyl
(PBN)
55 times the Kerr
constant of nitrobenzene

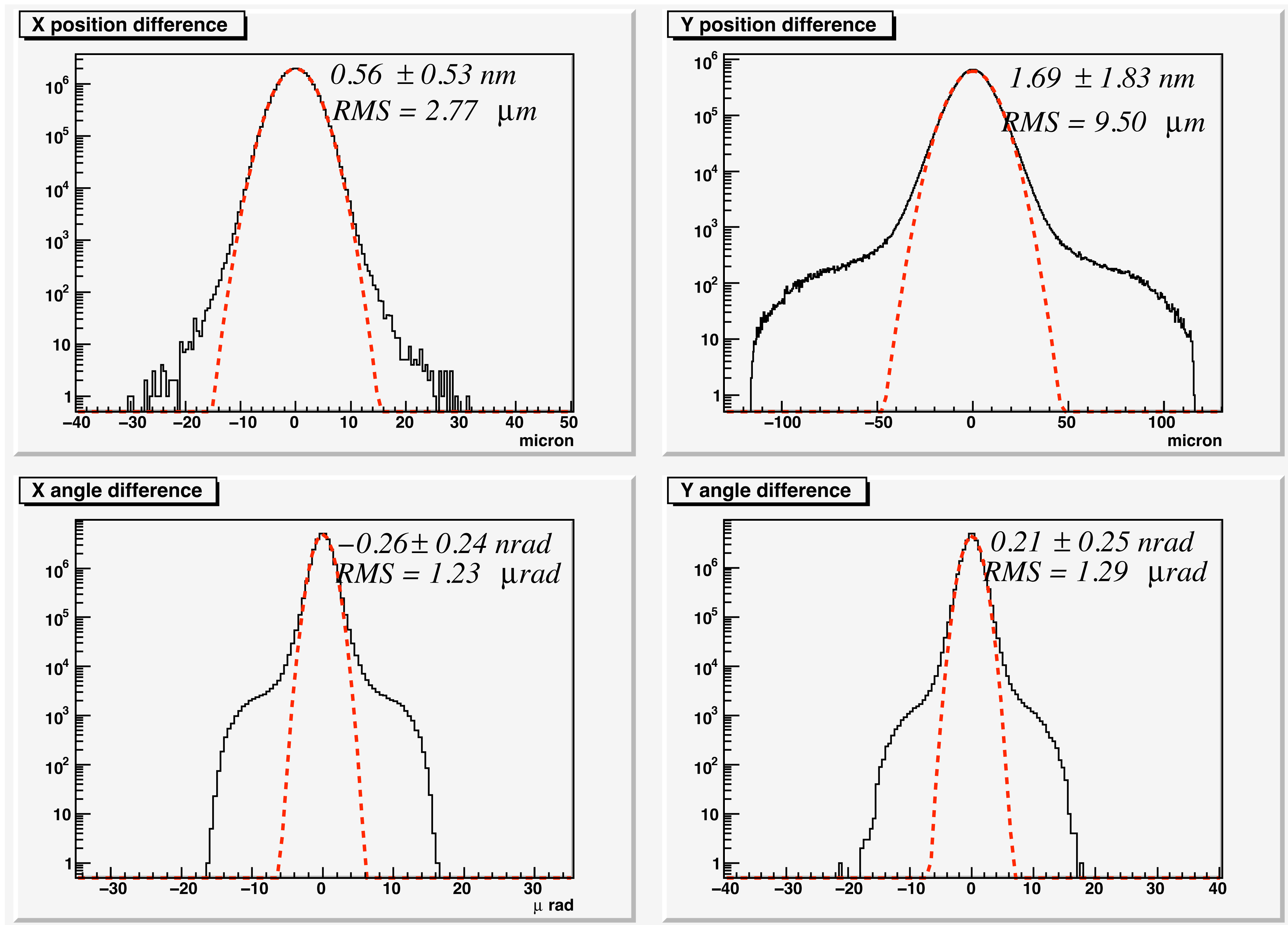
4'-n-heptyl-4-cyanobiphenyl
(HBN)
30 times



Chemically and photochemically stable. Temperature must be carefully controlled.

Position Differences in Hall

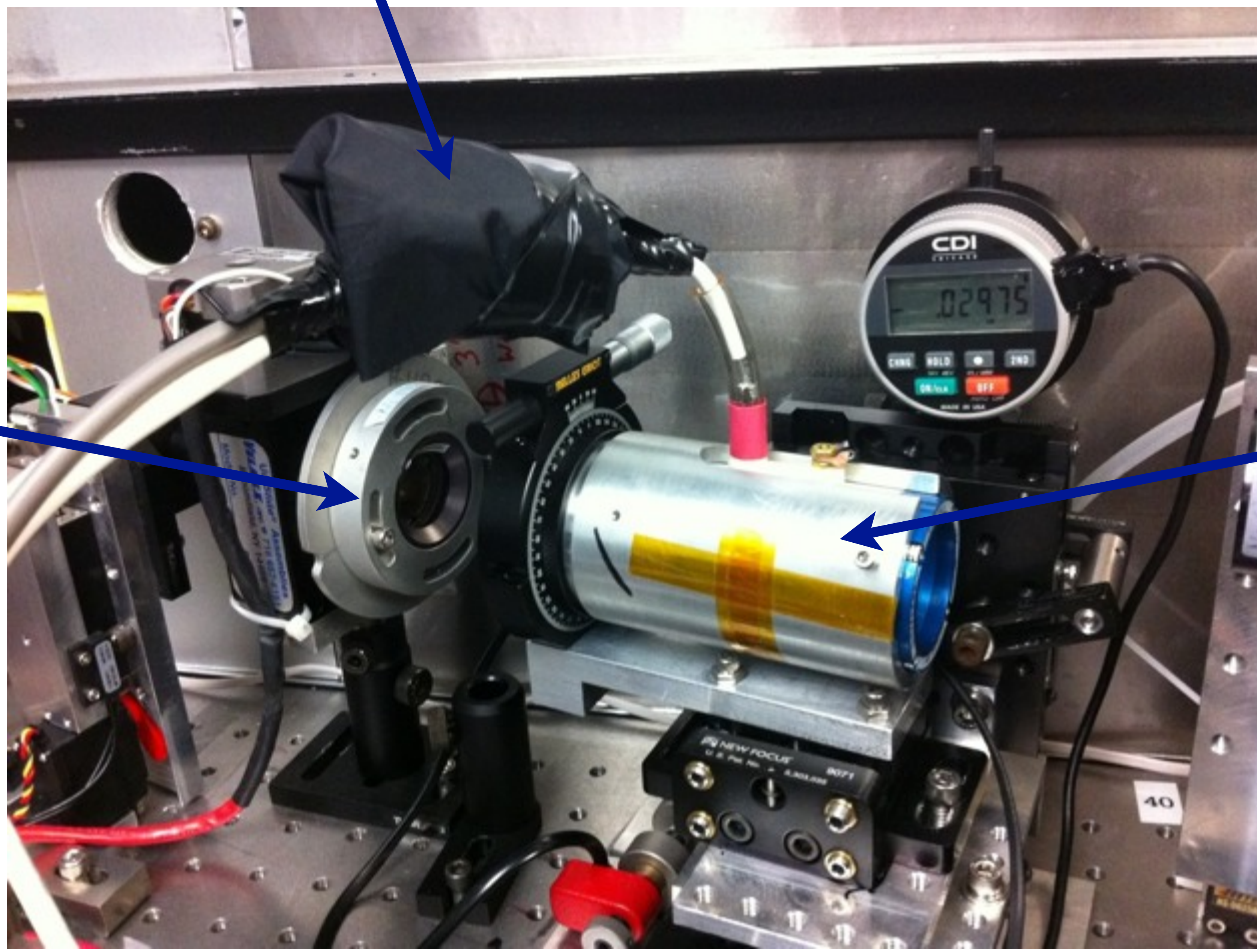
Over the ~20 million pairs measured in HAPPEX-II, the average position was not different between the two helicity states by more than 1 nanometer



Laser Table View

High voltage switch

Rotating Half-Wave plate



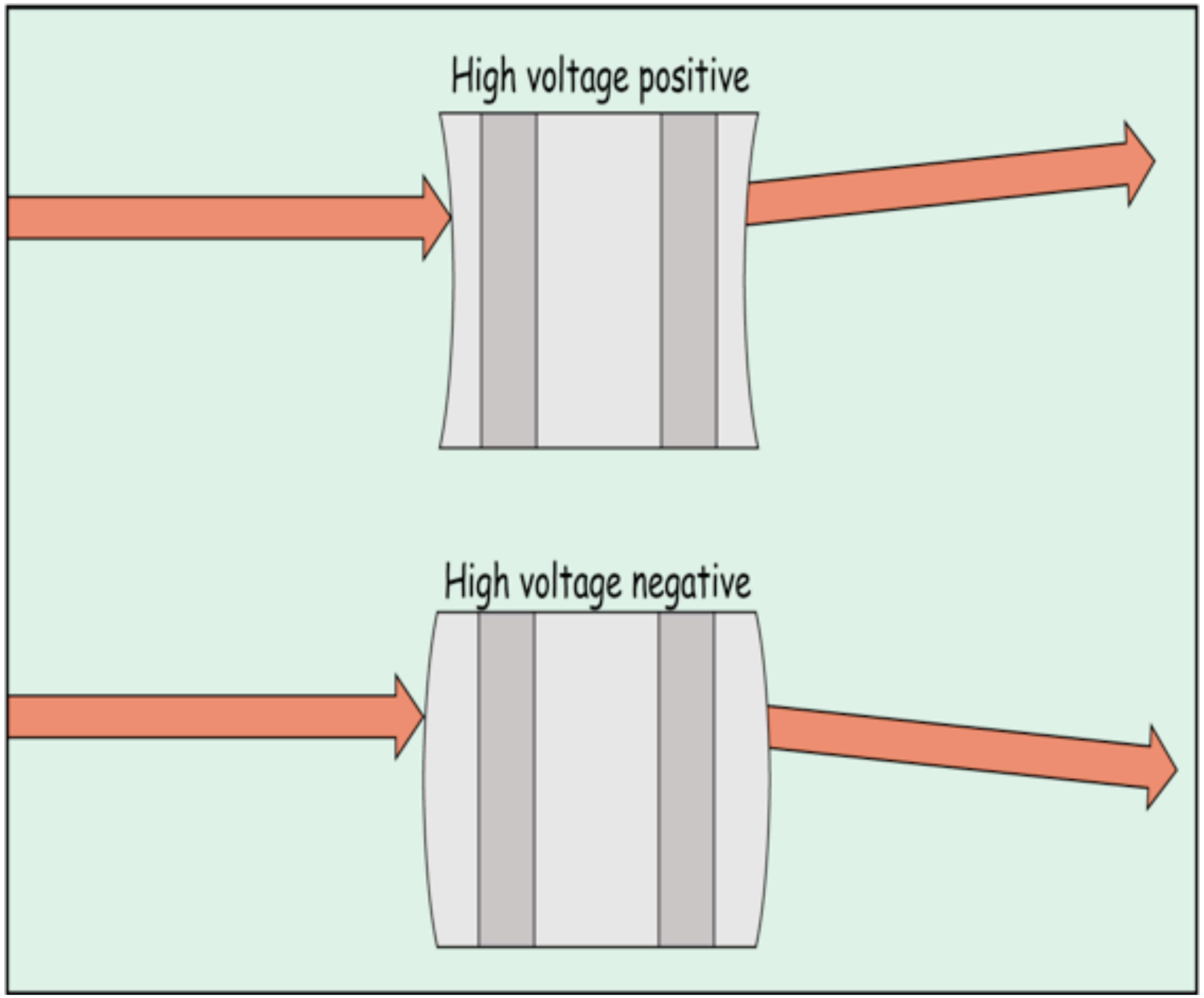
Pockels Cell

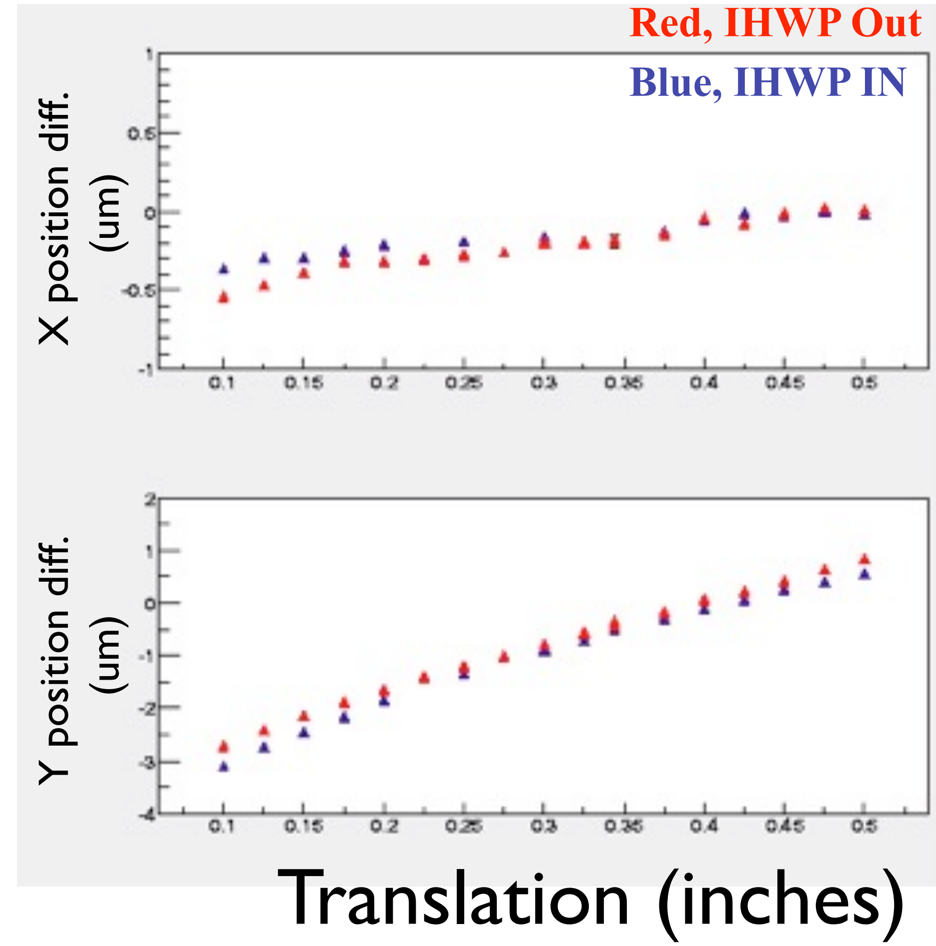
Sources of Helicity Differences

- Steering effects – Pockels cell
- Imperfect circularly polarized light
    - Intrinsic birefringence of the Pockels cell
    - Other birefringent beamline elements (vacuum window)
    - Phase gradient in beam before Pockels Cell
    - Laser divergence in the Pockels cell
    - Quantum Efficiency Anisotropy Gradient
- Beam element/helicity electronics pickup
- Quantum Efficiency Variation ("QE holes")
- Cross-talk between different beams: cathode effects or cross-talk in electron-beam transport

Steering

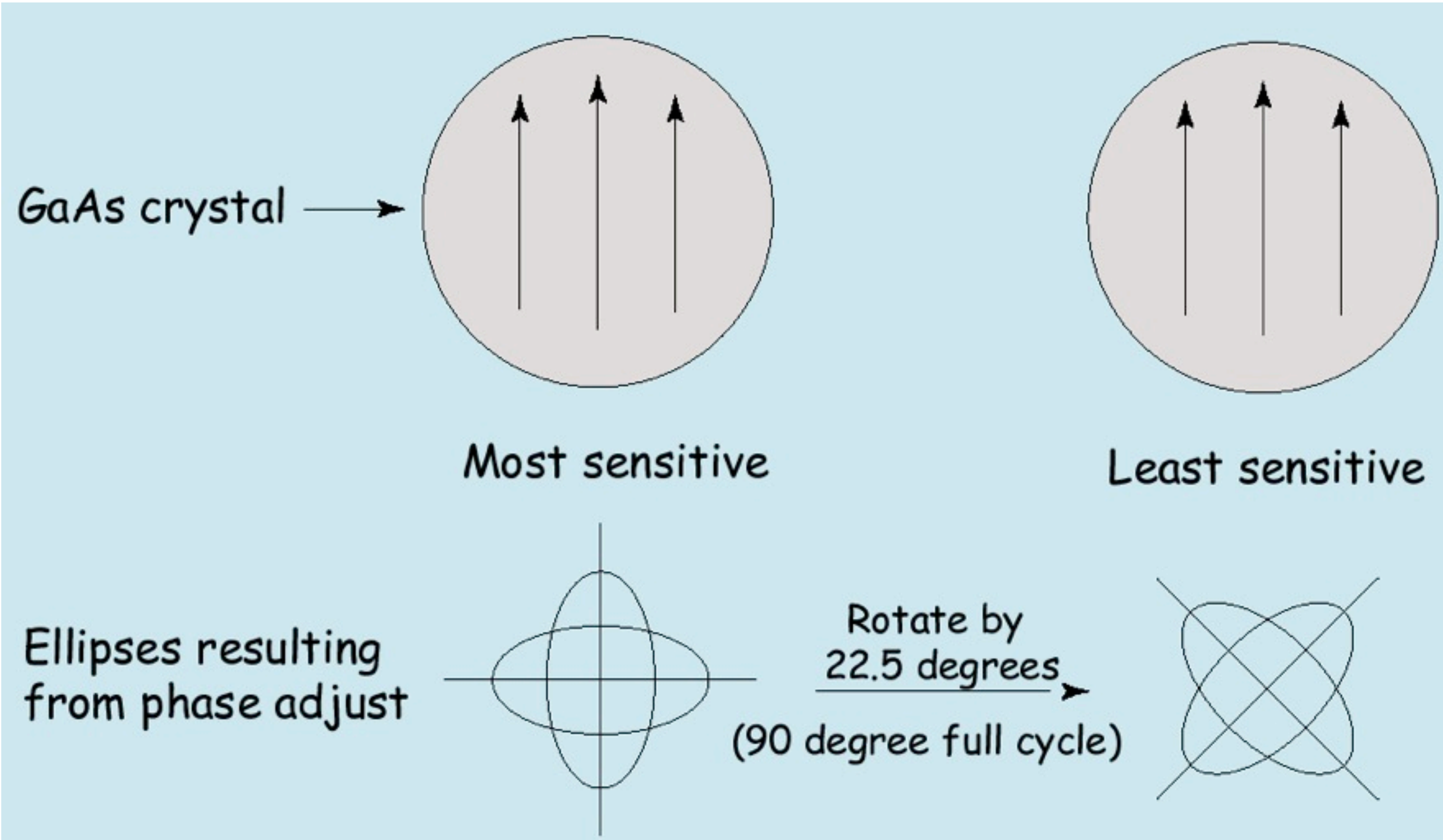
The piezoelectric Pockels Cell acts as "active" lens





Cathode Analyzing Power

Cathode Analyzing Power



Solutions

Differences must be minimised and corrected for:

Some cannot be measured

Experience suggests that the error on the correction cannot be determined much better than about 10% of itself.

Understand their origins and make them as SMALL as possible.

Measure them and make appropriate corrections. Be prepared to judiciously apply feedback.

-

Sometimes this is essential, particularly if you cannot measure them with small enough errors to correct for them quickly.

If detector is sufficiently symmetric, higher-order effects will be dominant!

Use lots of flips!

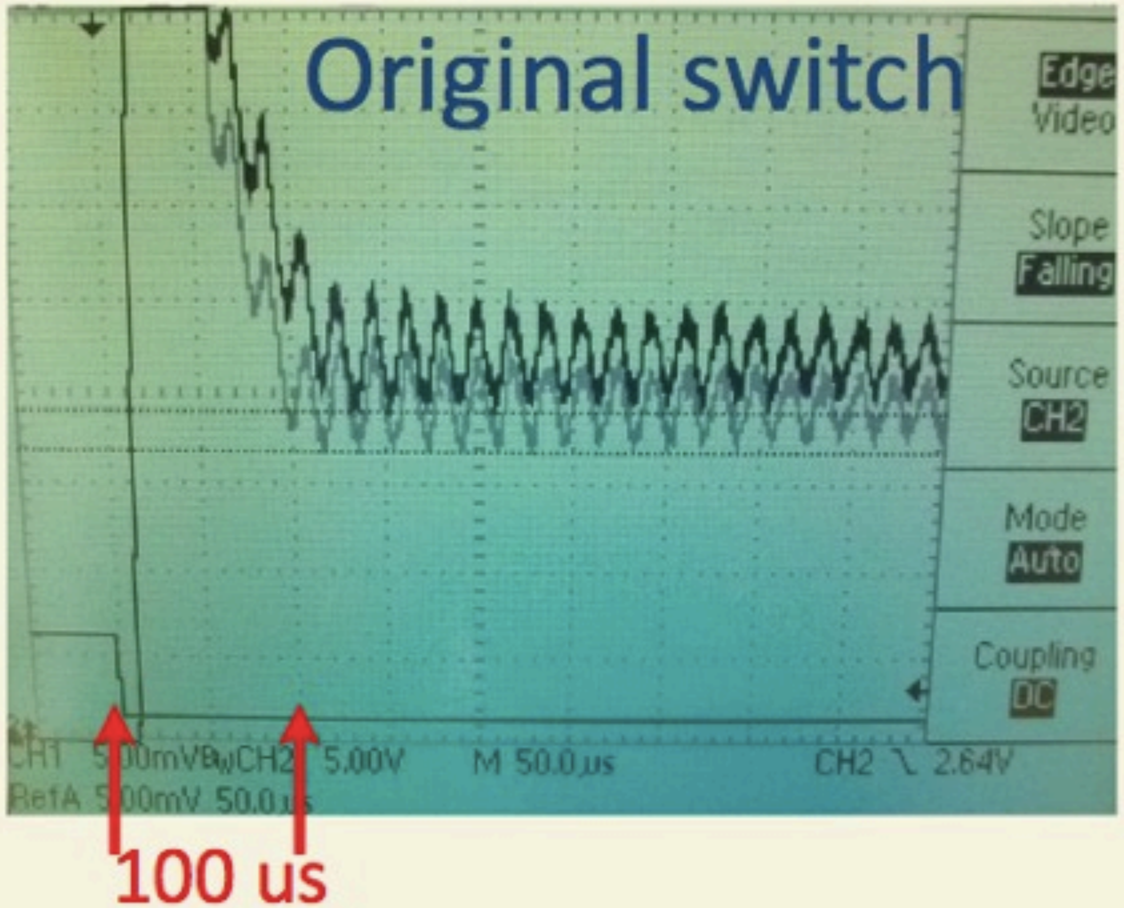
One needs to be careful to focus on the largest problems and develop systems for measuring, removing, and/or estimating corrections for higher order helicity-correlated beam parameters. (Not in this talk.)

PREx Source Summary

Source Setup
- didn't start by checking transitions -
best Pockels cell died, the current PC is not as good as Sam (or Arwen) -
rotating HWP has few percent phase offset. (physical limit or imperfect element?) -
new vacuum window has large birefringence -
cathode showed significant analyzing power gradient (Aq -> Δx)

What was GREAT:
- the ability to rotate the photocathode limits the effect of the vacuum window
- For the first +me, the ability to measure spot size asymmetry with the produc+on laser. Results: spot size asymmetry bound at few x 10-5 due to laser effects. (PREX required bound of 10-4, Qweak can afford nearly 10-3)
- Posi+on jiler in injector, now at ~3 microns at 30Hz. Injector studies can measure to high precision, quickly!
- Acer spot move, new cathode spot had 4x less gradient in analyzing power. This should allow an excellent zeroing of posi+on differences

PREx Experience

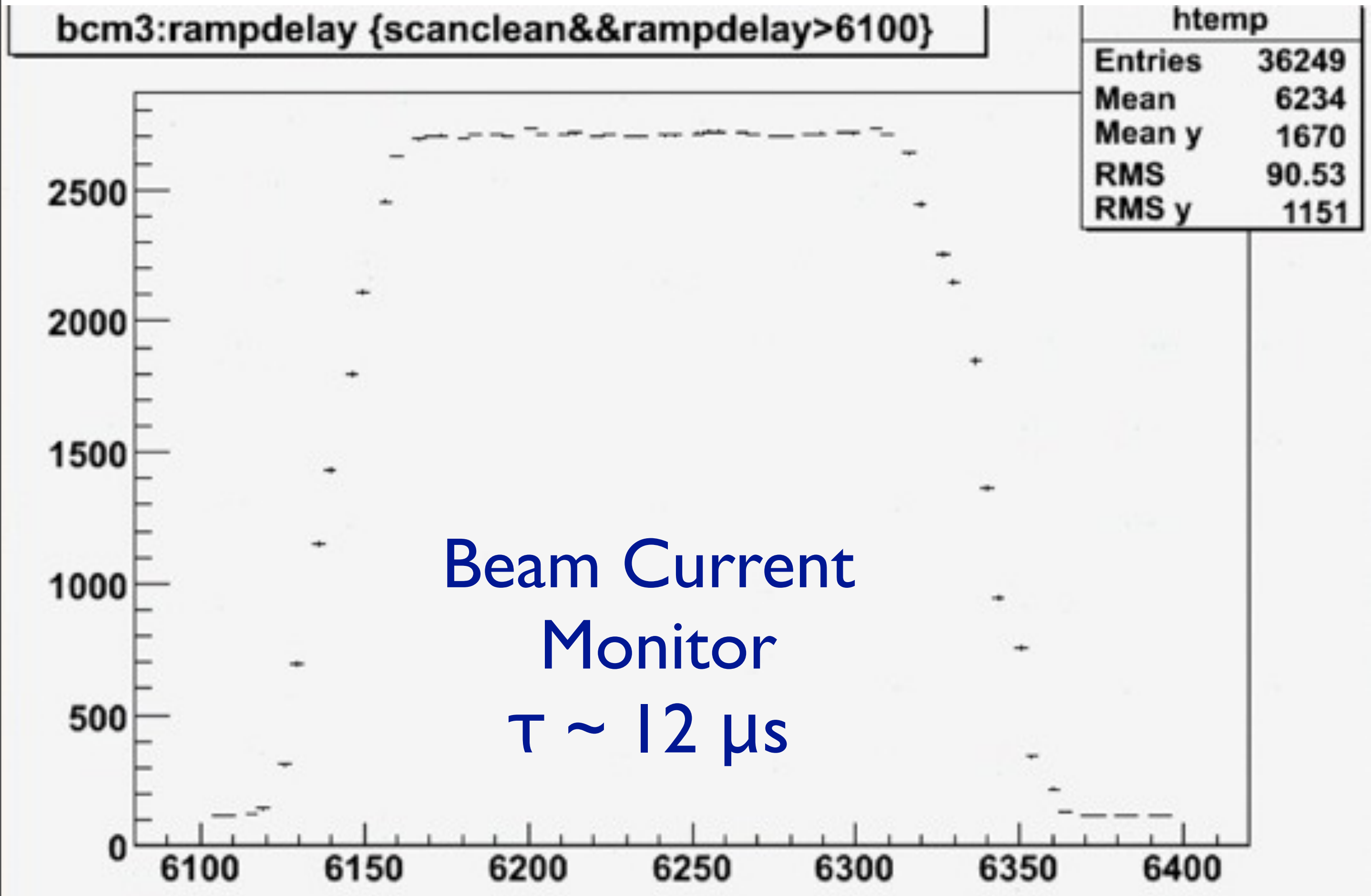


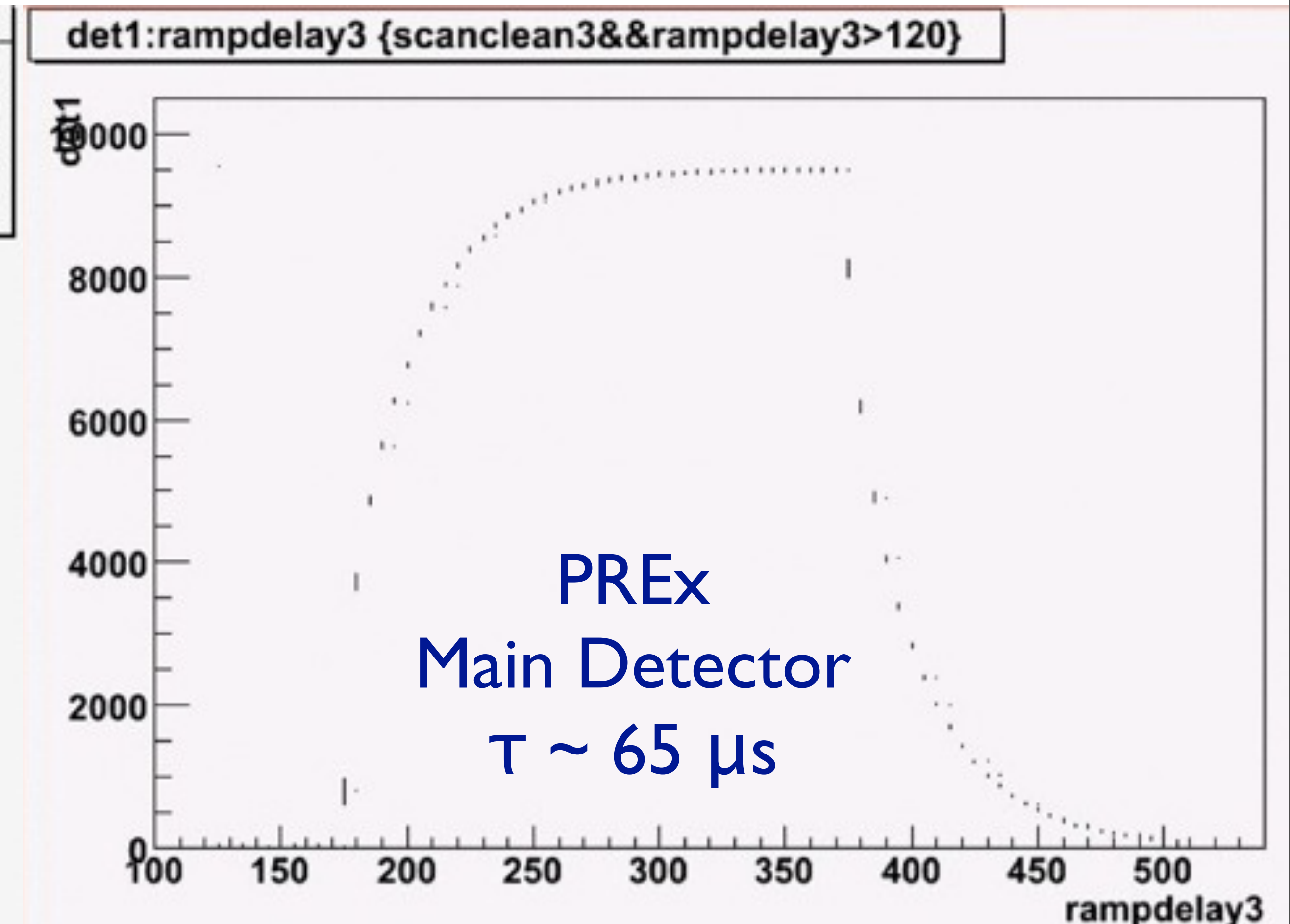
- Slower than expected transition (slightly over 100 µs)
- ringing (out to very long timescales, ~18 µs period)
- asymmetric transition

- Transition ~80 µs
- ringing down by ~3x
- transition more symmetric

DAQ "Ramp Delay" increased to 500 µs

Detector Time Constants (PREx)

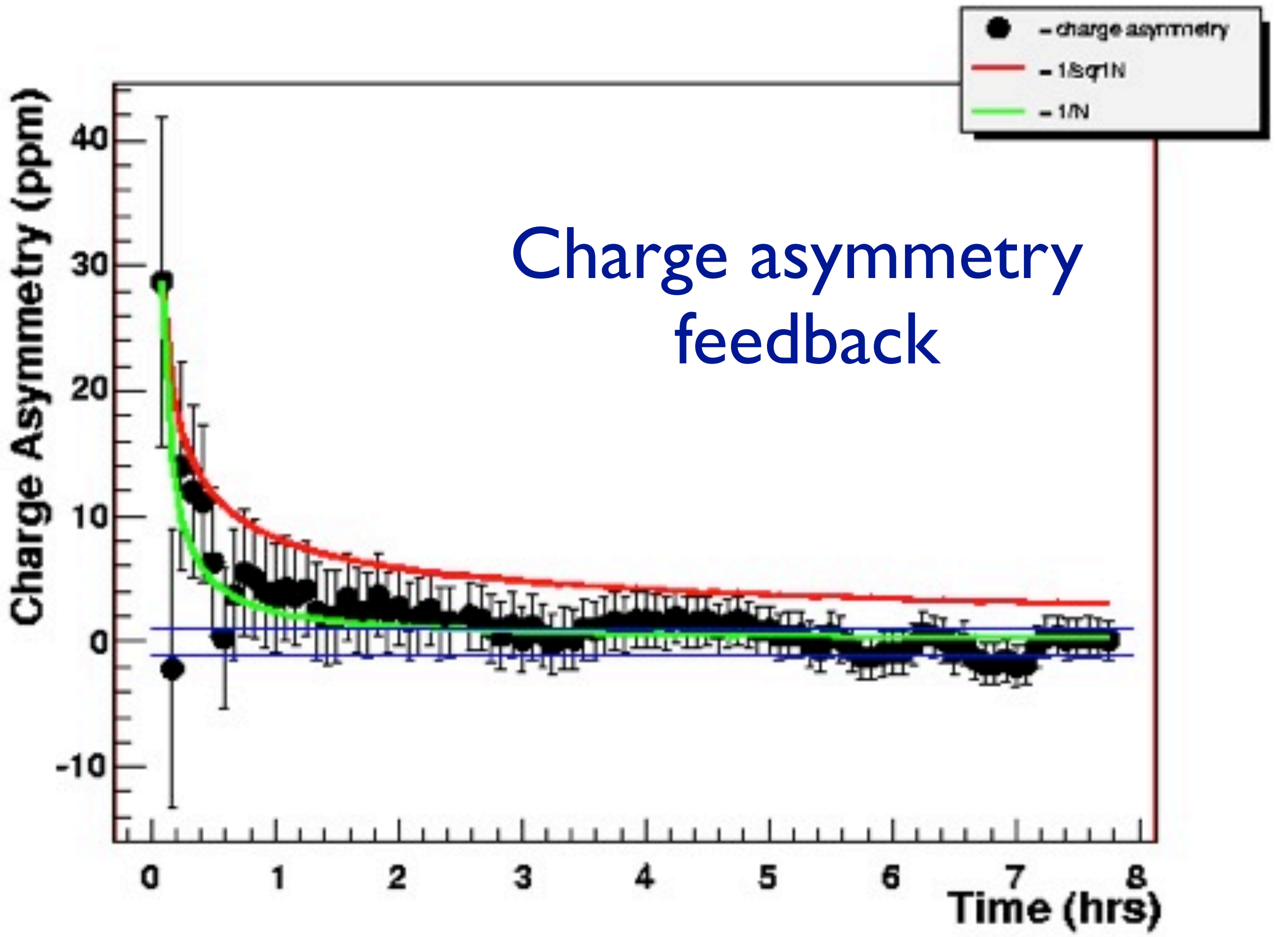


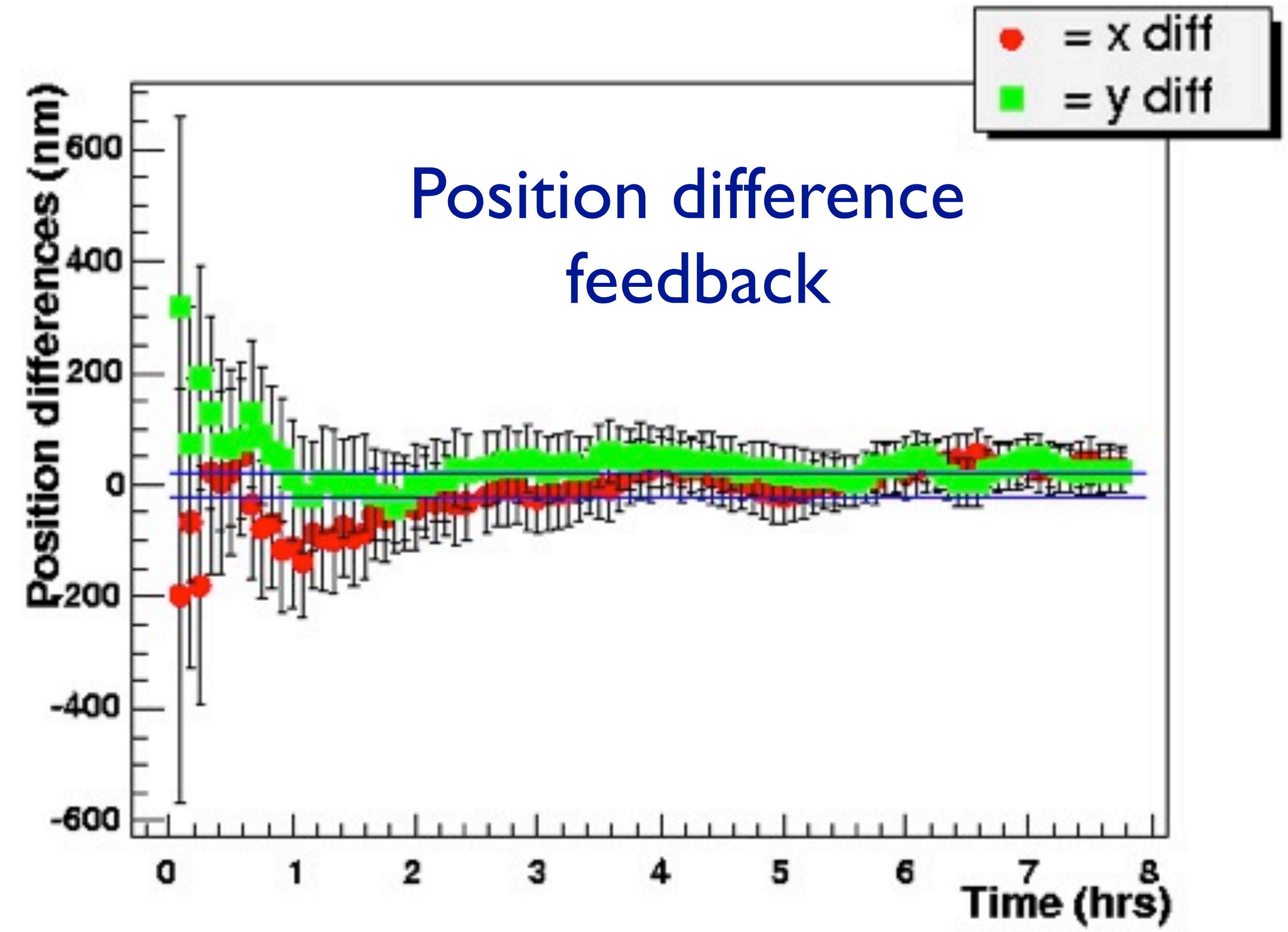


Electron beam test:
direct test of beam monitor (and detector) time constants -
100 microsecond pulse - short integrate gate with flexible delay

BCM ~ 12 μs
Detectors ~65 μs (cable capacitance)
- now about 15 μs (twinax cable)

Feedback





This works, but these are heavy hammers for a subtle problem.
Does nothing to fix higher-order problems, may even create them.
Preferred strategy: configure system with care to minimize effects.
If you do it right, all problems get small together*!
If you do your best there, you can use feedback to go the last mile (or nanometer).