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

The PREX and CREX Experiments

Measurements of Parity-Violating Electron Scattering Asymmetries off ^{208}Pb and ^{48}Ca:

The first PREX Result at Jefferson Laboratory and Future Plans

Krishna S. Kumar
University of Massachusetts, Amherst

3rd International Symposium on Nuclear Symmetry Energy,
NSCL/FRIB, East Lansing, MI
July 25, 2013

Outline

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

PRL 108 (2012) 112502

PRC 85 (2012) 032501

- **Future Plans**
  - Improvements for Approved PREX-II Apparatus
  - Recent PAC Approval of the CREX Experiment
  - New idea for an improved Pb measurement at Mainz
- **Conclusion and Outlook**

Outline

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

PRL 108 (2012) 112502

PRC 85 (2012) 032501

Challenging experimental technique has been successfully demonstrated

- **Future Plans**
  - Improvements for Approved PREX-II Apparatus
  - Recent PAC Approval of the CREX Experiment
  - New idea for an improved Pb measurement at Mainz
- **Conclusion and Outlook**

Outline

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

PRL 108 (2012) 112502

PRC 85 (2012) 032501

Challenging experimental technique has been successfully demonstrated

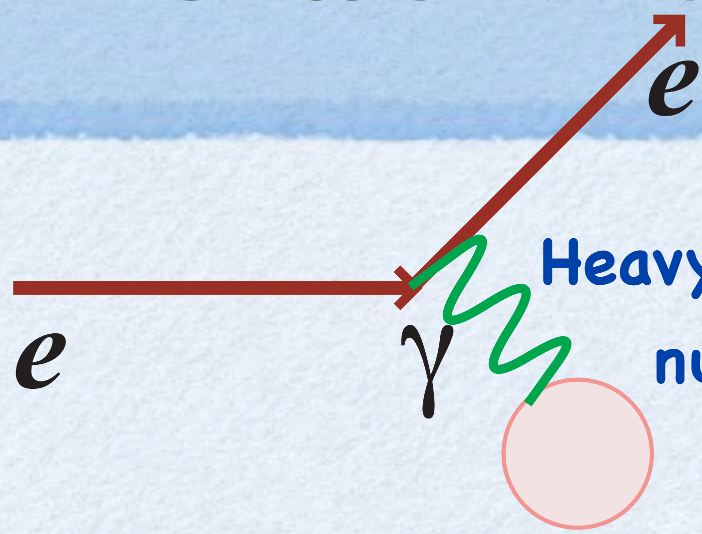
- **Future Plans**
  - Improvements for Approved PREX-II Apparatus
  - Recent PAC Approval of the CREX Experiment
  - New idea for an improved Pb measurement at Mainz
- **Conclusion and Outlook**

Definite plans to obtain higher statistics

Introduction to Parity-Violating Electron Scattering

Relativistic Electron Scattering

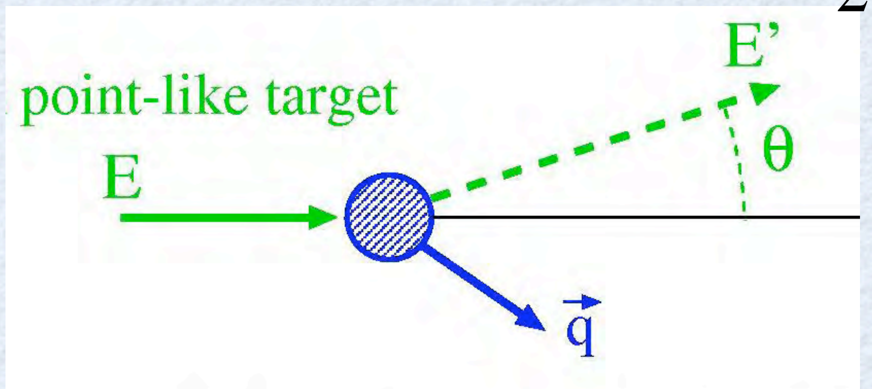
and nuclear size



Heavy, spinless nucleus

Q^2: -(4-momentum)^2 of the virtual photon

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



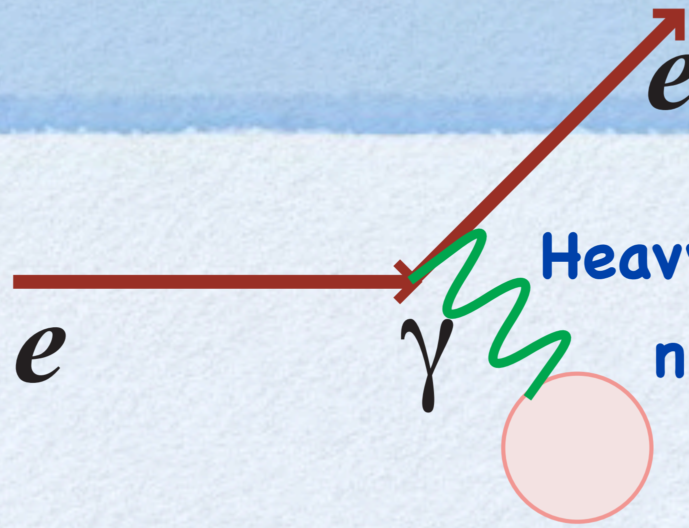
$$Q \approx \frac{hc}{\lambda}$$

Differential Cross Section

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

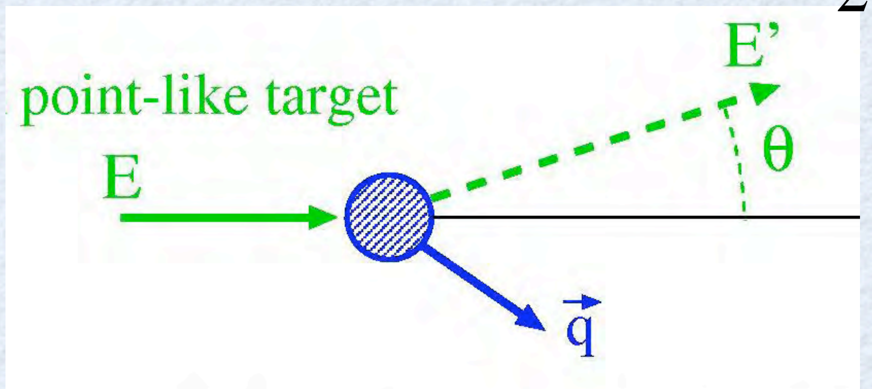
Relativistic Electron Scattering

and nuclear size



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

Q^2: -(4-momentum)^2
of the virtual photon



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

Differential Cross Section

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

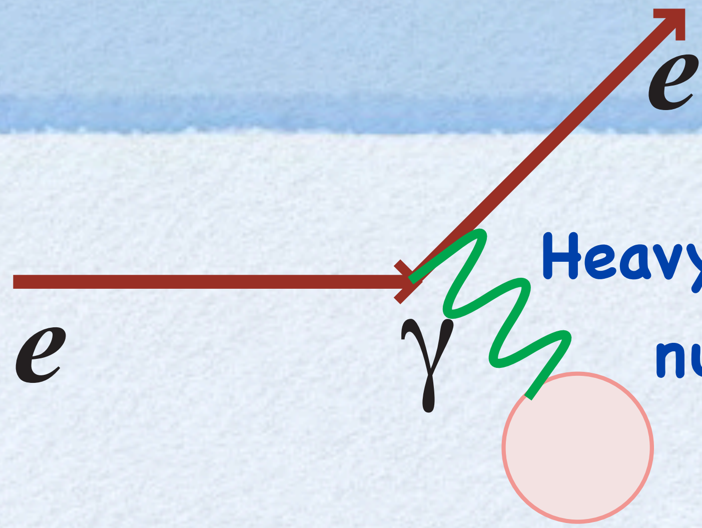
$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{\mathrm{Mott}} \left| F(q) \right|^2$$

As Q increases, nuclear size modifies formula

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

Relativistic Electron Scattering

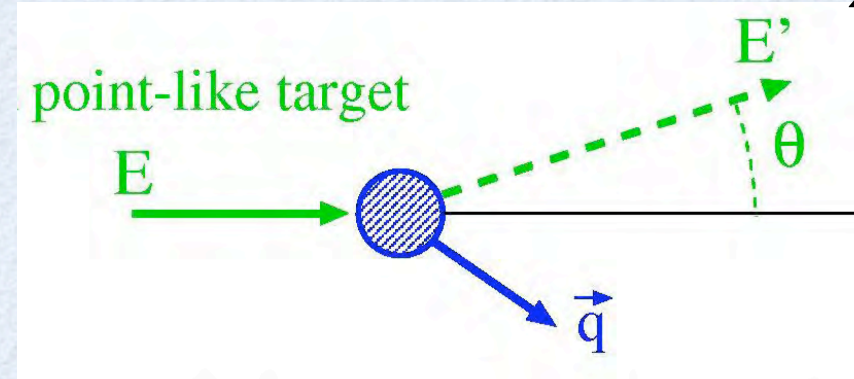
and nuclear size



Heavy, spinless nucleus

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

Q^2: -(4-momentum)^2 of the virtual photon



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

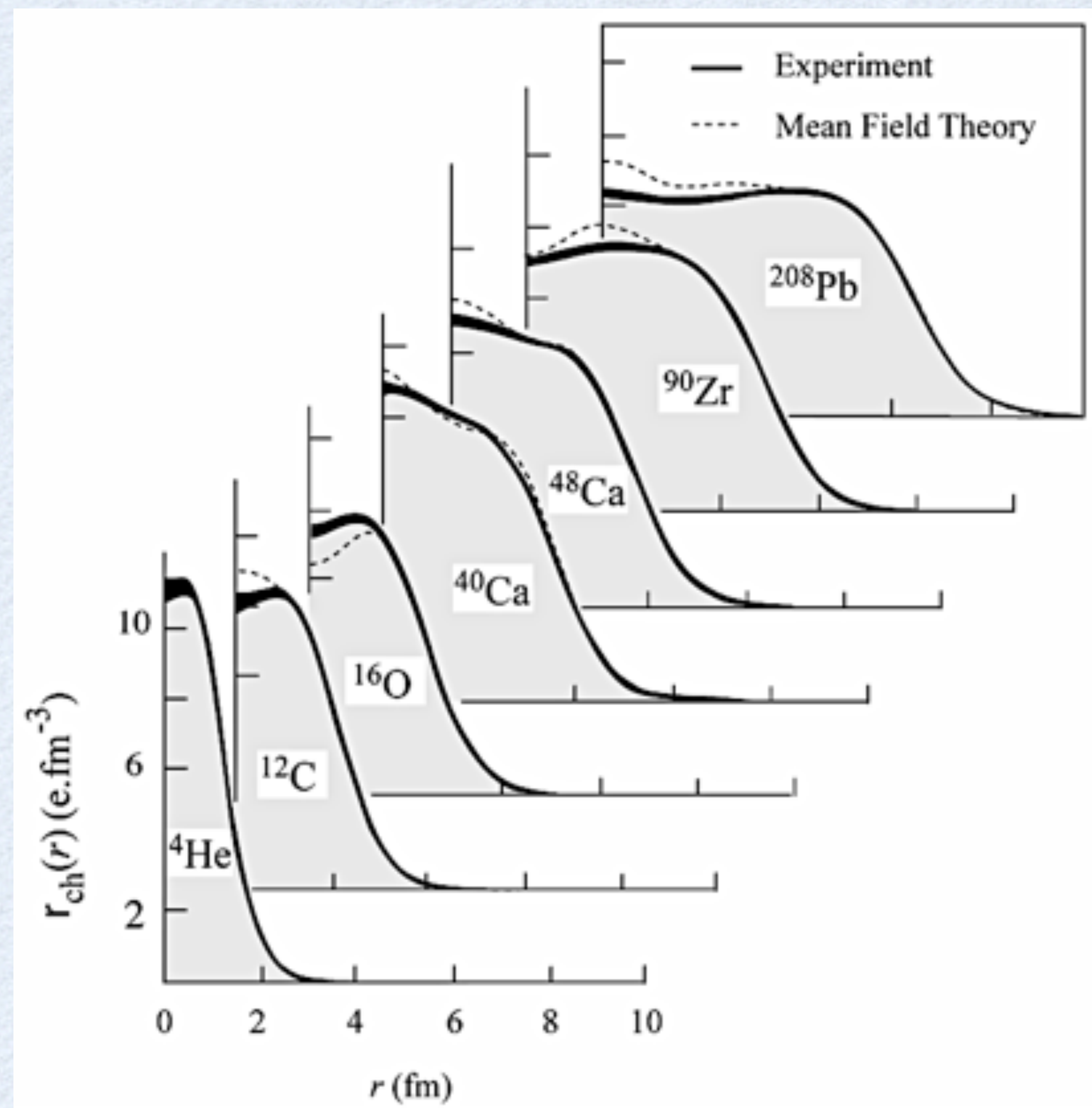
Differential Cross Section

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

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

As Q increases, nuclear size modifies formula

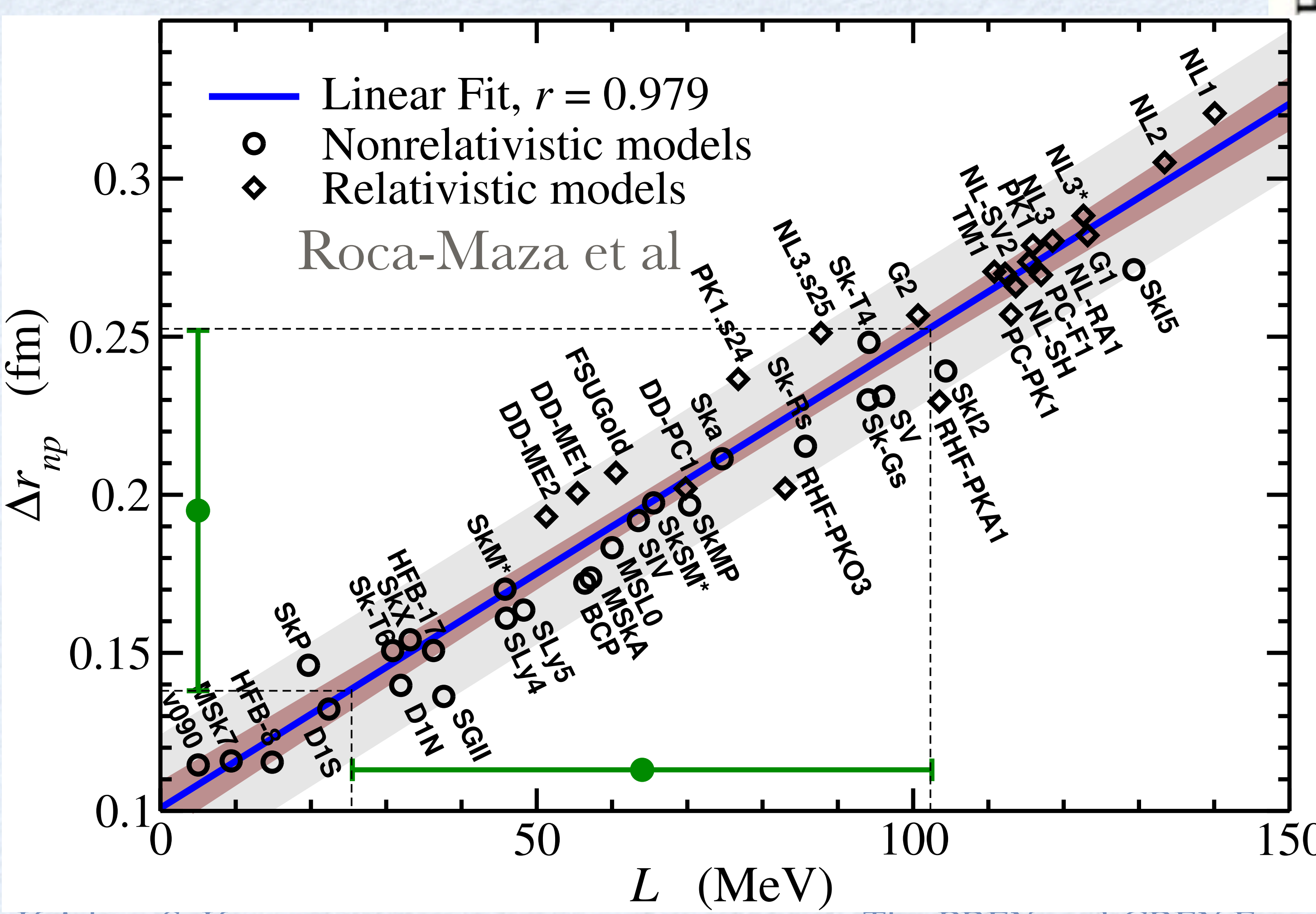
Neglecting recoil, form factor *F(q)* is the Fourier transform of charge distribution

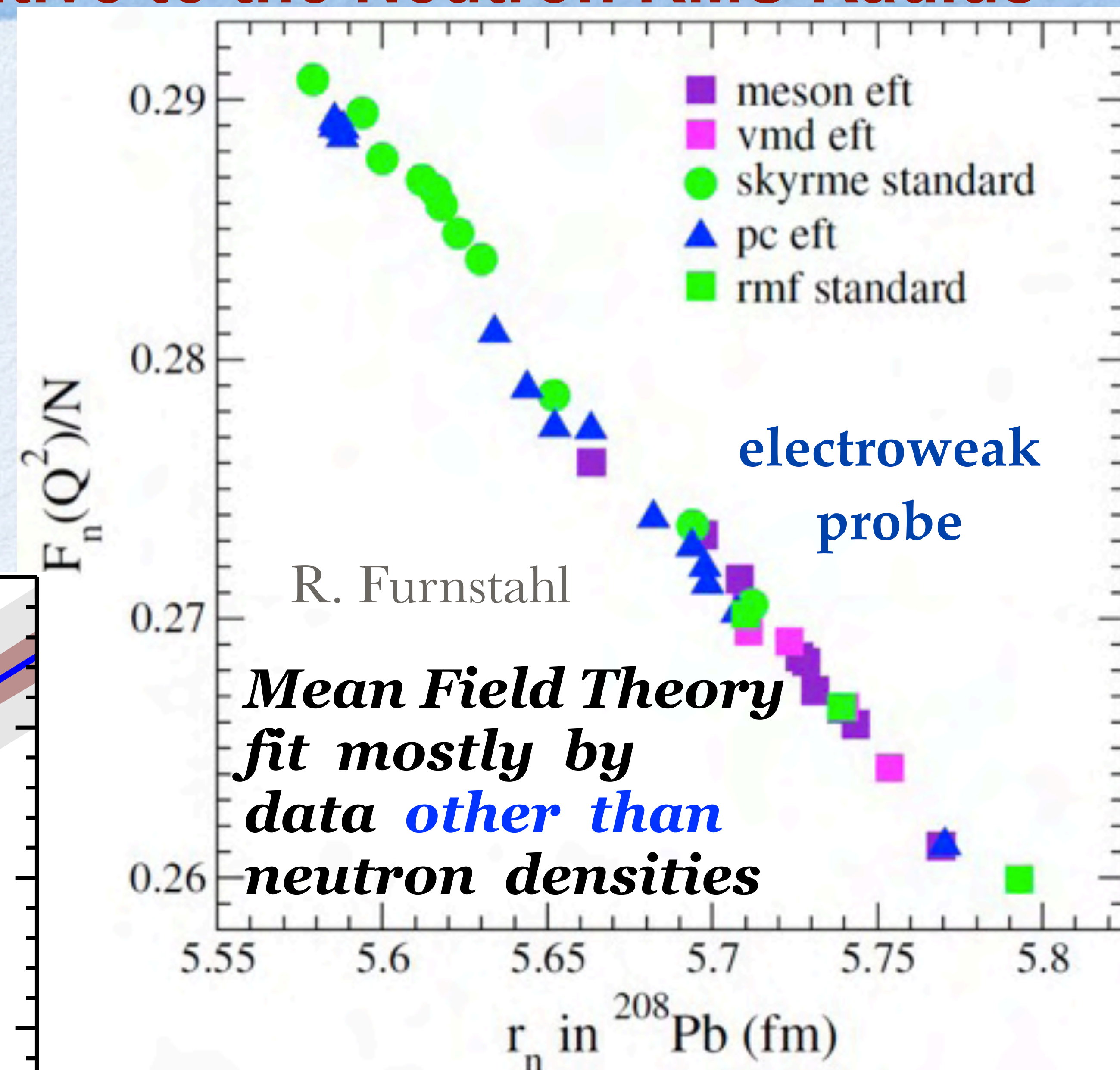


Measurement Approach

An Electroweak Observable Sensitive to the Neutron RMS Radius

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

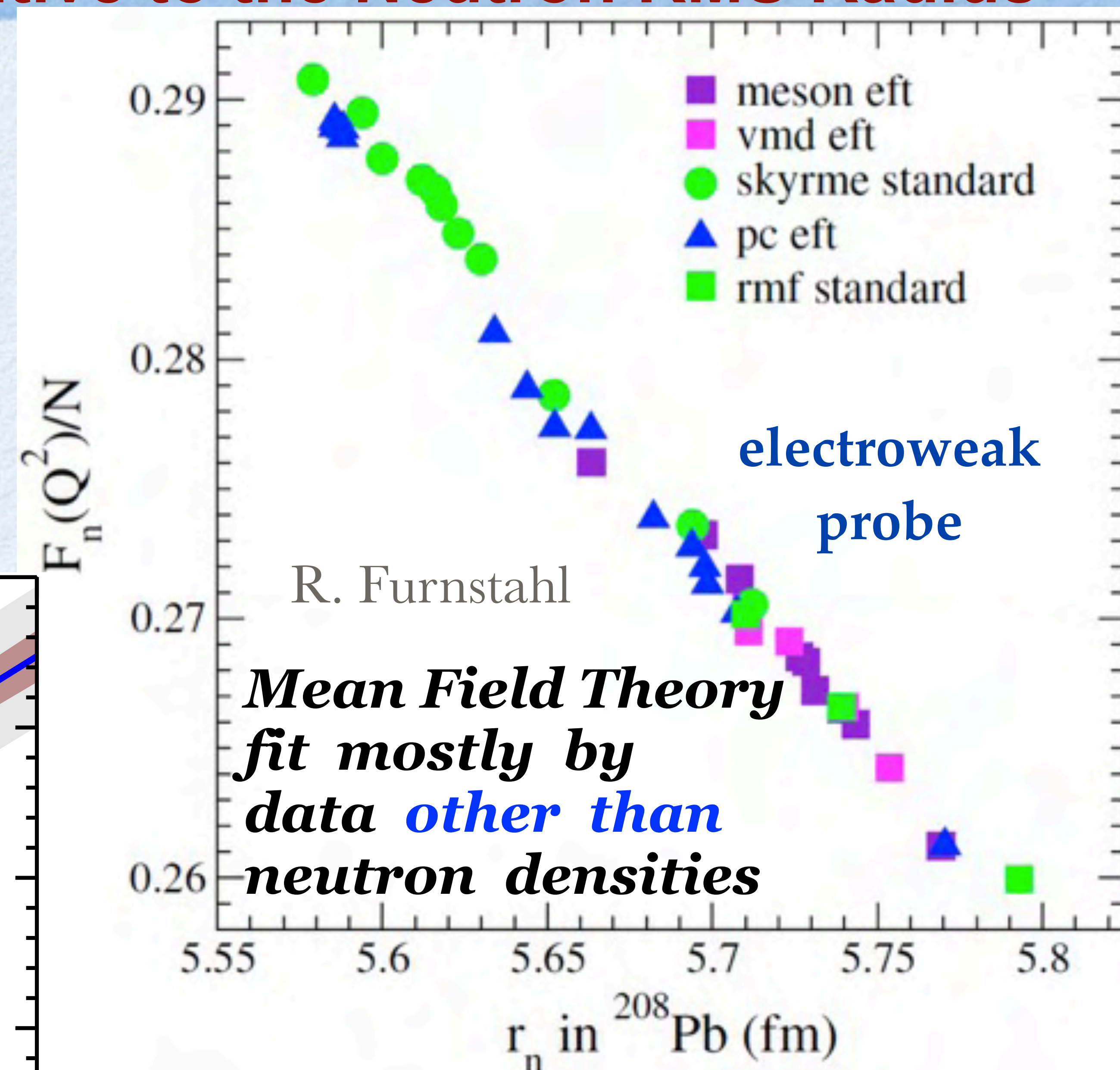


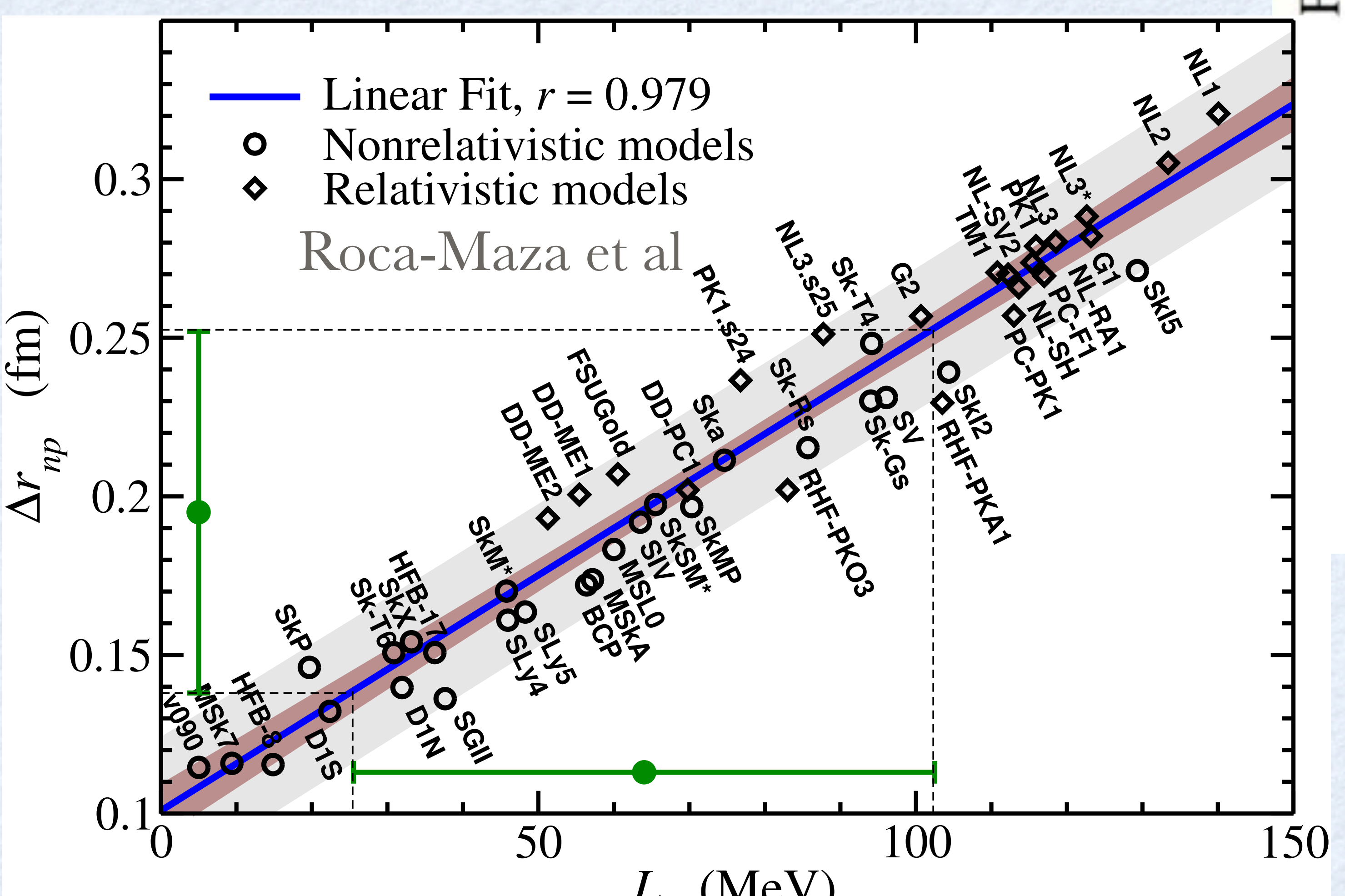


Measurement Approach

An Electroweak Observable Sensitive to the Neutron RMS Radius

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



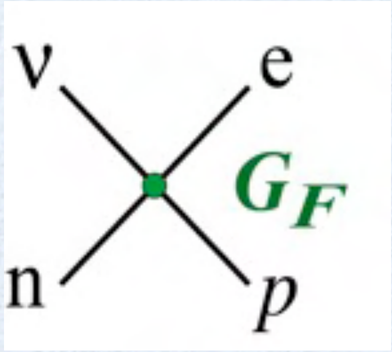


In the following, I focus on the measurements; other talks, including the one following mine, address interpretation and potential implications

Note: R. Michaels (JLab) here during the last week

Weak Interactions

Neutron & nuclear β Decay



charge and flavor-changing

Fermi Theory for weak interactions

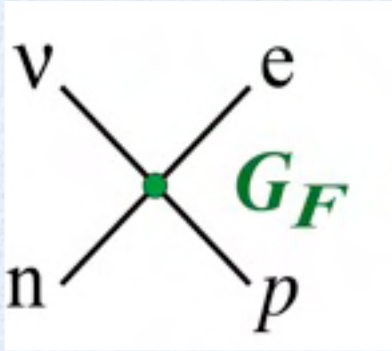
Universal strength: coupling constant G_F

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

Weak Interactions

Observed NOT to be invariant under parity transformations

Neutron & nuclear β Decay



charge and flavor-changing

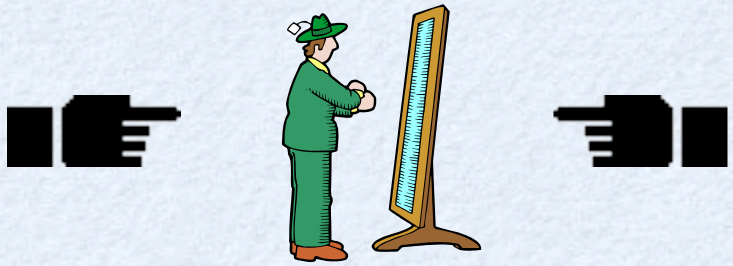
Fermi Theory for weak interactions

Universal strength: coupling constant G_F

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

parity transformation (reflection)

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



$$\vec{p} = -\vec{p}$$

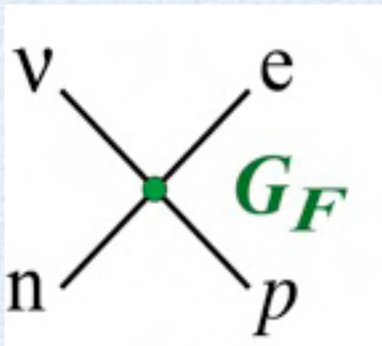
$$\vec{L} = \vec{L}$$

$$\vec{s} = \vec{s}$$

Weak Interactions

Observed NOT to be invariant under parity transformations

Neutron & nuclear β Decay



charge and flavor-changing

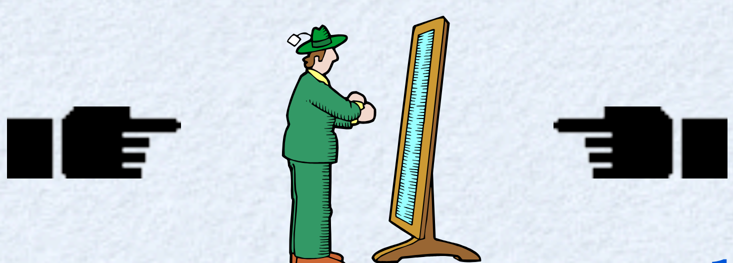
Fermi Theory for weak interactions

Universal strength: coupling constant G_F

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

parity transformation (reflection)

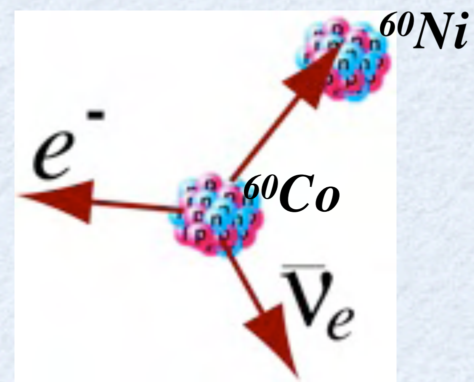
$$x, y, z \rightarrow -x, -y, -z$$



$$\vec{p} = -\vec{p}$$

$$\vec{L} = \vec{L}$$

$$\vec{s} = \vec{s}$$

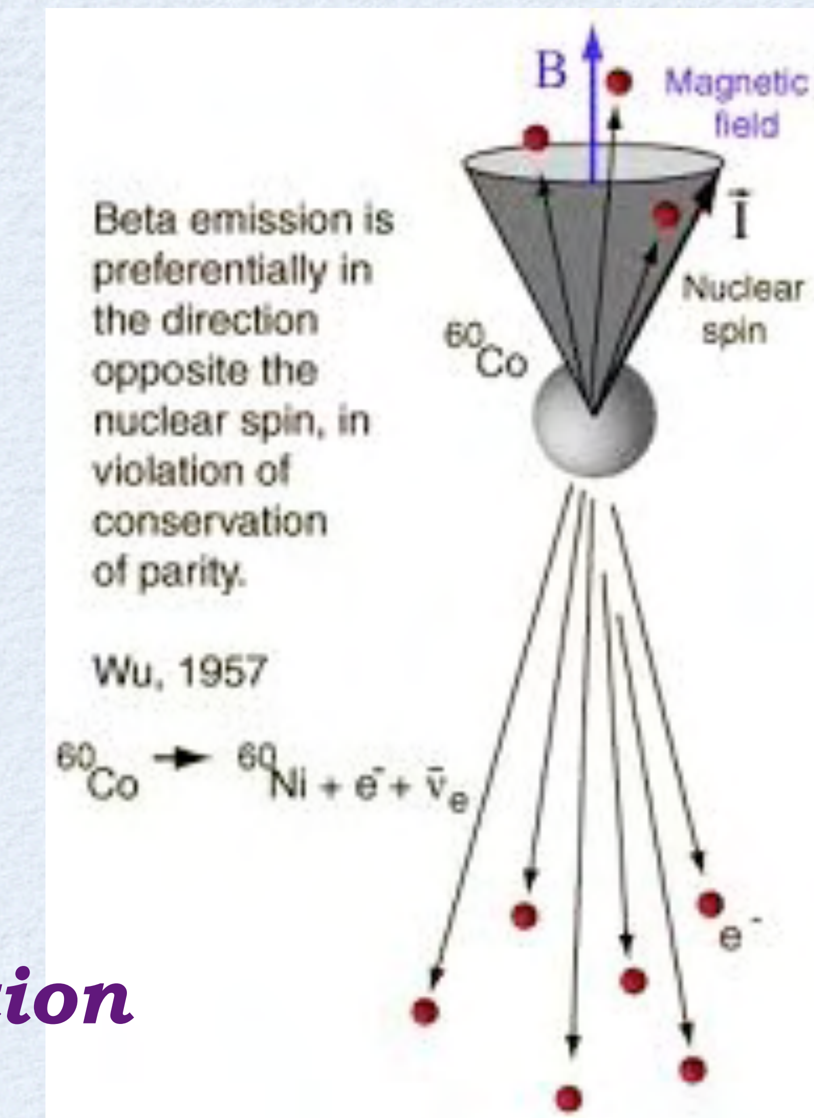


Weak decay of ^{60}Co Nucleus

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

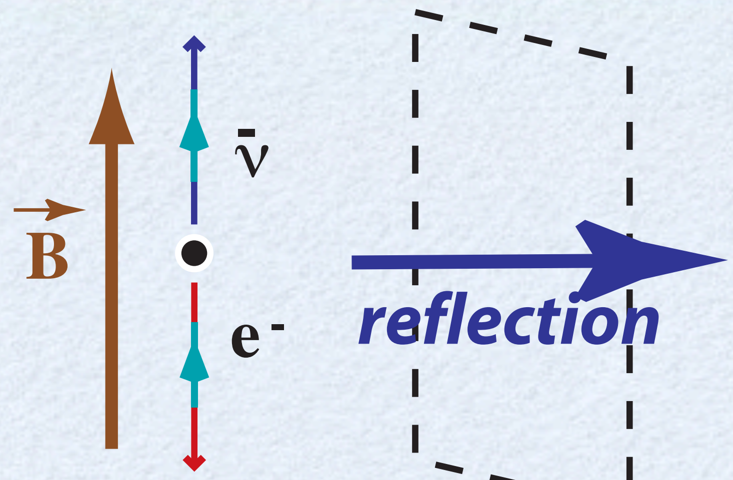
1957

signature of parity violation



Weak Interactions

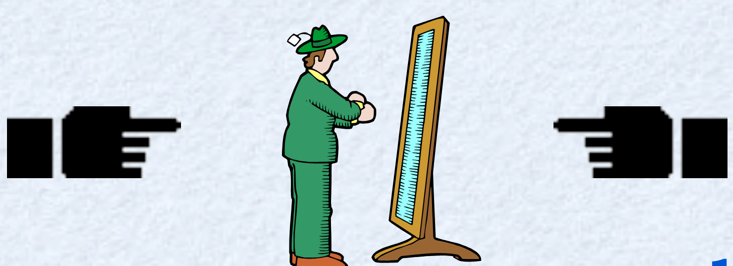
Observed NOT to be invariant under parity transformations



observed **not observed**

parity transformation (reflection)

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



$$\vec{p} = -\vec{p}$$

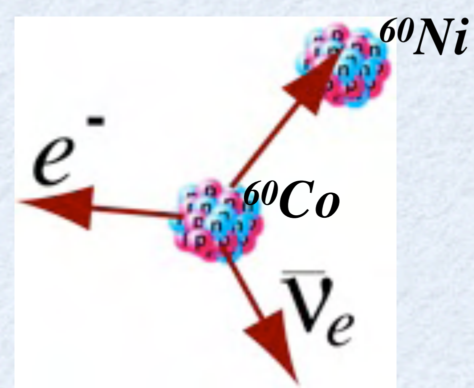
$$\vec{L} = \vec{L}$$

$$\vec{s} = \vec{s}$$

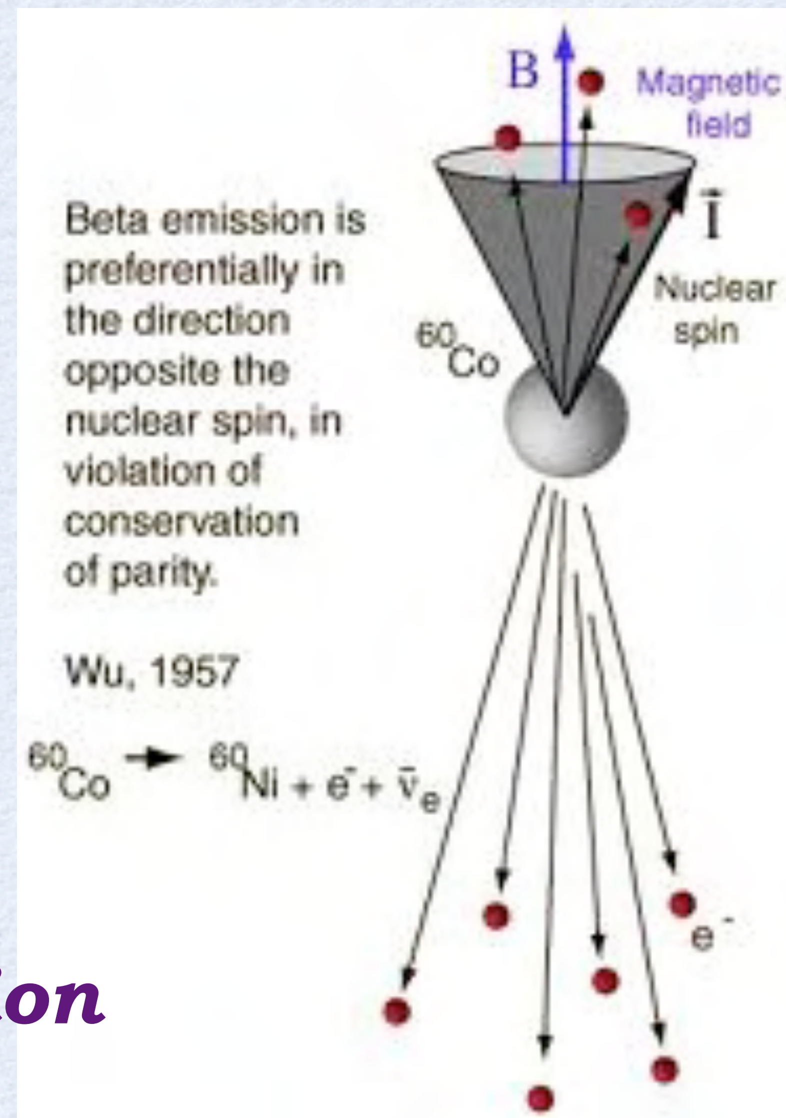
Fermi Theory for weak interactions

Universal strength: coupling constant G_F

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



Weak decay of ^{60}Co Nucleus



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

1957

signature of parity violation

Charge/Flavor Conserving Analog?

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

WE assume that besides the weak interaction that causes beta decay,

$$g(\bar{P}ON)(\bar{e}^- O\nu) + \text{Herm. conj.}, \qquad (1)$$

there exists an interaction

$$\boxed{g(\bar{P}OP)(\bar{e}^- O e^-)} \qquad (2)$$

with $g \approx 10^{-49}$ and the operator $O = \gamma_\mu(1 + i\gamma_5)$ characteristic[1] of processes in which parity is not conserved.*

Then in the scattering of electrons by protons the interaction (2) will interfere with the Coulomb scattering, and the nonconservation of parity will appear in terms of the first order in the small quantity g. Owing to this it becomes possible to test the hypothesis used here experimentally and to determine the sign of g.

In the scattering of fast ($\sim 10^9$ ev) longitudinally polarized electrons through large angles by unpolarized target nuclei it can be expected that the cross-sections for right-hand and left-hand electrons (i.e., for electrons with $\sigma \cdot p > 0$ and $\sigma \cdot p < 0$) can differ by 0.1 to 0.01 percent. Such an effect is a specific test for an interaction not conserving parity.

1958

Charge/Flavor Conserving Analog?

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

We assume that besides the weak interaction that causes beta decay,

$$g(\bar{P}ON)(\bar{e}^- O\nu) + \text{Herm. conj.,} \qquad (1)$$

there exists an interaction

$$\boxed{g(\bar{P}OP)(\bar{e}^- O e^-)} \qquad (2)$$

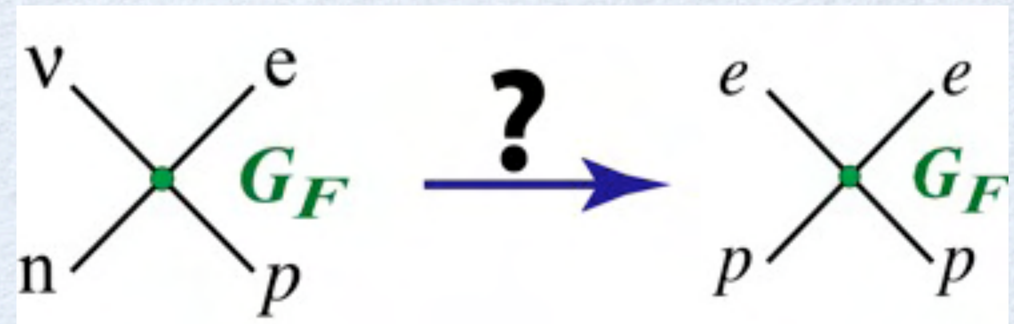
with $g \approx 10^{-49}$ and the operator $O = \gamma_\mu(1 + i\gamma_5)$ characteristic[1] of processes in which parity is not conserved.*

Then in the scattering of electrons by protons the interaction (2) will interfere with the Coulomb scattering, and the nonconservation of parity will appear in terms of the first order in the small quantity g. Owing to this it becomes possible to test the hypothesis used here experimentally and to determine the sign of g.

In the scattering of fast ($\sim 10^9$ ev) longitudinally polarized electrons through large angles by unpolarized target nuclei it can be expected that the cross-sections for right-hand and left-hand electrons (i.e., for electrons with $\sigma \cdot p > 0$ and $\sigma \cdot p < 0$) can differ by 0.1 to 0.01 percent. Such an effect is a specific test for an interaction not conserving parity.

Neutron β Decay

Electron-proton Weak Scattering



Charge/Flavor Conserving Analog?

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

We assume that besides the weak interaction that causes beta decay,

$$g\,(\bar{P}ON)(\bar{e}^{-}O\nu) + \text{Herm. conj.}, \qquad (1)$$

there exists an interaction

$$\boxed{g\,(\bar{P}OP)(\bar{e}^{-}Oe^{-})} \qquad (2)$$

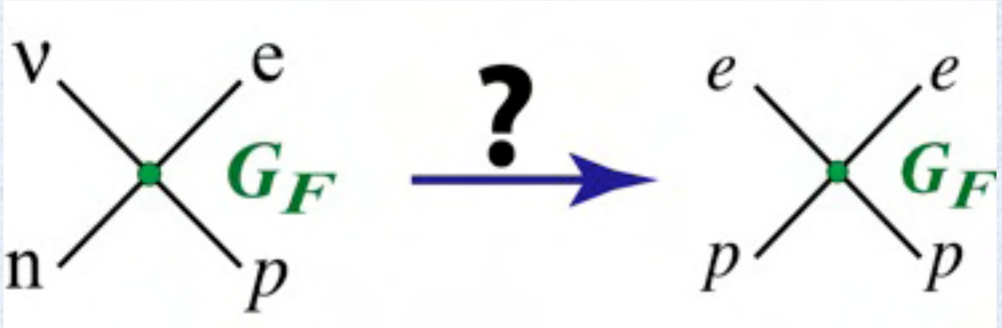
with $g \approx 10^{-49}$ and the operator $O = \gamma_\mu(1 + i\gamma_5)$ characteristic[1] of processes in which parity is not conserved.*

Then in the scattering of electrons by protons the interaction (2) will interfere with the Coulomb scattering, and the nonconservation of parity will appear in terms of the first order in the small quantity g. Owing to this it becomes possible to test the hypothesis used here experimentally and to determine the sign of g.

In the scattering of fast ($\sim 10^9$ ev) longitudinally polarized electrons through large angles by unpolarized target nuclei it can be expected that the cross-sections for right-hand and left-hand electrons (i.e., for electrons with $\sigma \cdot p > 0$ and $\sigma \cdot p < 0$) can differ by 0.1 to 0.01 percent. Such an effect is a specific test for an interaction not conserving parity.

Neutron β Decay

Electron-proton Weak Scattering



$$\sigma \;\alpha\; \left|A_{EM} + A_{weak}\right|^2$$
$$\sim \left|A_{EM}\right|^2 + 2A_{EM}A^{*}_{weak} + \ldots$$

Charge/Flavor Conserving Analog?

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

We assume that besides the weak interaction that causes beta decay,

$$g(\bar{P}ON)(\bar{e}^-O\nu) + \text{Herm. conj.}, \tag{1}$$

there exists an interaction

$$\boxed{g(\bar{P}OP)(\bar{e}^-Oe^-)} \tag{2}$$

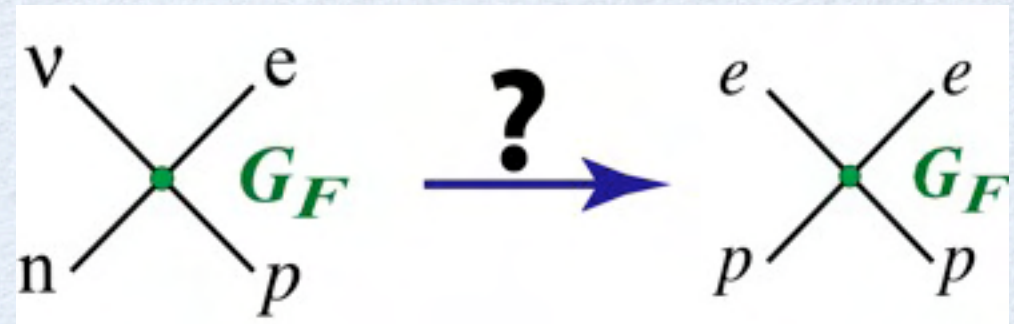
with $g \approx 10^{-49}$ and the operator $O = \gamma_\mu(1 + i\gamma_5)$ characteristic[1] of processes in which parity is not conserved.*

Then in the scattering of electrons by protons the interaction (2) will interfere with the Coulomb scattering, and the nonconservation of parity will appear in terms of the first order in the small quantity g. Owing to this it becomes possible to test the hypothesis used here experimentally and to determine the sign of g.

In the scattering of fast ($\sim 10^9$ ev) longitudinally polarized electrons through large angles by unpolarized target nuclei it can be expected that the cross-sections for right-hand and left-hand electrons (i.e., for electrons with $\sigma \cdot p > 0$ and $\sigma \cdot p < 0$) can differ by 0.1 to 0.01 percent. Such an effect is a specific test for an interaction not conserving parity.

Neutron β Decay

Electron-proton Weak Scattering



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

$$\sim \left|A_{EM}\right|^2 + \boxed{2A_{EM}A^*_{weak}} + \ldots$$

Parity-violating

1958

Charge/Flavor Conserving Analog?

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

WE assume that besides the weak interaction that causes beta decay,

$$g\,(\bar{P}ON)(\bar{e}^{-}O\nu) + \text{Herm. conj.,} \qquad (1)$$

there exists an interaction

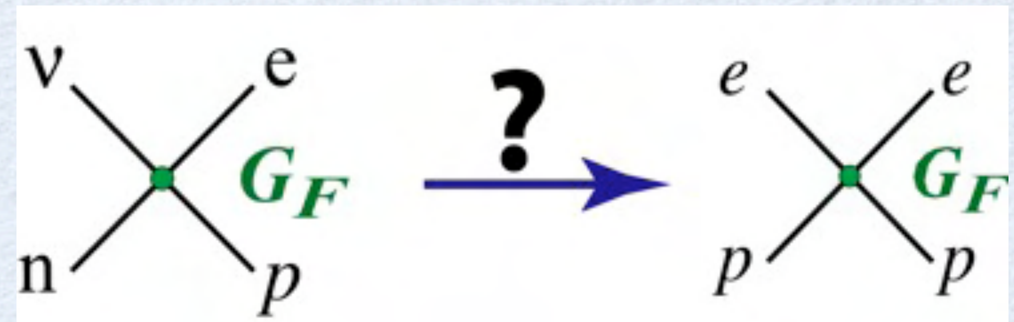
$$\boxed{g\,(\bar{P}OP)(\bar{e}^{-}Oe^{-})} \qquad (2)$$

with $g \approx 10^{-49}$ and the operator $O = \gamma_\mu(1 + i\gamma_5)$ characteristic[1] of processes in which parity is not conserved.*

Then in the scattering of electrons by protons the interaction (2) will interfere with the Coulomb scattering, and the nonconservation of parity will appear in terms of the first order in the small quantity g. Owing to this it becomes possible to test the hypothesis used here experimentally and to determine the sign of g.

In the scattering of fast ($\sim 10^9$ ev) longitudinally polarized electrons through large angles by unpolarized target nuclei it can be expected that the cross-sections for right-hand and left-hand electrons (i.e., for electrons with $\sigma \cdot p > 0$ and $\sigma \cdot p < 0$) can differ by 0.1 to 0.01 percent. Such an effect is a specific test for an interaction not conserving parity.

Neutron β Decay   *Electron-proton Weak Scattering*



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

$$\sim |A_{EM}|^2 + \boxed{2A_{EM}A^*_{weak}} + \dots$$

Parity-violating

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

1958

Charge/Flavor Conserving Analog?

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

WE assume that besides the weak interaction that causes beta decay,

$$g\,(\bar{P}ON)(\bar{e}^{-}O\nu) + \text{Herm. conj.}, \qquad (1)$$

there exists an interaction

$$\boxed{g\,(\bar{P}OP)(\bar{e}^{-}Oe^{-})} \qquad (2)$$

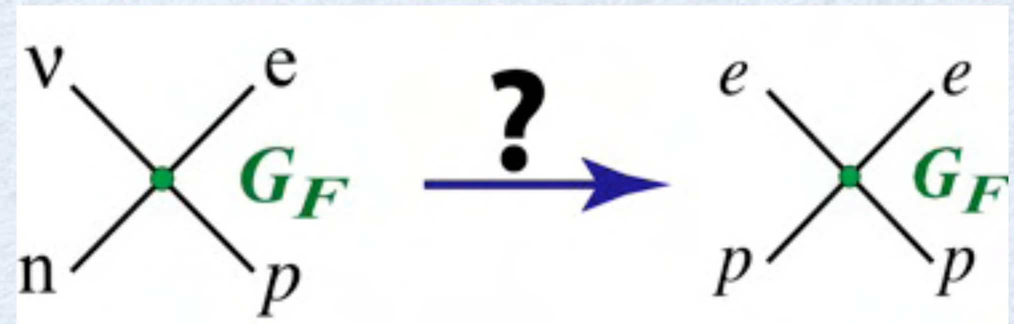
with $g \approx 10^{-49}$ and the operator $O = \gamma_\mu(1 + i\gamma_5)$ characteristic[1] of processes in which parity is not conserved.*

Then in the scattering of electrons by protons the interaction (2) will interfere with the Coulomb scattering, and the nonconservation of parity will appear in terms of the first order in the small quantity g. Owing to this it becomes possible to test the hypothesis used here experimentally and to determine the sign of g.

In the scattering of fast ($\sim 10^9$ ev) longitudinally polarized electrons through large angles by unpolarized target nuclei it can be expected that the cross-sections for right-hand and left-hand electrons (i.e., for electrons with $\sigma \cdot p > 0$ and $\sigma \cdot p < 0$) can differ by 0.1 to 0.01 percent. Such an effect is a specific test for an interaction not conserving parity.

Neutron β Decay

Electron-proton Weak Scattering

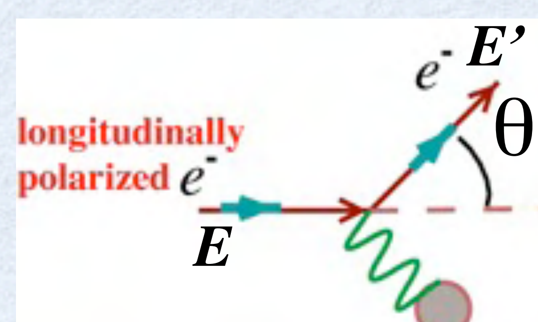


$$\sigma \;\alpha\; |A_{EM} + A_{weak}|^2$$

$$\sim |A_{EM}|^2 + \boxed{2A_{EM}A^*_{weak}} + \ldots$$

Parity-violating

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

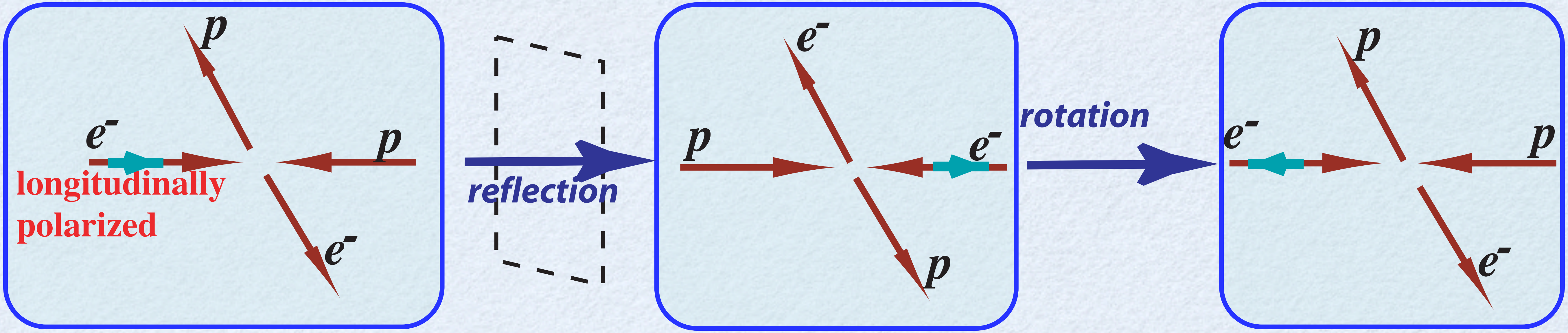


4-momentum transfer

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

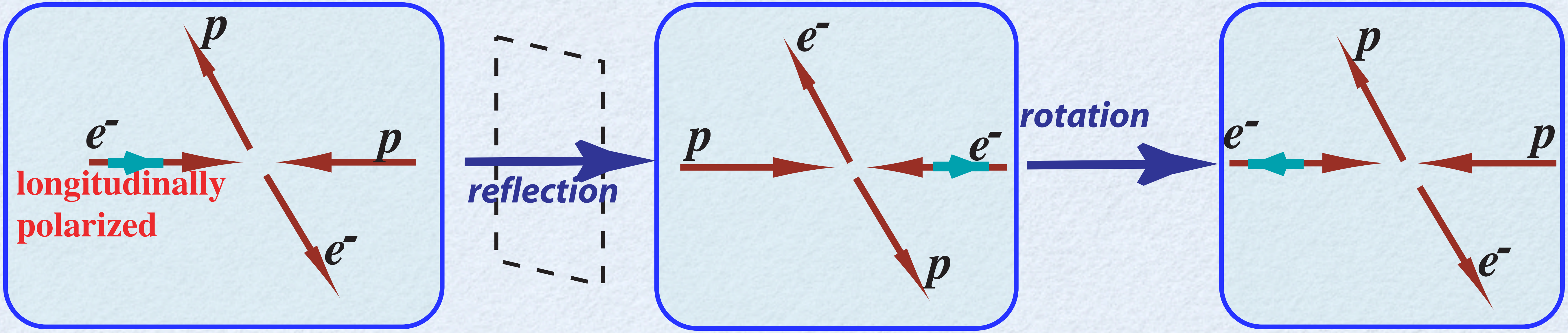
Parity Violation Signature

How to observe parity violation in electron scattering



Parity Violation Signature

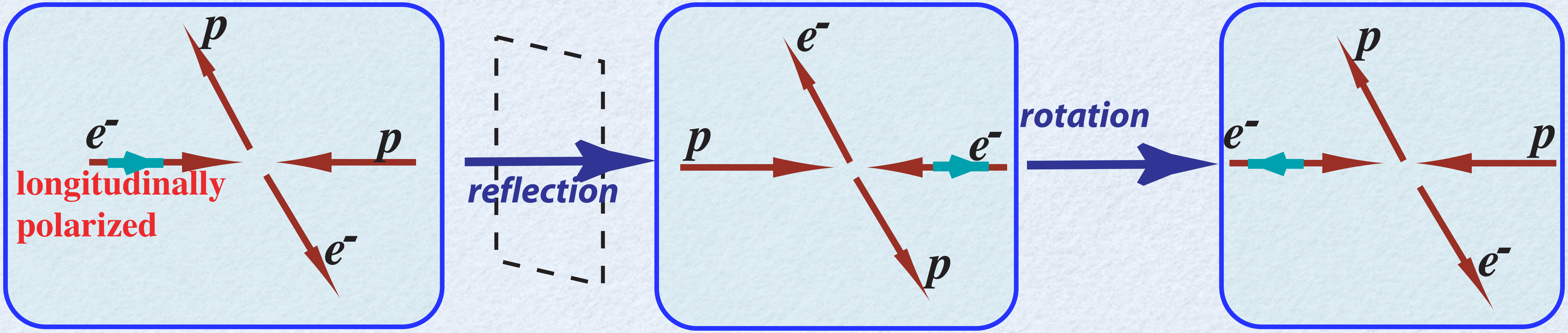
How to observe parity violation in electron scattering



- *One of the incident beams longitudinally polarized*
- *Change sign of longitudinal polarization*
- *Measure fractional rate difference*

Parity Violation Signature

How to observe parity violation in electron scattering

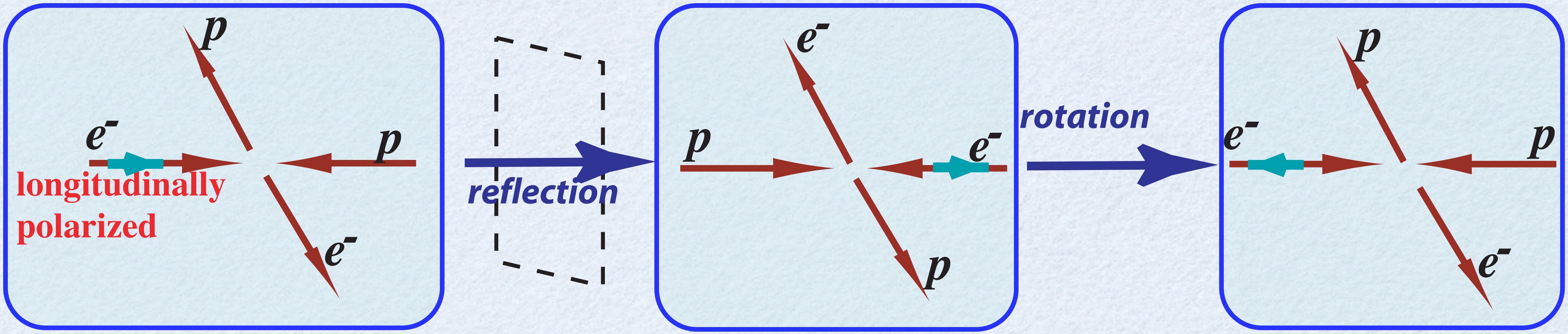


- *One of the incident beams longitudinally polarized*
- *Change sign of longitudinal polarization*
- *Measure fractional rate difference*

The matrix element of the Coulomb scattering is of the order of magnitude e^2/k^2, where k is the momentum transferred ($\hbar = c = 1$). Consequently, the ratio of the interference term to the Coulomb term is of the order of gk^2/e^2. Substituting $g = 10^{-5}/M^2$, where M is the mass of the nucleon, we find that for $k \sim M$ the parity non-conservation effects can be of the order of 0.1 to 0.01 percent.

Parity Violation Signature

How to observe parity violation in electron scattering



- *One of the incident beams longitudinally polarized*
- *Change sign of longitudinal polarization*
- *Measure fractional rate difference*

The matrix element of the Coulomb scattering is of the order of magnitude e^2/k^2, where k is the momentum transferred ($\hbar = c = 1$). Consequently, the ratio of the interference term to the Coulomb term is of the order of gk^2/e^2. Substituting $g = 10^{-5}/M^2$, where M is the mass of the nucleon, we find that for $k \sim M$ the parity non-conservation effects can be of the order of 0.1 to 0.01 percent.

$$A_{PV} = \frac{\sigma_{\uparrow} - \sigma_{\downarrow}}{\sigma_{\uparrow} + \sigma_{\downarrow}} \sim \frac{A_{weak}}{A_{EM}} \sim \frac{G_F Q^2}{4\pi\alpha}$$

$$A_{PV} \sim 10^{-4} \cdot Q^2 (\mathrm{GeV}^2)$$

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
Z Charge	$T - q \sin^2 \theta_W$	$-q \sin^2 \theta_W$

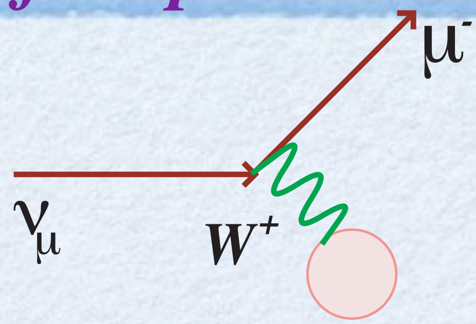
Glashow, Weinberg and Salam: $SU(2)_L \times U(1)_Y$

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
Z Charge	$T - q\sin^2\theta_W$	$-q\sin^2\theta_W$



Charged Current

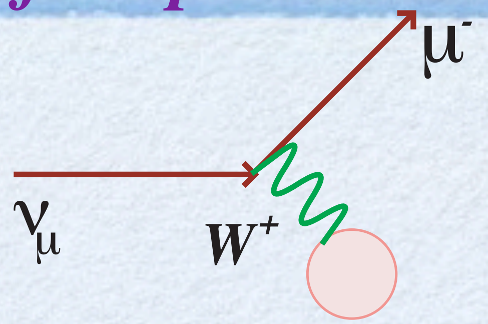
Glashow, Weinberg and Salam: $SU(2)_L X U(1)_Y$

Neutral Weak Interaction Theory

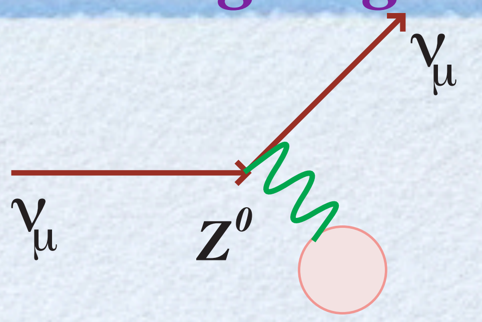
The Z boson incorporated

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
Z Charge	$T - q\sin^2\theta_W$	$-q\sin^2\theta_W$



Charged Current



Neutral Current

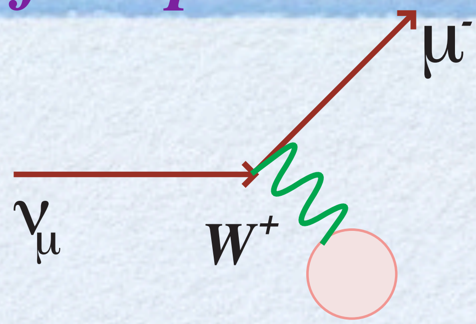
Glashow, Weinberg and Salam: $SU(2)_L \times U(1)_Y$

Neutral Weak Interaction Theory

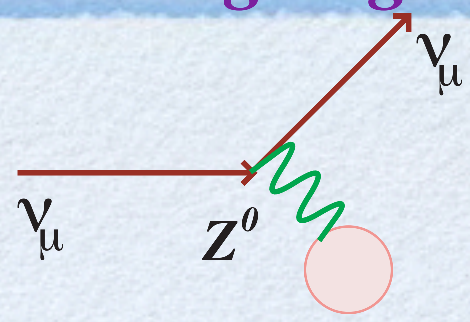
The Z boson incorporated

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
Z Charge	$T - q\sin^2\theta_W$	$-q\sin^2\theta_W$



Charged Current



Neutral Current

$$\frac{g}{\cos\theta_W} Z_\mu \bar{f}\gamma^\mu (T_{3f} - 2Q_f \sin^2\theta_W - T_{3f}\gamma_5) f, \quad T_{3f} = \pm 1/2$$

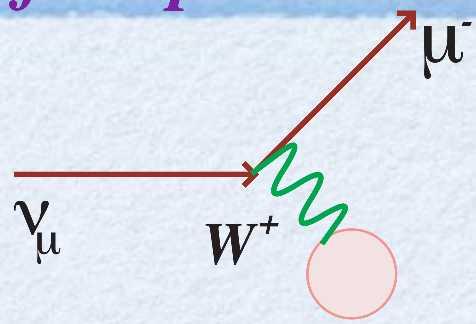
Glashow, Weinberg and Salam: $SU(2)_L \times U(1)_Y$

Neutral Weak Interaction Theory

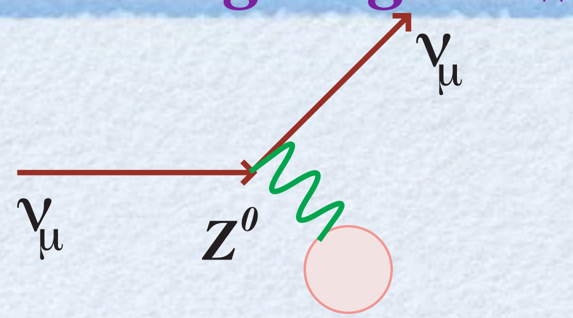
The Z boson incorporated

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
Z Charge	$T-q\sin^2\theta_W$	$-q\sin^2\theta_W$



Charged Current



Neutral Current

$$\frac{g}{\cos\theta_W} Z_\mu \bar{f}\gamma^\mu (T_{3f} - 2Q_f \sin^2\theta_W - T_{3f}\gamma_5) f, \quad T_{3f} = \pm 1/2$$

Do lepton-nucleon neutral current interactions exhibit parity violation?

$$\begin{pmatrix}\nu\\ e\end{pmatrix}_l \quad (e)_r$$

or

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

Weinberg model

Parity is violated

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

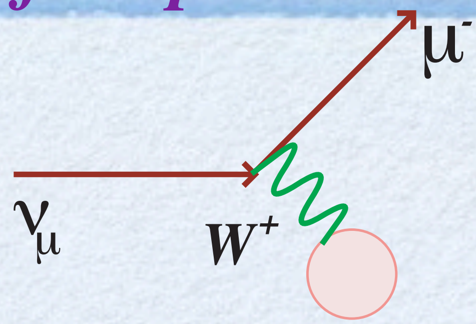
Parity is conserved

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

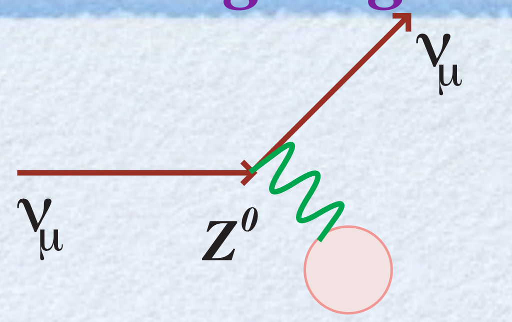
Neutral Weak Interaction Theory

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

	Left-	Right-
γ Charge	$0,\pm1,\pm\frac{1}{3},\pm\frac{2}{3}$	$0,\pm1,\pm\frac{1}{3},\pm\frac{2}{3}$
W Charge	$T=\pm\frac{1}{2}$	zero
Z Charge	$T-q\sin^2\theta_W$	$-q\sin^2\theta_W$



Charged Current



Neutral Current

$$\frac{g}{\cos\theta_W} Z_\mu \bar{f}\gamma^\mu (T_{3f} - 2Q_f \sin^2\theta_W - T_{3f}\gamma_5) f, \quad T_{3f} = \pm 1/2$$

Do lepton-nucleon neutral current interactions exhibit parity violation?

$$\begin{pmatrix}\nu \\ e\end{pmatrix}_l \quad (e)_r$$

Weinberg model

Parity is violated

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

or

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

Parity is conserved

First table-top atomic parity violation searches: negative!

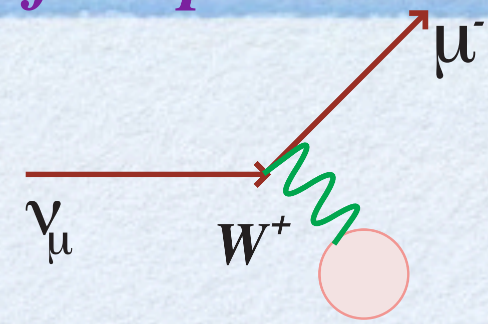
Glashow, Weinberg and Salam: $SU(2)_L X\ U(1)_Y$

Neutral Weak Interaction Theory

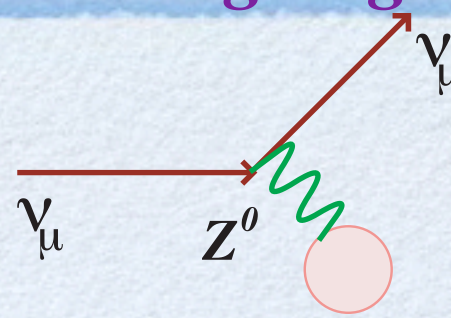
The Z boson incorporated

	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

$$\frac{g}{\cos\theta_W} Z_\mu \bar{f}\gamma^\mu (T_{3f} - 2Q_f \sin^2\theta_W - T_{3f}\gamma_5) f, \quad T_{3f} = \pm 1/2$$

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

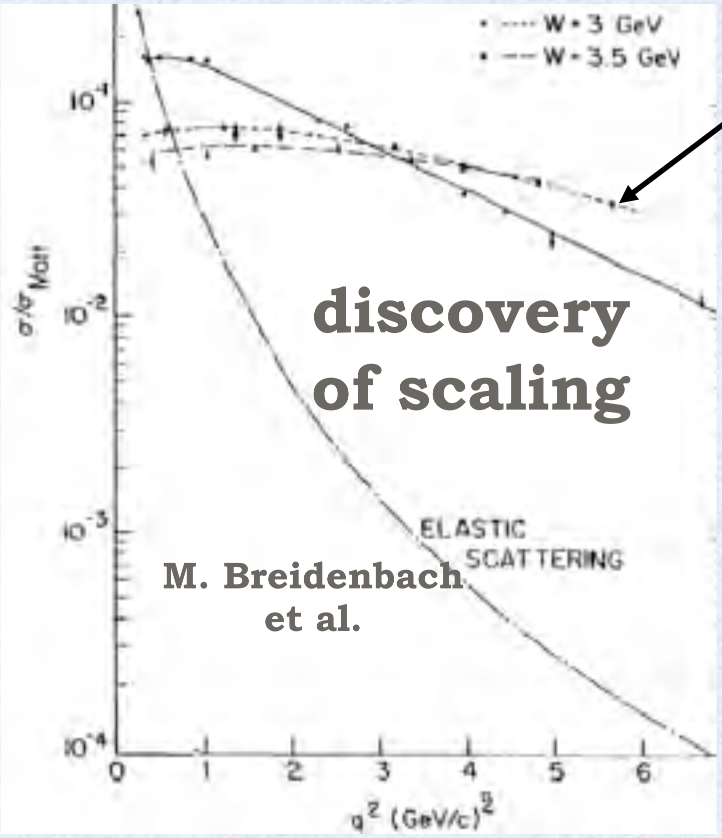
$$A_{PV} \sim 10^{-4}$$

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

Parity is conserved

First table-top atomic parity violation searches: negative!

large rate at large Q^2



electron-nucleon deep inelastic scattering

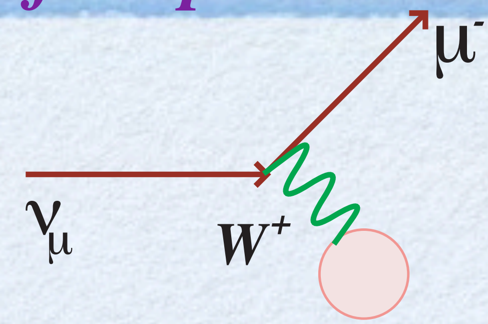
Glashow, Weinberg and Salam: $SU(2)_L \times U(1)_Y$

Neutral Weak Interaction Theory

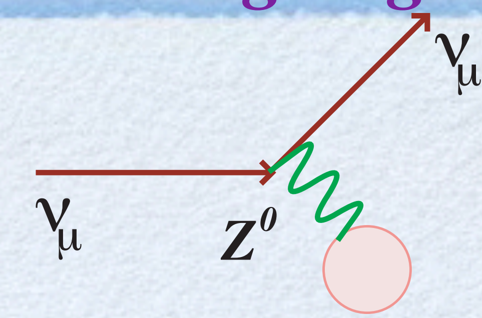
The Z boson incorporated

	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

$$\frac{g}{\cos\theta_W} Z_\mu \bar{f}\gamma^\mu (T_{3f} - 2Q_f \sin^2\theta_W - T_{3f}\gamma_5) f, \quad T_{3f} = \pm 1/2$$

Do lepton-nucleon neutral current interactions exhibit parity violation?

$$\begin{pmatrix}\nu\\ e\end{pmatrix}_l \quad (e)_r$$

Weinberg model

Parity is violated

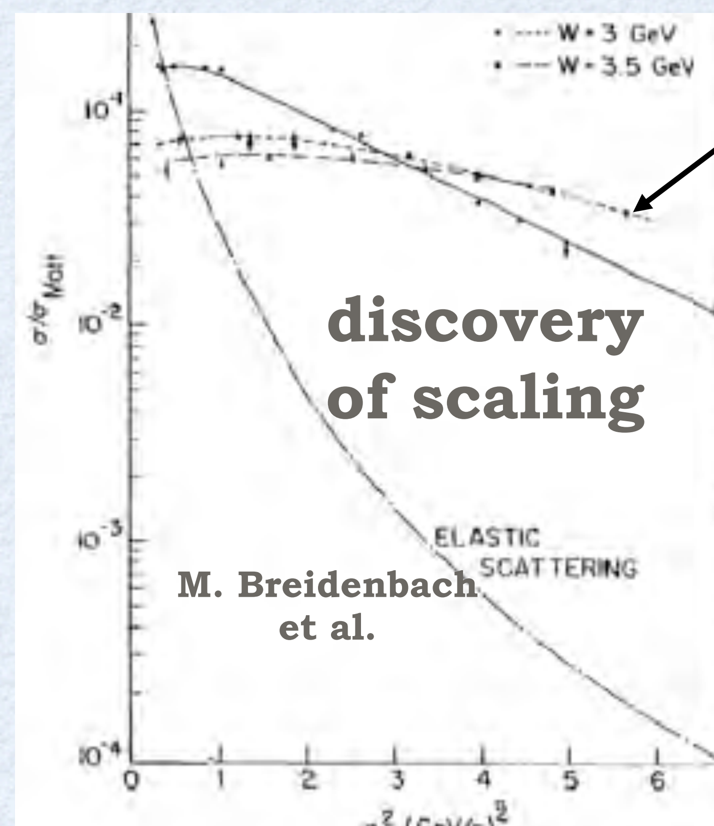
or

$$\begin{pmatrix}\nu\\ e\end{pmatrix}_l \quad \begin{pmatrix}E^0\\ e\end{pmatrix}_r$$

Parity is conserved

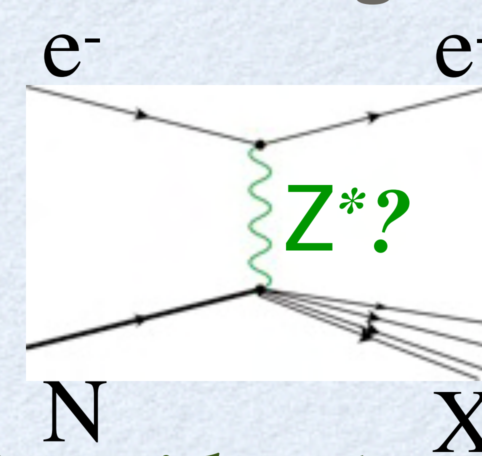
$$A_{PV} \sim 10^{-4}$$

First table-top atomic parity violation searches: negative!



large rate at large Q^2

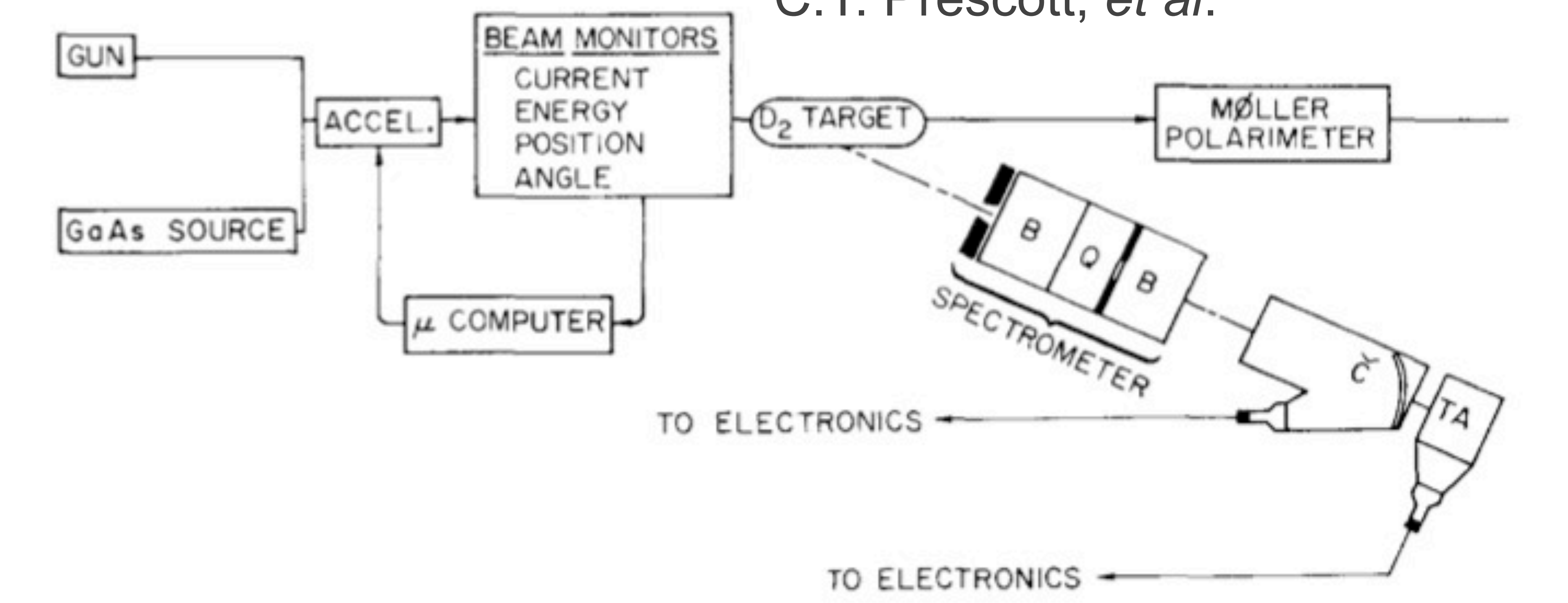
electron-nucleon deep inelastic scattering



pressing problem in mid-70's

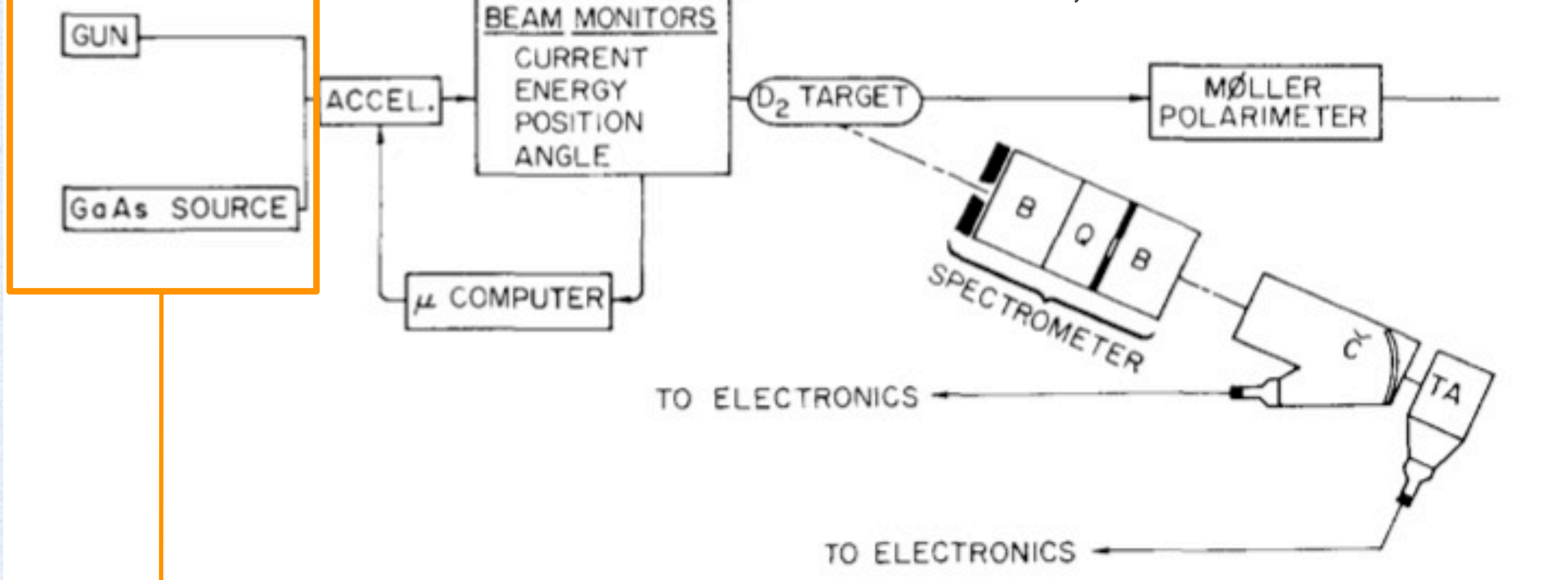
Anatomy of a Parity Experiment

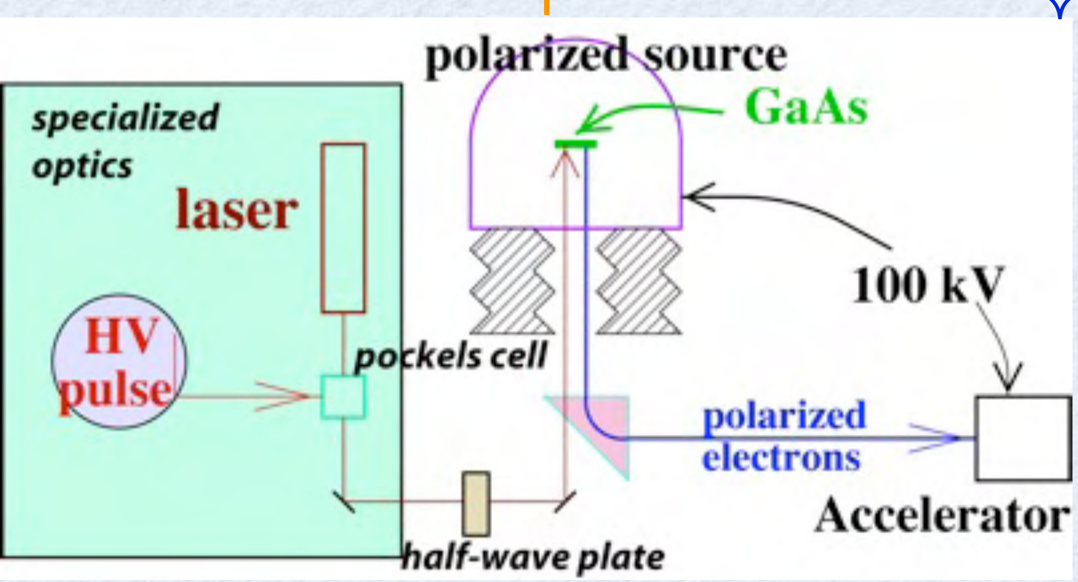
C.Y. Prescott, *et al.*



Anatomy of a Parity Experiment

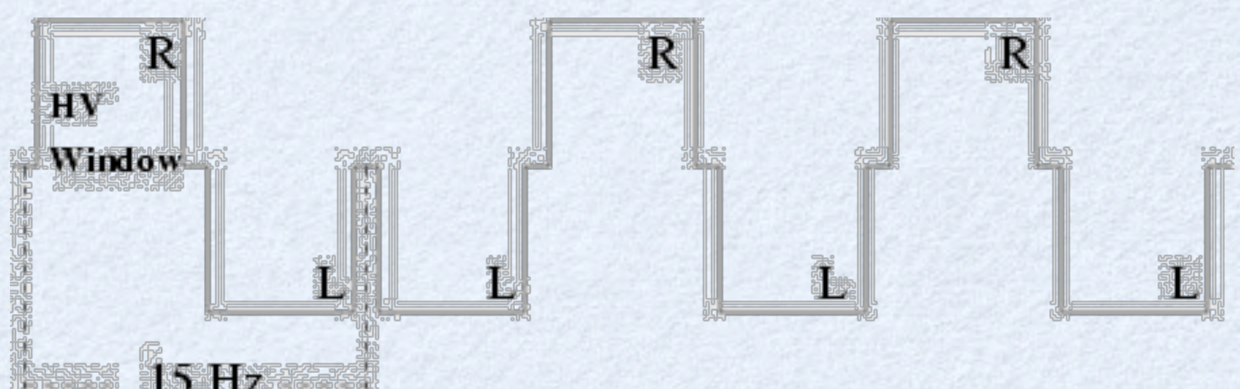
C.Y. Prescott, *et al.*



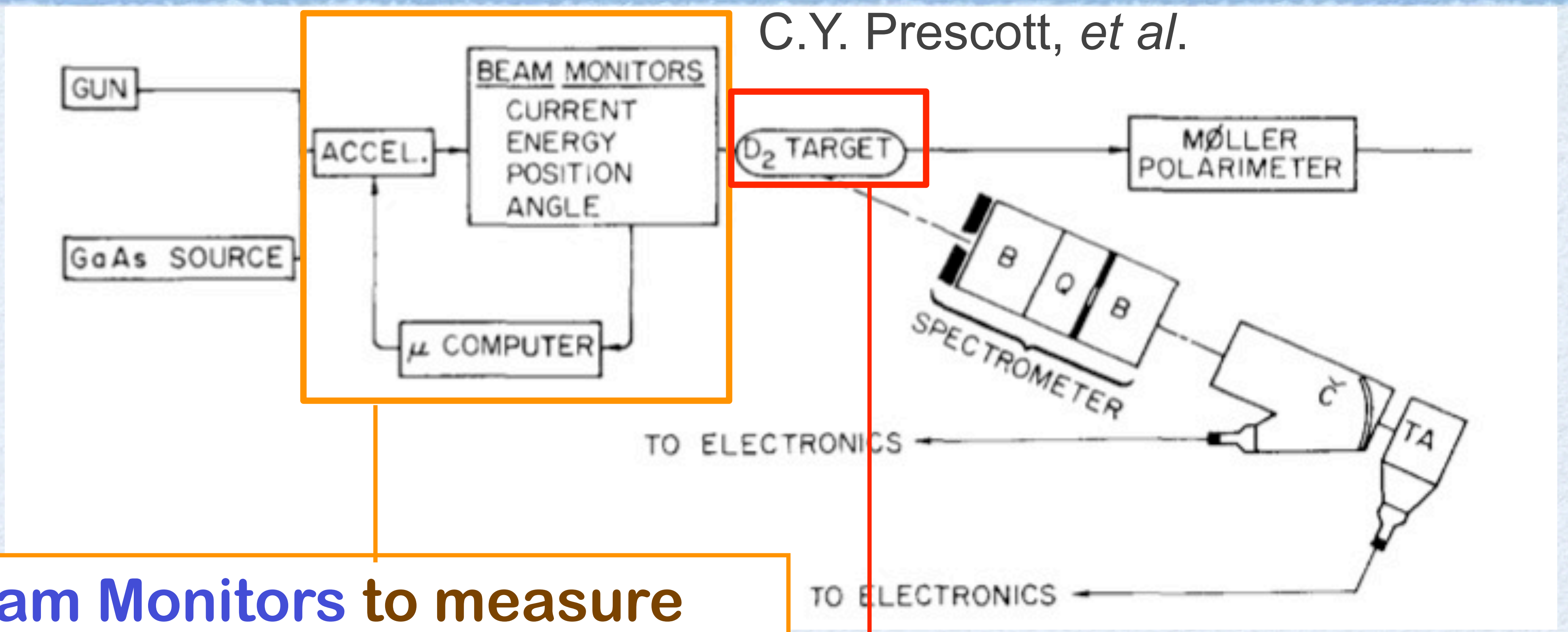


✧ **Beam helicity sequence is chosen pseudo-randomly**

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



Anatomy of a Parity Experiment

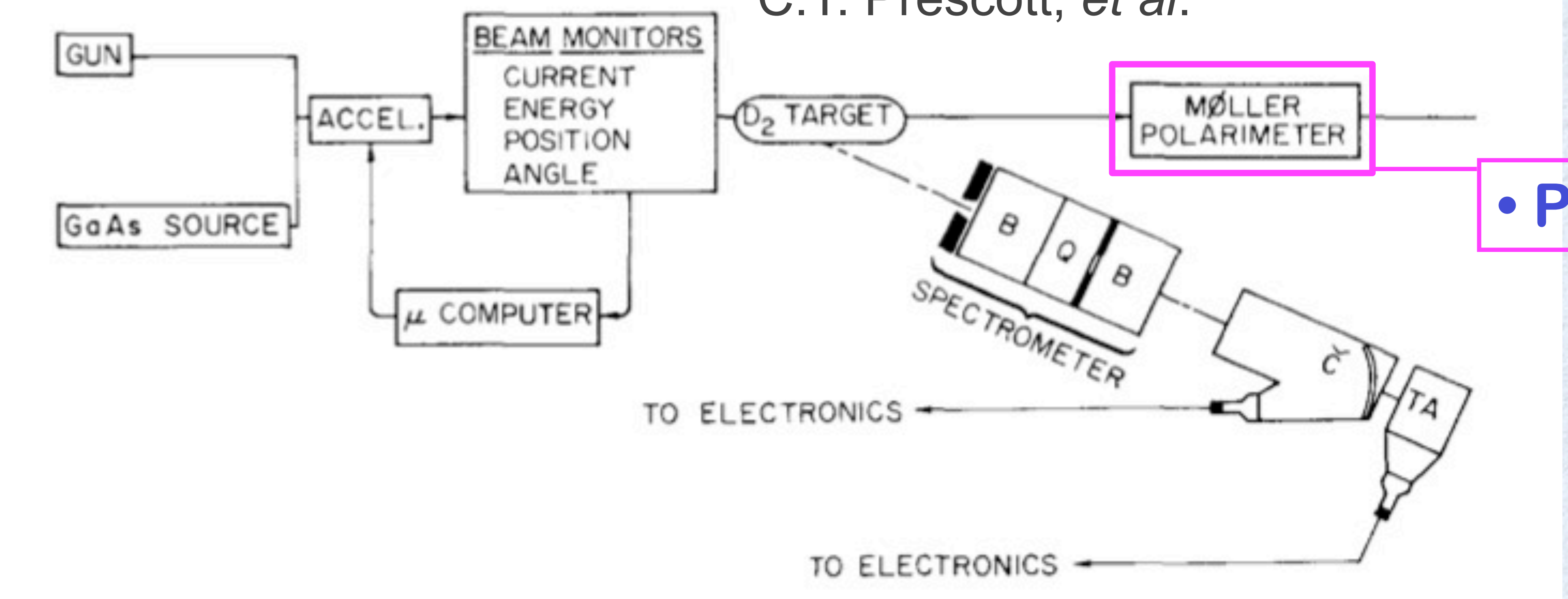


- **Beam Monitors** **to measure helicity-correlated changes in beam parameters**

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

Anatomy of a Parity Experiment

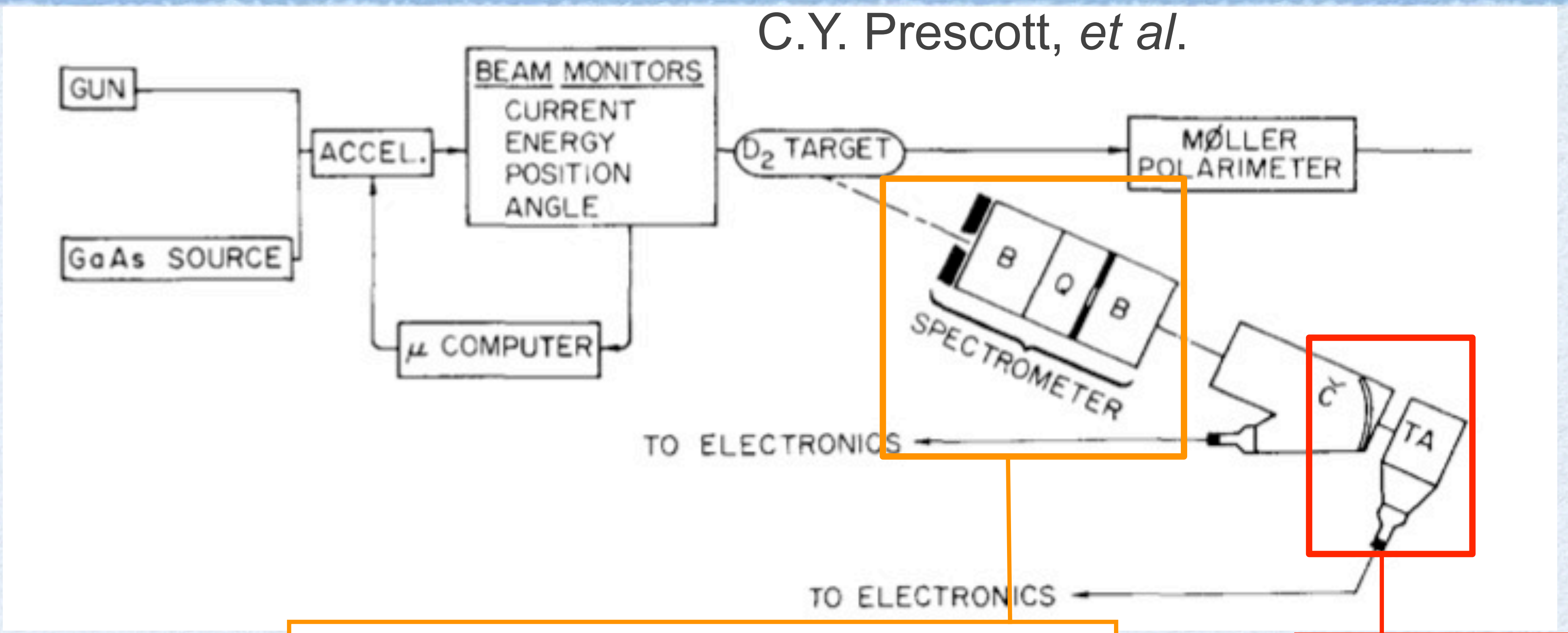
C.Y. Prescott, *et al.*



- **Polarimetry**

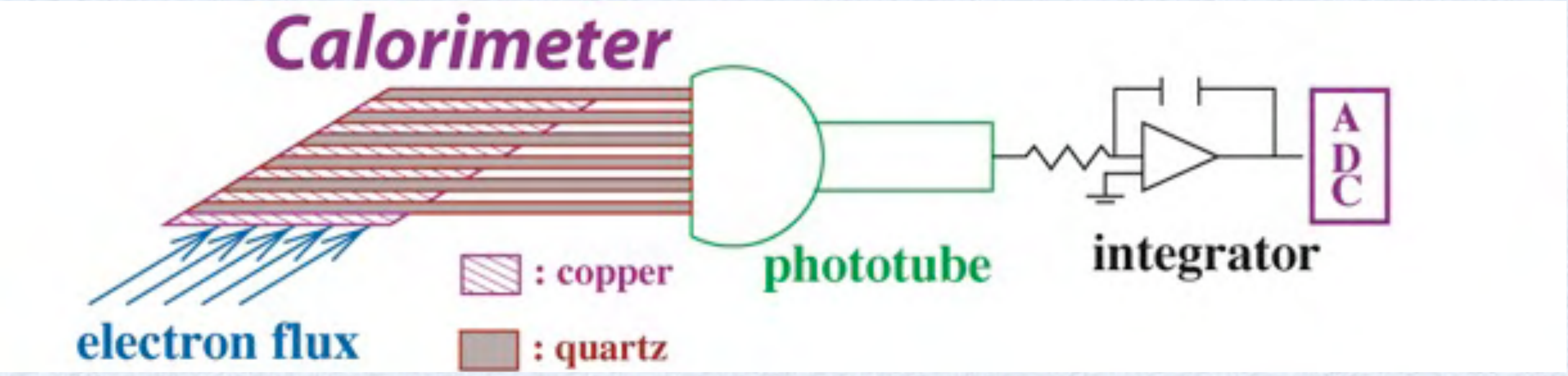
Anatomy of a Parity Experiment

C.Y. Prescott, *et al.*



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

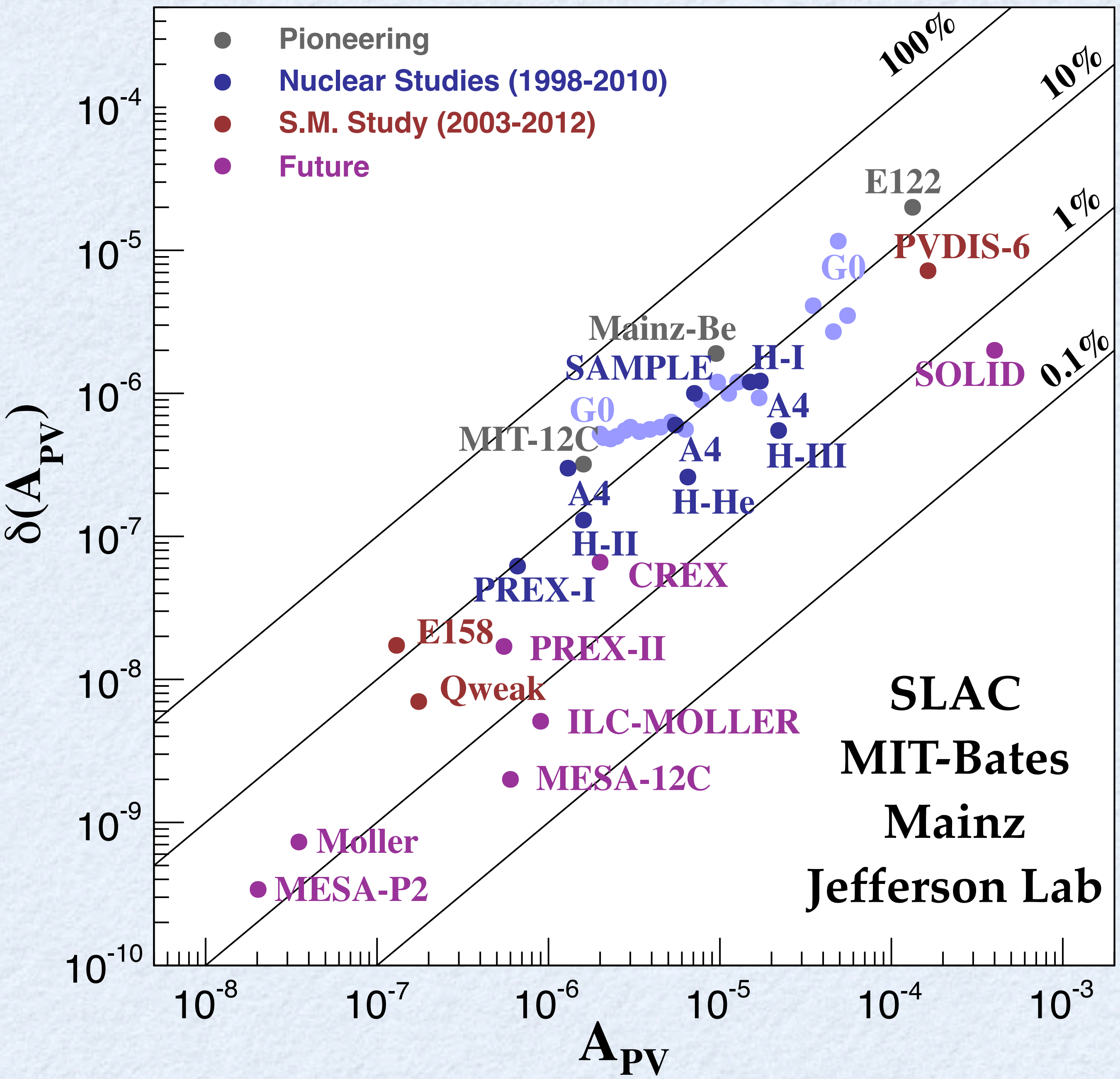
• **Flux Integration** measures high rate without deadtime



3 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

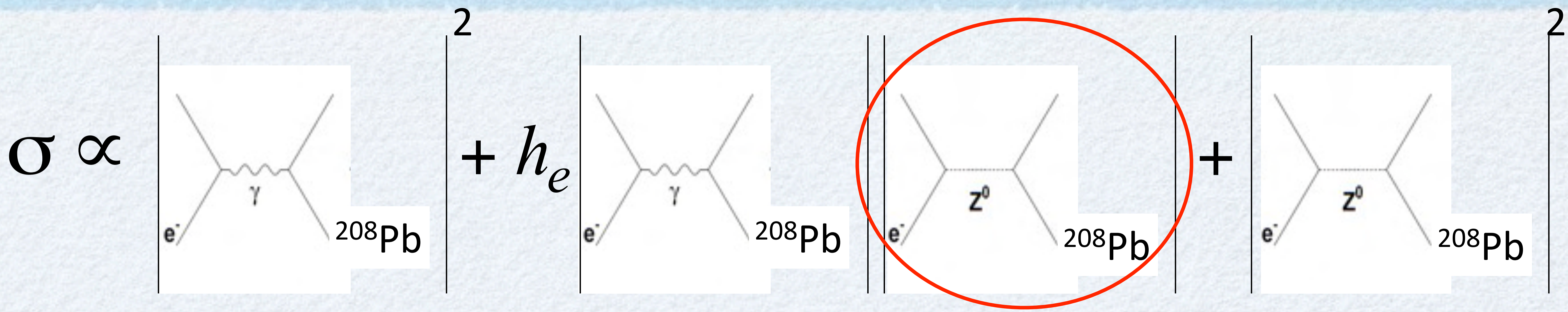
E158 at SLAC measured PV Møller scattering

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

PREX at Jefferson Lab



PREX Concept

Pb-Radius EXperiment

$$M^{EM} = \frac{4\pi\alpha}{Q^2} F_p(Q^2) \qquad M_{PV}^{NC} = \frac{G_F}{\sqrt{2}}\left[\left(1-4\sin^2\theta_W\right)F_p(Q^2) - F_n(Q^2)\right]$$

$Q^p_{EM} \sim 1$ $\quad$ $Q^n_{EM} \sim 0$

$Q^n_W \sim -1$ $\quad$ $Q^p_W \sim 1 - 4\sin^2\theta_W$

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

$Q^2 \sim 0.01$ GeV^2
5^o scattering angle

$\Rightarrow$

$A_{PV} \sim 0.6$ ppm

Rate ~ 1 GHz

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

	proton	neutron
Electric charge	**1**	**0**
Weak charge	**~0.08**	**-1**

PREX Concept

Pb-Radius EXperiment

$$M^{EM} = \frac{4\pi\alpha}{Q^2} F_p(Q^2)$$

$$M_{PV}^{NC} = \frac{G_F}{\sqrt{2}} \left[\left(1 - 4\sin^2\theta_W\right) F_p(Q^2) - F_n(Q^2) \right]$$

$Q^p_{EM} \sim 1$ $Q^n_{EM} \sim 0$

$Q^n_W \sim -1$ $Q^p_W \sim 1 - 4\sin^2\theta_W$

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

$Q^2 \sim 0.01$ GeV^2

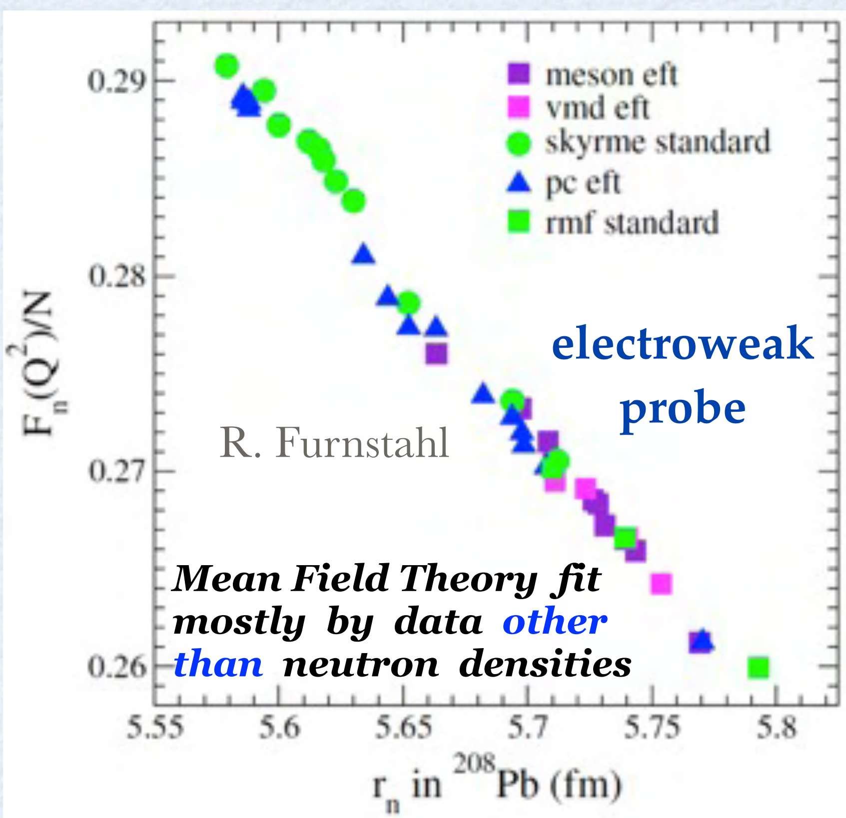
5^o scattering angle

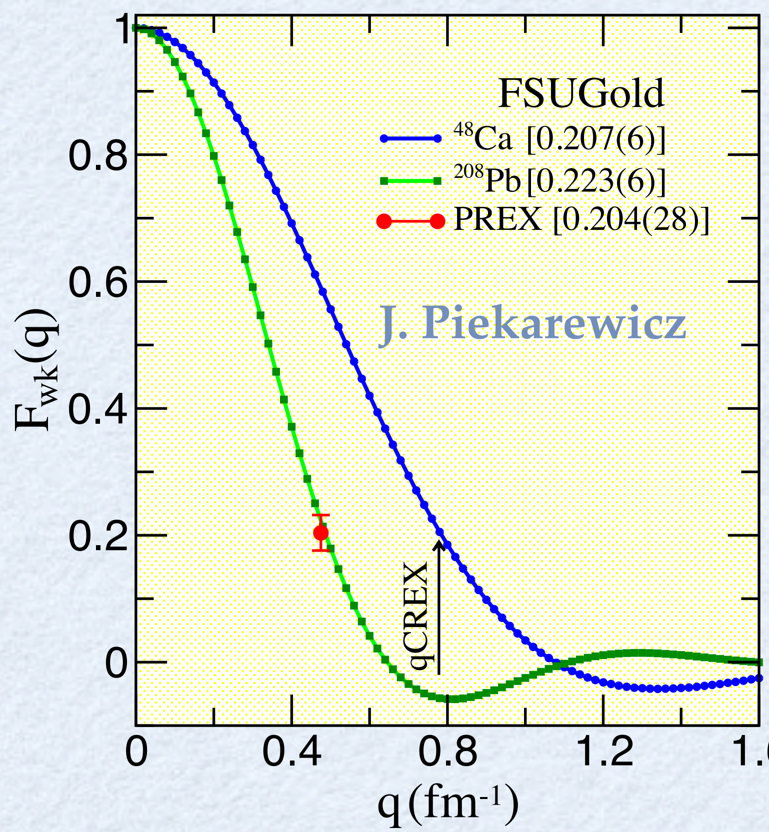
$A_{PV} \sim 0.6$ ppm

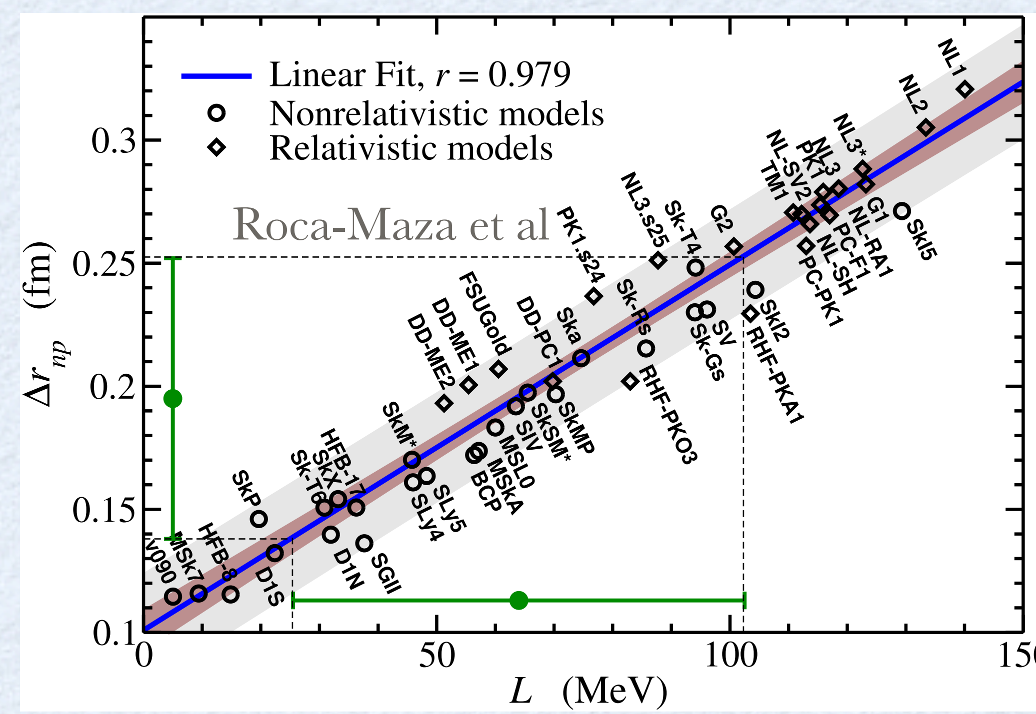
Rate ~ 1 GHz

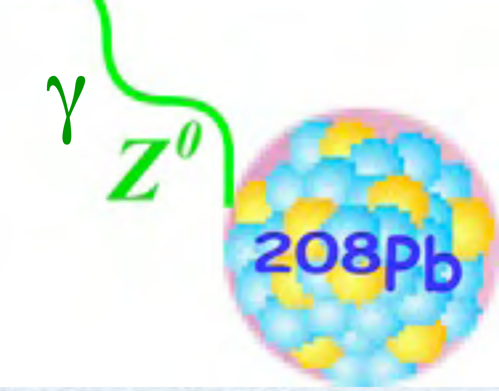
$\delta(A_{PV}) \sim 20$ ppb!

	proton	neutron
Electric charge	1	0
Weak charge	~0.08	-1









PREX Concept

Pb-Radius EXperiment

$$M^{EM} = \frac{4\pi\alpha}{Q^2} F_p(Q^2) \qquad M_{PV}^{NC} = \frac{G_F}{\sqrt{2}}\left[\left(1-4\sin^2\theta_W\right)F_p(Q^2) - F_n(Q^2)\right]$$

$Q^p_{EM} \sim 1$ $\quad Q^n_{EM} \sim 0$

$Q^n_W \sim -1$ $\quad Q^p_W \sim 1 - 4\sin^2\theta_W$

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

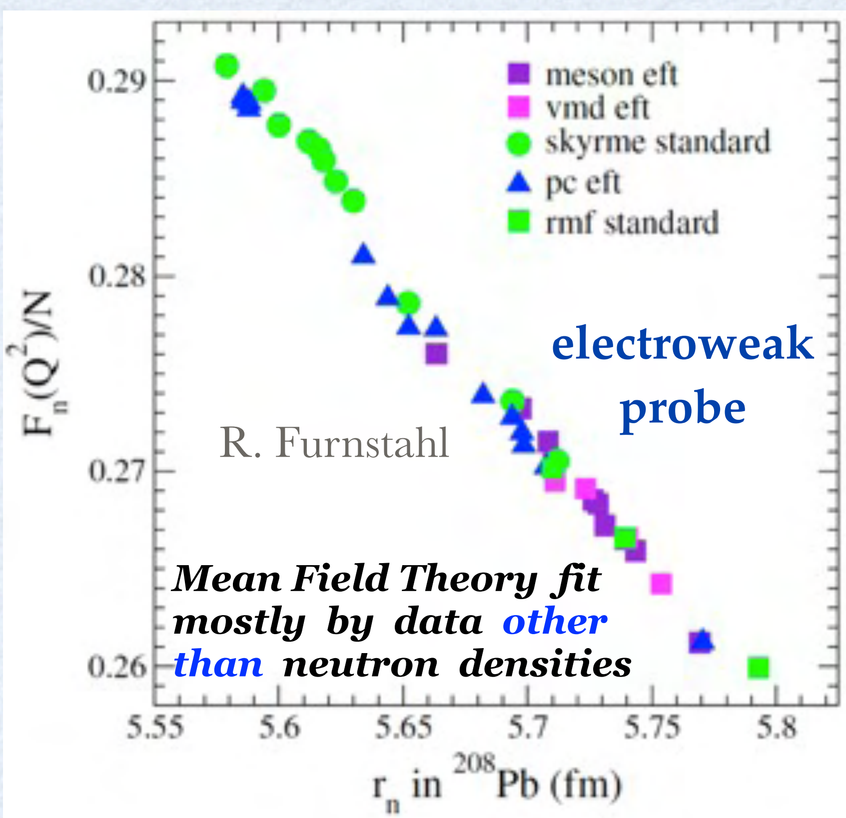
$Q^2 \sim 0.01$ GeV^2
5^o scattering angle

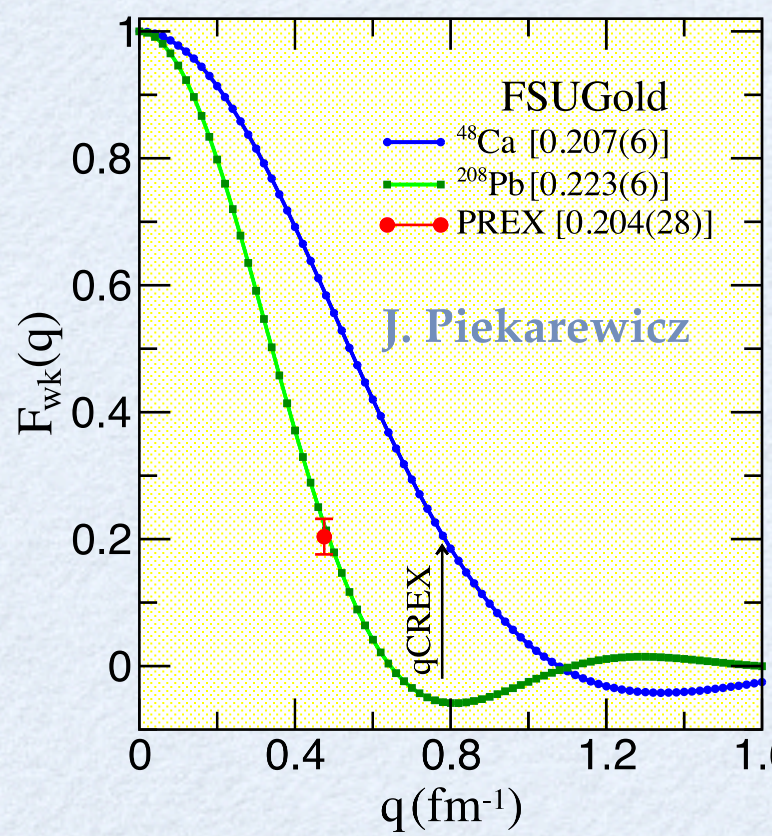
$A_{PV} \sim 0.6$ ppm

Rate ~ 1 GHz

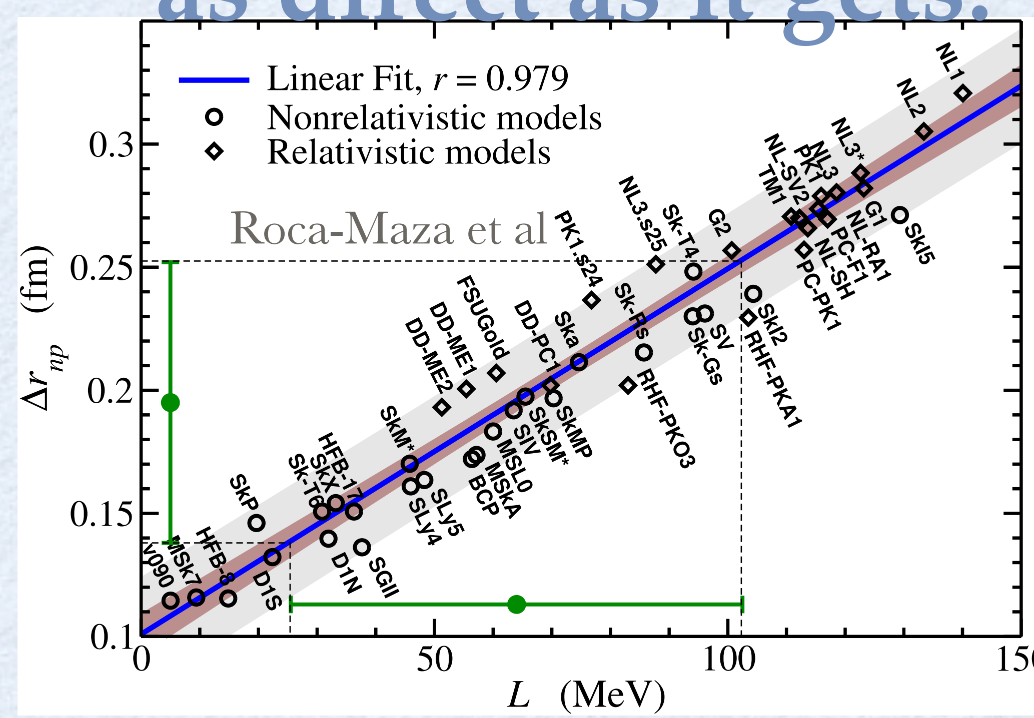
$\delta(A_{PV}) \sim 20$ ppb!

	proton	neutron
Electric charge	1	0
Weak charge	~0.08	-1





as direct as it gets!

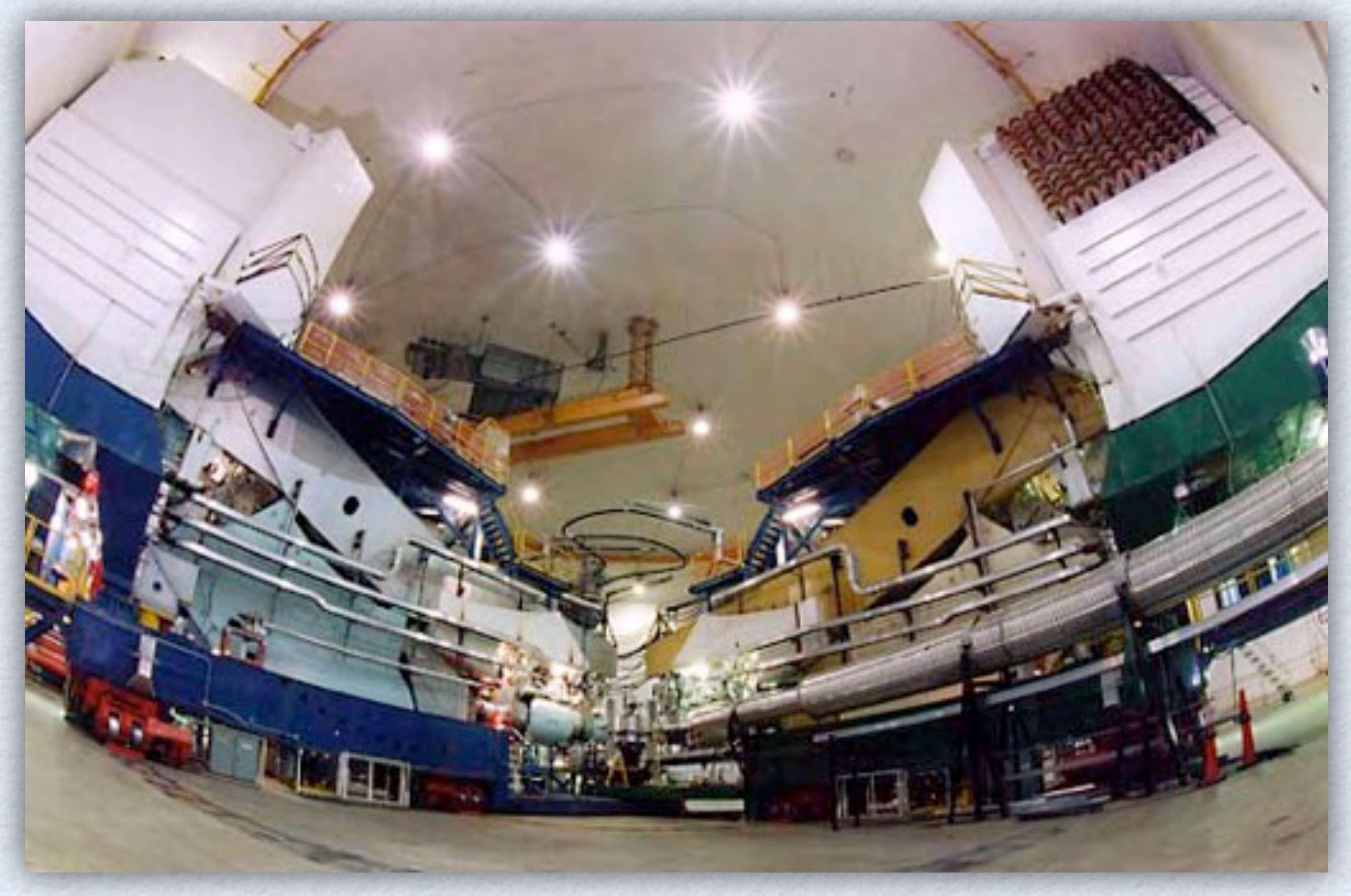


PREX Overview

1 GeV electron beam, 50-70 µA

high polarization, ~89%

helicity reversal at 120 Hz



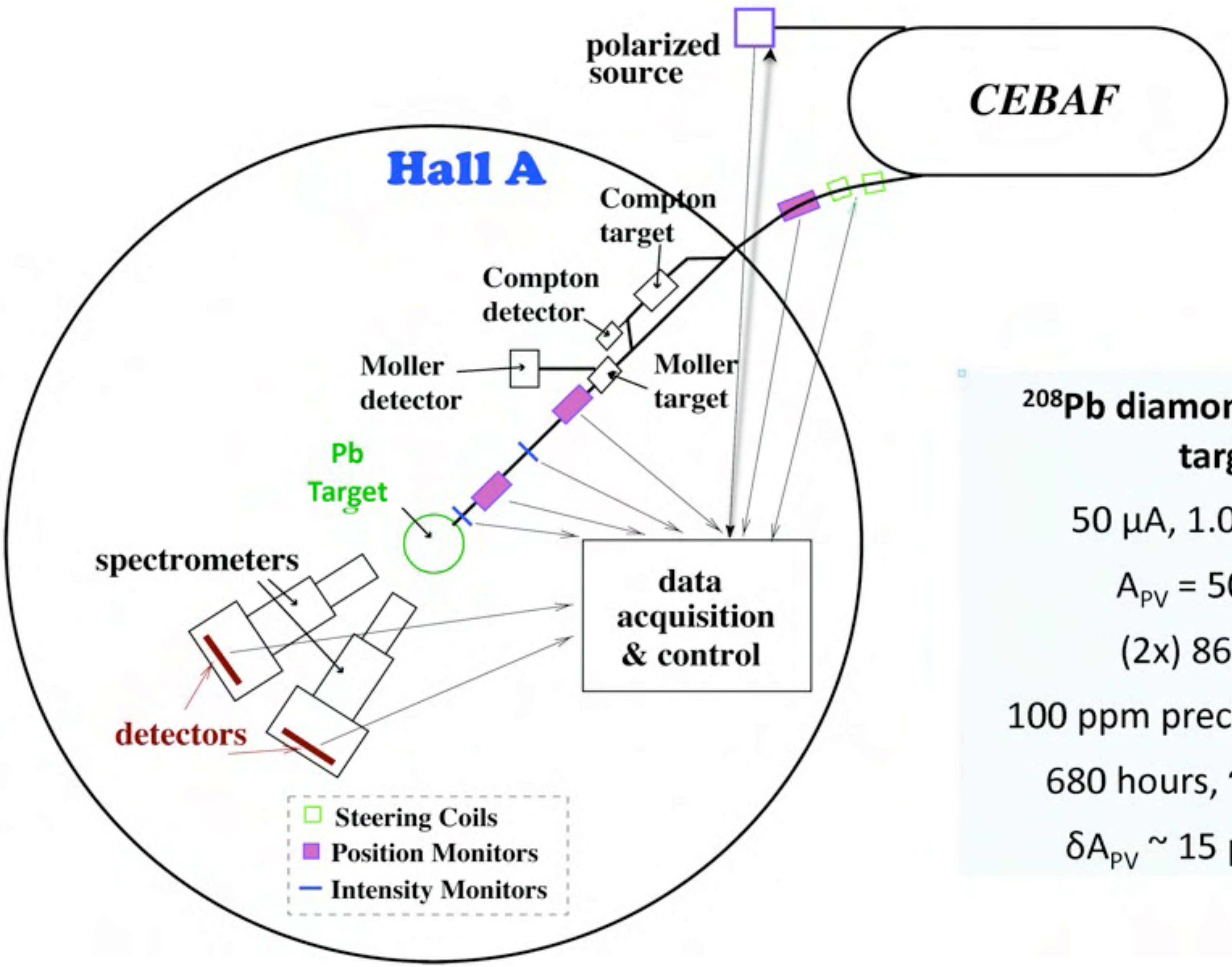
0.5 mm isotopically pure ^{208}Pb target

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

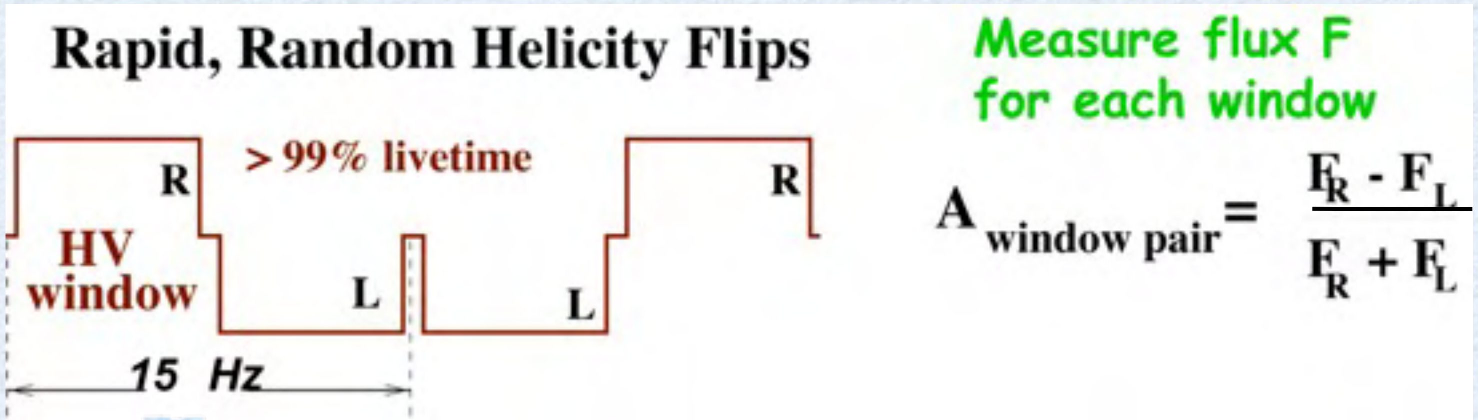
100 ppm precision at 15 Hz

680 hours, ~35M pairs

δA_{PV} ~ 15 ppb (3%)

HRS at JLab

Hall A High Resolution Spectrometers

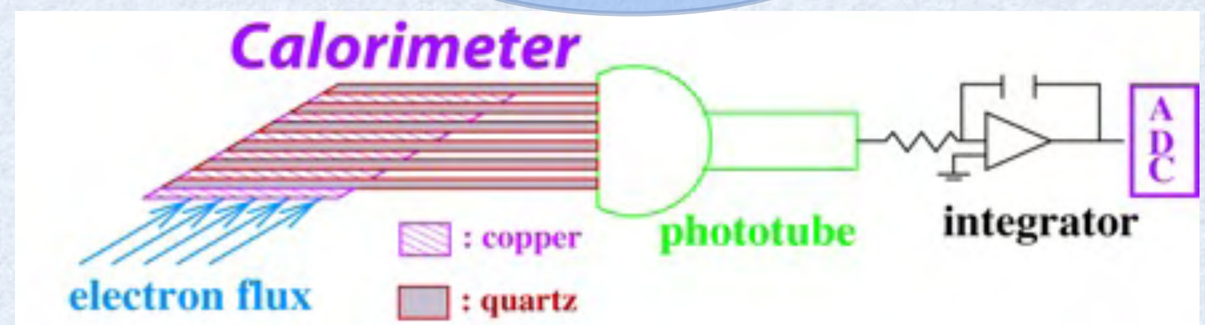


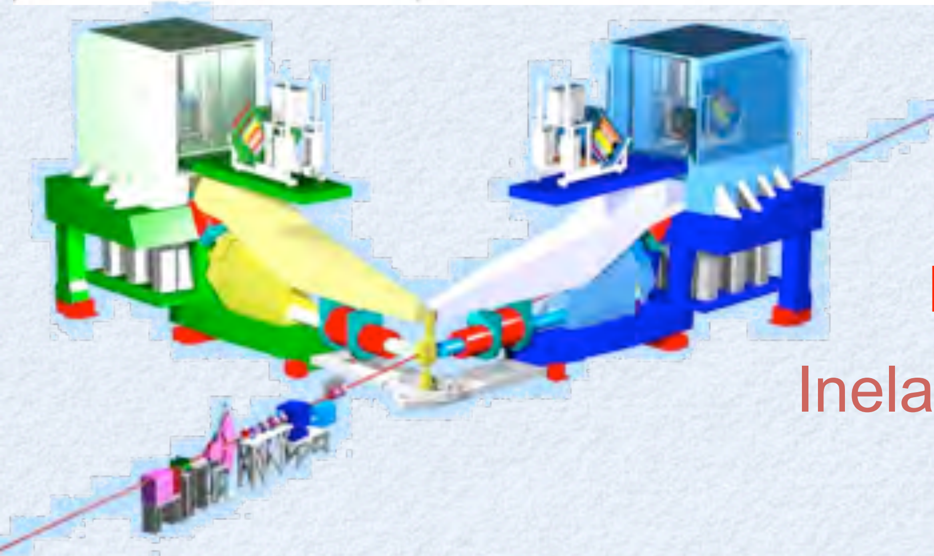
Flux Integration Technique

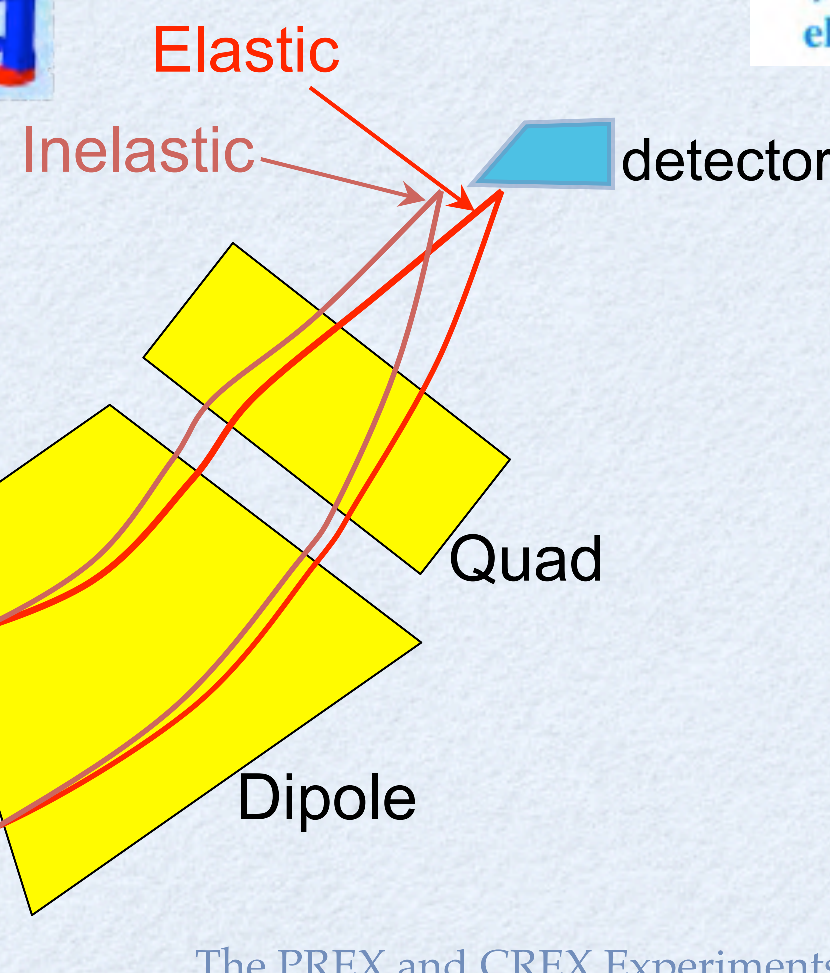
HAPPEX: 2 MHz

HAPPEXII: 100 MHz

PREX: 1 GHz

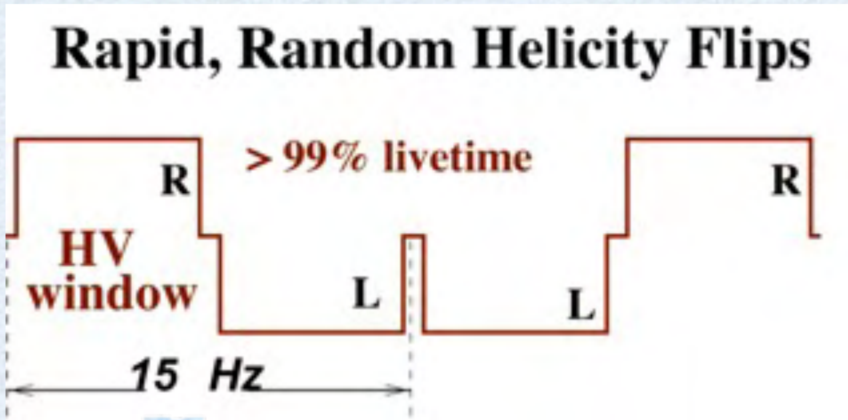






HRS at JLab

Hall A High Resolution Spectrometers



Measure flux F for each window

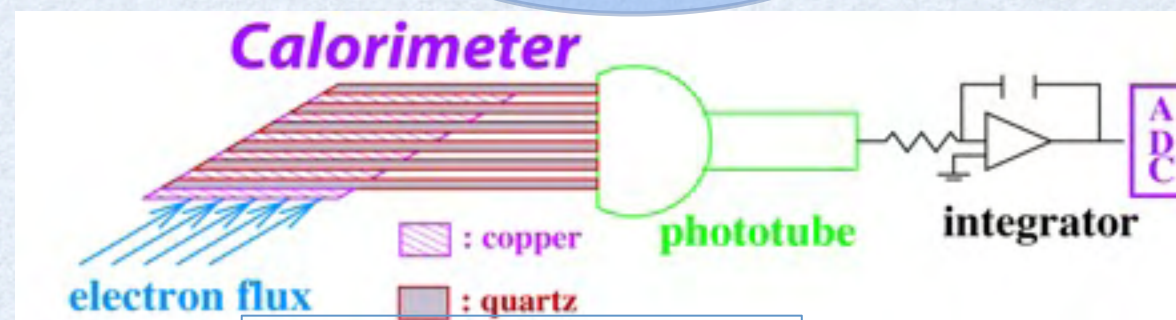
$$A_{\text{window pair}} = \frac{F_R - F_L}{F_R + F_L}$$

Flux Integration Technique

HAPPEX: 2 MHz

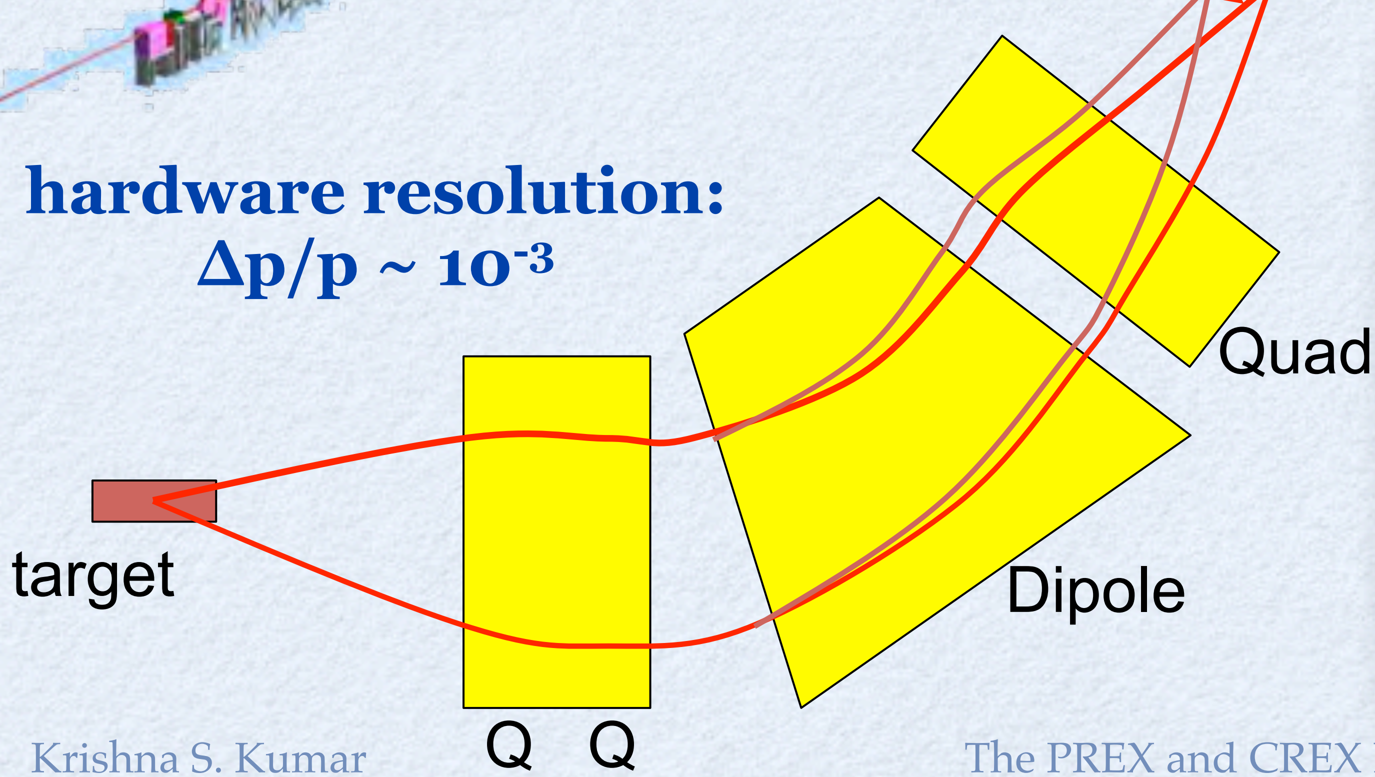
HAPPEXII: 100 MHz

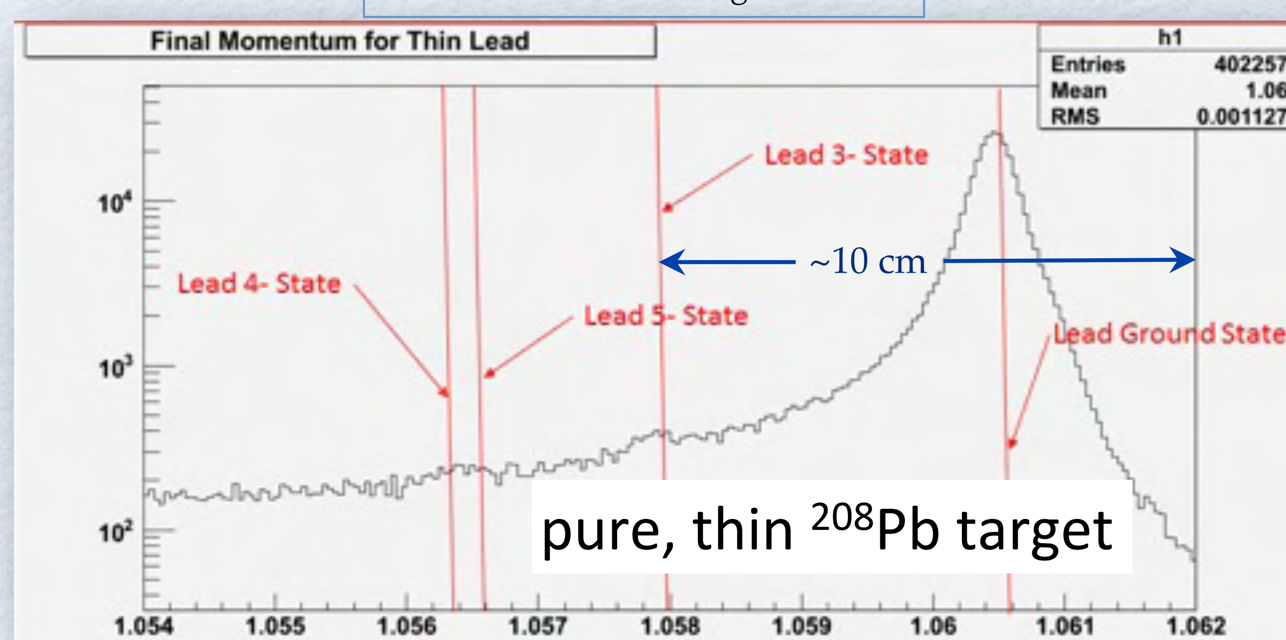
PREX: 1 GHz



$$A_{sig} = \frac{A_{corr} - A_{back}\, f_{back}}{f_{sig}}$$

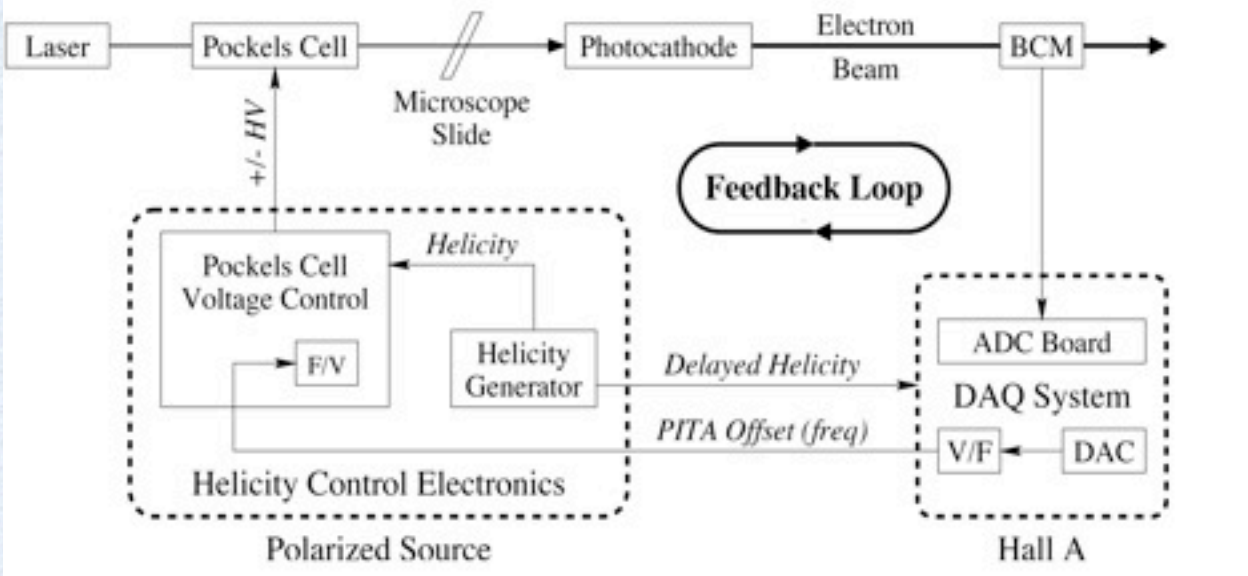
hardware resolution:
$\Delta p/p \sim 10^{-3}$





"Parity Quality" Beam

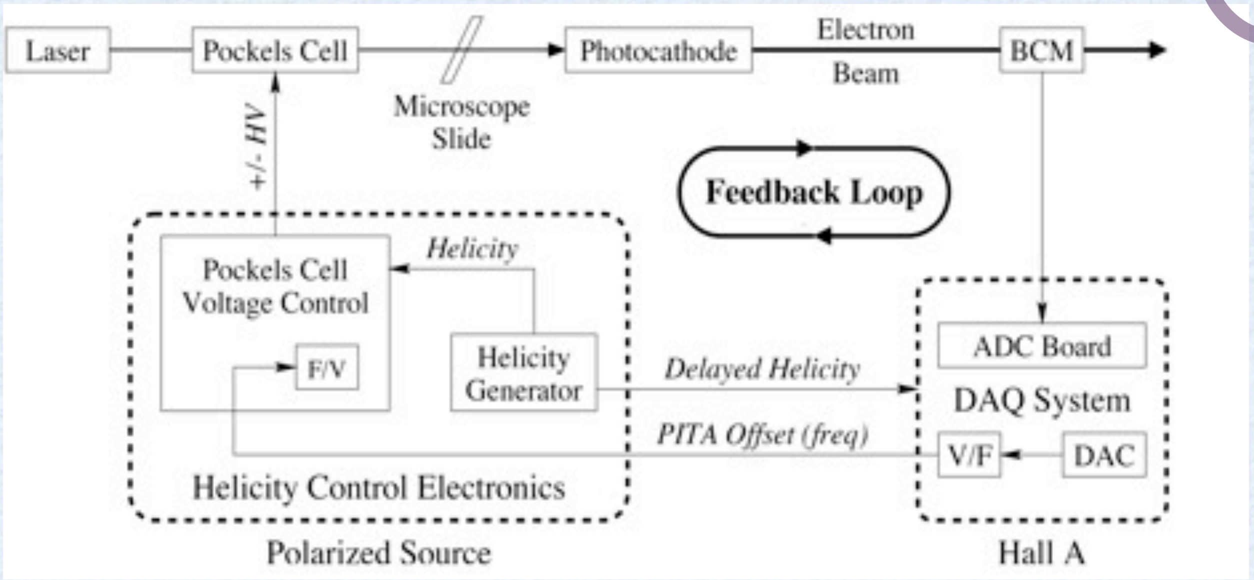
$A_{phys} \sim 500$ ppb $A_{corr} = A_{det} - A_Q + \alpha\, \Delta_E + \Sigma\beta_i\, \Delta x_i$



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

"Parity Quality" Beam

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

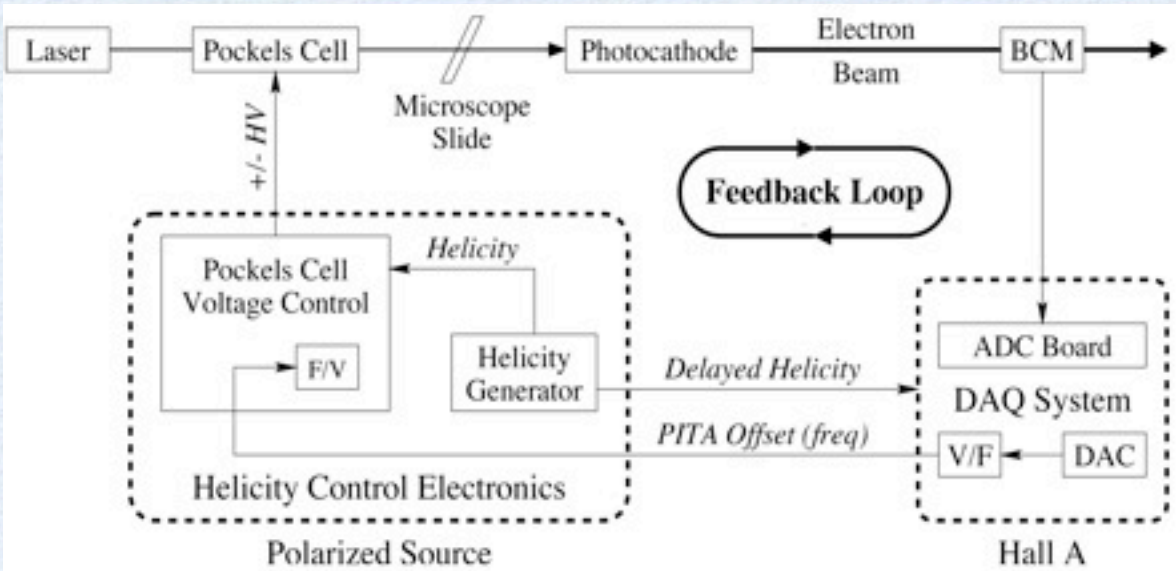


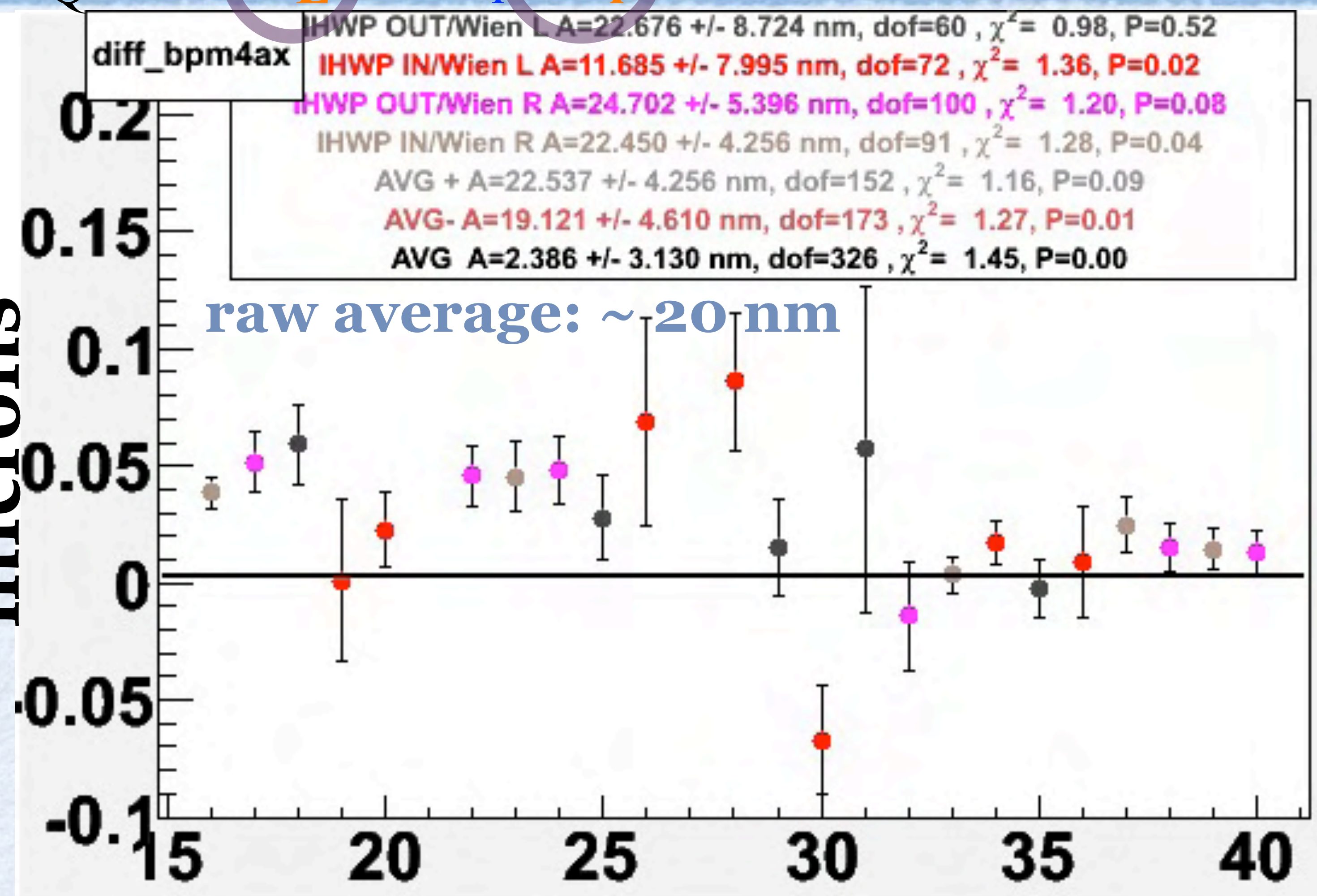
- *Active feedback of charge asymmetry*
- *Careful laser alignment*
- *Precision beam position monitoring*
- *Active calibration of detector slopes*

“Parity Quality” Beam

A_{phys} ~ 500 ppb

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

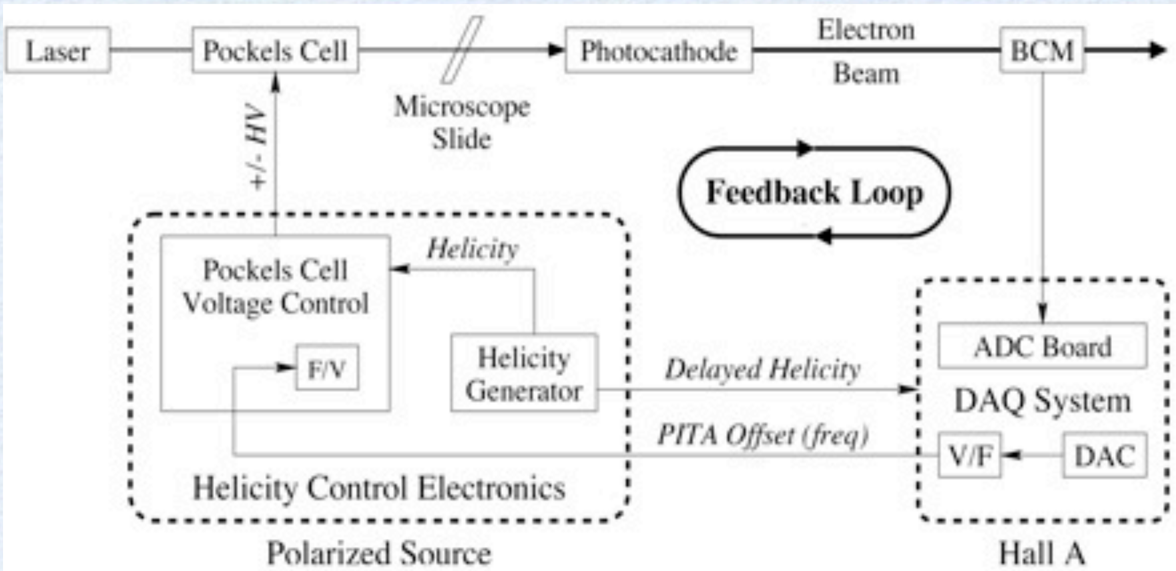


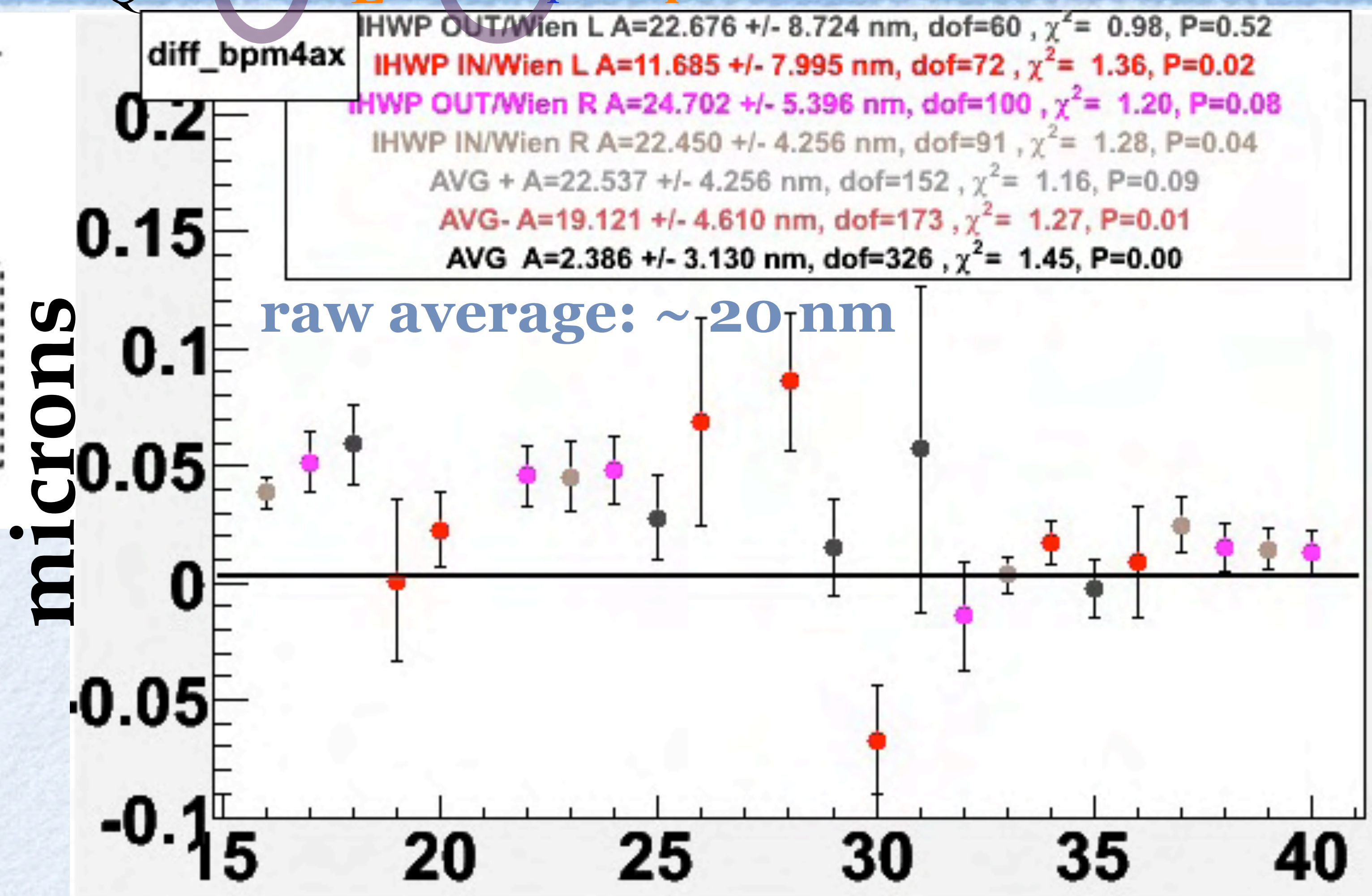


- *Active feedback of charge asymmetry*
- *Careful laser alignment*
- *Precision beam position monitoring*
- *Active calibration of detector slopes*

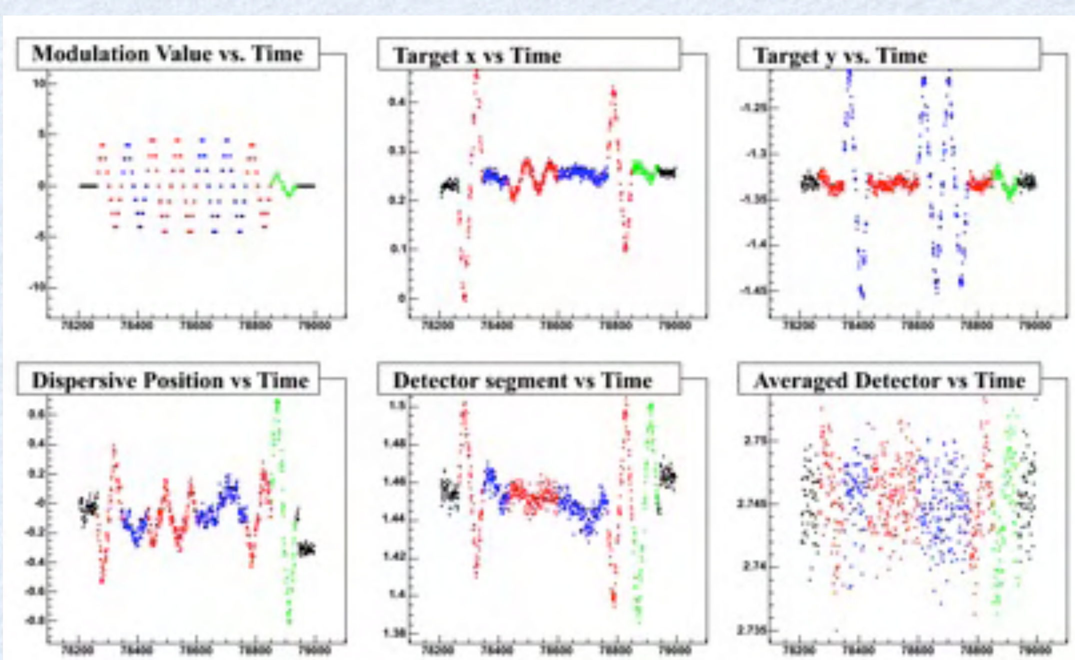
“Parity Quality” Beam

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





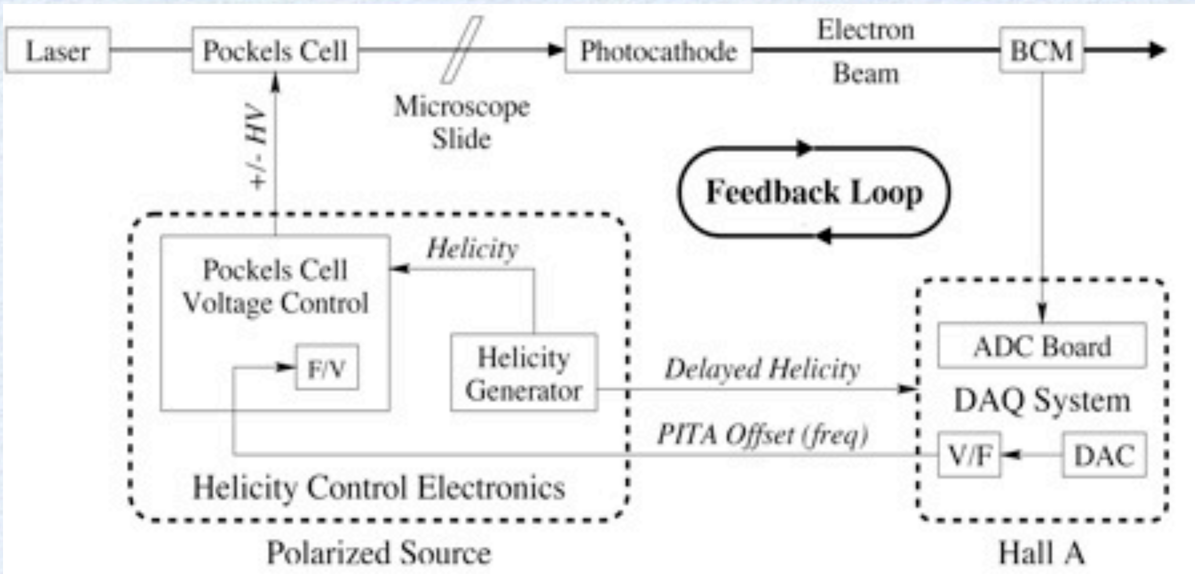
- *Active feedback of charge asymmetry*
- *Careful laser alignment*
- *Precision beam position monitoring*
- *Active calibration of detector slopes*

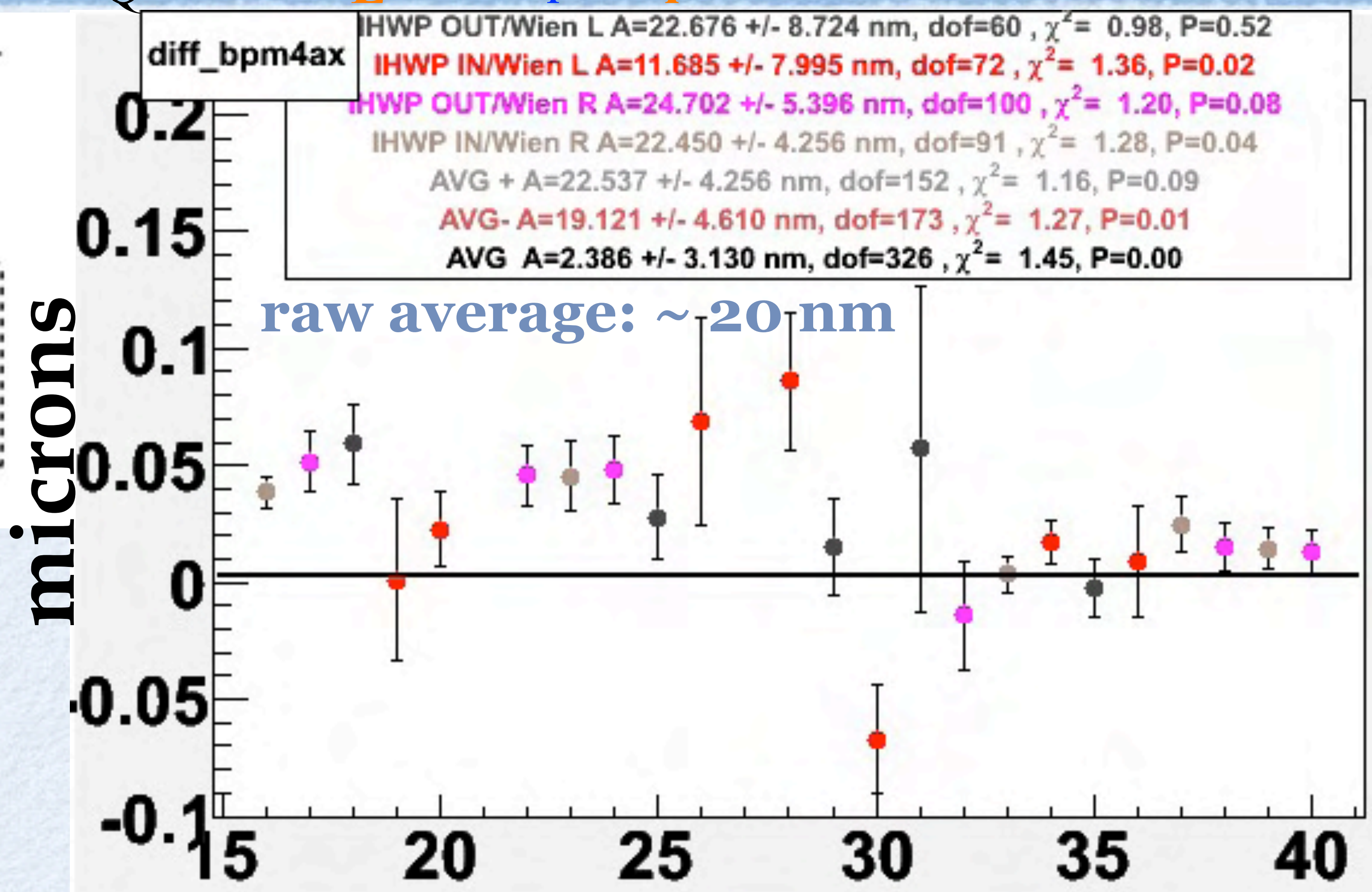


“Parity Quality” Beam

A_{phys} ~ 500 ppb

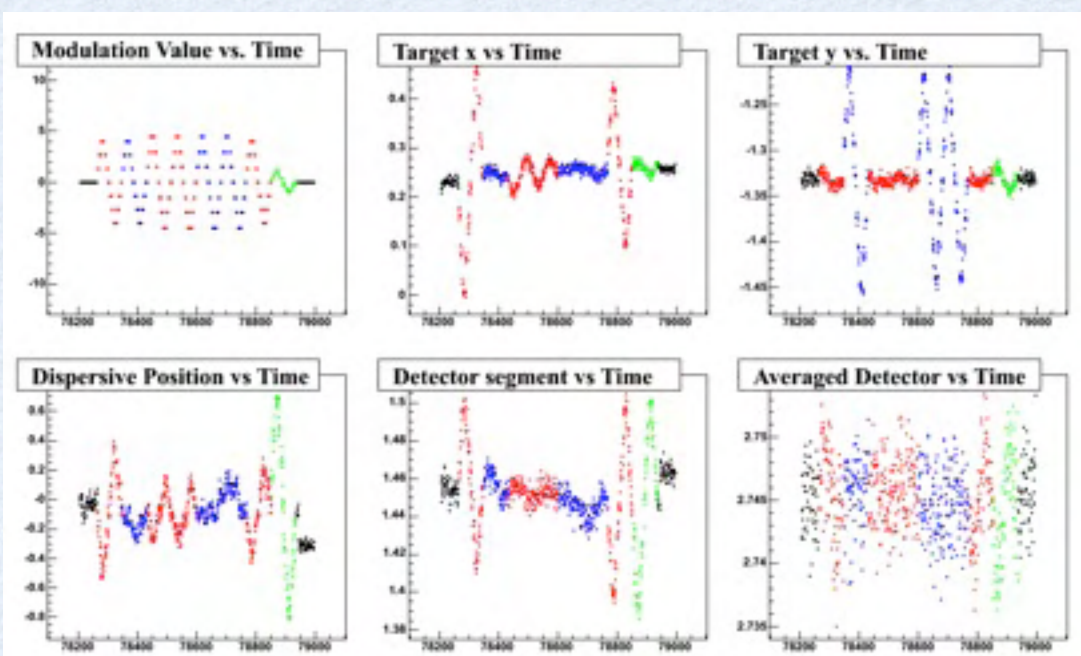
$$A_{corr} = A_{det} - A_Q + \alpha\, \Delta_E + \Sigma\beta_i\, \Delta x_i$$

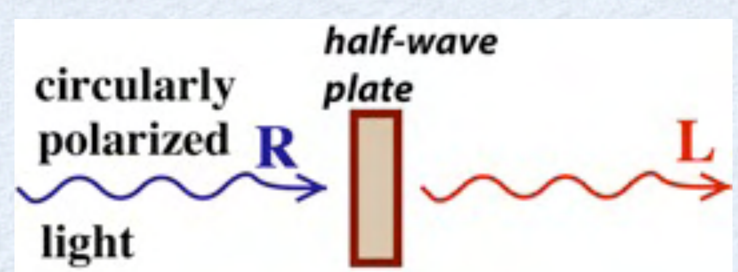




- *Active feedback of charge asymmetry*
- *Careful laser alignment*
- *Precision beam position monitoring*
- *Active calibration of detector slopes*

2 methods of “slow” reversal

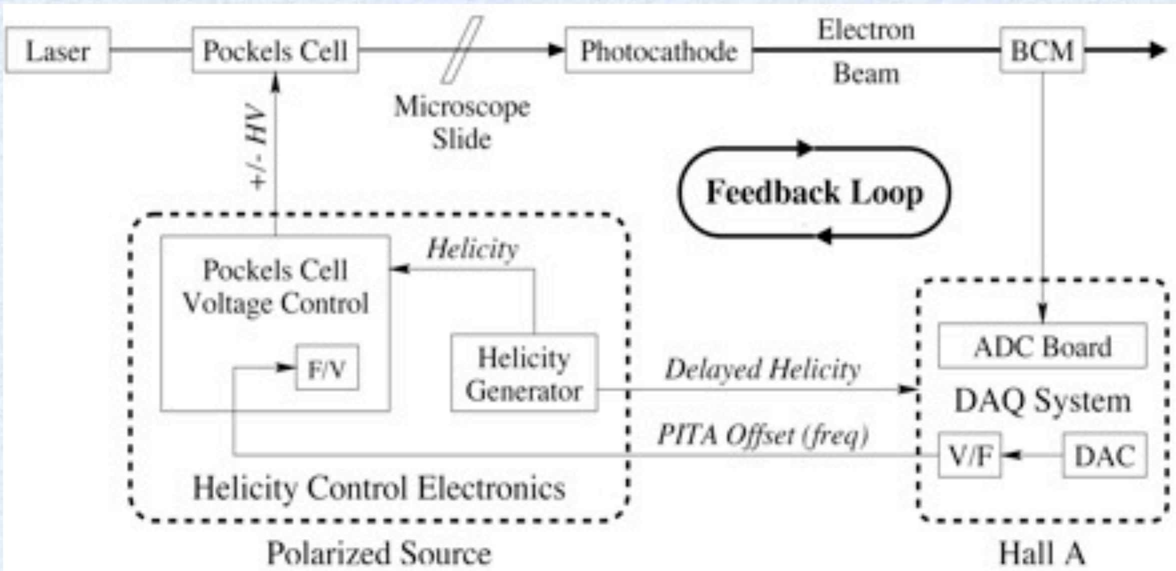


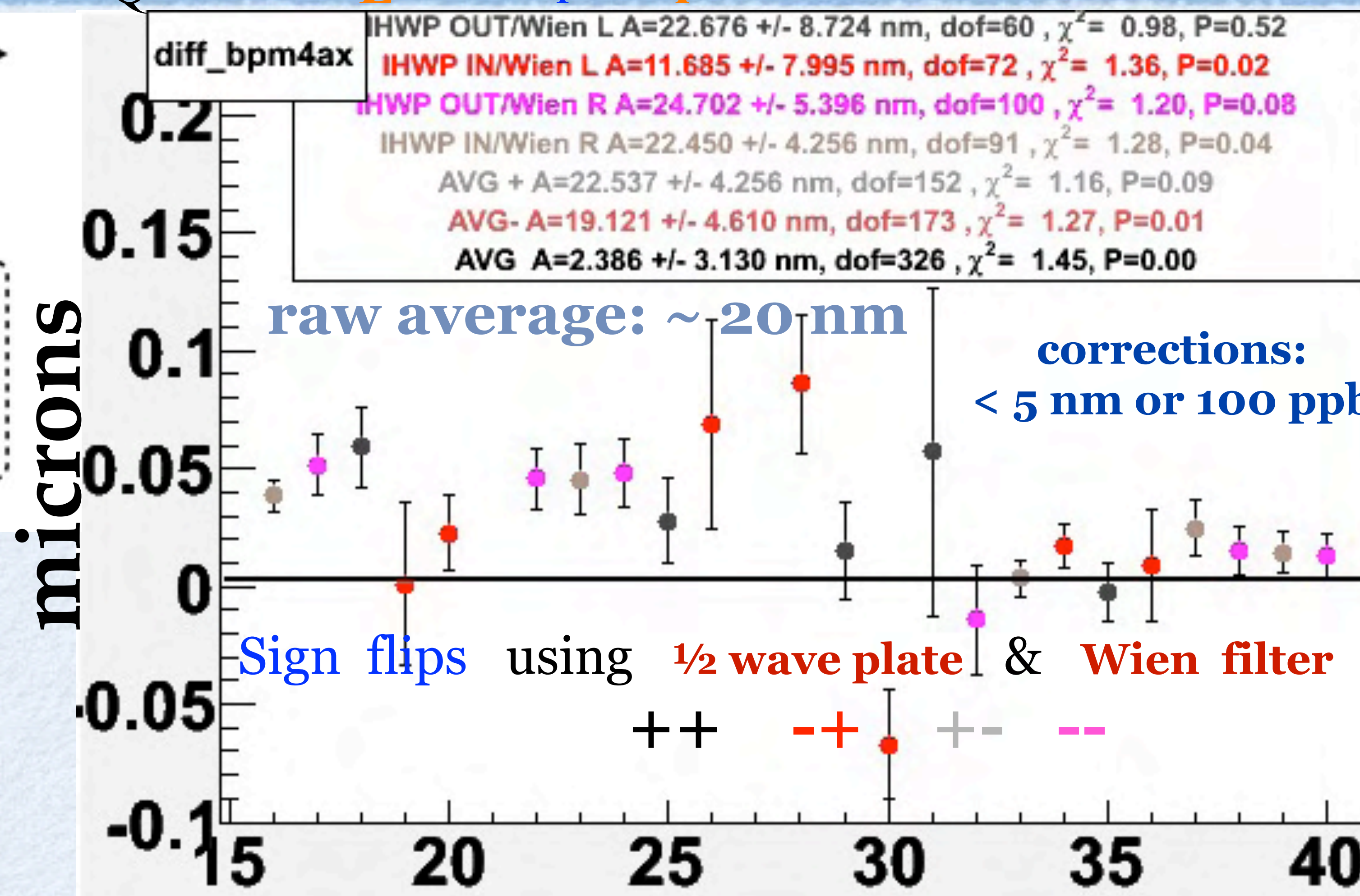


"Parity Quality" Beam

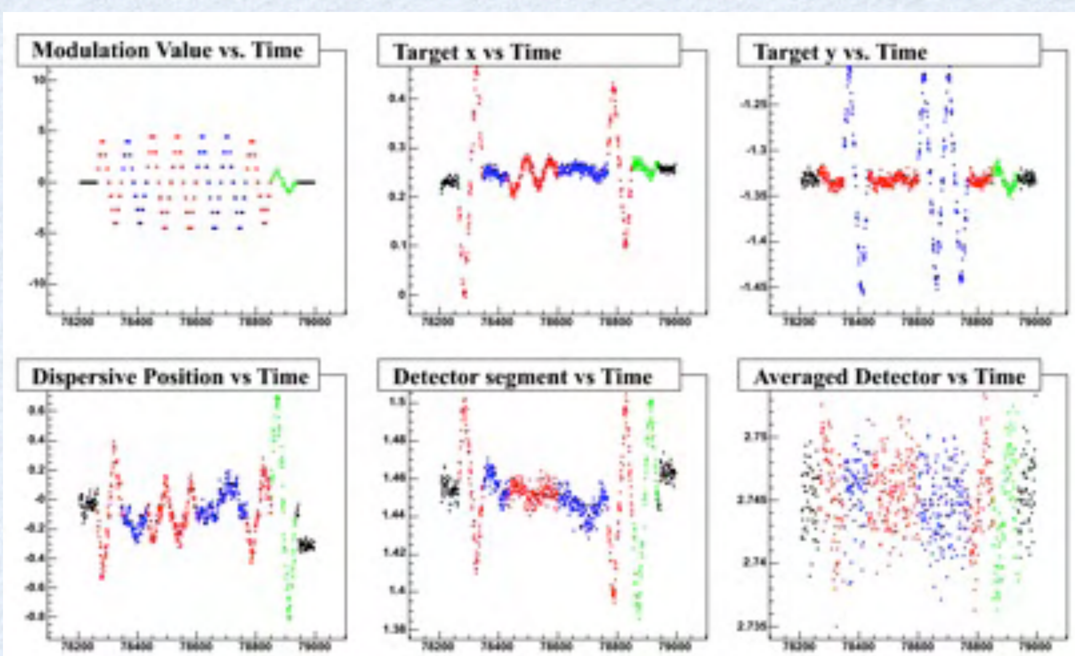
$A_{phys} \sim 500$ ppb

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

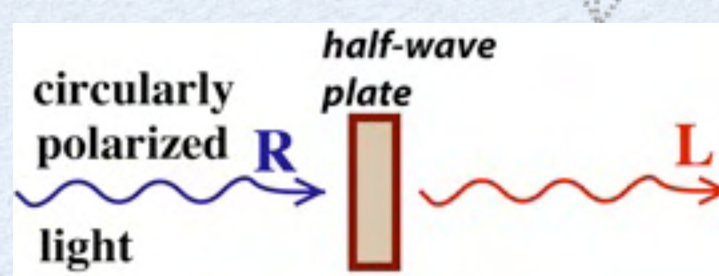


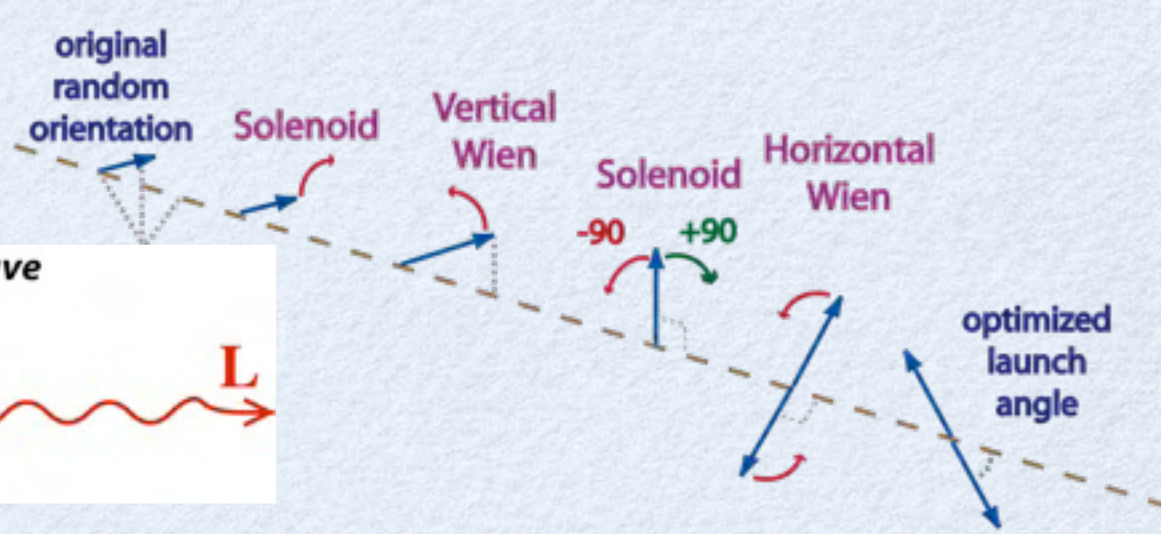


- *Active feedback of charge asymmetry*
- *Careful laser alignment*
- *Precision beam position monitoring*
- *Active calibration of detector slopes*

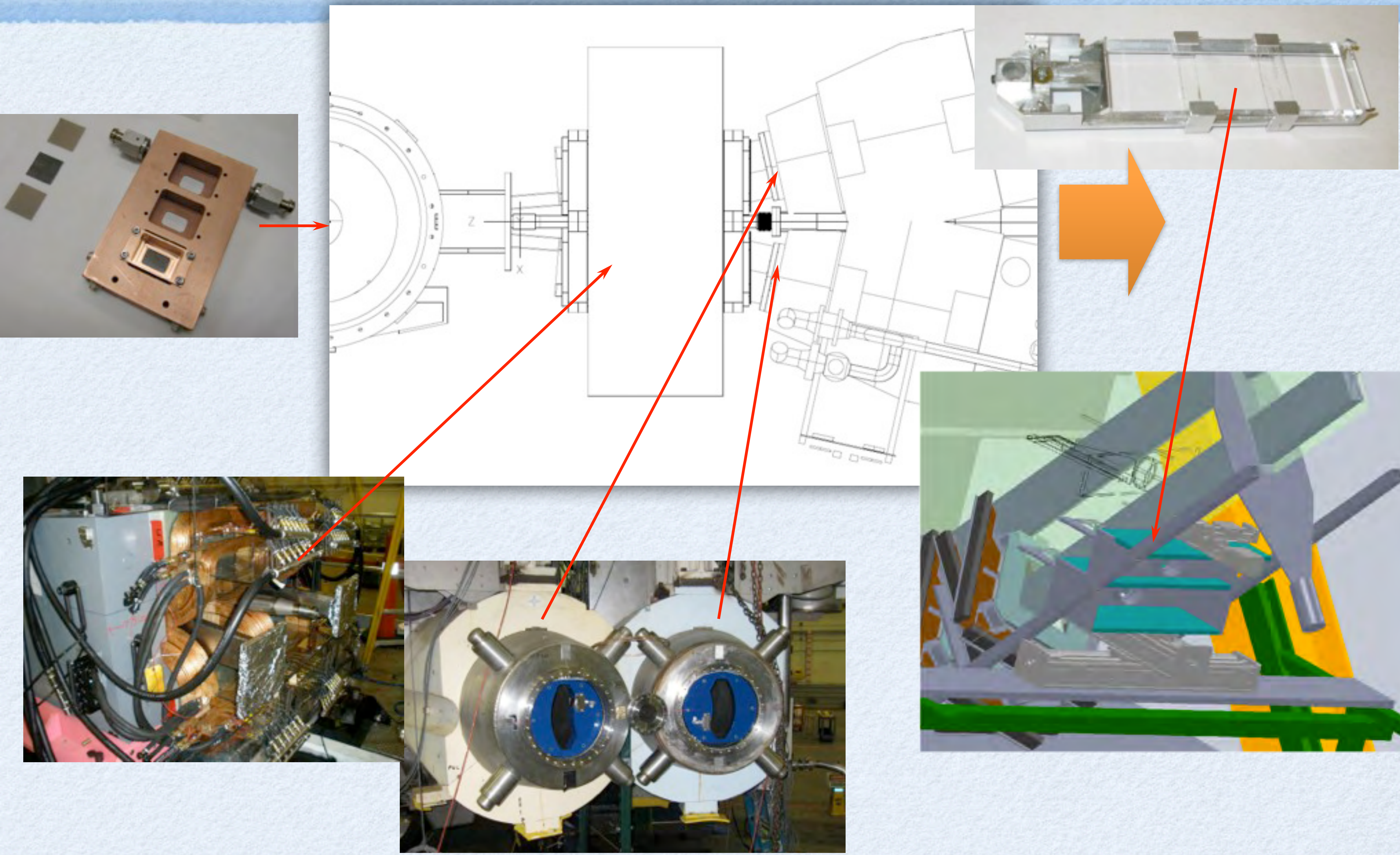


2 methods of "slow" reversal



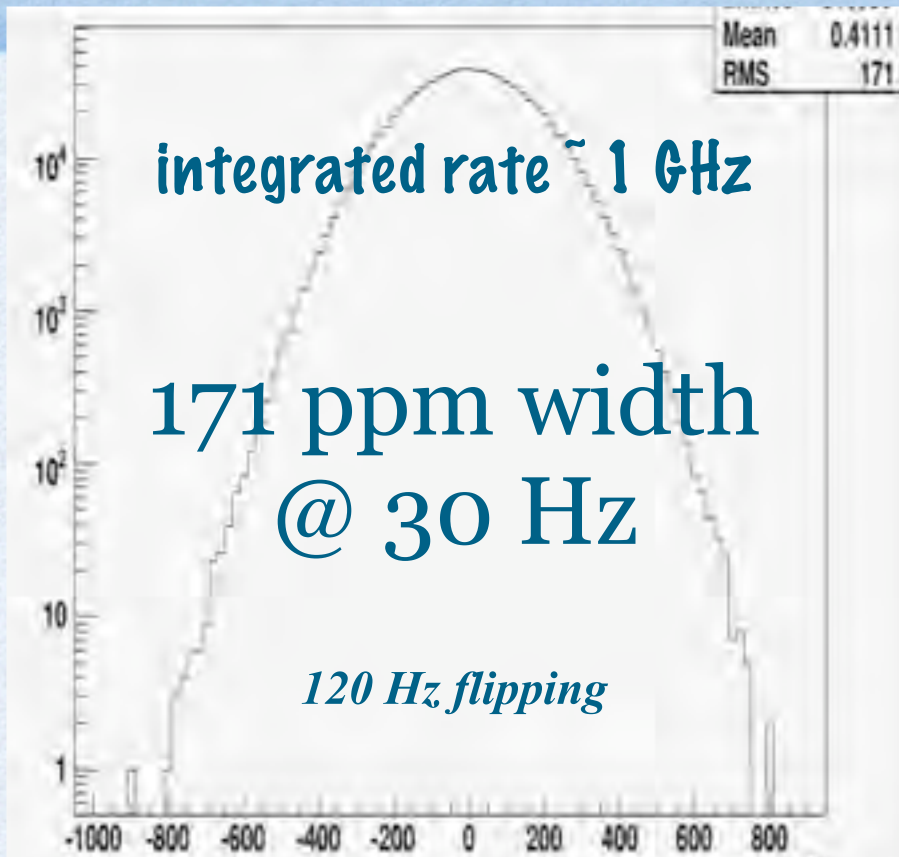


Aspects of the Apparatus



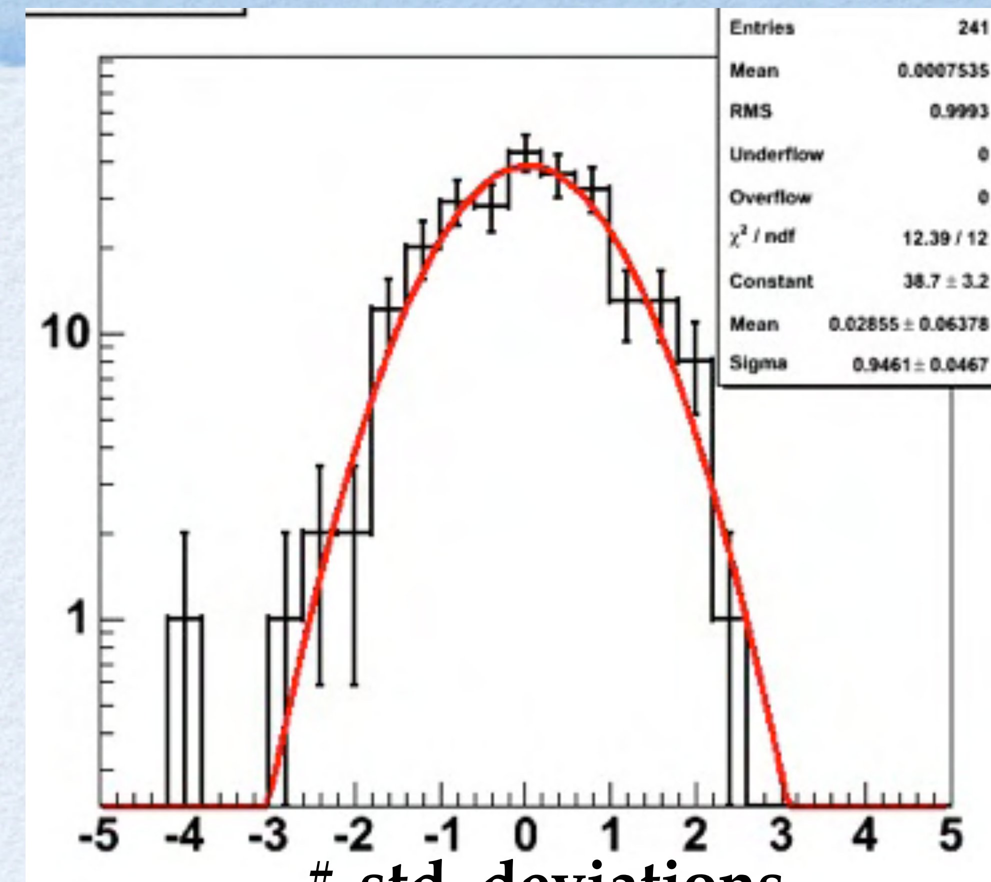
Physics Data: April/May 2010

Raw Asymmetry Data



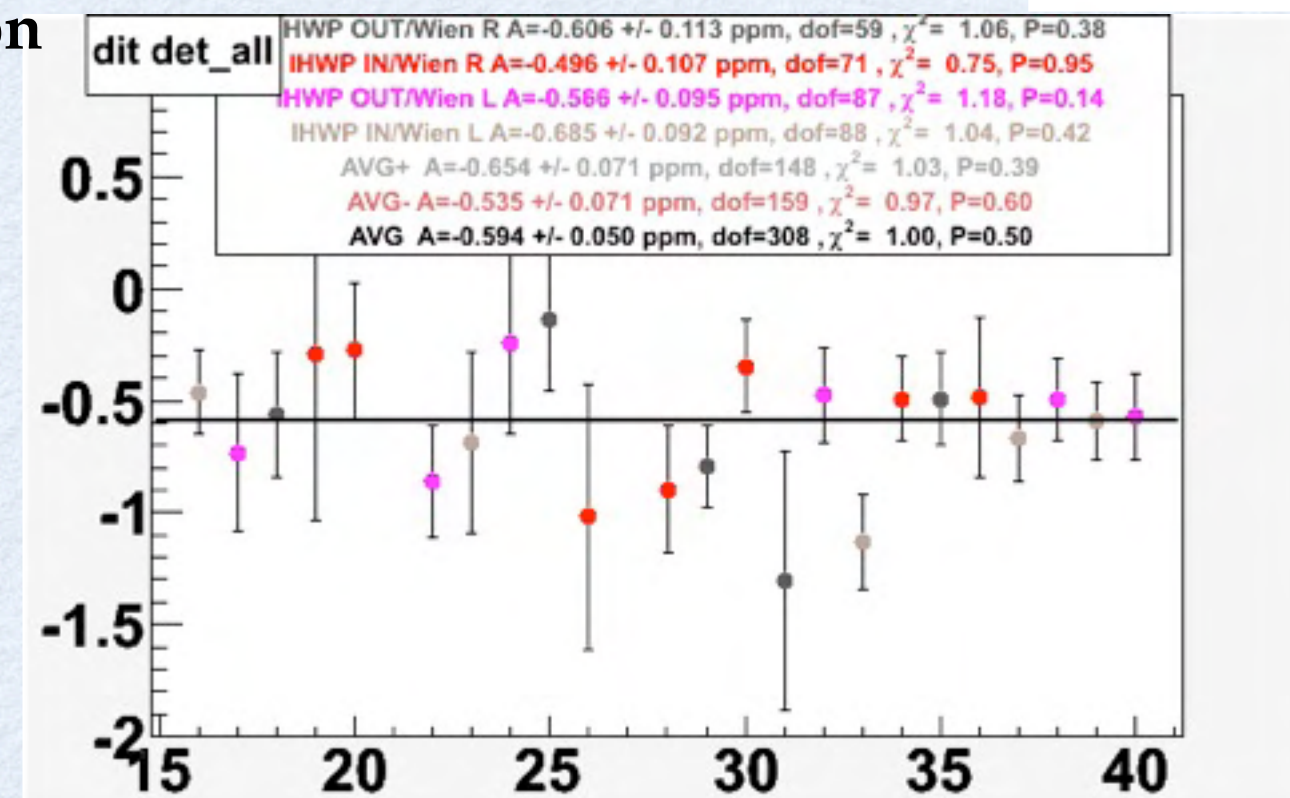
parts per million

Statistical behavior of data consistent with detector noise being dominated by electron counting statistics



\# std. deviations

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



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

594 ± 50
parts per billion (ppb)

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

Normalization Errors

Goal for total systematic error ~ 2% achieved!

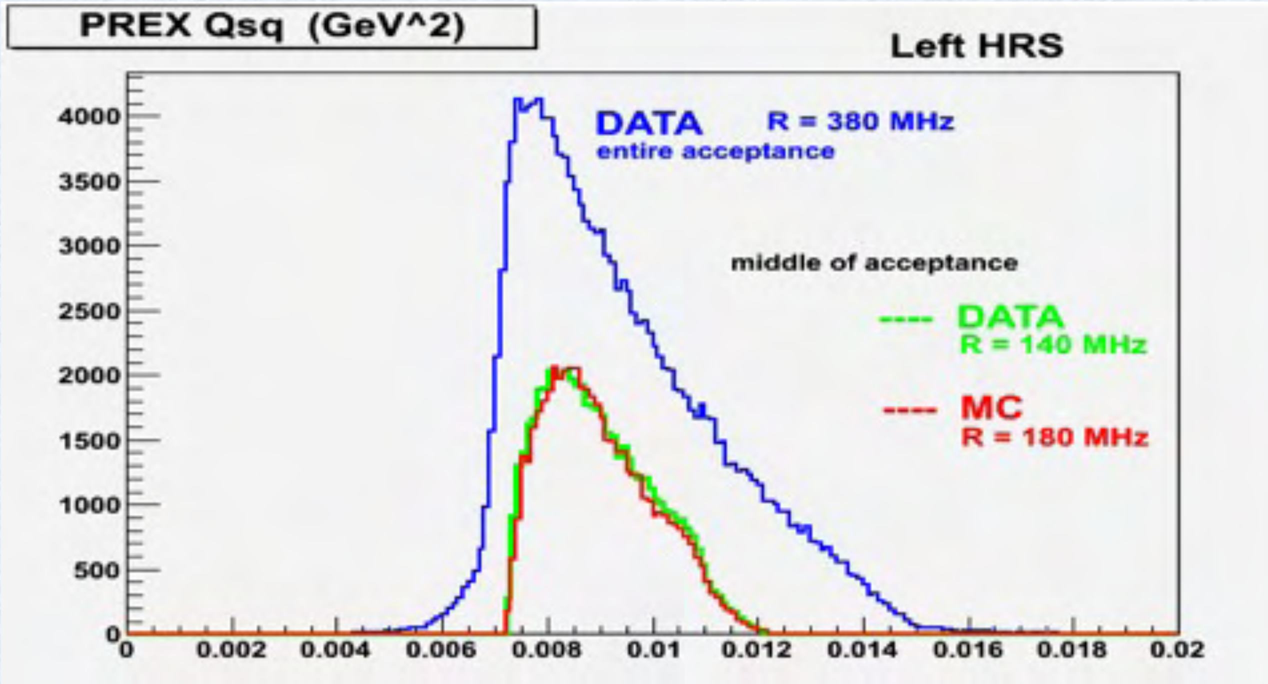
Systematic Error	Absolute (ppm)	Relative (%)
Polarization	0.0083	1.3
Detector Linearity	0.0076	1.2
Beam current normalization	0.0015	0.2
Rescattering	0.0001	0
Transverse Polarization	0.0012	0.2
Q^2	0.0028	0.4
Target Backing	0.0026	0.4
Inelastic States	0	0
TOTAL	0.0140	2.1

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



Normalization Errors

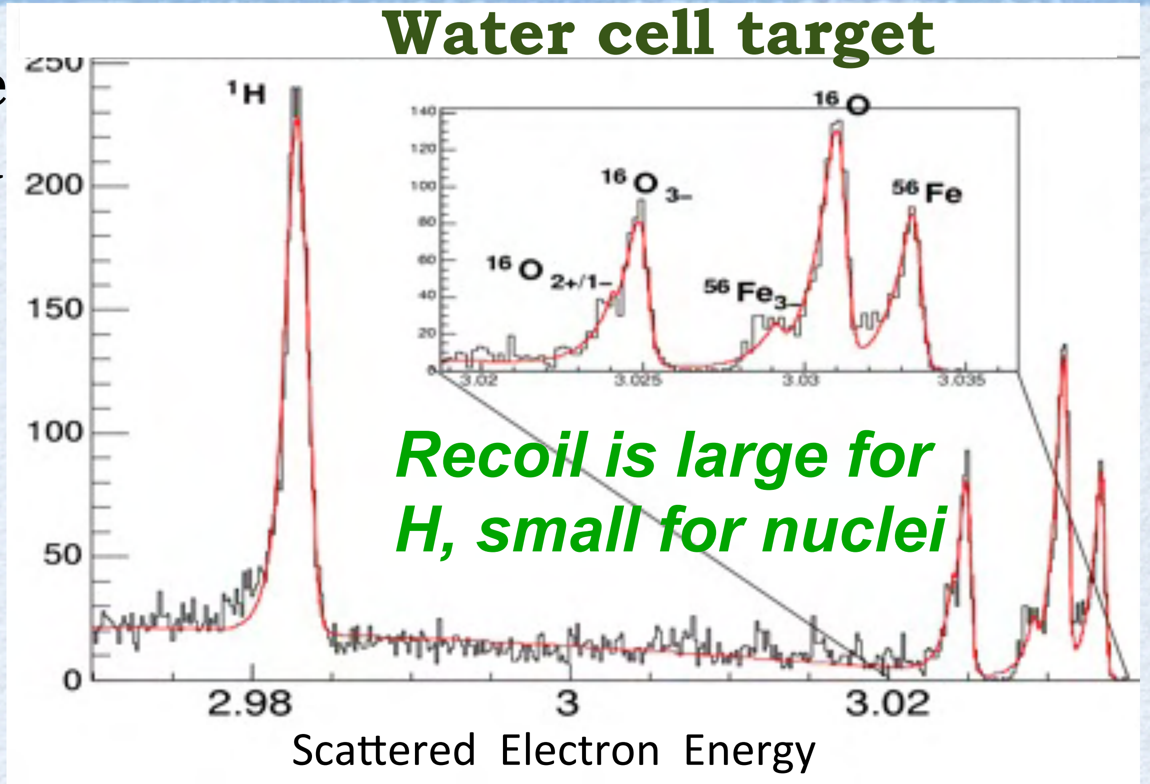
Goal for total systematic error ~ 2% achieved!

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

Absolute angle calibration via nuclear recoil variation

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

Water cell target



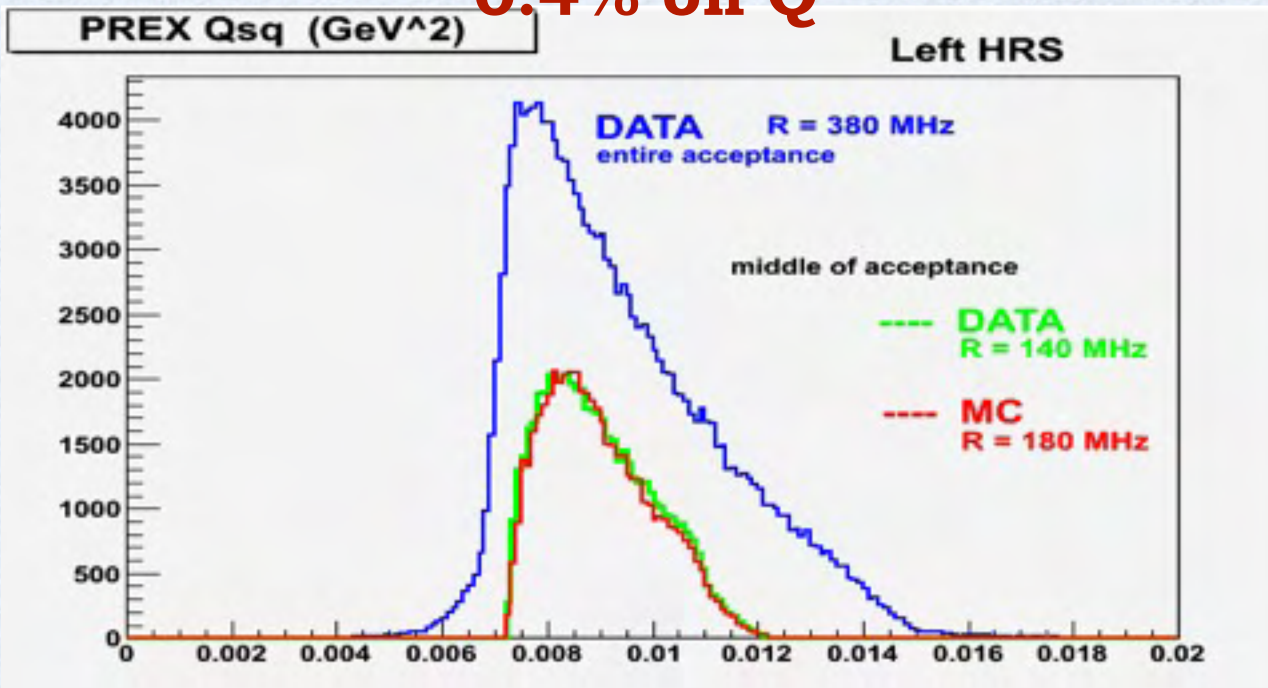
0.2% absolute calibration achieved:
0.4% on Q^2

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



Final Result

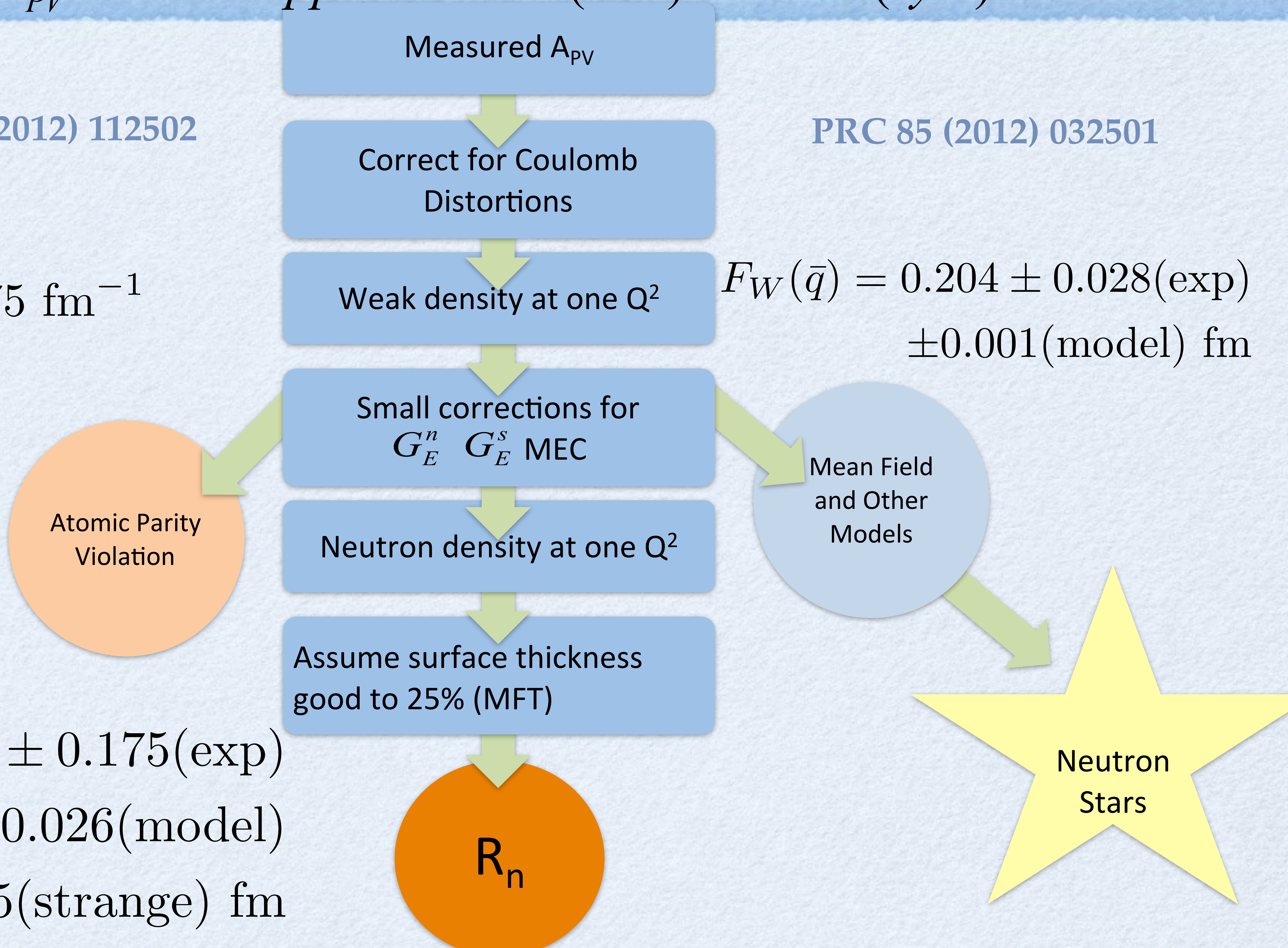
$$A_{PV} = 0.656\ ppm \pm\ 0.060(stat) \pm 0.014(syst)$$

PRL 108 (2012) 112502

PRC 85 (2012) 032501

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

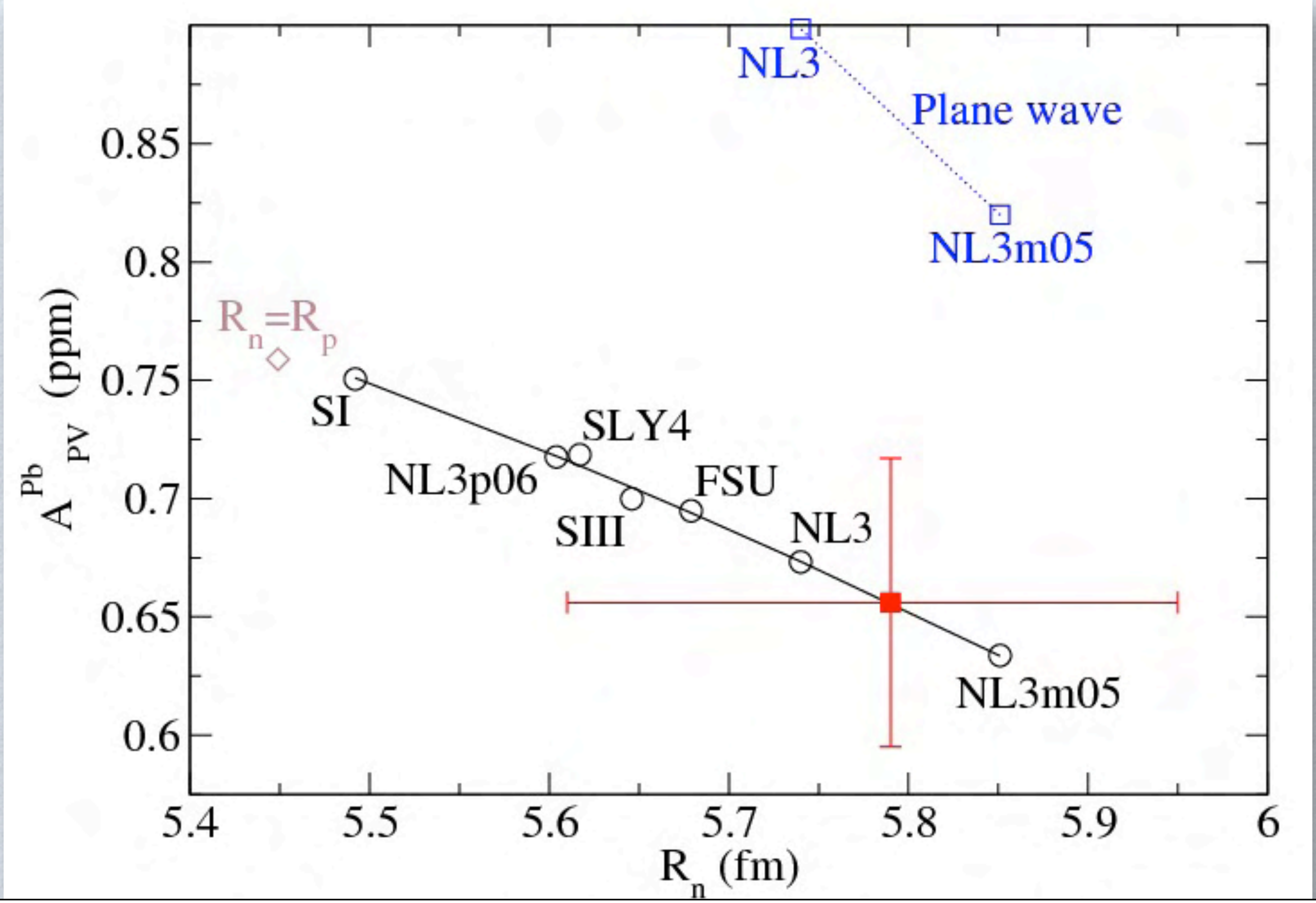
$$F_W(\bar{q}) = 0.204 \pm 0.028(\mathrm{exp}) \pm 0.001(\mathrm{model})\ \mathrm{fm}$$



$$R_n = 5.751 \pm 0.175(\mathrm{exp}) \pm 0.026(\mathrm{model}) \pm 0.005(\mathrm{strange})\ \mathrm{fm}$$

The Neutron Skin

$$R_n - R_p = 0.302 \pm 0.175(\text{exp}) \pm 0.026(\text{model}) \pm 0.005(\text{strange})\ \text{fm}$$

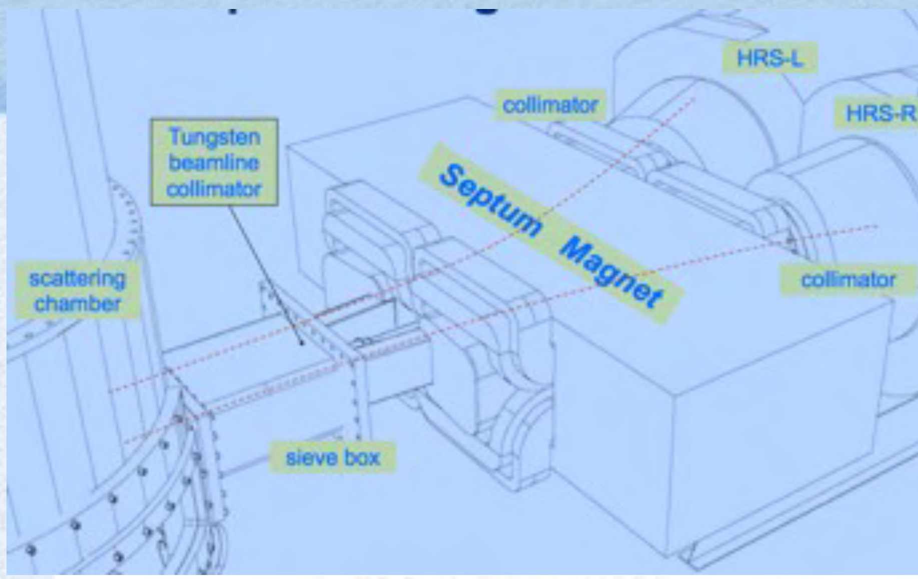


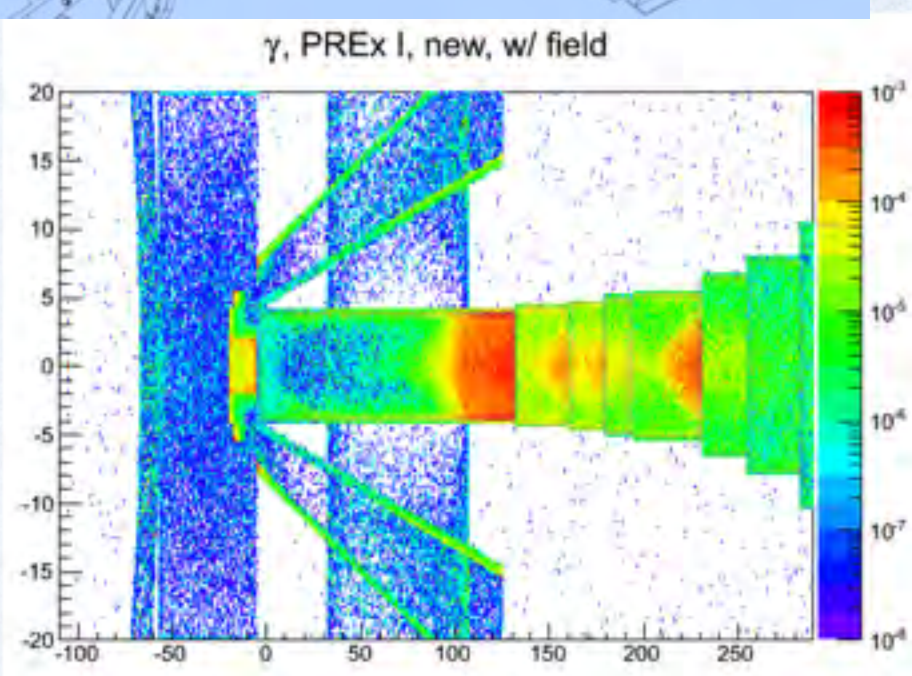
First electroweak indication of a neutron skin of a heavy nucleus (CL ~ 90-95%)

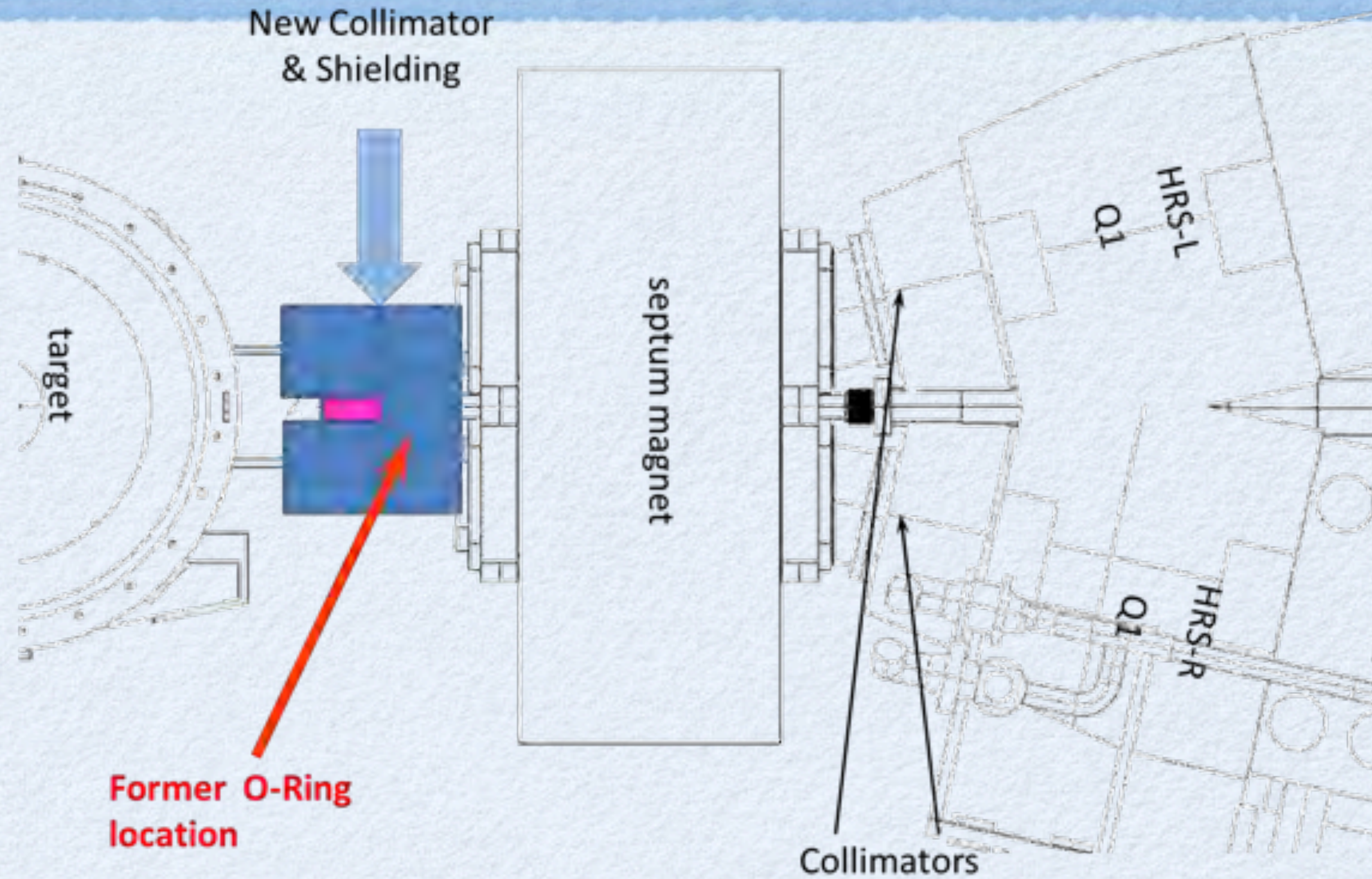
PREX-II Proposal

Achieve original proposal goal for accumulated statistics

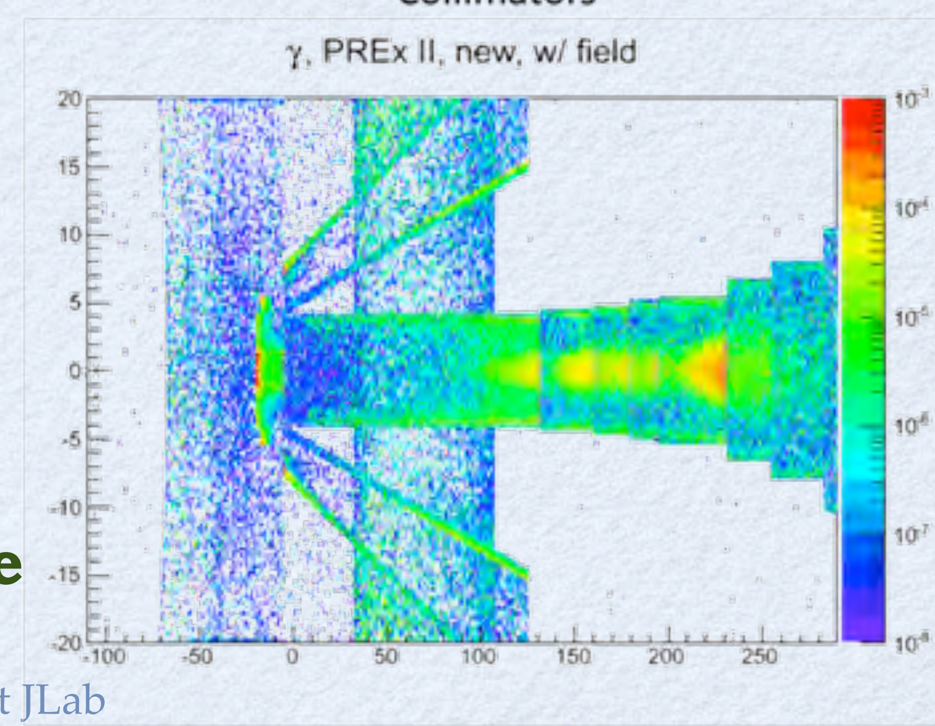
New Beamline Design







- 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 Proposal

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

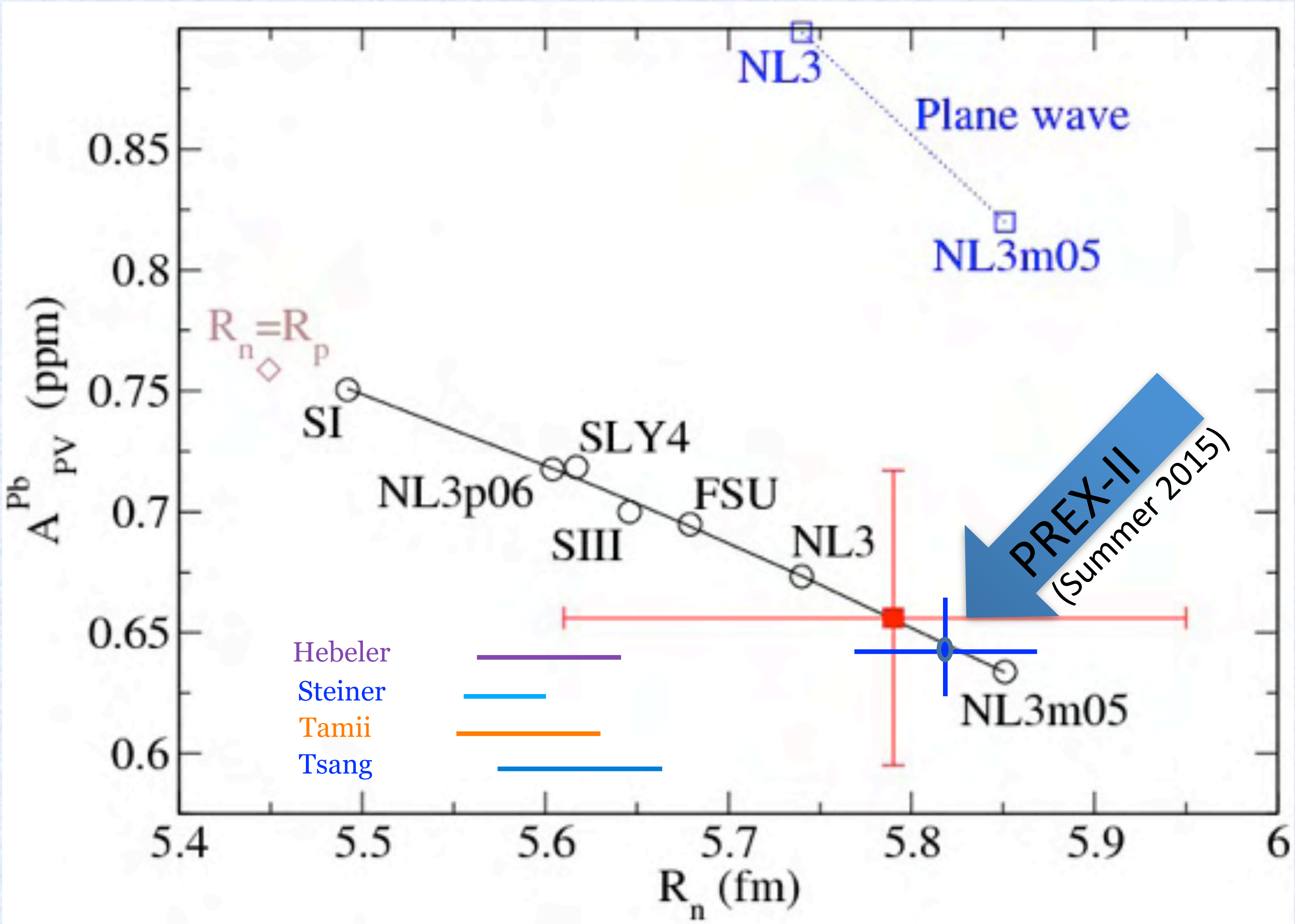
Full precision in 25 additional PAC days

PREx II improvements

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

$\delta(A_{PV})/A_{PV} \sim 3\%$
$\delta(R_n)/R_n \sim 1\%$

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



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.

PREXII Proposal

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

PREx II improvements

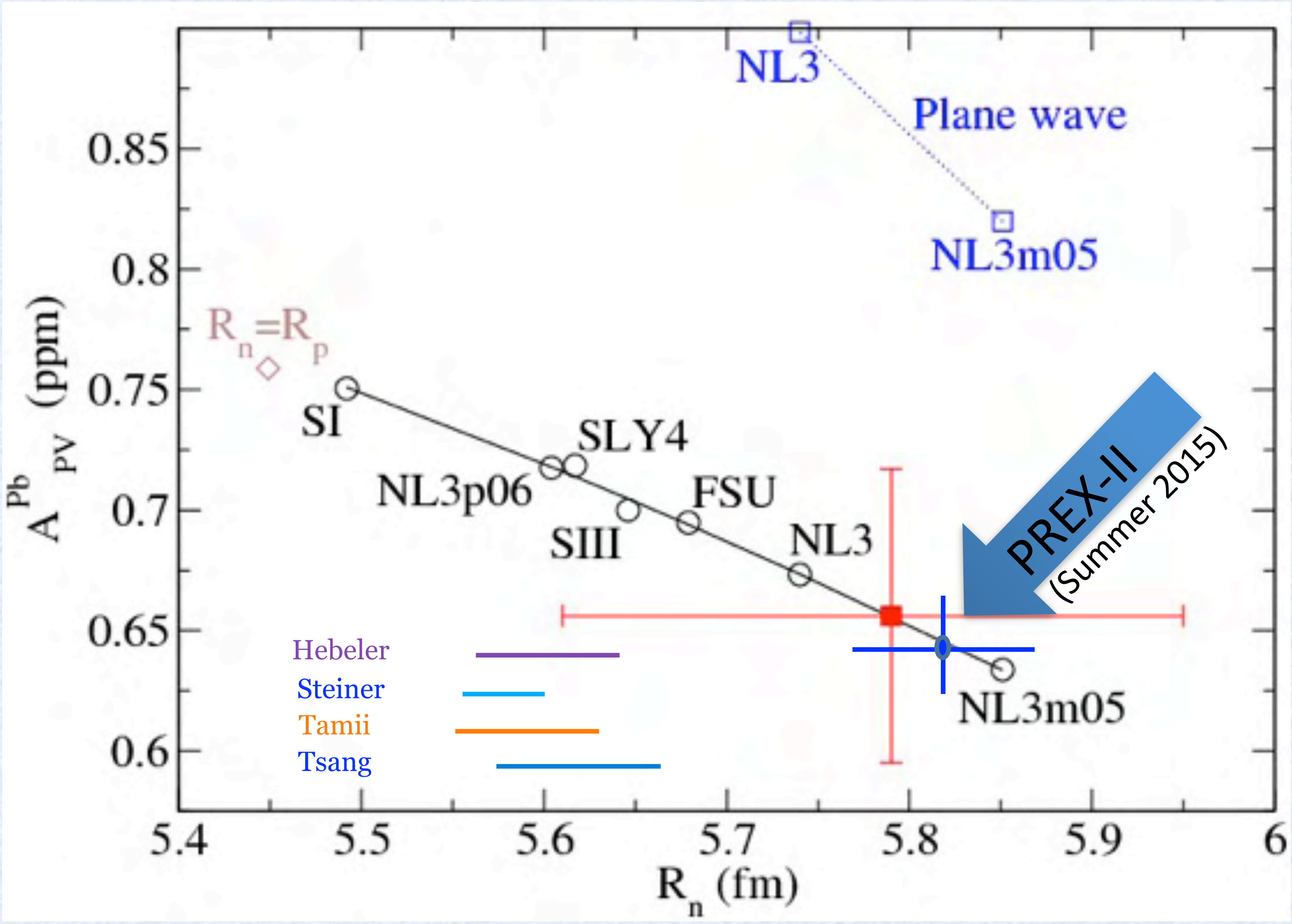
- **Metal o-rings**
- **Radiation hard electronics**
- **Reduce neutron backgrounds**

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

How badly does the community want this?



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.

Important Workshop in March 2013 at JLab

CREX Proposal

Measurement of A_{PV} in elastic scattering off ^{48}Ca

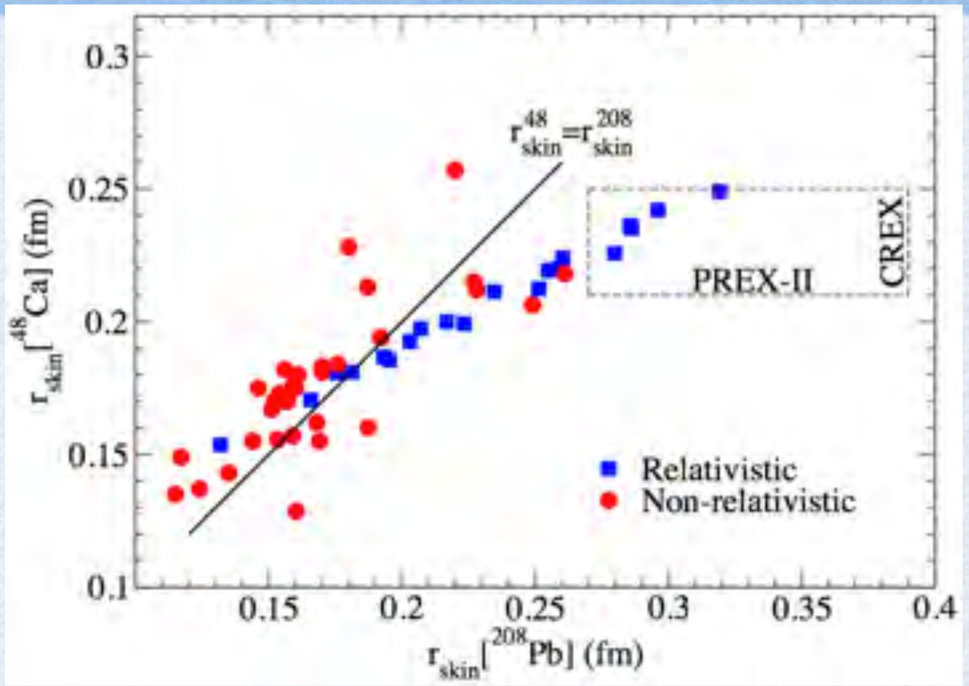
Approved by PAC last month!

CREX at JLab

Approved by JLab PAC in Summer 2013

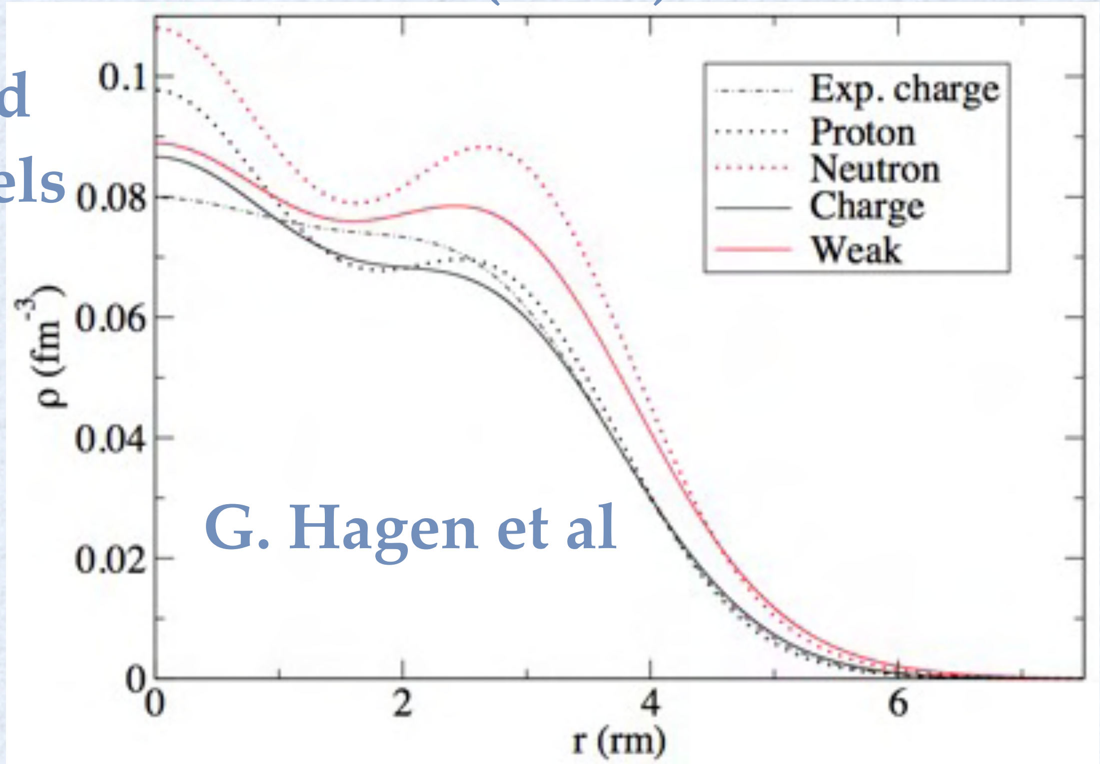
Measured Asymmetry (p_e A)	2 ppm
Scattering Angle	4°
Detected Rate (each HRS)	140 MHz
Statistical Uncertainty of A_{PV}	2.1%
Systematic Uncertainty of A_{PV}	1.2%
Statistical Uncertainty of A_T	0.4 ppm

$\delta(R_n) \sim \pm 0.02$ fm



PRL 109 (2012) 032502

test coupled cluster models

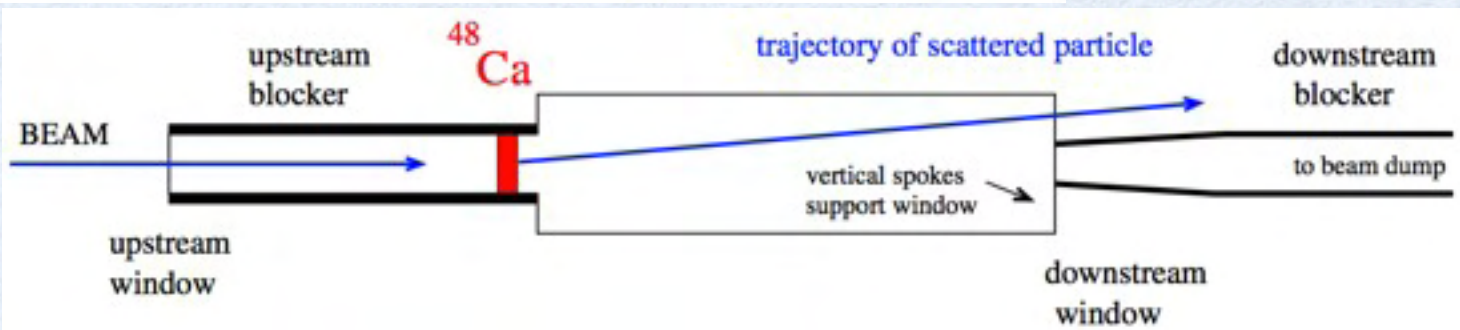


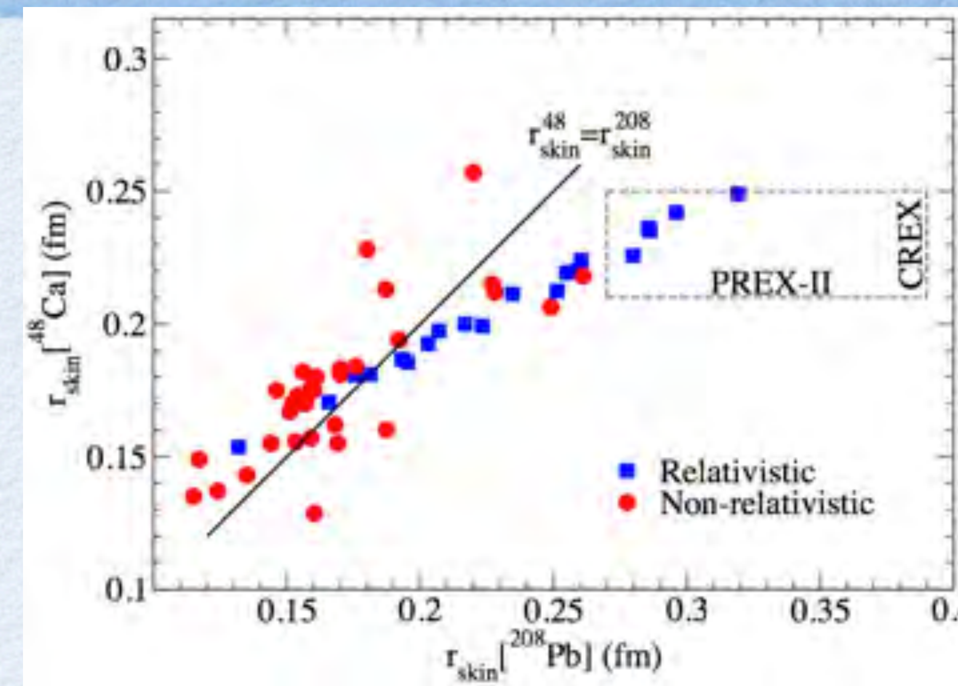
CREX at JLab

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

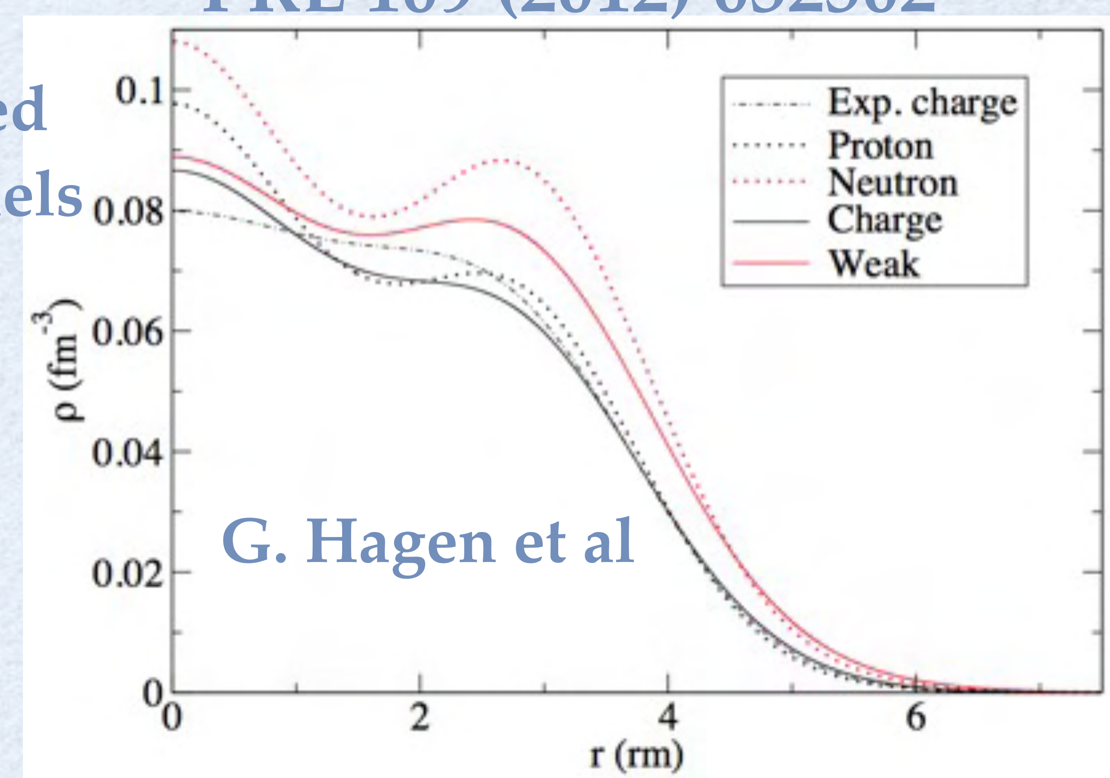
$\delta(R_n) \sim \pm\, 0.02$ fm





PRL 109 (2012) 032502

test coupled
cluster models



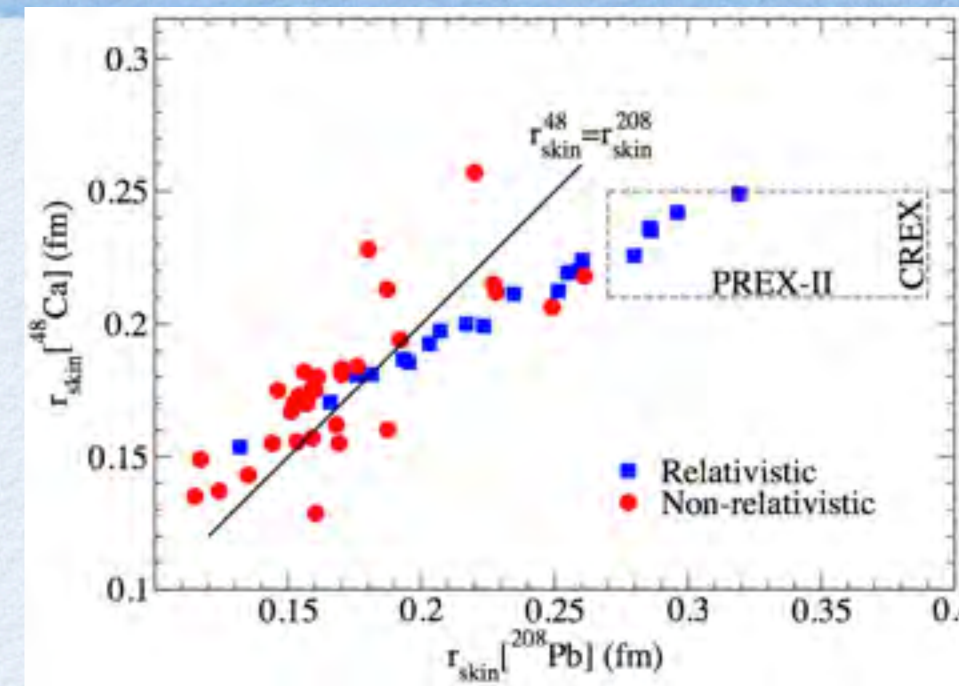
G. Hagen et al

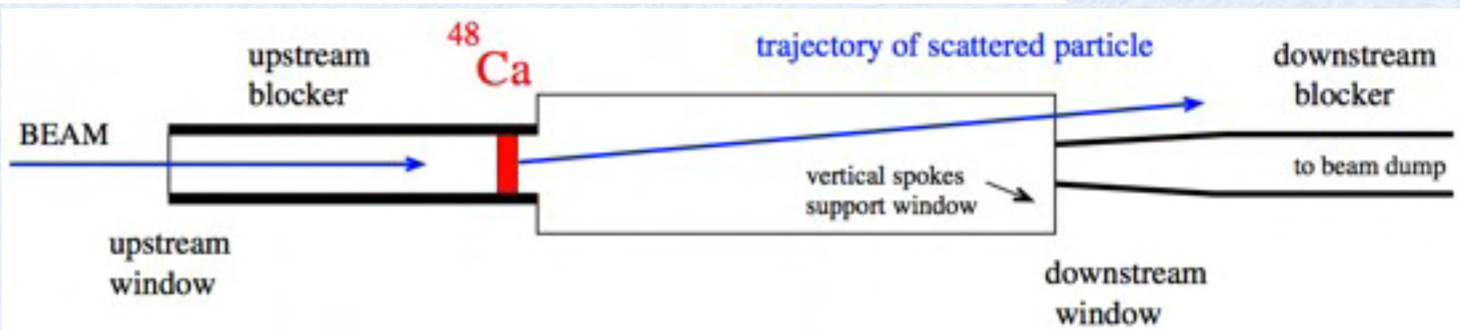
CREX at JLab

Approved by JLab PAC in Summer 2013

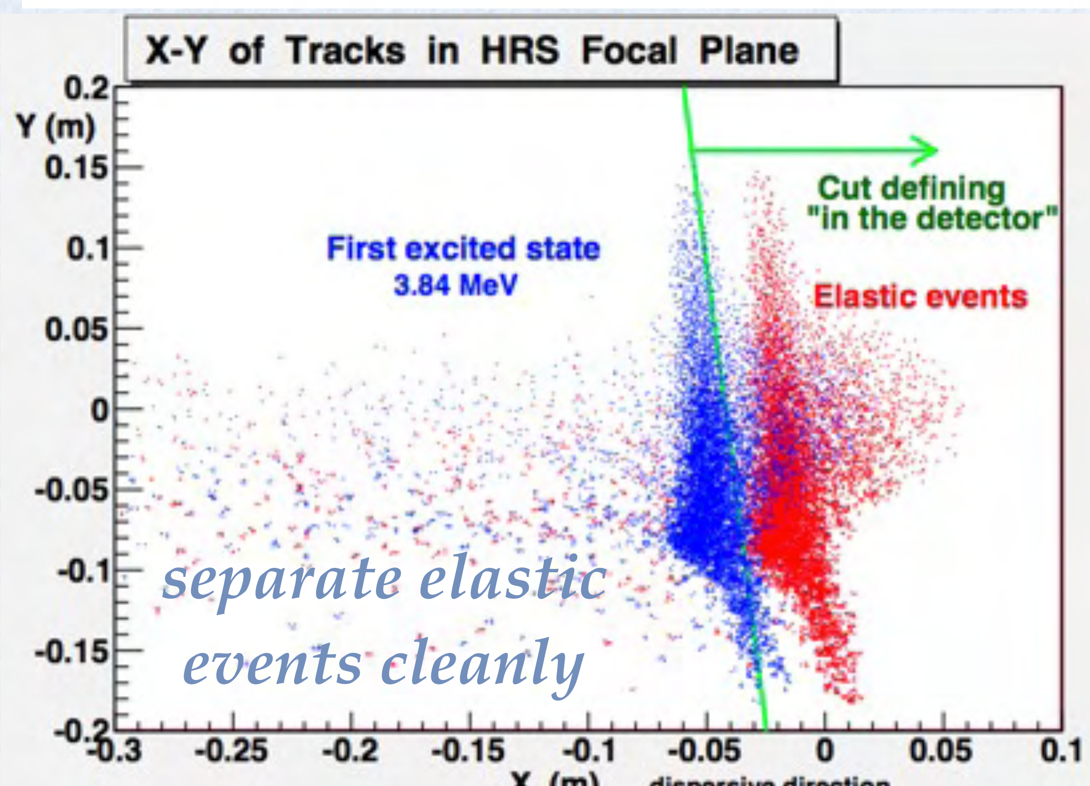
Measured Asymmetry (p_e A)	2 ppm
Scattering Angle	4°
Detected Rate (each HRS)	140 MHz
Statistical Uncertainty of A_{PV}	2.1%
Systematic Uncertainty of A_{PV}	1.2%
Statistical Uncertainty of A_T	0.4 ppm

$\delta(R_n) \sim \pm 0.02$ *fm*



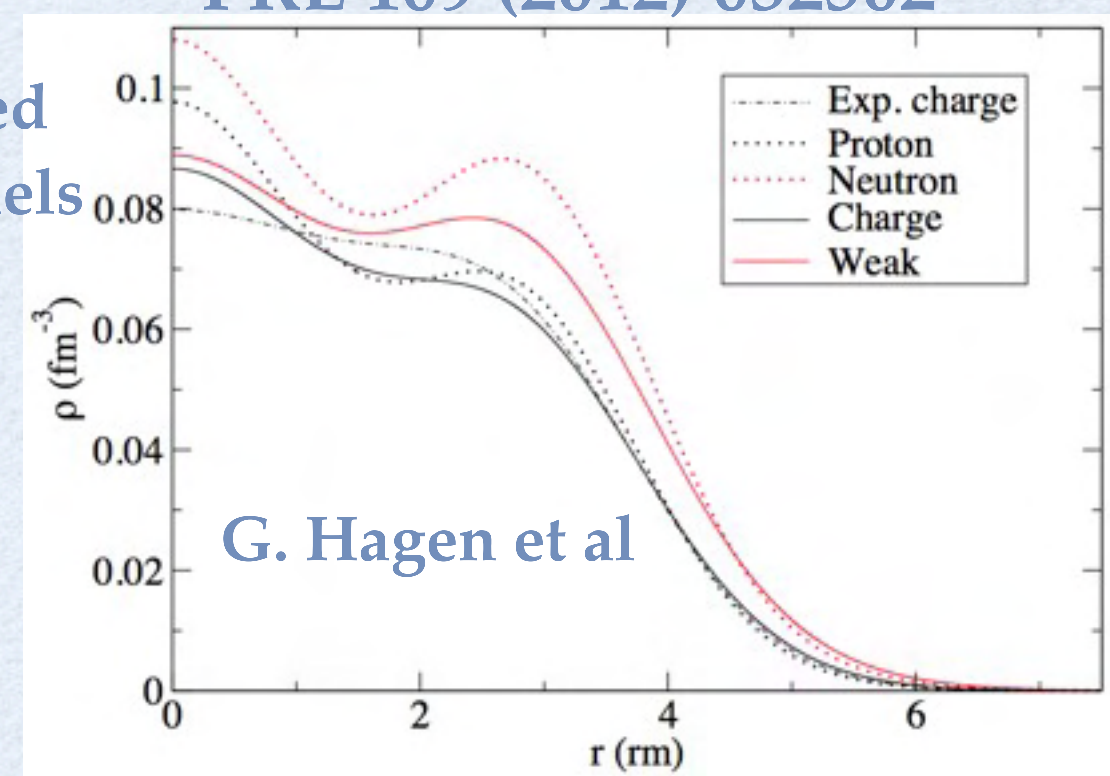


PRL 109 (2012) 032502



separate elastic events cleanly

test coupled cluster models



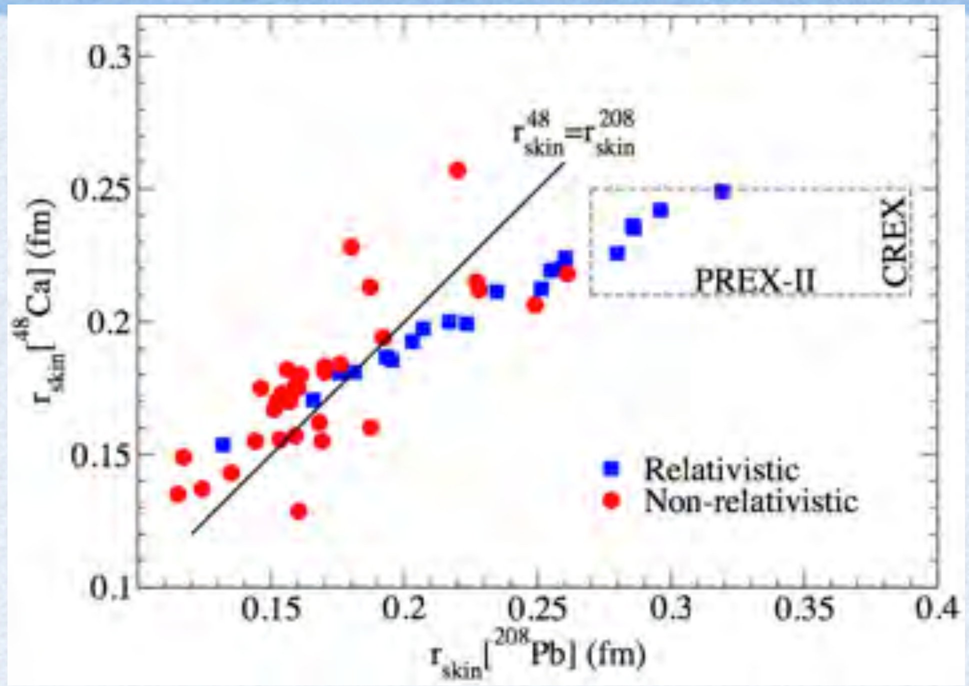
G. Hagen et al

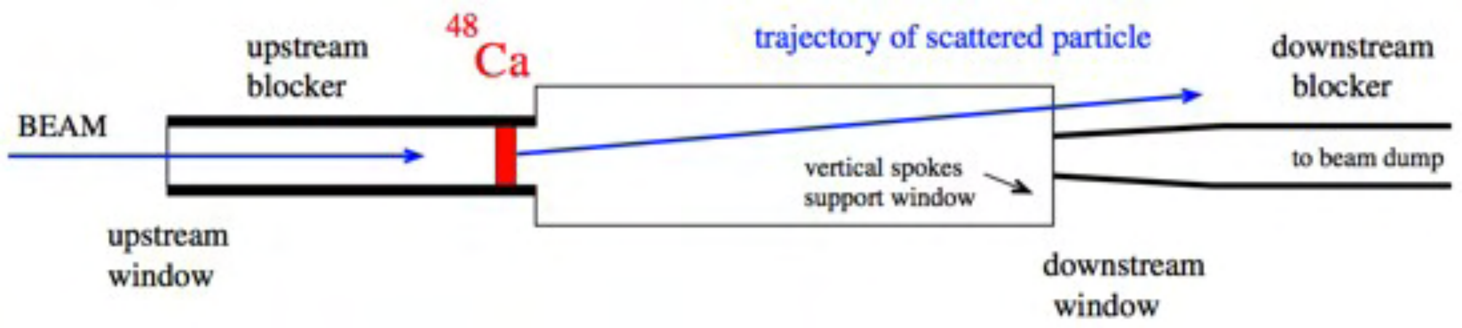
CREX at JLab

Approved by JLab PAC in Summer 2013

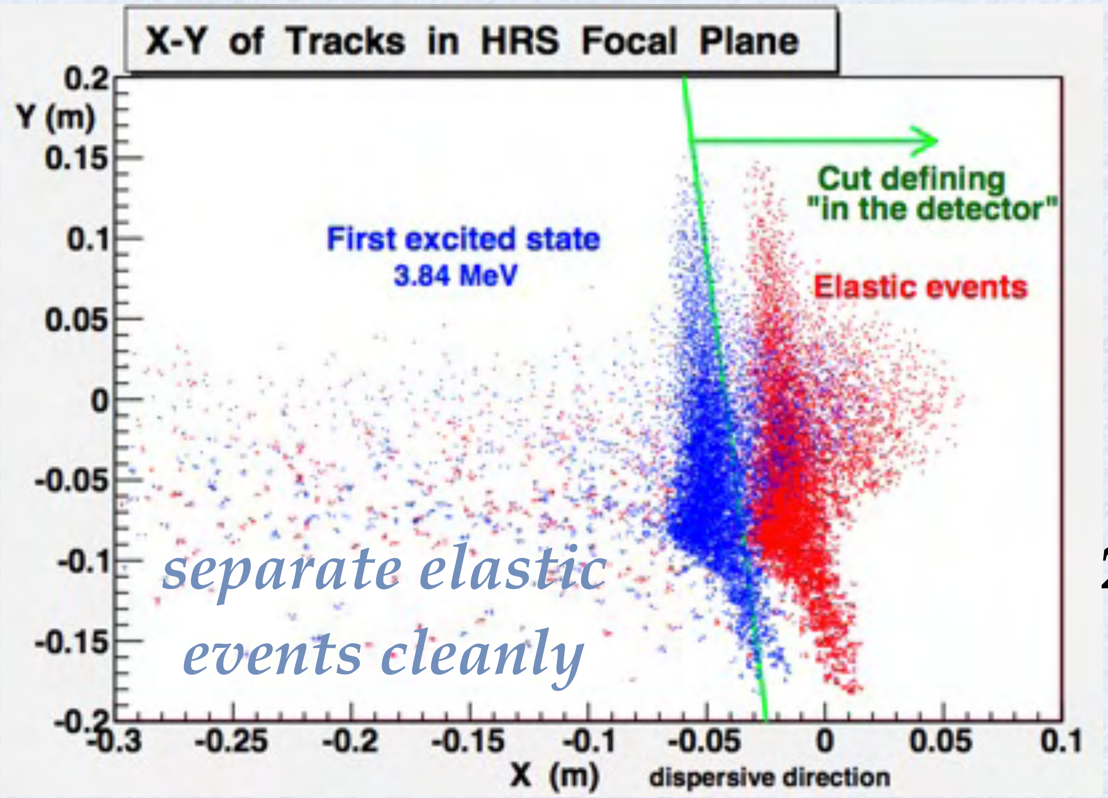
Measured Asymmetry (p_e A)	2 ppm
Scattering Angle	4°
Detected Rate (each HRS)	140 MHz
Statistical Uncertainty of A_{PV}	2.1%
Systematic Uncertainty of A_{PV}	1.2%
Statistical Uncertainty of A_T	0.4 ppm

$\delta(R_n) \sim \pm\ 0.02$ fm





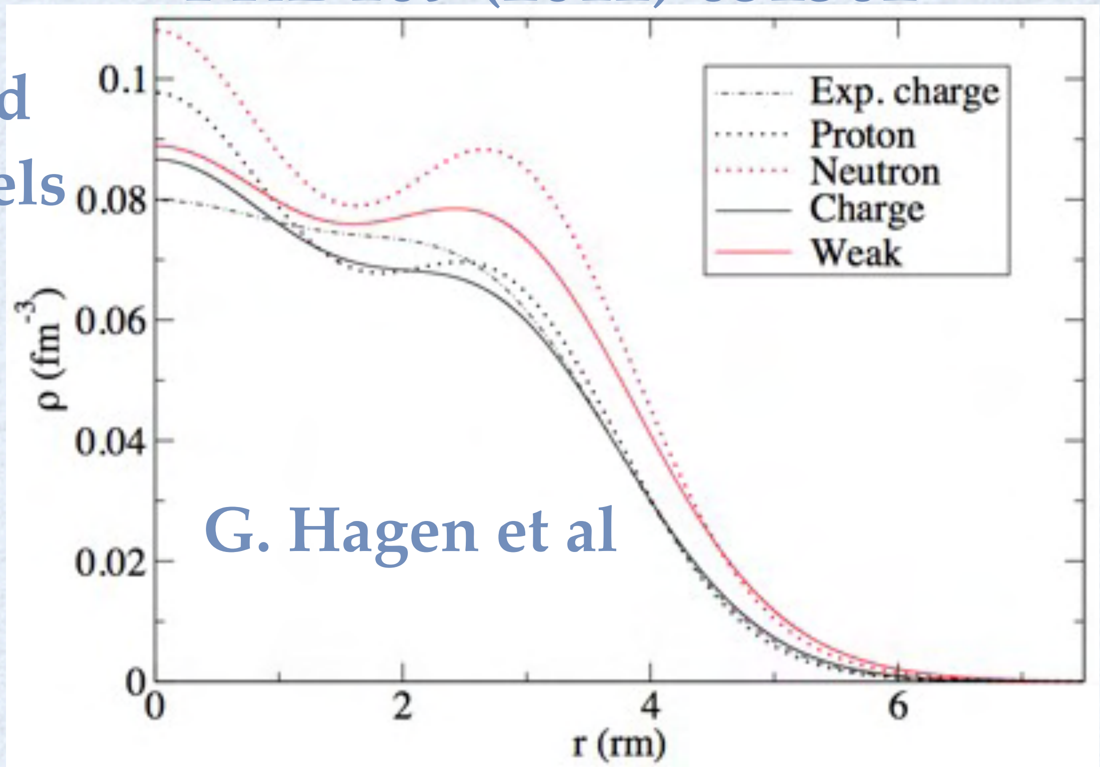
PRL 109 (2012) 032502



separate elastic events cleanly

test coupled cluster models

Could run in 2016 depending on schedule and funding



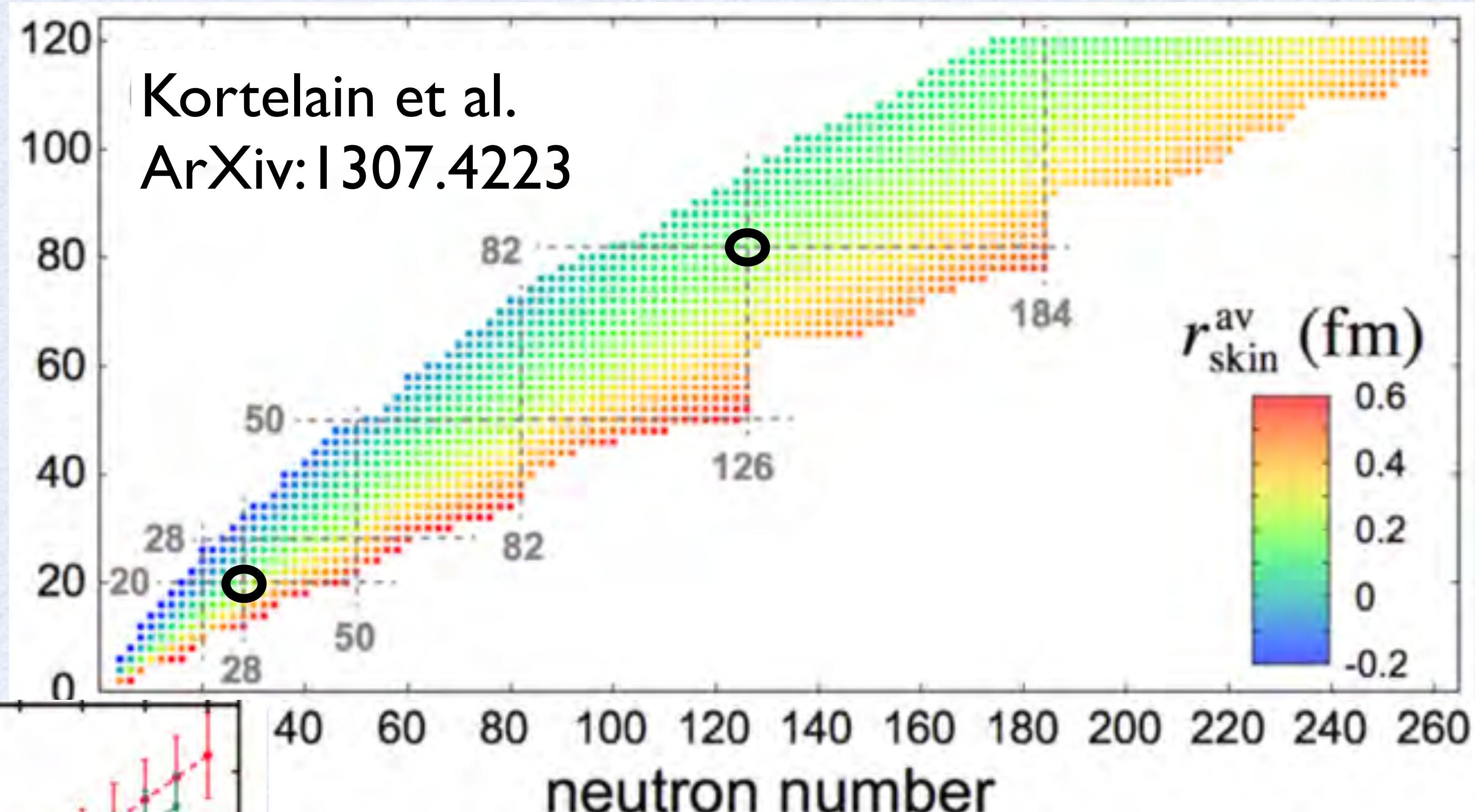
G. Hagen et al

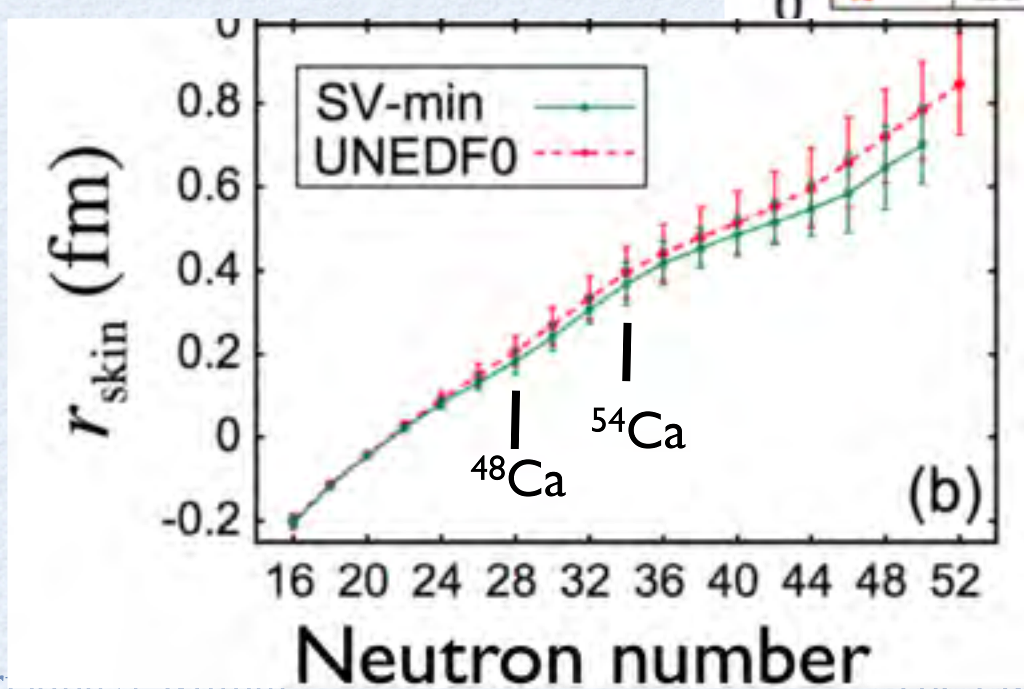
FRIB and PVES

C. Horowitz

- Less precise measurements of thicker neutron skins with radioactive beams complimentary to precise parity violating measurements on stable nuclei.

Neutron skins predicted by average of 4 Skyrme energy functionals smoothly increase with neutron #. ^{48}Ca skin slightly larger than ^{208}Pb.





Skin of Ca isotopes increases with N. Example measure (nearly twice as large vs ^{48}Ca?) skin in ^{54}Ca with hadronic probe using radioactive beam. Calibrate hadronic reaction mechanism by comparing with CREX for ^{48}Ca.

Improved ^{208}Pb R_n?

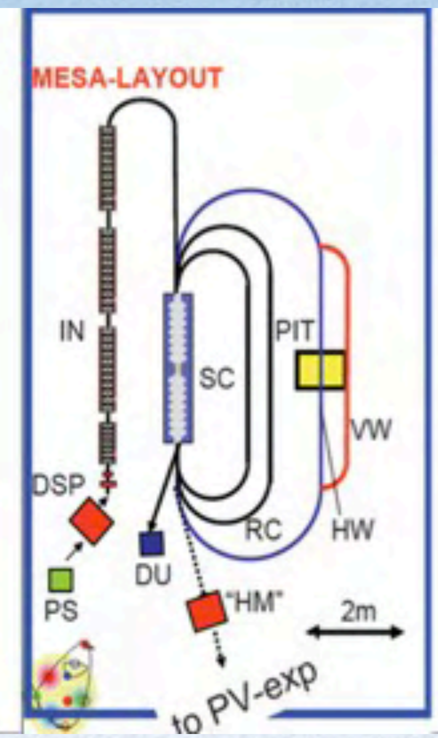
C. Sfienti
M. Thiel
K.K.

Future: MESA/P2 at Mainz

New ERL complex will also support a high-current extracted beam suitable for a PV measurement of proton weak charge

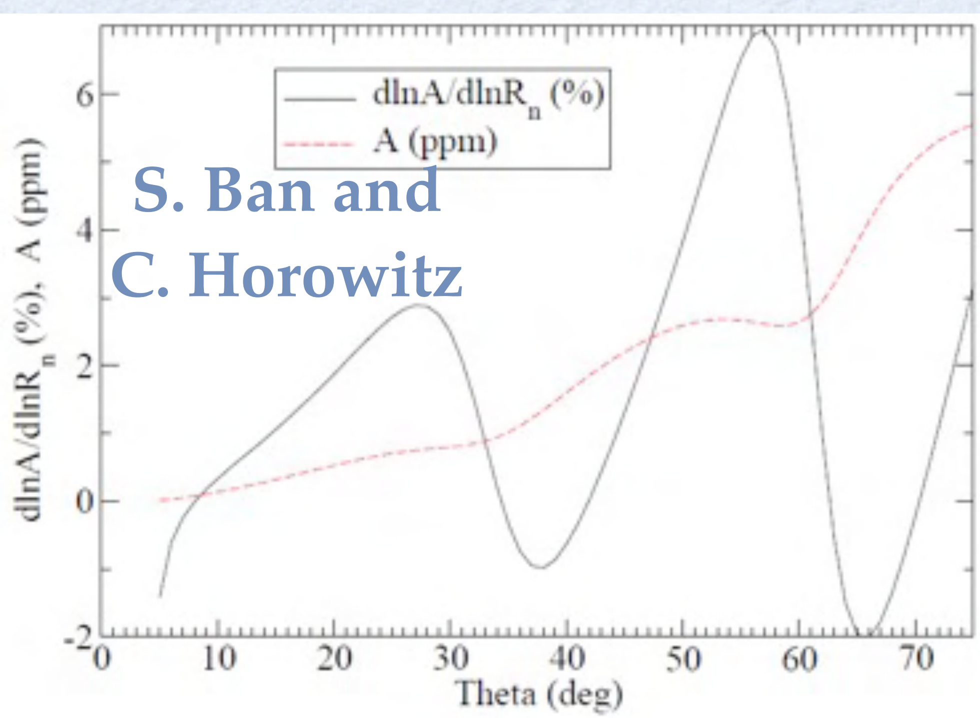
- A_{PV} = -20 ppb to 2.1% (0.4ppb)
- $\delta(\sin^2\theta_W)$ = 0.2%

- Funding approved from DFG
- Development starting now
- Planned running 2017-2020



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

200 MeV
FOM peaks around 25 degrees



S. Ban and C. Horowitz

Improved ^{208}Pb R_n?

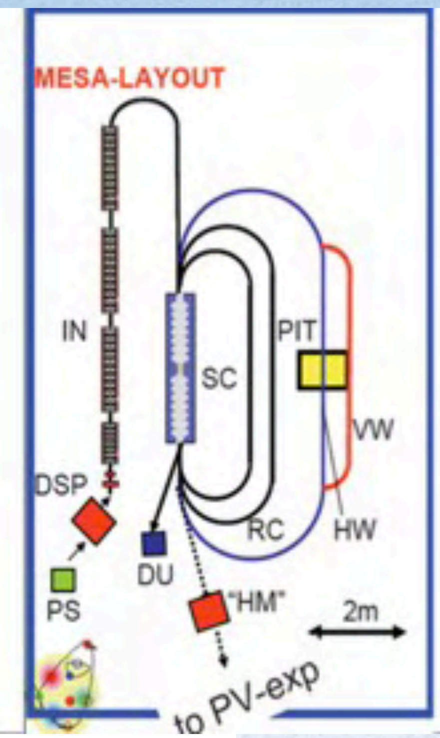
C. Sfienti
M. Thiel
K.K.

Future: MESA/P2 at Mainz

New ERL complex will also support a high-current extracted beam suitable for a PV measurement of proton weak charge

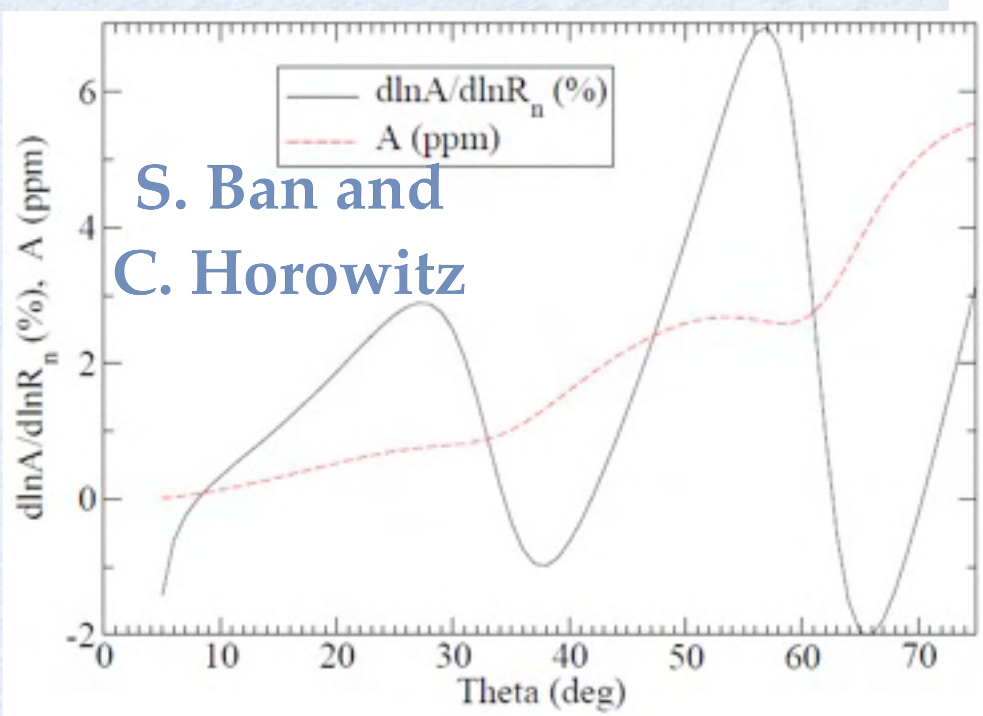
- A_{PV} = -20 ppb to 2.1% (0.4ppb)
- $\delta(\sin^2\theta_W)$ = 0.2%

- Funding approved from DFG
- Development starting now
- Planned running 2017-2020

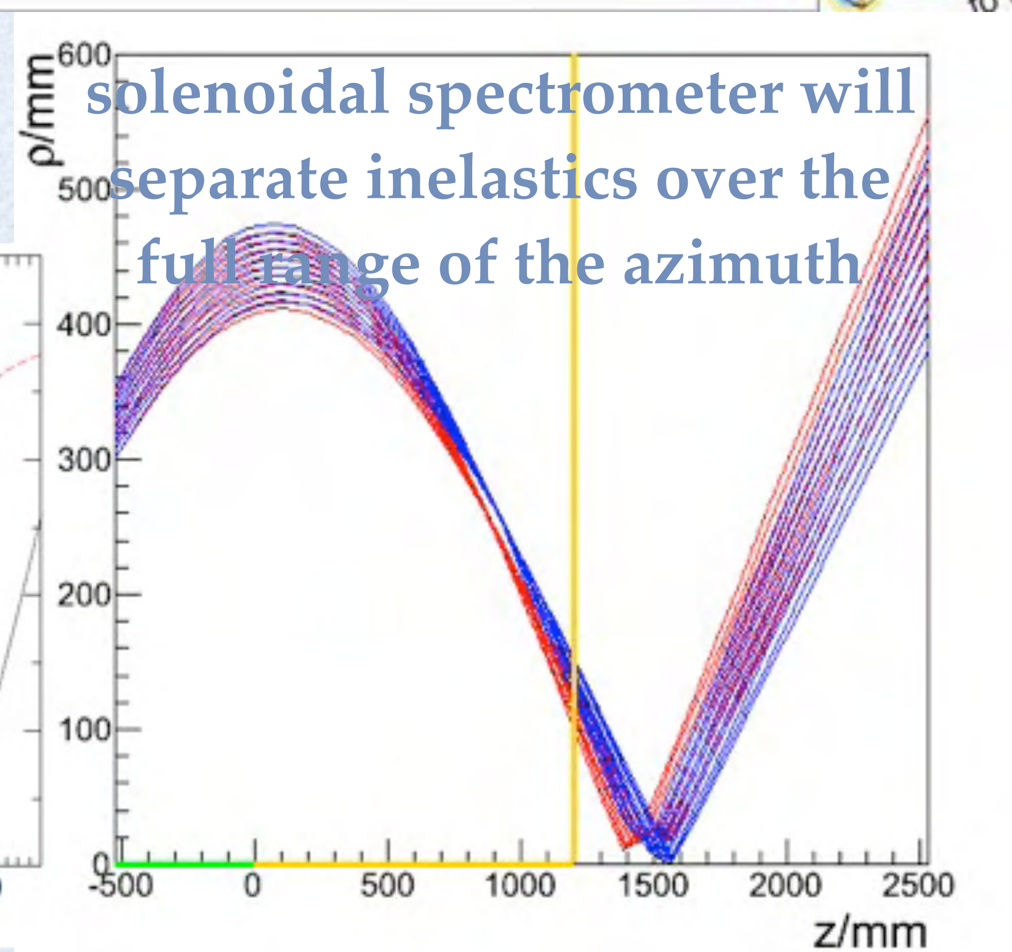


Explore a PREX-style measurement using same solenoidal magnet to be used for P2

200 MeV
FOM peaks around 25 degrees



S. Ban and
C. Horowitz



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

Improved ^{208}Pb R_n?

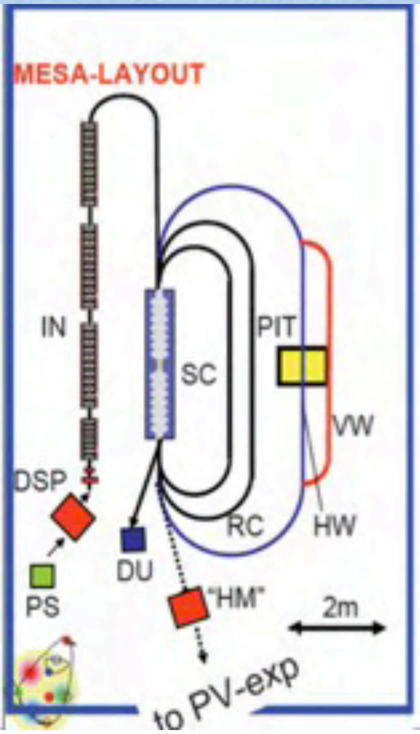
C. Sfienti
M. Thiel
K.K.

Future: MESA/P2 at Mainz

New ERL complex will also support a high-current extracted beam suitable for a PV measurement of proton weak charge

- A_{PV} = -20 ppb to 2.1% (0.4ppb)
- $\delta(\sin^2\theta_W)$ = 0.2%

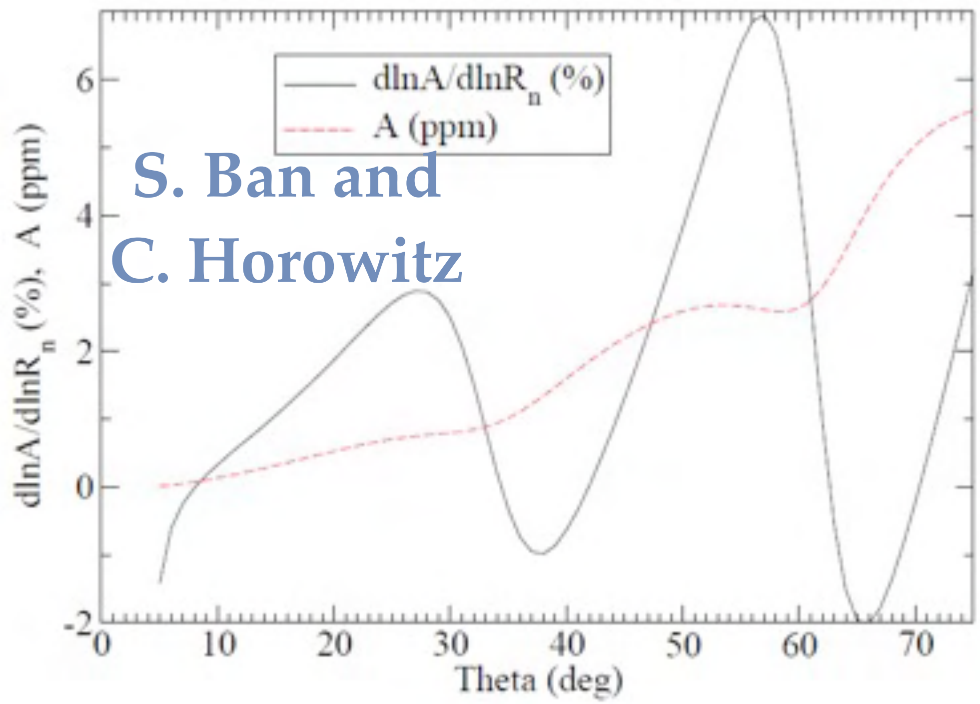
- Funding approved from DFG
- Development starting now
- Planned running 2017-2020



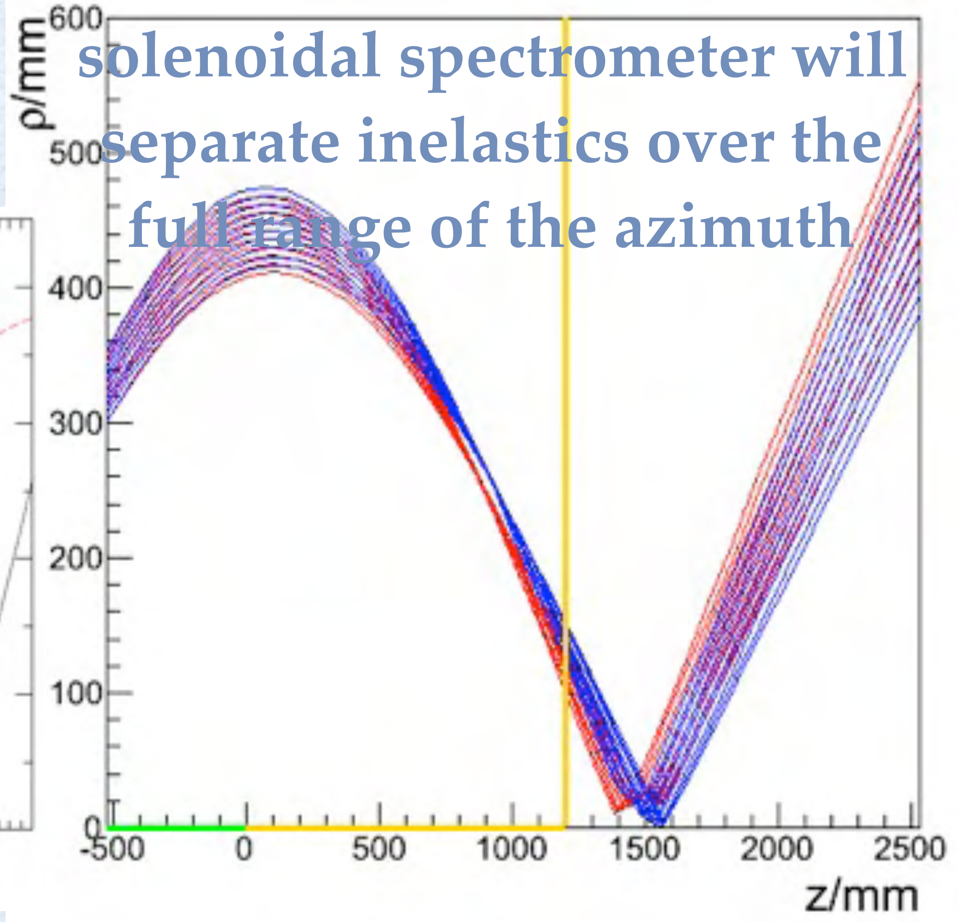
Explore a PREX-style measurement using same solenoidal magnet to be used for P2

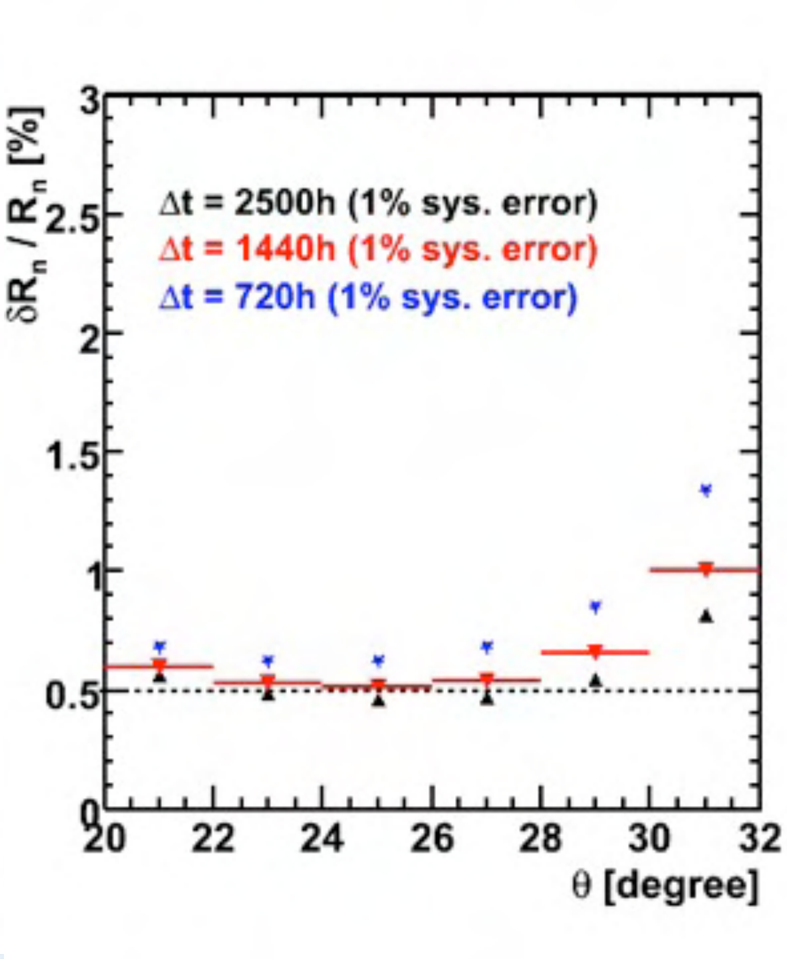
200 MeV
FOM peaks around 25 degrees

S. Ban and
C. Horowitz



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





Improved ^{208}Pb R_n?

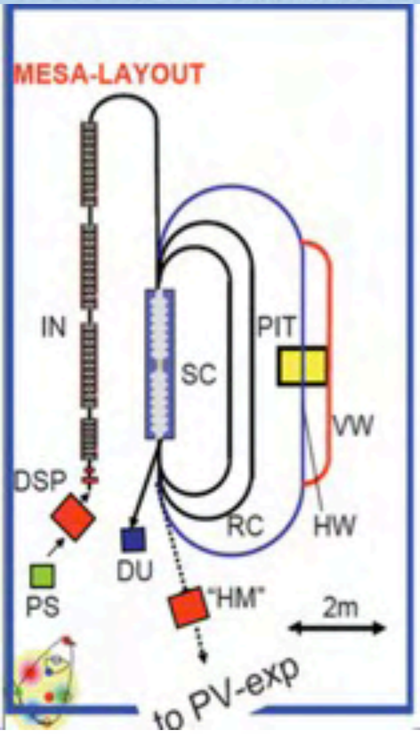
C. Sfienti
M. Thiel
K.K.

Future: MESA/P2 at Mainz

New ERL complex will also support a high-current extracted beam suitable for a PV measurement of proton weak charge

- A_{PV} = -20 ppb to 2.1% (0.4ppb)
- $\delta(\sin^2\theta_W)$ = 0.2%

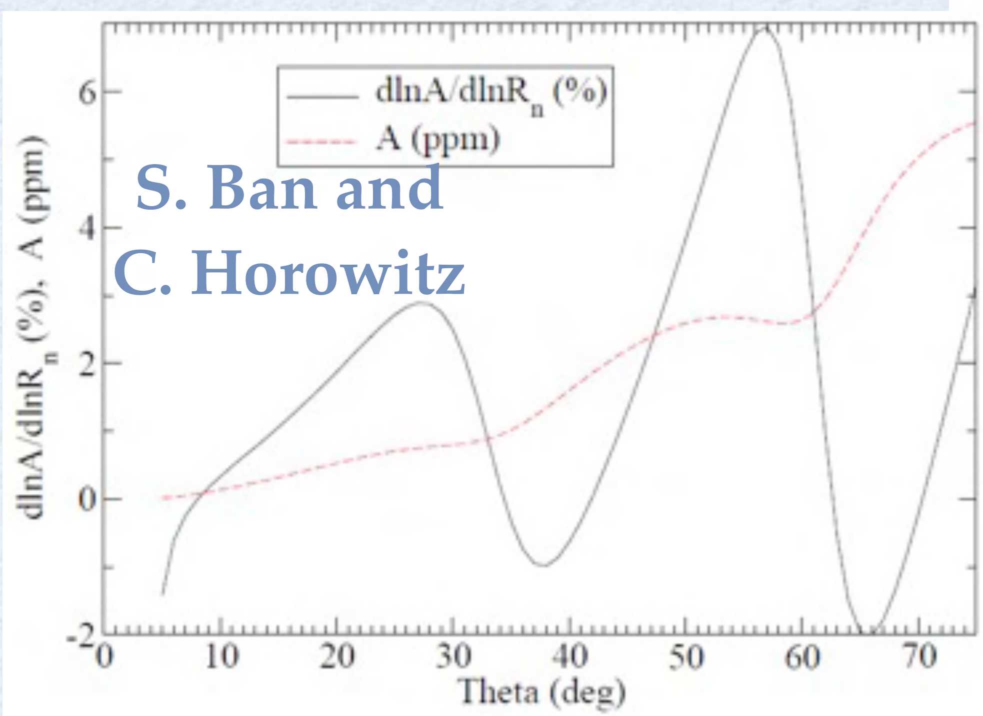
- Funding approved from DFG
- Development starting now
- Planned running 2017-2020



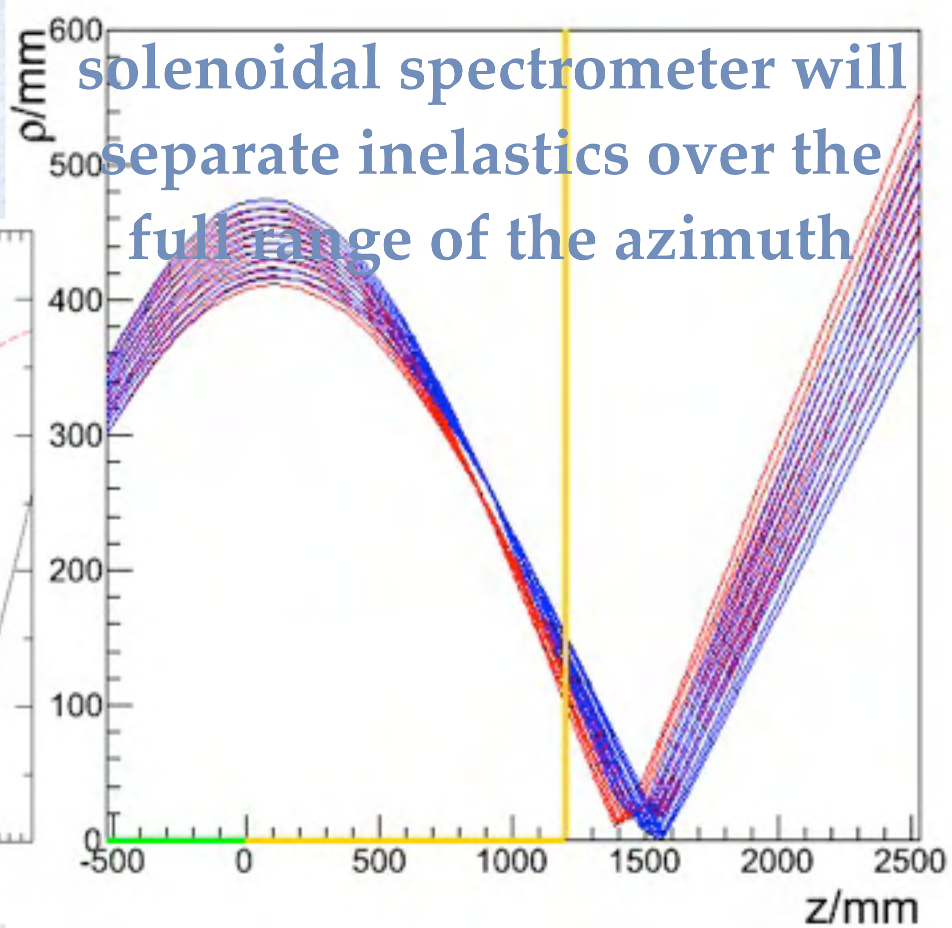
Explore a PREX-style measurement using same solenoidal magnet to be used for P2

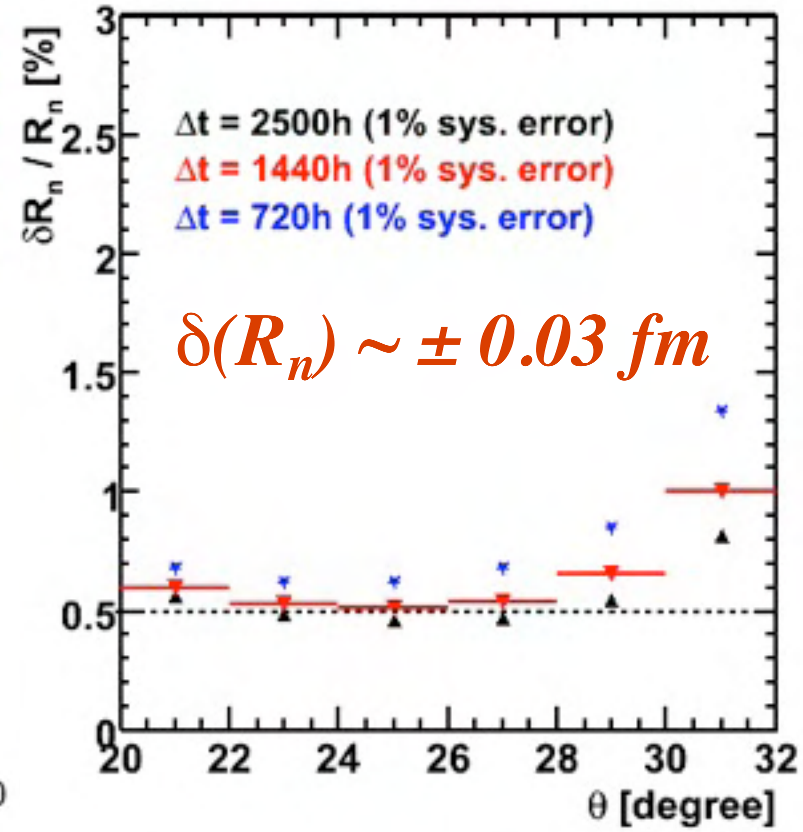
200 MeV
FOM peaks around 25 degrees

S. Ban and
C. Horowitz



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





Conclusions

- **PREX 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**
    - Likely to be scheduled to run in mid-2015 (after first commissioning of beams after JLab upgrade shutdown)
- **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

Personal Remarks

Thank you for your support:
critical for obtaining beamtime allocation for PREX-I

- **We are in an era of constrained budgets**
  - PREX and CREX running time must compete with a diverse program
  - How important are these measurements to the community?
    - I believe these measurements form critical anchors for Symmetry Energy constraints
    - But if the community is lukewarm about these measurements, they wont happen!
    - So, if you are enthusiastic about these measurements, keep making it known!
    - For example, a Mainz experiment will not materialize unless there is sustained interest
- **Shameless plug**
  - I am about to advertise for a postdoc position to work on JLab PV program
    - Please direct your best graduating students to look for my ad in the next few weeks!