Acknowledgements:
The PREX, CREX, E158 and MOLLER Collaboration
The Accelerator Divisions at SLAC & Jefferson Laboratory
V. Cirigliano, J. Erler, C. Horowitz, W. Marciano, M. Ramsey-Musolf, J. Piekerewicz

The PREX, CREX and MOLLER Experiments at Jefferson Lab

Krishna S. Kumar
Stony Brook University

Bridging the Standard Model to New Physics with the Parity Violation Program at MESA
MITP Workshop
Mainz, April 30, 2018

Outline

- **Introduction to Parity-Violating Electron Scattering**
  - *Relativistic electron scattering and nuclear size*
  - *Neutral weak interactions*
  - *Overview of an electron beam parity violation experiment*

Basic introduction for practitioners in other subfields

- **Elastic Scattering off a Heavy Spinless Nucleus**
  - *PREX Experimental Overview*
  - *First Physics Run (March-June 2010)*
  - *Preparations for PREX-II and CREX*

PRL 108 (2012) 112502

PRC 85 (2012) 032501

- **Electron-Electron (Møller) Scattering**
  - *Quick review of SLAC E158*
  - *The MOLLER Experiment*

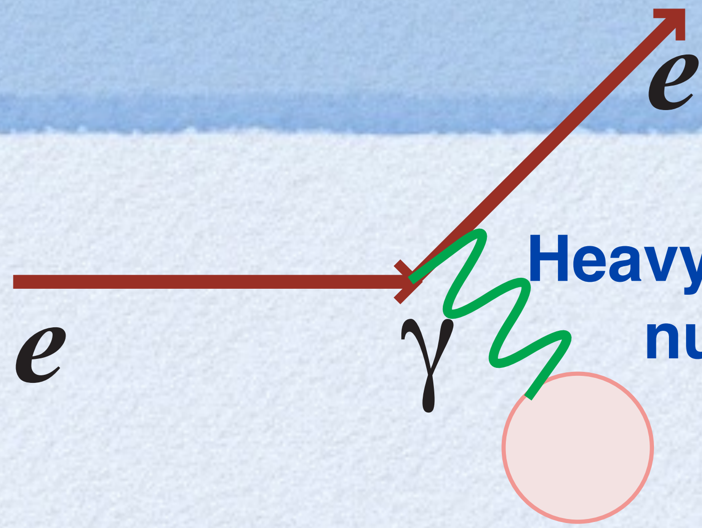
PRL 95 (2005) 081601

- **Summary and Outlook**

Introduction to Parity-Violating Electron Scattering

Relativistic Electron Scattering

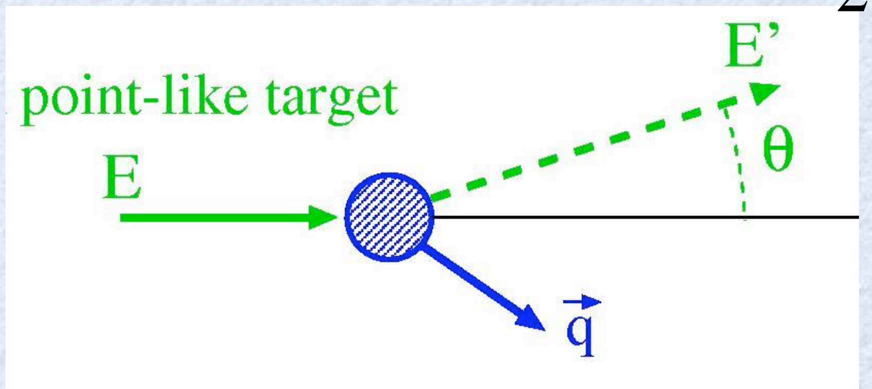
and nuclear size



Heavy, spinless nucleus

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

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



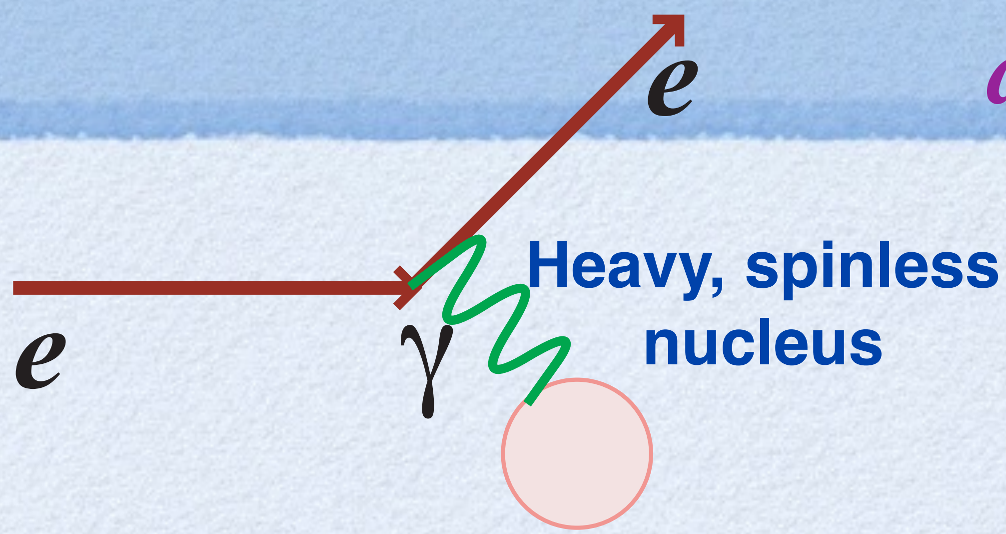
$$Q \approx \frac{hc}{\lambda}$$

Differential Cross Section

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

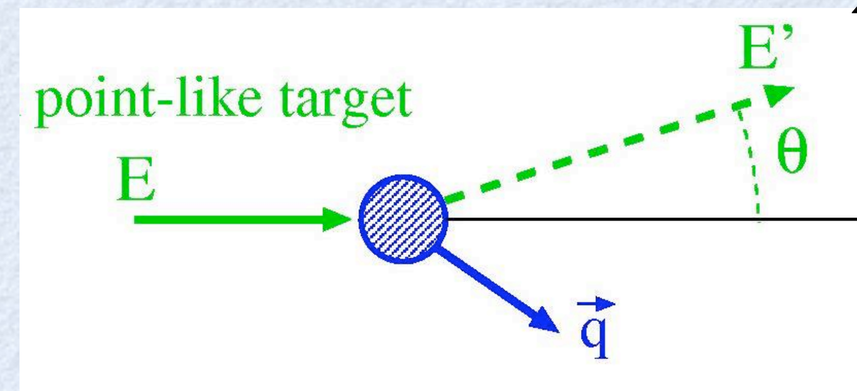
Relativistic Electron Scattering

and nuclear size



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

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

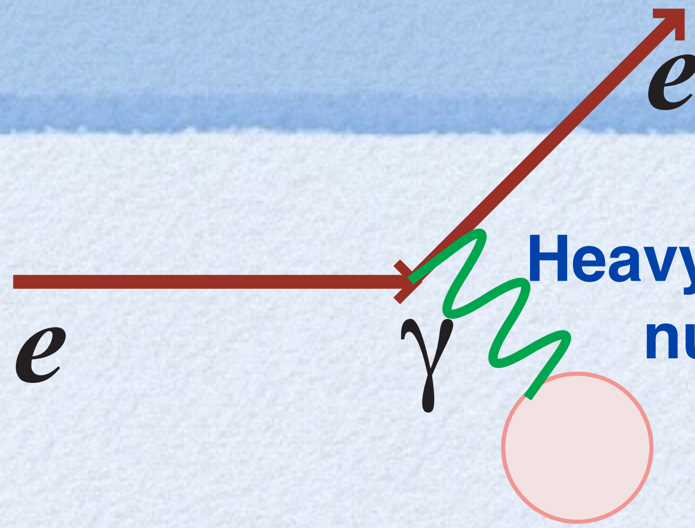
$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{\mathrm{Mott}} \left| F(q) \right|^2$$

As Q increases, nuclear size modifies formula

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

Relativistic Electron Scattering

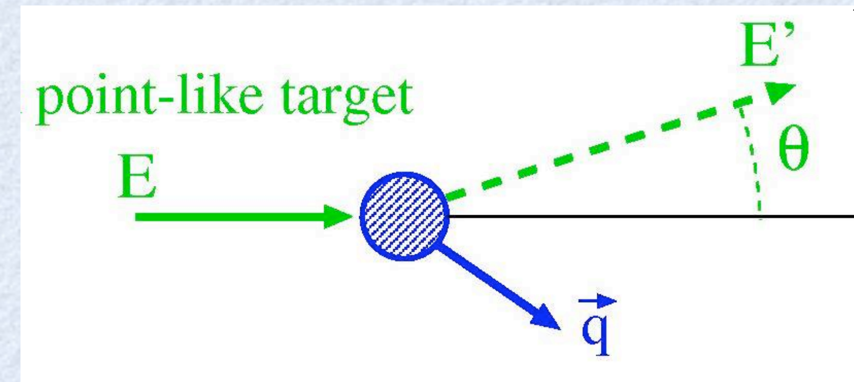
and nuclear size



Heavy, spinless nucleus

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

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



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

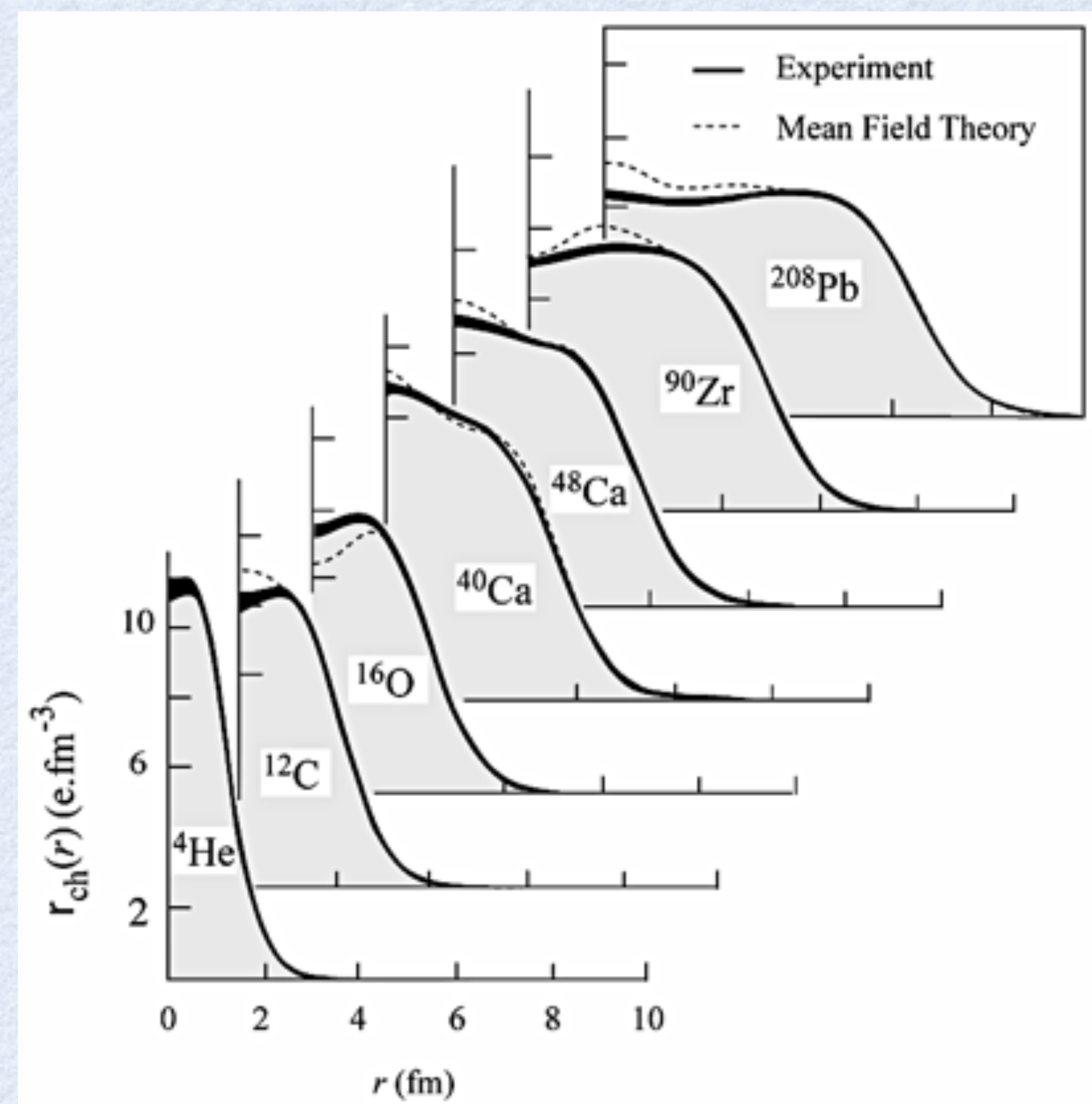
Differential Cross Section

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

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

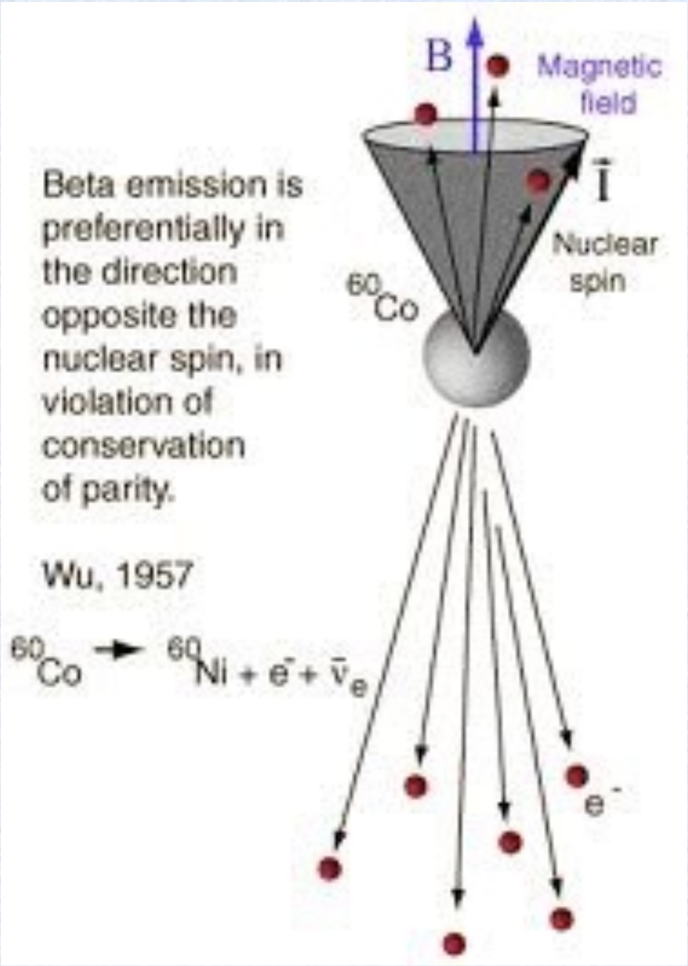
As Q increases, nuclear size modifies formula

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

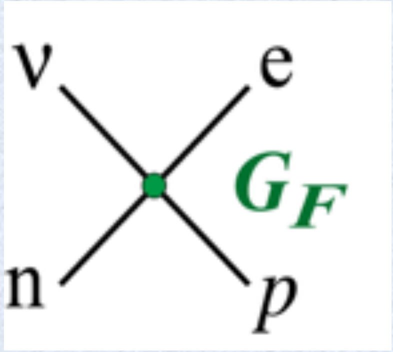


Electroweak Scattering

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



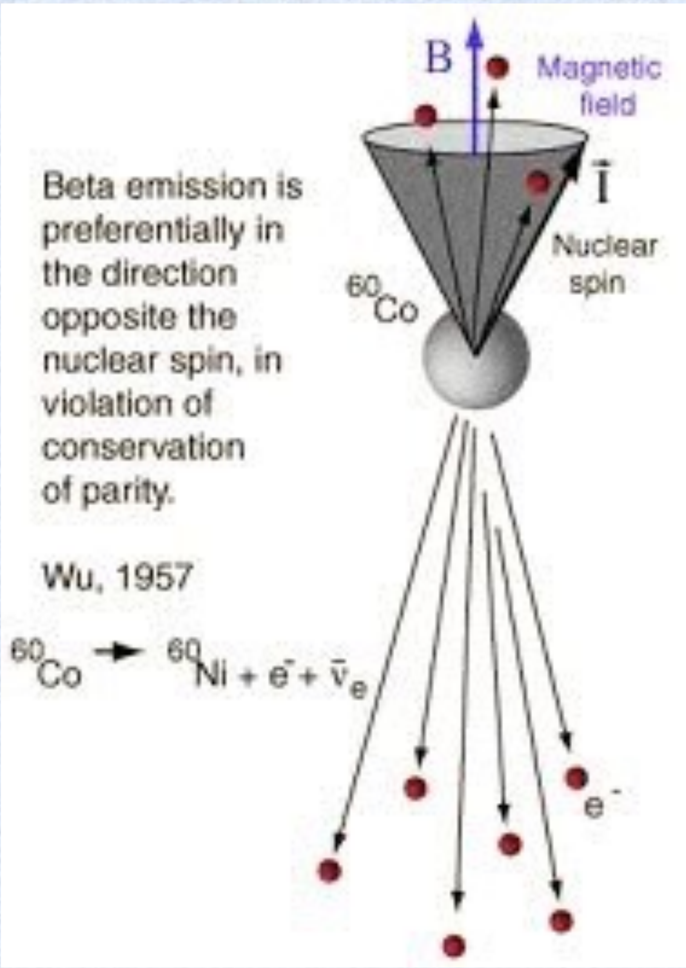
Nuclear β Decay

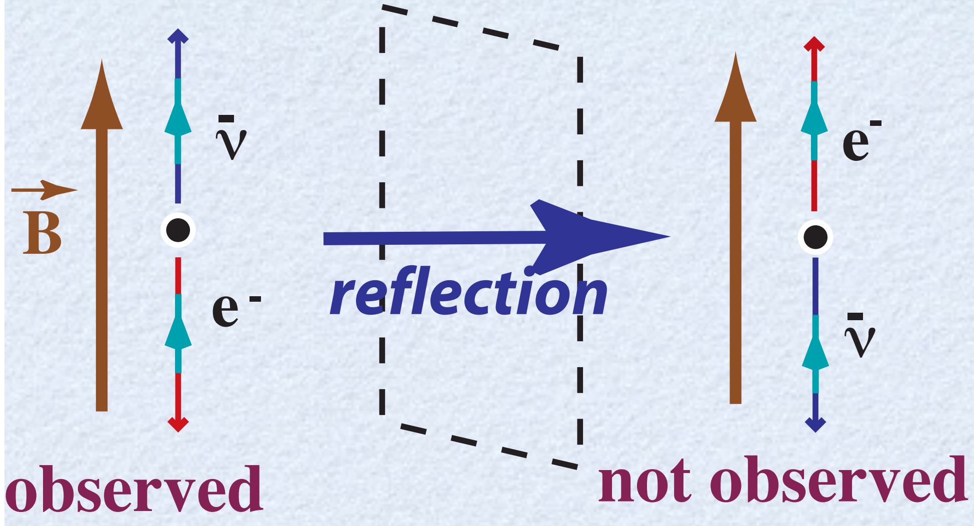


charge and flavor-changing

Electroweak Scattering

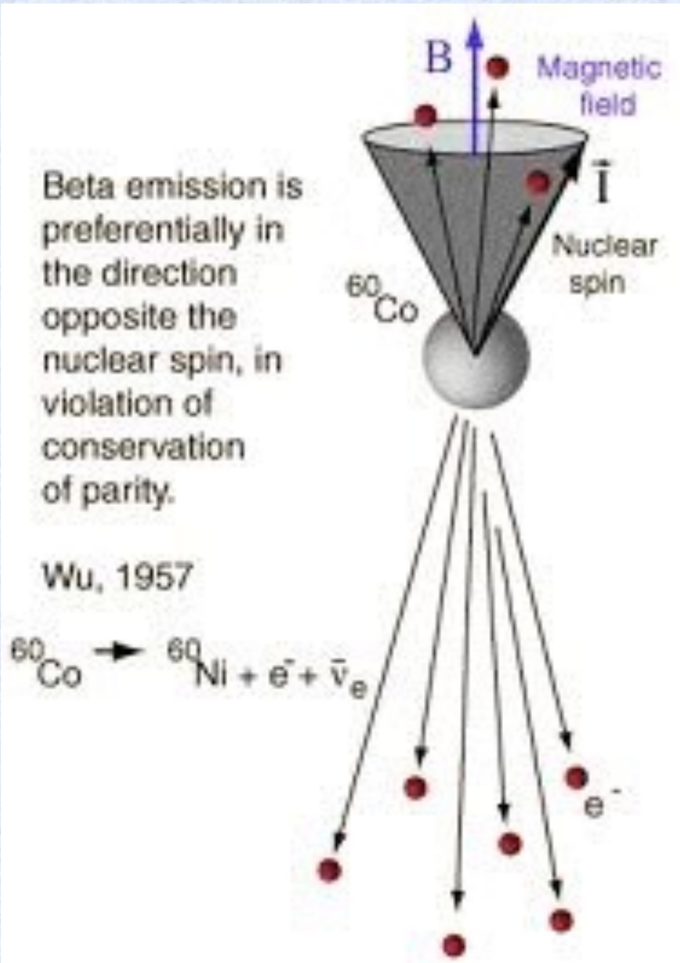
Zel'dovich speculation: Is Electron Scattering Parity-Violating?

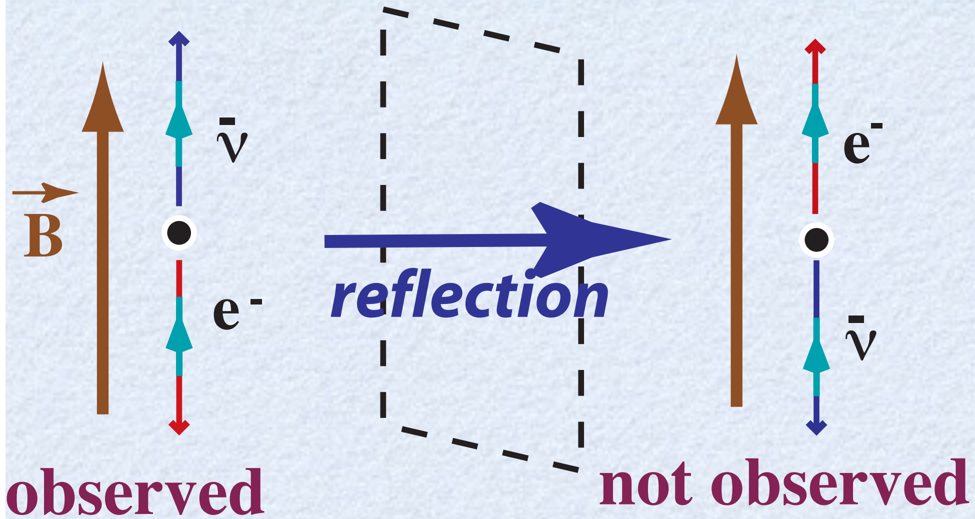




Electroweak Scattering

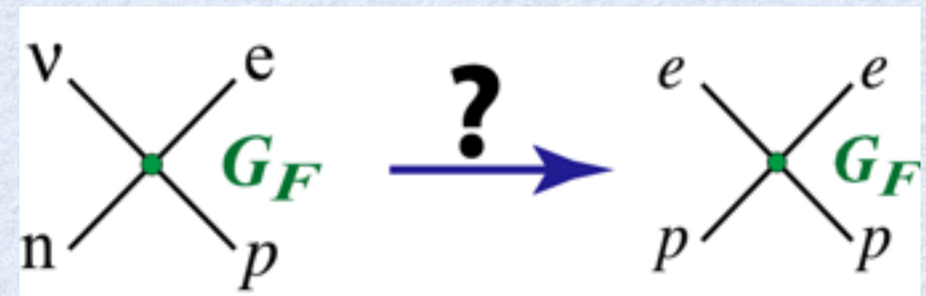
Zel'dovich speculation: Is Electron Scattering Parity-Violating?





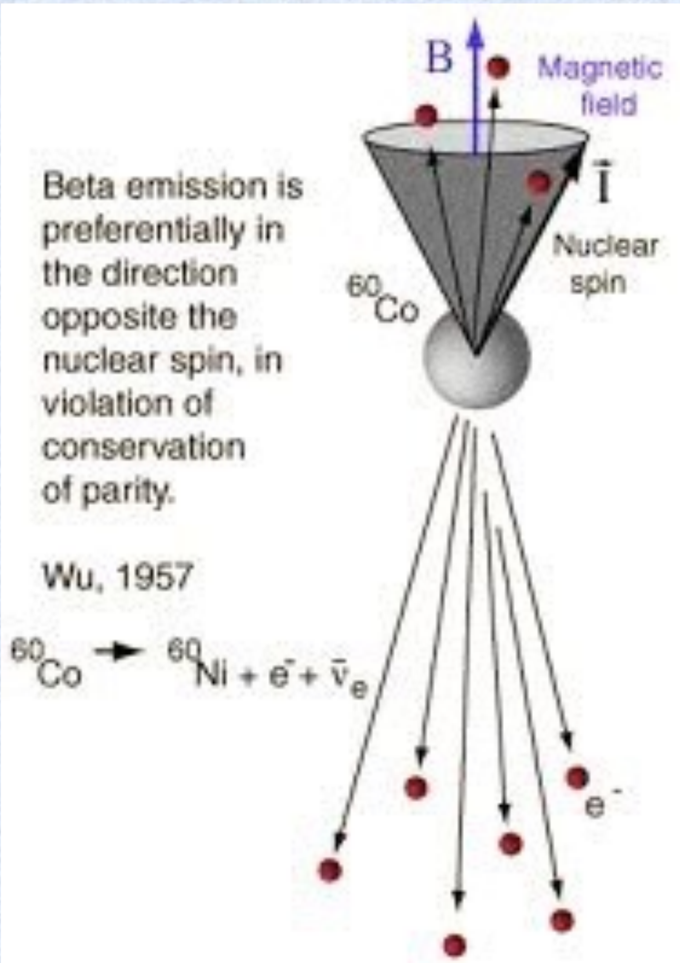
Neutron β Decay

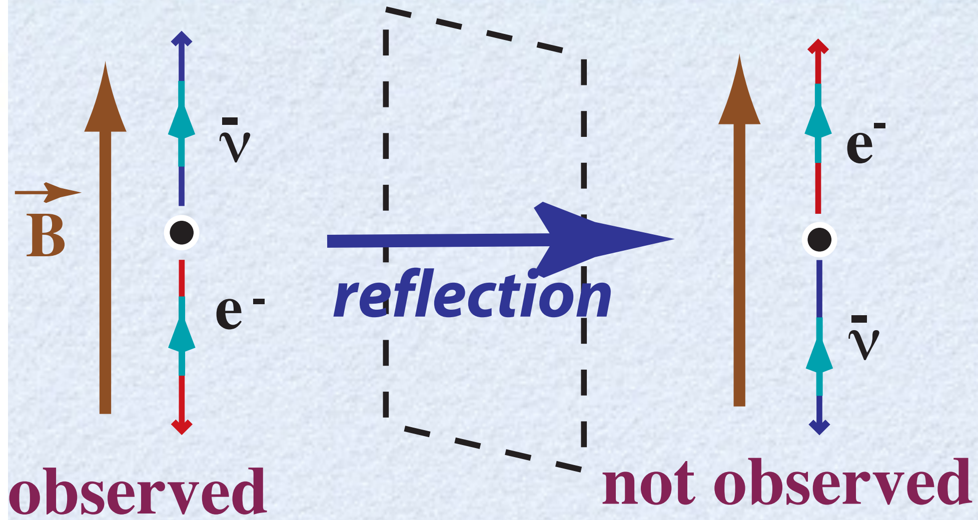
Electron-proton Weak Scattering



Electroweak Scattering

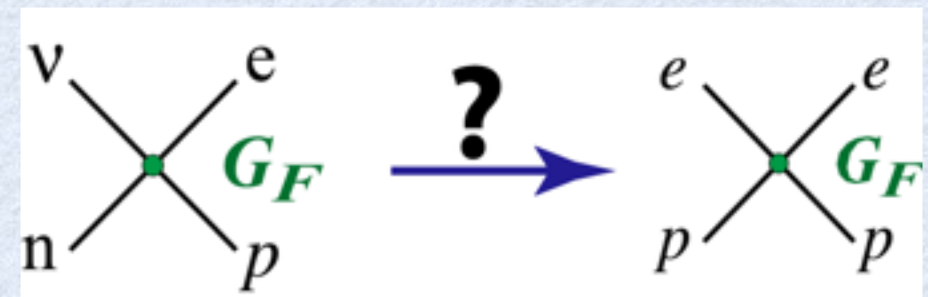
Zel'dovich speculation: Is Electron Scattering Parity-Violating?





Neutron β Decay

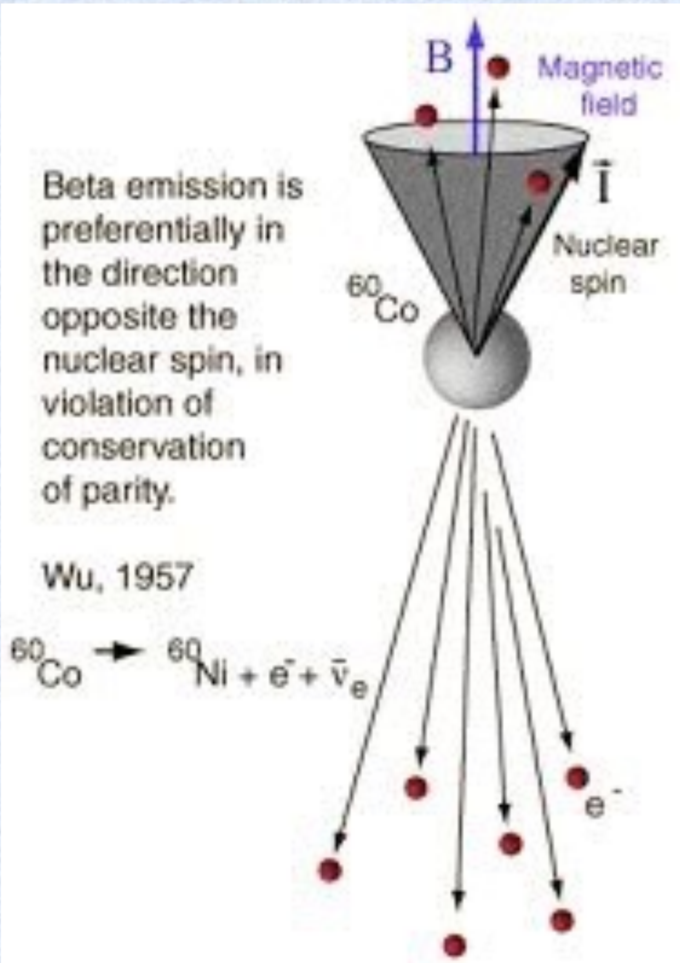
Electron-proton Weak Scattering

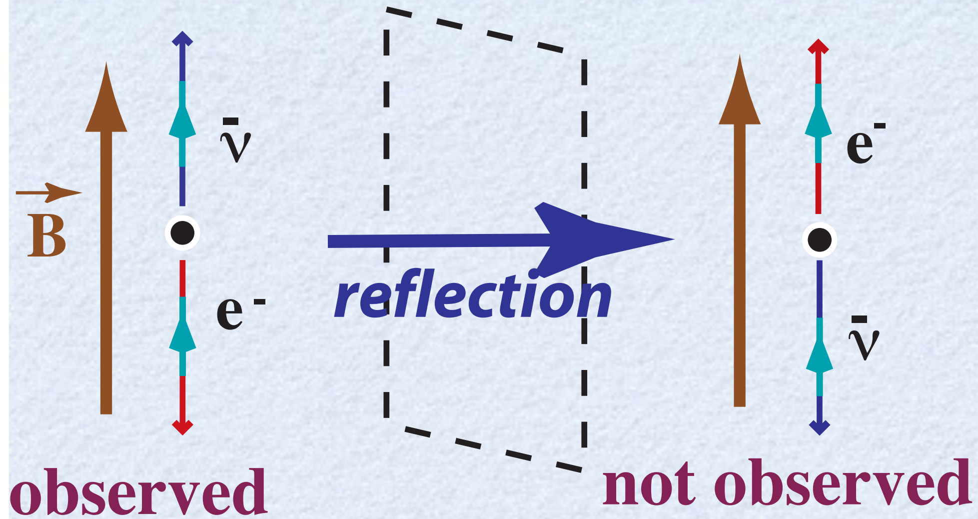


$$\sigma \;\alpha\; \left|A_{EM} + A_{weak}\right|^2$$
$$\sim \left|A_{EM}\right|^2 + 2A_{EM}A^*_{weak} + \ldots$$

Electroweak Scattering

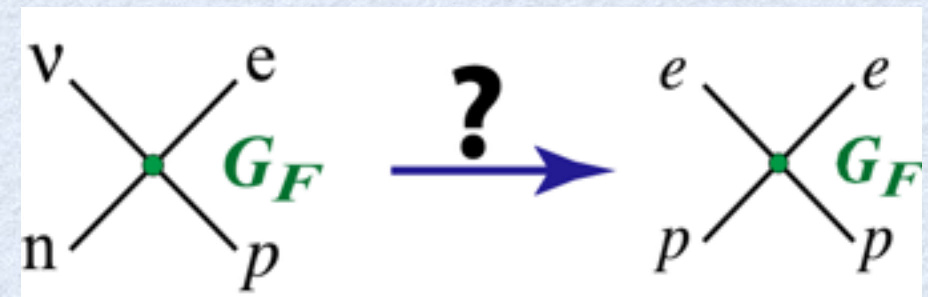
Zel'dovich speculation: Is Electron Scattering Parity-Violating?





Neutron β Decay

Electron-proton Weak Scattering

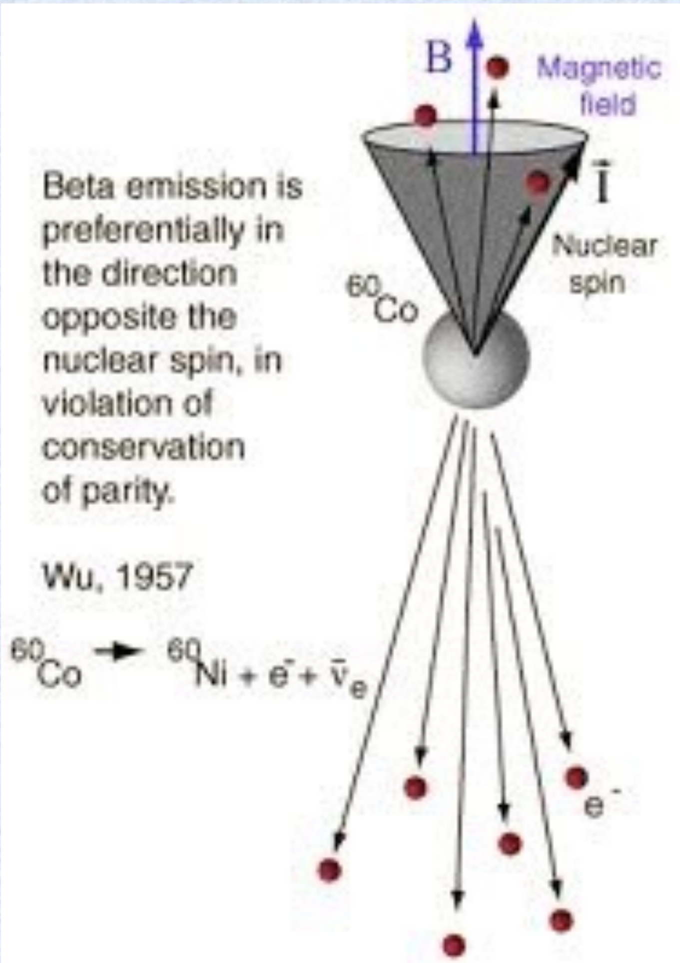


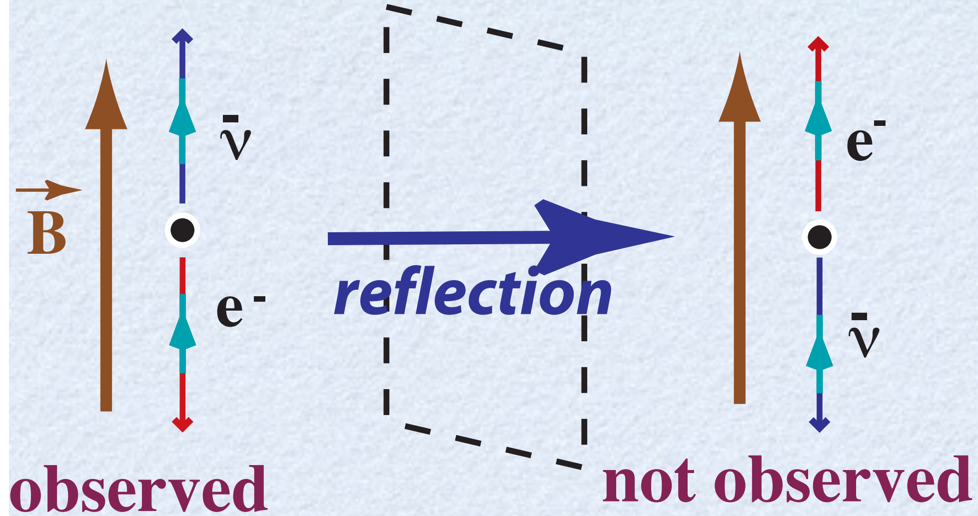
$$\sigma \;\alpha\; \left|A_{EM} + A_{weak}\right|^2$$
$$\sim \left|A_{EM}\right|^2 + \boxed{2A_{EM}A^*_{weak} +} \ldots$$

Parity-violating

Electroweak Scattering

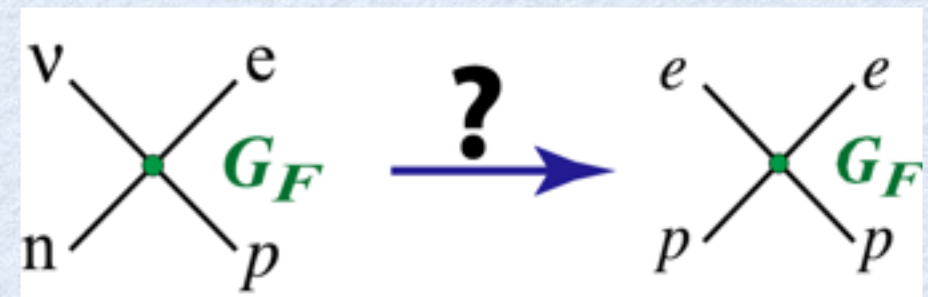
Zel'dovich speculation: Is Electron Scattering Parity-Violating?





Neutron β Decay

Electron-proton Weak Scattering



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

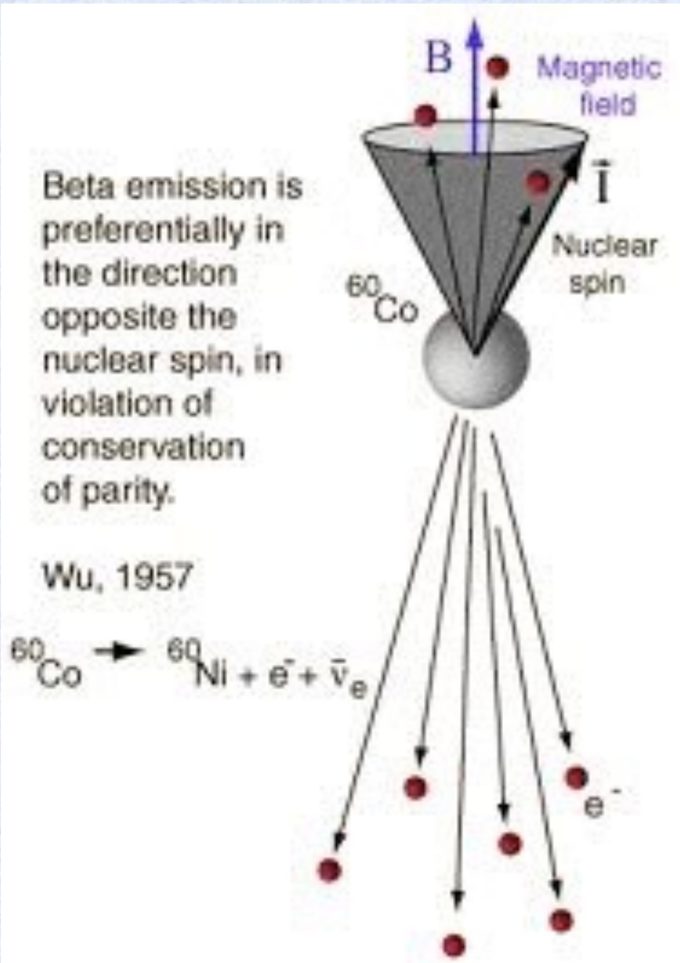
$$\sigma \;\alpha\; |A_{EM} + A_{weak}|^2$$

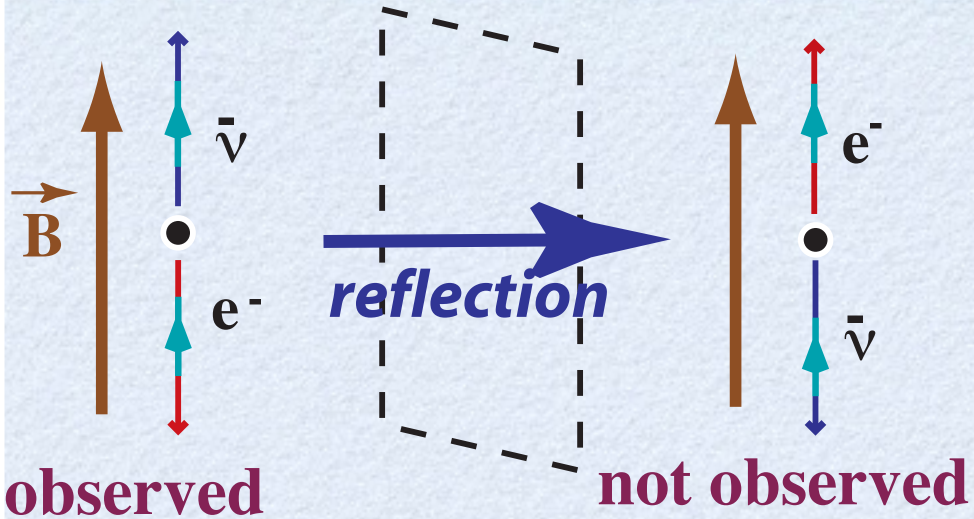
$$\sim |A_{EM}|^2 + \boxed{2A_{EM}A^*_{weak} +} \ldots$$

Parity-violating

Electroweak Scattering

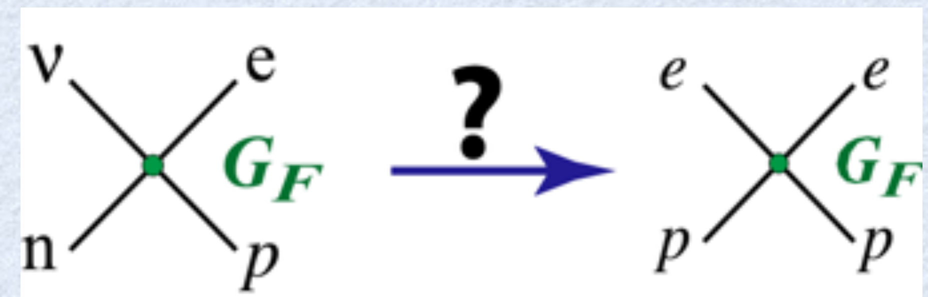
Zel'dovich speculation: Is Electron Scattering Parity-Violating?





Neutron β Decay

Electron-proton Weak Scattering



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

$$\sim \frac{A_{weak}}{A_{EM}} \sim \frac{G_F Q^2}{4\pi\alpha}$$

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

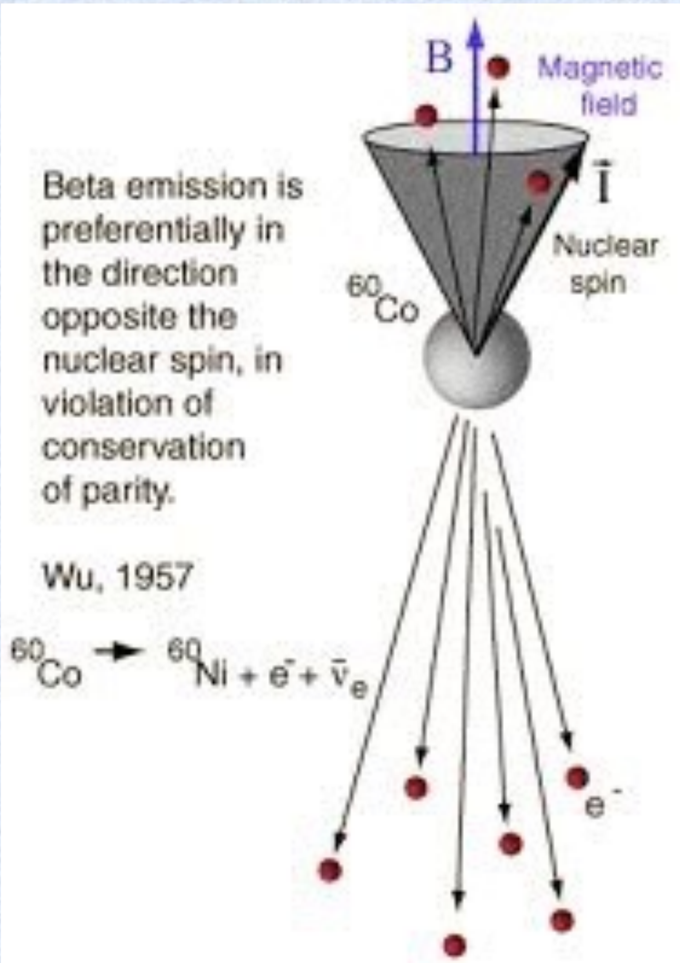
$$\sim |A_{EM}|^2 + \boxed{2A_{EM}A^*_{weak} +} \ldots$$

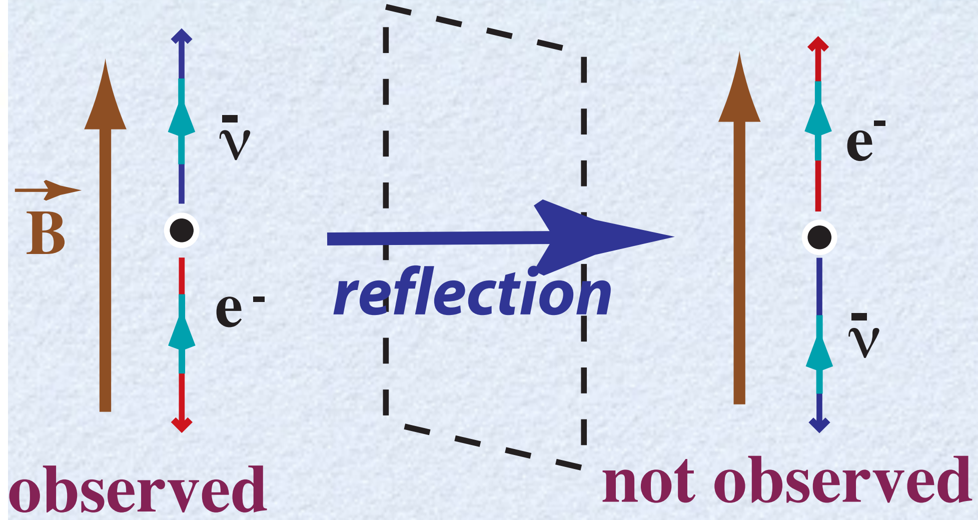
Parity-violating

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

Electroweak Scattering

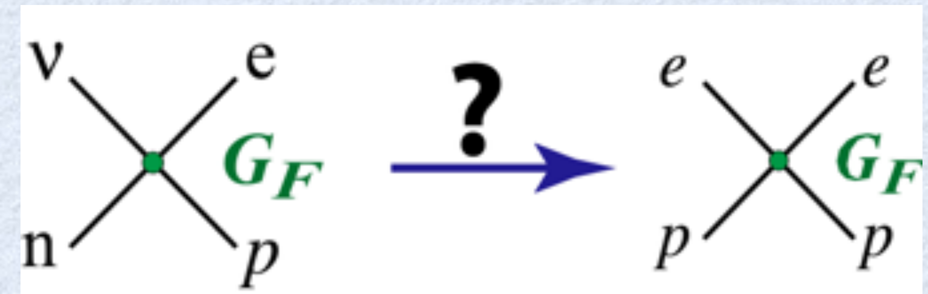
Zel'dovich speculation: Is Electron Scattering Parity-Violating?





Neutron β Decay

Electron-proton Weak Scattering



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

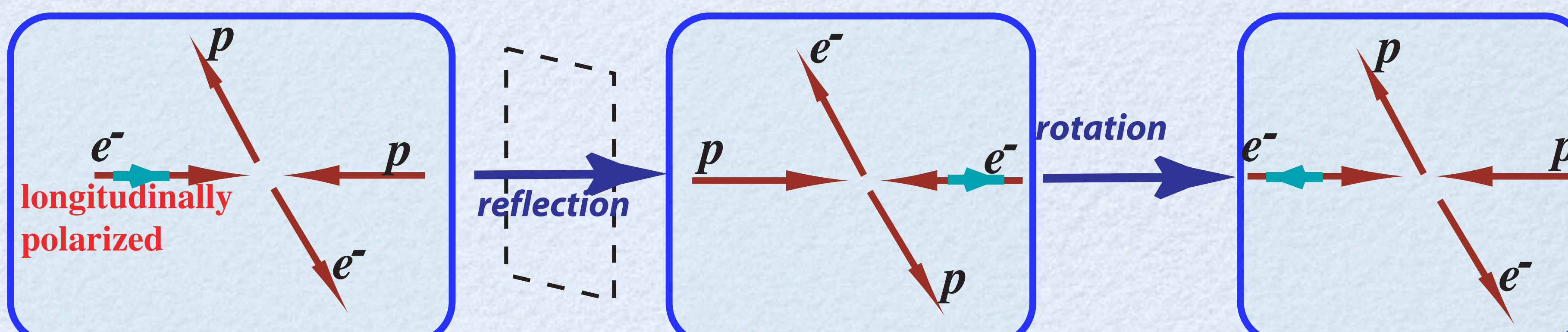
$$\sim \frac{A_{weak}}{A_{EM}} \sim \frac{G_F Q^2}{4\pi\alpha}$$

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

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

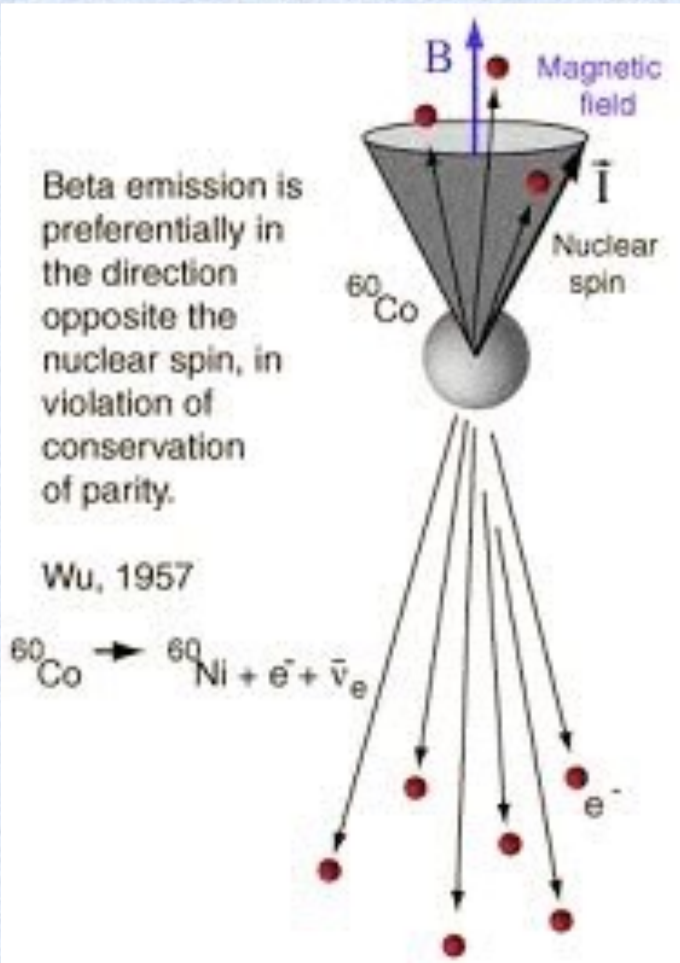
Parity-violating

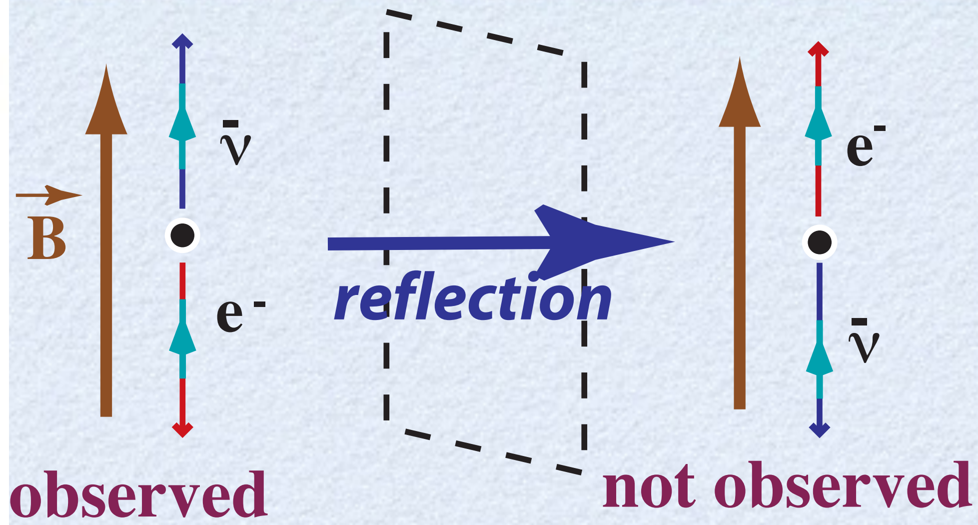
$$A_{PV} \sim 10^{-4} \cdot Q^2 \;(\mathrm{GeV}^2)$$



Electroweak Scattering

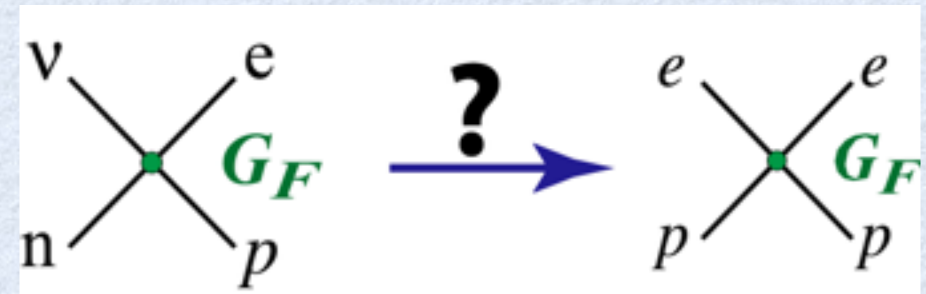
Zel'dovich speculation: Is Electron Scattering Parity-Violating?





Neutron β Decay

Electron-proton Weak Scattering



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

$$\sim \frac{A_{weak}}{A_{EM}} \sim \frac{G_F Q^2}{4\pi\alpha}$$

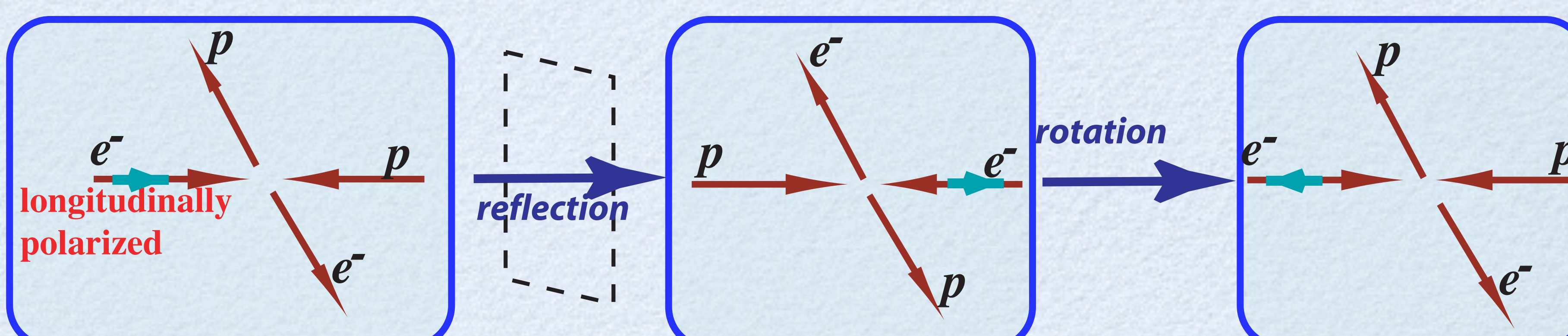
$$\sigma \;\alpha\; |A_{EM} + A_{weak}|^2$$

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

Parity-violating

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

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



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

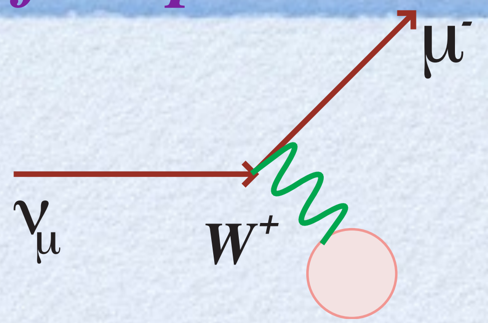
Glashow, Weinberg and Salam: $SU(2)_L$ X $U(1)_Y$

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

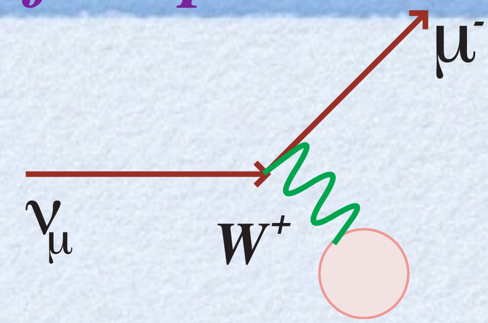
Glashow, Weinberg and Salam: $SU(2)_L \times U(1)_Y$

Neutral Weak Interaction Theory

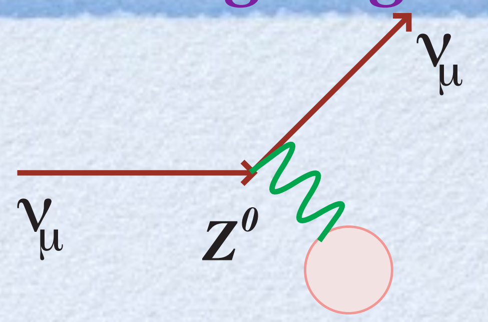
The Z boson incorporated

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

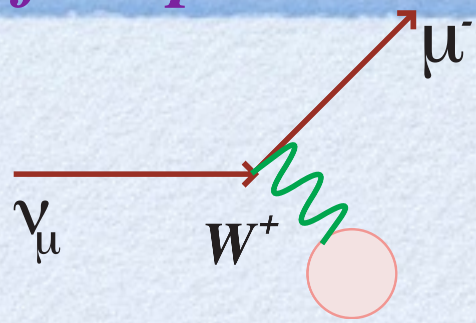
Glashow, Weinberg and Salam: $SU(2)_L \times U(1)_Y$

Neutral Weak Interaction Theory

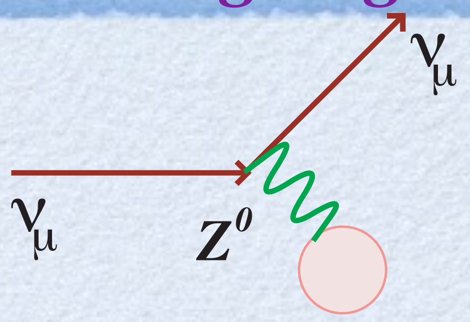
The Z boson incorporated

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

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

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

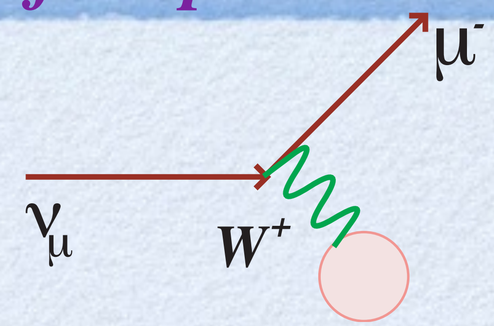
Parity is conserved

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

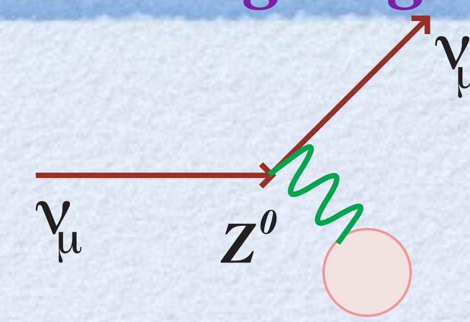
Neutral Weak Interaction Theory

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

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

First table-top atomic parity violation searches: negative!

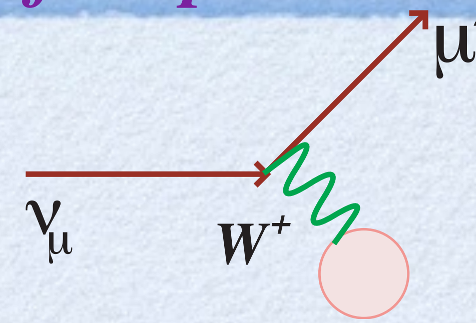
Glashow, Weinberg and Salam: $SU(2)_L \times U(1)_Y$

Neutral Weak Interaction Theory

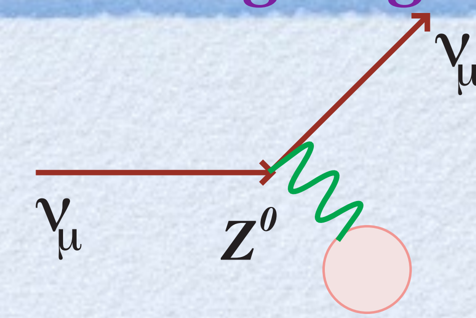
The Z boson incorporated

	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

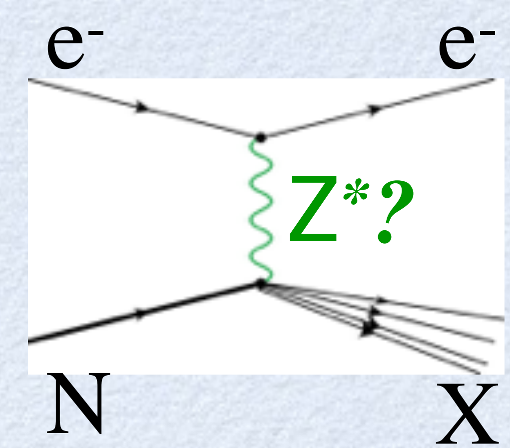
$$A_{PV} \sim 10^{-4}$$

or

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

Parity is conserved

electron-nucleon deep inelastic scattering



pressing problem in mid-70's

First table-top atomic parity violation searches: negative!

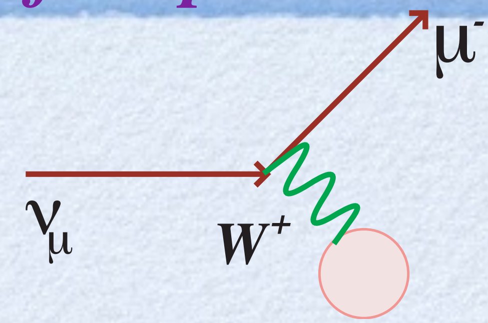
Glashow, Weinberg and Salam: $SU(2)_L \times U(1)_Y$

Neutral Weak Interaction Theory

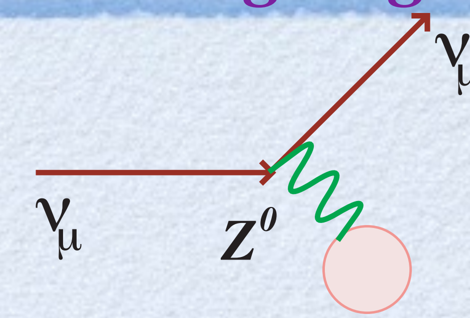
The Z boson incorporated

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

One free parameter: weak mixing angle θ_W



Charged Current



Neutral Current

Do lepton-nucleon neutral current interactions exhibit parity violation?

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

or

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

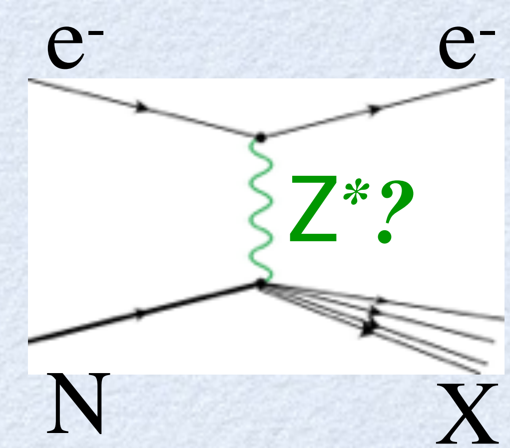
Weinberg model

Parity is violated

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

Parity is conserved

electron-nucleon deep inelastic scattering



pressing problem in mid-70's

Seminal Experimental Measurement: E122 at the Stanford Linear Accelerator Center

First table-top atomic parity violation searches: negative!

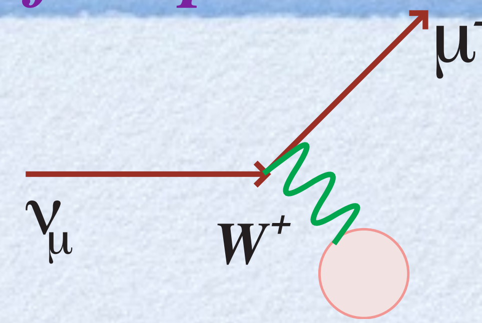
Glashow, Weinberg and Salam: $SU(2)_L \times U(1)_Y$

Neutral Weak Interaction Theory

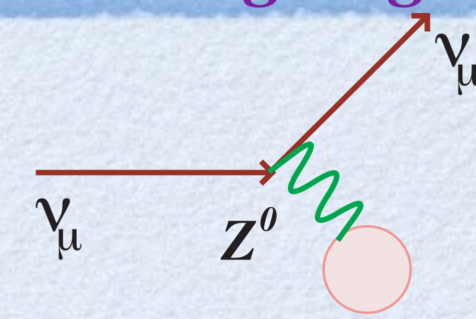
The Z boson incorporated

	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

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

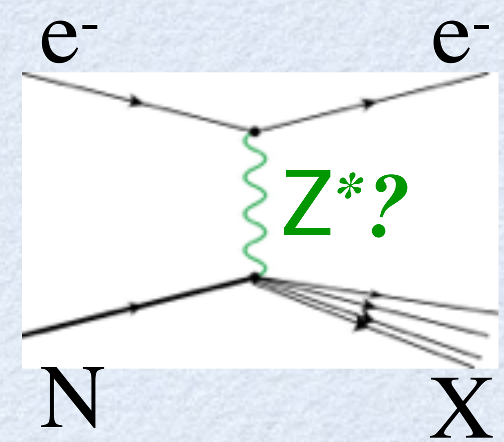
or

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

Parity is conserved

First table-top atomic parity violation searches: negative!

electron-nucleon deep inelastic scattering



pressing problem in mid-70's

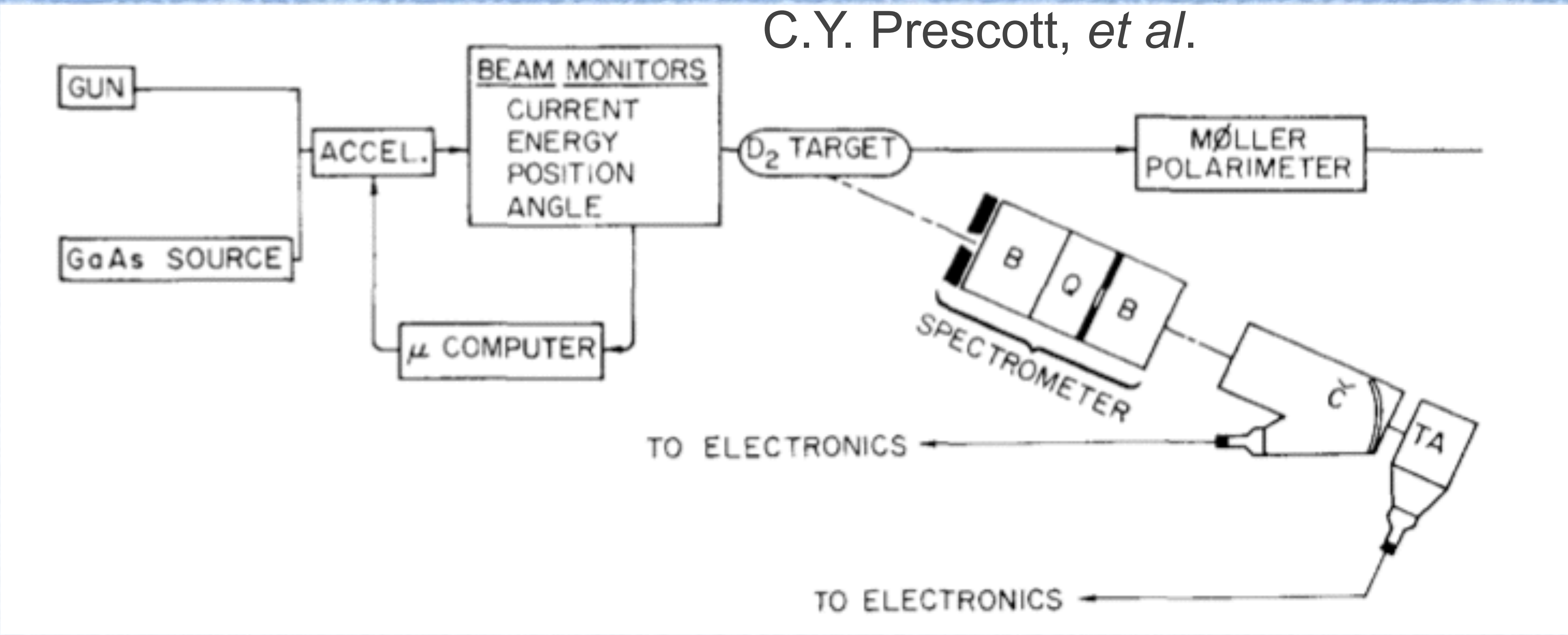
Seminal Experimental Measurement: E122 at the Stanford Linear Accelerator Center

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

Anatomy of a Parity Experiment

The E122 Experiment at the Stanford Linear Accelerator Center

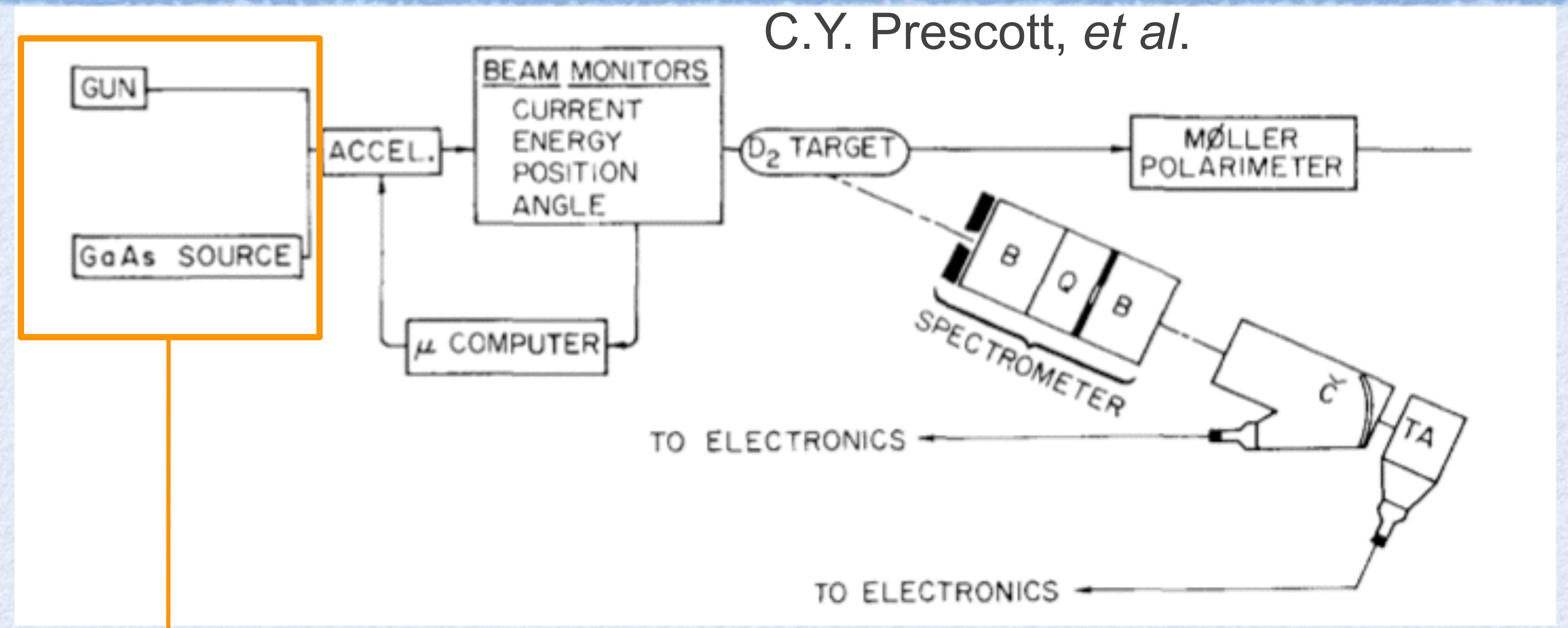
C.Y. Prescott, *et al.*

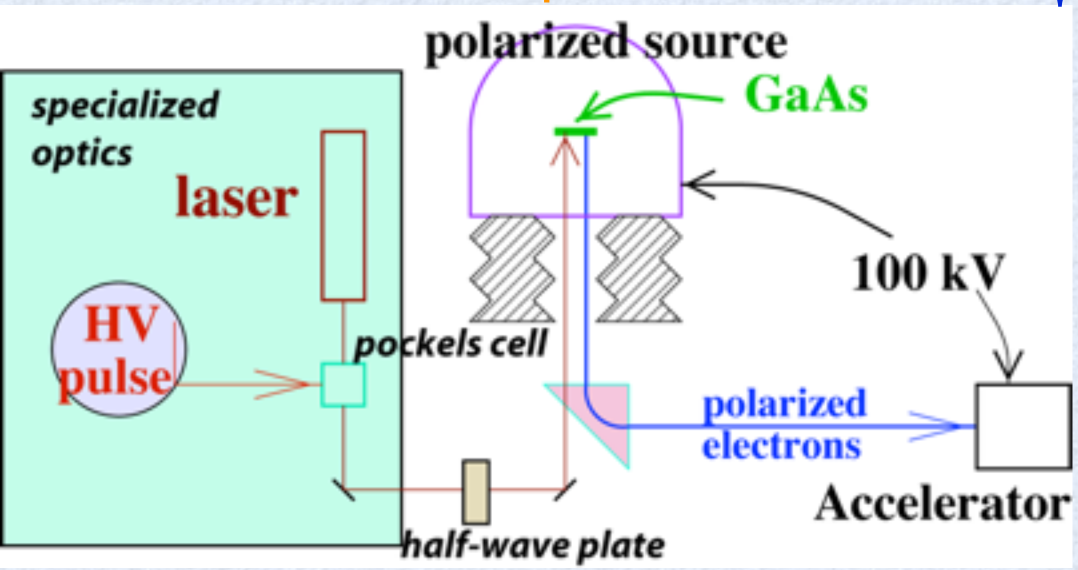


Anatomy of a Parity Experiment

The E122 Experiment at the Stanford Linear Accelerator Center

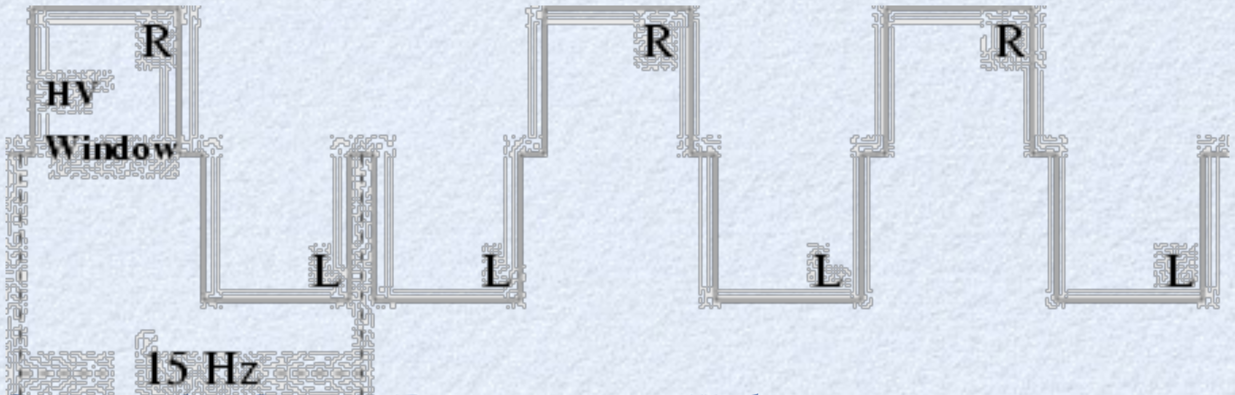
C.Y. Prescott, *et al*.





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

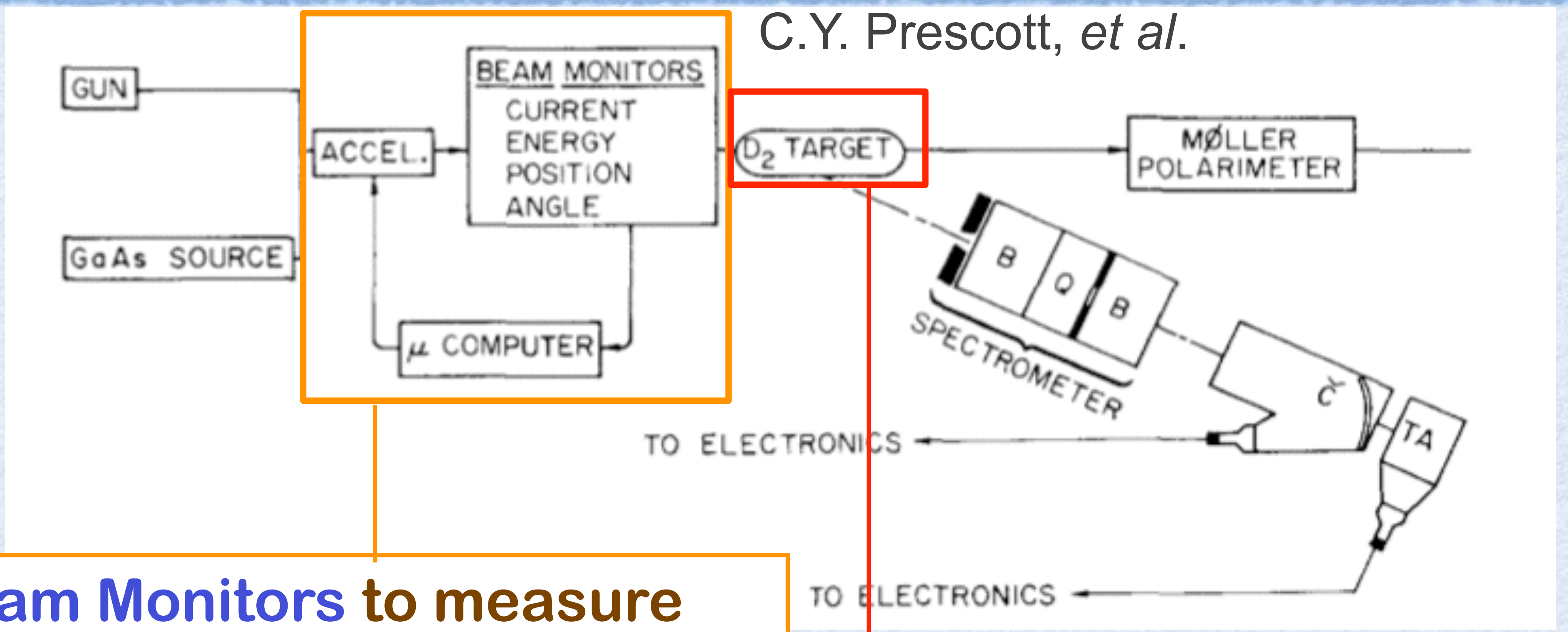
- Helicity state, followed by its complement
- Data analyzed as "pulse-pairs"



Anatomy of a Parity Experiment

The E122 Experiment at the Stanford Linear Accelerator Center

C.Y. Prescott, *et al.*



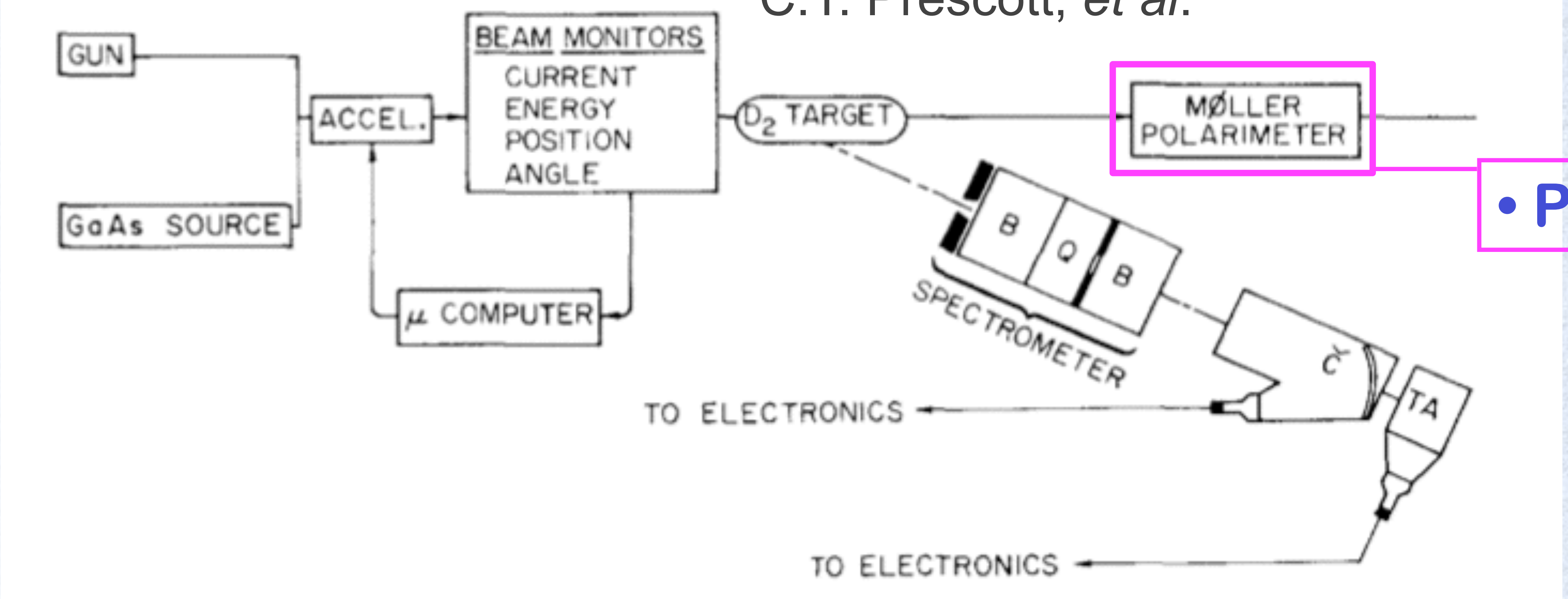
- **Beam Monitors to measure helicity-correlated changes in beam parameters**

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

Anatomy of a Parity Experiment

The E122 Experiment at the Stanford Linear Accelerator Center

C.Y. Prescott, *et al.*

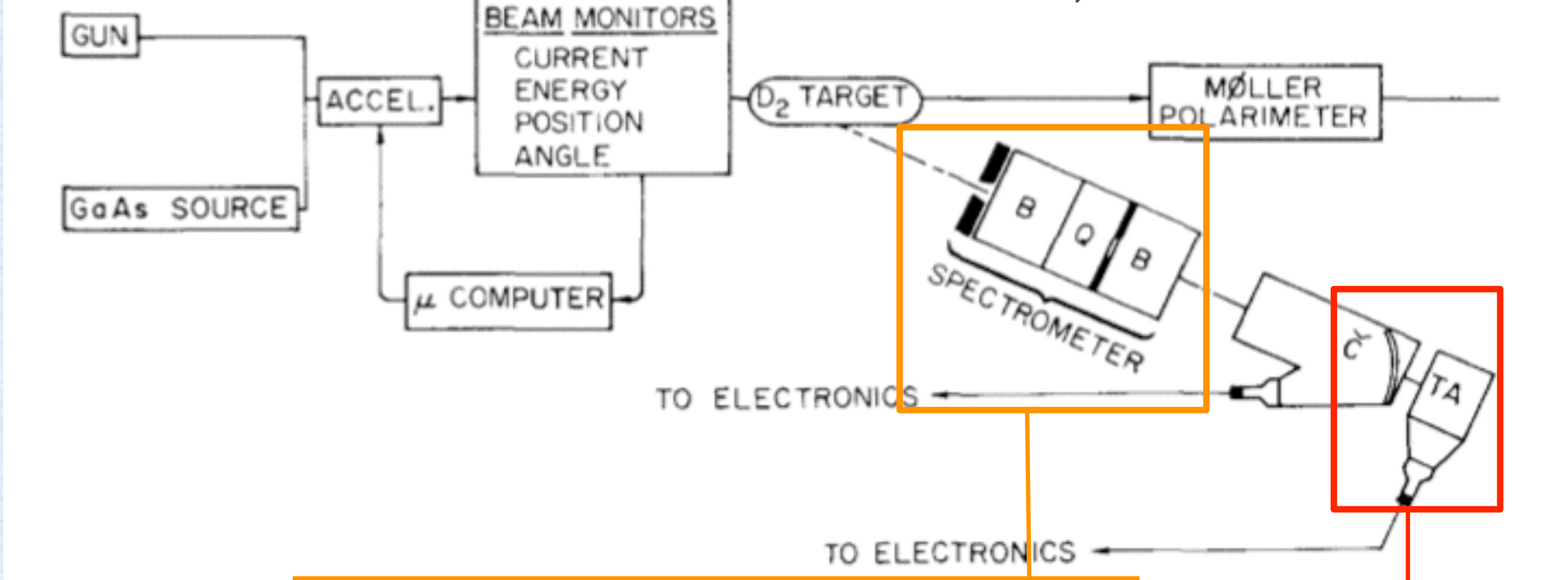


• **Polarimetry**

Anatomy of a Parity Experiment

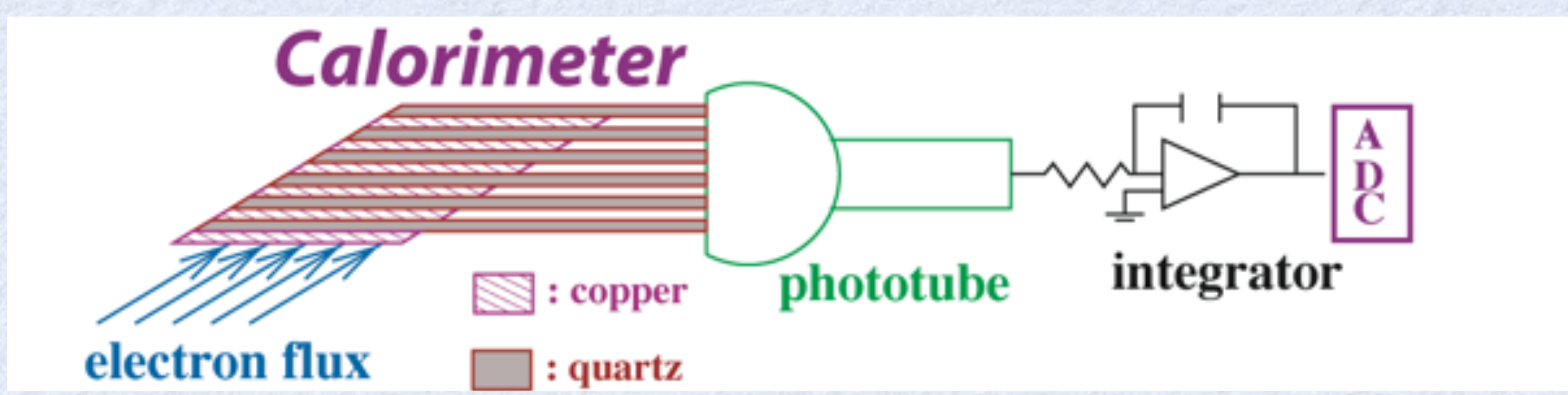
The E122 Experiment at the Stanford Linear Accelerator Center

C.Y. Prescott, *et al.*



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

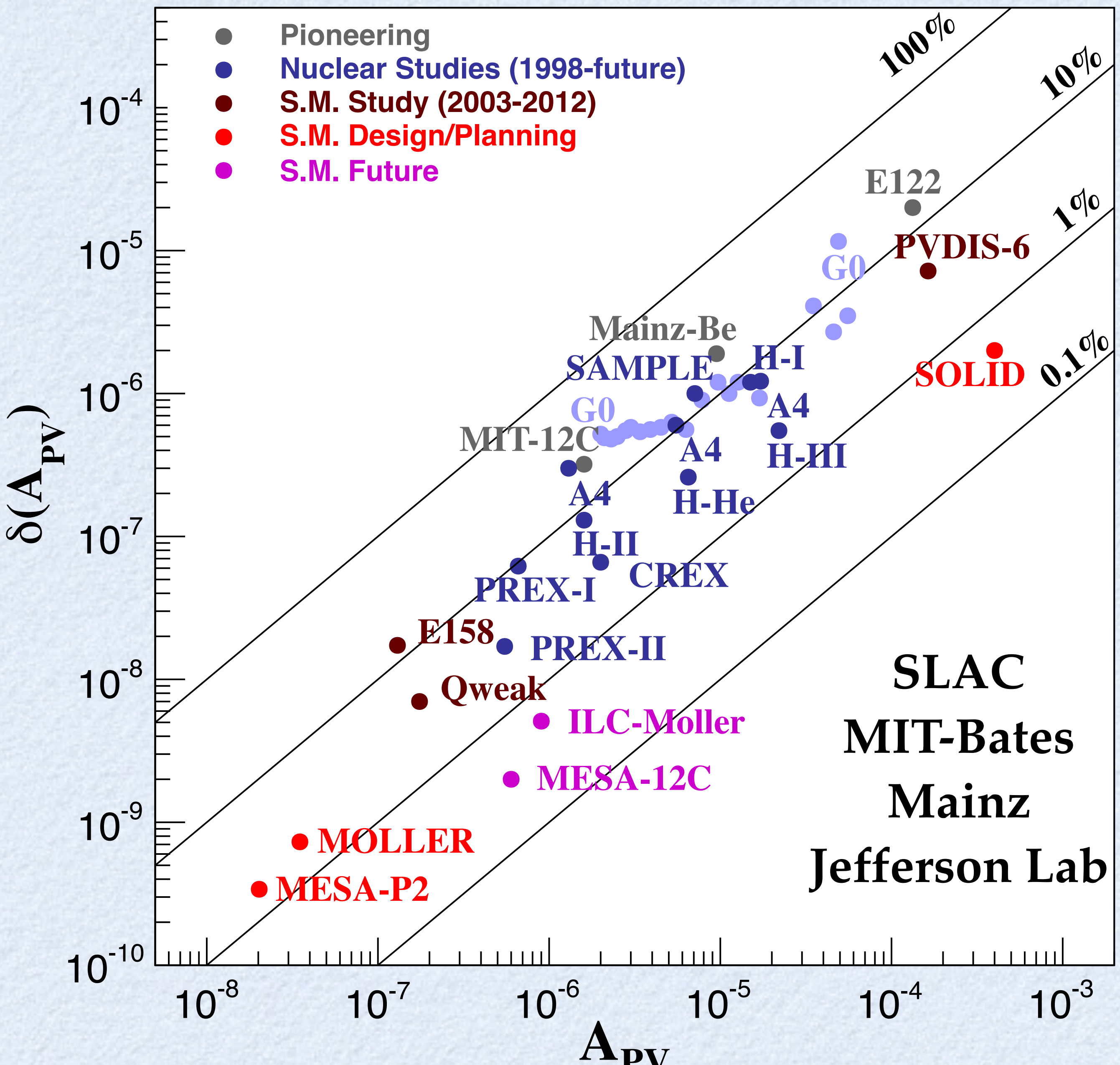
- **Flux Integration** measures high rate without deadtime



4 Decades of Technical Progress

Continuous interplay between probing hadron structure and electroweak physics

Parity-violating electron scattering has become a precision tool



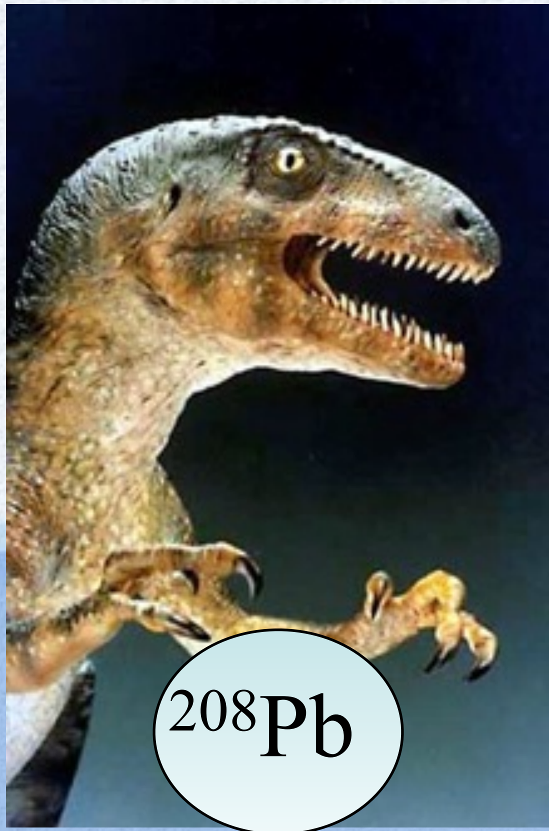
- *Beyond Standard Model Searches*
- *Strange quark form factors*
- *Neutron skin of a heavy nucleus*
- *QCD structure of the nucleon*

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

T. W. Donnelly

Center for Theoretical Physics
Laboratory for Nuclear Science and Department of Physics
Massachusetts Institute of Technology
Cambridge, Massachusetts 02139 USA

and

J. Dubach

Department of Physics and Astronomy†
University of Massachusetts
Amherst, Massachusetts 01003 USA

and

Continuous Electron Beam Accelerator Facility
12000 Jefferson Avenue, Newport News, Va. 23606

and

Ingo Sick

Department of Physics
University of Basel
CH–4056 Basel, Switzerland

Parity Violating Measurements of Neutron Densities

Phys.Rev. C63 (2001) 025501

C. J. Horowitz*

Dept. of Physics and Nuclear Theory Center
Indiana University
Bloomington, Indiana 47405 USA

S. J. Pollock†

Dept. of Physics , CB 390
University of Colorado
Boulder, CO 80309 USA

P. A. Souder‡

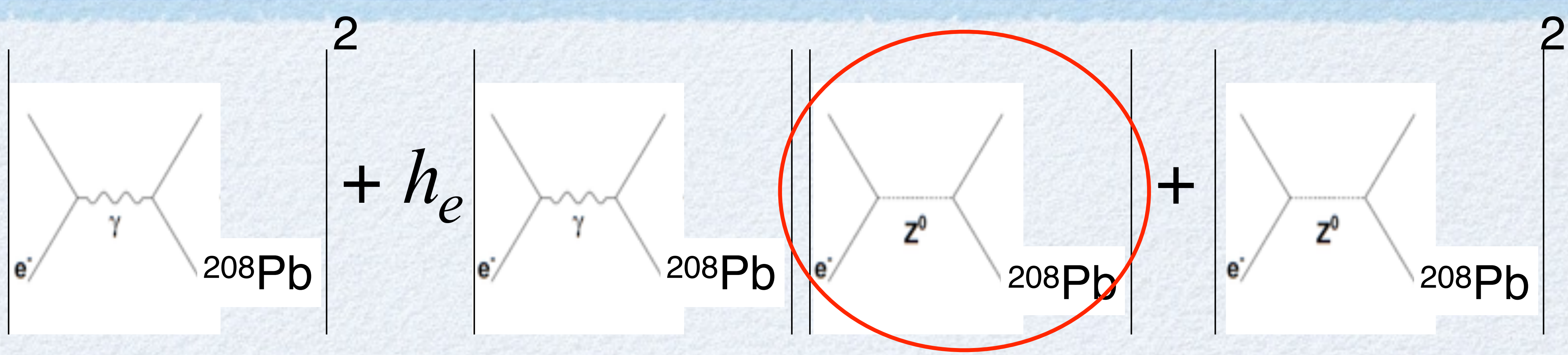
Dept. of Physics
Syracuse University
Syracuse, N.Y., USA

R. Michaels§

Thomas Jefferson National Accelerator Facility
Newport News, VA, USA

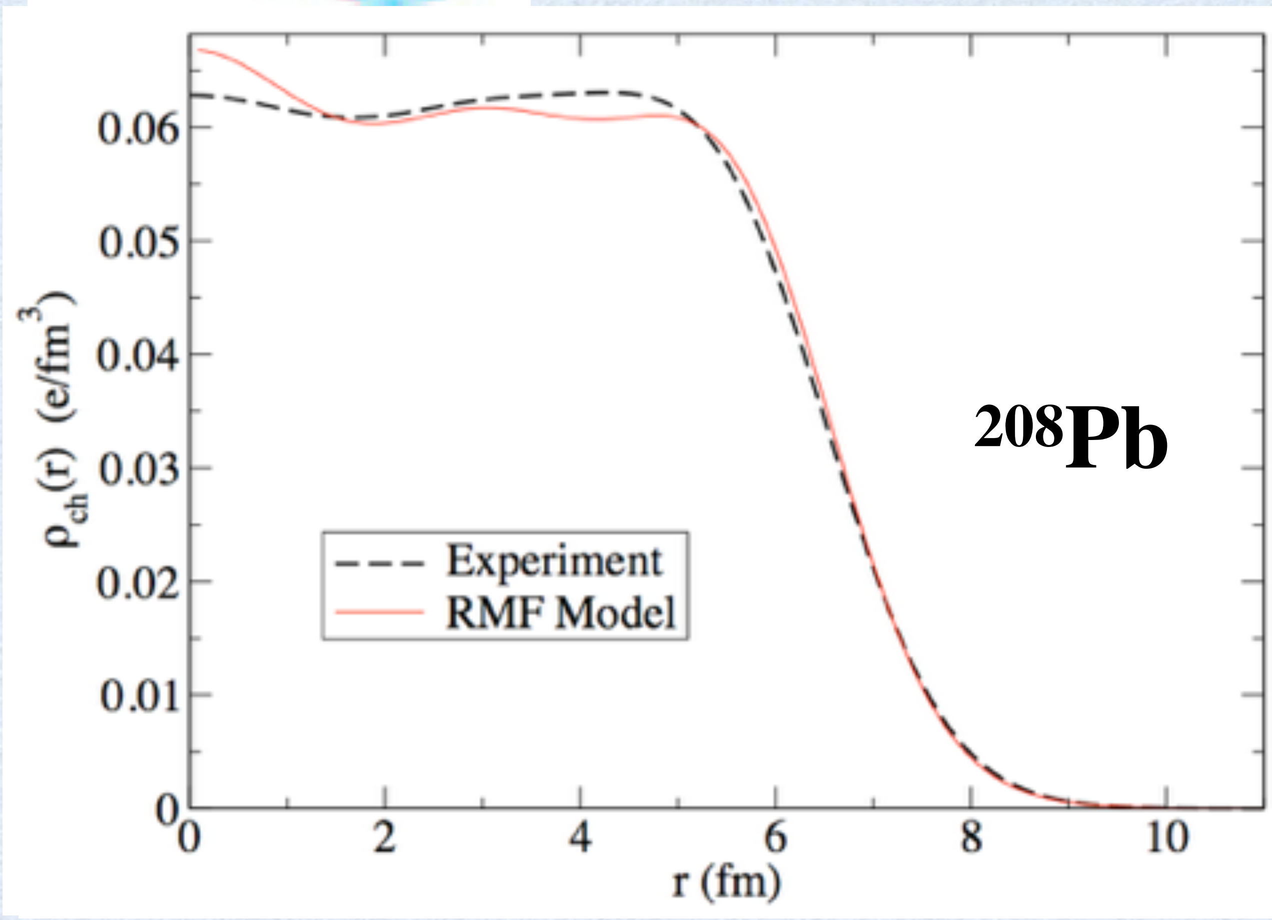
PREX at Jefferson Lab

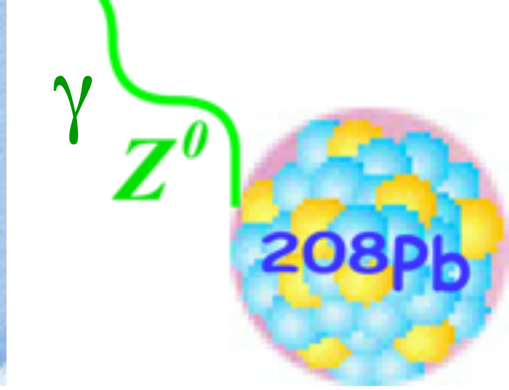
$\sigma \propto$



PREX Concept

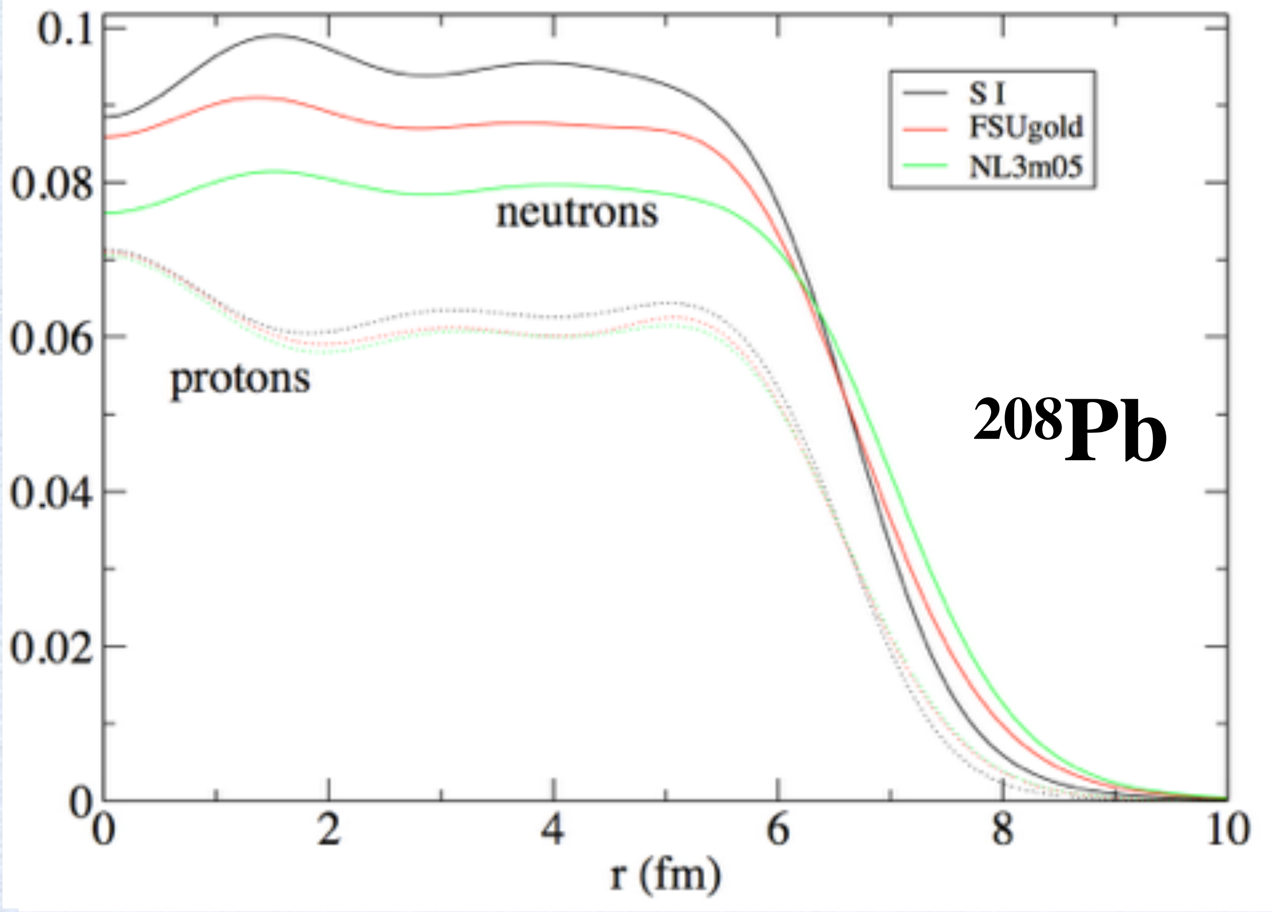
Pb-Radius EXperiment





PREX Concept

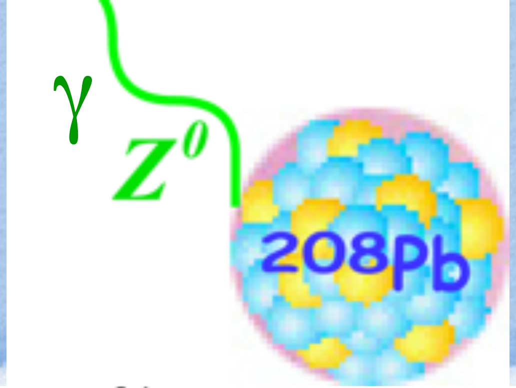
Pb-Radius EXperiment

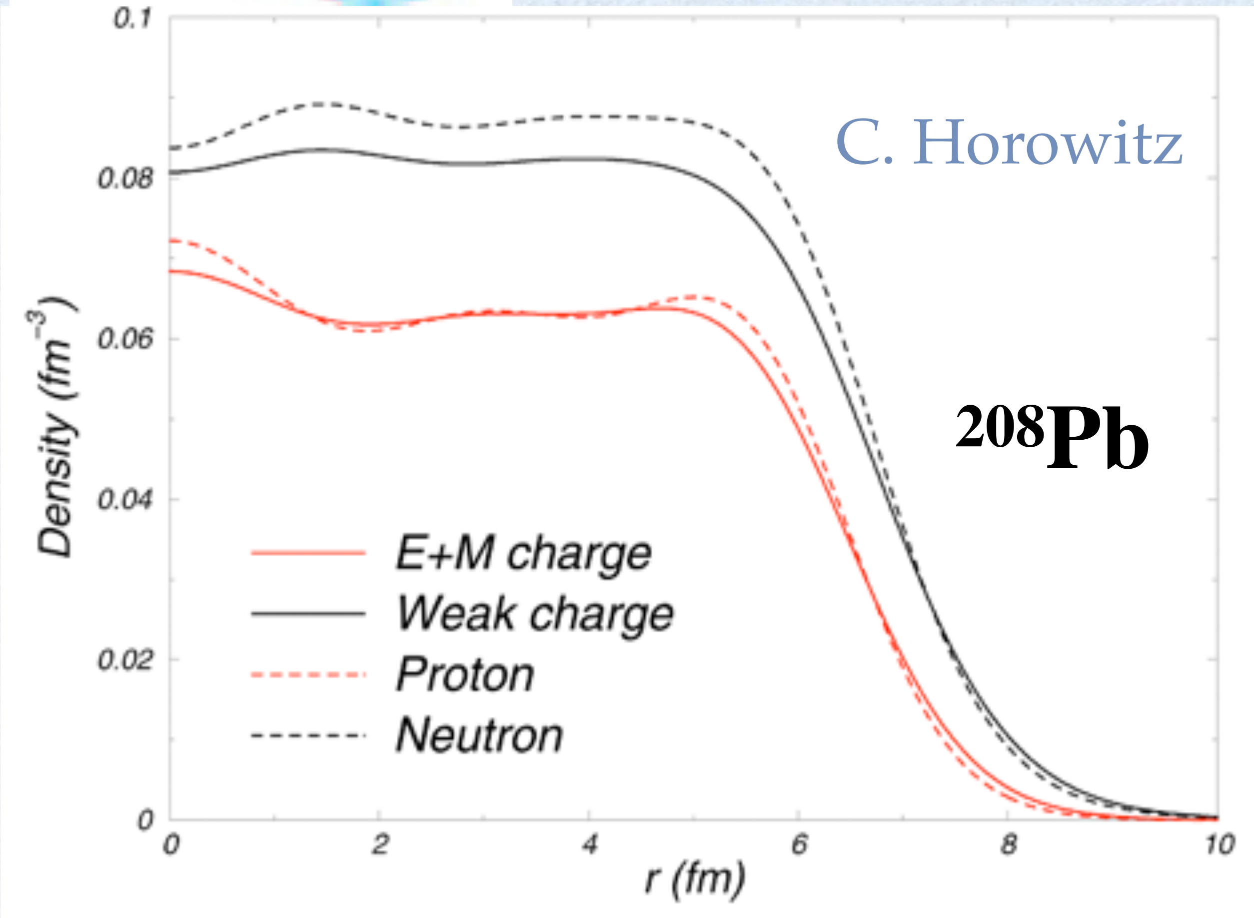


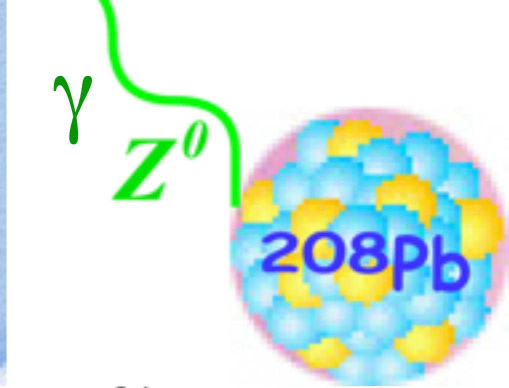
$Q^p_{EM} \sim 1$ $Q^n_{EM} \sim 0$ $Q^n_W \sim -1$ $Q^p_W \sim 1 - 4\sin^2\theta_W$

PREX Concept

Pb-Radius EXperiment



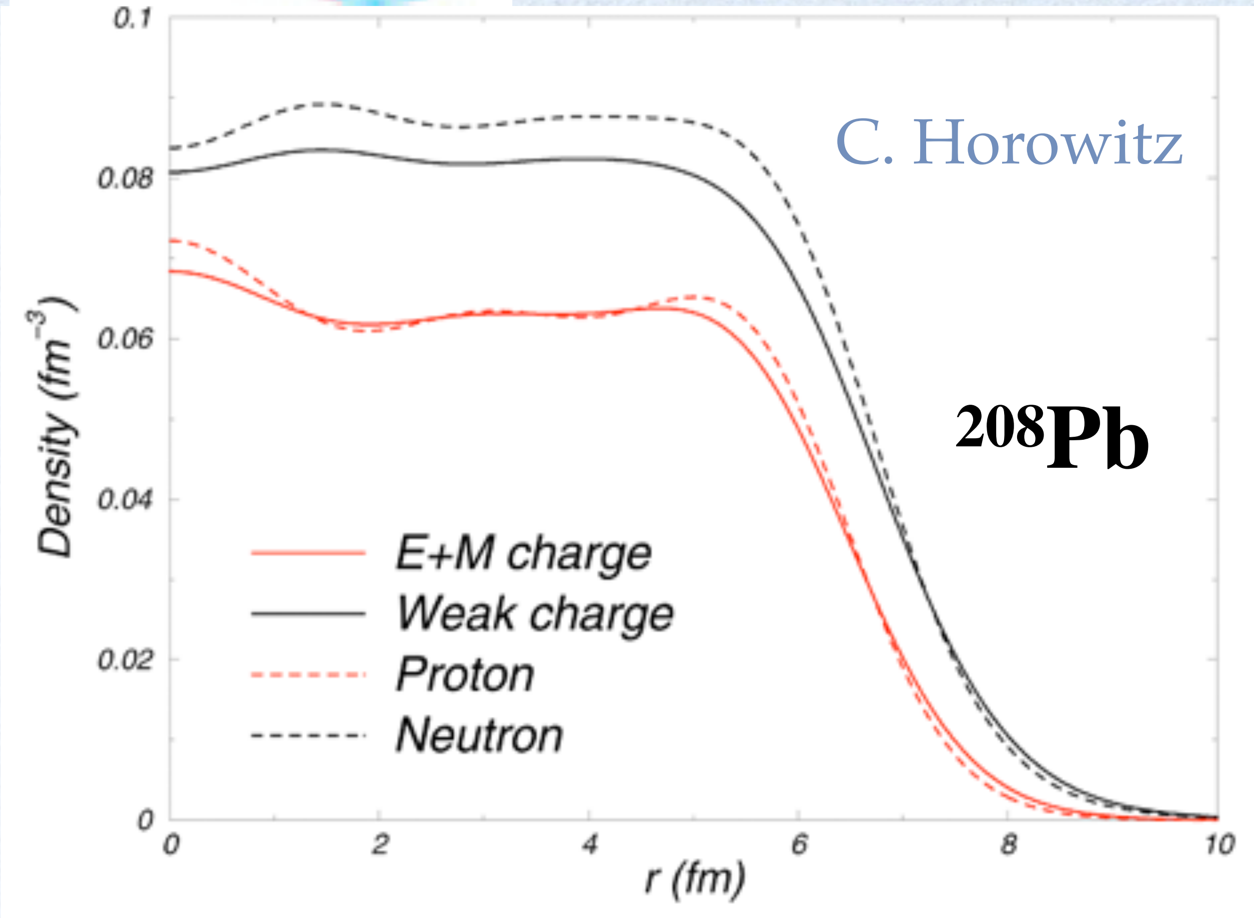




$Q^p_{EM} \sim 1$ $Q^n_{EM} \sim 0$ $Q^n_W \sim -1$ $Q^p_W \sim 1 - 4\sin^2\theta_W$

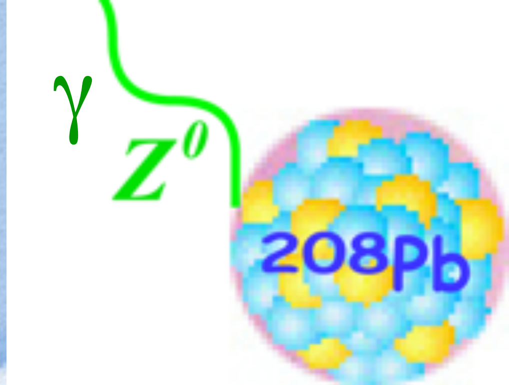
PREX Concept

Pb-Radius EXperiment



$$\mathcal{M}_{EM} \propto \frac{4\pi\alpha}{Q^2} F_{ch}(Q^2)$$

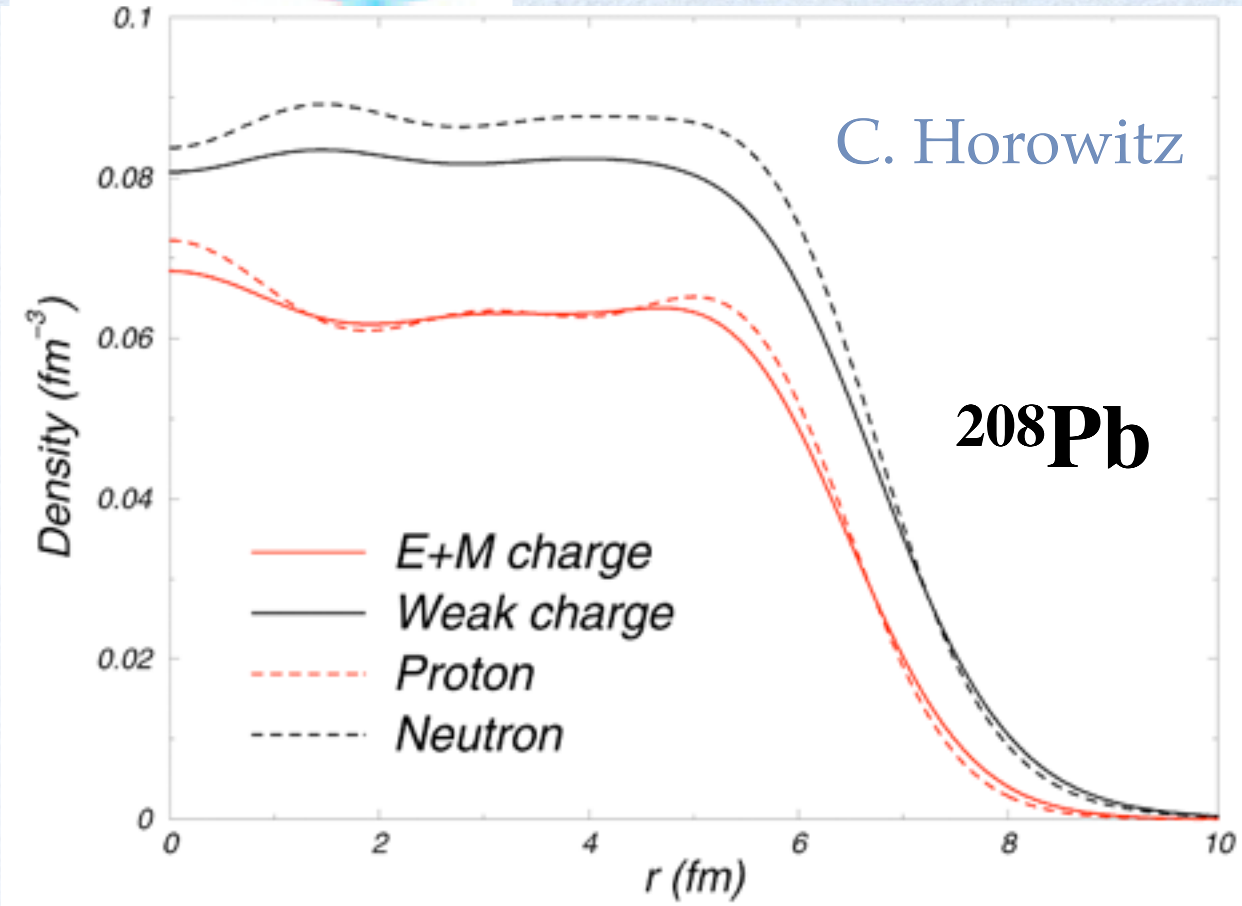
$$\mathcal{M}_{Weak} \propto \frac{G_F}{\sqrt{2}} \gamma_5 F_W(Q^2)$$



$Q^p_{EM} \sim 1$ $Q^n_{EM} \sim 0$ $Q^n_W \sim -1$ $Q^p_W \sim 1 - 4\sin^2\theta_W$

PREX Concept

Pb-Radius EXperiment



$$\mathcal{M}_{EM} \propto \frac{4\pi\alpha}{Q^2} F_{ch}(Q^2)$$

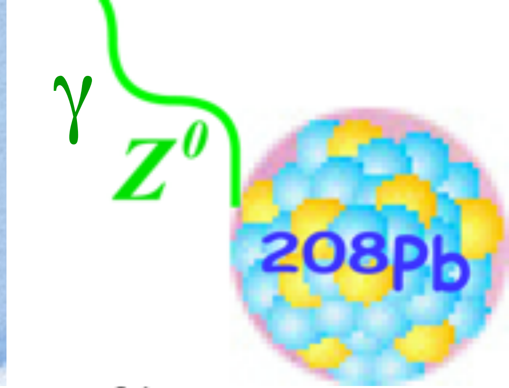
$$\mathcal{M}_{Weak} \propto \frac{G_F}{\sqrt{2}} \gamma_5 F_W(Q^2)$$

F_{ch} and F_W: Functions of single nucleon form factors F_p and F_n

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

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

$Q^p_{EM} \sim 1$ $Q^n_{EM} \sim 0$ $Q^n_W \sim -1$ $Q^p_W \sim 1 - 4\sin^2\theta_W$

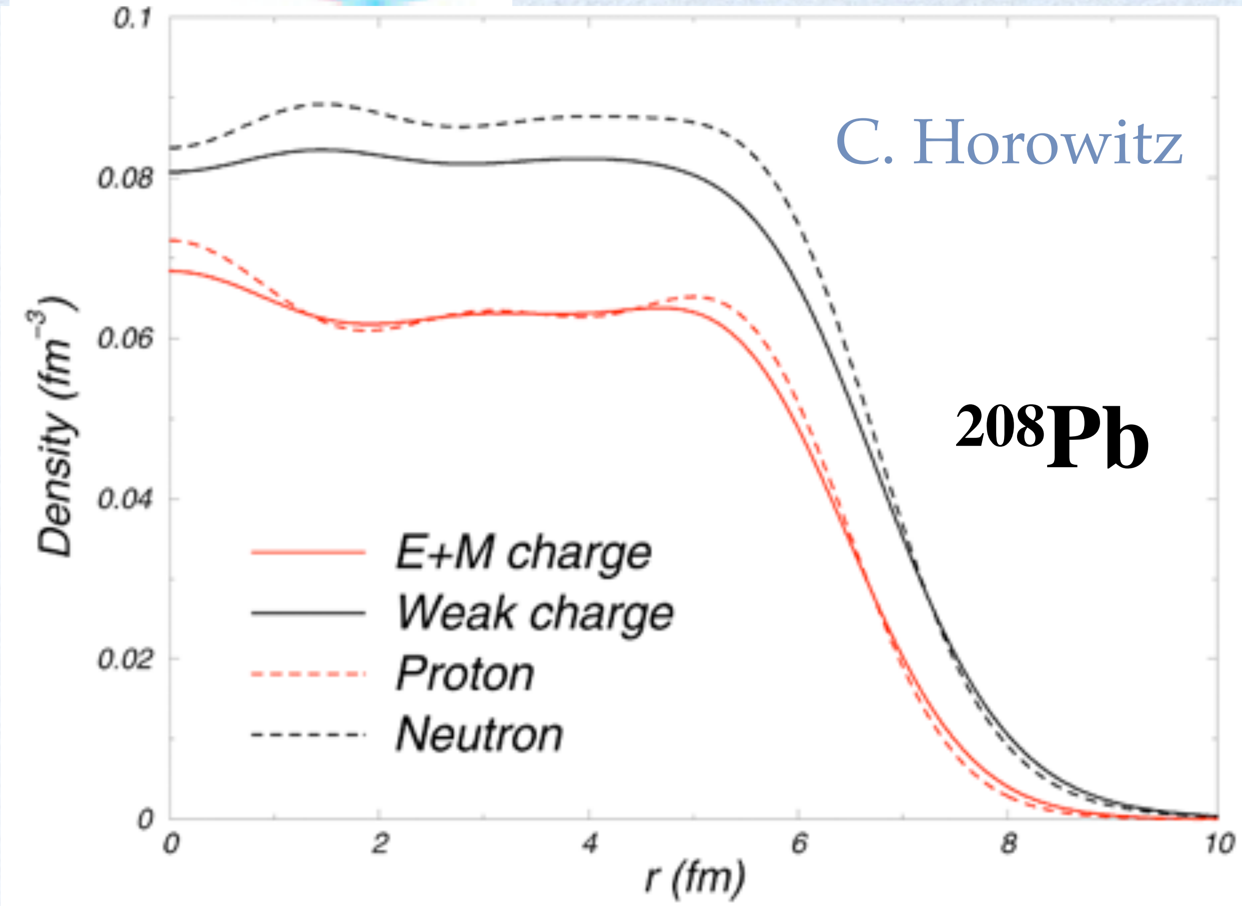


PREX Concept

Pb-Radius EXperiment

$$\mathcal{M}_{EM} \propto \frac{4\pi\alpha}{Q^2} F_{ch}(Q^2)$$

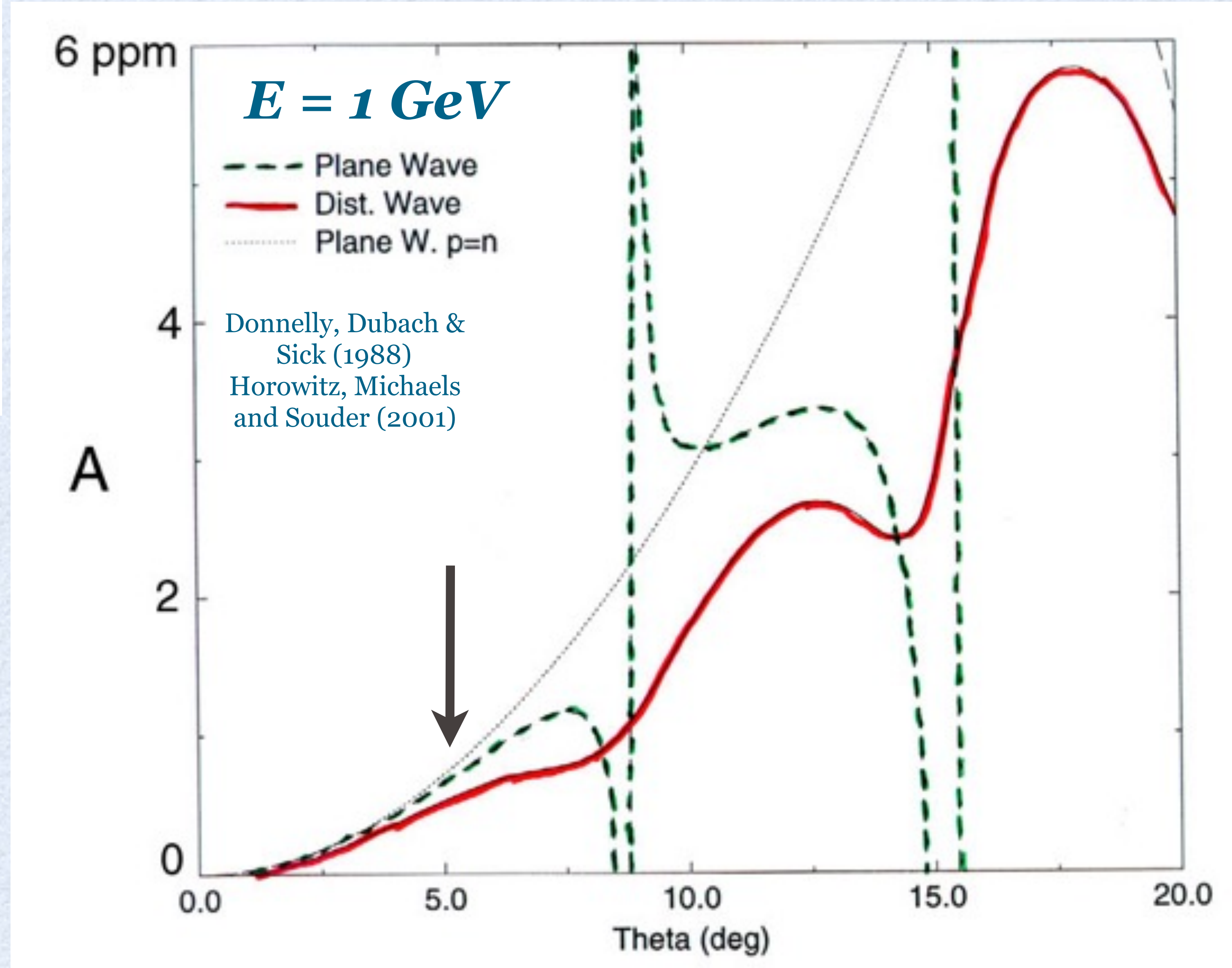
$$\mathcal{M}_{Weak} \propto \frac{G_F}{\sqrt{2}} \gamma_5 F_W(Q^2)$$



F_{ch} and F_W: Functions of single nucleon form factors F_p and F_n

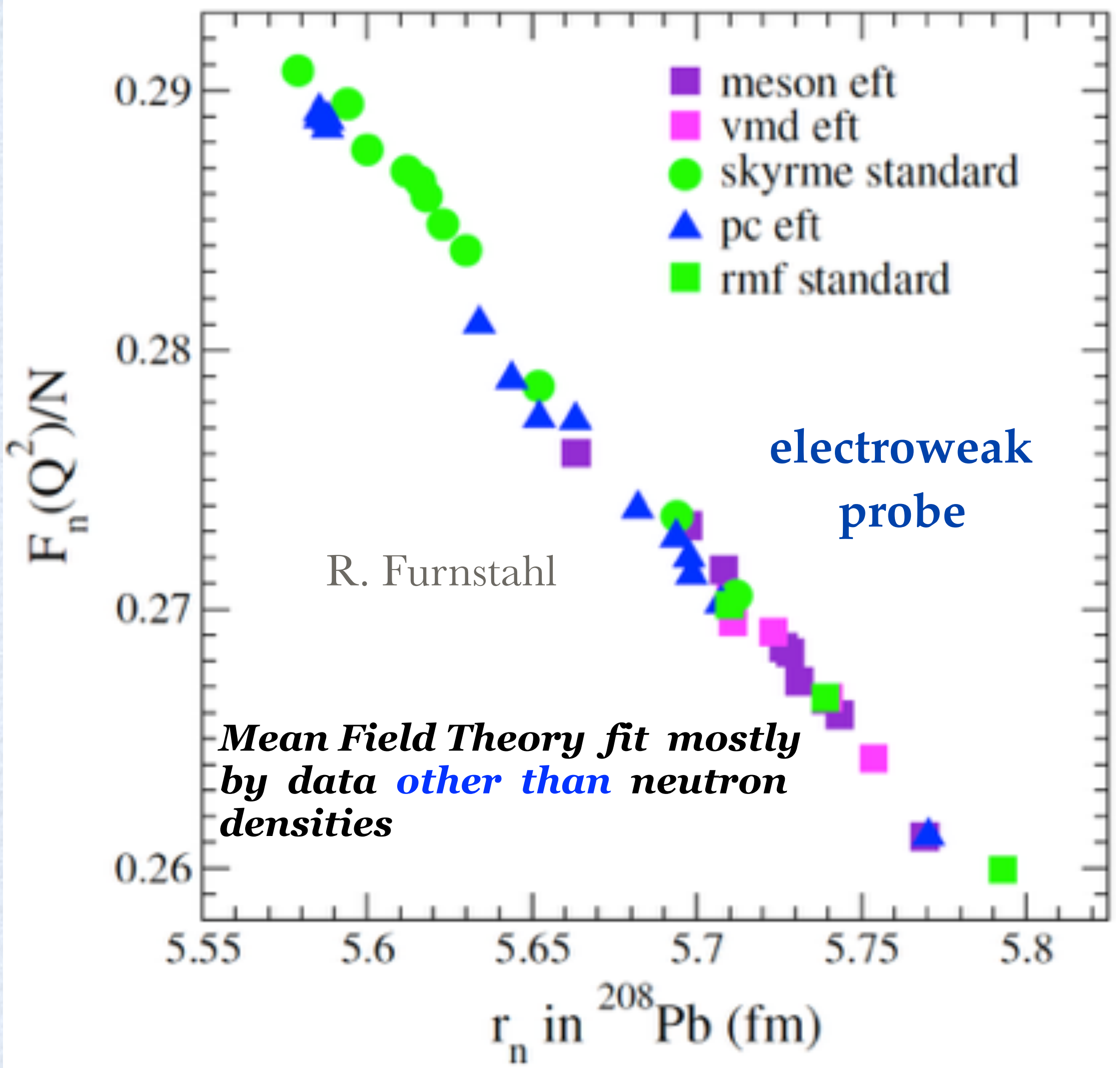
$$A_{PV} \approx \frac{G_F Q^2}{4\pi\alpha\sqrt{2}} \frac{F_n(Q^2)}{F_p(Q^2)} + \ldots$$

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



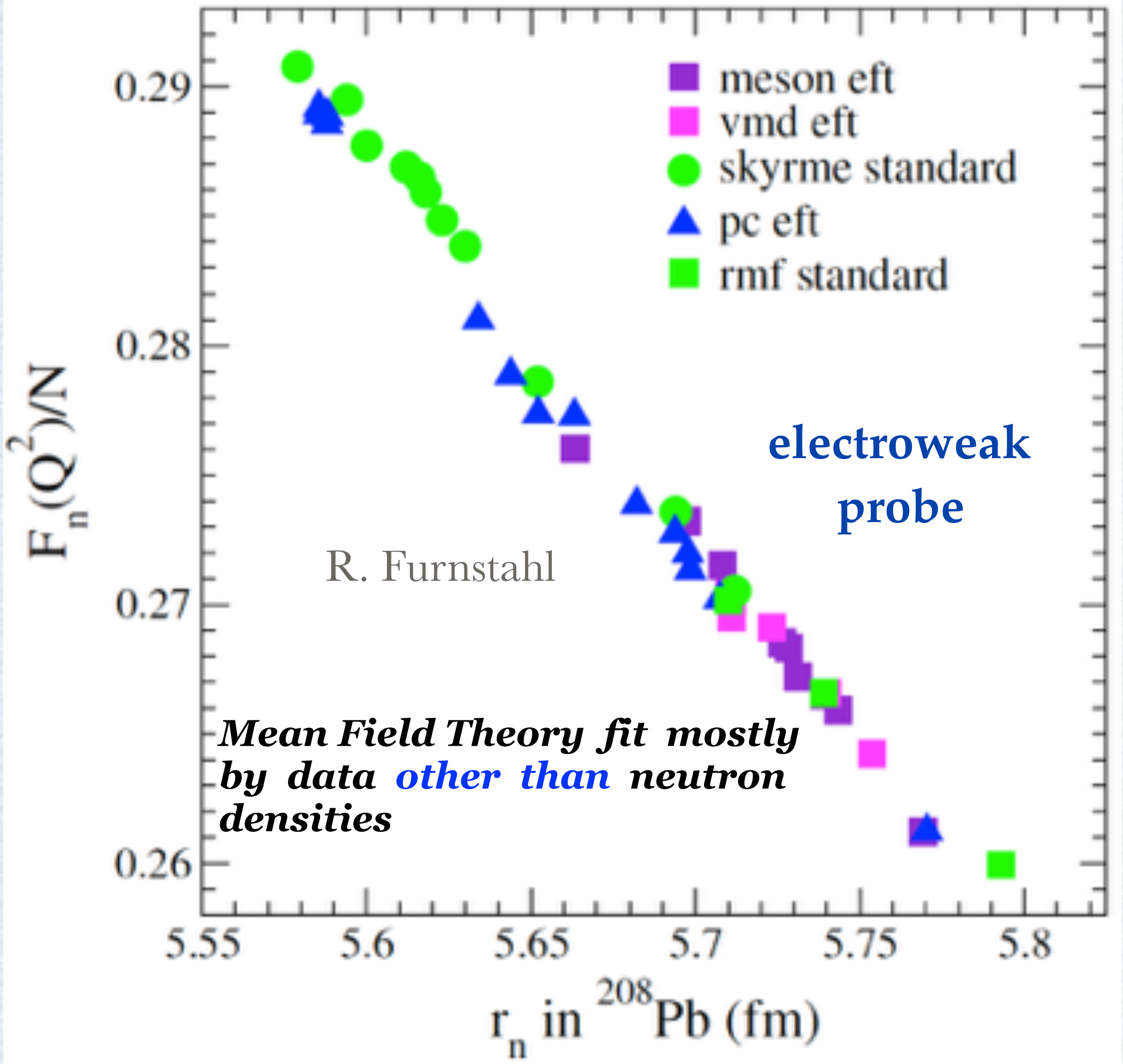
Cleanly Interpretable?

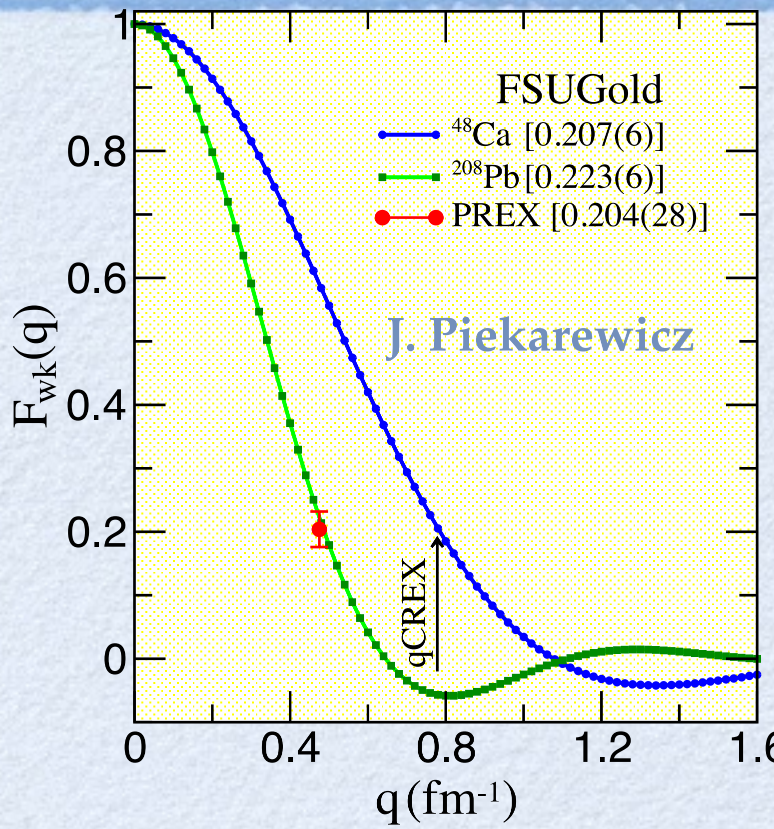
Pb-Radius EXperiment

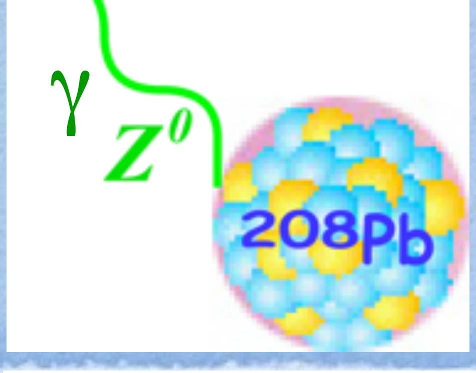


Cleanly Interpretable?

Pb-Radius EXperiment

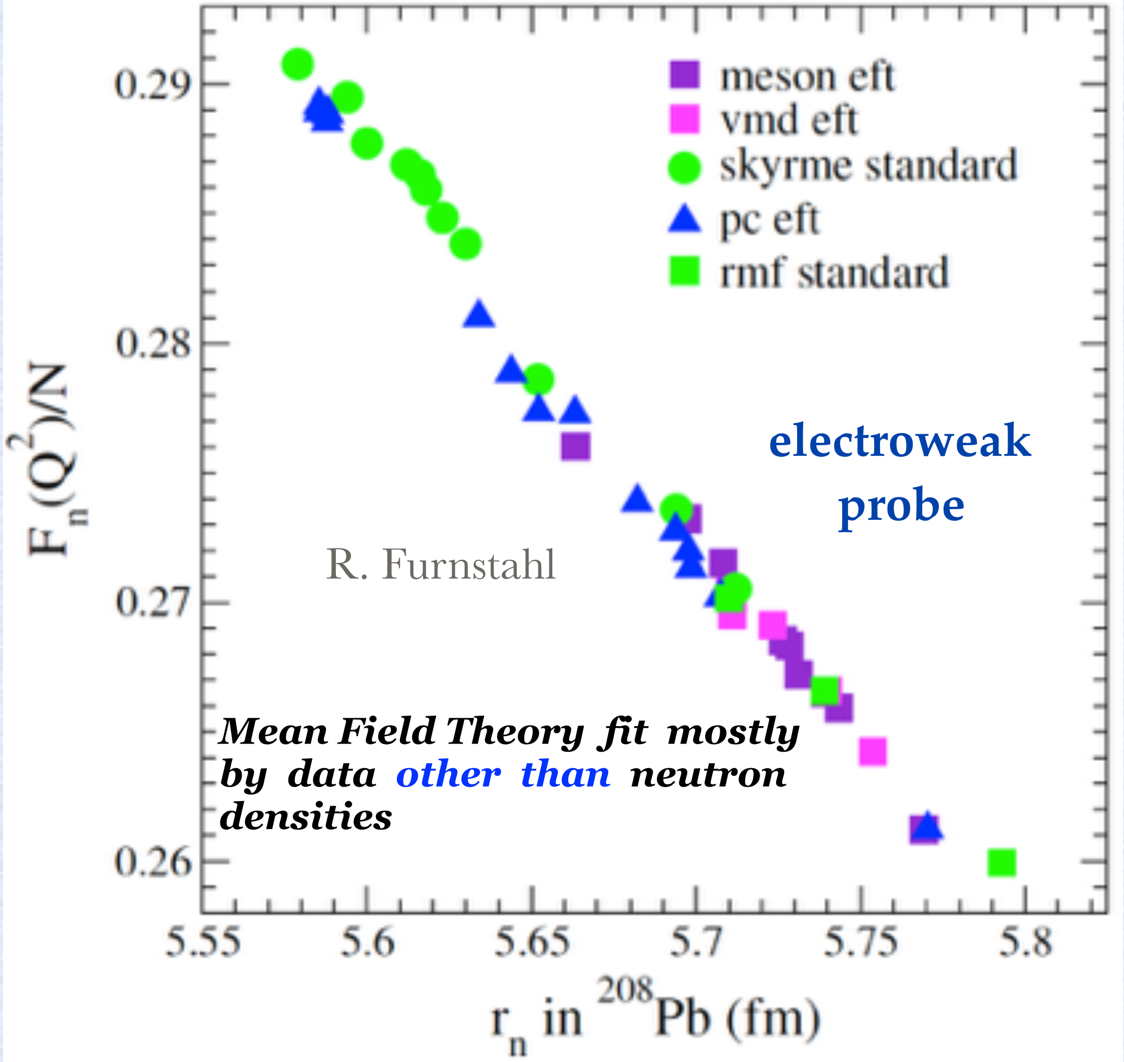






Cleanly Interpretable?

Pb-Radius EXperiment



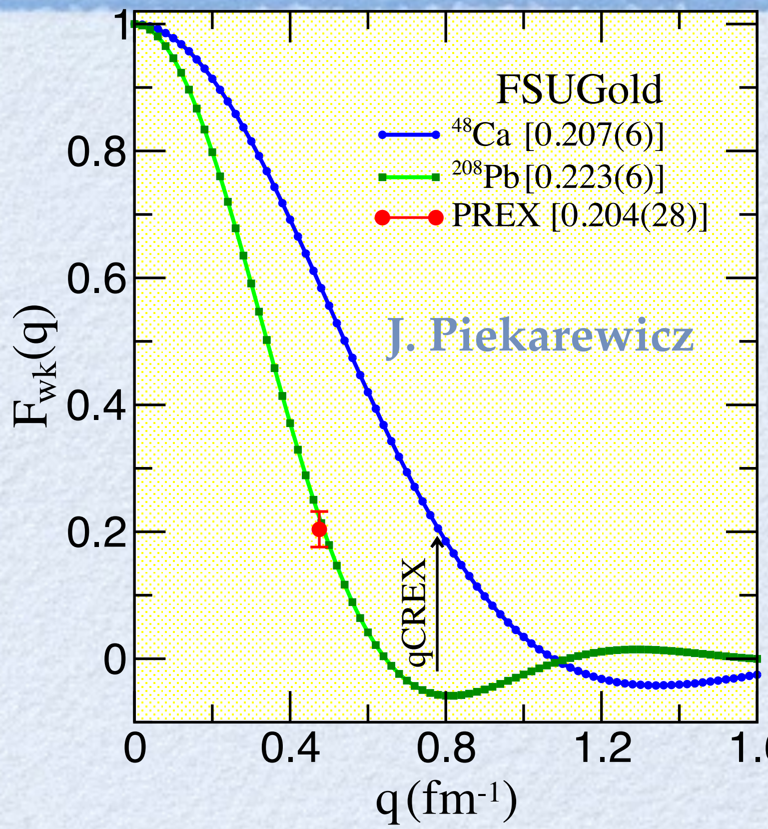
Q^2 ~ 0.01 GeV^2

5^o scattering angle

A_{PV} ~ 0.7 ppm

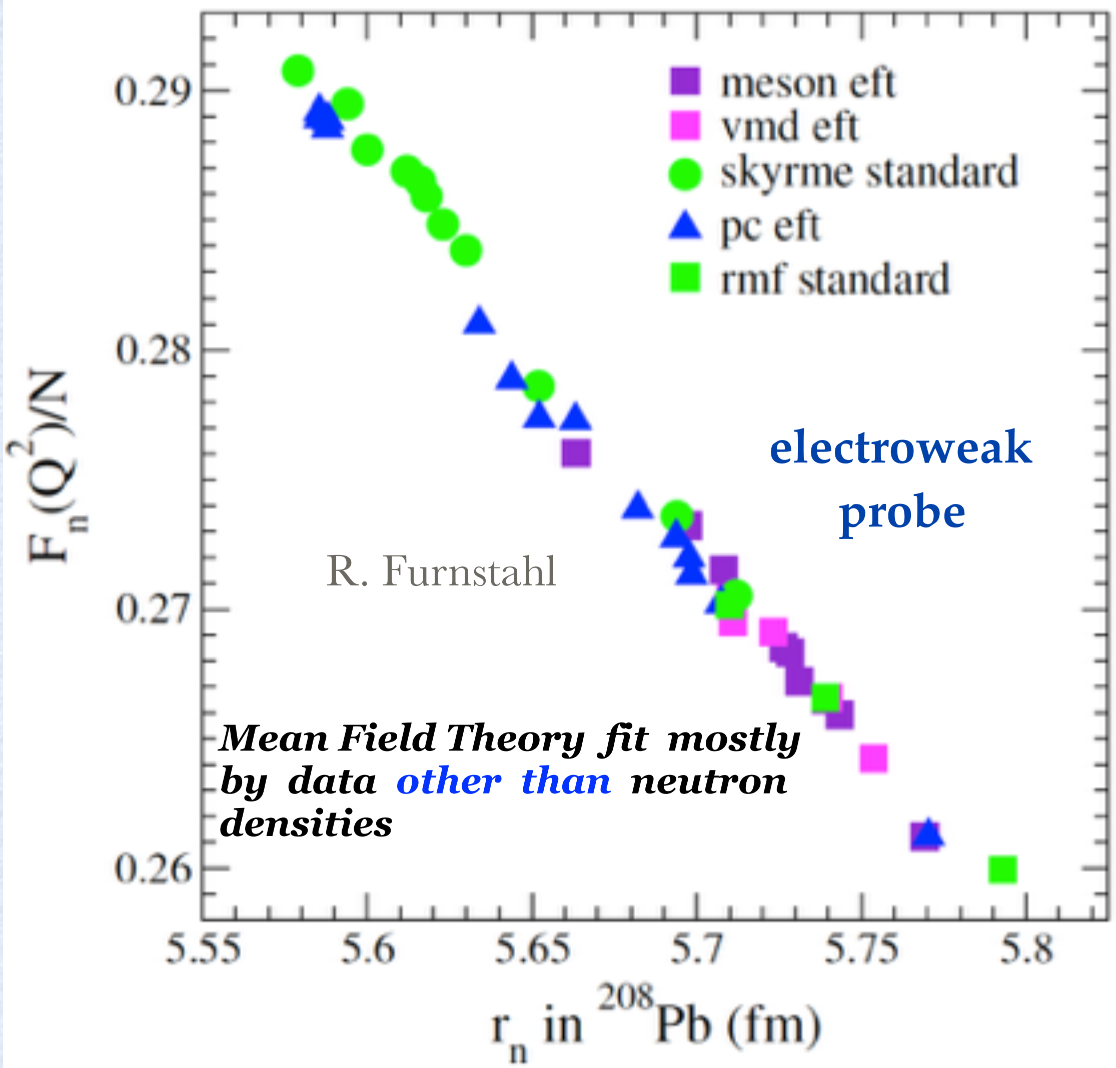
Rate ~ 1 GHz

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



Cleanly Interpretable?

Pb-Radius EXperiment



Q^2 ~ 0.01 GeV^2

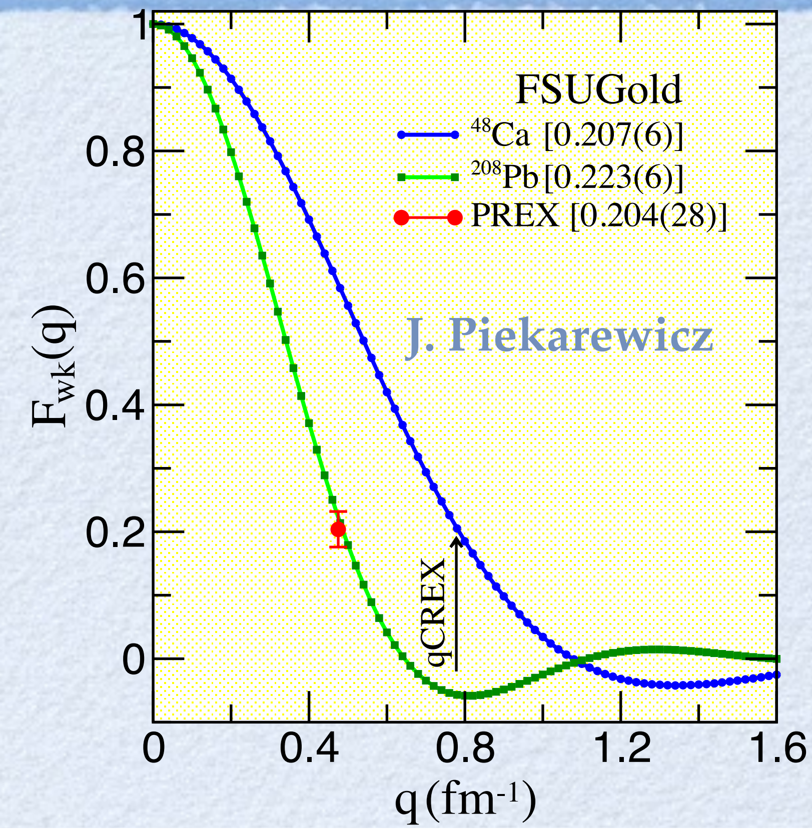
5^o scattering angle

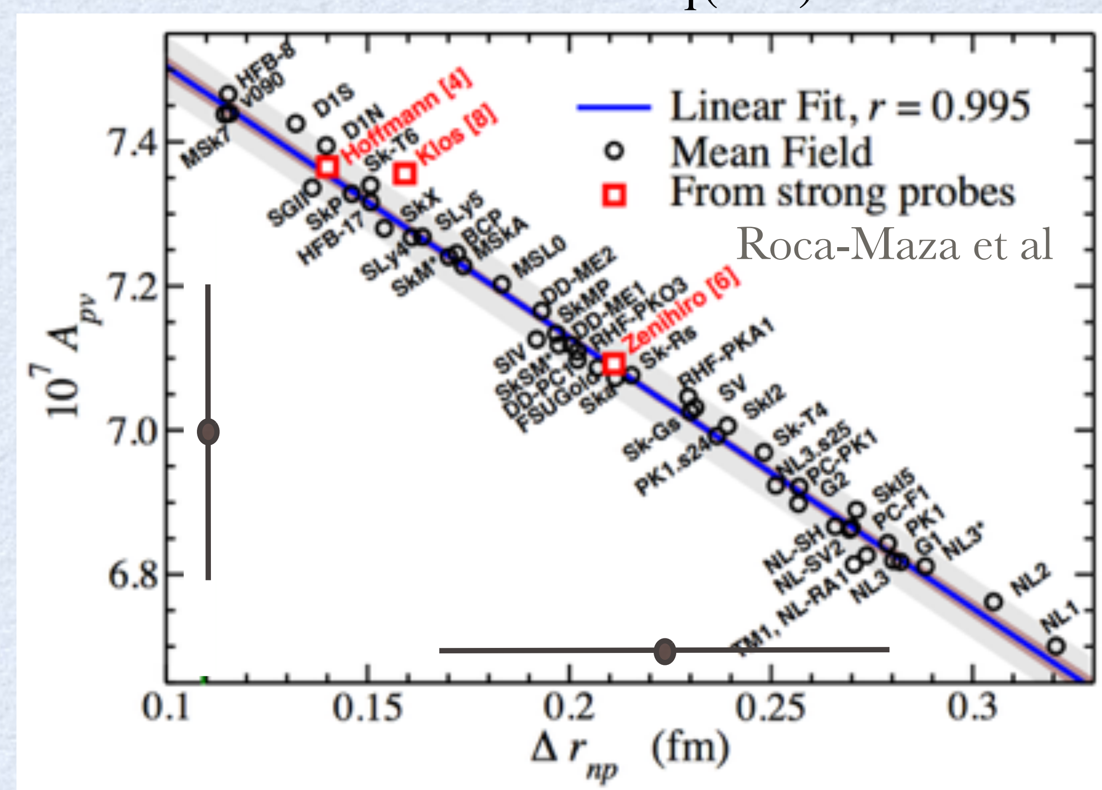
⇩

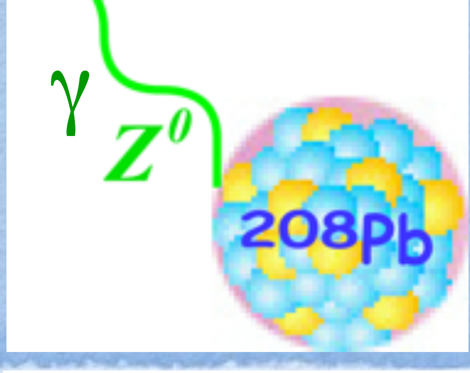
A_{PV} ~ 0.7 ppm

Rate ~ 1 GHz

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

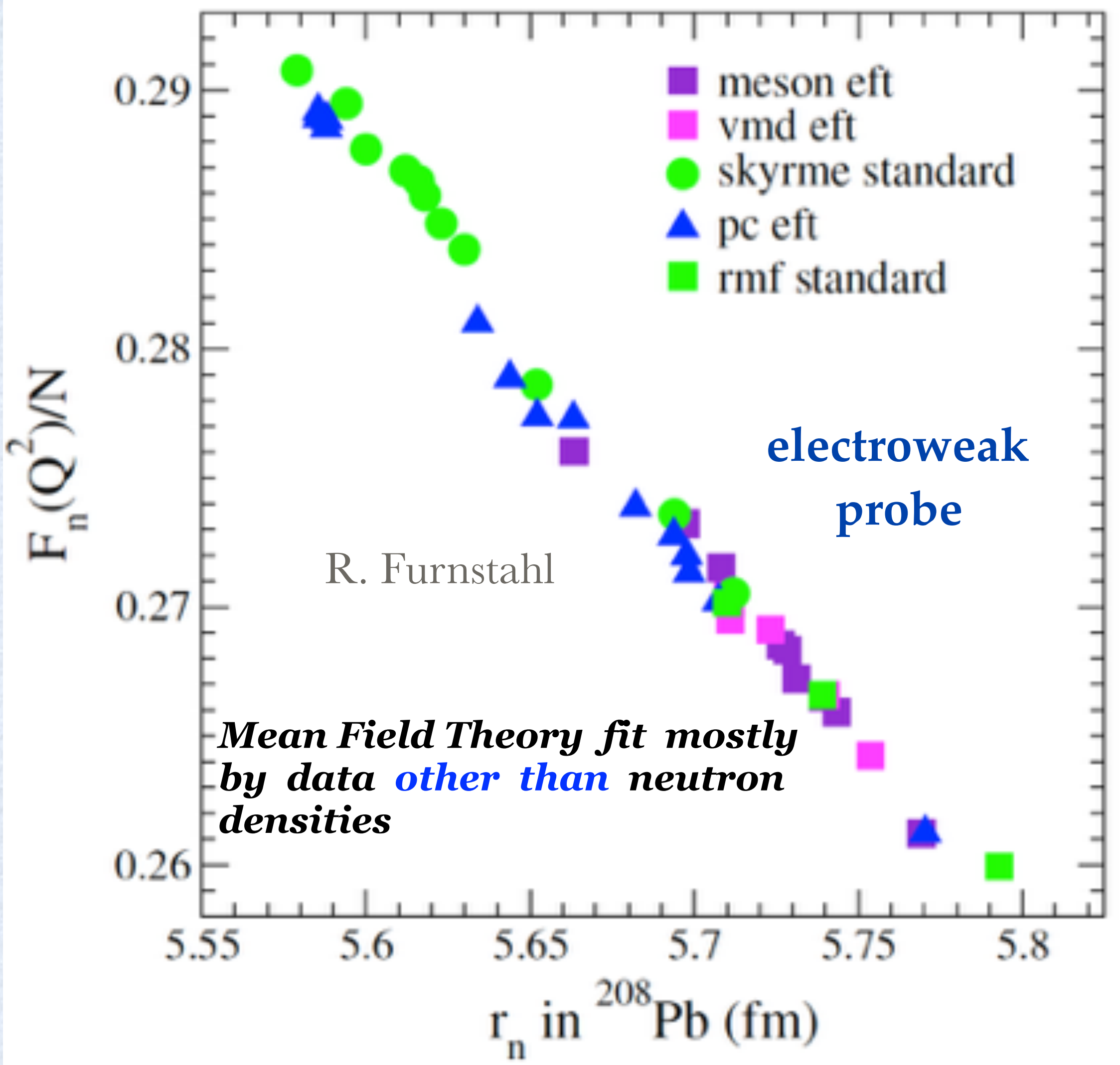






Cleanly Interpretable?

Pb-Radius EXperiment



Q^2 ~ 0.01 GeV^2

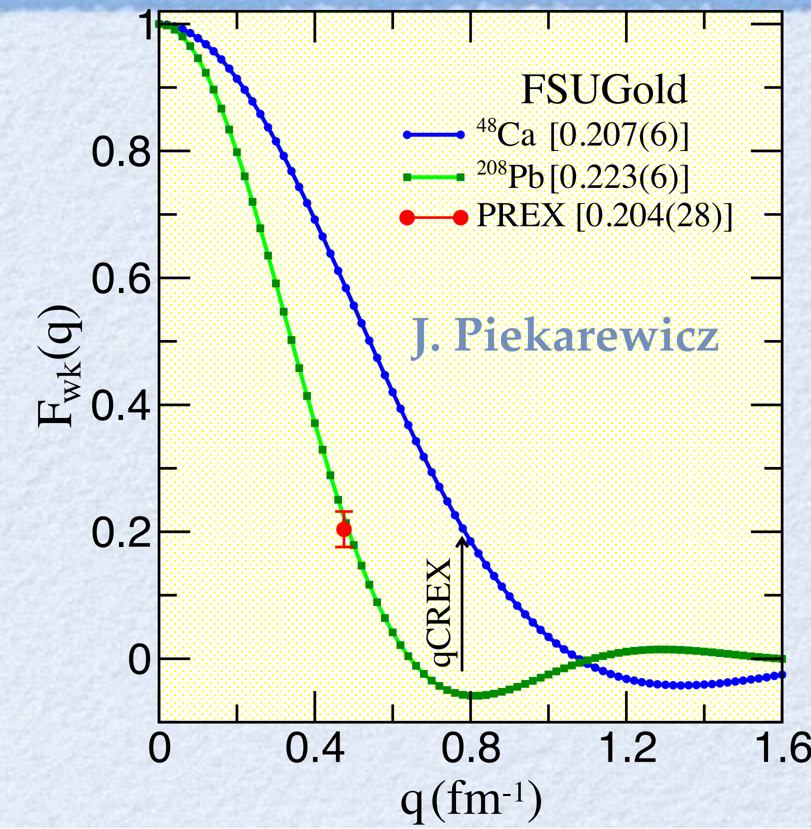
5° scattering angle

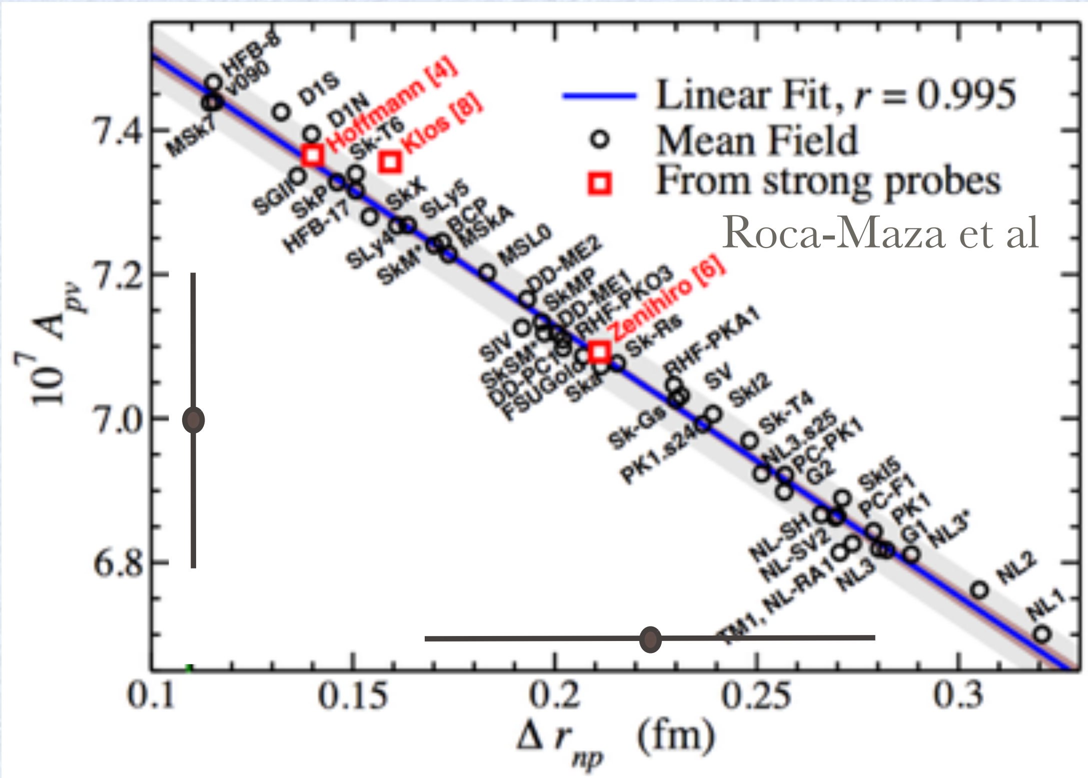
⇩

A_{PV} ~ 0.7 ppm

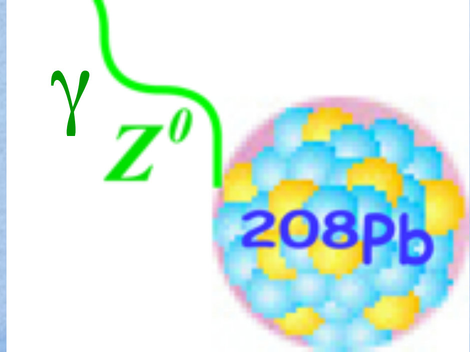
Rate ~ 1 GHz

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



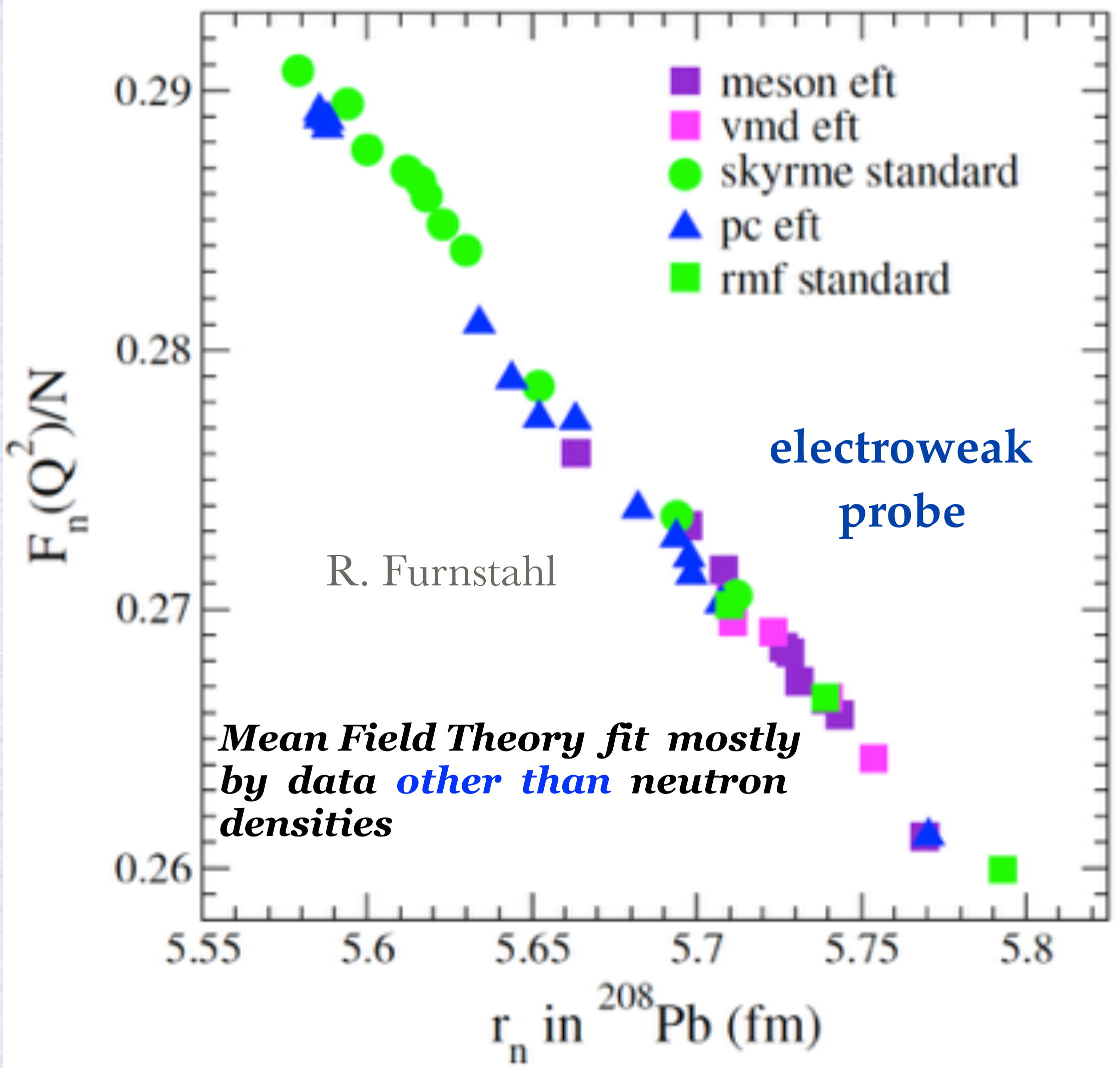


- ***Clean "translation" from A_{PV} uncertainty to neutron RMS radius uncertainty***
- ***A_{PV} uncertainty dominated by statistics!***



Cleanly Interpretable?

Pb-Radius EXperiment



Q^2 ~ 0.01 GeV^2

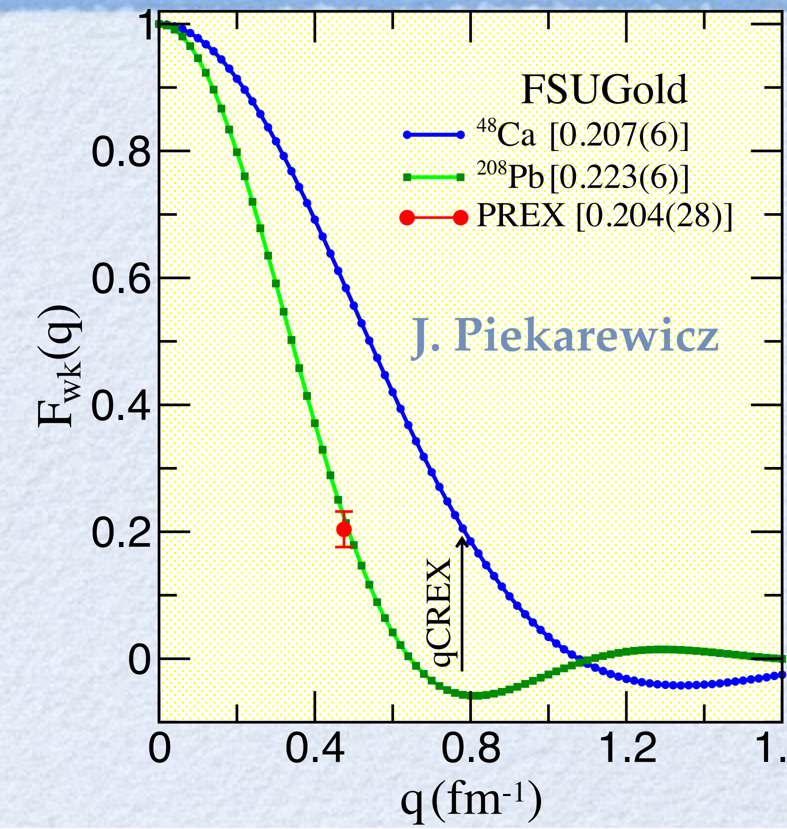
5^o scattering angle

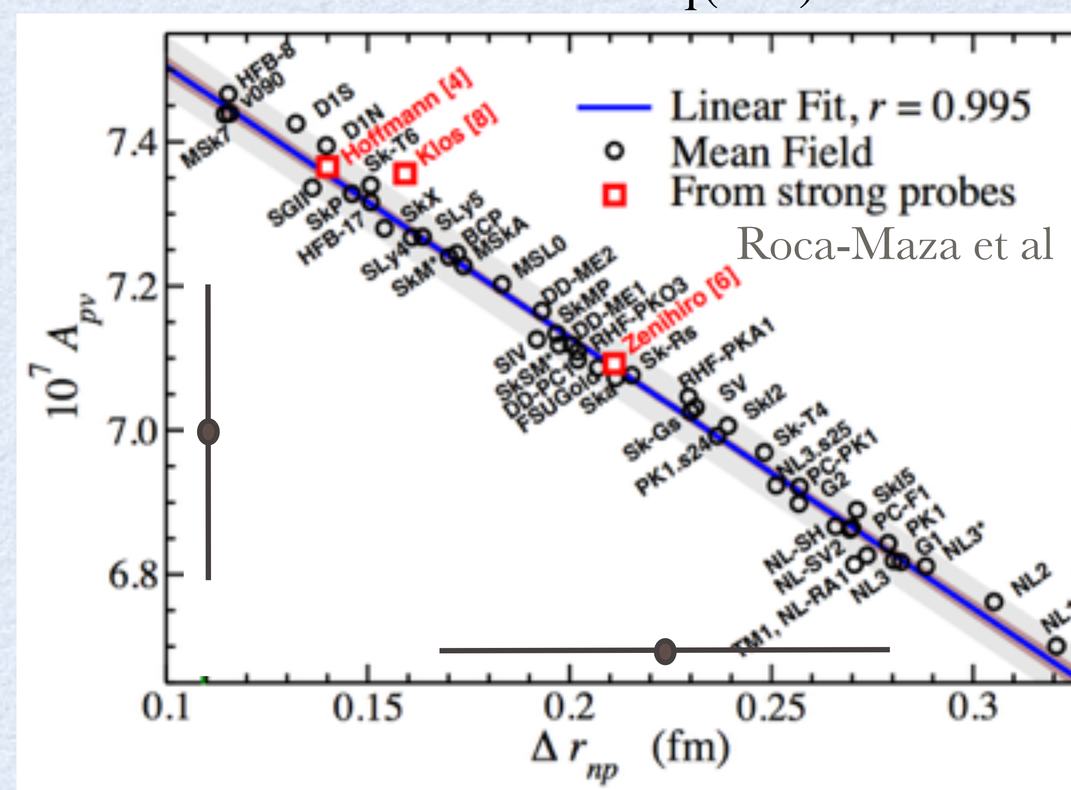
⇩

A_{PV} ~ 0.7 ppm

Rate ~ 1 GHz

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





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

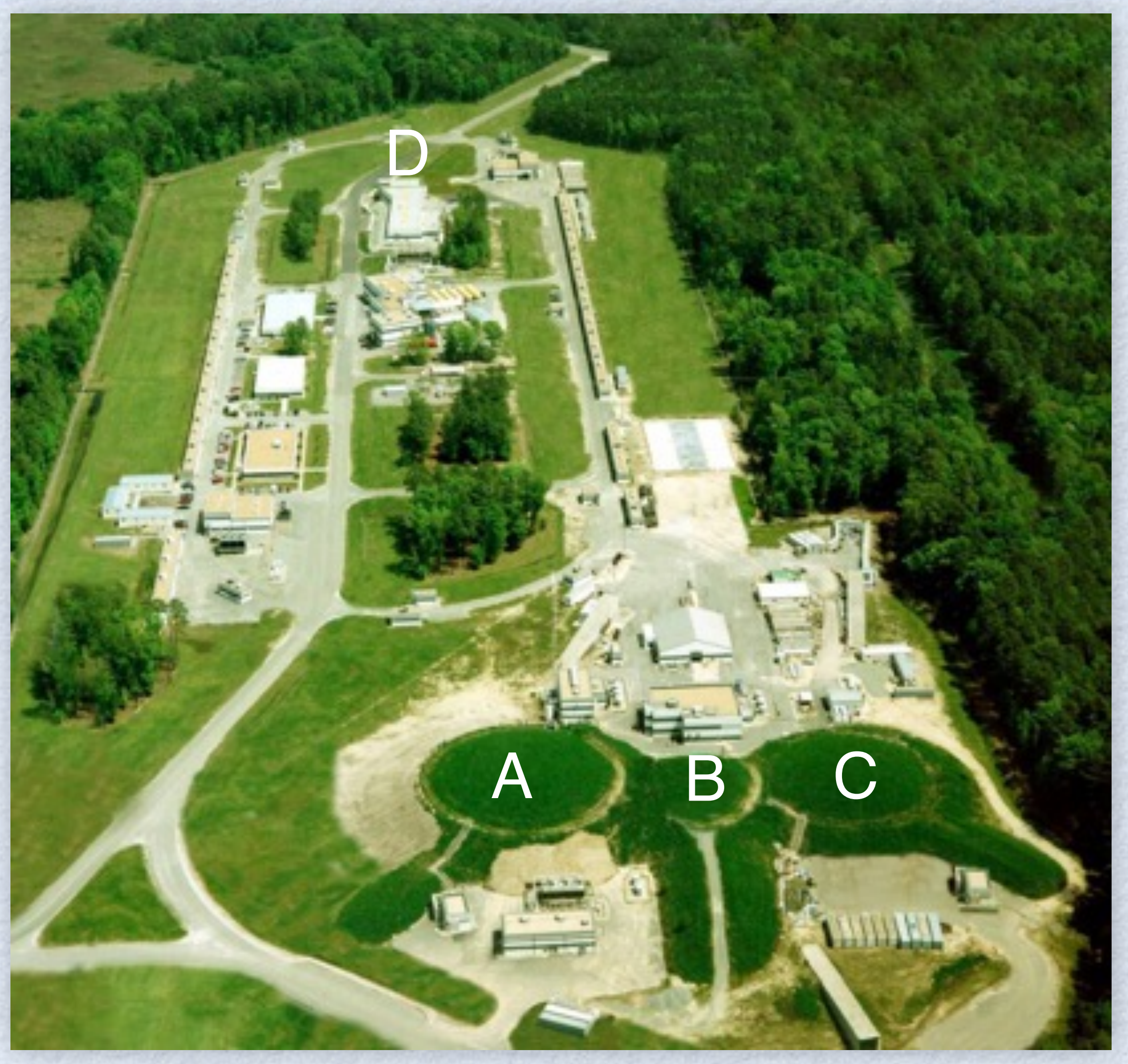
At this level of precision, one must account carefully for radiative corrections

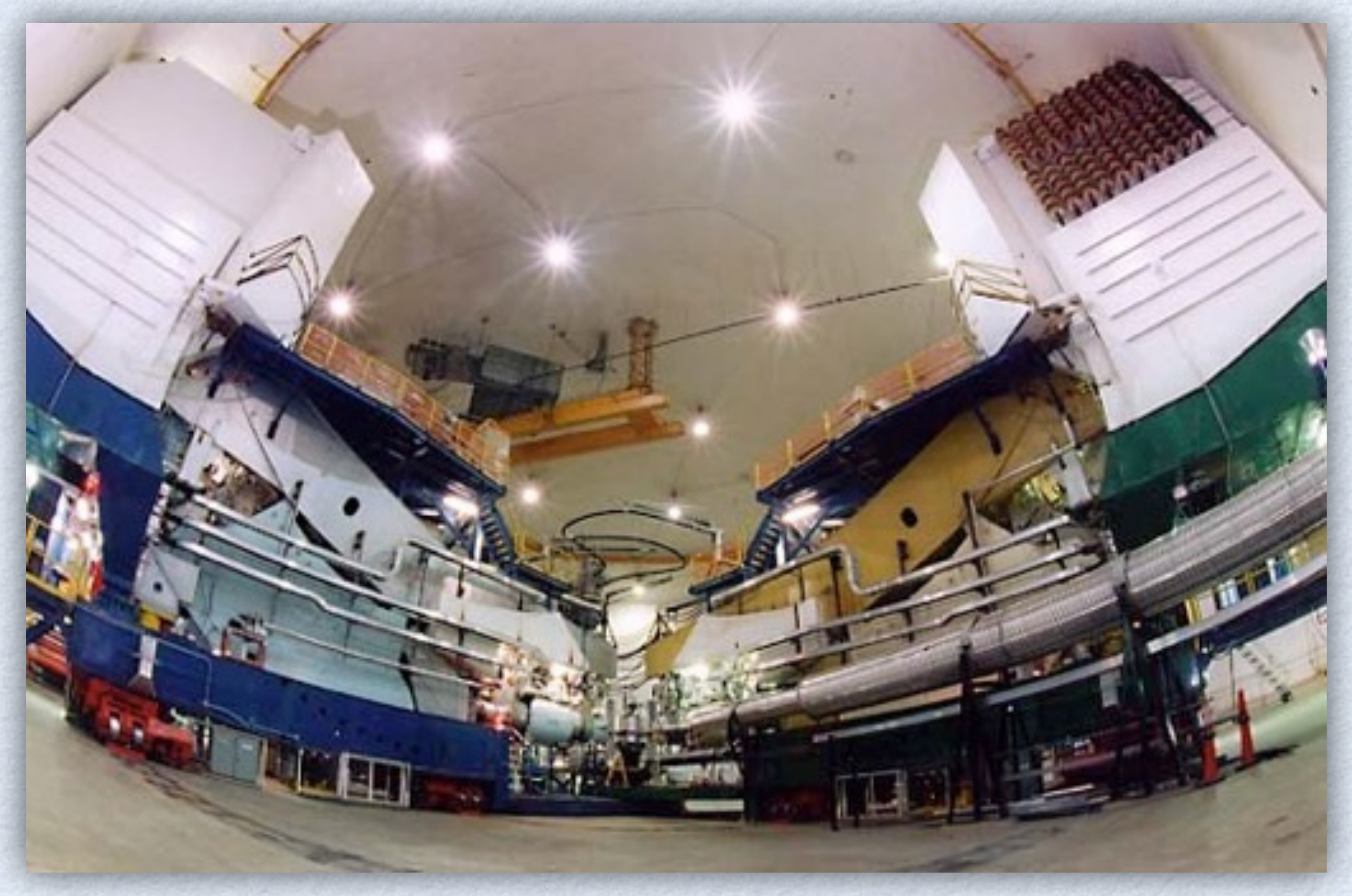
PREX Overview

1 GeV electron beam, 50-70 μA

high polarization, ~89%

helicity reversal at 120 Hz





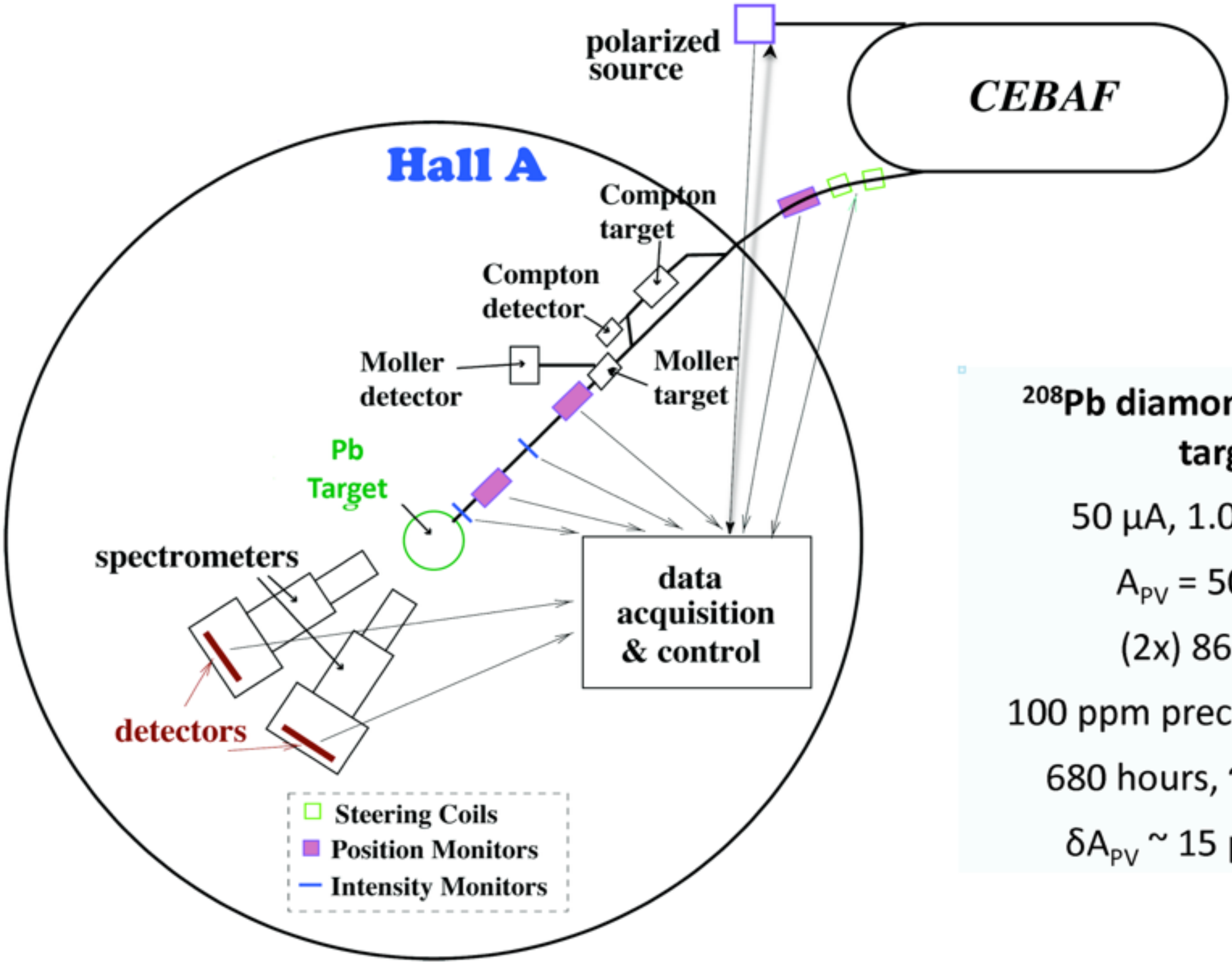
0.5 mm isotopically pure ^{208}Pb target

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

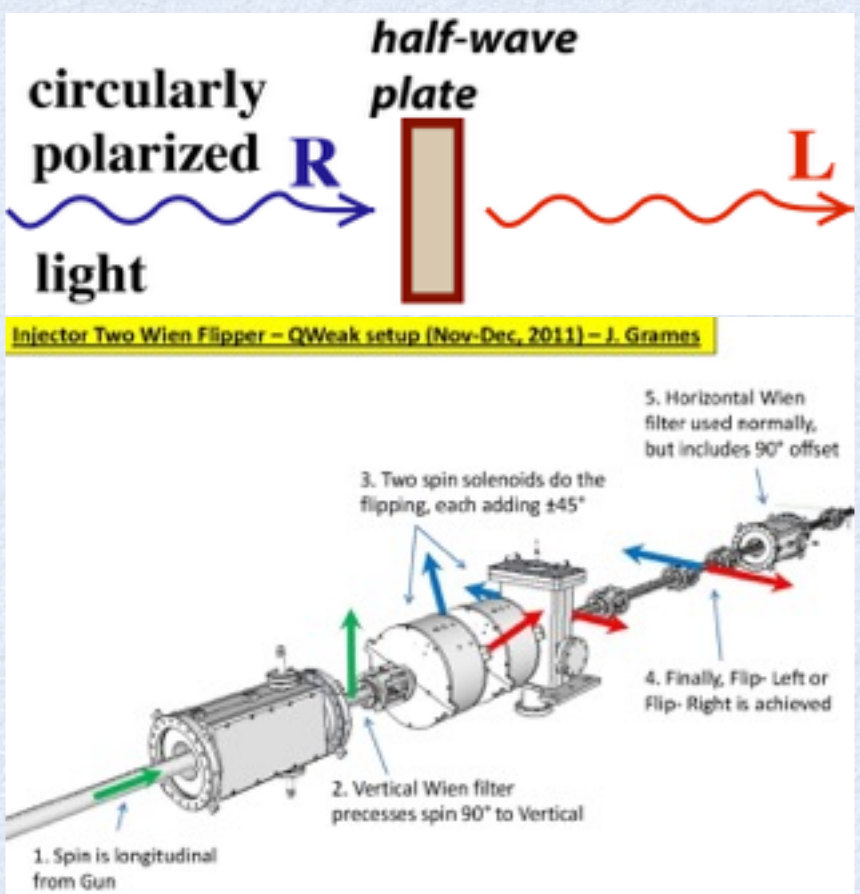
Record Performance (2012):
180 μA at 89% polarization

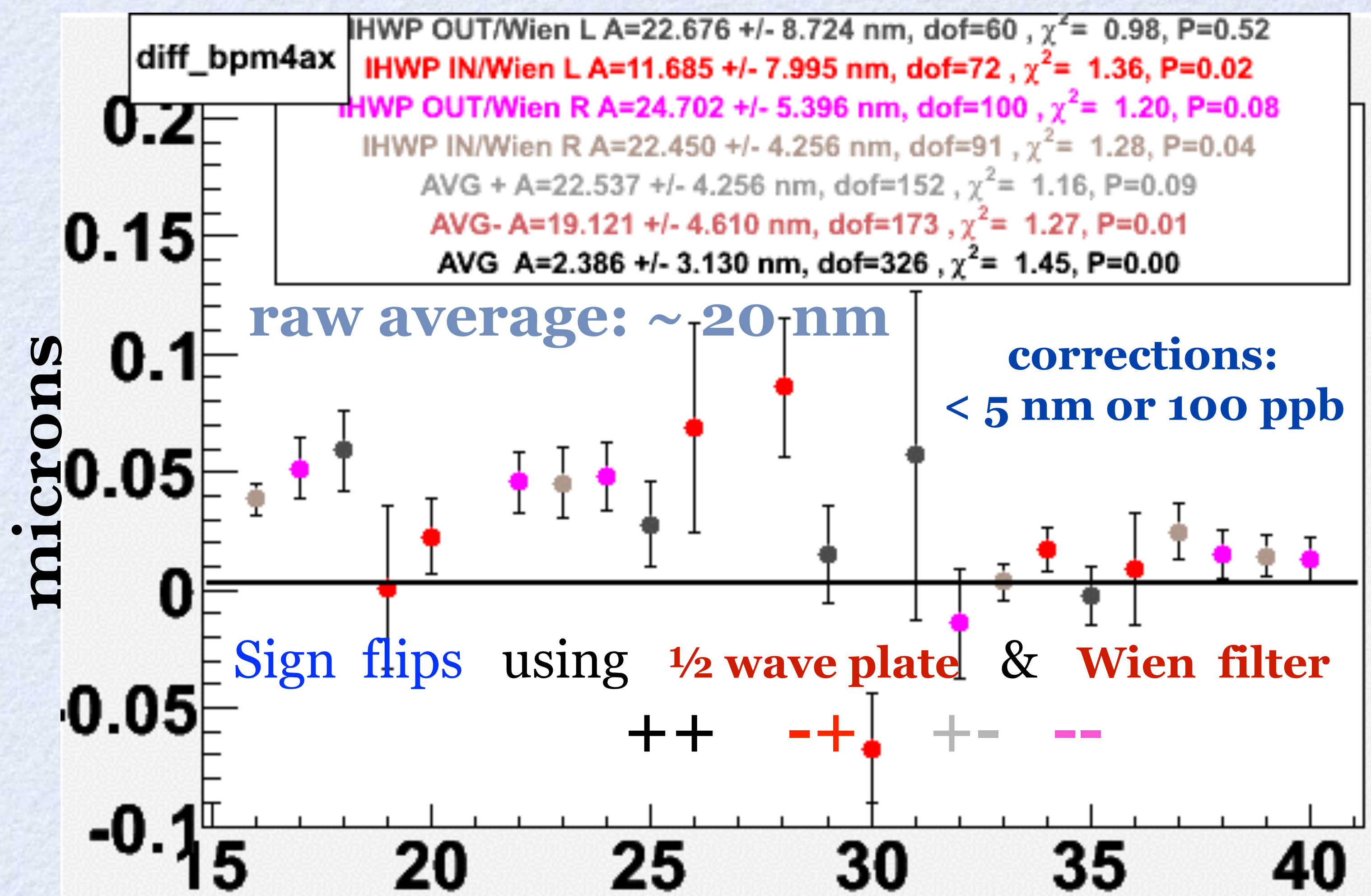
Electron Gun Requirements

- Ultrahigh vacuum
- No field emission
- Maintenance-free

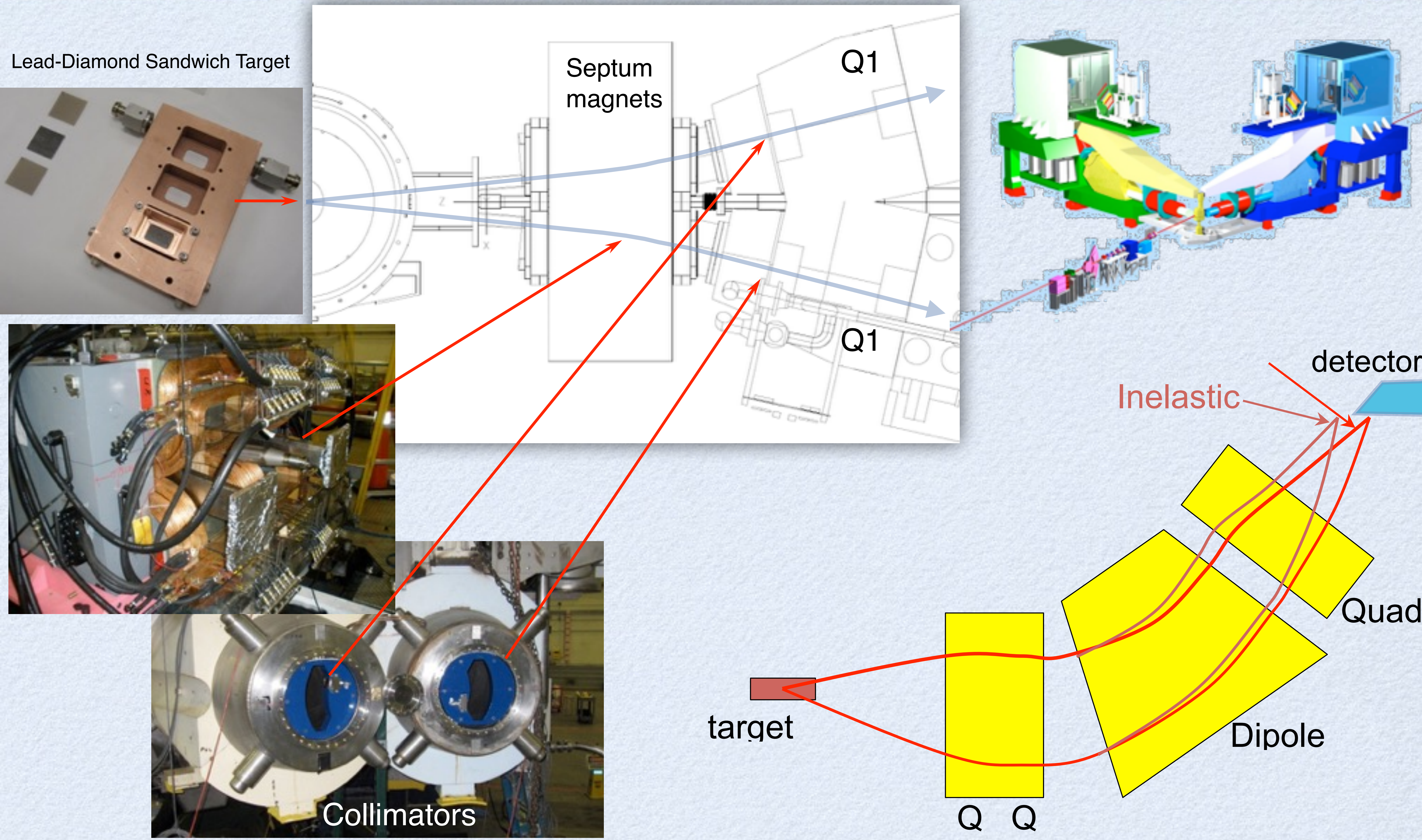
$A_{raw} \sim 500$ ppb

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



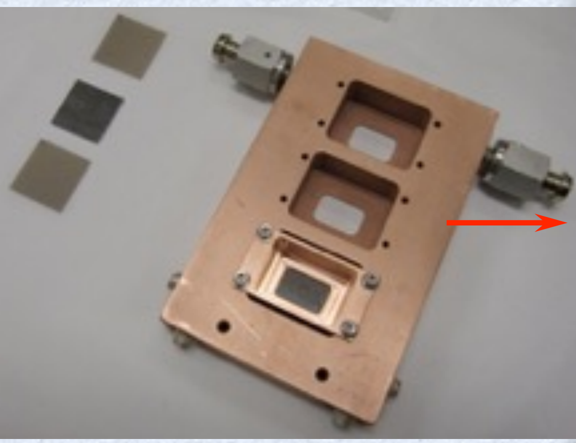


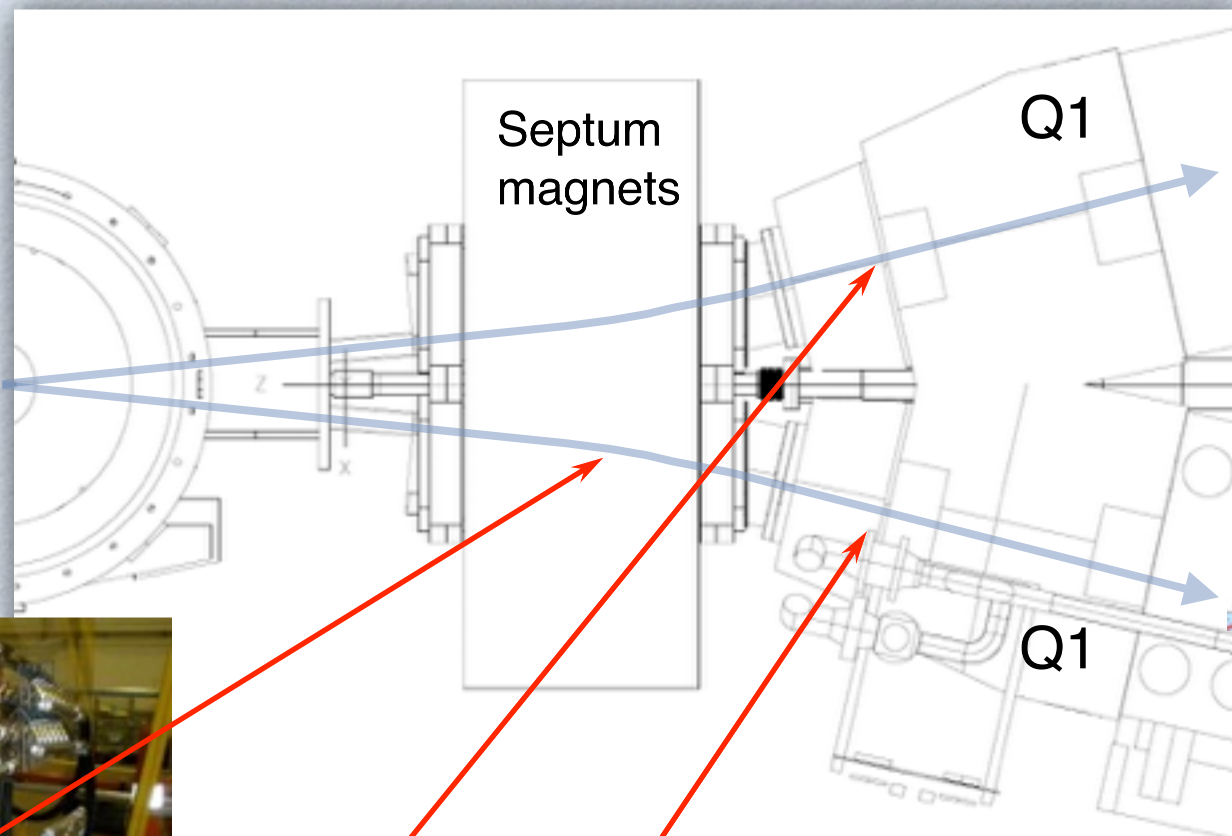
Target and Spectrometers

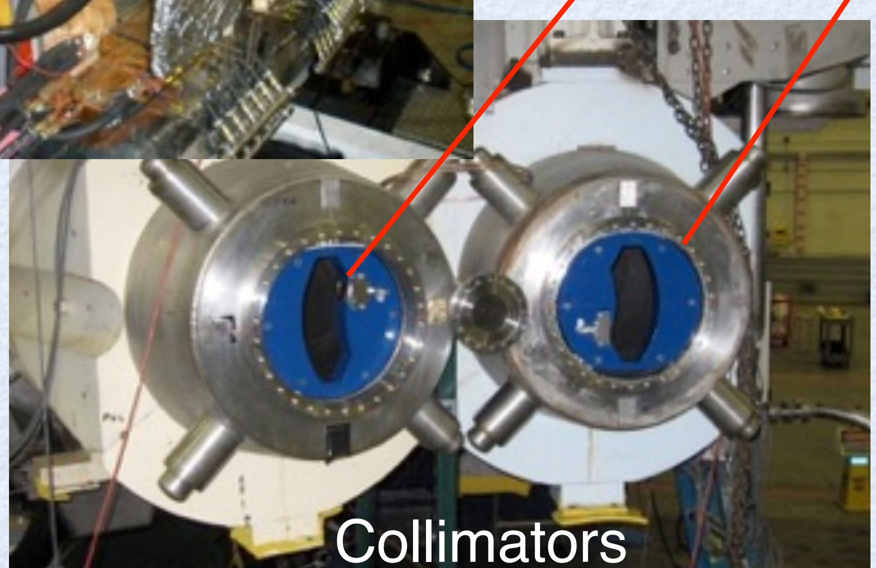


Target and Spectrometers

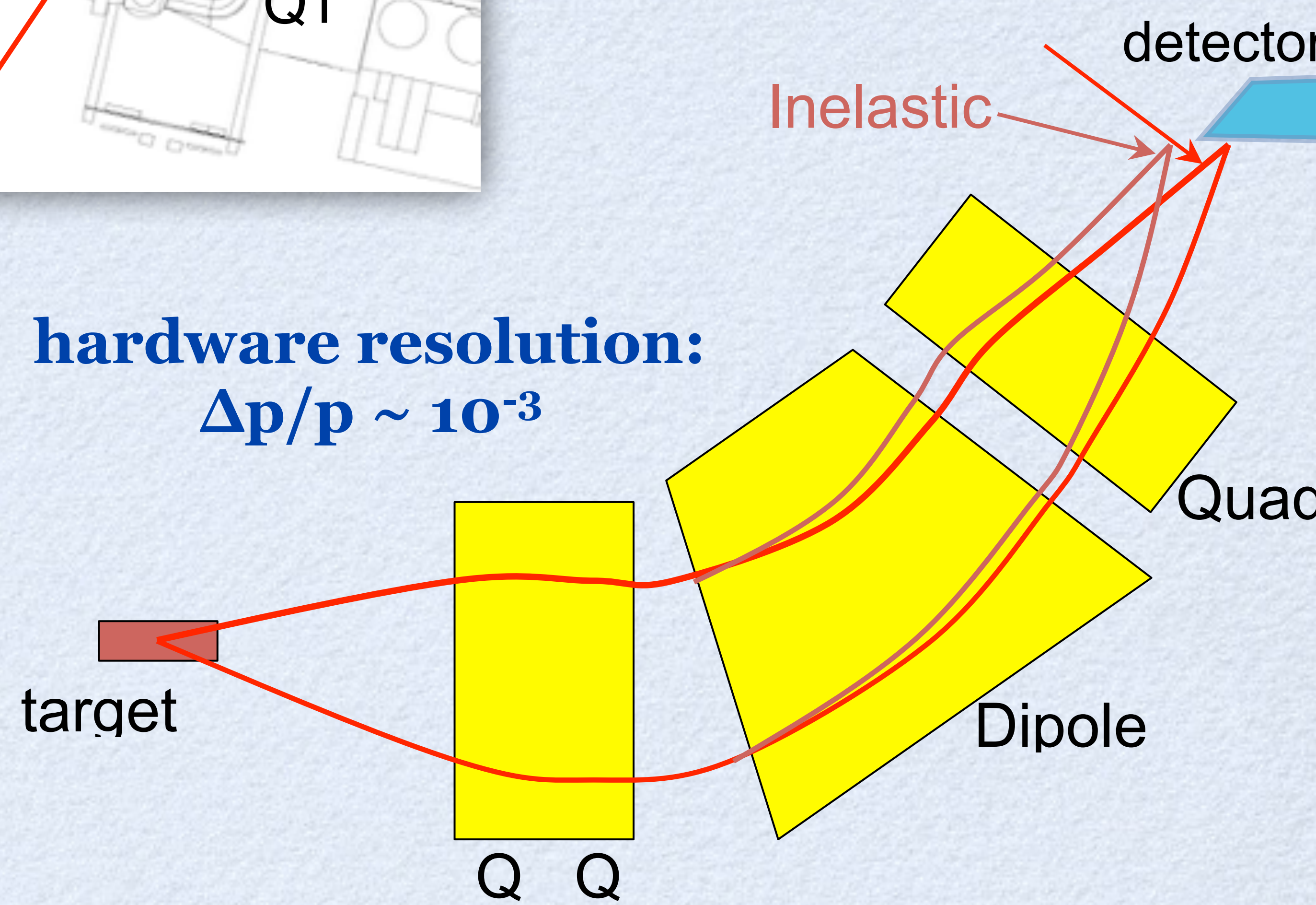
Lead-Diamond Sandwich Target





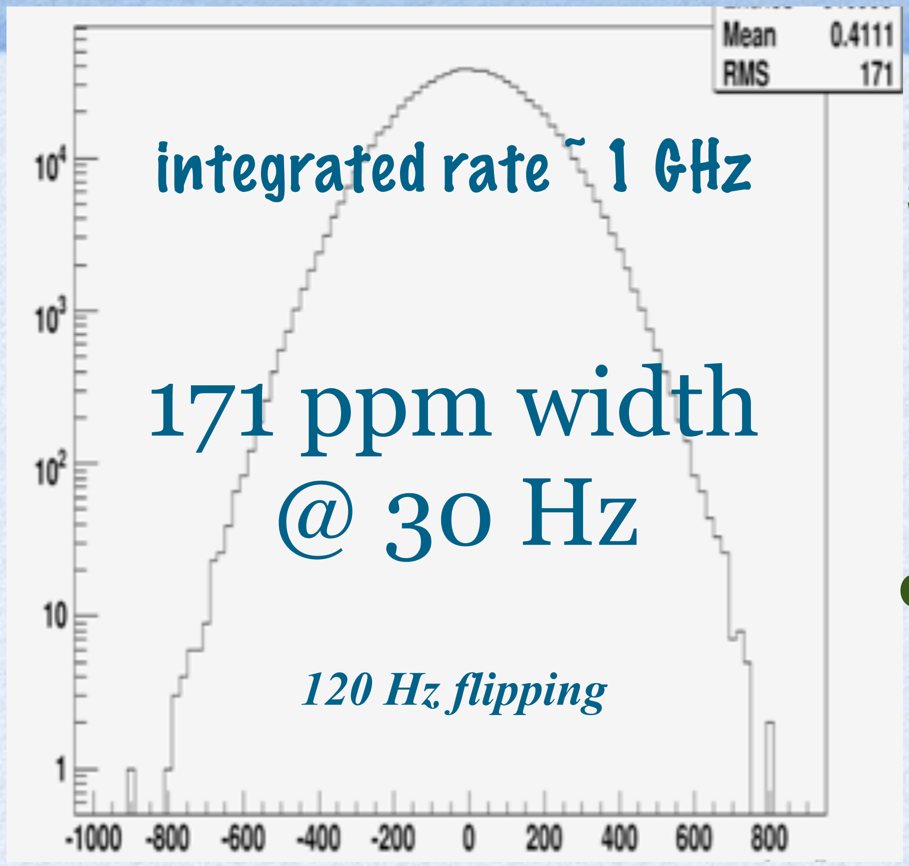


hardware resolution:
$\Delta p/p \sim 10^{-3}$



Physics Data: April/May 2010

Raw Asymmetry Data

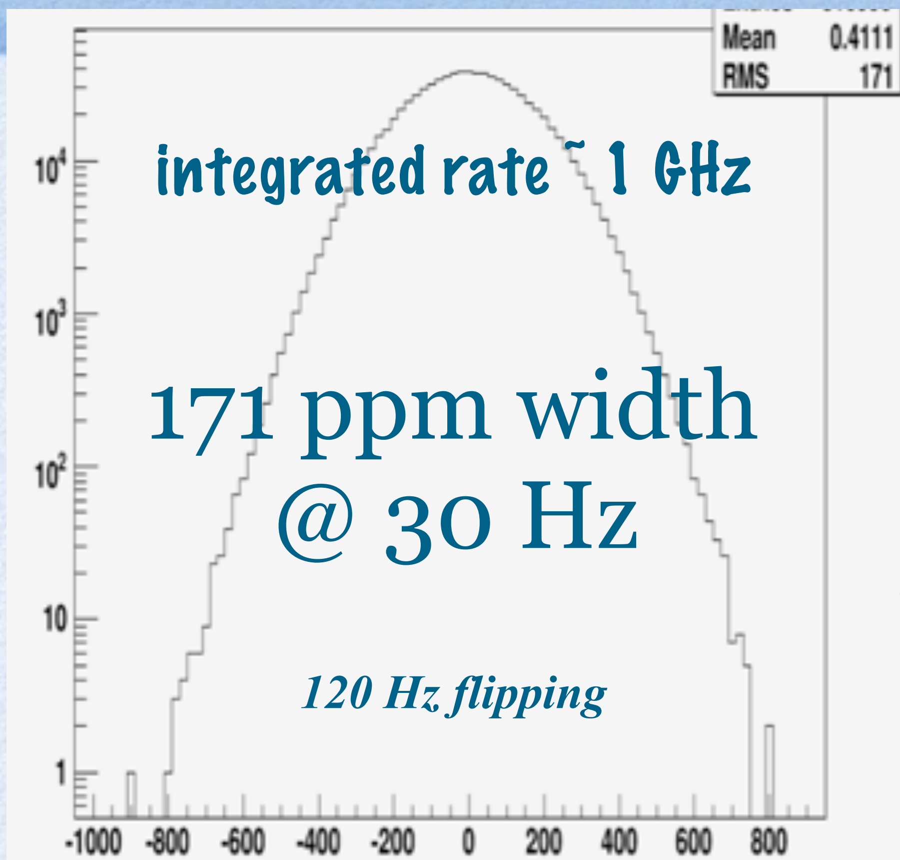


parts per million

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

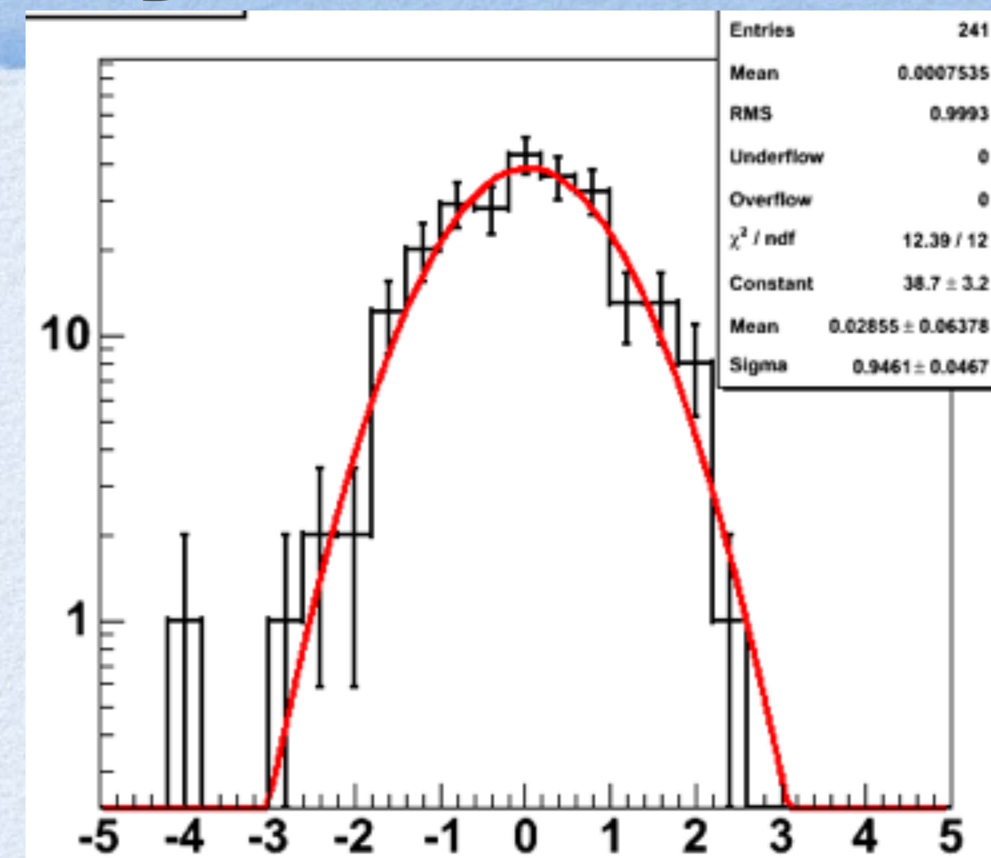
Physics Data: April/May 2010

Raw Asymmetry Data



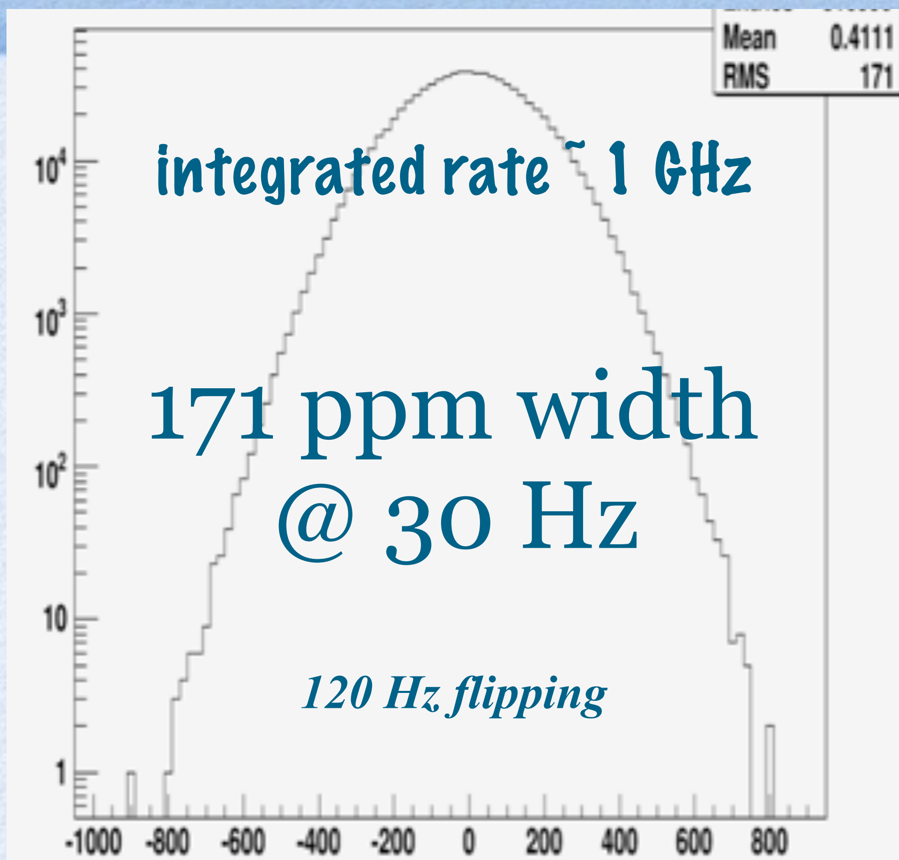
parts per million

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



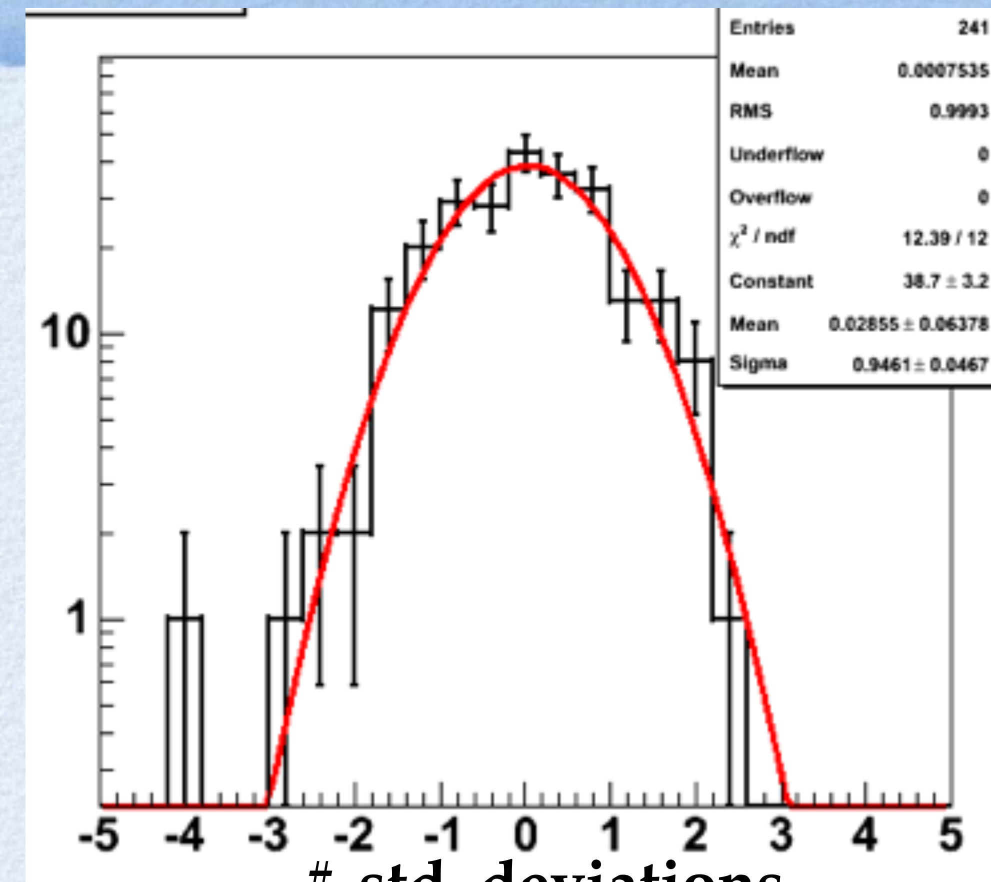
std. deviations

Raw Asymmetry Data

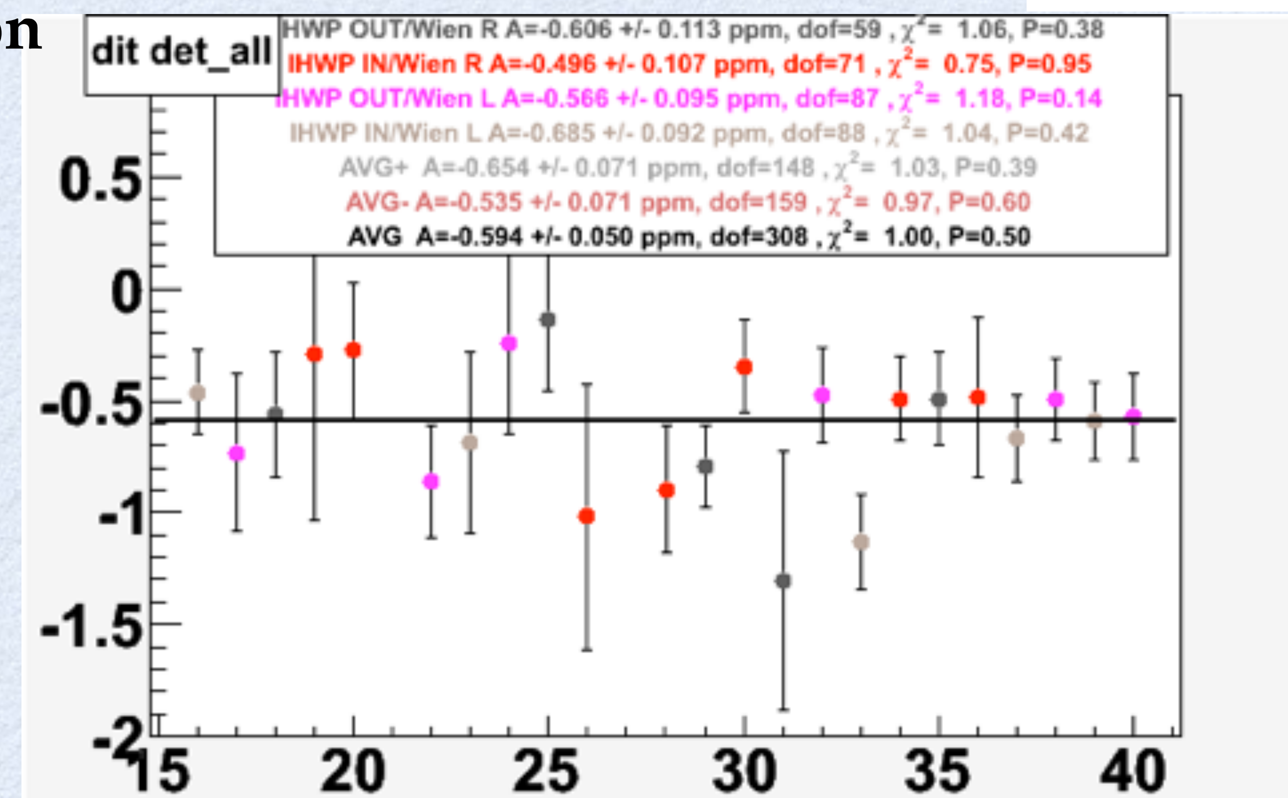


parts per million

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

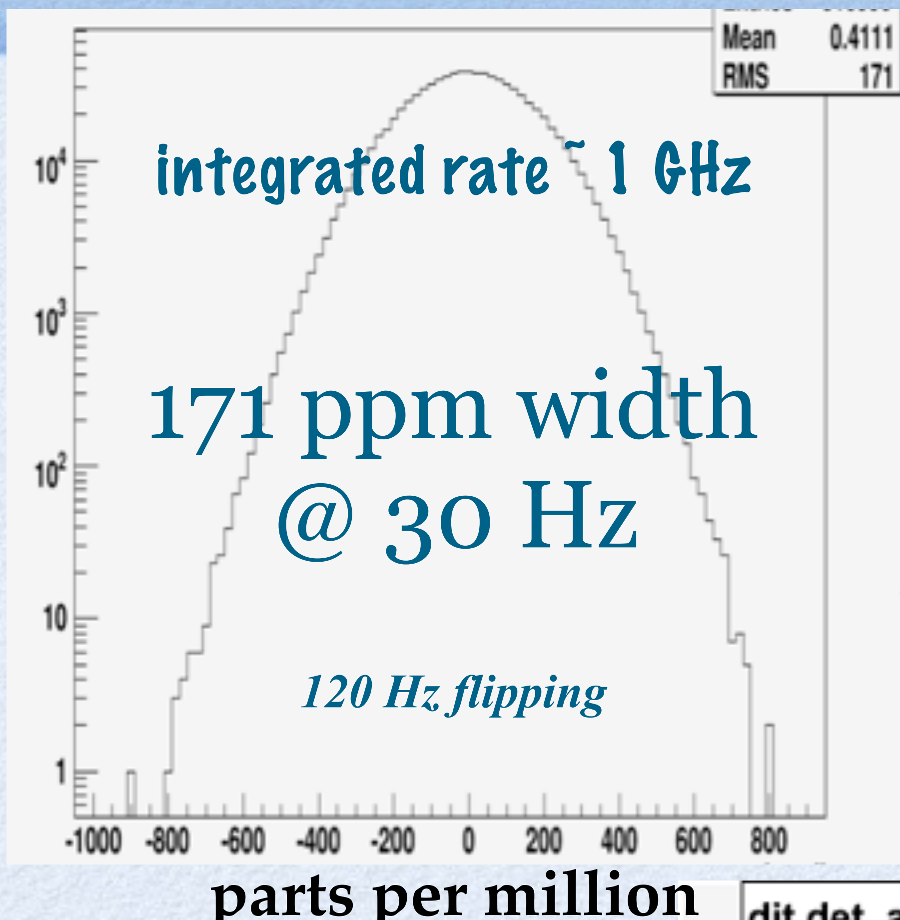


std. deviations

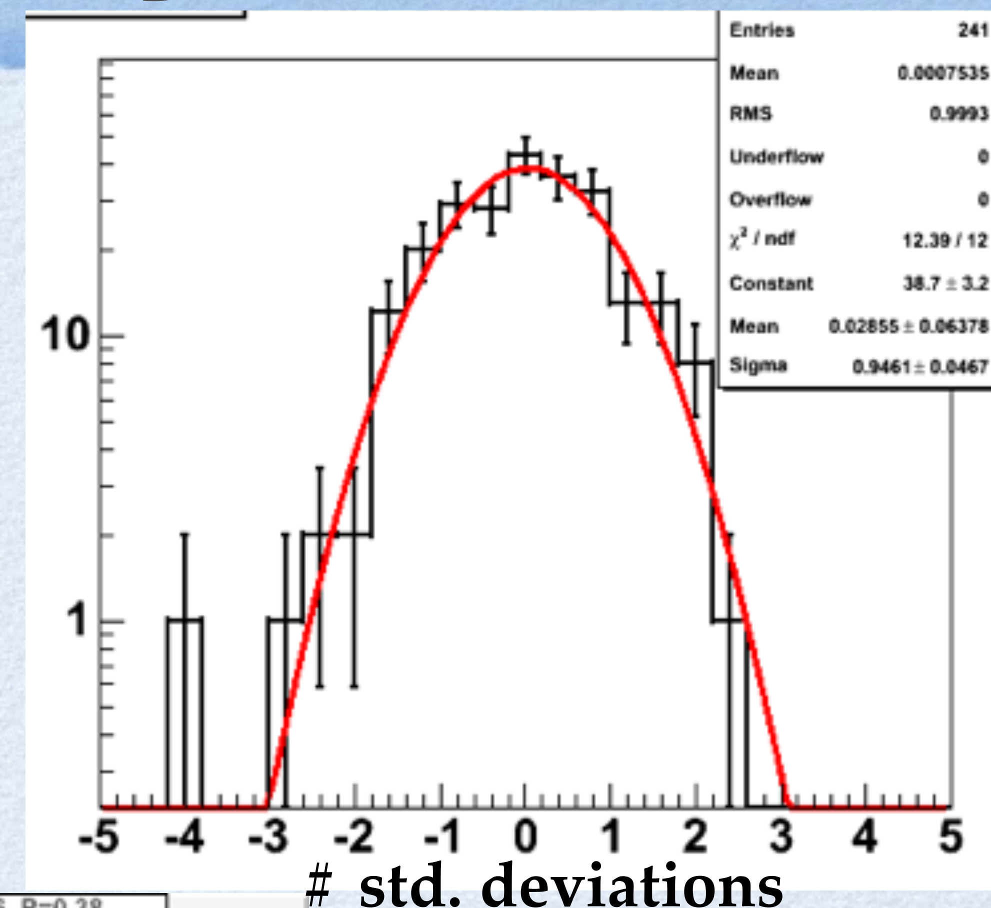


Physics Data: April/May 2010

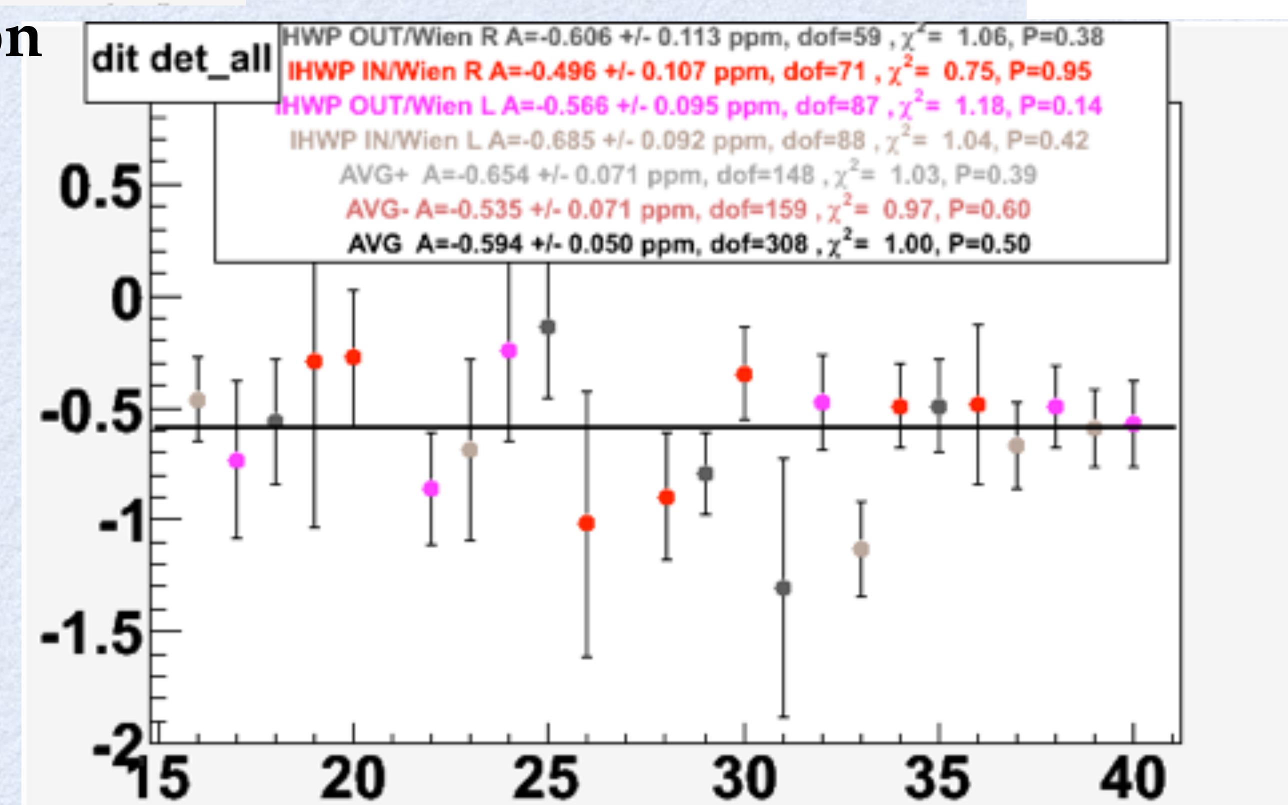
Raw Asymmetry Data



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

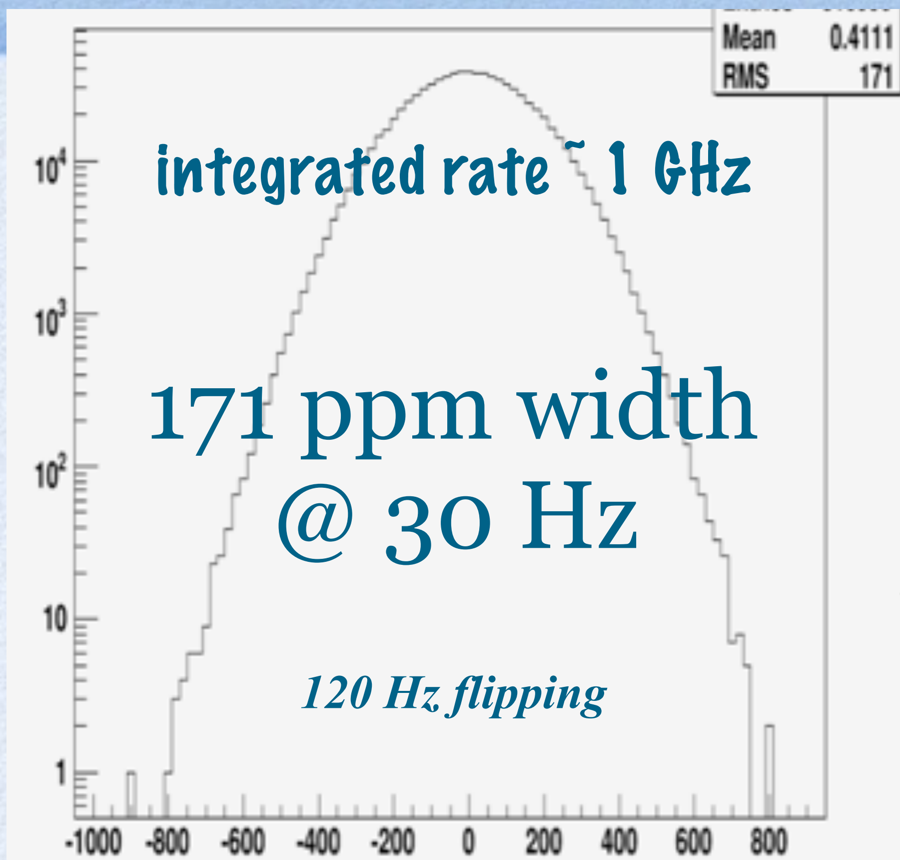


Grand averages of all 4 combinations of slow reversal flips are statistically consistent



Physics Data: April/May 2010

Raw Asymmetry Data

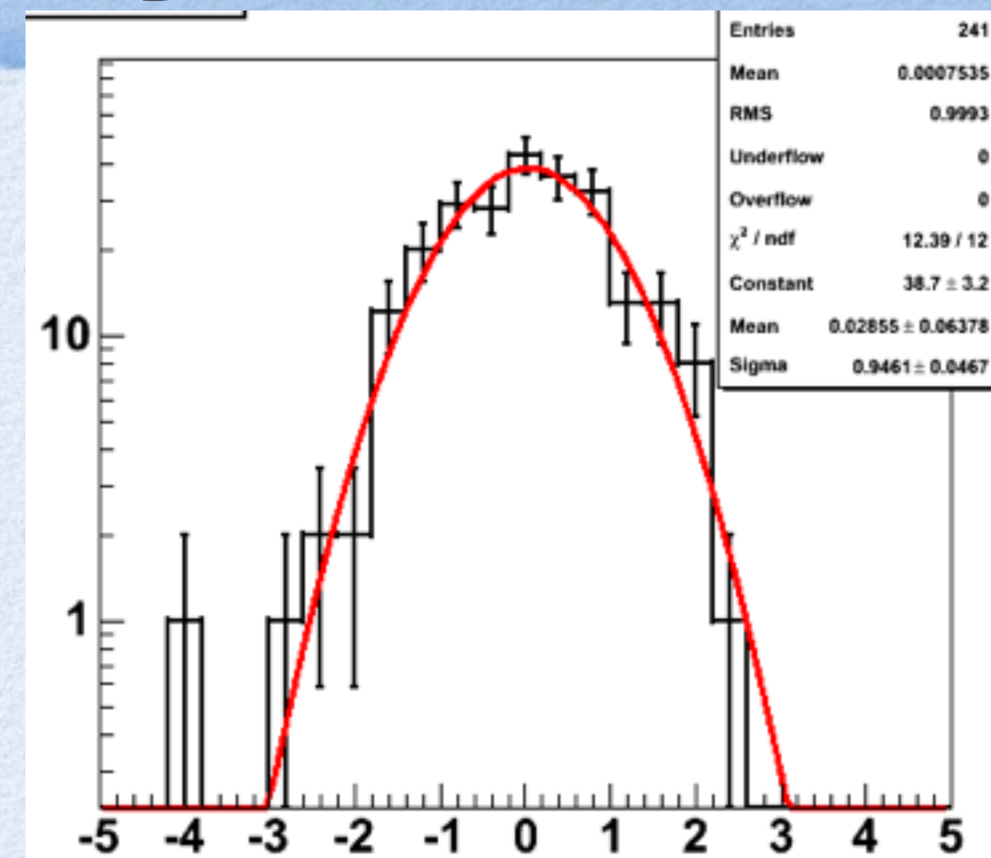


integrated rate ~ 1 GHz

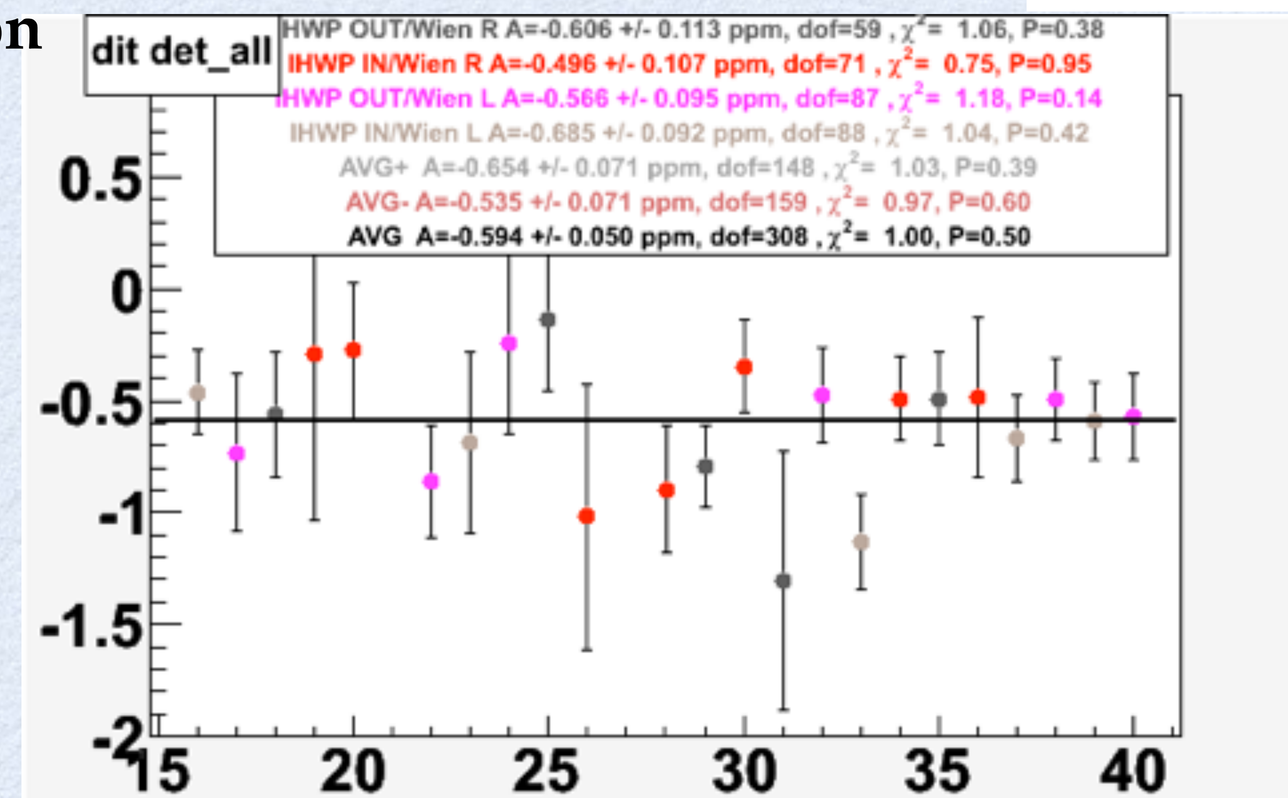
171 ppm width @ 30 Hz

120 Hz flipping

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



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

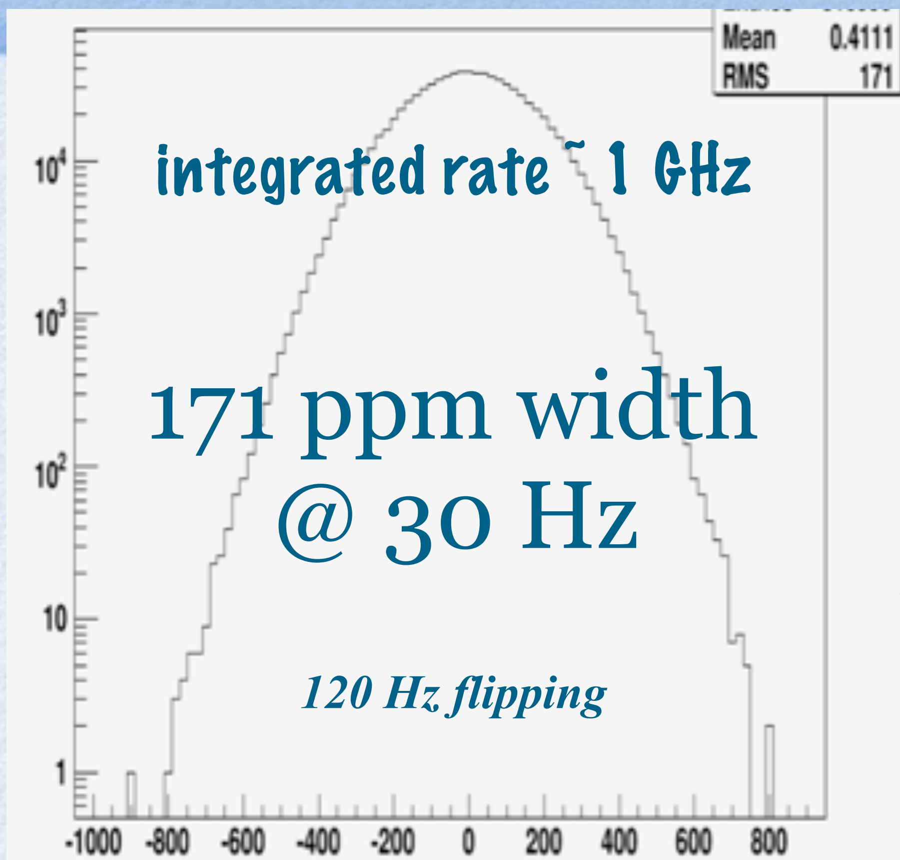


606 ± 113
496 ± 107
566 ± 095
685 ± 092

594 ± 50
parts per billion (ppb)

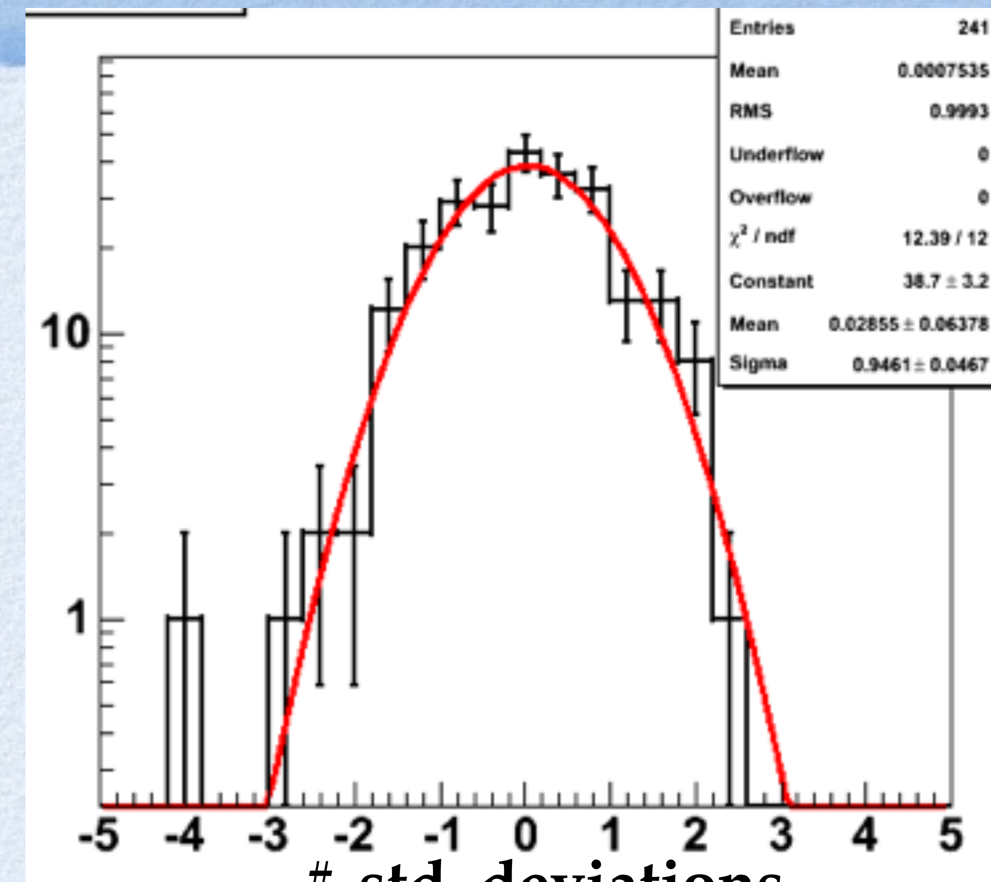
Physics Data: April/May 2010

Raw Asymmetry Data



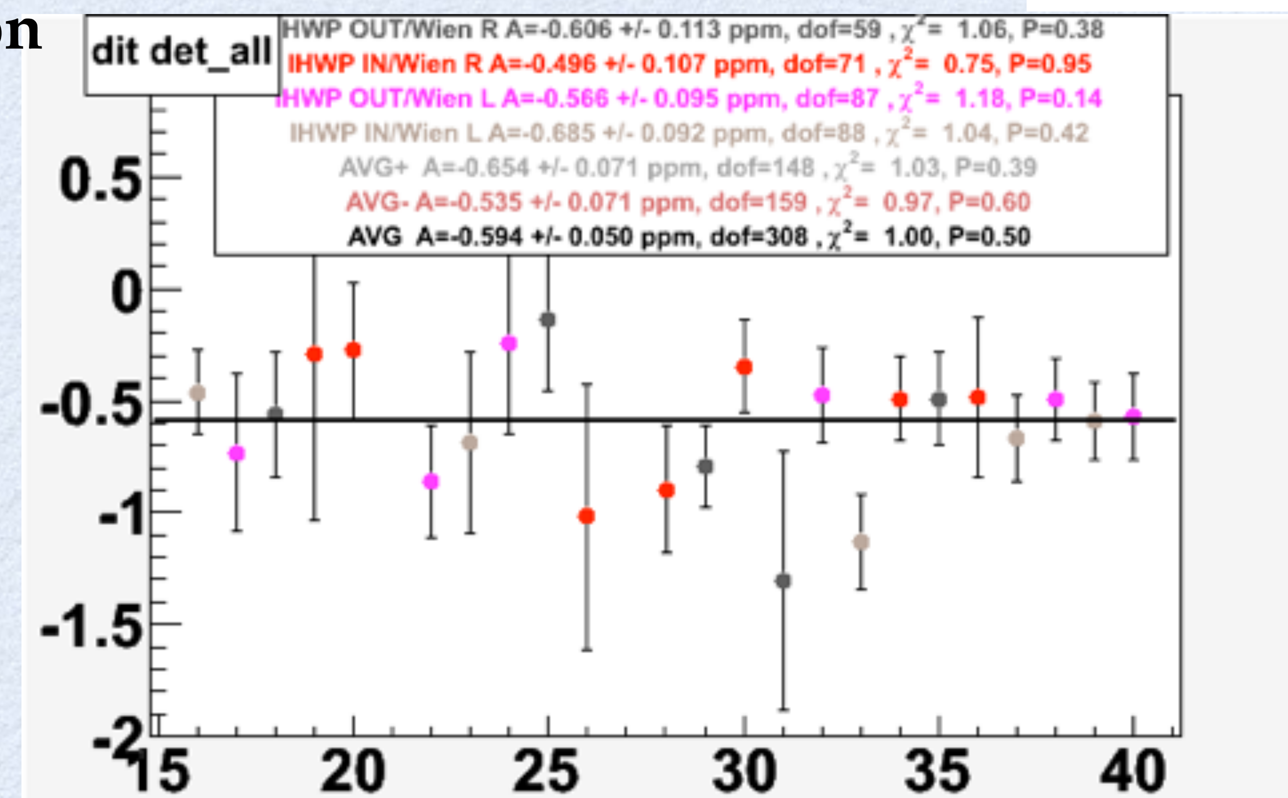
parts per million

Statistical behavior of data consistent with fluctuations in integrated detector response 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

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

Two independent methods, polarized Møller and Compton Scattering

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

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

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

Two independent methods, polarized Møller and Compton Scattering

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

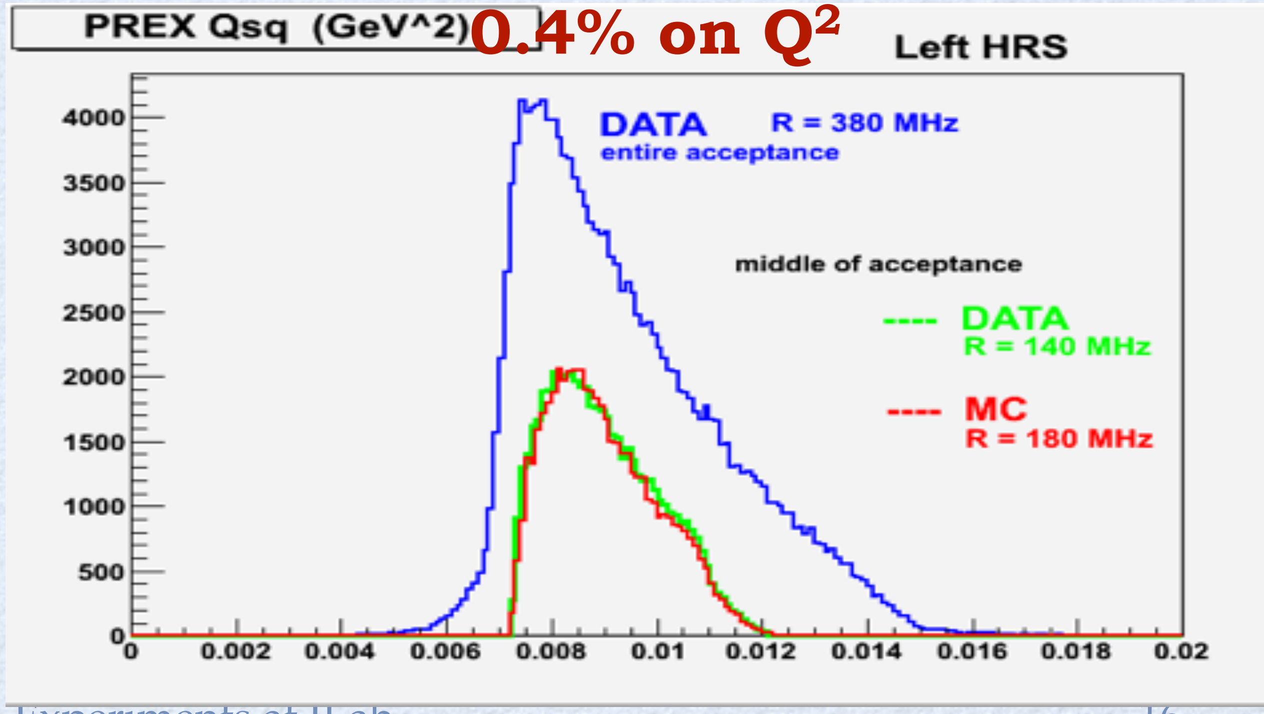
4-momentum transfer $Q^2 = 4EE'\sin^2\frac{\theta}{2}$

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:



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

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

Two independent methods, polarized Møller and Compton Scattering

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

Absolute angle calibration via nuclear recoil variation

Recoil is large for H, small for nuclei

Water cell target

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

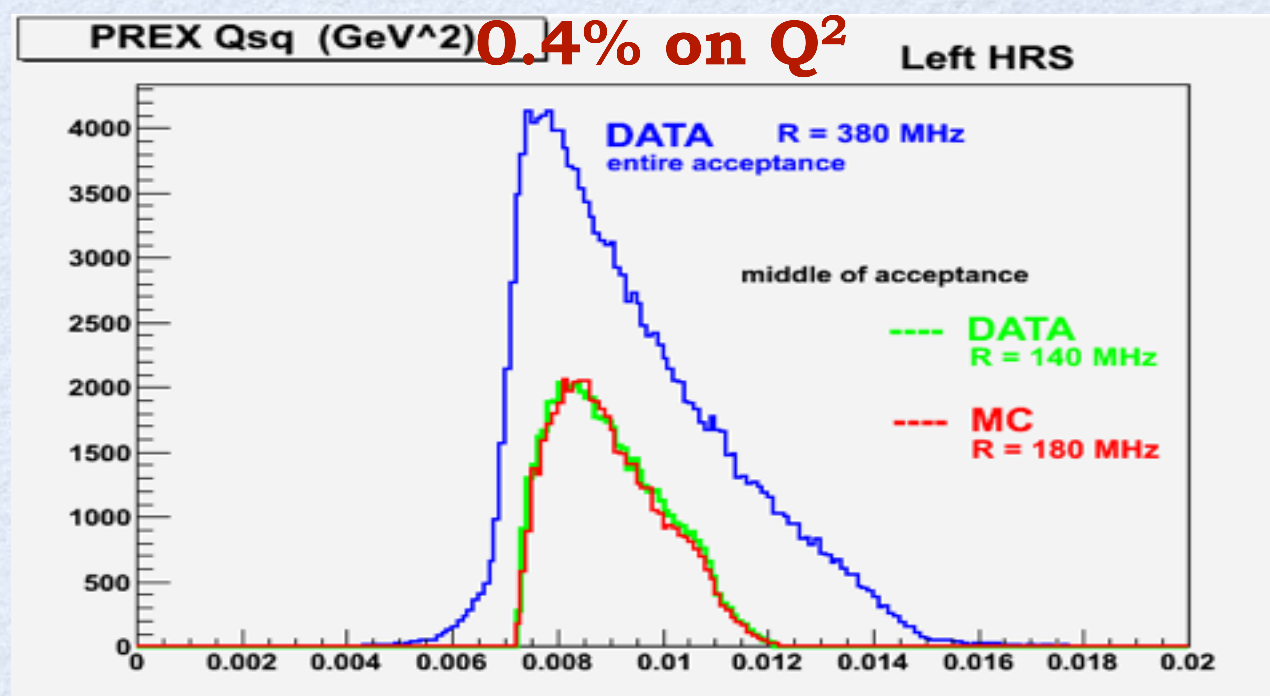
4-momentum transfer $Q^2 = 4EE'\sin^2\frac{\theta}{2}$

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:



Final Result

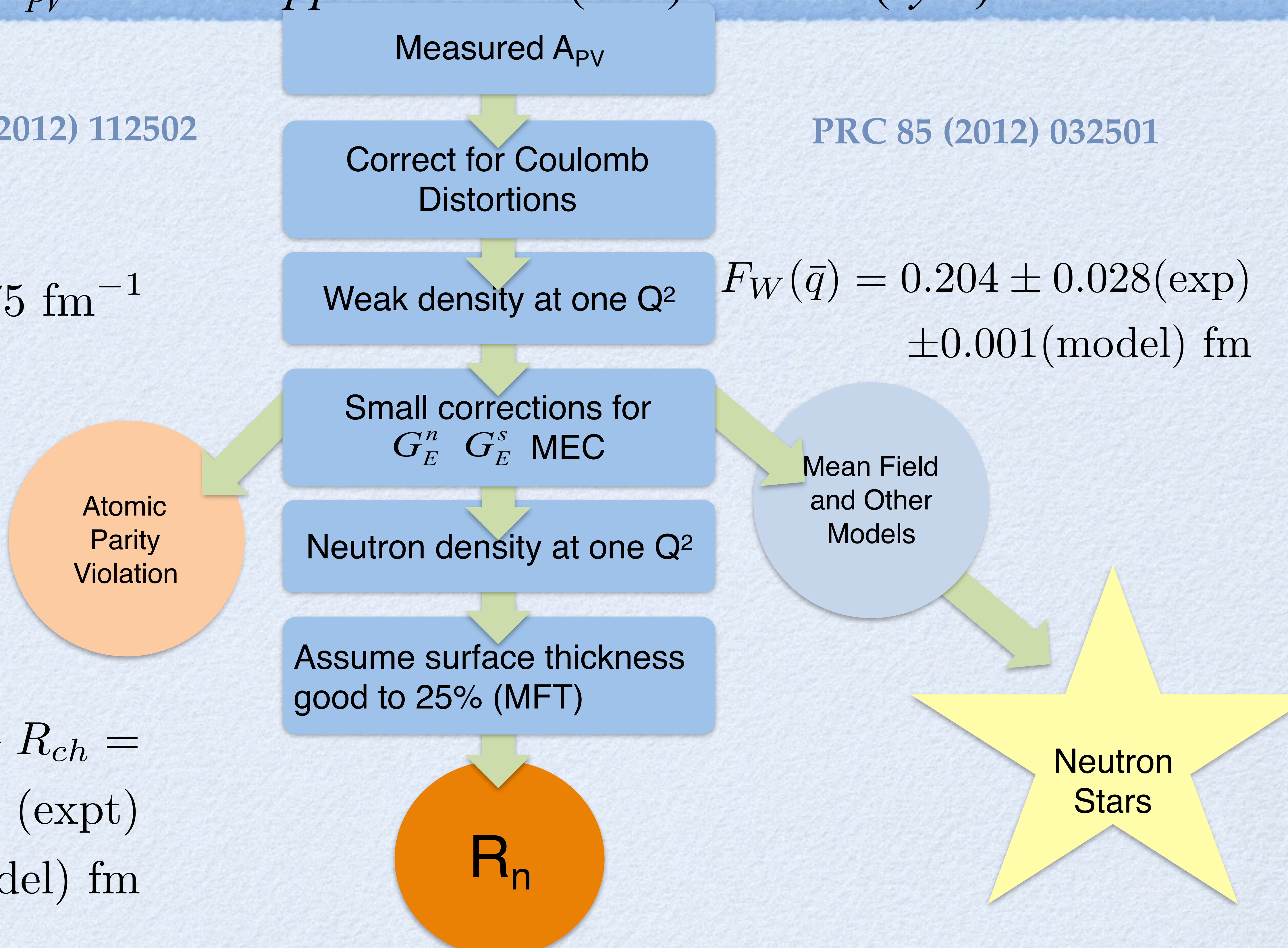
$$A_{PV} = 0.656\ ppm \pm 0.060(stat) \pm 0.014(syst)$$

PRL 108 (2012) 112502

PRC 85 (2012) 032501

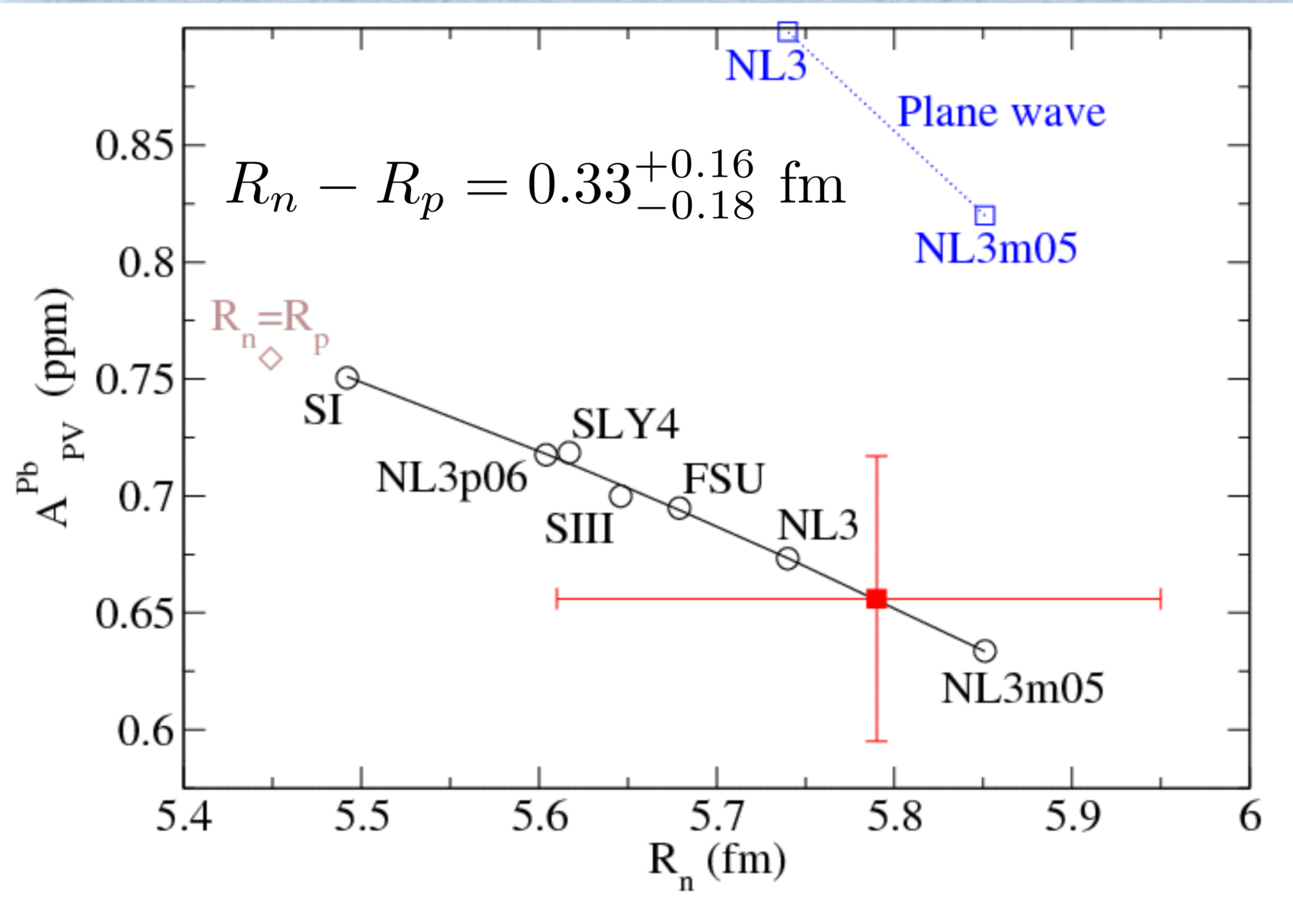
$$\bar{q} = 0.475\ \mathrm{fm}^{-1}$$

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



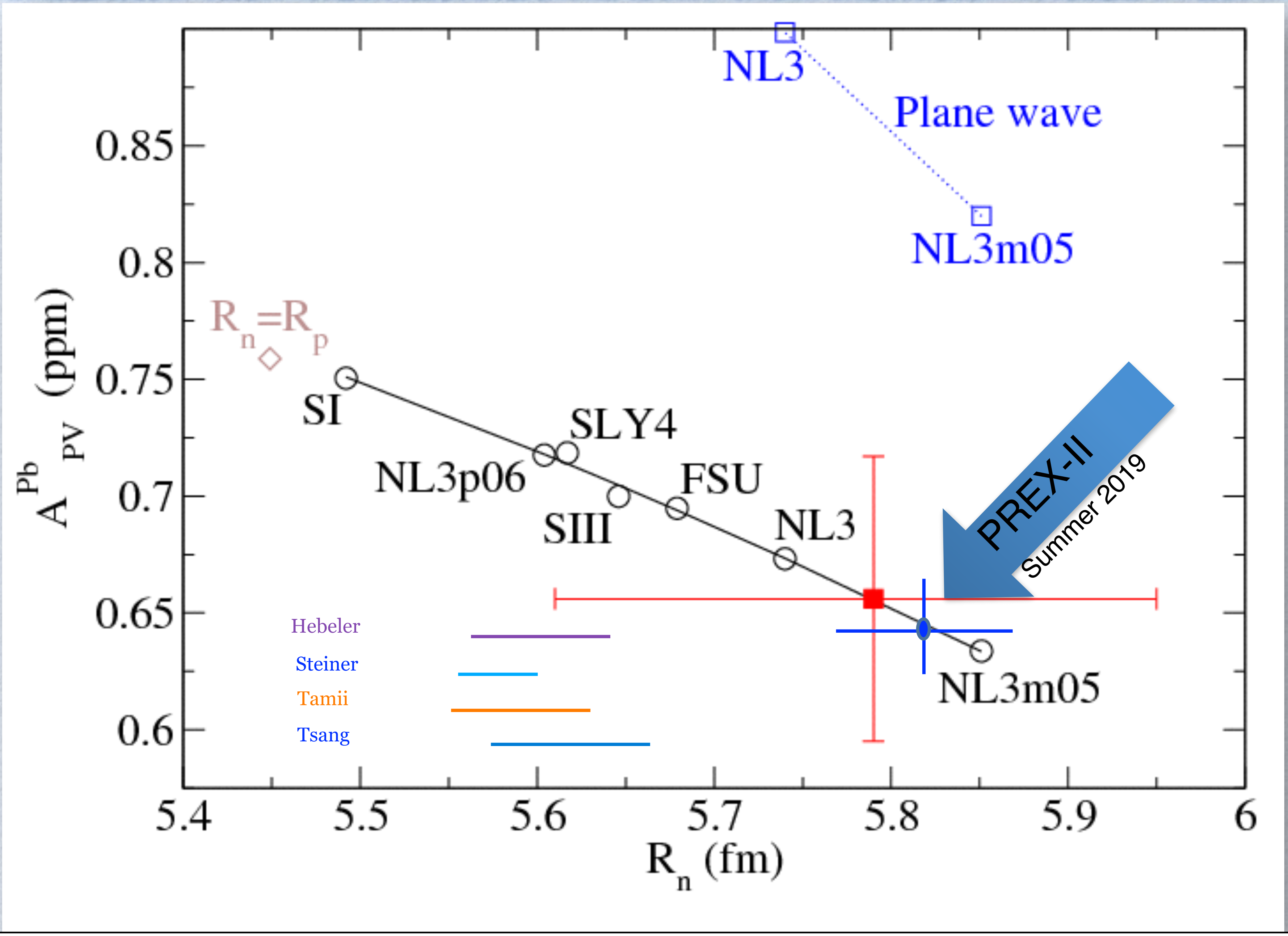
$$R_W - R_{ch} = 0.32 \pm 0.12\ (\mathrm{expt}) \pm 0.03\ (\mathrm{model})\ \mathrm{fm}$$

The Neutron Skin



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

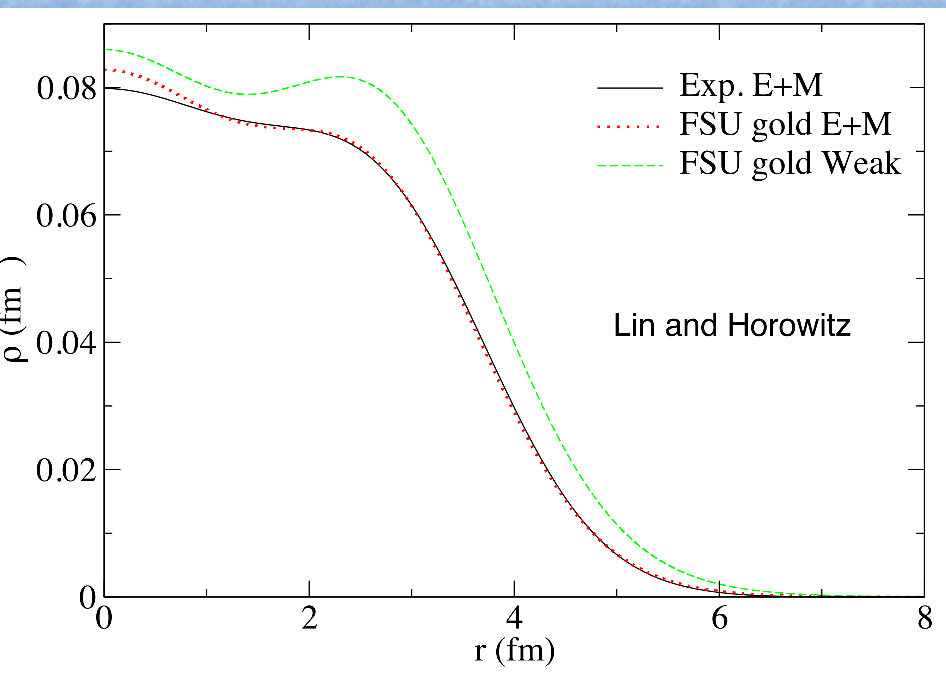
The Neutron Skin



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

CREX

CREX Motivation



Optimum Q ~ 160 MeV

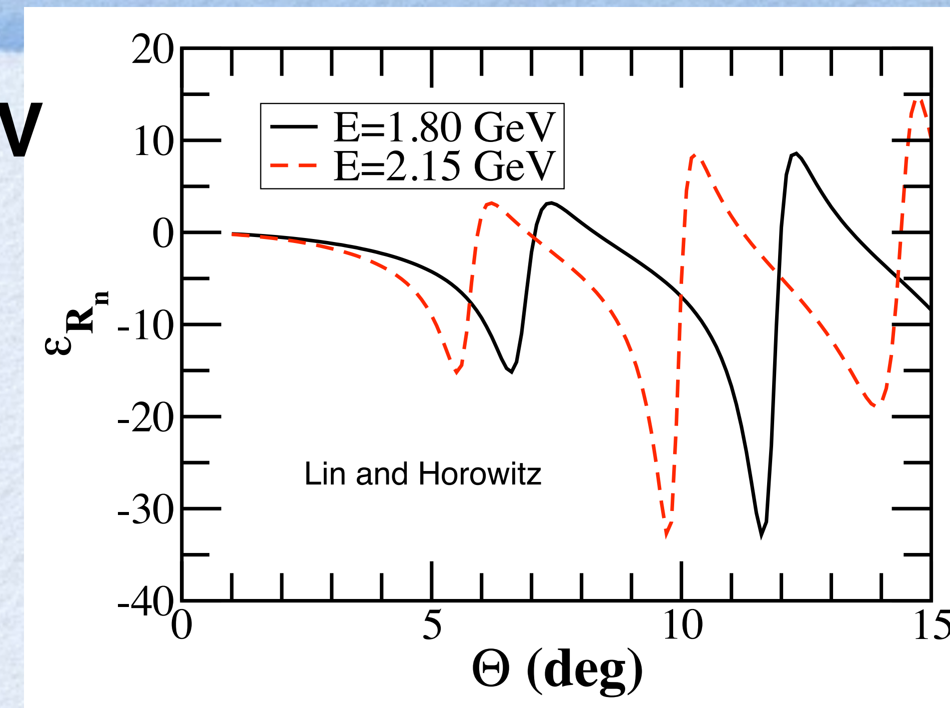
2 GeV → 5 degrees

A_{PV} ~ 3.8 ppm

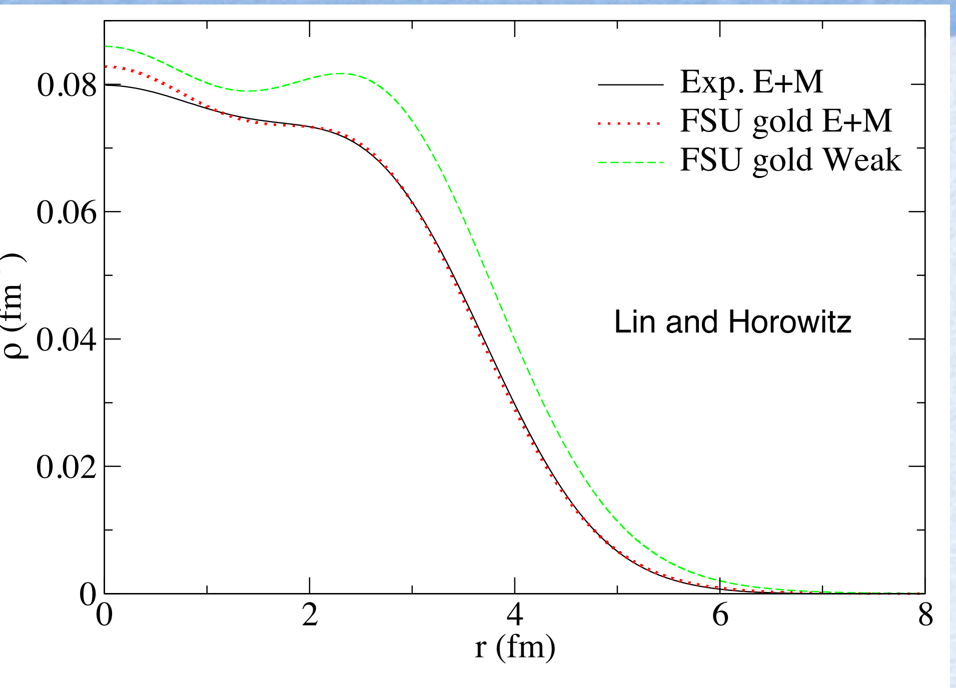
Rate ~ 40 MHz

$\delta(A_{PV})$ ~ 3 %

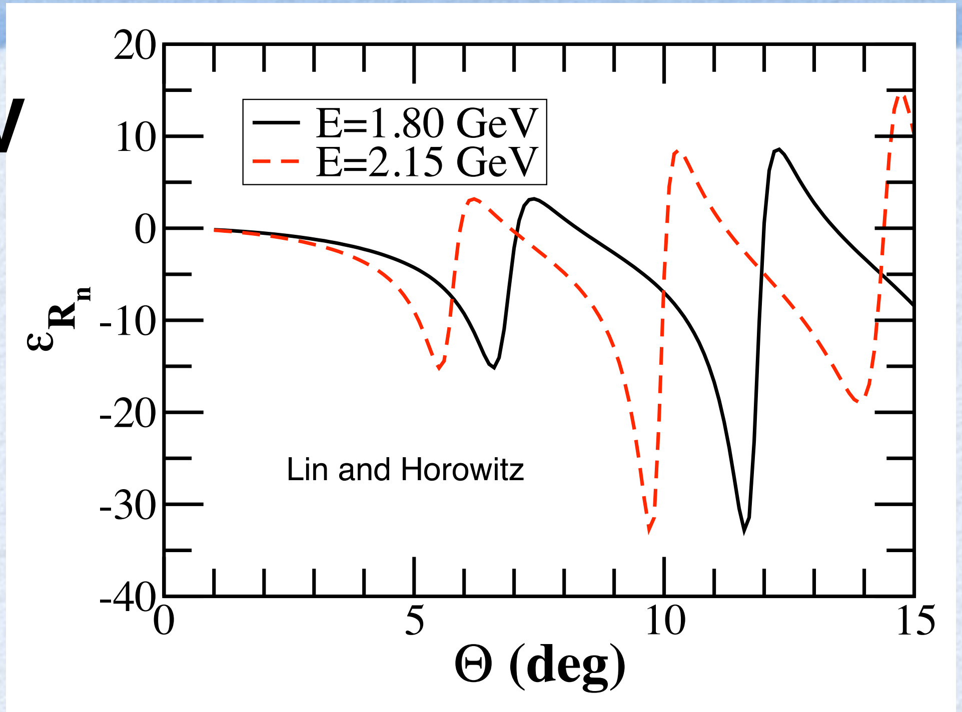
$\delta(R_n) \sim \pm 0.02$ fm

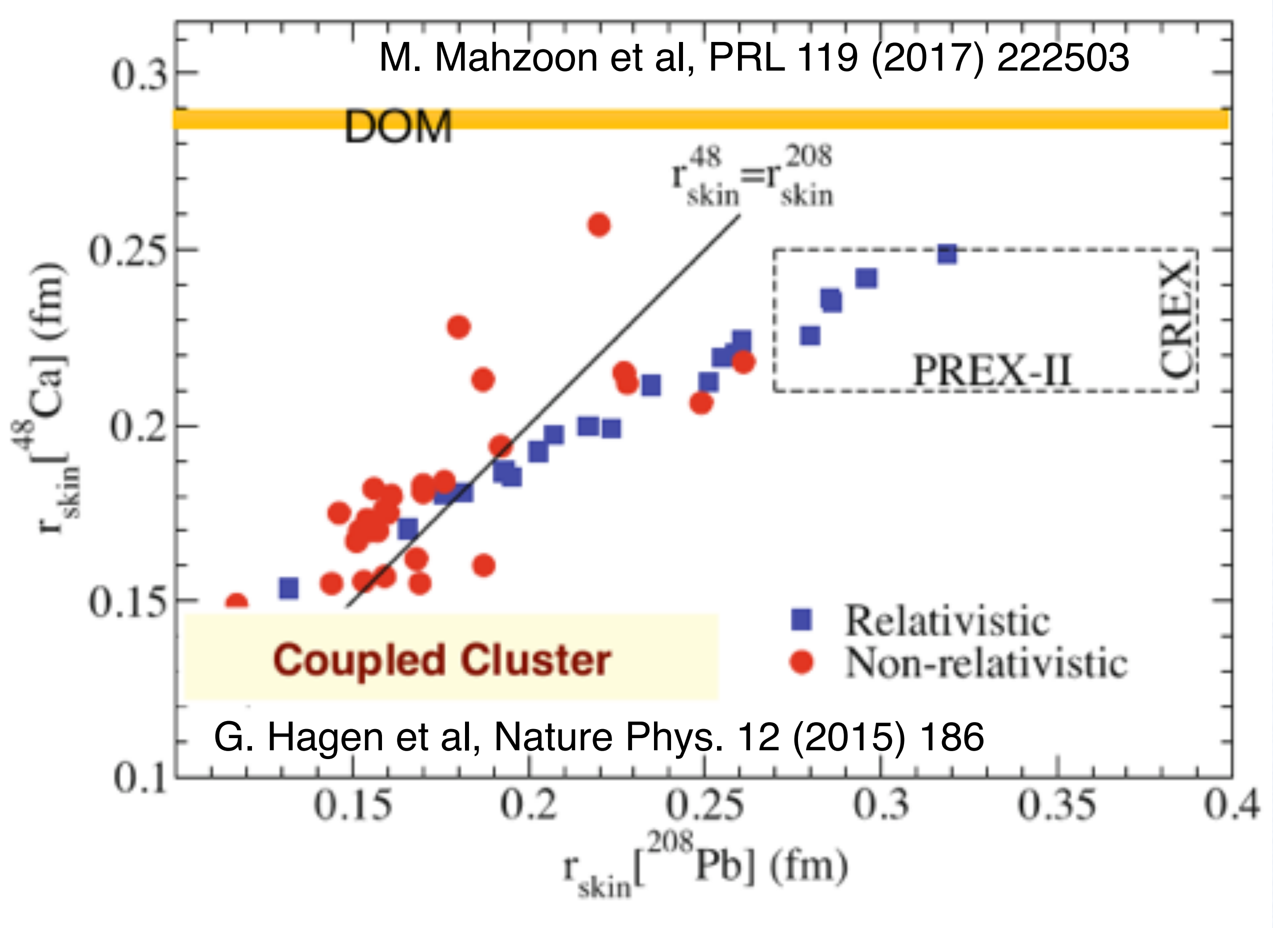


CREX Motivation



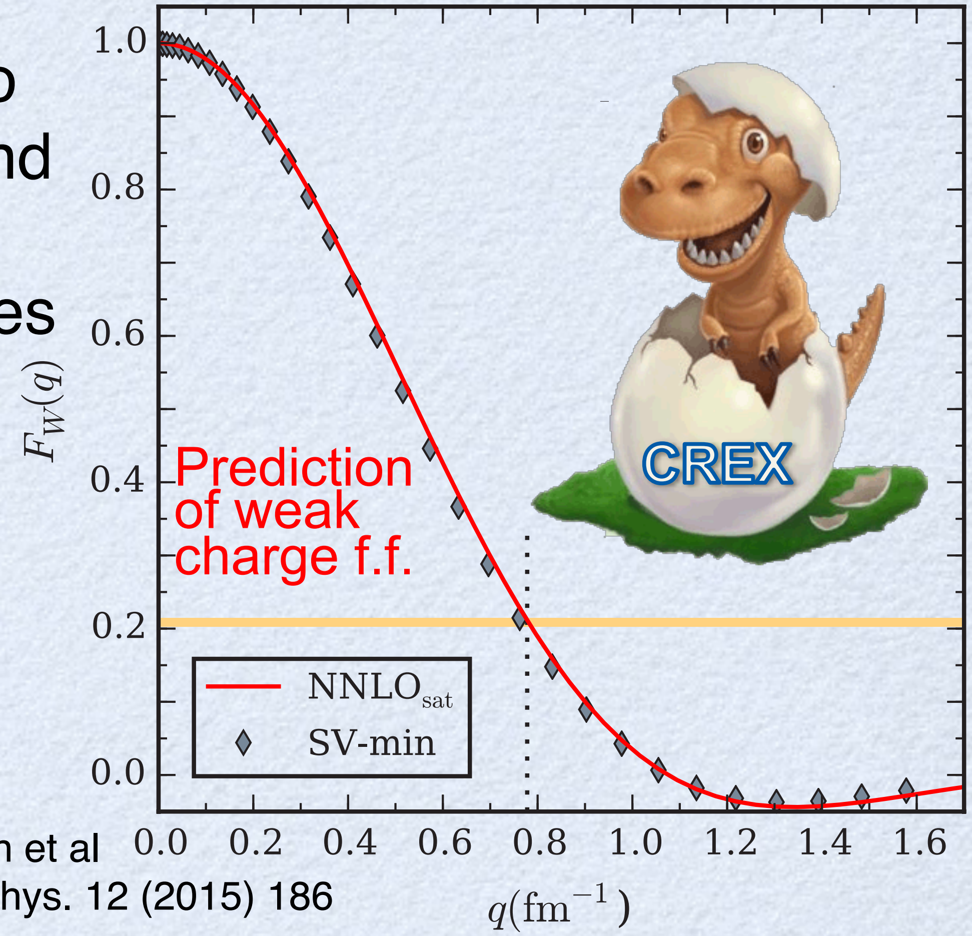
Optimum Q ~ 160 MeV
2 GeV → 5 degrees
A_{PV} ~ 3.8 ppm
Rate ~ 40 MHz
$\delta(A_{PV}) \sim 3$ %
$\delta(R_n) \sim \pm 0.02$ fm





- Bridge ab initio calculations and and DFT
- 3 neutron forces

Two very different predictions!



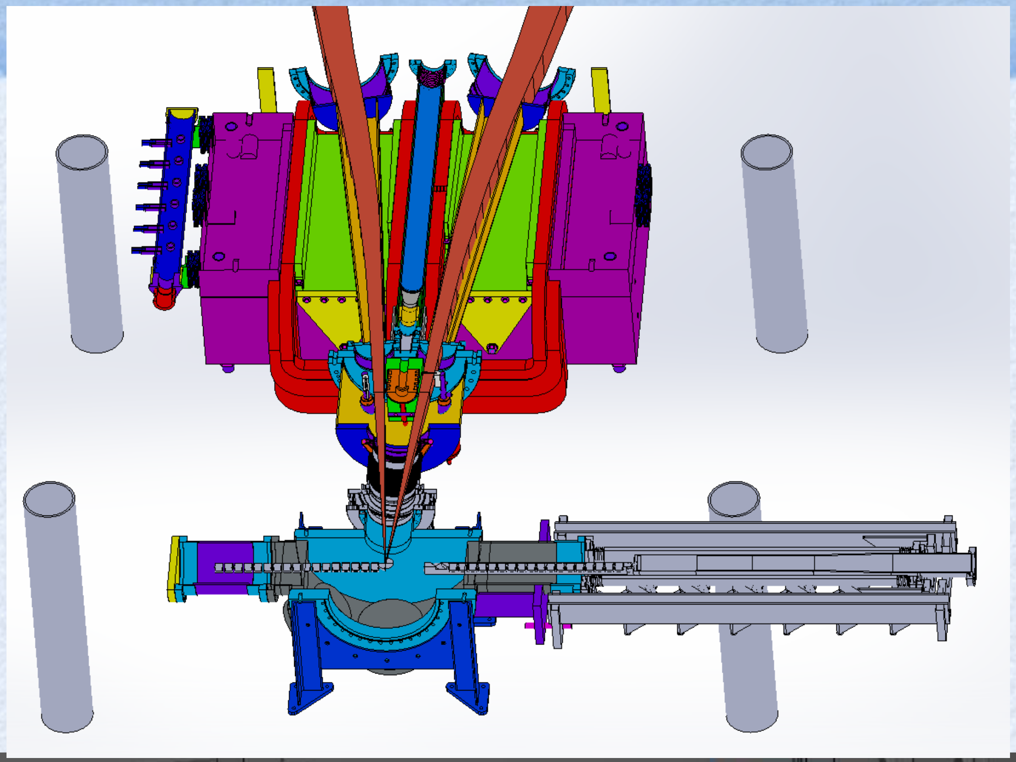
G. Hagen et al Nature Phys. 12 (2015) 186

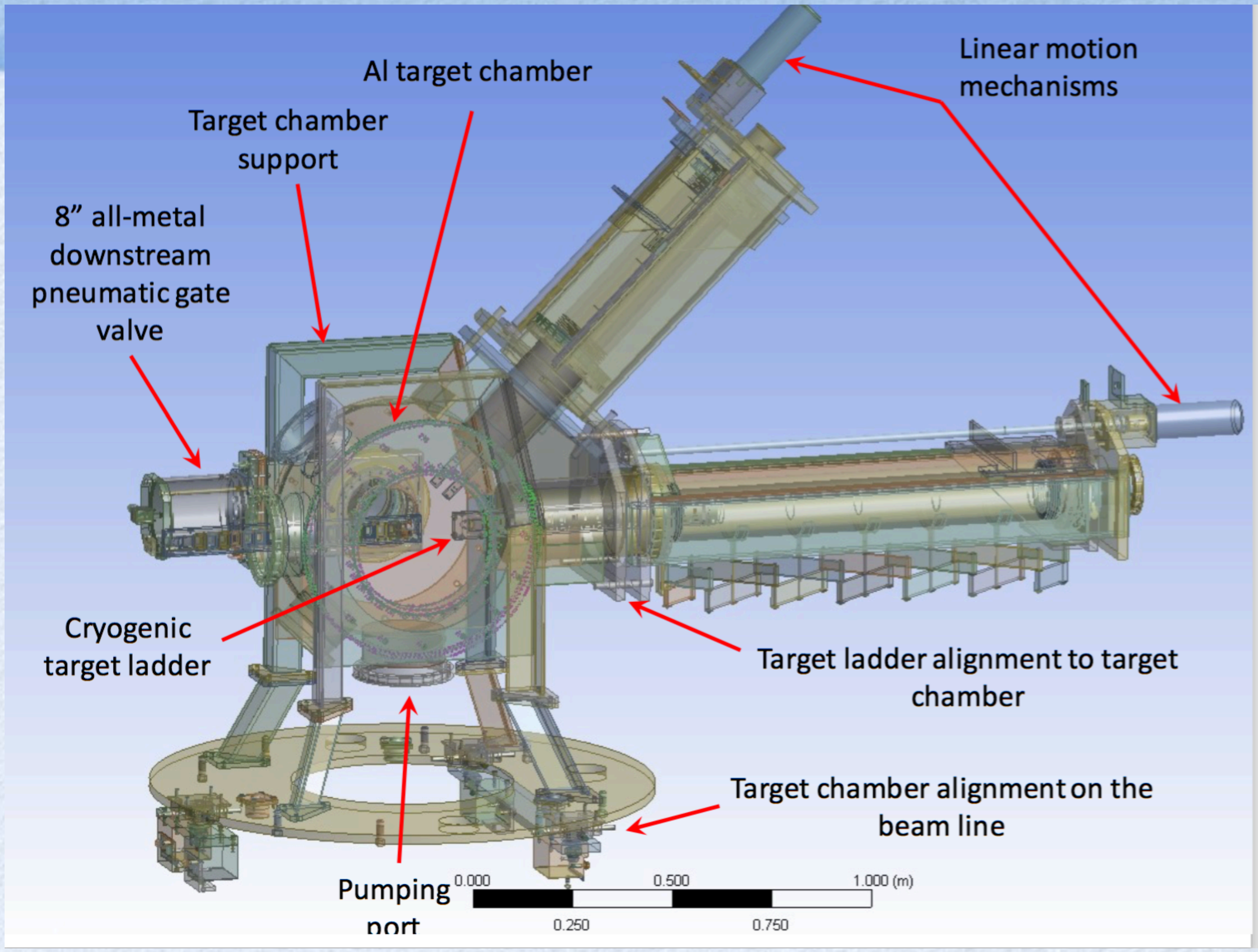
PREX/CREX Parameters

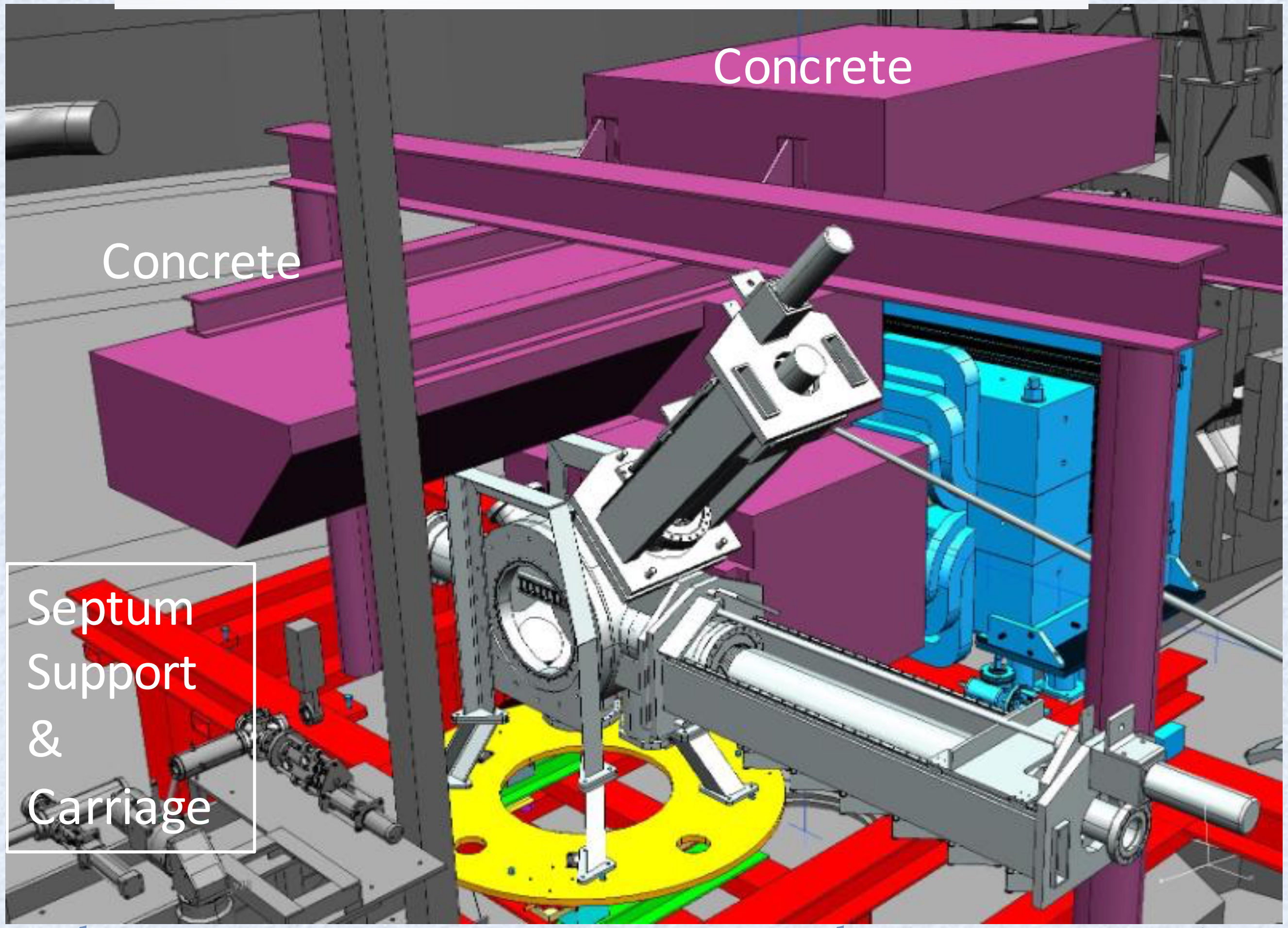
	PREX-I	PREX-II	CREX
Ebeam	1.0 GeV	1.0 GeV	2.1 GeV
A_{PV}	0.65 ppm	0.65 ppm	2.5 ppm
Rate	1 GHz	1.5 GHz	40 MHz
$\delta(A_{PV})_{stat}$	9%	3.5%	4%
$\delta(R_n)$	0.18 fm	0.07 fm	0.02 fm
Charge	0.1%	0.1%	0.1%
Beam	1.1%	0.5%	0.3%
Non-linearity	1.0%	0.3%	0.3%
Transverse	0.2%	0.2%	0.1%
Beam Polarization	1.1%	0.8%	0.8%
Inelastics	0.1%	0.1%	0.2%
Effective Q^2	0.4%	0.4%	0.4%
Total Systematic	2%	1.1%	1%

PREX-II and CREX Preparations

Target Region Redesign

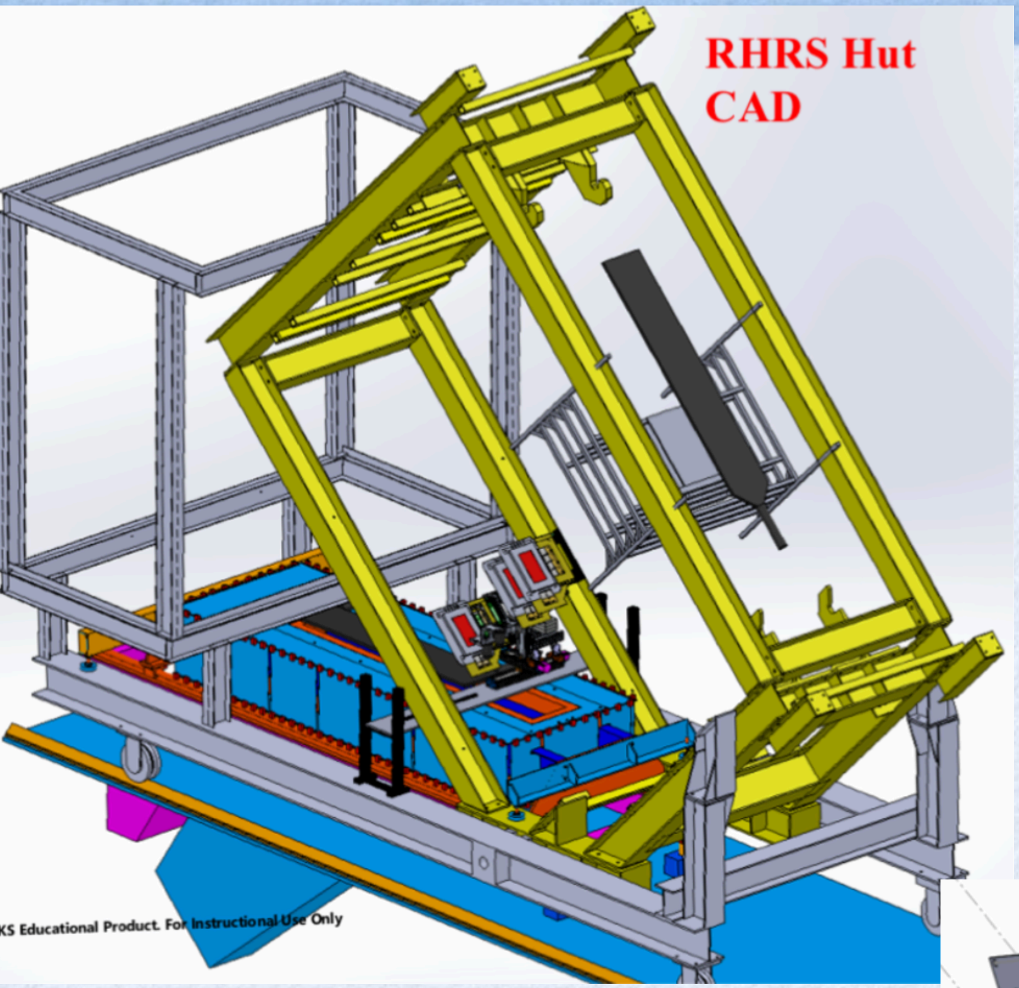


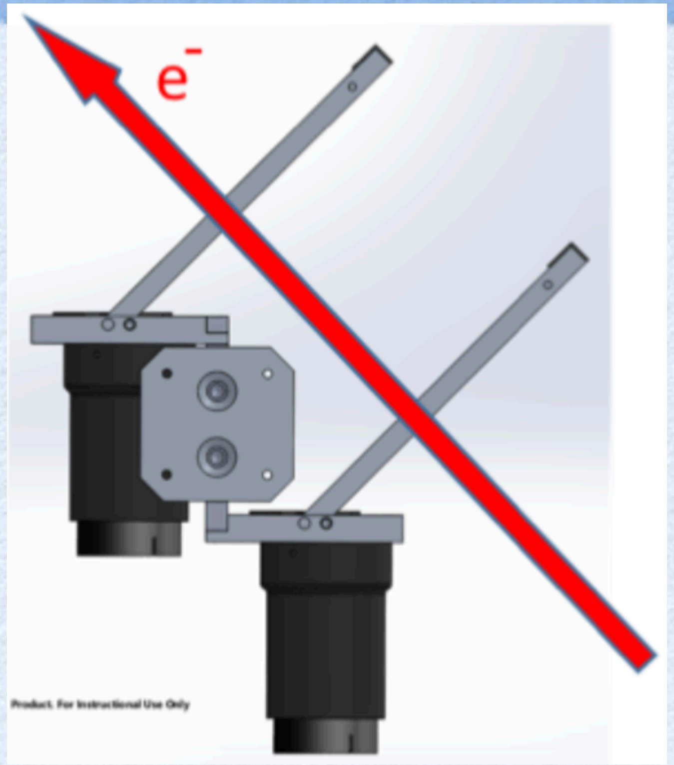




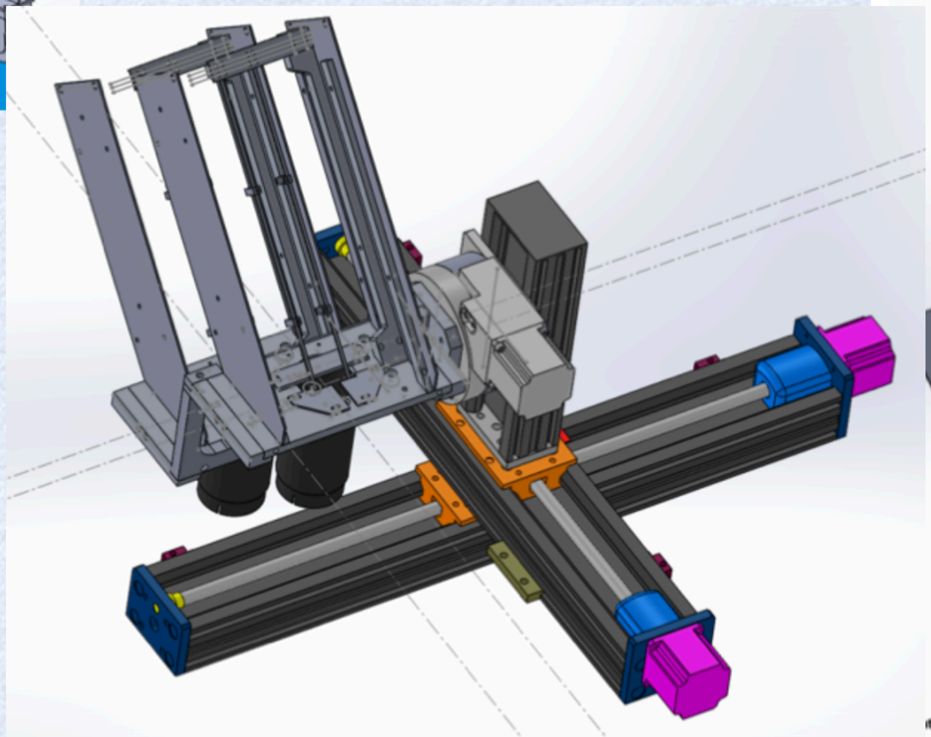
Extensive simulation, design and engineering effort ongoing for robust, efficient and safe operation of these high luminosity experiments

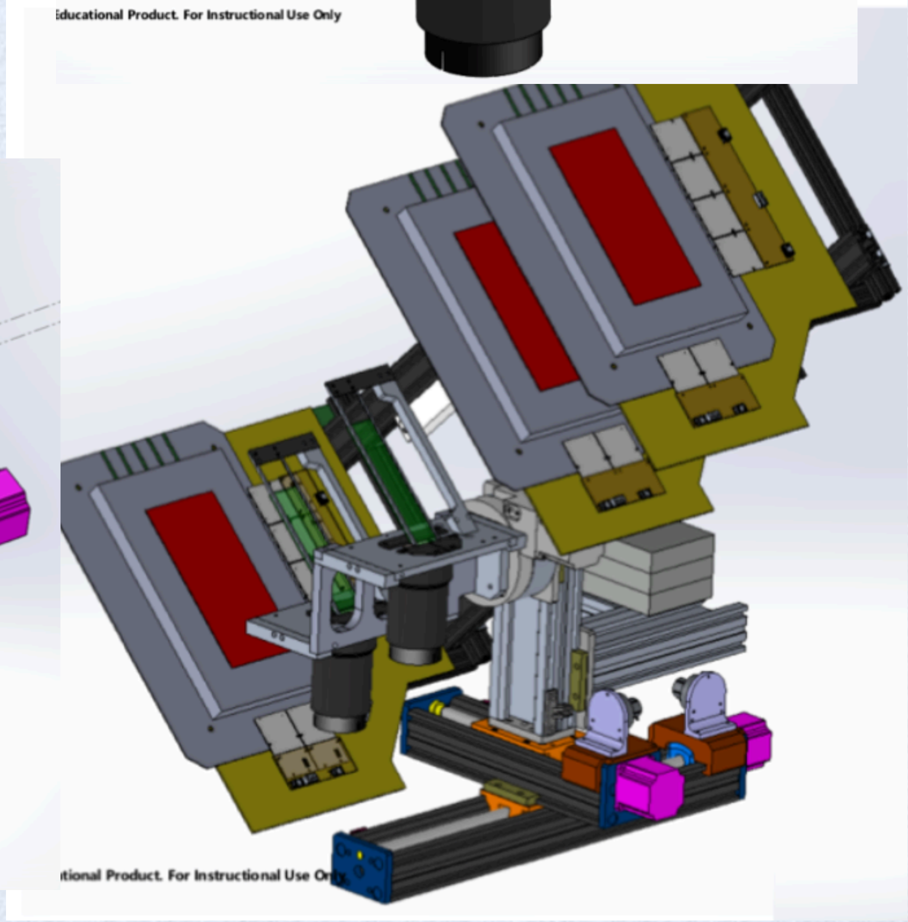
Focal Plane Detectors





Mechanical design that combines the “counting” mode “Q² detectors” with the integrating mode main detectors





PREX/CREX Schedule & Plans

- Funding profile for US Nuclear Physics in FY ’18 & ’19 has enabled JLab to propose a healthy beam schedule
- PREX/CREX installation to begin in March ’19
- Special 1 GeV summer run proposed for June/July 2019
- PREX requires 2 months of calendar time
- Fall of 2019: CREX will run at 2.2 GeV along with full 4-Hall JLab program (~ 3 months of calendar time)
- PREX-II and CREX collaboration actively preparing for the run: At least 8 PhD students, likely close to 10 or 11
- From past experience: analysis roughly 12 months i.e. expectation of results by end of calendar 2020

Physics Beyond the Standard Model with PVES

Physics down to a length scale of 10^{-19} m well understood but.....

Modern Electroweak Physics

Many questions still unanswered….

The High Energy Frontier: **Collider Physics**

The Cosmic Frontier: **Particle, Nuclear and Gravitational Astrophysics**

A comprehensive search for clues requires, in addition:

The Intensity/Precision Frontier

Physics down to a length scale of 10^{-19} m well understood but.....

Modern Electroweak Physics

Many questions still unanswered….

The High Energy Frontier: Collider Physics

The Cosmic Frontier: Particle, Nuclear and Gravitational Astrophysics

A comprehensive search for clues requires, in addition:

The Intensity/Precision Frontier

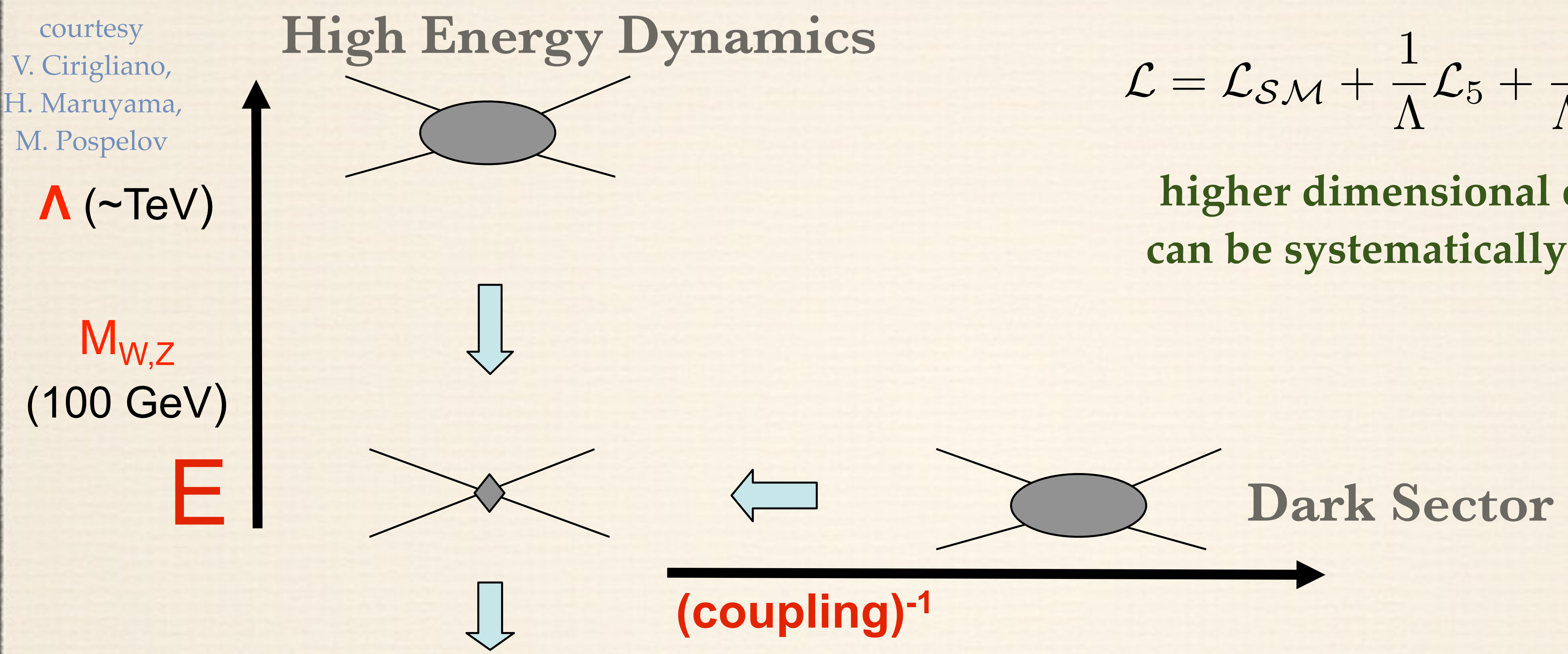
- ✦ **Violation of Accidental (?) Symmetries**
  - ★ Neutrinoless Double-Beta Decay, Electric Dipole Moments...
- ✦ **Direct Detection of Dark Matter**
- ✦ **Measurements of Neutrino Masses and Mixing**
- ✦ **Precise Measurements of SM observables**

Intense beams, ultra-high precision, exotic nuclei, table-top experiments, rare processes....

Indirect Clues

Electroweak Interactions at scales much lower than the W/Z mass

courtesy
V. Cirigliano,
H. Maruyama,
M. Pospelov



$$\mathcal{L} = \mathcal{L}_{\mathcal{SM}} + \frac{1}{\Lambda}\mathcal{L}_5 + \frac{1}{\Lambda^2}\mathcal{L}_6 + \cdots$$

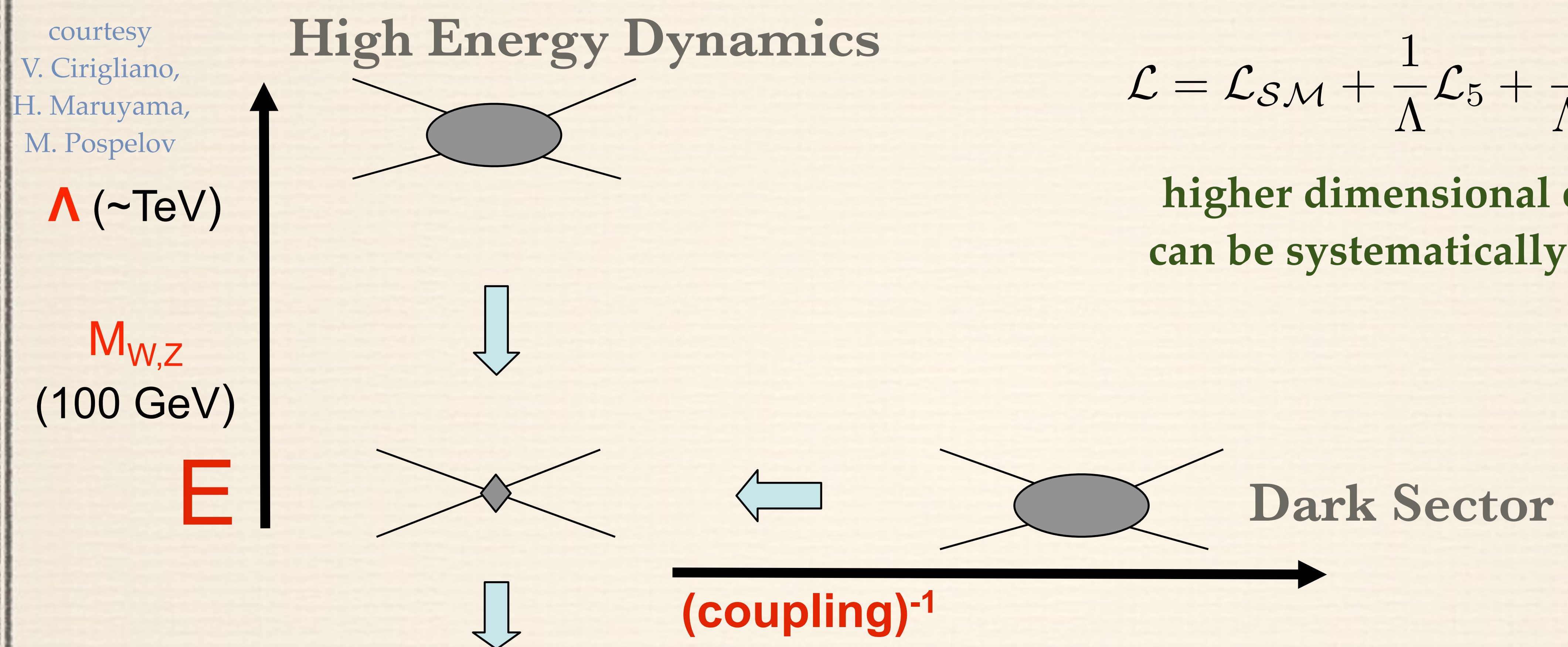
higher dimensional operators
can be systematically classified

Heavy Z's, light (dark) Z's, L-R models, compositeness, extra dimensions, SUSY…

Indirect Clues

Electroweak Interactions at scales much lower than the W/Z mass

courtesy
V. Cirigliano,
H. Maruyama,
M. Pospelov

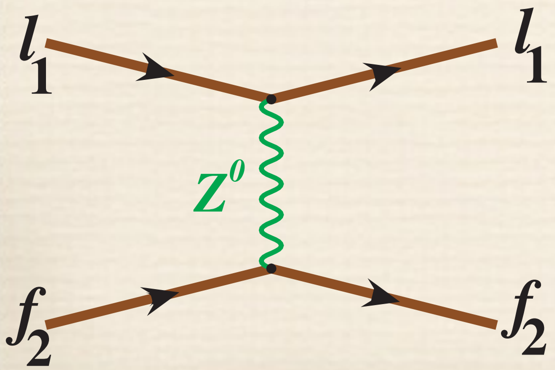


$$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{\Lambda}\mathcal{L}_5 + \frac{1}{\Lambda^2}\mathcal{L}_6 + \cdots$$

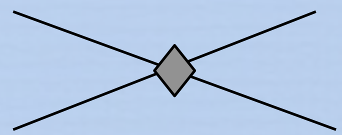
higher dimensional operators
can be systematically classified

Heavy Z's, light (dark) Z's, L-R models, compositeness, extra dimensions, SUSY…

Search for new neutral superweak forces



Look for tiny but measurable deviations from precisely calculable predictions for SM processes



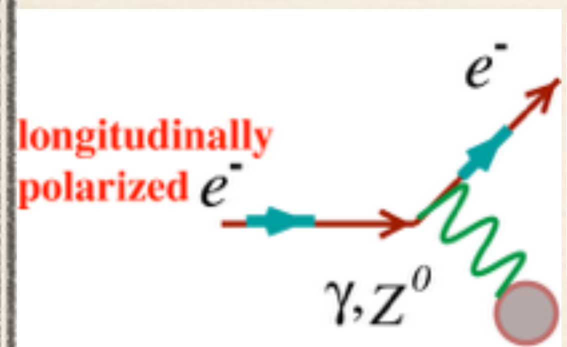
$$\frac{1}{\Lambda^2}\mathcal{L}_6$$

must reach Λ ~ several TeV

All flavor-conserving weak neutral current amplitudes are functions of $\sin^2\theta_W$

Electron's Weak Charge

Parity-violating Electron-Electron Scattering



$$-A_{LR} = A_{PV} = \frac{\sigma_\uparrow - \sigma_\downarrow}{\sigma_\uparrow + \sigma_\downarrow} \sim \frac{A_{weak}}{A_\gamma} \sim \frac{G_F Q^2}{4\pi\alpha}\left(g_A^e \boxed{g_V^T} + \beta\, g_V^e g_A^T\right)$$

g_V and g_A are function of $\sin^2\theta_W$

Weak Charge Q_W

electron target:

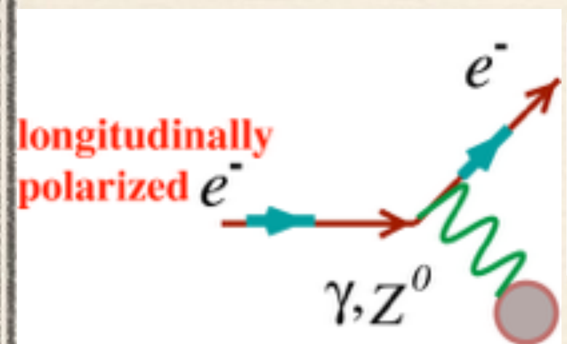
$$Q_W = 1 - 4\sin^2\theta_W$$

small SM weak charge

All flavor-conserving weak neutral current amplitudes are functions of $\sin^2\theta_W$

Electron's Weak Charge

Parity-violating Electron-Electron Scattering



$$-A_{LR} = A_{PV} = \frac{\sigma_\uparrow - \sigma_\downarrow}{\sigma_\uparrow + \sigma_\downarrow} \sim \frac{A_{weak}}{A_\gamma} \sim \frac{G_F Q^2}{4\pi\alpha} (g_A^e \boxed{g_V^T} + \beta\, g_V^e g_A^T)$$

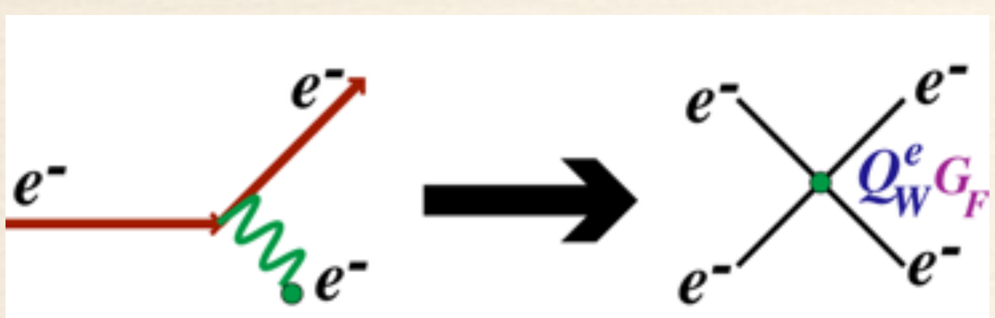
g_V and g_A are function of $\sin^2\theta_W$

Weak Charge Qw

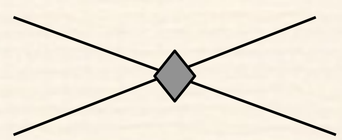
electron target:

$$Q_W = 1 - 4\sin^2\theta_W$$

small SM weak charge



$+$

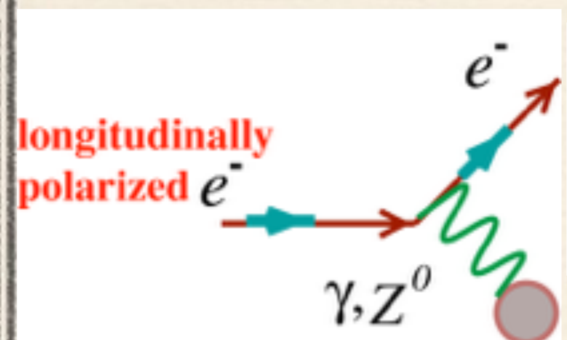


$$\frac{1}{\Lambda^2}\mathcal{L}_6$$

All flavor-conserving weak neutral current amplitudes are functions of $\sin^2\theta_W$

Electron's Weak Charge

Parity-violating Electron-Electron Scattering



$$-A_{LR} = A_{PV} = \frac{\sigma_\uparrow - \sigma_\downarrow}{\sigma_\uparrow + \sigma_\downarrow} \sim \frac{A_{weak}}{A_\gamma} \sim \frac{G_F Q^2}{4\pi\alpha}\left(g_A^e \boxed{g_V^T} + \beta\, g_V^e g_A^T\right)$$

g_V and g_A are function of $\sin^2\theta_W$

Weak Charge Qw

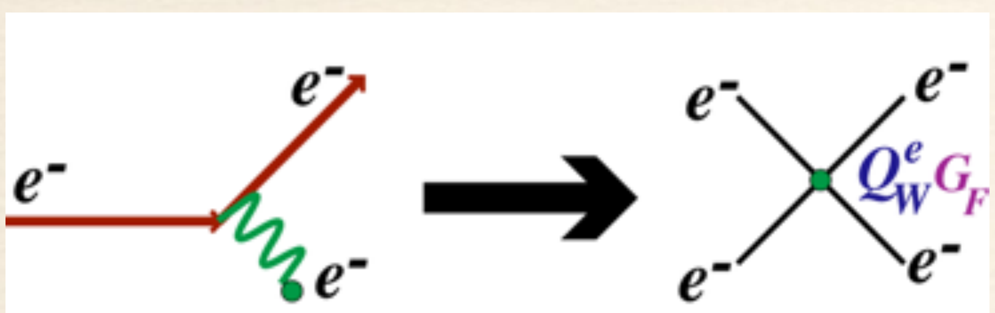
electron target:

$$Q_W = 1 - 4\sin^2\theta_W$$

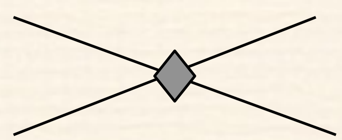
small SM weak charge

$$A_{PV} \approx 8 \times 10^{-8} E_{beam} (1 - 4\sin^2\vartheta_W)$$

$\Rightarrow$ **Tiny!**



$+$

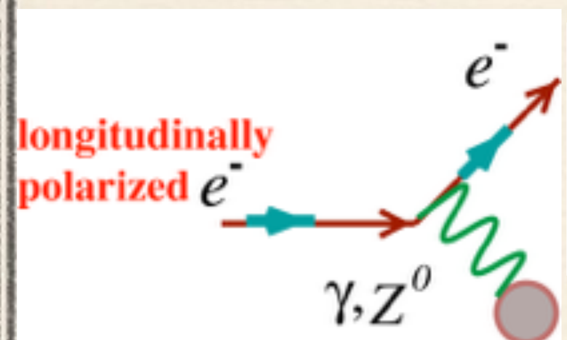


$$\frac{1}{\Lambda^2}\mathcal{L}_6$$

All flavor-conserving weak neutral current amplitudes are functions of $\sin^2\theta_W$

Electron's Weak Charge

Parity-violating Electron-Electron Scattering



$$-A_{LR} = A_{PV} = \frac{\sigma_\uparrow - \sigma_\downarrow}{\sigma_\uparrow + \sigma_\downarrow} \sim \frac{A_{weak}}{A_\gamma} \sim \frac{G_F Q^2}{4\pi\alpha}\left(g_A^e \boxed{g_V^T} + \beta\, g_V^e g_A^T\right)$$

g_V and g_A are function of $\sin^2\theta_W$

Weak Charge Q_W

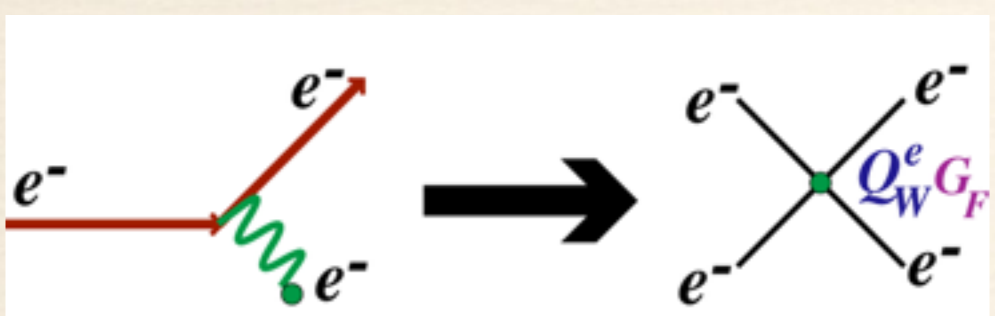
electron target:

$$Q_W = 1 - 4\sin^2\theta_W$$

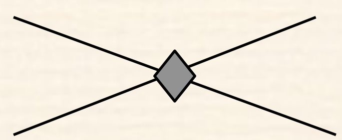
small SM weak charge

$$A_{PV} \approx 8\times 10^{-8} E_{beam}\left(1 - 4\sin^2\vartheta_W\right)$$

⇒ **Tiny!**



$+$

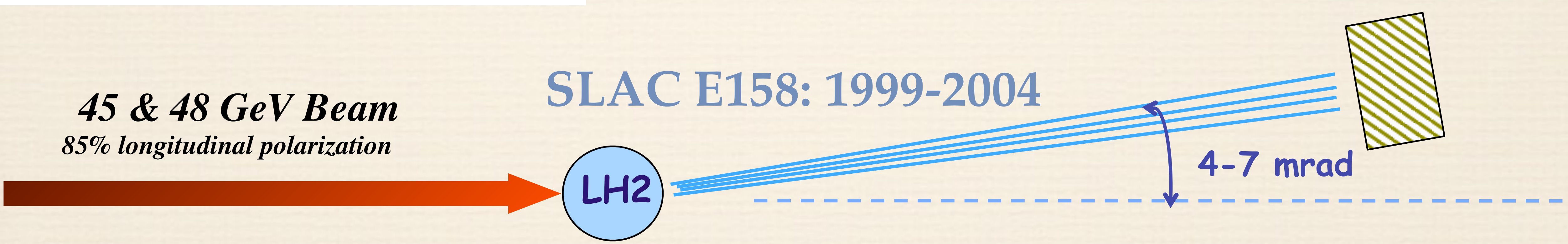


$$\frac{1}{\Lambda^2}\mathcal{L}_6$$

SLAC E158: 1999-2004

45 & 48 GeV Beam

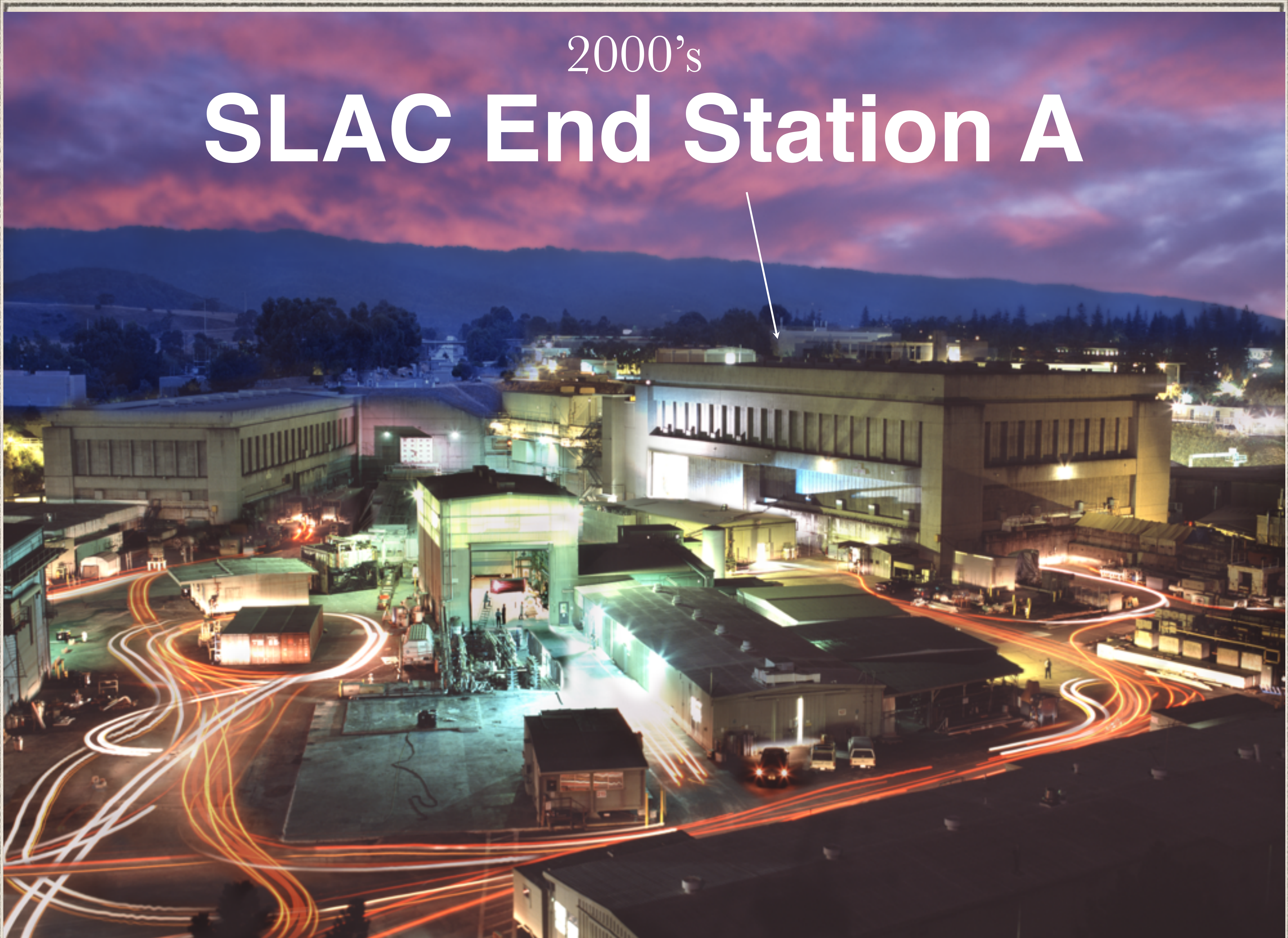
85% longitudinal polarization



End Station A at the Stanford Linear Accelerator Center (SLAC)

2000's

SLAC End Station A



Tree-level prediction: ~ 250 ppb

E158 Implications

Tree-level prediction: ~ 250 ppb

A_{PV} = (-131 ± 14 ± 10) x 10^{-9}

Final E158 Result

E158 Implications

Phys. Rev. Lett. **95** 081601 (2005)

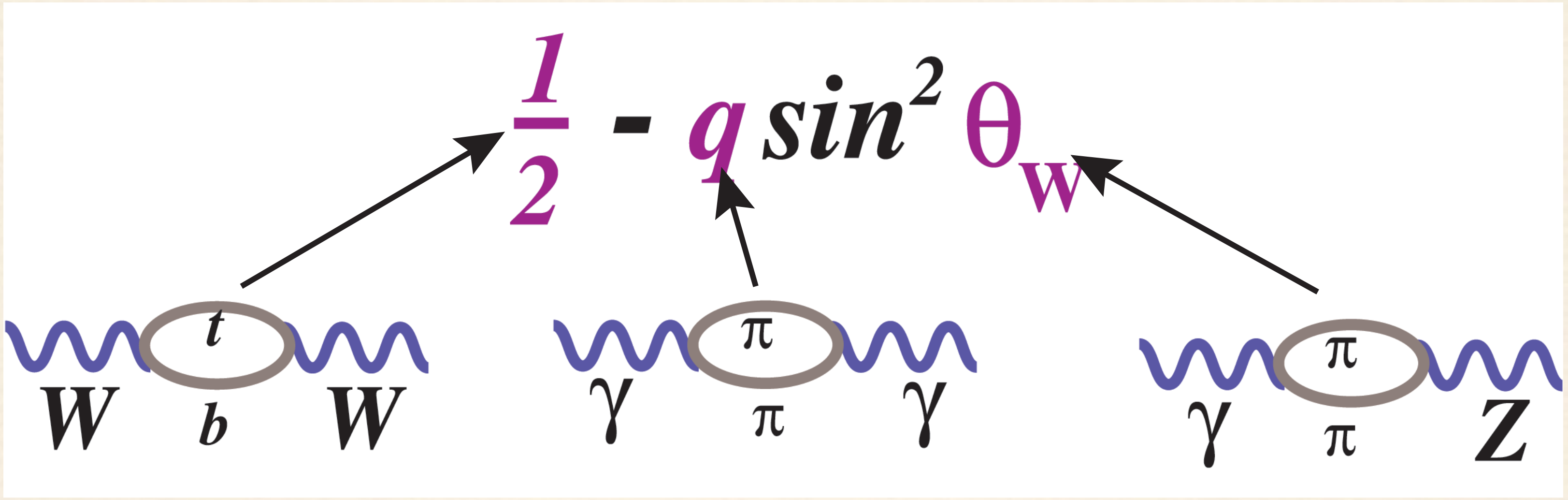
Tree-level prediction: ~ 250 ppb

$A_{PV} = (-131 \pm 14 \pm 10) \times 10^{-9}$

Final E158 Result

E158 Implications

Phys. Rev. Lett. **95** 081601 (2005)



Tree-level prediction: ~ 250 ppb

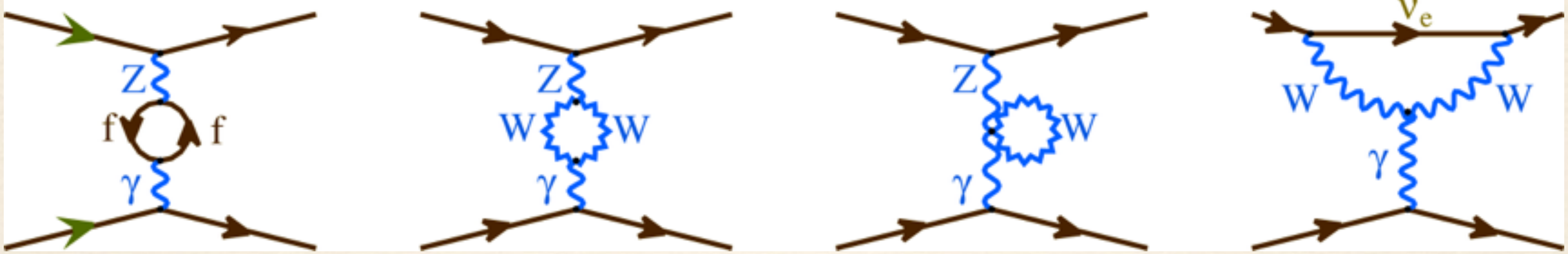
$A_{PV} = (-131 \pm 14 \pm 10) \times 10^{-9}$

Final E158 Result

E158 Implications

Phys. Rev. Lett. **95** 081601 (2005)

Czarnecki and Marciano (1995)



Tree-level prediction: ~ 250 ppb

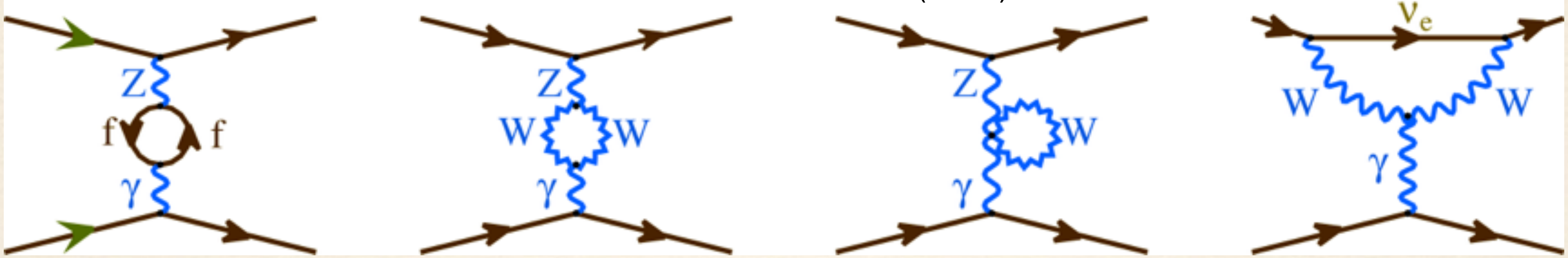
A_{PV} = (-131 ± 14 ± 10) x 10^{-9}

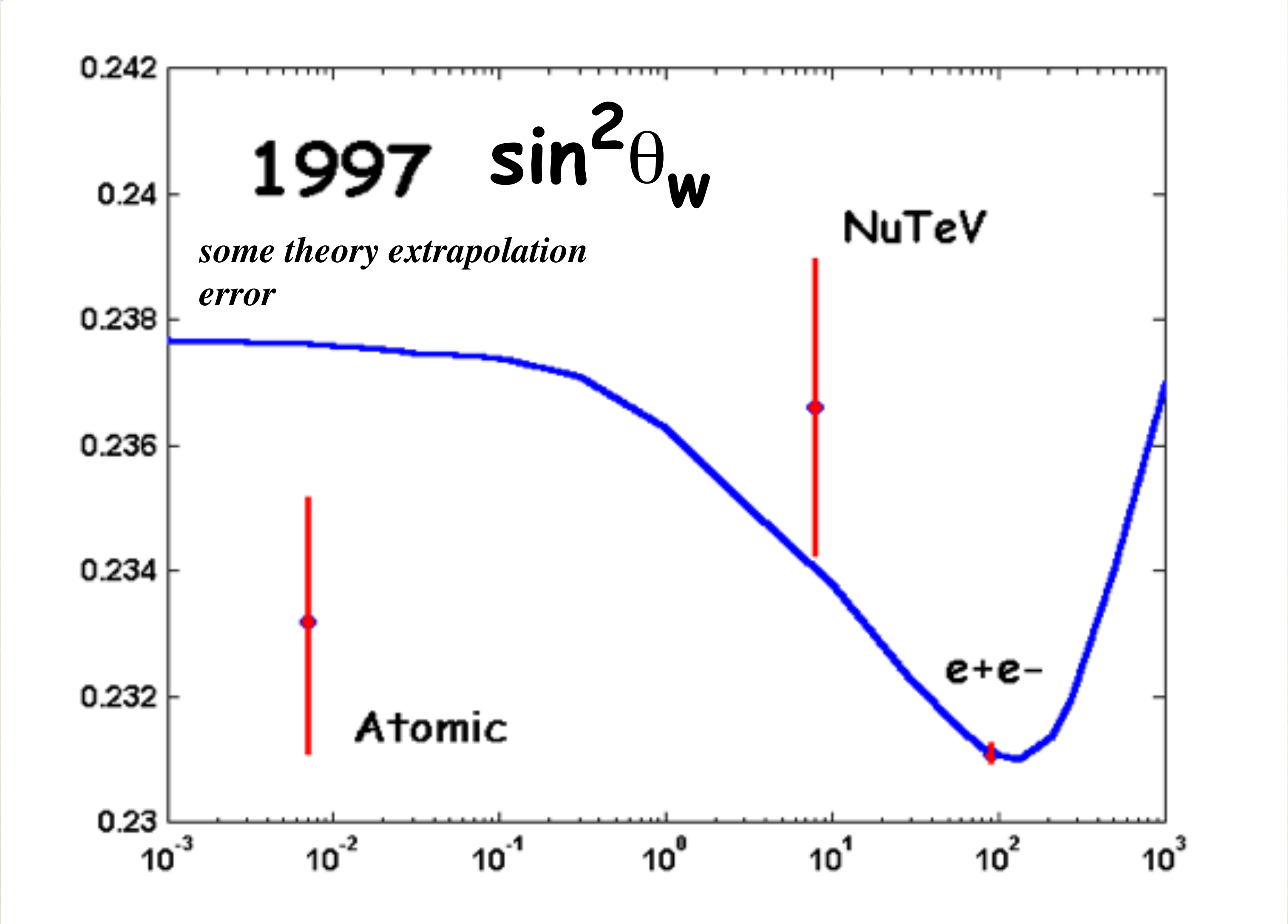
Final E158 Result

E158 Implications

Phys. Rev. Lett. **95** 081601 (2005)

Czarnecki and Marciano (1995)





Tree-level prediction: ~ 250 ppb

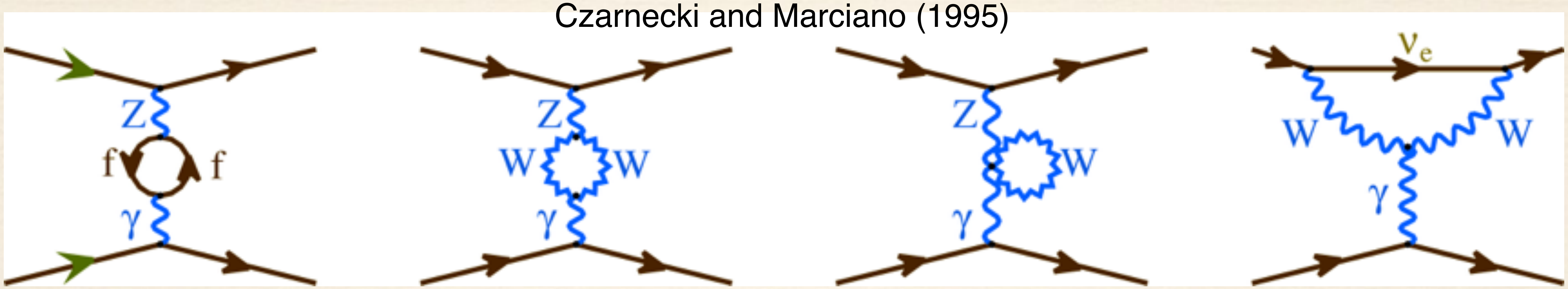
$A_{PV} = (-131 \pm 14 \pm 10) \times 10^{-9}$

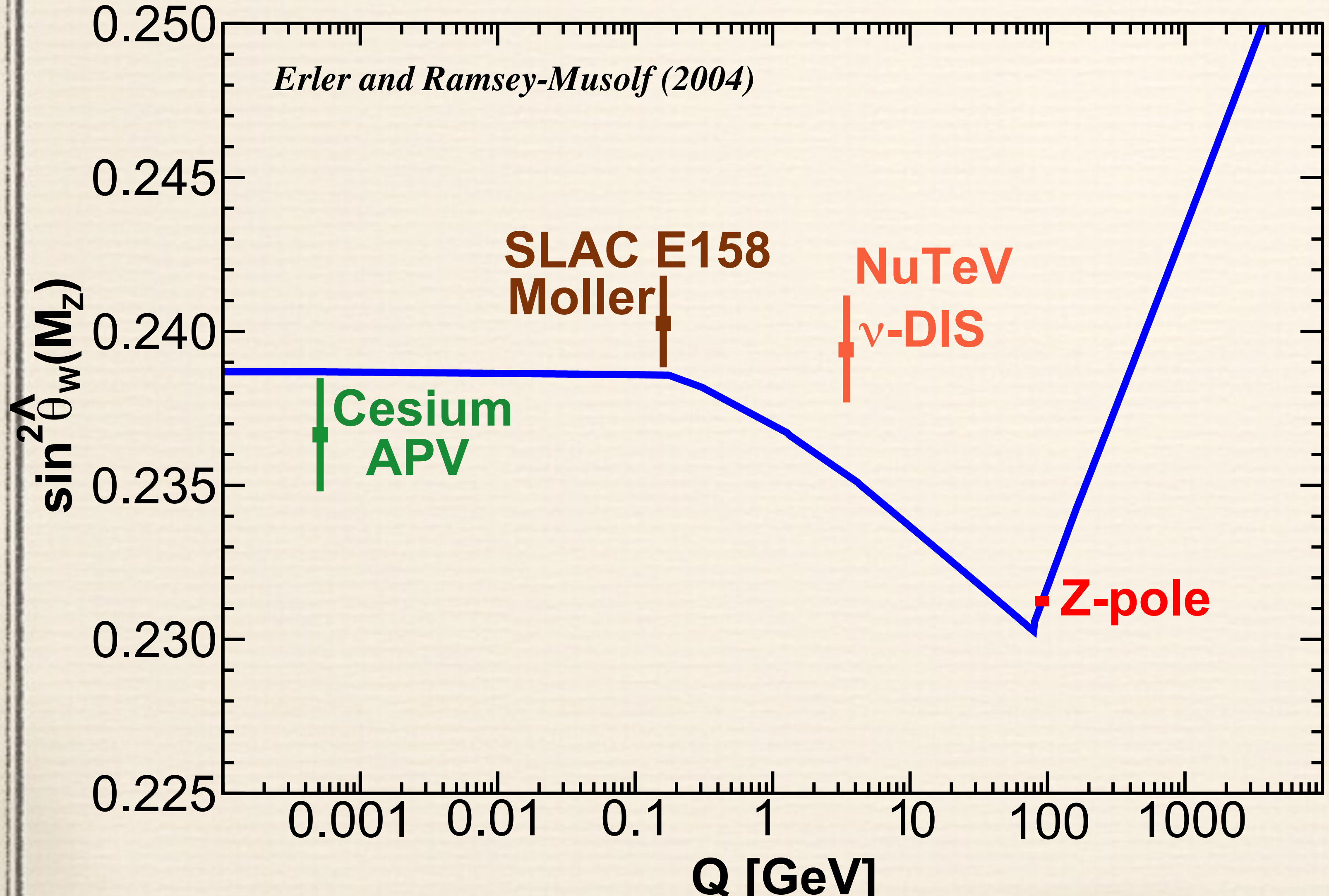
Final E158 Result

E158 Implications

Phys. Rev. Lett. **95** 081601 (2005)

Czarnecki and Marciano (1995)





Tree-level prediction: ~ 250 ppb

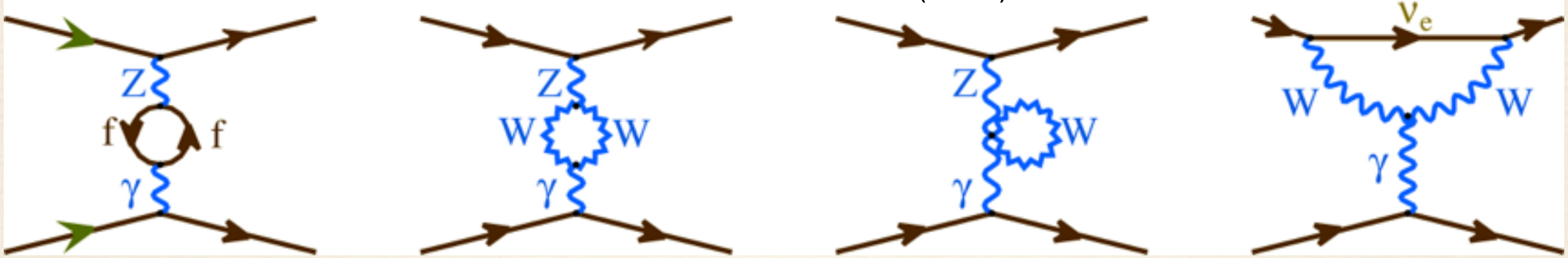
$A_{PV} = (-131 \pm 14 \pm 10) \times 10^{-9}$

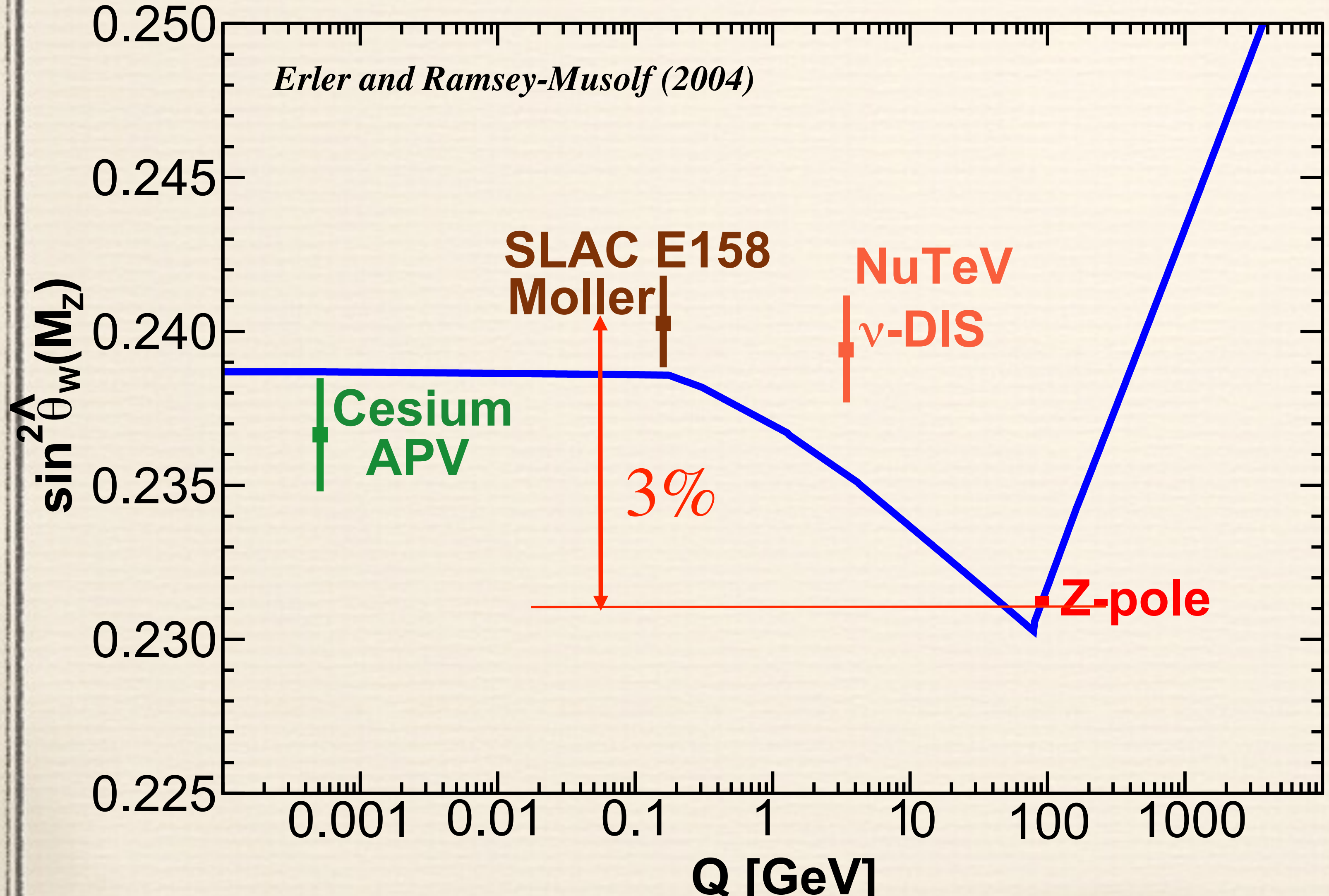
Final E158 Result

E158 Implications

Phys. Rev. Lett. **95** 081601 (2005)

Czarnecki and Marciano (1995)





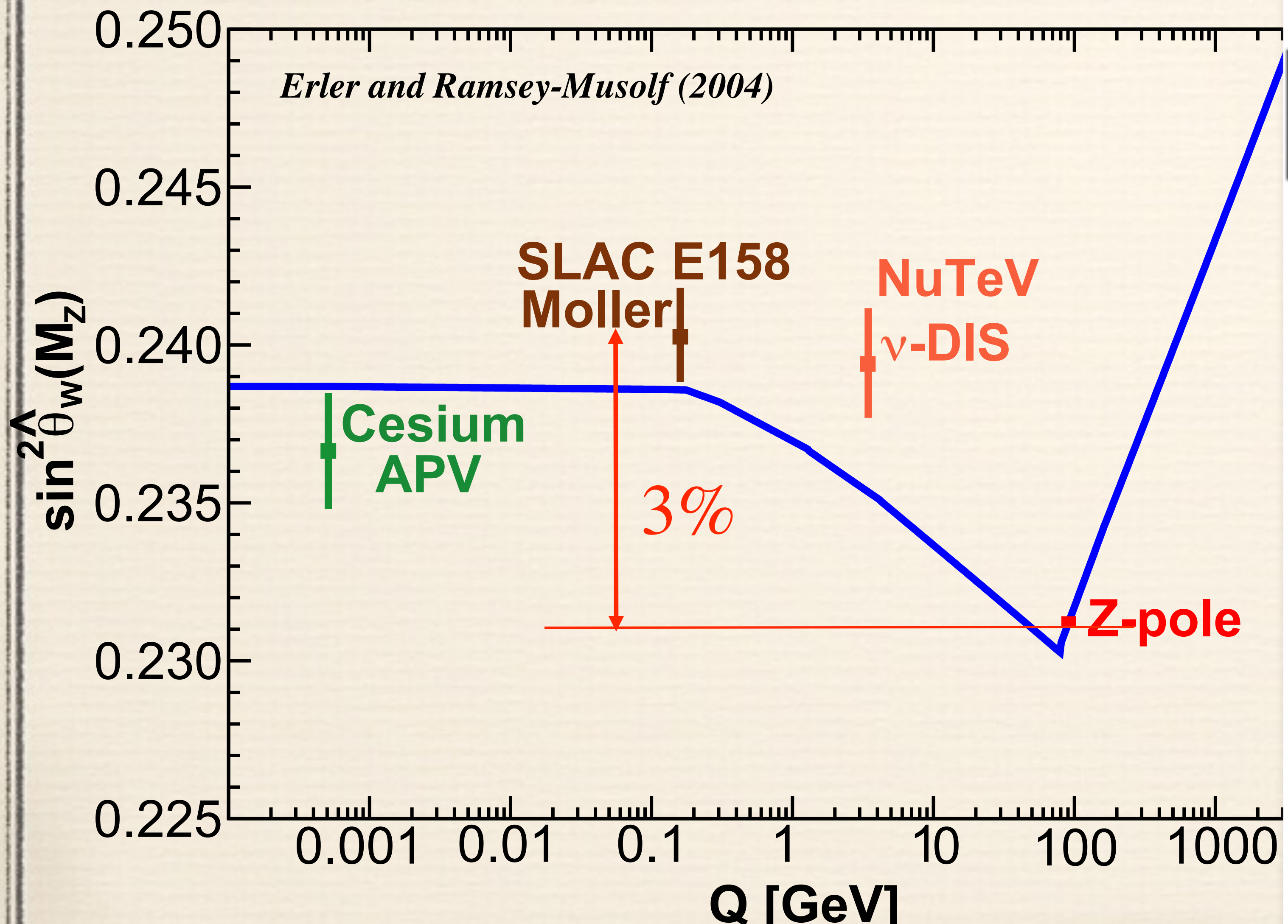
Tree-level prediction: ~ 250 ppb

$A_{PV} = (-131 \pm 14 \pm 10) \times 10^{-9}$

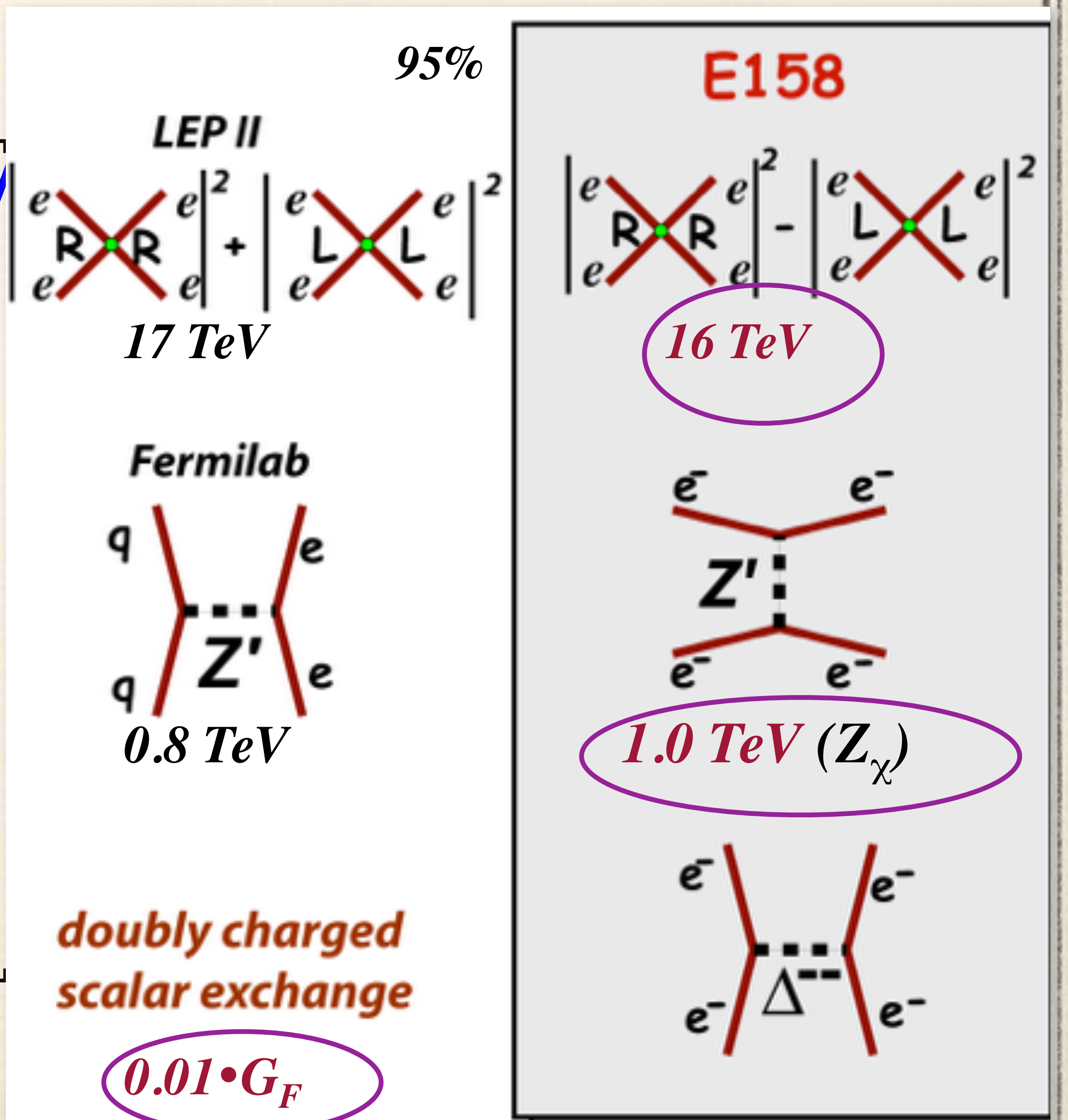
Final E158 Result

E158 Implications

Phys. Rev. Lett. **95** 081601 (2005)



Limits on "New" Physics



$A_{PV} = (-131 \pm 14 \pm 10) \times 10^{-9}$

Final E158 Result

Nature
Vol 435 26 May 2005
NEWS AND VIEWS

E158 Implications

Phys. Rev. Lett. **95** 081601 (2005)

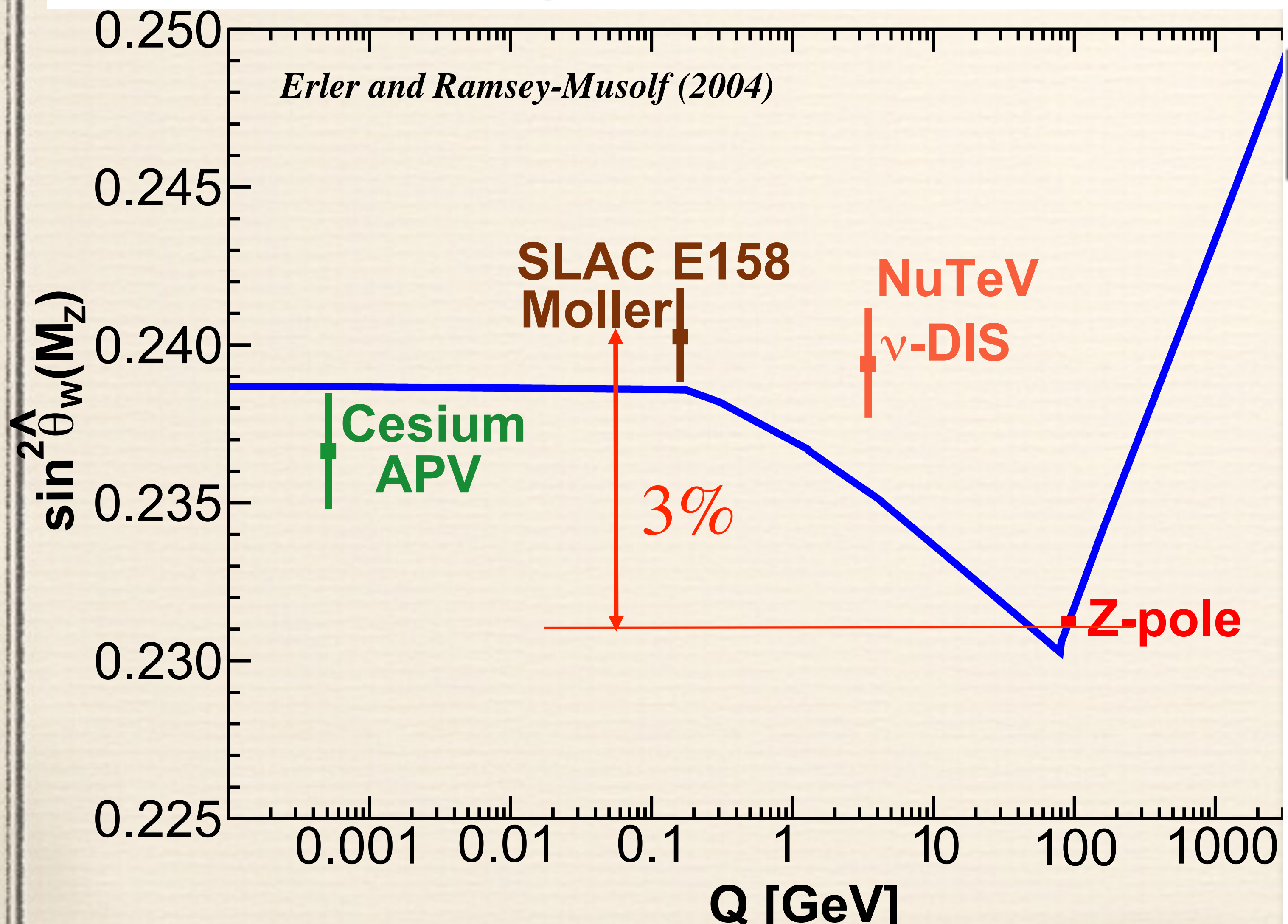
PARTICLE PHYSICS

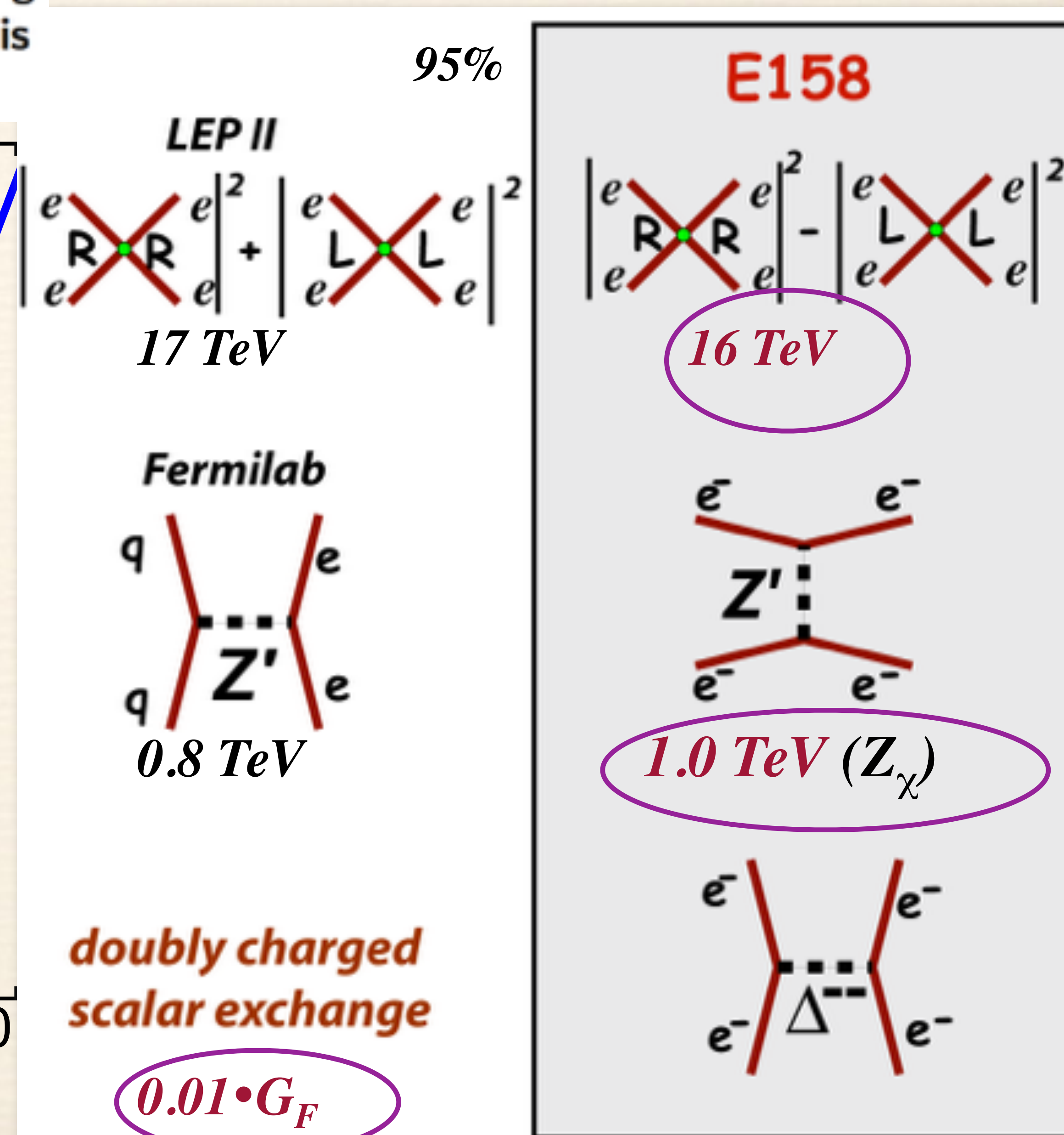
Electrons are not ambidextrous

Andrzej Czarnecki and William J. Marciano

The best low-energy measurement yet obtained of the electroweak mixing angle — a central parameter of the standard model of particle physics — is the last hurrah for Stanford's powerful two-mile linear accelerator.

Limits on "New" Physics





$A_{PV} = (-131 \pm 14 \pm 10) \times 10^{-9}$

Final E158 Result

E158 Implications

Phys. Rev. Lett. **95** 081601 (2005)

Nature
Vol 435 26 May 2005
NEWS AND VIEWS

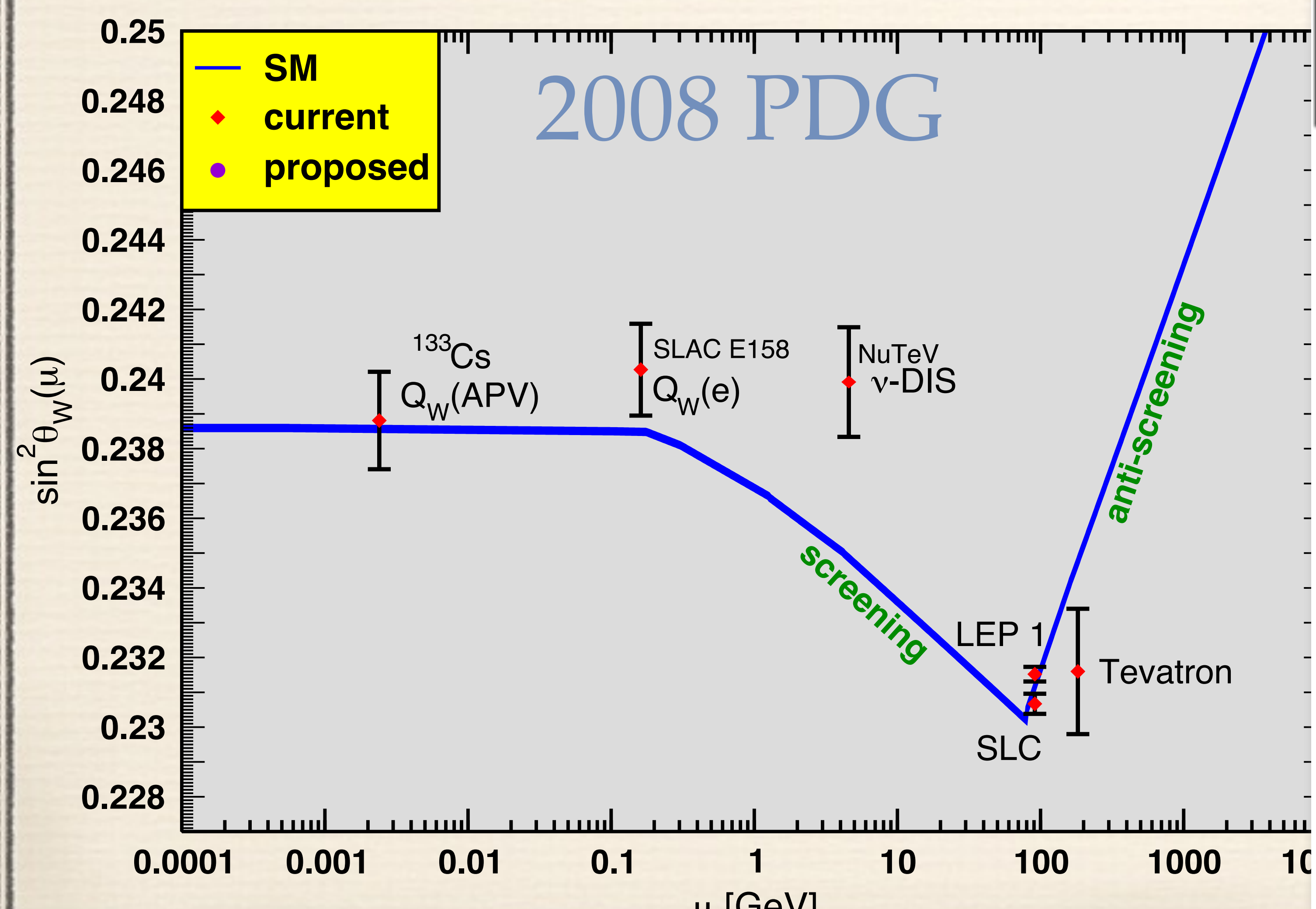
PARTICLE PHYSICS

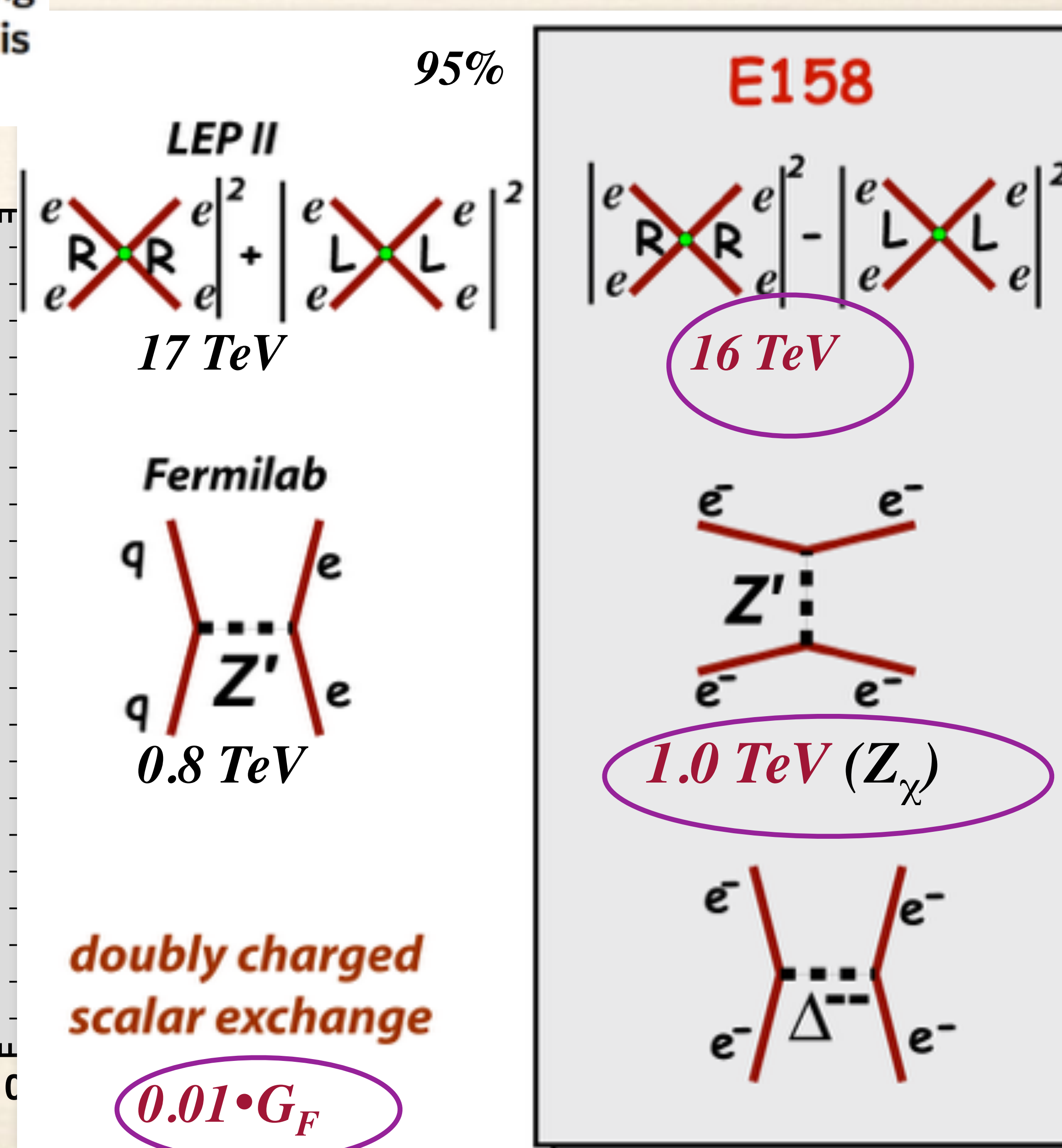
Electrons are not ambidextrous

Andrzej Czarnecki and William J. Marciano

The best low-energy measurement yet obtained of the electroweak mixing angle — a central parameter of the standard model of particle physics — is the last hurrah for Stanford's powerful two-mile linear accelerator.

Limits on "New" Physics





$A_{PV} = (-131 \pm 14 \pm 10) \times 10^{-9}$

Final E158 Result

Nature
Vol 435 26 May 2005
NEWS AND VIEWS

E158 Implications

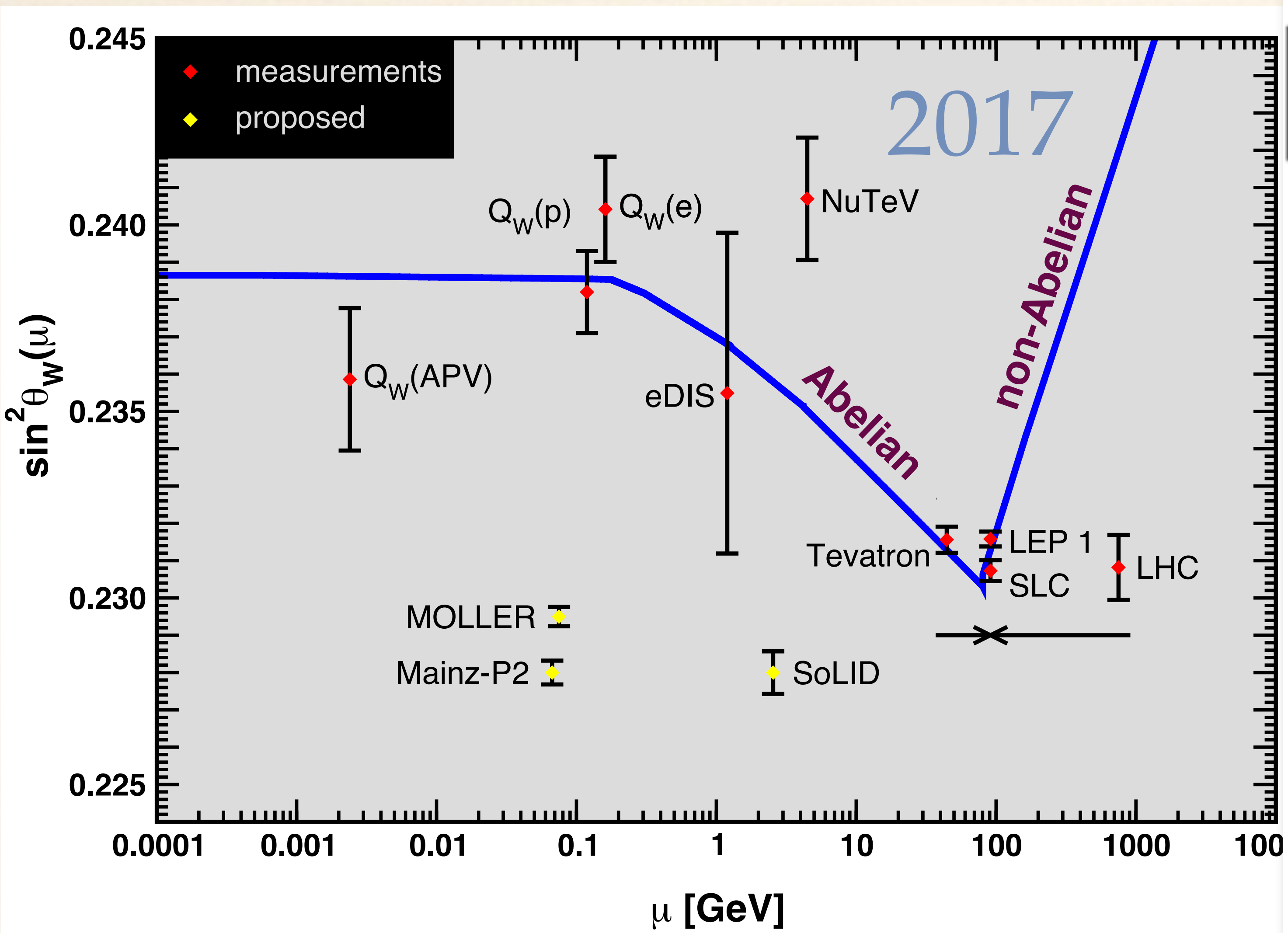
Phys. Rev. Lett. **95** 081601 (2005)

PARTICLE PHYSICS

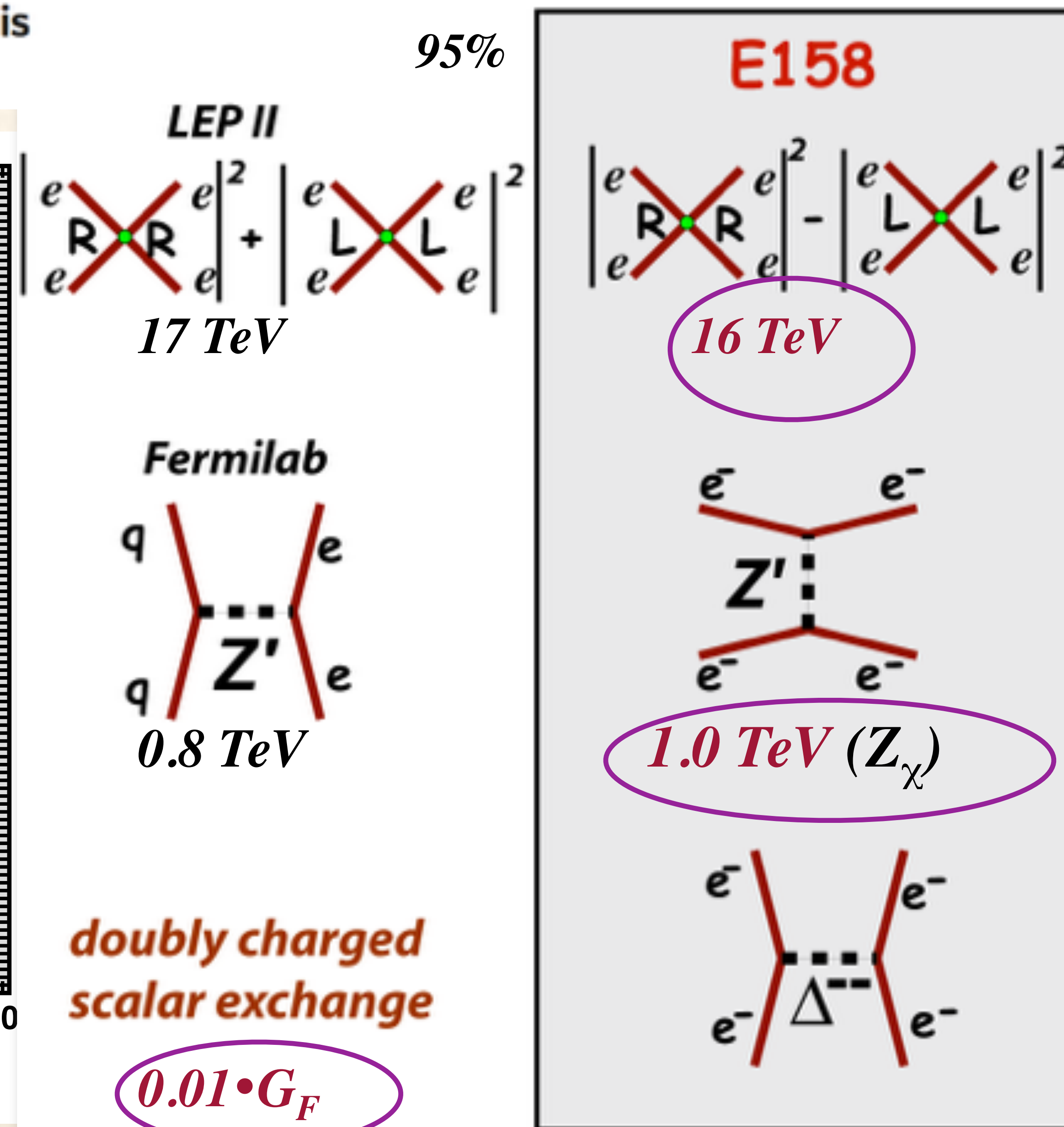
Electrons are not ambidextrous

Andrzej Czarnecki and William J. Marciano

The best low-energy measurement yet obtained of the electroweak mixing angle — a central parameter of the standard model of particle physics — is the last hurrah for Stanford's powerful two-mile linear accelerator.



Limits on "New" Physics



$A_{PV} = (-131 \pm 14 \pm 10) \times 10^{-9}$

Final E158 Result

E158 Implications

Phys. Rev. Lett. **95** 081601 (2005)

Nature
Vol 435 26 May 2005

NEWS AND VIEWS

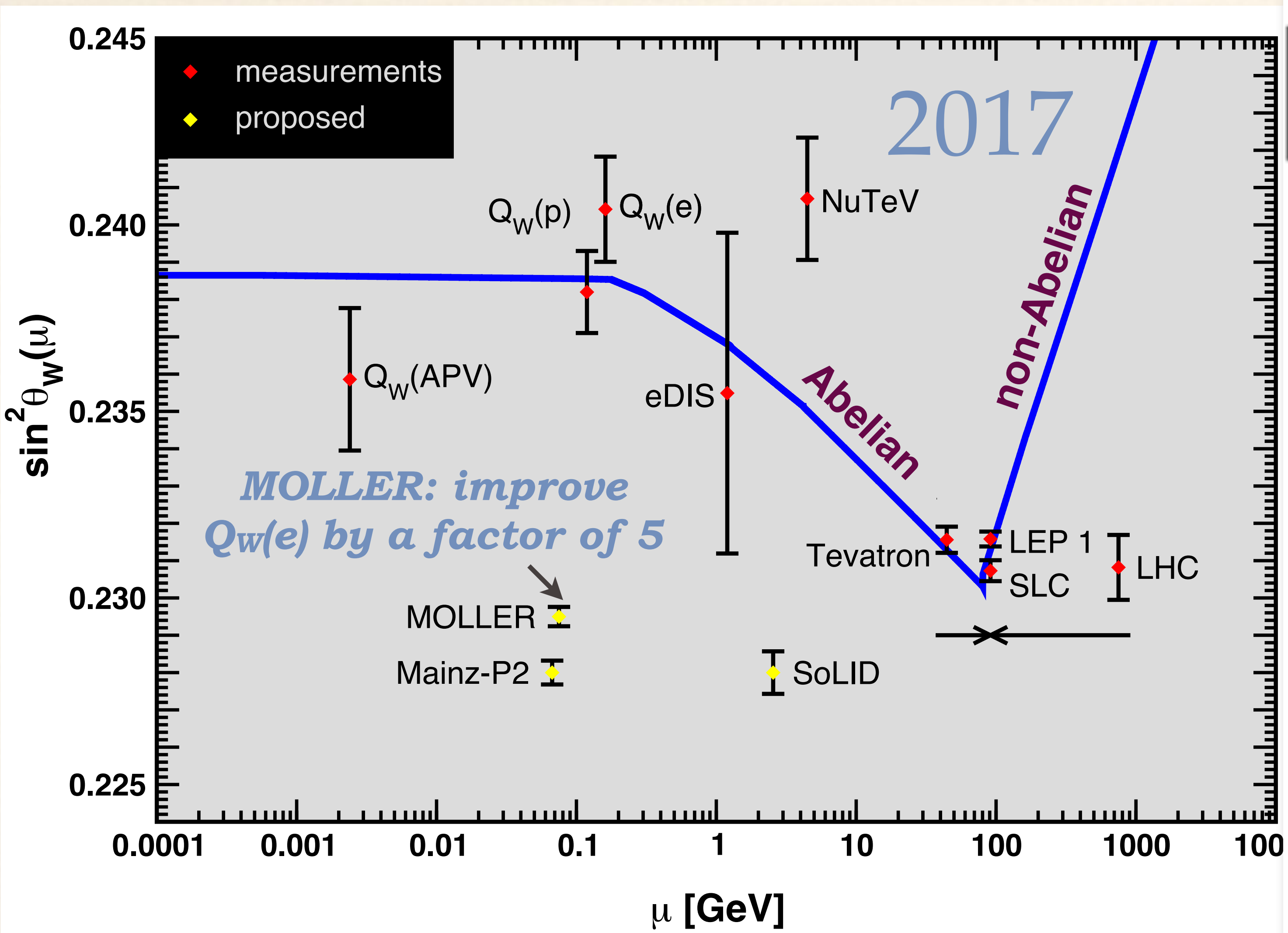
PARTICLE PHYSICS

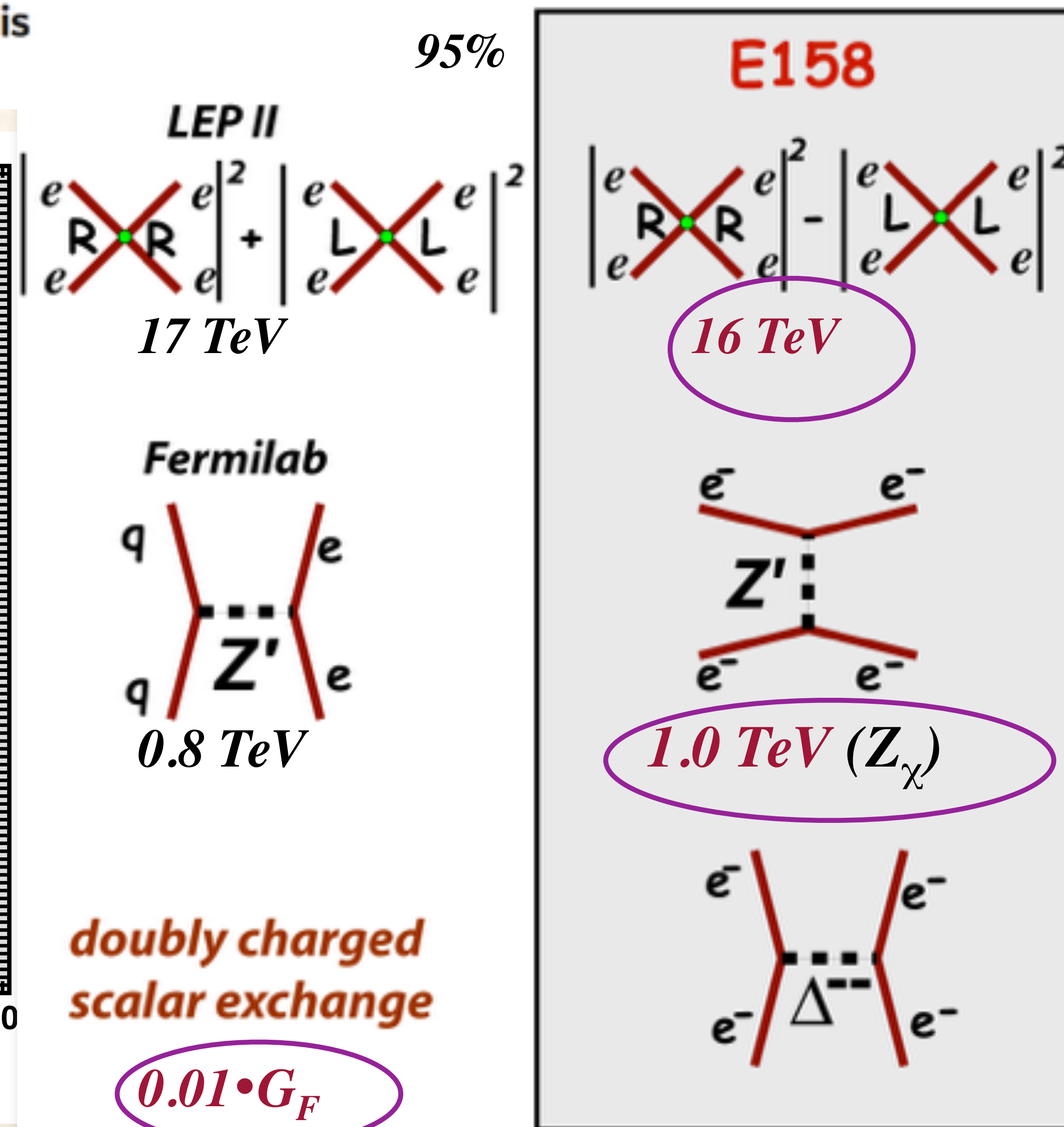
Electrons are not ambidextrous

Andrzej Czarnecki and William J. Marciano

The best low-energy measurement yet obtained of the electroweak mixing angle — a central parameter of the standard model of particle physics — is the last hurrah for Stanford's powerful two-mile linear accelerator.

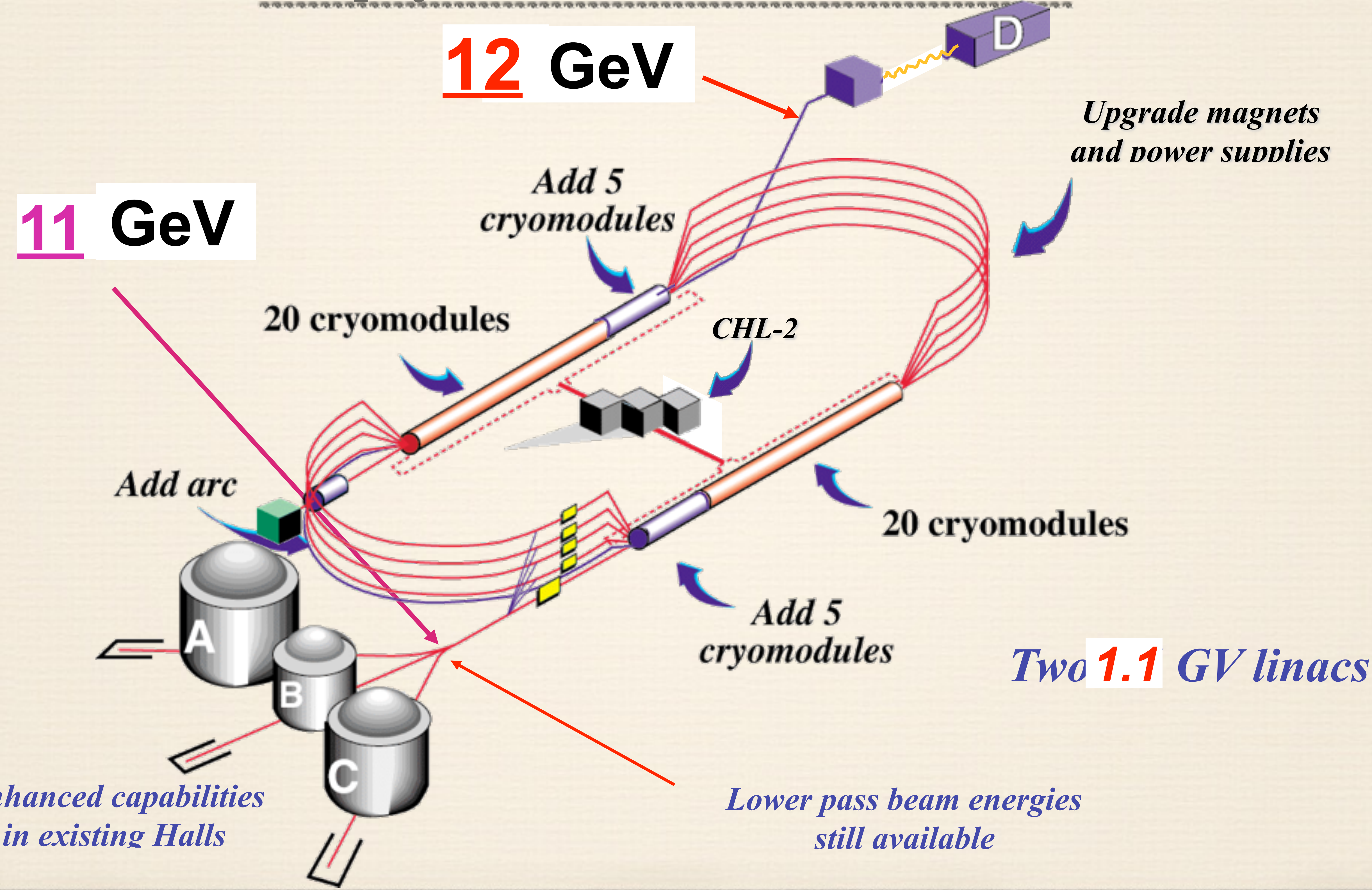
Limits on "New" Physics





The 12 GeV Upgrade of JLab

First physics beams to Hall A in 2014



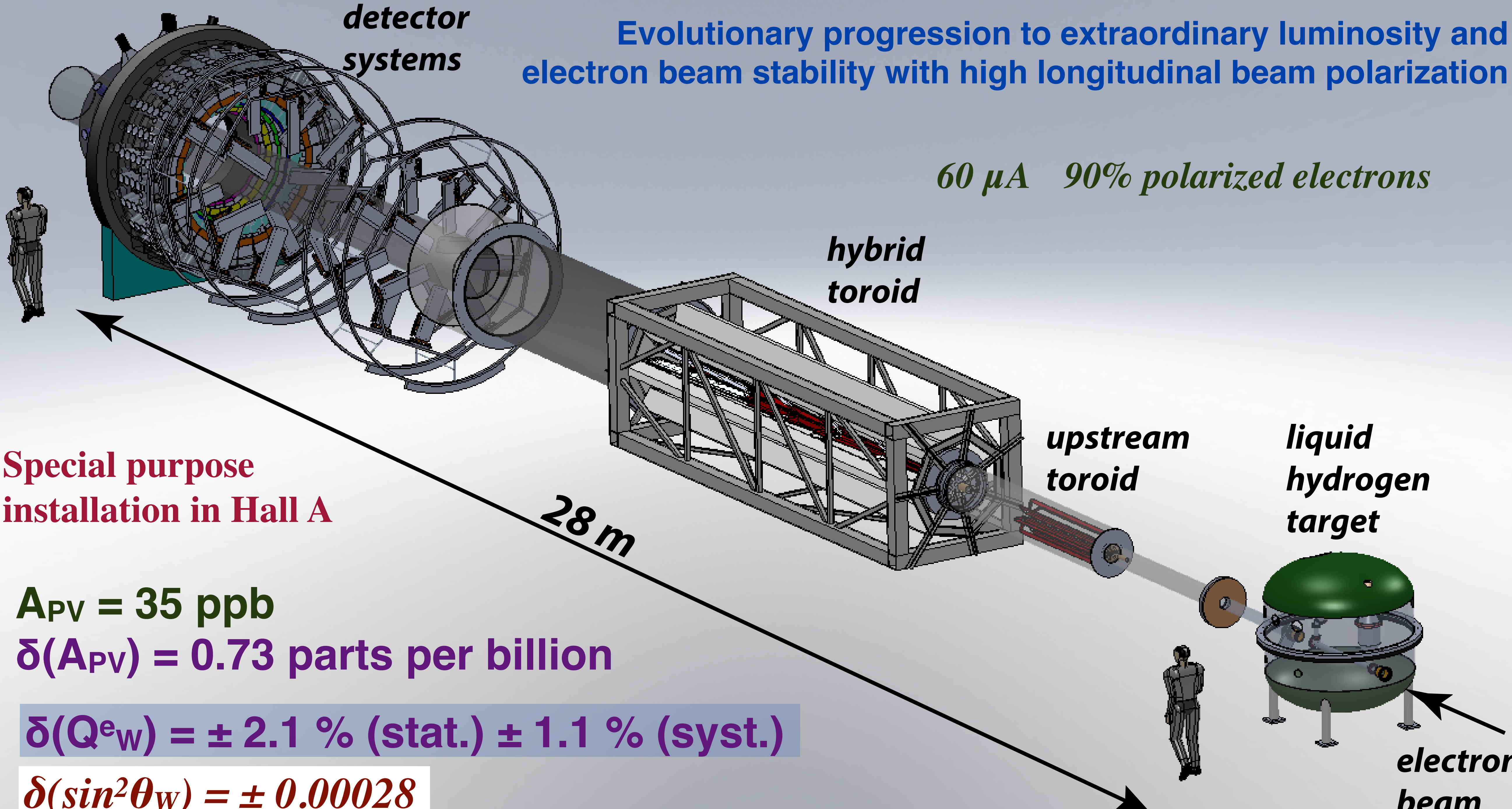
Parity-Violating Fixed Target 11 GeV electron-electron (Møller) scattering

MOLLER at JLab

Unique opportunity leveraging the 12 GeV Upgrade investment

Evolutionary progression to extraordinary luminosity and electron beam stability with high longitudinal beam polarization

60 μA   90% polarized electrons



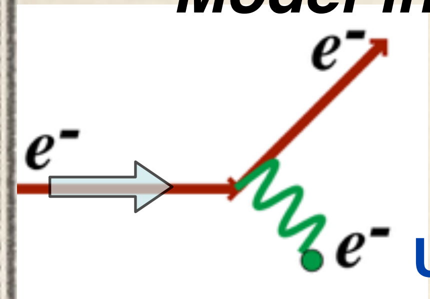
Special purpose installation in Hall A

A_{PV} = 35 ppb

$\delta(A_{PV})$ = 0.73 parts per billion

$\delta(Q^e_W) = \pm$ 2.1 % (stat.) $\pm$ 1.1 % (syst.)

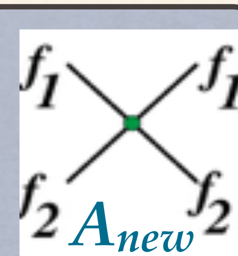
$\delta(\sin^2\theta_W) = \pm 0.00028$



MOLLER Reach

Use Common Language for Low Energy and High Energy Measurements

New heavy physics: no direct coupling to SM gauge bosons



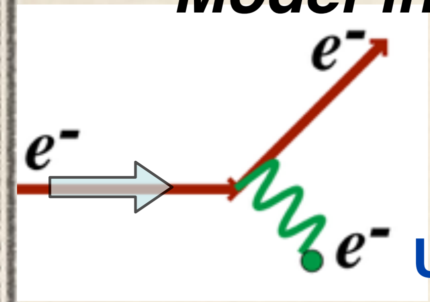
on Z_0 resonance: A_Z is imaginary

$$\left|A_Z + A_{\mathrm{new}}\right|^2 \to A_Z^2\left[1 + \left(\frac{A_{\mathrm{new}}}{A_Z}\right)^2\right]$$

no interference term!

Additionally, A_{new} could be mediated by a new light boson: "dark Z"

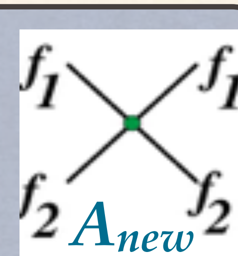
Model-independent Picture of 4-Fermion Flavor Diagonal Contact Interactions



MOLLER Reach

Use Common Language for Low Energy and High Energy Measurements

New heavy physics: no direct coupling to SM gauge bosons



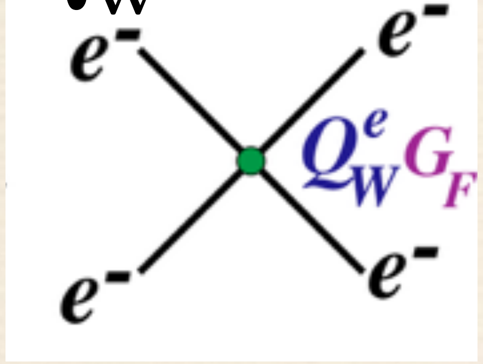
on Z_0 resonance: A_Z is imaginary

$$\left|A_Z + A_{new}\right|^2 \to A_Z^2\left[1 + \left(\frac{A_{new}}{A_Z}\right)^2\right]$$

no interference term!

Additionally, A_{new} could be mediated by a new light boson: "dark Z"

$$Q_W^e \sim 0.045$$

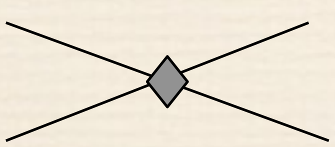


$$\frac{\delta Q_W^e}{Q_W^e} = 2.4\%$$

$$A_{new} \sim 0.001 \cdot G_F$$

unprecedented sensitivity!

$$\mathcal{L}_{e_1 e_2} = \sum_{i,j=L,R} \frac{g_{ij}^2}{2\Lambda^2} \bar{e}_i \gamma_\mu e_i \bar{e}_j \gamma^\mu e_j$$

\+  $\frac{1}{\Lambda^2}\mathcal{L}_6$

$$\frac{\Lambda}{\sqrt{|g_{RR}^2 - g_{LL}^2|}} = 7.5 \text{ TeV}$$

95% C. L. Reach

Comparison with e⁺e⁻ Collisions

Best reach on purely leptonic contact interaction amplitudes: LEP200

$$\mathcal{L}_{e_1 e_2} = \sum_{\mathbf{i,j=L,R}} \frac{\mathbf{g_{ij}^2}}{\mathbf{2\Lambda^2}} \bar{\mathbf{e}}_\mathbf{i}\gamma_\mu \mathbf{e_i}\bar{\mathbf{e}}_\mathbf{j}\gamma^\mu \mathbf{e_j}$$

$$g_{ij} = 4\pi\eta_{ij}$$

Model	η^f_{LL}	η^f_{RR}	η^f_{LR}	η^f_{RL}
$LL^\pm$	±1	0	0	0
$RR^\pm$	0	±1	0	0
$VV^\pm$	±1	±1	±1	±1

LEP200 Reach $\Lambda^{ee}_{LL} \sim \mathbf{8.3}$ TeV

E158 Reach $\Lambda^{ee}_{LL} \sim \mathbf{12}$ TeV

MOLLER Reach $\Lambda^{ee}_{LL} \sim \mathbf{27}$ TeV

MOLLER is accessing discovery space that cannot be reached until the advent of a new lepton collider or neutrino factory

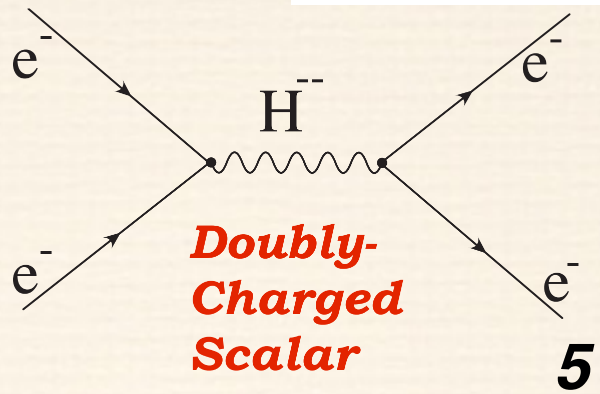
Unique Opportunity: Purely Leptonic Reaction at $Q^2 \ll M_Z^2$

New Physics Examples

Deviations From Theory Prediction Interpretable as New Physics

Many different scenarios give rise to effective 4-electron contact interaction amplitudes: significant discovery potential

Lepton Number Violation



$$\left|\frac{\Delta Q_W^e}{Q_W^e}\right| = 0.14 \frac{|h_{ee}|^2}{(M_\Delta/1\ \mathrm{TeV})^2}$$

$5\,\sigma$ for $h_{ee} \sim 1$ and $M_\Delta \sim 1$ TeV

See Michael's talk! (and send me the slides!)

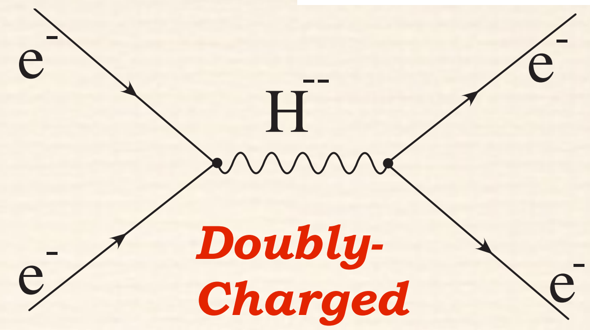
Unique Opportunity: Purely Leptonic Reaction at $Q^2 << M_Z^2$

New Physics Examples

Deviations From Theory Prediction Interpretable as New Physics

Many different scenarios give rise to effective 4-electron contact interaction amplitudes: significant discovery potential

Lepton Number Violation

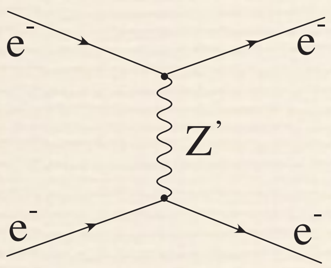


Doubly-Charged Scalar

$$\left|\frac{\Delta Q_W^e}{Q_W^e}\right| = 0.14\frac{|h_{ee}|^2}{(M_\Delta/1\ \mathrm{TeV})^2}$$

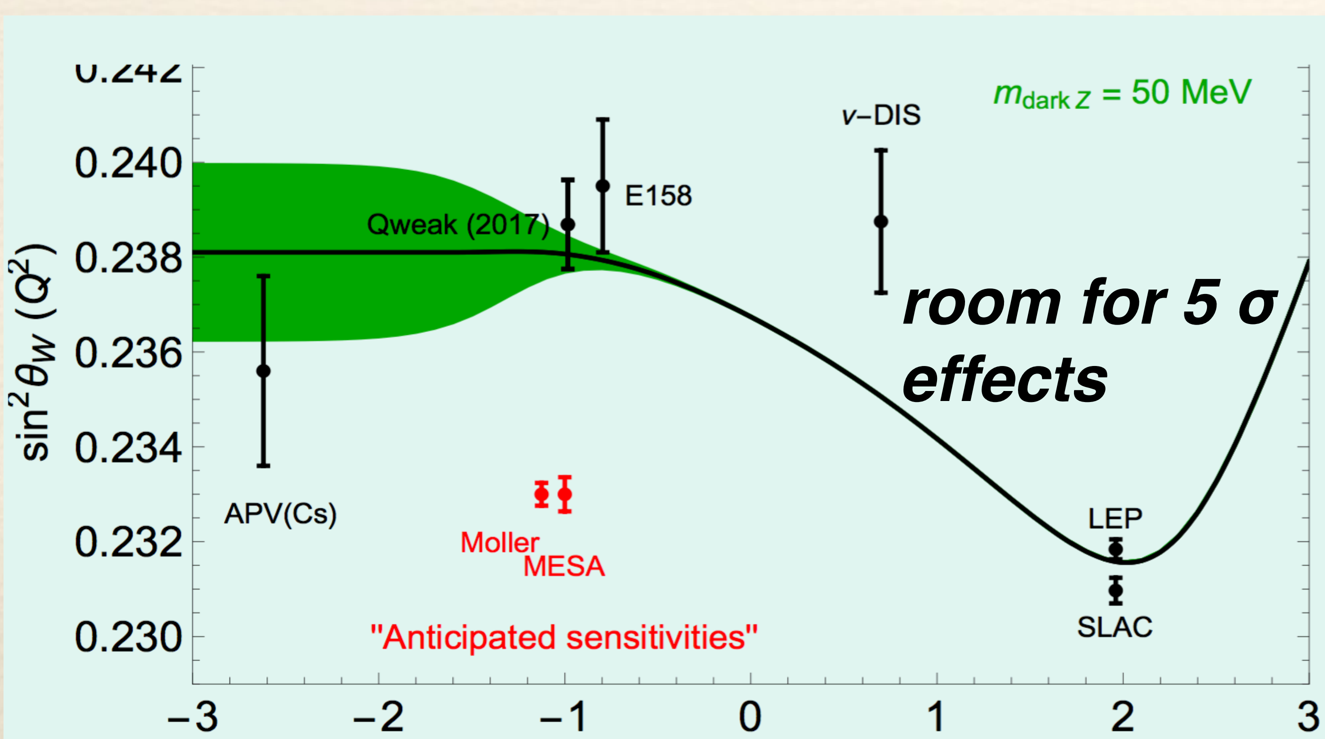
5 σ for h_{ee} ~ 1 and M_Δ ~ 1 TeV

See Michael’s talk! (and send me the slides!)



Heavy Photons (A’ mixed with Z_0): The Dark Z

H. Davoudiasl, H-S. Lee and W. Marciano



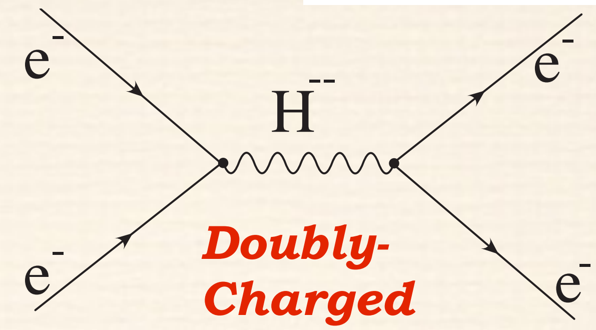
Unique Opportunity: Purely Leptonic Reaction at $Q^2 << M_Z^2$

New Physics Examples

Deviations From Theory Prediction Interpretable as New Physics

Many different scenarios give rise to effective 4-electron contact interaction amplitudes: significant discovery potential

Lepton Number Violation

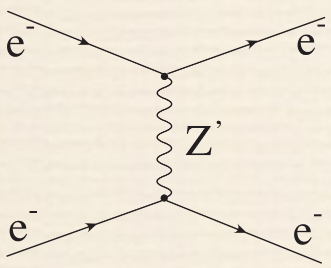


Doubly-Charged Scalar

$$\left|\frac{\Delta Q_W^e}{Q_W^e}\right| = 0.14 \frac{|h_{ee}|^2}{(M_\Delta/1\ \mathrm{TeV})^2}$$

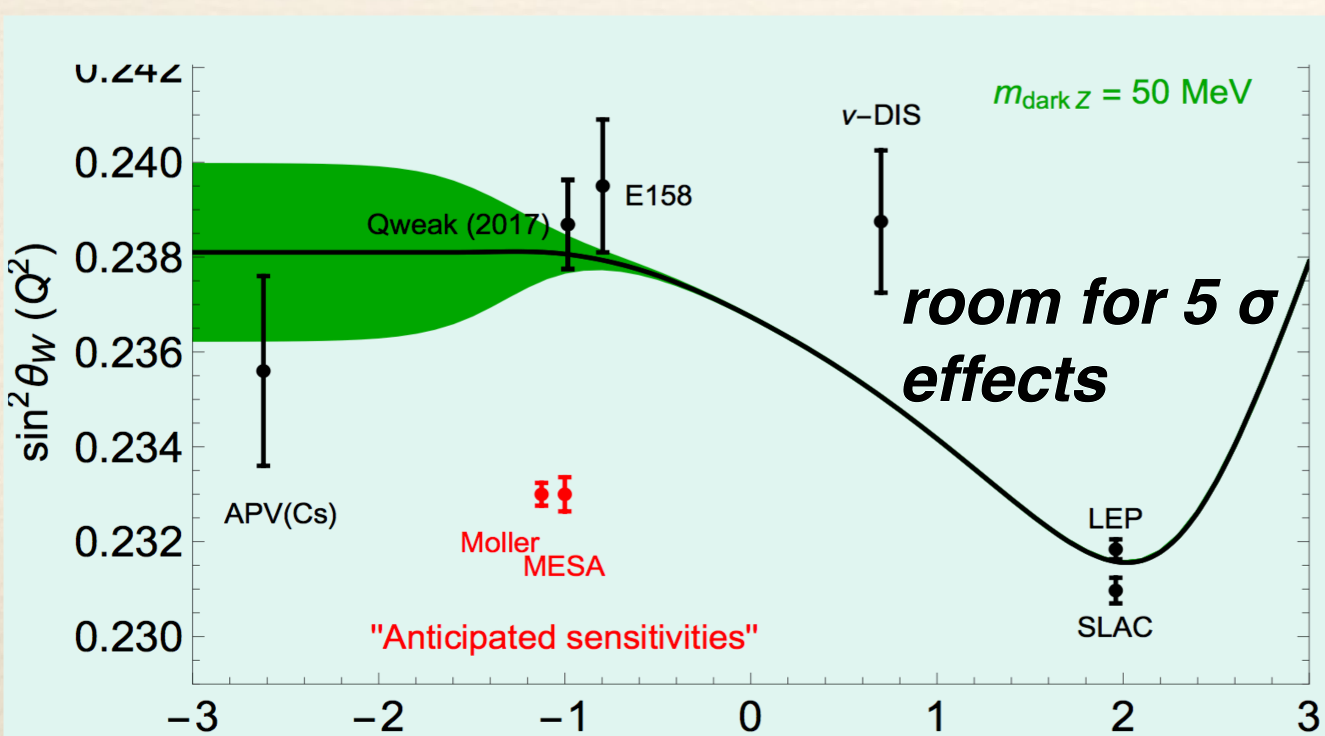
5 σ for h_{ee} ~ 1 and M_Δ ~ 1 TeV

See Michael's talk! (and send me the slides!)



Heavy Photons (A' mixed with Z_0): The Dark Z

H. Davoudiasl, H-S. Lee and W. Marciano



Constraining Lorentz Invariance

Ralf Lehnert, J. Phys.: Conf. Ser. **952** (2018) 012008

$$\begin{aligned}\delta A(t) &= \frac{G_F}{\sqrt{2}\pi\alpha}\,\frac{E_k\,y\,(1-y)\sin^2\theta_W}{(y^2-y+1)^2}\,\vec{k}(t)\cdot\vec{\xi}\\ &= \frac{G_F}{\sqrt{2}\pi\alpha}\,\frac{E_k^2\,y\,(1-y)\sin^2\theta_W}{(y^2-y+1)^2}\times\\ &\quad\left[\sqrt{\xi_X^2+\xi_Y^2}\sqrt{1-\cos^2\alpha\sin^2\chi}\,\cos\Omega_\oplus t + c_0\right]\end{aligned}$$

Unique Opportunity: Purely Leptonic Reaction at $Q^2 << M_Z^2$

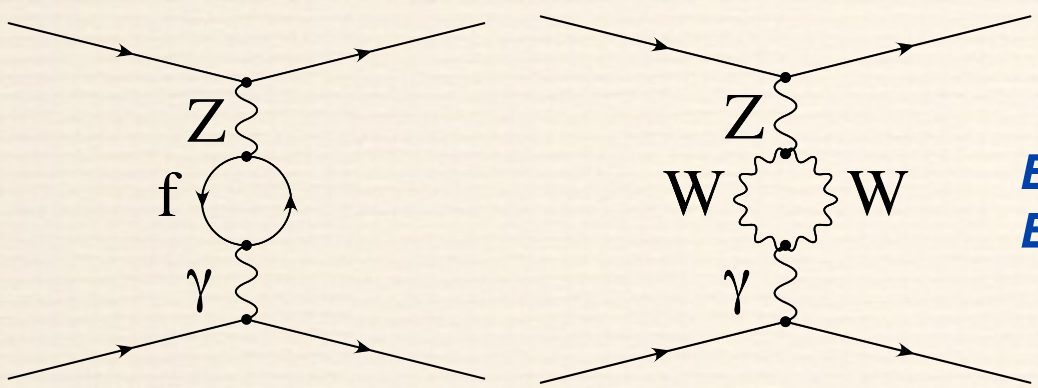
Electroweak Theory

EW Theory Prediction Uncertainty Well Below Projected Experimental Uncertainty

Czarnecki and Marciano (1995)

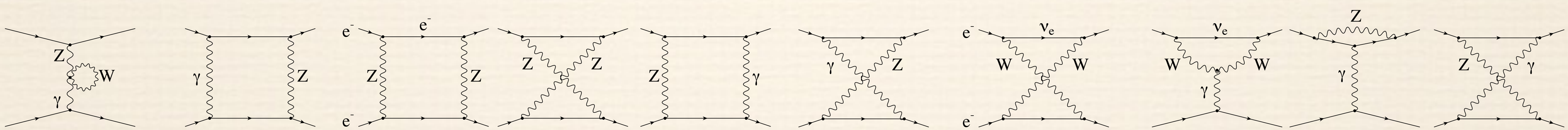
$$A_{PV}(ee) \propto \rho G_F \left[1 - 4\kappa(0)\sin^2\theta_W(m_Z)_{\overline{\mathrm{MS}}}\right] + \cdots$$

Dominant Contribution at 1-loop



κ(0) known better than 1% of itself

Erler and Ramsey-Musolf (2003)
Erler and Ferro-Hernandez (2018)



$\delta(Q^e_W)$ (theory) = 0.6%, another factor of 2 improvement with full two-loop calculation

See talks by:
- **A. Aleksejev**
- **A. Freitas**
- **R. Ferro Hernandez**
- **H. Patel**
- **M. Ramsey-Musolf**

MOLLER **$\delta(Q^e_W)$ goal = ± 2.1 % (stat.) ± 1.1 % (syst.)**

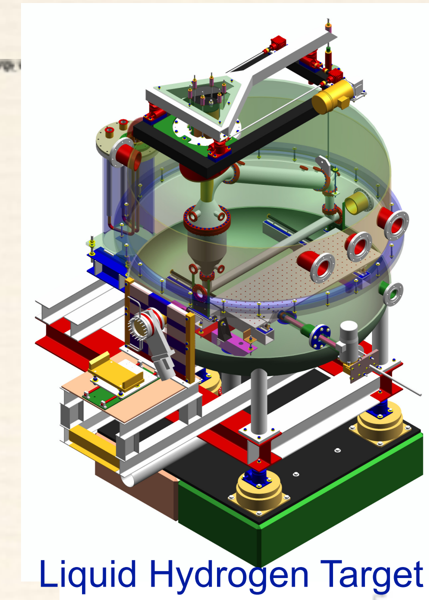
MOLLER Apparatus

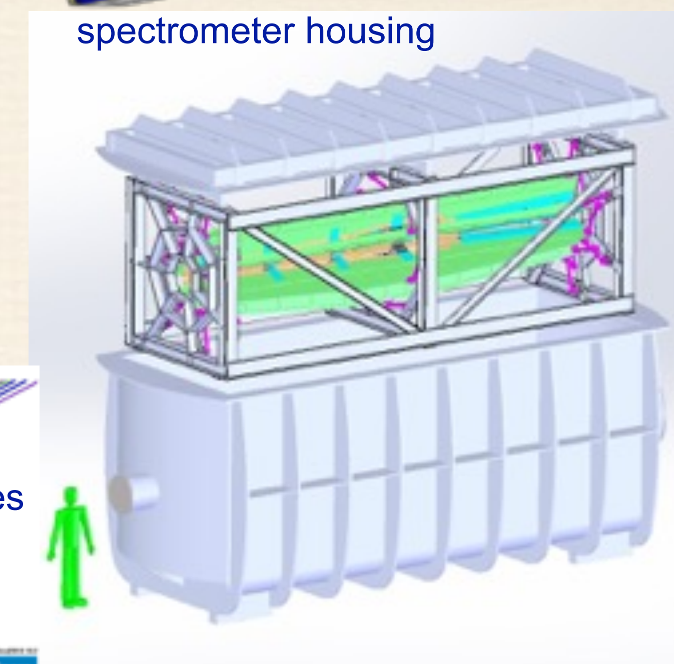
Technical Challenges

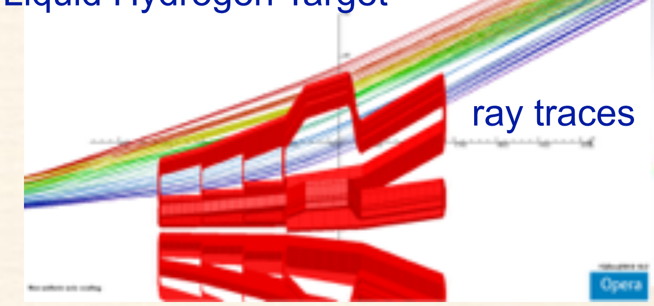
Evolutionary Improvements from Technology of Third Generation Experiments

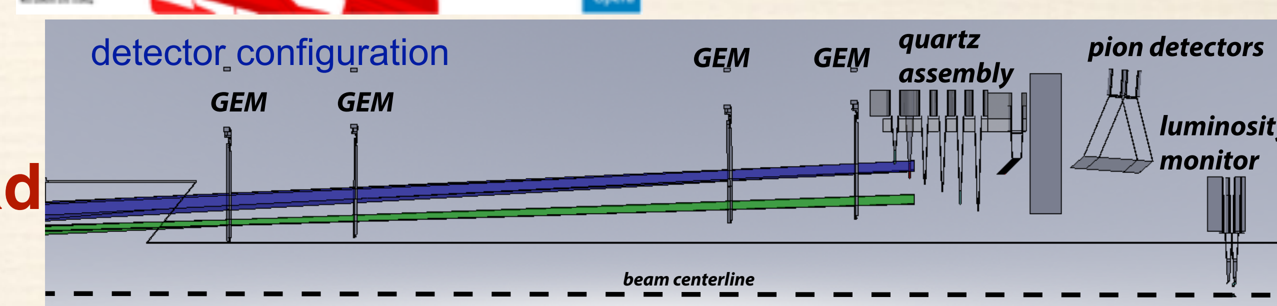
- **~ 150 GHz scattered electron rate**
- **1 nm control of beam centroid on target**
- **> 10 gm/cm² liquid hydrogen target**
  - **1.5 m: ~ 5 kW @ 85 μA**
- **Full Azimuthal acceptance w/ θ_{lab} ~ 5 mrad**
  - **novel toroidal spectrometer pair**
  - **radiation hard, highly segmented integrating detectors**
- **Robust & Redundant 0.4% beam polarimetry**

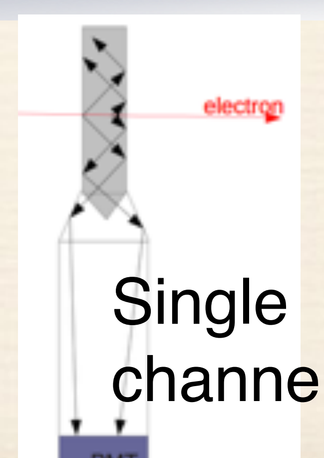
hybrid spectrometer coil

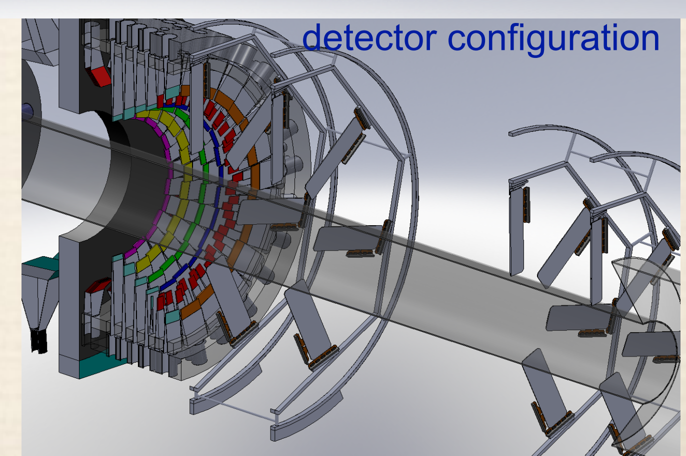












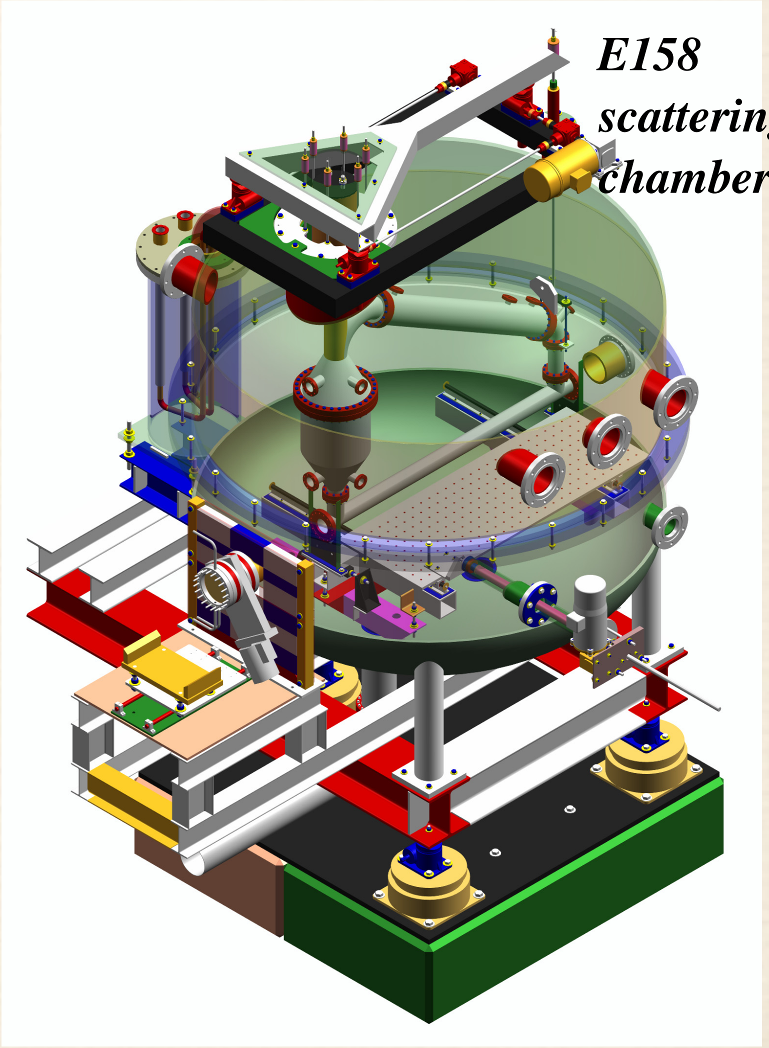
Liquid Hydrogen Target

- **Most thickness for least radiative losses**
- **No nuclear scattering background**
- **Small sensitivity to EM field induced polarization**

•*Need as much target thickness as technically feasible*
•*Tradeoff between statistics and systematics*
•*Default: Same geometry as E158*

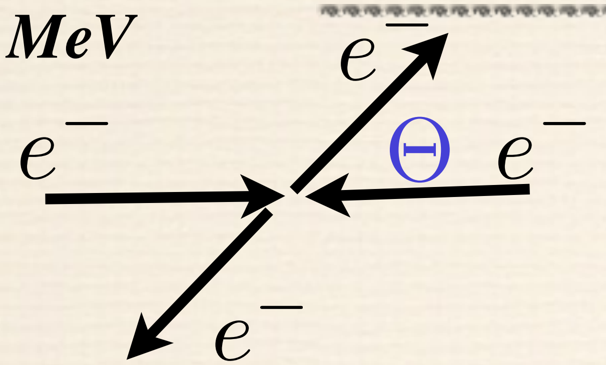
parameter	value
length	*150 cm*
thickness	*10.7 gm/cm^2*
X_0	*17.5%*
p,T	*35 psia, 20K*
power	*5000 W*

Progressive evolution of sophistication over generations of PVES experiments; most recently, Qweak

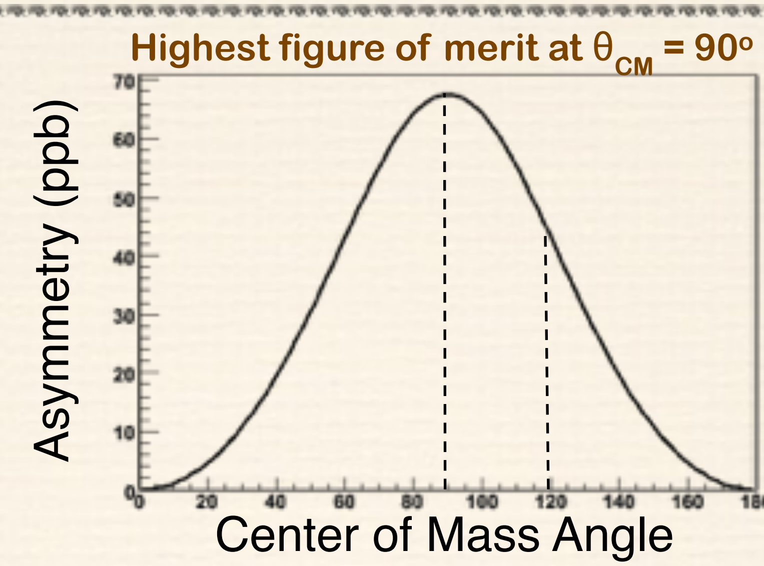


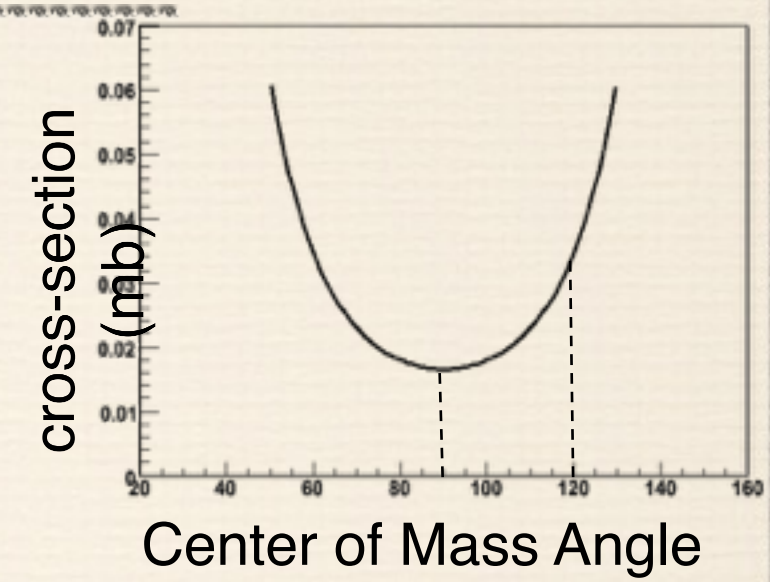
Møller Kinematics

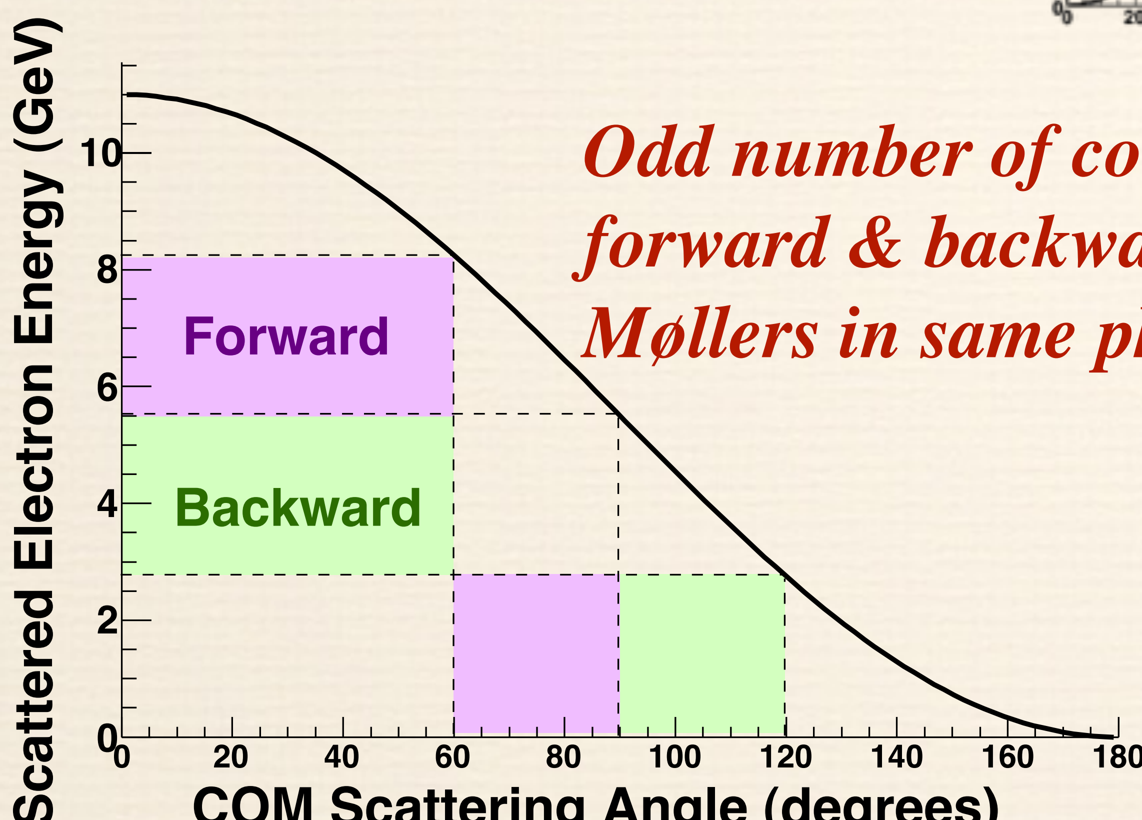
E_{COM} = 53 MeV



identical particles!

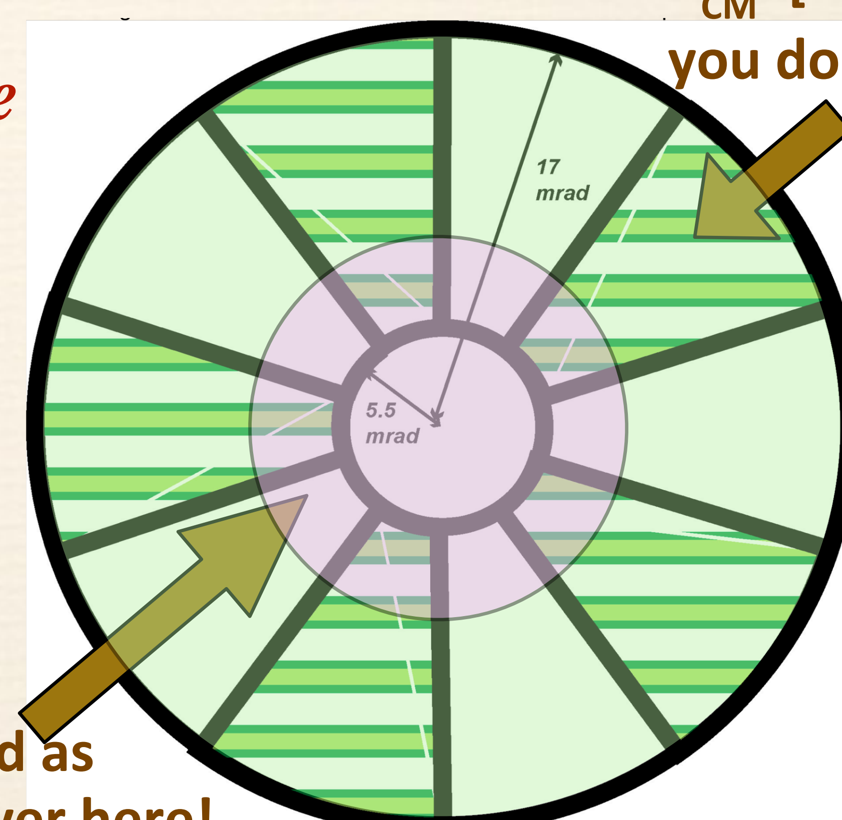






Odd number of coils: both forward & backward Møllers in same phi-bite

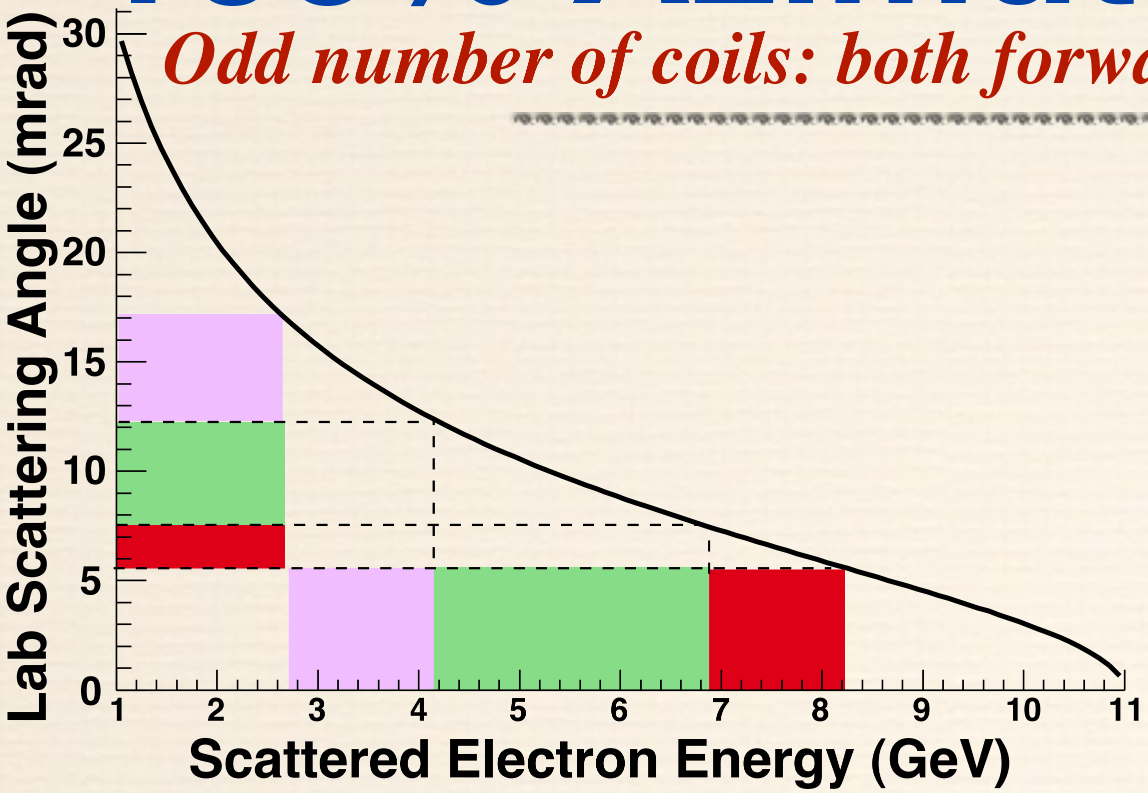
All of those rays of θ_{CM}=[90,120] that you don't get here…

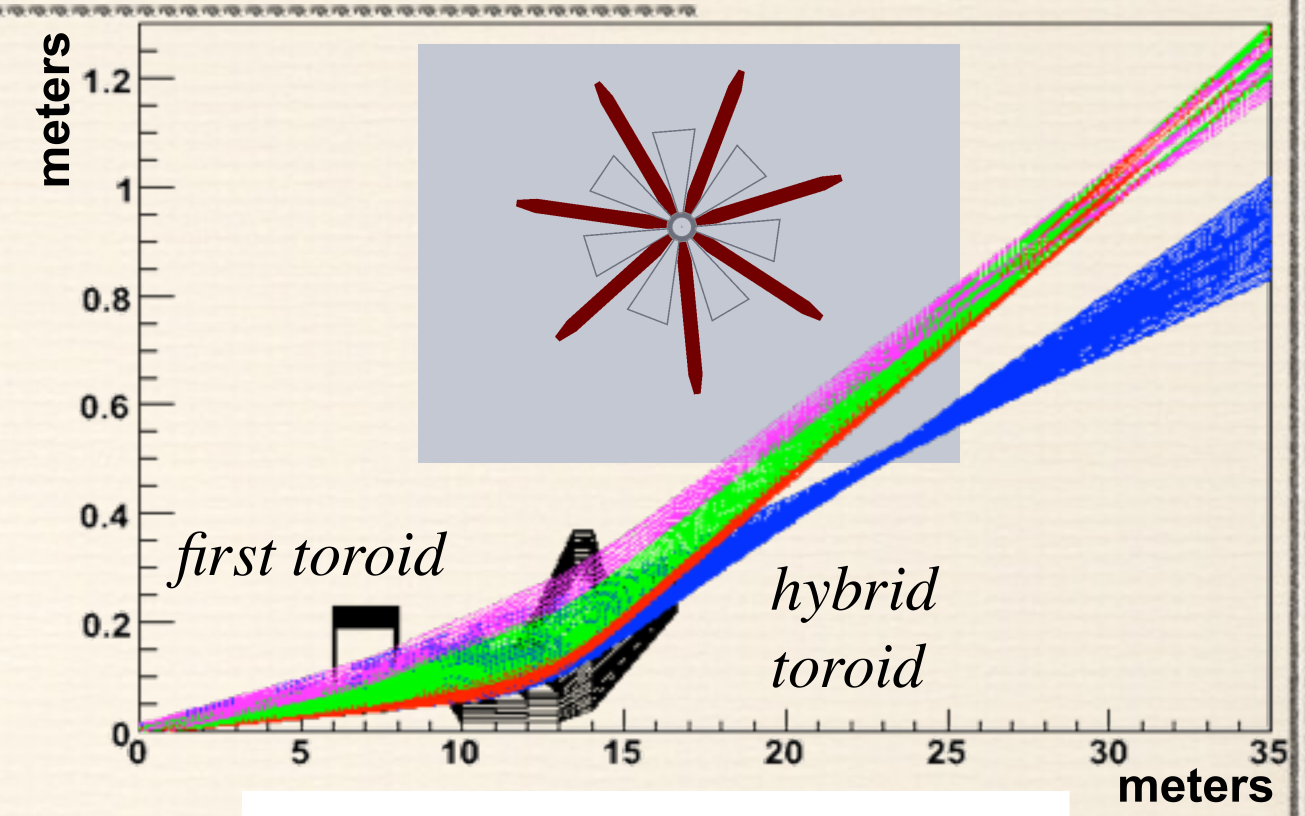


… are collected as θ_{CM}=[60,90] over here!

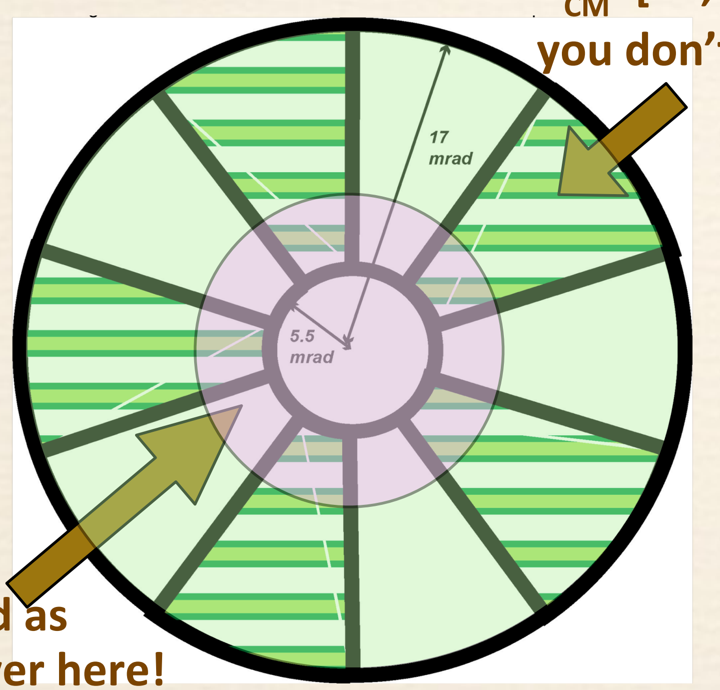
100% Azimuthal Acceptance

Odd number of coils: both forward & backward Møllers in same phi-bite

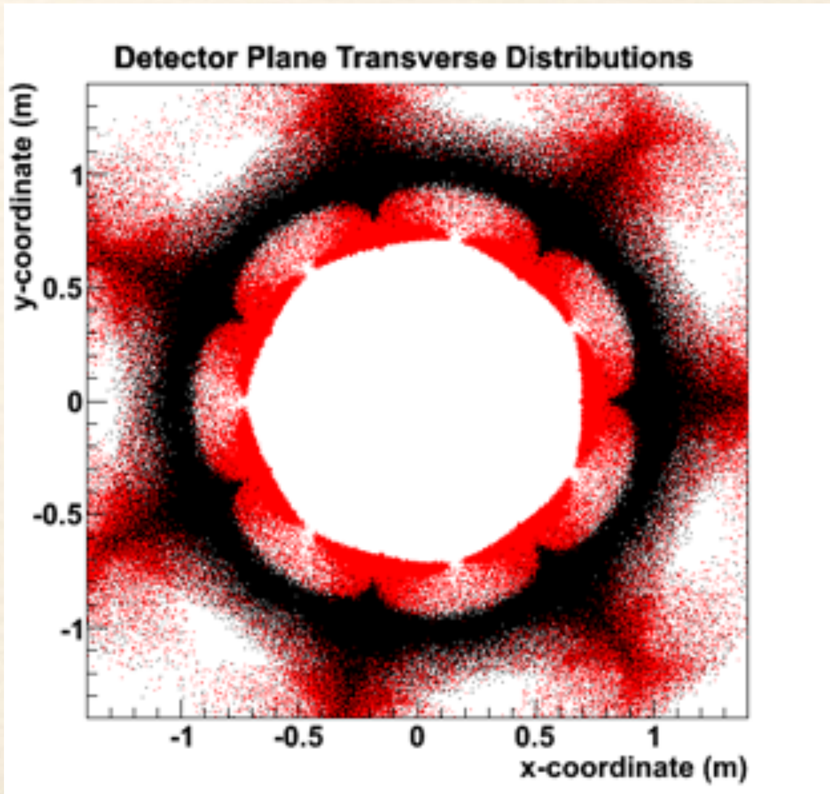




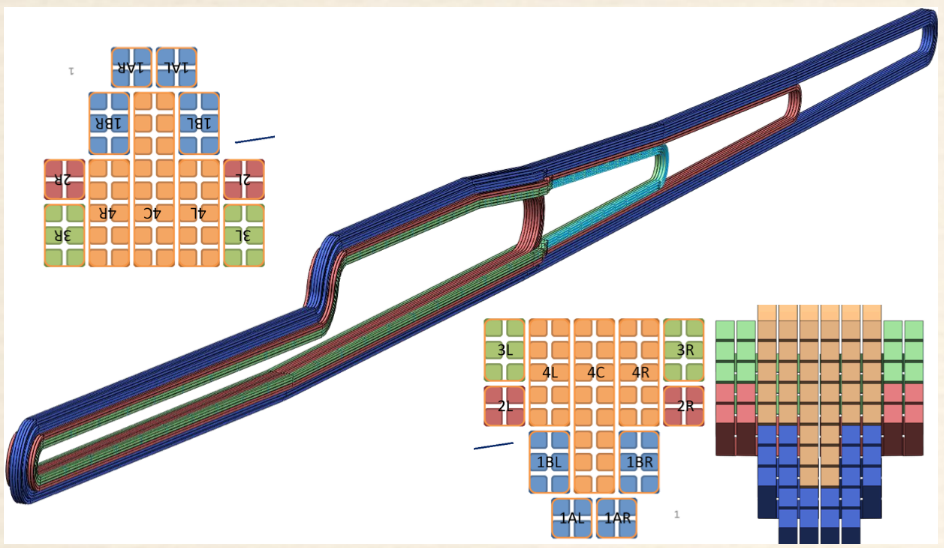
All of those rays of θ_{CM}=[90,120] that you don't get here...

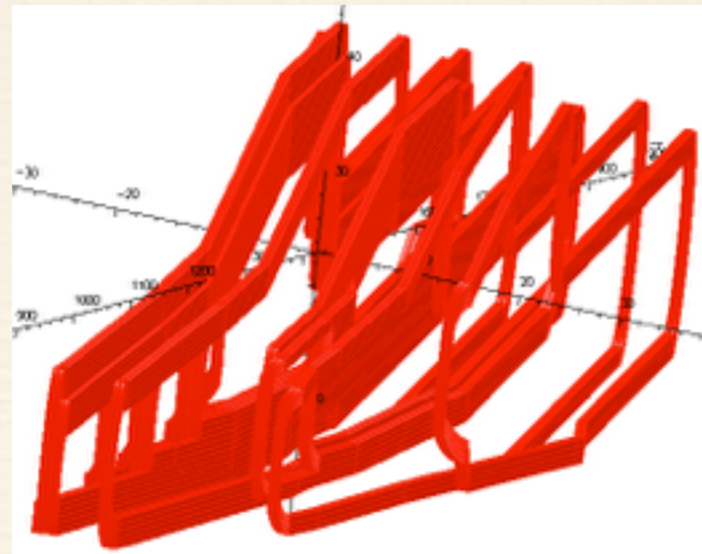


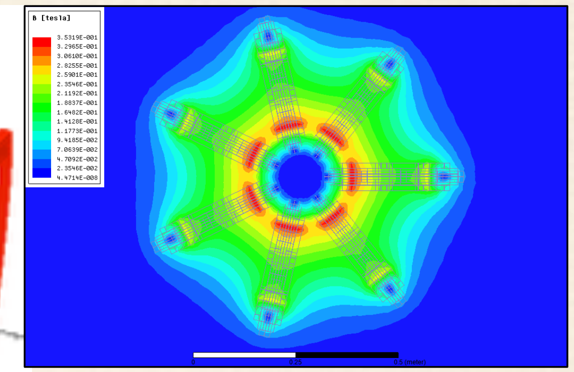
... are collected as θ_{CM}=[60,90] over here!

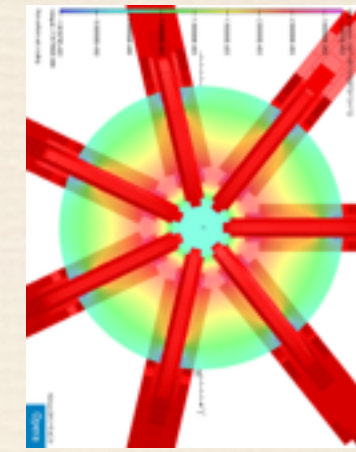


Spectrometer Engineering



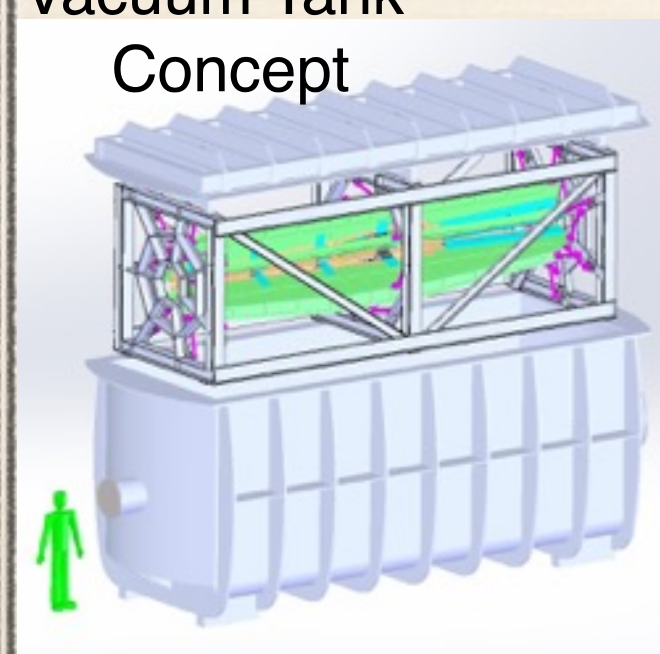


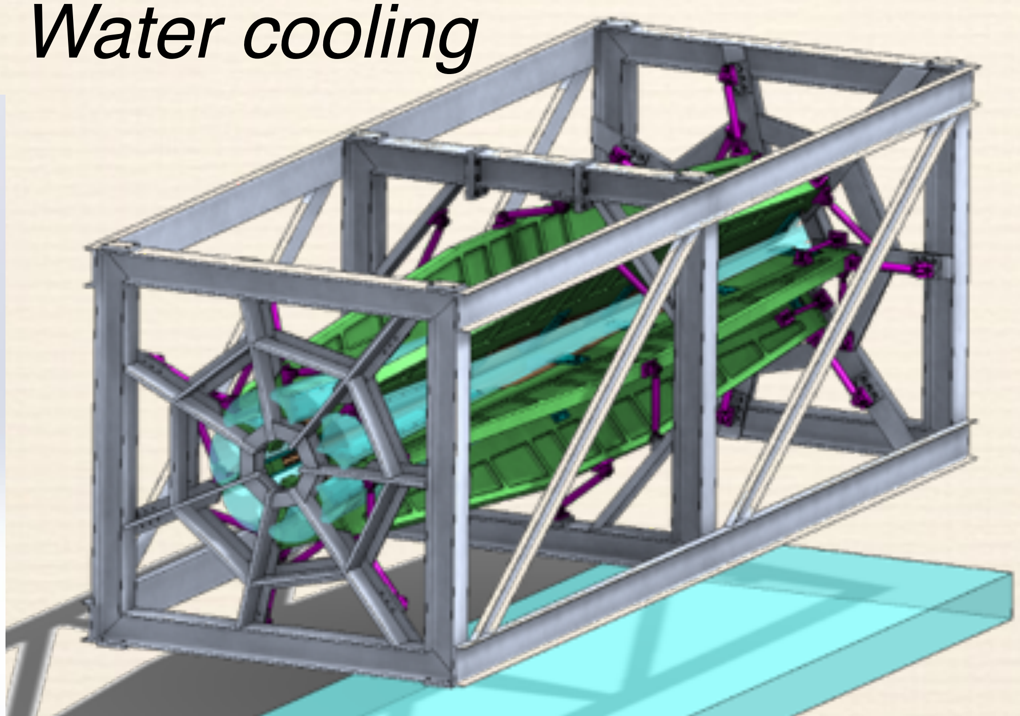




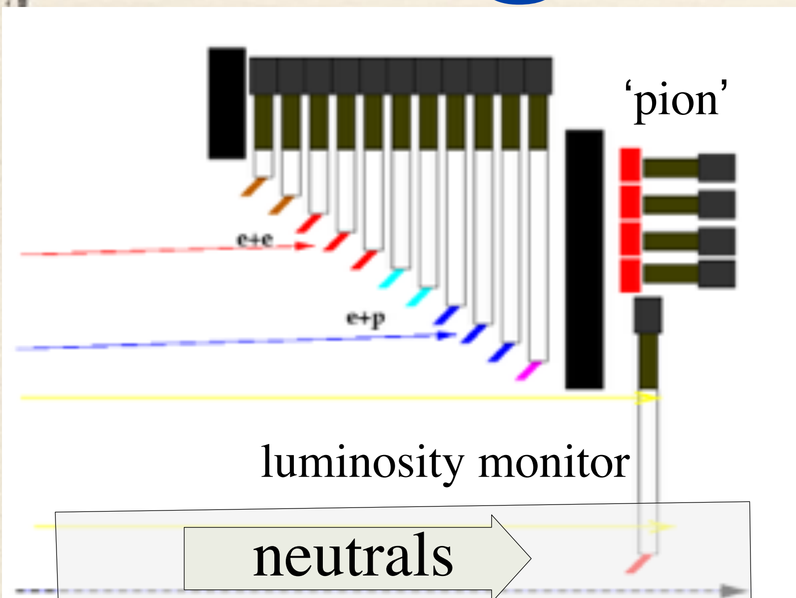
- *Full Azimuthal Acceptance*
- *Warm copper coils*
- *Water cooling*

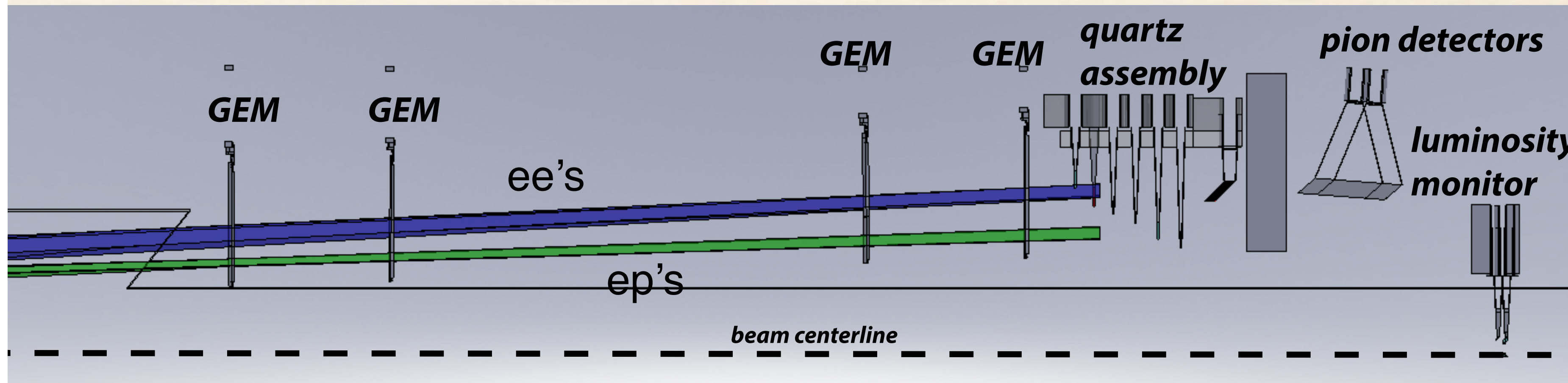
Vacuum Tank Concept

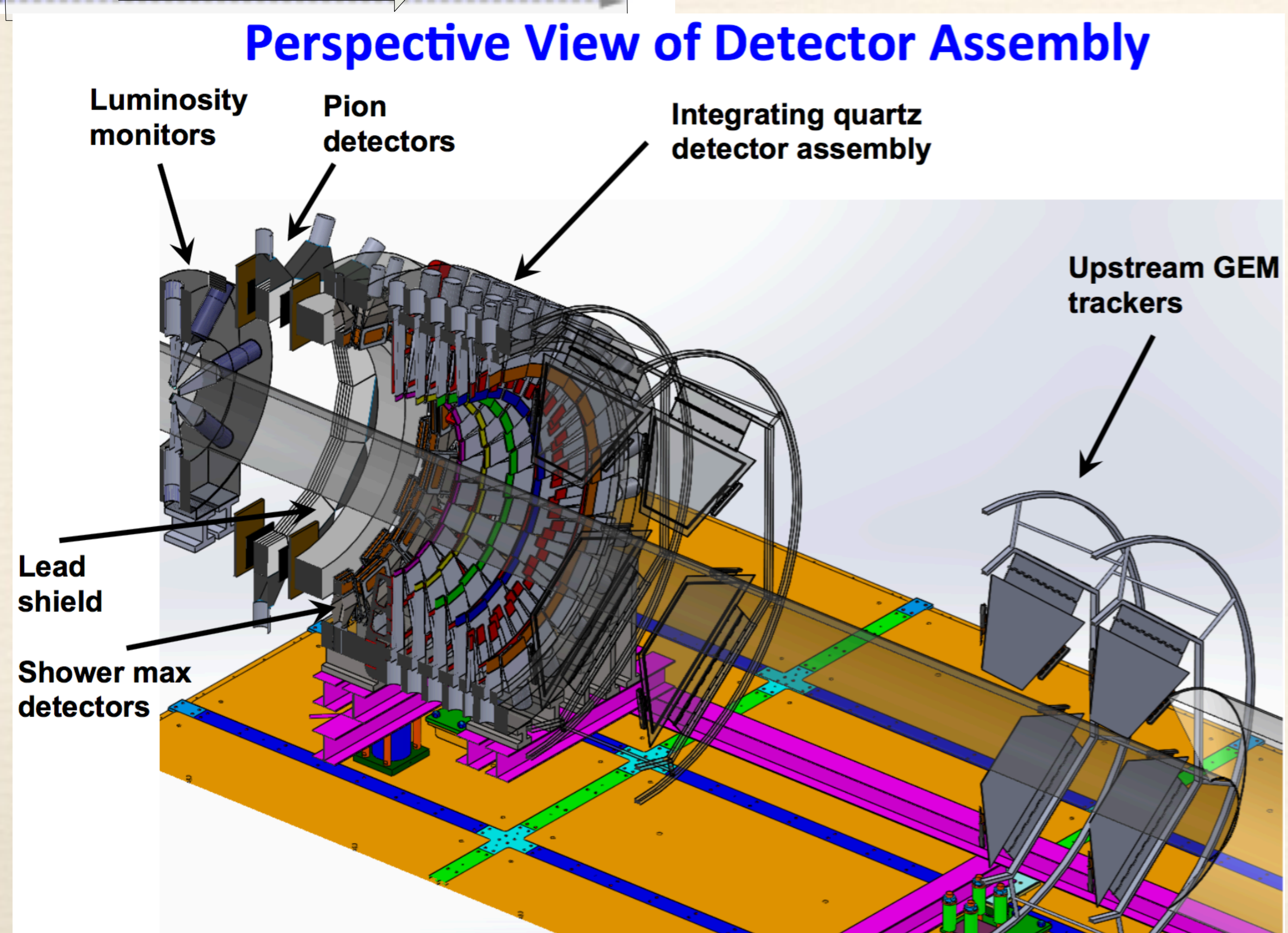




Integrating Detector Concept

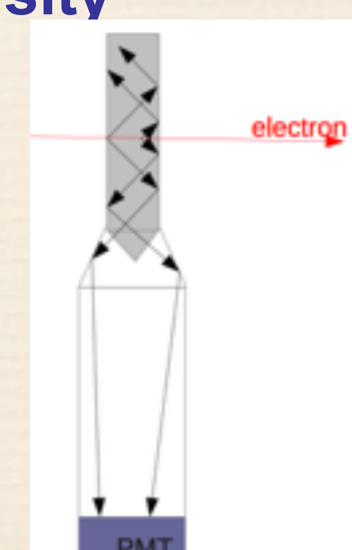






- Møller and e-p electrons:
  - radial and azimuthal segmentation
  - quartz with air lightguides
- Pions and muons:
  - quartz sandwich detector
- Luminosity monitors
  - beam & target density

Single channel

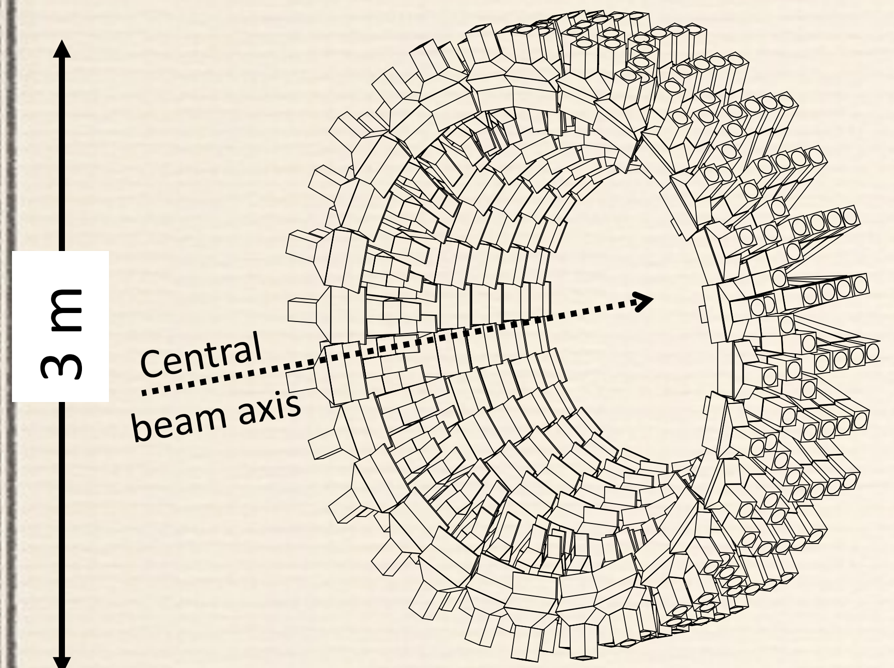


First MOLLER publication: investigation of air lightguide backgrounds

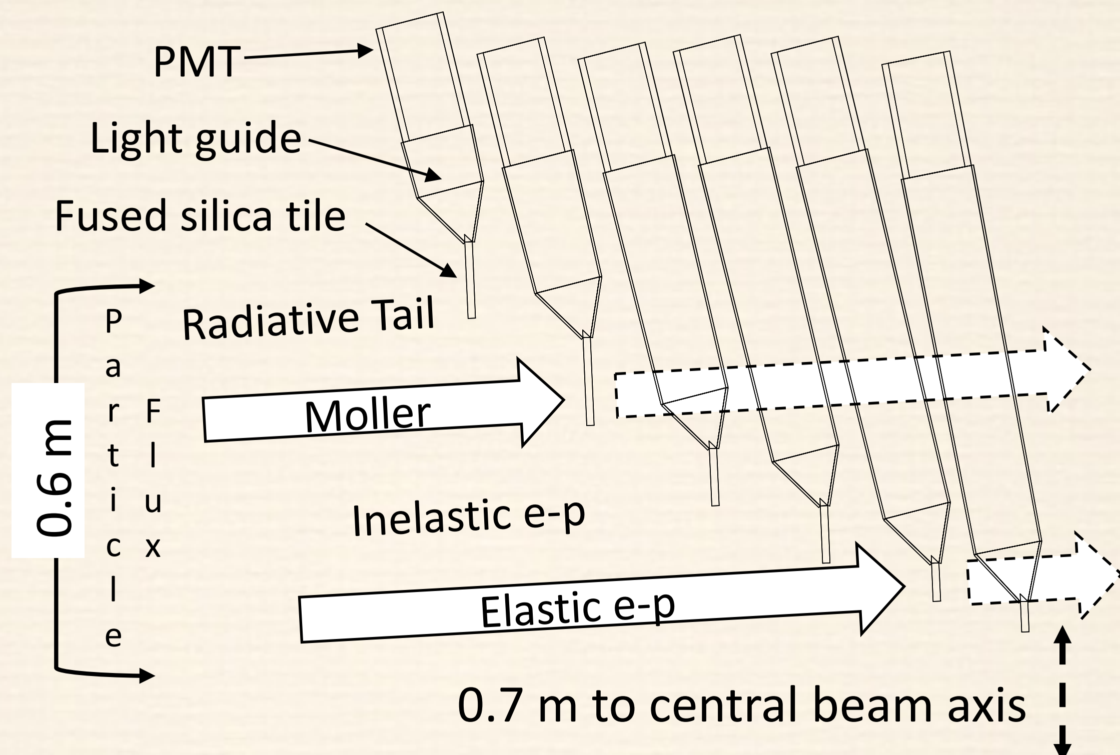
NIM A 896 (2018) 96–102

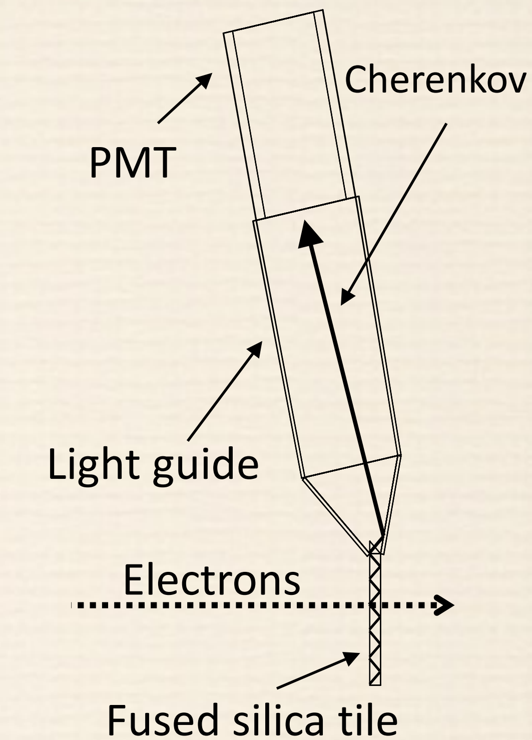
Detector R&D

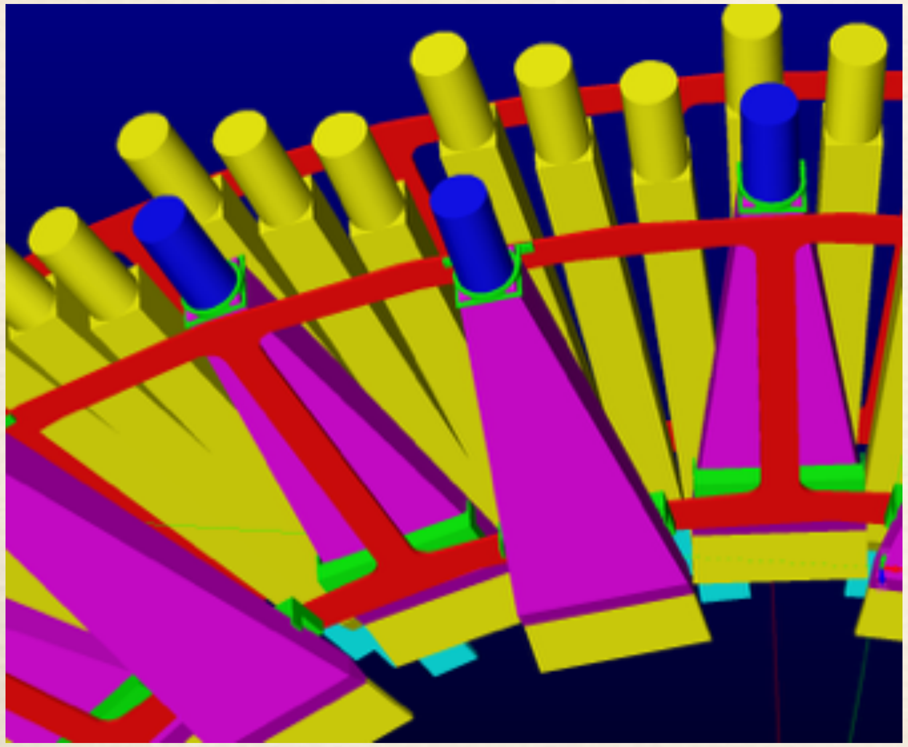
Collaboration with Mainz group and availability of test beams has been critical

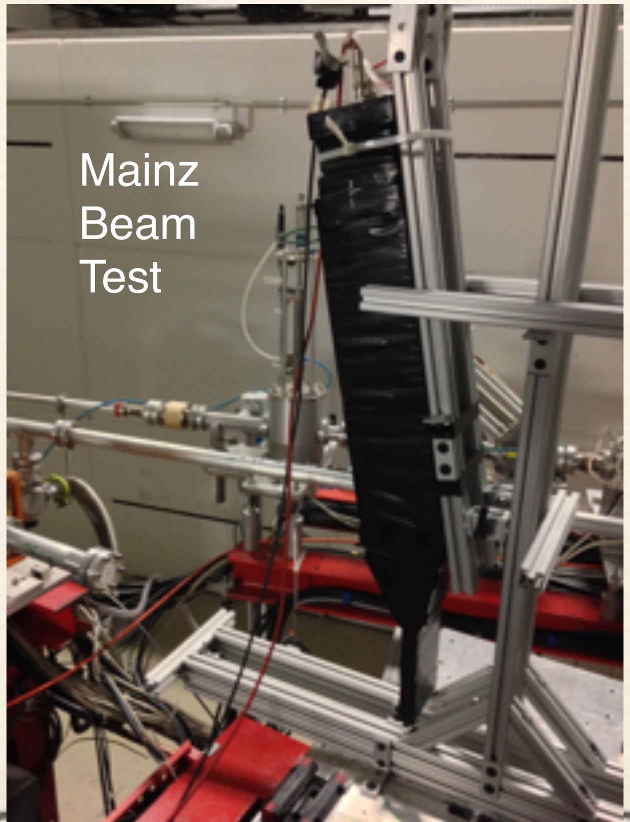


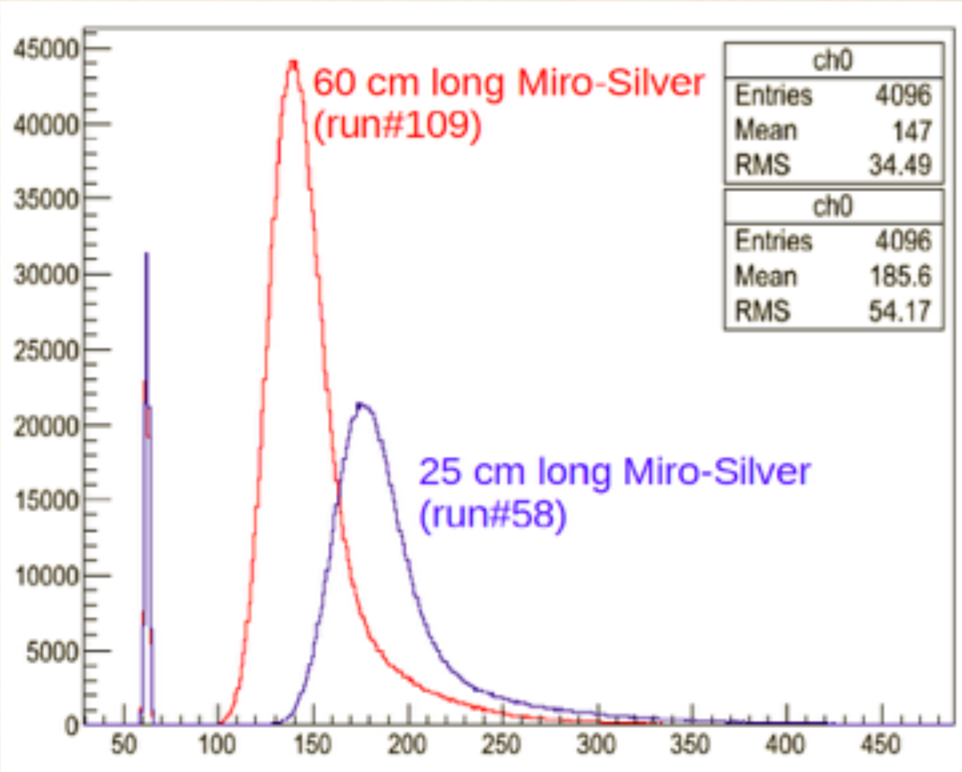
Detector assembly











MOLLER Uncertainty Table

Beam Property	Assumed Sensitivity	Accuracy of Correction	Required 2 kHz random fluctuations	Required cumulative helicity-correlation	Systematic contribution
Intensity	1 ppb / ppb	$\sim$1%	$<$ 1000 ppm	$<$ 10 ppb	$\sim$ 0.1 ppb
Energy	-1.4 ppb / ppb	$\sim$10%	$<$ 108 ppm	$<$ 0.7 ppb	$\sim$ 0.05 ppb
Position	0.85 ppb / nm	$\sim$10%	$<$ 47 μm	$<$ 1.2 nm	$\sim$ 0.05 ppb
Angle	8.5 ppb / nrad	$\sim$10%	$<$ 4.7 μrad	$<$ 0.12 nrad	$\sim$ 0.05 ppb

Error Source	Fractional Error (%)
Statistical	**2.1**
Absolute Normalization of the Kinematic Factor	0.5
Beam (second order)	0.4
Beam polarization	0.4
$e + p(+\gamma) \rightarrow e + X(+\gamma)$	0.4
Beam (position, angle, energy)	0.4
Beam (intensity)	0.3
$e + p(+\gamma) \rightarrow e + p(+\gamma)$	0.3
$\gamma^{(*)} + p \rightarrow (\pi, \mu, K) + X$	0.3
Transverse polarization	0.2
Neutral background (soft photons, neutrons)	0.1
Total systematic	**1.1**

All systematics required at sub-1% level

Expertise from several generations of successful parity experiments

MOLLER Status

- **MOLLER Collaboration**
  - 120 authors, 30 institutions, 5 countries
  - Experience from SAMPLE, A4, HAPPEX, G0, PREX, Qweak, E158
  - 4th generation PVES experiment at JLab

- ~25M$ DOE NP MIE
- goal: construction ’19 - ‘22

The US NSAC Long Range Plan highlighted MOLLER in the Fundamental Symmetries chapter. The Plan also calls for new investments in Major Items of Equipment (MIEs)

- **Science Review: Sep 10, 2014**
  - by DOE Office of Nuclear Physics

Rigorous review by a panel of two nuclear theorists, two HEP theorists and two fundamental symmetries experimentalists

★ Very positive outcome of Science Review

- *Highlighted unique opportunity: strong endorsement for the measurement*
- *theoretical cleanliness (purely leptonic!)*

★ JLab Director’s Review in December 2016

- *CD-0 granted by DOE-NP on December 21, 2016!*
- *Awaiting project start; DOE Office of Science budgets are under heavy stress*

Latest indication is that an FY ’19 start for the project is likely

MOLLER Context Summary

best contact interaction reach for leptons at low OR high energy:
similar to LHC reach with semi-leptonic amplitudes
To do better for a 4-lepton contact interaction would require:
Giga-Z factory, linear collider, neutrino factory or muon collider

$\delta(\sin^2\theta_W) = \pm\, 0.00024\ (stat.) \pm 0.00013\ (syst.)$ ⇒ $\sim 0.1\%$

Best projected uncertainty among projects being considered over next 10 years

- **If LHC sees ANY anomaly in Runs 2 or 3 (~2022)**
  - The unique discovery space probed by MOLLER will become a pressing need, like other sensitive probes (e.g. g-2 anomaly)
- **Discovery scenarios beyond LHC signatures**
  - Purely Leptonic Contact Interactions
  - Lepton Number Violating Amplitudes
  - Light Dark Matter Mediators
  - Lorentz Violation
  - ...

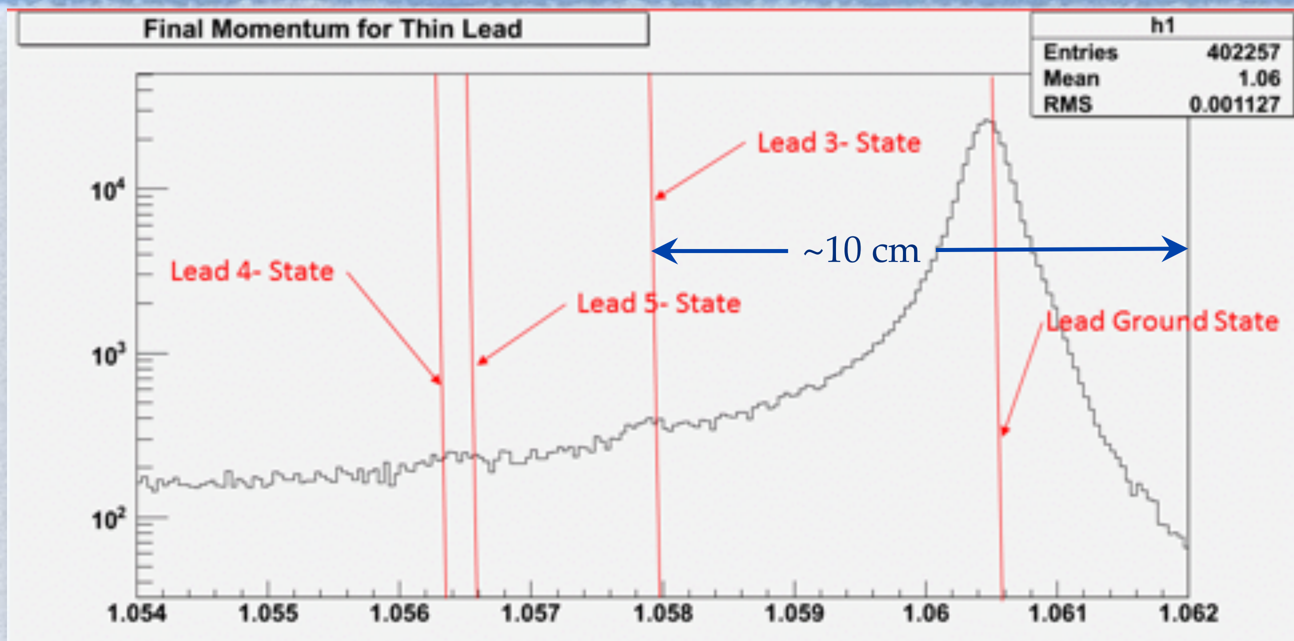
Summary and Outlook

- ✦ **Parity-Violating Electron Scattering**
  - ★ Enabled unique studies of the weak force
  - ★ Technical progress has enabled unprecedented precision
  - ★ flagship experiments at electron accelerators
- ✦ **Fundamental Nuclear/Nucleon Physics**
  - ★ Neutron RMS radii of heavy nuclei (PREX, CREX, MREX...)
  - ★ valence quark structure of protons and neutrons (SOLID)
- ✦ **Fundamental Electroweak Physics**
  - ★ Search for new dynamics at the TeV scale (P2, MOLLER, SOLID)
    - *complementary to colliders; would help interpret potential anomalies*
    - *precision measurement of the weak mixing angle*

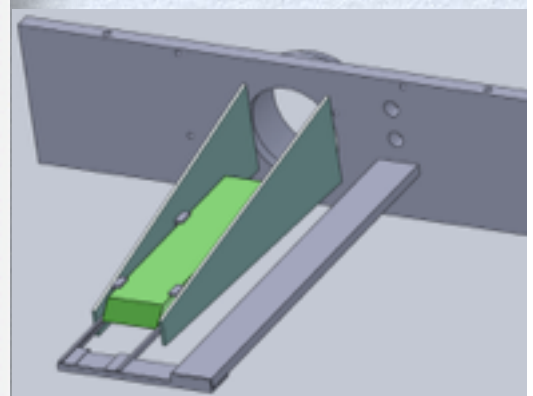
The next five years promise to be exciting!

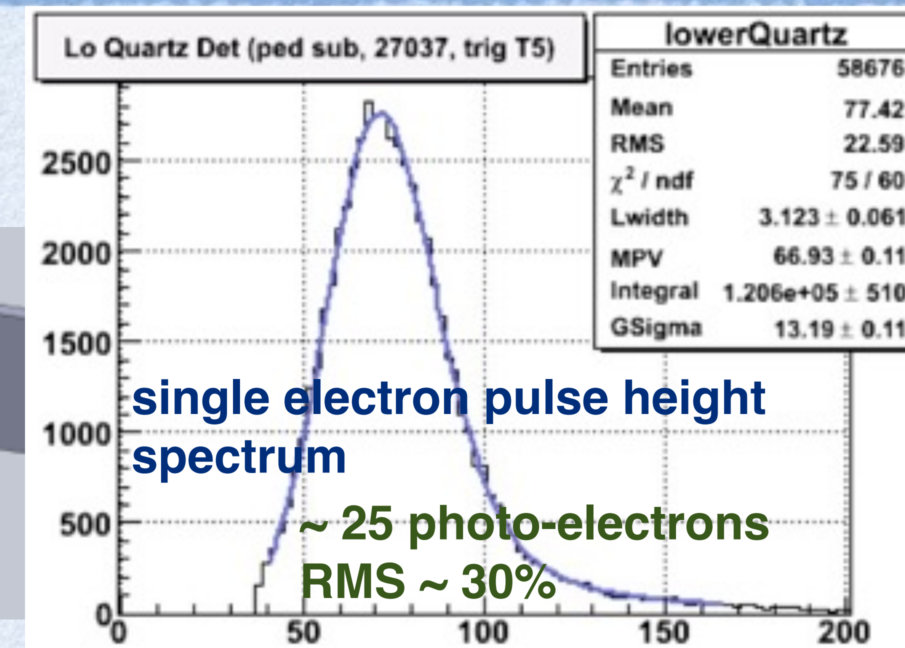
Integrating Detectors

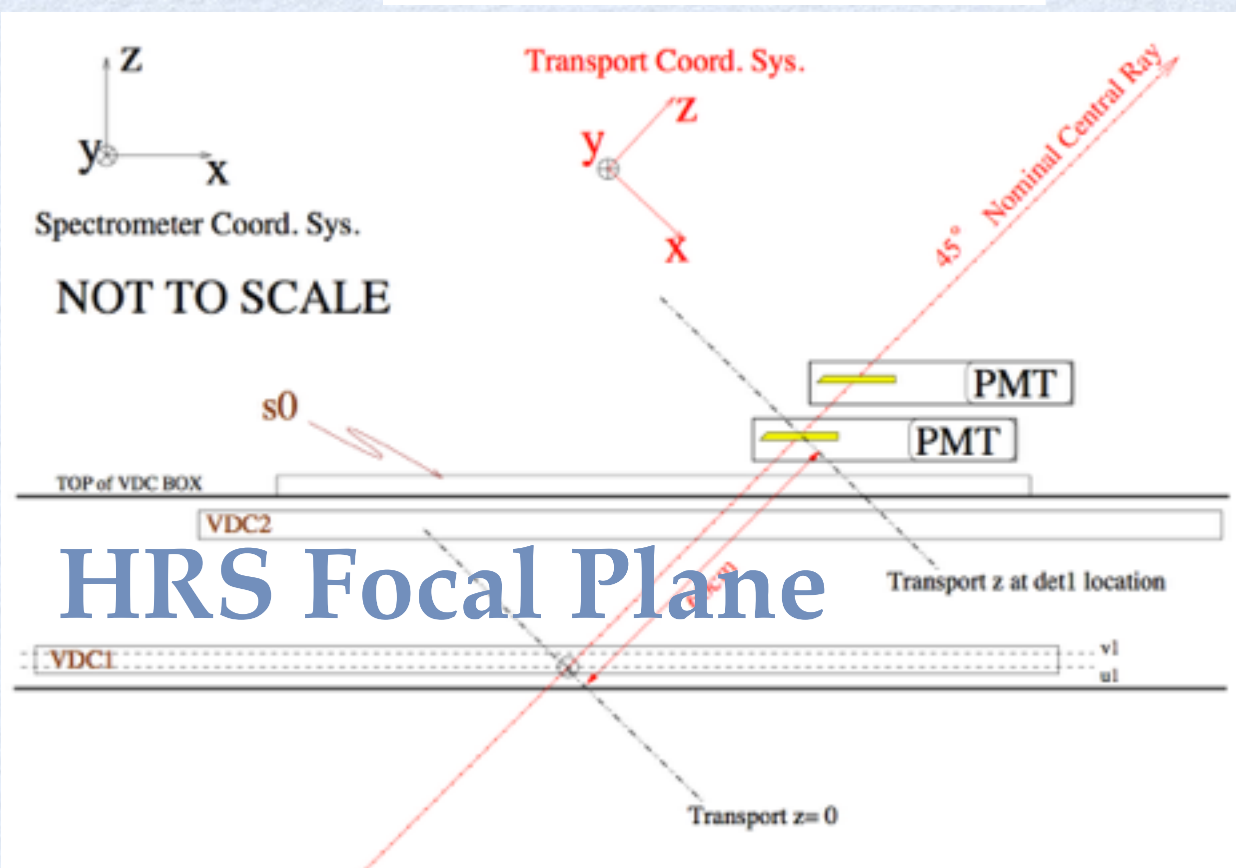
Background negligible thanks to Hall A HRS spectrometer pair



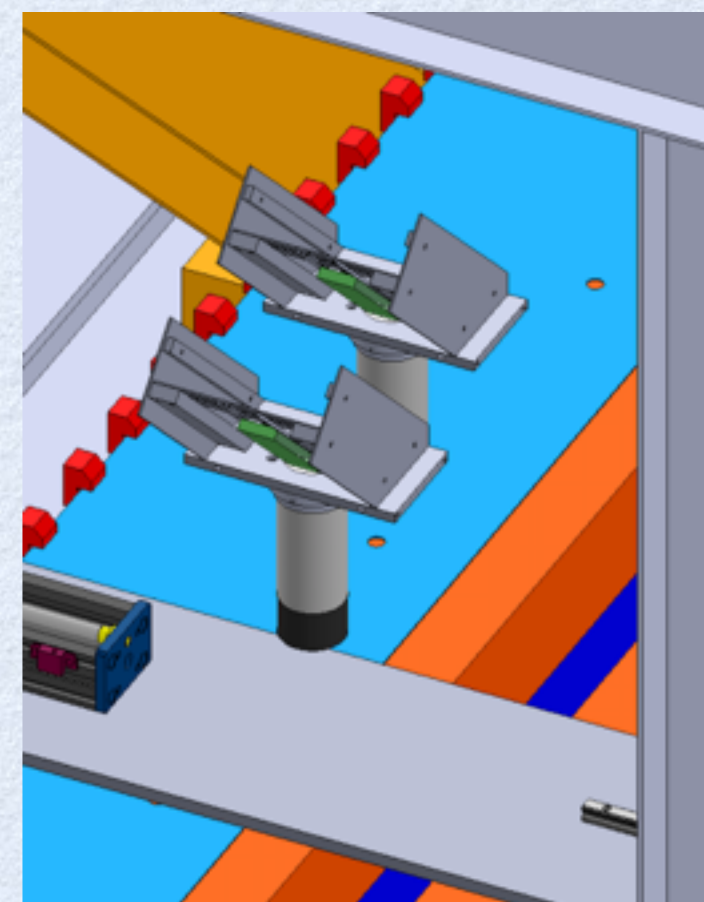
pure, thin ^{208}Pb target





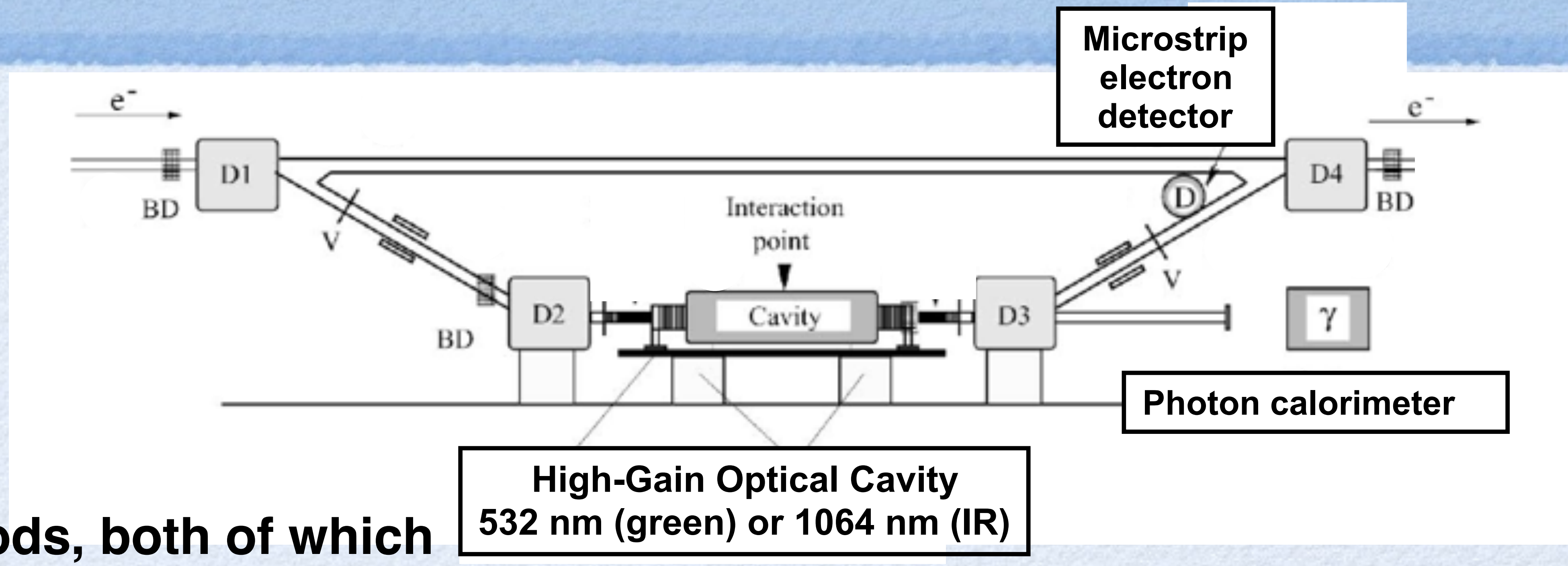


- *1 GHz rate: extreme radiation hardness*
- *1 GeV: calorimeter sandwich RMS ~ 50%*
- *Thin fused silica: optimize RMS*
  - *thick: higher photo-electron yield*
  - *thin: smaller RMS degradation*



Beam Polarimetry

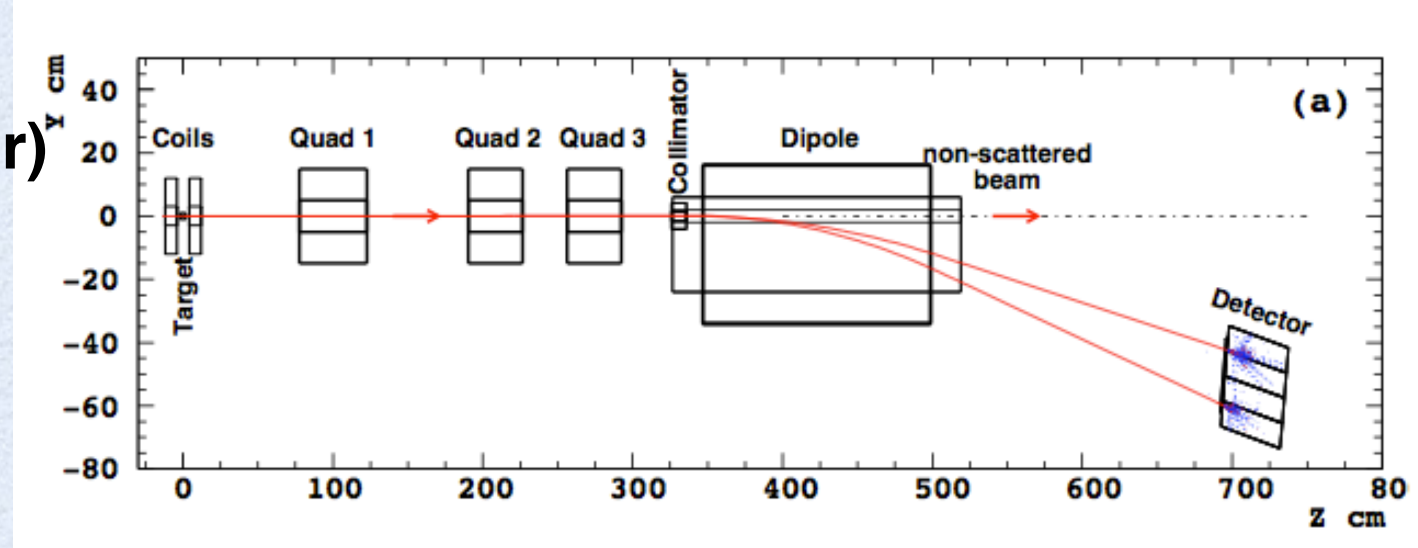
$$A_{phys} = \frac{A_{sig}}{P_{beam}}$$



Two independent methods, both of which received recent upgrades

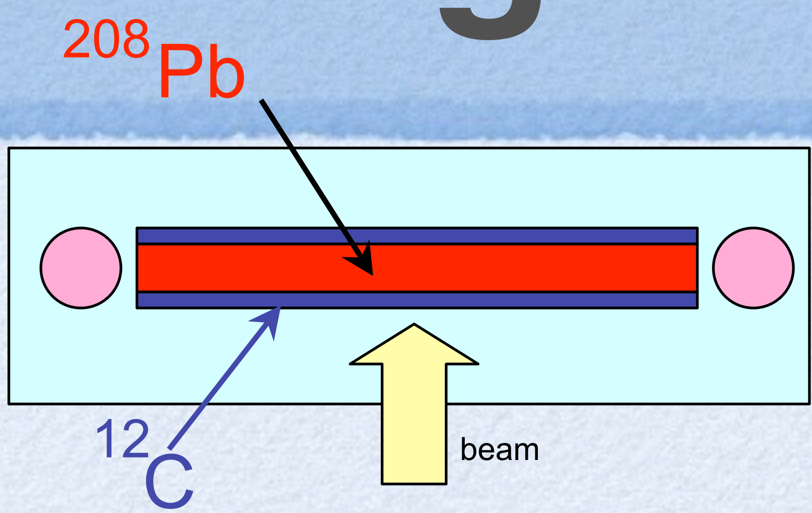
Both methods expected to reach sub-1% for future measurements: ultimate goal is sub-0.5%

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



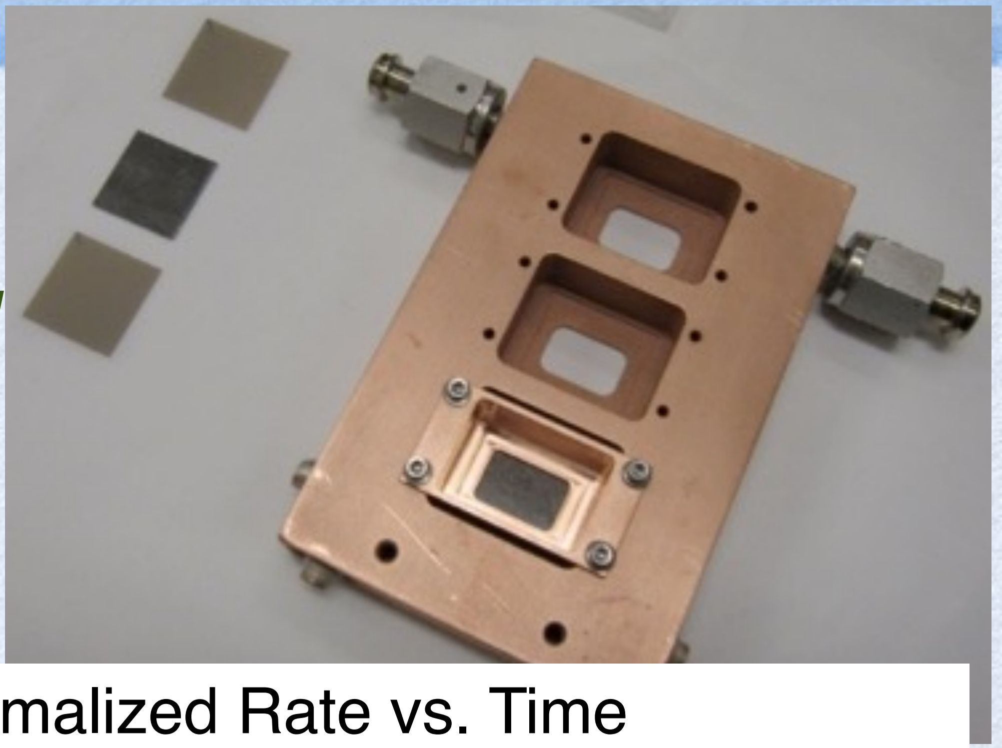
- Møller Polarimeter
  - electronics and DAQ
  - High field magnet for foil saturation: improved calibration of foil polarization

High Luminosity Target

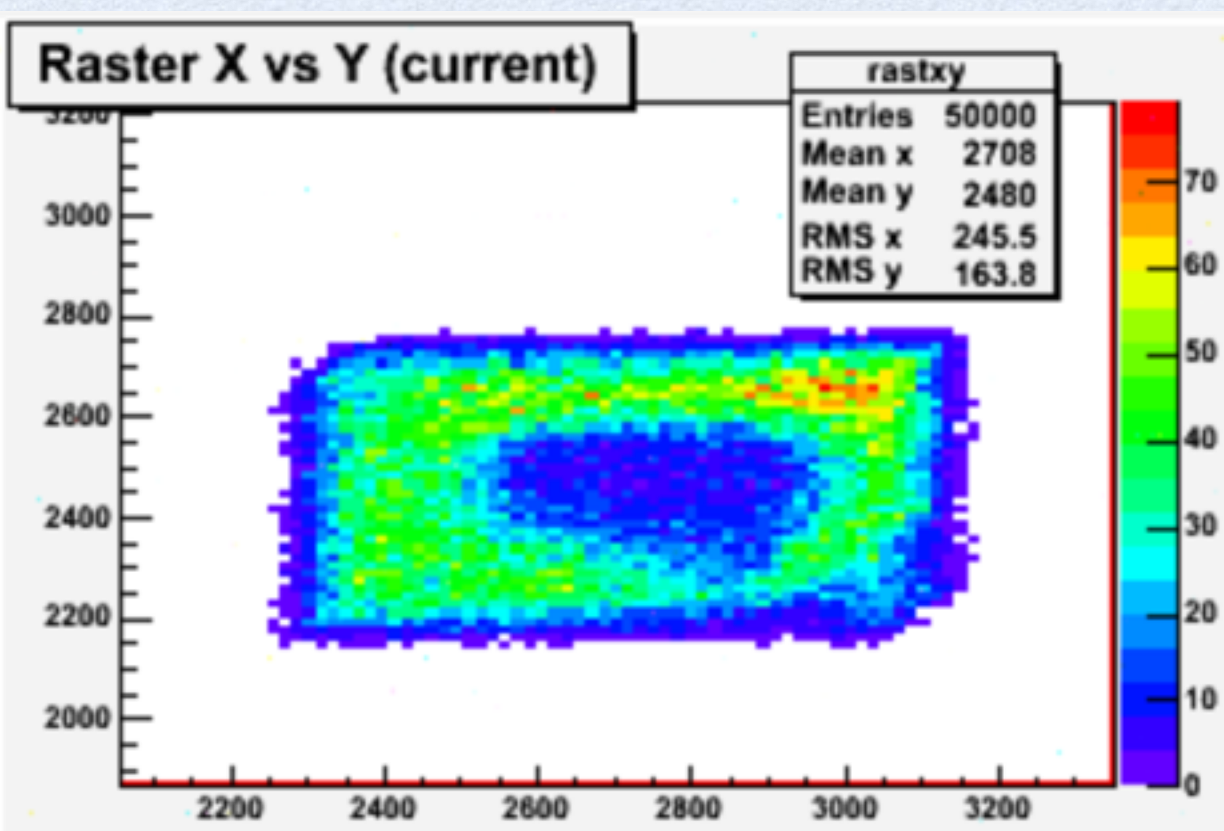


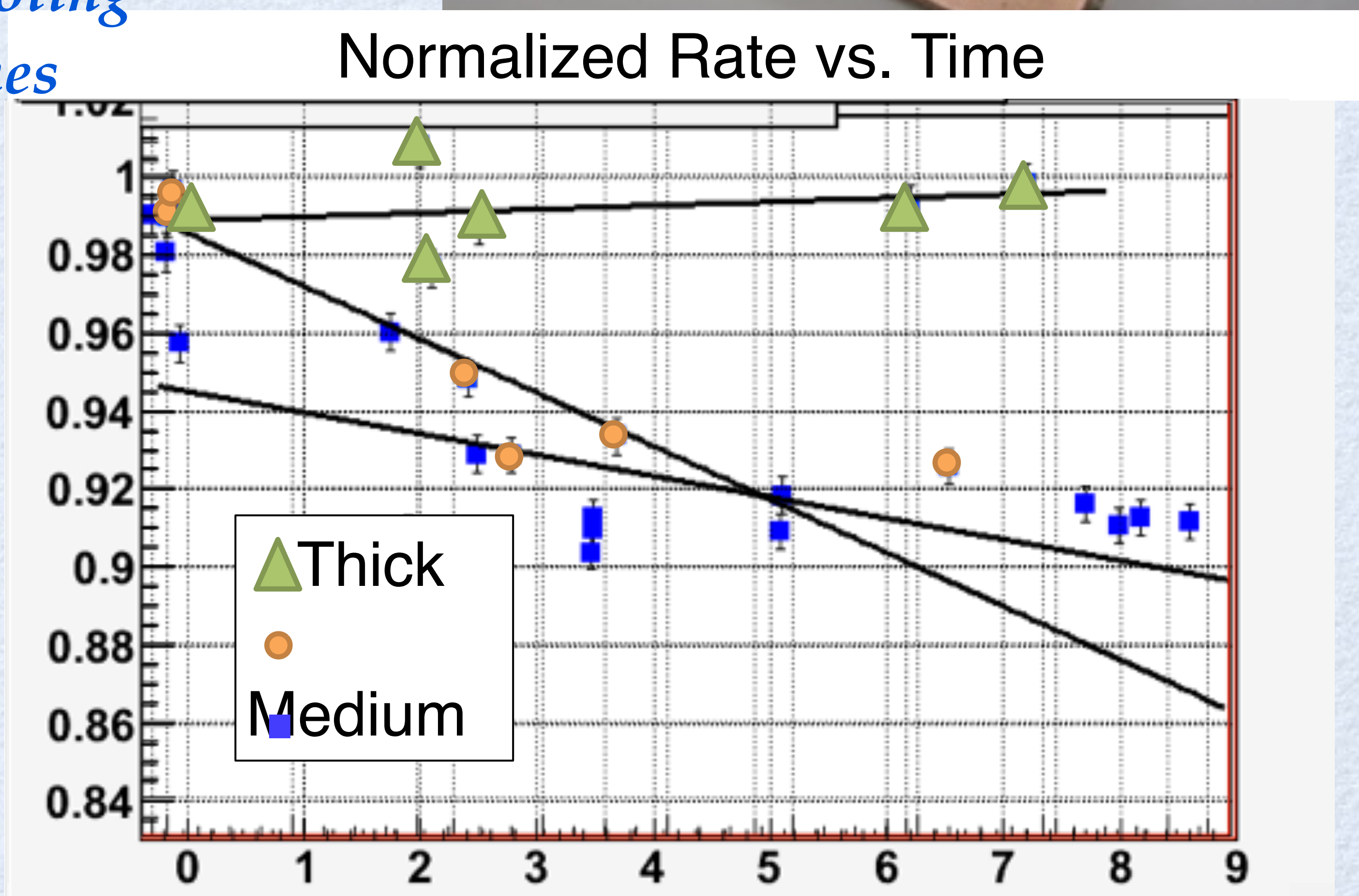
Targets with thin diamond backing (4.5%) degraded fastest

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



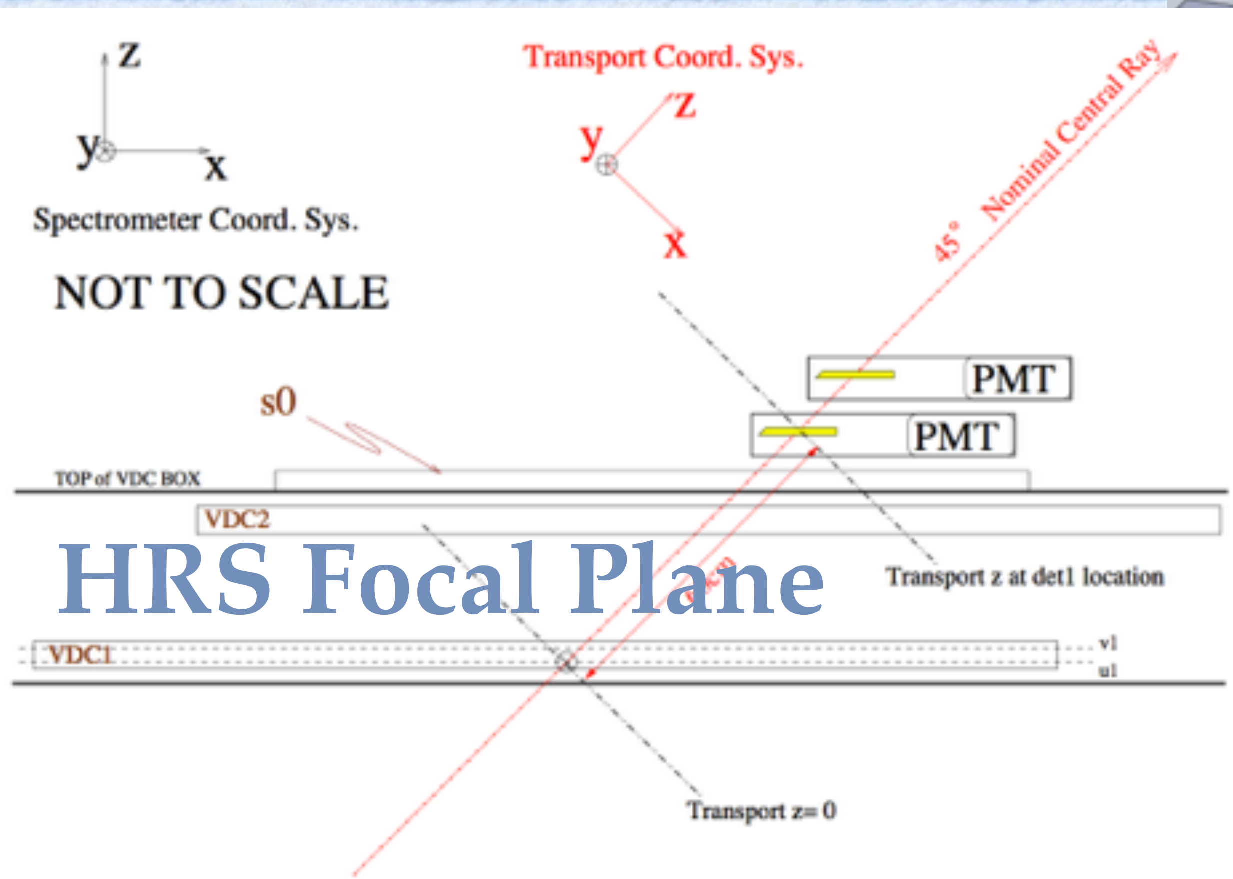
- *Pb-Diamond sandwich*
- *Diamond backing provides conductive cooling*
- *Active cryo-cooling with available He lines*

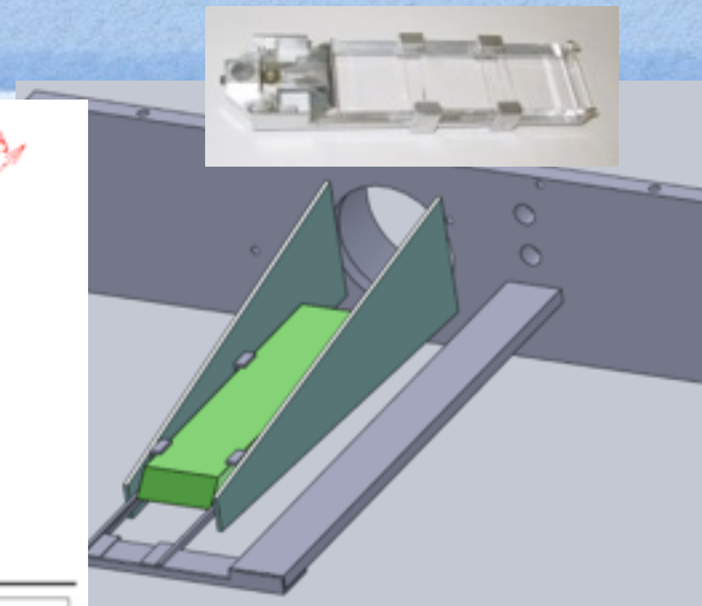


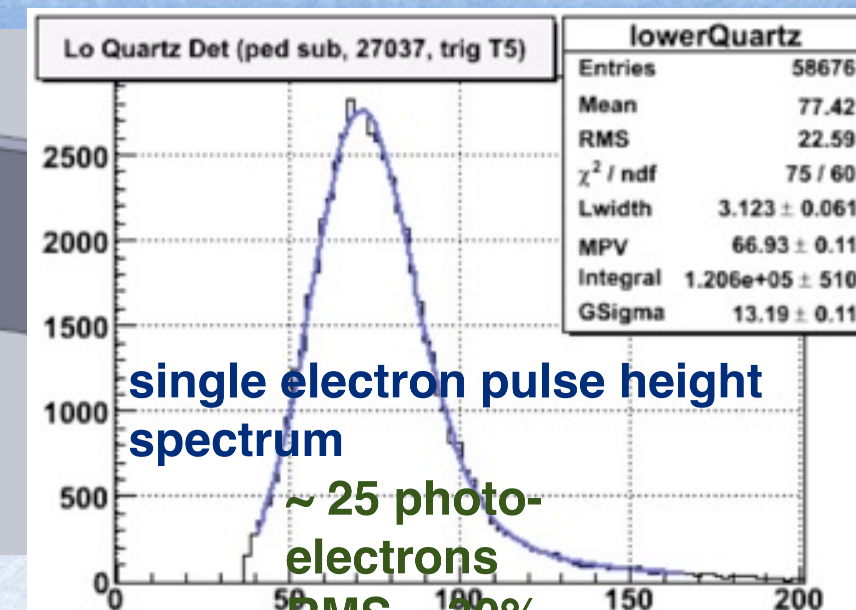


PREX-II plans on having 6-10 targets

Integrating Detectors

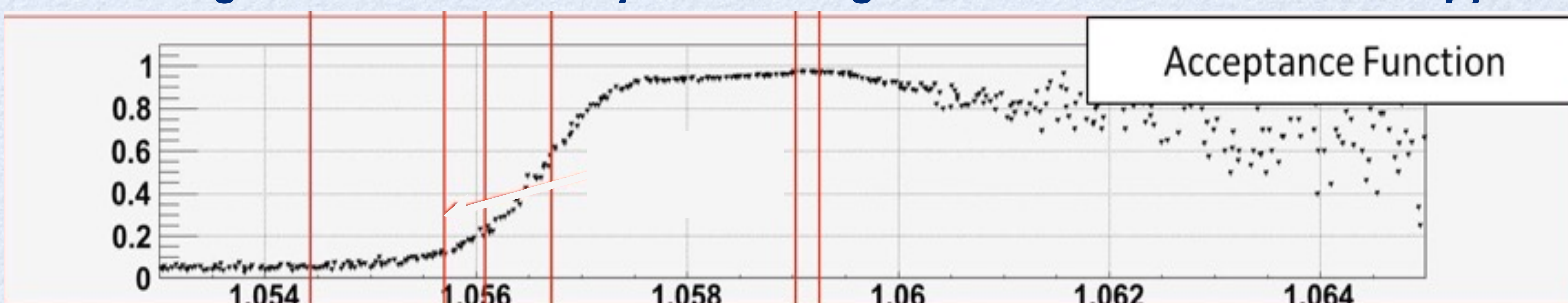






- *1 GHz rate: extreme radiation hardness*
- *1 GeV: calorimeter sandwich RMS ~ 50%*
- *Thin fused silica: optimize RMS*
  - *thick: higher photo-electron yield*
  - *thin: smaller RMS degradation*

Detector integrates the elastic peak: Backgrounds from inelastics suppressed



$A_{raw} \sim 500$ ppb

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

Beam Stability Performance

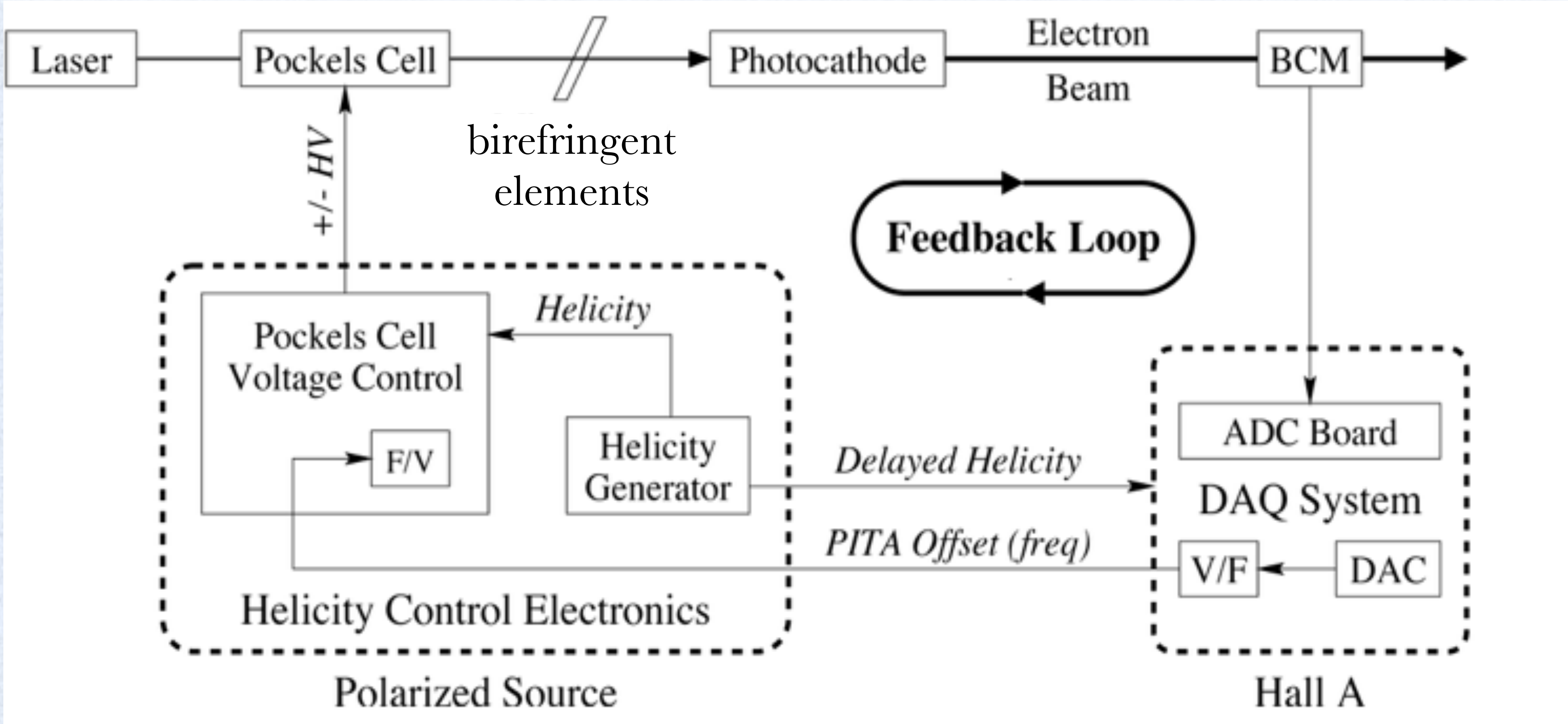
PREX-I ran from March to May 2011

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

Beam Stability Performance

PREX-I ran from March to May 2011

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

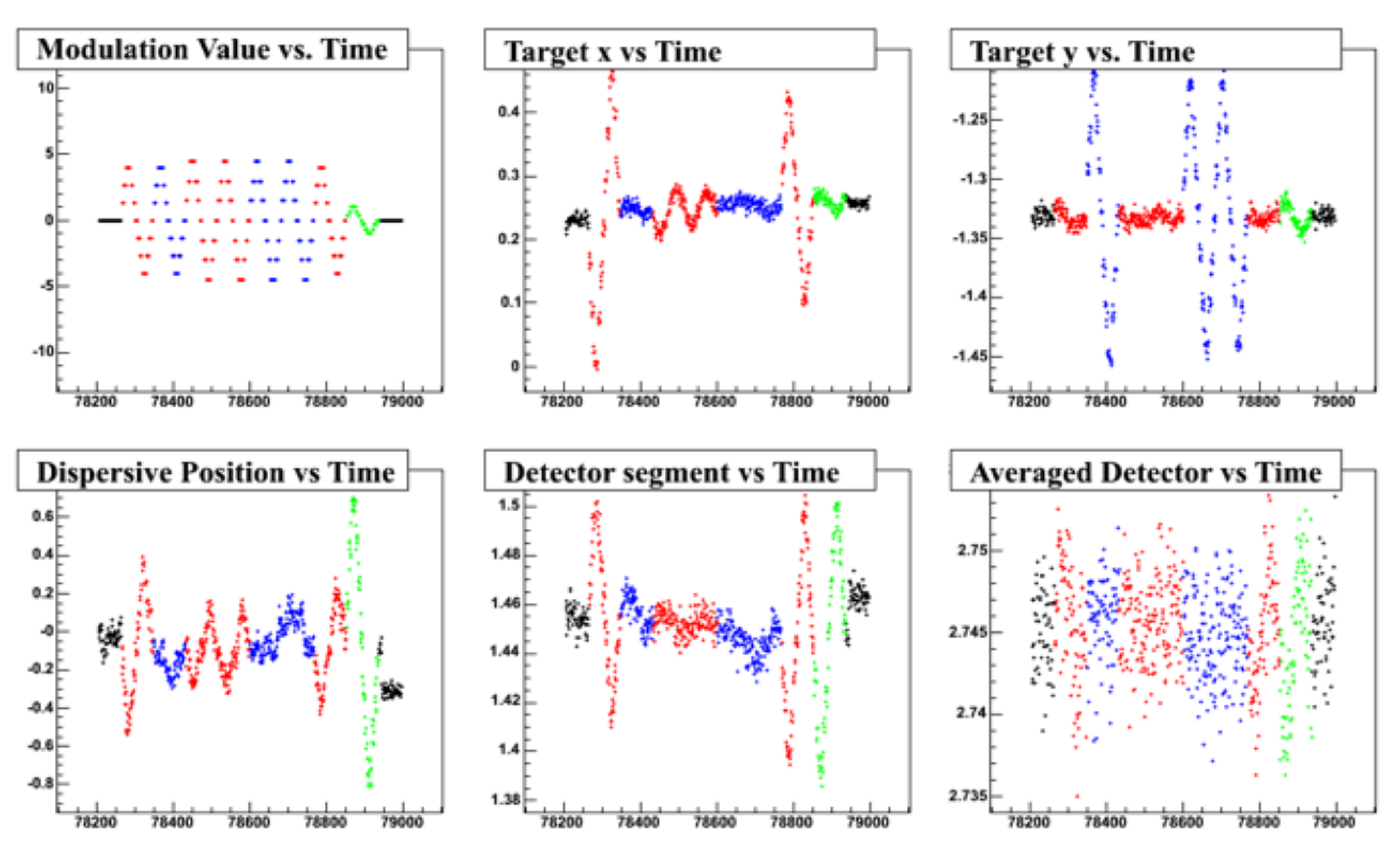


$A_{raw} \sim 500$ ppb

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

Beam Stability Performance

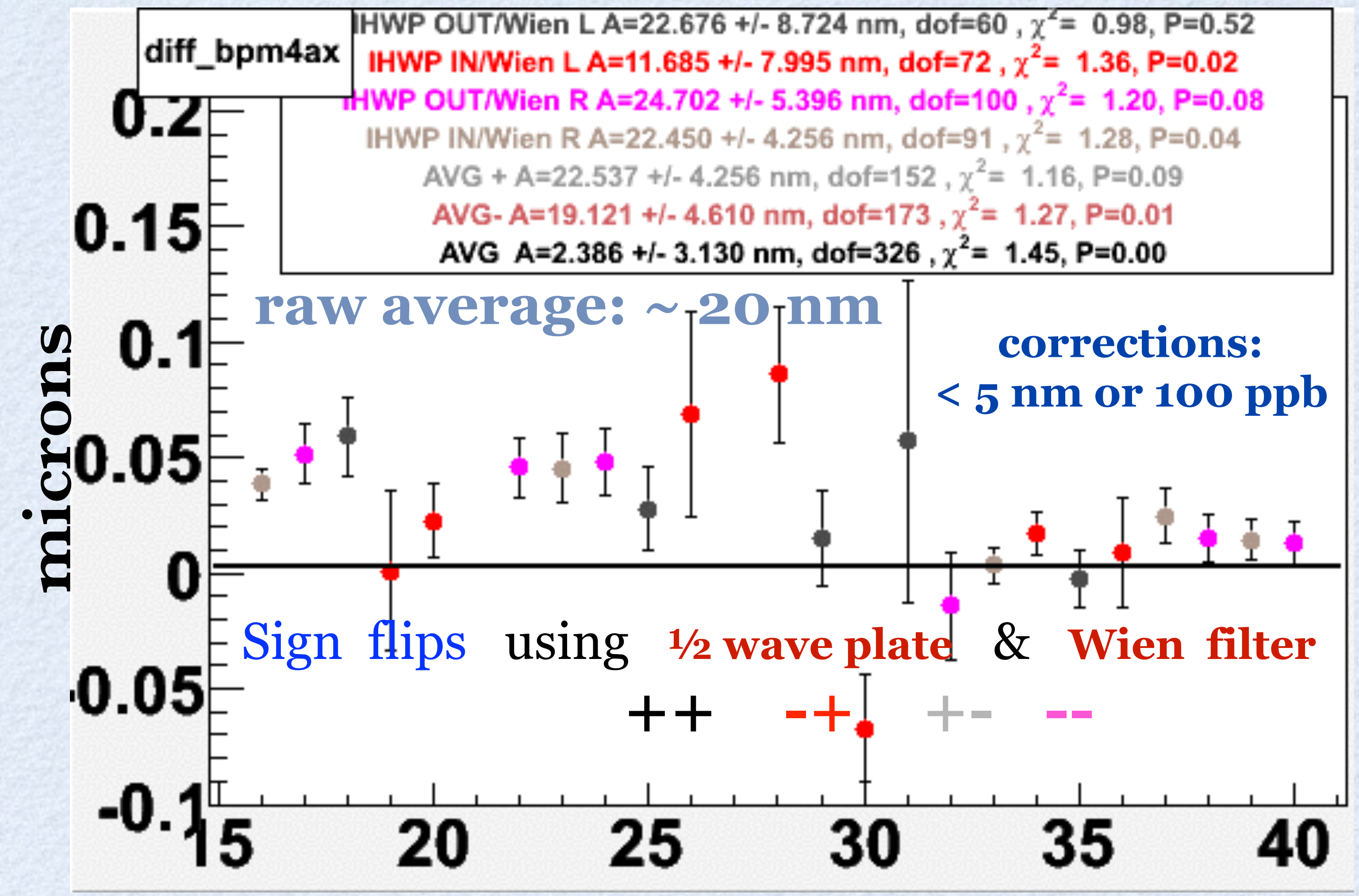
PREX-I ran from March to May 2011



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

Beam Stability Performance

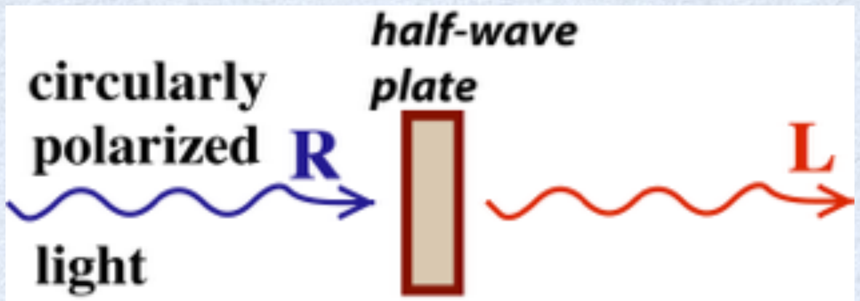
PREX-I ran from March to May 2011

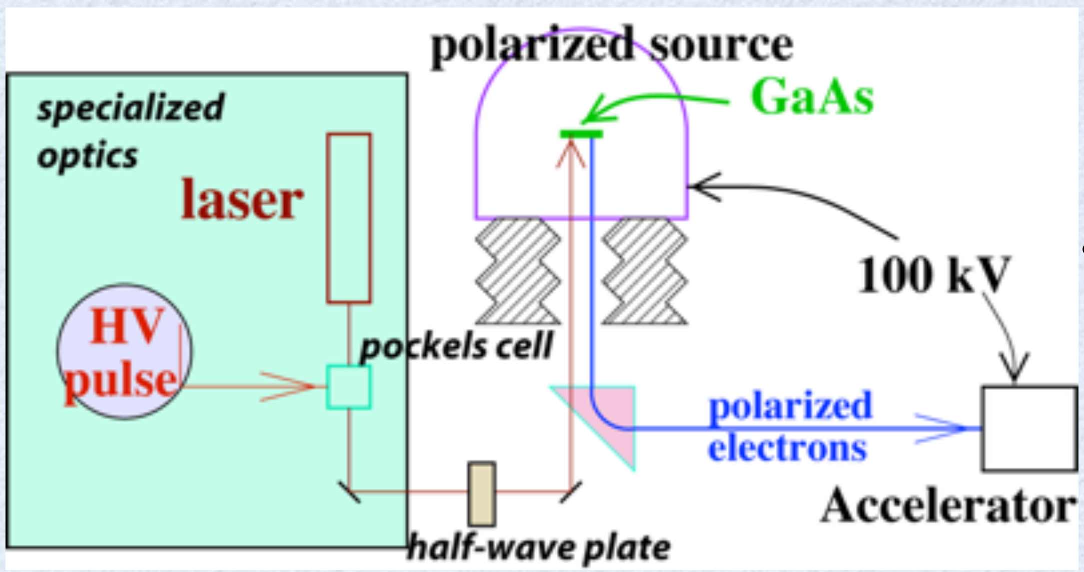


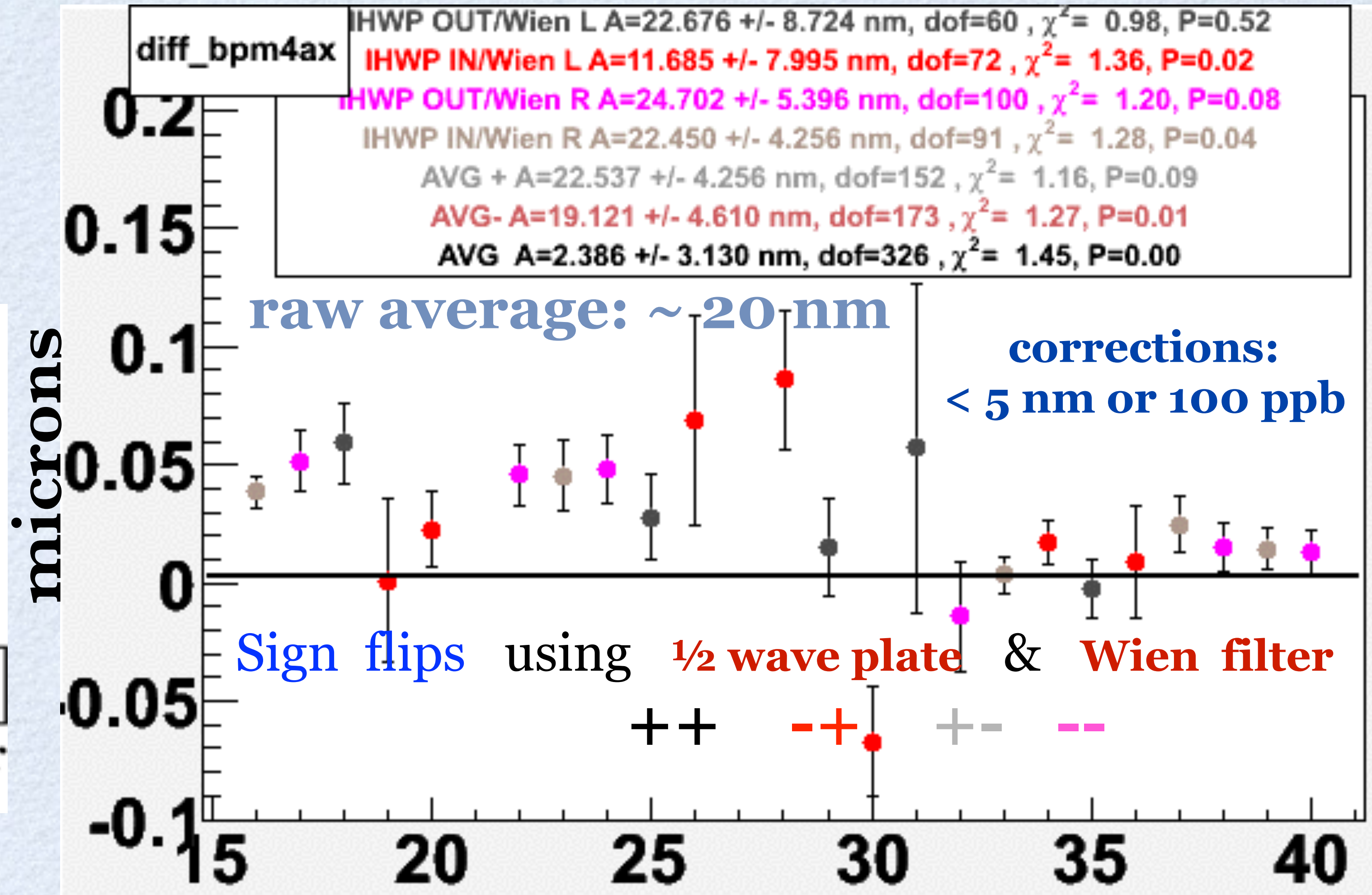
$A_{raw} \sim 500$ ppb $\quad A_{corr} = A_{det} - A_Q + \alpha\, \Delta_E + \Sigma \beta_i\, \Delta x_i$

Beam Stability Performance

2 methods of "slow" reversal



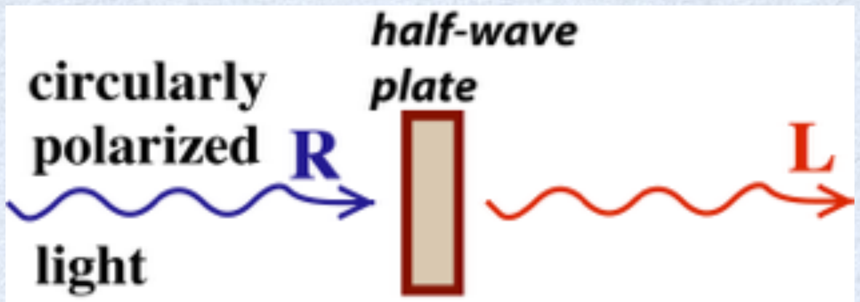


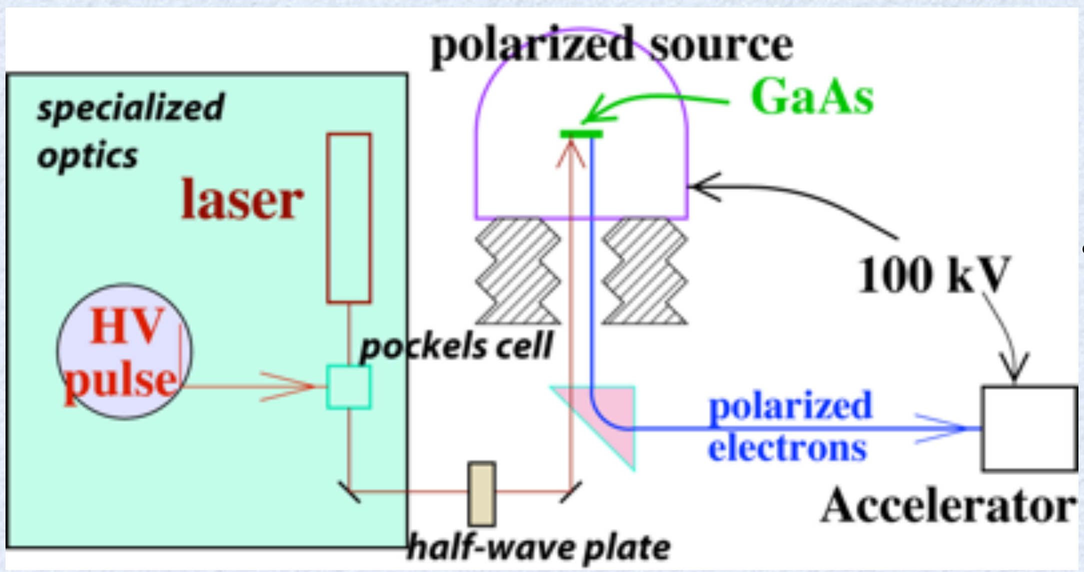


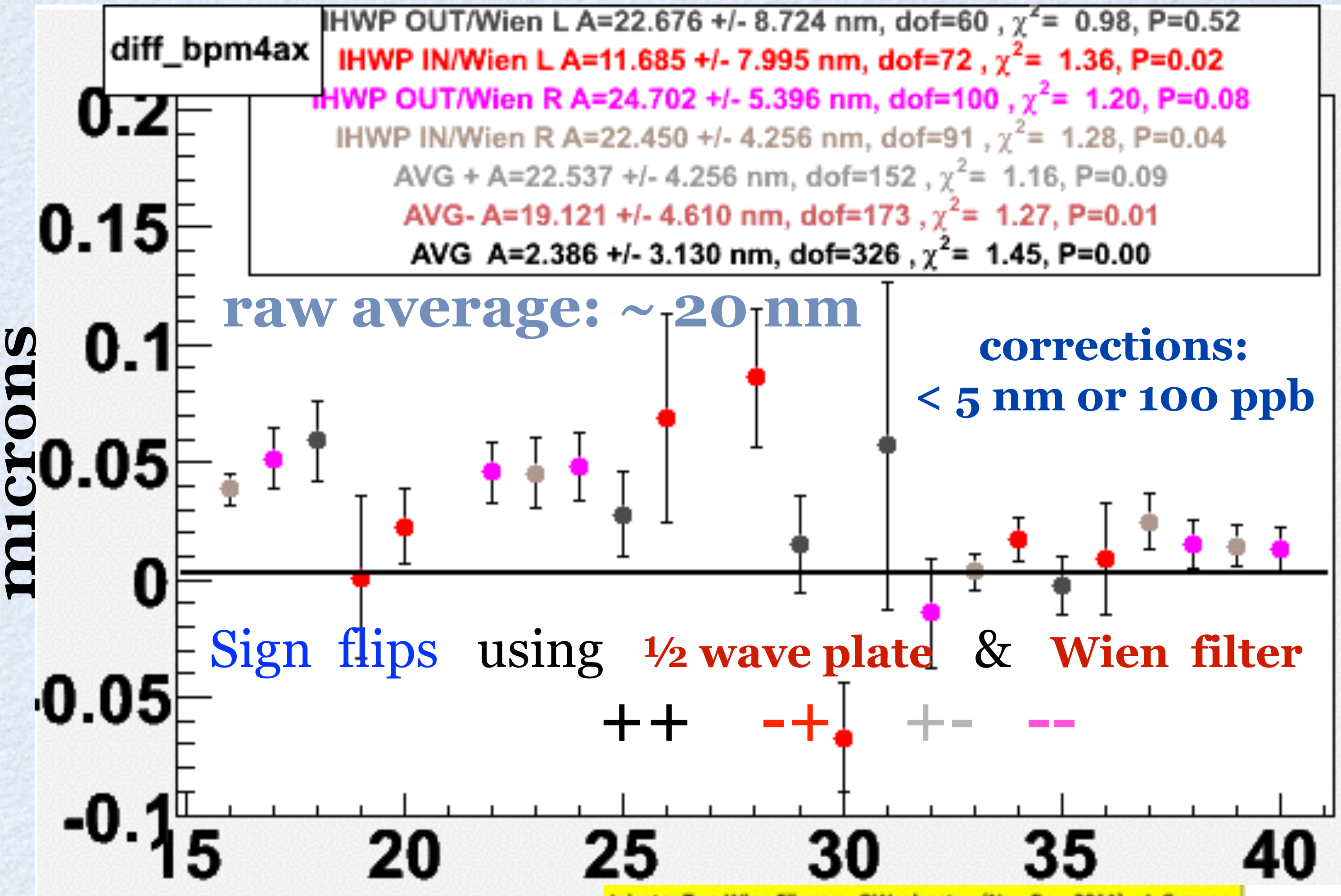
$A_{raw} \sim 500$ ppb $\quad A_{corr} = A_{det} - A_Q + \alpha\, \Delta_E + \Sigma \beta_i\, \Delta x_i$

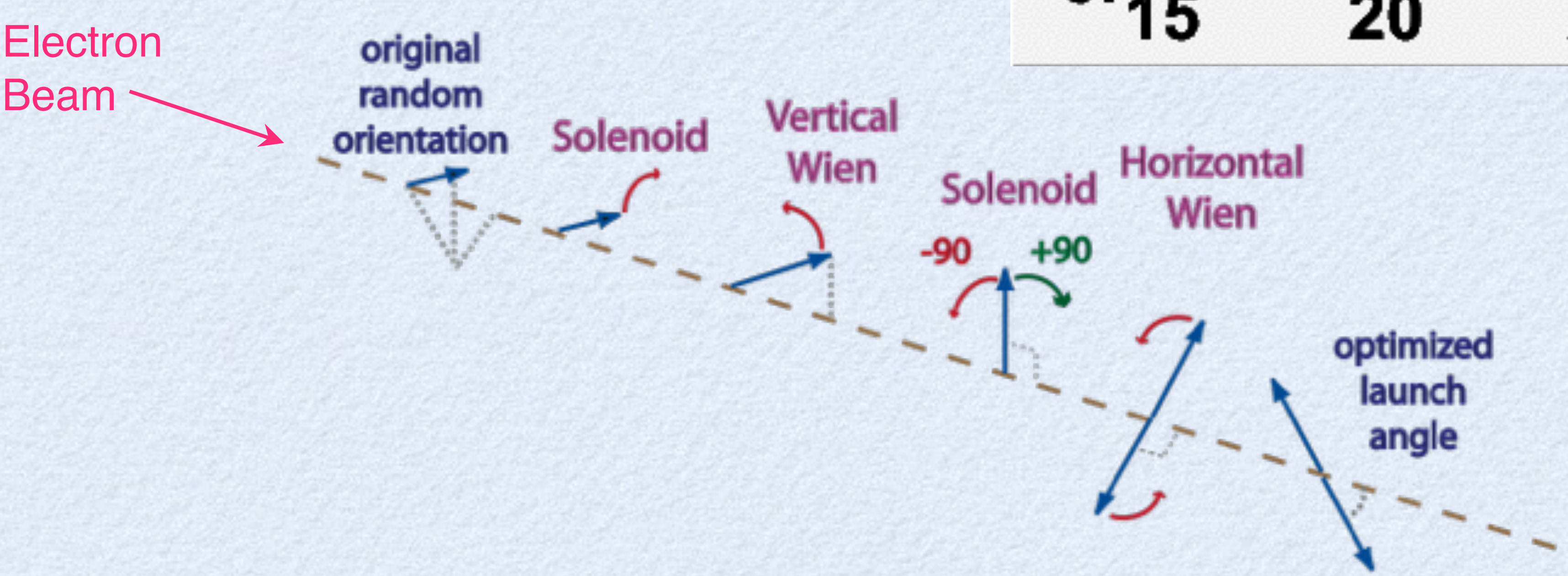
Beam Stability Performance

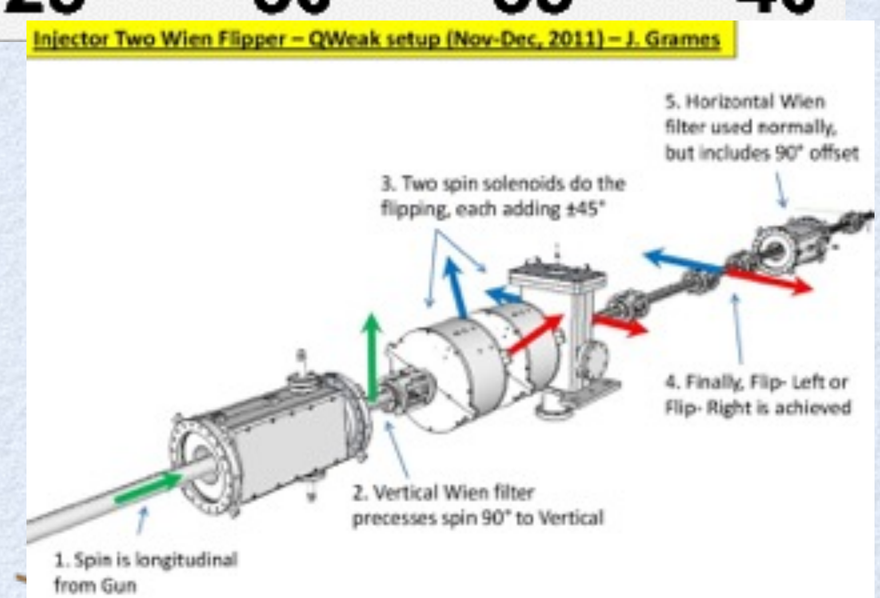
2 methods of “slow” reversal



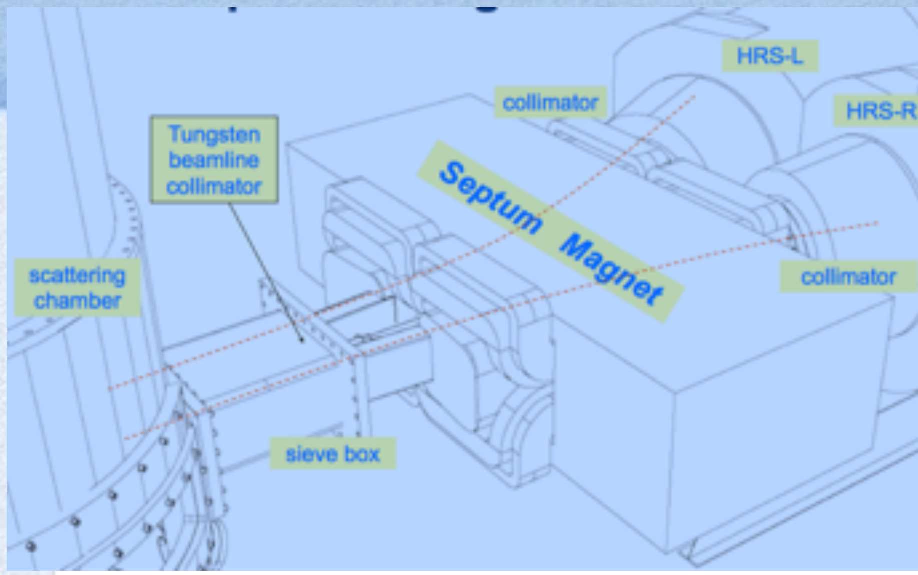


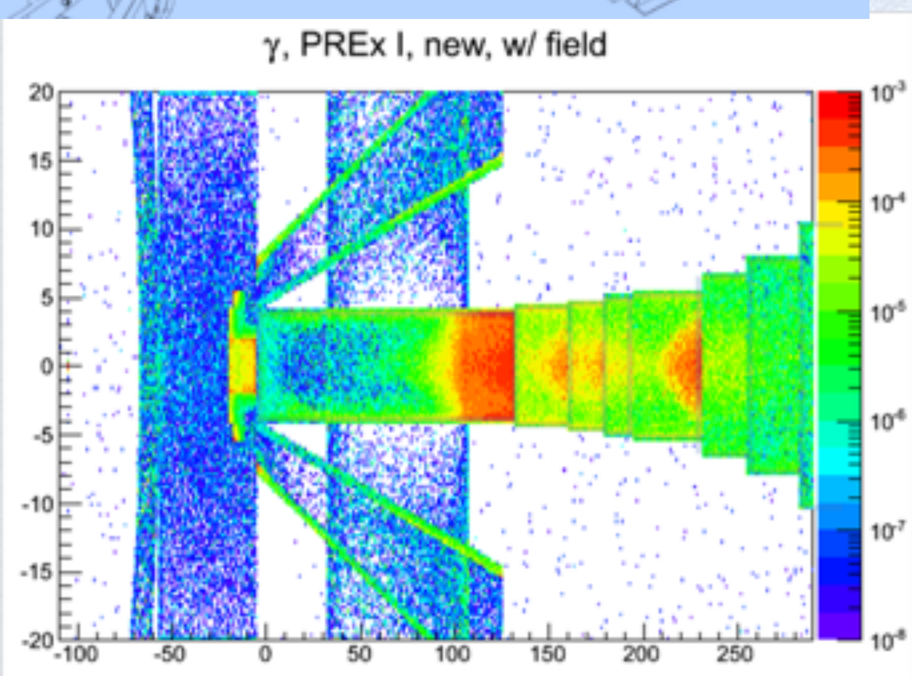


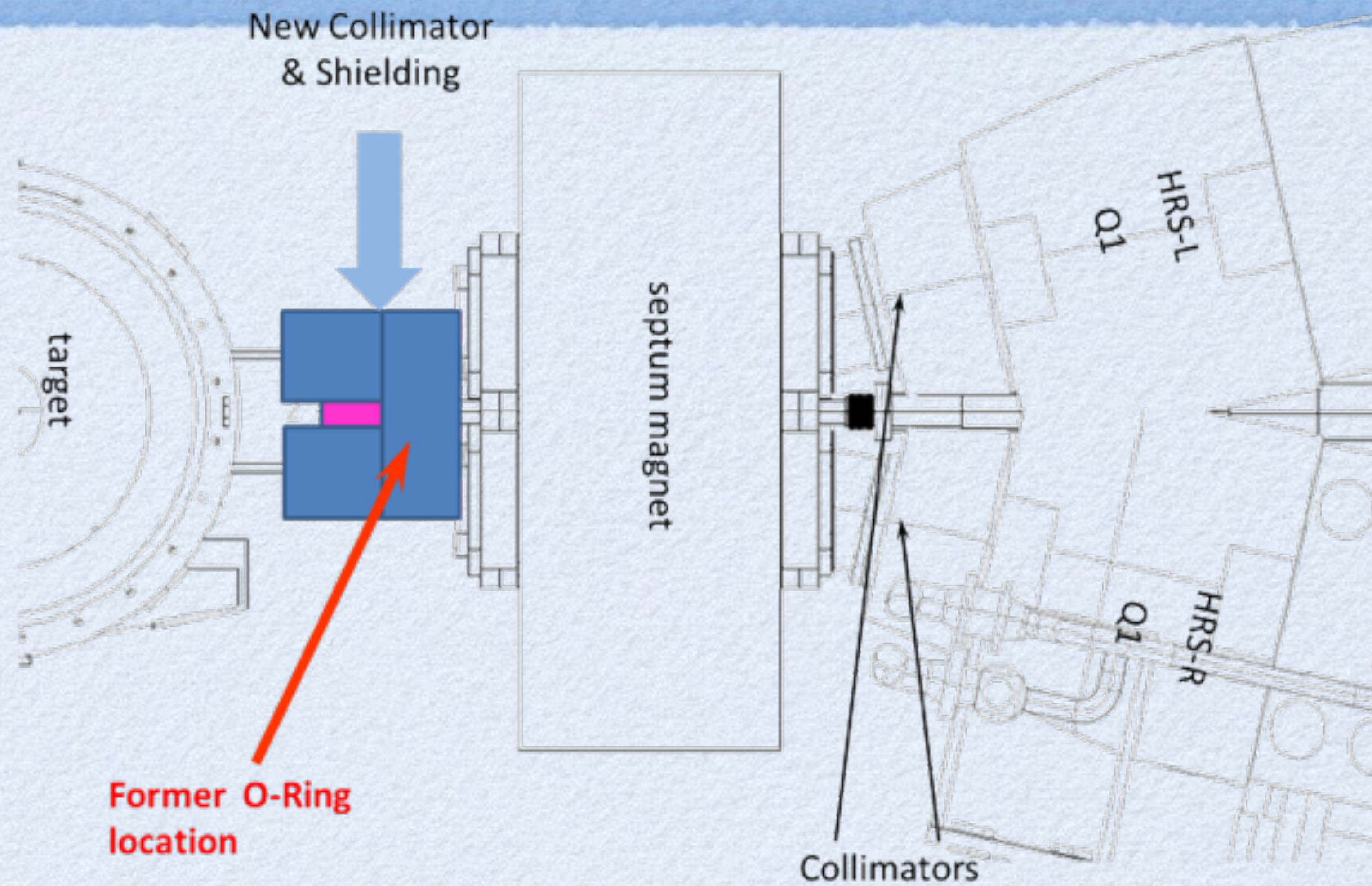


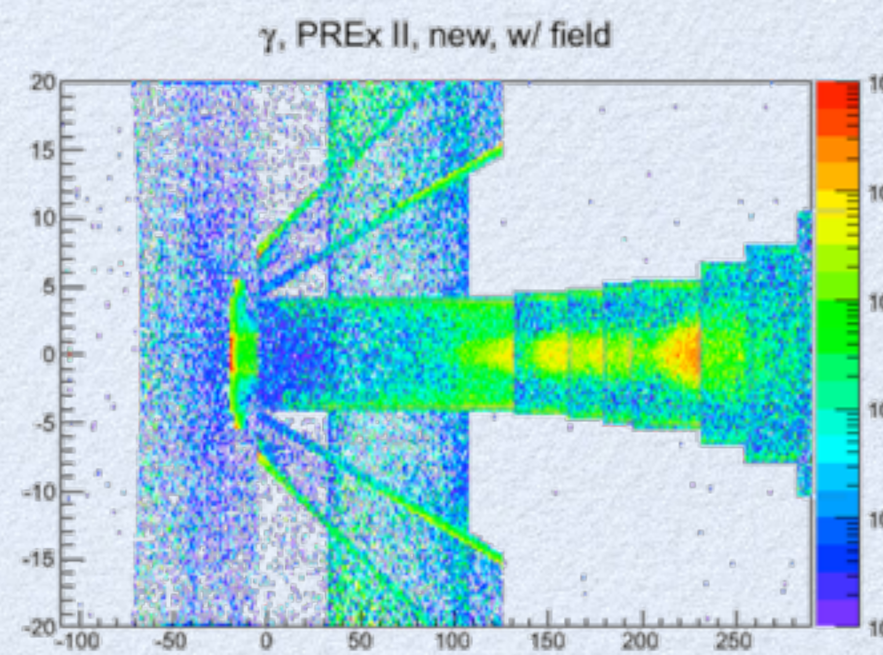


New Beamline Design









- **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**

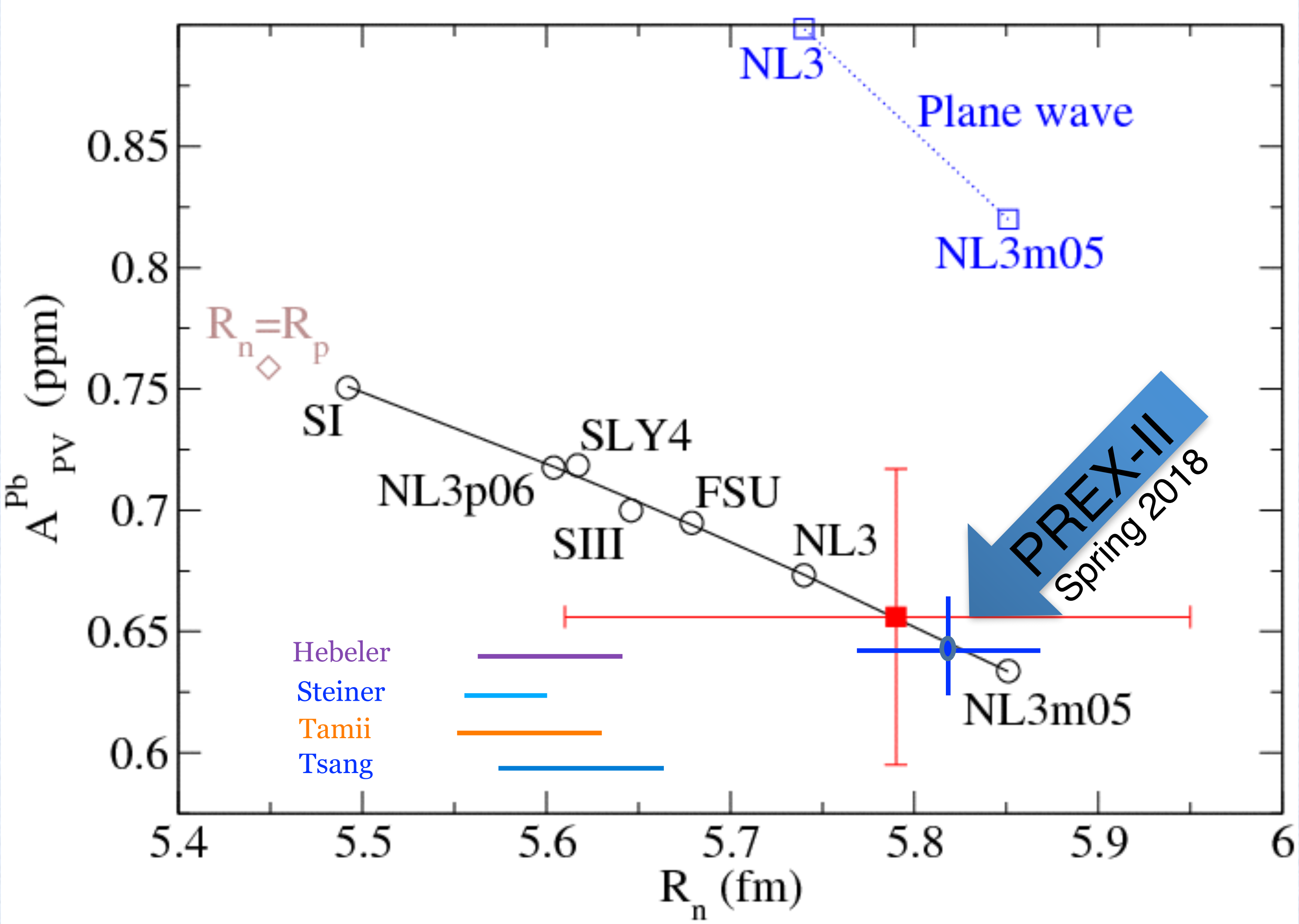
Full precision in 25 additional PAC days

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

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

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

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



Recent R_n predictions:

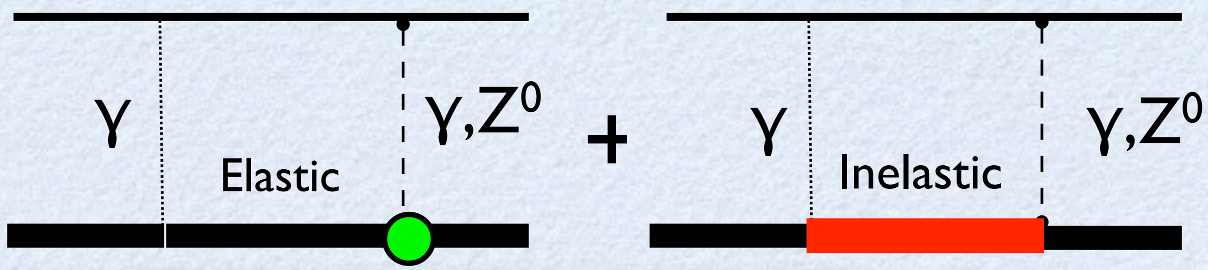
Hebeler et al. Chiral EFT calculation of neutron matter. Correlation of pressure with neutron skin by Brown. Three-neutron forces!

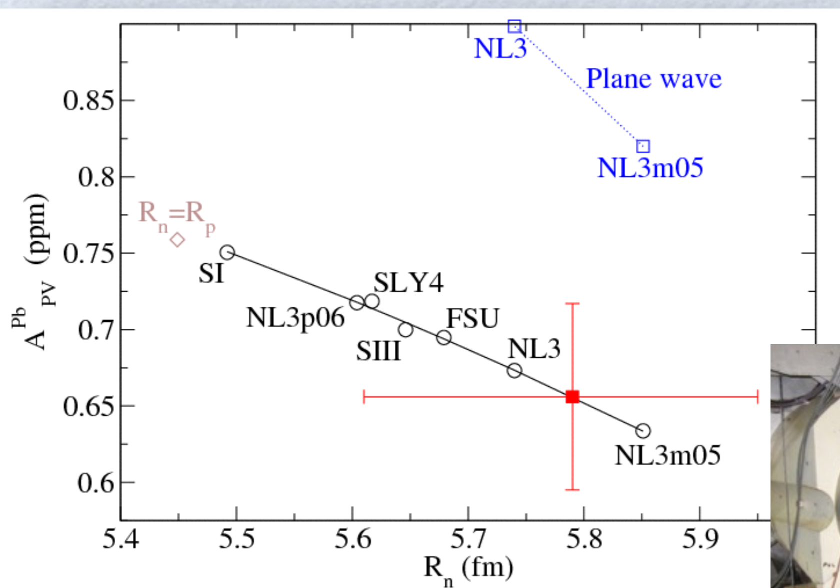
Steiner et al. X-Ray n-star mass and radii observation + Brown correlation. (Ozel et al finds softer EOS, would suggest smaller R_n).

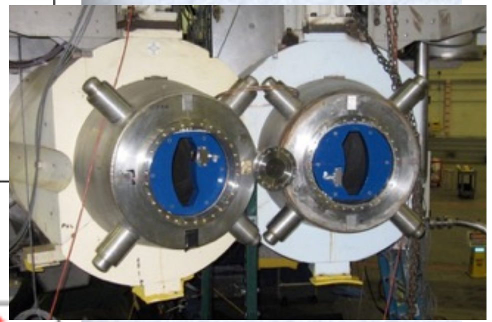
Tamii et al. Measurement of electric dipole polarizability of ^{208}Pb + model correlation with neutron skin.

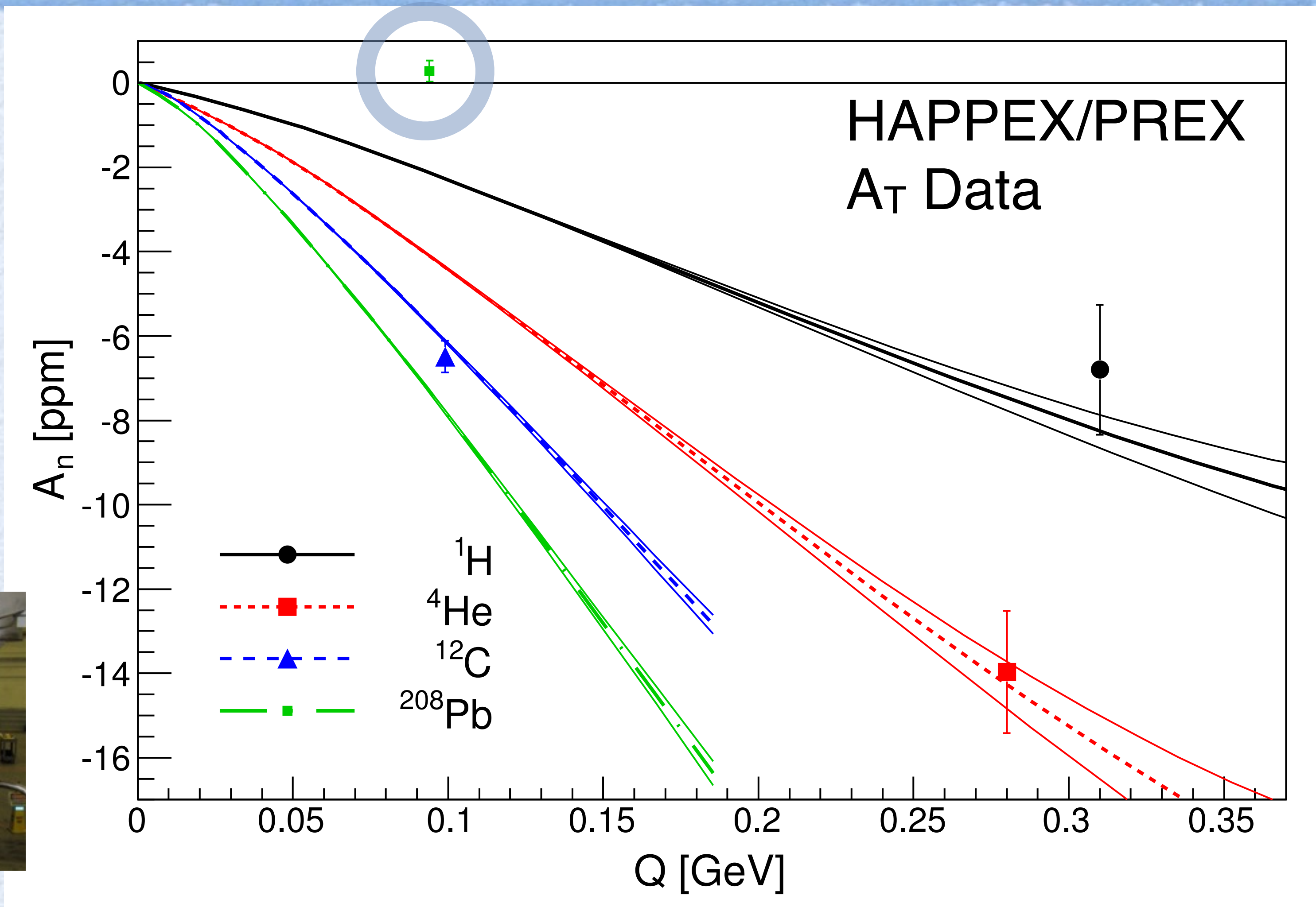
Tsang et al. Isospin diffusion in heavy ion collisions, with Brown correlation and quantum molecular dynamics transport model.

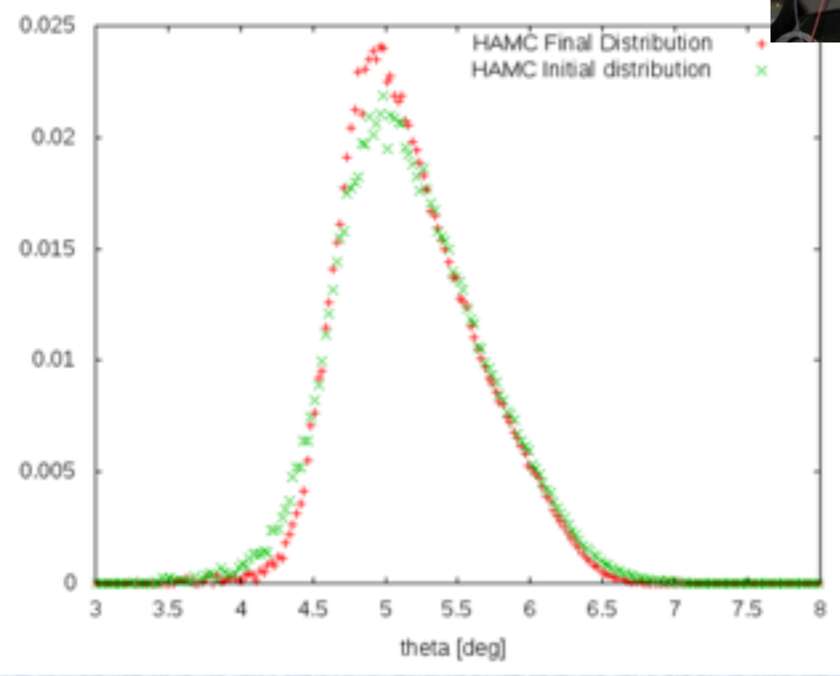
Input from Vector Analyzing Power







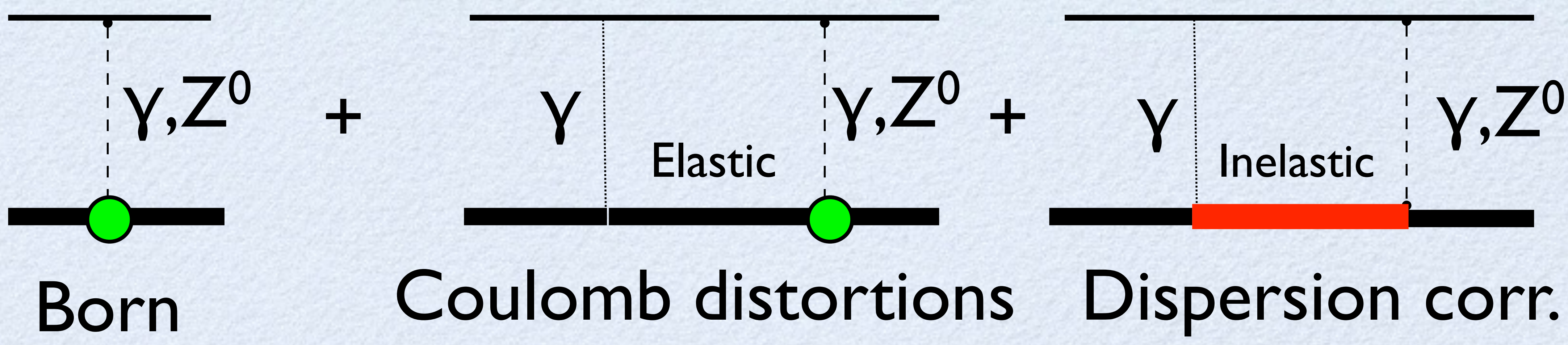




- **What does the Pb-208 A_T result imply?**
  - *dispersion corrections on top of Coulomb distortions?*
  - *What if it is a very sensitive cancellation?*
    - What happens when we run again at slightly different kinematics?
    - What if Ca-48 doesn't have this accidental cancellation?
  - *should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

Radiative Corrections

C.Horowitz

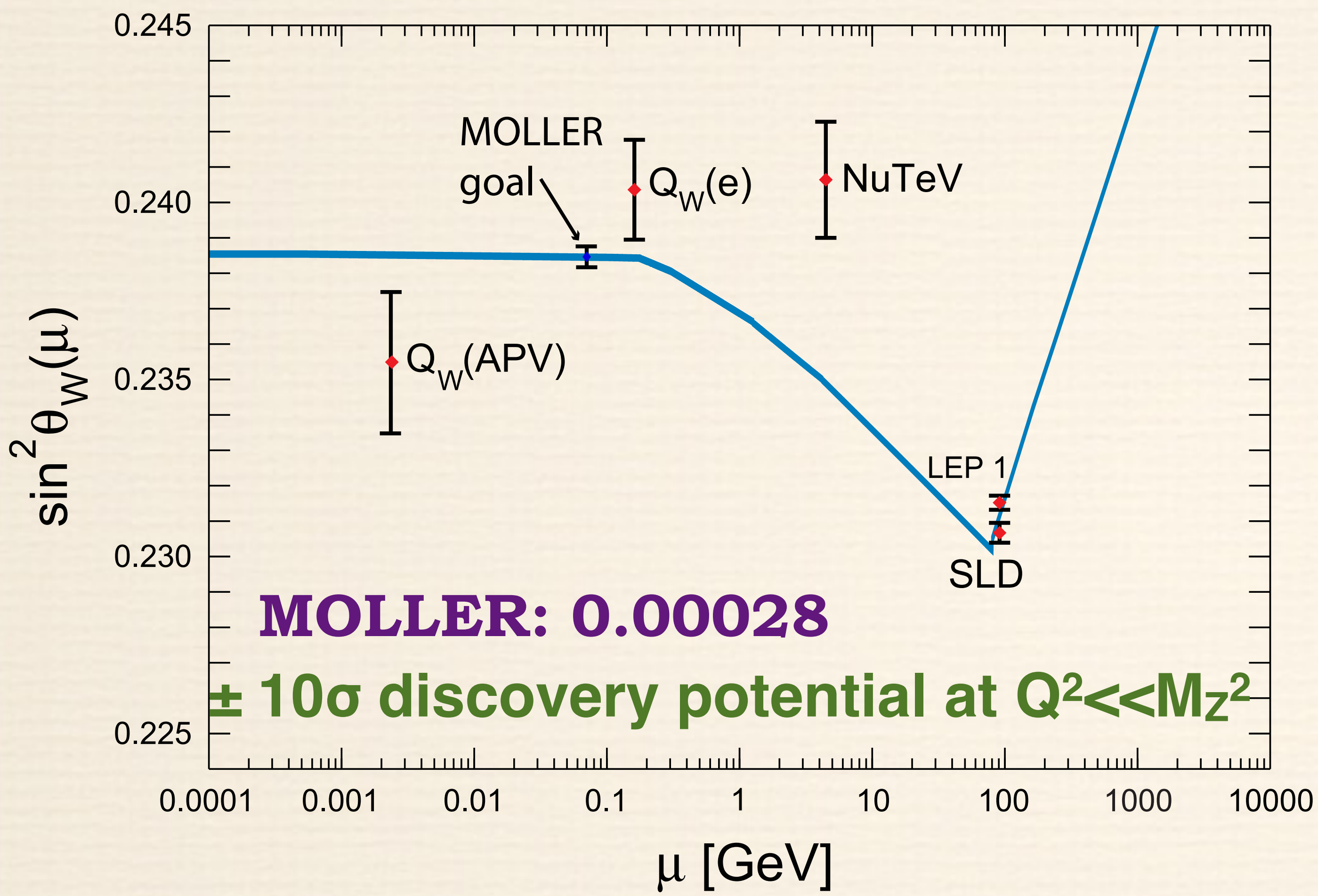


- Coulomb distortions are coherent, order Zα. Important for PREX (Z=82)
  - Sum elastic intermediate states to all orders in Zα by solving Dirac equation for electron moving in coulomb (V) + weak potential (A) of nucleus.
  - Coulomb distortions reduce A_{pv} by ~30%, but accurately calculated (uncertainty 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

A Fundamental Parameter of the Electroweak Theory

$\sin^2\theta_W$

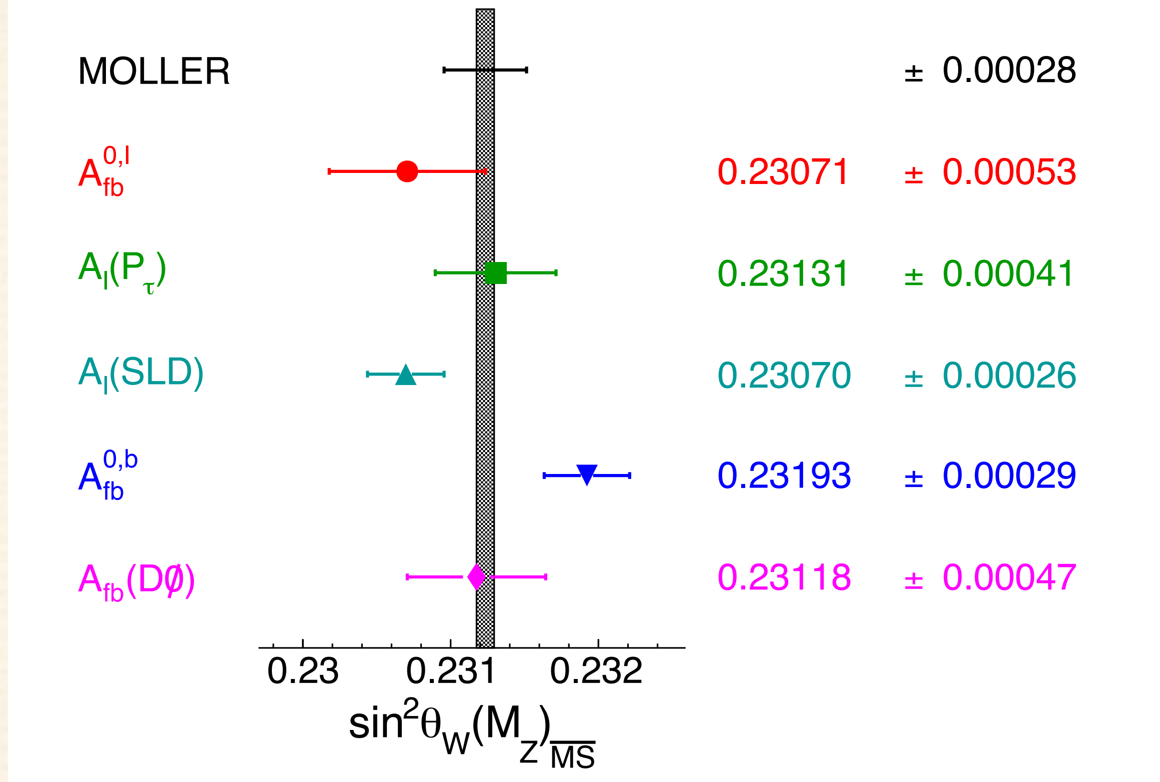
MOLLER Projection: *$\delta(\sin^2\theta_W) = \pm\, 0.00024$ (stat.) $\pm\, 0.00013$ (syst.)*



MOLLER: 0.00028

± 10σ discovery potential at $Q^2 \ll M_Z^2$

Z resonance measurements: no interference term



Future projections (similar time scale)

Mainz P2: ~ 0.00032

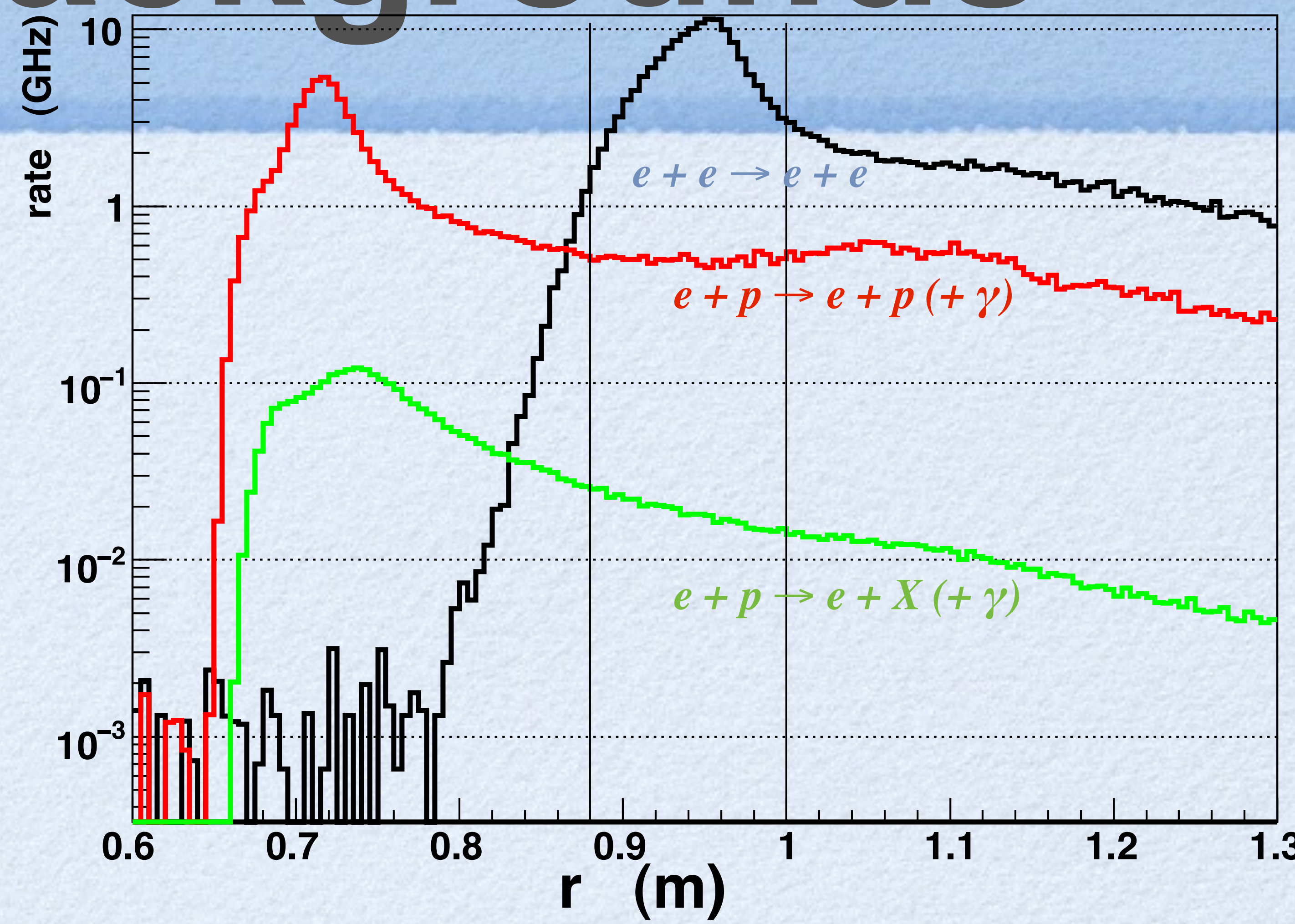
Final Tevatron: ~ 0.00041

LHC 14 TeV, 300 fb^{-1} : ~ 0.00036

Note: systematics-dominated (pdf uncertainties)

Signal & Backgrounds

parameter	value
cross-section	*45.1 μBarn*
Rate @ 75 μA	*135 GHz*
pair stat. width (1 kHz)	*82.9 ppm*
$\delta(A_{raw})$ (6448 hrs)	*0.544 ppb*
$\delta(A_{stat})/A$ (80% pol.)	*2.1%*
$\delta(\sin^2\theta_W)_{stat}$	*0.00026*

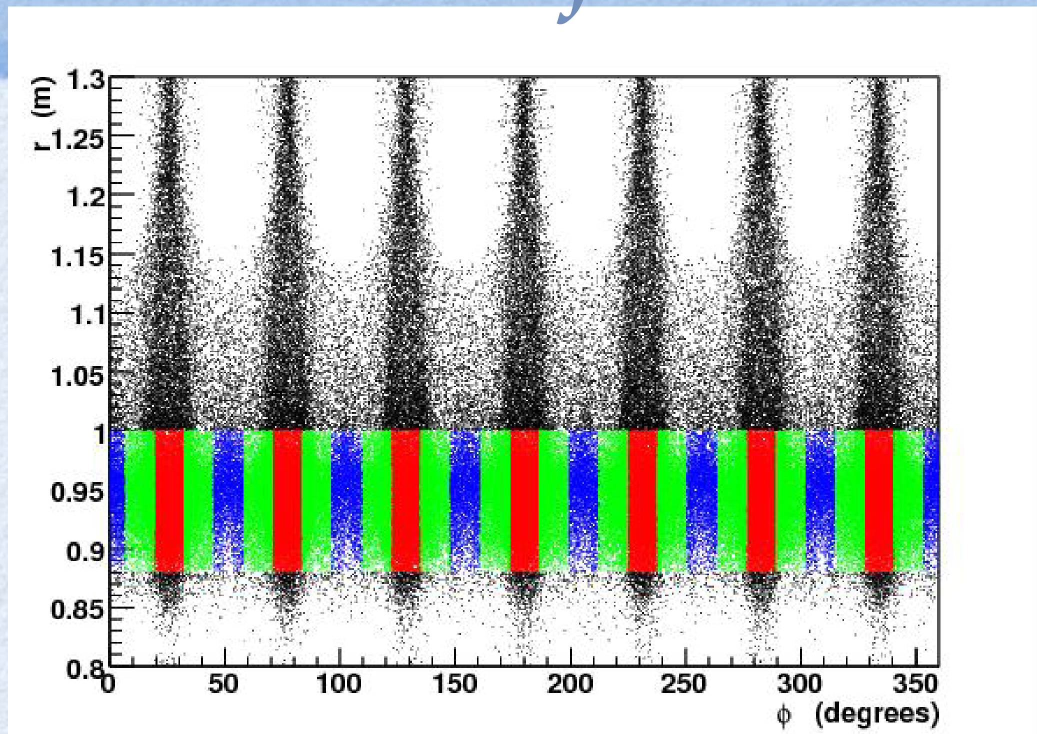


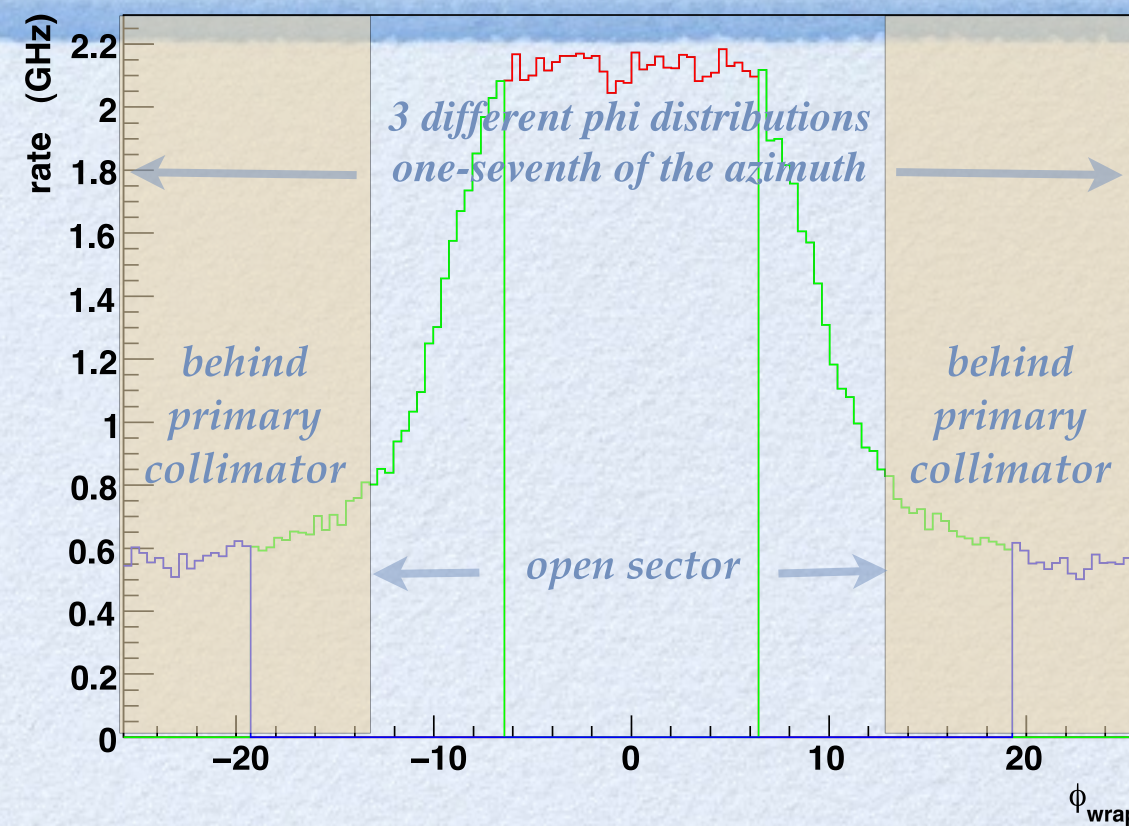
- photons and neutrons
  - mostly 2-bounce collimation system
  - dedicated runs to measure "blinded" response
- pions and muons
  - real and virtual photo-production and DIS
  - prepare for continuous parasitic measurement
  - estimate 0.5 ppm asymmetry @ 0.1% dilution

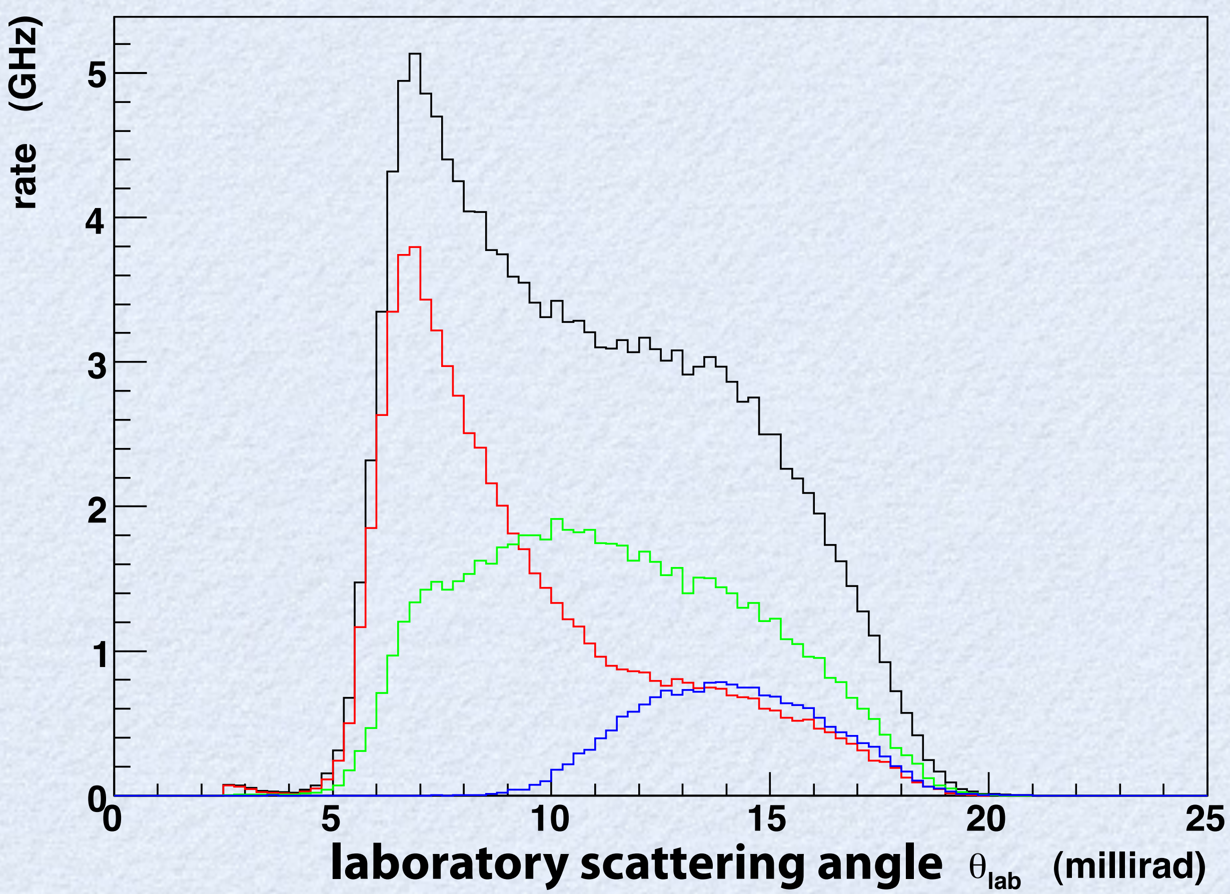
- **Elastic e-p scattering**
  - *well-understood and testable with data*
  - *8% dilution, 7.5±0.4% correction*
- **Inelastic e-p scattering**
  - *sub-1% dilution*
  - *large EW coupling, 4±0.4% correction*
  - *variation of A_{PV} with r and φ*

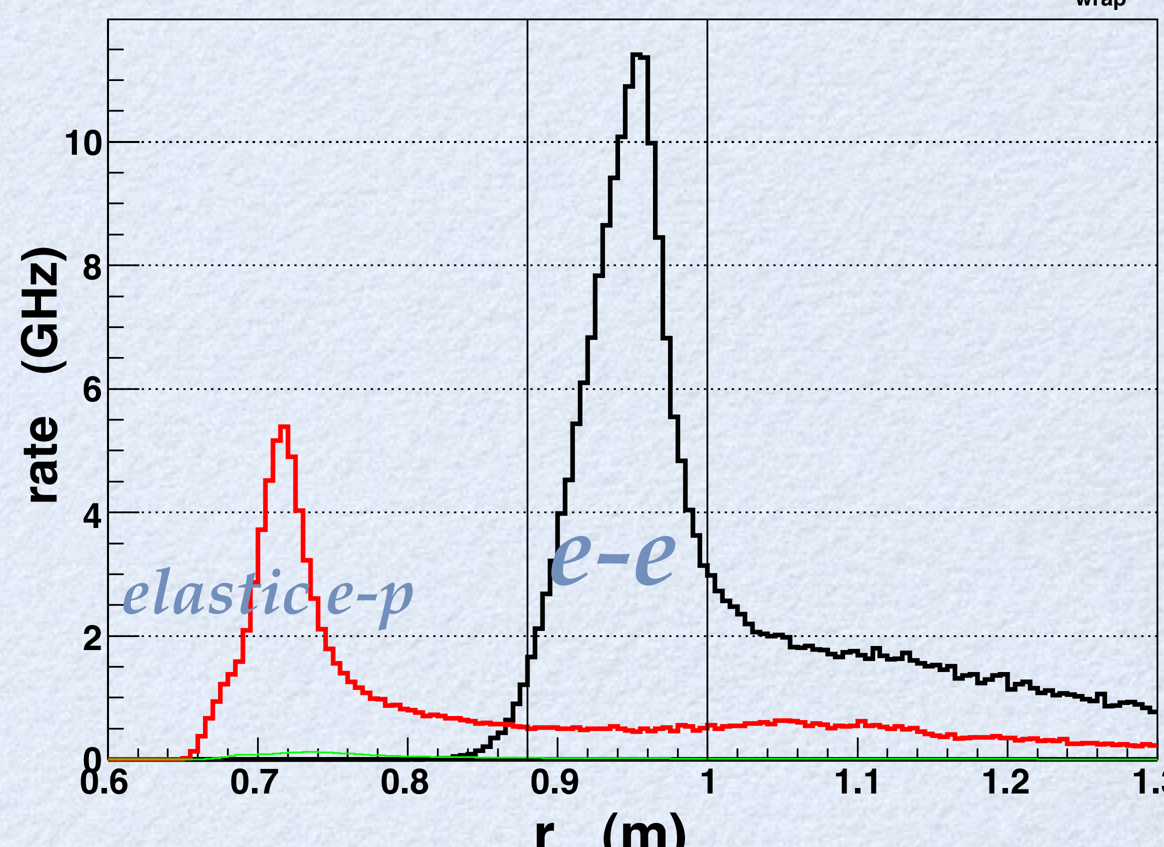
Simulations

Initial and final state radiation effects in target

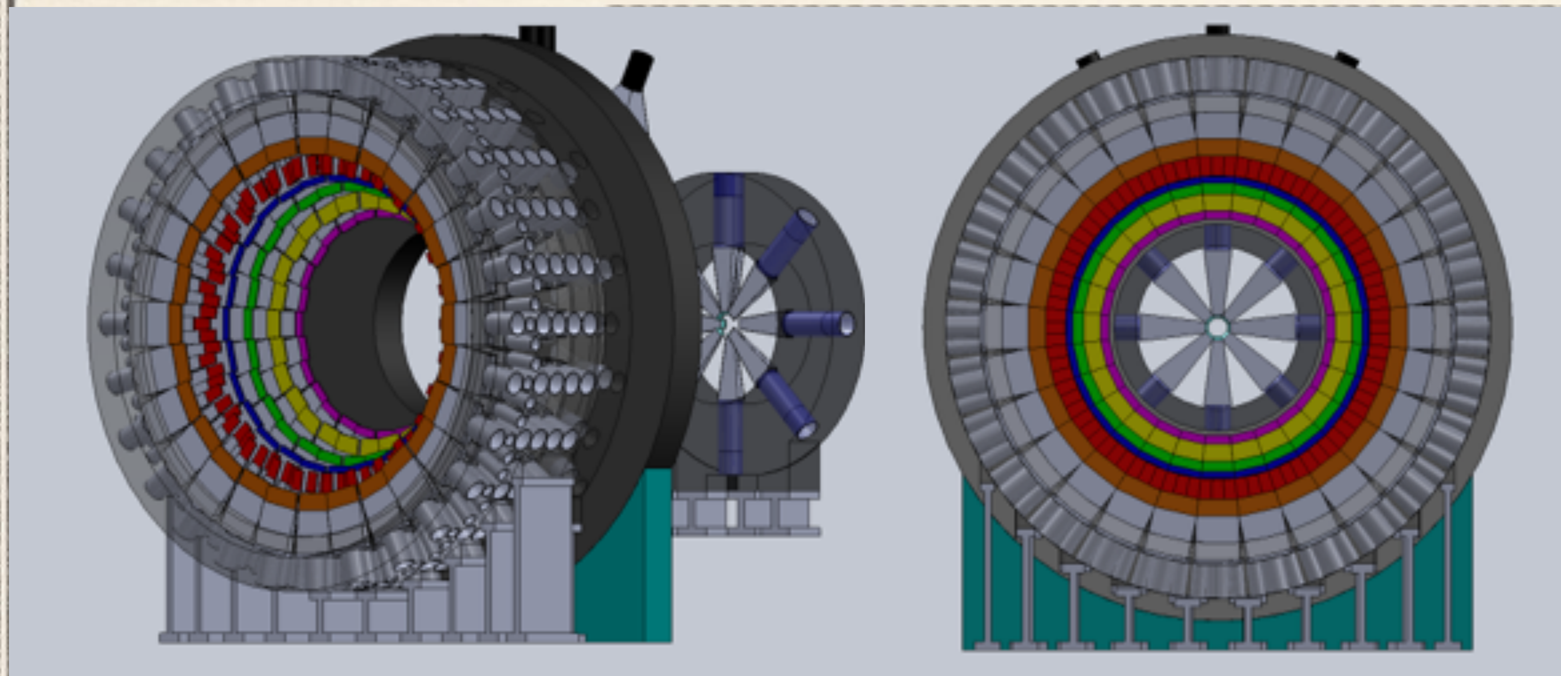


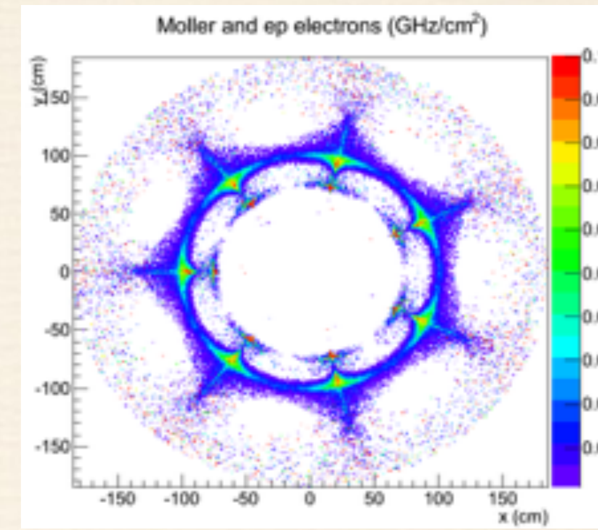


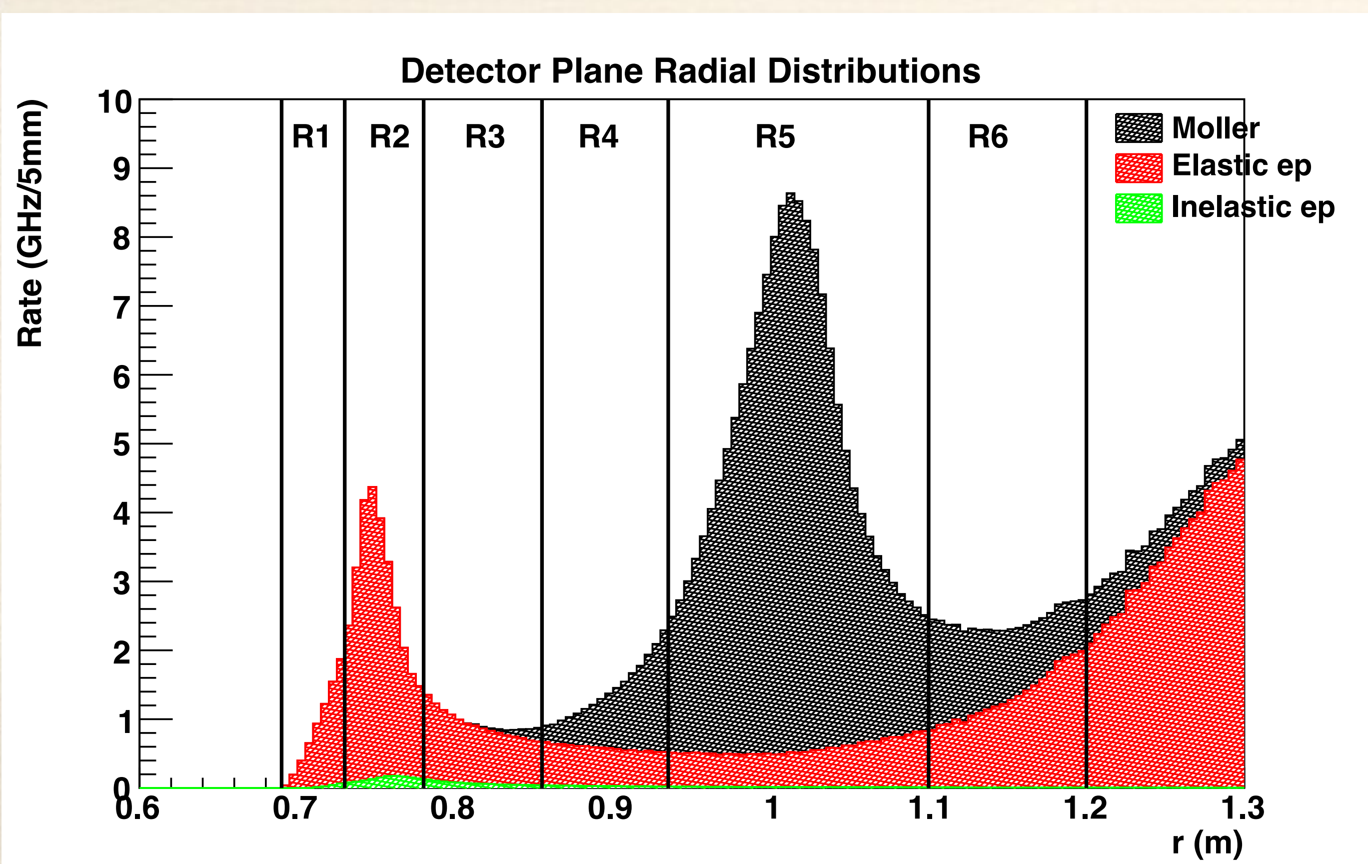


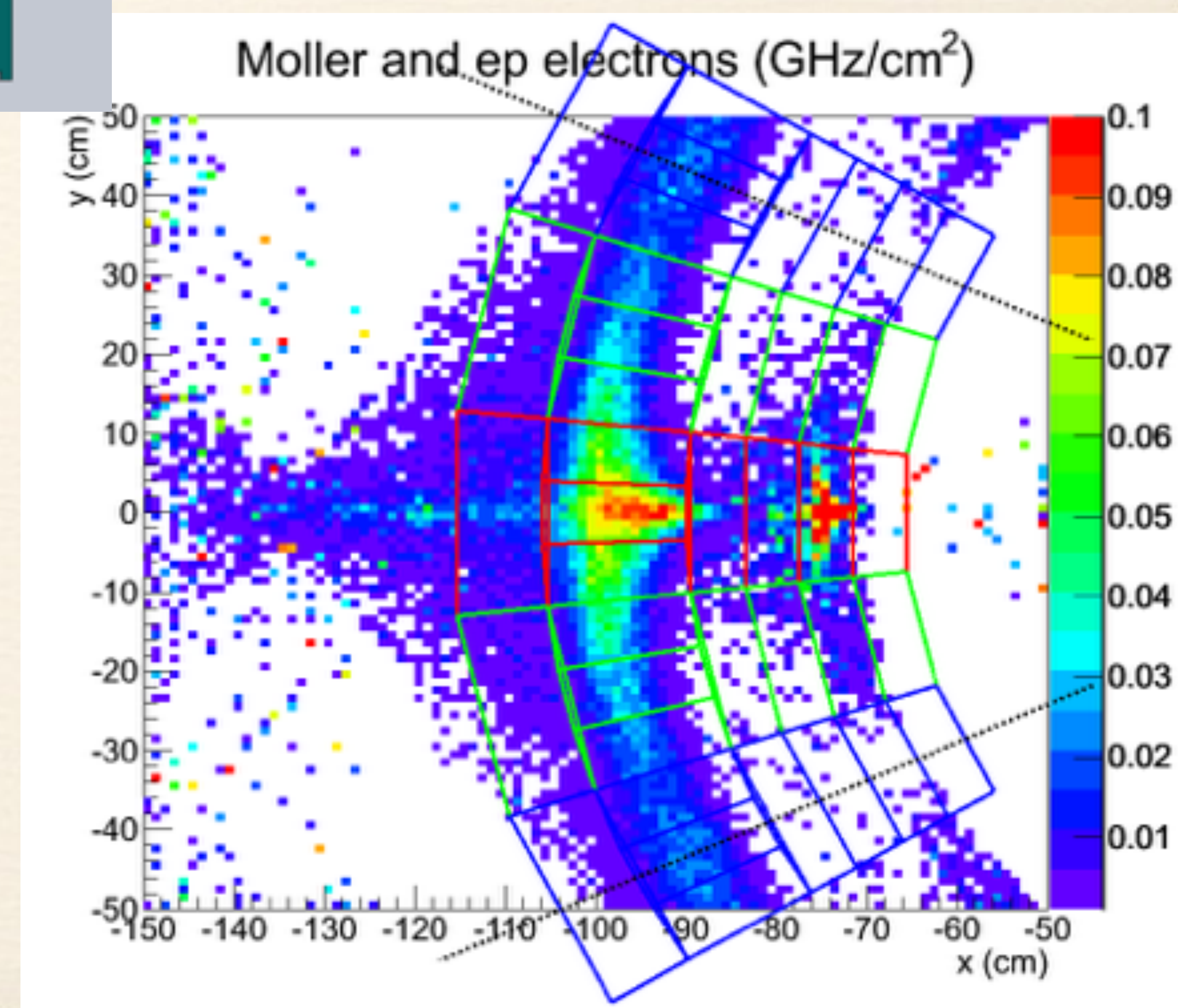


Detector Plane Distributions

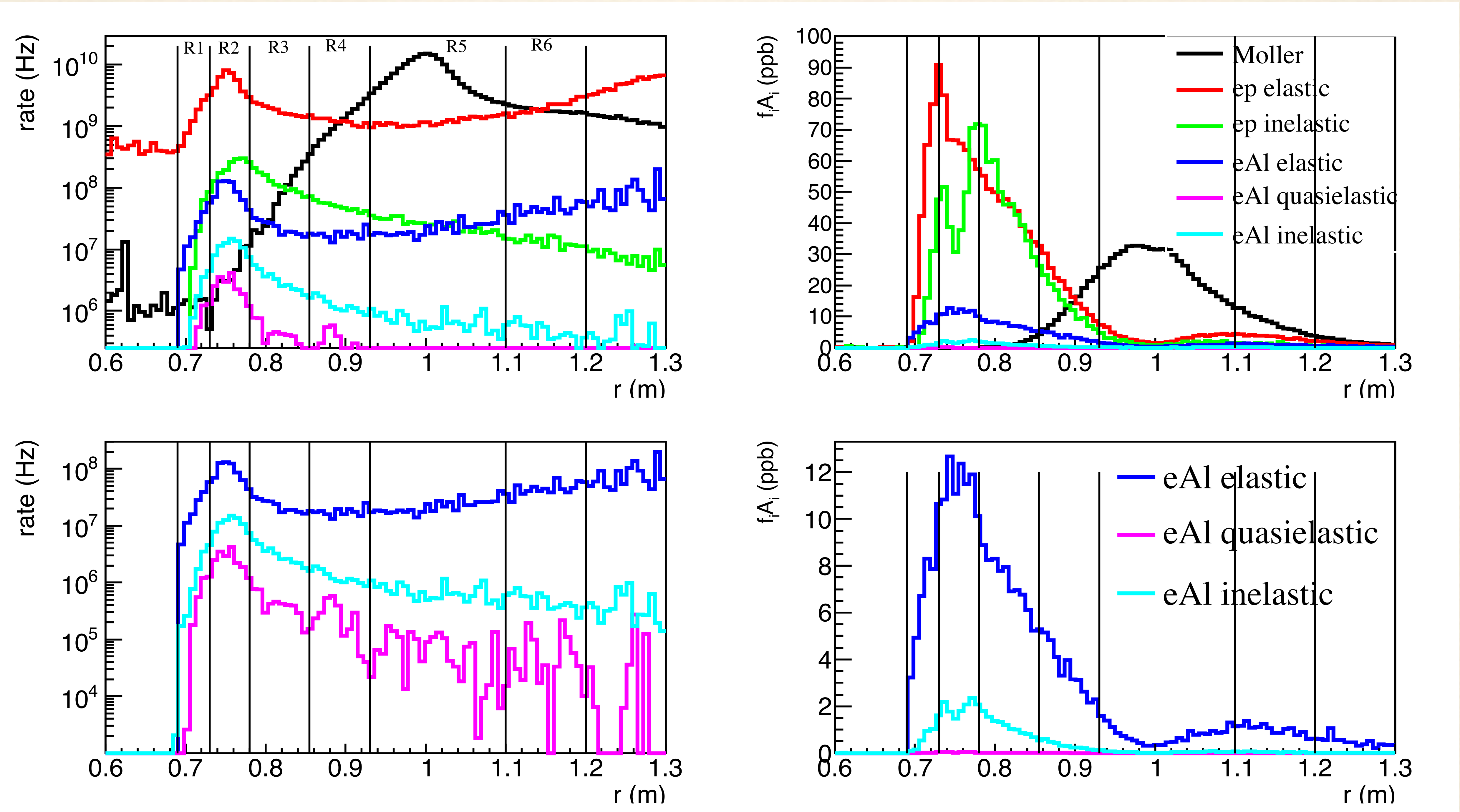








Rate and Asymmetry



Additional Azimuthal Discrimination