Parity Quality Electron Beam for the MOLLER Experiment

and Recent Parity Violation Electron Scattering Experiments

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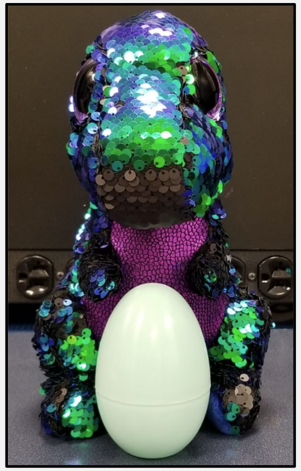
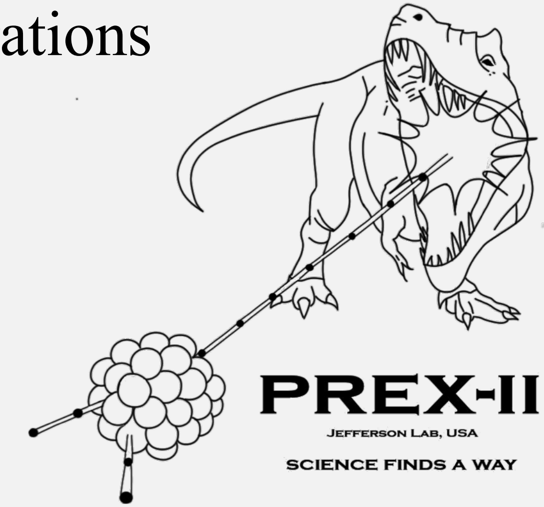
MOLLER, PREX, and CREX Collaborations

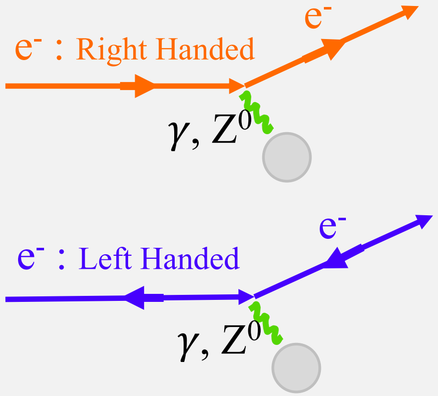


CREX

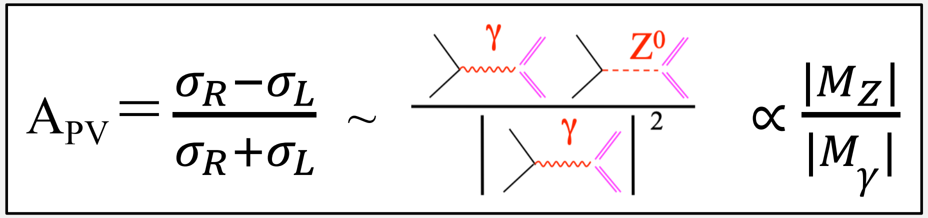


*Artwork by Marisa Petrusky

PARITY VIOLATION ELECTRON SCATTERING



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

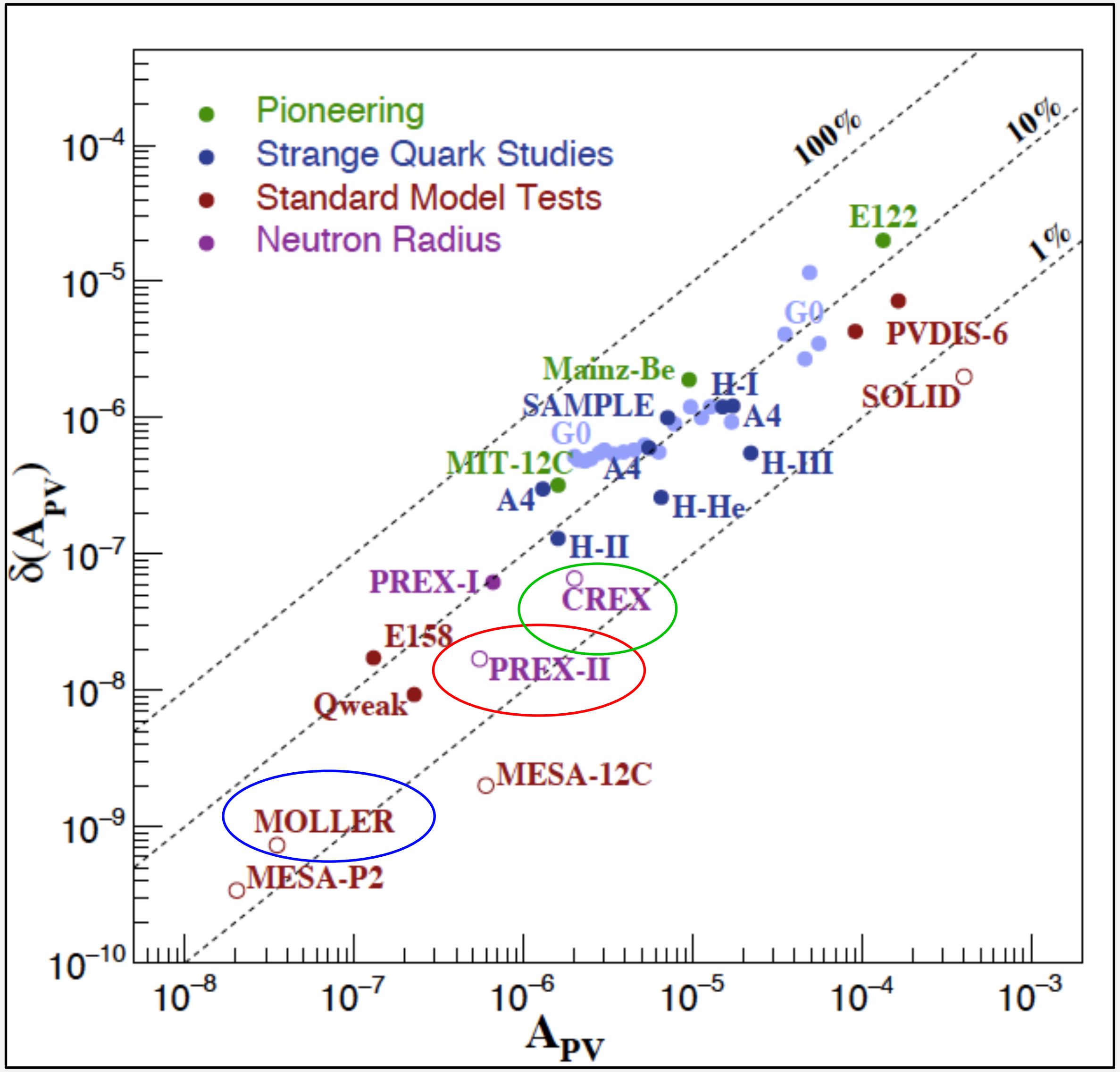


$$A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \sim$$

$$\propto \frac{|M_Z|}{|M_\gamma|}$$

- *Weak interaction is parity violating*
- *Harness parity violation as a signature of the weak interaction to do precision measurements*
- *Longitudinally polarized beam is incident on an unpolarized target*
- *Change sign of longitudinal polarization*
- *Measure fractional rate difference*
- *Interference term between the electro-magnetic and weak amplitudes gives rise to parity-violating asymmetry*

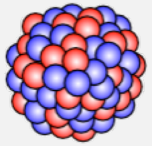
PVES Measurement is a Precision Tool



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

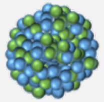
PREX

^{208}Pb

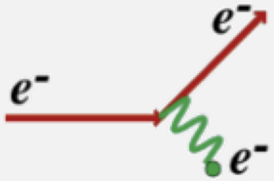


CREX

^{48}Ca



MOLLER



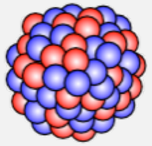
- PREX and CREX are recent PVES measurements probing the neutron skin thickness around Pb208 and Ca48 nuclei
- *MOLLER is a super-precise PVES measurement probing the weak charge of the electron*

PVES Experiments: Probing Weak Interaction

WEAK CHARGE DISTRIBUTION IN NUCLEI

PREX

^{208}Pb



Implied neutron skin thickness

$$R_n - R_p = 0.283 \pm 0.071\ \text{fm}$$

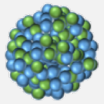
$$A_{PV} = 550 \pm 16(\text{stat}) \pm 8\ (\text{syst})$$

2.9% (stat)+- 1.5% (syst)

19 days

CREX

^{48}Ca



Implied neutron skin thickness

R_n-R_p= 0.126 ± 0.026 ± 0.024fm

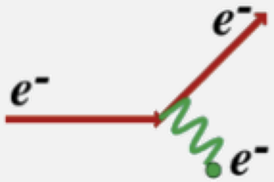
A_{PV}= 2668 ± 106 ppb

3.7% (stat) +-1.5% (syst)

~40 days

WEAK CHARGE OF THE ELECTRON

MOLLER



2.4% relative measurement of $Q^e_W = 0.0435$ at low Q^2

~0.1% measurement of $\sin^2\vartheta_W$

A_{PV} ~ 33ppb ± 0.8ppb (10-100X)

2.1% (stat) +- 1.1% (syst) (1X)

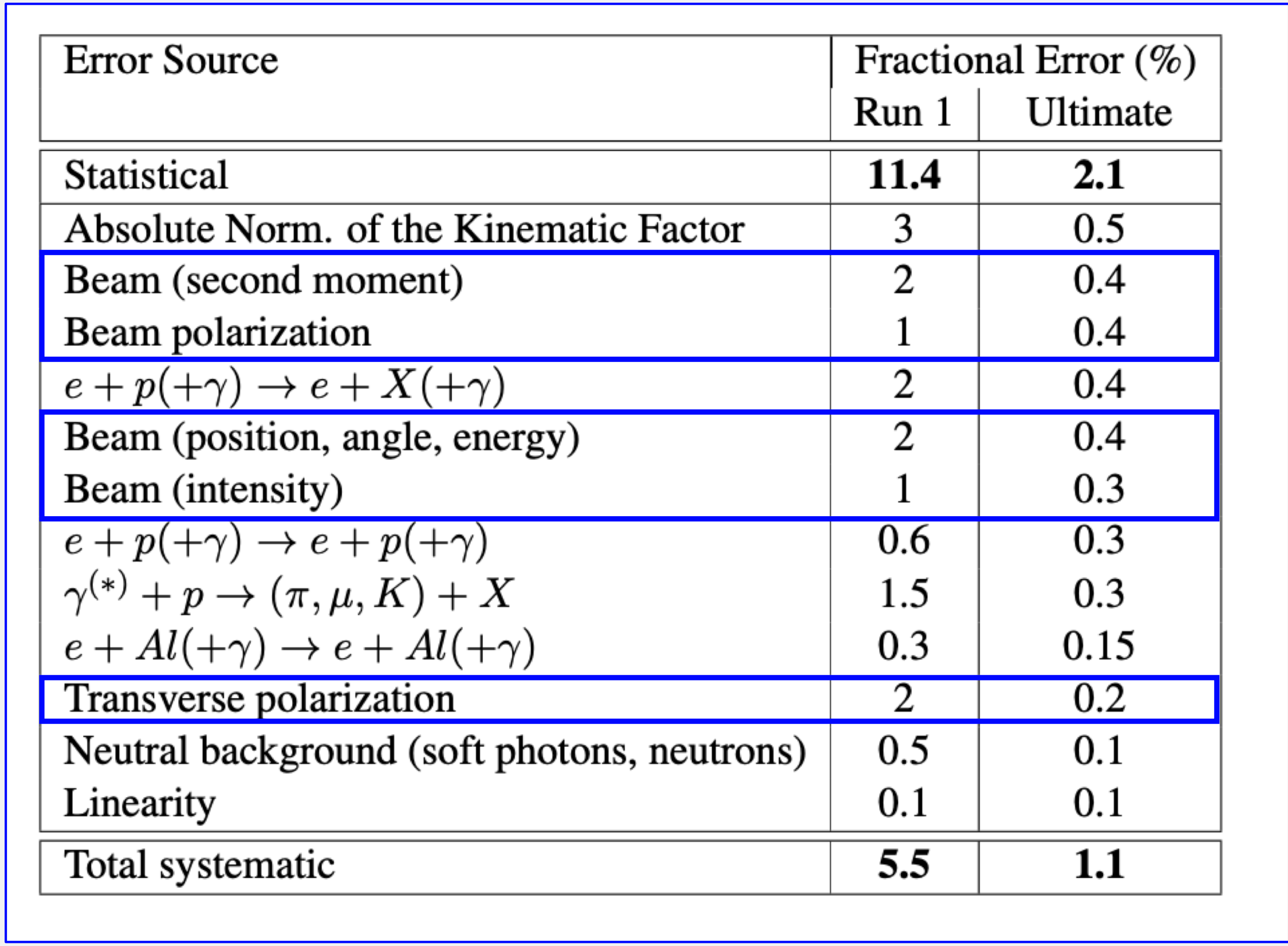
344 days

Beam Systematic Uncertainty Contributors

Systematic Uncertainty Contributors

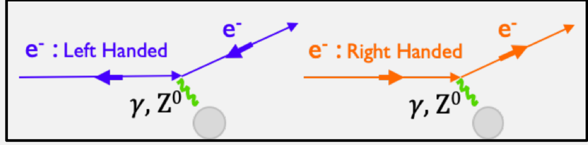
1. Beam Corrections: trajectory & energy & charge & 2nd moment
2. Beam Polarization
3. Transverse Beam Polarization

MOLLER



Error Source	Fractional Error (%)	
	Run 1	Ultimate
Statistical	**11.4**	**2.1**
Absolute Norm. of the Kinematic Factor	3	0.5
Beam (second moment)	2	0.4
Beam polarization	1	0.4
$e + p(+\gamma) \to e + X(+\gamma)$	2	0.4
Beam (position, angle, energy)	2	0.4
Beam (intensity)	1	0.3
$e + p(+\gamma) \to e + p(+\gamma)$	0.6	0.3
$\gamma^{(*)} + p \to (\pi, \mu, K) + X$	1.5	0.3
$e + Al(+\gamma) \to e + Al(+\gamma)$	0.3	0.15
Transverse polarization	2	0.2
Neutral background (soft photons, neutrons)	0.5	0.1
Linearity	0.1	0.1
Total systematic	**5.5**	**1.1**

1. Beam Corrections



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

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

- Beam Asymmetries must be very small to minimize systematic uncertainty
  - A_Q Charge Asymmetry – a difference in beam current between R & L helicity states
  - Δ_E Position Differences – a difference in the beam position between R & L helicity states
  - Δx_i Energy Differences - a difference in the beam energy between R & L helicity states
  - Spot size asymmetry - a difference in the beam size between R & L helicity states

- Sensitivities of detector signal to beam position and energy must be measured very precisely
  - α, β_i determination is critical to minimizing systematic uncertainty
  - Also crucial for reaching statistical goal on A_{PV} by eliminating beam noise in A_{raw} thereby reducing detector widths

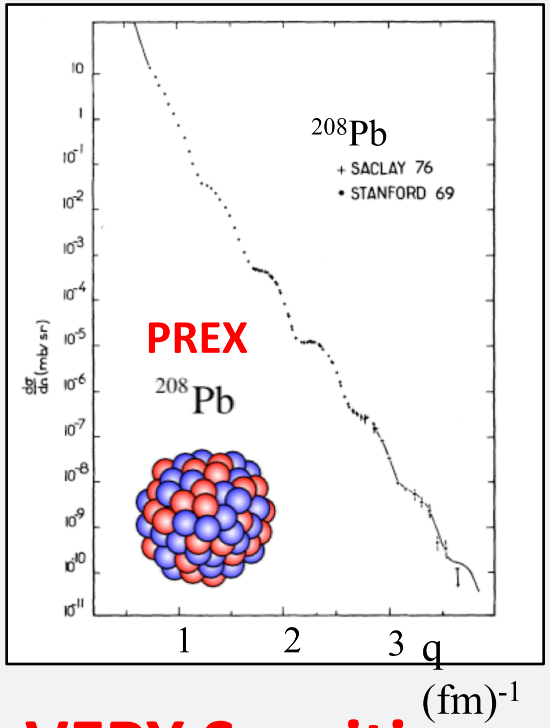
PREX Beam Corrections

Differential cross-section

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

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

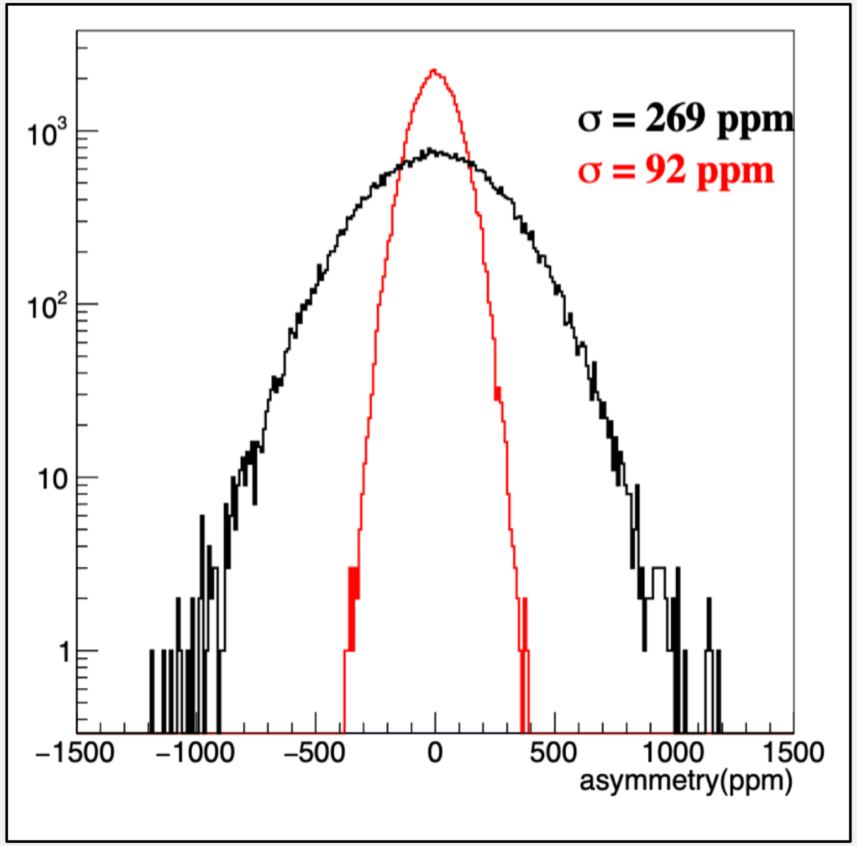
STEEP Form Factor



VERY Sensitive

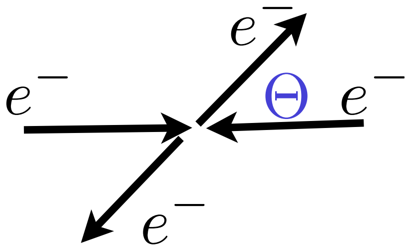
- Steep form-factor and very forward angle: very sensitive to beam corrections.
- Beam jitter noise several times greater than counting statistics

$$A = A_{raw} - A_Q - \sum_i \beta_i \Delta x_i - \beta_E A_E$$



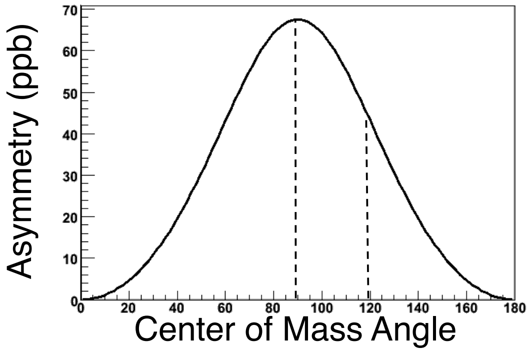
- Potential for systematic error if average beam asymmetries are not well corrected
- Multiple techniques used to calibrate correction factors (β_i)

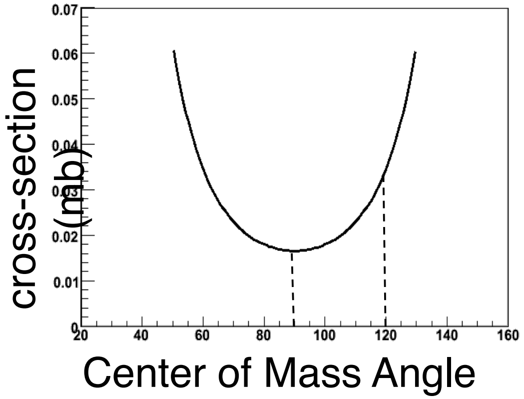
Moller Kinematics



identical particles!

Highest figure of merit at $\theta_{CM} = 90^o$

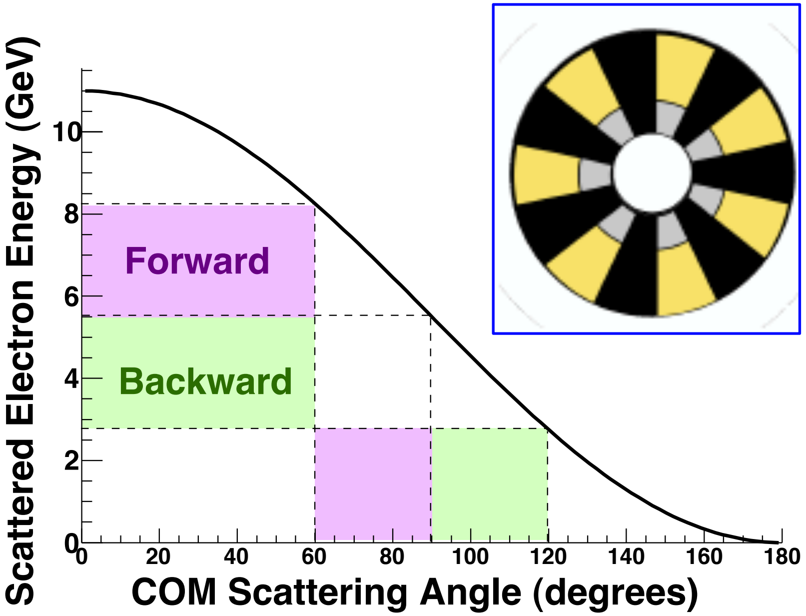




Toroid solution for 100% azimuthal coverage!

- collect both forward and back scatters

Far more forgiving in terms of sensitivity

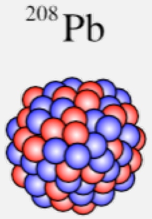


PVES Experiments: Probing Weak Interaction

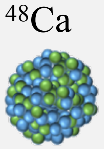
WEAK CHARGE DISTRIBUTION IN NUCLEI

WEAK CHARGE OF THE ELECTRON

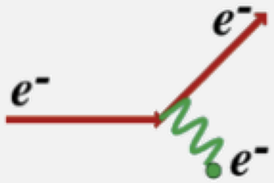
PREX



CREX



MOLLER



$A_{PV} = 550 \pm 16(\text{stat}) \pm 8\ (\text{syst})$

A_{PV}= 2668 ± 106 ppb

A_{PV} ~ 33ppb ± 0.8ppb (20-100X)

2.9% (stat)+- 1.5% (syst)

3.7% (stat) +-1.5% (syst)

2.1% (stat) +- 1.1% (syst) (1X)

Systematic Uncertainties : Beam Correction - trajectory & energy (correction ppb, uncertainty %)

−60.4+-3.0 ppb, 0.54%
Dx = 2.2+-4nm

68±7ppb, 0.26%
Dx =-5.2+-3.6nm

<3+-0.15ppb (10X), < 0.4 % (1X)
Dx < 0.6nm+-0.03nm (10X)

The total asymmetry and sensitivity of form factor to beam changes is what determines how precisely we must control the beam trajectory

Recipe to suppress Beam Asymmetries and for PVES Experiments

Beam Setup Pre-Experiment:

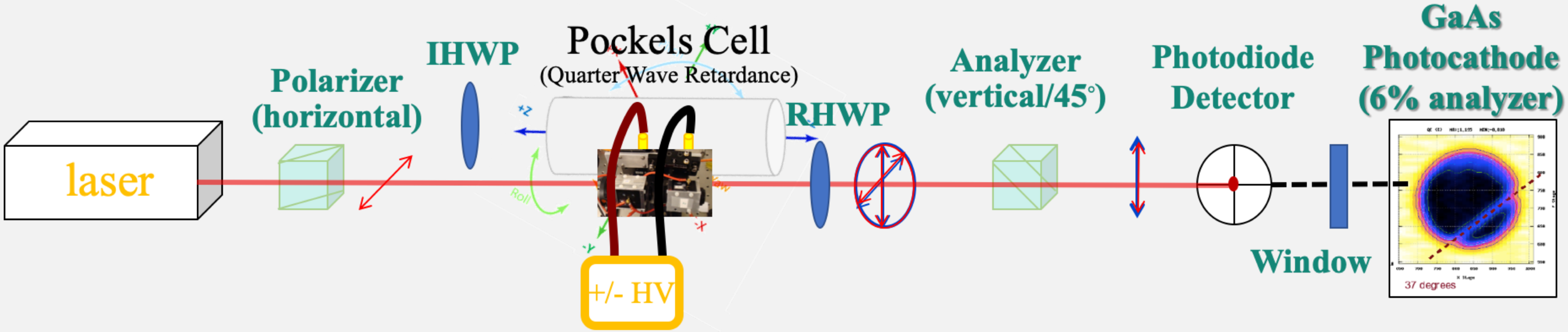
- *Laser Table Alignment : minimize HCBA*
- *Injector setup: minimize HCBA*
- *Slow Reversals Symmetry*

Beam Corrections During Experiment:

- *Aq Feedback*
- *RTP Position Difference Corrections*
- *Beam Modulation*
- *Fast feedback*

Beam Setup Pre-Experiment: *Laser Beam Source Alignment*

Minimize Laser Beam Asymmetries



laser

Polarizer (horizontal)

IHWP

Pockels Cell
(Quarter Wave Retardance)

RHWP

Analyzer (vertical/45°)

Photodiode Detector

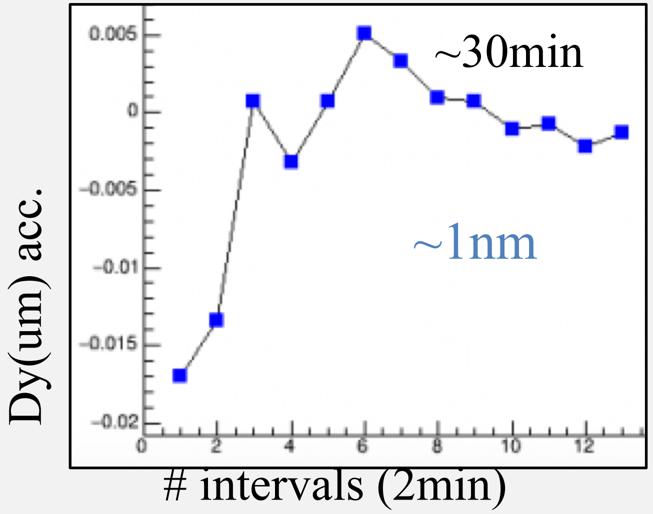
GaAs Photocathode (6% analyzer)

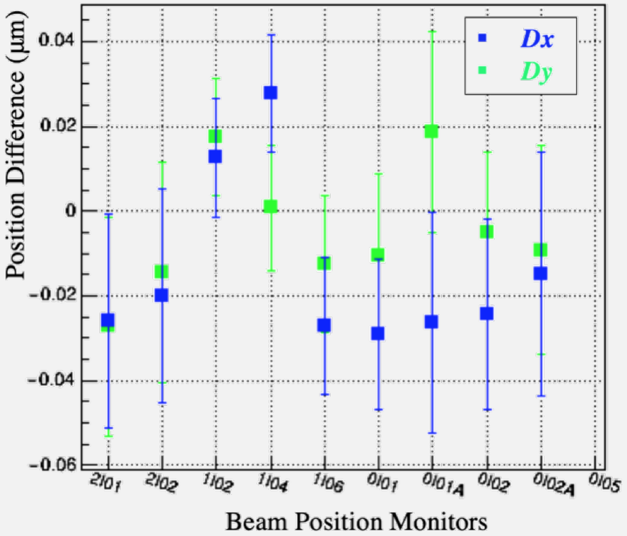
Window

+/- HV

Beam Setup Pre-Experiment: *Injector - Low Energy Electron Source*

Minimize position differences in injector





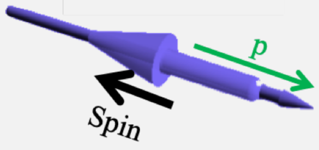
<30nm

Beam Setup Pre-Experiment: *Reversal Symmetry of Electron Spin Manipulation*

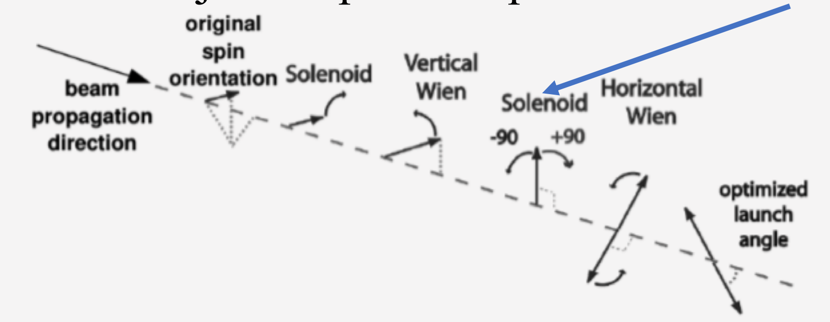
Slow Electron Spin Reversal:

e- : Right handed

e- : Left handed



Injector spin manipulation:

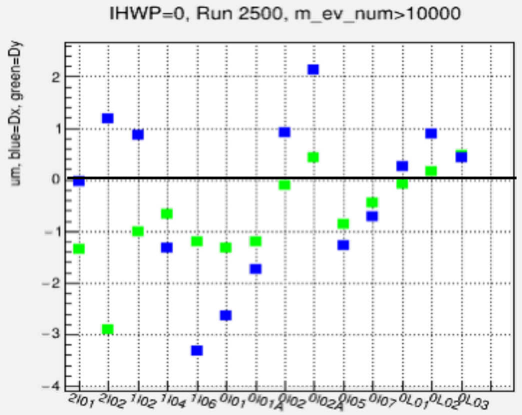


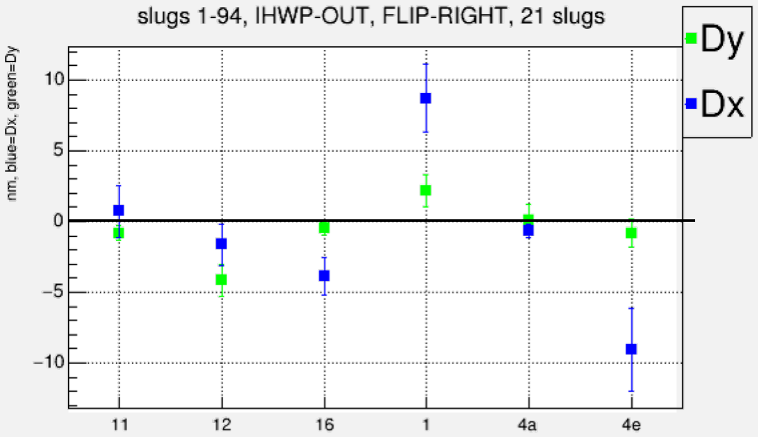
- ExB for 1π precession
- Symmetry – good for position difference cancellation, also good for spot size asymmetry cancellation

Pre Experiment: low energy injector

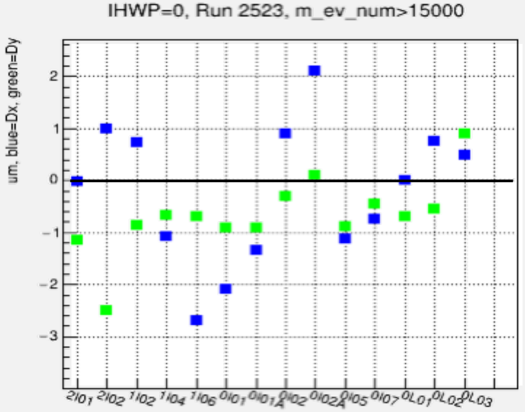
After experiment: experimental hall

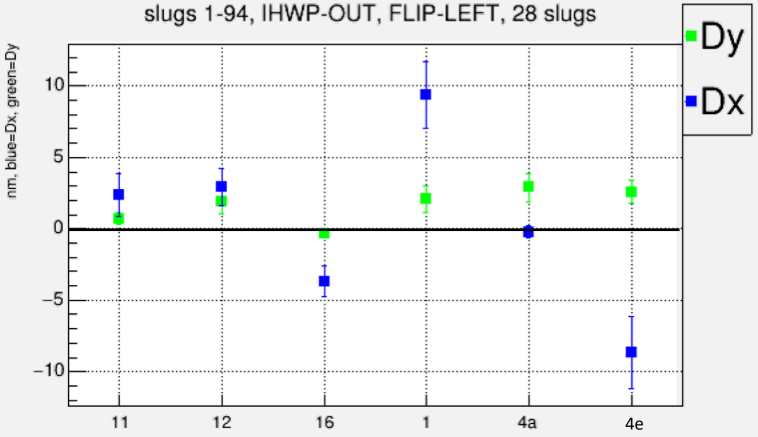
Flip Right:





Flip Left:





BPM name

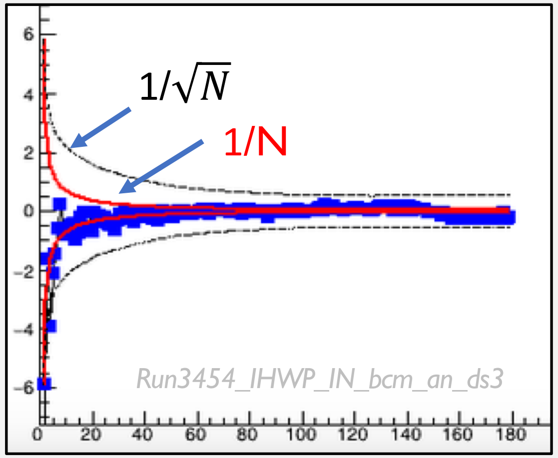
BPM name

Run2523_VWeinMinus89p9deg_FlipLeft_IHWPout_AposUm3000_AposVm3000.png
Run2500_VWein88deg_FlipRight_IHWPout_AposUm3000_AposVm3000.png

https://logbooks.jlab.org/entry/3685216

Beam corrections during experiment : *Feedback on Aq*

Feedback: Interval (sub-10sec, 120Hz)



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

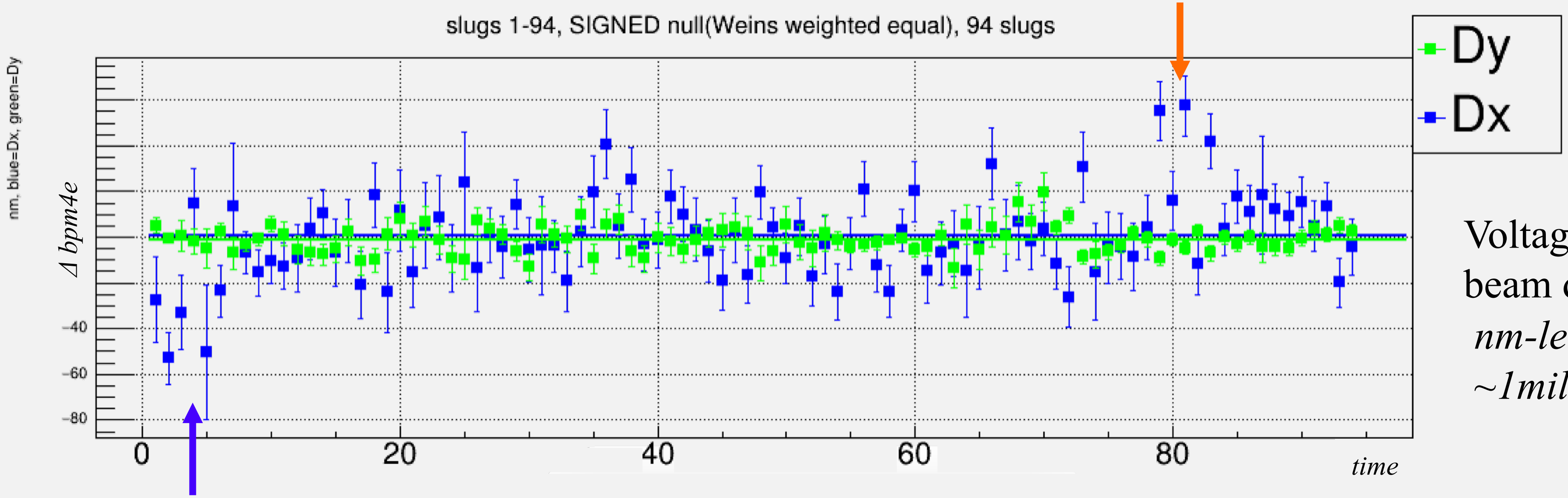
- NEED Aq to converge faster than $1/\sqrt{N}$ statistics
- Must do active feedback on integrated Aq using Pockels Cell voltages to correct Aq

Beam corrections during experiment : *RTP Position Difference Corrections*

Monitor position differences and try to drive average position difference down

Sign Corrected Data

$D_x = \Delta x/2 = (x_0-x_1)/2$



Voltage controlled beam direction

nm-level control

~1mile downstream

Demonstration of ability to control position differences to the precision they can be measured

Beam corrections during experiment : *Fast Feedback and Beam Modulation*

Precisely measuring sensitivities is just as important as minimizing HCBAs

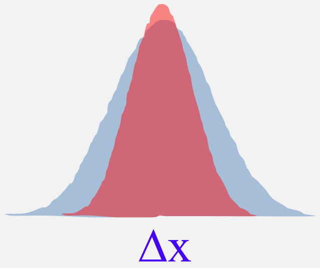
$$A_{raw} = A_{det} - A_Q + \alpha\Delta_E + \Sigma\beta_i\Delta x_i$$

- Sensitivities of detector signal to beam position and energy must be measured very precisely
  - α, β_i determination is critical to minimizing systematic uncertainty and eliminating beam noise in A_{raw}

Δ_E & Δx_i

Fast Feedback

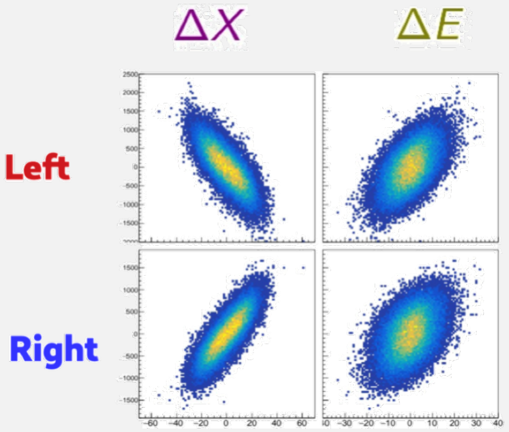
- Too much noise is bad
- Compromises ability to measure/bound position differences
- If can't measure small HCBA, can't reach systematic goals



α & β_i

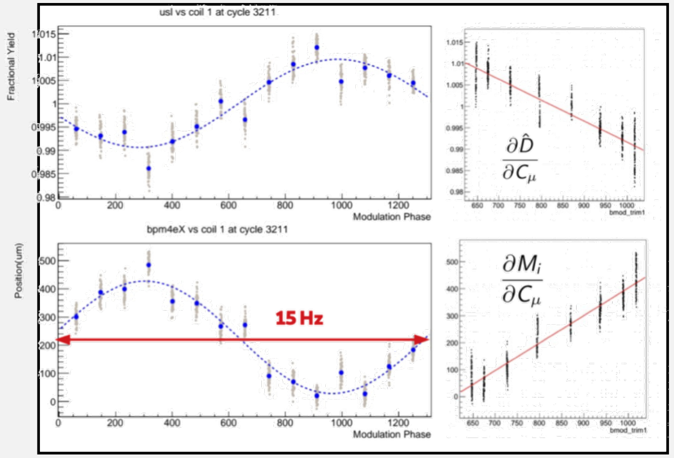
Regression

- Some beam noise is good to measure correlations with detectors and monitors
- regression is precise but can be wrong - resolution affects slopes



Beam Modulation

- Intentionally modulate beam position in X,Y, angle, energy, dedicate data time to this, large modulations to measure sensitivities well throughout experiment
- modulation is good but not as precise



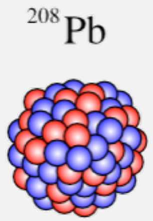
We use regression constrained by modulation to get the best of both worlds

2. Beam Polarization

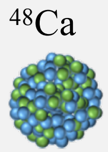
The beam-corrected asymmetry A_{corr} must be further corrected for the beam polarization (P_b), and the background dilutions (f_i) and asymmetries (A_i) to obtain A_{meas} : $A_{corr} = A_{det} - A_Q + \alpha\Delta_E + \Sigma\beta_i\Delta x_i$

$$A_{PV}^{meas} = \frac{1}{\boxed{P_b}} \frac{A_{corr} - P_b \sum_i A_i f_i}{1 - \sum_i f_i}$$

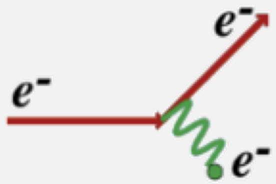
PREX



CREX



MOLLER



Systematic Uncertainties : Beam Polarization

P_e=(89.7 ± 0.8)%

P_e=87.09 +/- (0.44% dP/P)

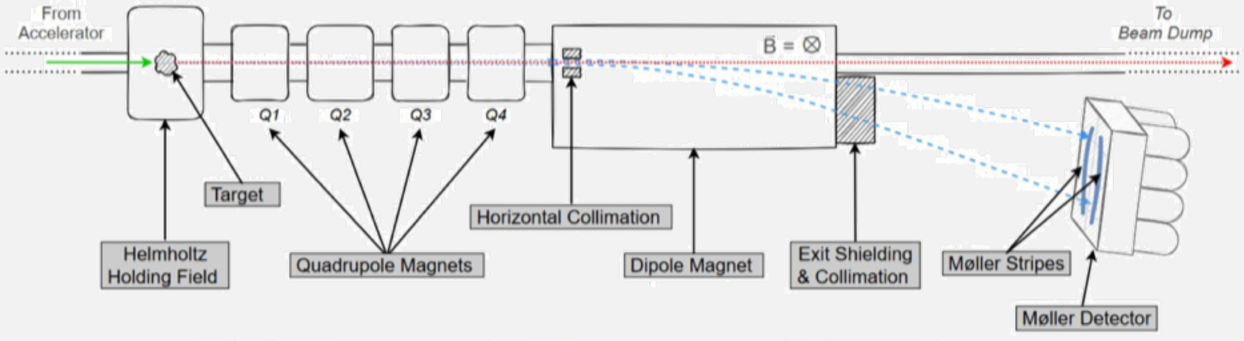
P_e~90%, 0.4% uncertainty

Polarimetry

Goal: 0.4% with two, independent measurements which can be cross-checked

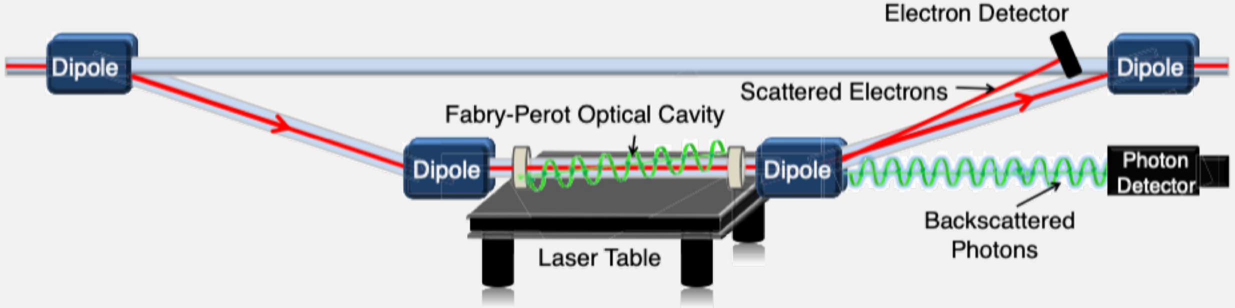
Møller Polarimeter

- “high field” iron target - well-known magnetization at saturation
- Coincidence of identical particles - low background
- QQQQD spectrometer



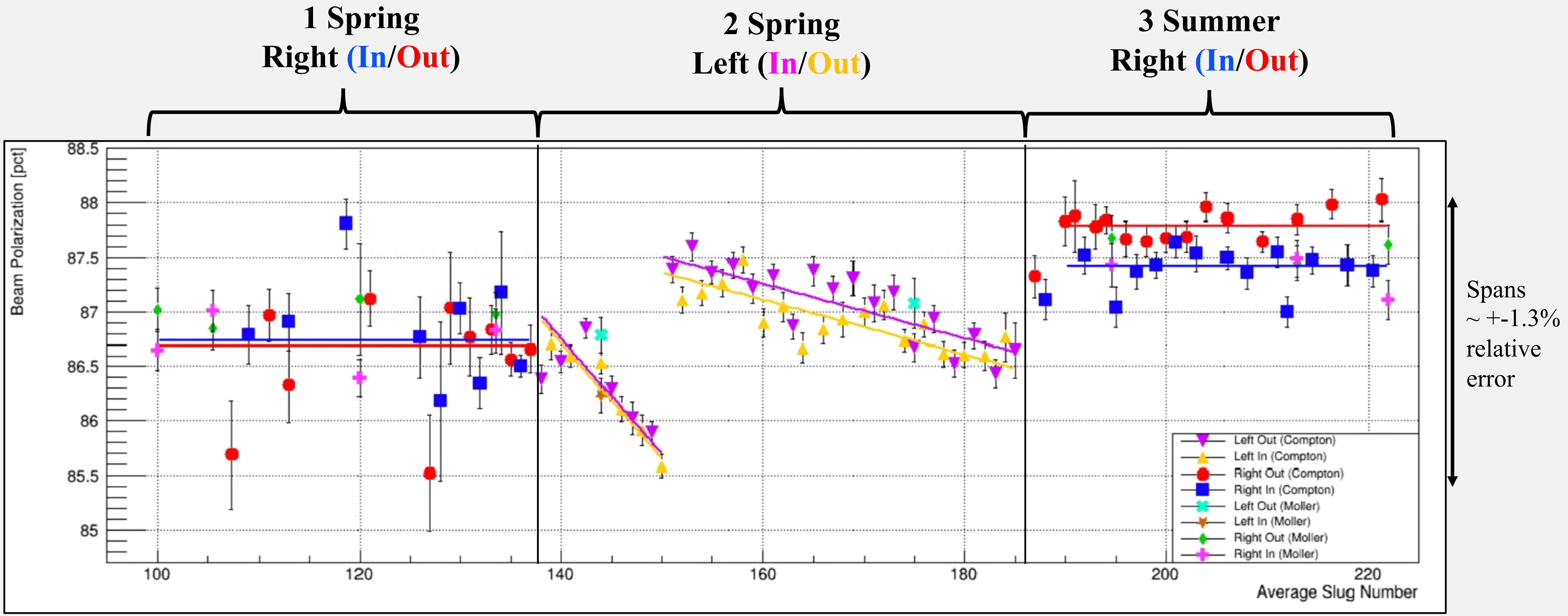
Compton

- Detection of backscattered photons and recoil electrons from laser light
- Independent photon and electron analyses are possible
- New publication: dP/P = 0.36% https://doi.org/10.1103/PhysRevC.109.024323



Both systems have important upgrades underway (detectors, laser system, DAQ, analysis, and simulation studies). Ironically, the Møller polarimeter is closer to ready for high precision at 11 GeV.

CREX: Compton + Moller polarimeter results, over the run



1 Spring
Right (In/Out)

2 Spring
Left (In/Out)

3 Summer
Right (In/Out)

Spans ~ +-1.3% relative error

Acknowledgments: A.J. Zec, J. C. Cornejo, M. Dalton, C. Gal, D. Gaskell, C. Palatchi, K. Paschke, A. Premithilake, B. Quinn

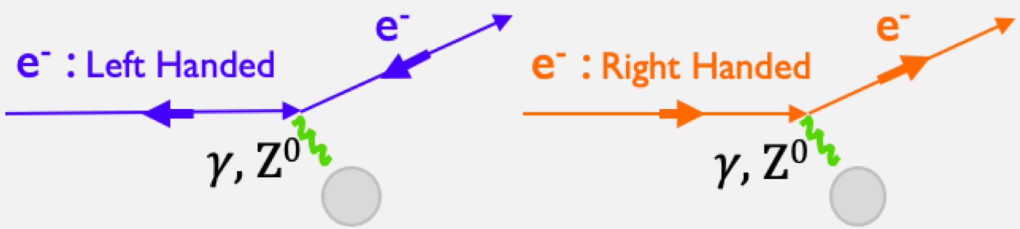
Average Compton polarization:
87.10 ± (0.52% dP/P)

CREX Polarimetry Result:
P_e=87.09 +/- (0.44% dP/P)

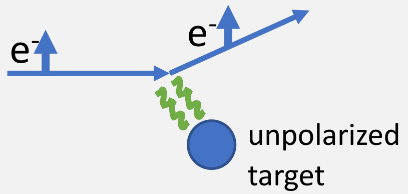
Average Moller polarization:
87.06 ± (0.85% dP/P)

3. Transverse Beam Polarization

Longitudinal Polarization



Transverse Polarization



A_{phys} extraction requires effort on multiple fronts:

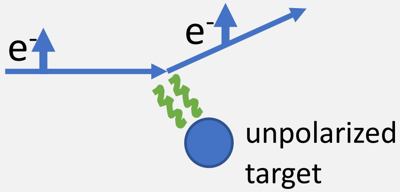
$R_{radcorr}$	(radiative correction)
R_{accept}	(acceptance)
R_{Q2}	(Q^2-scaling)
P_L	(beam polarization)
$\frac{1}{1-\sum_i f_i}$	(Overall background dilution)
$P_L \sum_i f_i A_i$	(backgrounds)
A_{corr}	(Corrected Asymmetry)
A_{beam}	(Beam corrections)
A_{trans}	**(Transverse asymmetry correction)**
A_{nonlin}	(Detector nonlinearity)
A_{blind}	(Blinding factor)

$$A_{phys} = R_{radcorr}\, R_{accept}\, R_{Q^2} \frac{A_{corr} - P_L \sum_i f_i A_i}{P_L(1 - \sum_i f_i)}$$

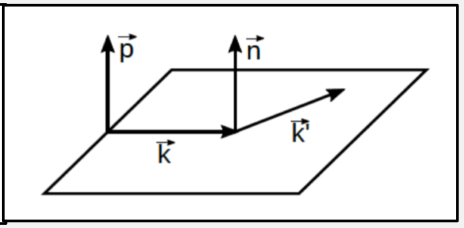
$$A_{corr} = A_{det} - A_{beam} - \boldsymbol{A_{trans}} - A_{nonlin} - A_{blind}$$

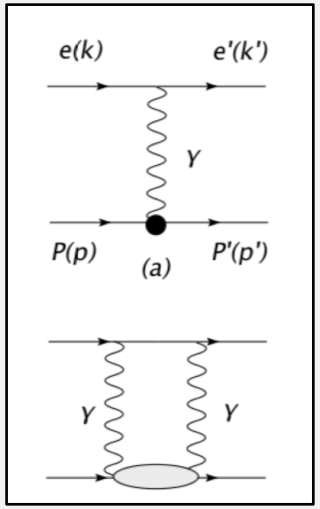
A_T Measurements Purpose

A_T is a direct probe of higher-order photon exchange

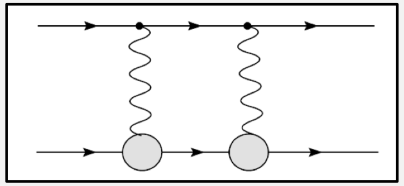


$$A_n = \frac{\sigma_\uparrow - \sigma_\downarrow}{\sigma_\uparrow + \sigma_\downarrow}$$

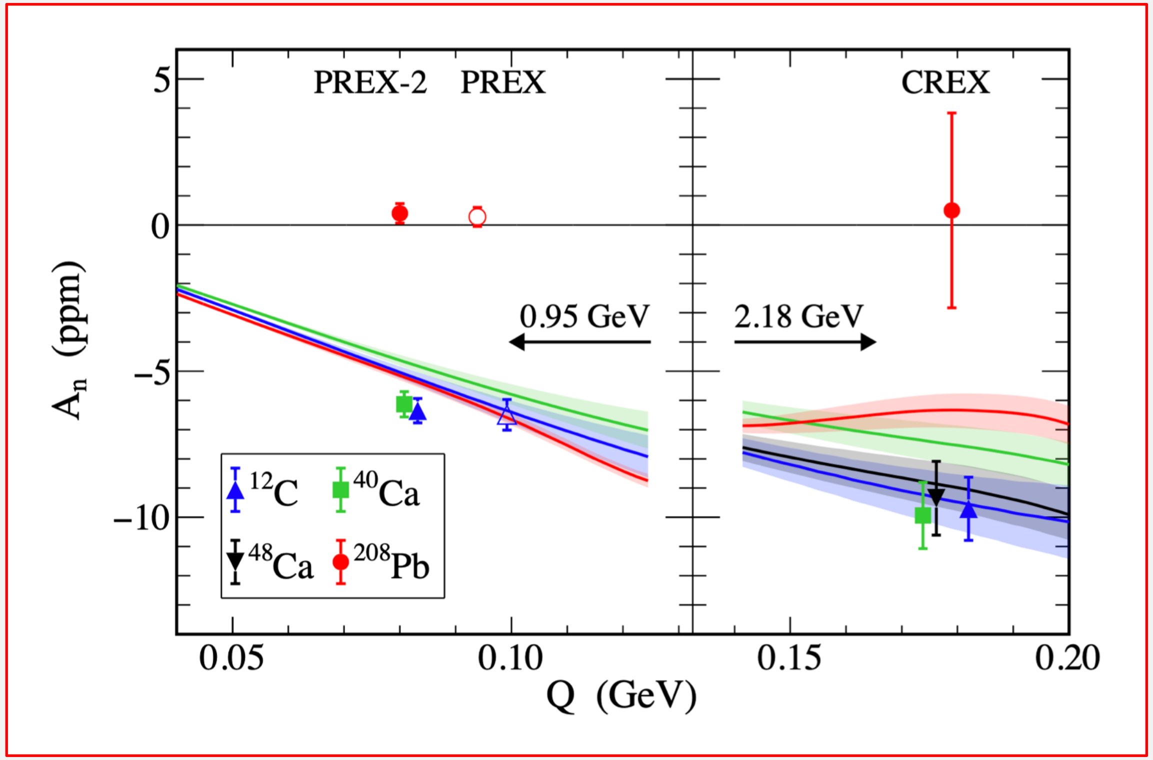




https://arxiv.org/pdf/0801.4575.pdf



- *Incident beam is vertically polarized*
- *Change sign of vertical polarization*
- *Measure fractional rate difference*



- A_T can contribute systematic uncertainty to the extracted A_{PV} if the beam polarization has a transverse component and the apparatus lacks perfect symmetry

A_T Uncertainty Contribution

- Essentially Zero for PREX
- Finite size (bounded) for CREX, careful alignment of beam and dedication AT detectors

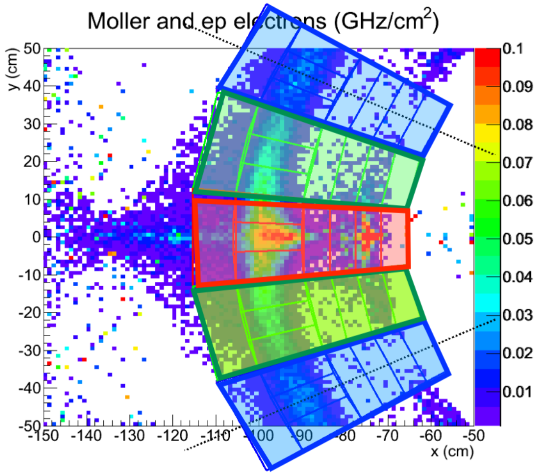
Transverse Polarization **MOLLER**

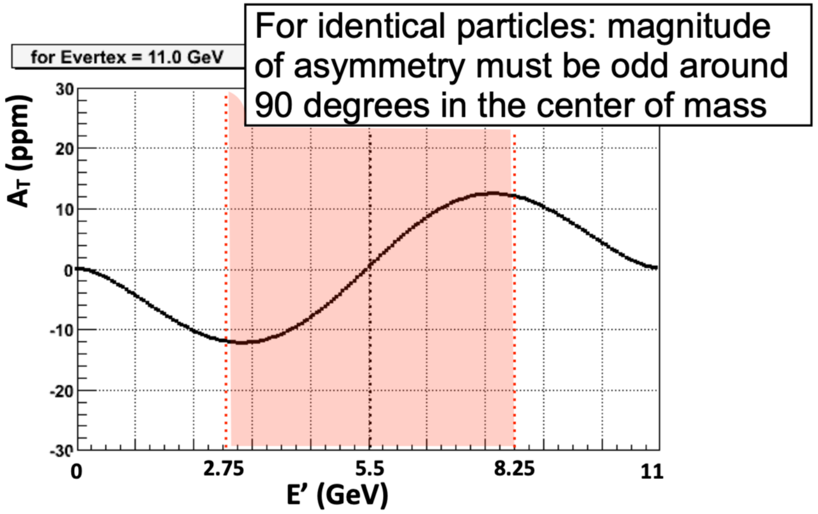
Transverse polarization has a left/right analyzing power

- Well known (both measured and calculated) for *ee* scattering, large in magnitude relative to A_{PV}
- Cancels over azimuthal acceptance, but must be controlled to avoid contributions from imperfect cancellation
- Zero at 90° center of mass, so detector segmentation will have a clear signature for non-zero transverse polarization

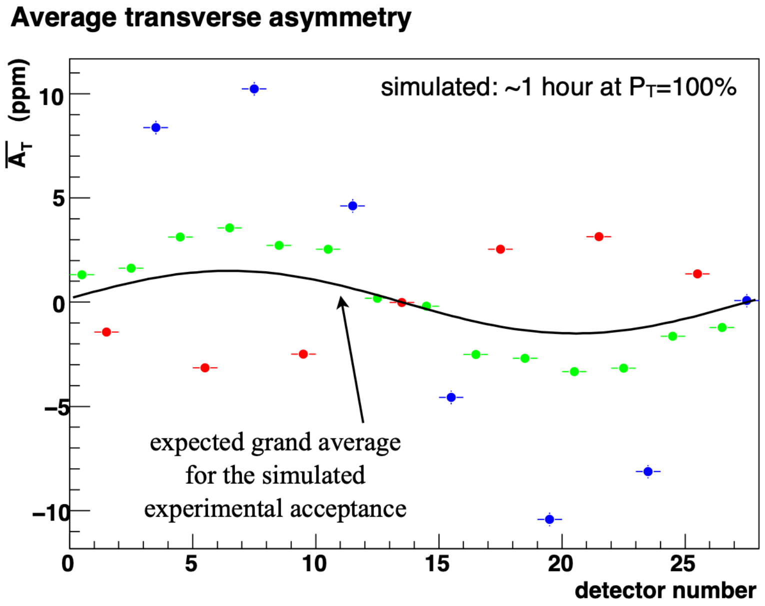
Acceptance symmetry in center-of-mass polar angle

Azimuthal acceptance symmetry





For identical particles: magnitude of asymmetry must be odd around 90 degrees in the center of mass



Systematic error in A_{PV} suppressed by

- Initial beam setup ~ 1-2 degrees *(Small transverse polarization)*
- Unique signature of transverse beam polarization
- 50 ppb error on A_T*P_b in 4 hours: 1 degree precision
- Over entire run: feedback with precession angle will hold transverse polarization small (<<1 degree)

Can measure, adjust, and minimize during experimental running

Summary

- PVES Experiments harness parity violation as a signature of the weak interaction to do precision measurements

1. Any change in the polarized beam, correlated to helicity reversal, can be a potential source for a false asymmetry
    - The total asymmetry and form factor sensitivity is what determines how precisely we must control the beam
    - Recipe to suppress HCBA and achieve Parity Quality Beam for PVES Experiments:
        - Beam Setup Pre-Experiment, Beam Corrections During Experiment, and Beam Transport Considerations
        - Laser Table Alignment, Injector setup, Slow Reversals Symmetry, Aq Feedback, RTP Position Difference Corrections, Beam Modulation, Fast feedback
    - HCBA's are expected to contribute ~0.14 ppb uncertainty for MOLLER(344 days) compared to ~10ppb for PREX-II (20 days)
2. Beam Polarization must be high (90%) and measured continuously / frequently, expected 0.4% precision
3. Transverse Beam Polarization
    - amount of suppression required depends on A_T
    - non-existent for PREX, finite but small and well measured for CREX.
    - For MOLLER $A_T >> A_{PV}$ but well known, cancels azimuthally, carries a clear signature in detectors, can be adjusted during running to minimize

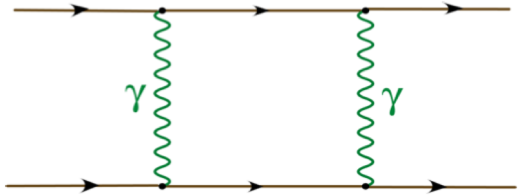
Extras

Transverse Analyzing Power

MOLLER

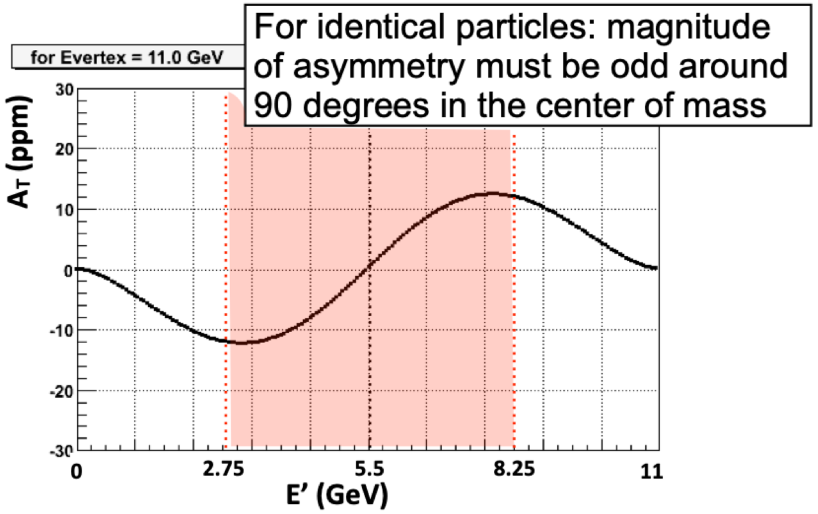
Can measure, adjust, and minimize during experimental running

Interference between one- and two-photon exchange



electron beam polarized transverse to beam direction

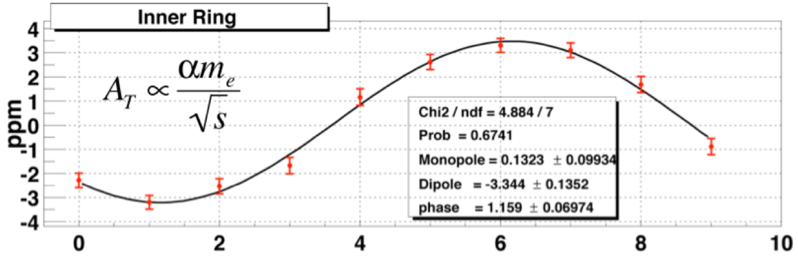
$$A_T \equiv \frac{2\pi}{\sigma^{\uparrow}+\sigma^{\downarrow}} \frac{d(\sigma^{\uparrow}-\sigma^{\downarrow})}{d\phi} \propto \vec{S}_e \bullet (\vec{k}_e \times \vec{k}'_e)$$



For identical particles: magnitude of asymmetry must be odd around 90 degrees in the center of mass

Potential systematic error in A_{PV}.
Suppressed by
- small transverse polarization
- azimuthal acceptance symmetry
- acceptance symmetry in c.m.s. polar angle

Measured at E158



$$A_T \propto \frac{\alpha m_e}{\sqrt{s}}$$

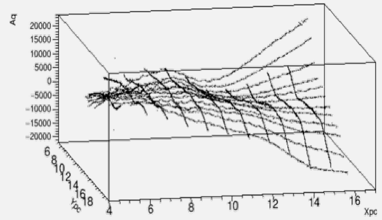
Chi2 / ndf = 4.884 / 7
Prob = 0.6741
Monopole = 0.1323 ± 0.09934
Dipole = -3.344 ± 0.1352
phase = 1.159 ± 0.06974

Theory References:

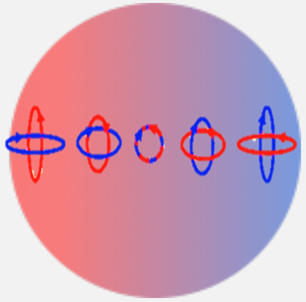
1. A. O. Barut and C. Fronsdal, (1960)
2. L. L. DeRaad, Jr. and Y. J. Ng (1975)
3. Lance Dixon and Marc Schreiber:hep/ph-0402221

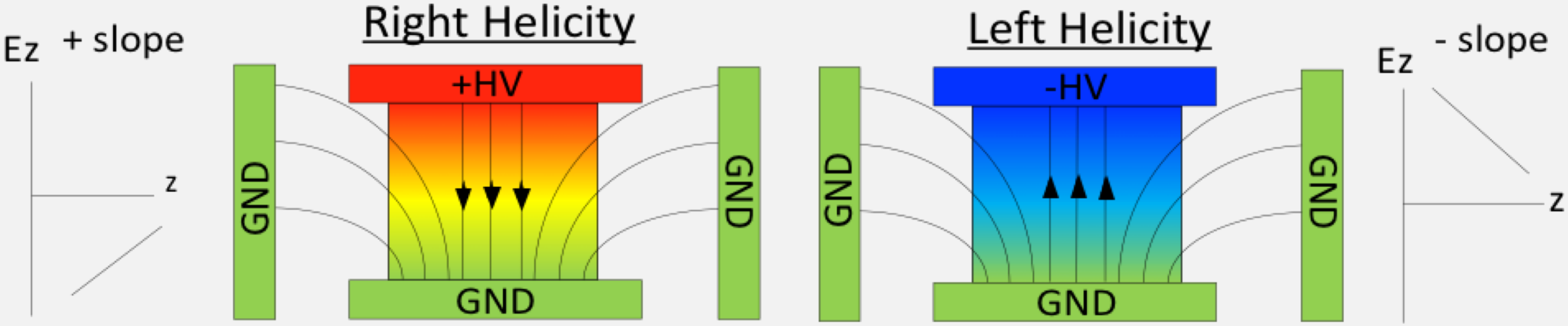
RTP cell advantages: Position Difference Control

Innovation: Cancel Position Differences by Applying Ambient Field



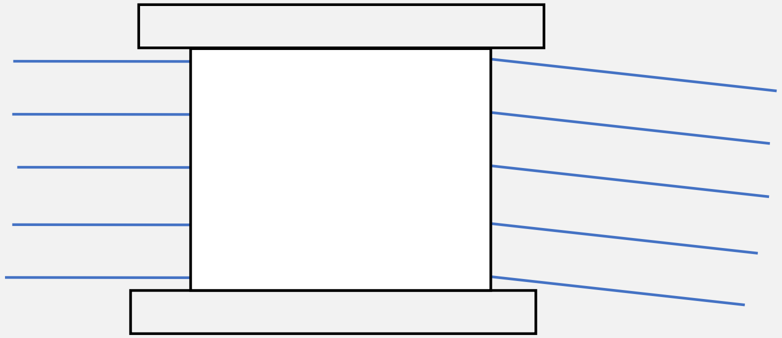
Position differences from asymmetry gradients

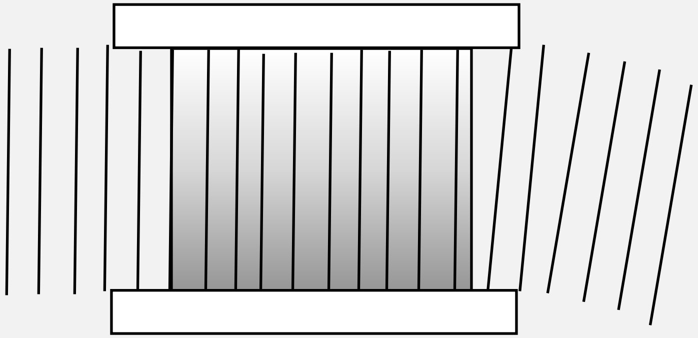




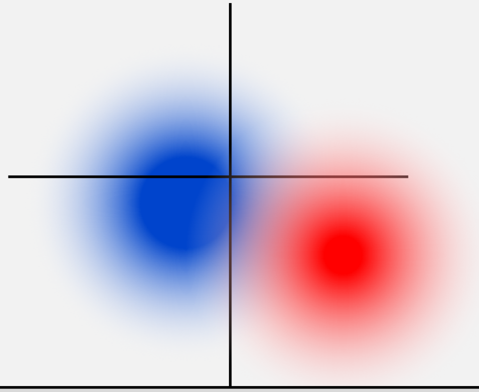
Asymmetric electrode voltages relative to grounded housing

Steer Beam Direction



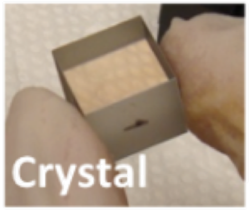


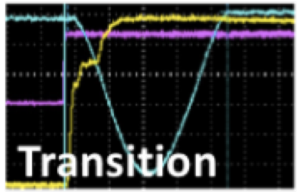
Steering Cancellation

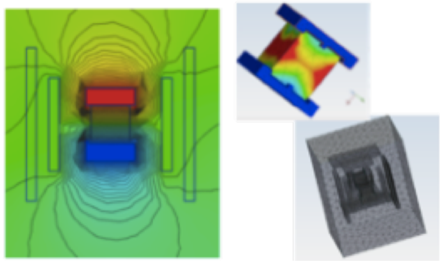


New Pockels Cell: RTP Cell 8HV system

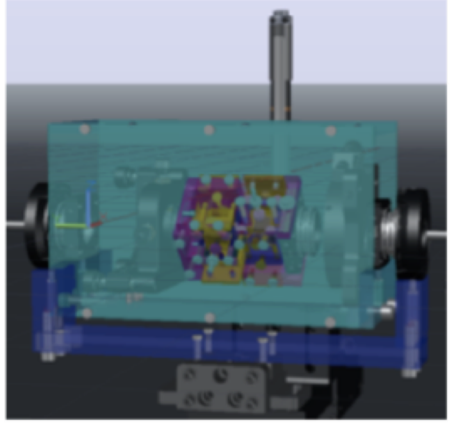
To achieve these systematic and statistical error goals for Moller, we had to innovate!
Designed an built a new Pockels Cell



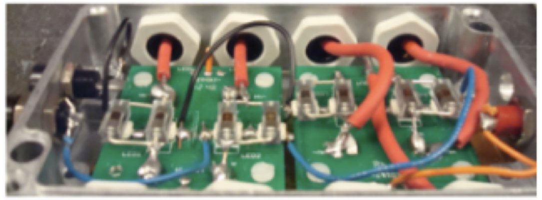


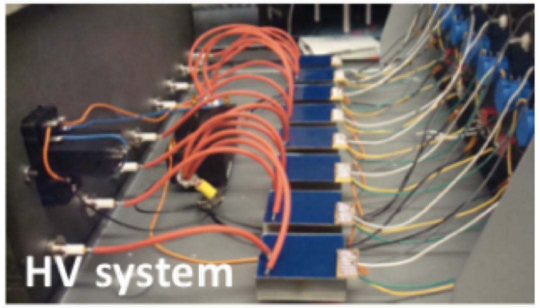


Field Modeling

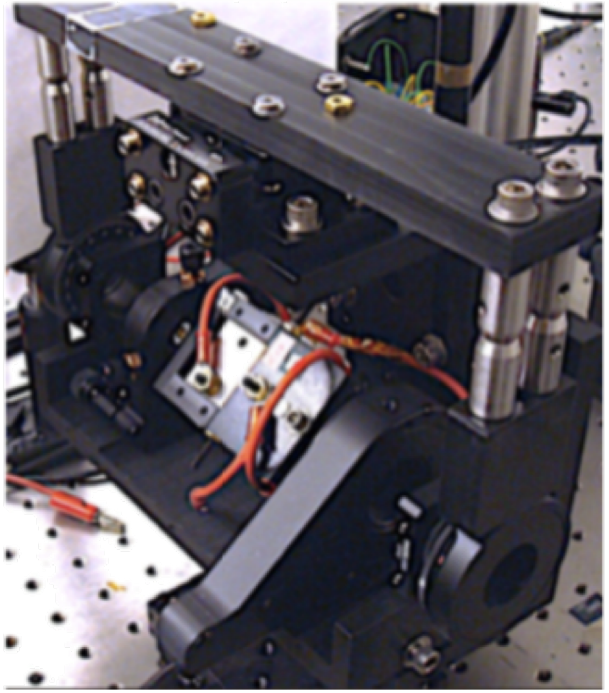


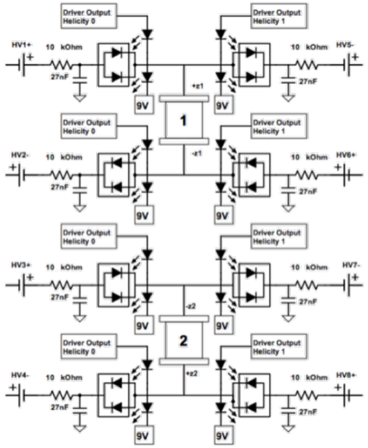
CAD design



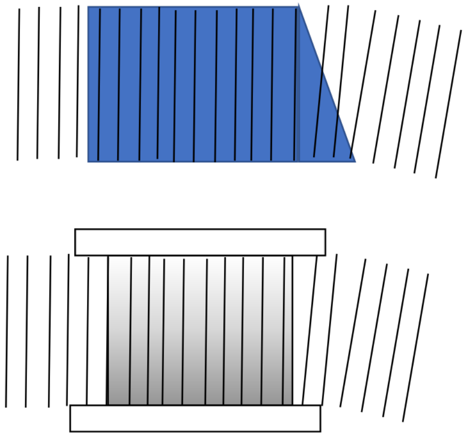


(Rubidium Titanyle Phosphate)



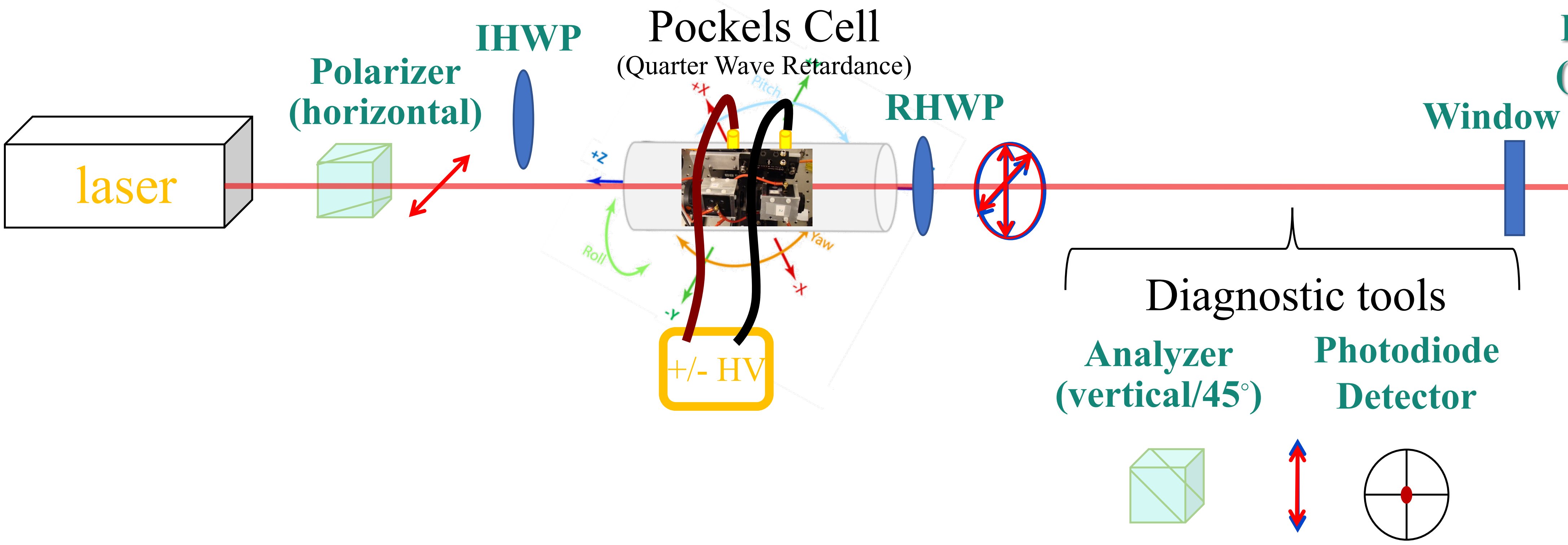


E-field gradient steers beam -
use effect for position feedback



Then we used the RTP cell during PREX-II and CREX

Laser Beam Source Optics



Polarizer (horizontal)

IHWP

Pockels Cell
(Quarter Wave Retardance)

+/- HV

RHWP

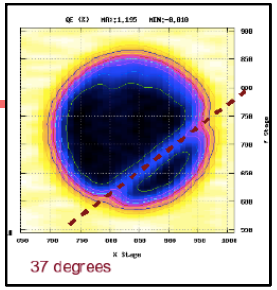
Diagnostic tools

Analyzer (vertical/45°)

Photodiode Detector

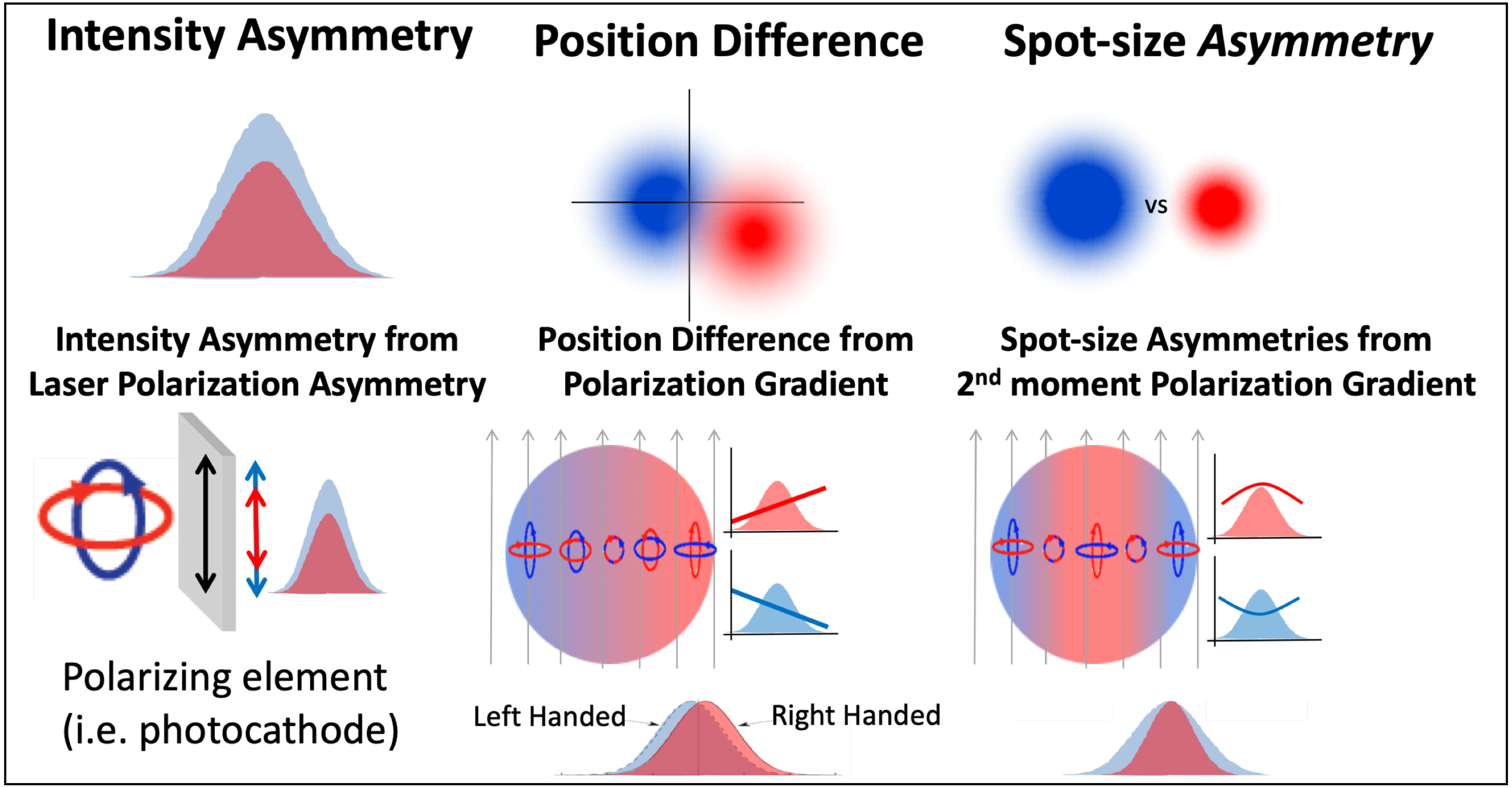
Window

GaAs Photocathode (6% analyzer)



37 degrees

Electron Beam Asymmetries arise from Laser Beam Asymmetries



Intensity Asymmetry | **Position Difference** | **Spot-size *Asymmetry***

Intensity Asymmetry from Laser Polarization Asymmetry

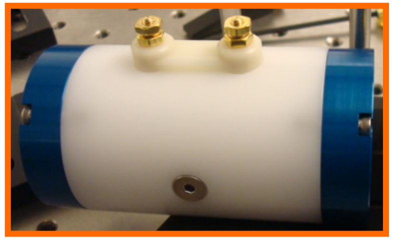
Position Difference from Polarization Gradient

Spot-size Asymmetries from 2^{nd} moment Polarization Gradient

Polarizing element (i.e. photocathode)

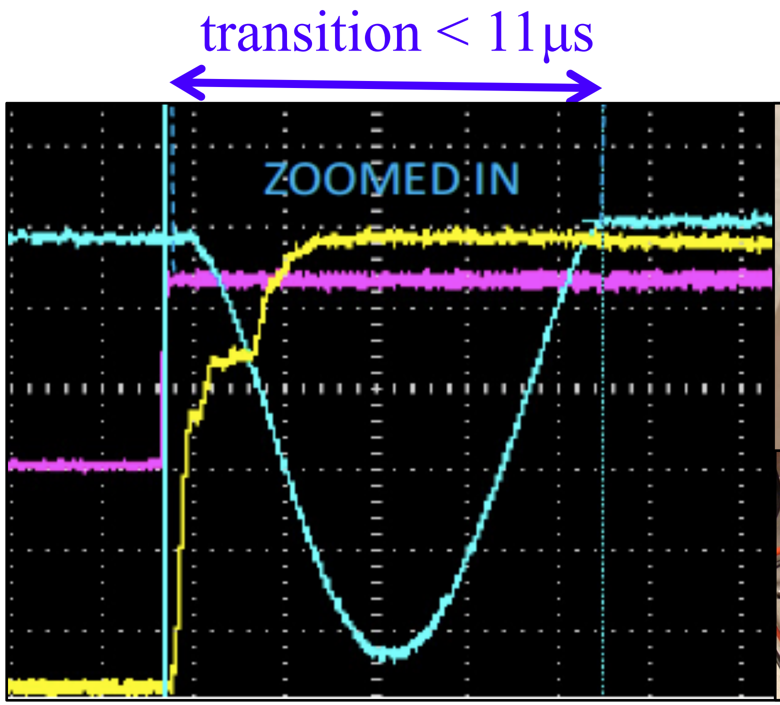
RTP Pockels used cell during PREX-II and CREX could flip faster and control beam asymmetries better

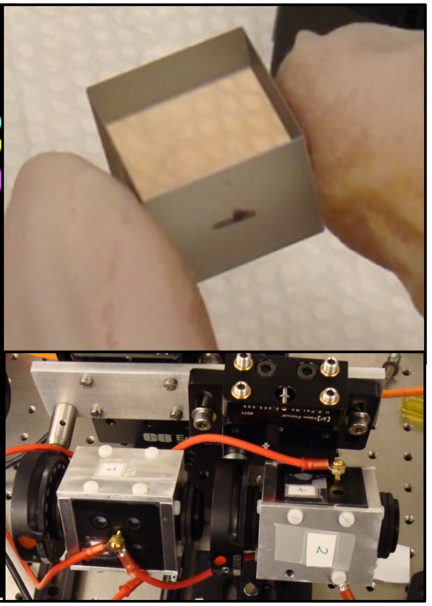
RTP cell advantages: Switching faster



RTP Cell

(Rubidium Titanyle Phosphate)

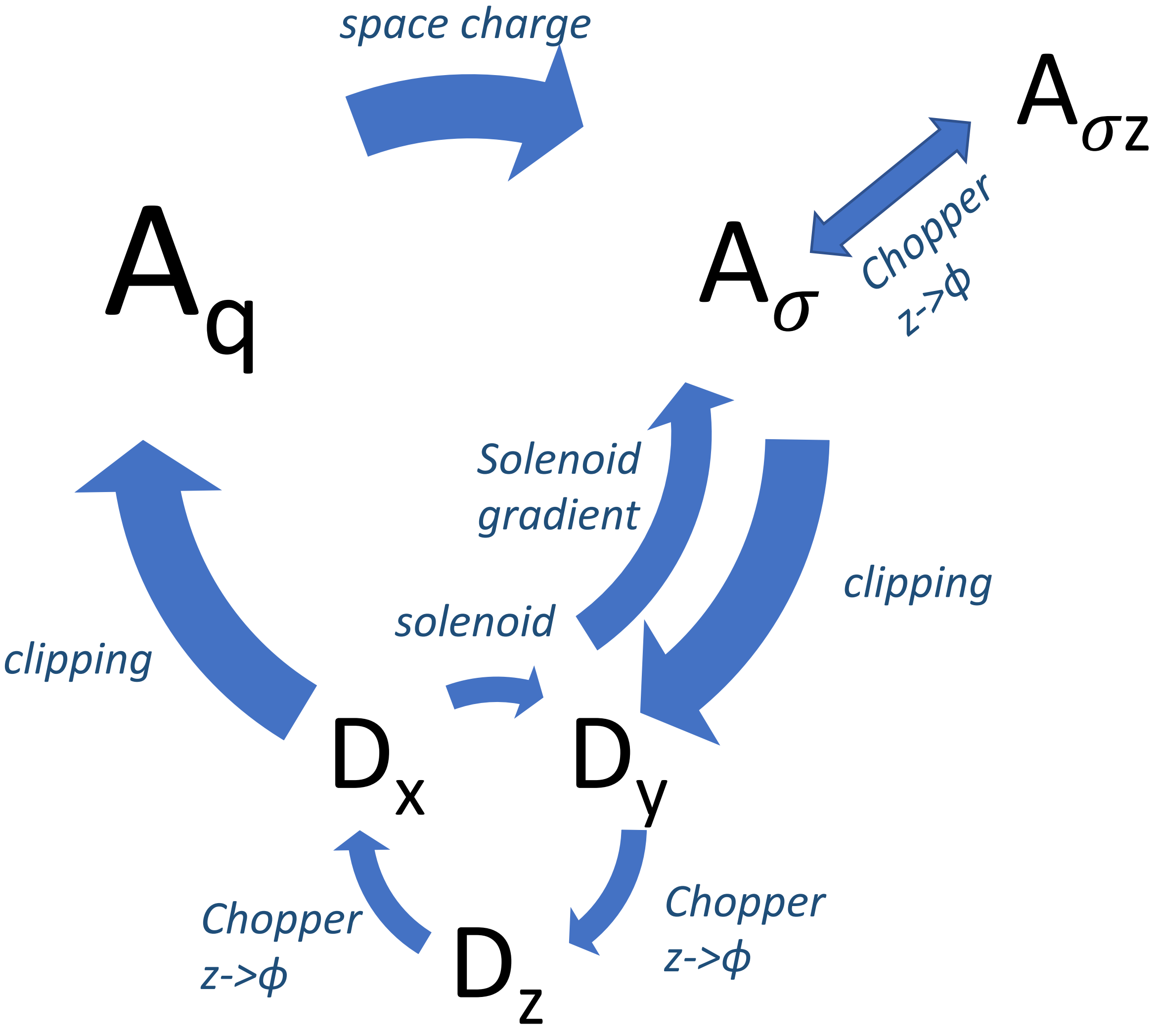




- Standard KD*P cell: Suffers from piezoelectric ringing
- transition + ringing ~ 100μs
- ~20% loss of data from deadtime

- New RTP cell:
- Two crystals, transverse field
- No piezoelectric ringing up to 100kHz
- **<11μs transition (used for PREXII & CREX)**

HCBA Transport in Electron Beams



Recipe to suppress HCBA and achieve Parity Quality Beam for PVES Experiments

Beam Setup Pre-Experiment:

- *Laser Table Alignment : minimize HCBA*
- *Injector setup: minimize HCBA*
- *Slow Reversals Symmetry*

Beam Corrections During Experiment:

- *Aq Feedback*
- *RTP Position Difference Corrections*
- *Beam Modulation*
- *Fast feedback*

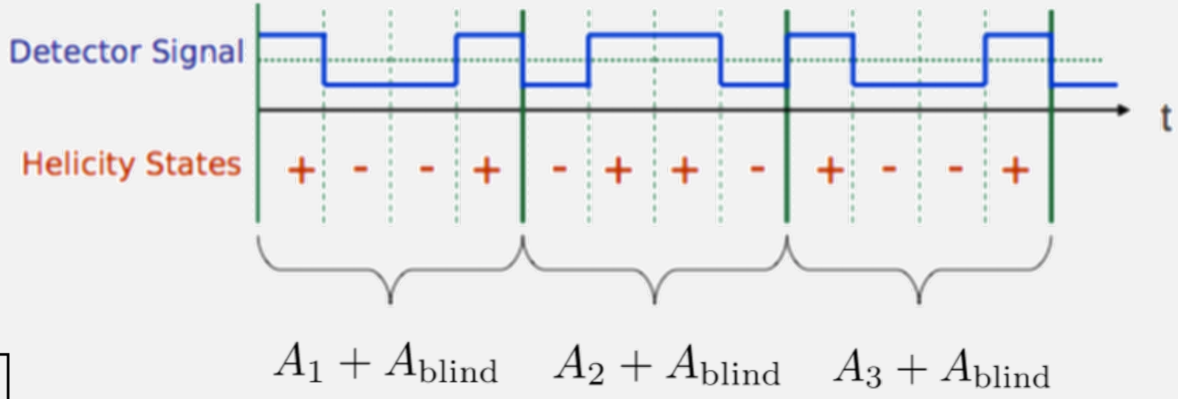
Beam Transport Considerations:

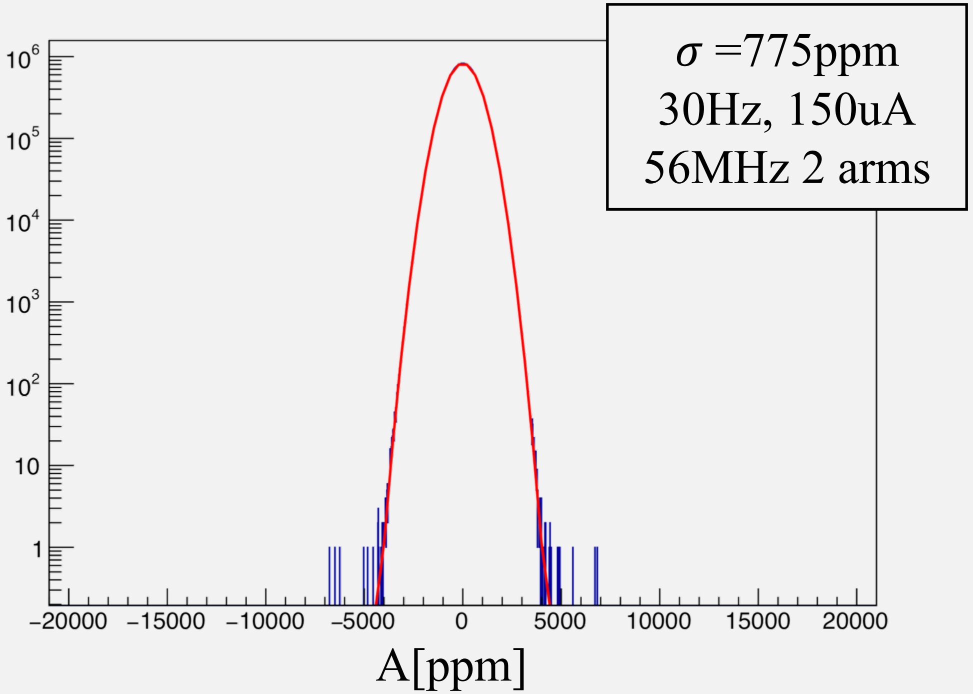
- *High Transmission*
- *Adiabatic Damping/Optics Match*

Goal: measure beam-helicity-correlated elastic scattering asymmetry to high precision

Measuring small asymmetry

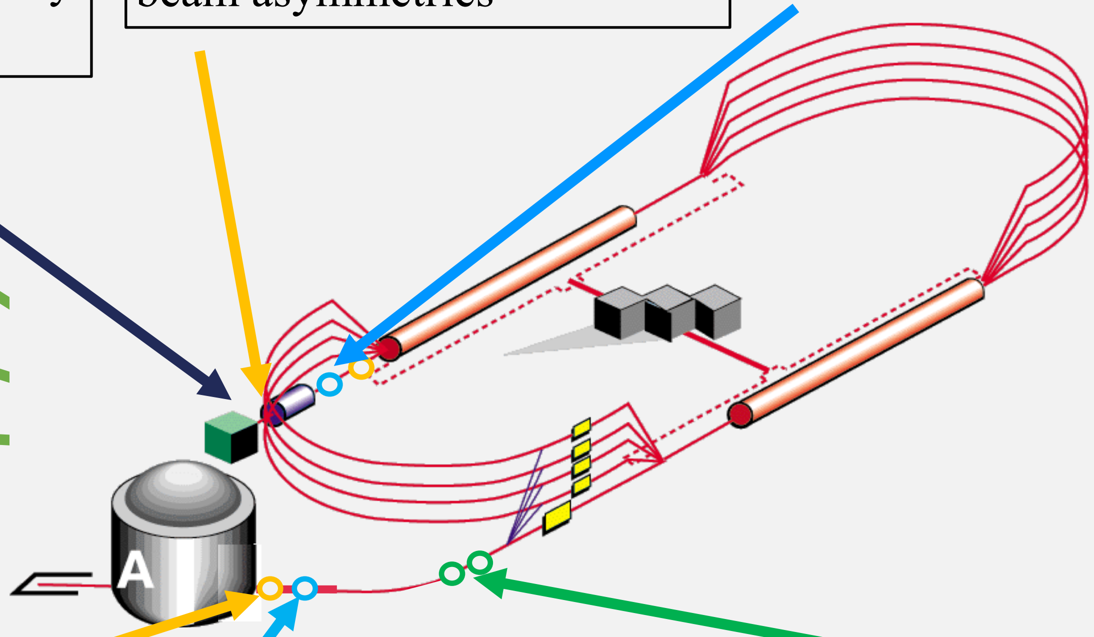
$$A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L}$$





- Integrating, not counting (total number of detected electrons was ~$2.4\text{x}10^{21}$, ~383 C)
- Online analysis showed we were dominated by counting statistics fairly early in the experiment
- Number of flips ~ 300 million, quartets ~ 80 million
- *Technique built for big rates and small asymmetries (PREX 4GHz, 0.55ppm)*
- *CREX less challenging in terms of rate (CREX 50MHz, 1% of PREX rate, larger asymmetry)*

Preparing the beam



Injector laser setup crucial towards minimizing beam asymmetries

Double Wien allowed us to further electromagnetically flip the electron beam helicity every few weeks

Beam monitors allowed for injector setup with small beam asymmetries

Mott polarimeter confirm high beam polarization

Pockels cell allowed us to flip the electron helicity at 120 or 240 Hz

Half Wave Plate allowed us to independently flip the laser polarization every few hours

Beam monitors allow us to determine beam properties in front of the target

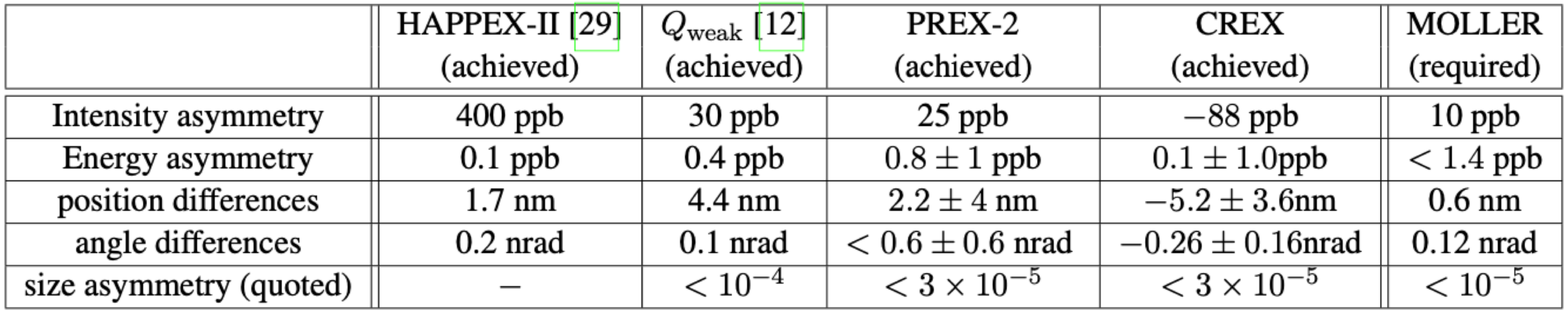
Polarimeters allow us to monitor polarization and check machine setup

Beam modulation system allows us to span the phase space of beam motion

Aq 20.7 +- 0.2ppb correction

Charge asymmetry
112+-1ppb correction

Charge asym unc 0.3 %



	HAPPEX-II [29] (achieved)	Q_{weak} [12] (achieved)	PREX-2 (achieved)	CREX (achieved)	MOLLER (required)
Intensity asymmetry	400 ppb	30 ppb	25 ppb	-88 ppb	10 ppb
Energy asymmetry	0.1 ppb	0.4 ppb	0.8 ± 1 ppb	0.1 ± 1.0ppb	< 1.4 ppb
position differences	1.7 nm	4.4 nm	2.2 ± 4 nm	-5.2 ± 3.6nm	0.6 nm
angle differences	0.2 nrad	0.1 nrad	$< 0.6 \pm 0.6$ nrad	-0.26 ± 0.16nrad	0.12 nrad
size asymmetry (quoted)	–	$< 10^{-4}$	$< 3 \times 10^{-5}$	$< 3 \times 10^{-5}$	$< 10^{-5}$

- CREX result is consistent with a thin neutron skin prediction (e.g. coupled cluster calculations) and is strongly inconsistent with predictions of a very thick skin
- At this point it appears potentially challenging for DFT models to reproduce both the CREX result of a thin skin in ^{48}Ca and the PREX result of a relatively thick skin in ^{208}Pb.

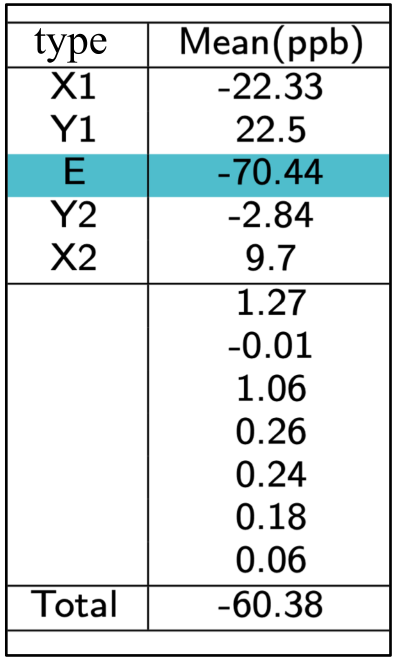
Beam correction summary

- Use Lagrange Multiplier Regression, 3% slope uncertainty
- Three independent techniques agree

- Left/right symmetric detectors, so correction dominated by energy

Careful configuration of the polarized source kept beam difference averages very small

Δx_i	Mean (nm)	Convergence (nm)
Target x	-1.1 nm	2.0 nm
Target y	1.1 nm	0.5 nm
Angle x	-0.28 nrad	0.32 nrad
Angle y	0.14 nrad	0.09 nrad
Energy BPM	2.3 nm	1.1 nm



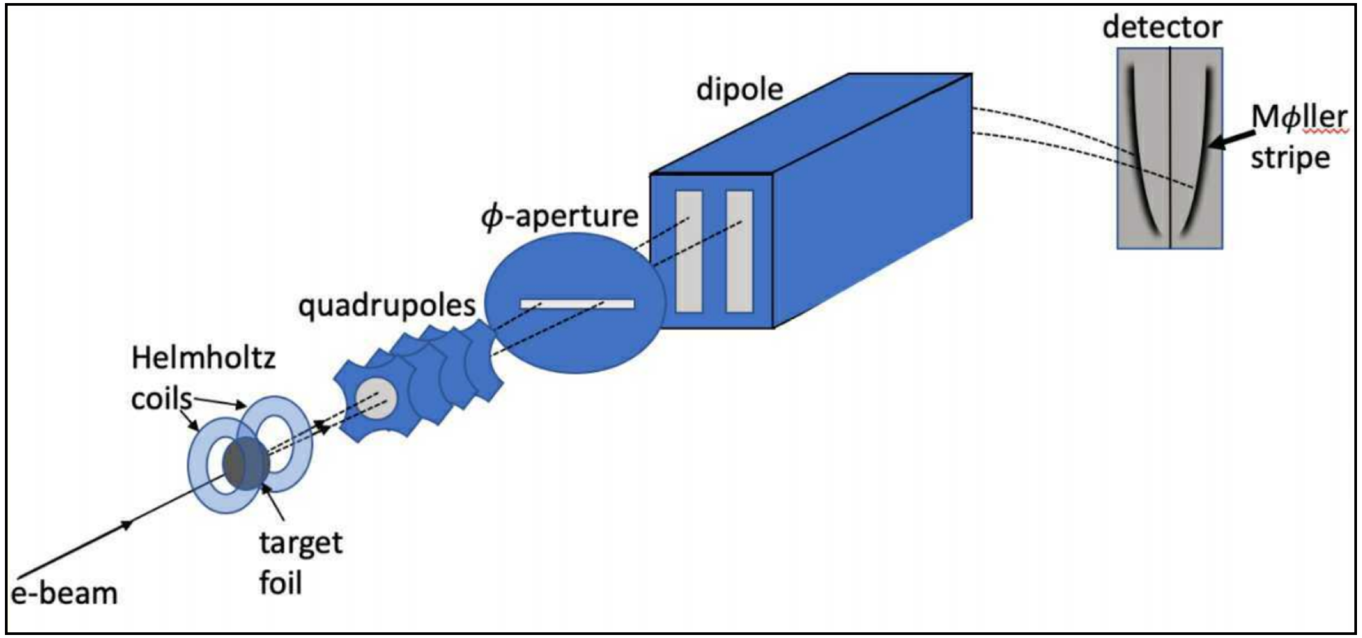
type	Mean(ppb)
X1	-22.33
Y1	22.5
E	-70.44
Y2	-2.84
X2	9.7
	1.27
	-0.01
	1.06
	0.26
	0.24
	0.18
	0.06
Total	-60.38

Total beam corrections:

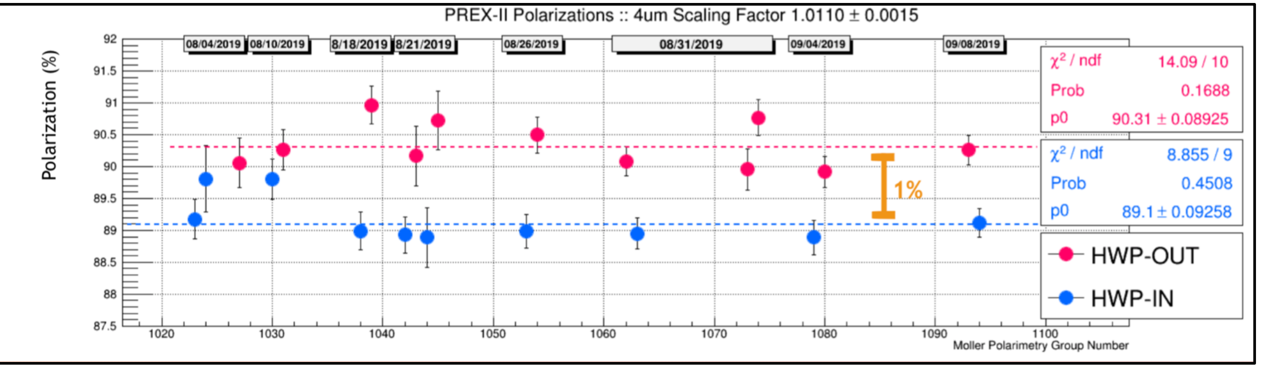
(60.4 ± 2.5) ppb

Moller Polarimetry

- Low-current, invasive measurement
- 3-4T field provides saturated magnetization perpendicular to the foil
- Spectrometer redesigned for 11 GeV



PREX- II
Average polarization:
(89.7 ± 0.8)%



- PREX-II reoptimized the spectrometer tune (and detector configuration), to provide high precision and sensitivity to systematic effects
- Polarimeter runs were taken approximately every week and established no significant fluctuations in beam polarization over the course of the run

Recipe to suppress HCBA and achieve Parity Quality Beam for PVES Experiments

Beam Setup Pre-Experiment:

- *Laser Table Alignment : minimize HCBA*
- *Injector setup: minimize HCBA*
- *Slow Reversals Symmetry*

Beam Corrections During Experiment:

- *Aq Feedback*
- *RTP Position Difference Corrections*
- *Beam Modulation*
- *Fast feedback*

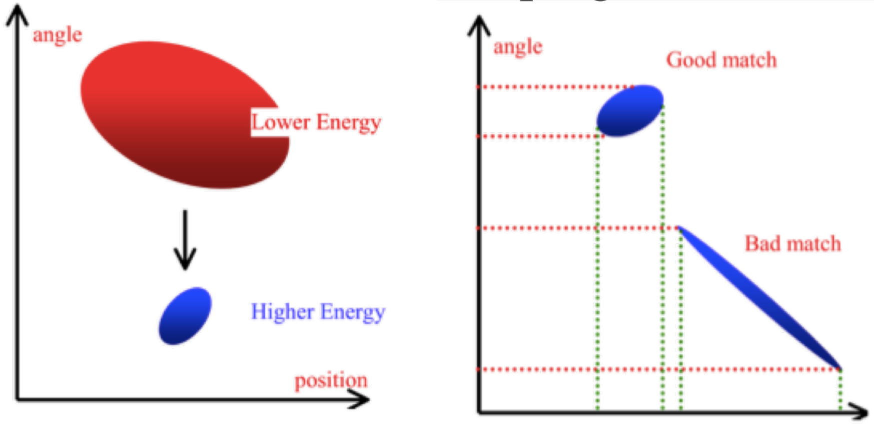
Beam Transport Considerations:

- *High Transmission*
- *Adiabatic Damping/Optics Match*

Beam Transport Considerations: *Adiabatic Damping/Optics Match*

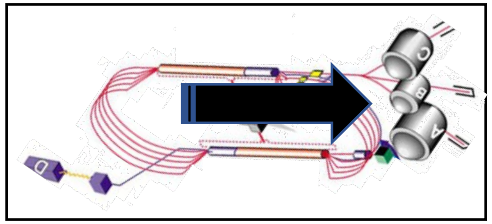
Good optical transport throughout the injector and accelerator is crucial

Adiabatic Damping



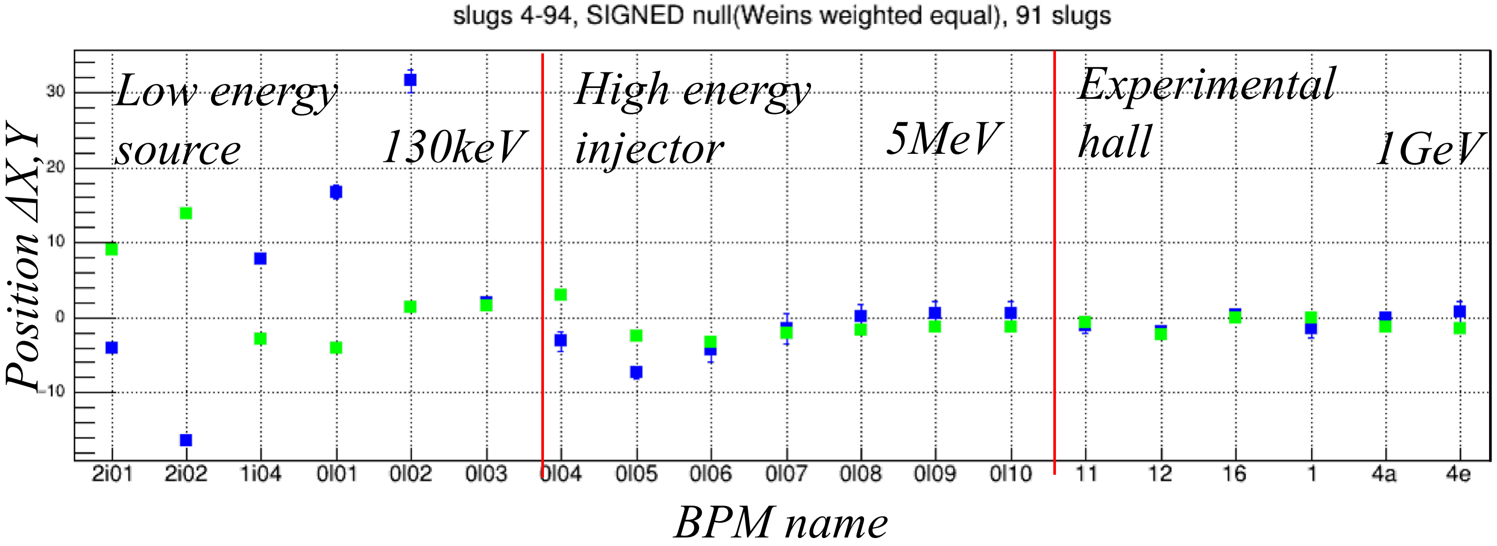
- From relativistic boost, transverse d.o.f. matter less
- Area of beam distribution in the phase space (emittance) is inversely proportional to p
- Good Match: Position Difference suppression ~ $\sqrt{\frac{p_0}{p}}$
- Bad Match: Coupling in transverse phase space spreads the emittance out

Injector



Experimental Hall

PREX-II Damping on average



Avoid building in phase space correlations: If beam optics deviate from design, significant correlations can develop

Beam Asymmetries Previously Achieved and Future Goals

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

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

HCBA's are expected to contribute ~0.14 ppb uncertainty for Moller *(~10ppb for PREXII)*

(Helicity Correlated Beam Asymmetries)

HCBA Contributors

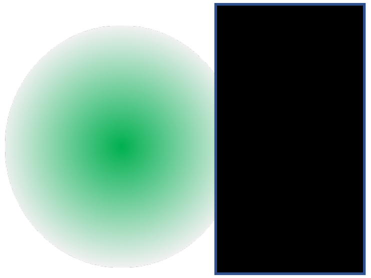
	PREX-2 (achieved)	CREX (achieved)	MOLLER (required)
Intensity asymmetry	25 ppb	−88 ppb	10 ppb
Energy asymmetry	0.8 ± 1 ppb	0.1 ± 1.0ppb	< 1.4 ppb
position differences	2.2 ± 4 nm	-5.2 ± 3.6nm	0.6 nm
angle differences	$< 0.6 \pm 0.6$ nrad	-0.26 ± 0.16nrad	0.12 nrad
size asymmetry (quoted)	$< 3 \times 10^{-5}$	$< 3 \times 10^{-5}$	$< 10^{-5}$
	19 days	~40 days	344 days

Constrained at nm, nrad, ppb level

How were these small beam asymmetries achieved and how can we meet our future goals?

Beam Transport Considerations: High Transmission (no clipping)

Clipping – High Transmission needed



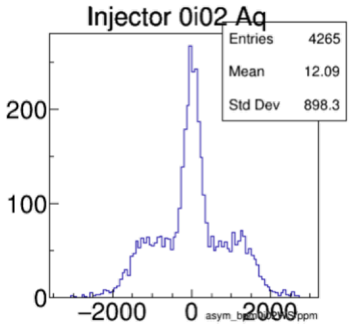
= noise + HCBA intercoupling

$$D_x \Rightarrow A_q$$

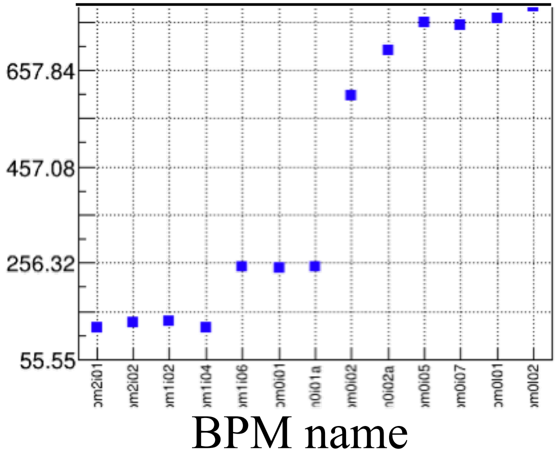
noise

HCBA intercoupling

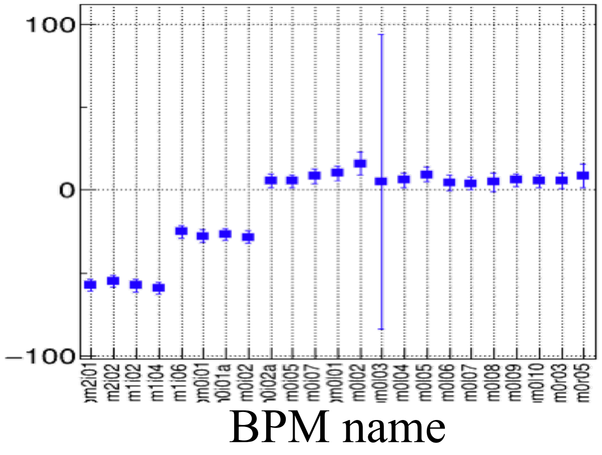
Aq distribution



Aq RMS



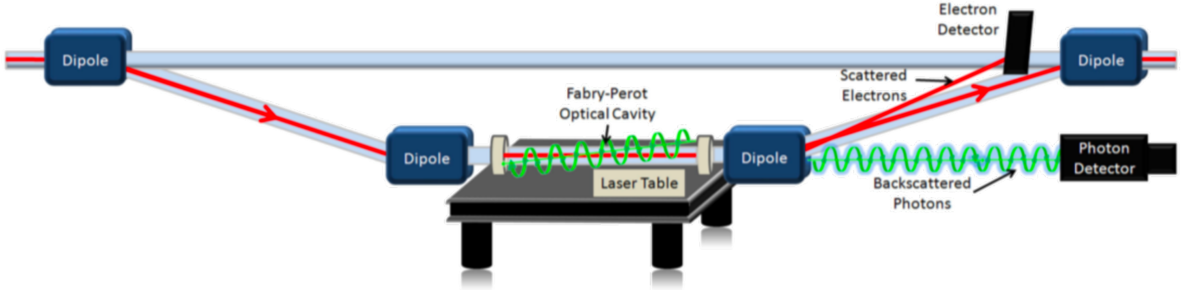
<Aq>



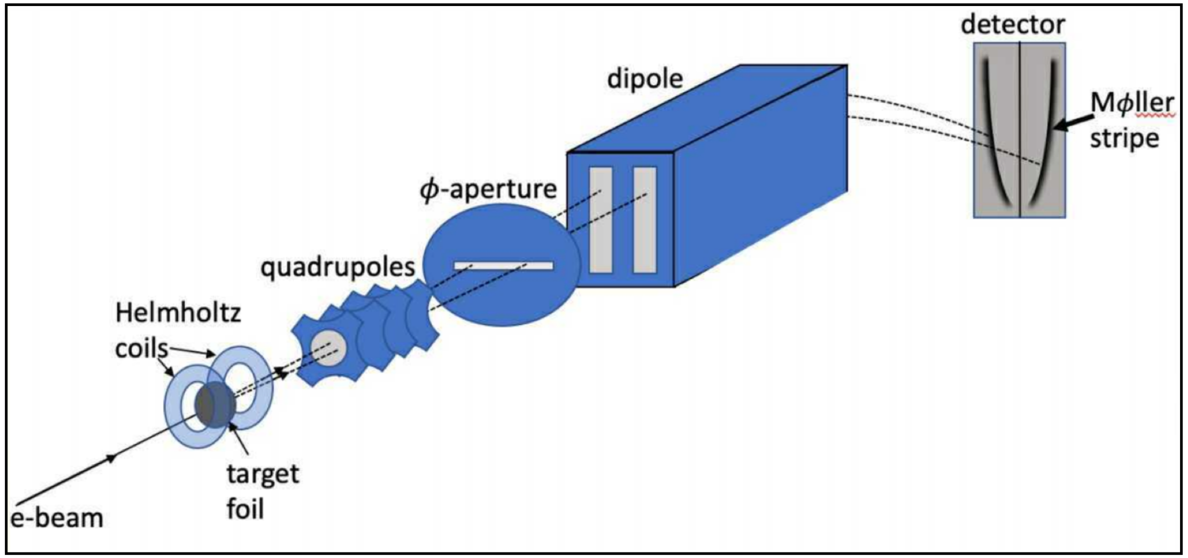
Poor Beam Transport Can Mess things up BADLY

Beam Polarization

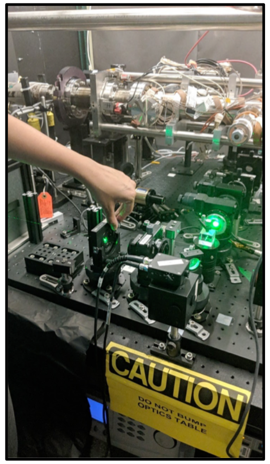
Compton Polarimetry



Moller Polarimetry



Acknowledgments: S. Malace, E. King, D. Jones, P. Souder



- Continuous, non-invasive measurement
- Utilized integrating technique with photon detector
- Evaluated systematic uncertainty
- Polarimeter runs taken continuously alongside main detector data

- Low-current, invasive measurement
- 3-4T field provides saturated magnetization perpendicular to the foil
- Spectrometer redesigned for 11 GeV
- CREX reoptimized the spectrometer tune (and detector configuration), to provide high precision and sensitivity to systematic effects
- Polarimeter runs were taken approximately every week

Beam corrections during experiment : *Fast Feedback and Beam Modulation*

Precisely measuring sensitivities is just as important as minimizing HCBAs

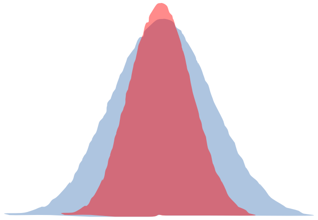
$$A_{raw} = A_{det} - A_Q + \alpha\Delta_E + \Sigma\beta_i\Delta x_i$$

- Sensitivities of detector signal to beam position and energy must be measured very precisely
  - α, β_i determination is critical to minimizing systematic uncertainty and eliminating beam noise in A_{raw}

Δ_E & Δx_i

Fast Feedback

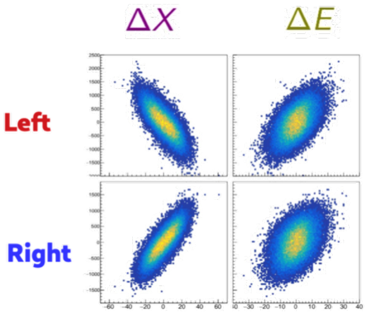
- Too much noise is bad
- Compromises ability to measure/bound position differences
- If can't measure small HCBA, can't reach systematic goals



α & β_i

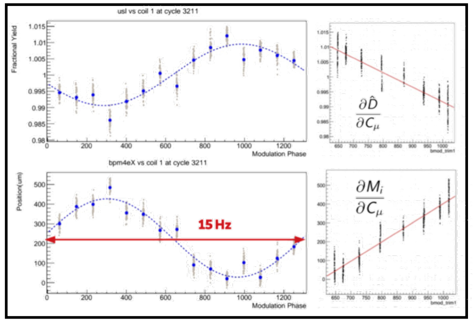
Regression

- Some beam noise is good to measure correlations with detectors and monitors
- online analysis
- Produces narrow detector widths, filtering beam noise out well, but resolution affects slopes
- regression is precise but can be wrong



Beam Modulation

- Intentionally modulate beam position in X,Y, angle, energy, dedicate data time to this, large modulations to measure sensitivities well throughout experiment
- offline analysis
- Measure betas well, but filtered detector widths aren't as narrow
- modulation is good but not precise



We use regression constrained by modulation (Lagrange multipliers) to get the best of both worlds