Acknowledgements:
The PREX, CREX and Hall A Collaboration and
the Accelerator Division at Jefferson Laboratory
C. Horowitz, J. Piekerewicz

The PREX-I Result

Introduction to Parity-Violating Electron Scattering

The Neutral Weak Form Factor of Pb-208 at Q ~ 85 MeV/c

Krishna S. Kumar
Stony Brook University and ACFI

Neutron Skins of Nuclei
MITP Workshop
Mainz, May 17, 2016

Outline

- **Introduction to Parity-Violating Electron Scattering**
  - *Relativistic electron scattering and nuclear size*
  - *Parity Violation (PV) in weak interactions*
  - *Neutral weak interactions*
  - *Overview of an electron beam parity violation experiment*
- **PREX at Jefferson Laboratory**
  - *Experimental Overview*
    - Unique features of Jefferson Lab Hall A
  - *Physics Run (March-June 2010)*
    - PREX first result
    - Statistics and Systematics
- **Conclusion and Outlook**

Basic introduction for practitioners in other subfields

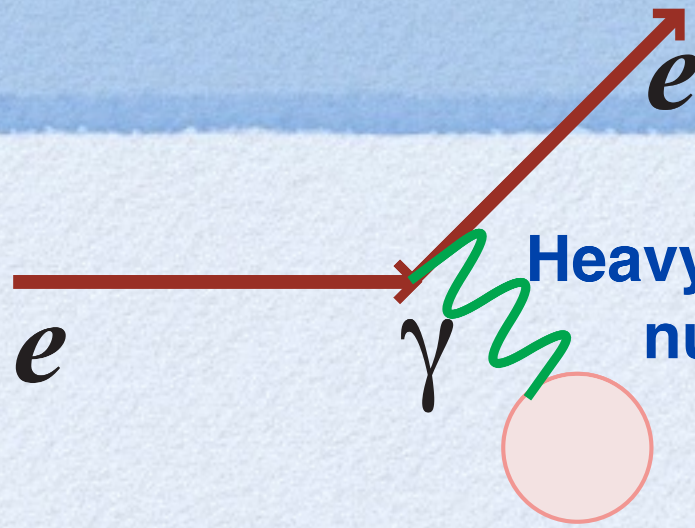
PRL 108 (2012) 112502

PRC 85 (2012) 032501

Introduction to Parity-Violating Electron Scattering

Relativistic Electron Scattering

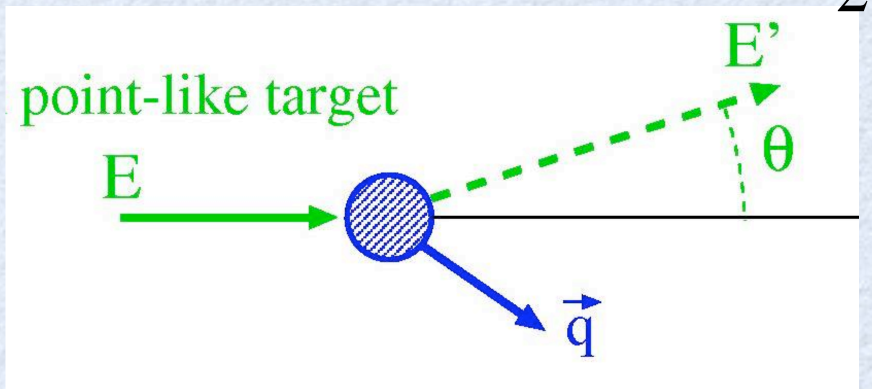
and nuclear size



Heavy, spinless nucleus

4-momentum transfer $q^2 = -4EE'\sin^2\frac{\theta}{2}$

Q²: -(4-momentum)² of the virtual photon



$$Q \approx \frac{hc}{\lambda}$$

Differential Cross Section

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

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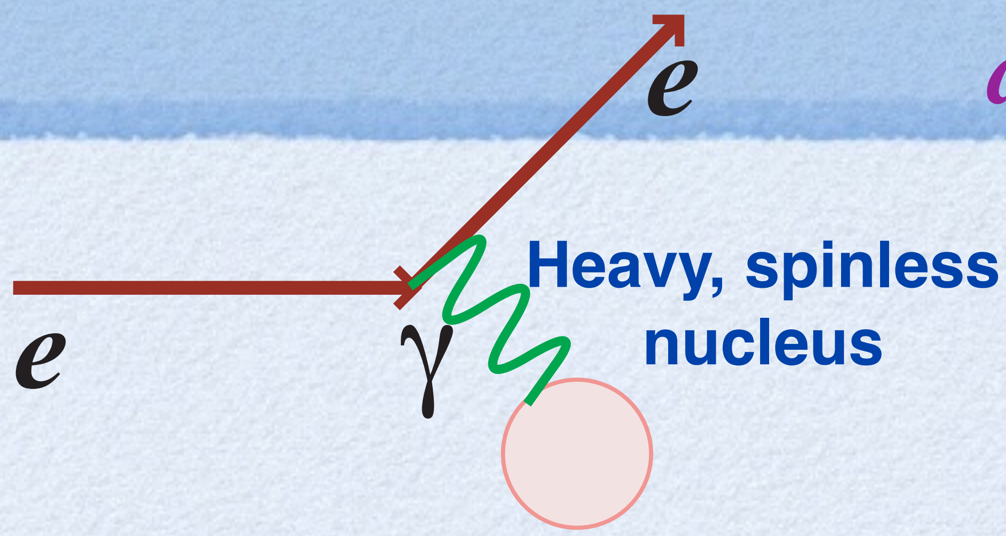

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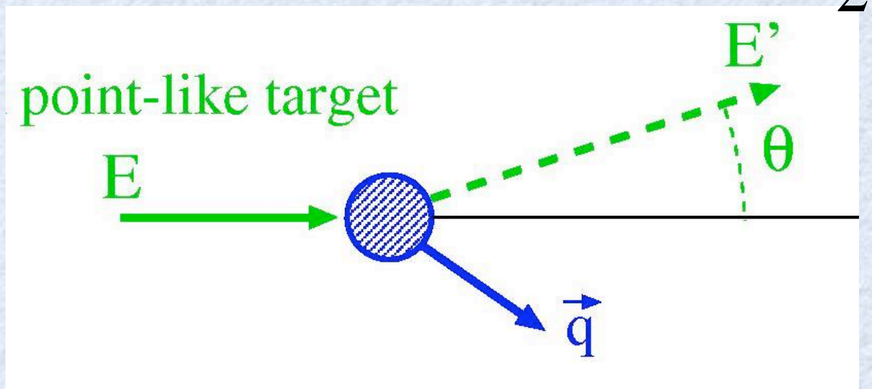

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As Q increases, nuclear size modifies formula

Neglecting recoil, form factor *F(q)* is the Fourier transform of charge distribution

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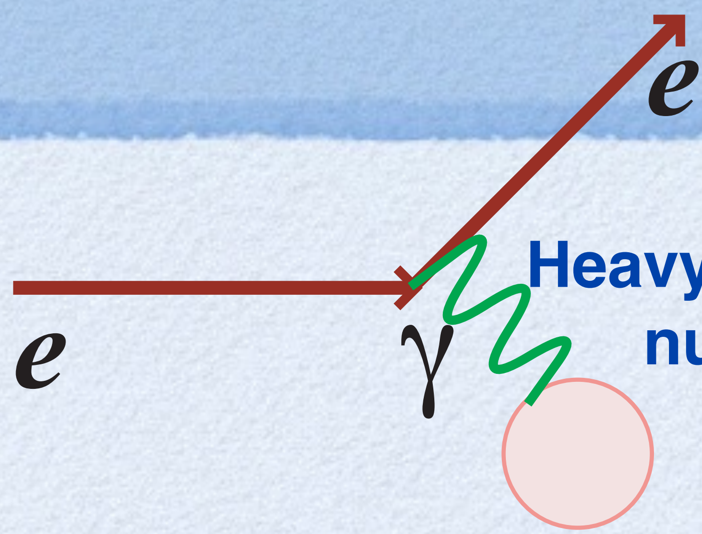

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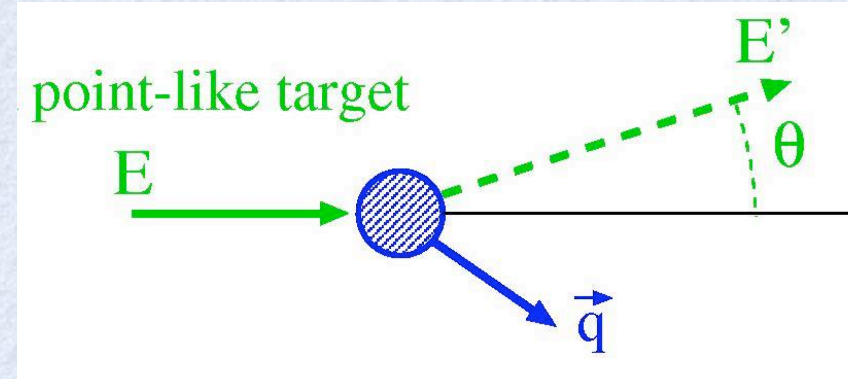

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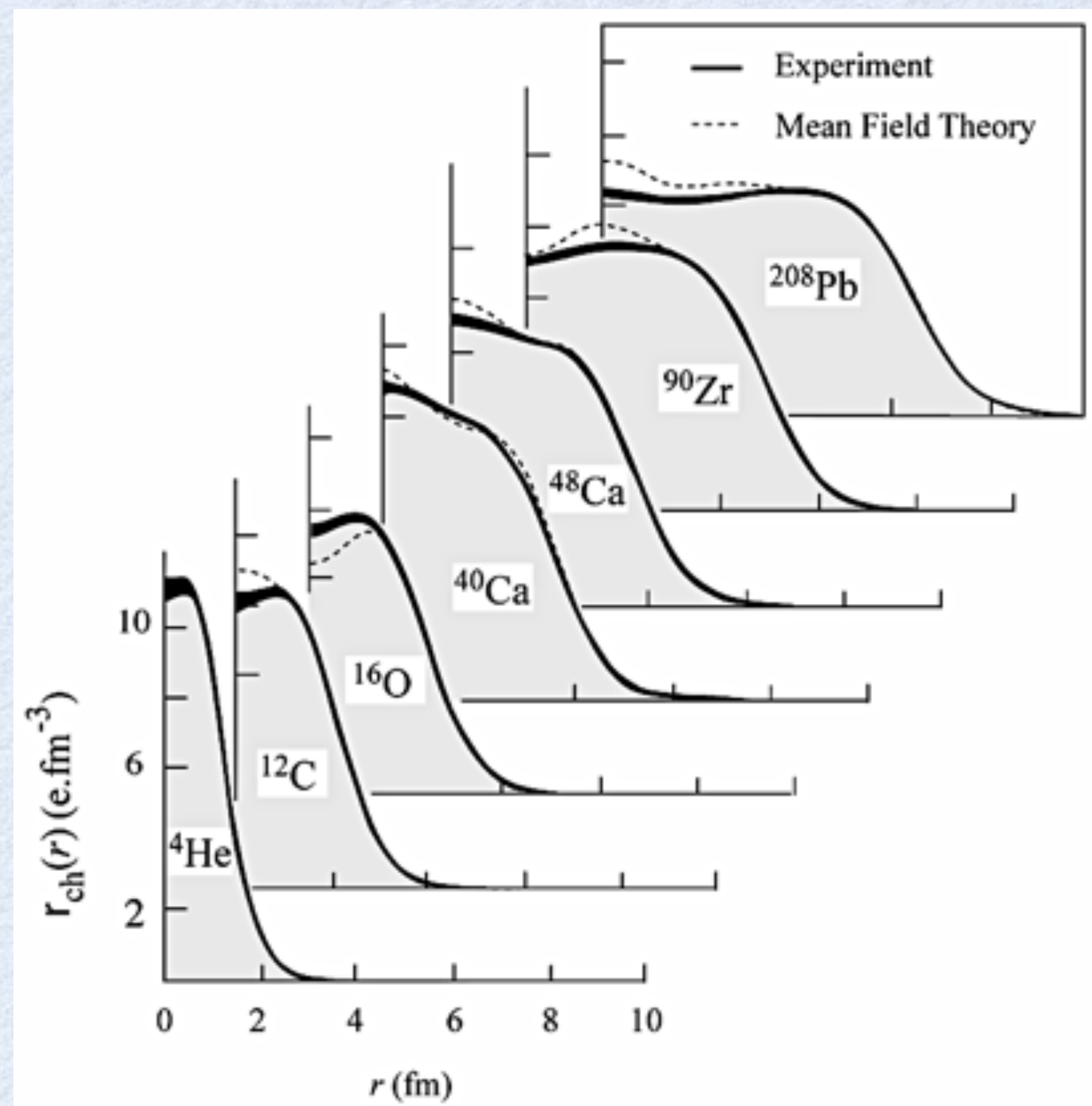
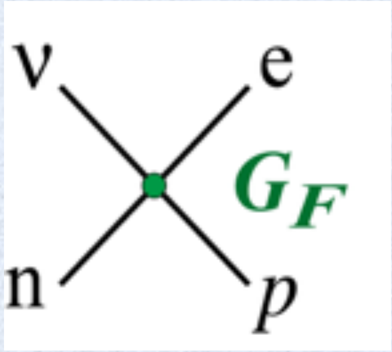


Weak Interactions

Neutron & nuclear β Decay



charge and flavor-changing

Fermi Theory for weak interactions

Universal strength: coupling constant G_F

"Effective" low energy theory that explains many observed properties of radioactive nuclear decays

Weak Interactions

Observed NOT to be invariant under parity transformations

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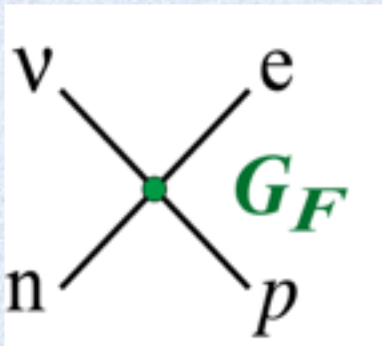

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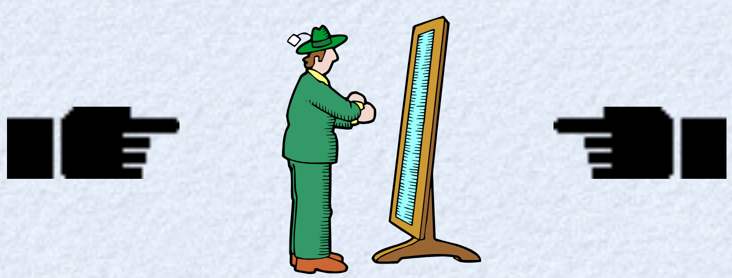

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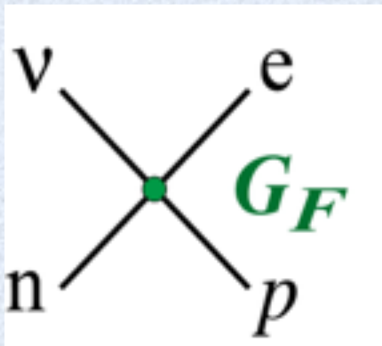

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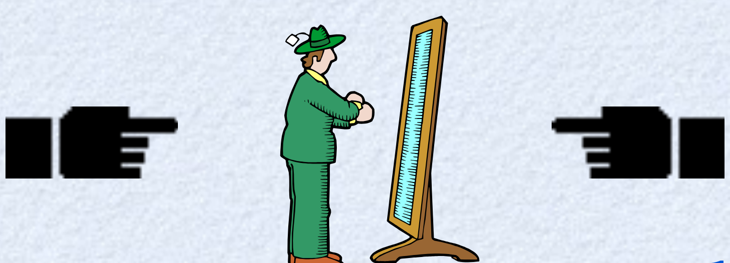

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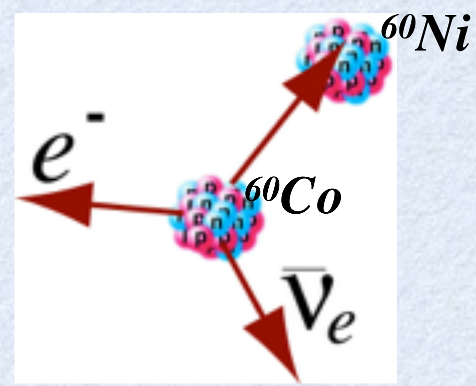
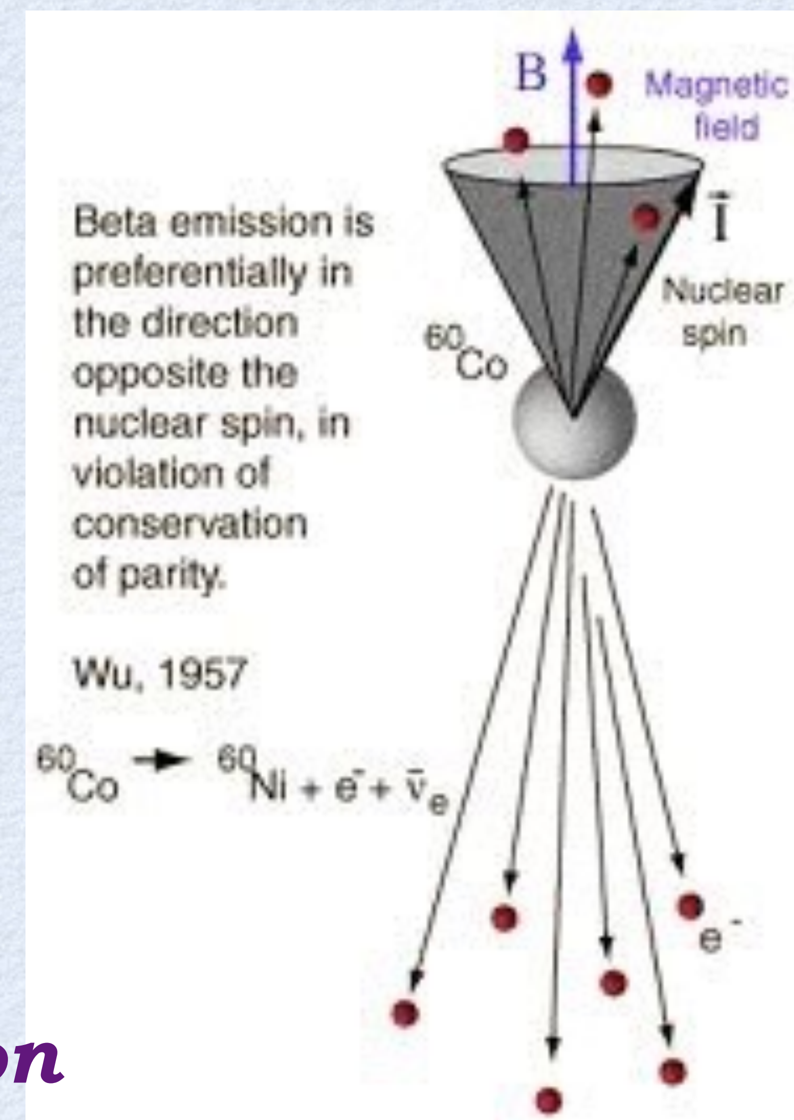


Weak decay of ^{60}Co Nucleus

observed anisotropy in beta-emission when nuclei aligned to a magnetic field

1957



signature of parity violation

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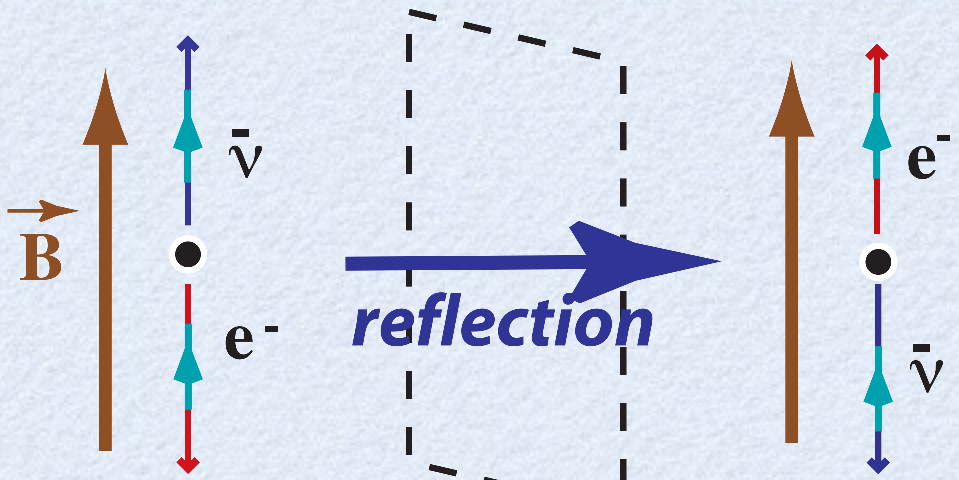

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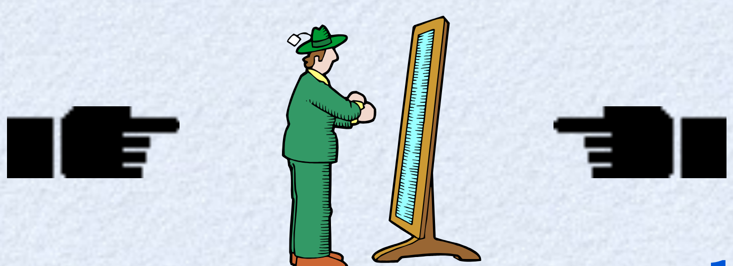

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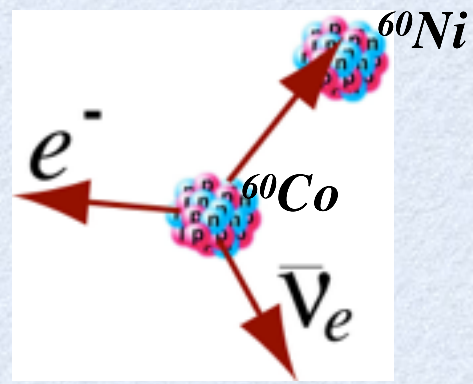

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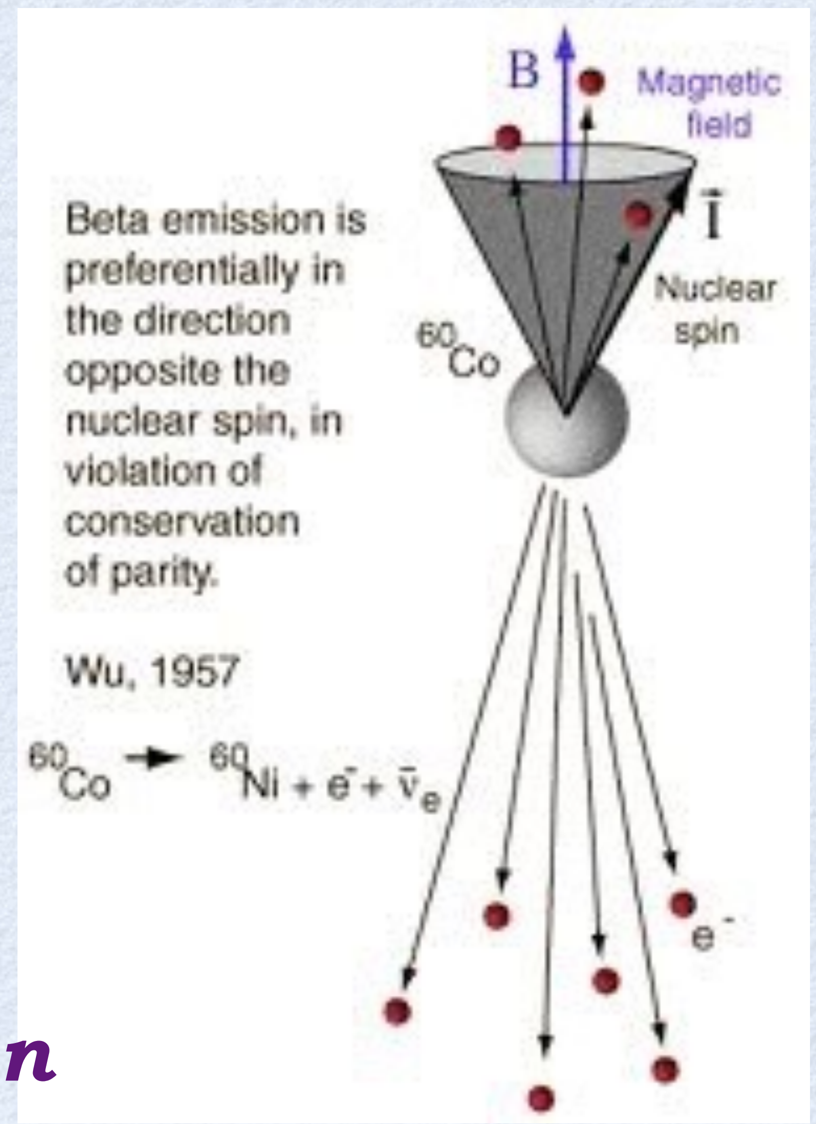

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Parity Violation Signature

Zel'dovich speculation: Is Electron Scattering Parity-Violating?

JETP **36**, pp 964-66 (1959)

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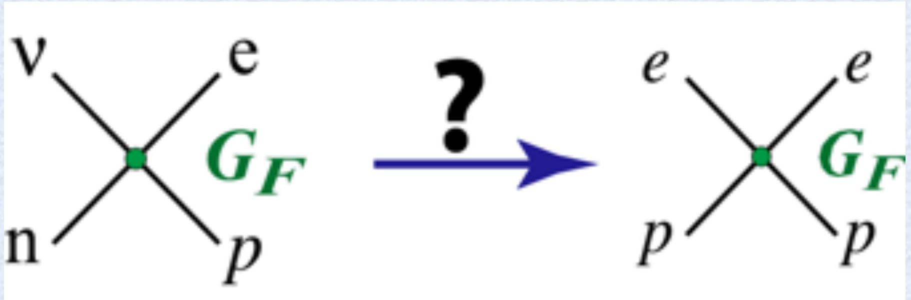
Electron-proton Weak Scattering



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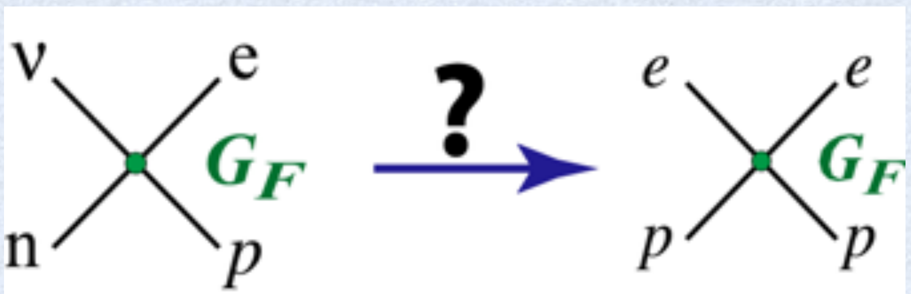

$$\sigma \;\alpha\; \left|A_{EM} + A_{weak}\right|^2$$
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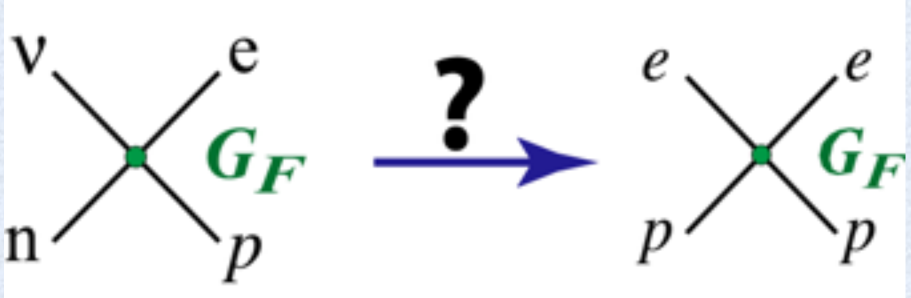

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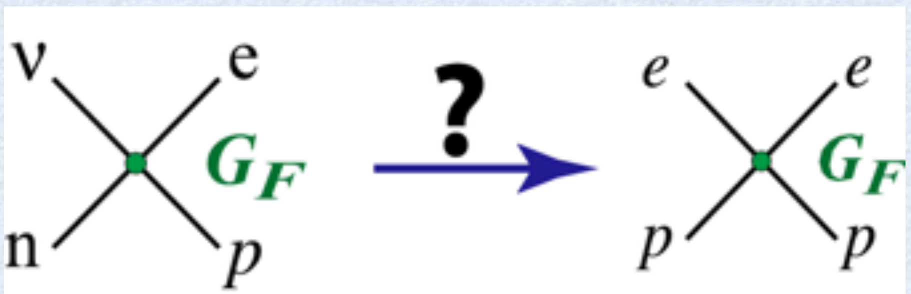

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$$A_{PV} = \frac{\sigma_{\uparrow} - \sigma_{\downarrow}}{\sigma_{\uparrow} + \sigma_{\downarrow}} = -A_{LR}$$

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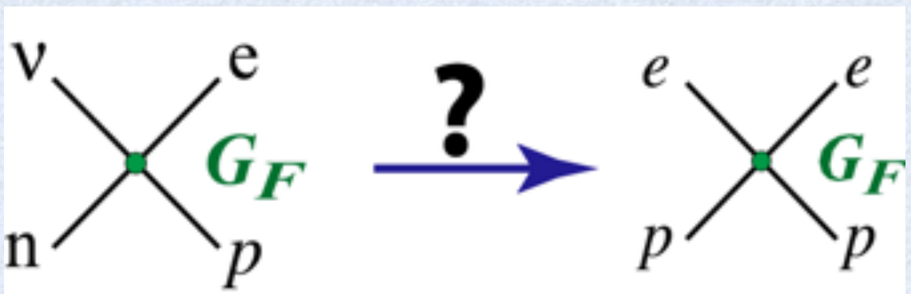

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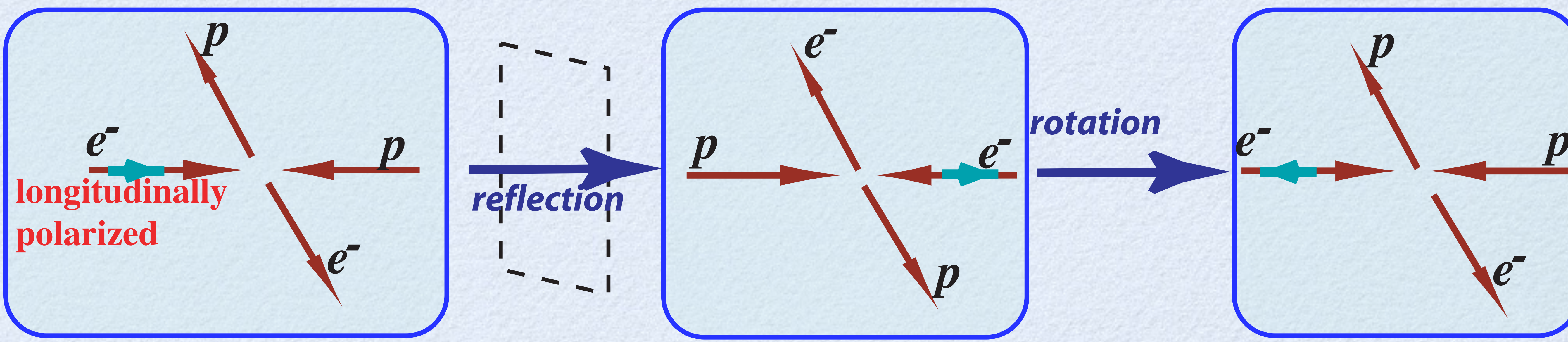

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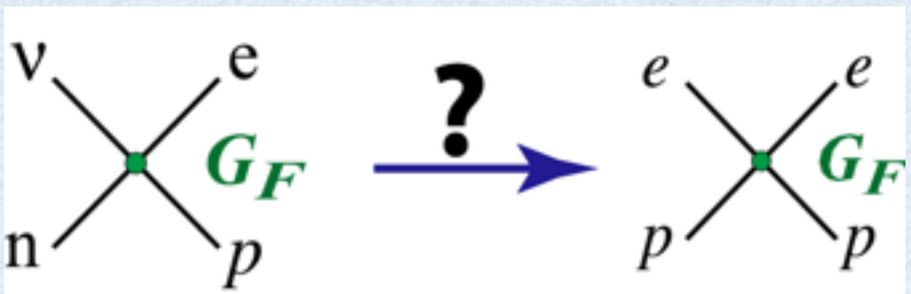

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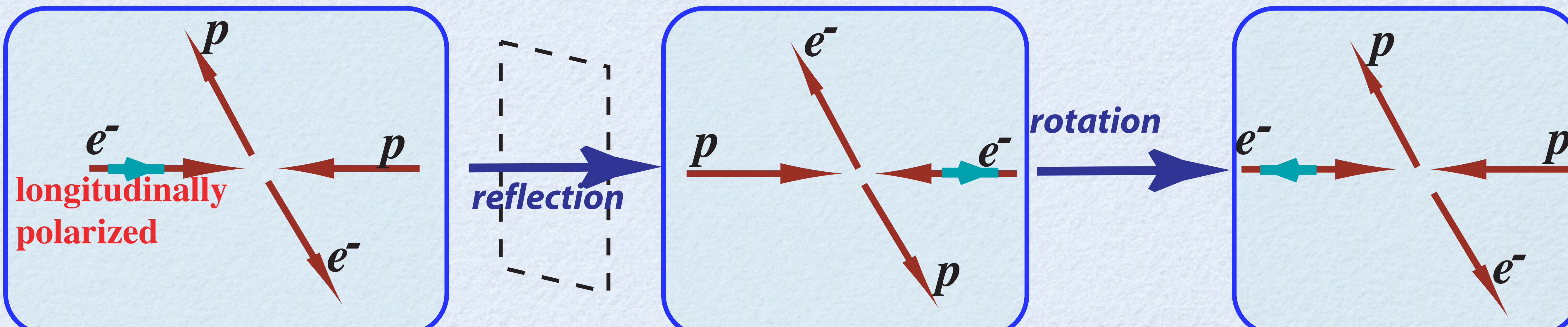

- *longitudinally polarize one beam with the ability to change its sign*
- *Measure fractional rate difference with a sensitivity of a part in 10,000*

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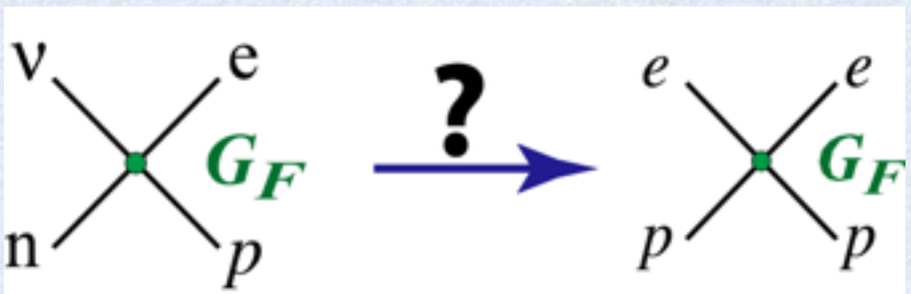

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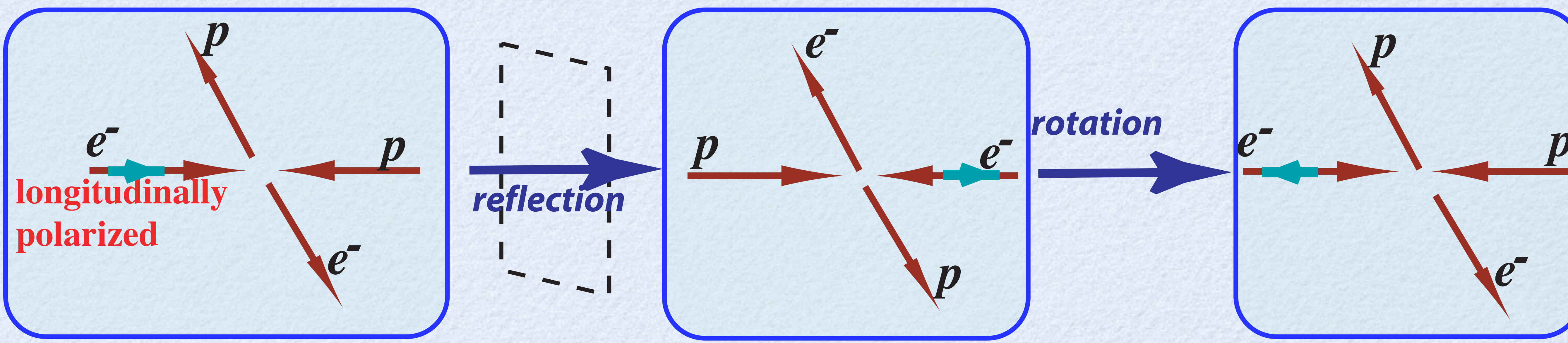

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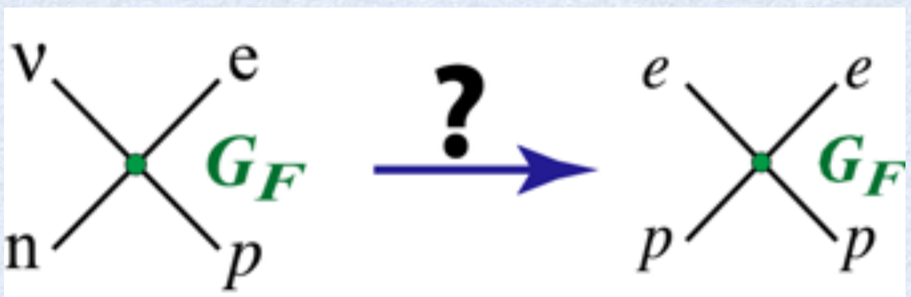

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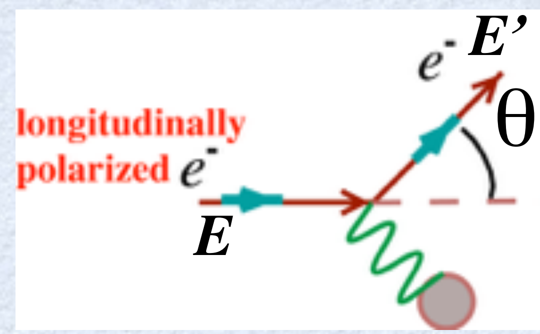

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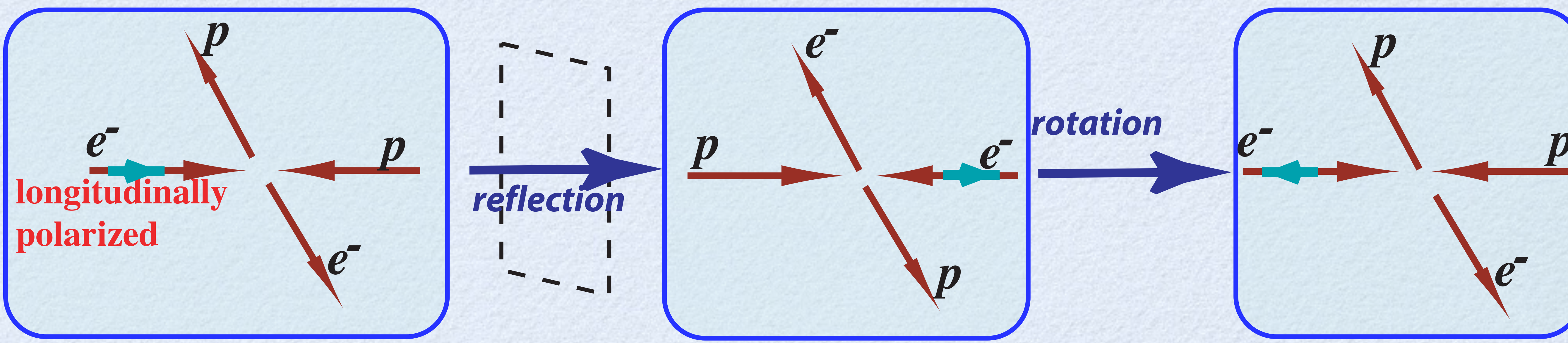

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Glashow, Weinberg and Salam: $SU(2)_L$ X $U(1)_Y$

Neutral Weak Interaction Theory

The Z boson incorporated *One free parameter: weak mixing angle θ_W*

	Left-	Right-
γ Charge	$0,\pm 1,\pm \frac{1}{3},\pm \frac{2}{3}$	$0,\pm 1,\pm \frac{1}{3},\pm \frac{2}{3}$
W Charge	$T = \pm \frac{1}{2}$	zero
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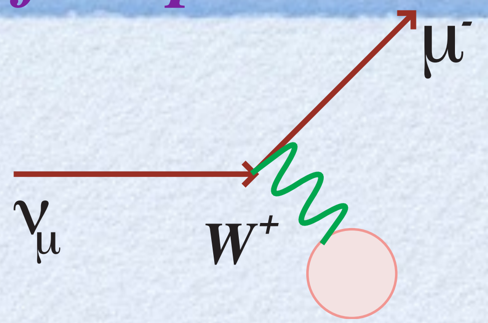

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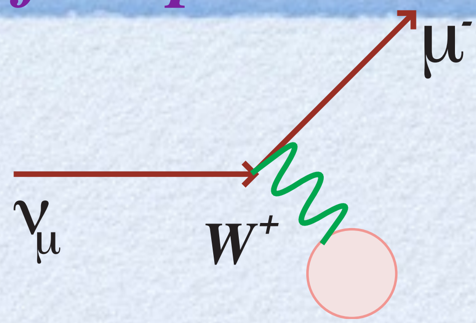

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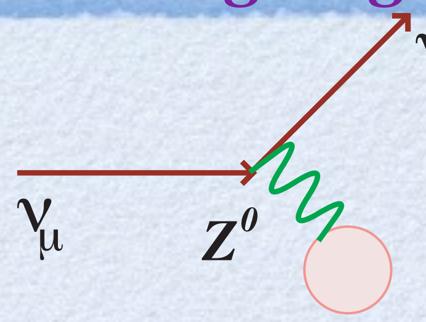

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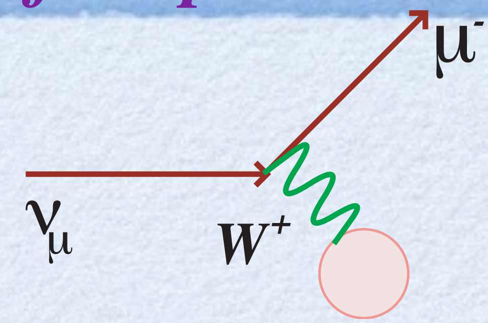

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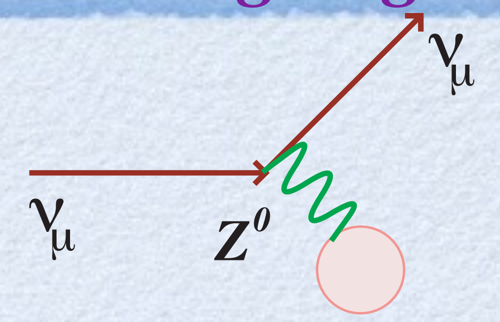

Neutral Current

Do lepton-nucleon neutral current interactions exhibit parity violation?

$$\binom{\nu}{e}_l \quad (e)_r$$

or

$$\binom{\nu}{e}_l \quad \binom{E^\circ}{e}_r$$

Weinberg model

Parity is violated

$$A_{PV} \sim 10^{-4}$$

Parity is conserved

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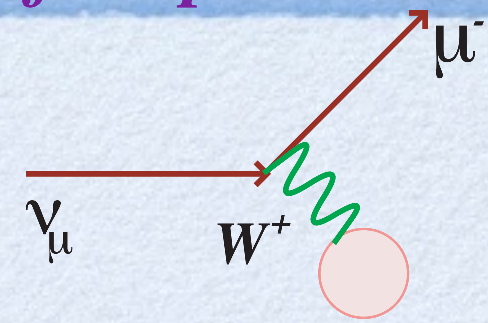

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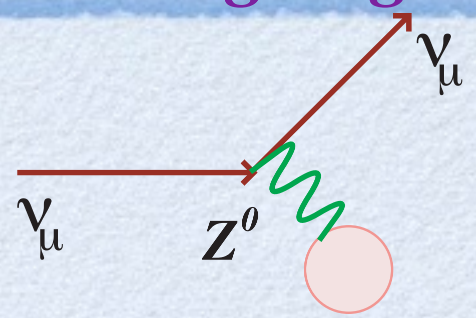

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Parity is conserved

First table-top atomic parity violation searches: negative!

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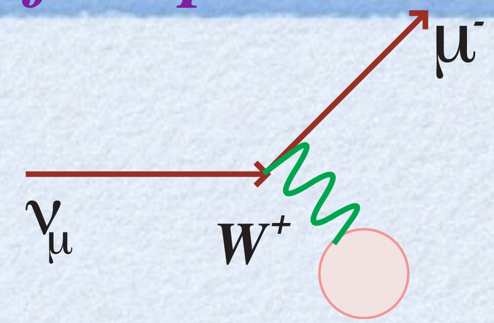

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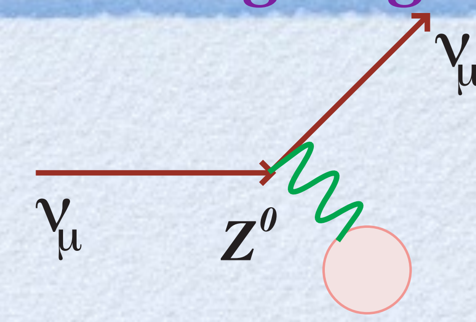

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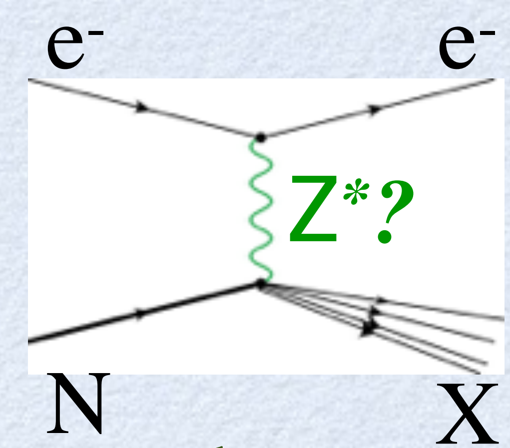
Parity is conserved

electron-nucleon deep inelastic scattering



pressing problem in mid-70's

First table-top atomic parity violation searches: negative!

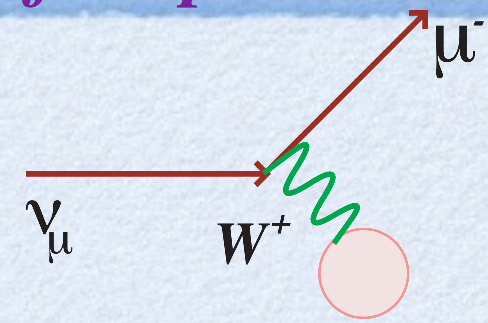
Glashow, Weinberg and Salam: $SU(2)_L \times U(1)_Y$

Neutral Weak Interaction Theory

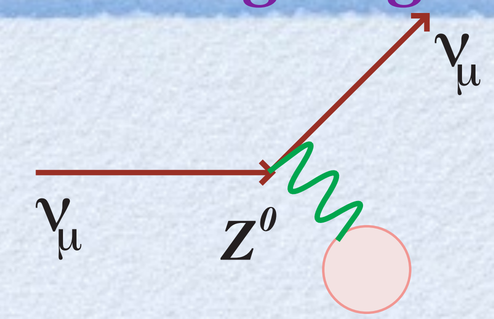
The Z boson incorporated

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

One free parameter: weak mixing angle θ_W



Charged Current



Neutral Current

Do lepton-nucleon neutral current interactions exhibit parity violation?

$\begin{pmatrix} \nu \\ e \end{pmatrix}_l \quad (e)_r$ ← *Weinberg model*

Parity is violated

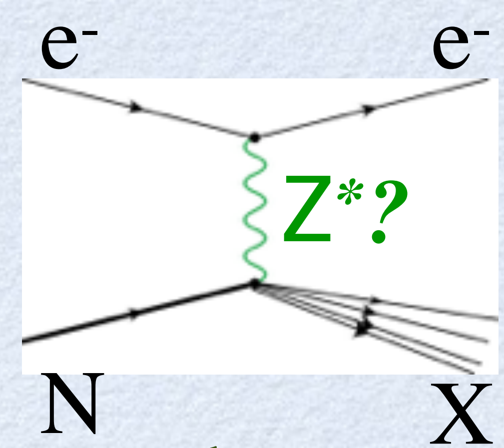
or

$\begin{pmatrix} \nu \\ e \end{pmatrix}_l \quad \begin{pmatrix} E^\circ \\ e \end{pmatrix}_r$

$$A_{PV} \sim 10^{-4}$$

Parity is conserved

electron-nucleon deep inelastic scattering



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Seminal Experimental Measurement: E122 at the Stanford Linear Accelerator Center

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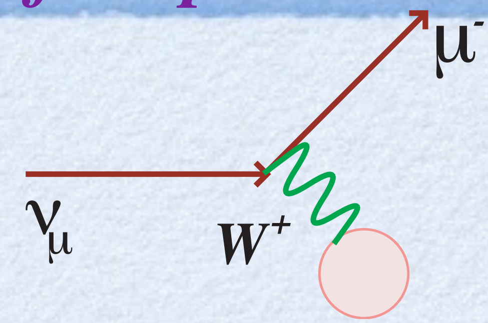

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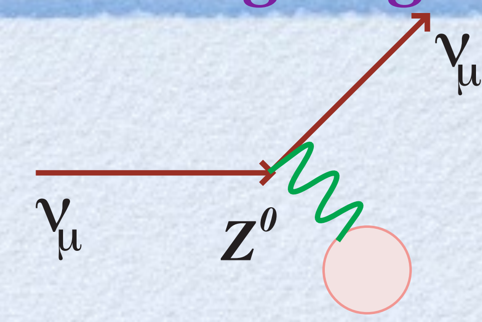

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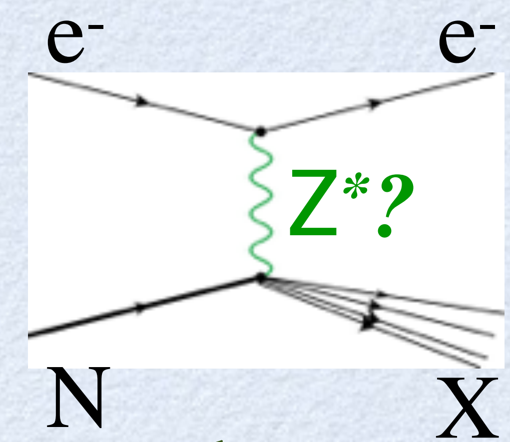


pressing problem in mid-70's

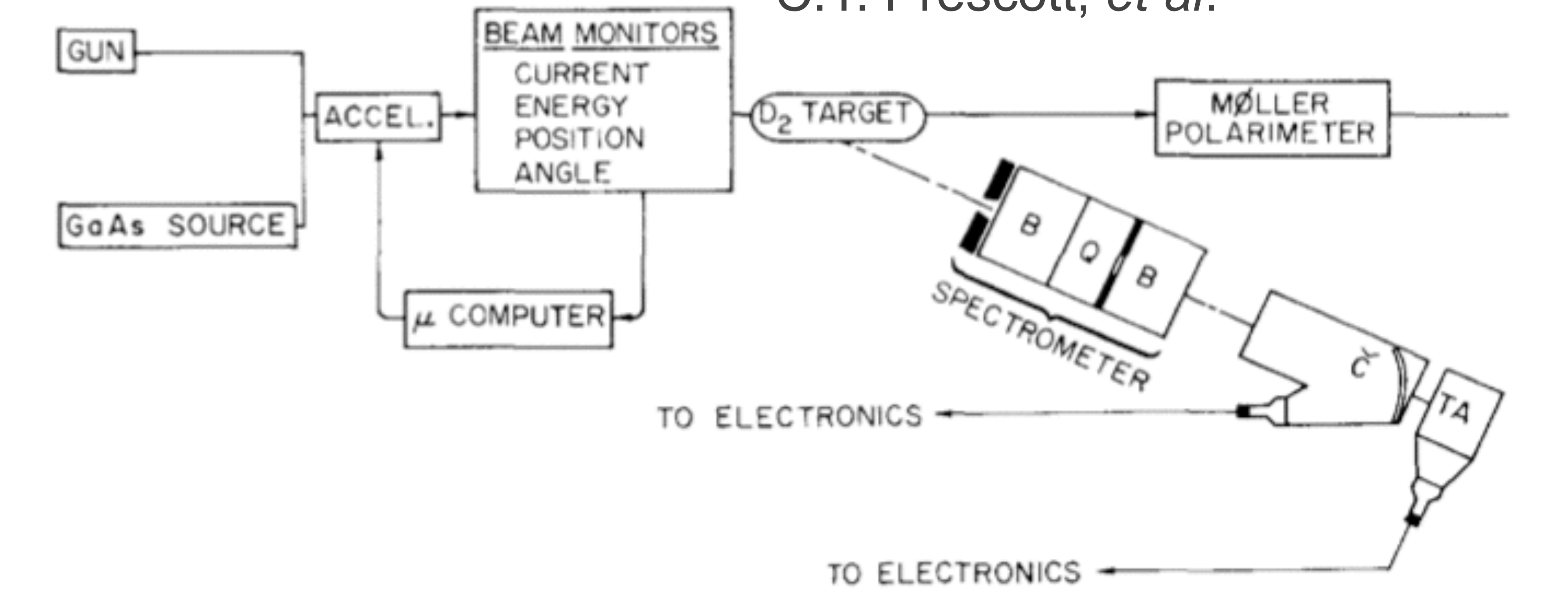
Seminal Experimental Measurement: E122 at the Stanford Linear Accelerator Center

- ***Parity Violation in Weak Neutral Current Interactions***
- ***$\sin^2\theta_W$ = 0.224 ± 0.020: same as in neutrino scattering***

Anatomy of a Parity Experiment

The E122 Experiment at the Stanford Linear Accelerator Center

C.Y. Prescott, *et al.*



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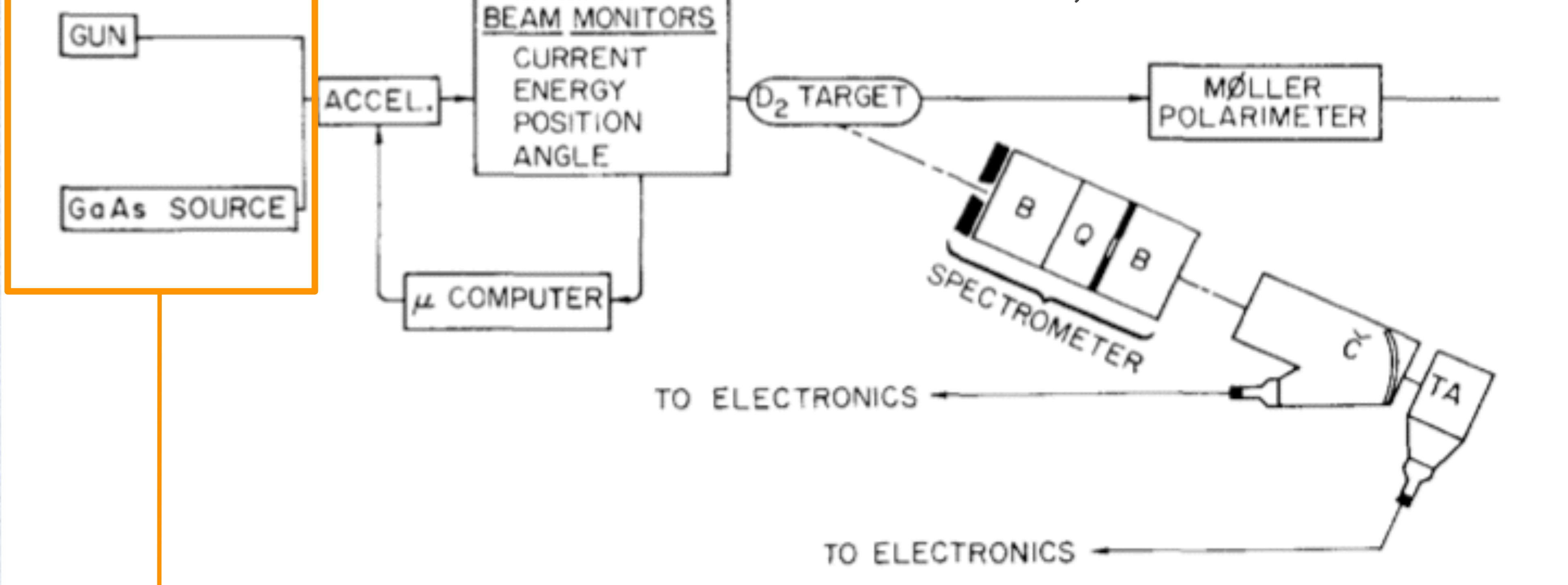
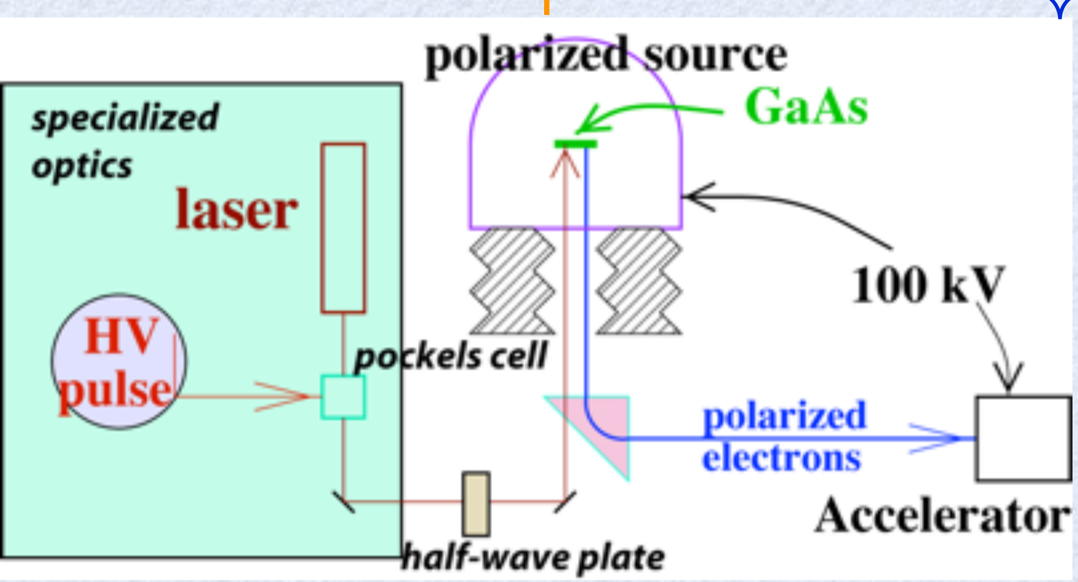
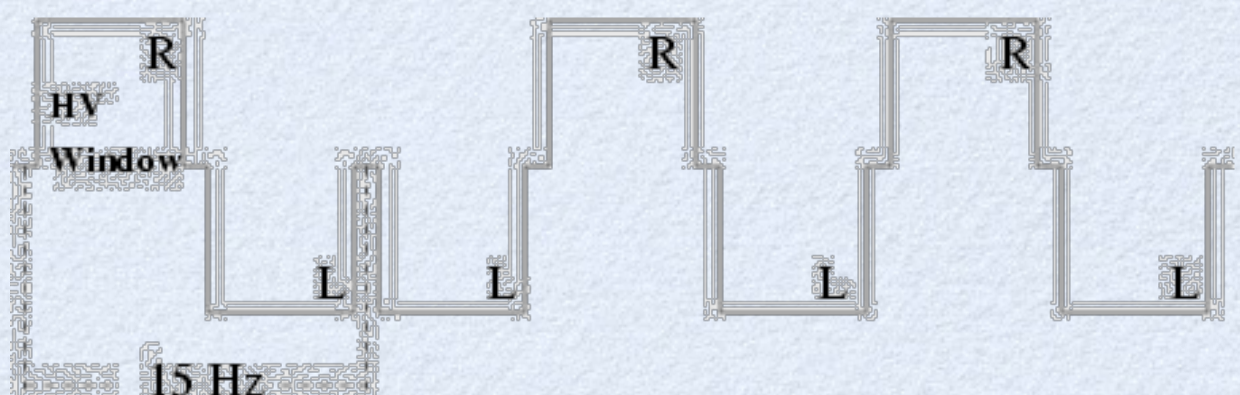




✧ **Beam helicity sequence is chosen pseudo-randomly**

- Helicity state, followed by its complement
- Data analyzed as “pulse-pairs”



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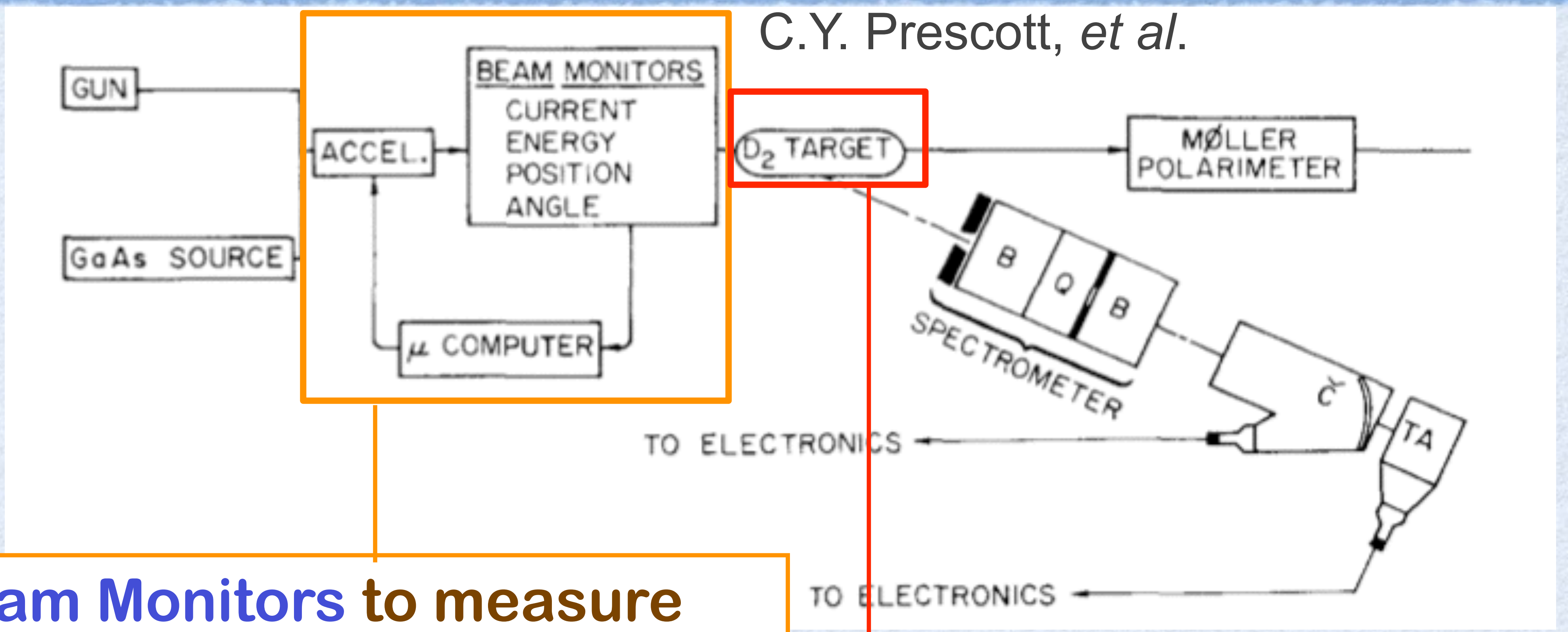

- **Beam Monitors** to measure helicity-correlated changes in beam parameters

- **High-power cryotarget** 30 cm long for high luminosity

Anatomy of a Parity Experiment

The E122 Experiment at the Stanford Linear Accelerator Center

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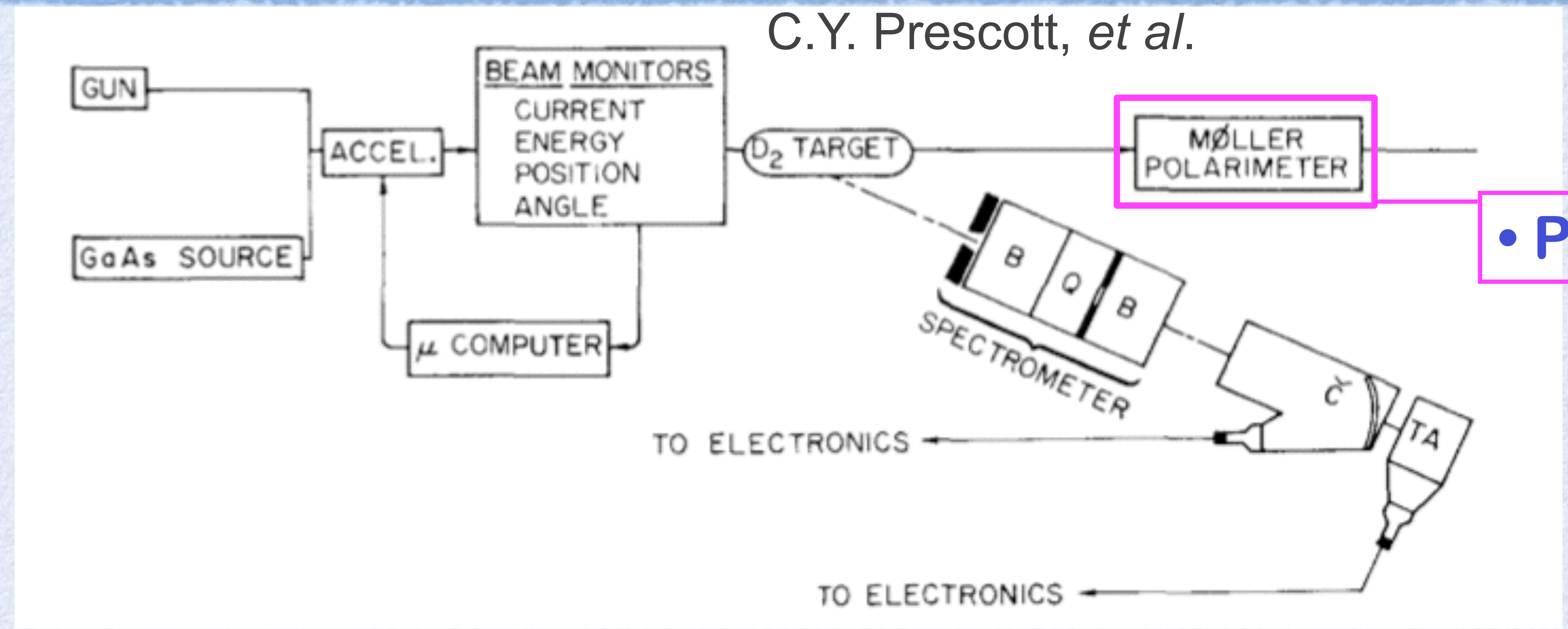

- **Polarimetry**

Anatomy of a Parity Experiment

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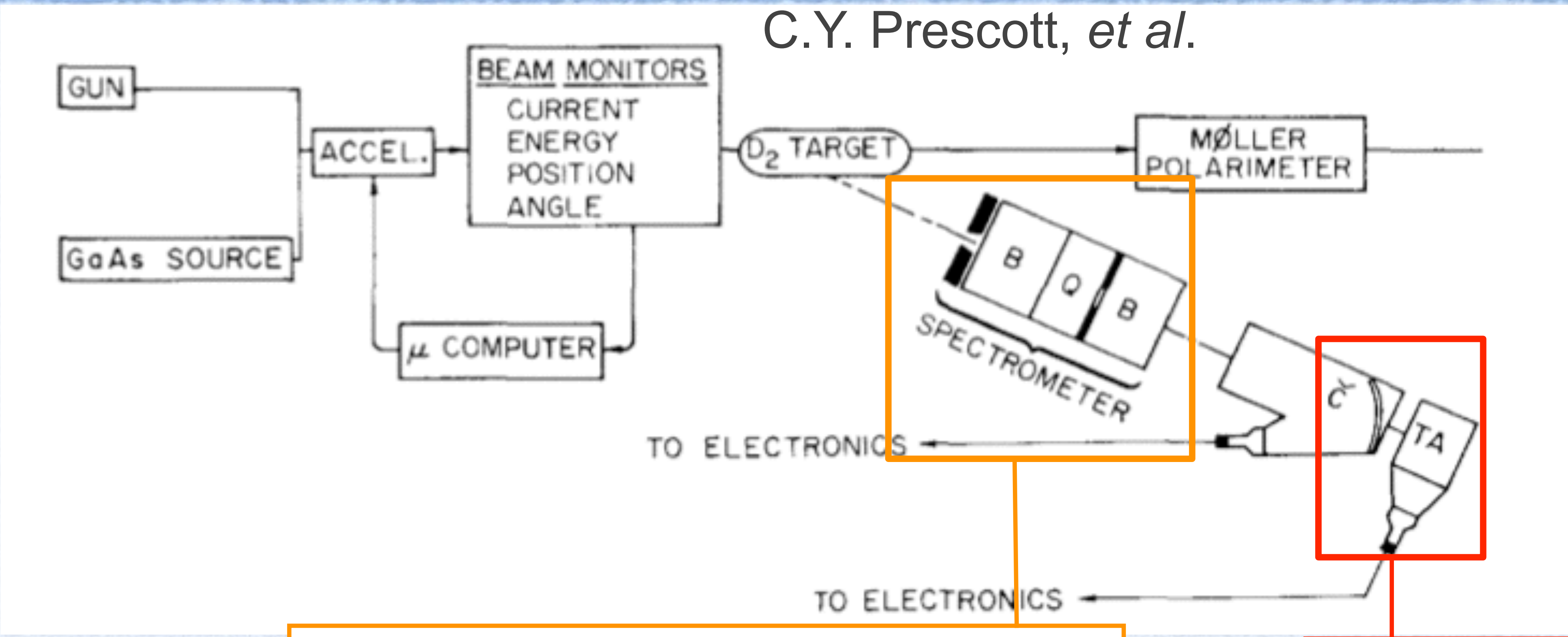
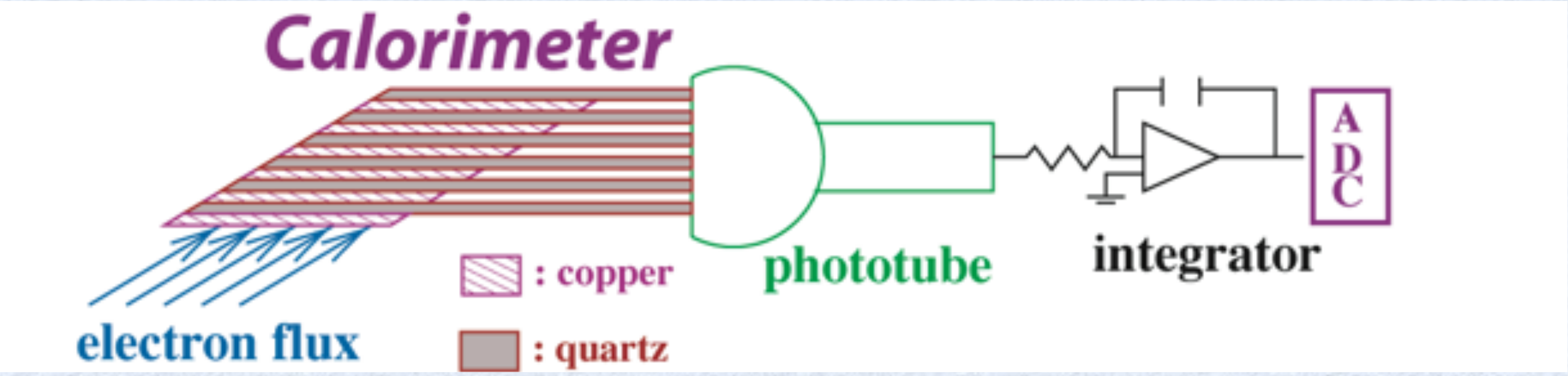


- **Magnetic spectrometer** directs flux to background-free region

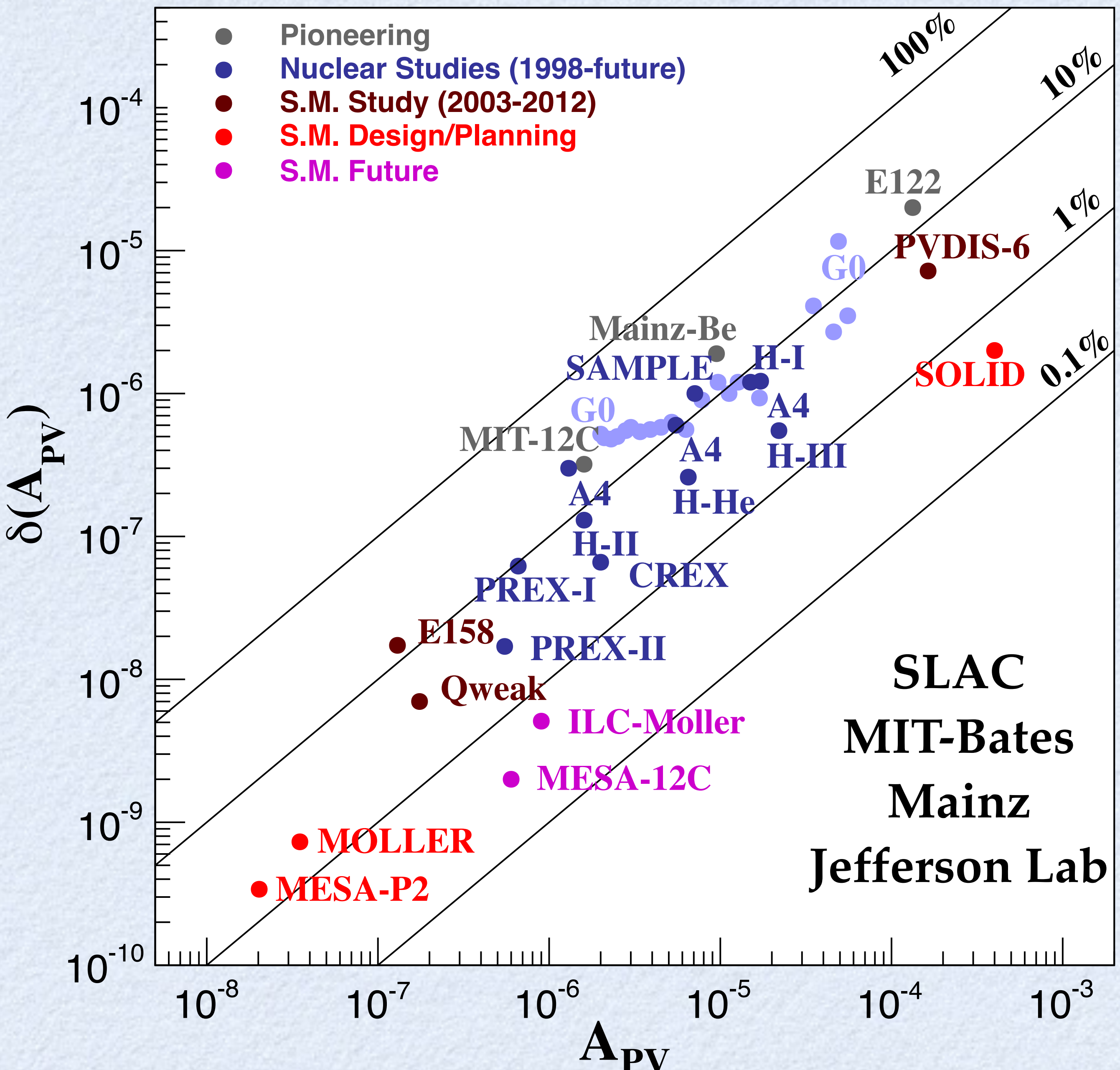
- **Flux Integration** measures high rate without deadtime



4 Decades of Technical Progress

Continuous interplay between probing hadron structure and electroweak physics

Parity-violating electron scattering has become a precision tool



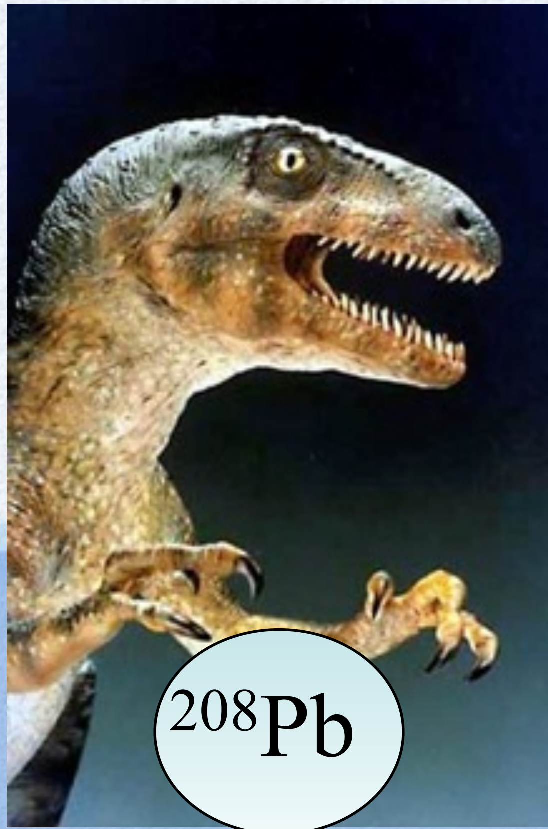
- *Beyond Standard Model Searches*
- *Strange quark form factors*
- *Neutron skin of a heavy nucleus*
- *QCD structure of the nucleon*

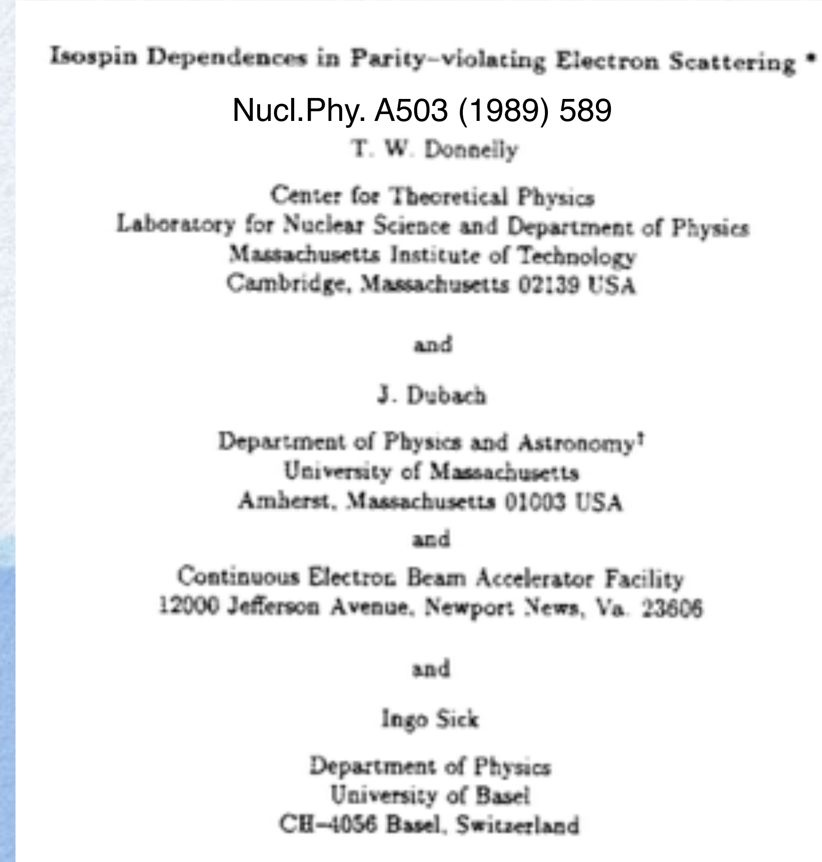
Mainz & MIT-Bates in the mid-80s
JLab program launched in the mid-90s
E158 at SLAC measured PV Møller scattering

State-of-the-art:

- ***sub-part per billion statistical reach and systematic control***
- ***sub-1% normalization control***

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




Isospin Dependences in Parity-violating Electron Scattering *

Nucl.Phy. A503 (1989) 589

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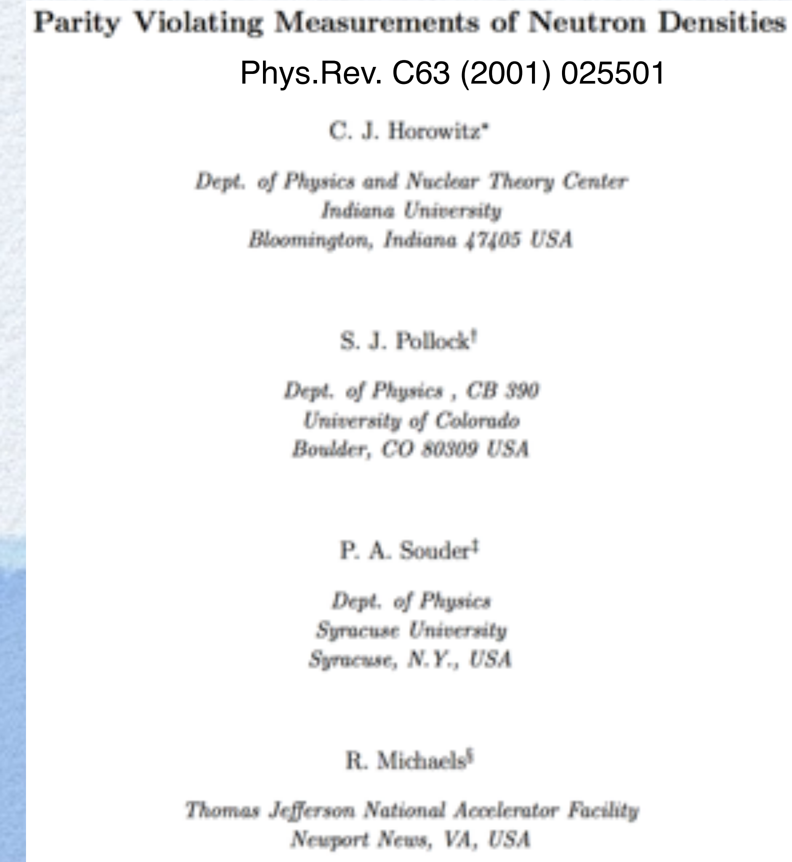
Parity Violating Measurements of Neutron Densities

Phys.Rev. C63 (2001) 025501

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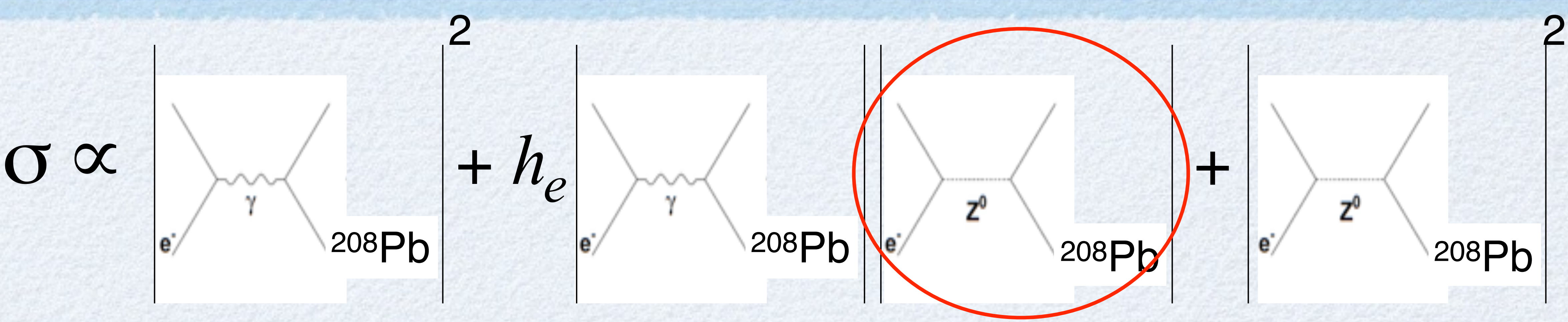
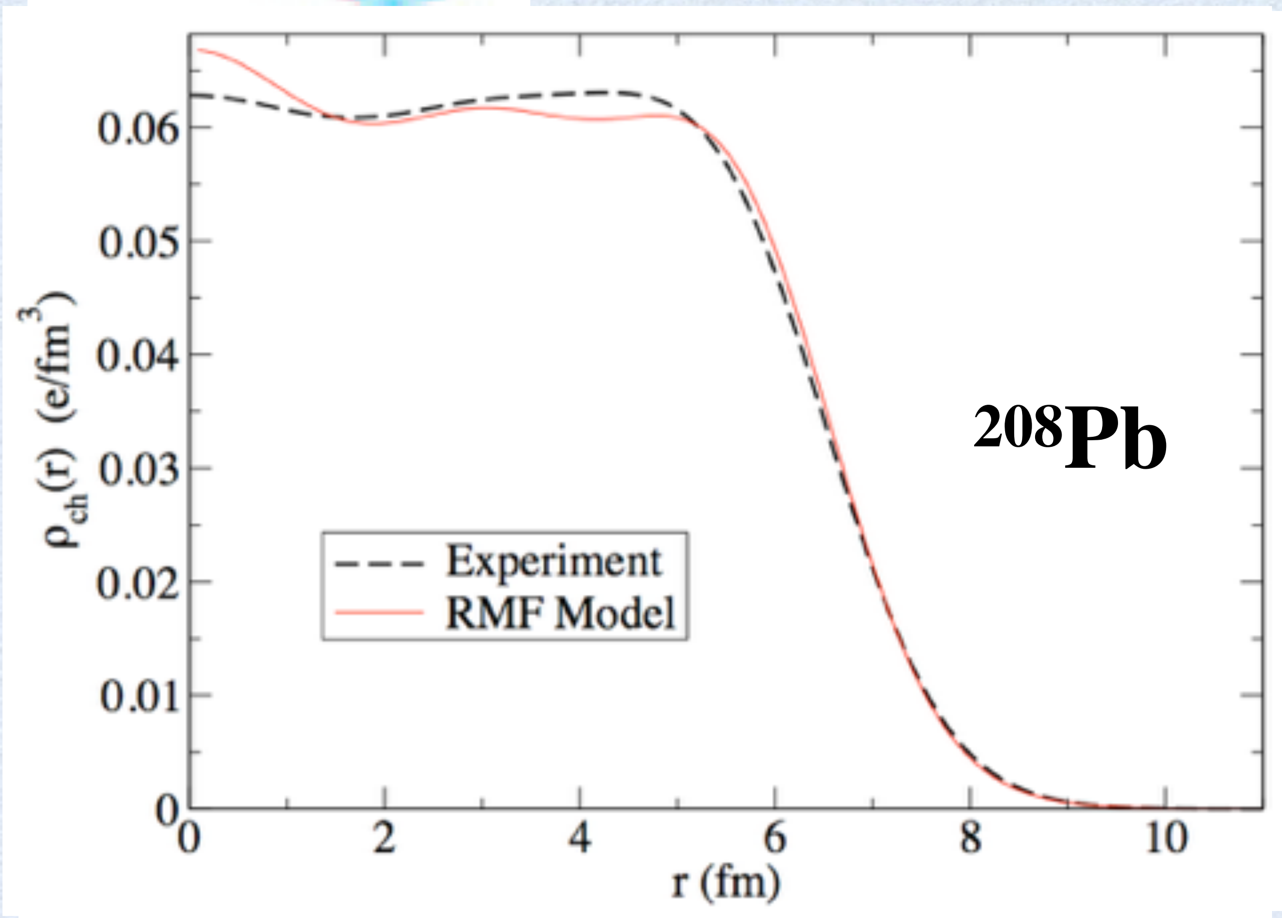
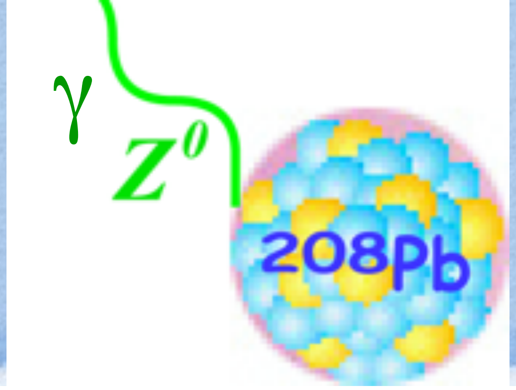
PREX at Jefferson Lab



PREX Concept

Pb-Radius EXperiment





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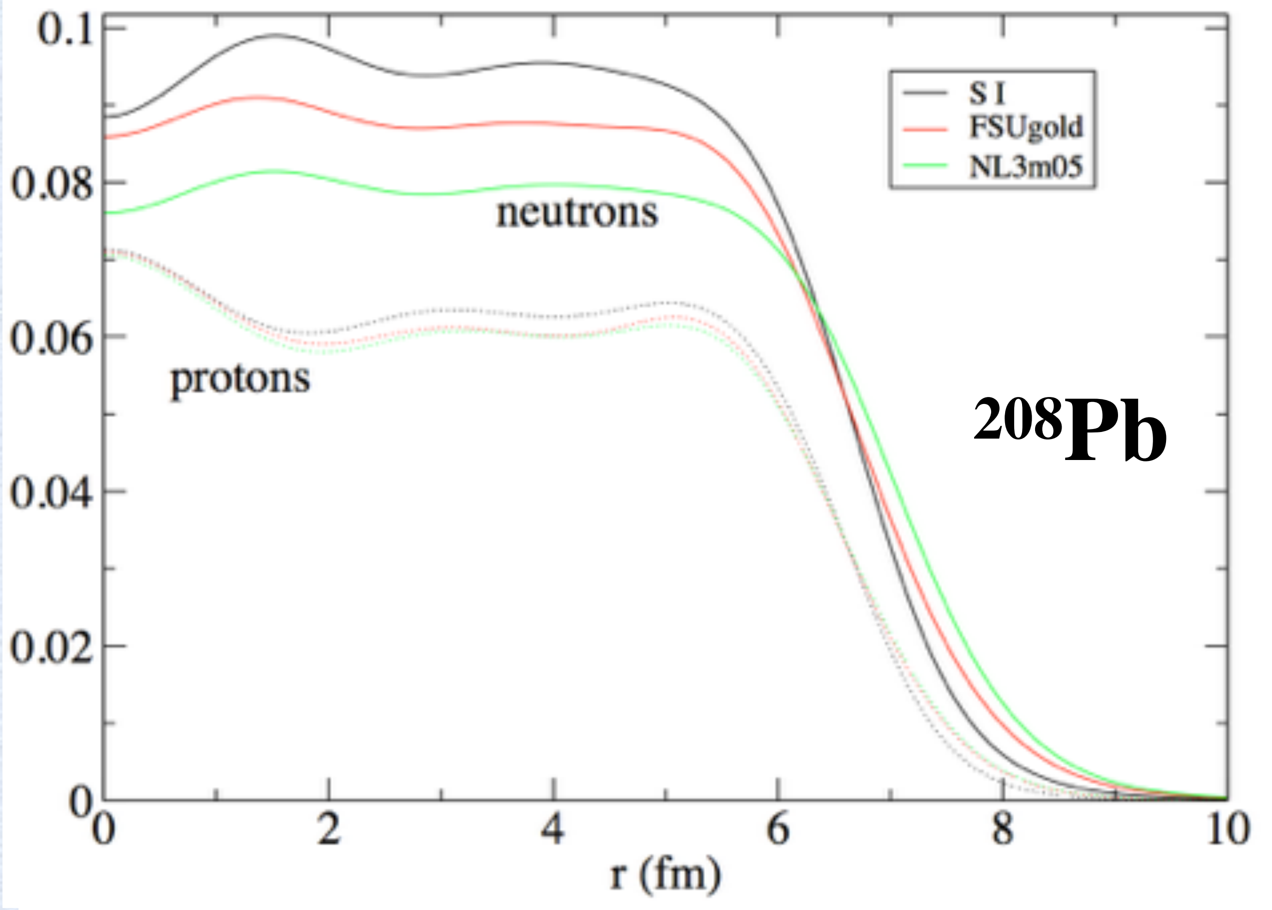

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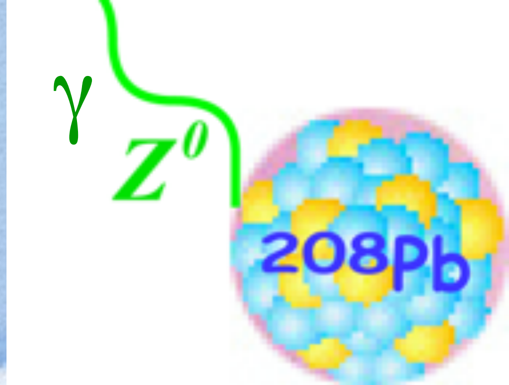

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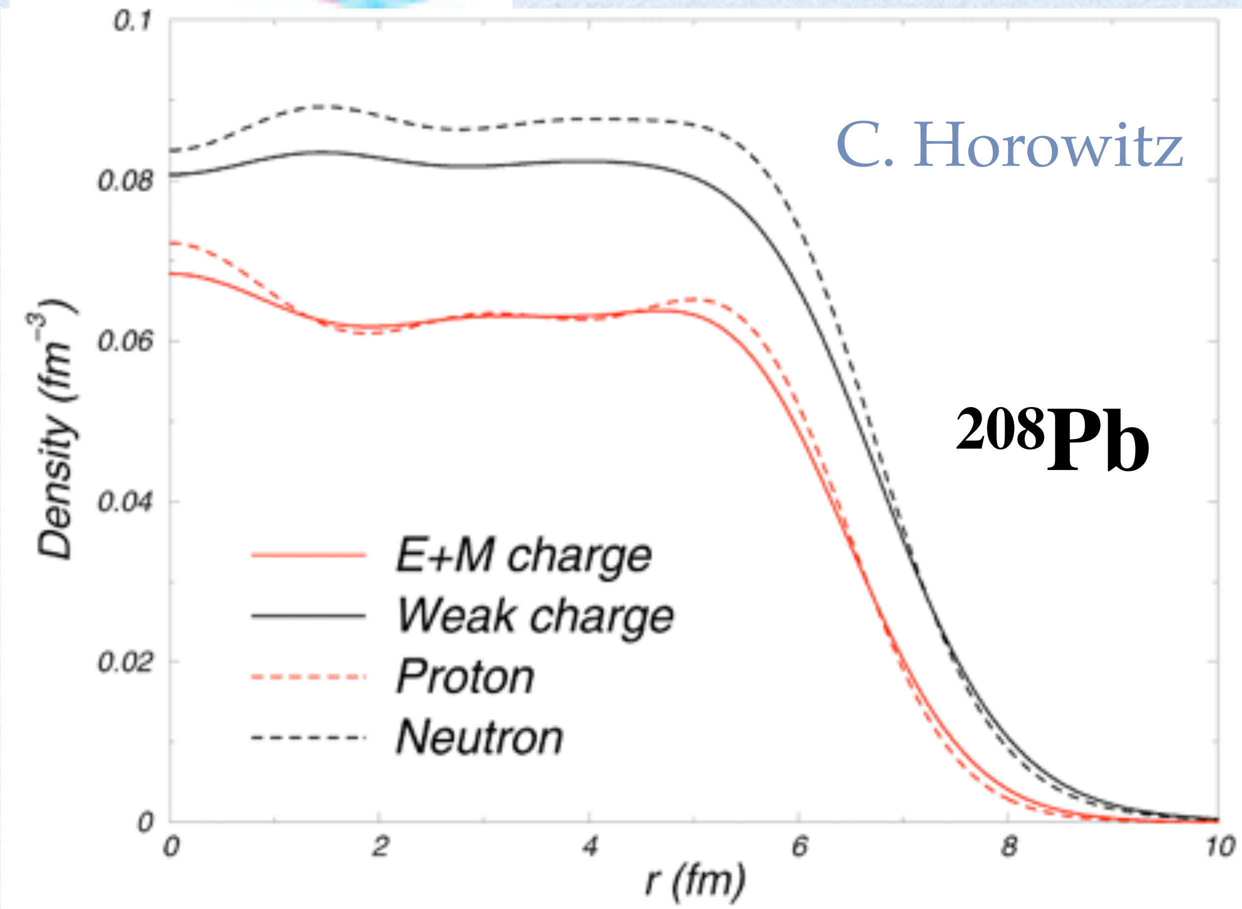

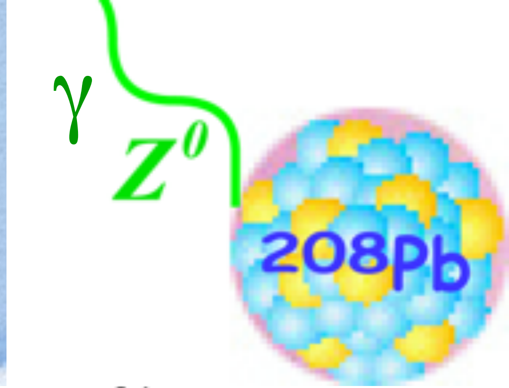

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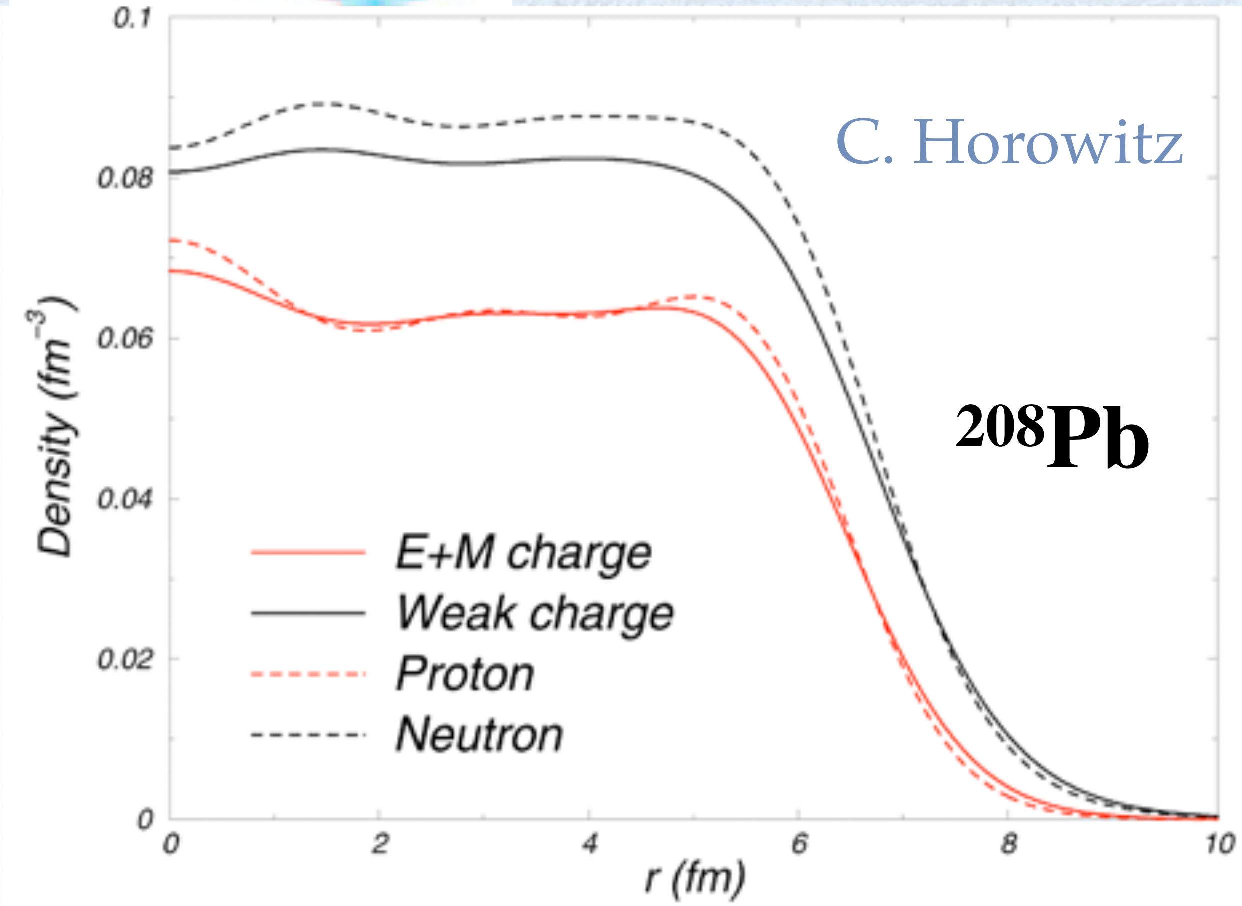

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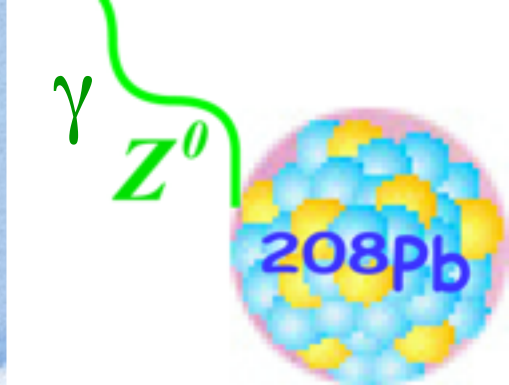

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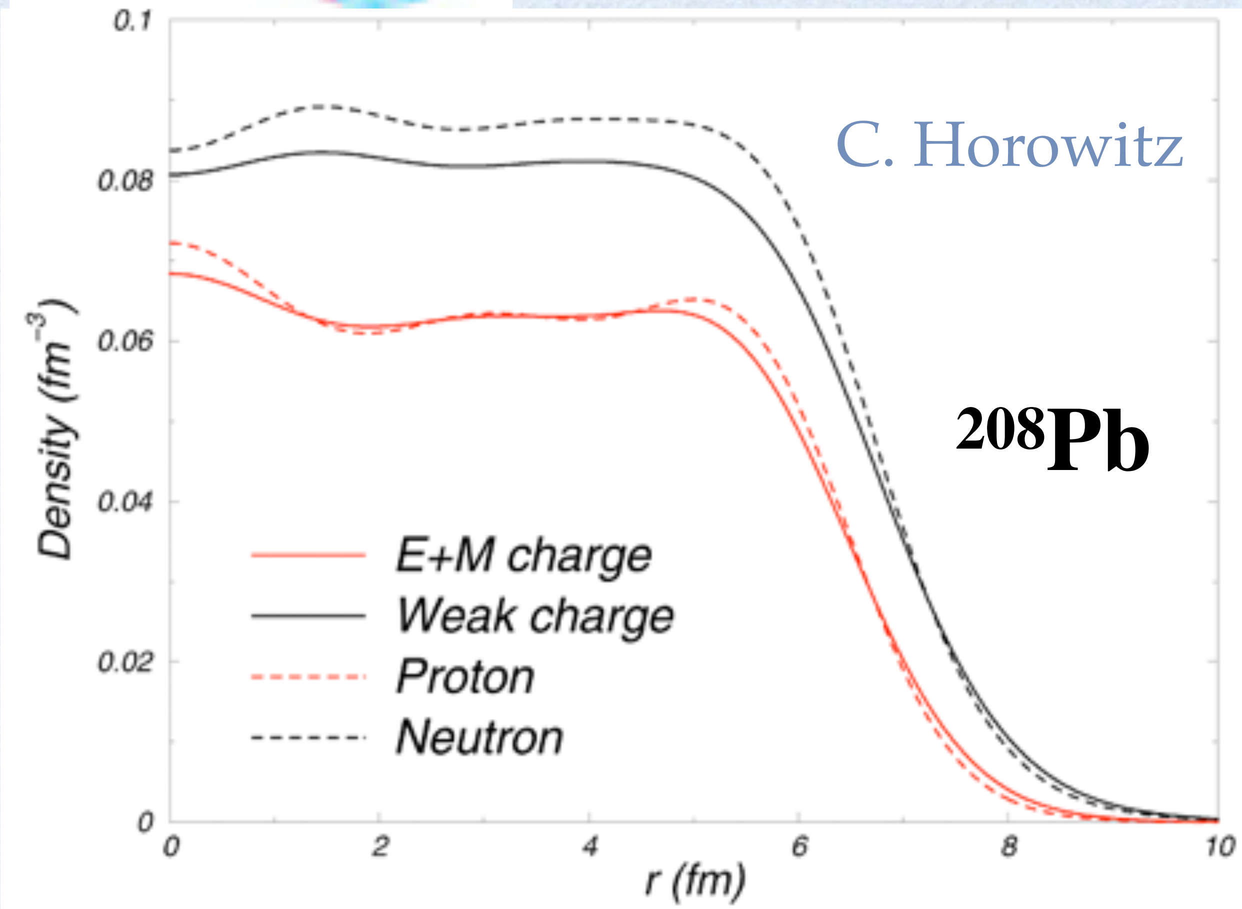

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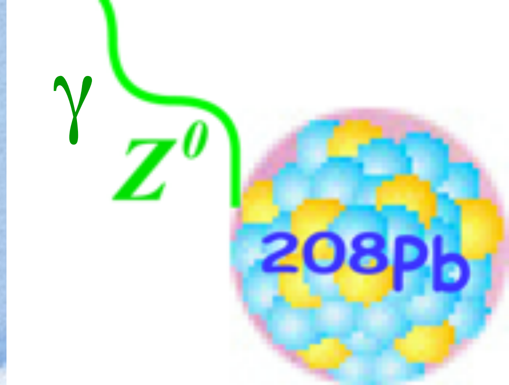
$$A_{PV} \approx \frac{G_F Q^2}{4\pi\alpha\sqrt{2}} \frac{F_n(Q^2)}{F_p(Q^2)} + \ldots$$

Small corrections involving electric form factors G_E (p,n,s)



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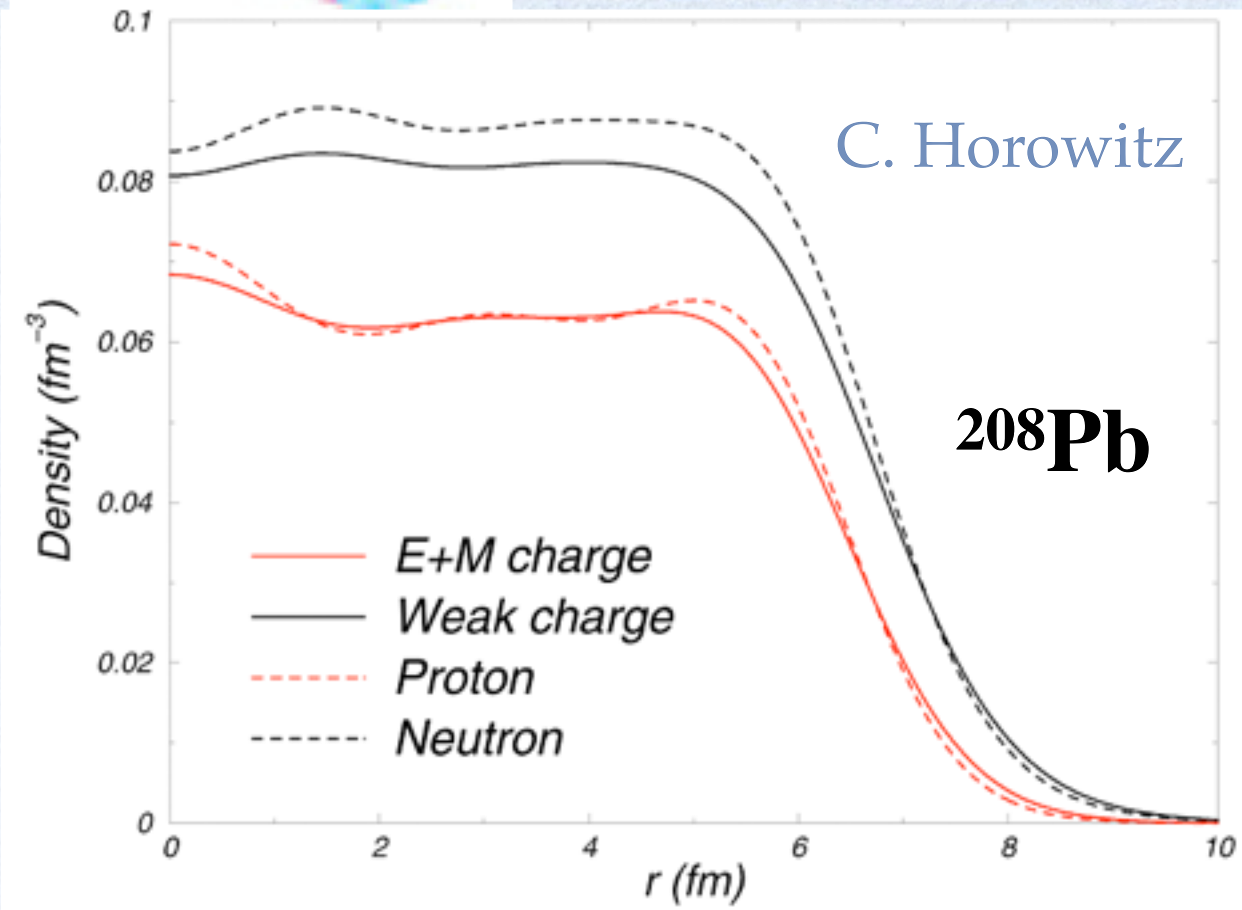

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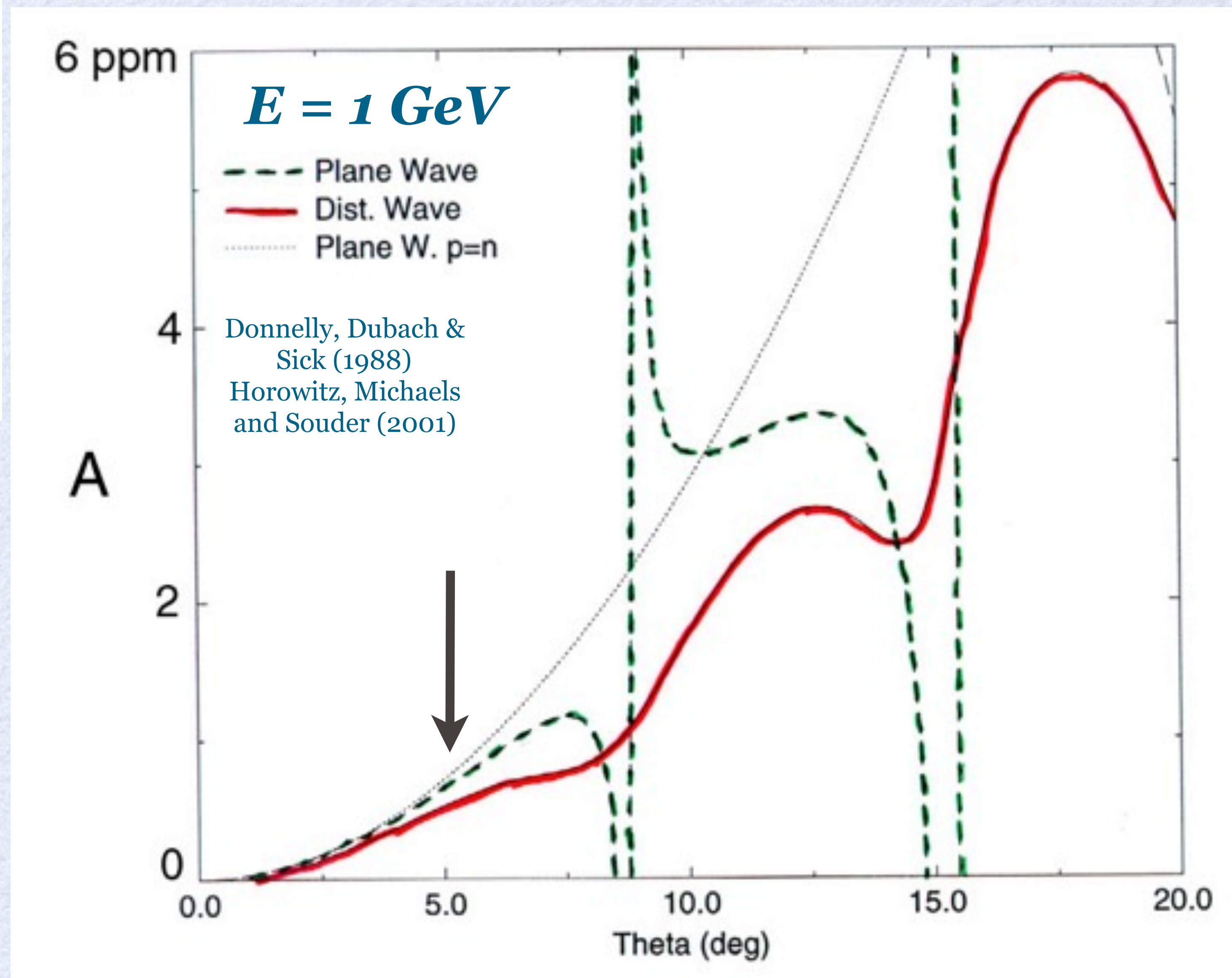

Cleanly Interpretable?

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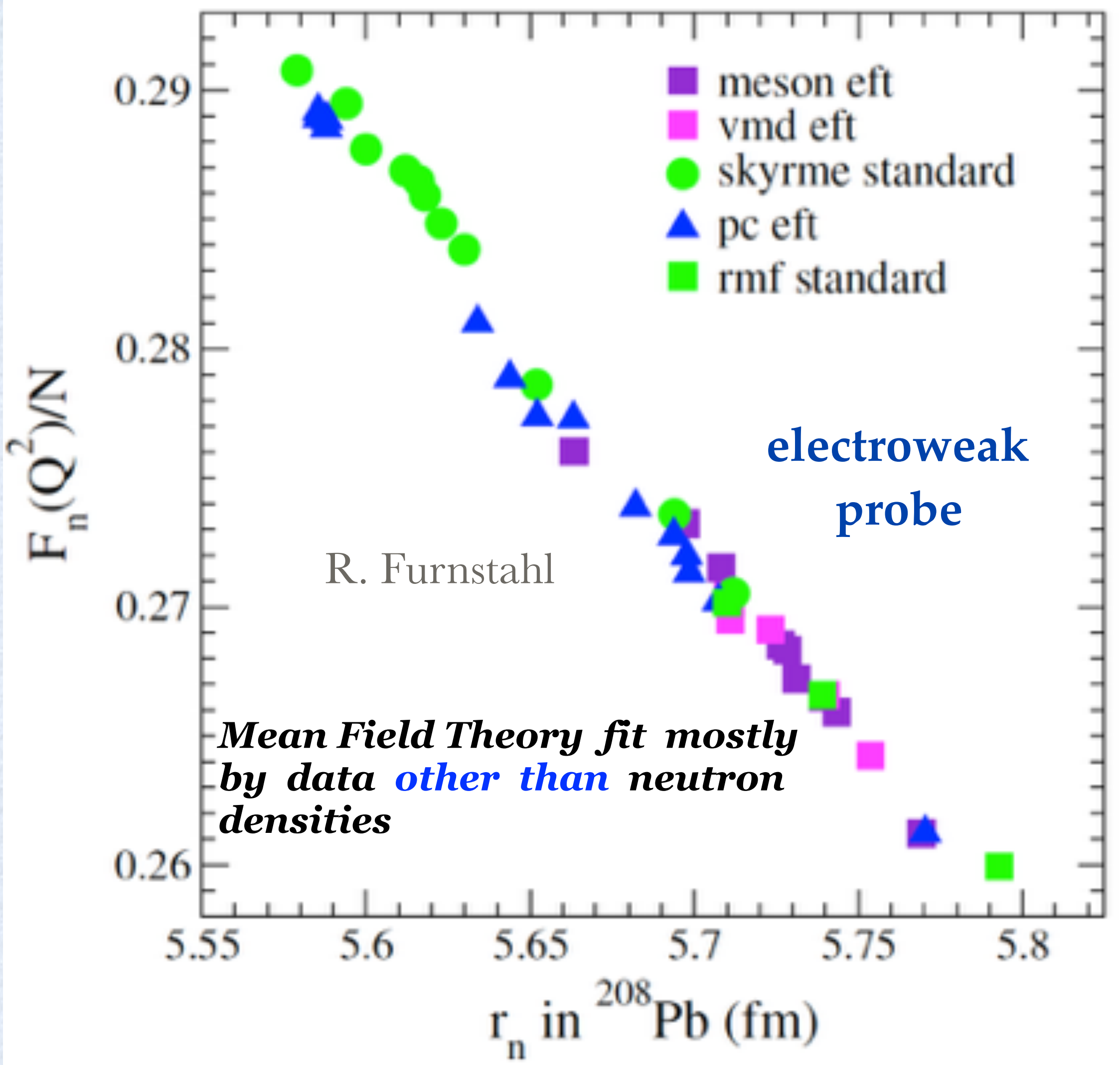

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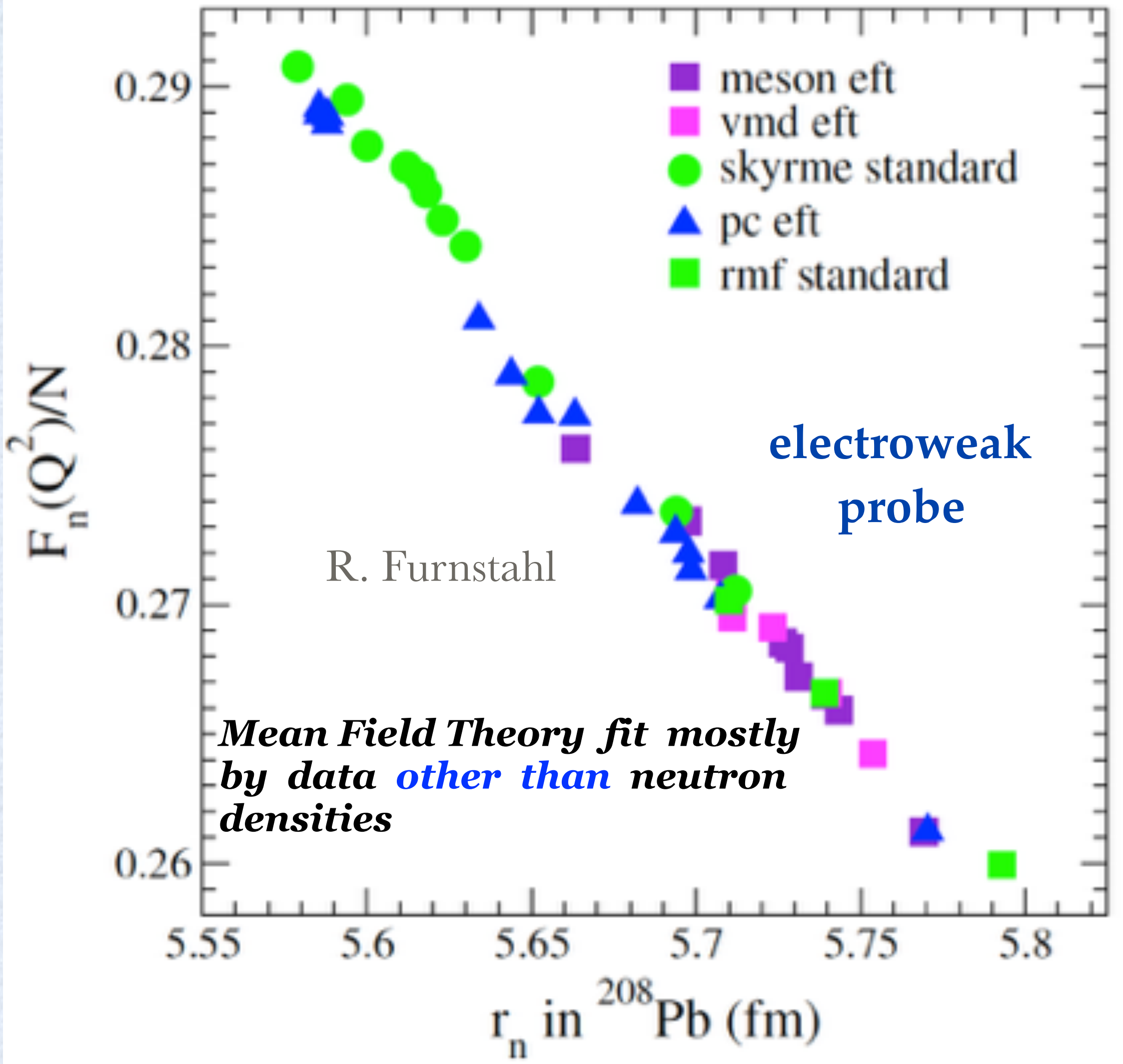

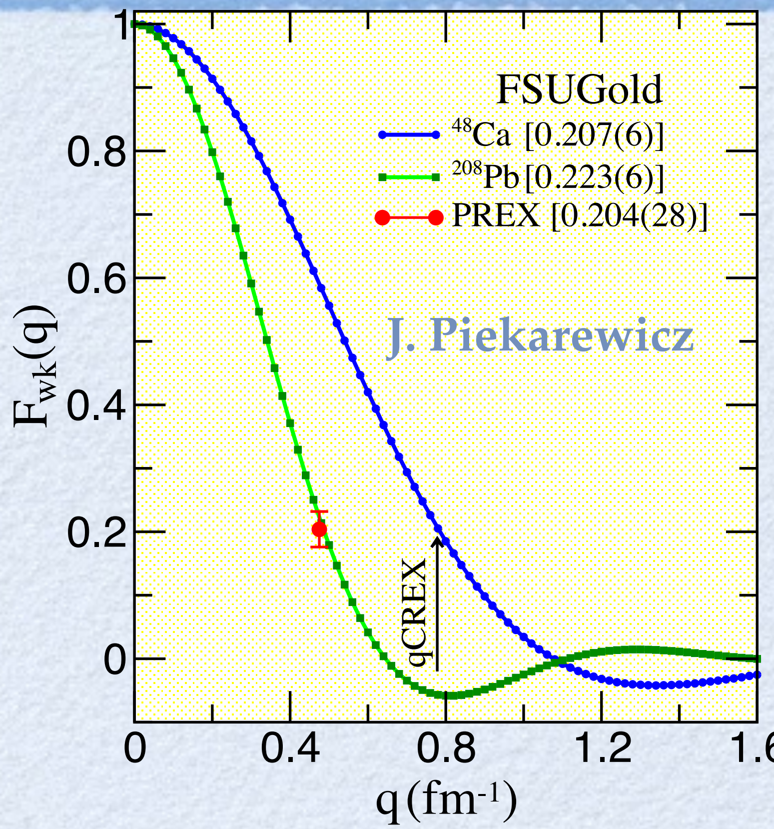

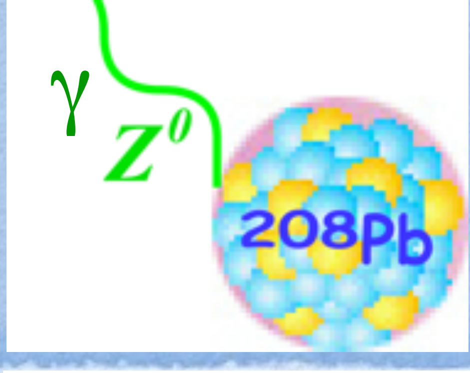

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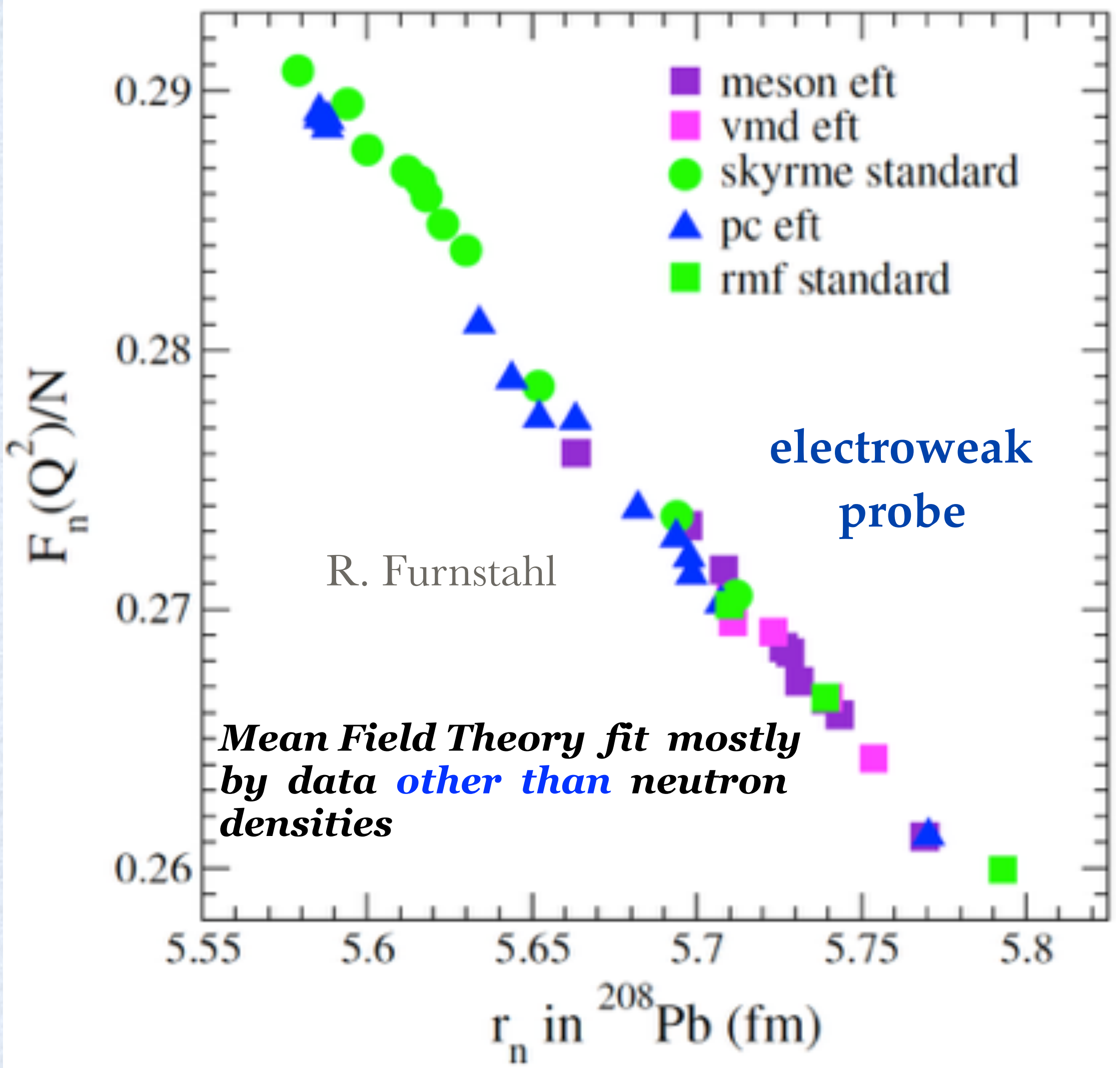


Q^2 ~ 0.01 GeV^2

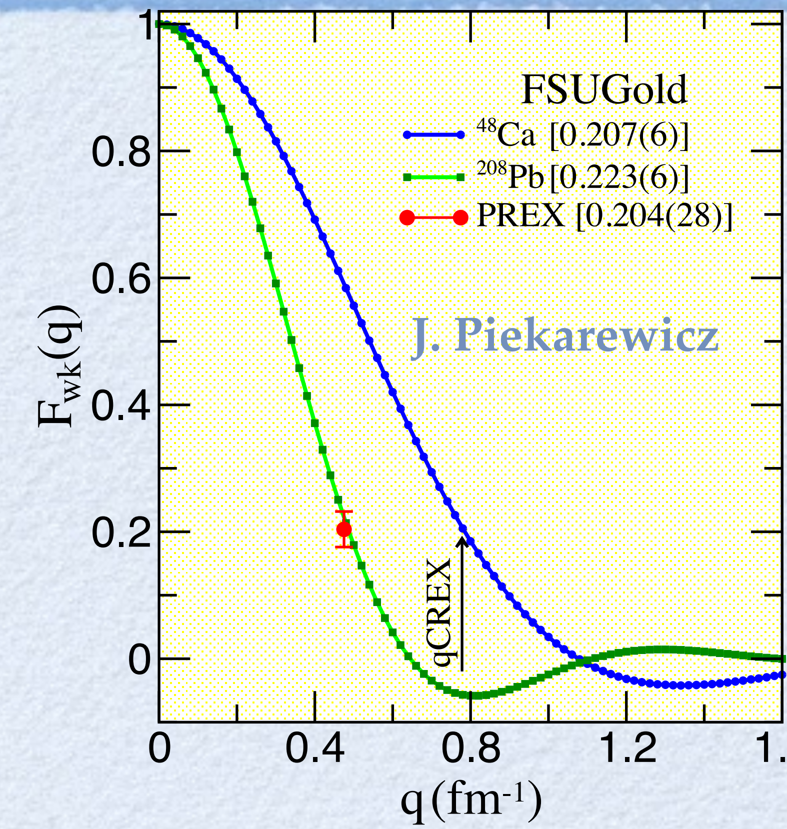
5^o scattering angle

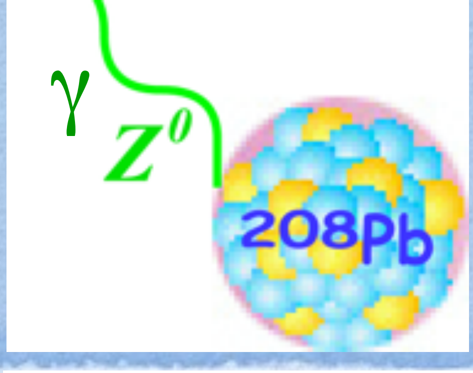
⇩

A_{PV} ~ 0.7 ppm

Rate ~ 1 GHz

$\delta(A_{PV})$ ~ 20 ppb!





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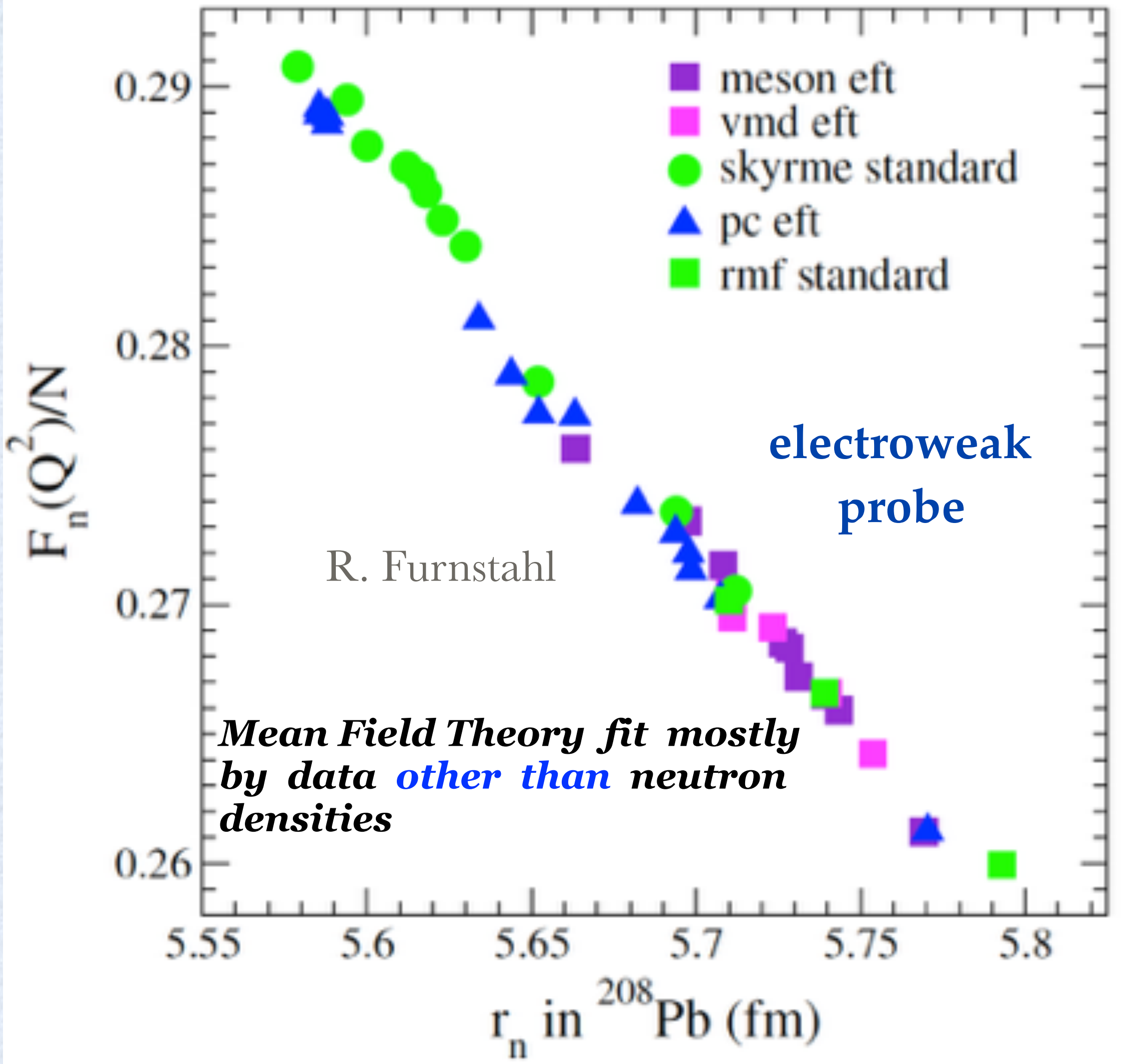

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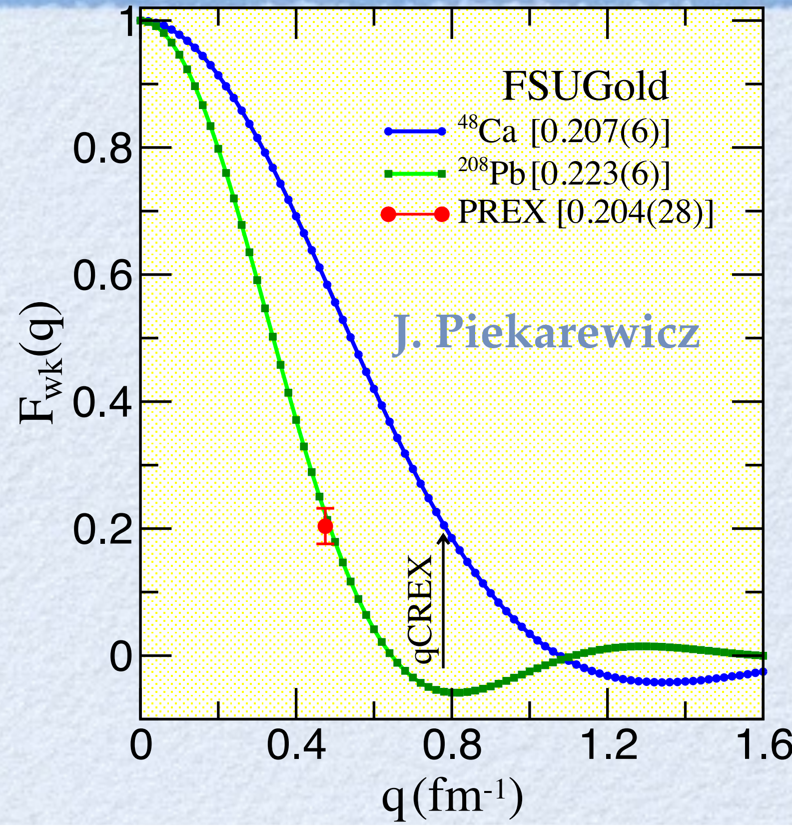

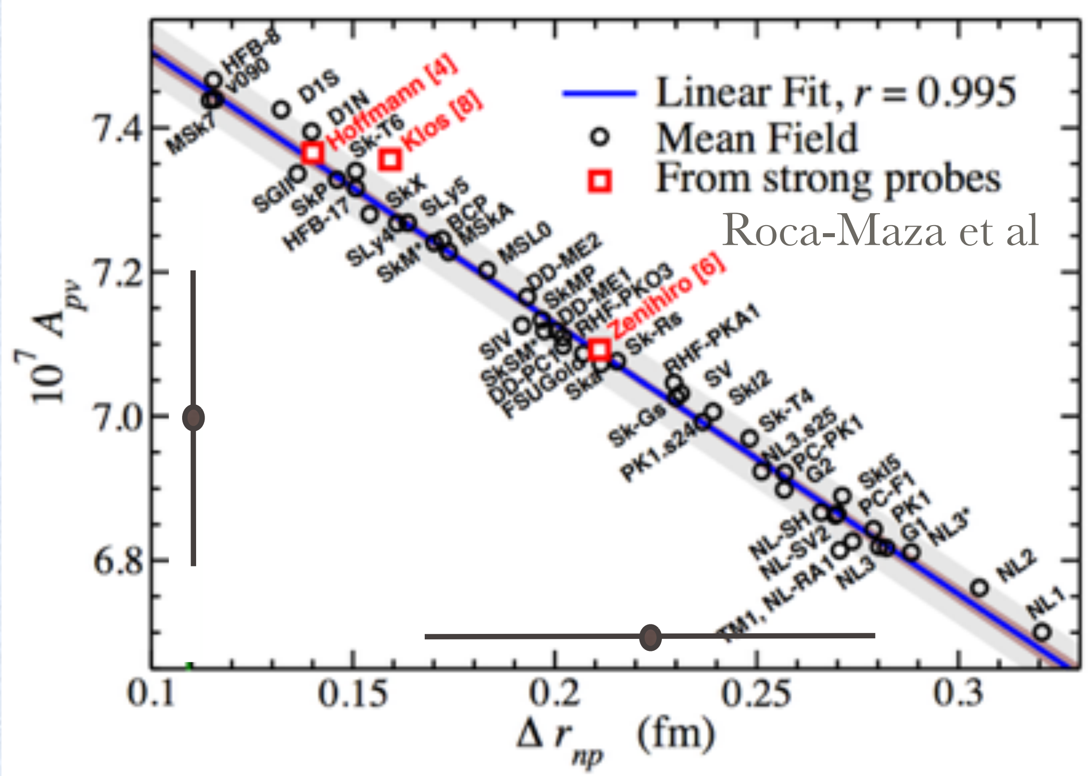

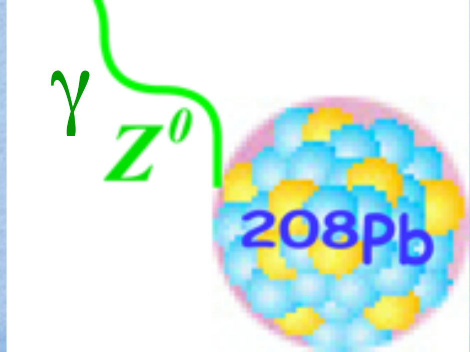

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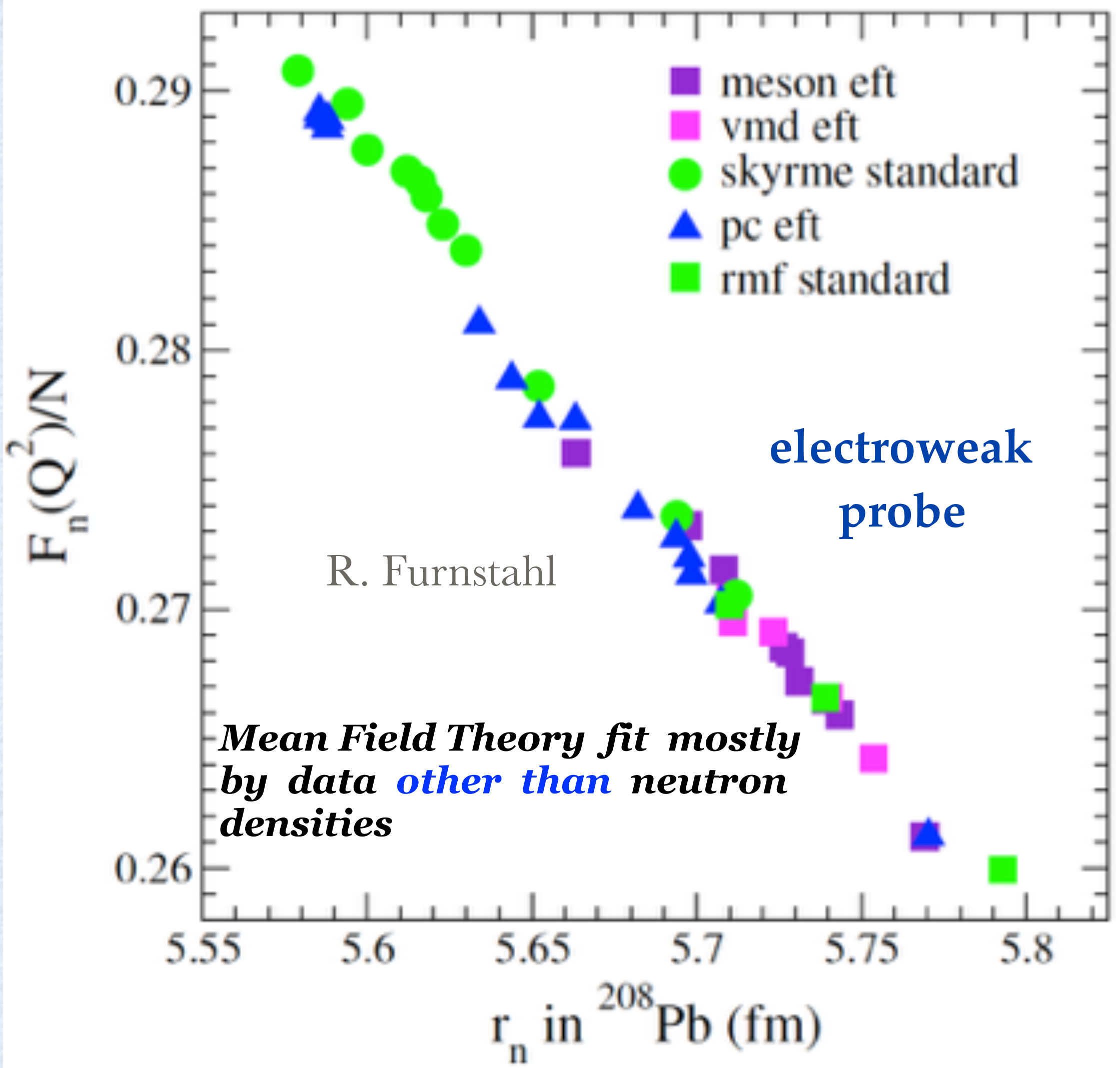

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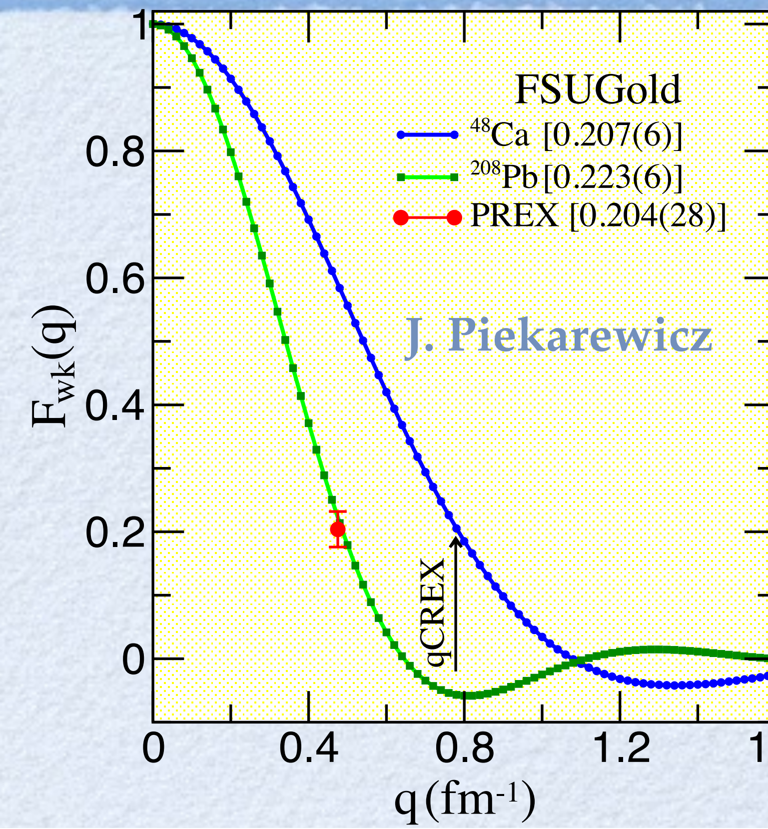
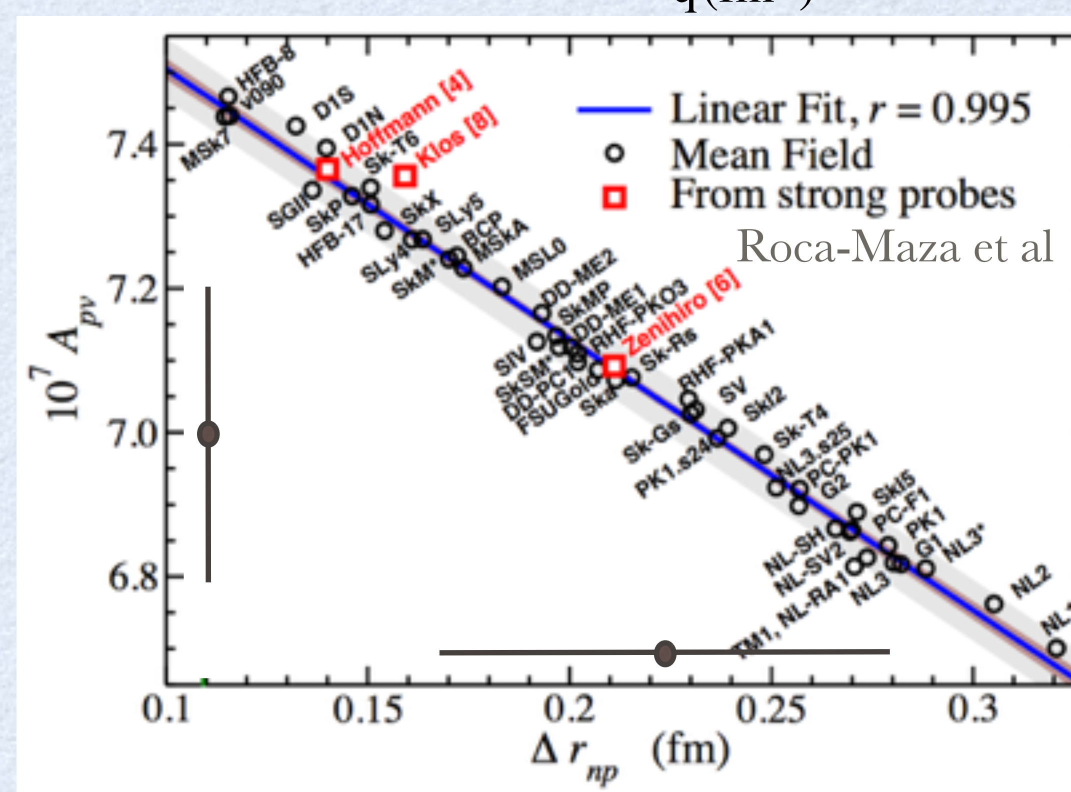
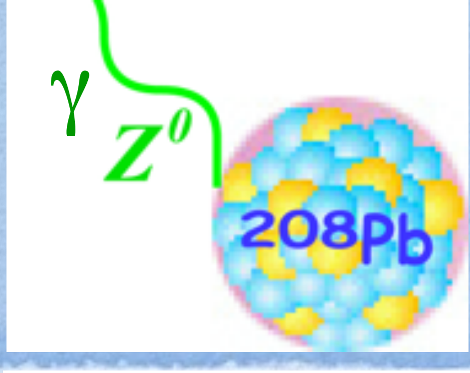




- ***Clean "translation" from A_{PV} uncertainty to neutron RMS radius uncertainty***
- ***A_{PV} uncertainty dominated by statistics!***



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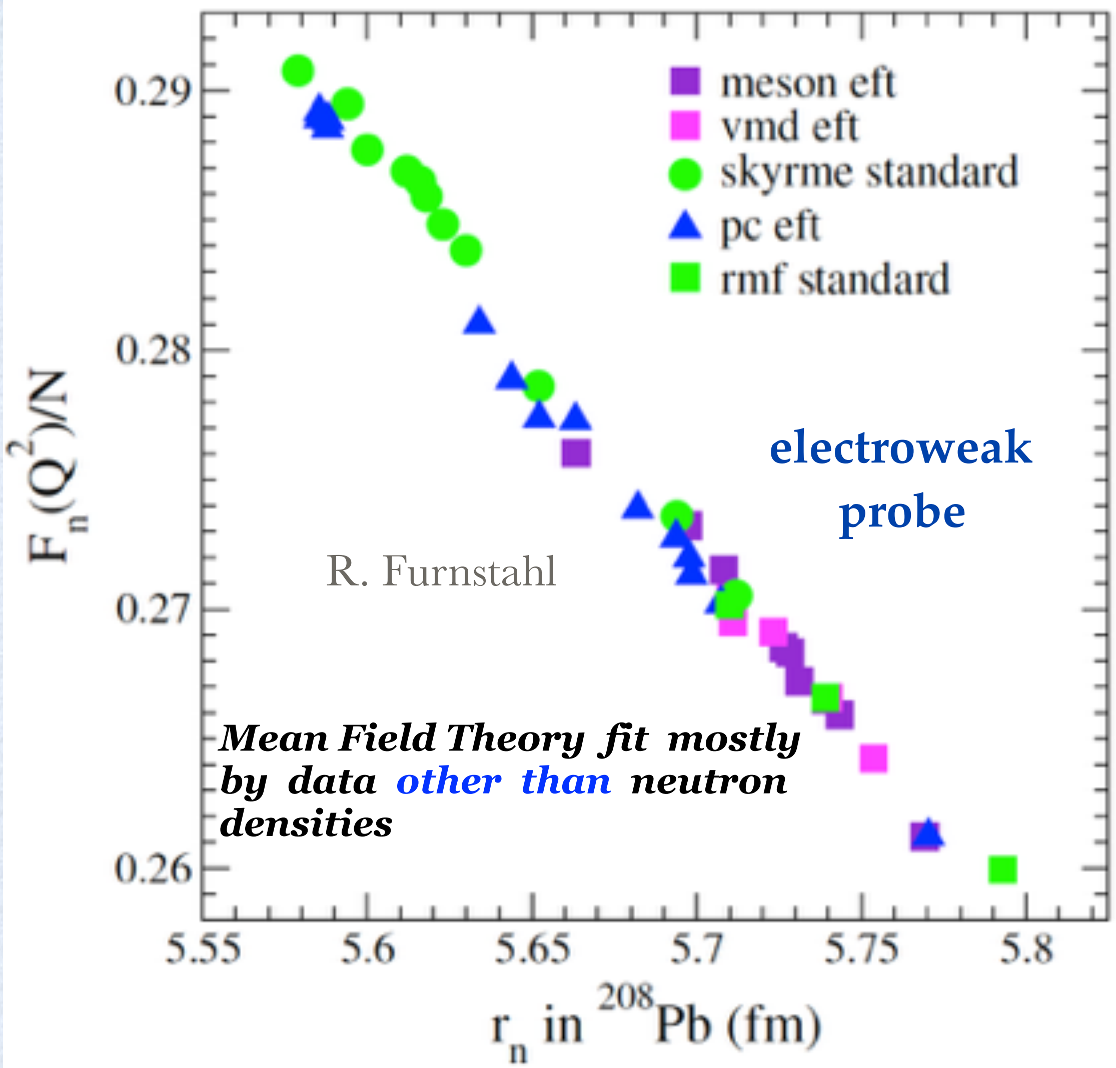

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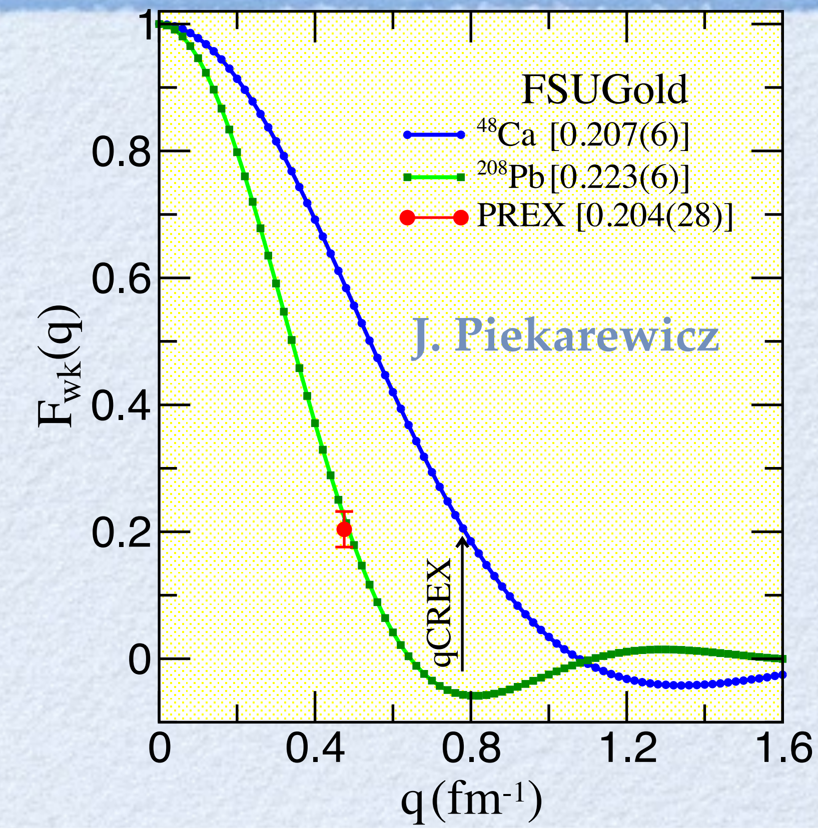

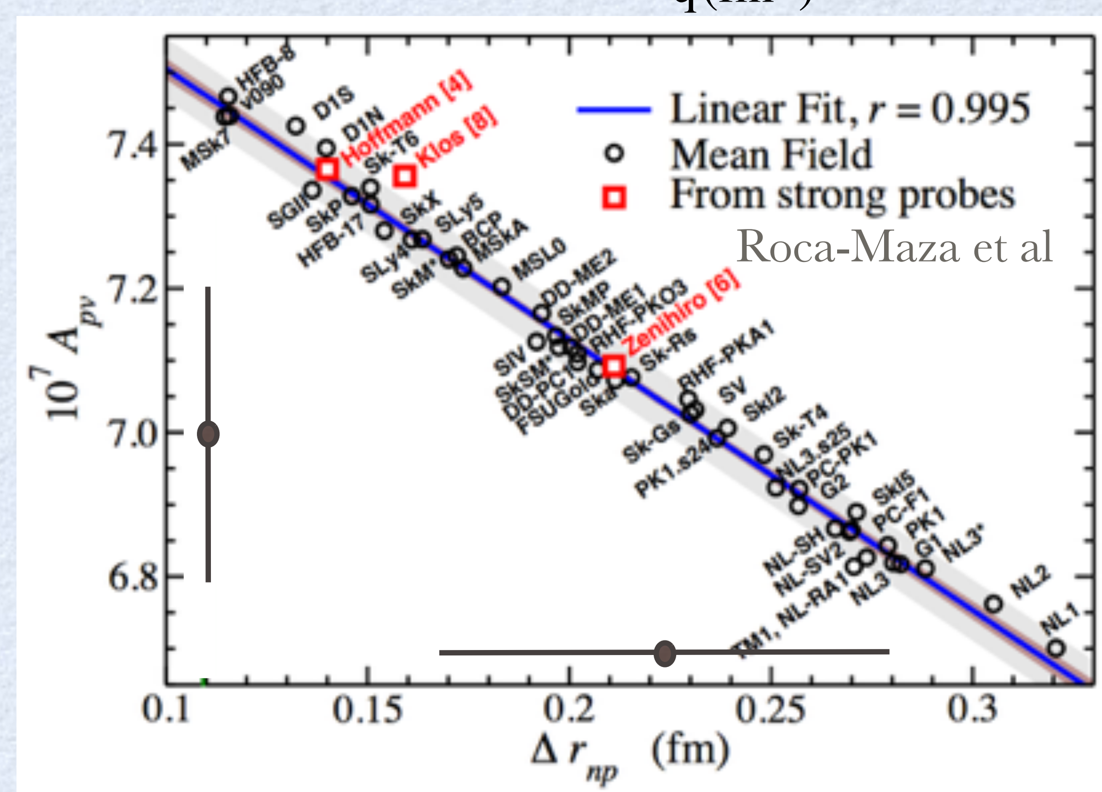

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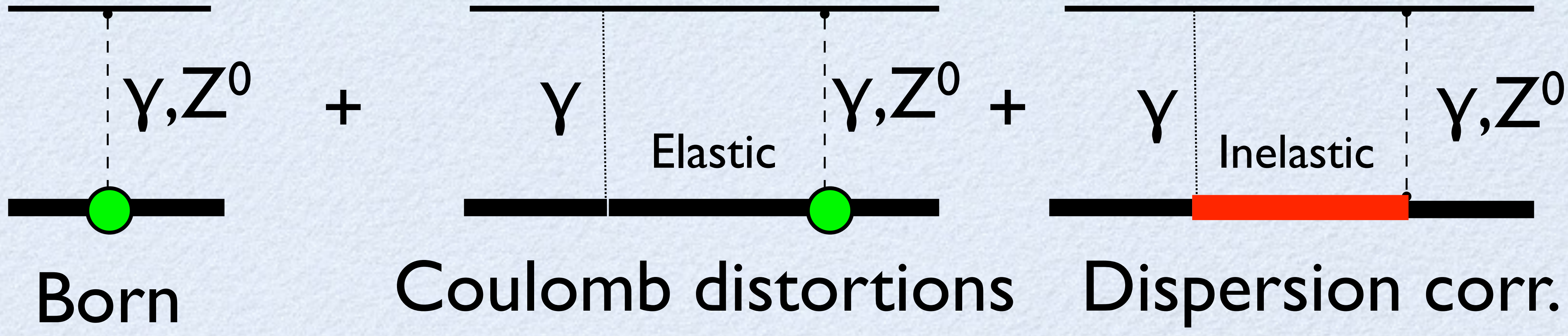
At this level of precision, one must account carefully for radiative corrections

C.Horowitz

Radiative Corrections



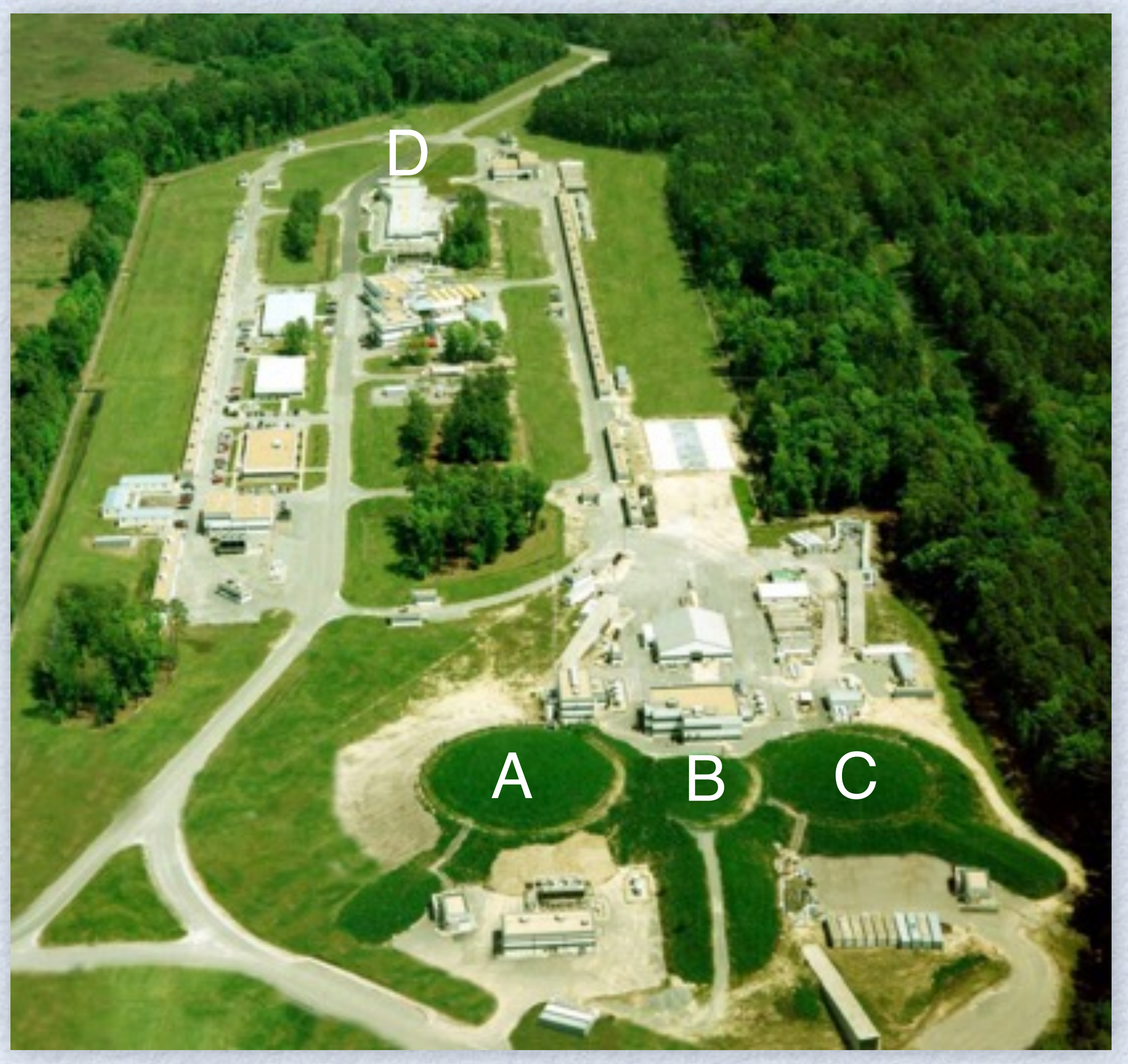
- Coulomb distortions are coherent, order Zα. Important for PREX (Z=82)
  - Sum elastic intermediate states to all orders in Zα by solving Dirac equation for electron moving in coulomb (V) + weak potential (A) of nucleus.
  - Coulomb distortions reduce A_{pv} by ~30%, but accurately calculated (uncertainty estimated to be sub-1% of correction)
- Dispersion corrections are of order α (not Zα).
- Note: Both Coulomb distortion and dispersion corrections can be important for Transverse Beam Asymmetry A_n for ^{208}Pb

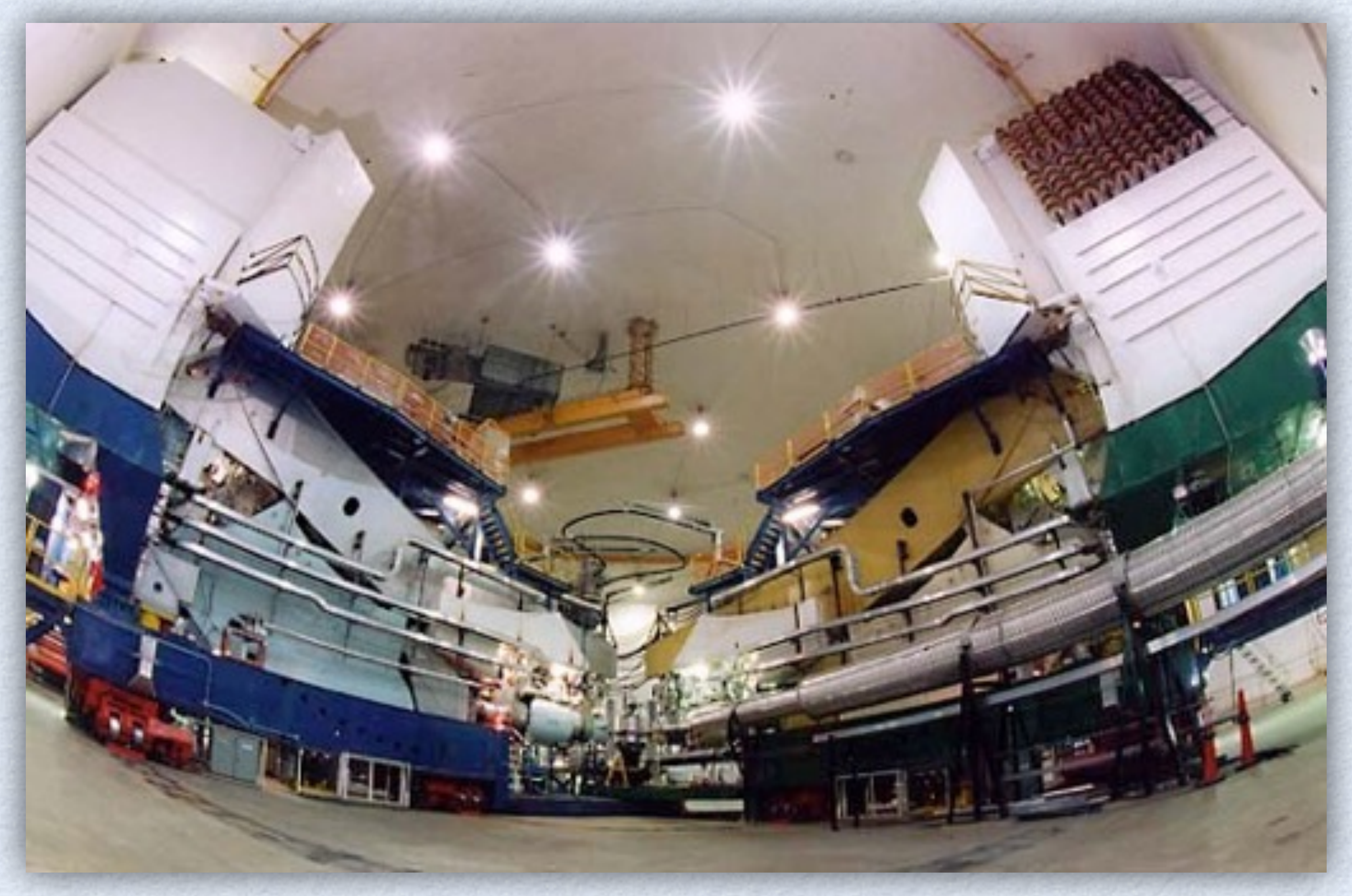
PREX Overview

1 GeV electron beam, 50-70 µA

high polarization, ~89%

helicity reversal at 120 Hz





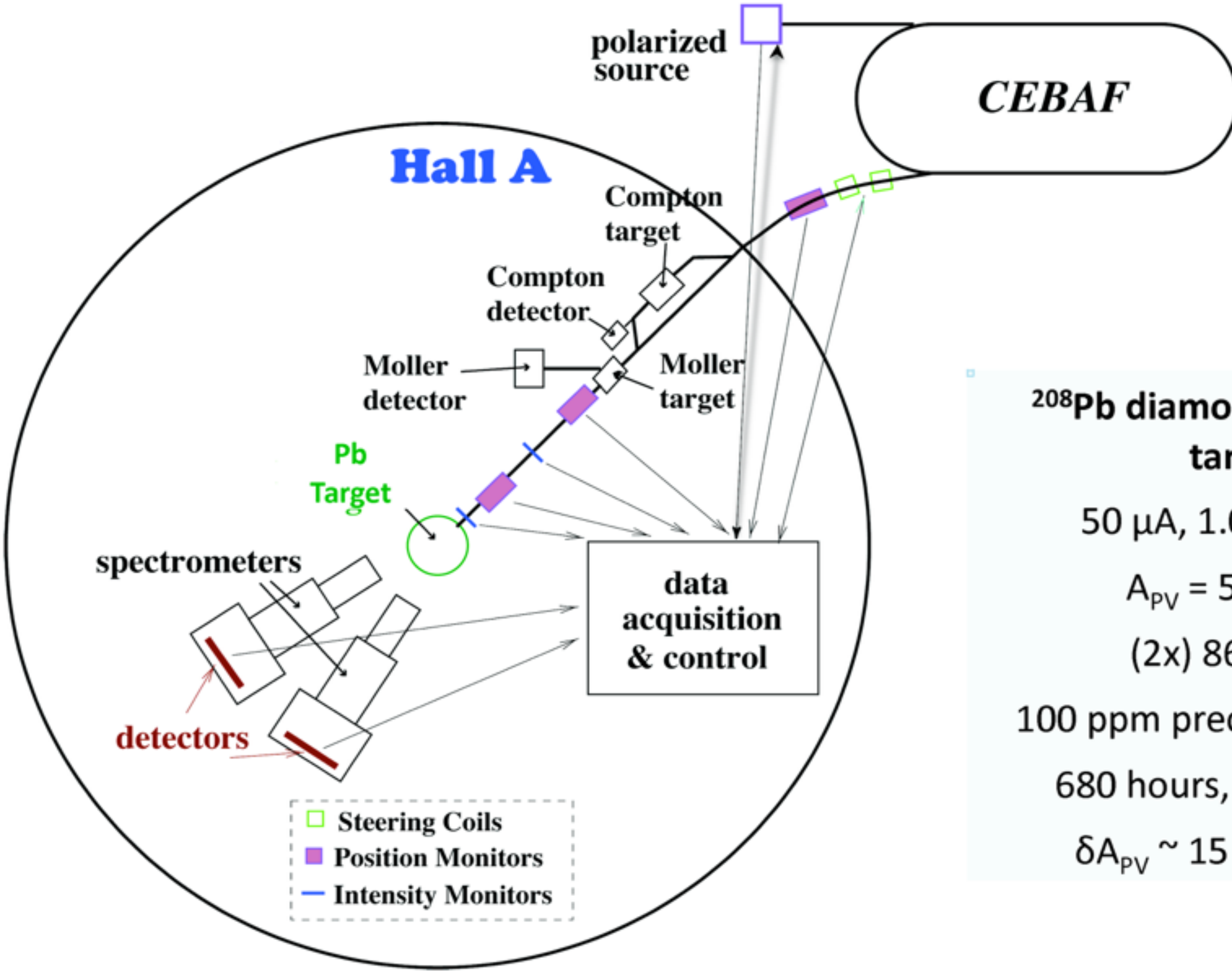
0.5 mm isotopically pure ^{208}Pb target

5° scattered electrons

Q^2 =0.0088 GeV^2/c^2

new thin quartz detectors

PREX Overview



^{208}Pb diamond-sandwich target

50 µA, 1.05 GeV, 5°

A_{PV} = 500 ppb

(2x) 860 MHz

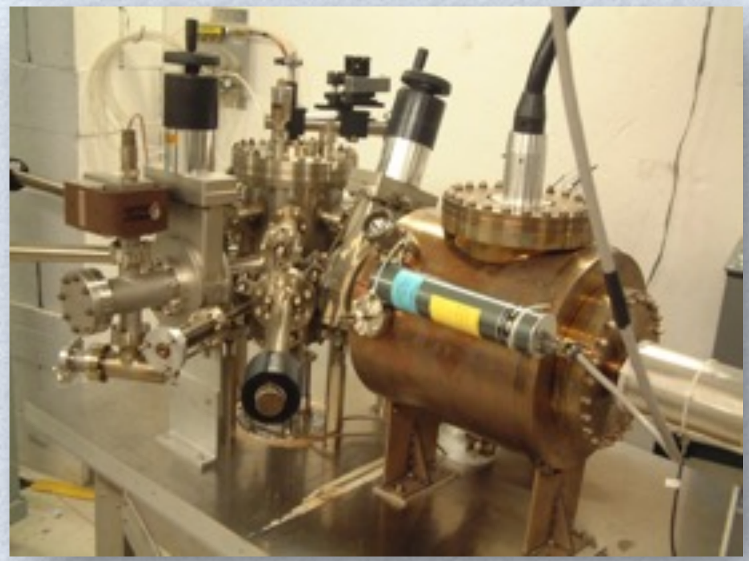
100 ppm precision at 15 Hz

680 hours, ~35M pairs

δA_{PV} ~ 15 ppb (3%)

PREX-I ran from March to May 2010

Polarized Beam at JLab



Record Performance (2012):
180 μA at 89% polarization

$A_{raw} \sim 500$ ppb

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

Electron Gun Requirements

- Ultrahigh vacuum
- No field emission
- Maintenance-free

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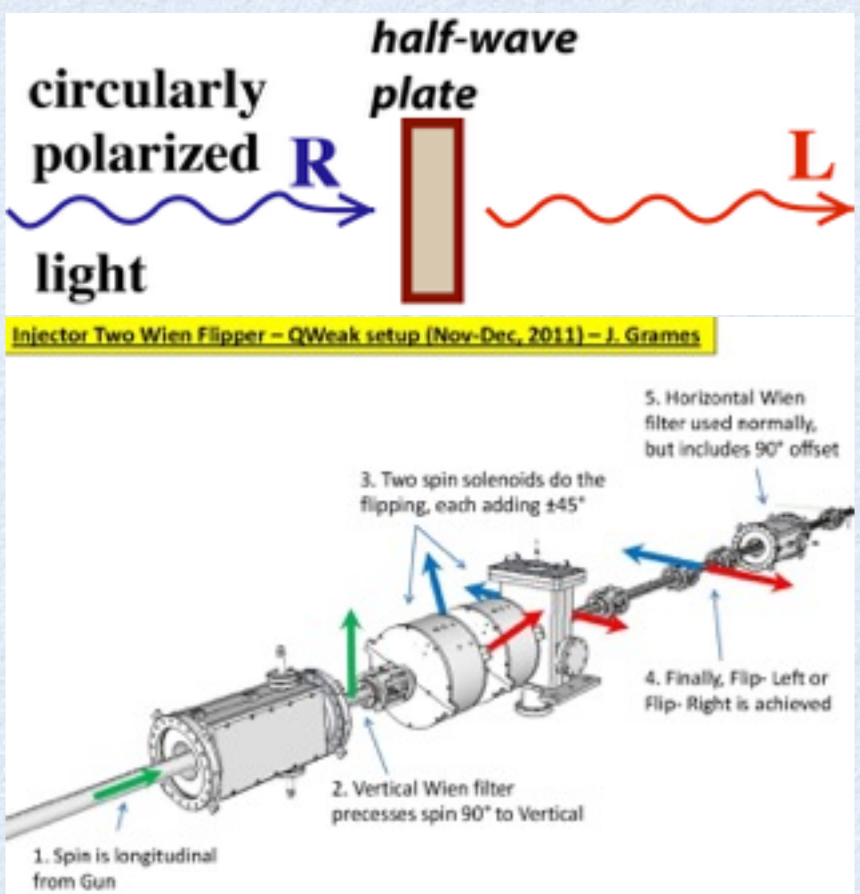

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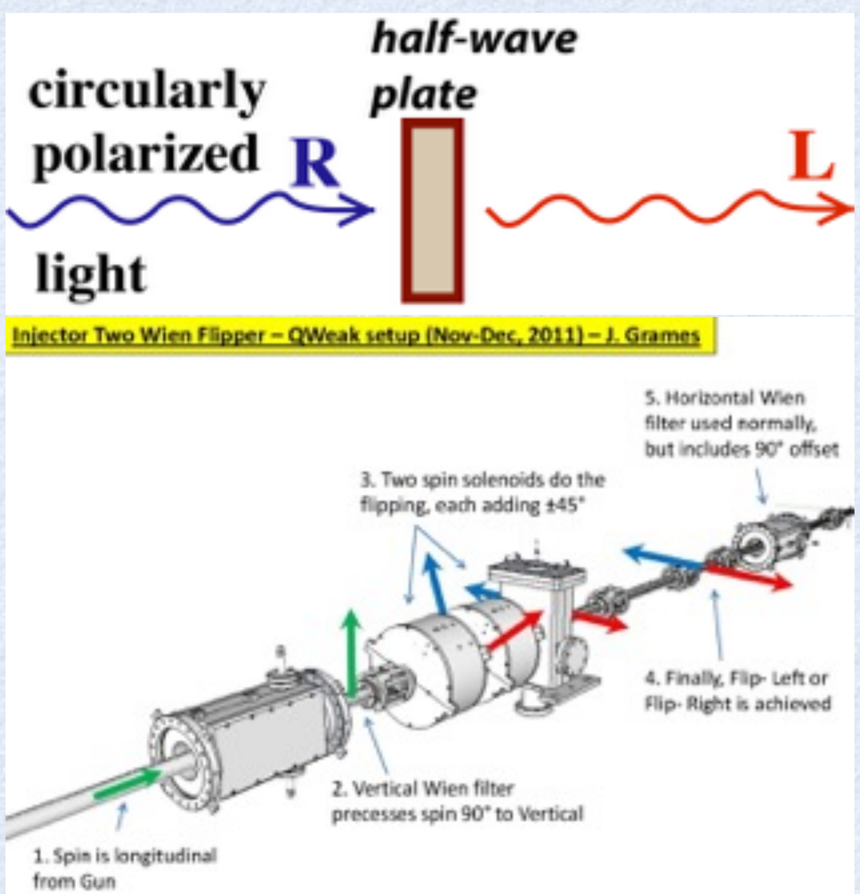
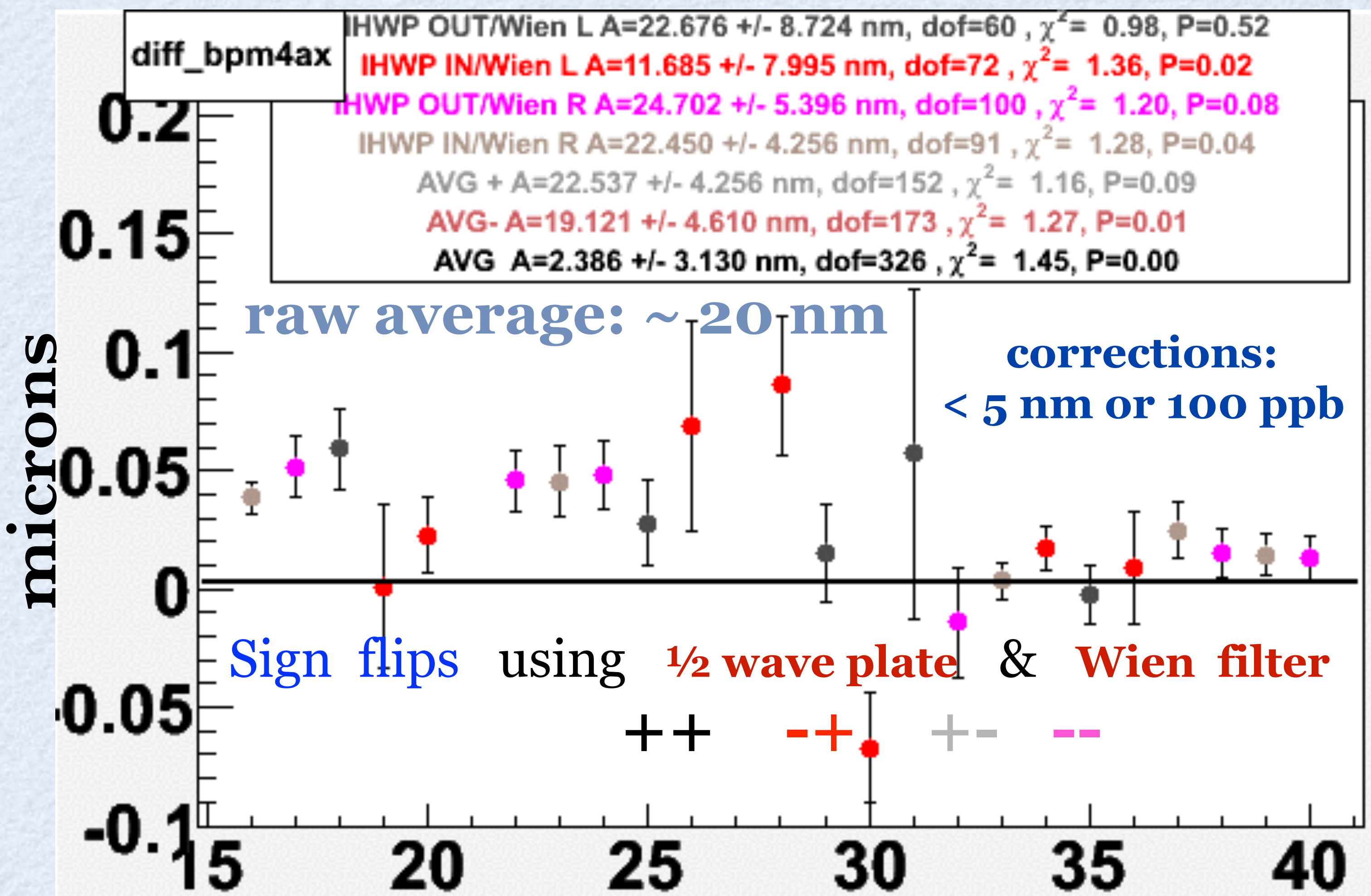
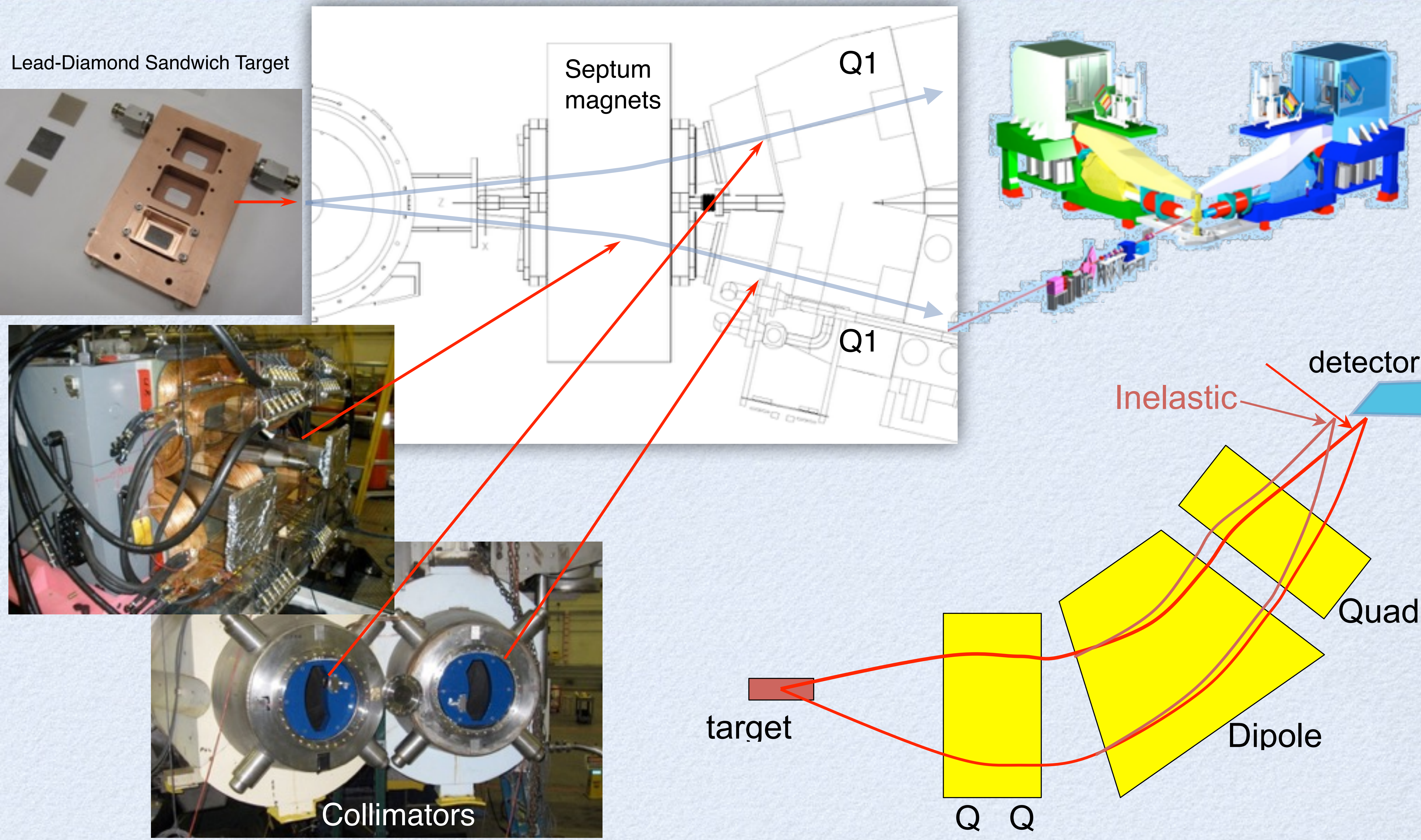




Target and Spectrometers



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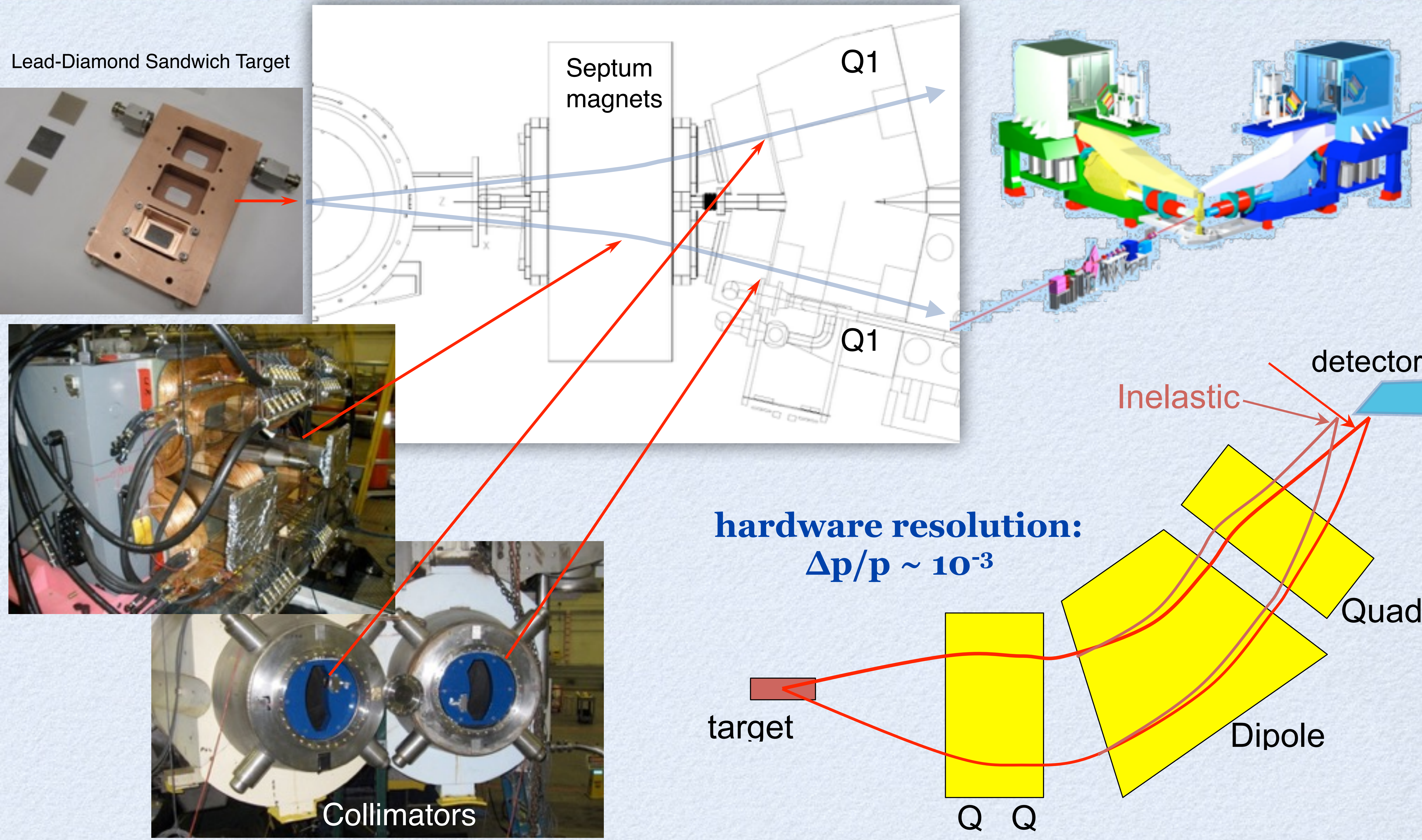
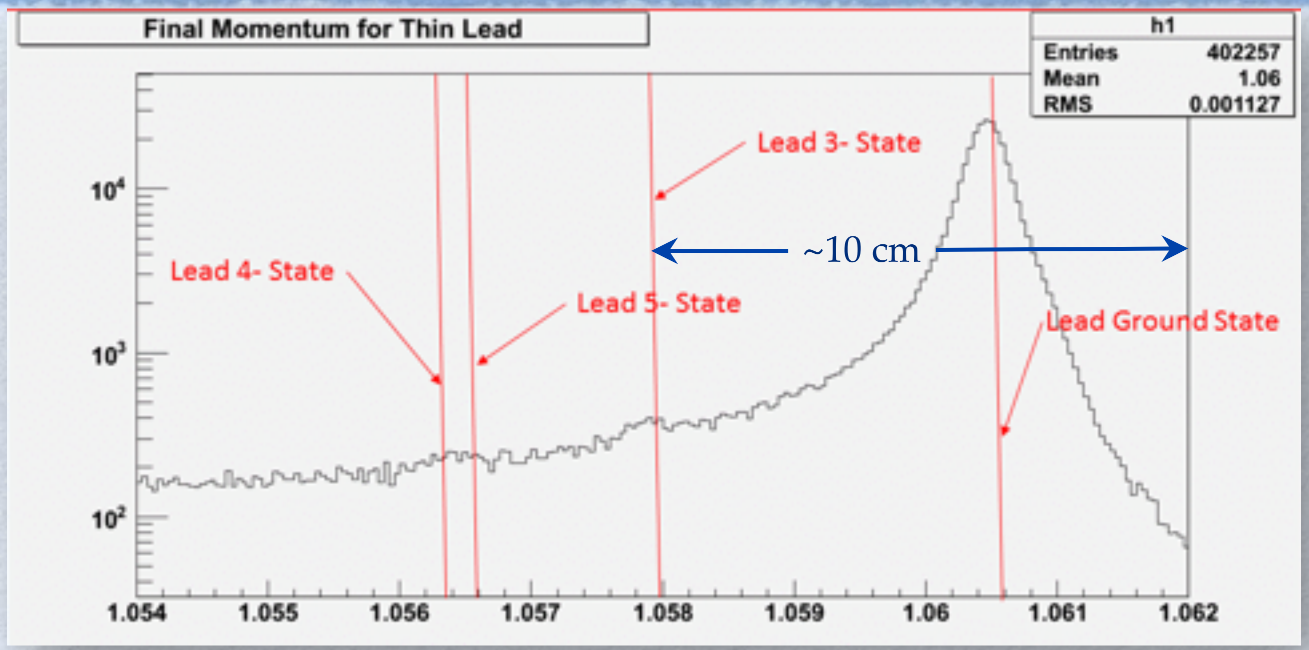


Integrating Detectors

Background negligible thanks to Hall A HRS spectrometer pair



pure, thin ^{208}Pb target

- *1 GHz rate: extreme radiation hardness*
- *1 GeV: calorimeter sandwich RMS ~ 50%*
- *Thin fused silica: optimize RMS*
  - *thick: higher photo-electron yield*
  - *thin: smaller RMS degradation*

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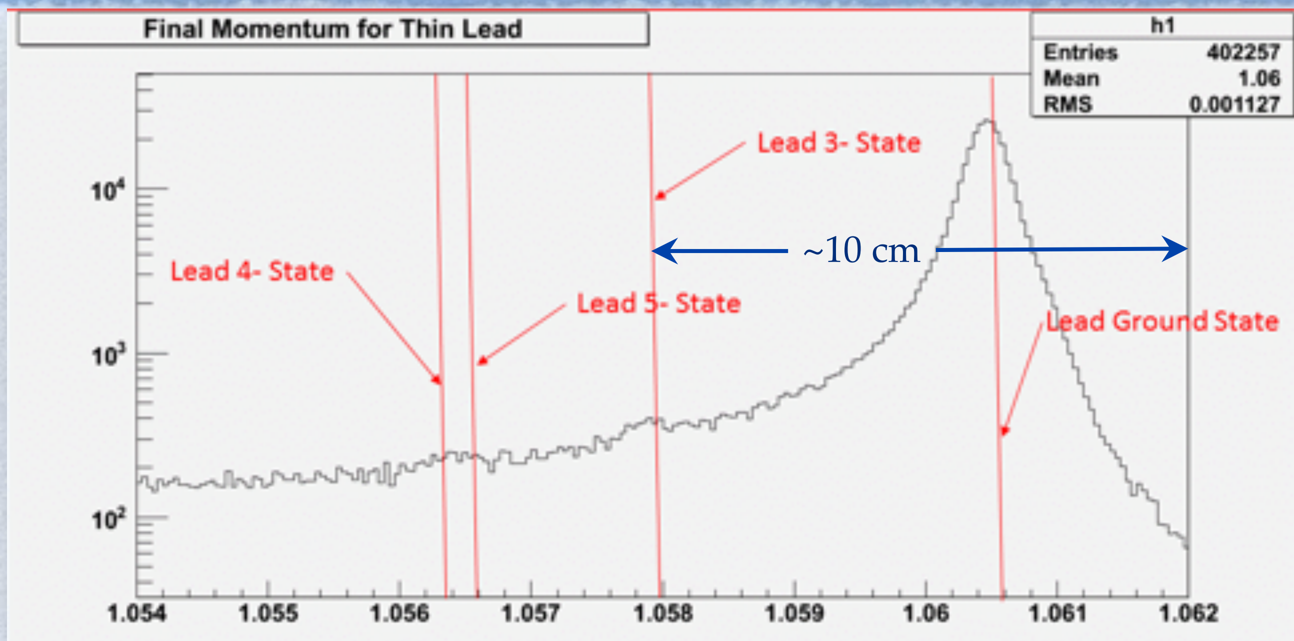

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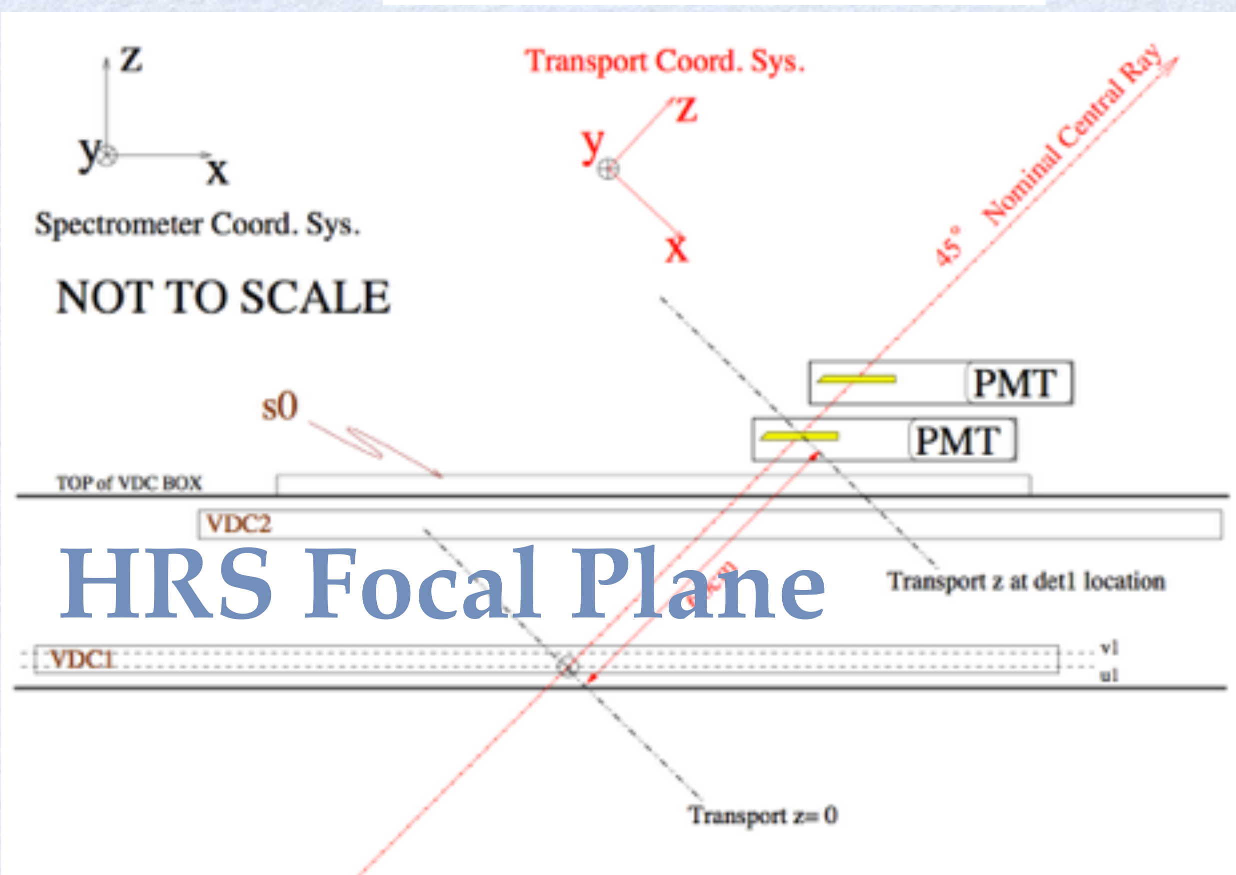

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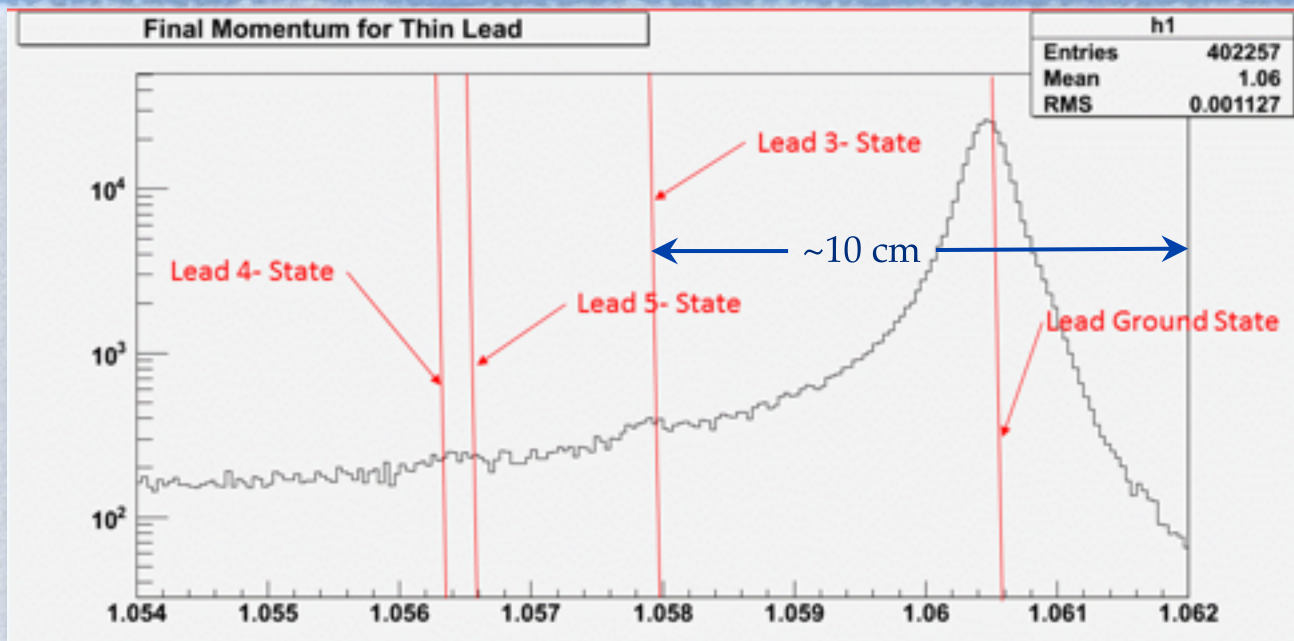

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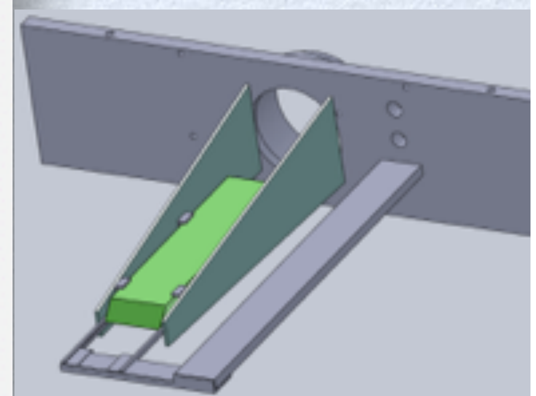

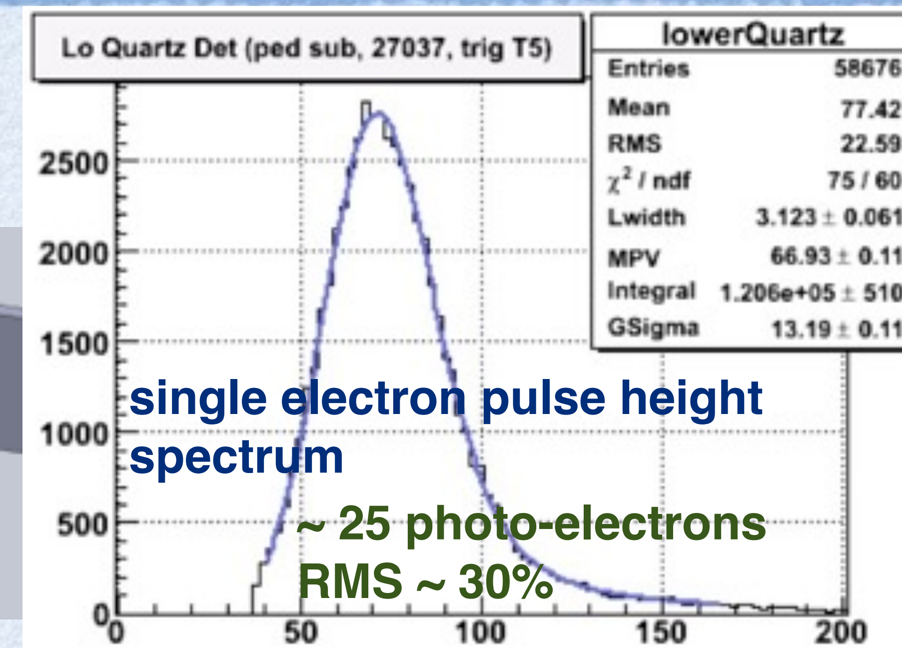

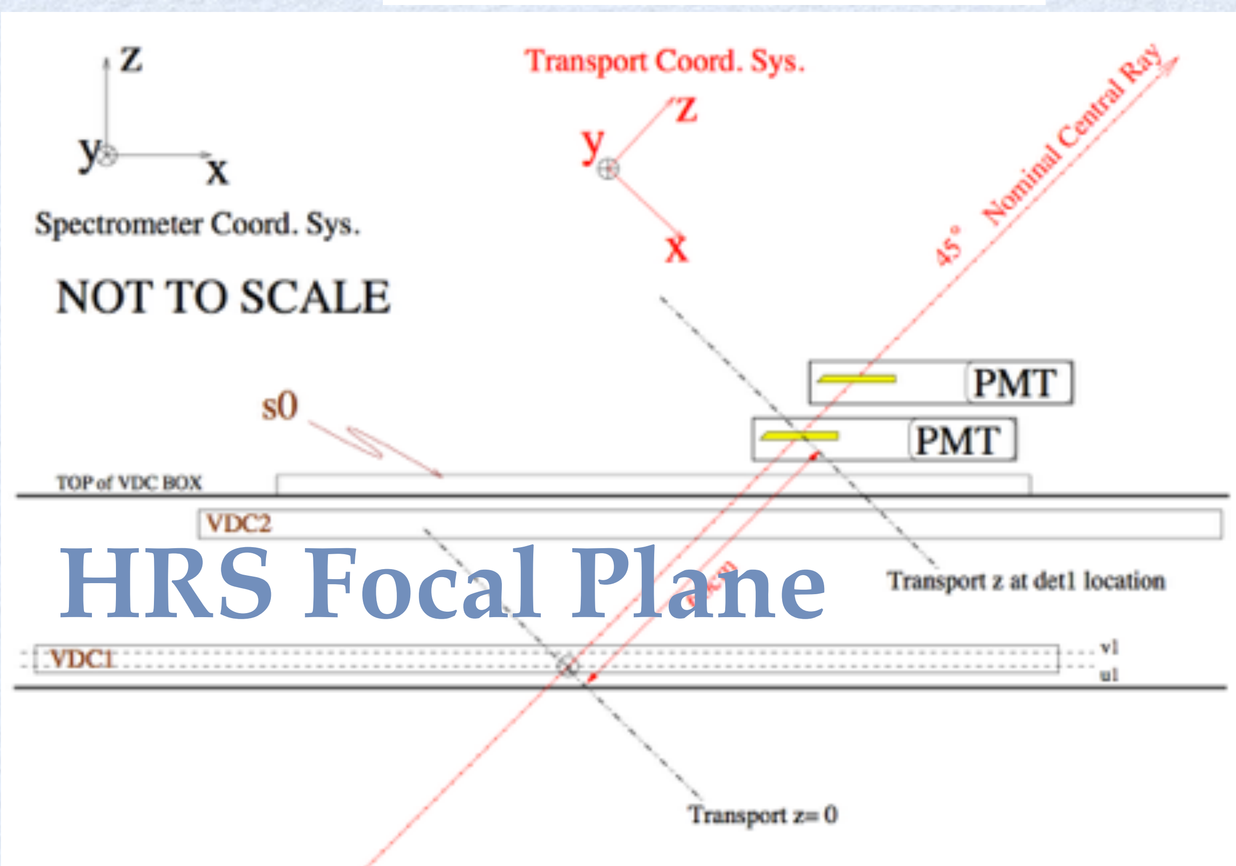

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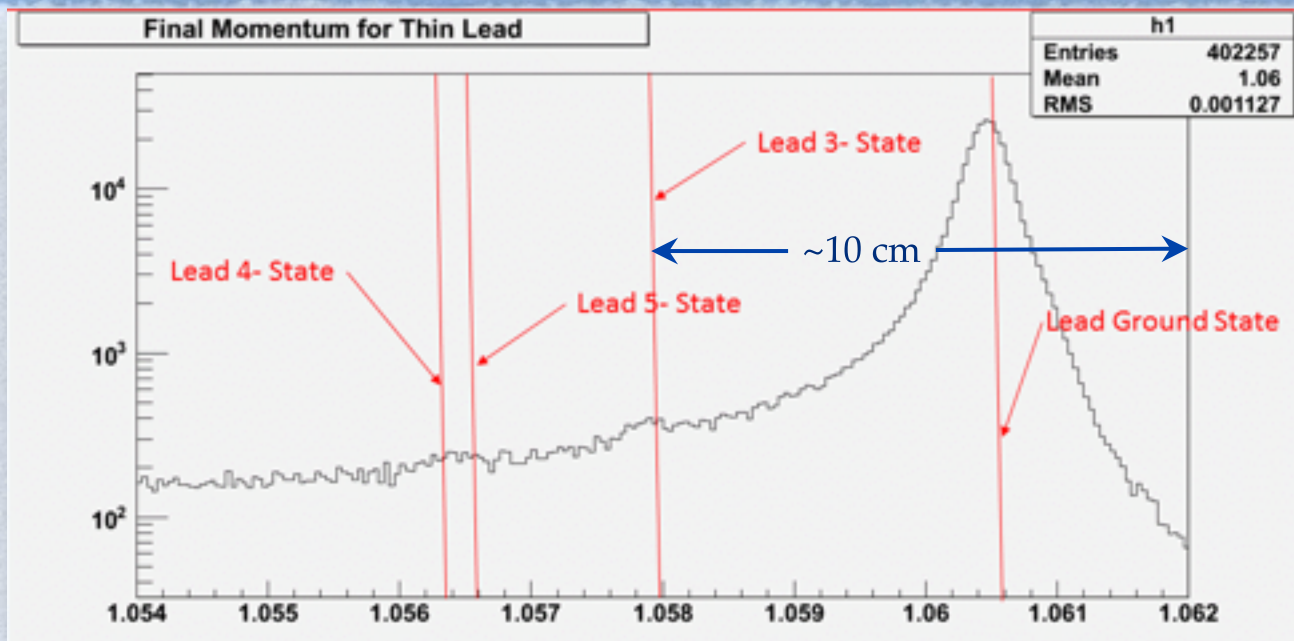

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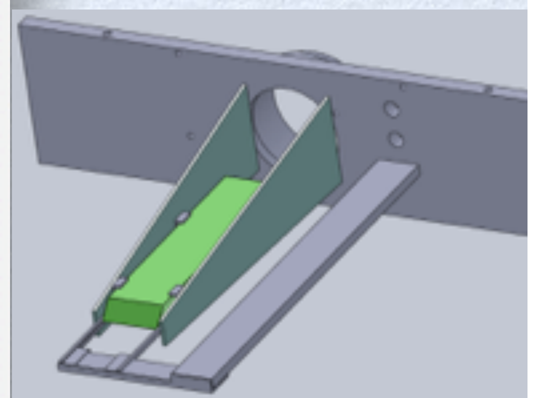

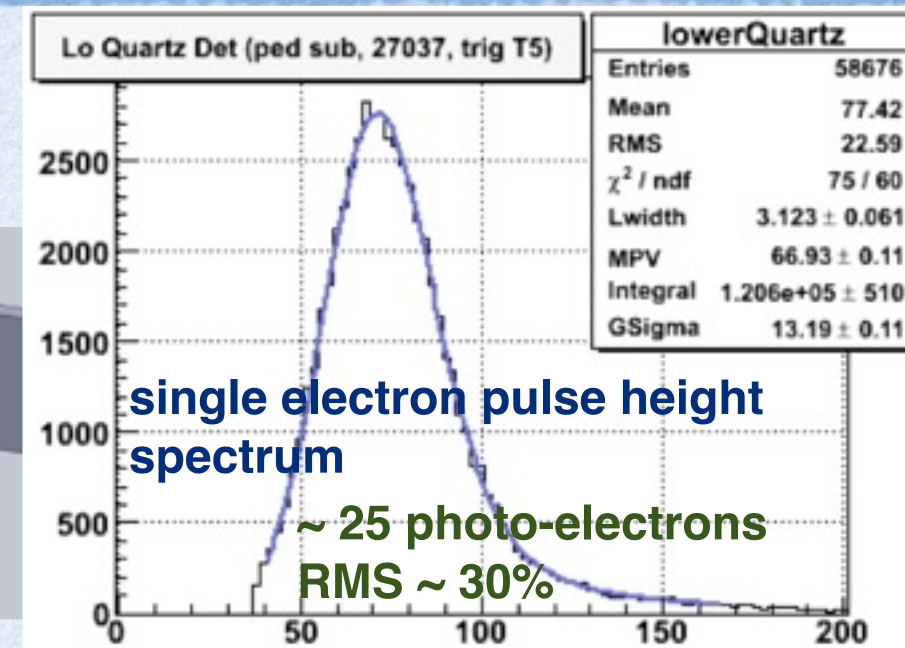

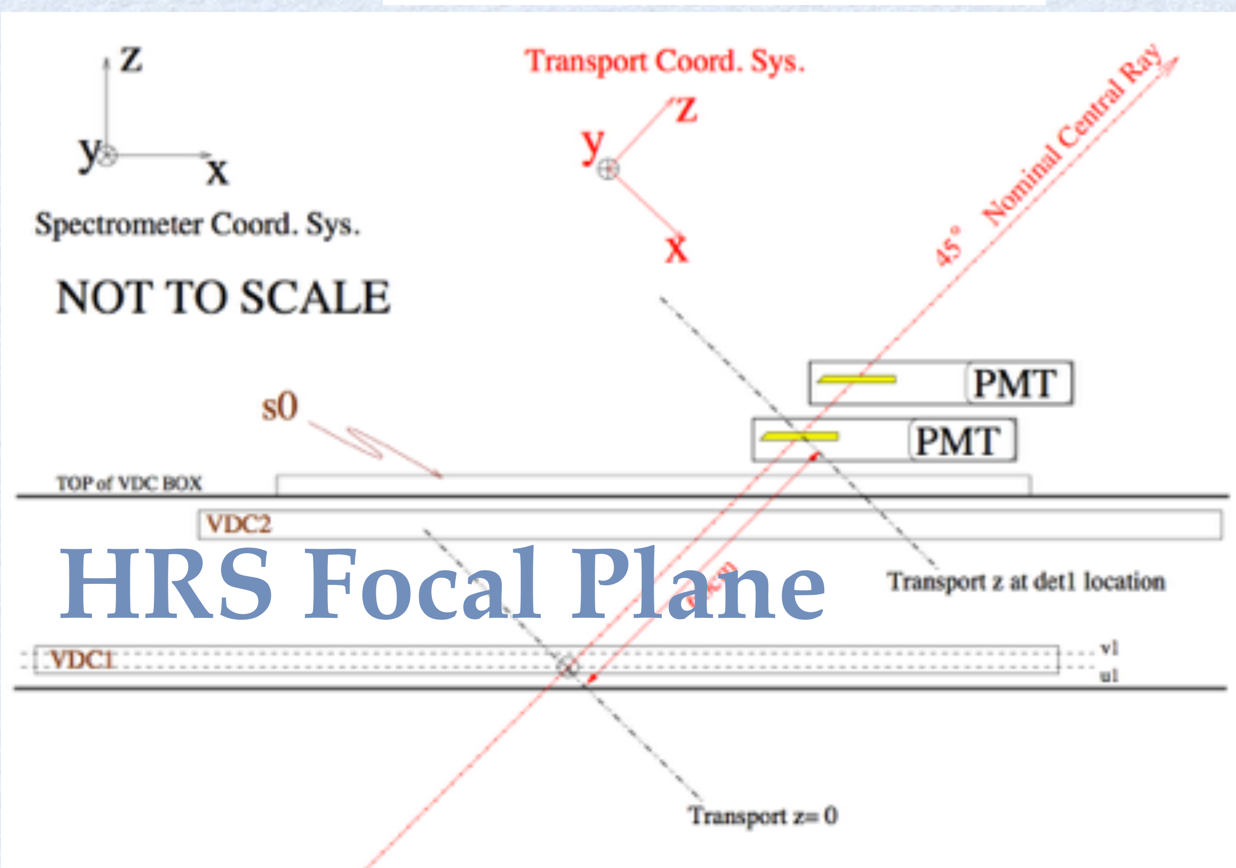

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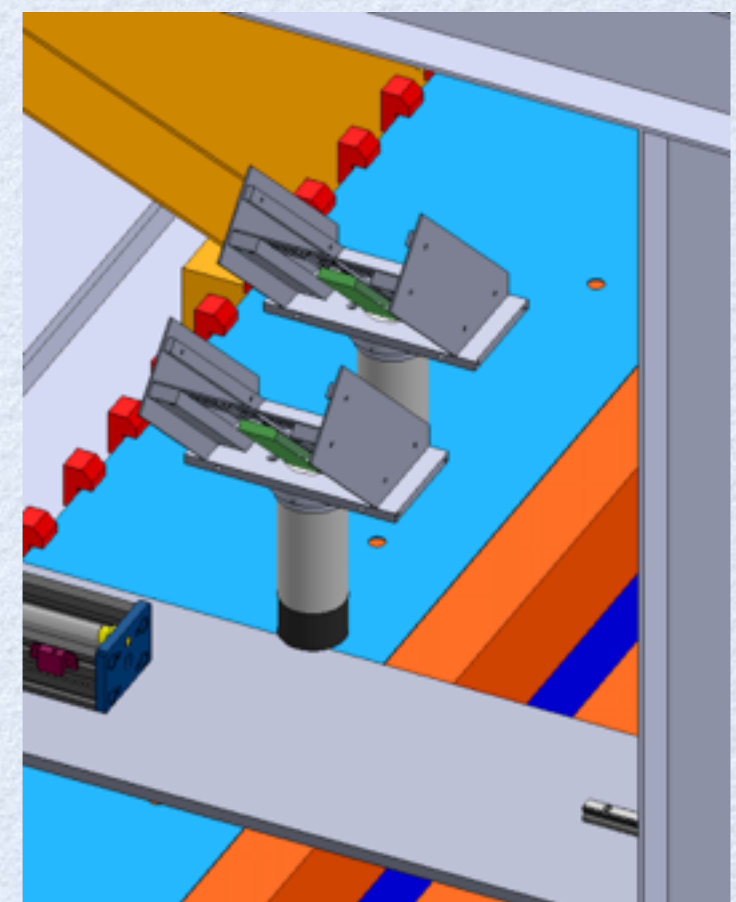
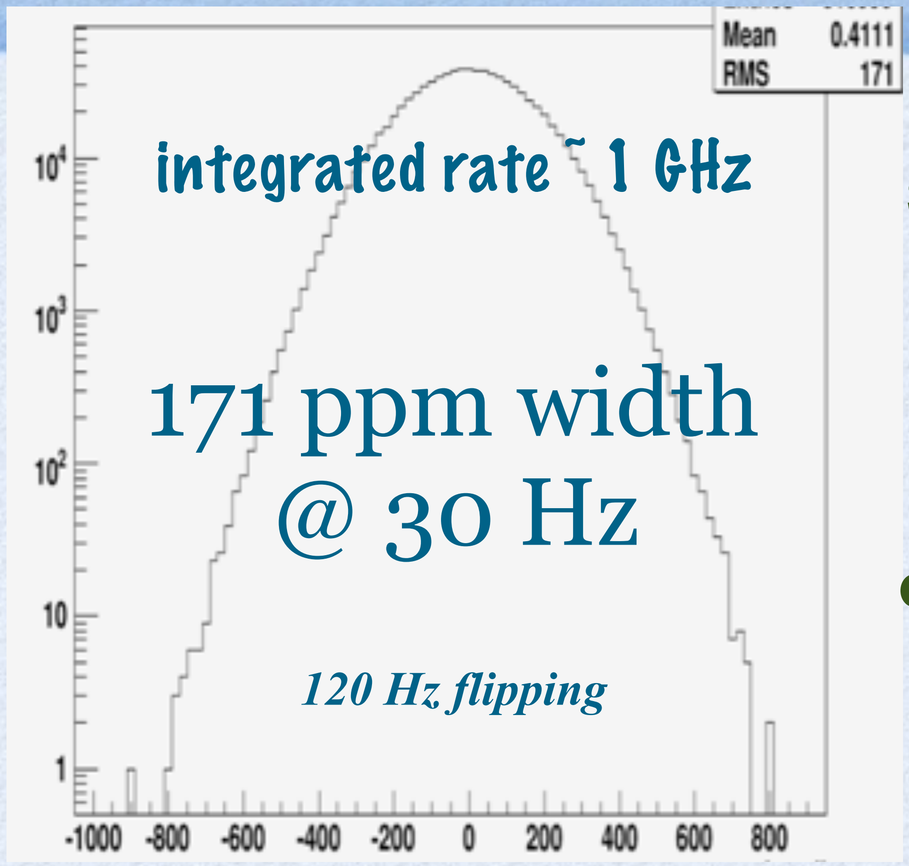


Raw Asymmetry Data



parts per million

Statistical behavior of data consistent with fluctuations in integrated detector response being dominated by electron counting statistics

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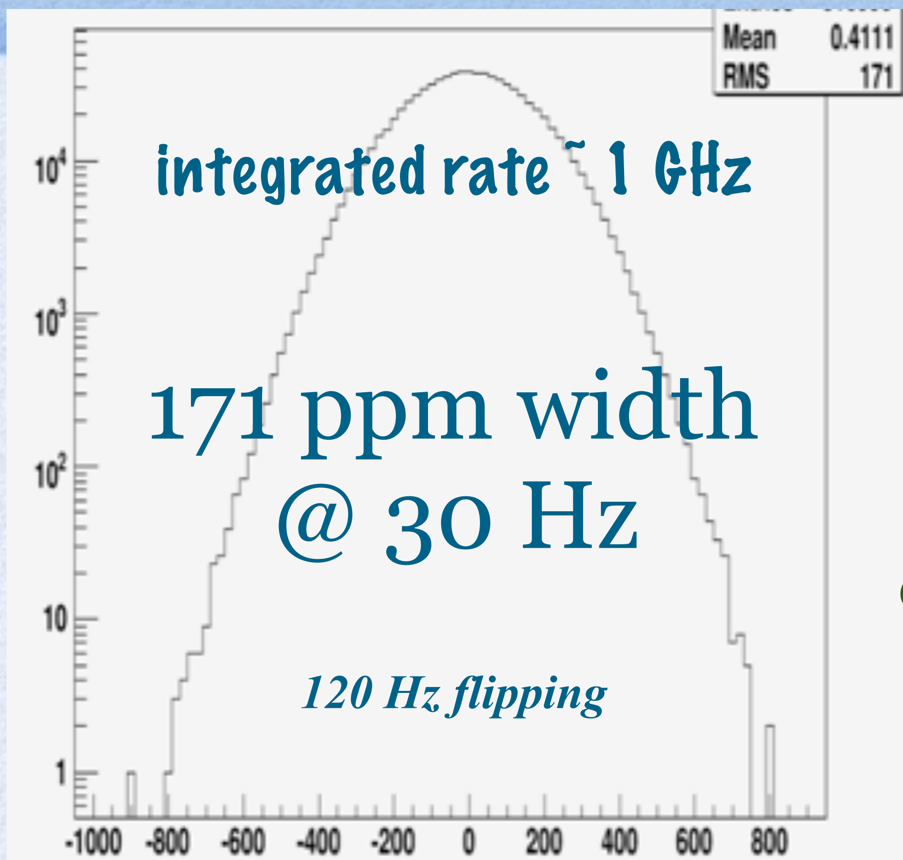

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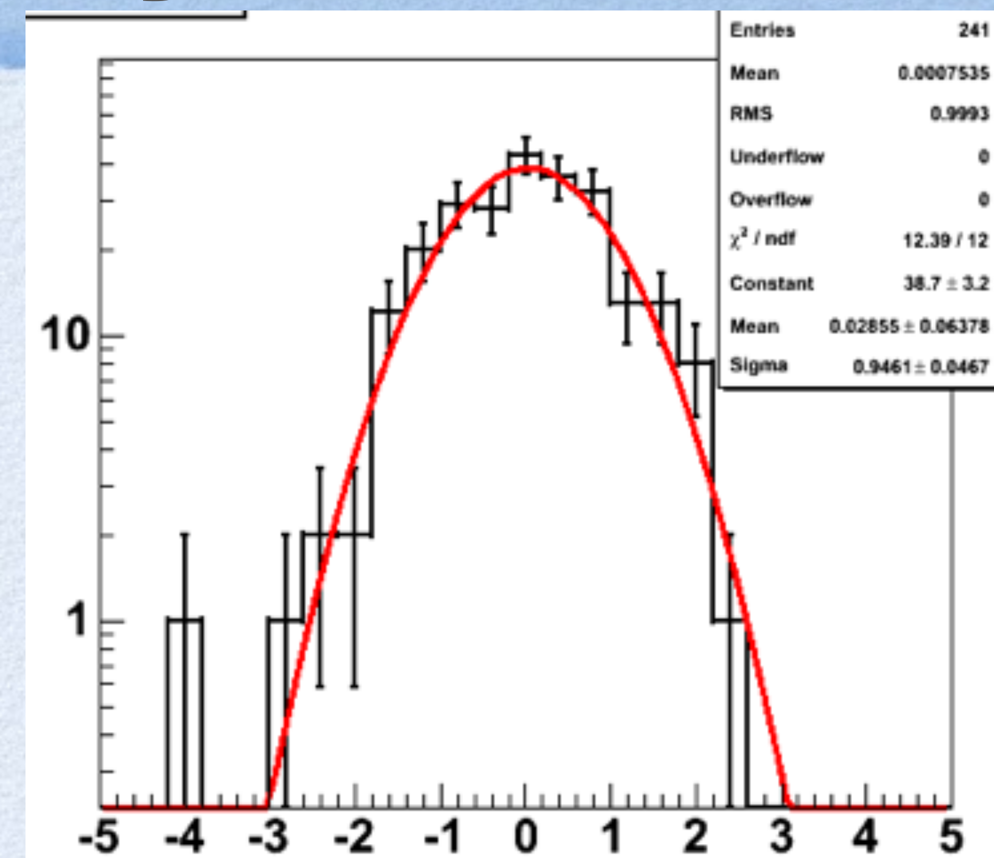

std. deviations

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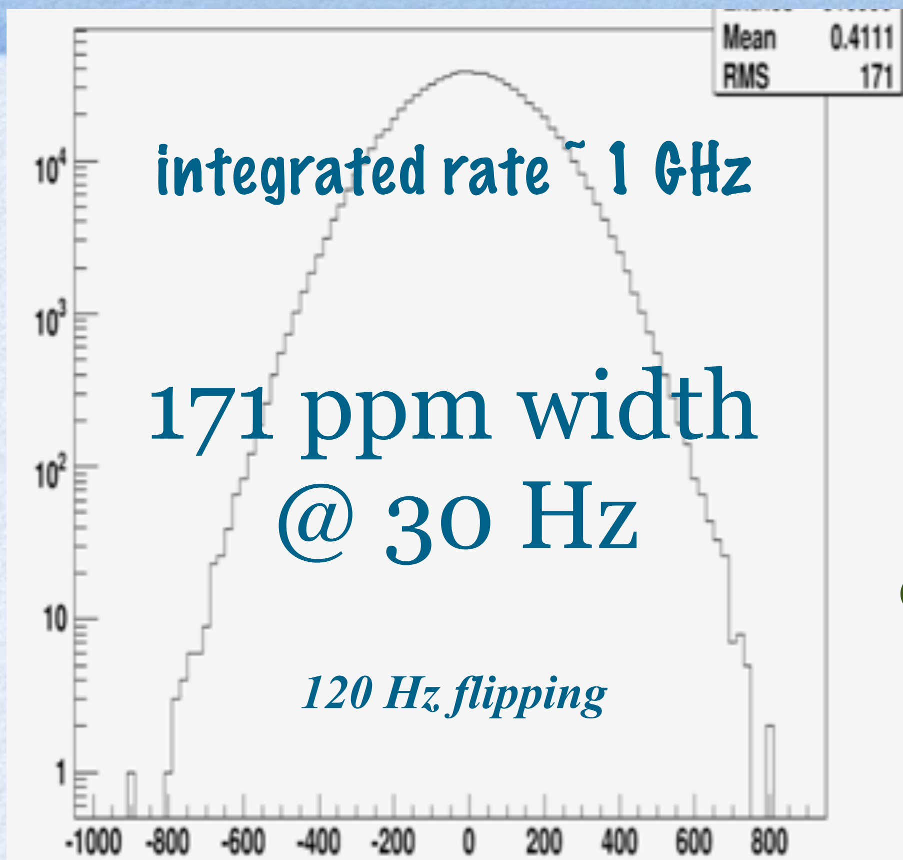

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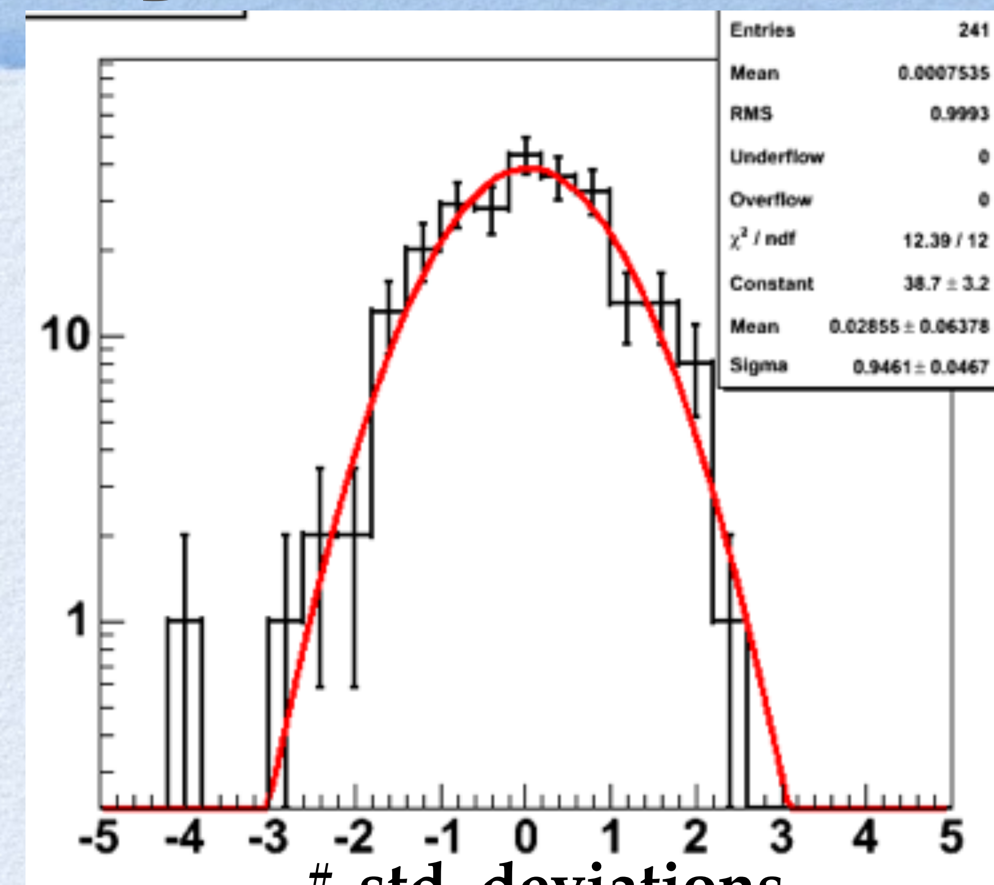

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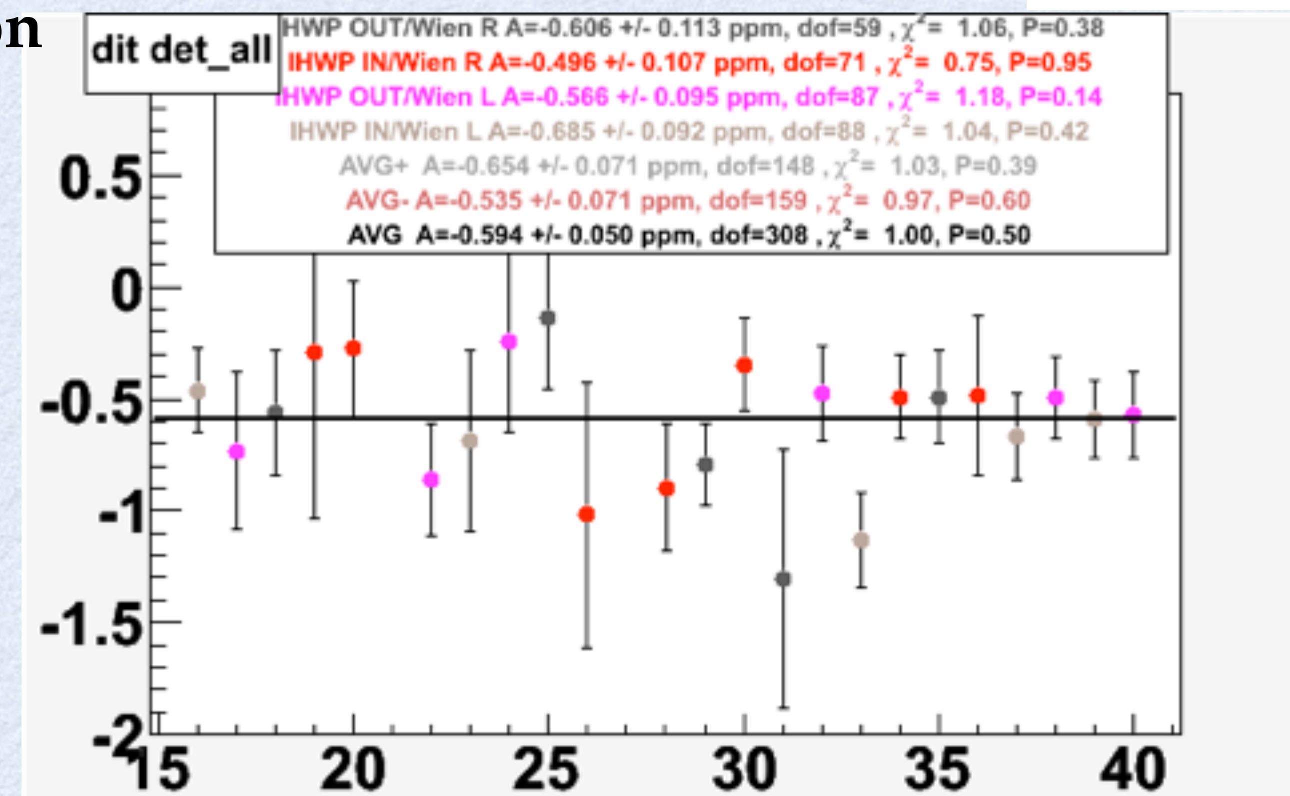

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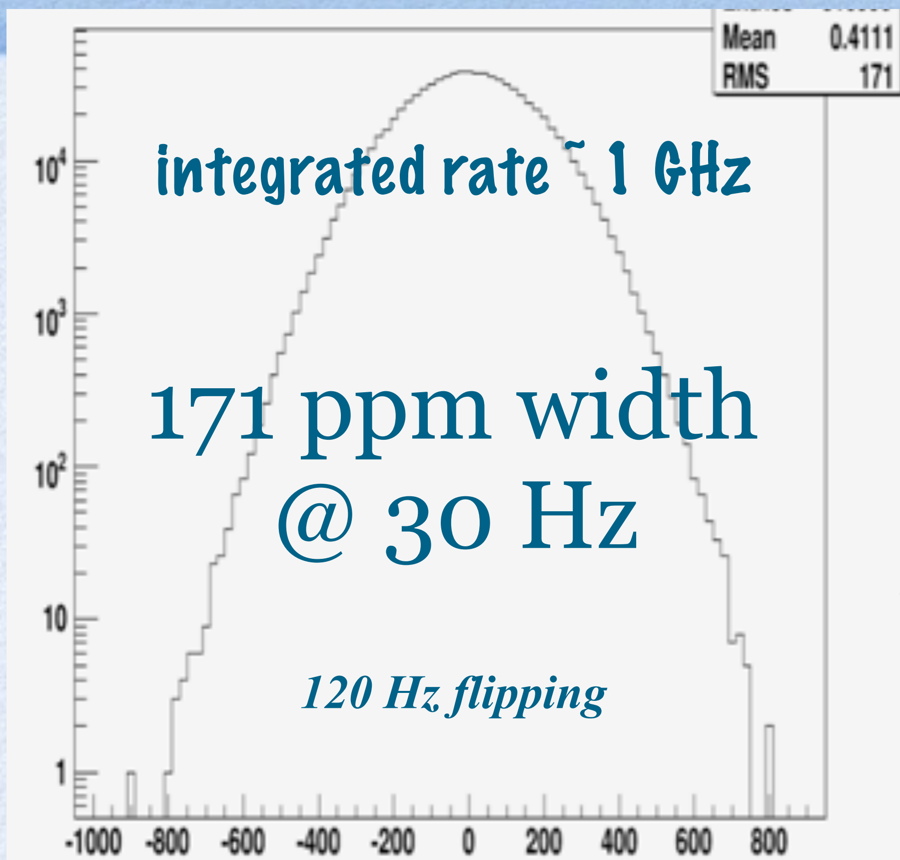

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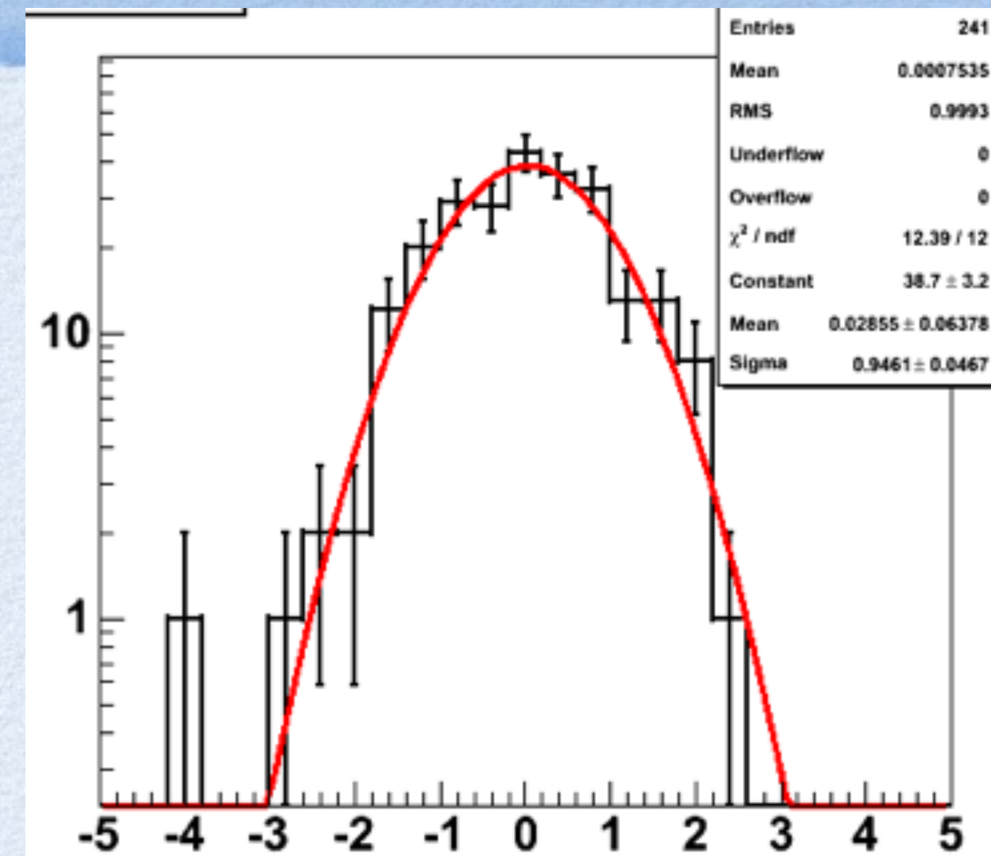

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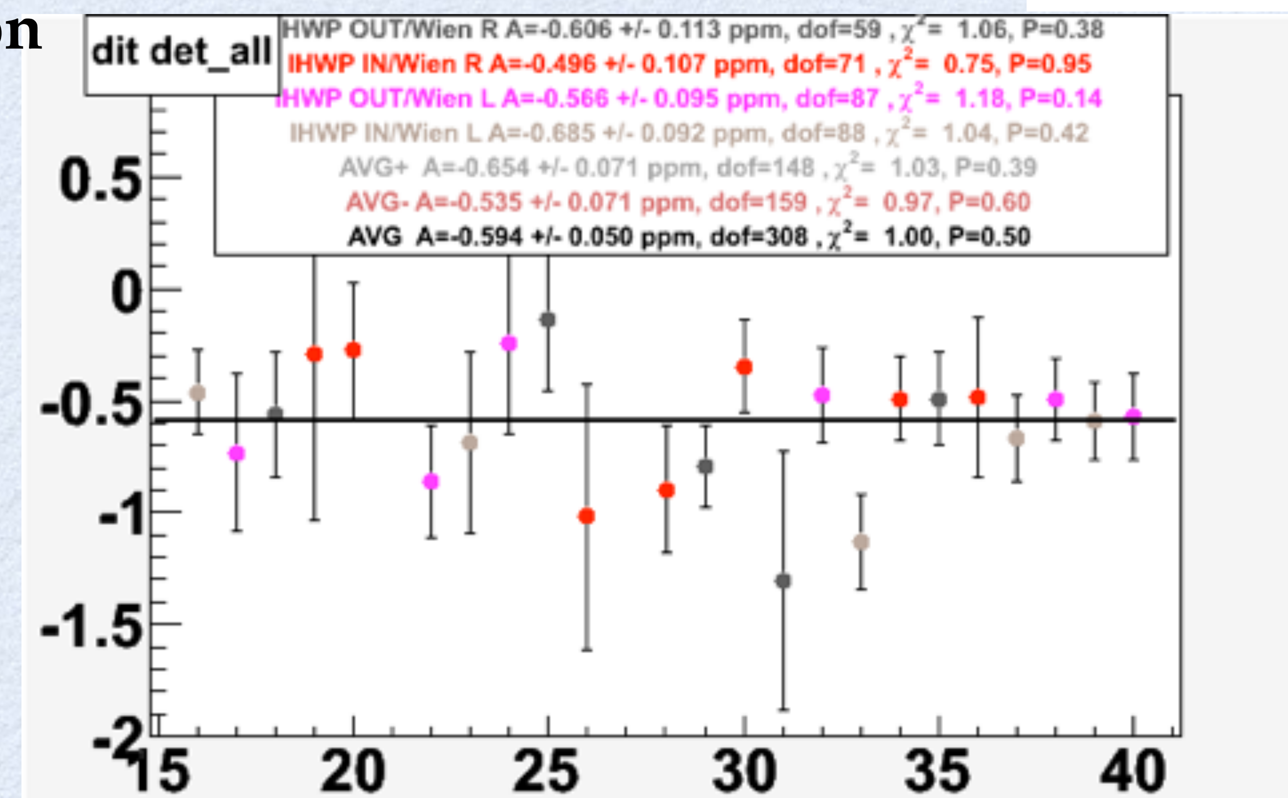
Grand averages of all 4 combinations of slow reversal flips are statistically consistent



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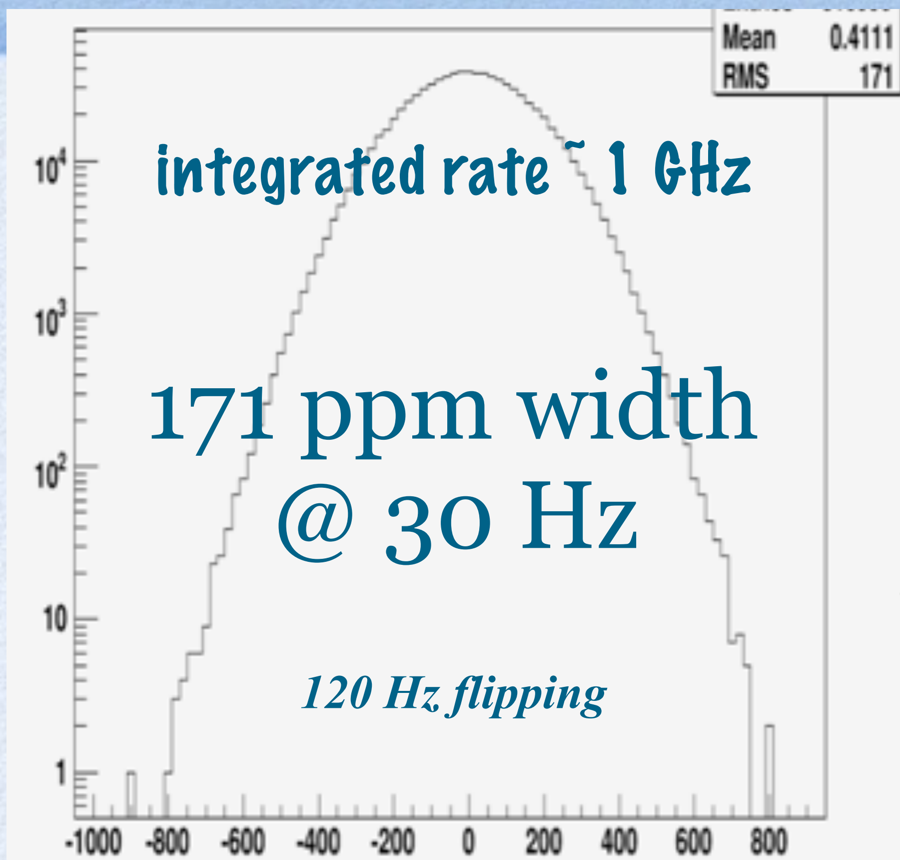

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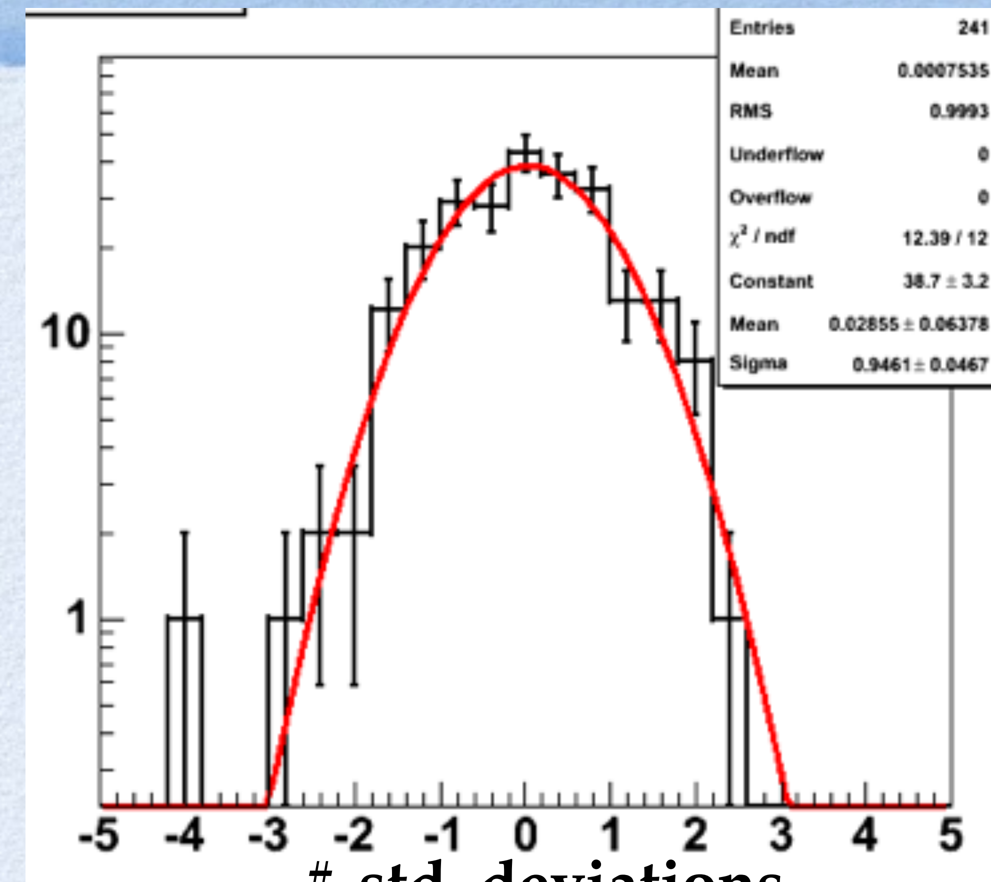

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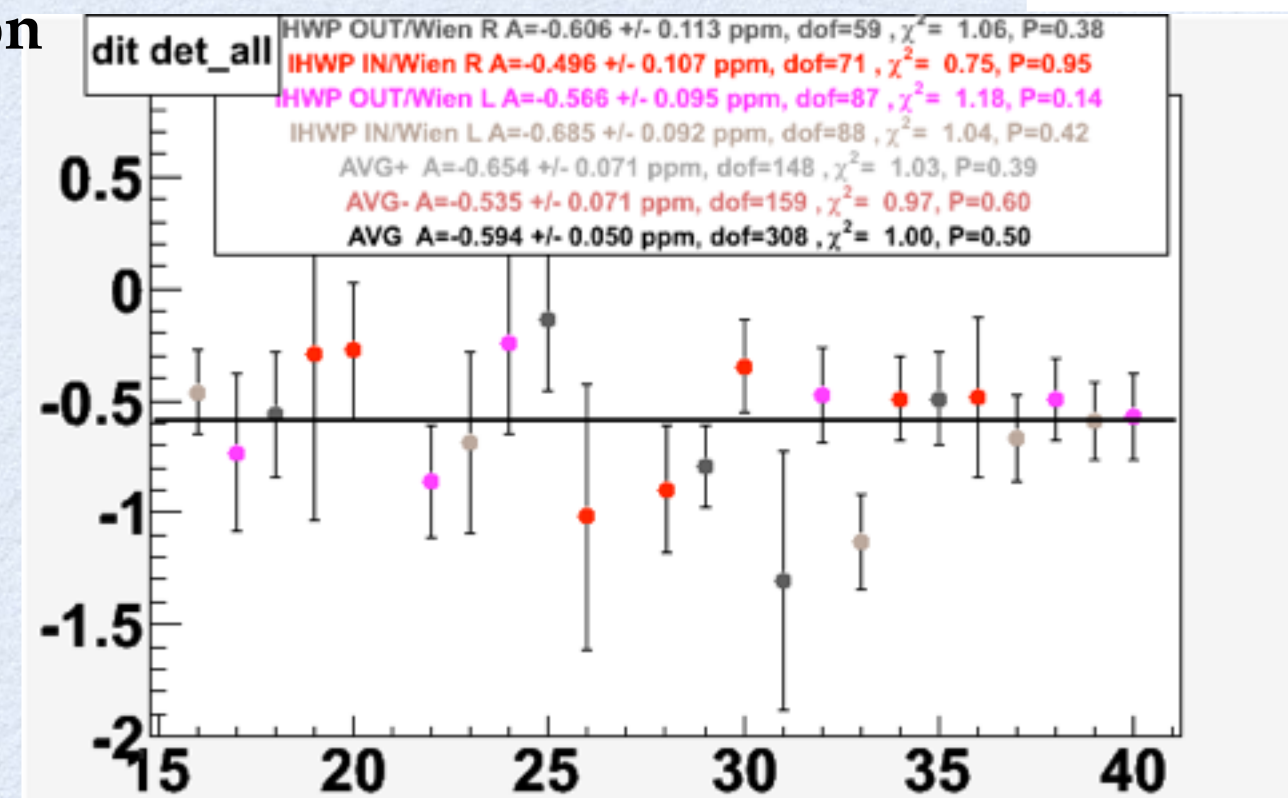
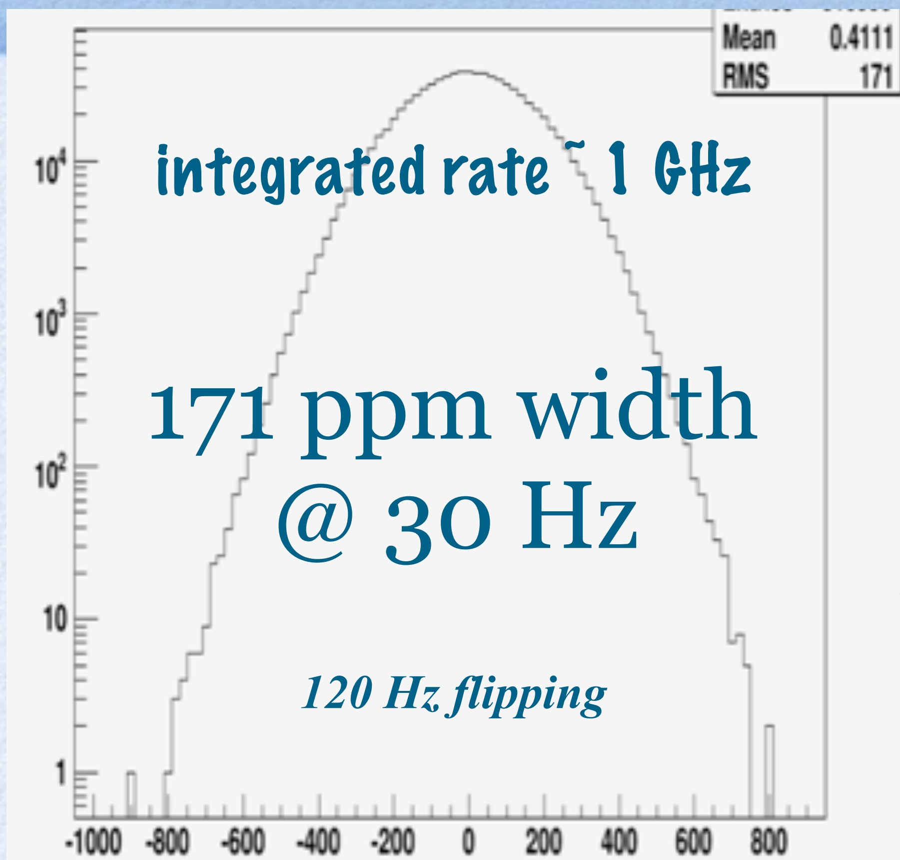


606 ± 113
496 ± 107
566 ± 095
685 ± 092

594 ± 50
parts per billion (ppb)

Physics Data: April/May 2010

Raw Asymmetry Data



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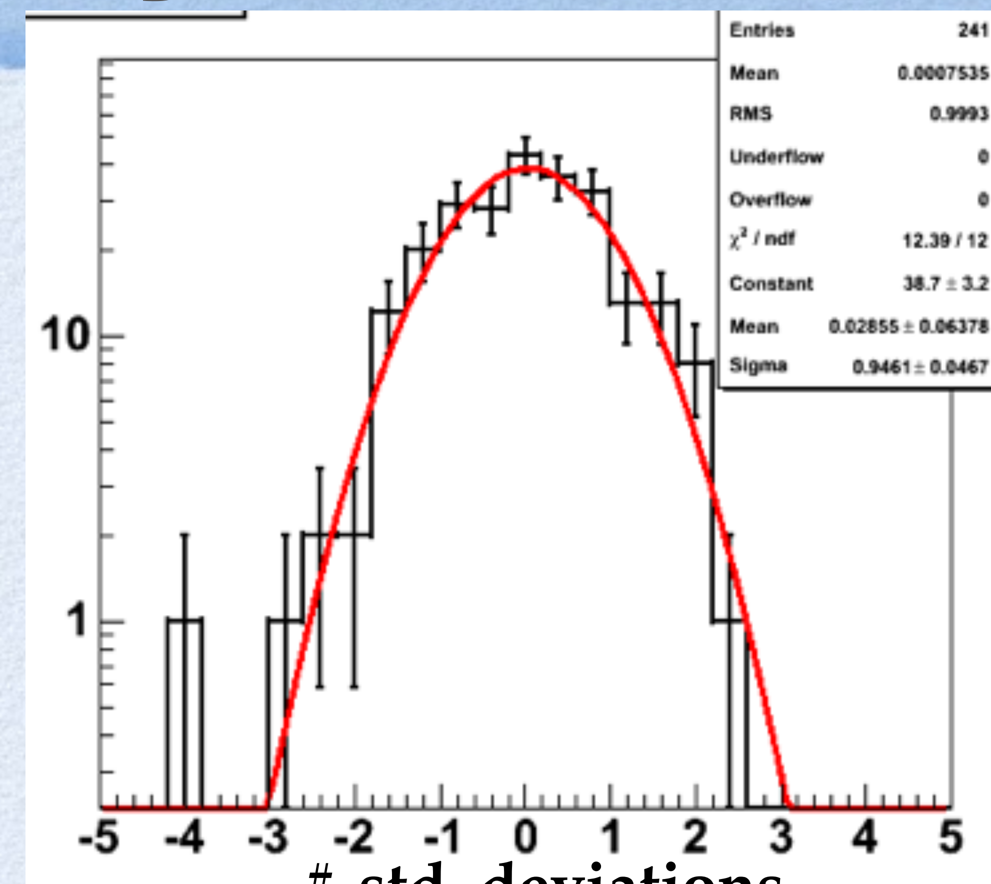

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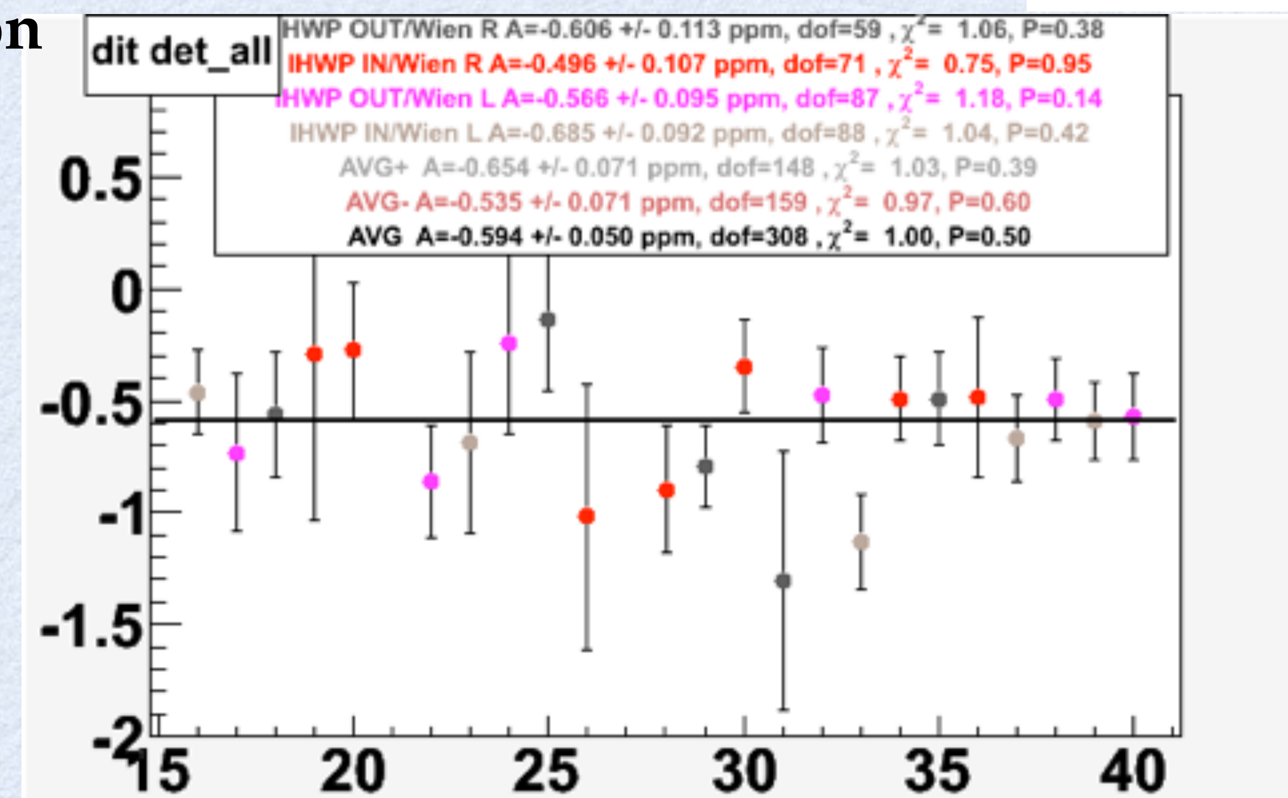

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systematic error due to beam fluctuations: 7 ppb

Normalization Errors

Goal for total systematic error ~ 2% achieved!

Systematic Error	Absolute (ppm)	Relative (%)
Polarization	0.0083	1.3
Detector Linearity	0.0076	1.2
Beam current normalization	0.0015	0.2
Rescattering	0.0001	0
Transverse Polarization	0.0012	0.2
Q^2	0.0028	0.4
Target Backing	0.0026	0.4
Inelastic States	0	0
TOTAL	0.0140	2.1

$$A_{phys} = \frac{A_{sig}}{P_{beam}}$$

Two independent methods, polarized Møller and Compton Scattering

Both methods achieved ~ 1.5%: expected to reach sub-1% for PREX-II/CREX

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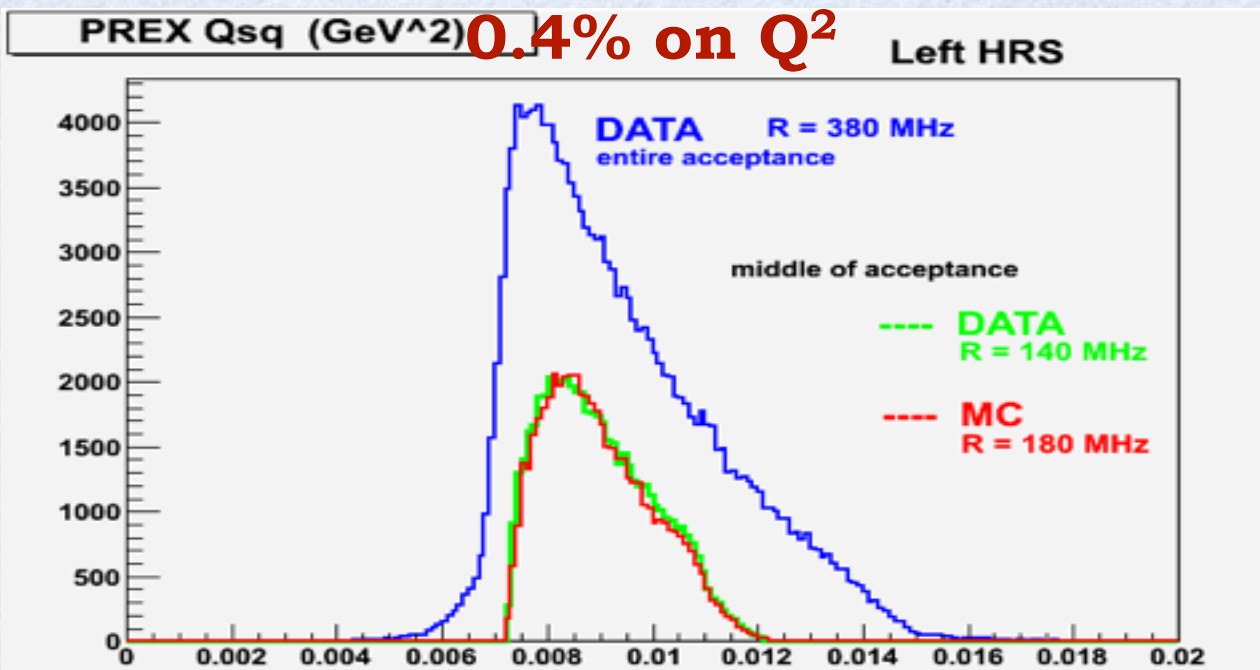
4-momentum transfer $Q^2 = 4EE'\sin^2\frac{\theta}{2}$

calibration

E: spin precession in machine
E': NMR in HRS B field
scattering angle: survey ~ 1 mr

Q^2 distribution obtained by low rate runs; trigger on quartz pulse-height

0.4% absolute calibration achieved:



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Absolute angle calibration via nuclear recoil variation

Recoil is large for H, small for nuclei

Water cell target

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

4-momentum transfer $Q^2 = 4EE'\sin^2\frac{\theta}{2}$

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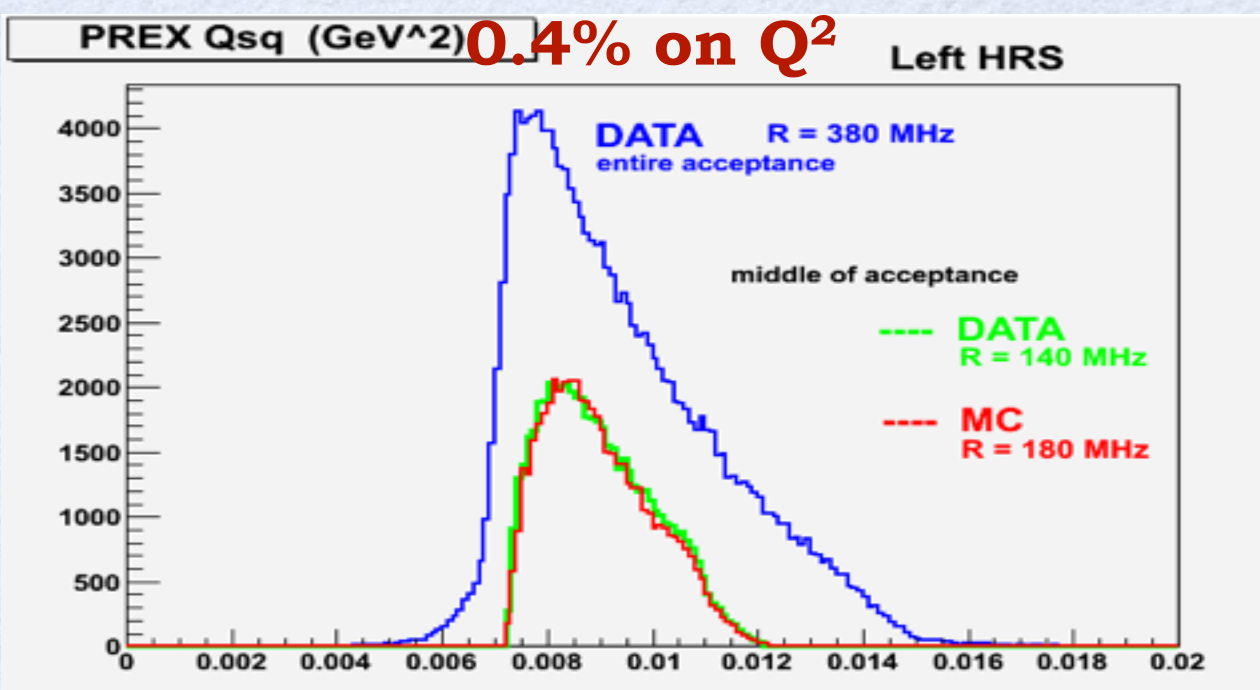


Final Result

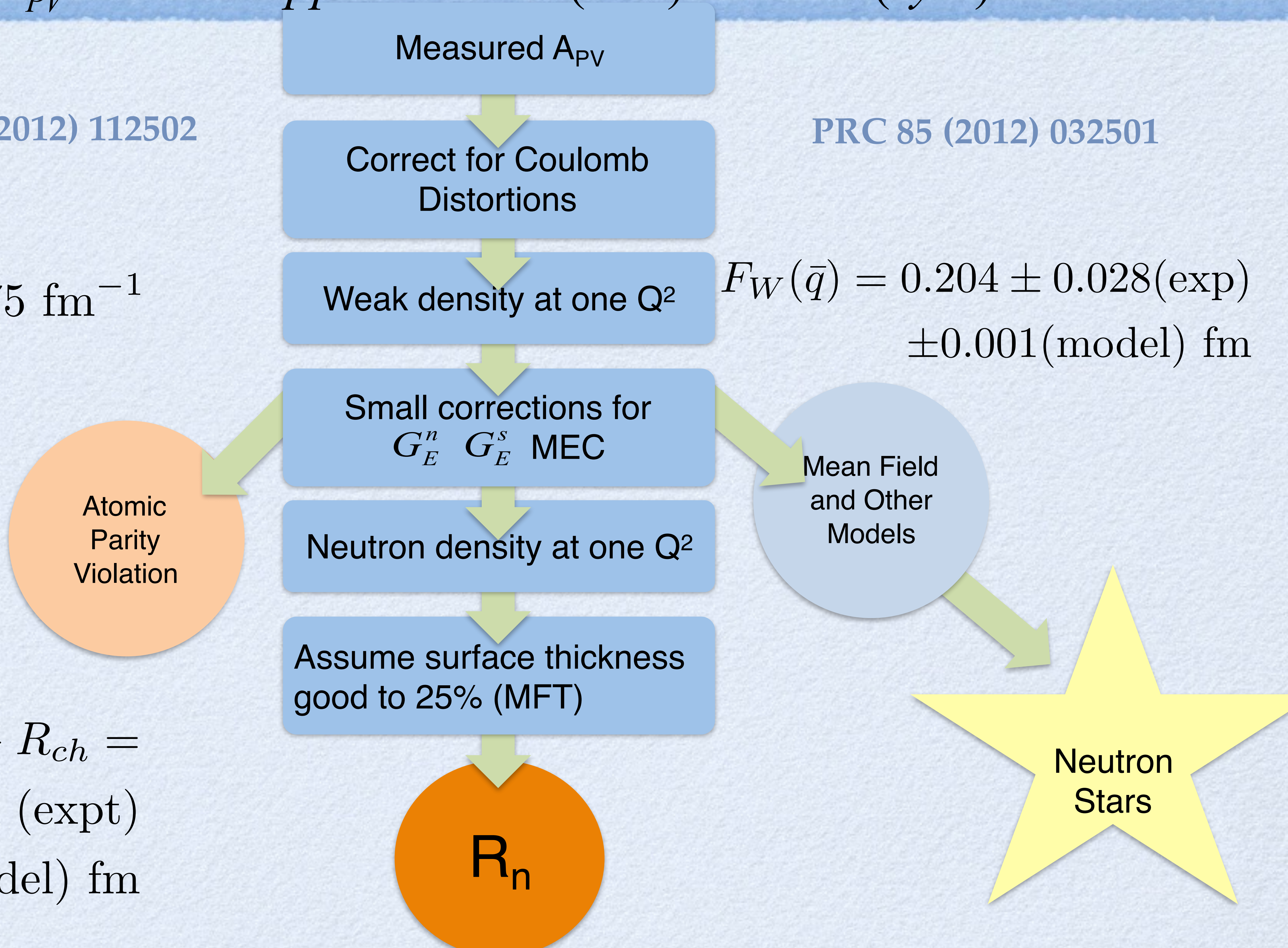
$$A_{PV} = 0.656\ ppm \pm 0.060(stat) \pm 0.014(syst)$$

PRL 108 (2012) 112502

PRC 85 (2012) 032501

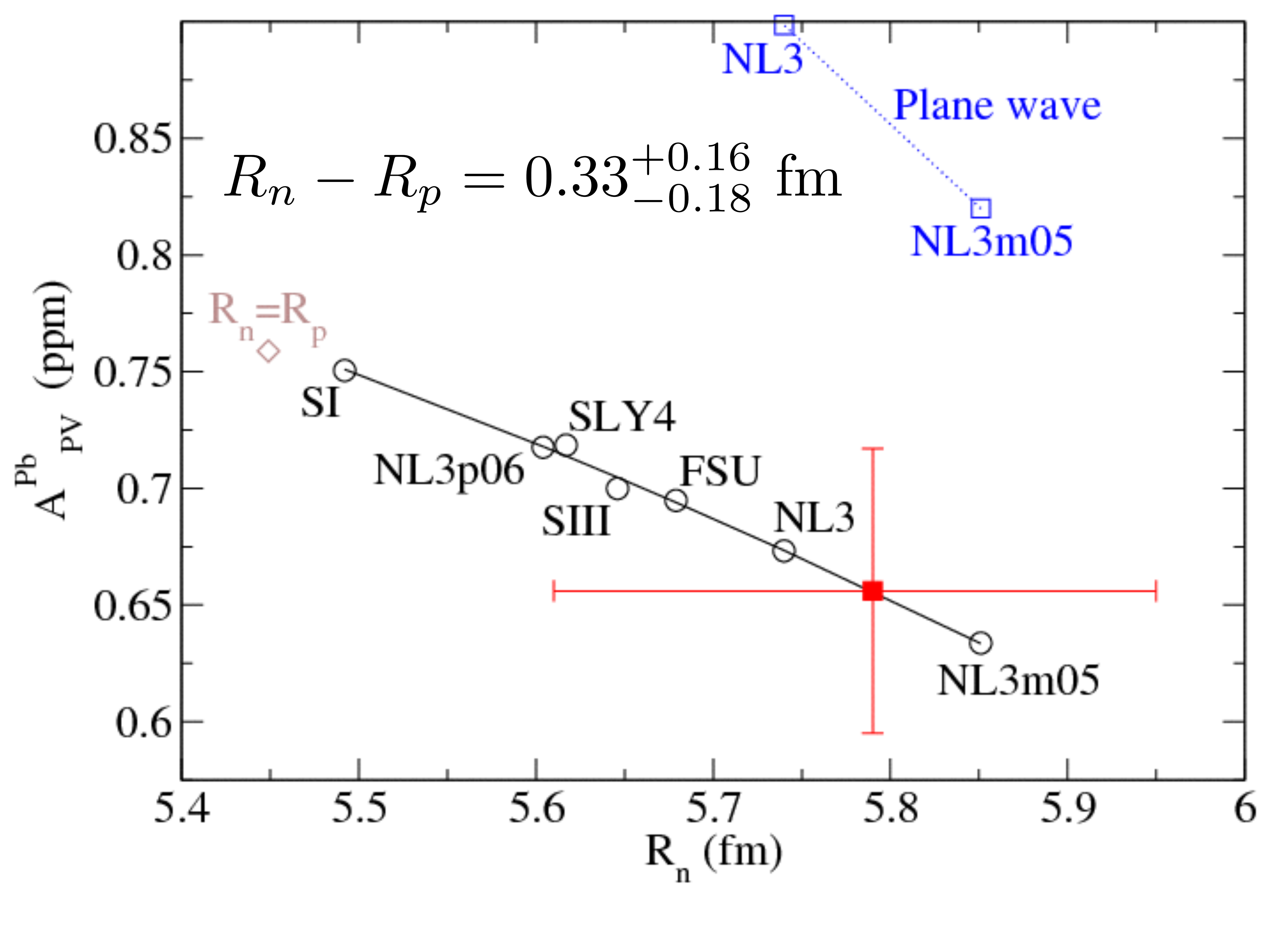
$$\bar{q} = 0.475\ \text{fm}^{-1}$$

$$F_W(\bar{q}) = 0.204 \pm 0.028(\text{exp}) \pm 0.001(\text{model})\ \text{fm}$$



$$R_W - R_{ch} = 0.32 \pm 0.12\ (\text{expt}) \pm 0.03\ (\text{model})\ \text{fm}$$

The Neutron Skin



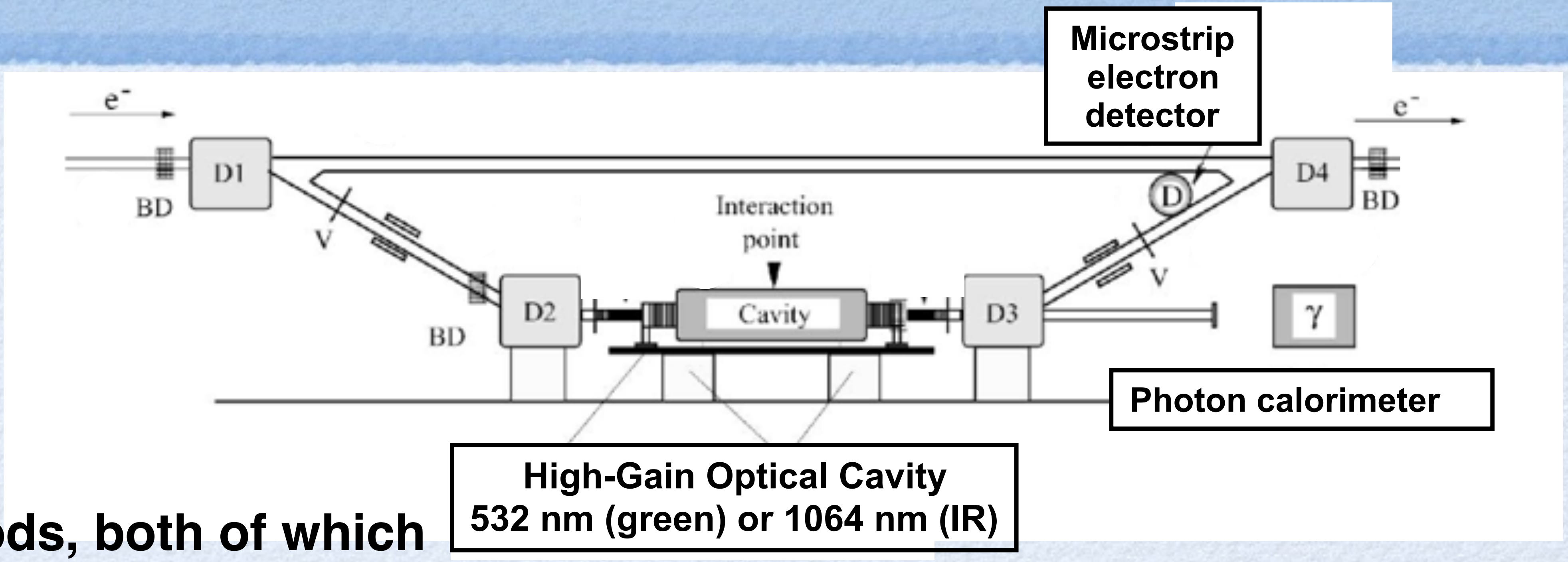
First electroweak indication of a neutron skin of a heavy nucleus (CL ~ 90-95%)

Conclusions & Outlook

- **PREX-I produced the first electroweak measurement of the neutron RMS radius in a heavy nucleus**
- **Many new technical challenges overcome**
    - ***High luminosity Pb target***
    - ***Precision 1 GeV polarimetry***
    - ***Spectrometer optics optimization to produce compact elastic footprint***
    - ***"Parity quality" beam***
    - ***Pb transverse asymmetry measured and introduces negligible uncertainty***
    - ***Novel integrating detectors can count at GHz rates***
- **Followup run approved by JLab PAC in Summer 2011**
    - ***First readiness review on June 1, likely to be scheduled in early 2018***
- **Potential for precise R_n measurements demonstrated**
    - ***PREX-II: allocated the beam time and demonstrated ability to achieve ±0.06 fm***
    - ***CREX approved: ^{48}Ca R_n goal: ±0.02 fm***
    - ***Potential to measure ^{208}Pb to ±0.03 fm at Mainz***
    - ***Motivation for a series of A_T measurements***

Beam Polarimetry

$$A_{phys} = \frac{A_{sig}}{P_{beam}}$$

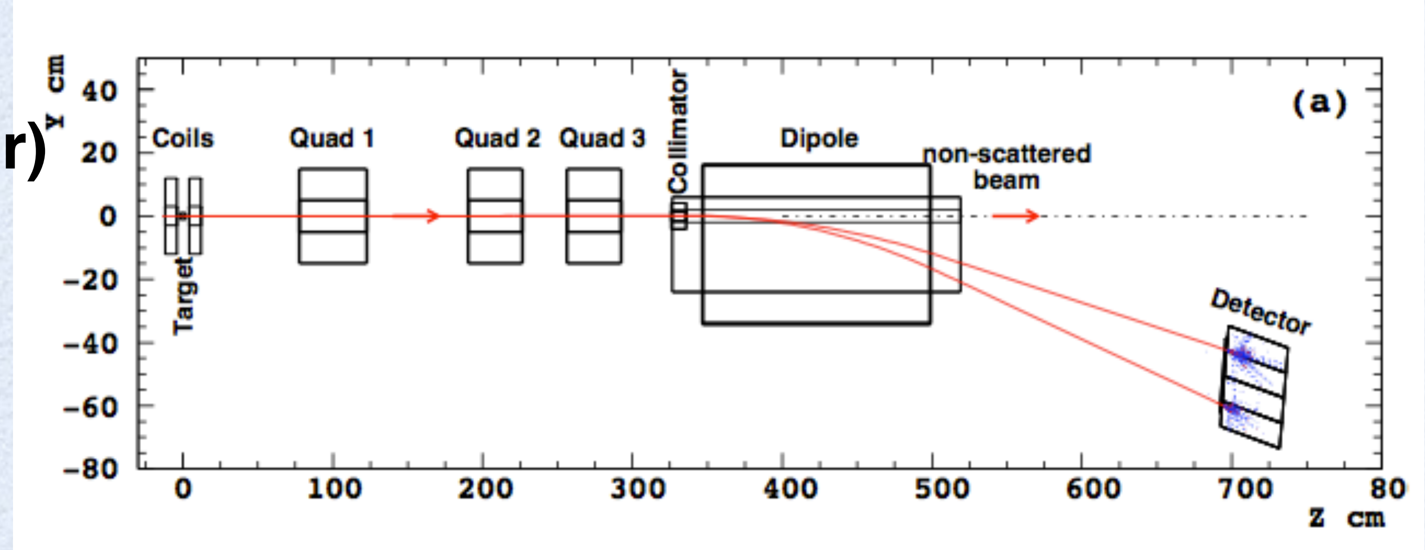


Two independent methods, both of which received recent upgrades

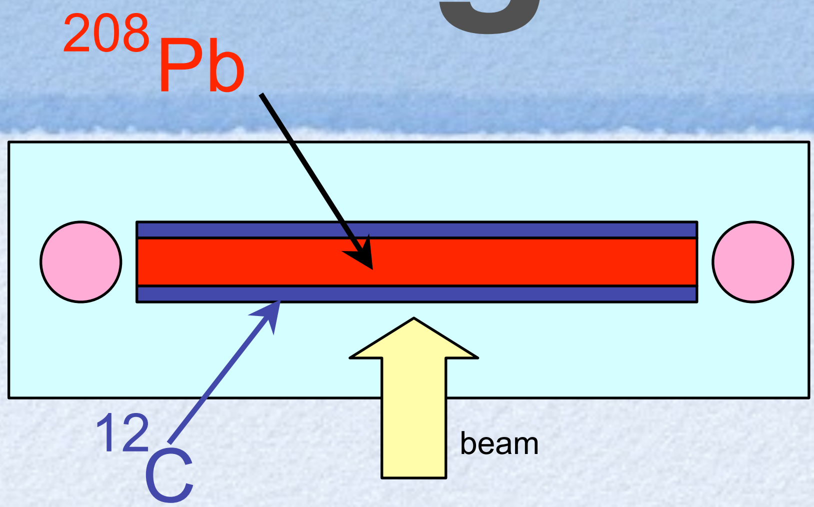
Both methods expected to reach sub-1% for future measurements: ultimate goal is sub-0.5%

- Compton Polarimeter
  - green laser (increased sensitivity at low E)
  - integrating method (analyzing power)
  - new photon & electron detectors

- Møller Polarimeter
  - electronics and DAQ
  - High field magnet for foil saturation: improved calibration of foil polarization

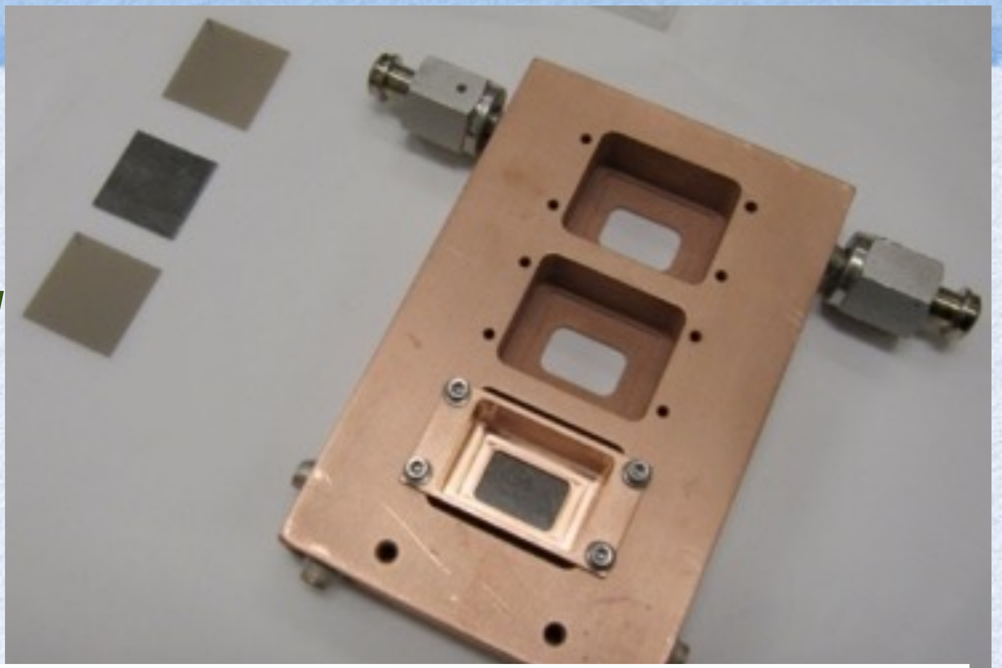


High Luminosity Target

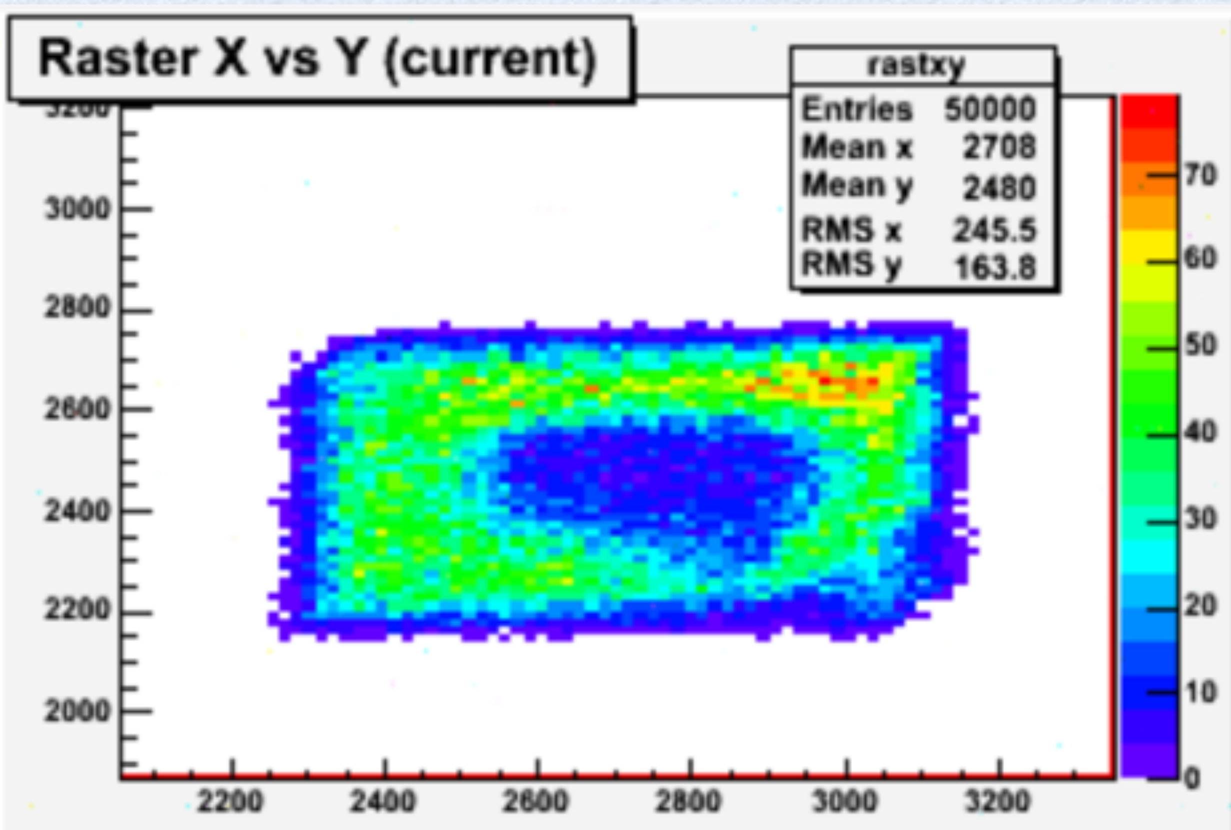


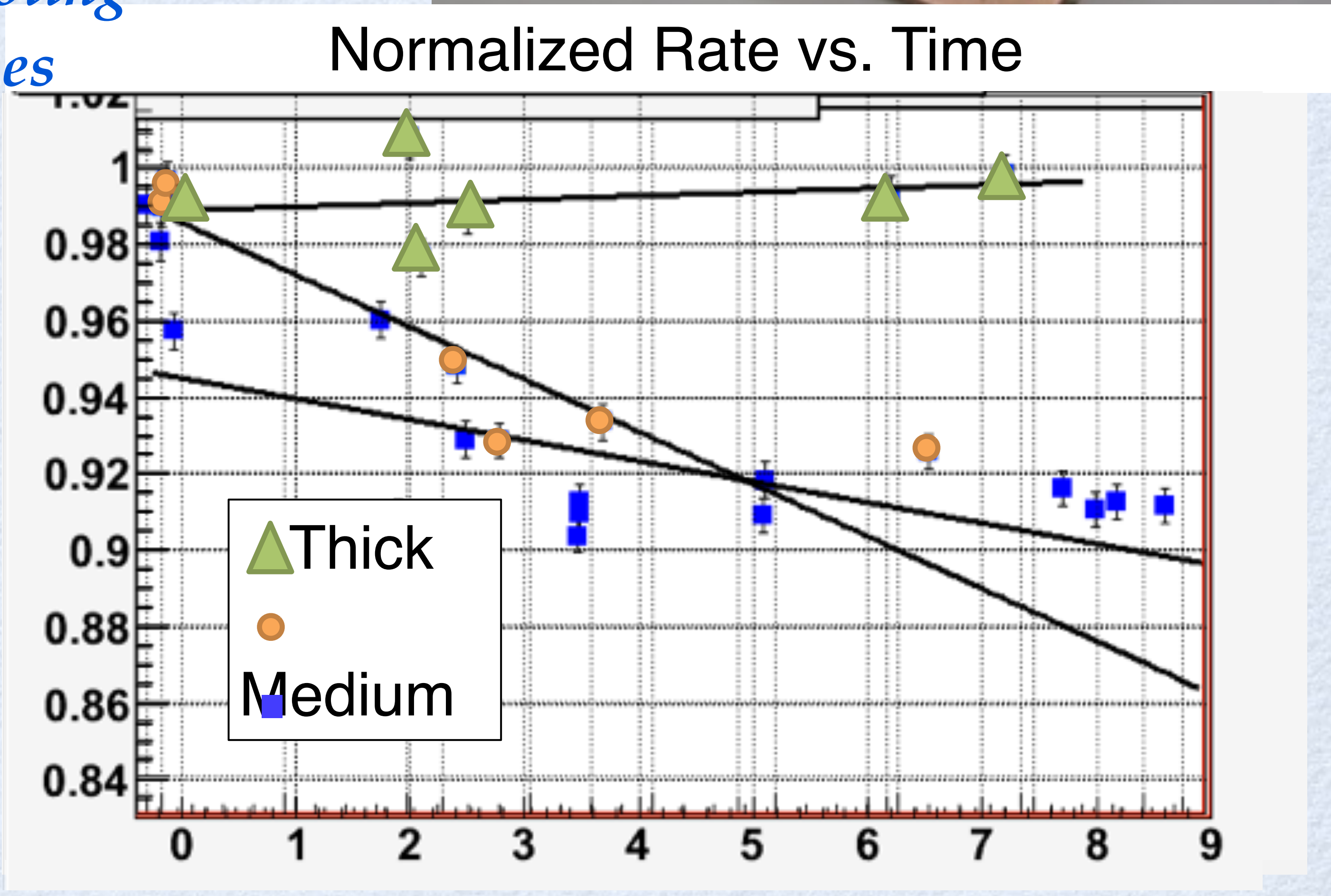
Targets with thin diamond backing (4.5%) degraded fastest

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



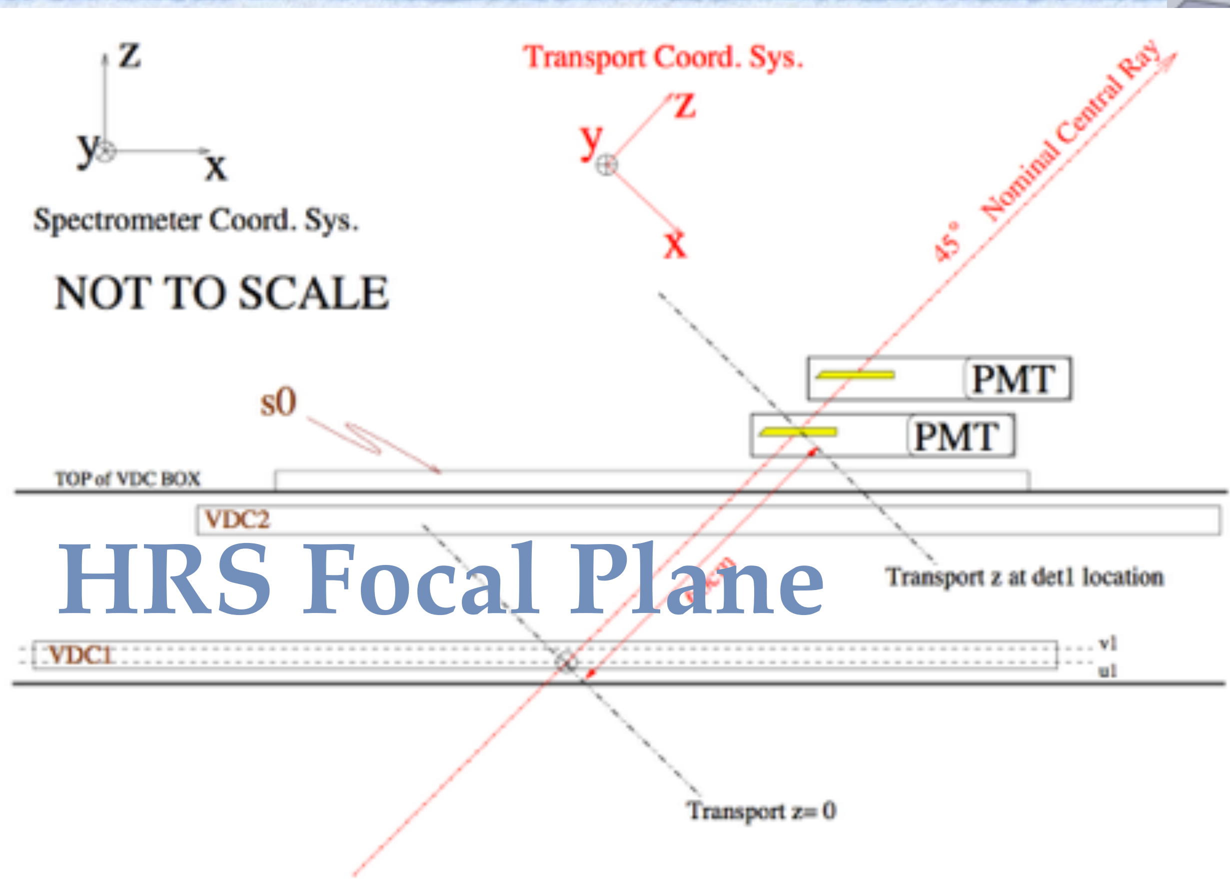
- *Pb-Diamond sandwich*
- *Diamond backing provides conductive cooling*
- *Active cryo-cooling with available He lines*

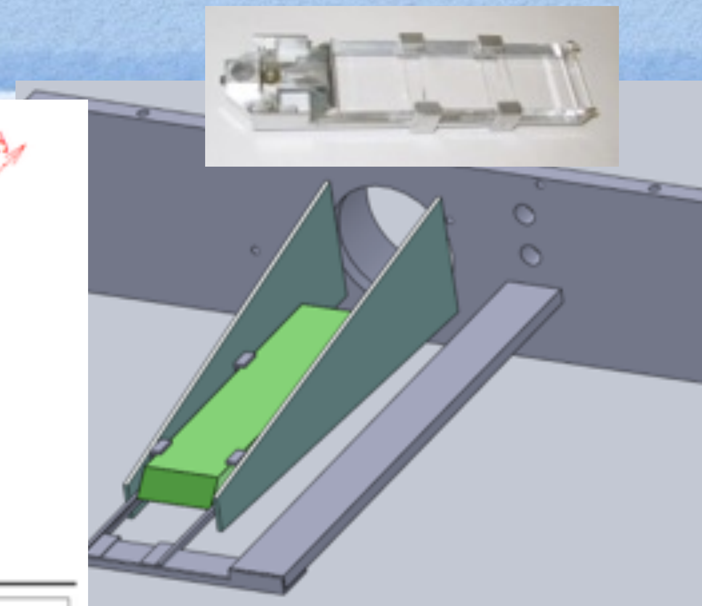


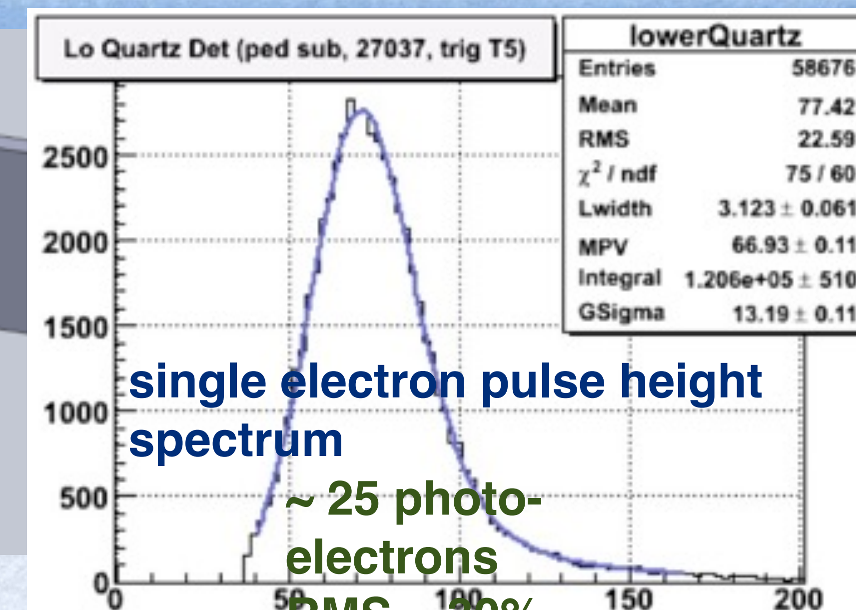


PREX-II plans on having 6-10 targets

Integrating Detectors







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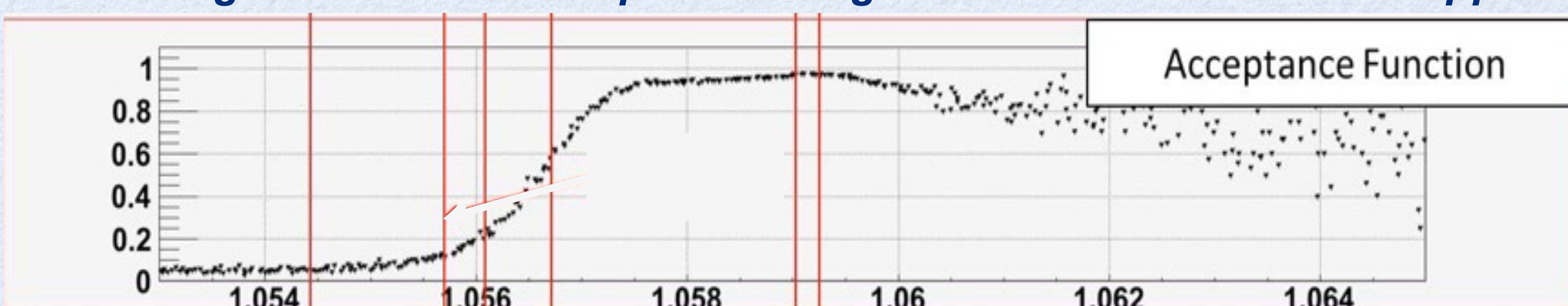
Detector integrates the elastic peak: Backgrounds from inelastics suppressed



Momentum (GeV/c)

C 1st excited state

4^- 5^- 3^-

Pb excited states

C Pb

Ground States

$A_{raw} \sim 500$ ppb $\quad A_{corr} = A_{det} - A_Q + \alpha\, \Delta_E + \Sigma \beta_i\, \Delta x_i$

Beam Stability Performance

PREX-I ran from March to May 2011

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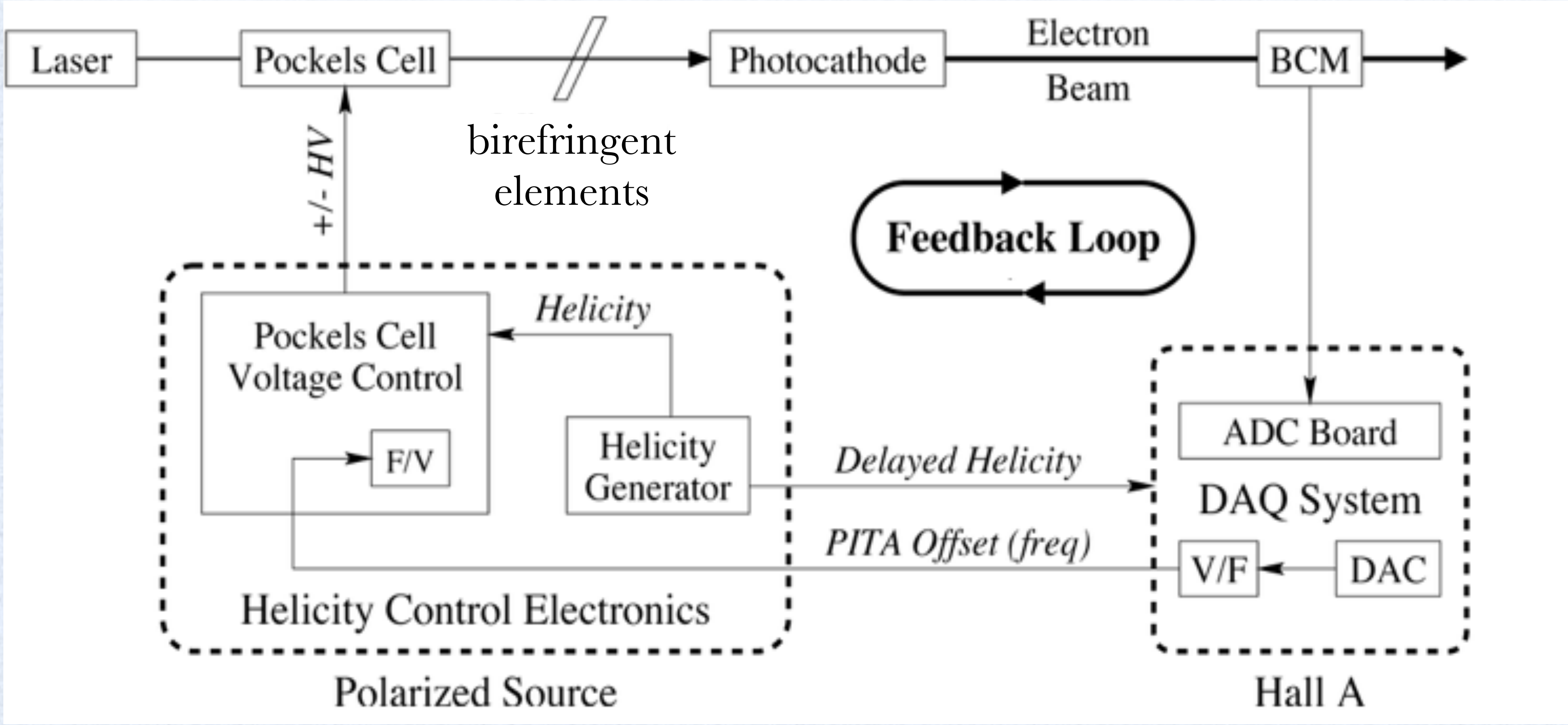
Beam Stability Performance

PREX-I ran from March to May 2011

- *Active feedback of charge asymmetry*
- *Careful laser alignment*
- *Precision beam position monitoring*
- *Active calibration of detector slopes*

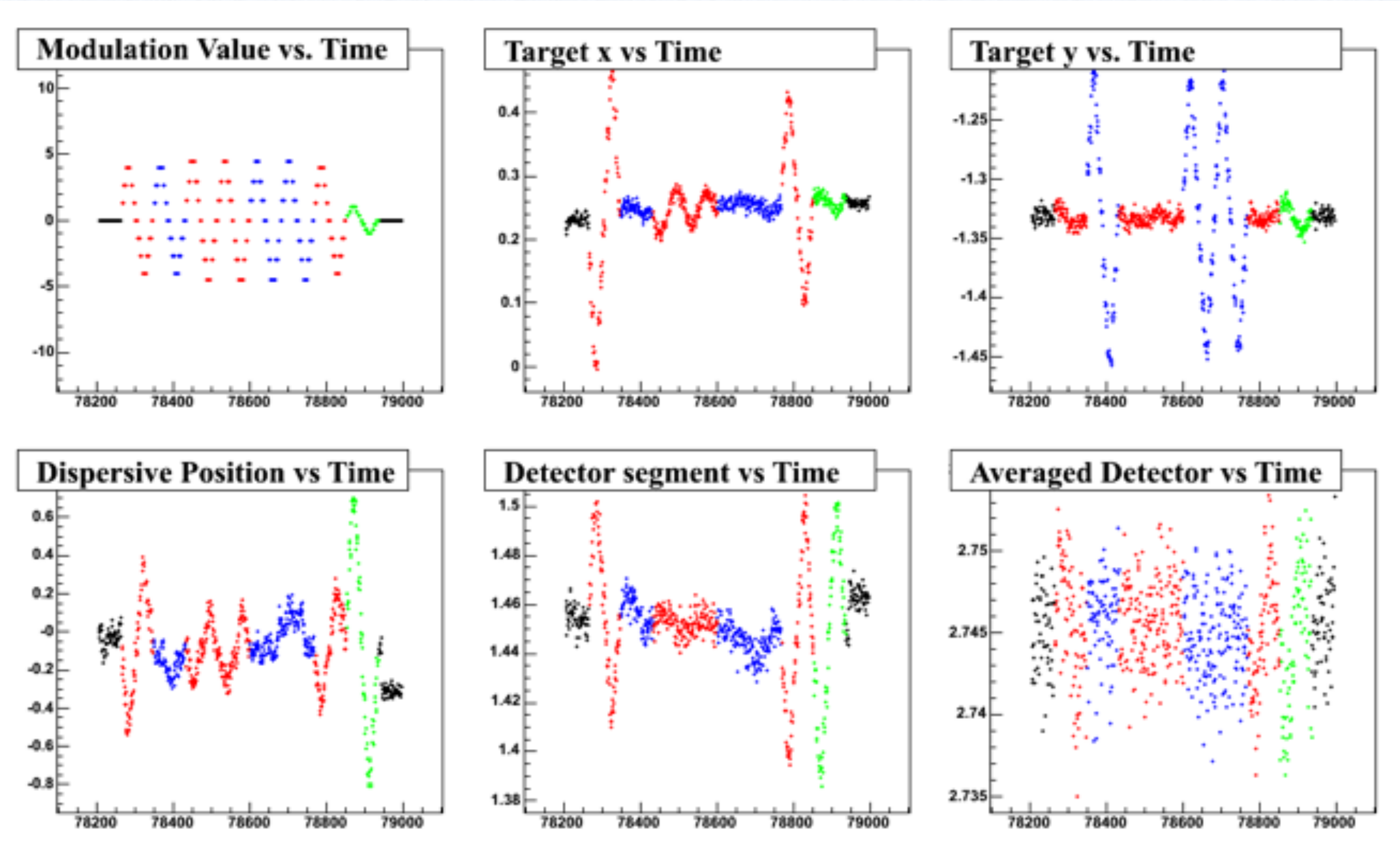


$A_{raw} \sim 500$ ppb

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

Beam Stability Performance

PREX-I ran from March to May 2011



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Beam Stability Performance

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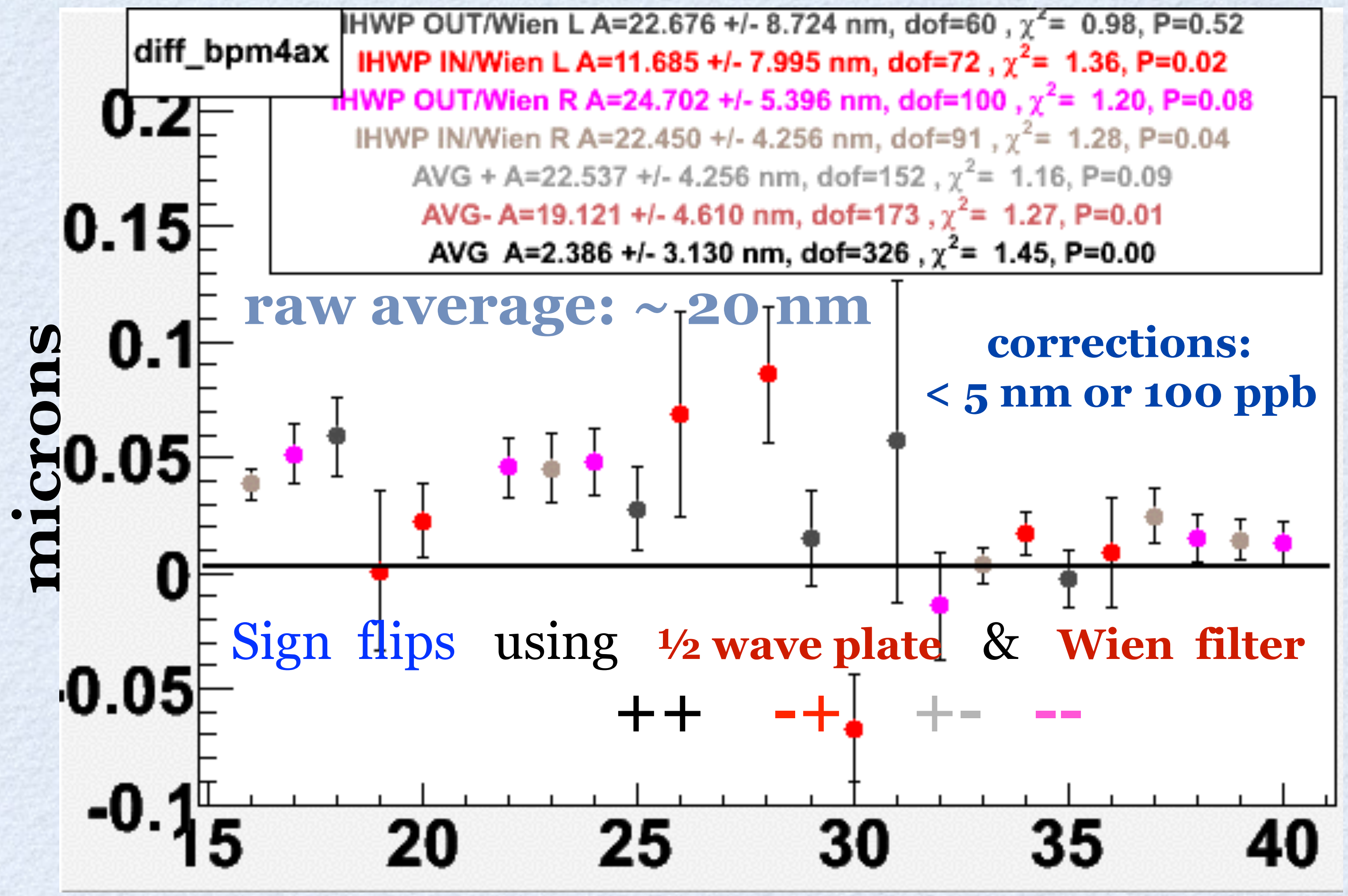
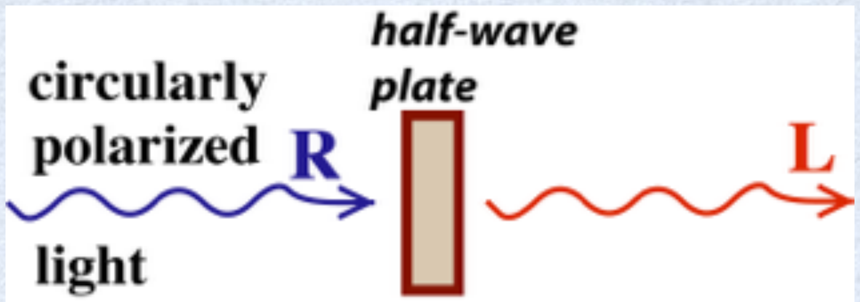
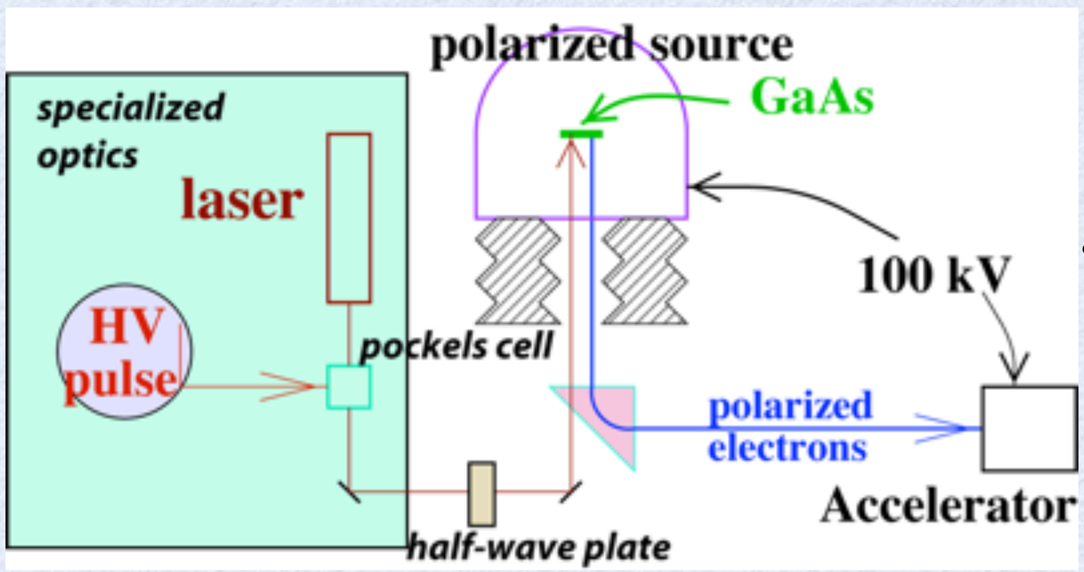


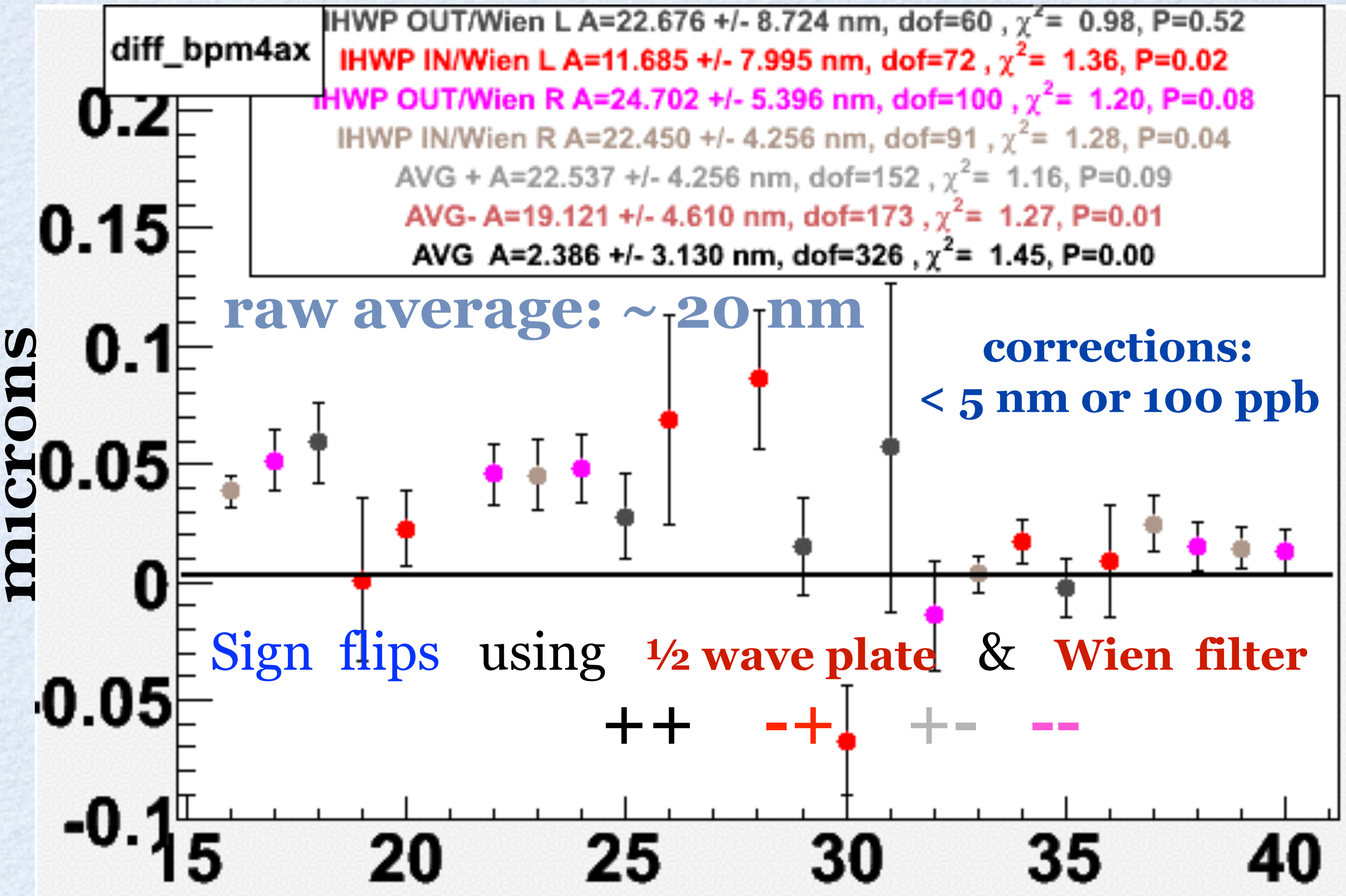
$A_{raw} \sim 500$ ppb $\quad A_{corr} = A_{det} - A_Q + \alpha\,\Delta_E + \Sigma\beta_i\,\Delta x_i$

Beam Stability Performance

2 methods of "slow" reversal







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Beam Stability Performance

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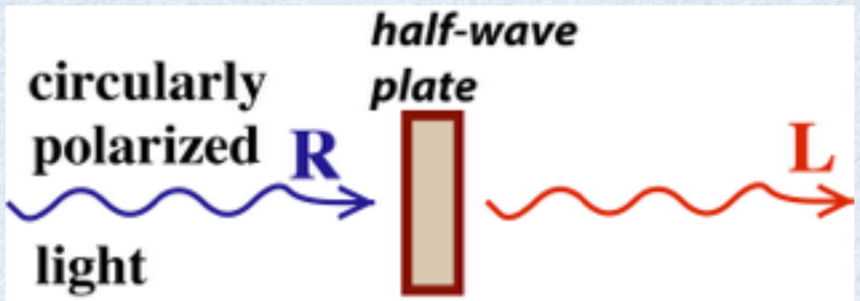
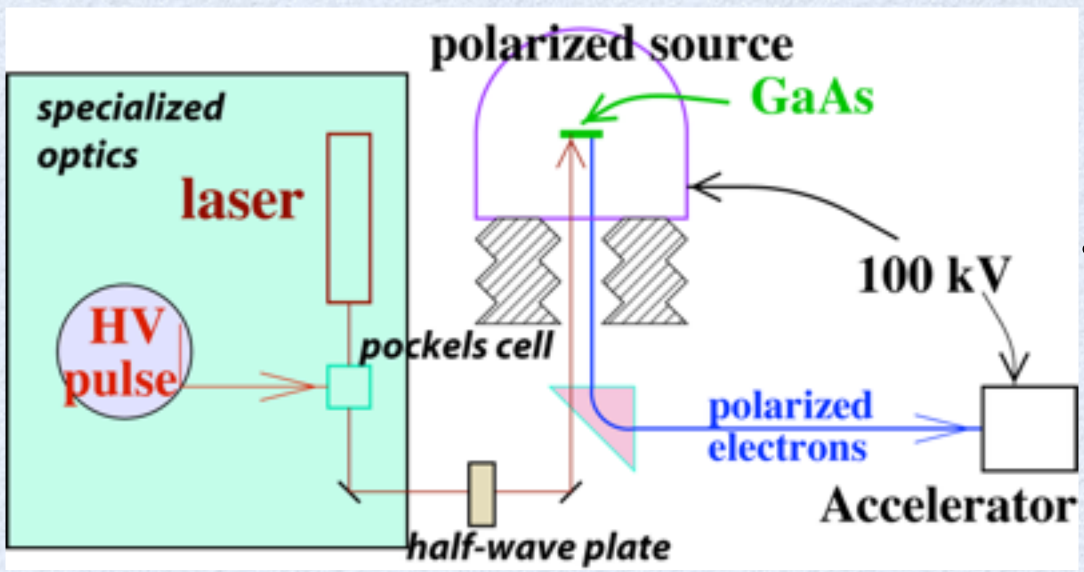
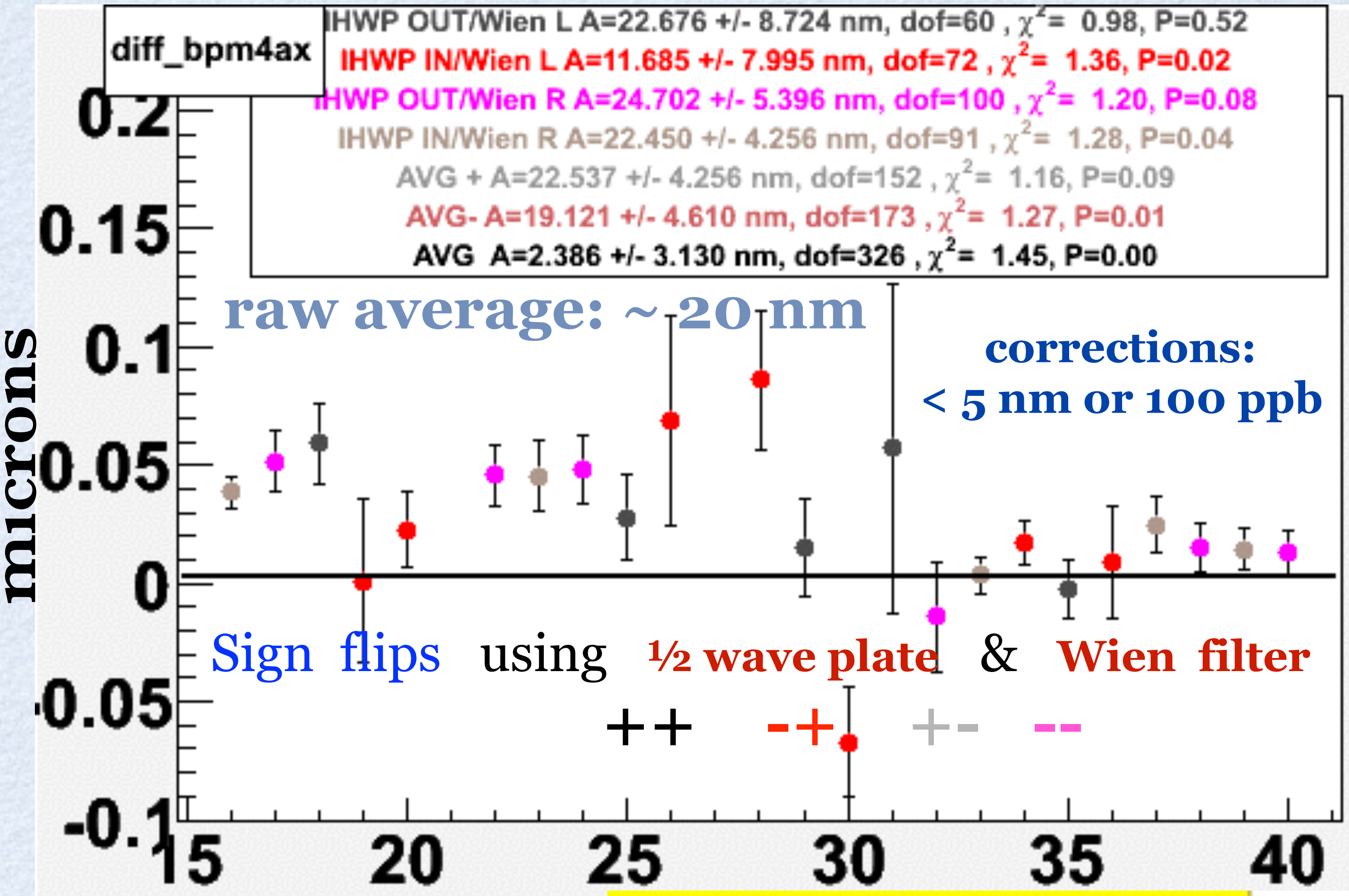
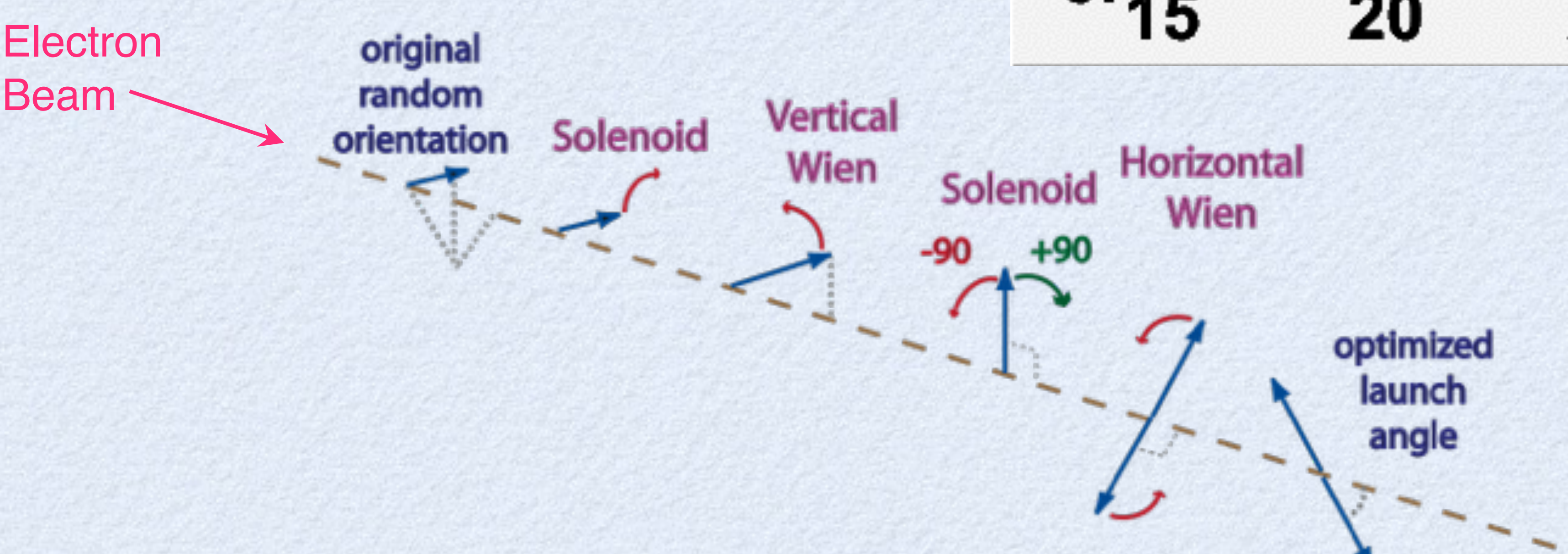
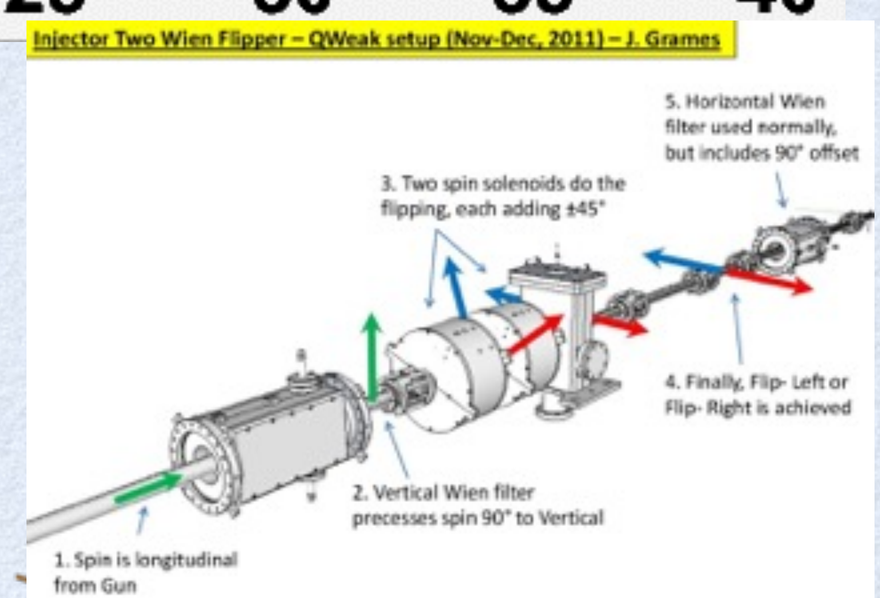


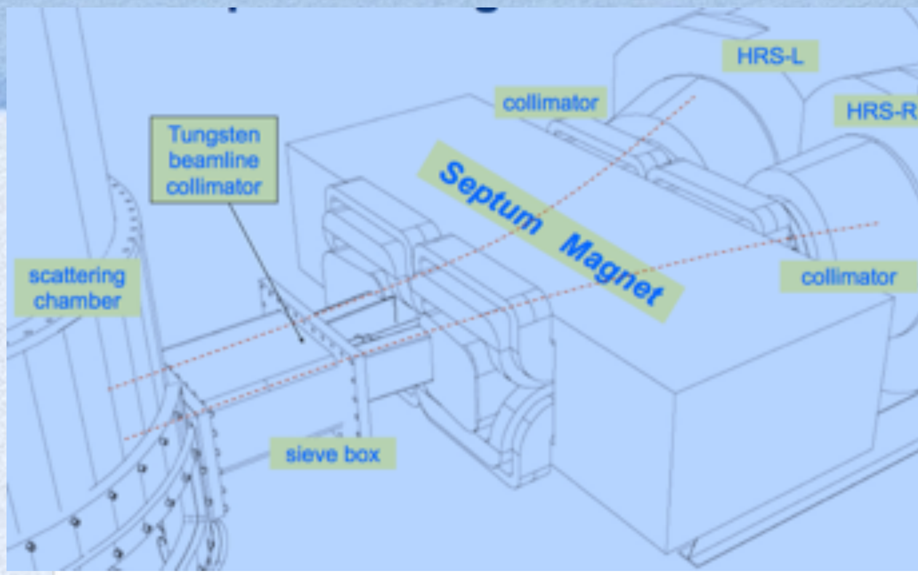


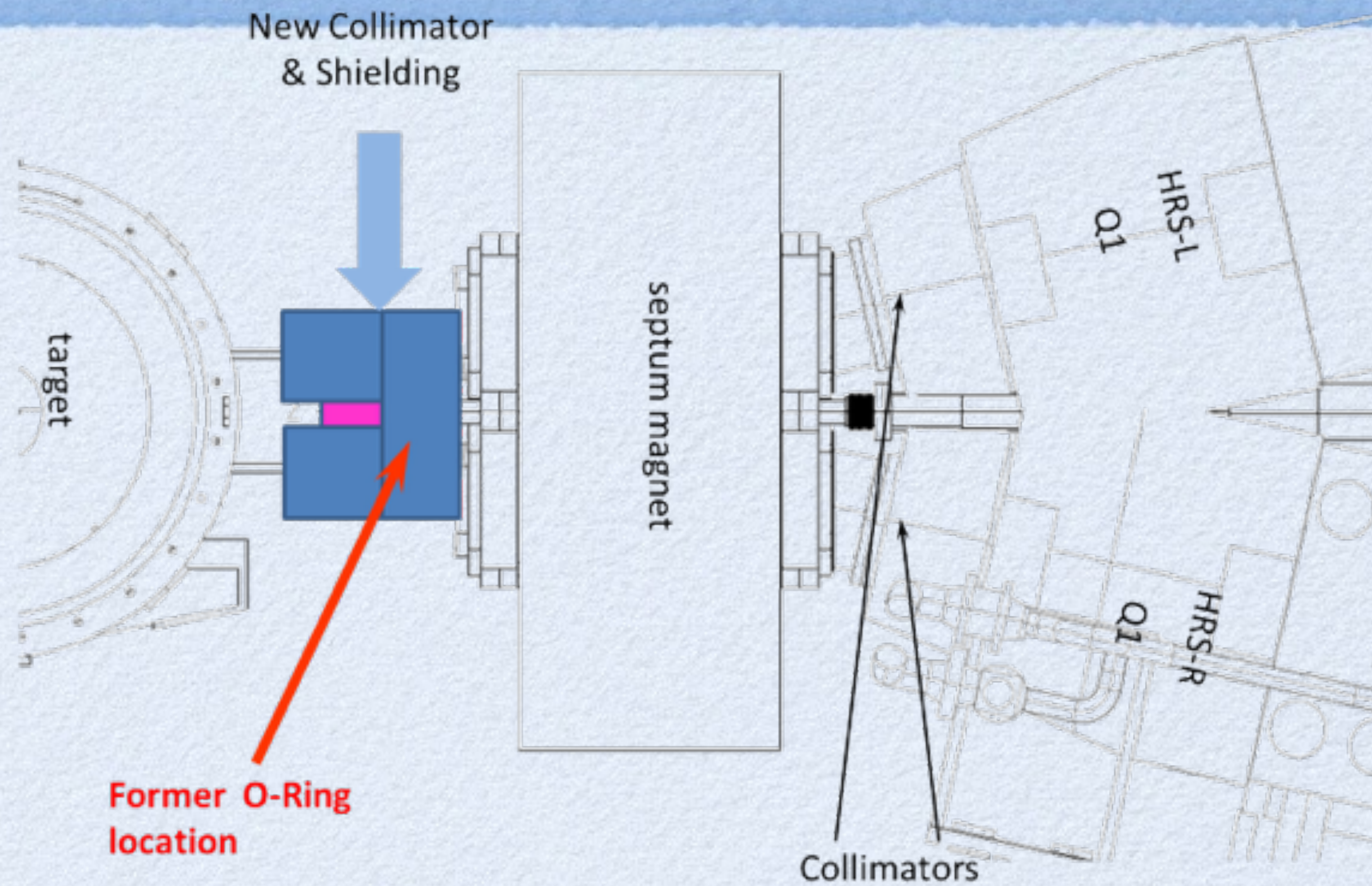


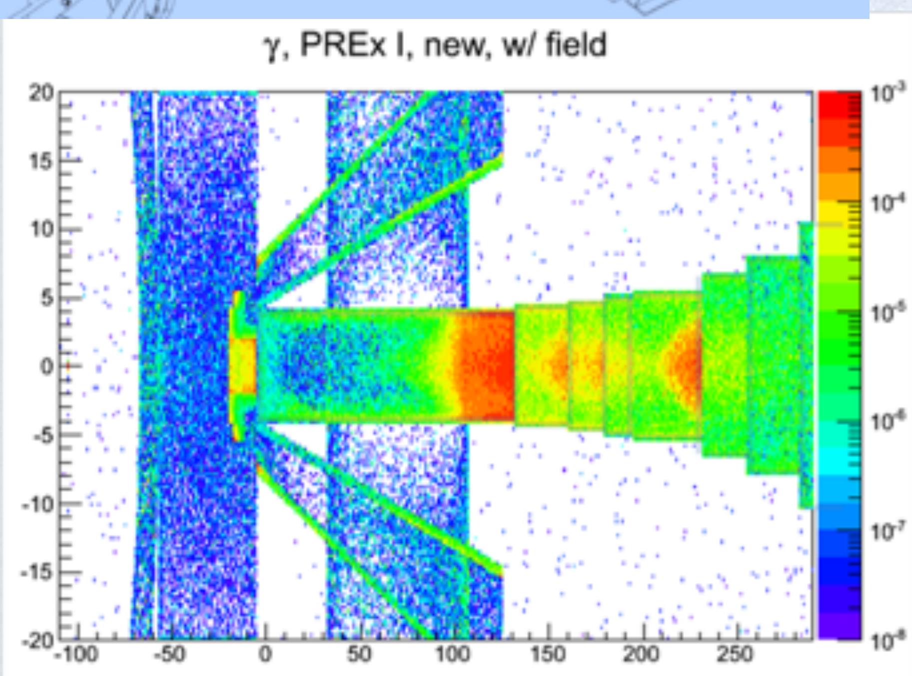


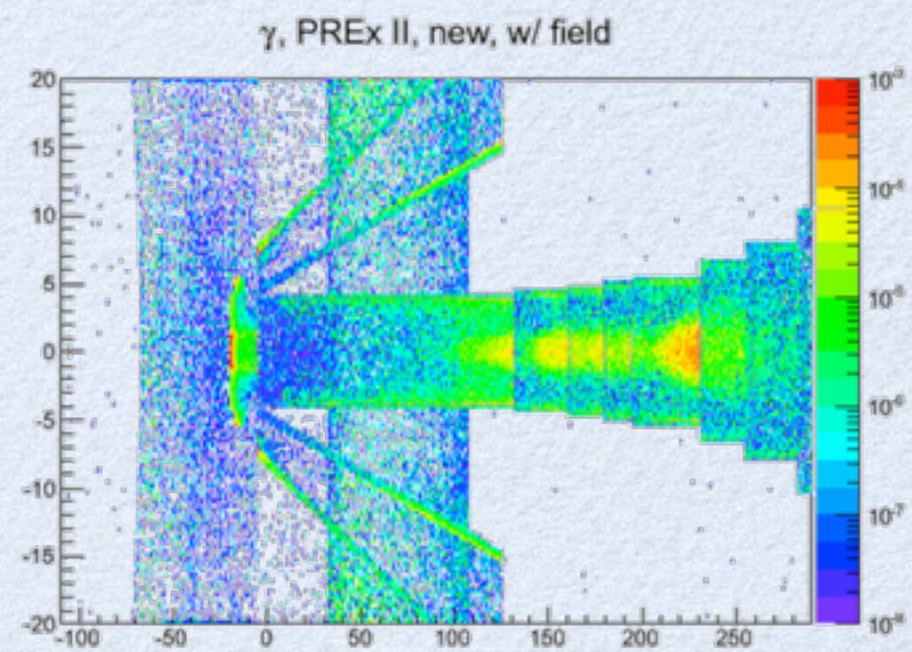


New Beamline Design









- **Redesign beamline seals to eliminate o-ring**
- **Neck down tungsten collimator to confine neutrons to one location and add water cooling**
- **Neutrons moderated by new shielding**
- **Small adjustment to septum current will realize an additional ~25% gain in statistical reach**

PREXII Projection

Presented to JLab PAC in June 2011: Approved with strong endorsement

PREx II improvements

- **Metal o-rings**
- **Radiation hard electronics**
- **Reduce neutron**

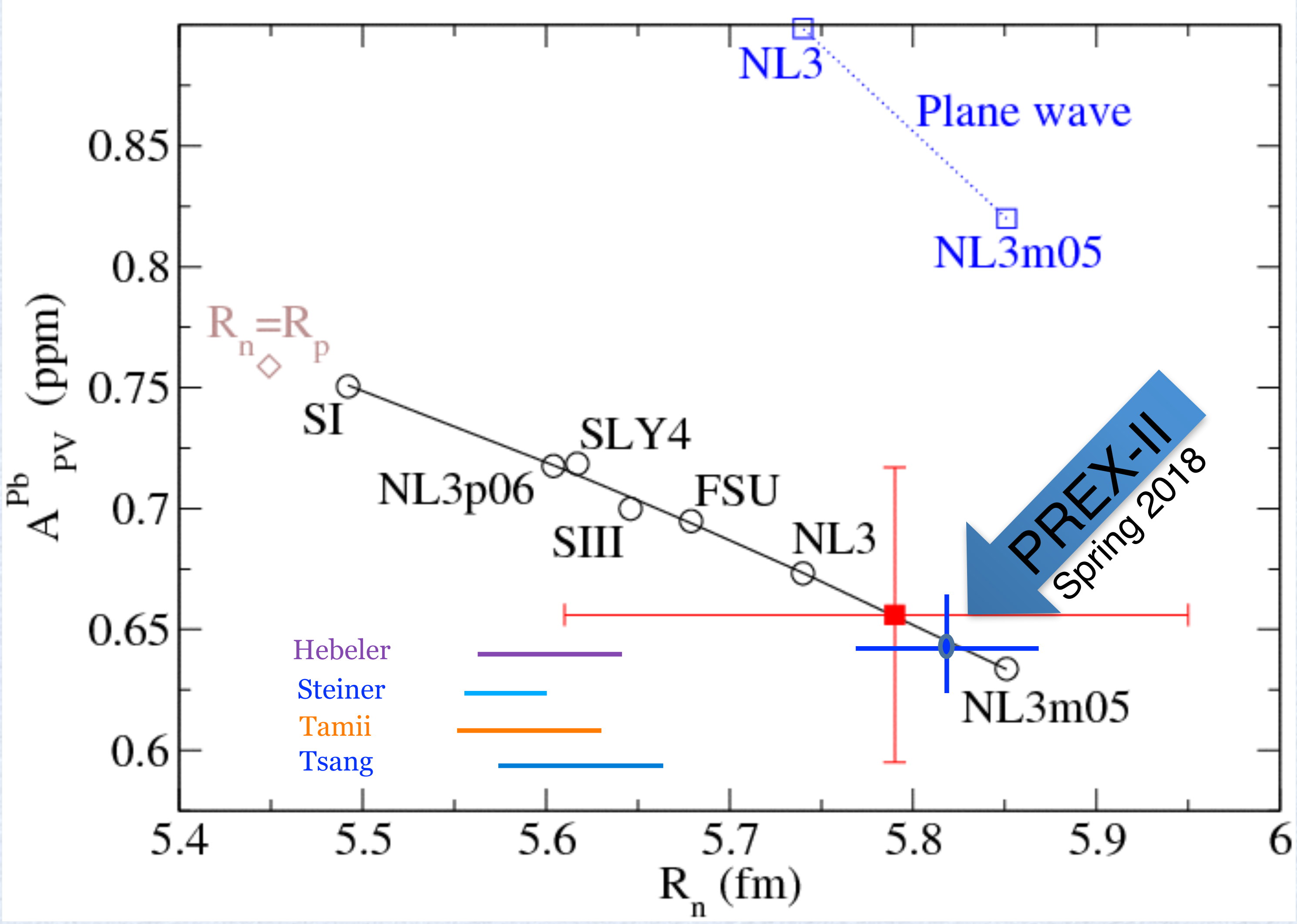
Full precision in 25 additional PAC days

$\delta(A_{PV})/A_{PV} \sim 3\%$

$\delta(R_n)/R_n \sim 1\%$

$\delta(R_n) \sim \pm 0.06$ fm

JLab has broad program: must continuously reiterate importance of PREX-II!



Recent R_n predictions:

Hebeler et al. Chiral EFT calculation of neutron matter. Correlation of pressure with neutron skin by Brown. Three-neutron forces!

Steiner et al. X-Ray n-star mass and radii observation + Brown correlation. (Ozel et al finds softer EOS, would suggest smaller R_n).

Tamii et al. Measurement of electric dipole polarizability of ^{208}Pb + model correlation with neutron skin.

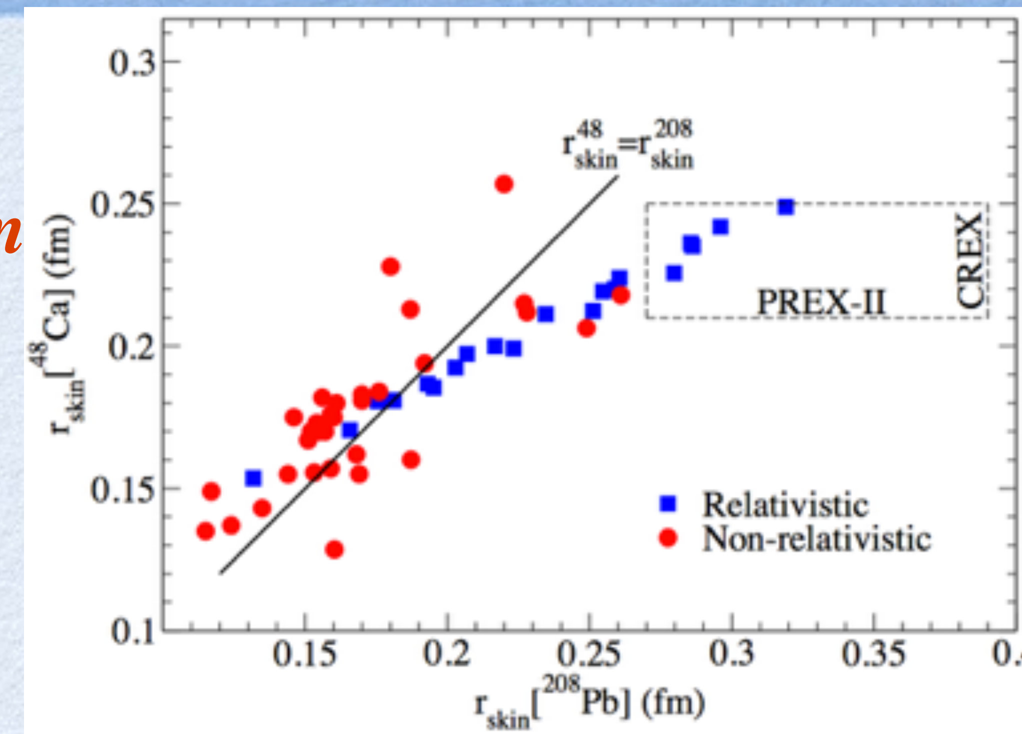
Tsang et al. Isospin diffusion in heavy ion collisions, with Brown correlation and quantum molecular dynamics transport model.

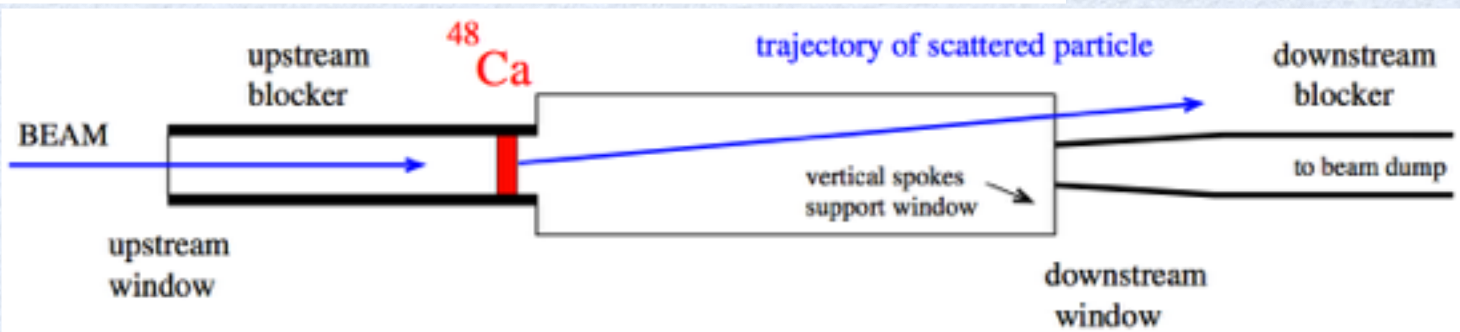
CREX at JLab

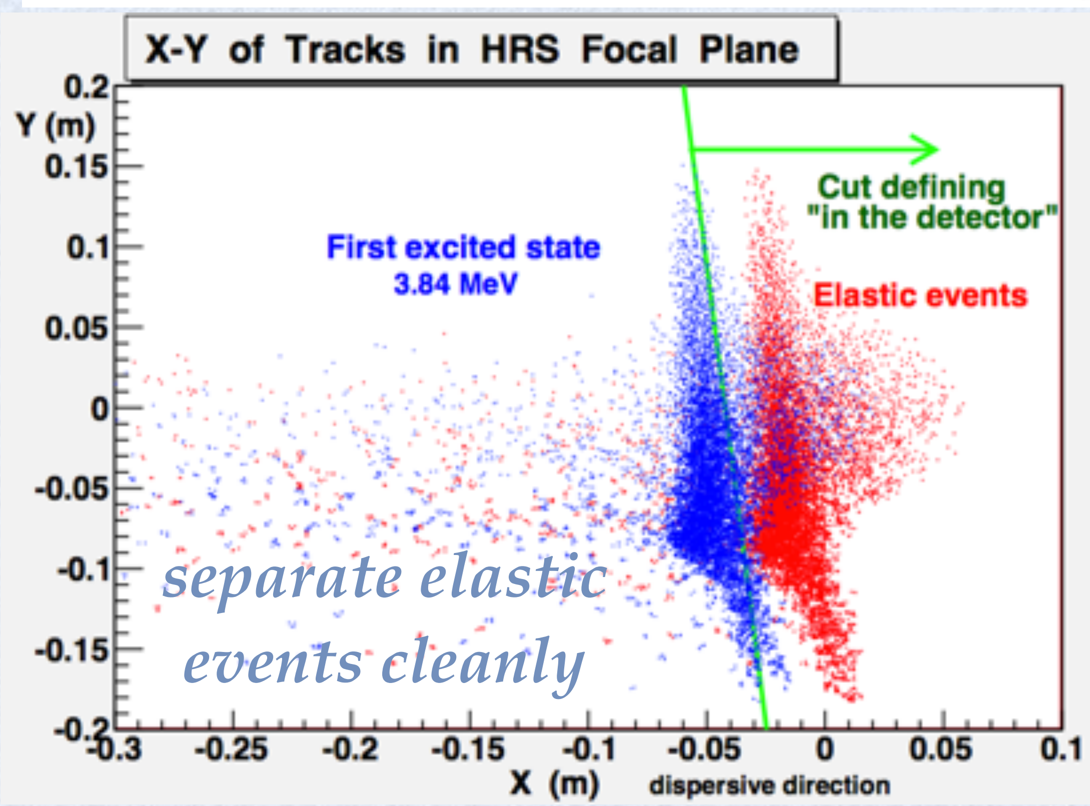
Approved by JLab PAC in Summer 2013

Measured Asymmetry (p_e A)	2 ppm
Scattering Angle	4°
Detected Rate (each HRS)	140 MHz
Statistical Uncertainty of A_{PV}	2.1%
Systematic Uncertainty of A_{PV}	1.2%
Statistical Uncertainty of A_T	0.4 ppm

δ(R_n) ~ ± 0.02 fm

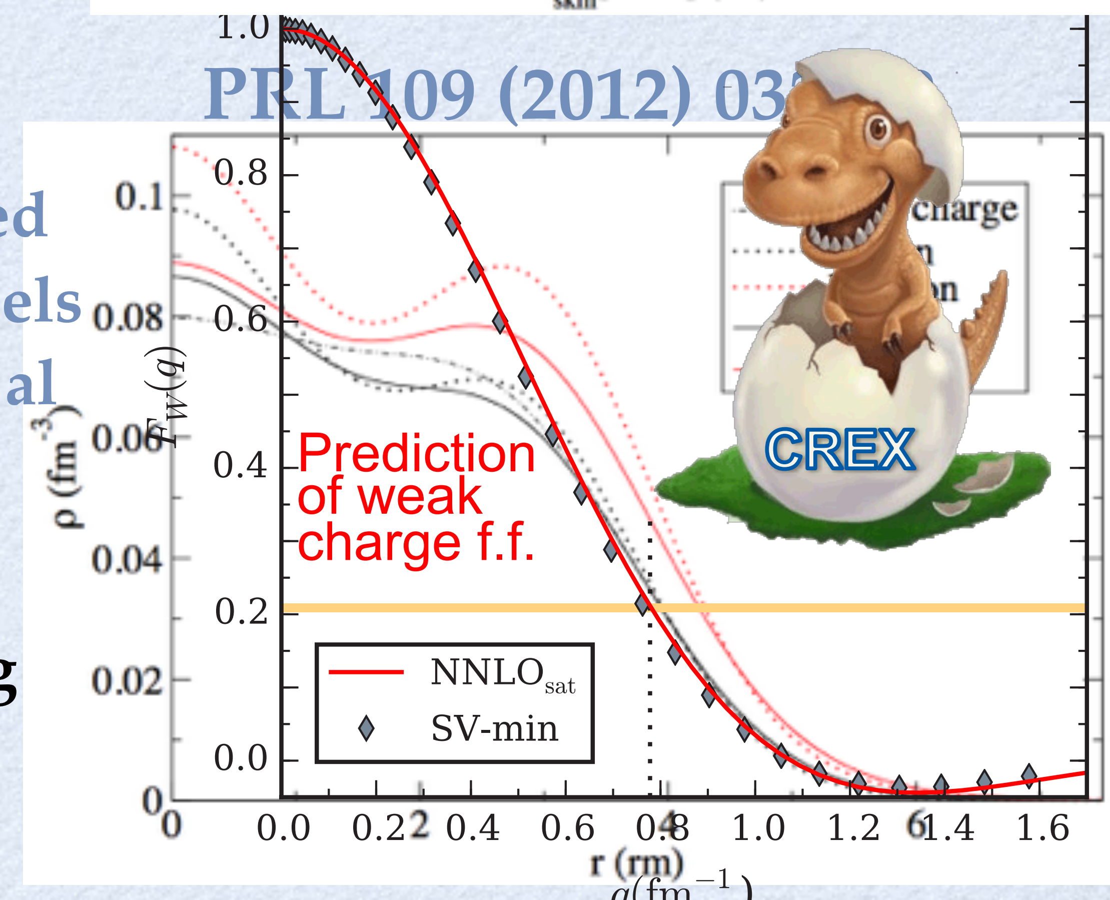






test coupled cluster models
G. Hagen et al

Could run in 2017 depending on schedule and funding



PREX/CREX Summary

With 30 days for PREX: 3% stat, 35 days for CREX 2% stat

PREX, $E = 1.1$ GeV, $A = 0.6$ ppm

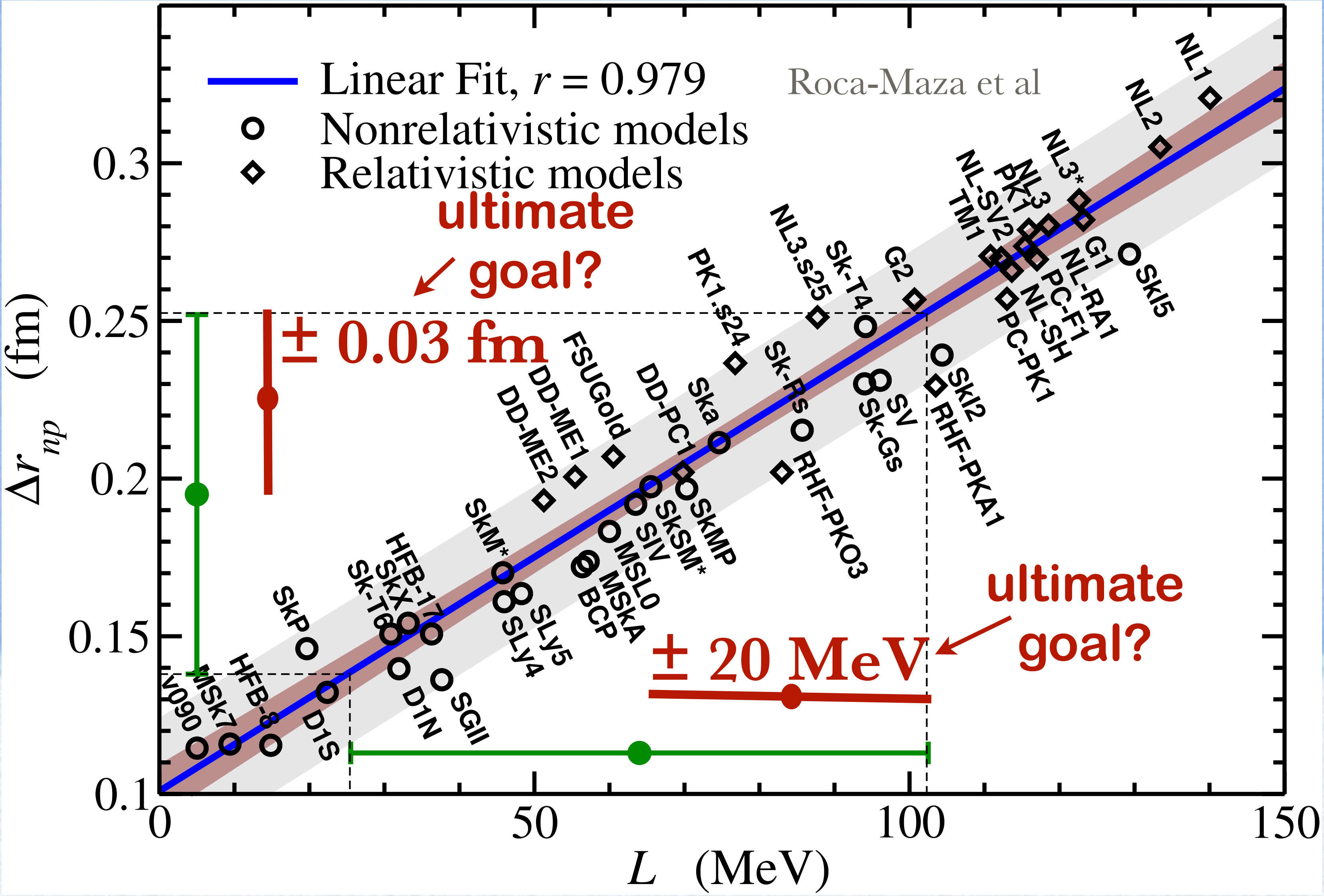
Charge Normalization	0.1%
Beam Asymmetries	1.1%
Detector Non-linearity	1.0%
Transverse	0.2%
Polarization	1.1%
Inelastic Contribution	$< 0.1\%$
Effective Q^2	0.4%
Total	2%

CREX, $E = 2.2$ GeV, $A = 2$ ppm

Charge Normalization	0.1%
Beam Asymmetries	0.3%
Detector Non-linearity	0.3%
Transverse	0.1%
Polarization	0.8%
Inelastic Contribution	0.2%
Effective Q^2	0.8%
Total	1.2%

- Polarimetry errors could improve with planned advances for Moller and SoLID
- CREX more sensitive to Q^2 uncertainty than PREX, angular resolution demonstrated using elastic *ep*

Possible MESA Experiment?



P2 at MESA

F. Maas et al

P2 at Mainz, Germany

Improve JLab Qweak by a factor of 2.5:

$\delta(\sin^2\theta_W) = \pm\, 0.00030$ (stat.) $\pm\, 0.00017$ (syst.)

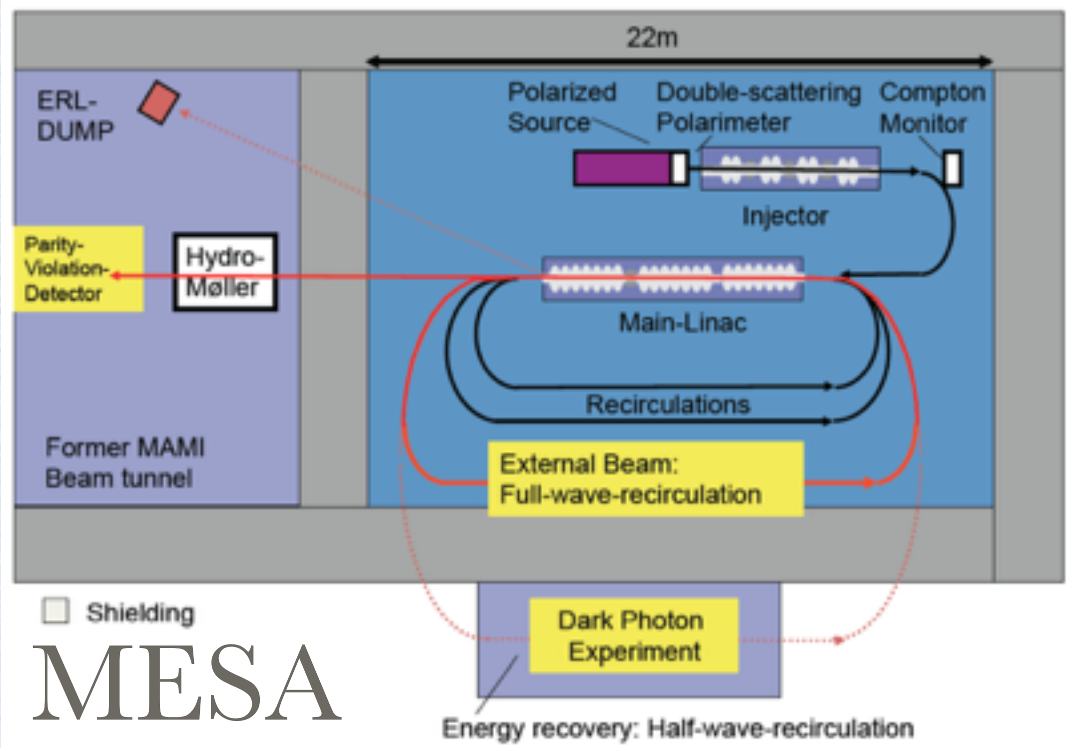
- R&D in progress
- Aim to run from 2017-20

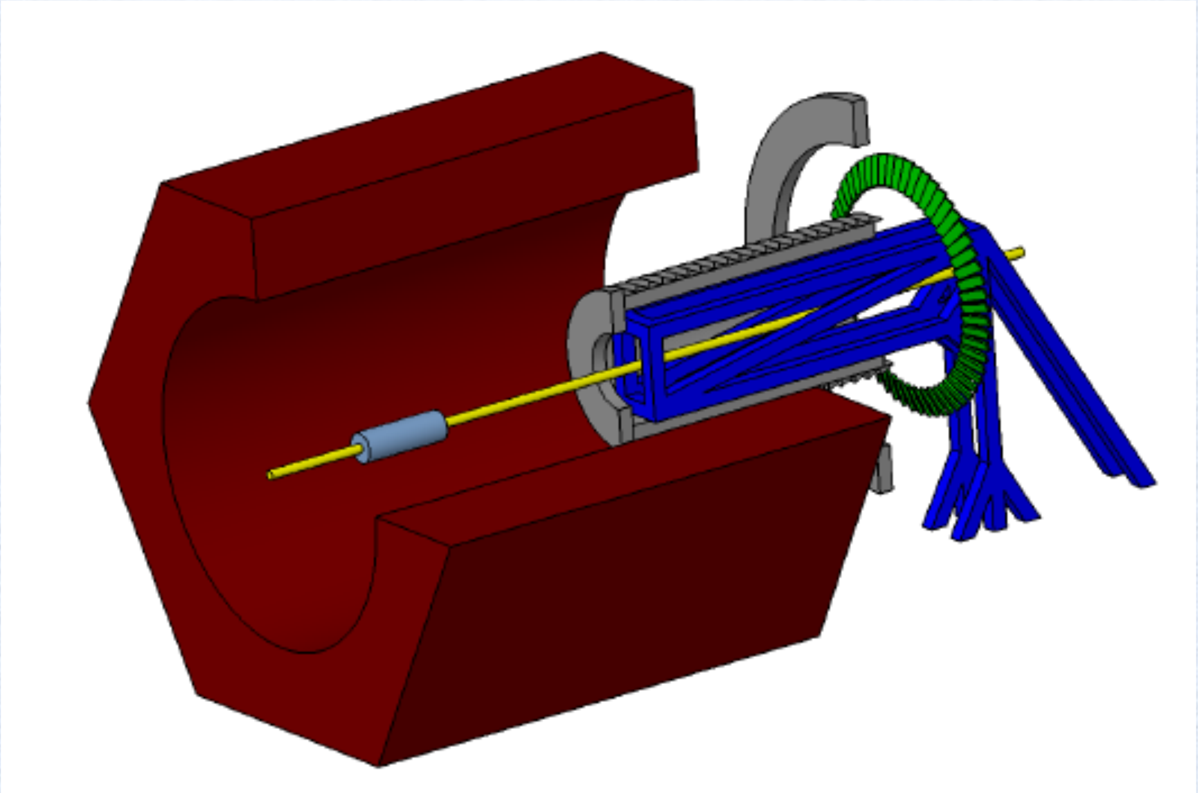
Technically challenging: great synergy with JLab program

Solenoid spectrometer with 1 m bore

0.5% Polarimetry Goal

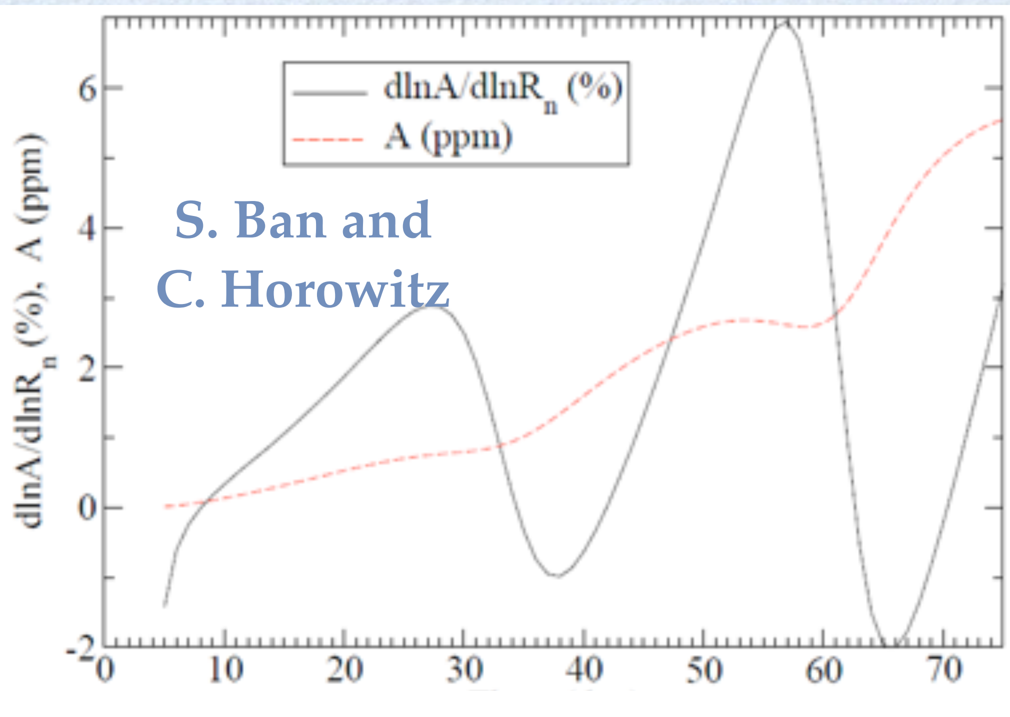
Explore a PREX-style measurement using same solenoidal magnet to be used for P2





MREX?

C. Sfienti
M. Thiel
K.K.



200 MeV: FOM peaks around 25 degrees

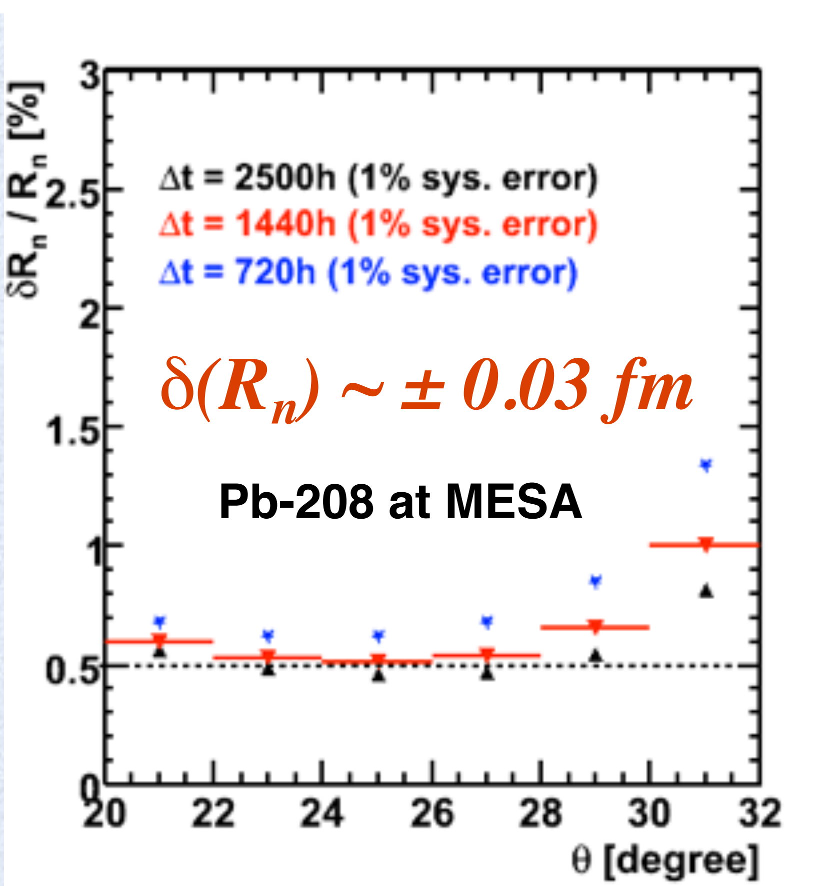
Not surprising: same Q^2 as PREX

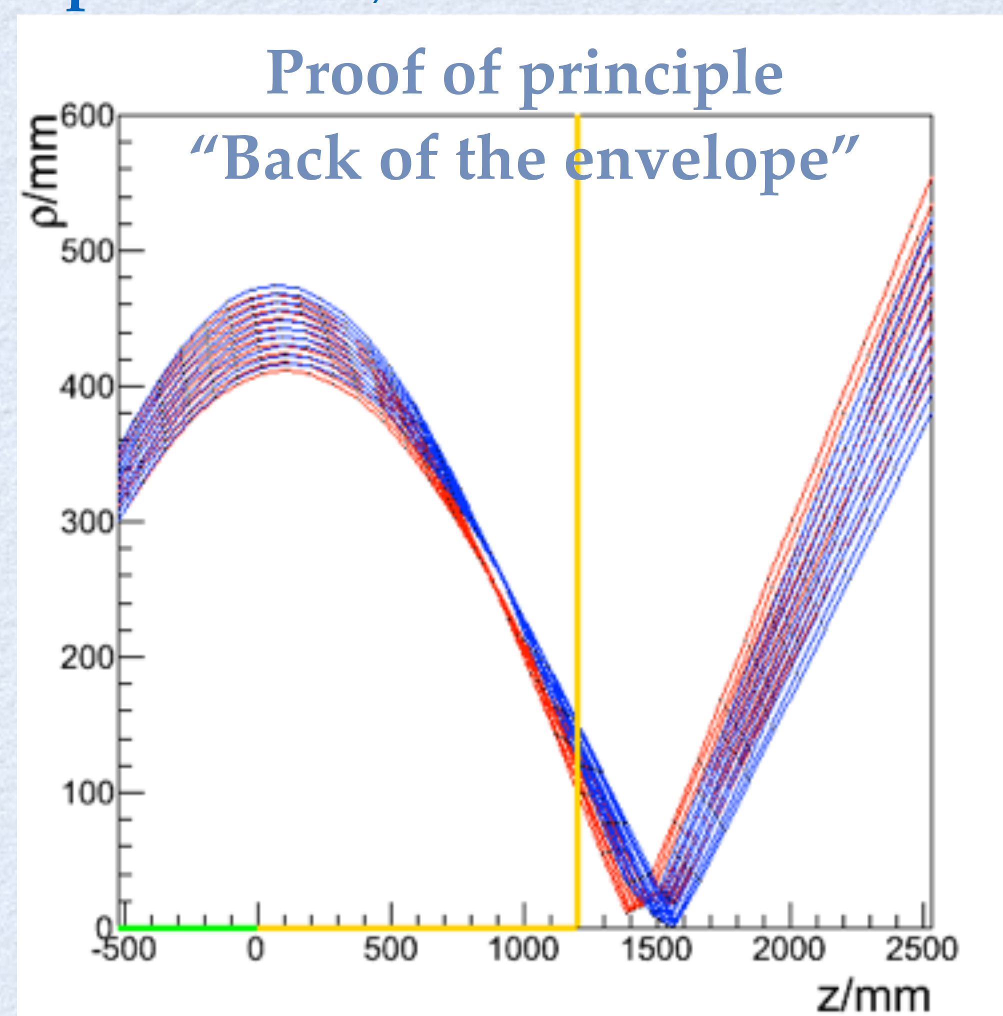
In elastic scattering, the only parameter is Q^2

Why might one do better than PREX-II? Very simple: HRS picks up about 25% of the azimuth

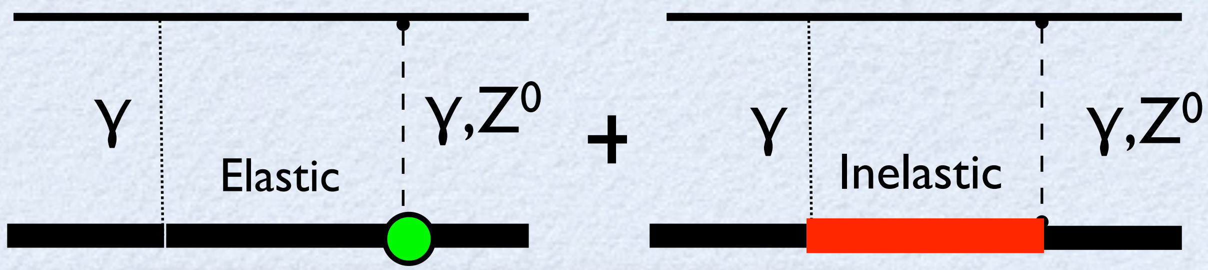
solenoidal spectrometer will separate inelastics over the full range of the azimuth

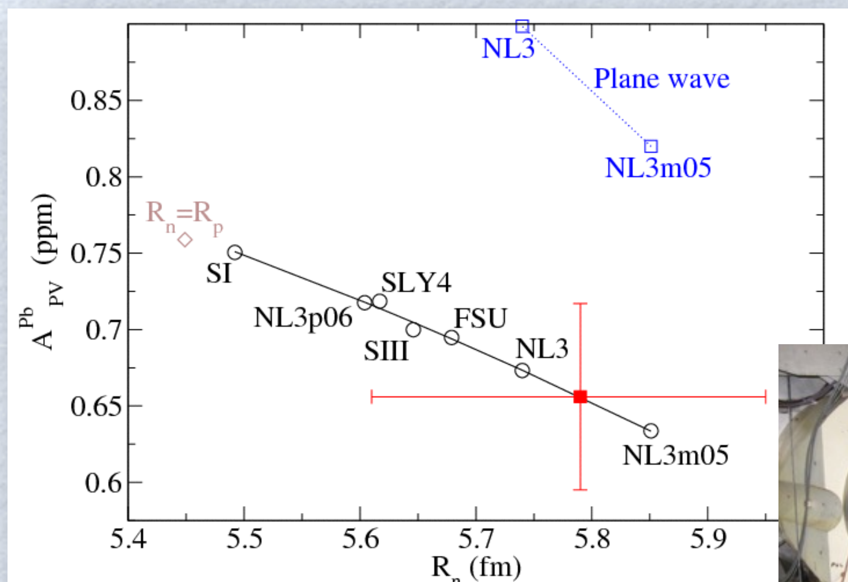
0.5% Rn in 1500 hours of running; same luminosity as PREX

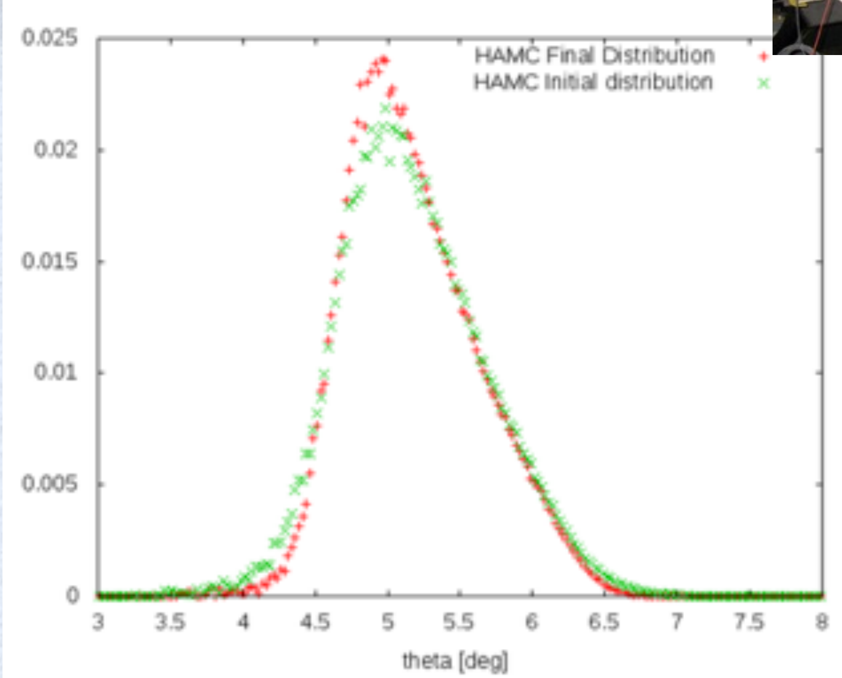


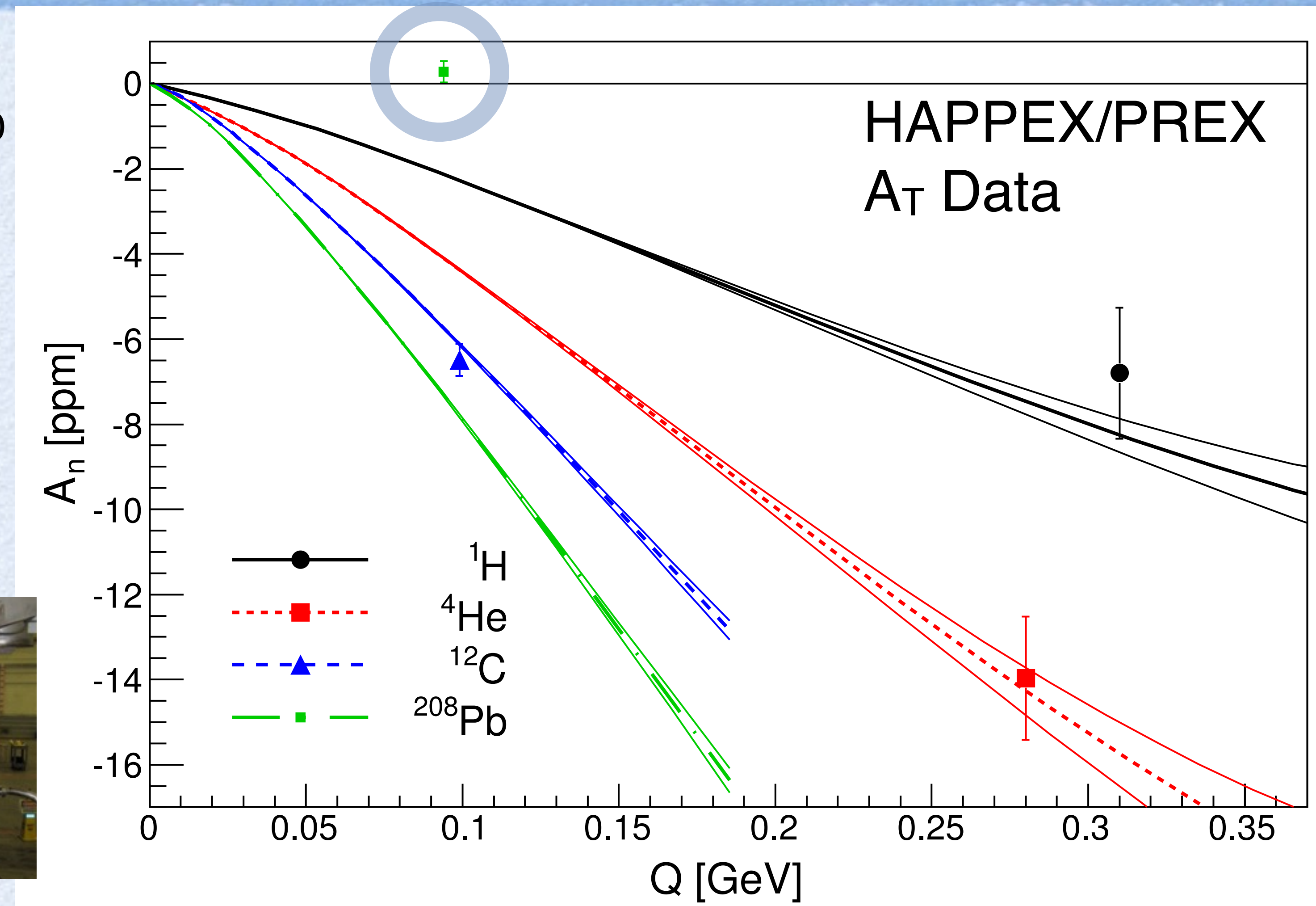


Any Issues for the Workshop?









- **What does the Pb-208 A_T result imply?**
  - *dispersion corrections on top of Coulomb distortions?*
  - *What if it is a very sensitive cancellation?*
    - What happens when we run again at slightly different kinematics?
    - What if Ca-48 doesn't have this accidental cancellation?
  - *should other electroweak corrections be revisited?*