PANIC 2014
Particles and Nuclei International Conference
Hamburg University, August 25-29, 2014

# *Parity Violating Electron Scattering*

# Recent Results and Future Prospects

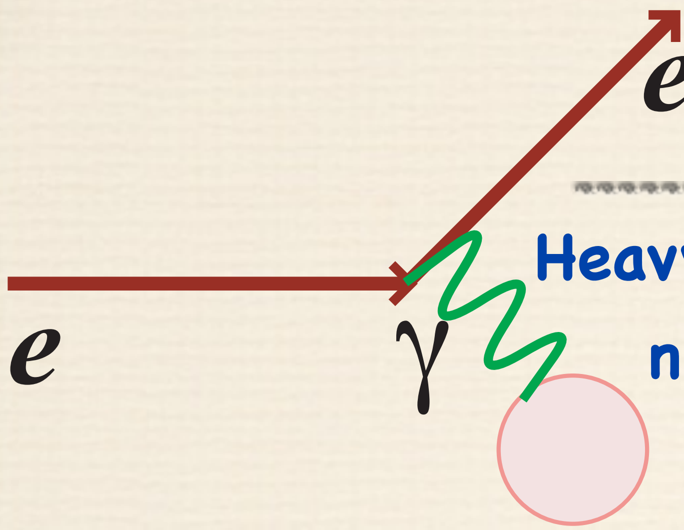
**Krishna Kumar**
UMass, Amherst & Stony Brook U.

# Outline

- ✦ **Historical Overview**
- ✦ **Electroweak Measurement of the Neutron Skin of a Heavy Nucleus**
  - ★ PREX and CREX at Jefferson Lab
- ✦ **Precision Measurements of Weak Charges**
  - ★ Future Program with the JLab 12 GeV Upgrade
  - ★ (Followup talks on 6 GeV program by P. King and V. Sulkosky)

# *Historical Perspective*

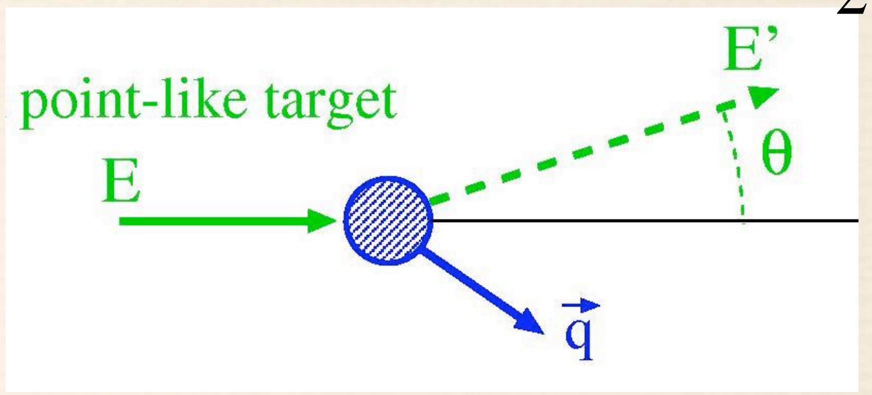
# Relavitistic Electron Scattering and Substucture




Heavy, spinless nucleus

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

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

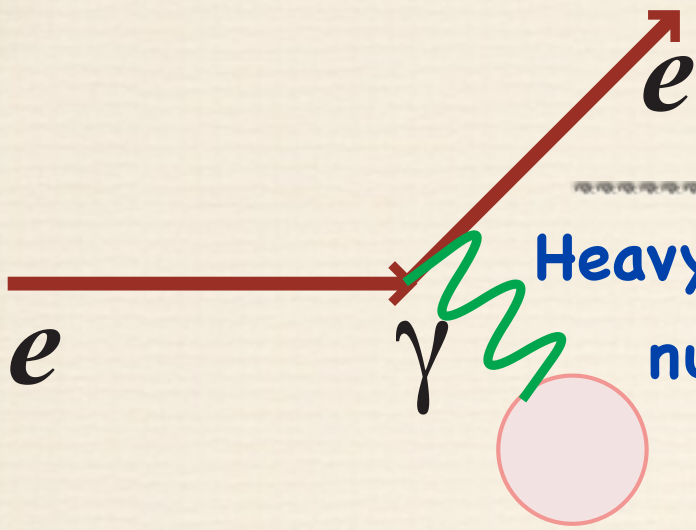



$$Q \approx \frac{hc}{\lambda}$$

***Differential Cross Section***

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

# Relavitistic Electron Scattering and Substucture

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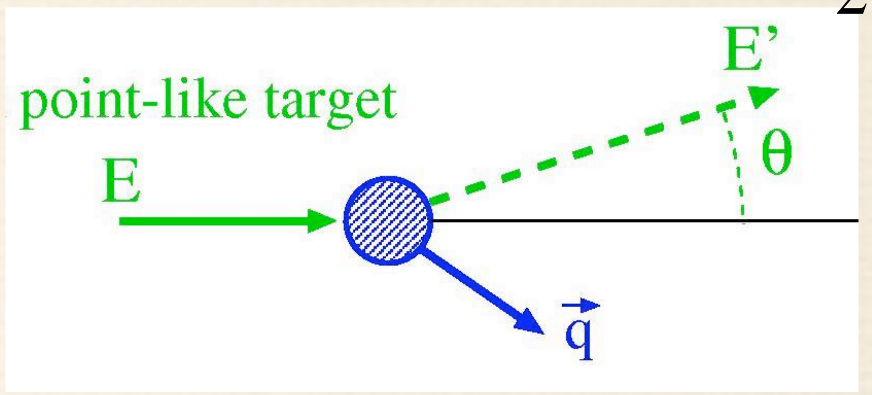


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***As Q increases, nuclear size modifies formula***

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

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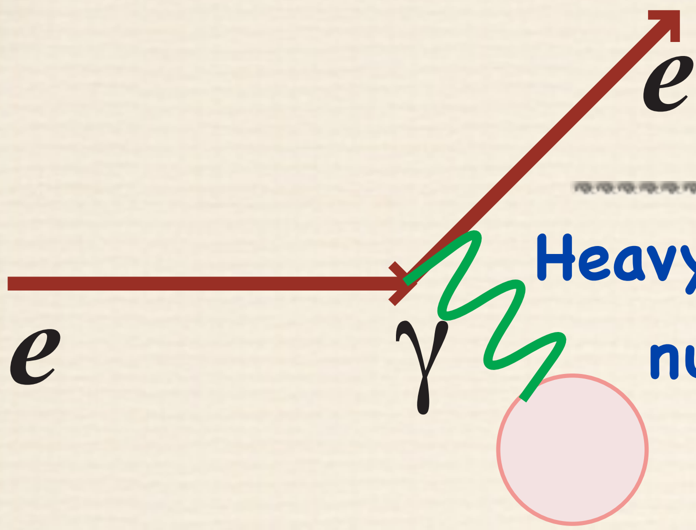


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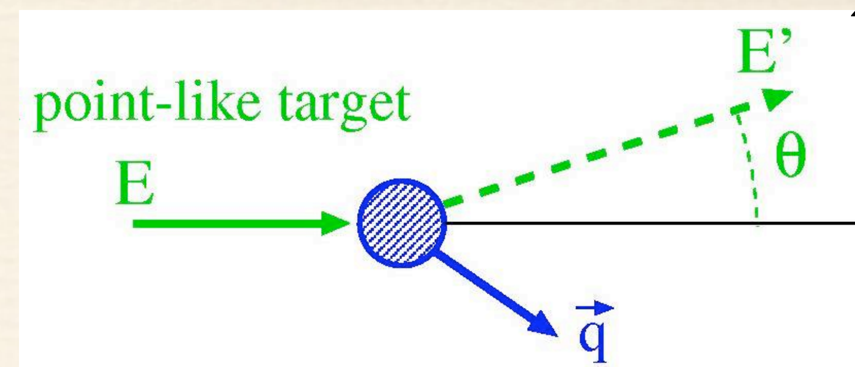


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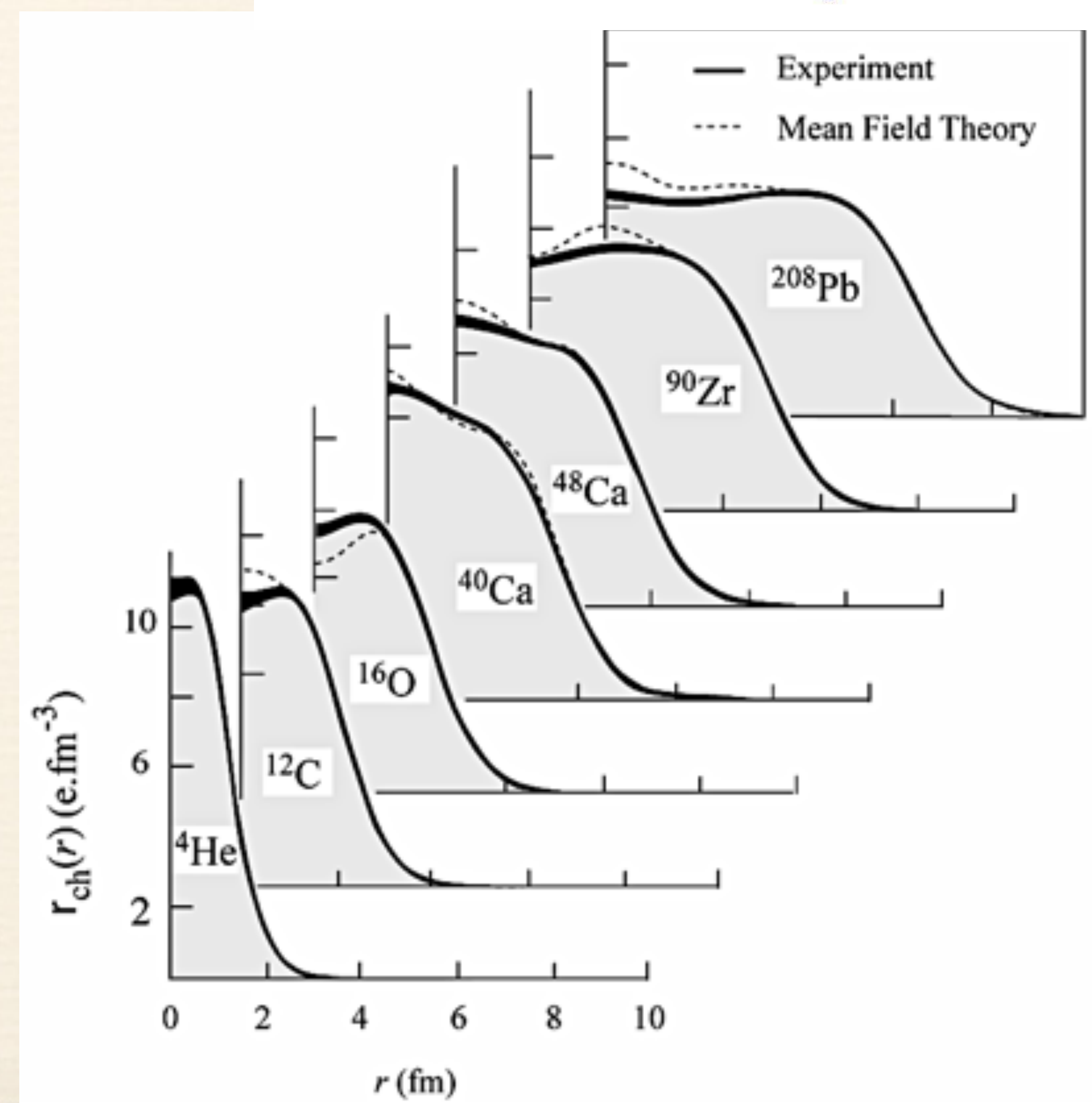


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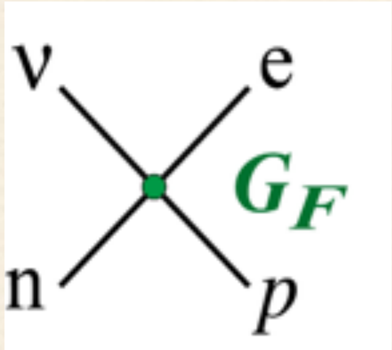
# Weak Interactions

*Neutron & nuclear β Decay*




*charge and flavor-changing*

**Fermi Theory for weak interactions**

**Universal strength: coupling constant $G_F$**

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

*Observed NOT to be invariant under parity transformations*

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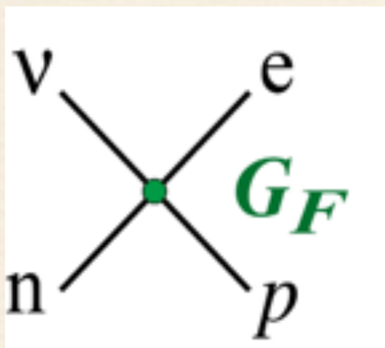


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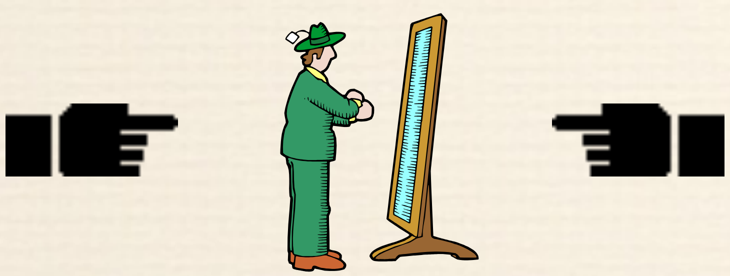
***parity transformation (reflection)***

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



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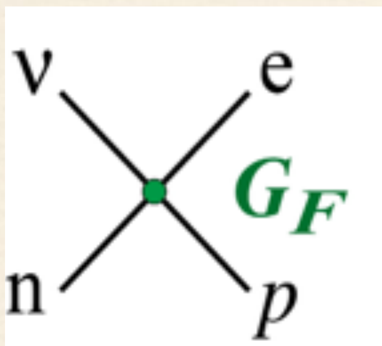


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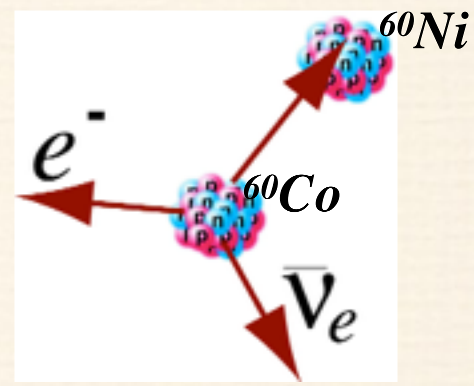
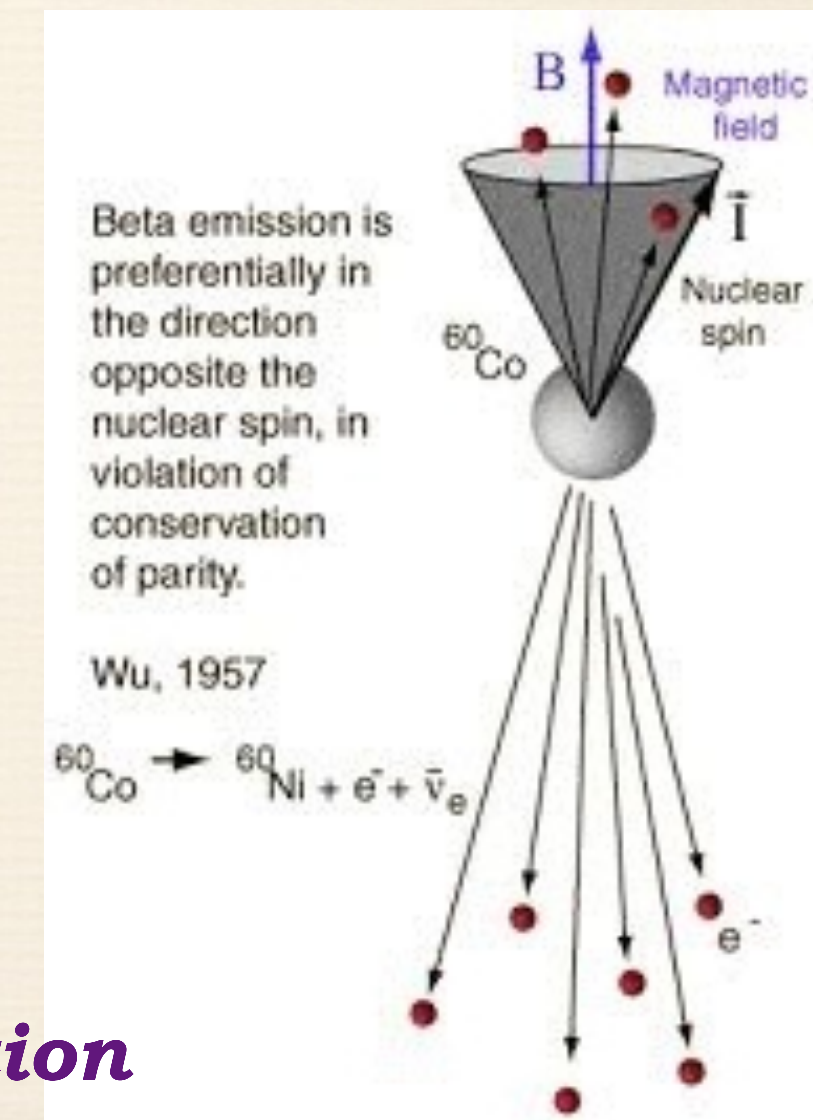



Weak decay of $^{60}$Co Nucleus

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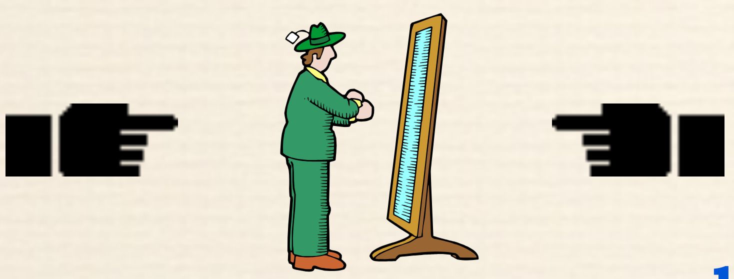

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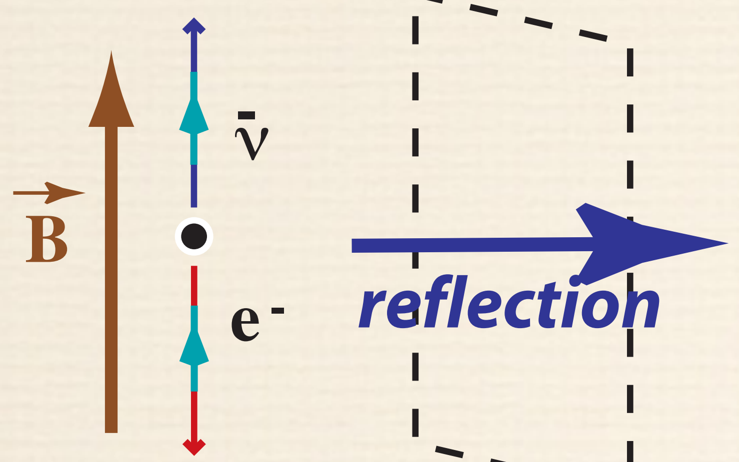


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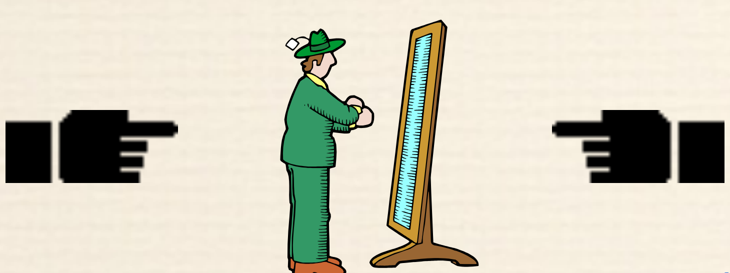

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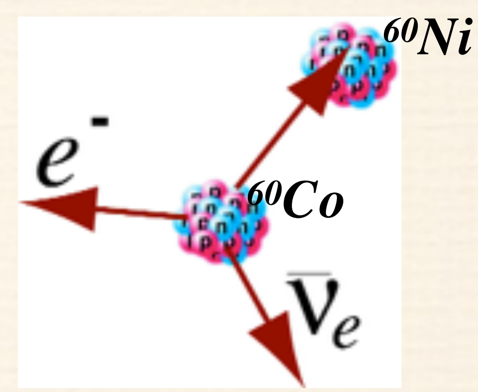


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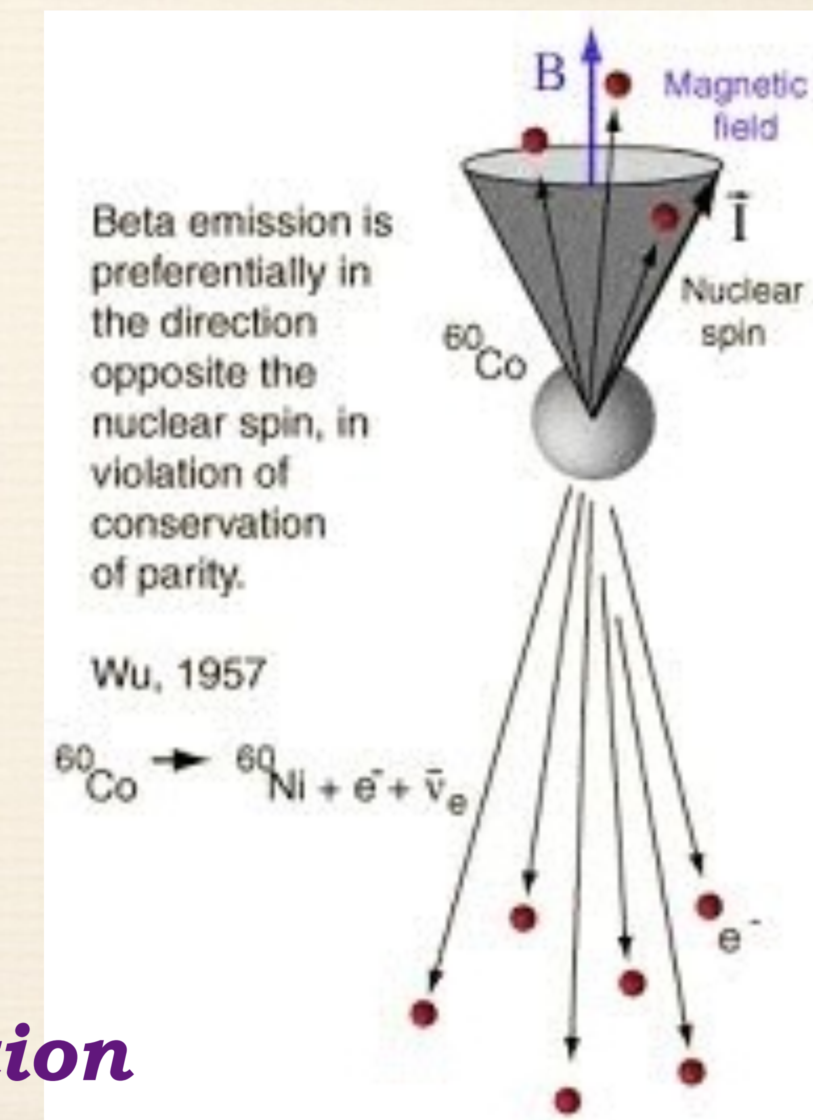


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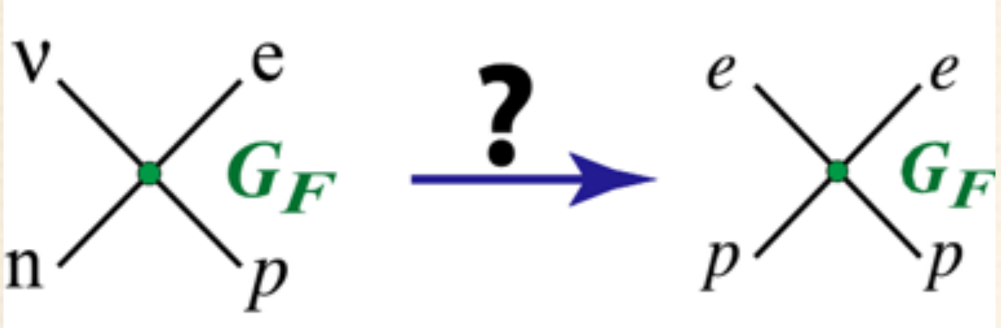

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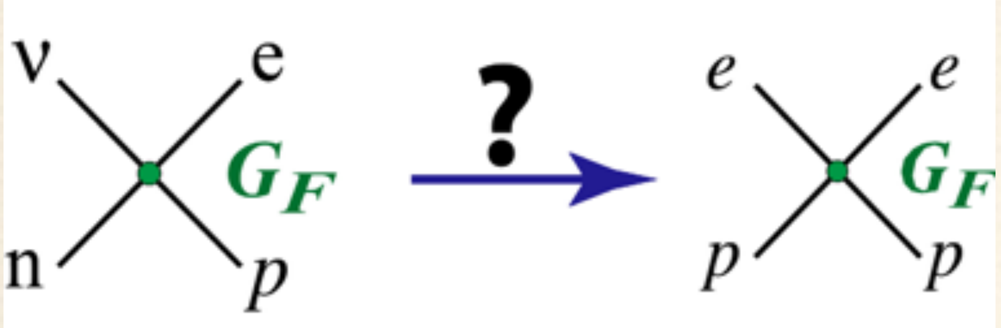


$$\sigma \;\alpha\; \left|A_{EM} + A_{weak}\right|^2$$

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

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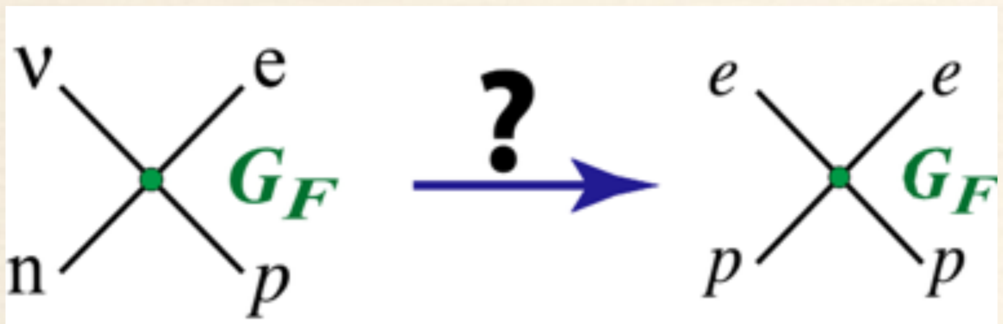


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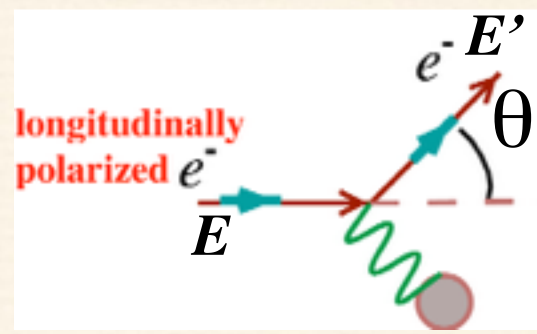


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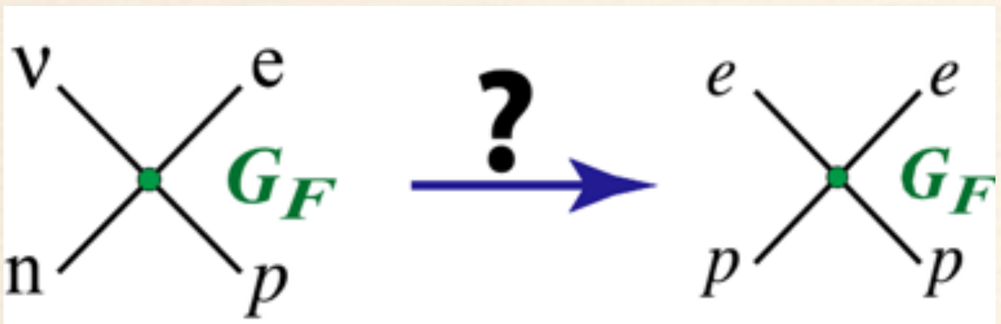


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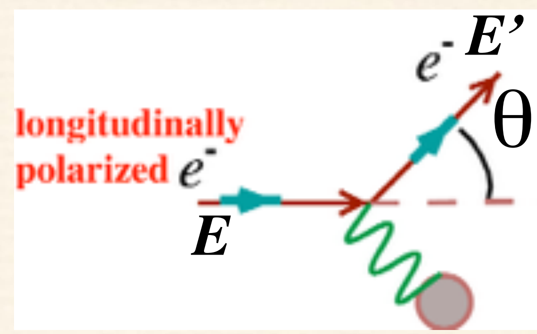


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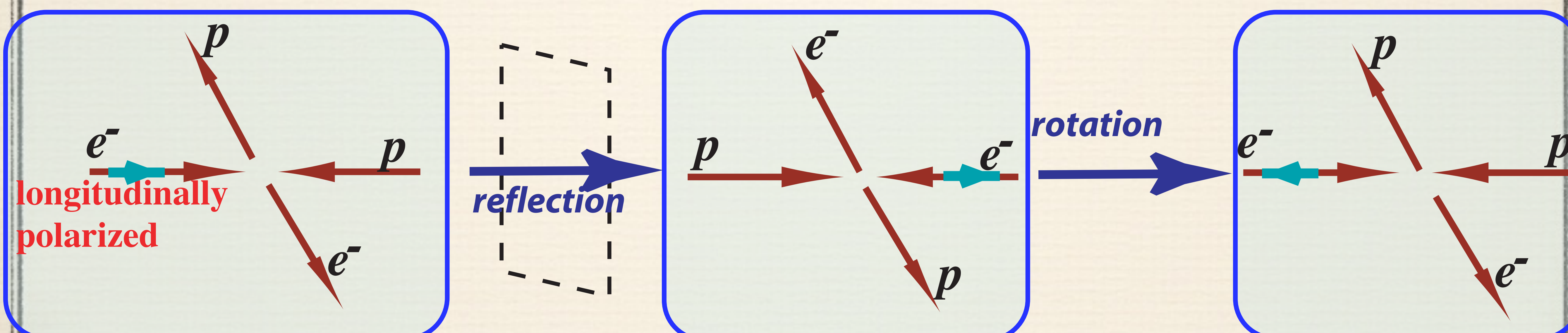

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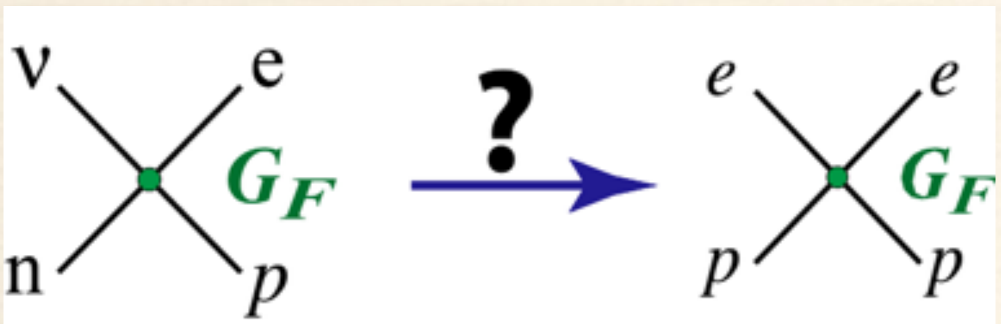


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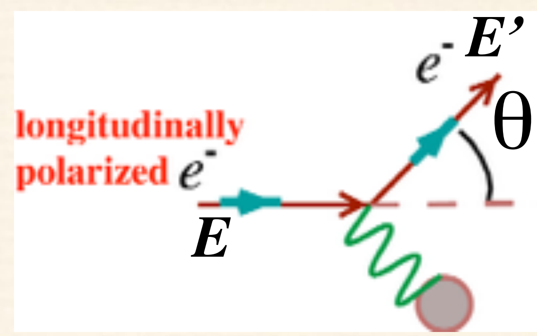


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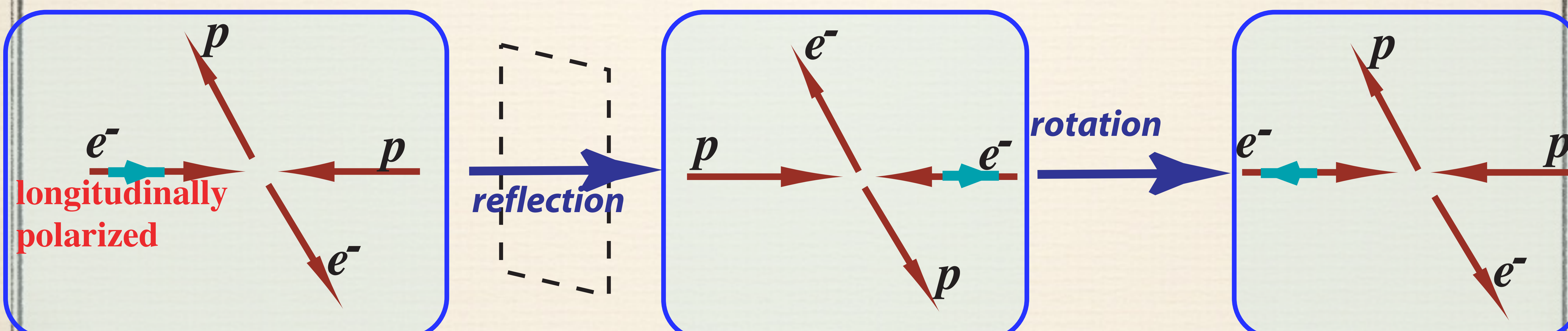


- *longitudinally polarize one beam with the ability to change its sign*
- *Measure fractional rate difference with a sensitivity of a part in 10,000*

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

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

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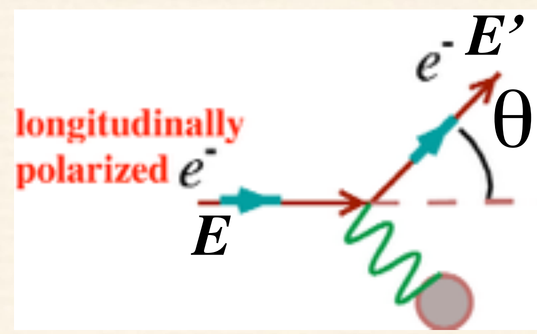


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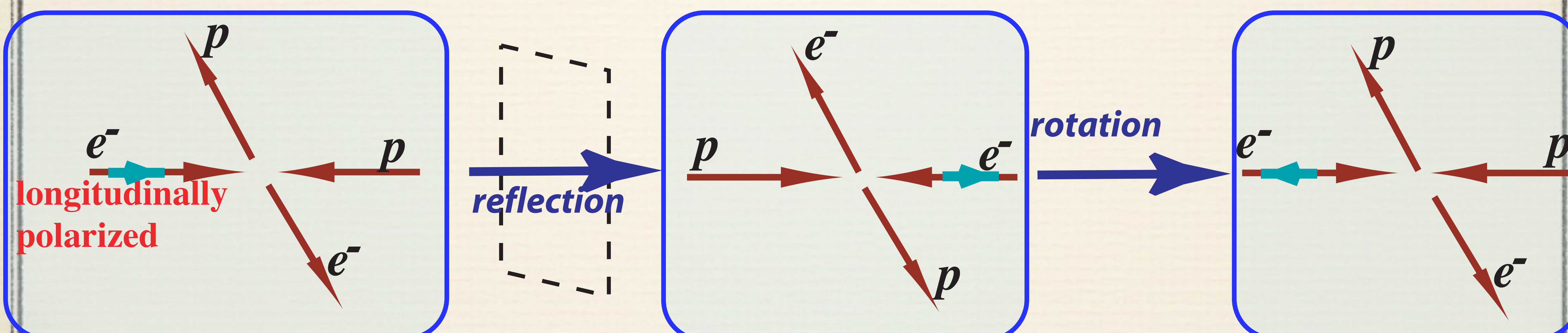


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*Glashow, Weinberg and Salam: $SU(2)_L$ X $U(1)_Y$*

# Weak Interaction Theory

*The Z boson incorporated*

*One free parameter: weak mixing angle $\theta_W$*

| | Left- | Right- |
|---|---|---|
| $\gamma$ 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 | $T-q\sin^2\theta_W$ | $-q\sin^2\theta_W$ |

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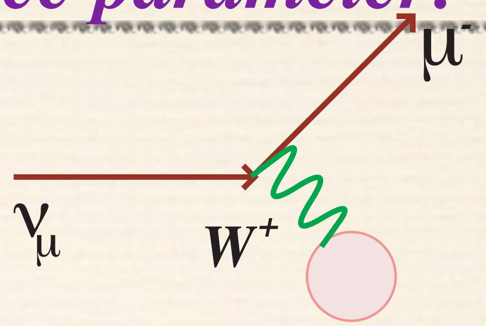


*Charged Current*

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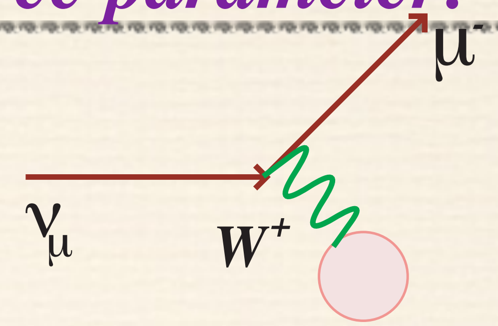


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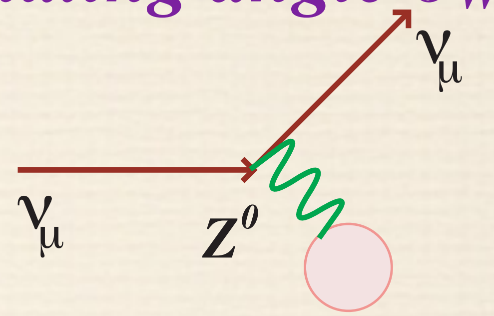


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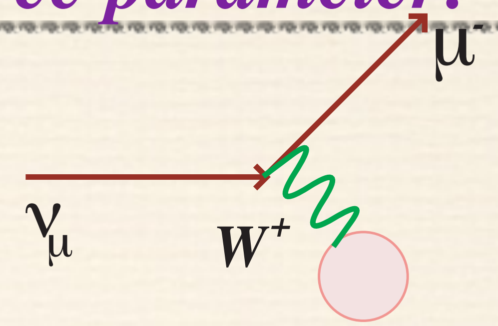


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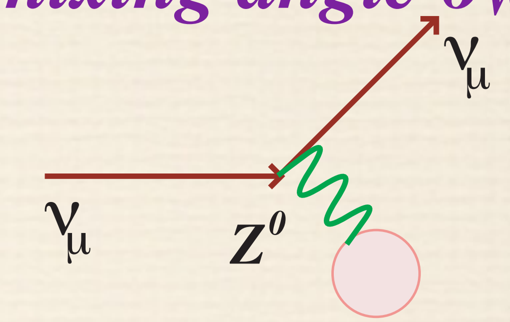


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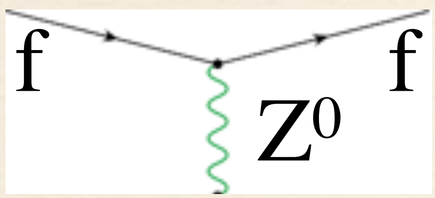


$$\frac{g}{\cos \theta_W} Z_\mu \bar{f} \gamma^\mu (T_{3f} - 2Q_f \sin^2 \theta_W - T_{3f}\gamma_5) f, \quad T_{3f} = \pm 1/2$$

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

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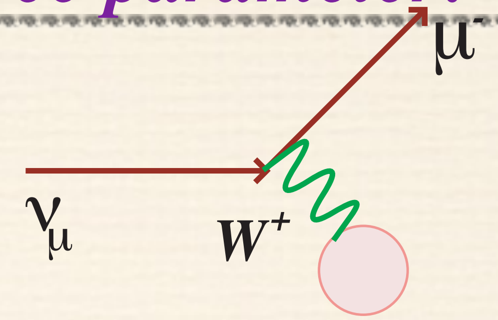


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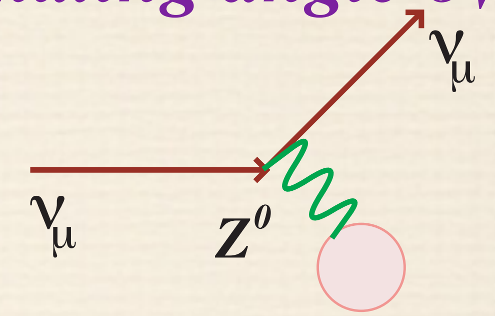


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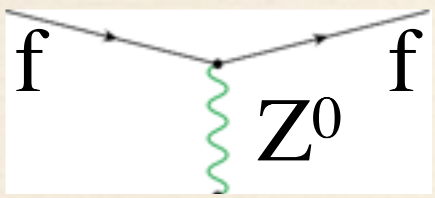


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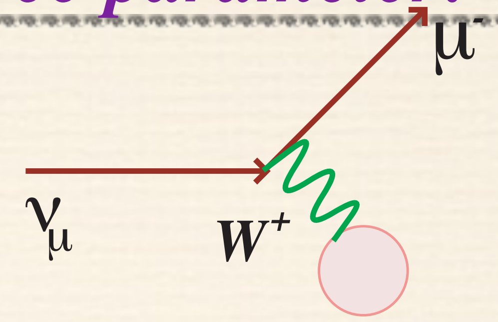
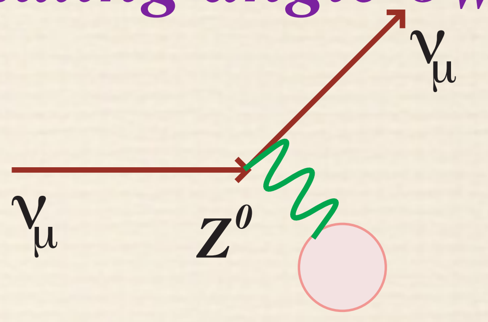
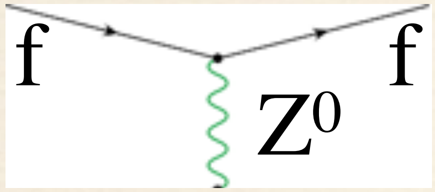



*Charged Current*




*Neutral Current*




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

**Do lepton-nucleon neutral current interactions exhibit parity violation?**

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

*Weinberg model*

Parity is violated

or

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

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Parity is conserved

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

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*The Z boson incorporated*

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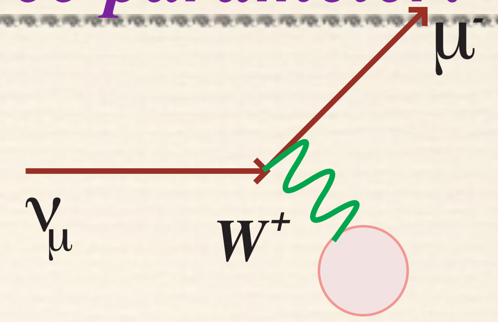


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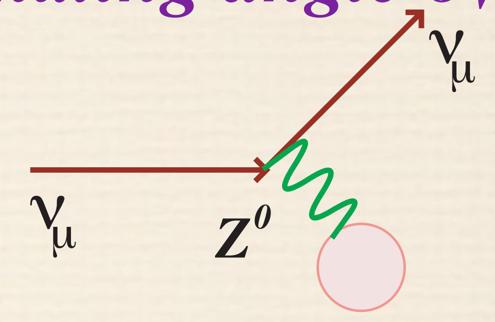


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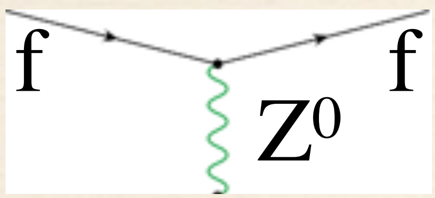


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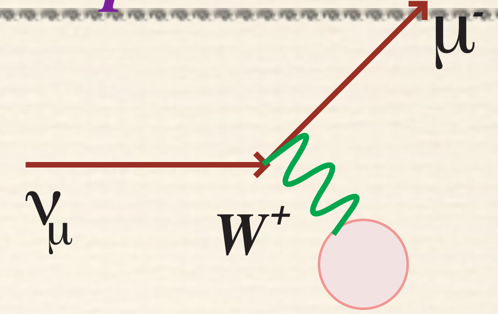


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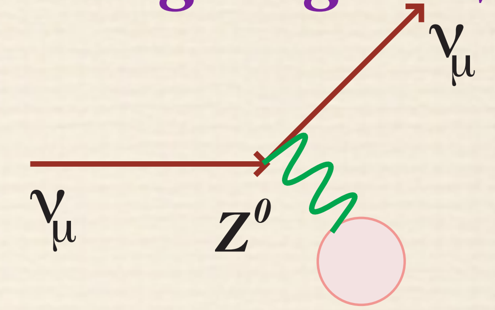


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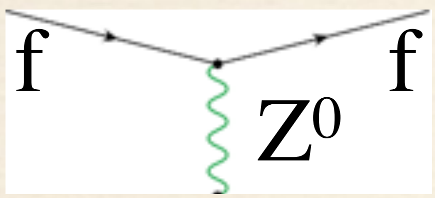


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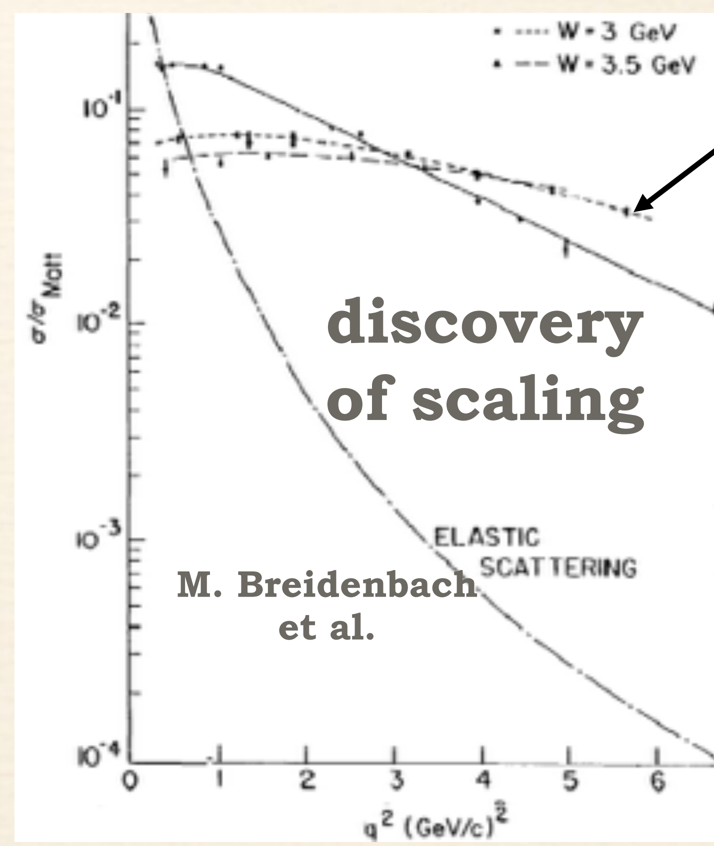


**discovery of scaling**

M. Breidenbach et al.

*large rate at large $Q^2$*

**electron-nucleon deep inelastic scattering**

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

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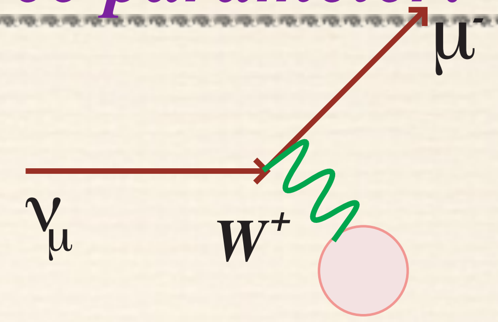


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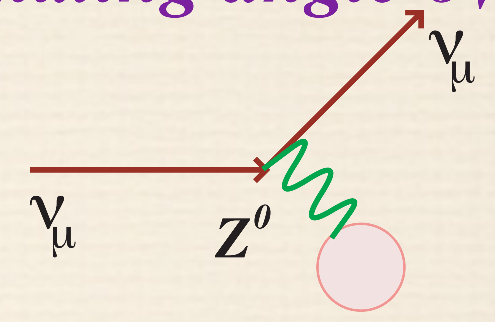


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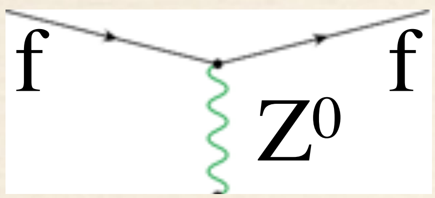


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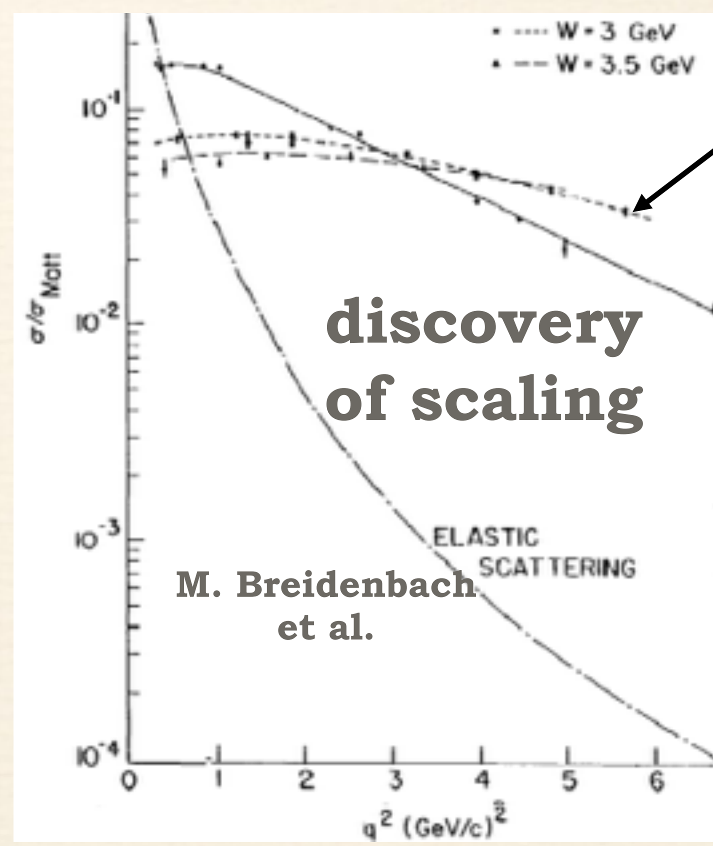


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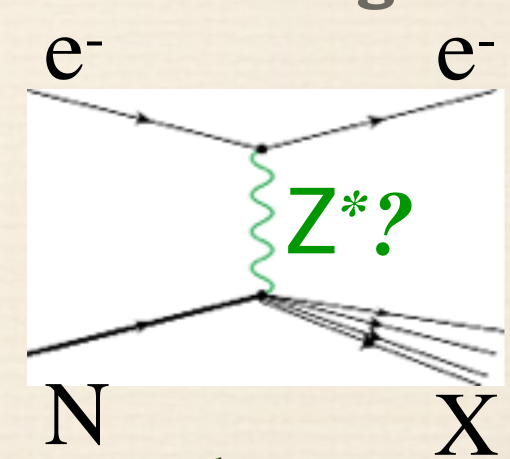
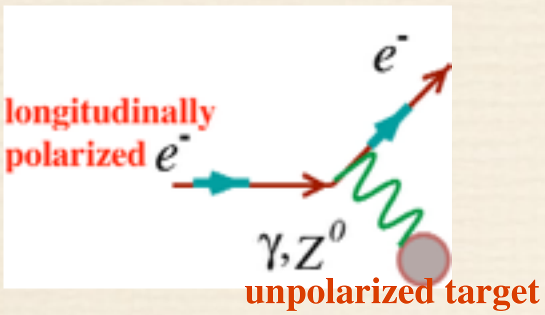



*pressing problem in mid-70's*

E122 at SLAC (1978): PV Deep Inelastic Scattering

# Anatomy of a Parity Experiment




$$\sigma \propto | A_\gamma + A_{weak} |^2$$

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

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

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

***Need few x $10^{11}$ events***

⇨ ***Count at ~ 100 kHz***

⇨ $\delta(A_{PV})$ ***~ few ppm***

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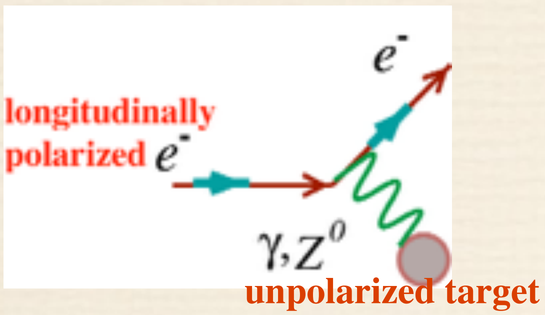


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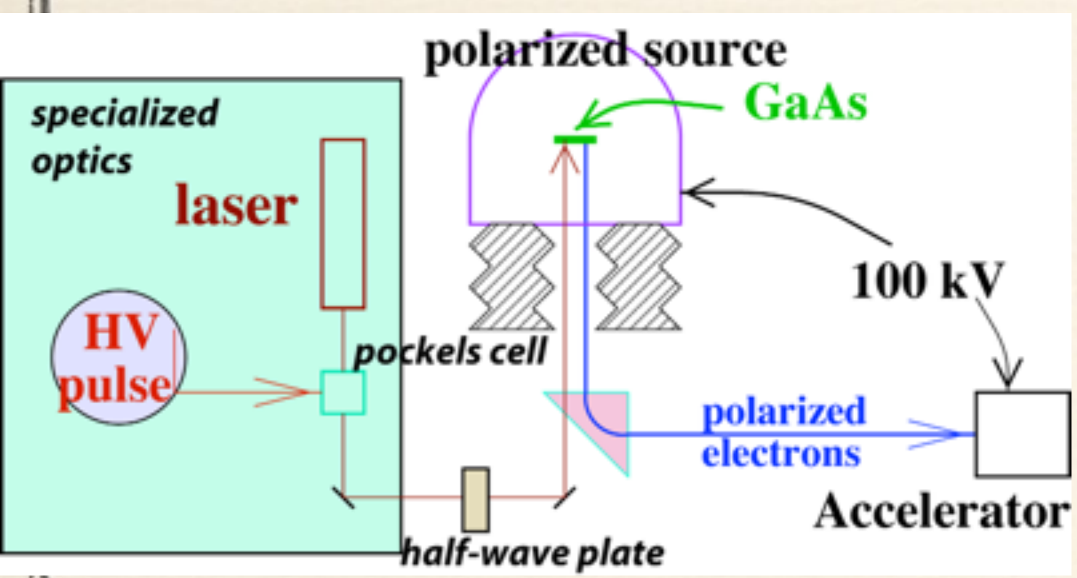


**·Optical pumping of a GaAs wafer: "black magic" chemical treatment to boost quantum efficiency**

**·Rapid helicity reversal: polarization sign flips ~ 100 Hz to minimize the impact of drifts**

**·Helicity-correlated beam motion: under sign flip, beam stability at the micron level**

E122 at SLAC (1978): PV Deep Inelastic Scattering

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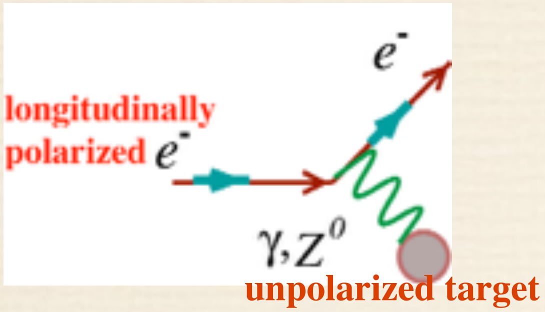


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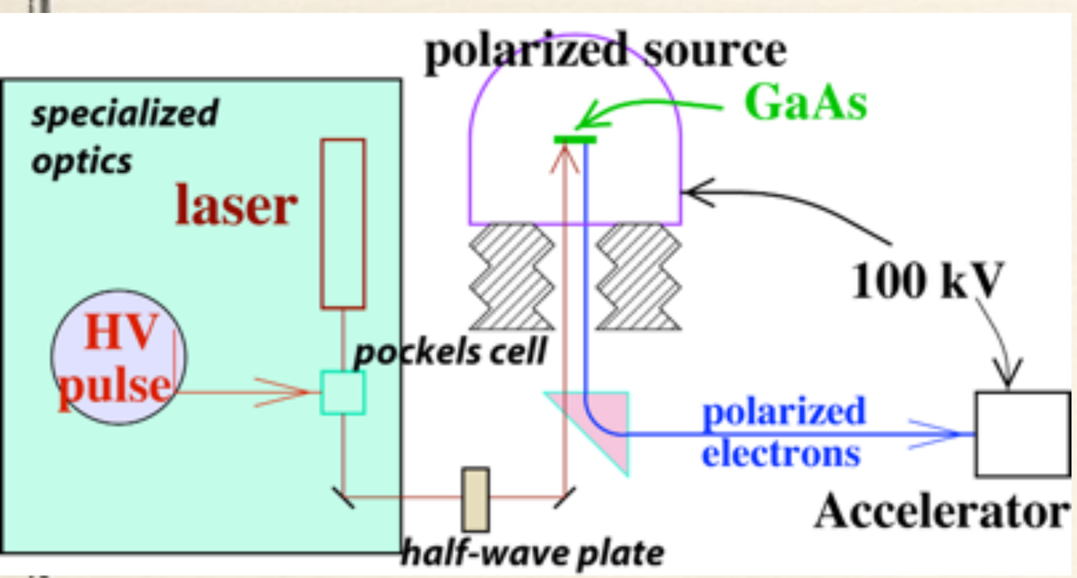


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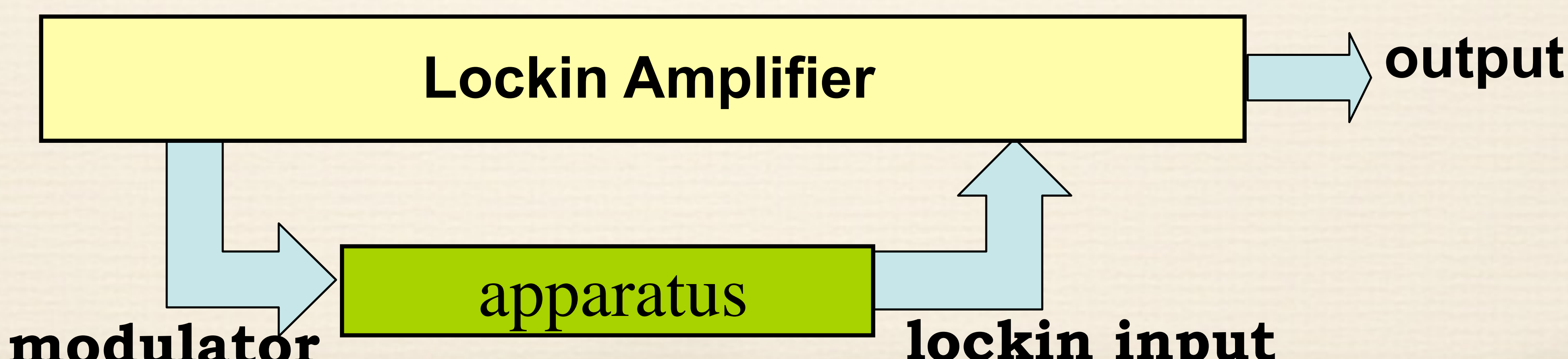
## Tiny signal buried in known background



E122 at SLAC (1978): PV Deep Inelastic Scattering

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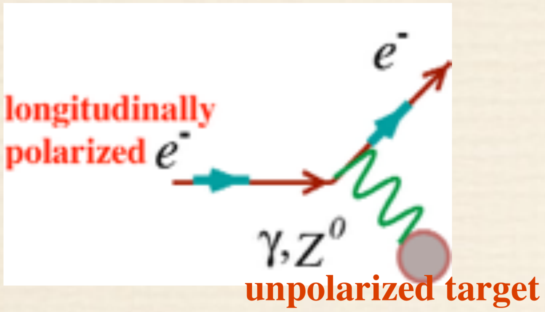


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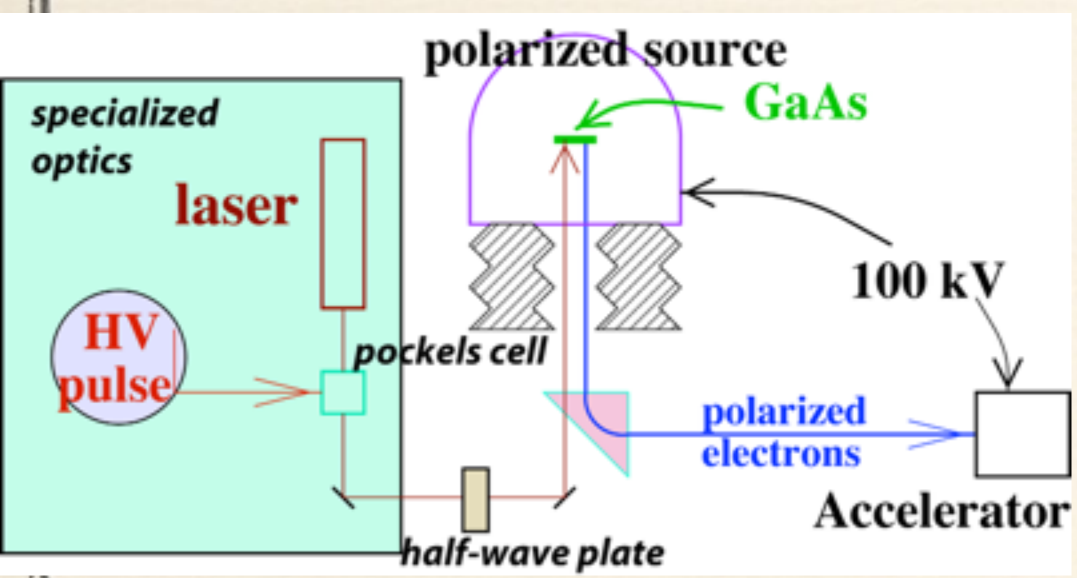


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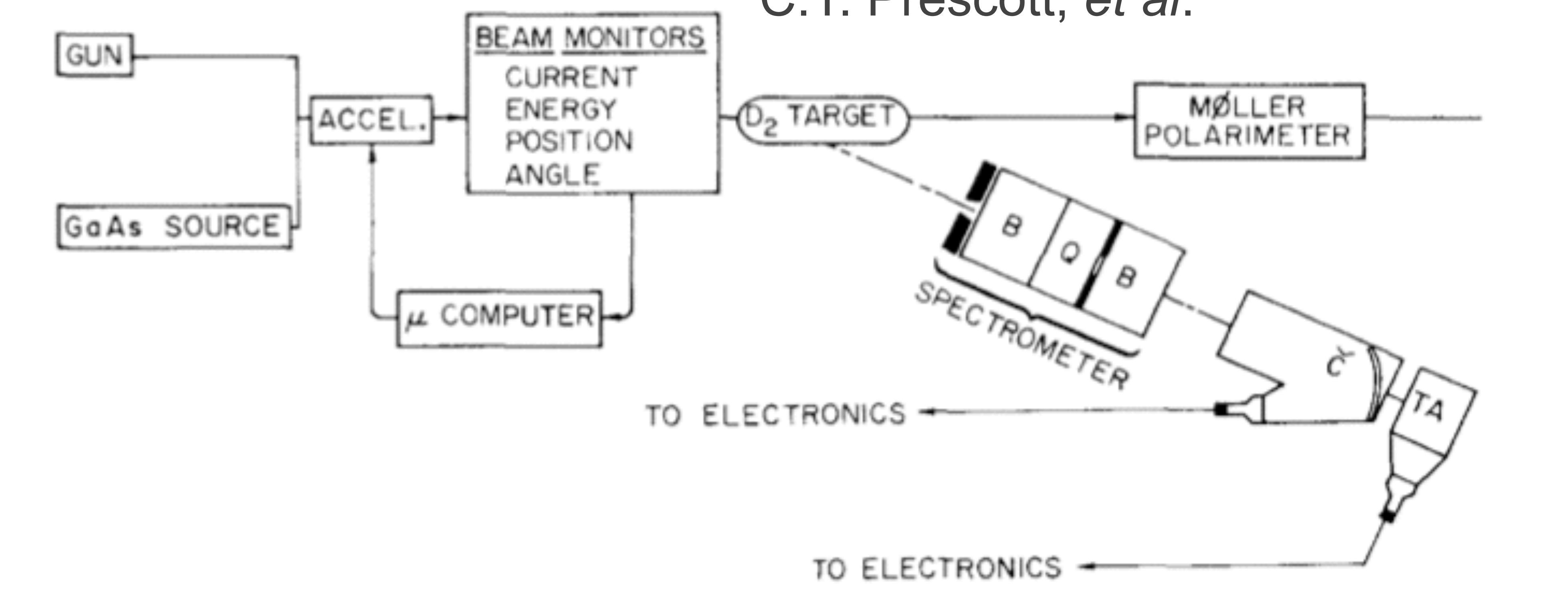
**Tiny signal buried in known background**

**Lockin Amplifier** ⇨ **output**

*injector* ⇨ *accelerator* ⇨ *target* ⇨ *spectrometer* ⇨ *detector*

# Anatomy of a Parity Experiment

C.Y. Prescott, *et al.*



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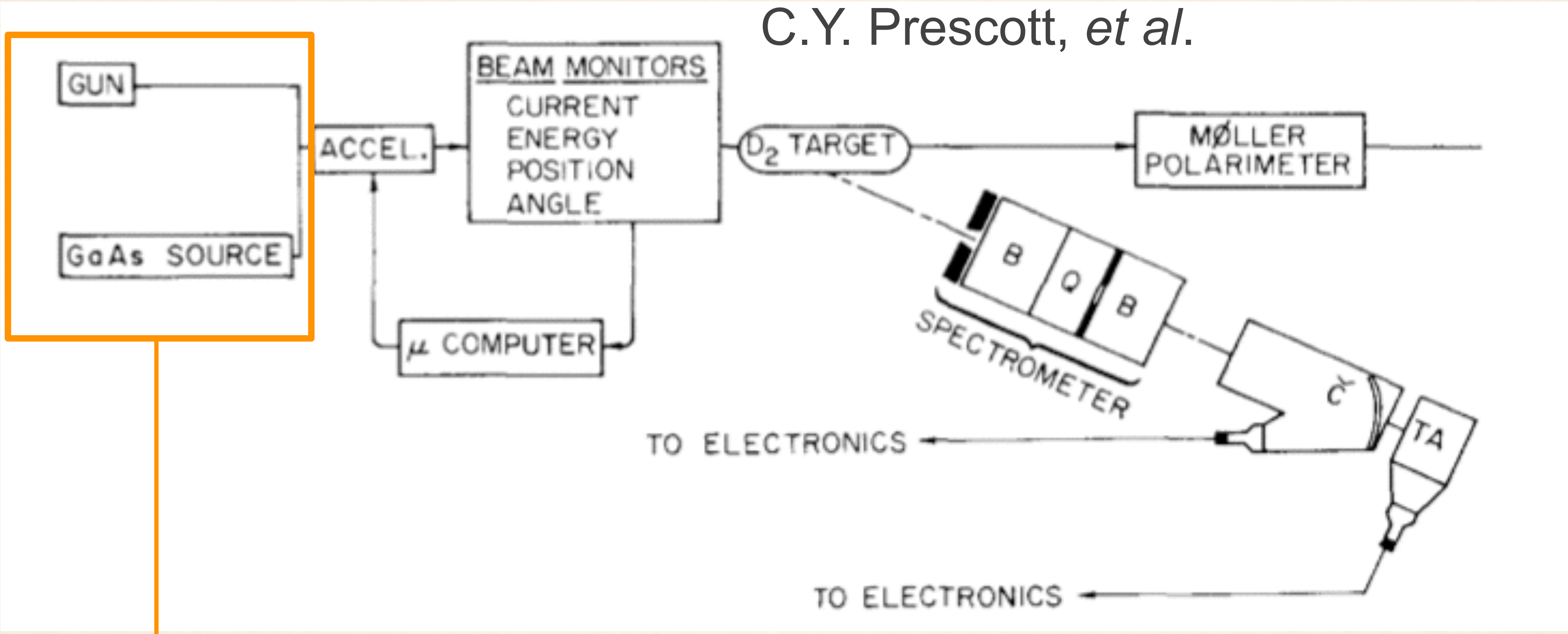
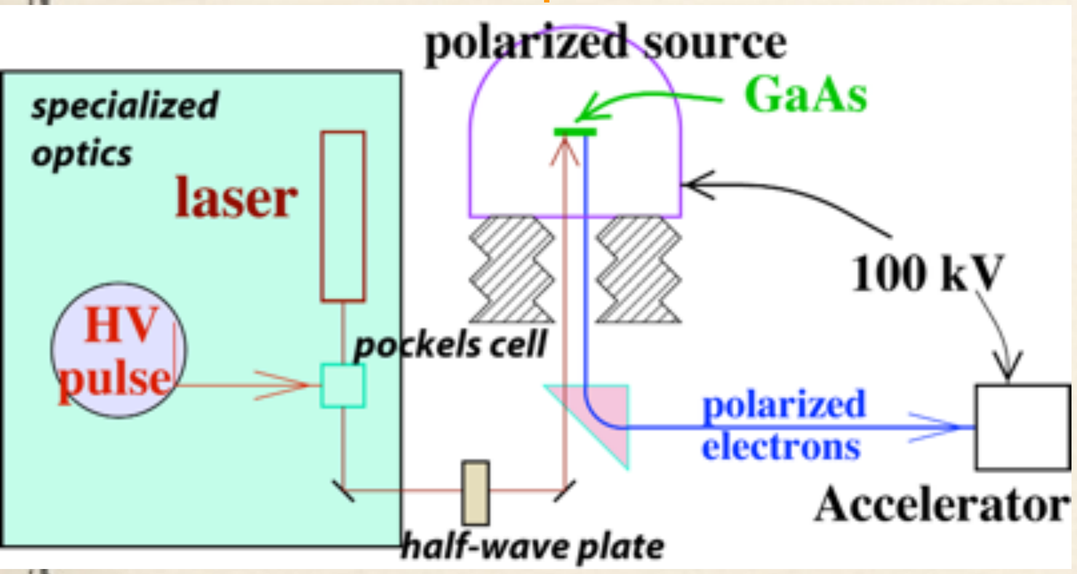
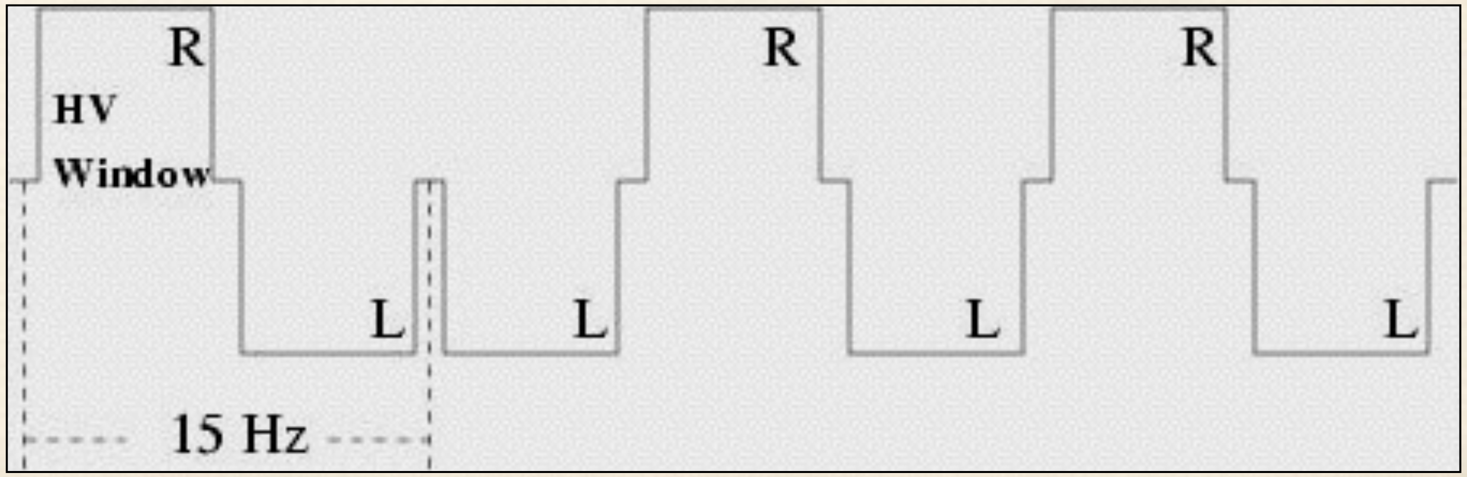



- **Beam helicity sequence is chosen pseudo-randomly**
  - Helicity state, followed by its complement
  - Data analyzed as “pulse-pairs”



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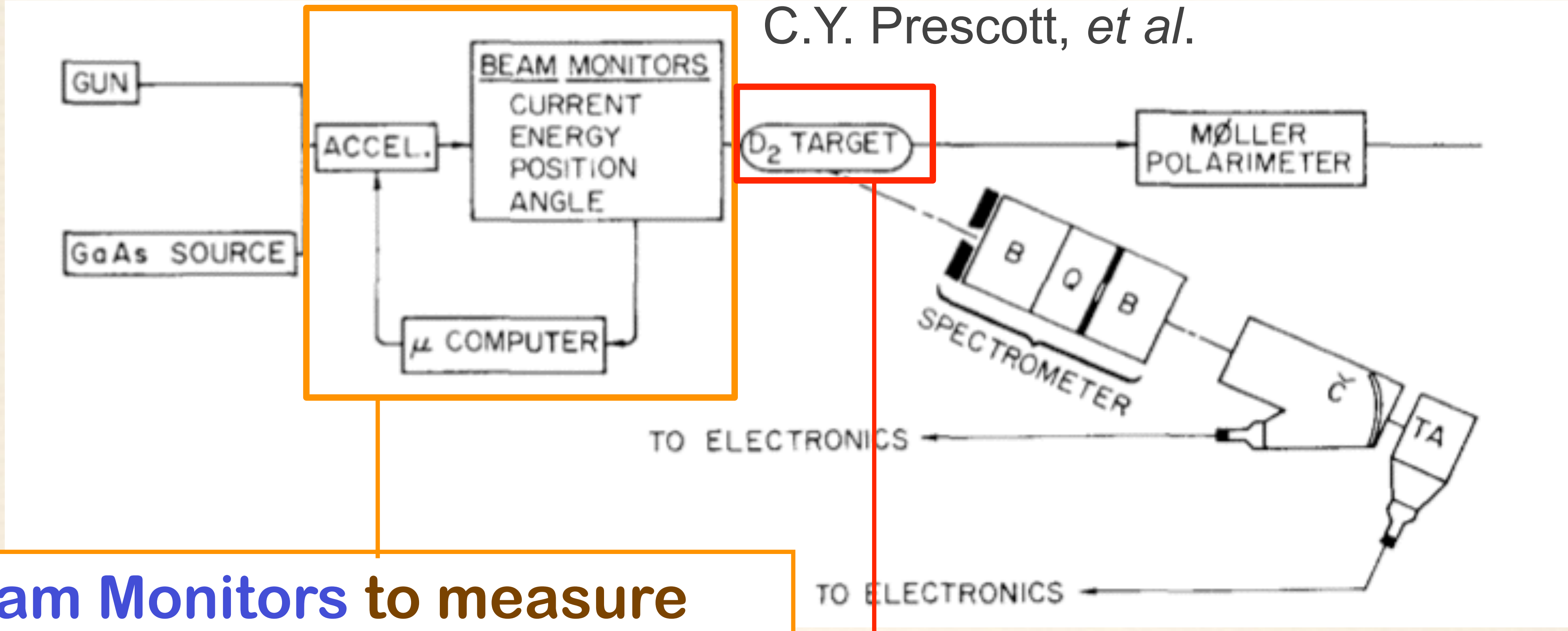


- **Beam Monitors** to measure helicity-correlated changes in beam parameters

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

# Anatomy of a Parity Experiment

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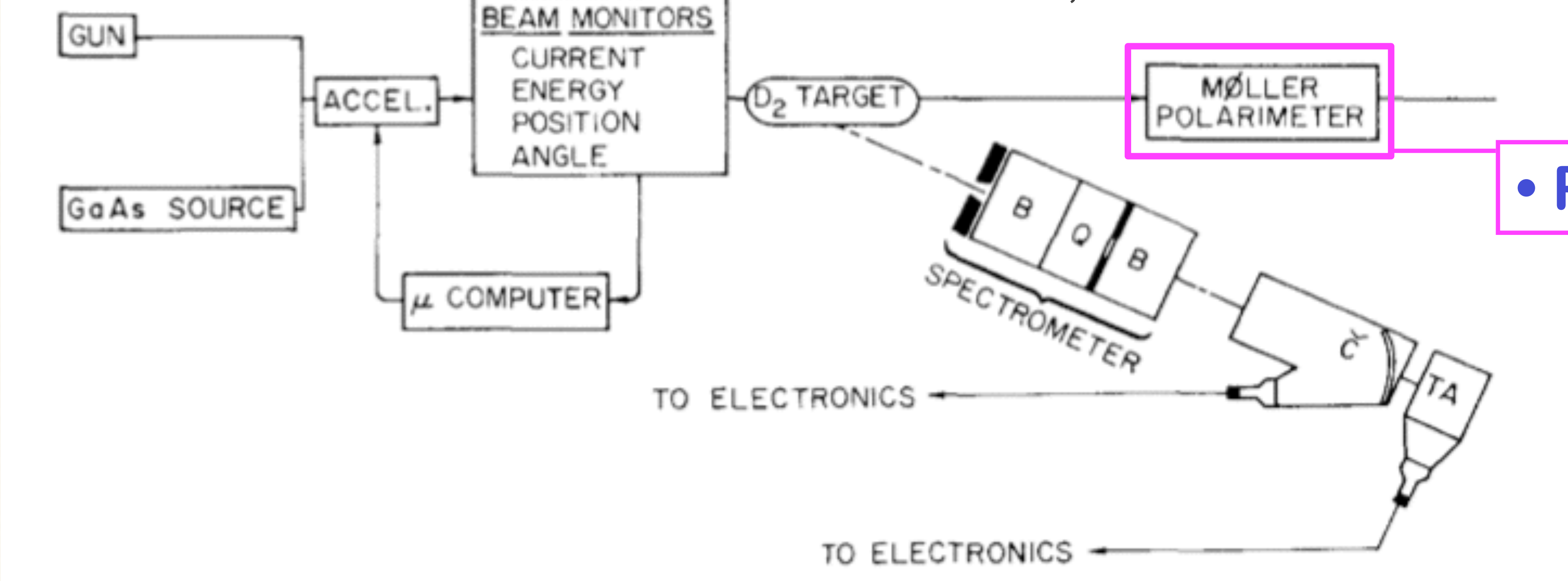


- **Polarimetry**

# Anatomy of a Parity Experiment

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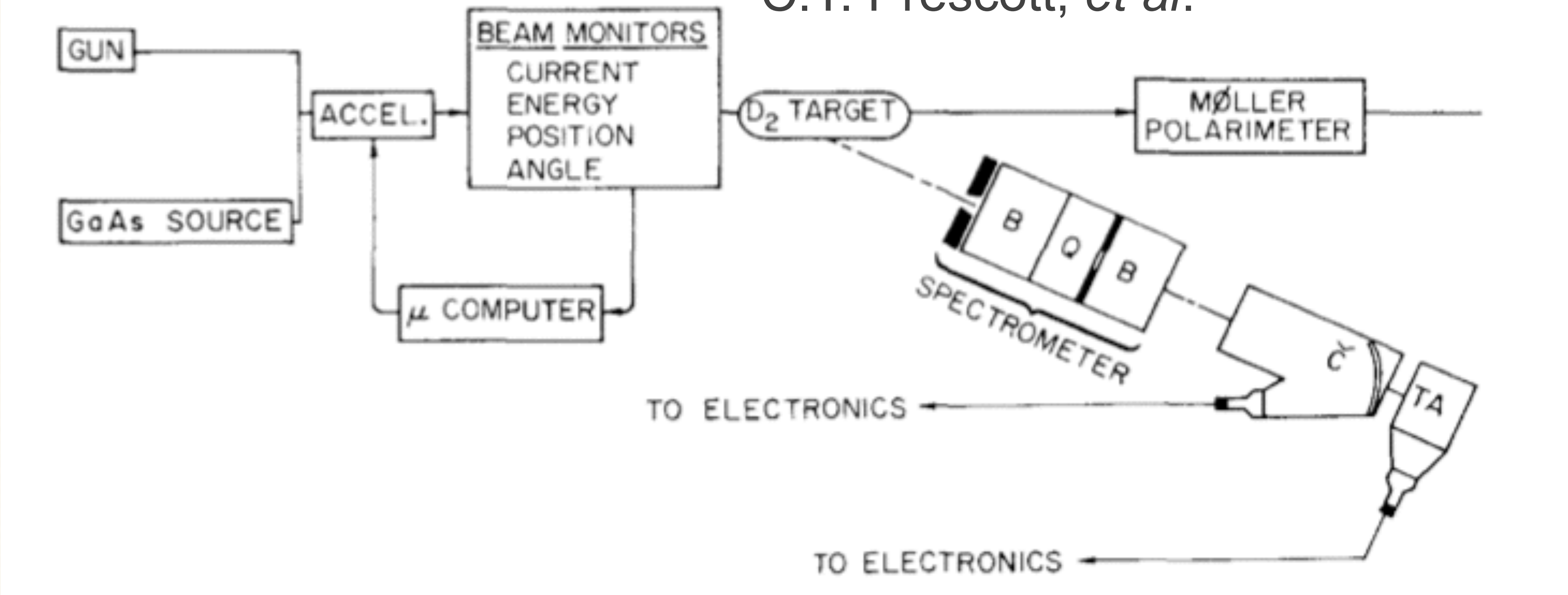
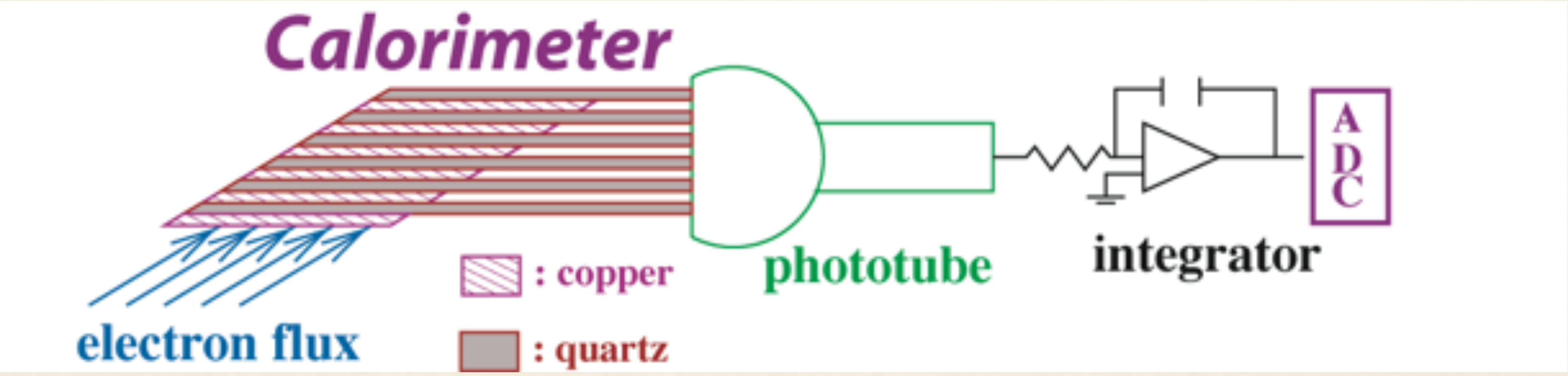



- **Magnetic spectrometer** directs flux to background-free region

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



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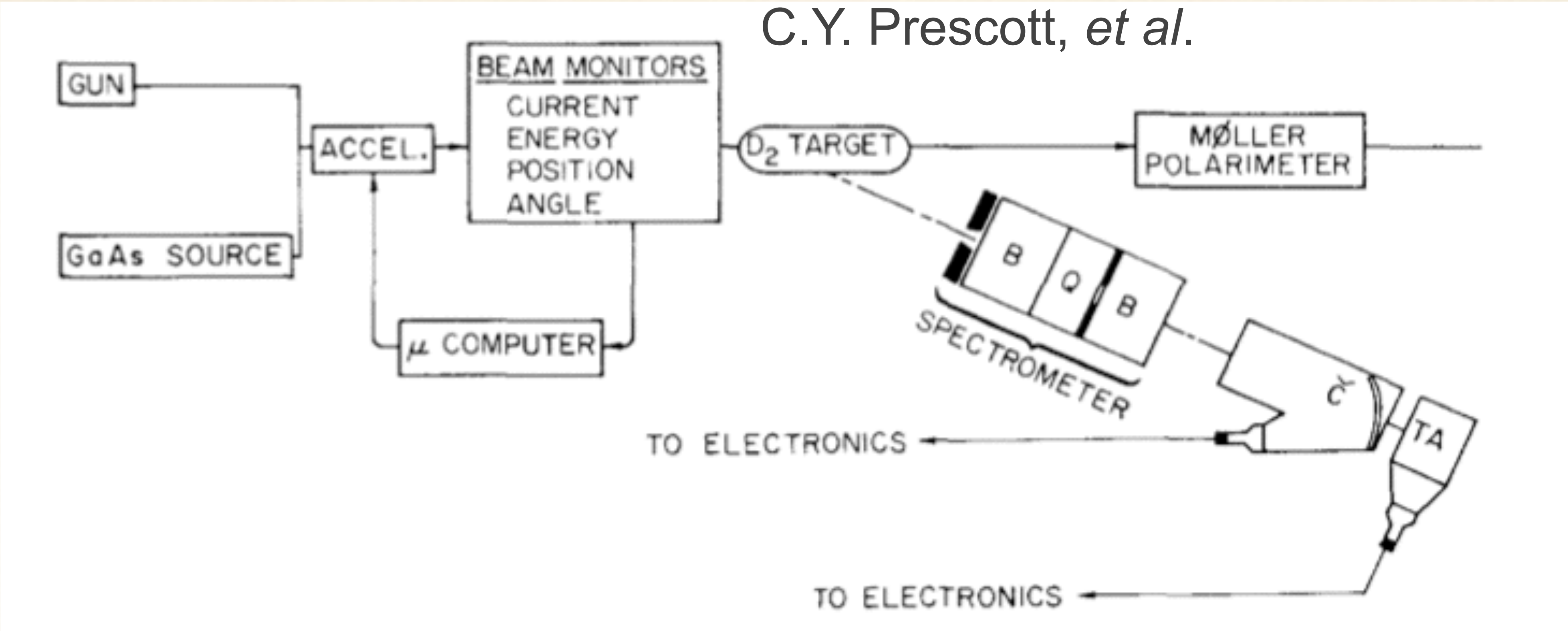
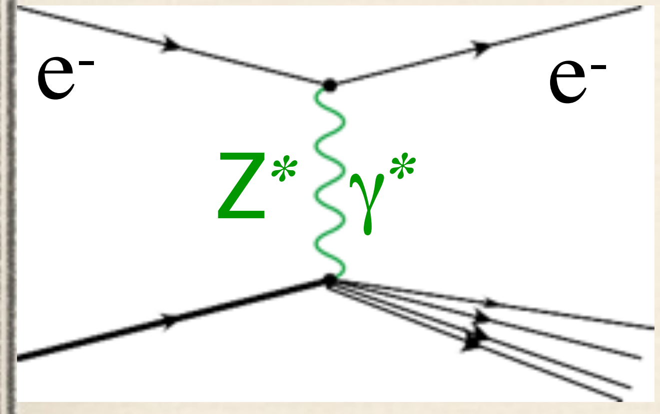



- ***Parity Violation in Weak Neutral Current Interactions***
- ***$\sin^2\theta_W$ = 0.224 ± 0.020: same as in neutrino scattering***

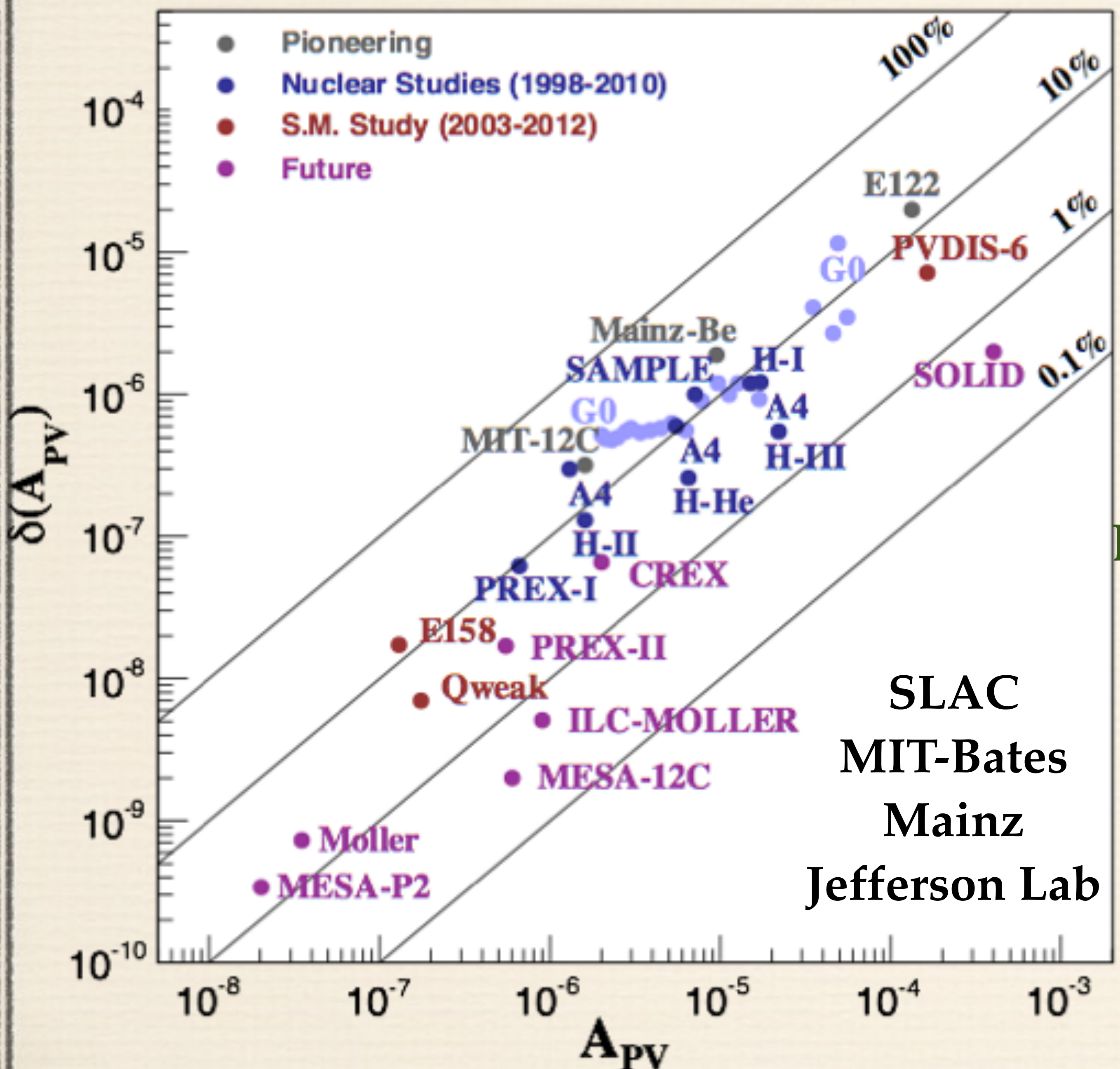
$$A_{PV} \sim 10^{-4}$$
$$\delta(A_{PV}) \sim 10^{-5}$$

***Glashow, Weinberg, Salam Nobel Prize awarded in 1979***

*Continuous interplay between probing hadron structure and electroweak physics*

# 4 Decades of Progress

**Parity-violating electron scattering has become a precision tool**




SLAC
MIT-Bates
Mainz
Jefferson Lab

- *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:***

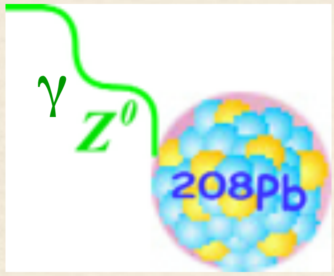
- ***sub-part per billion statistical reach and systematic control***
- ***sub-1% normalization control***

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

# *The Neutron Skin of a Heavy Nucleus*

Pb-Radius EXperiment

# EW Probe of Neutron Densities




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

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

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

Pb-Radius EXperiment

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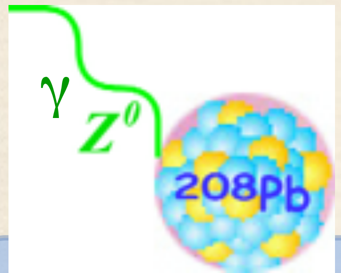


$$A_{PV} \approx \frac{G_F Q^2}{4\pi\alpha\sqrt{2}} \frac{F_n(Q^2)}{F_p(Q^2)}$$

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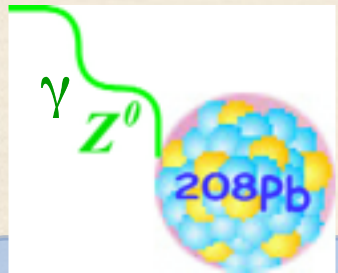


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$$A_{PV} \approx \frac{G_F Q^2}{4\pi\alpha\sqrt{2}} \frac{F_n(Q^2)}{F_p(Q^2)}$$

**$A_{PV}$ ~ 0.6 ppm**

**$Q^2$ ~ 0.01 GeV$^2$**
5° scattering angle ⇒

**Rate ~ 1 GHz**

**δ($A_{PV}$) ~ 20 ppb!**

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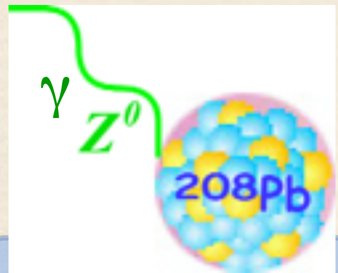


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**$Q^2 \sim 0.01$ GeV$^2$**
$5^o$ scattering angle ⇨ Rate ~ 1 GHz

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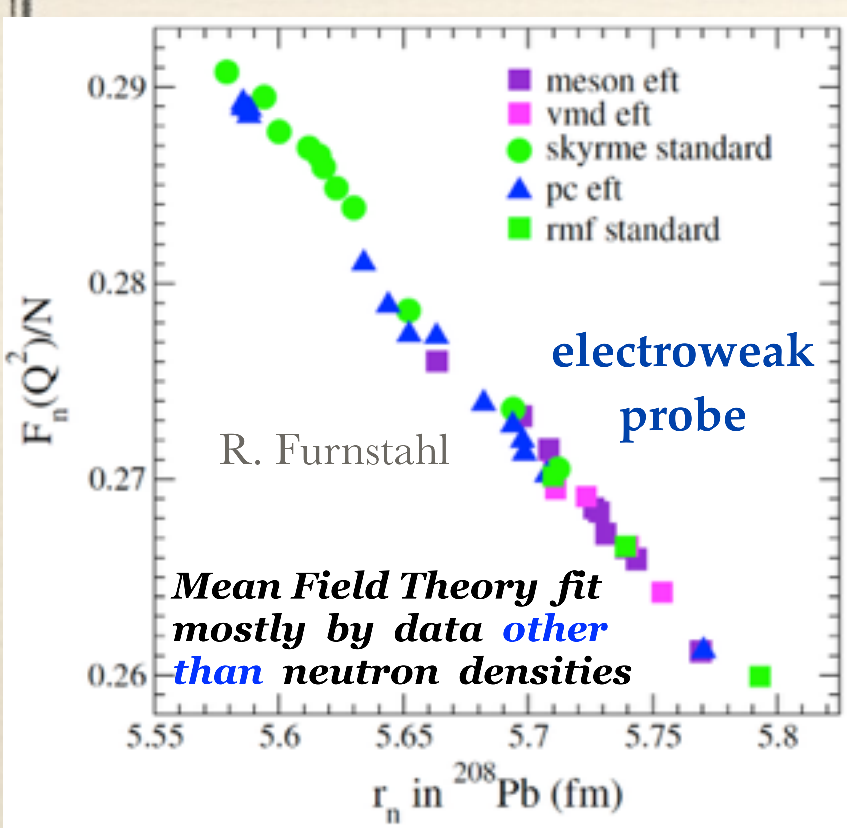
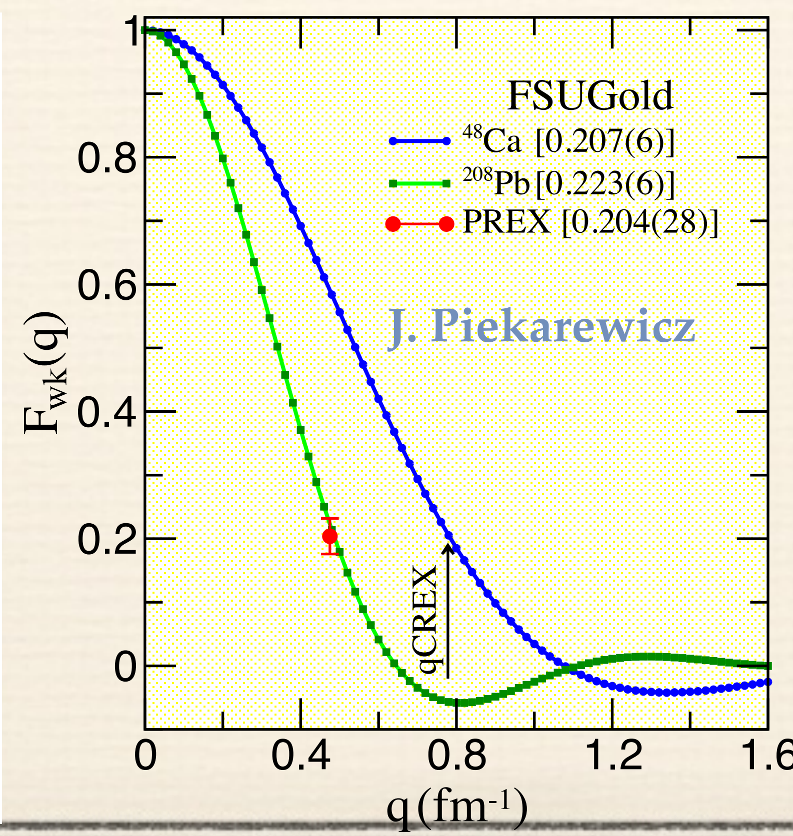
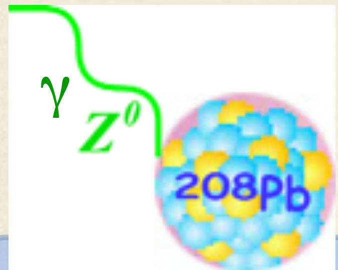


## Pb-Radius EXperiment

# EW Probe of Neutron Densities




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

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

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

$Q^2 \sim 0.01\ GeV^2$

$5^o$ scattering angle

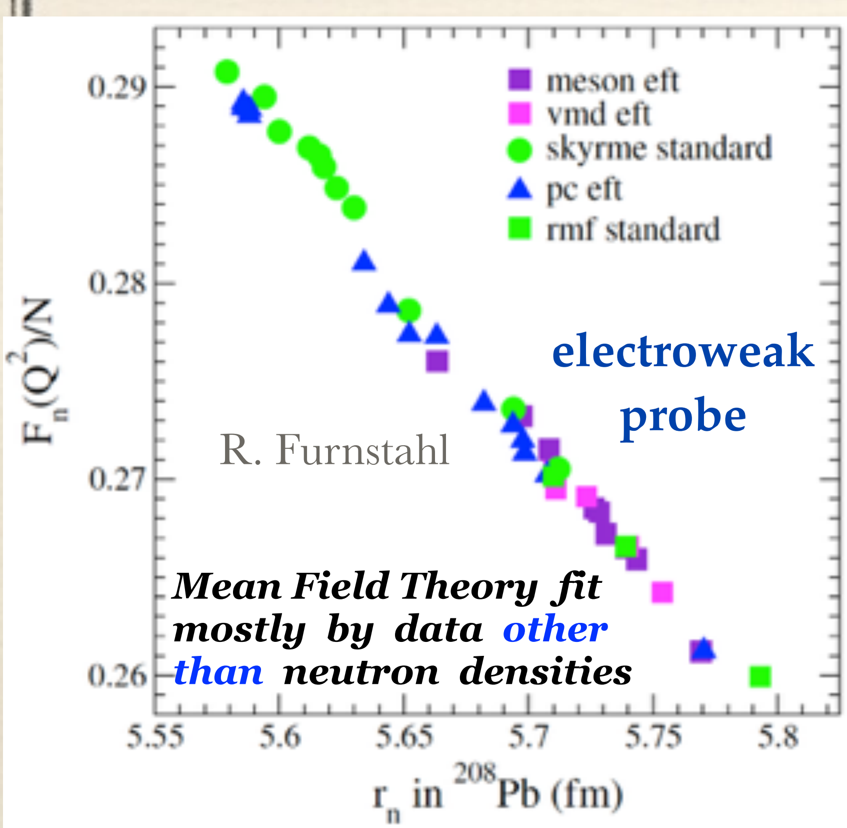
⇨

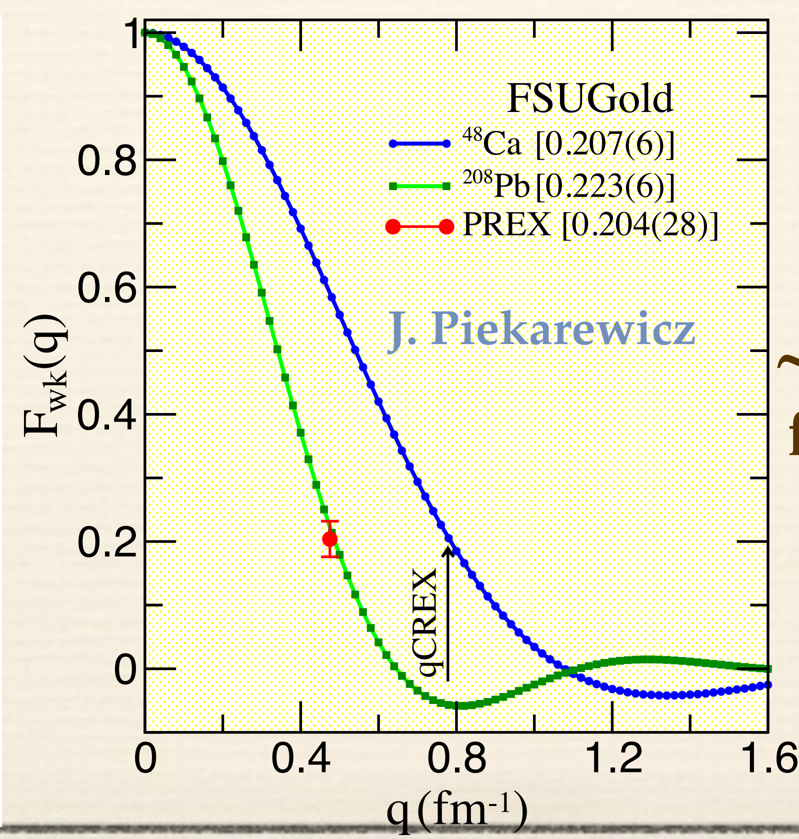
$A_{PV} \sim 0.6$ ppm

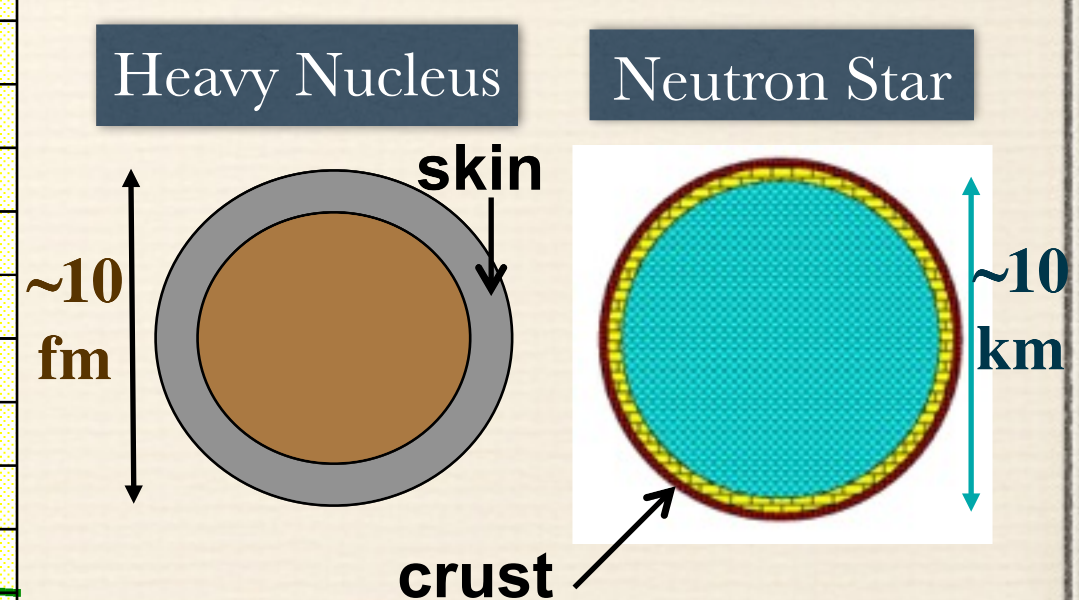
Rate ~ 1 GHz

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

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



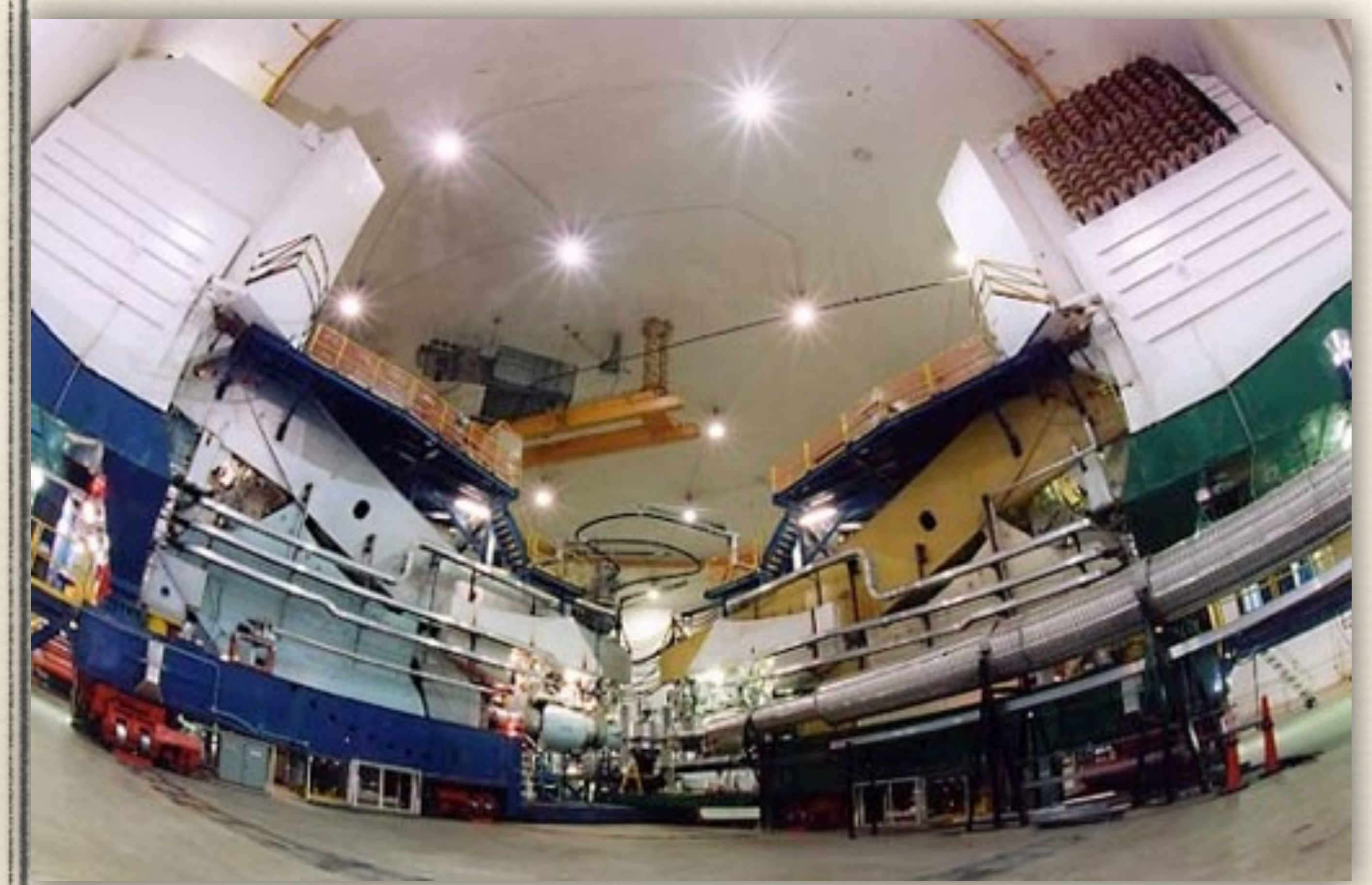

Horowitz and Piekarewicz, PRL 86 (2001)

# PREX at JLab

**1 GeV electron beam, 50-70 μA**

**high polarization, ~89%**

**helicity reversal at 120 Hz**



**0.5 mm isotopically pure $^{208}Pb$ target**

**$5^\circ$ scattered electrons**

**$Q^2 = 0.0088\ GeV^2/c^2$**

**new thin quartz detectors**

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

PRL 108 (2012) 112502

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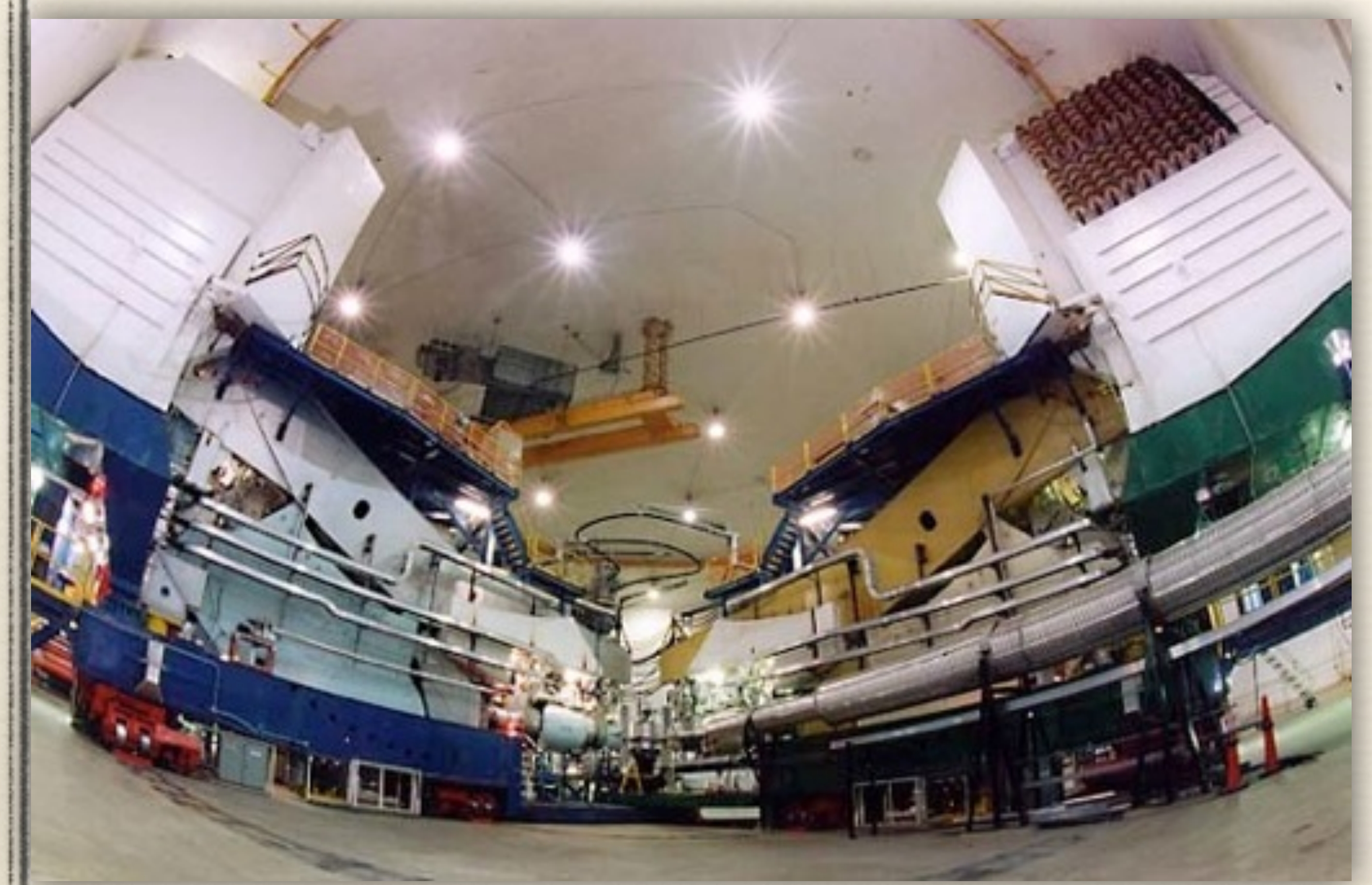

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# PREX at JLab

**1 GeV electron beam, 50-70 μA**

**high polarization, ~89%**

**helicity reversal at 120 Hz**

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

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

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

**0.5 mm isotopically pure $^{208}$Pb target**

**5° scattered electrons**

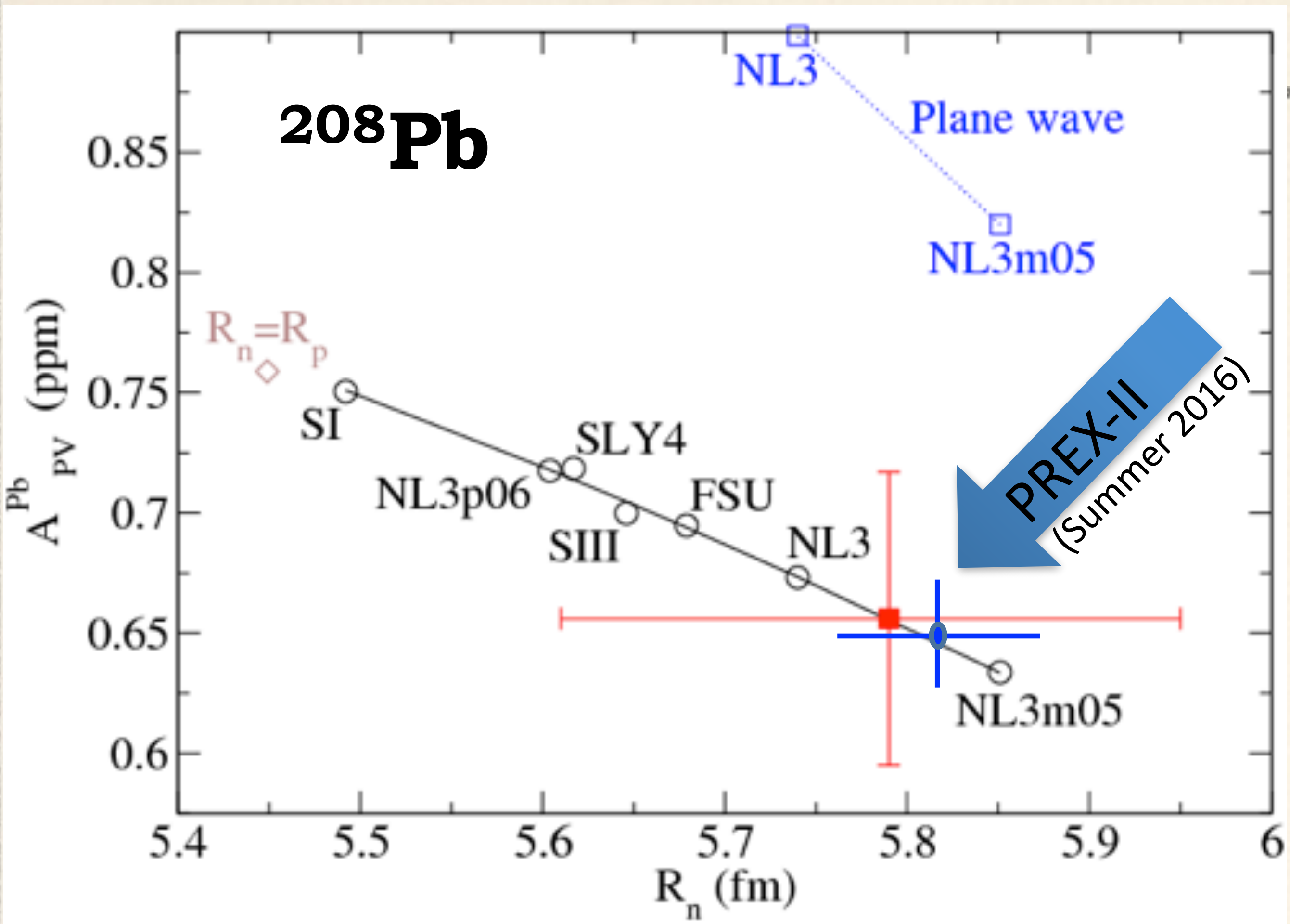
**$Q^2$ =0.0088 GeV$^2$/c$^2$**

**new thin quartz detectors**

**Establishes the existence of a neutron skin in a heavy nucleus at 95% C.L. with an electroweak probe**

*Presented to JLab PAC in 2011 and 2013: Approved with strong endorsement*

# PREX-II and CREX




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

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

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

Full precision in 25 additional PAC days

**PREX-II likely to run in late 2016**

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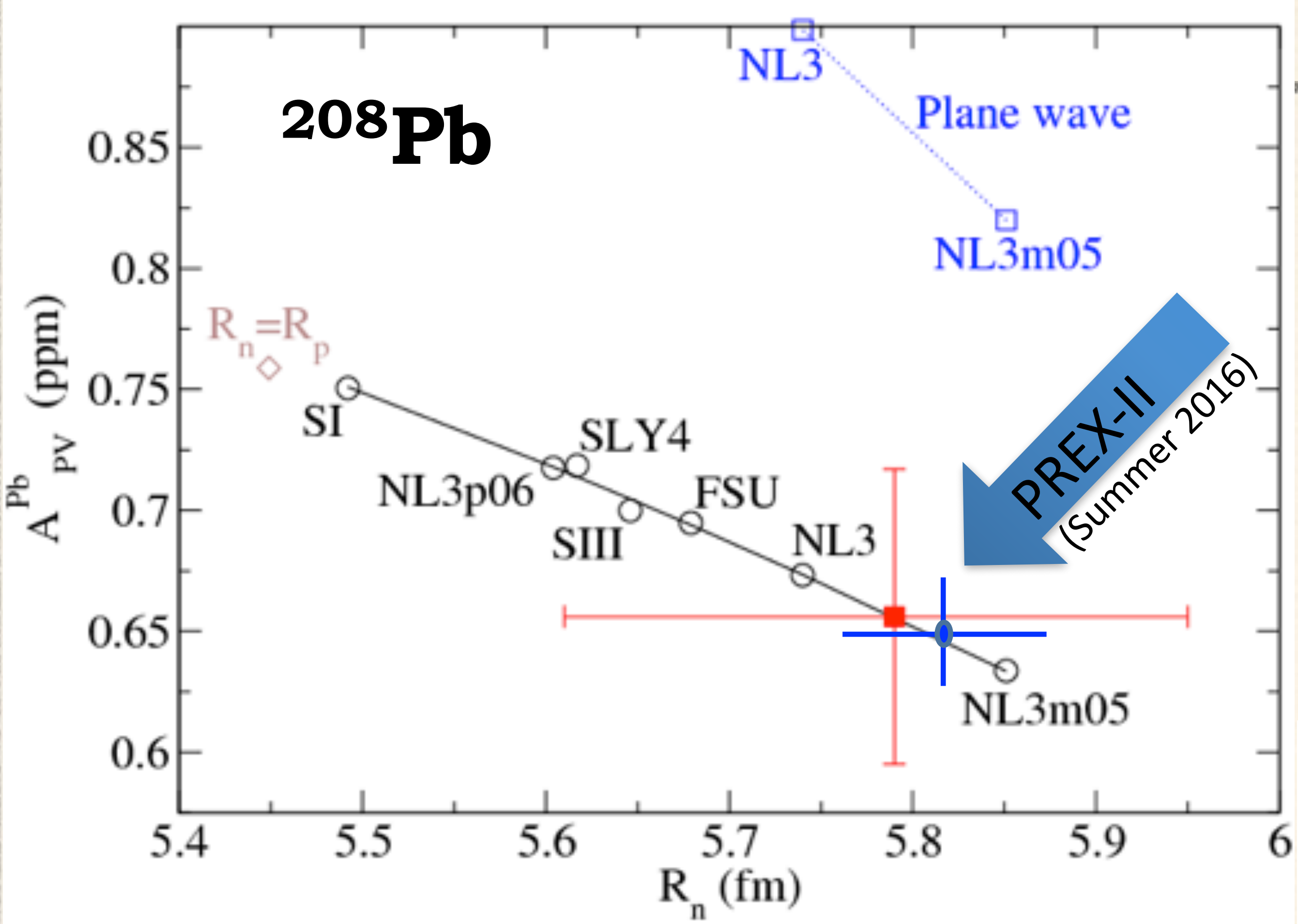


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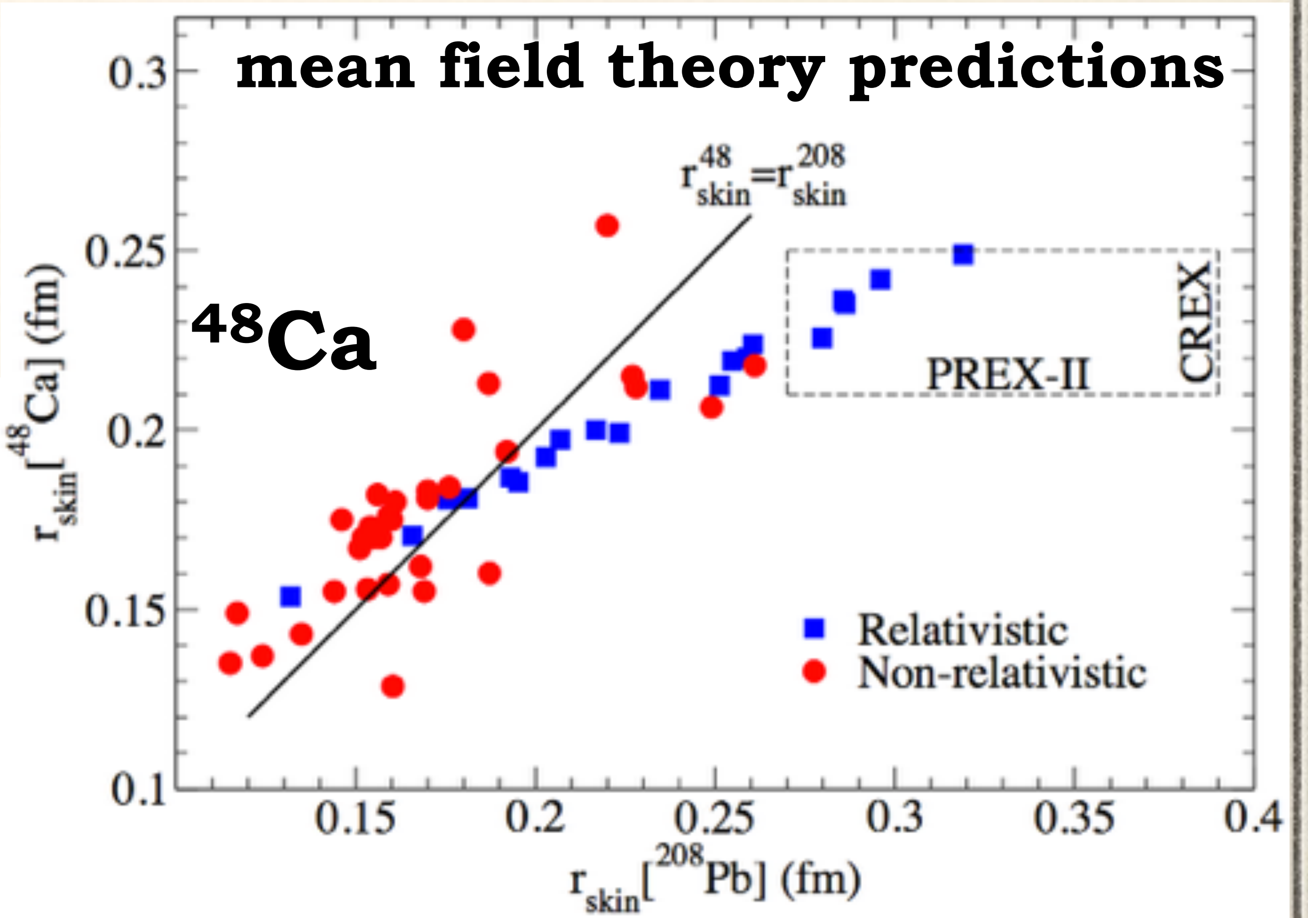
$\delta(R_n) \sim \pm\, 0.06$ fm

Full precision in 25 additional PAC days

**PREX-II likely to run in late 2016**

**CREX** → $\delta(R_n) \sim \pm\, 0.02$ fm

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



# *Precision Electroweak Physics*

# Indirect Clues

## NP: Fundamental Symmetries & HEP: The Intensity/Precision Frontier

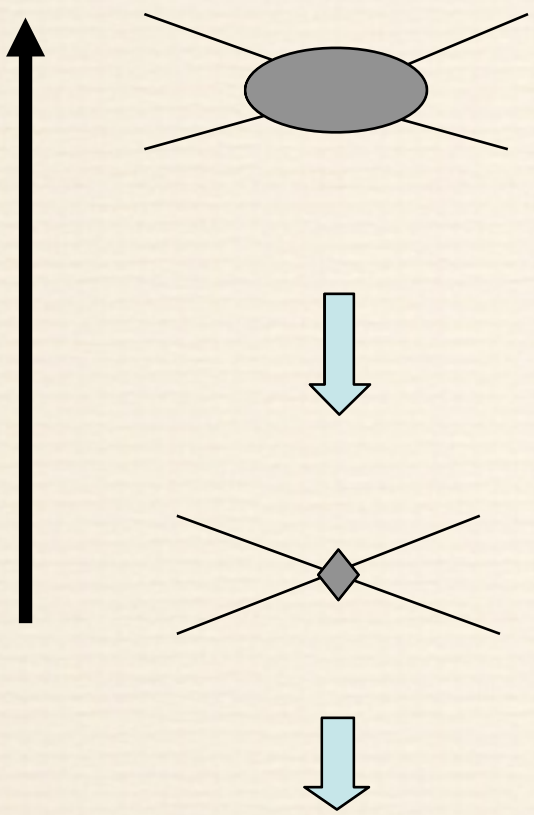
## High Energy Dynamics

E

Λ (~TeV)

$M_{W,Z}$
(100 GeV)

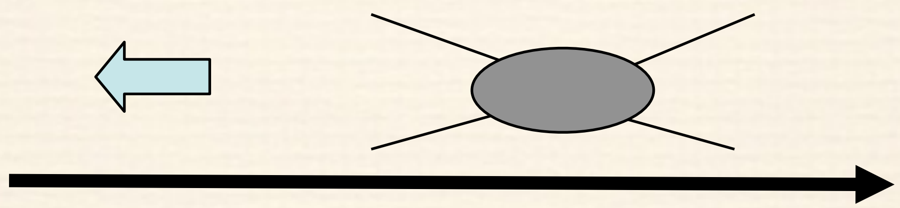
courtesy
V. Cirigliano,
H. Maruyama,
M. Pospelov



***SM amplitudes can be very precisely predicted***

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

higher dimensional
operators can be
systematically classified



## Dark Sector

(coupling)$^{-1}$

**Heavy Z's, light (dark) Z's, technicolor, compositeness, extra dimensions, SUSY…**

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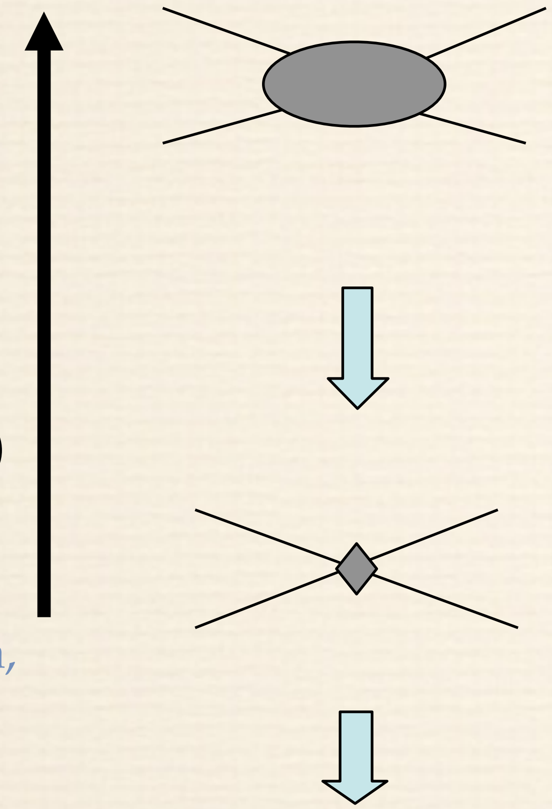

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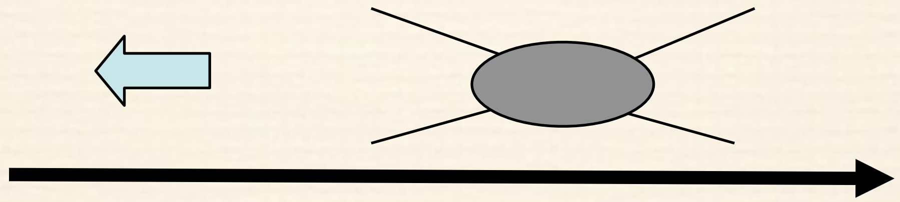

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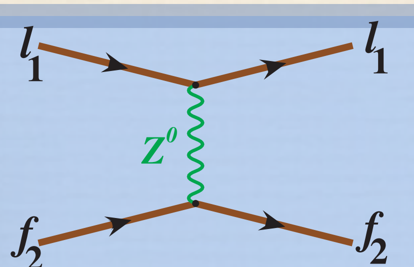
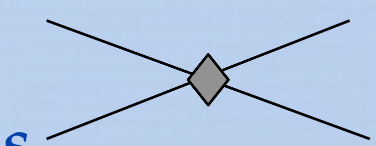



**Search for new flavor diagonal neutral currents**

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



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

**must reach Λ ~ 10 TeV**

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

# Indirect Clues

## NP: Fundamental Symmetries & HEP: The Intensity/Precision Frontier

## Interplay between electroweak and hadron dynamics

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$\Lambda$ (~TeV)

$M_{W,Z}$

(100 GeV)

courtesy
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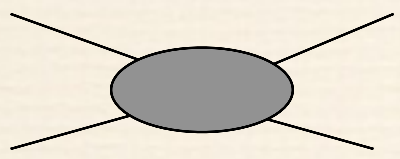

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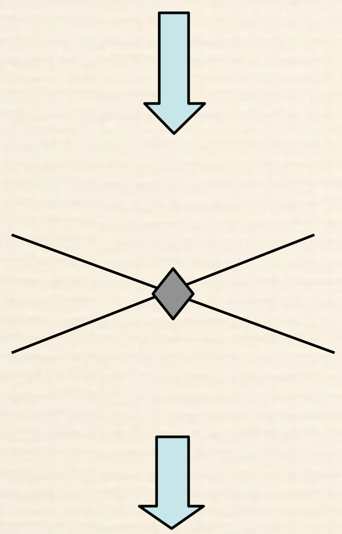

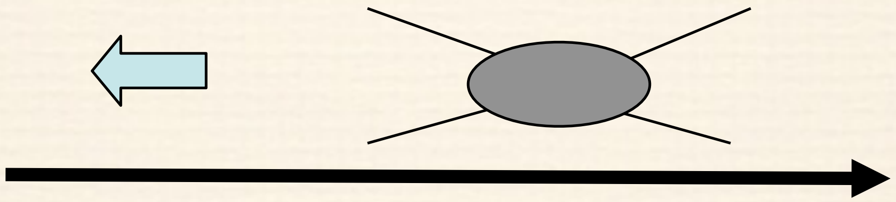

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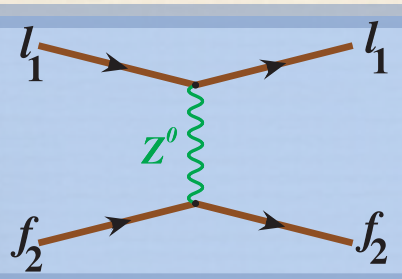


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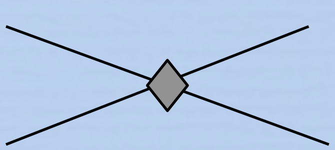

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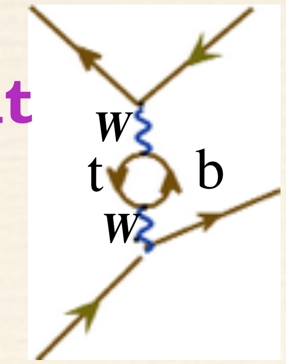
**must reach $\Lambda$ ~ 10 TeV**

# Weak Mixing Angle at 1-Loop

**For electroweak interactions, 3 input parameters needed:**

1. **Rb-87 mass + Ry constant**
2. **The muon lifetime**
3. **The Z line shape**

$\alpha_{QED} \quad G_F \quad M_Z$

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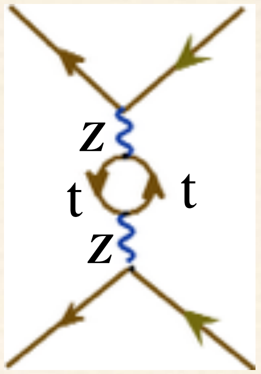
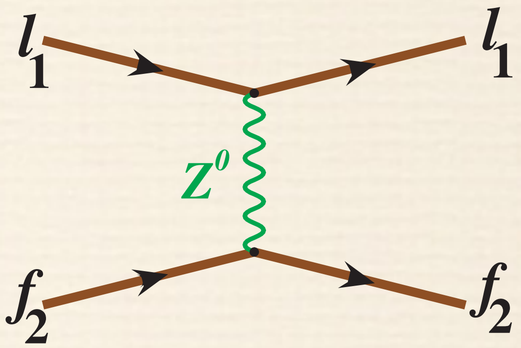



*Z production*

**4th and 5th best measured parameters: $M_W$ and $\sin^2\theta_W$**

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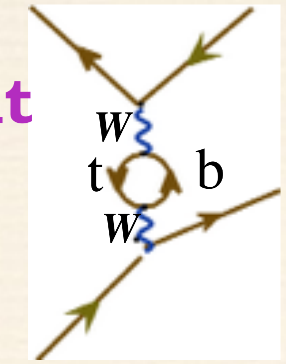


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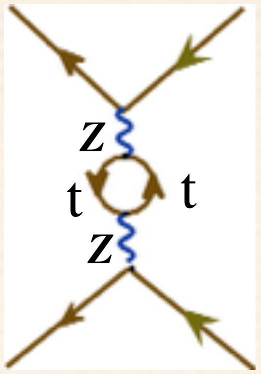


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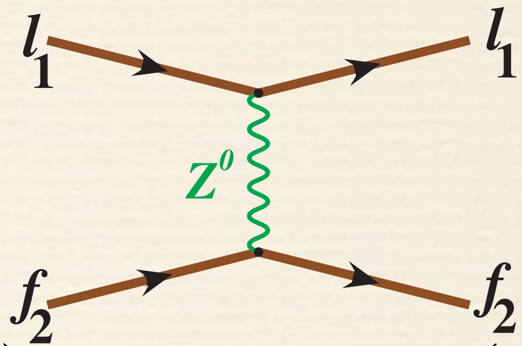


Weak Neutral Current interactions

*LEP-I, SLC, LEP-II, Tevatron*

**World Averages**

$$\sin^2\theta_W(m_Z)_{\overline{\mathrm{MS}}} = 0.23125(16)$$

$$M_W = 80.385(15)\ \mathrm{GeV}$$

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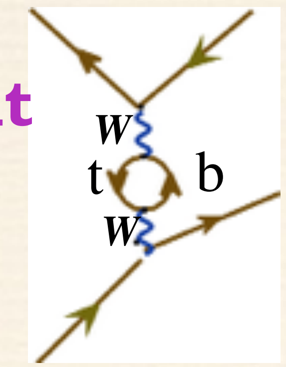


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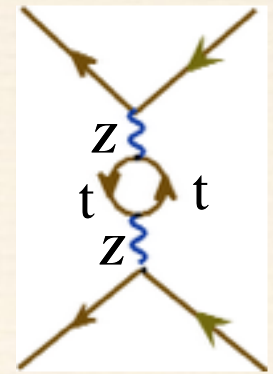


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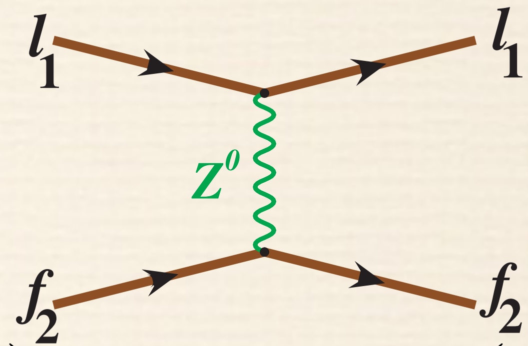


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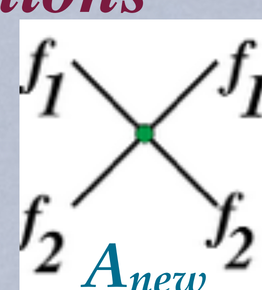
$$L_{f_1 f_2} = \sum_{i,j=L,R} \frac{4\pi}{\Lambda_{ij}^2}\eta_{ij}\bar{f}_{1i}\gamma_\mu f_{1i}\bar{f}_{2j}\gamma^\mu f_{2j}$$




**New heavy physics that does not couple directly to SM gauge bosons**

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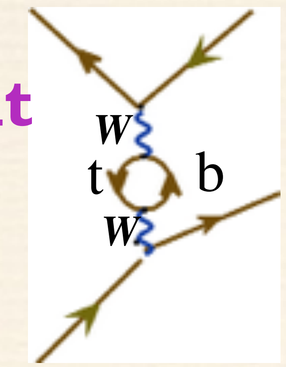


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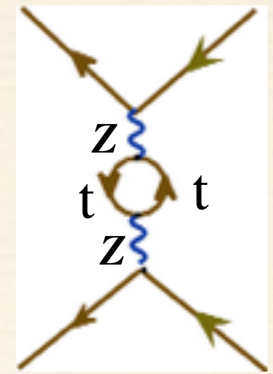


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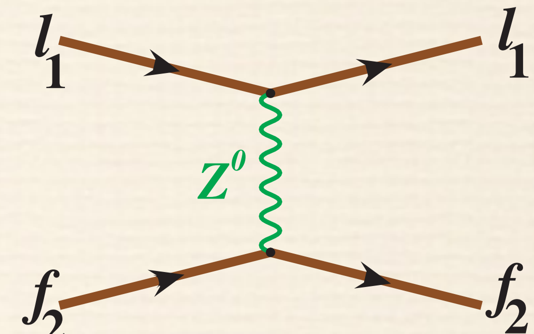


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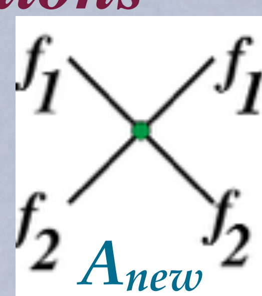



**New heavy physics that does not couple directly to SM gauge bosons**

*on resonance: $A_Z$ is imaginary*

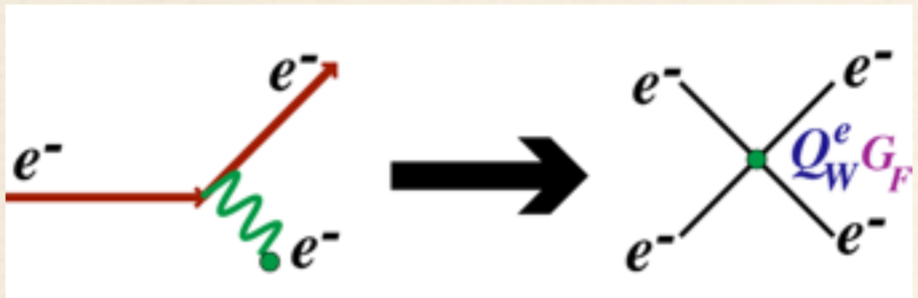
$$\left|\mathbf{A_Z} + \mathbf{A}_{\mathrm{new}}\right|^2 \rightarrow \mathbf{A_Z^2}\left[1 + \left(\frac{\mathbf{A}_{\mathrm{new}}}{\mathbf{A_Z}}\right)^2\right]$$

**no interference!**

New flavor diagonal interactions mediated by a new light boson such as the "dark Z"

$$\mathbf{Q^2 \ll M_Z^2}$$

# PV Electron-Electron Scattering



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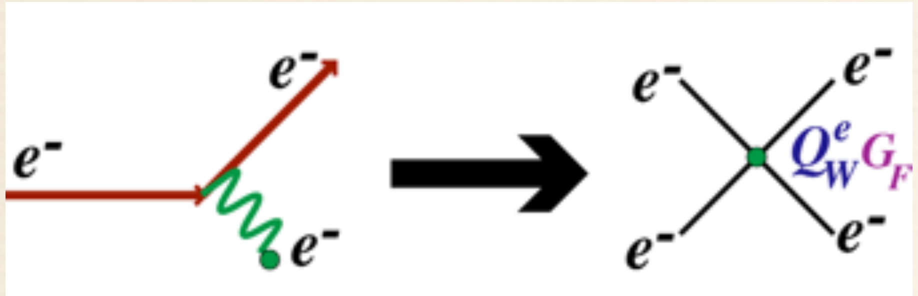


**electron target:**

$$\mathbf{Q_W = 1 - 4\sin^2\theta_W}$$

$$\frac{\delta(Q_W)}{Q_W} \sim 10\% \Longrightarrow \frac{\delta(\sin^2\theta_W)}{\sin^2\theta_W} \sim 0.5\%$$

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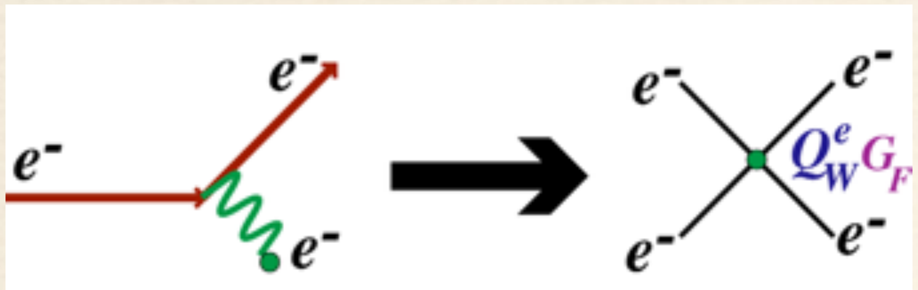
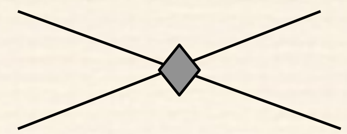



+ 

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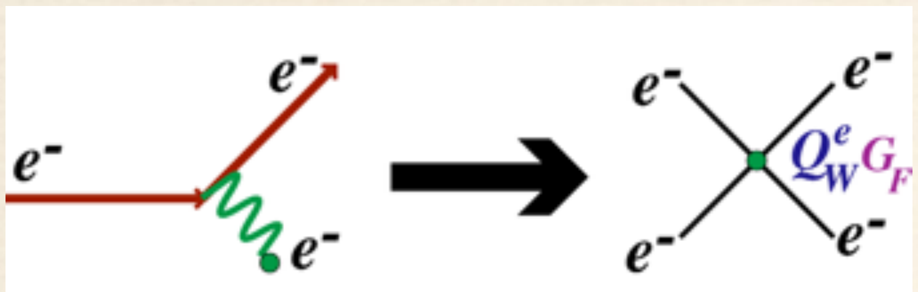


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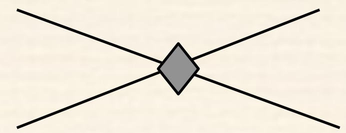

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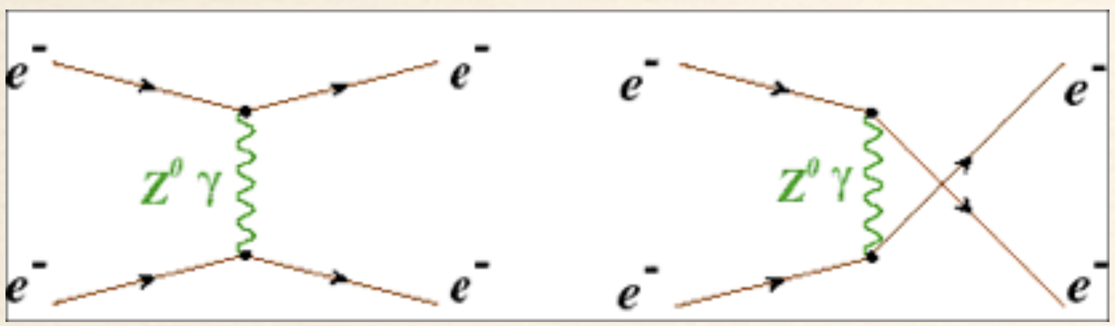


$$\left|\mathbf{A}_\gamma + \mathbf{A_Z} + \mathbf{A}_{\mathrm{new}}\right|^{\mathbf{2}} \rightarrow \mathbf{A}_\gamma^{\mathbf{2}}\left[\mathbf{1} + \mathbf{2}\left(\frac{\mathbf{A_Z}}{\mathbf{A}_\gamma}\right) + \mathbf{2}\left(\frac{\mathbf{A}_{\mathrm{new}}}{\mathbf{A}_\gamma}\right)\right]$$

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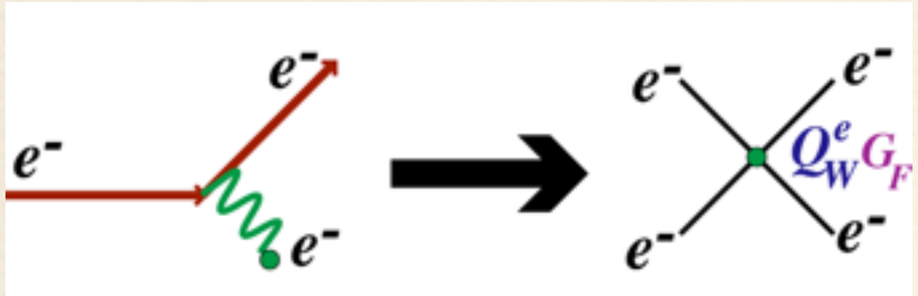


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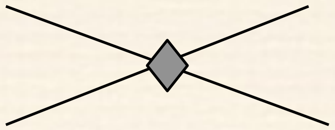

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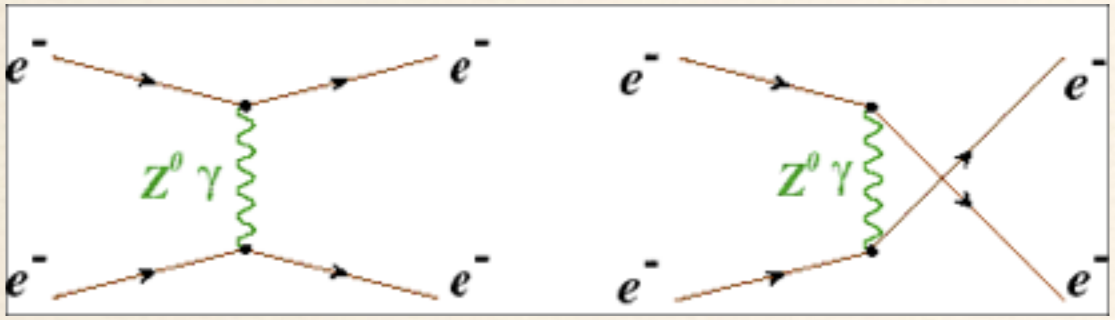


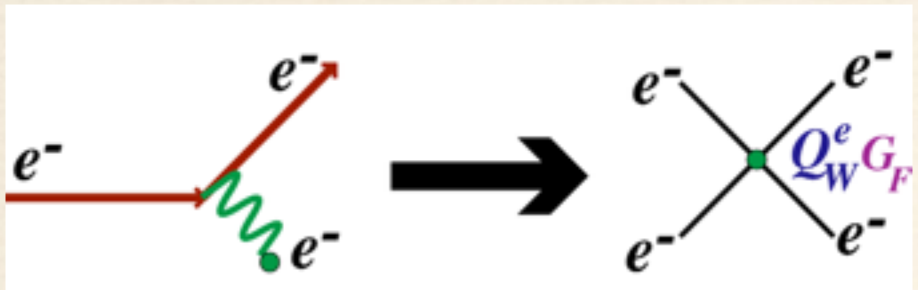

$$\left|\mathbf{A}_\gamma + \mathbf{A_Z} + \mathbf{A}_{\rm new}\right|^2 \to \mathbf{A}_\gamma^2\left[\mathbf{1} + \mathbf{2}\left(\frac{\mathbf{A_Z}}{\mathbf{A}_\gamma}\right) + \mathbf{2}\left(\frac{\mathbf{A}_{\rm new}}{\mathbf{A}_\gamma}\right)\right]$$

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

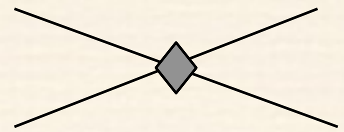
⇨ **Tiny!**

SLAC E158: First Measurement of the Electron's Weak Charge

# PV Electron-Electron Scattering




$+$

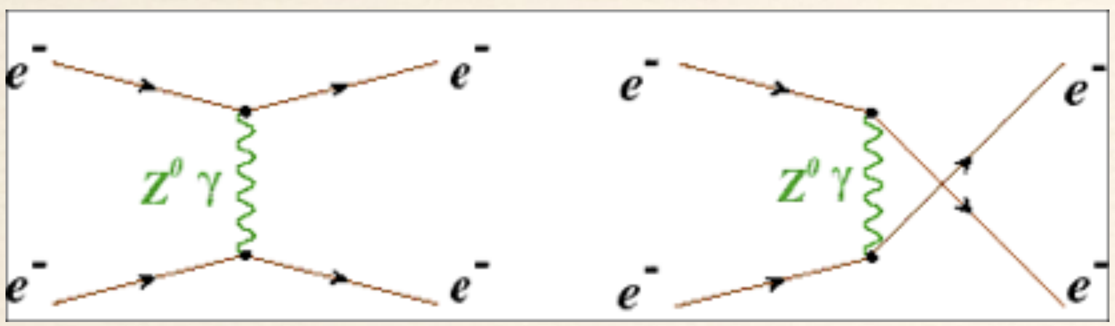


$\frac{1}{\Lambda^2}\mathcal{L}_6$

**electron target:**

$$\mathbf{Q_W = 1 - 4\sin^2\theta_W}$$

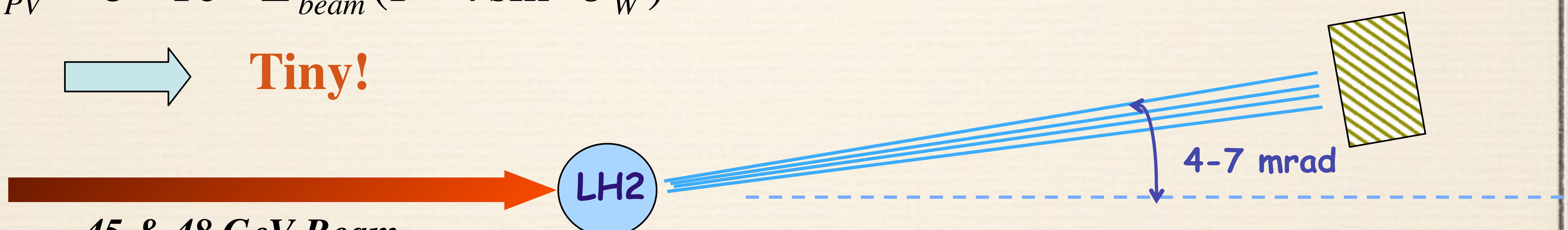
$$\frac{\delta(Q_W)}{Q_W} \sim 10\% \Longrightarrow \frac{\delta(\sin^2\theta_W)}{\sin^2\theta_W} \sim 0.5\%$$




$$\left|\mathbf{A}_\gamma + \mathbf{A_Z} + \mathbf{A}_{\text{new}}\right|^2 \to \mathbf{A}_\gamma^2\left[\mathbf{1} + \mathbf{2}\left(\frac{\mathbf{A_Z}}{\mathbf{A}_\gamma}\right) + \mathbf{2}\left(\frac{\mathbf{A}_{\text{new}}}{\mathbf{A}_\gamma}\right)\right]$$

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

**Tiny!**




***45 & 48 GeV Beam***

*85% longitudinal polarization*

**End Station A at SLAC**

**SLAC E158: 1997-2004**

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

Tree-level prediction: ~ 270 ppb

# Low $Q^2$: 3 Best Measurements

$A_{PV}$ = (-131 ± 14 ± 10) x $10^{-9}$

Tree-level prediction: ~ 270 ppb

# Low $Q^2$: 3 Best Measurements

**Prediction: -154 ppb**

Czarnecki and Marciano (1995)

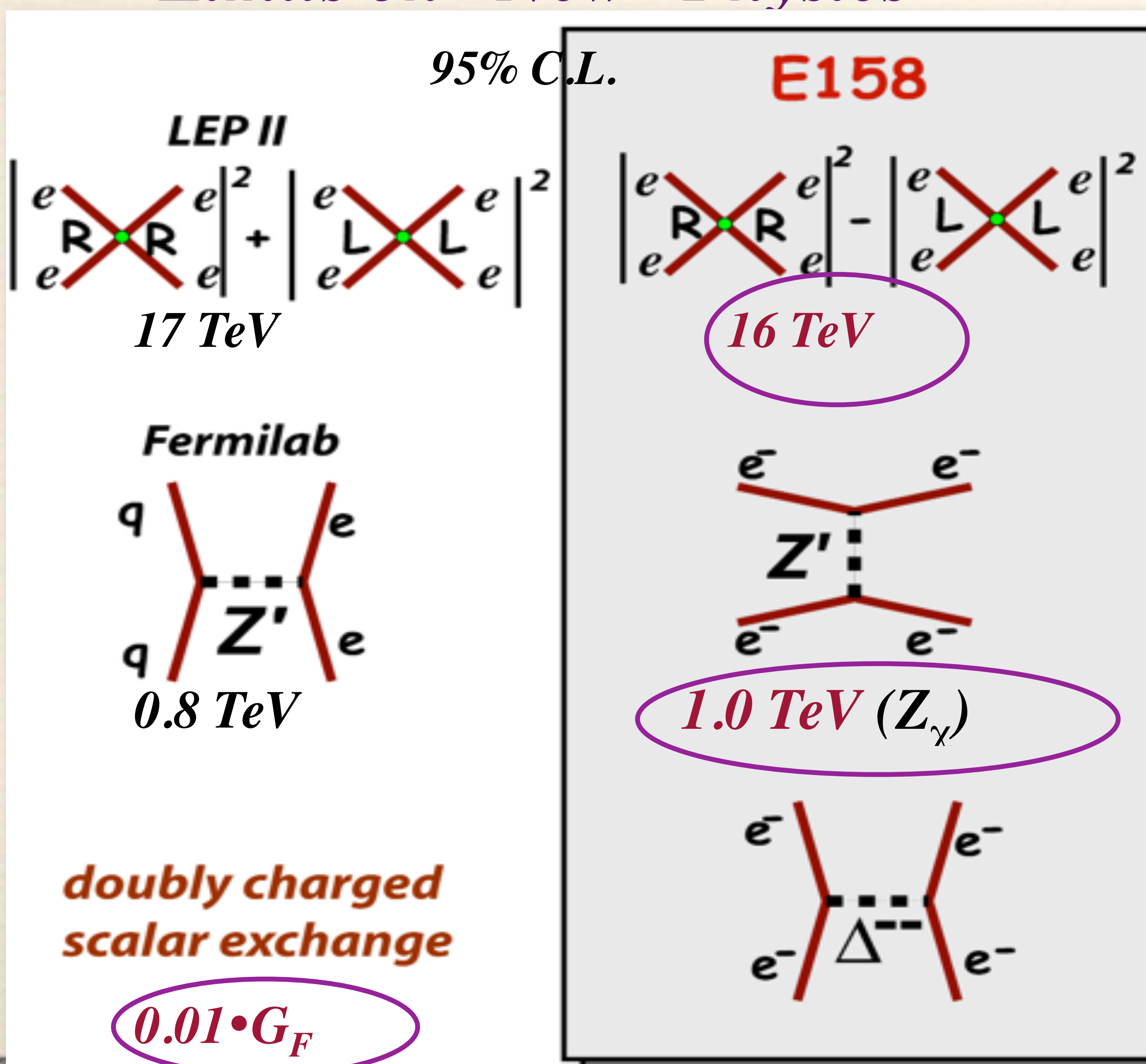
$A_{PV} = (-131 \pm 14 \pm 10) \times 10^{-9}$ Tree-level prediction: ~ 270 ppb

# Low Q²: 3 Best Measurements

**Prediction: -154 ppb**

Czarnecki and Marciano (1995)


*Limits on "New" Physics*



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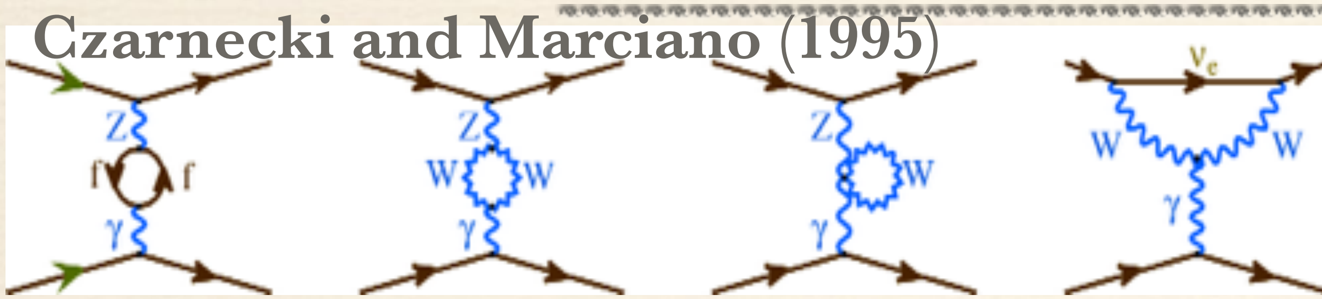
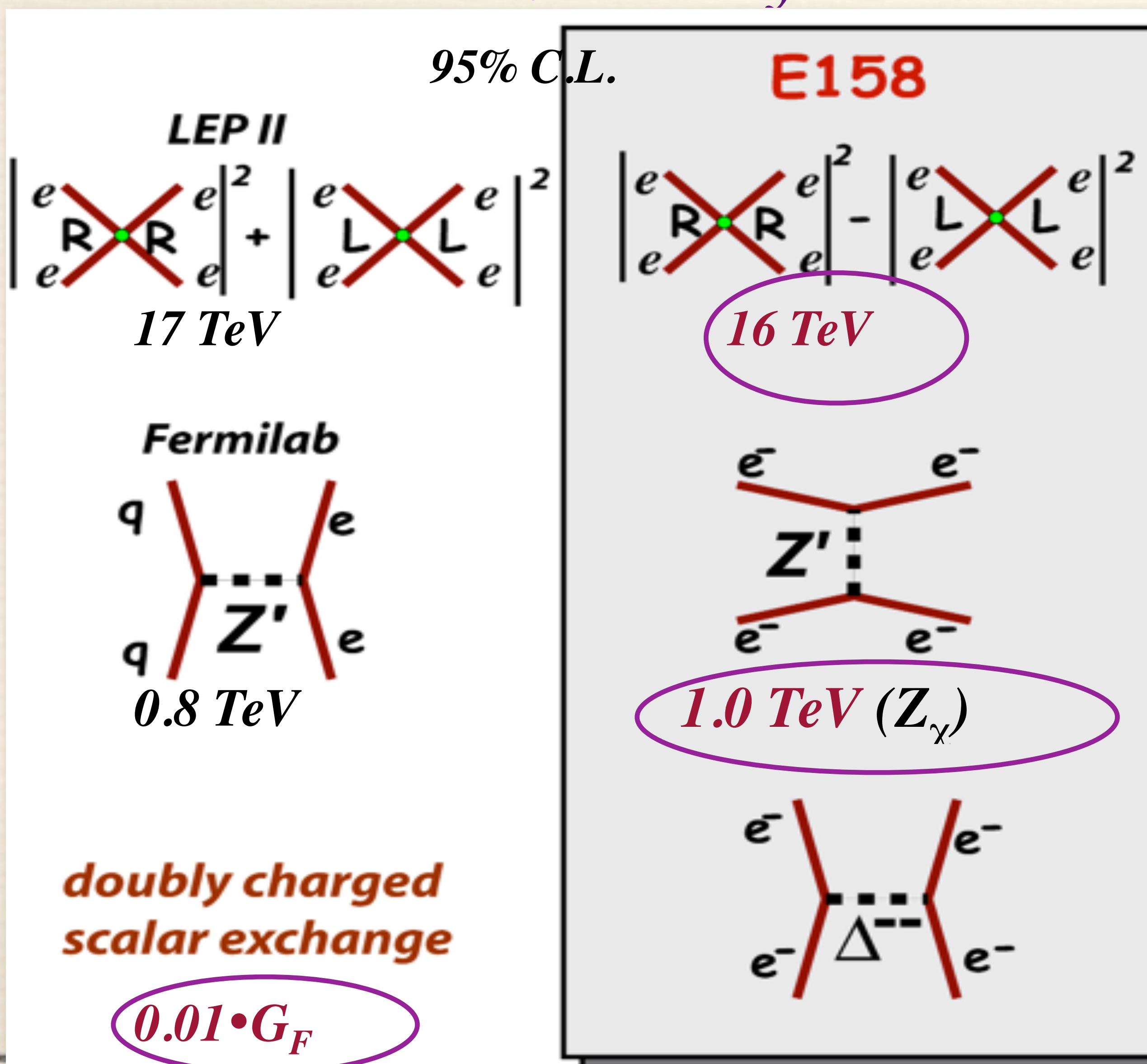
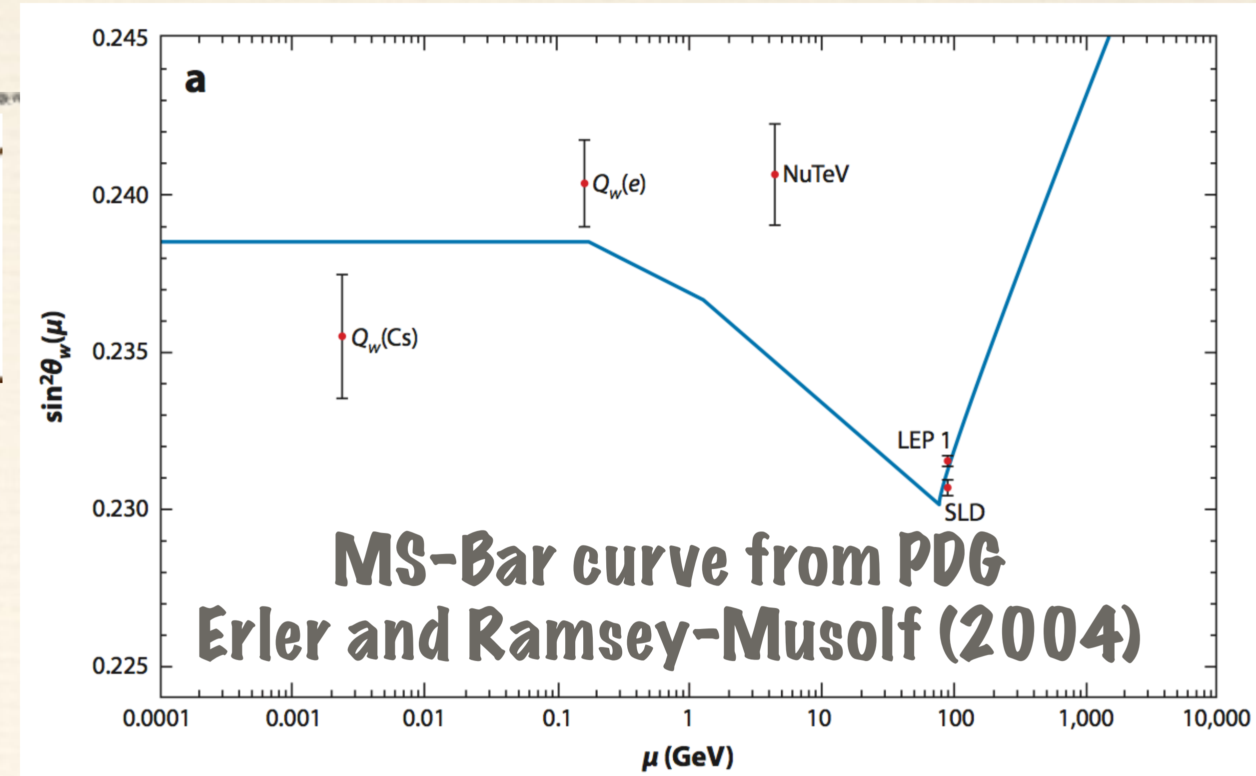
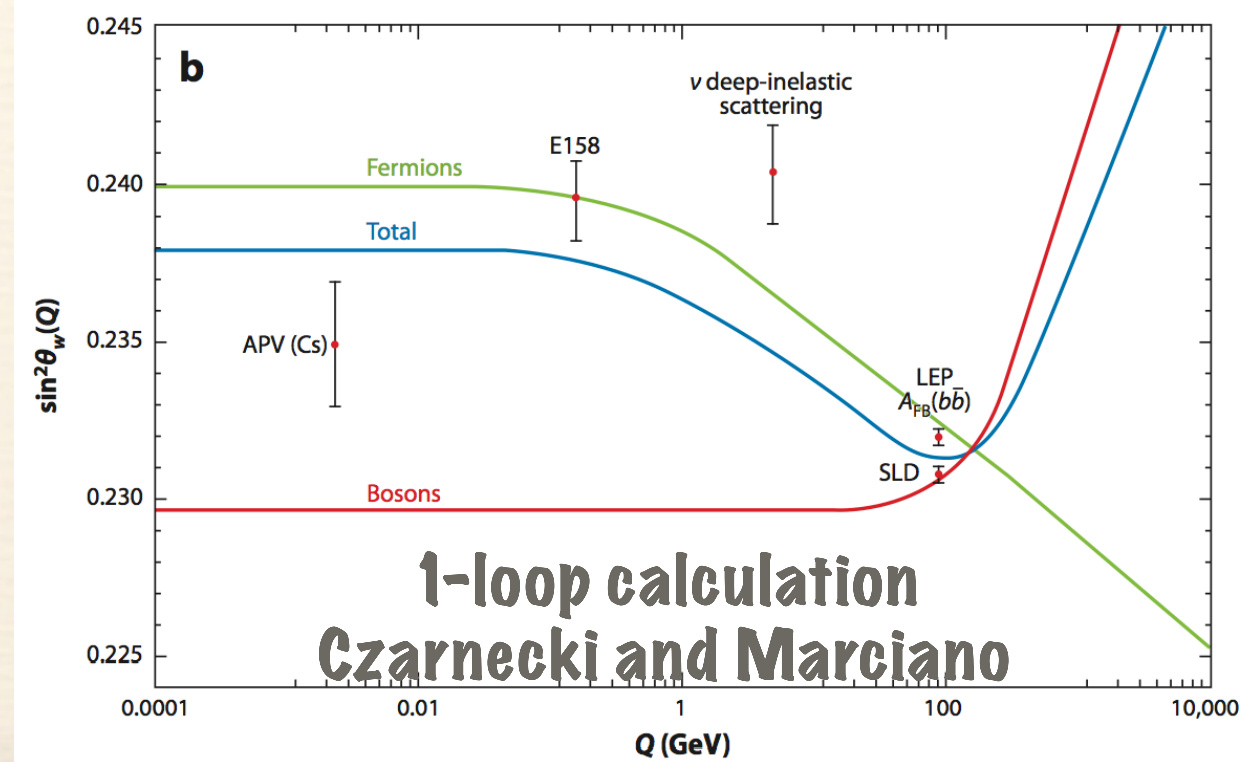



## *Limits on "New" Physics*



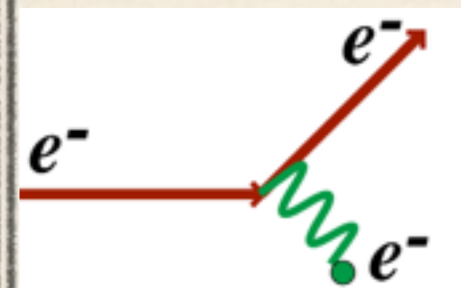



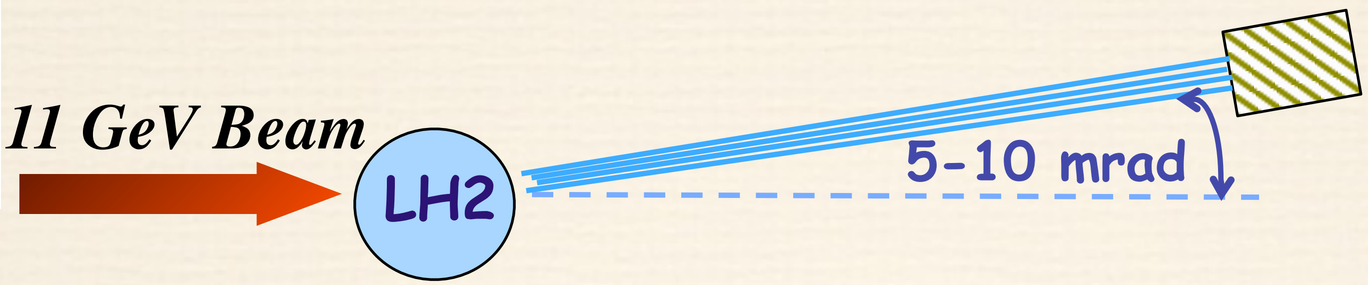
*An ultra-precise measurement of the weak mixing angle using Møller scattering*

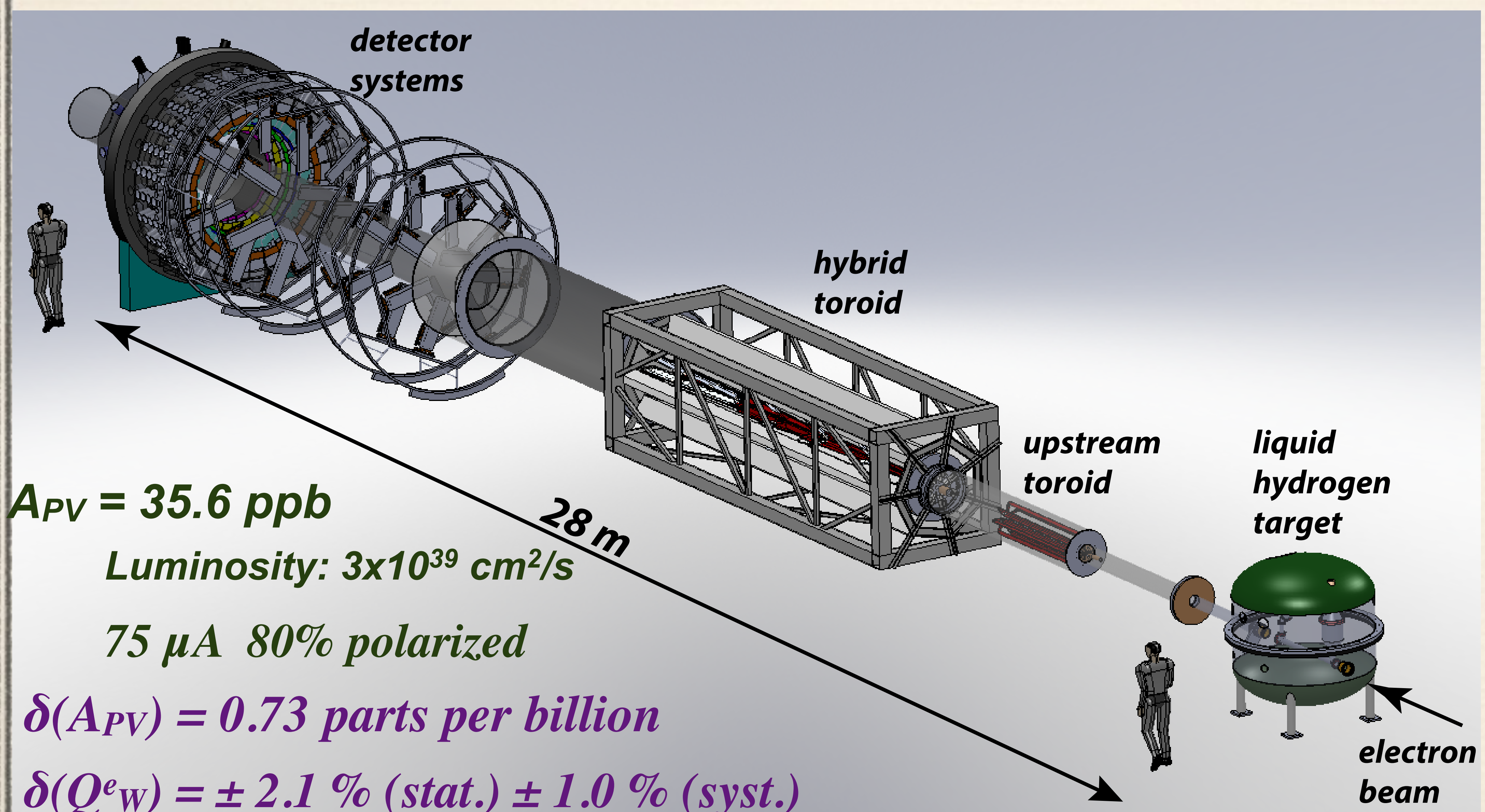
# MOLLER at JLab

## Measurement Of Lepton Lepton Electroweak Reaction

*11 GeV Møller scattering*




$A_{PV}$ = 35.6 ppb

Luminosity: $3\times10^{39}$ $cm^2/s$

75 μA 80% polarized

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

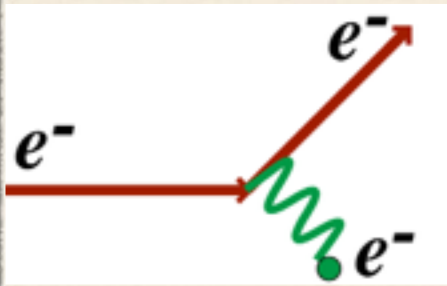
$\delta(Q^e_W) = \pm\, 2.1\ \%$ (stat.) $\pm\, 1.0\ \%$ (syst.)

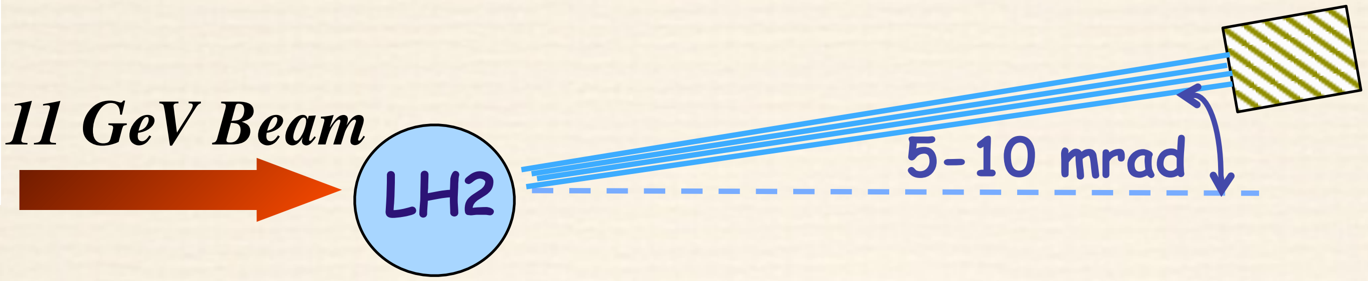
*An ultra-precise measurement of the weak mixing angle using Møller scattering*

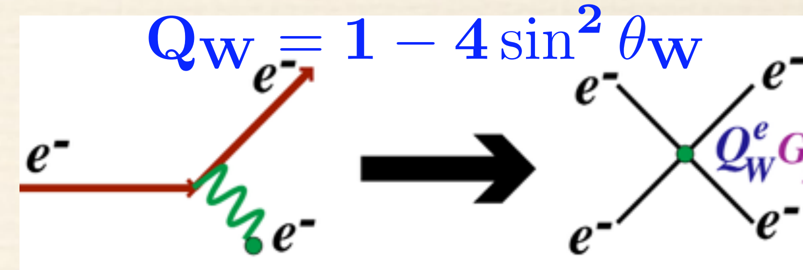
***11 GeV Møller scattering***

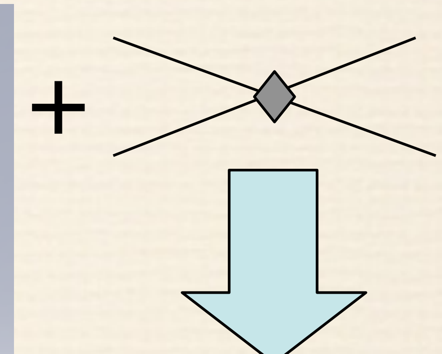
# MOLLER at JLab

## **M**easurement **O**f **L**epton **L**epton **E**lectroweak **R**eaction



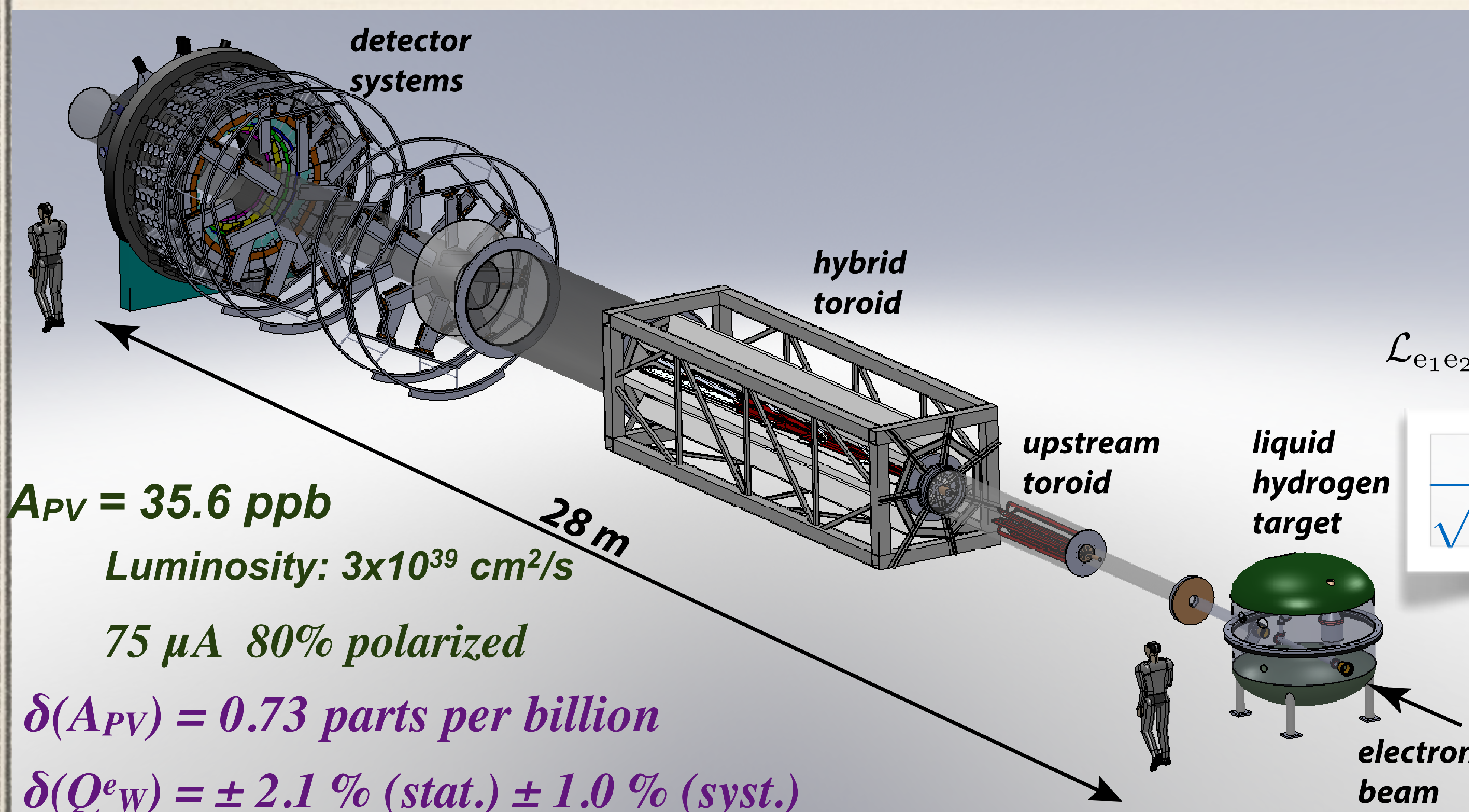




$$\frac{1}{\Lambda^2}\mathcal{L}_6$$

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

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

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*An ultra-precise measurement of the weak mixing angle using Møller scattering*

***11 GeV Møller scattering***

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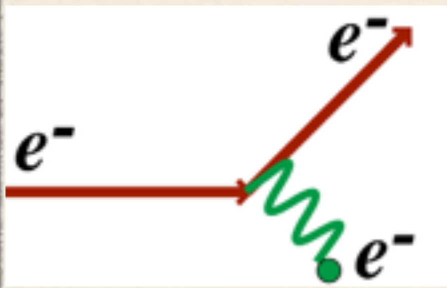



*11 GeV Beam*

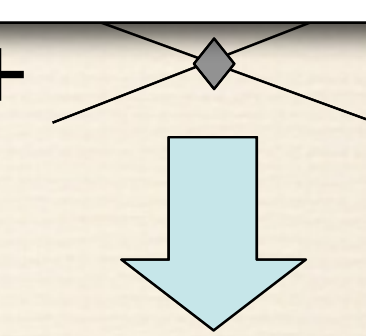
*$\delta(\sin^2\theta_W) = \pm\, 0.00026$ (stat.) $\pm\, 0.00012$ (syst.)* ⇨ *~ 0.1%*

Matches best collider (Z-pole) measurements!

***best contact interaction reach for leptons at low OR high energy***

**To do better for a 4-lepton contact interaction would require: Giga-Z factory, linear collider, neutrino factory or muon collider**

- **~ 20M$ MIE funding required**
- **Science review by DOE NP: September 10 at UMass, Amherst**



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

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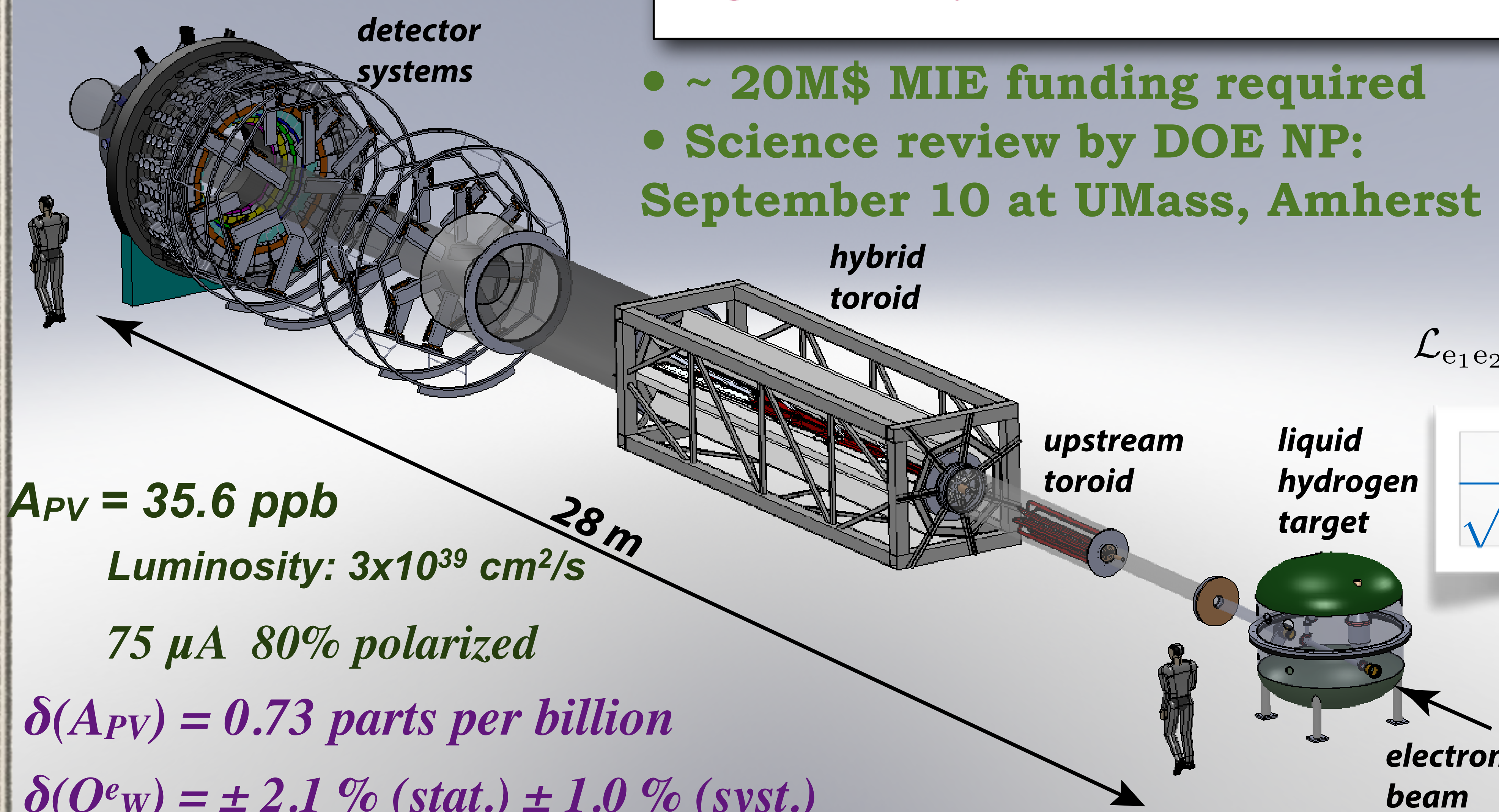


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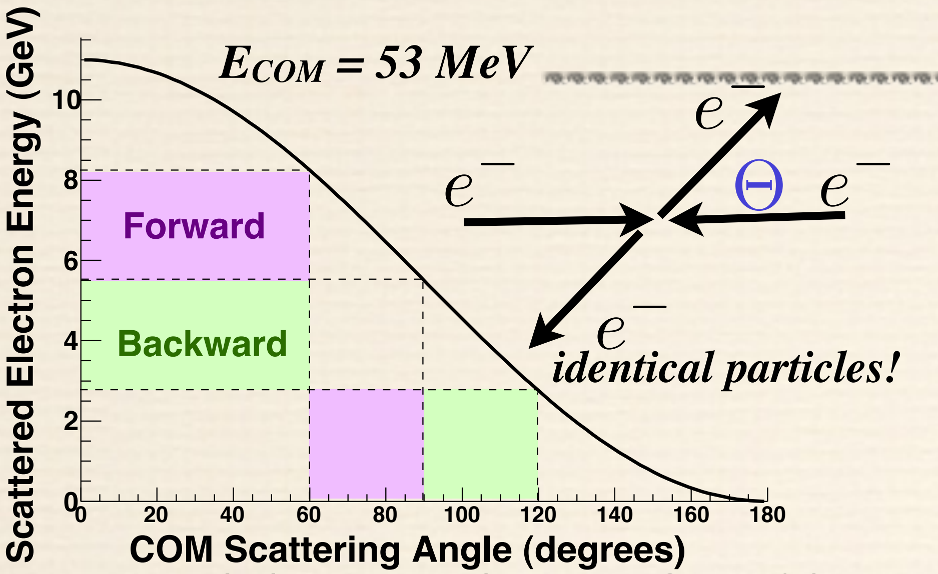
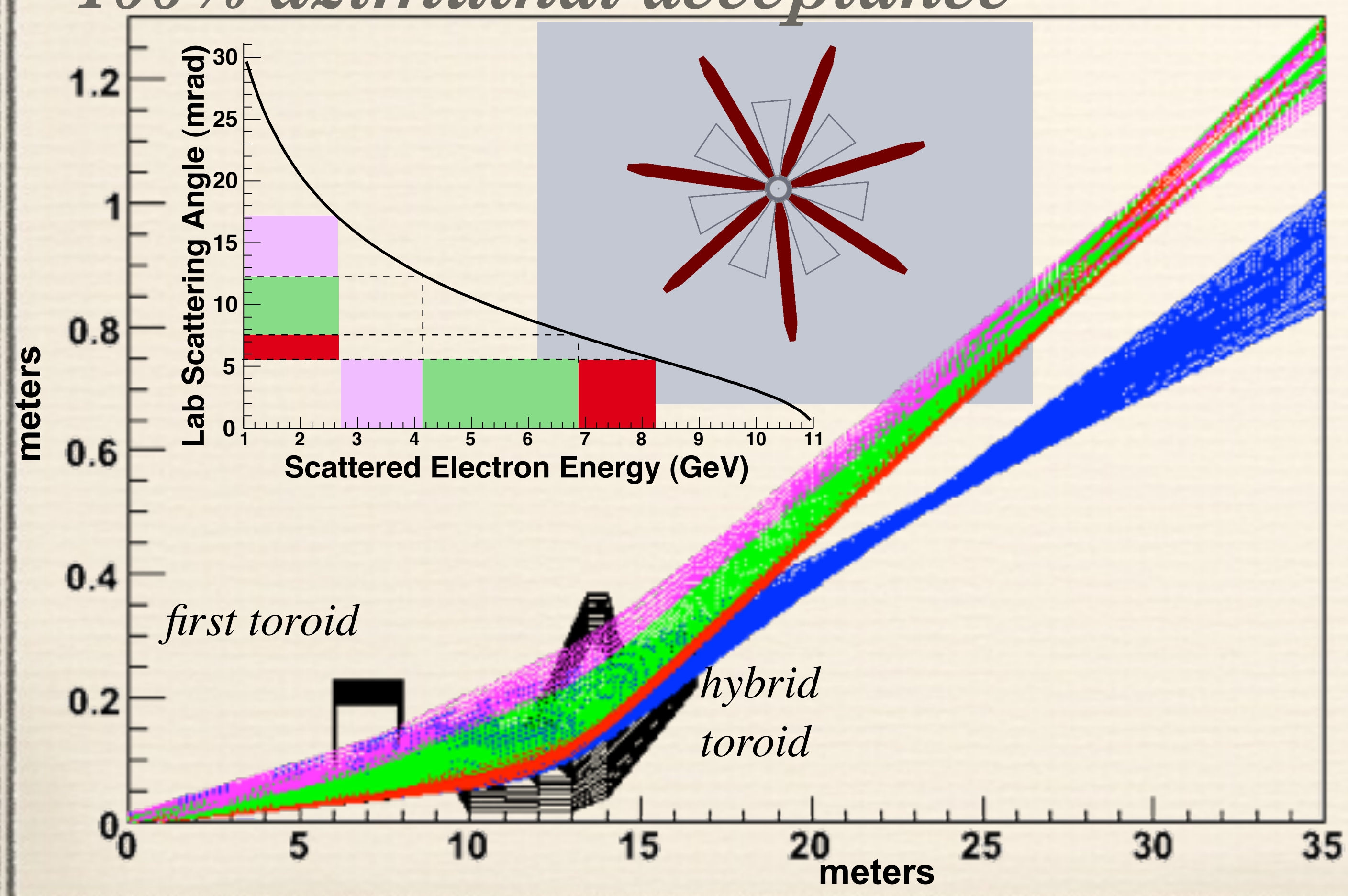
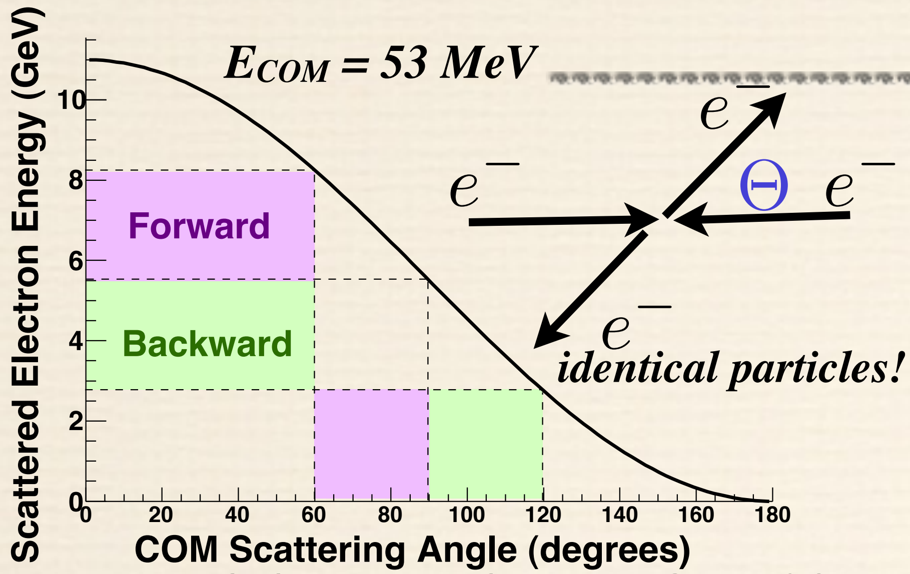
# Unique Spectrometer Concept

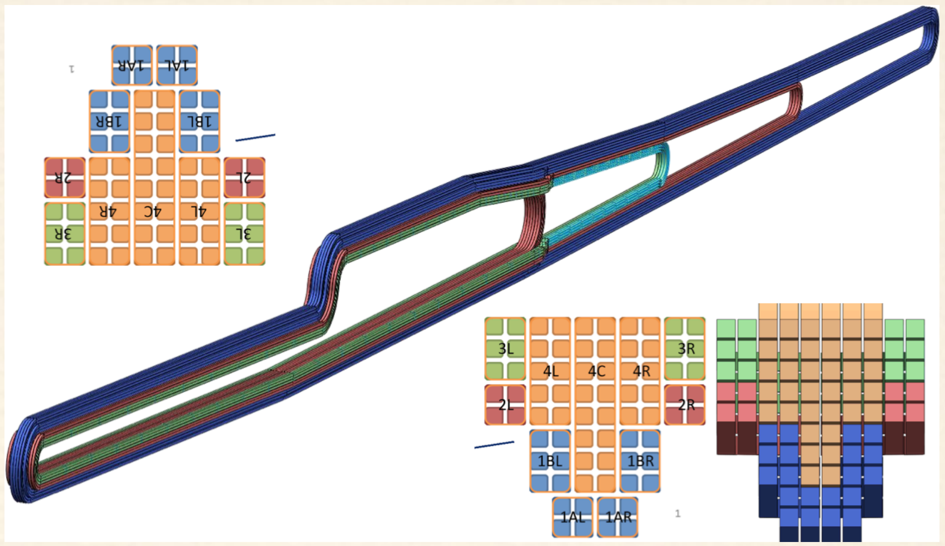


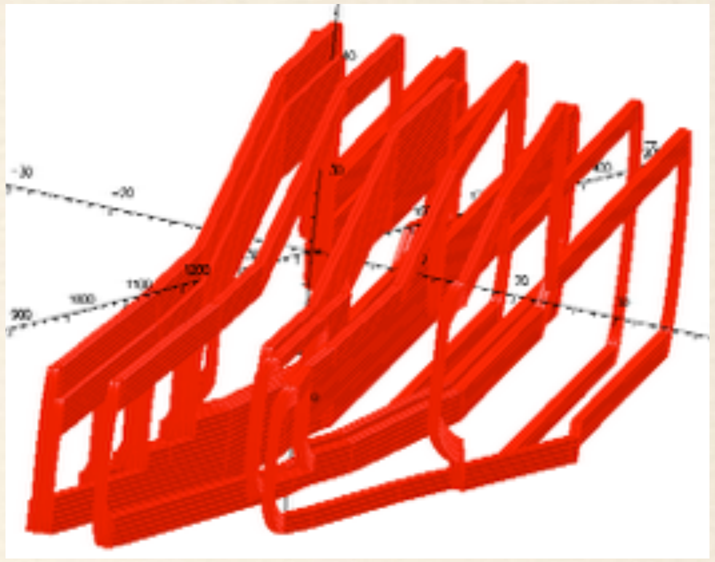

*odd number of coils:*
*100% azimuthal acceptance*



# Unique Spectrometer Concept





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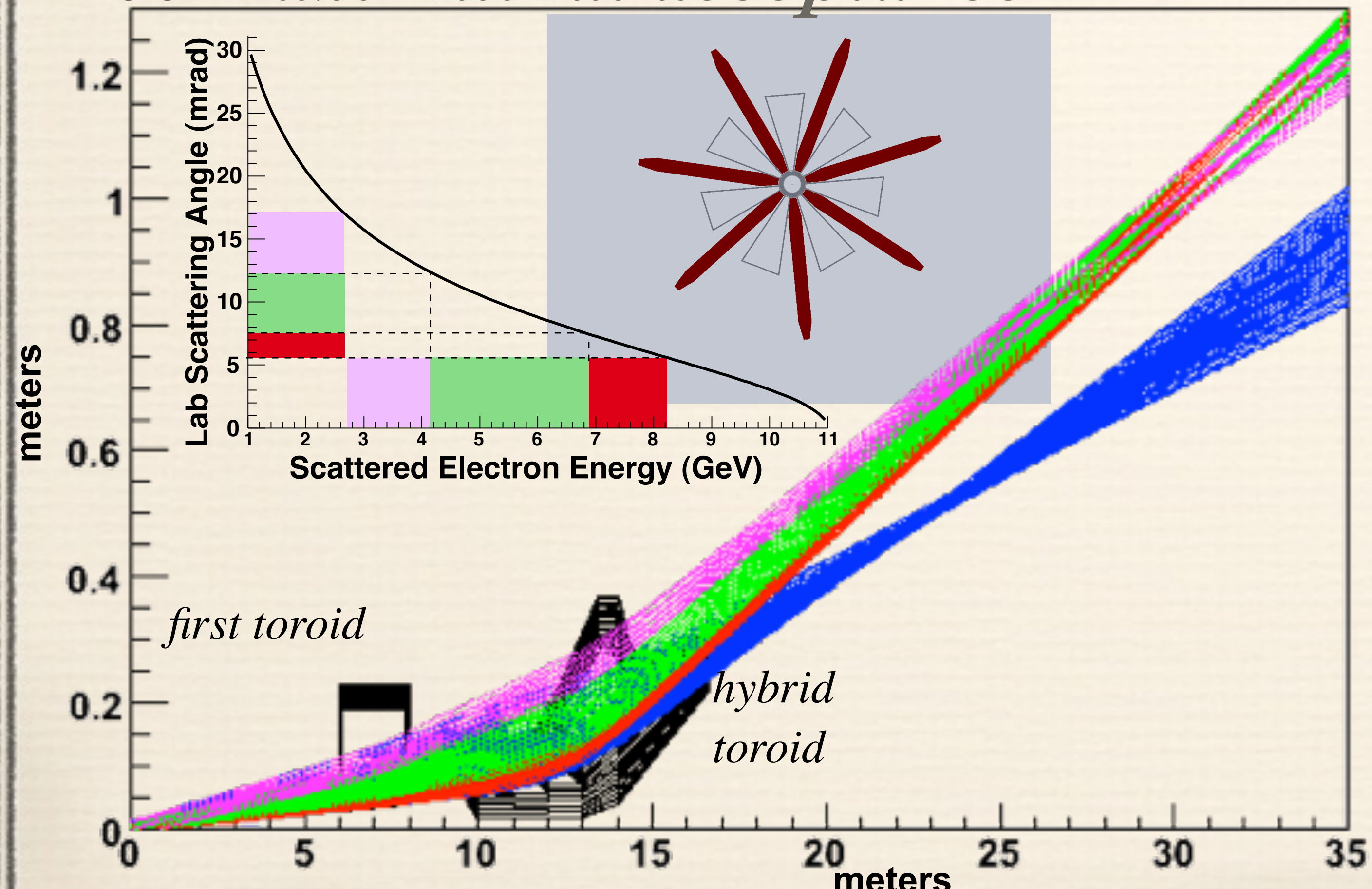
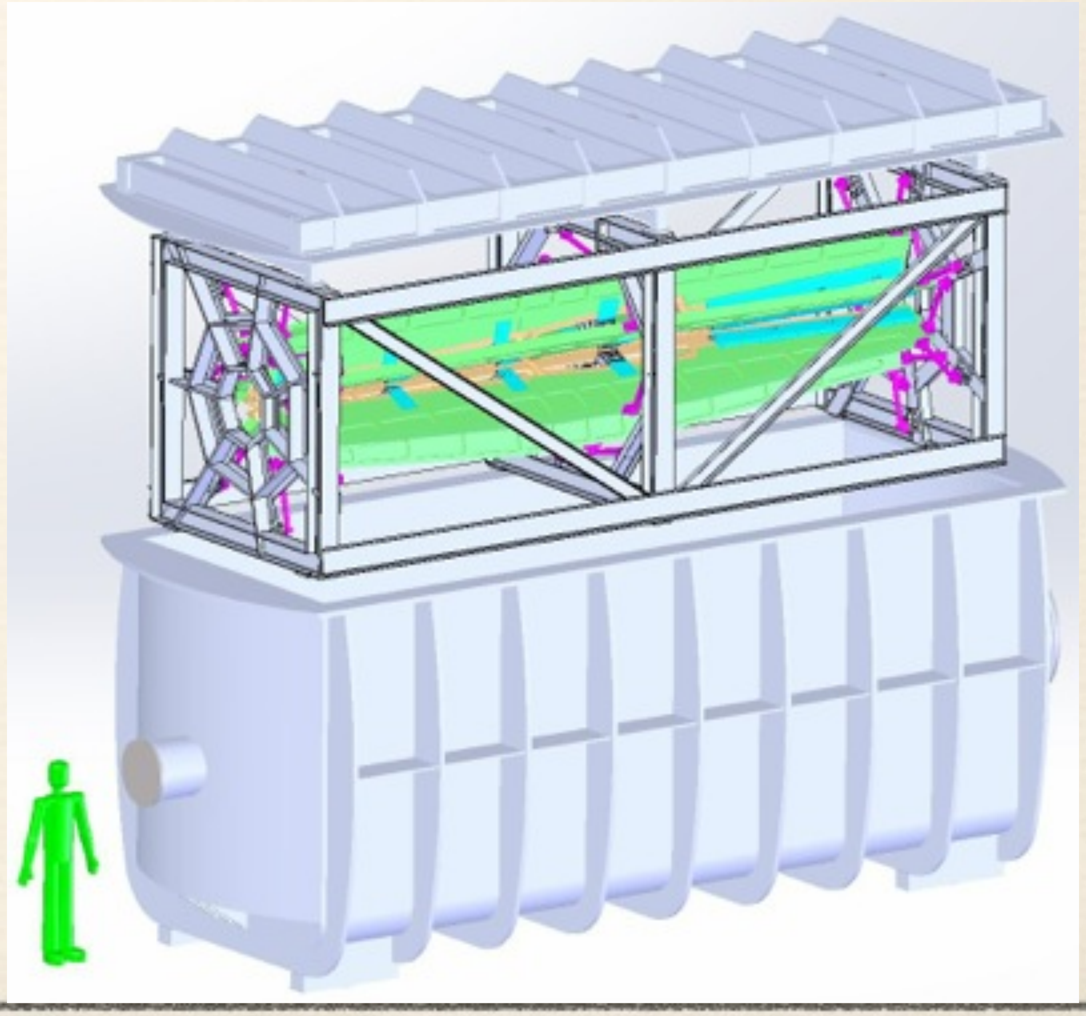


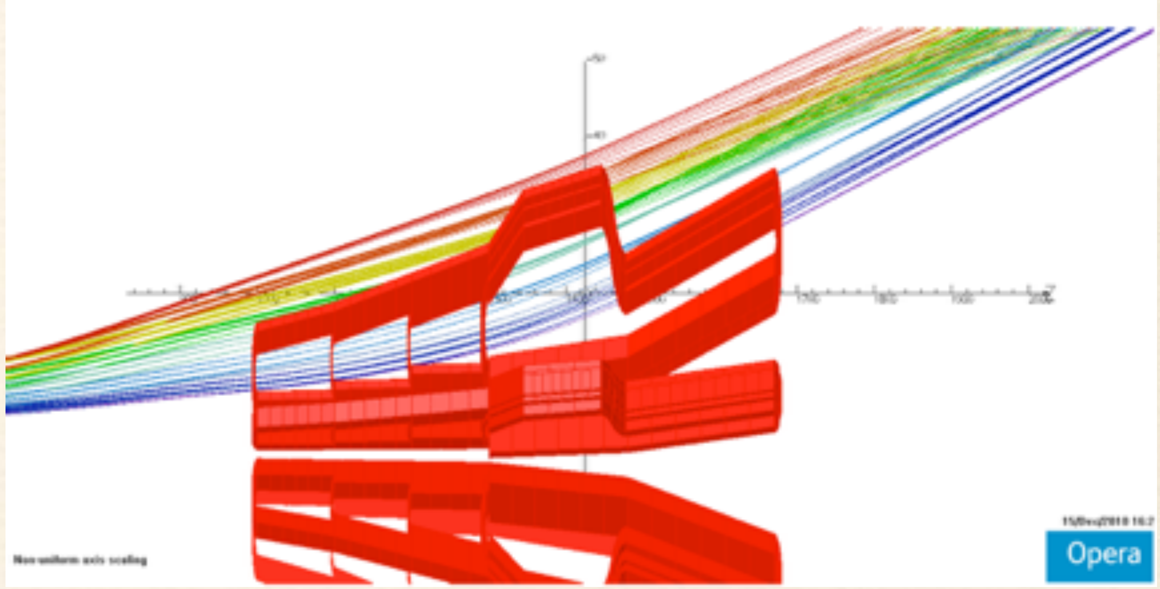
# MOLLER Status

Director's Review chaired by C. Prescott: strong, positive endorsement

## *Technical Challenges*

- ~ 150 GHz scattered electron rate
  - Design to flip Pockels cell ~ 2 kHz
  - 80 ppm pulse-to-pulse statistical fluctuations
- 1 nm control of beam centroid on target
  - Improved methods of "slow helicity reversal"
- > 10 gm/cm² liquid hydrogen target
  - 1.5 m: ~ 5 kW @ 85 μA
- Full Azimuthal acceptance with $\theta_{lab}$ ~ 5 mrad
  - novel two-toroid spectrometer
  - radiation hard, highly segmented integrating detectors
- Robust and Redundant 0.4% beam polarimetry
  - Pursue both Compton and Atomic Hydrogen techniques

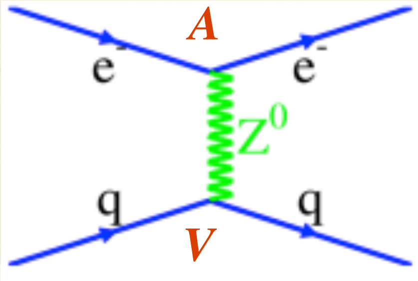
- **MOLLER Collaboration**
  - ~ 100 authors, ~ 30 institutions
  - Expertise from SAMPLE, A4, HAPPEX, G0, PREX, Qweak, E158
  - 4th generation JLab parity experiment



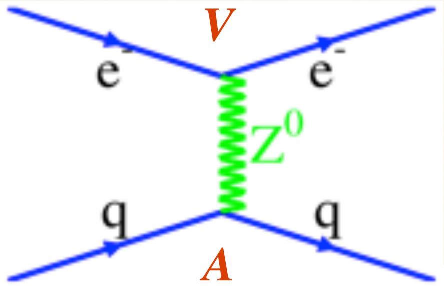

- **20M$ proposal to DoE NP**
- **2-3 years construction**
- **2-3 years running**
- **Science review scheduled**

## Elastic and deep-inelastic electron-nucleon scattering

# Semi-Leptonic Couplings




$C_{1i} \equiv 2g_A^e g_V^i$

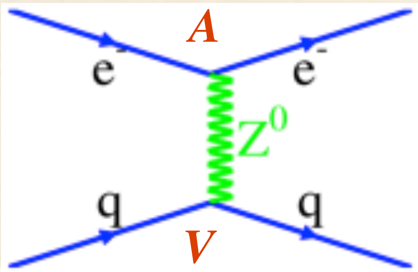



$C_{2i} \equiv 2g_V^e g_A^i$

$$\mathcal{L}^{PV} = \frac{G_F}{\sqrt{2}}[\bar{e}\gamma^\mu\gamma_5 e(C_{1u}\bar{u}\gamma_\mu u + C_{1d}\bar{d}\gamma_\mu d) + \bar{e}\gamma^\mu e(C_{2u}\bar{u}\gamma_\mu\gamma_5 u + C_{2d}\bar{d}\gamma_\mu\gamma_5 d)]$$

## Elastic and deep-inelastic electron-nucleon scattering

# Semi-Leptonic Couplings

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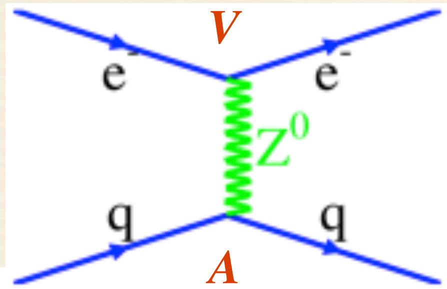


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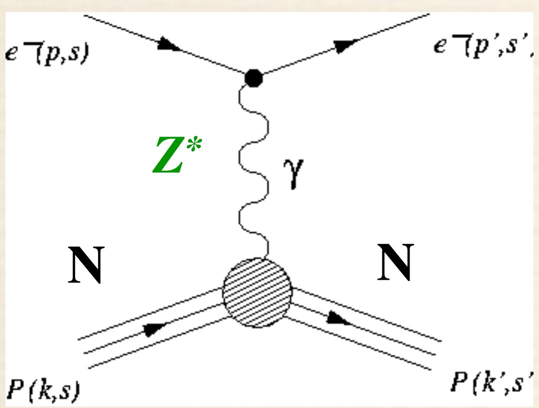
***$A_{PV}$ in elastic e-p scattering:***

*For a [1]H target, nucleon structure contribution well-constrained from measurements*

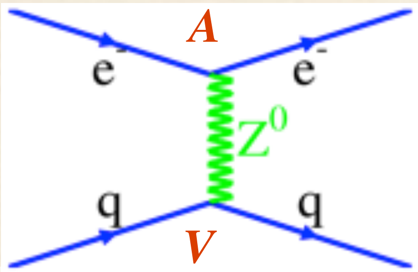



$$A(Q^2 \to 0) = -\frac{G_F}{4\pi\alpha\sqrt{2}}\left[Q^2 \boxed{Q^p_{weak}} + Q^4 B\left(Q^2\right)\right]$$

$$Q^p_{weak} = 2C_{1u} + C_{1d} \propto 1 - 4\sin^2\vartheta_W$$

## Elastic and deep-inelastic electron-nucleon scattering

# Semi-Leptonic Couplings

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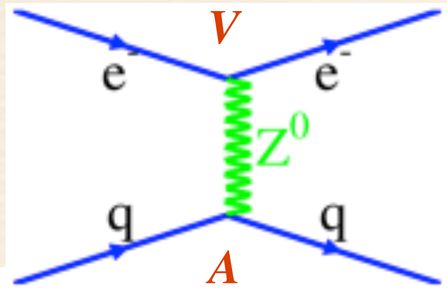


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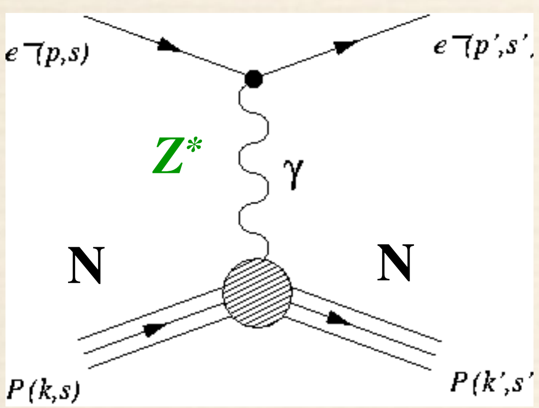


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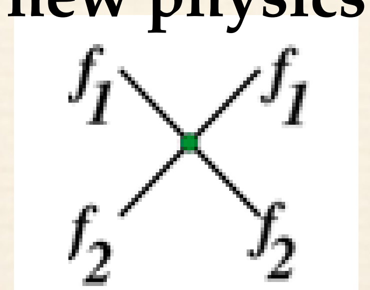
| | | | | |
|---|---|---|---|---|
| $C_{1u}$ | $=$ | $-\frac{1}{2}+\frac{4}{3}\sin^2\theta_W$ | $\approx$ | $-0.19$ |
| $C_{1d}$ | $=$ | $\frac{1}{2}-\frac{2}{3}\sin^2\theta_W$ | $\approx$ | $0.35$ |
| $C_{2u}$ | $=$ | $-\frac{1}{2}+2\sin^2\theta_W$ | $\approx$ | $-0.04$ |
| $C_{2d}$ | $=$ | $\frac{1}{2}-2\sin^2\theta_W$ | $\approx$ | $0.04$ |

**+**

**new physics**

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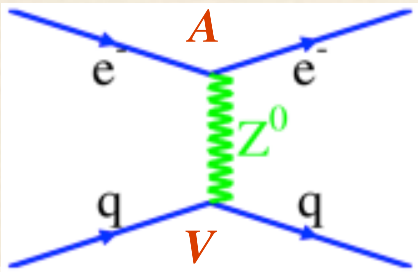
# Elastic and deep-inelastic electron-nucleon scattering

# Semi-Leptonic Couplings

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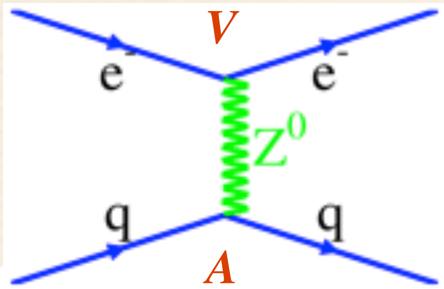


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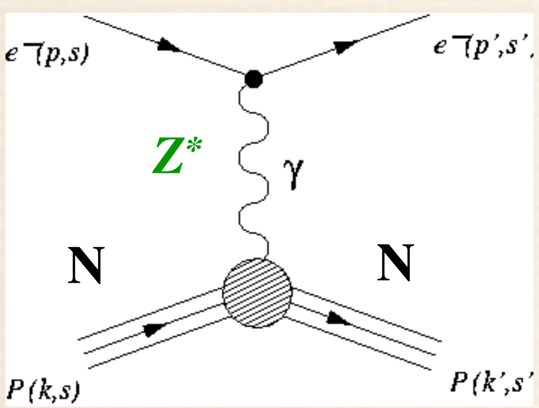


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| | | | | |
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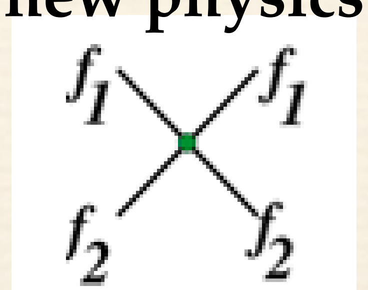
+

**new physics**

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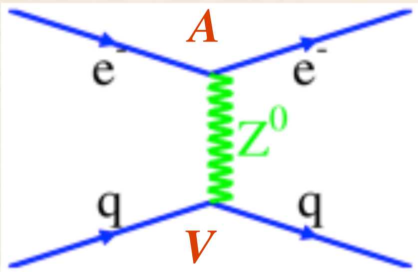
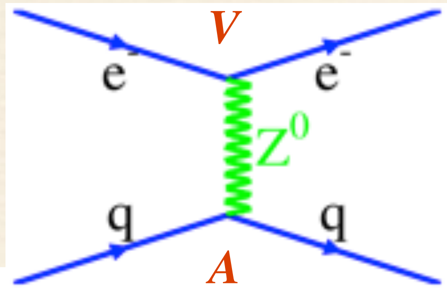
$$C_{1q} \propto (g^{eq}_{RR})^2 + (g^{eq}_{RL})^2 - (g^{eq}_{LR})^2 - (g^{eq}_{LL})^2 \Rightarrow$$

***PV elastic e-p scattering, Atomic parity violation***

# Elastic and deep-inelastic electron-nucleon scattering

# Semi-Leptonic Couplings

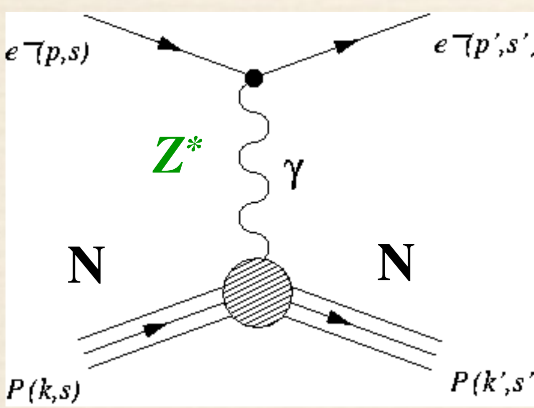



$C_{1i} \equiv 2g_A^e g_V^i$ $\qquad$ $C_{2i} \equiv 2g_V^e g_A^i$

$$\mathcal{L}^{PV} = \frac{G_F}{\sqrt{2}}[\bar{e}\gamma^\mu\gamma_5 e(C_{1u}\bar{u}\gamma_\mu u + C_{1d}\bar{d}\gamma_\mu d) + \bar{e}\gamma^\mu e(C_{2u}\bar{u}\gamma_\mu\gamma_5 u + C_{2d}\bar{d}\gamma_\mu\gamma_5 d)]$$

***$A_{PV}$ in elastic e-p scattering:***




*For a $^1$H target, nucleon structure contribution well-constrained from measurements*

$$A(Q^2 \to 0) = -\frac{G_F}{4\pi\alpha\sqrt{2}}\left[Q^2 \boxed{Q^p_{weak}} + Q^4 B(Q^2)\right]$$

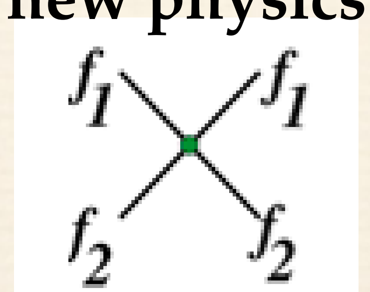
$$Q^p_{weak} = 2C_{1u} + C_{1d} \propto 1 - 4\sin^2\vartheta_W$$

**Qweak at JLab: talk by P. King**

| | | | | |
|---|---|---|---|---|
| $C_{1u}$ | $=$ | $-\frac{1}{2}+\frac{4}{3}\sin^2\theta_W$ | $\approx$ | $-0.19$ |
| $C_{1d}$ | $=$ | $\frac{1}{2}-\frac{2}{3}\sin^2\theta_W$ | $\approx$ | $0.35$ |
| $C_{2u}$ | $=$ | $-\frac{1}{2}+2\sin^2\theta_W$ | $\approx$ | $-0.04$ |
| $C_{2d}$ | $=$ | $\frac{1}{2}-2\sin^2\theta_W$ | $\approx$ | $0.04$ |

+

**new physics**




$$\mathcal{L}_{f_1 f_2} = \sum_{i,j=L,R} \frac{(g^{12}_{ij})^2}{\Lambda^2_{ij}} \bar{f}_{1i}\gamma_\mu f_{1i}\bar{f}_{2j}\gamma_\mu f_{2j}$$

$$C_{1q} \propto (g^{eq}_{RR})^2 + (g^{eq}_{RL})^2 - (g^{eq}_{LR})^2 - (g^{eq}_{LL})^2$$

***PV elastic e-p scattering, Atomic parity violation***

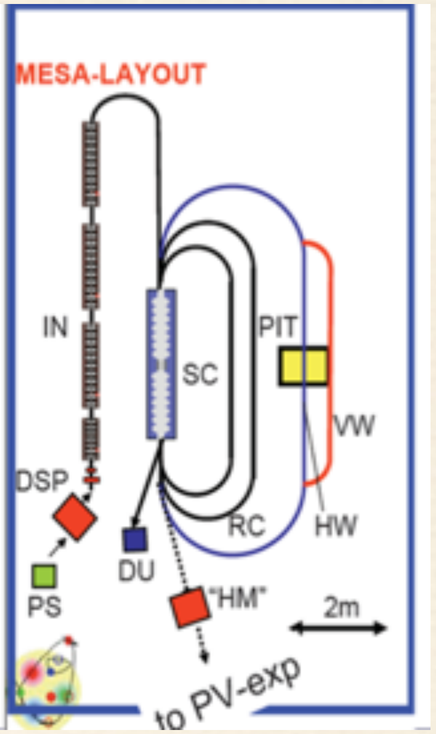
# Weak Charge and Neutron Skin at Mainz

## Future: MESA/P2 at Mainz

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

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

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



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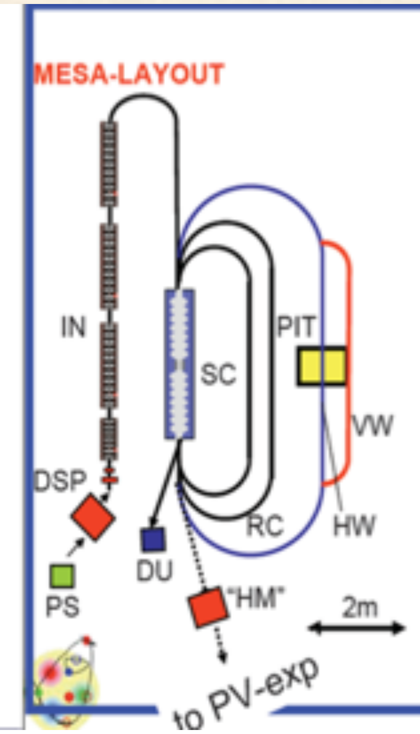
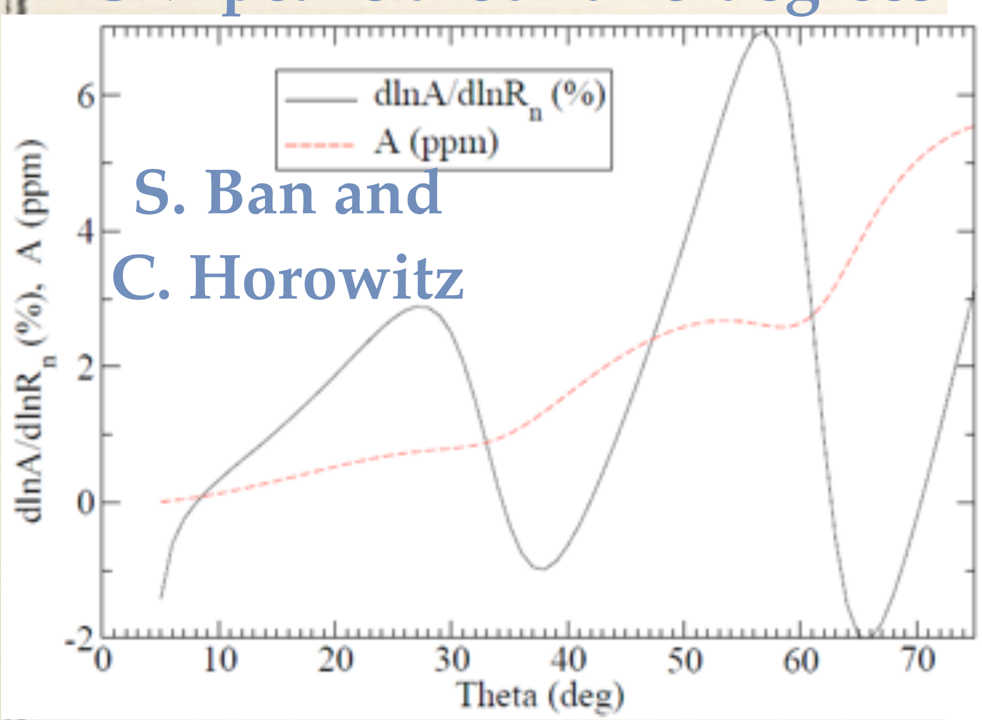
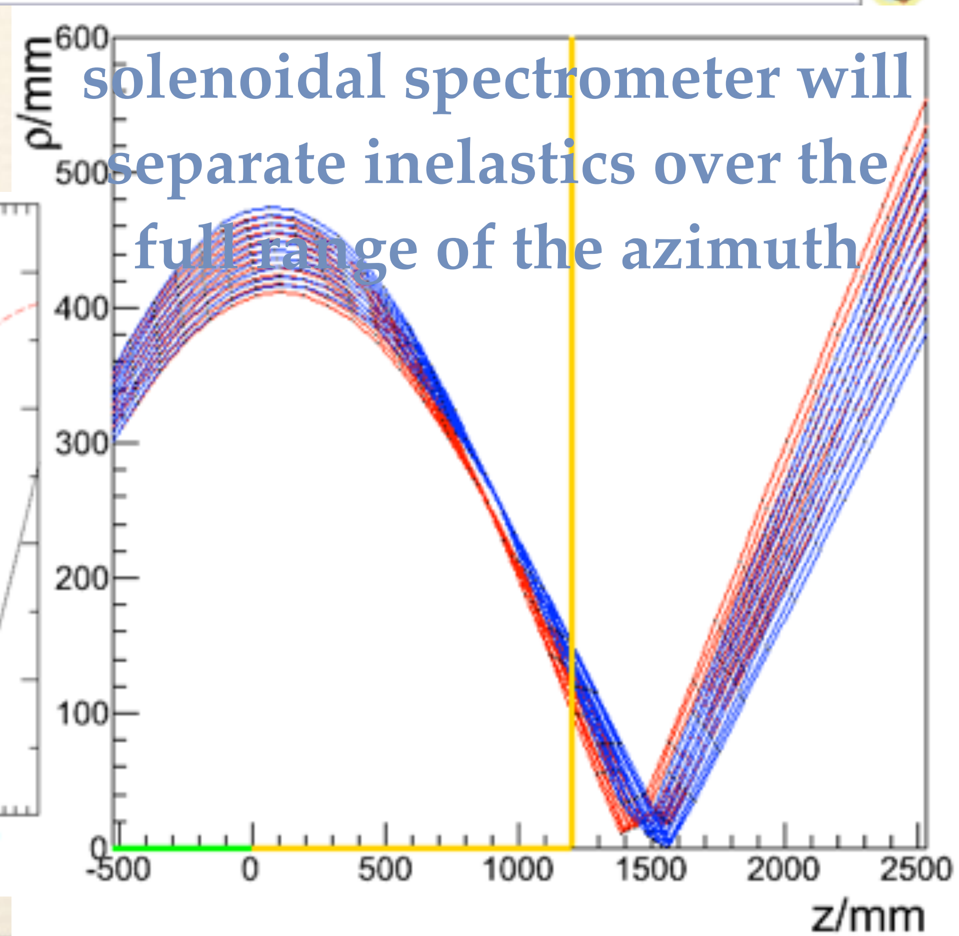



Explore a PREX-style measurement using same solenoidal magnet to be used for P2

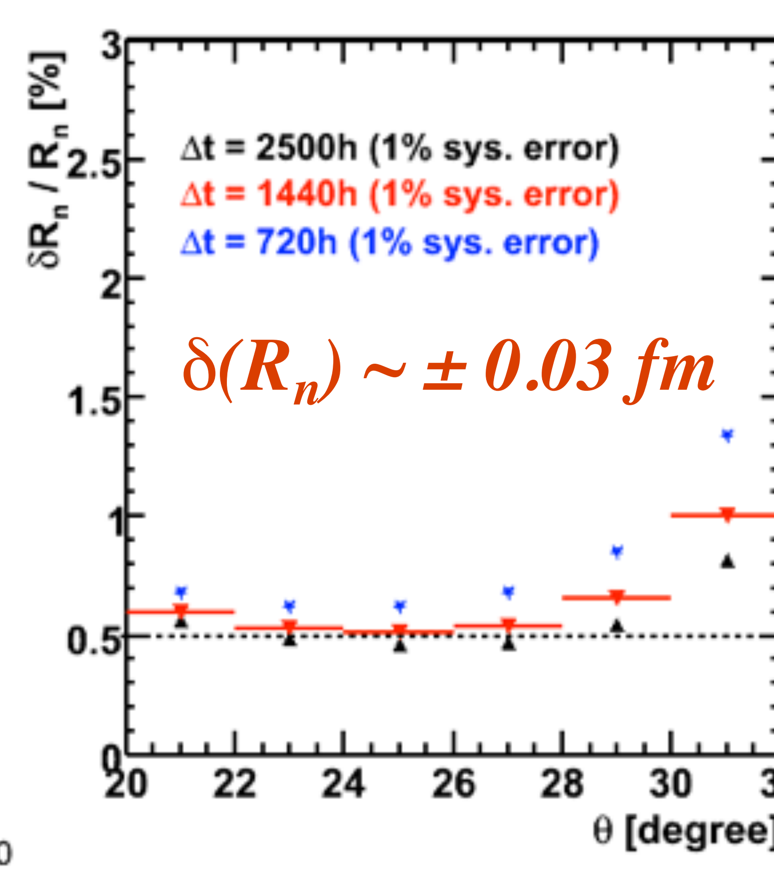
200 MeV
FOM peaks around 25 degrees




S. Ban and C. Horowitz



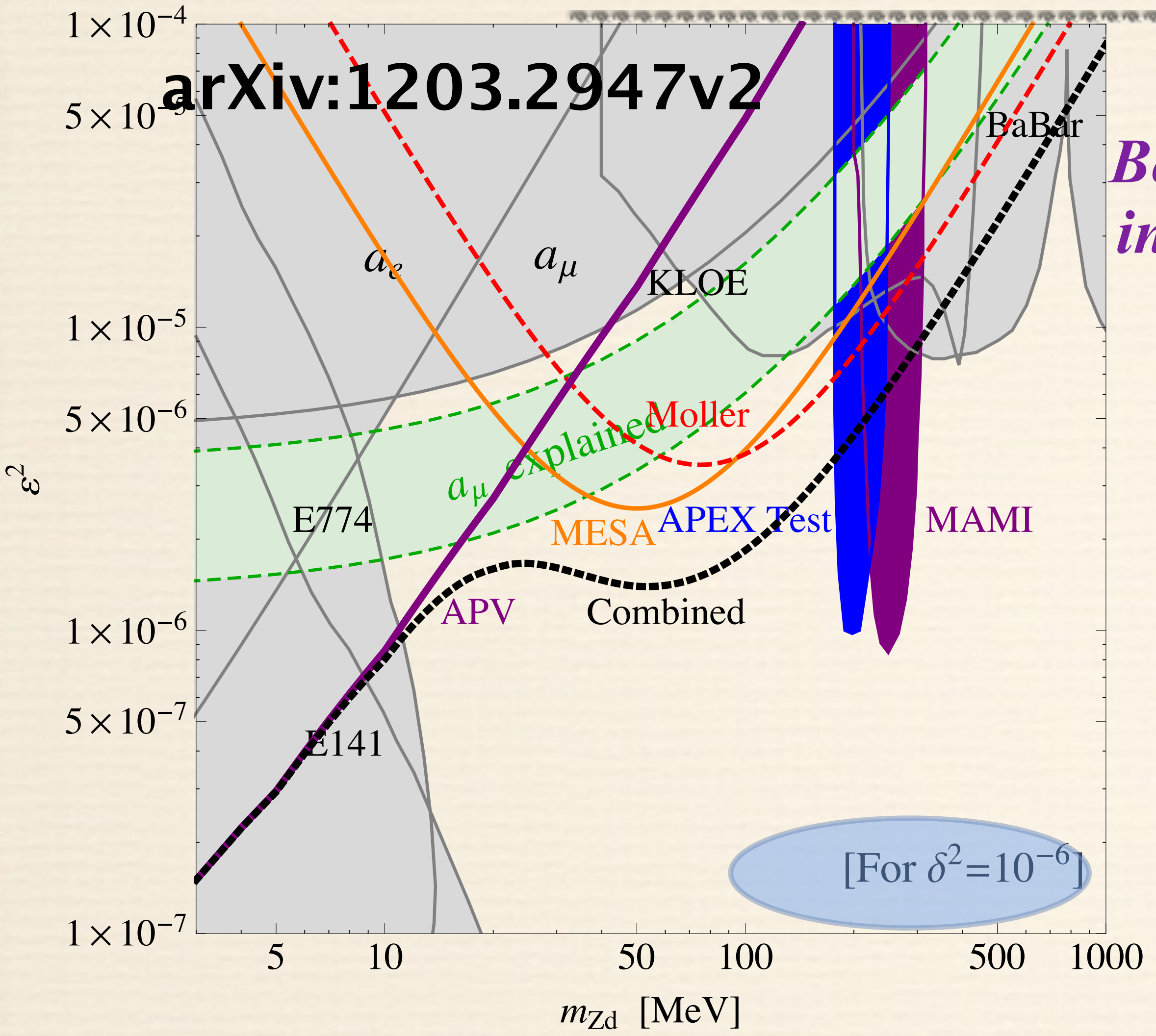

solenoidal spectrometer will separate inelastics over the full range of the azimuth




$\delta(R_n) \sim \pm 0.03$ fm

# Dark Z to Invisible Particles

[Davoudiasl](), [Lee](), [Marciano]()




***Dark Photons:***

***Beyond kinetic mixing; introduce mass mixing with the $Z^0$***

$$\epsilon_Z = \frac{m_{Z_d}}{M_Z}\delta$$

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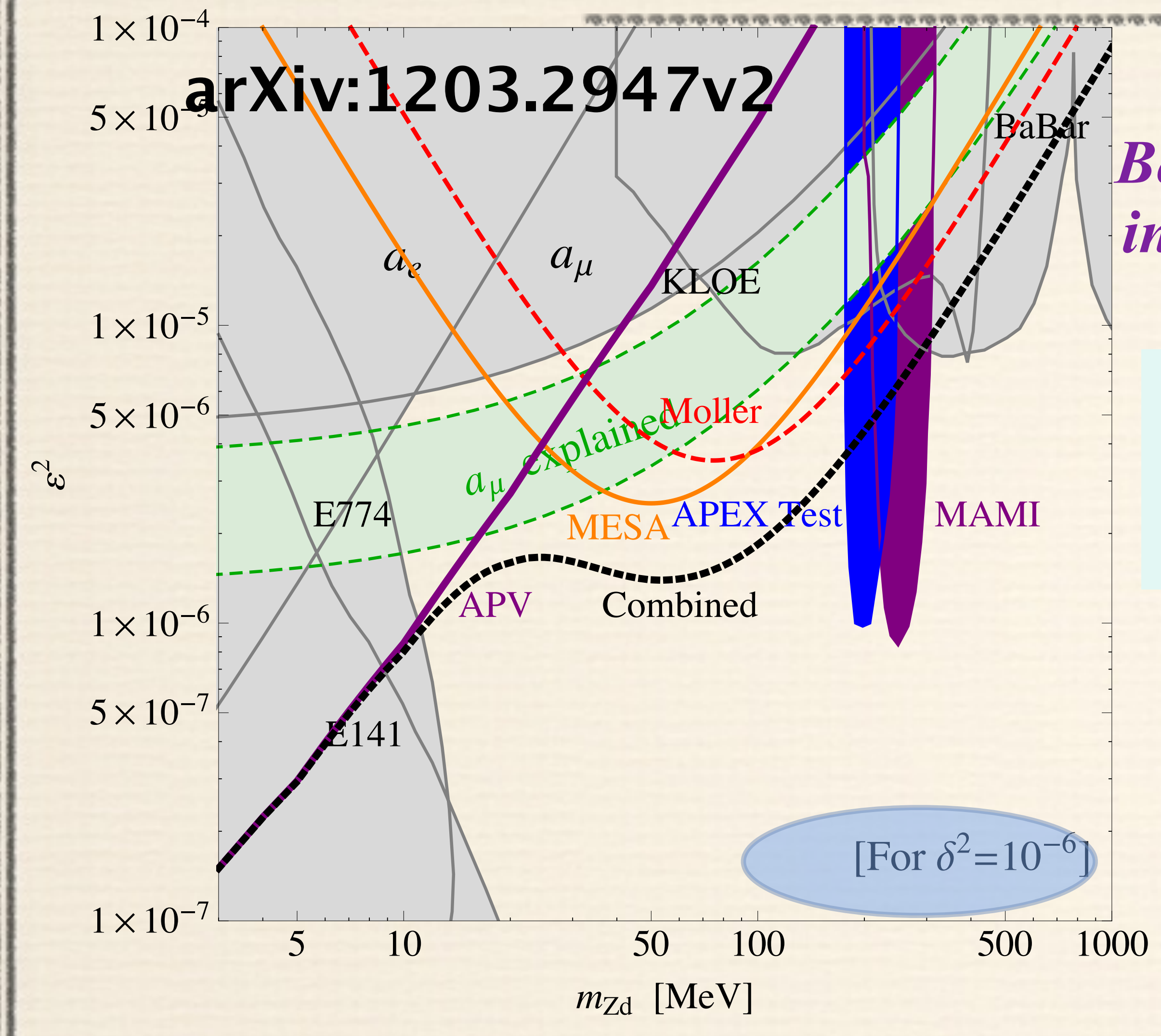


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- Potentially Observable Effects (for $\delta \geq 10^{-3}$)

  APV & Polarized Electron Scattering at low <Q>

  $BR(K \rightarrow \pi Z_d) \approx 4\times10^{-4}\delta^2$ $BR(B \rightarrow KZ_d) \approx 0.1\delta^2$

***$\delta^2$ roughly probed to $10^{-6}$***

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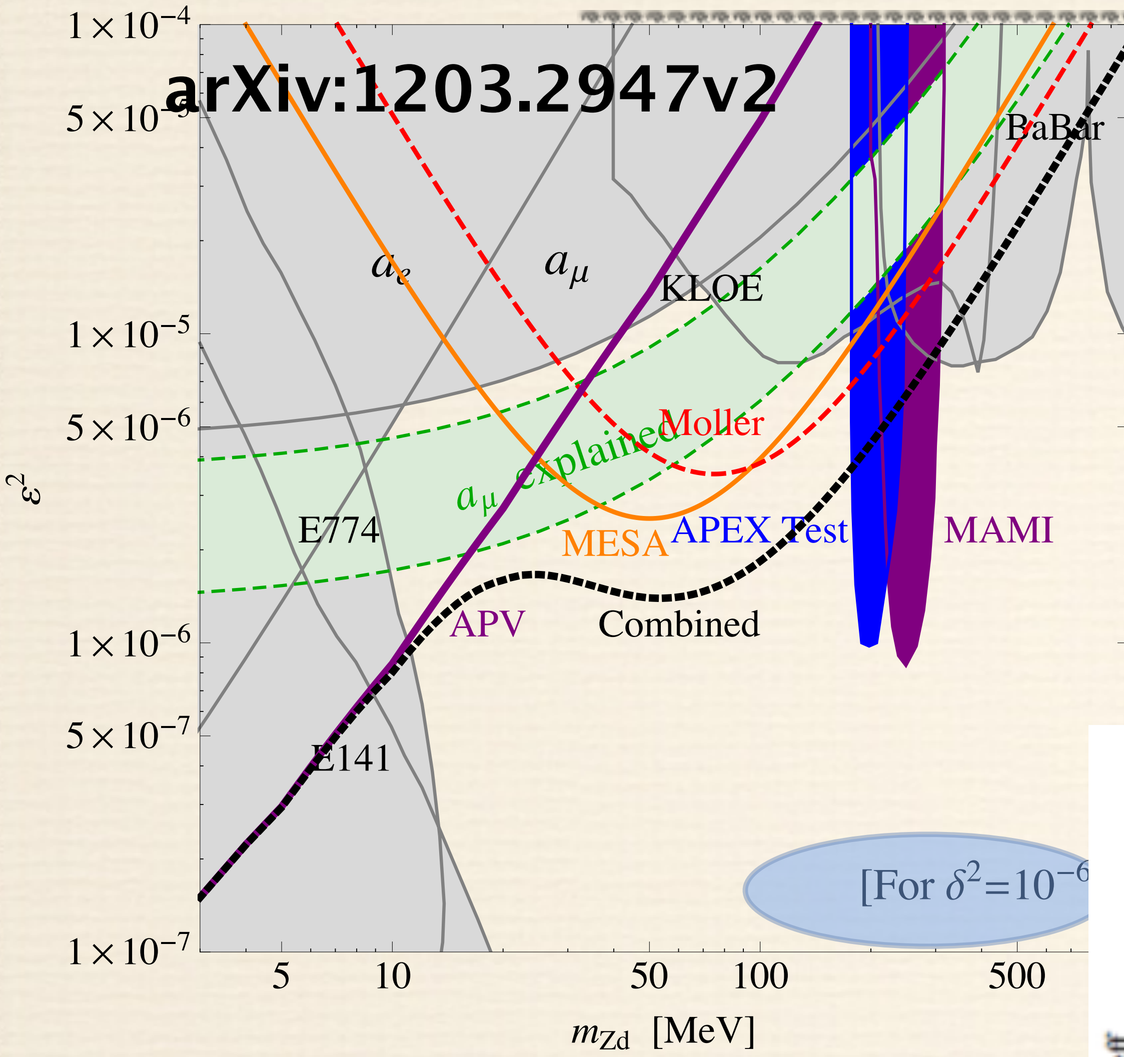


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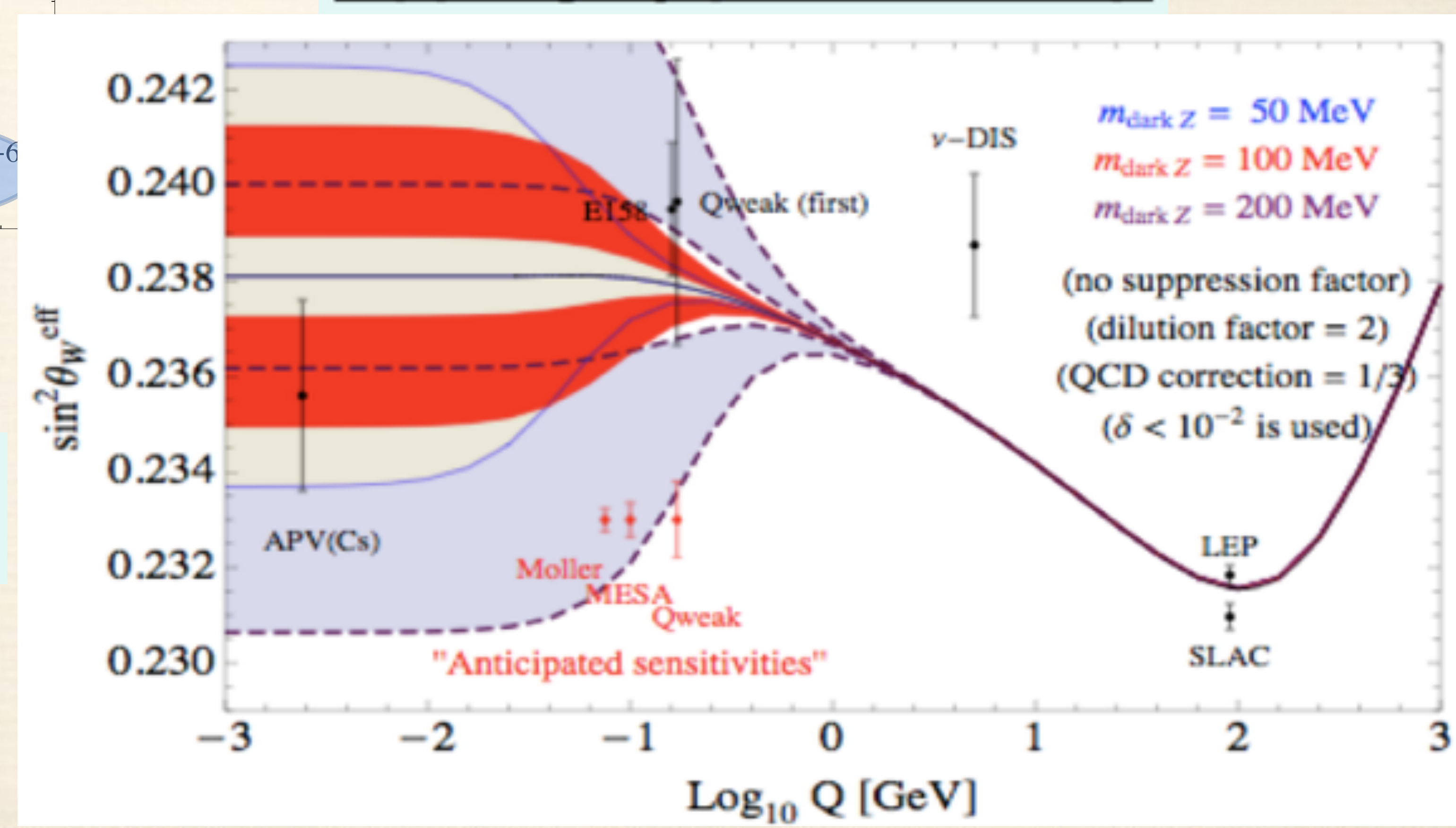


***$K \to \pi Z_d \to \pi$+"missing energy"***

***ε and δ effects could partially cancel!***

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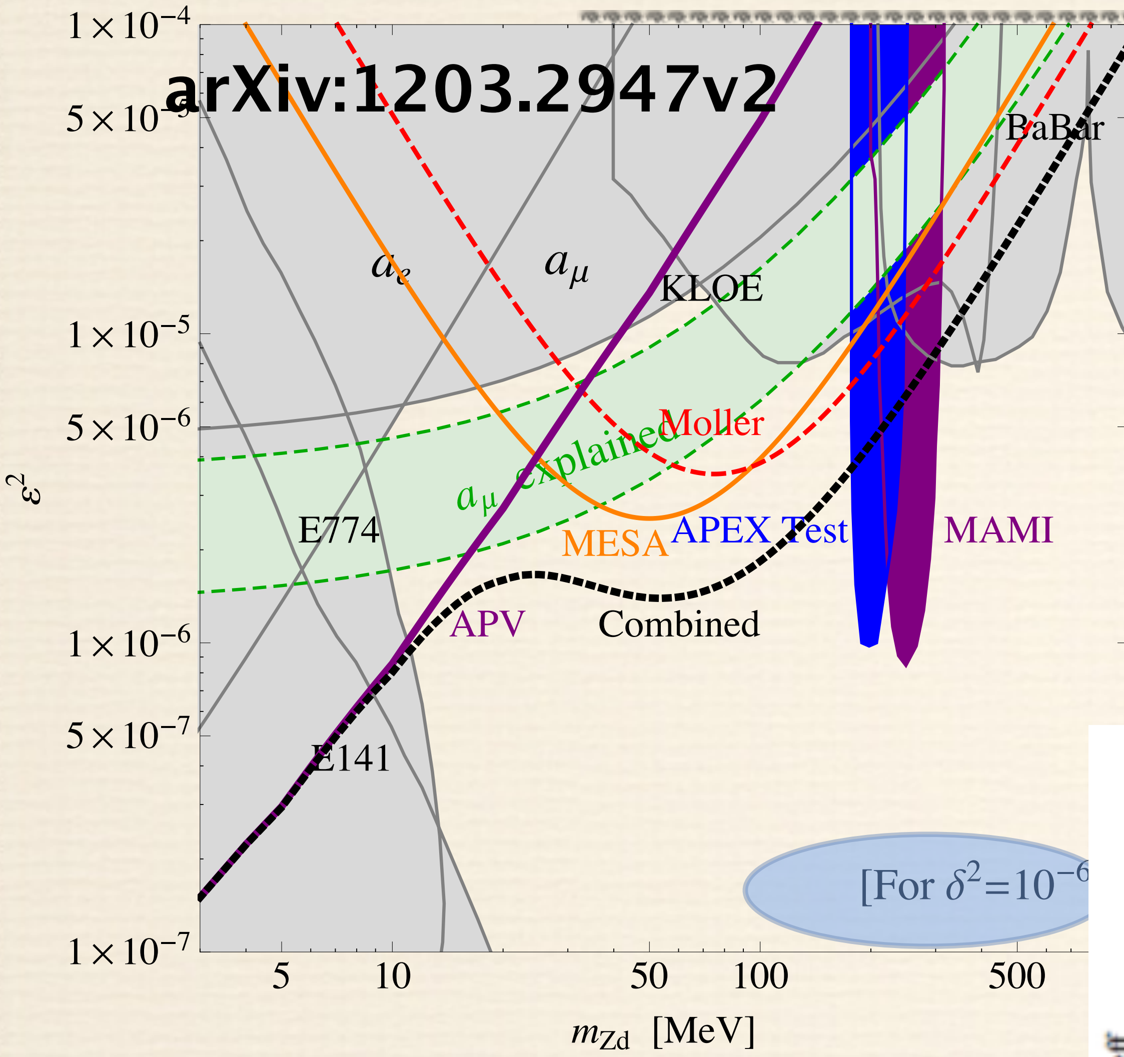


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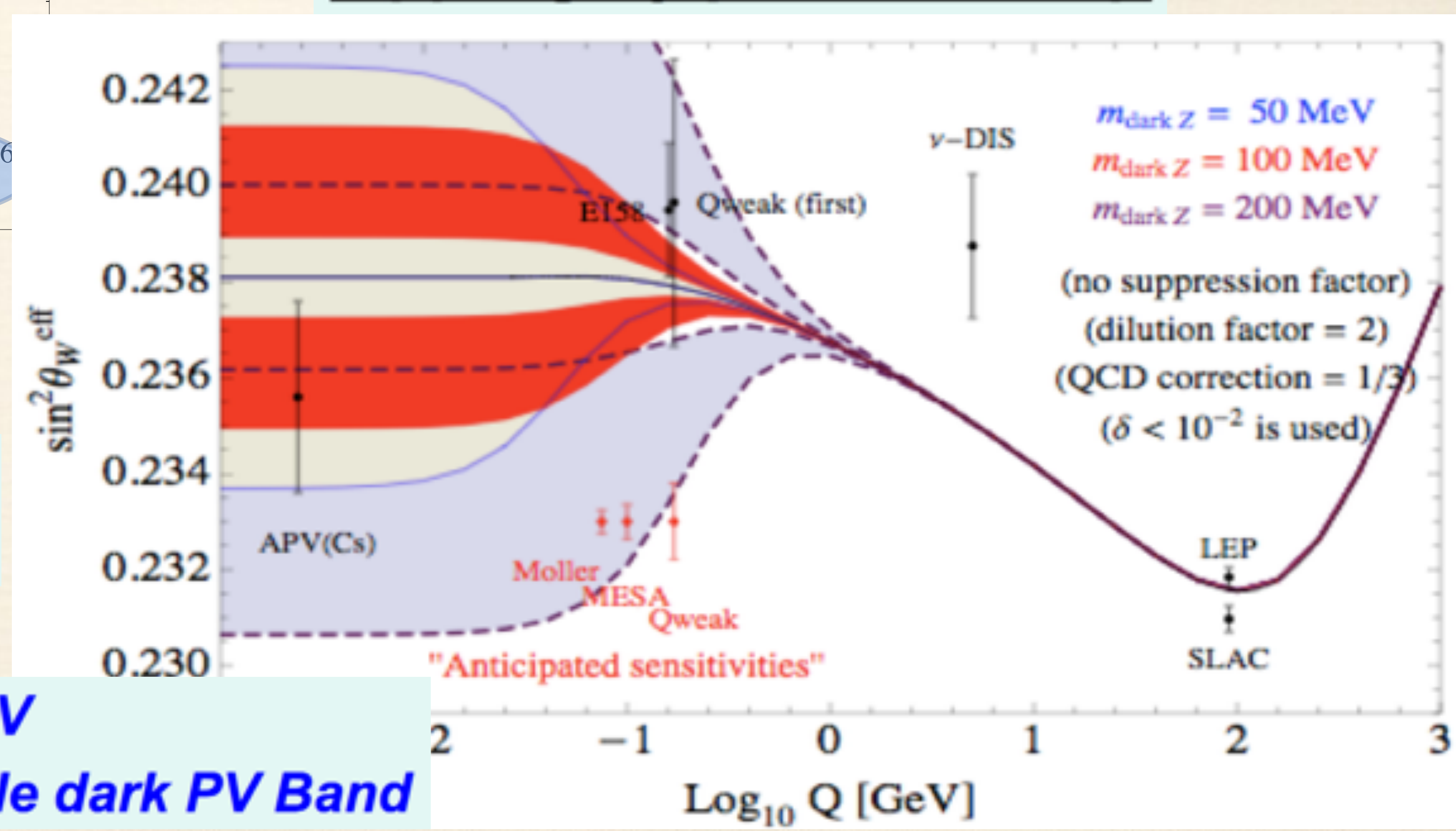



***$K \rightarrow \pi Z_d \rightarrow \pi$+"missing energy"***

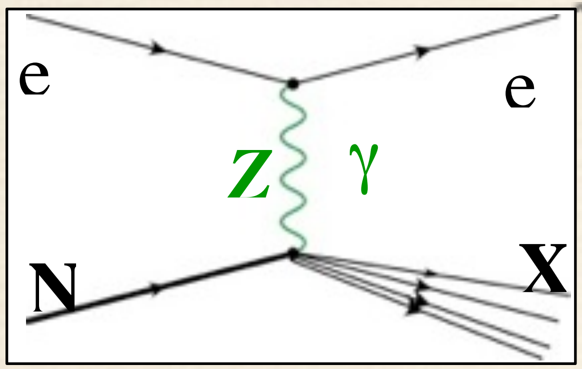
***ε and δ effects could partially cancel!***

***Suppression by ~1/6 allows $Z_d$~100MeV***

***Combined with muon g-2 → observable dark PV Band***

# PVDIS at JLab

## *Deuterium Target*




$$A_{PV} = \frac{G_F Q^2}{2\sqrt{2}\pi\alpha}\left[g_A \frac{F_1^{\gamma Z}}{F_1^{\gamma}} + g_V \frac{f(y)}{2}\frac{F_3^{\gamma Z}}{F_1^{\gamma}}\right]$$

***$Q^2 >> 1$ GeV$^2$ , $W^2 >> 4$ GeV$^2$***

$$C_{2q} \propto (g^{eq}_{RR})^2 - (g^{eq}_{RL})^2 + (g^{eq}_{LR})^2 - (g^{eq}_{LL})^2 \Rightarrow$$ ***PV deep inelastic scattering***

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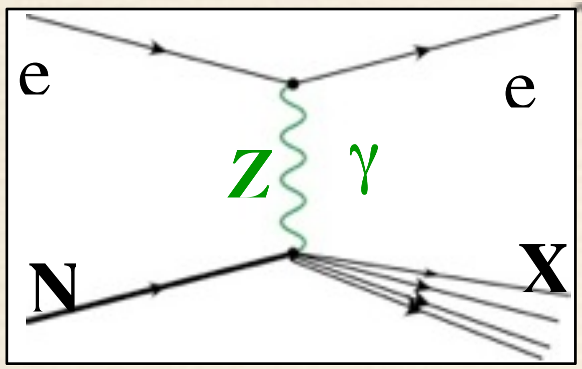


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**PVDIS at JLab 6 GeV: talk by V. Sulkosky**

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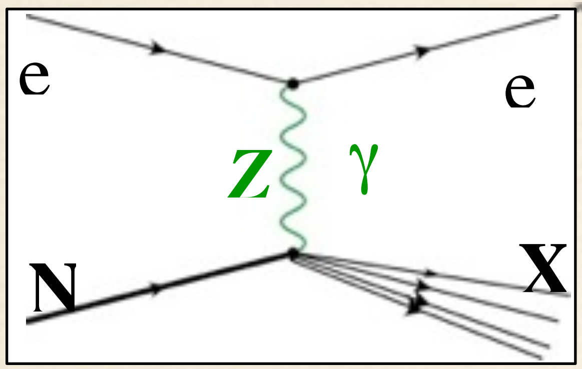


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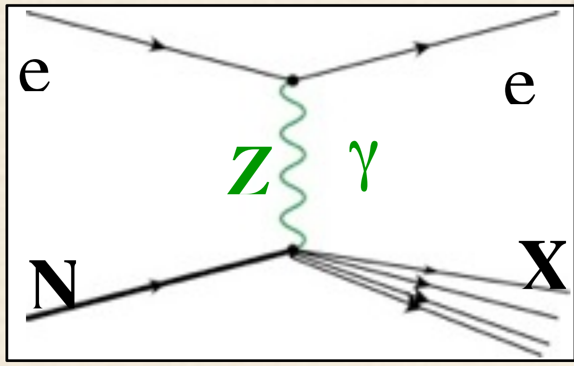


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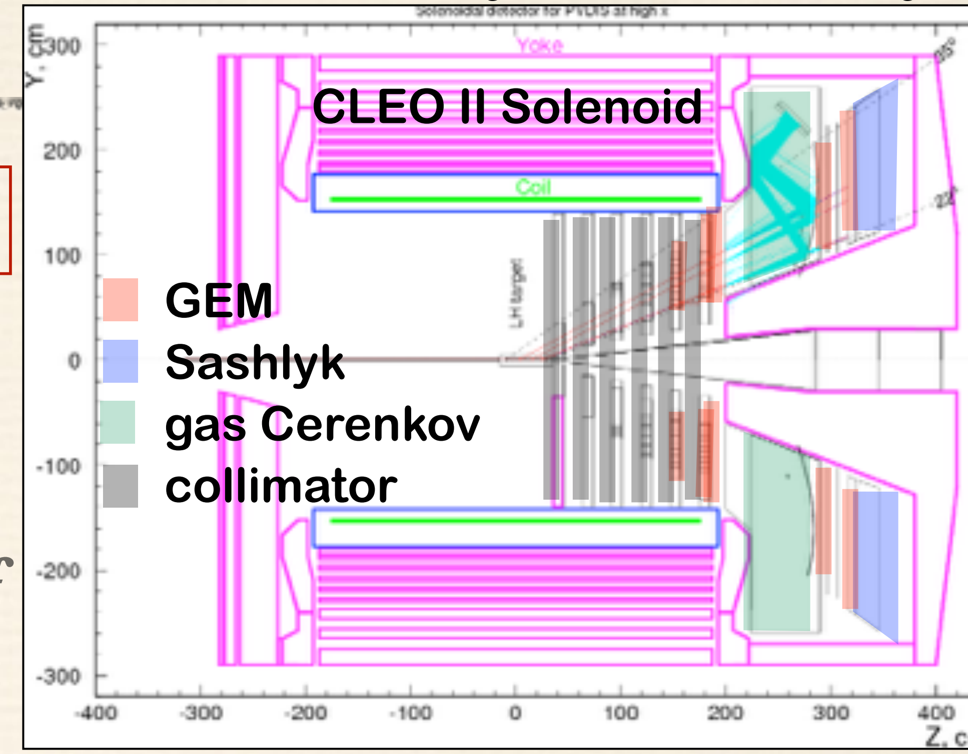


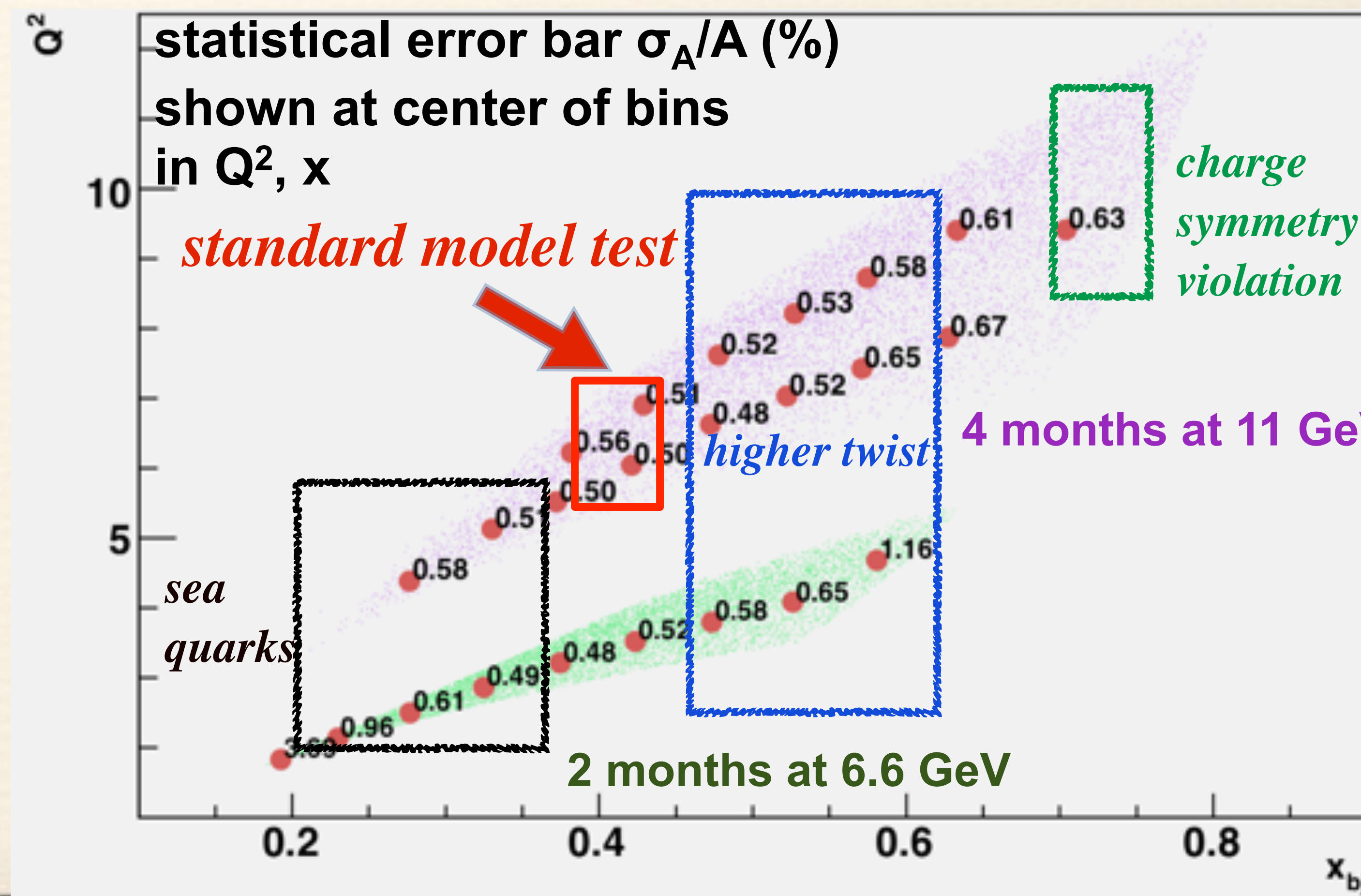

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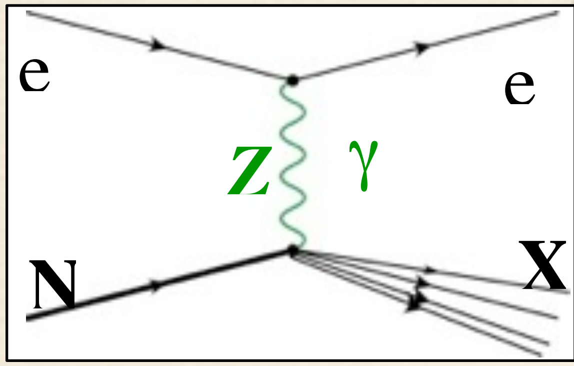


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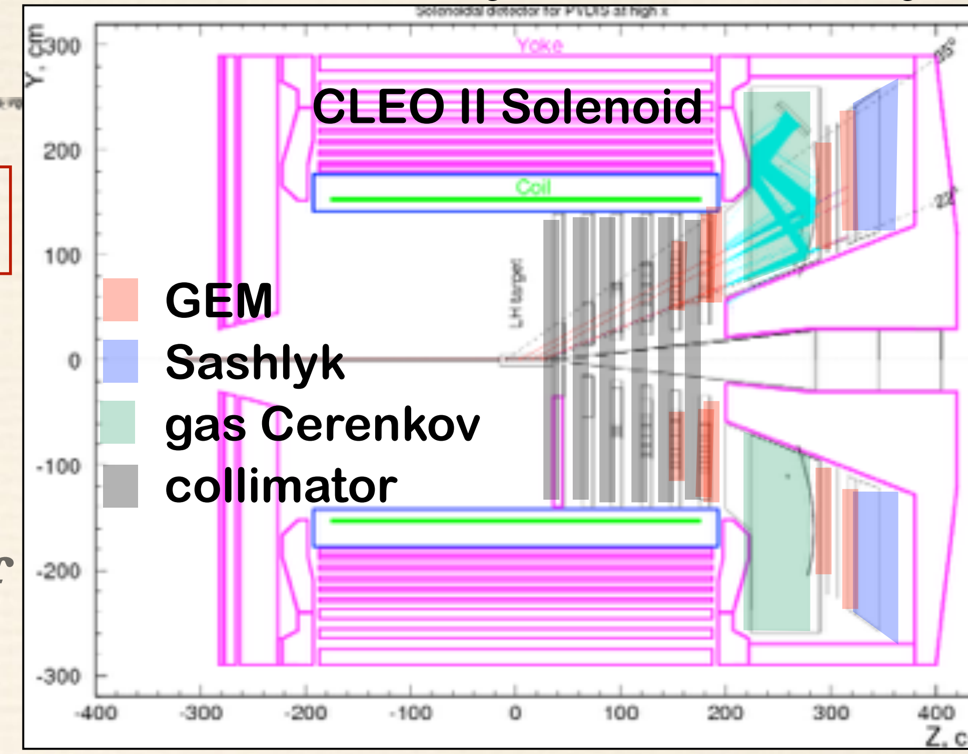


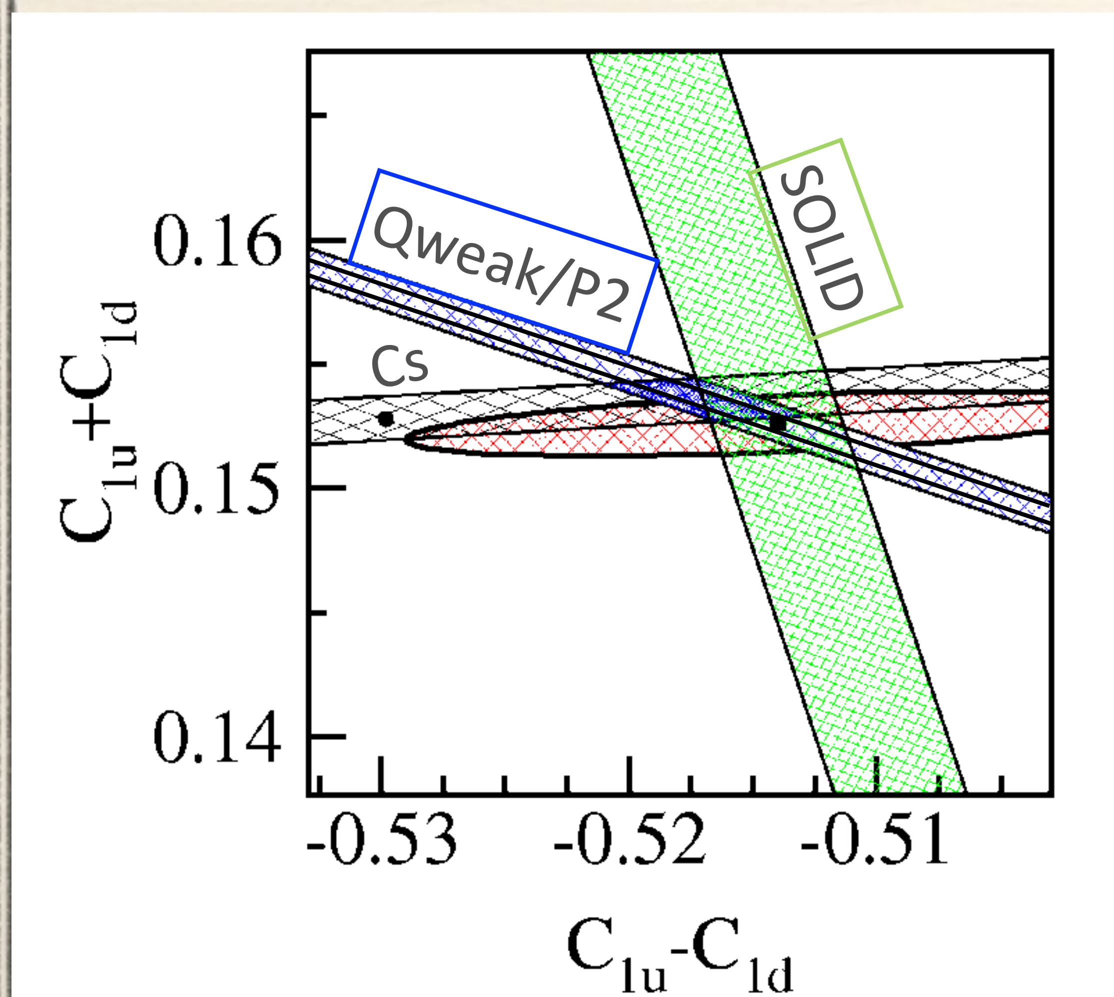


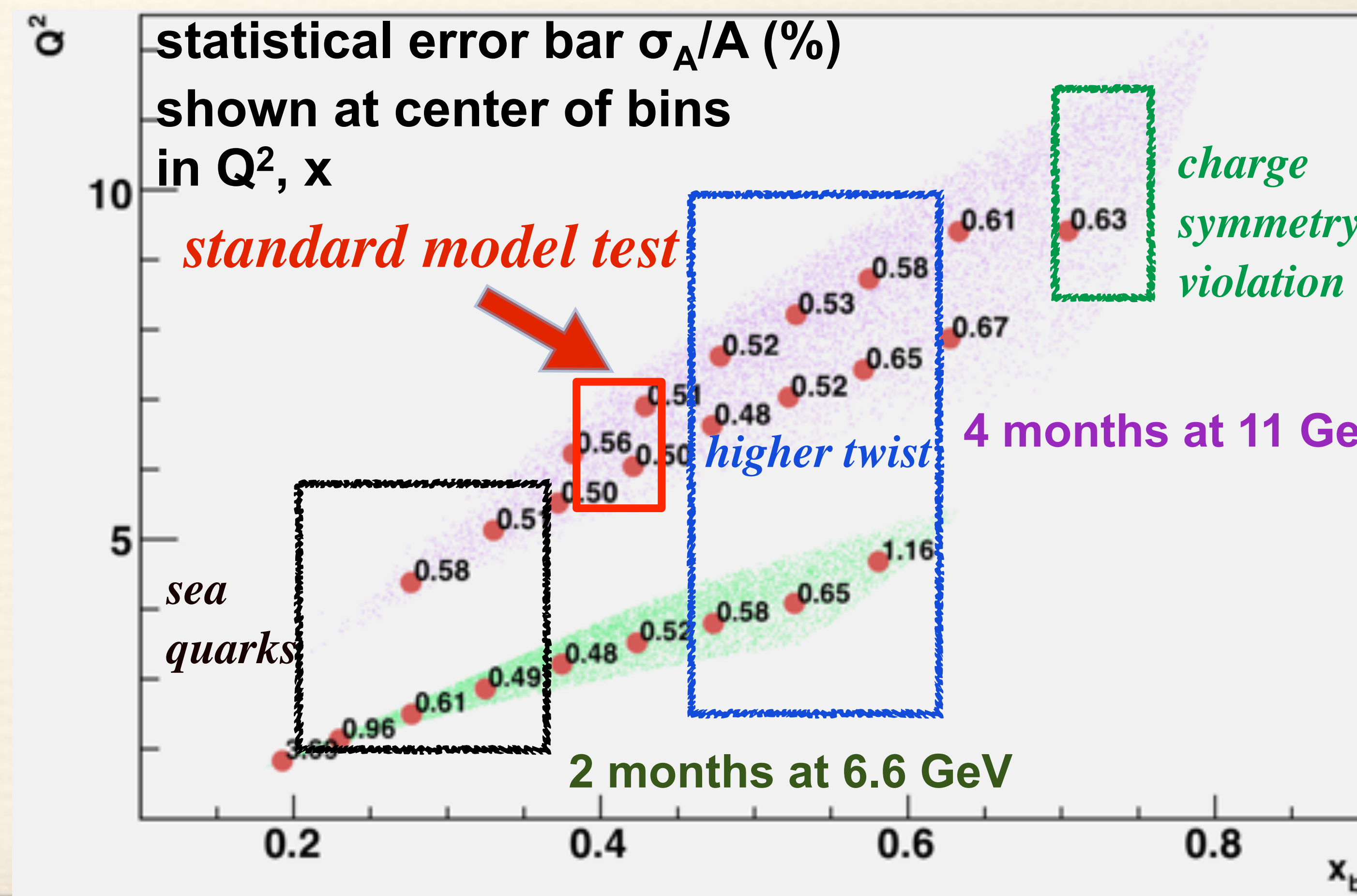

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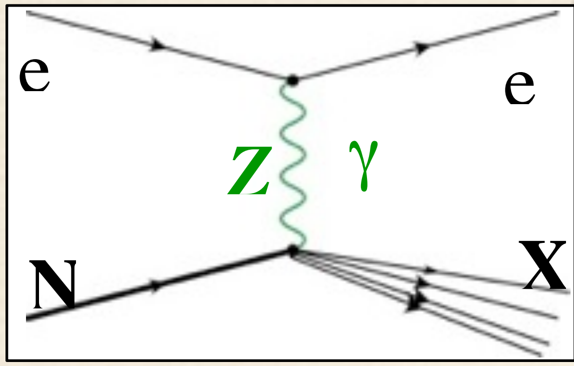
# SOLID **PVDIS at**

## *Deuterium Targ*

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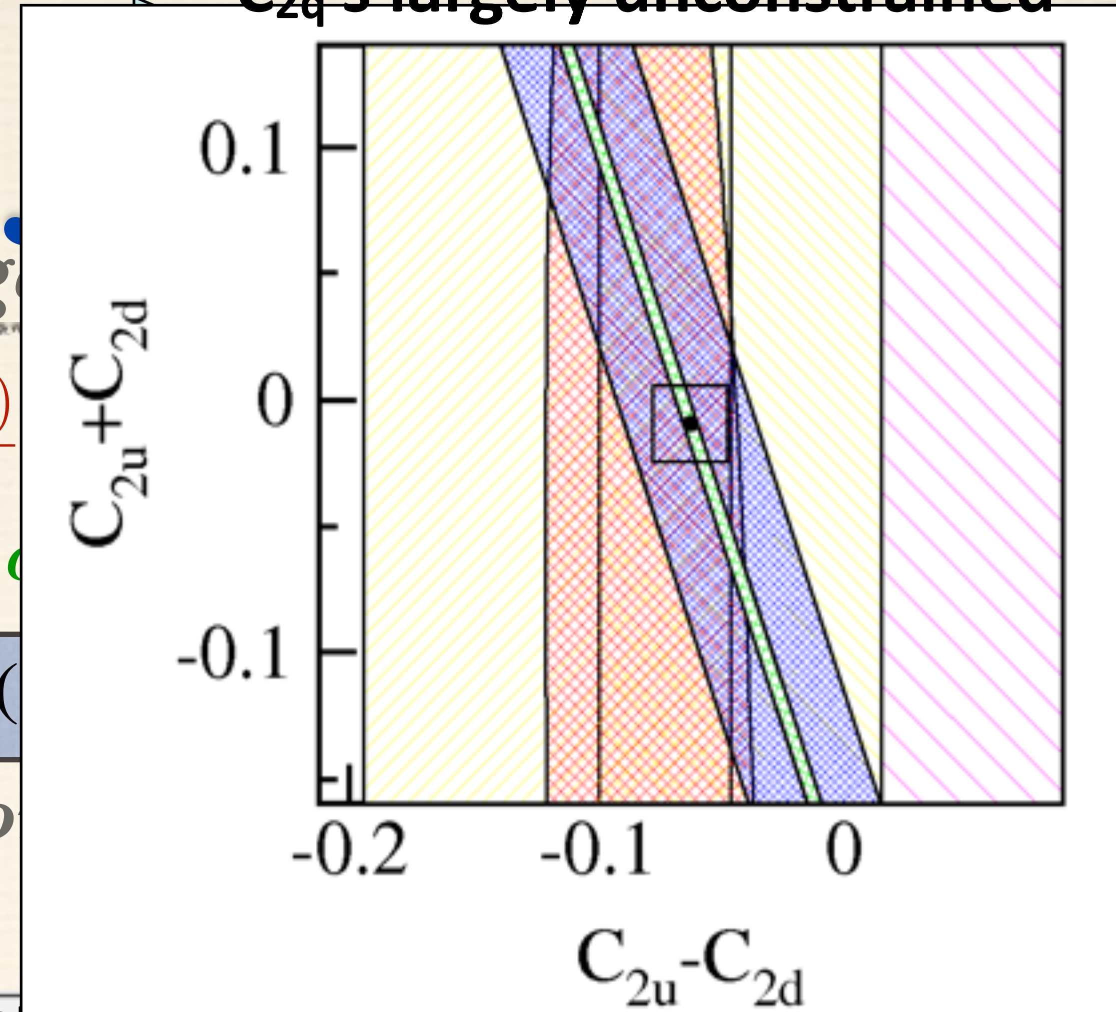
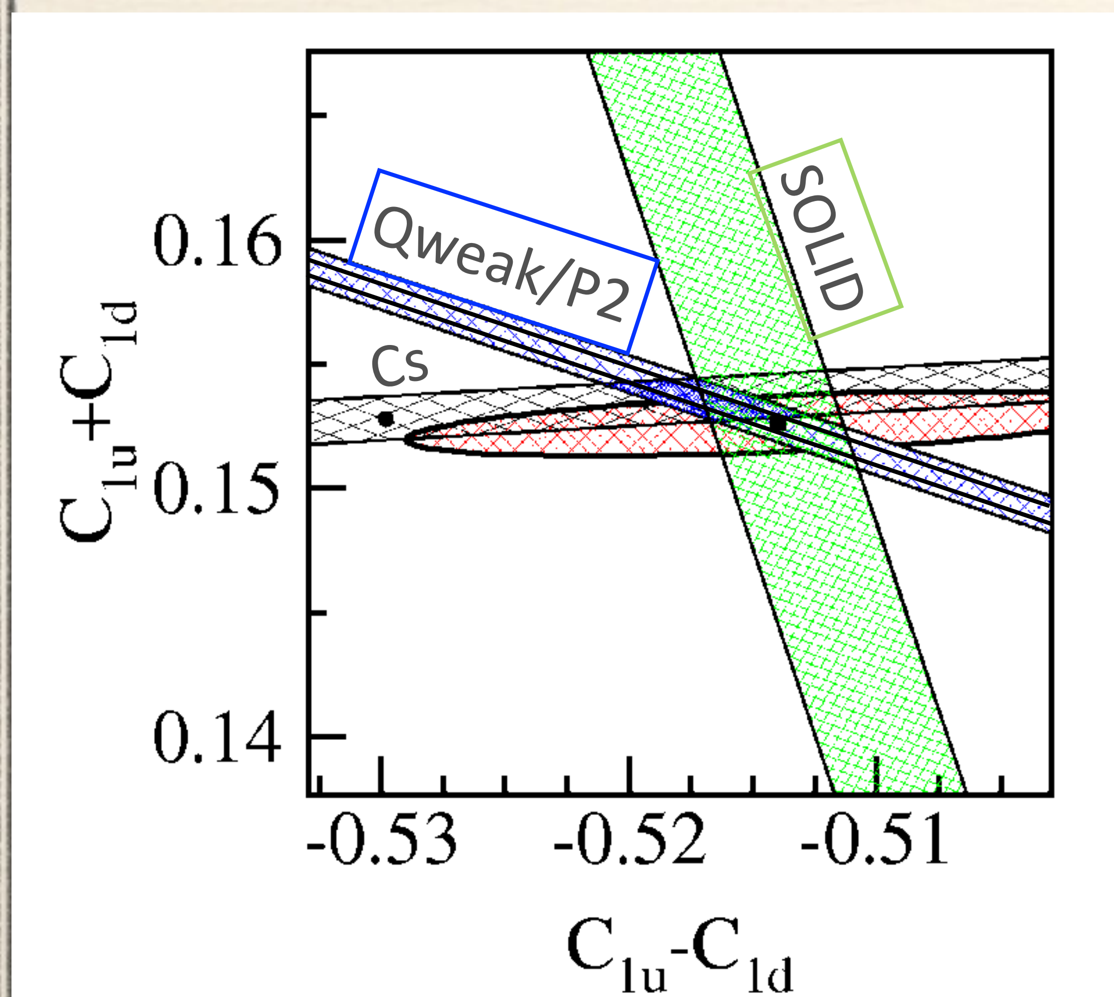
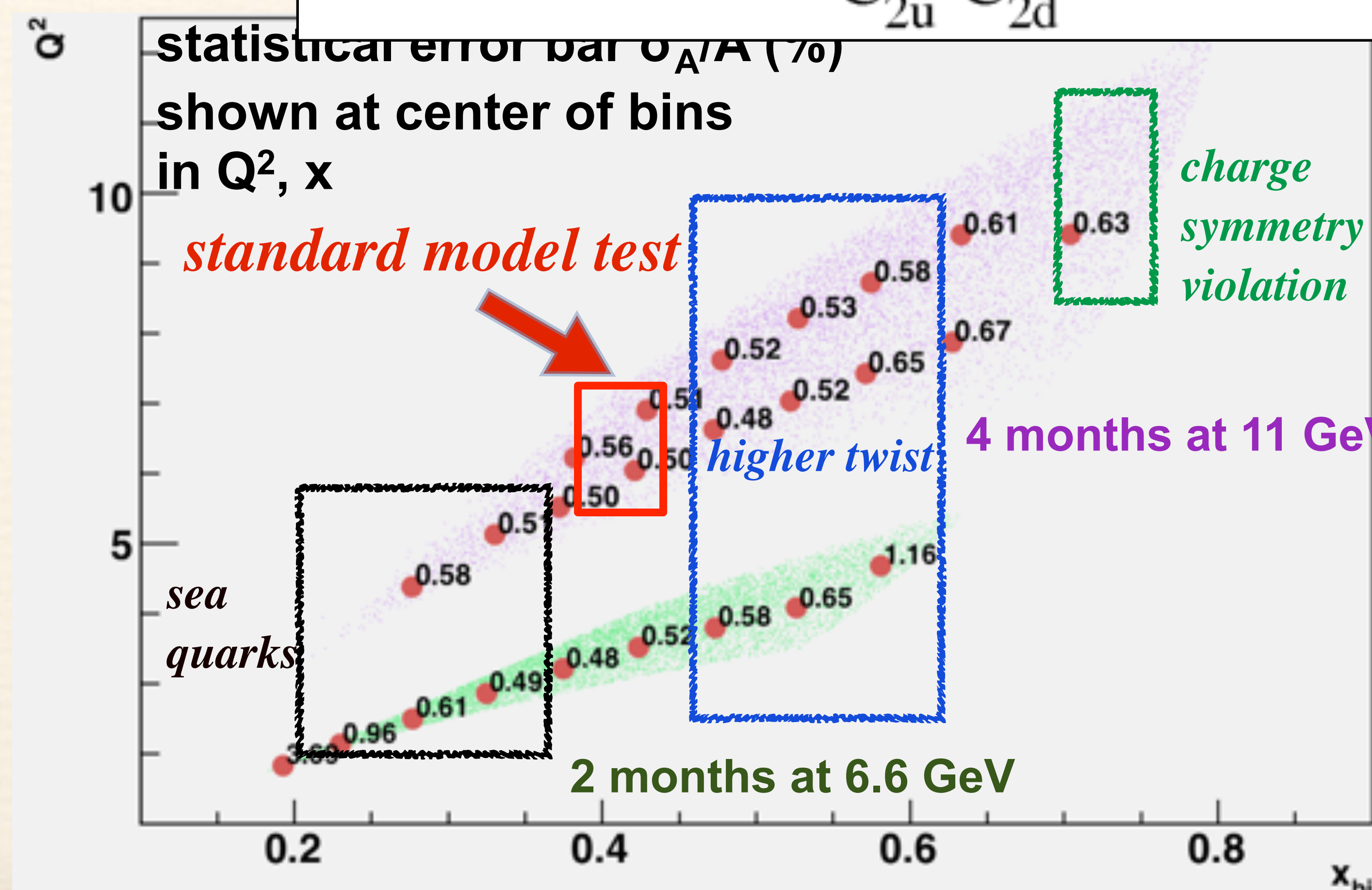
**C$_{2q}$'s largely unconstrained**



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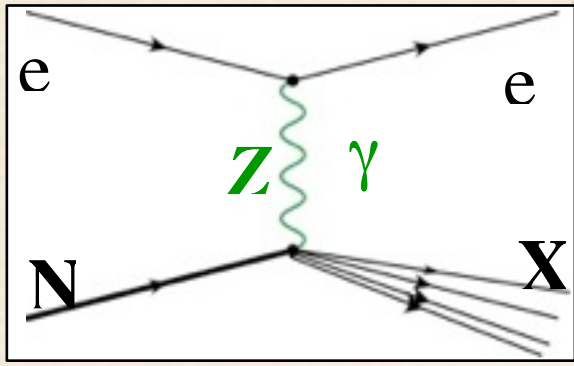


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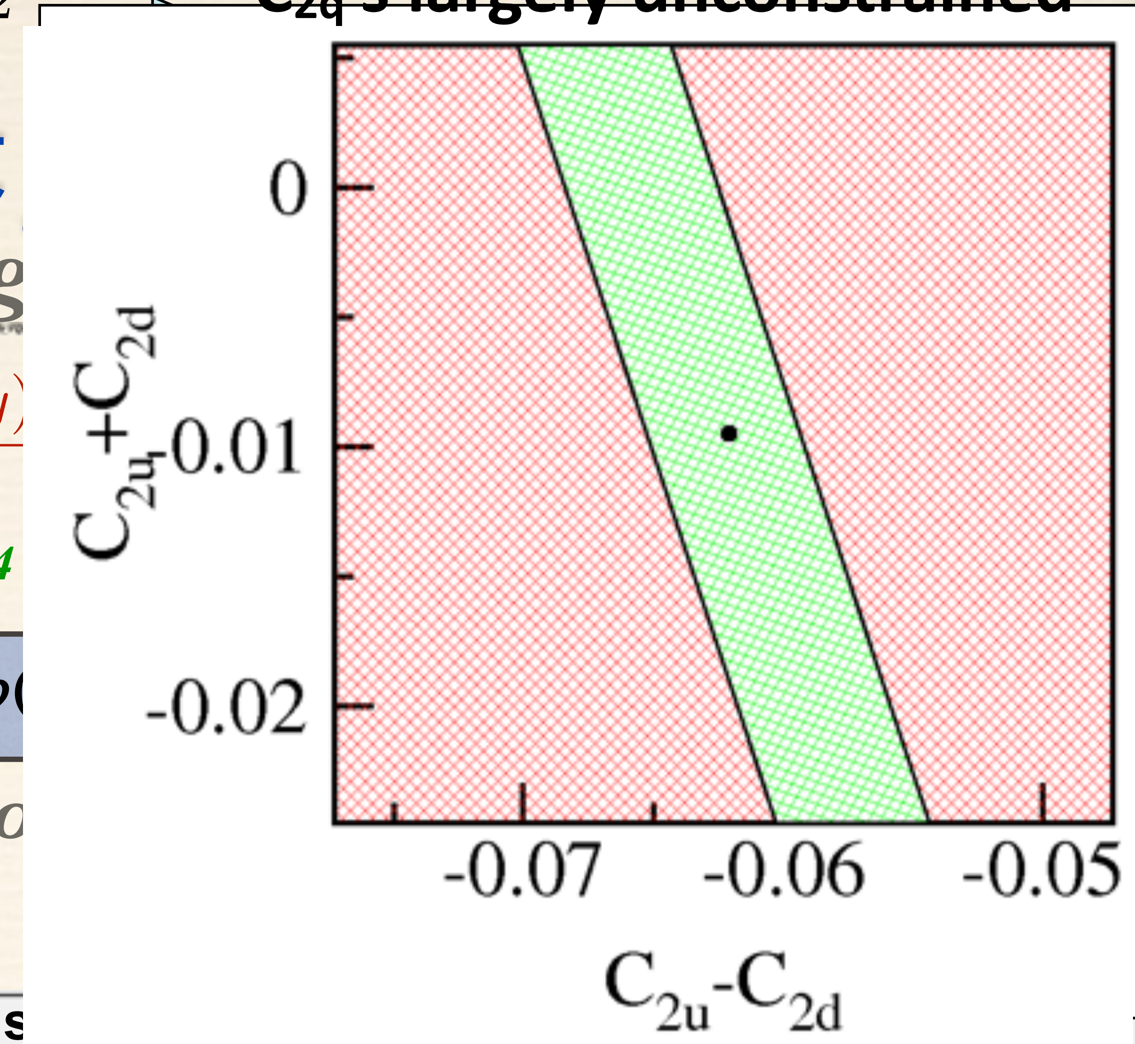
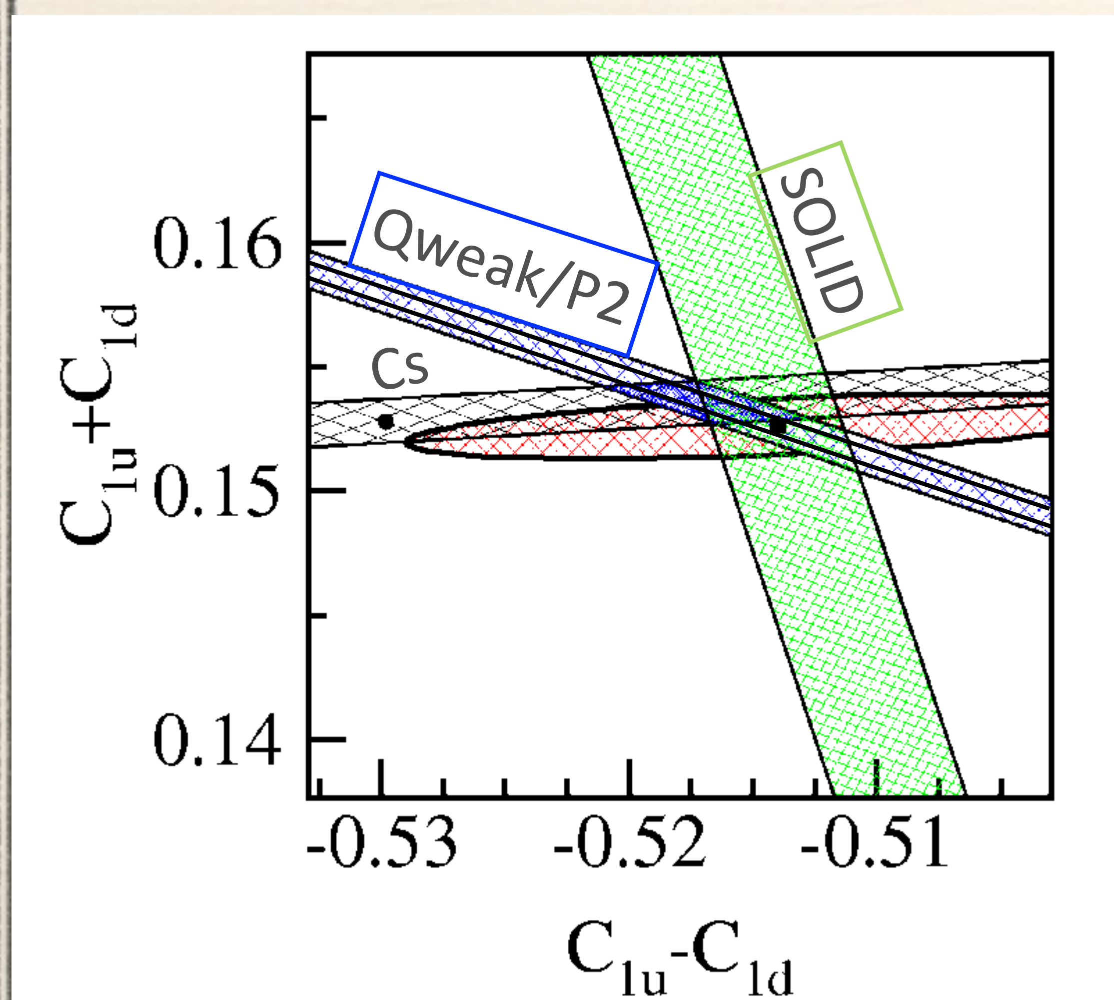
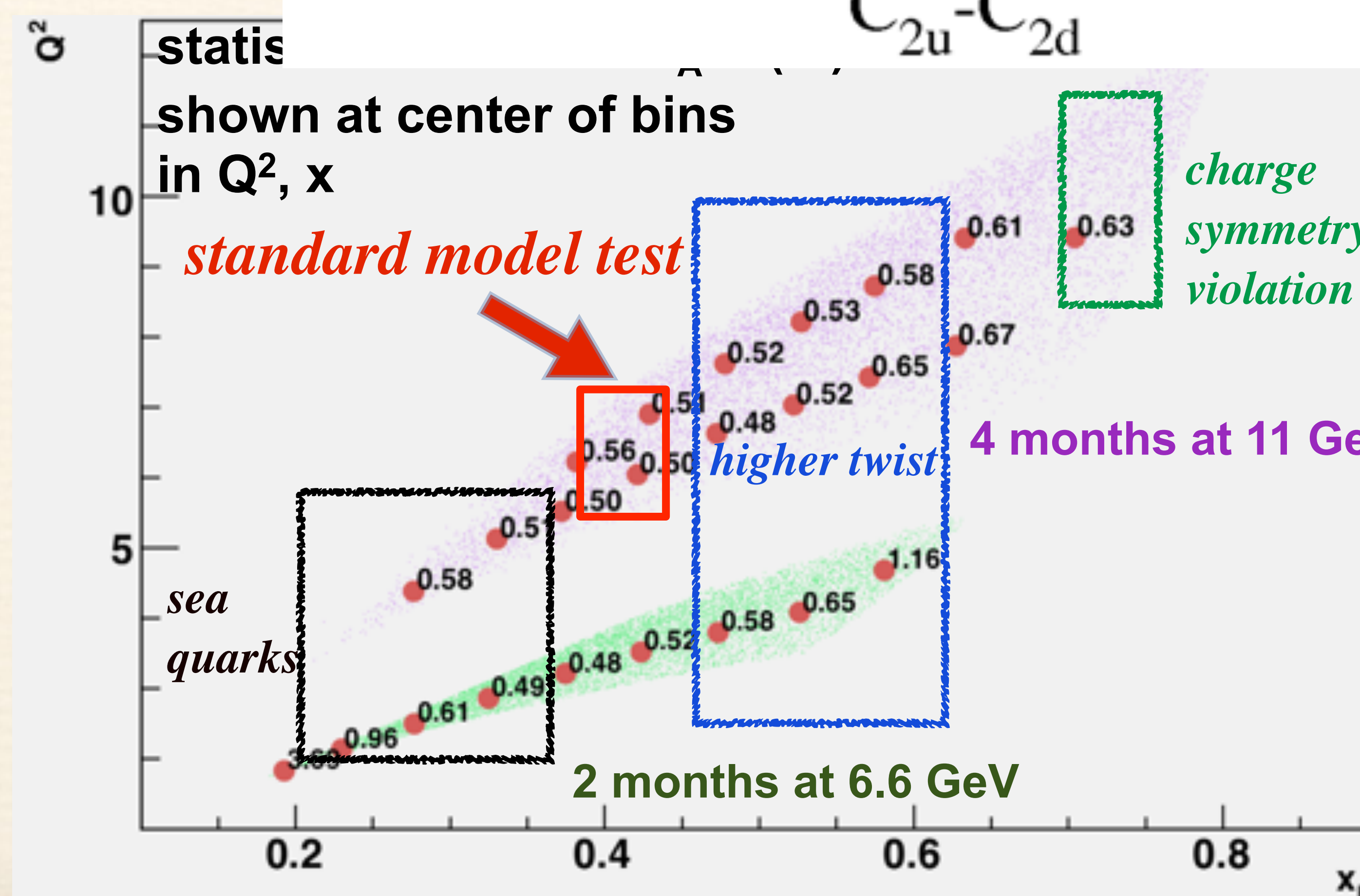
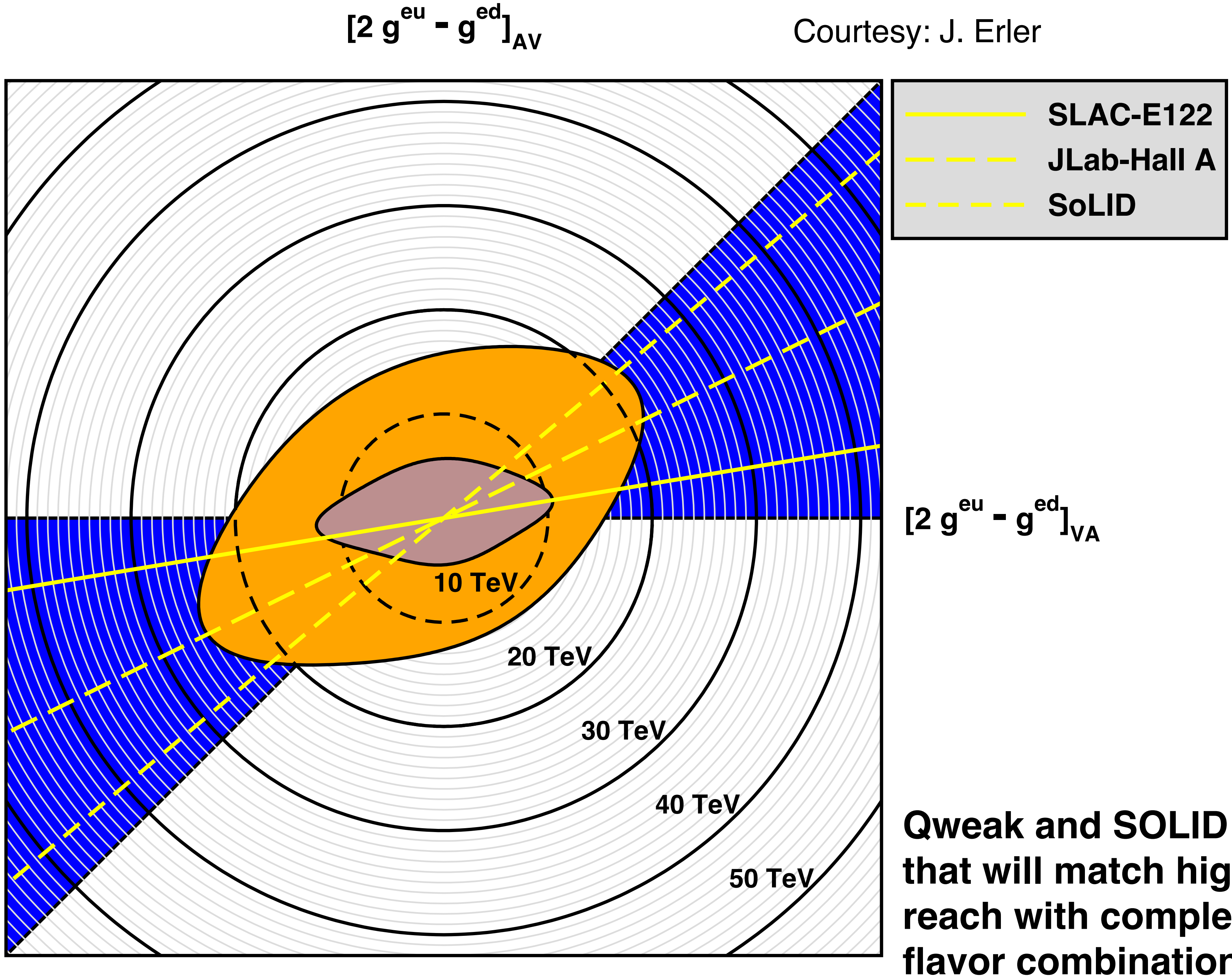


# SOLID Sensitivity




**Final Qweak result + projected SOLID**

**Qweak and SOLID will expand sensitivity that will match high luminosity LHC reach with complementary chiral and flavor combinations**

*Longstanding issue in proton structure*

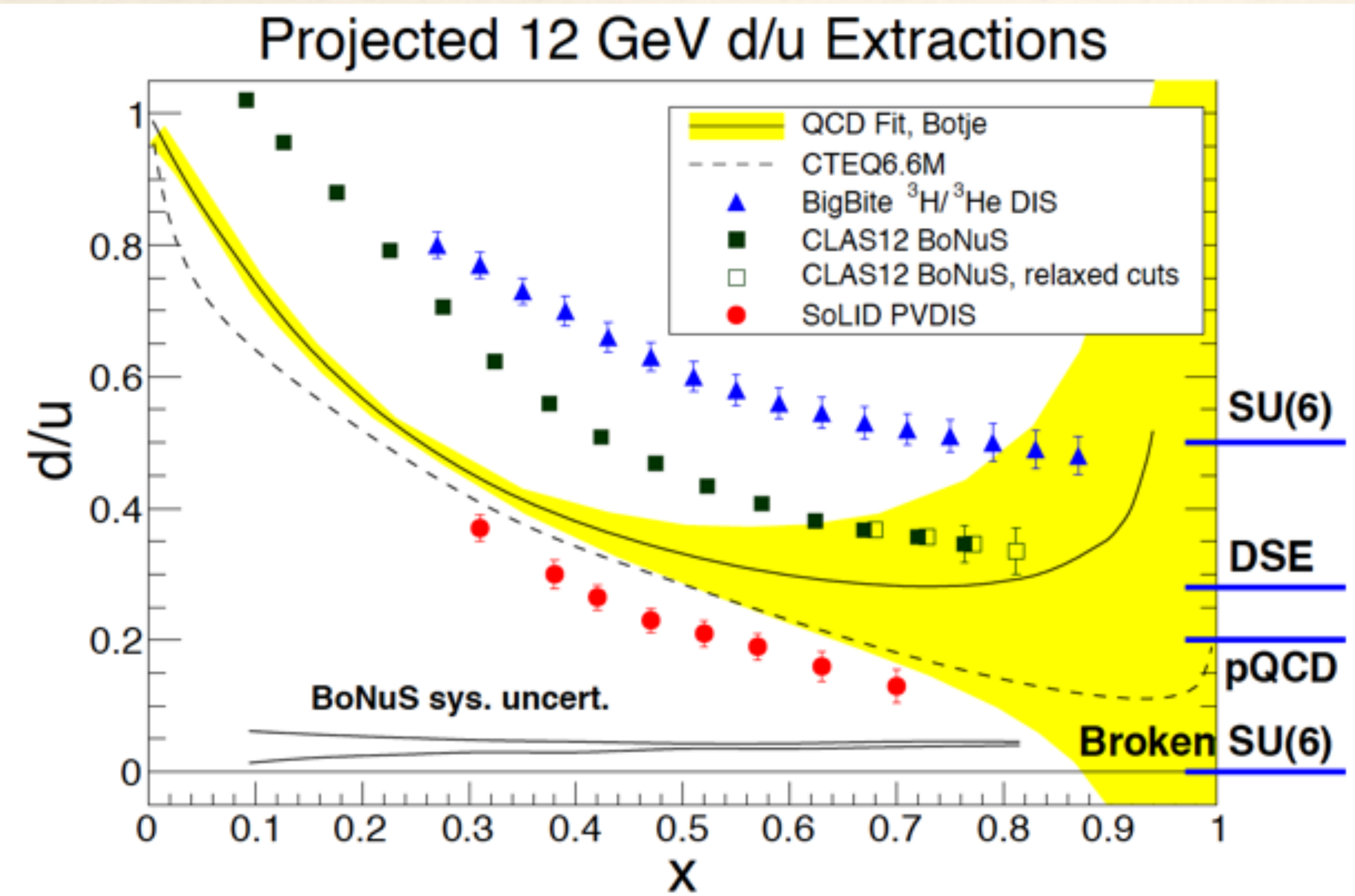
# d/u at high x

**PV-DIS off the proton (hydrogen target)**

$$A_{PV} = \frac{G_F Q^2}{\sqrt{2}\pi\alpha}\left[a(x) + f(y)b(x)\right]$$

*SU(6): d/u~1/2*
*Valence Quark: d/u~0*
*Perturbative QCD: d/u~1/5*

$$a^P(x) \approx \frac{u(x) + 0.91d(x)}{u(x) + 0.25d(x)}$$




- Three JLab 12 GeV experiments:
  - CLAS12 BoNuS - spectator tagging
  - BigBite - DIS $^3H/^3He$ Ratio
  - SoLID - PVDIS *ep*
- The SoLID extraction of $d/u$ is made directly from *ep* DIS: *no nuclear corrections*

# Summary

- ✦ **Parity-Violating Electron Scattering**
  - ★ Technical progress has enabled unprecedented precision
  - ★ flagship experiments at electron accelerators
  - ★ Nuclear/Nucleon Physics
    - *Neutron RMS radii of heavy nuclei: JLab (PREX, CREX) & MESA*
    - *valence quark structure of protons and neutrons: SOLID*
  - ★ Electroweak Physics
    - *Qweak, 6 GeV PVDIS, MOLLER, SOLID (JLab) and P2 (MESA)*
    - *Search for new dynamics at the multi-TeV scale and the 100 MeV scale*
    - *precision measurements of the weak mixing angle at various $Q^2$ values*

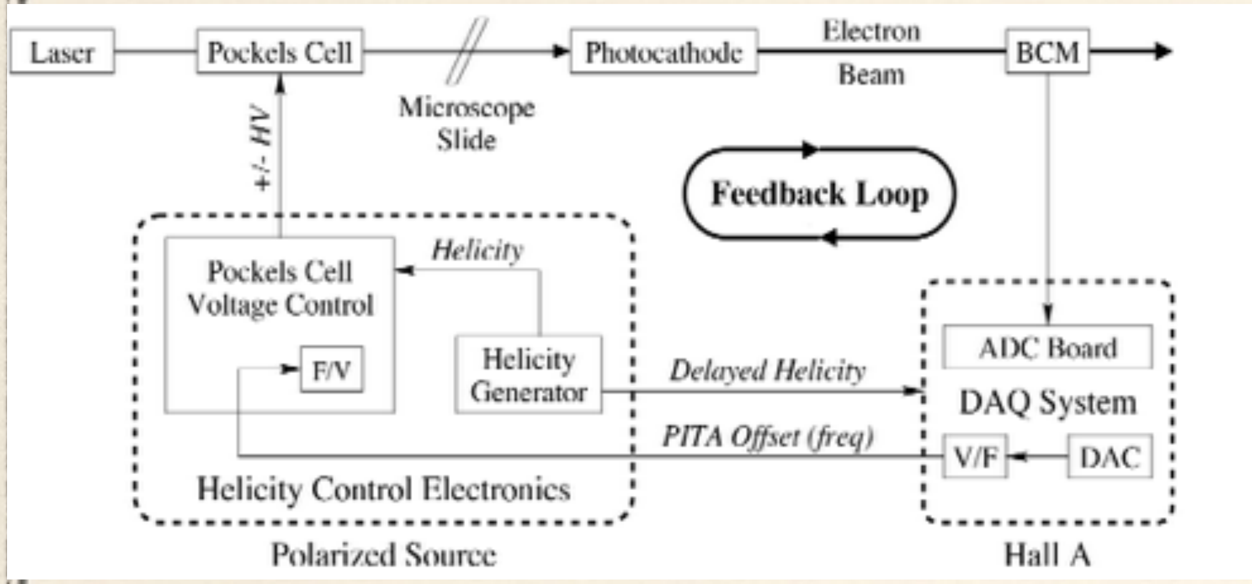
**A rich experimental program over the next 5 to 10 years at Jefferson Laboratory and the new Mainz MESA facility**

# *Backup*

$A_{phys} \sim 500$ ppb

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

# Parity Quality Beam




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

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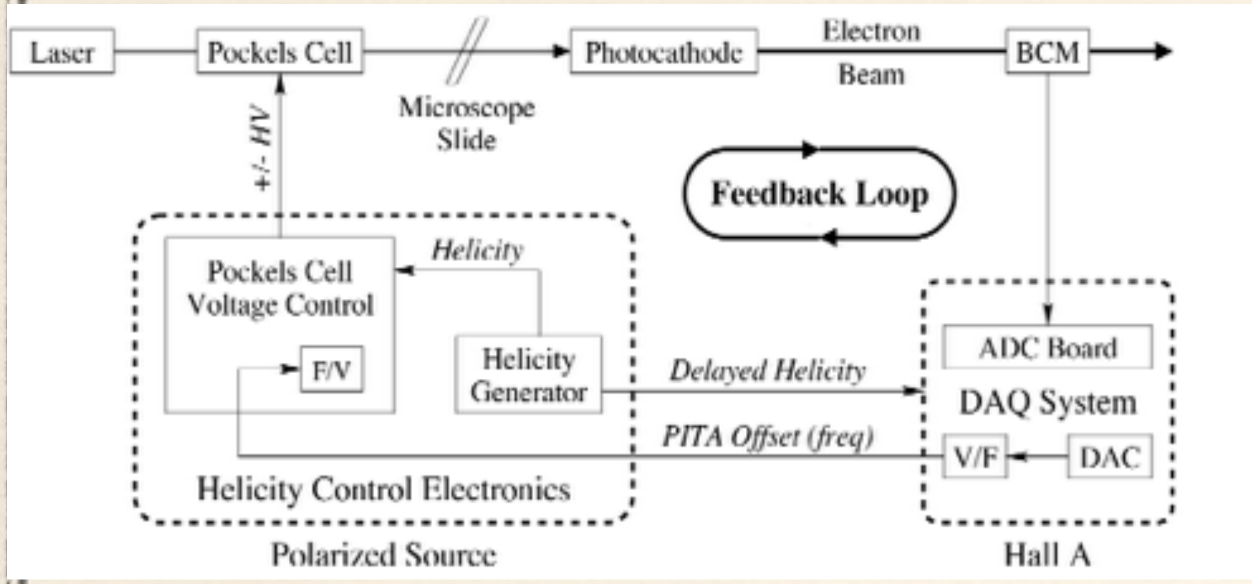


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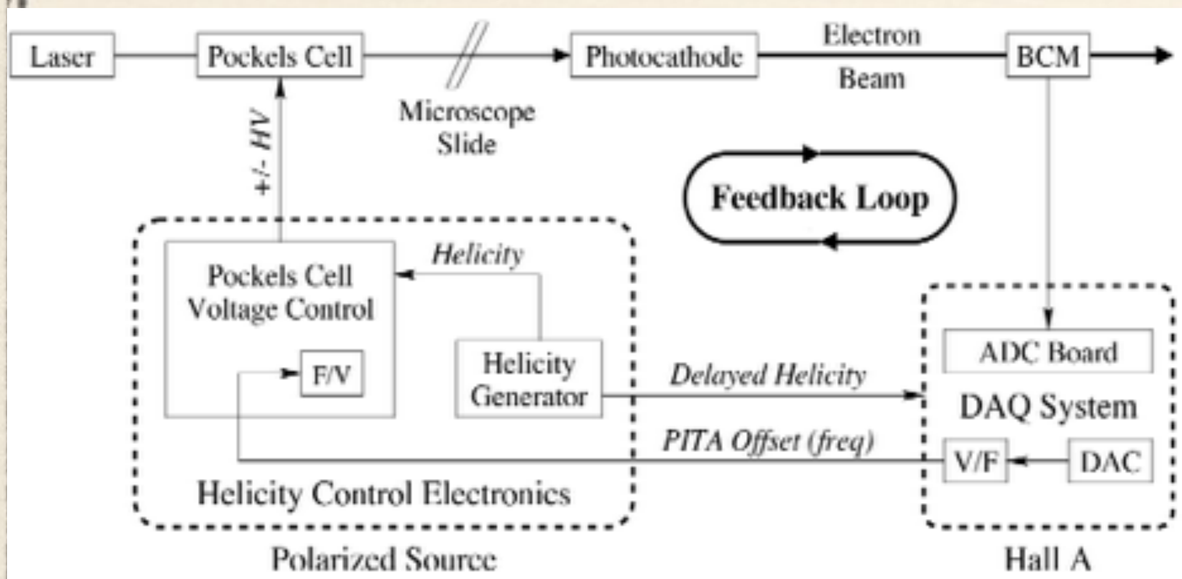


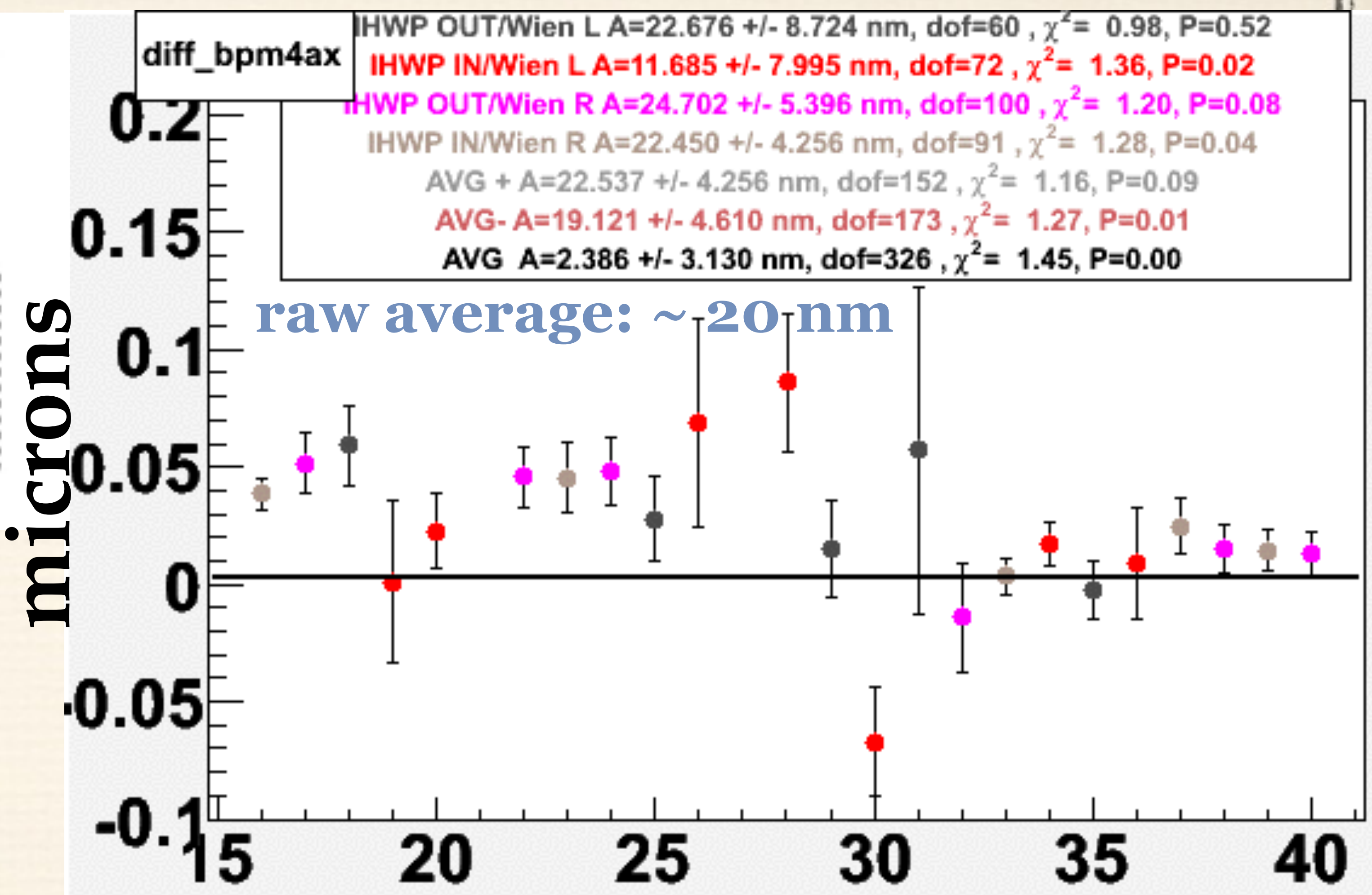


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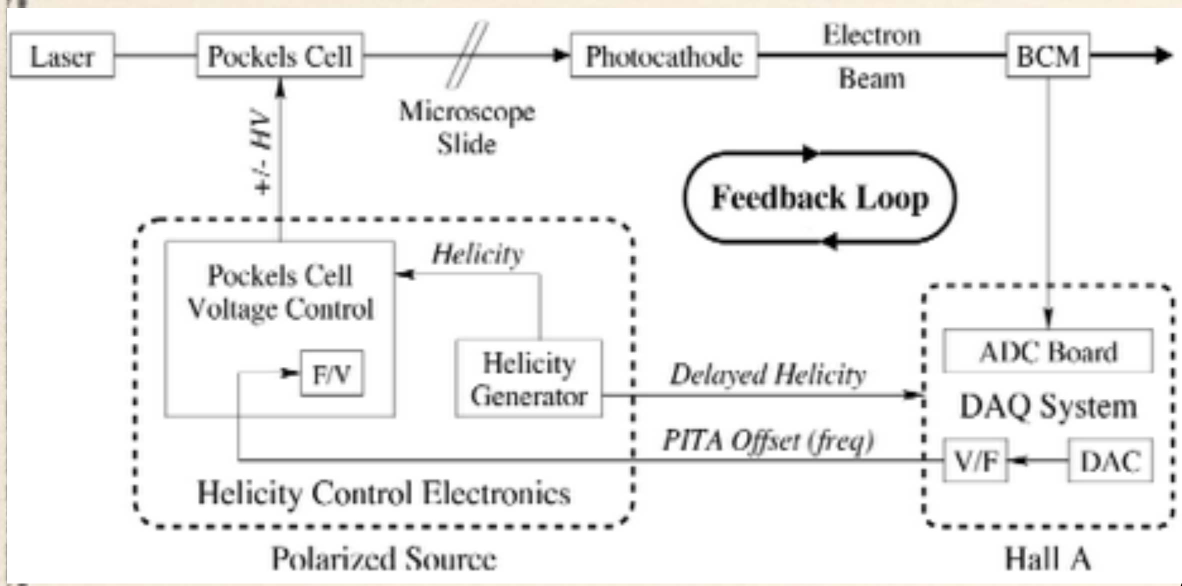
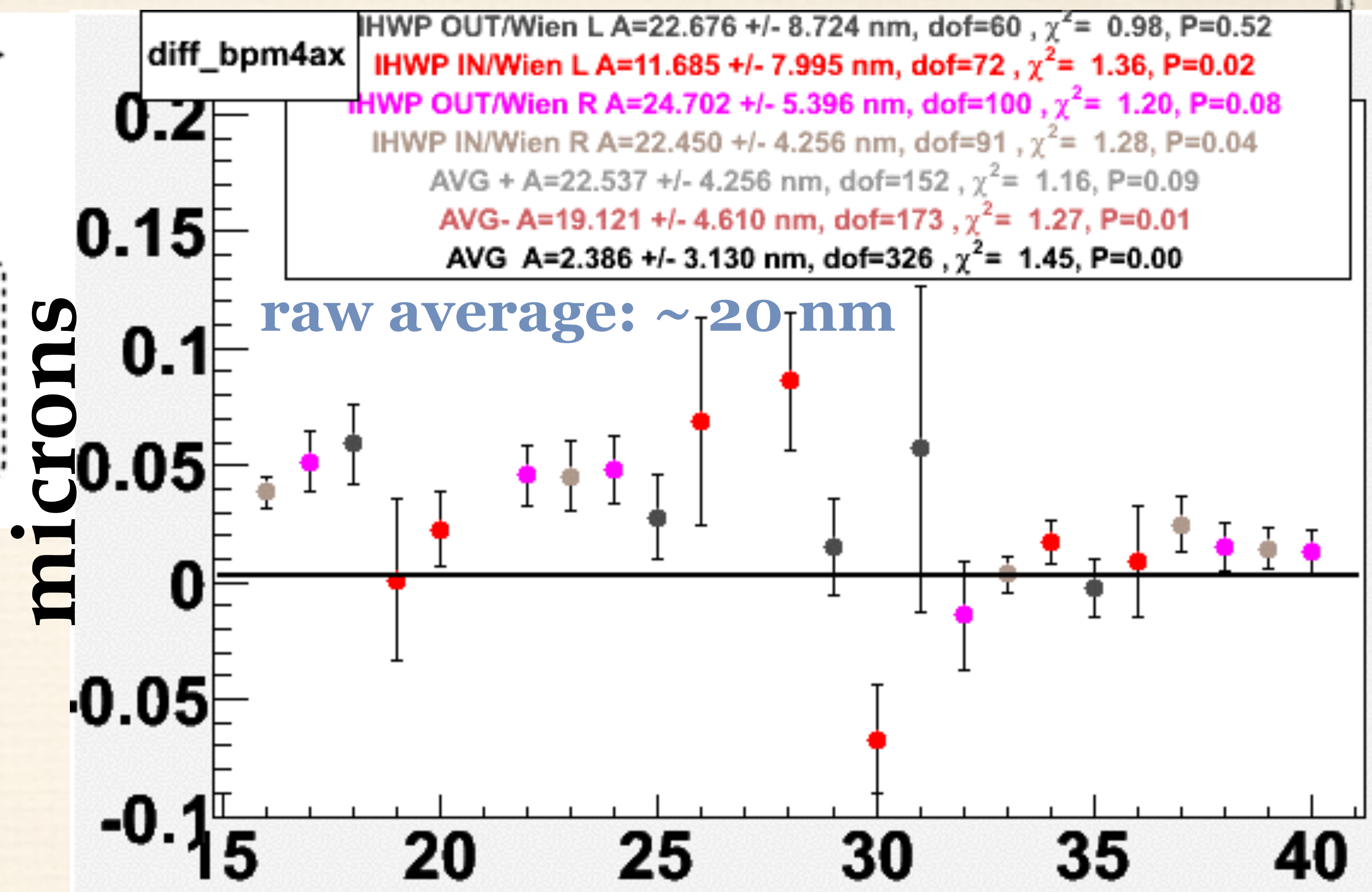
- *Careful laser alignment*
- *Precision beam position monitoring*
- *Active calibration of detector slopes*

$A_{phys} \sim 500$ ppb

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

# Parity Quality Beam

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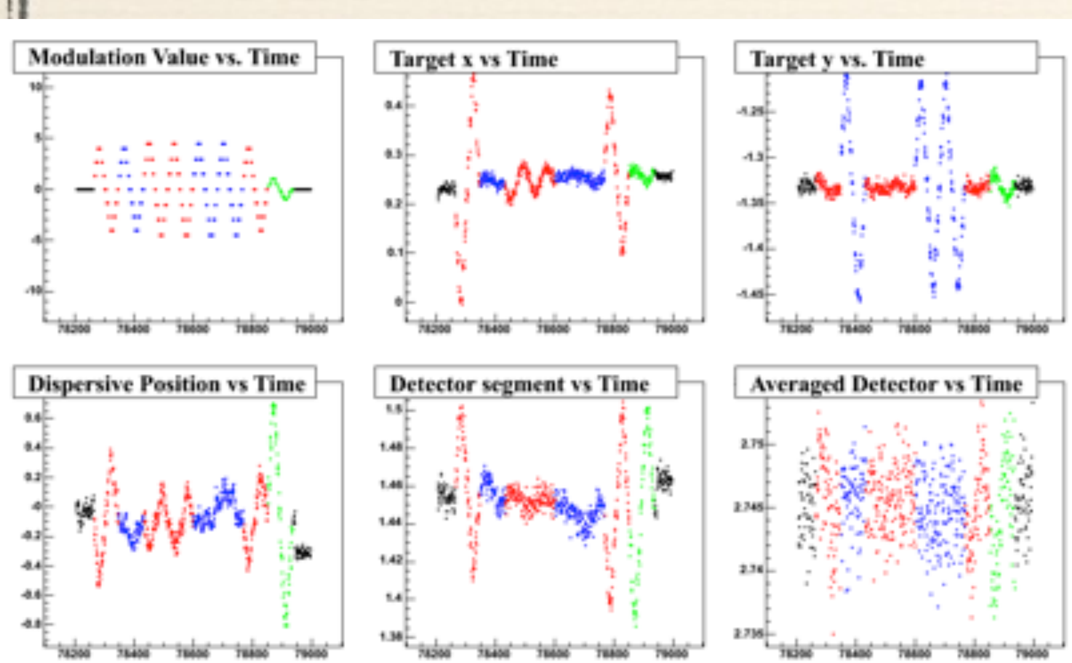

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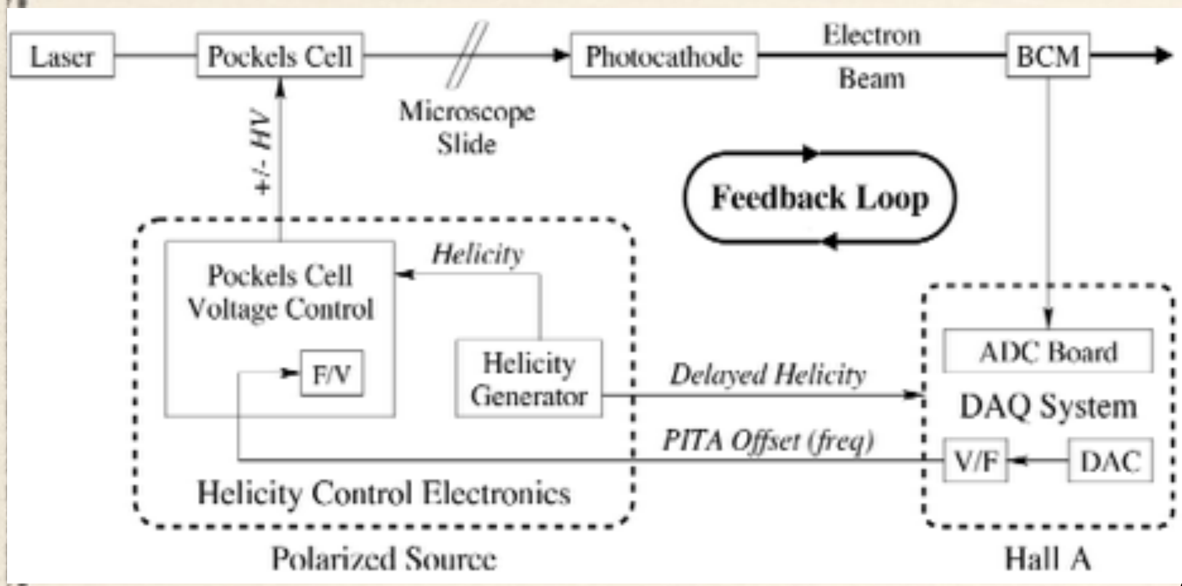


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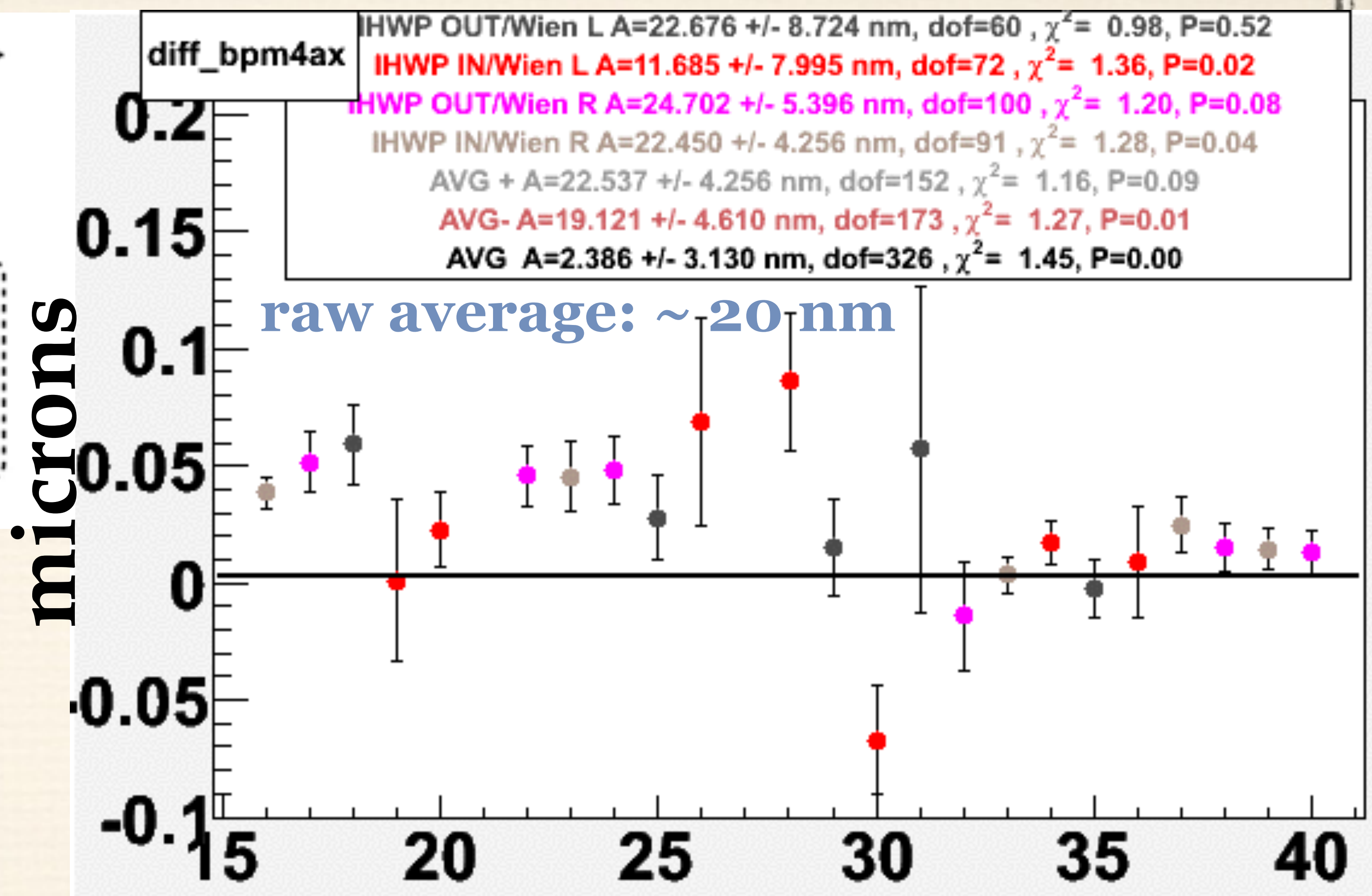
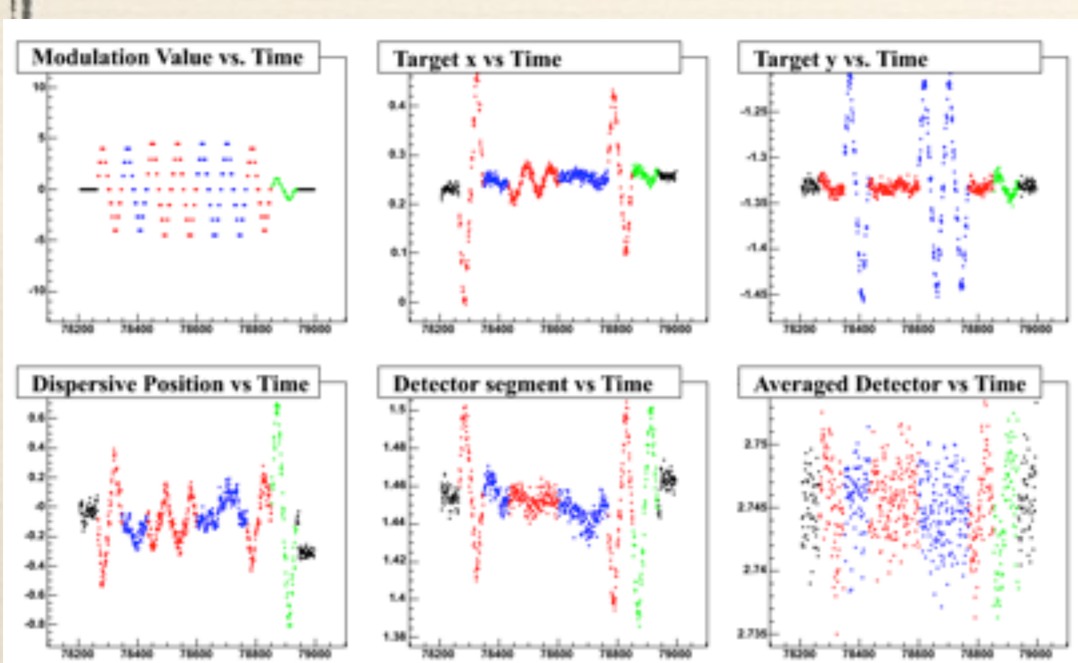
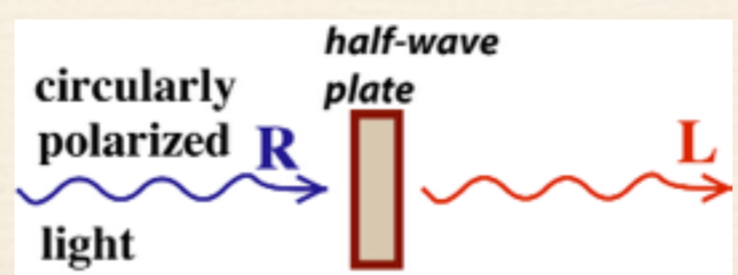



**2 methods of "slow" reversal**



$A_{phys} \sim 500$ ppb

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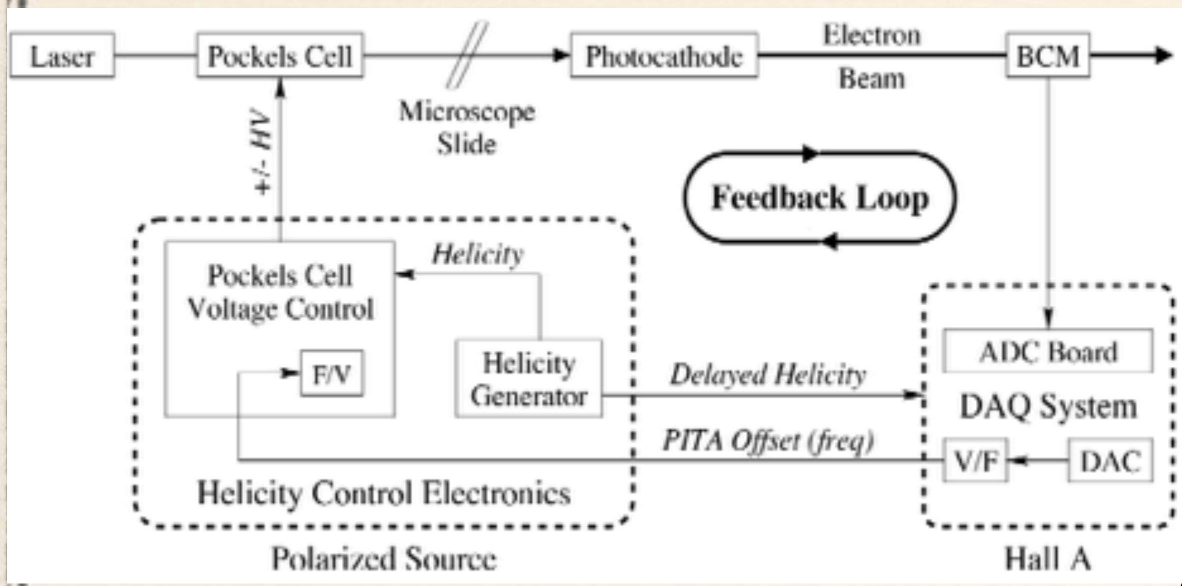


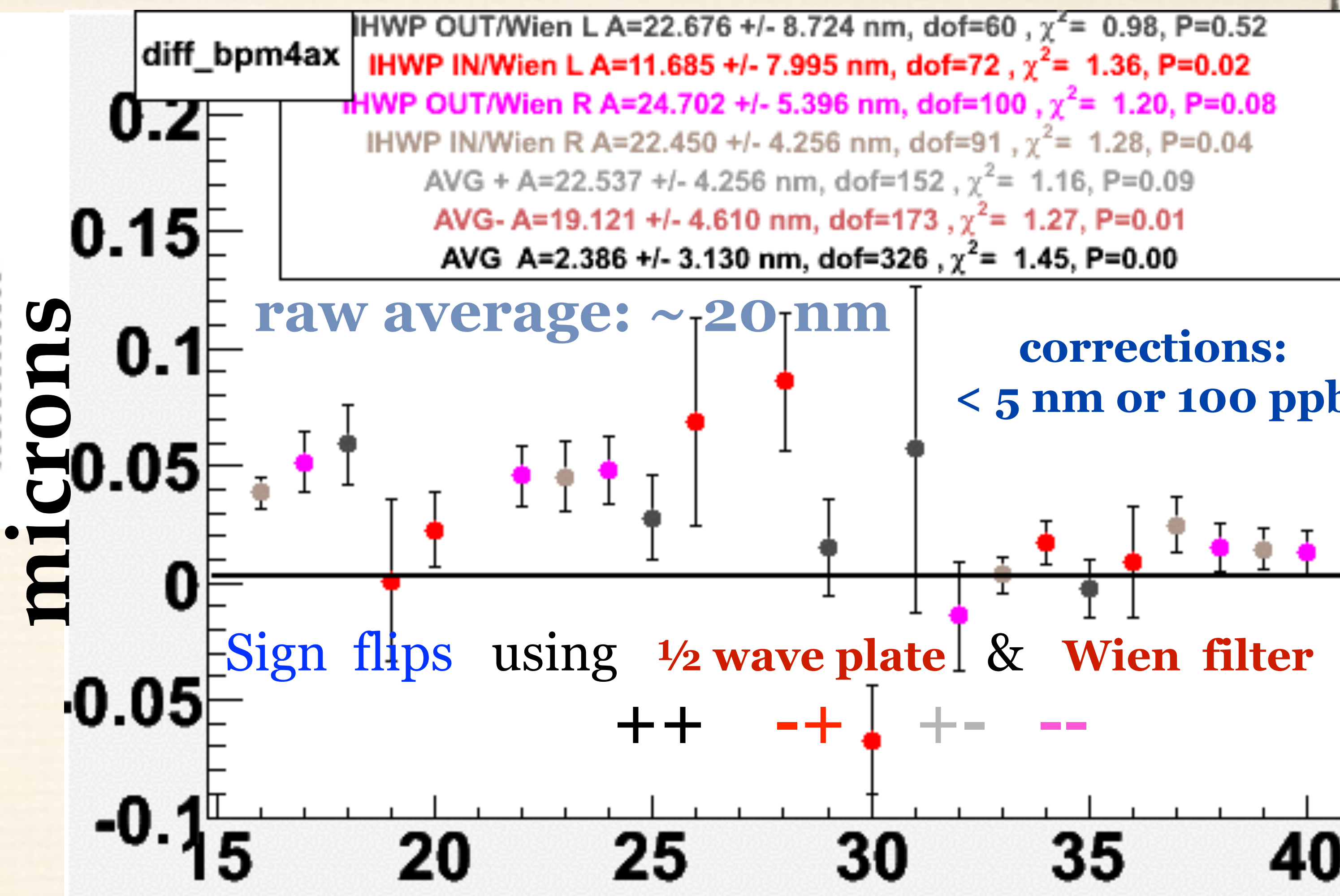


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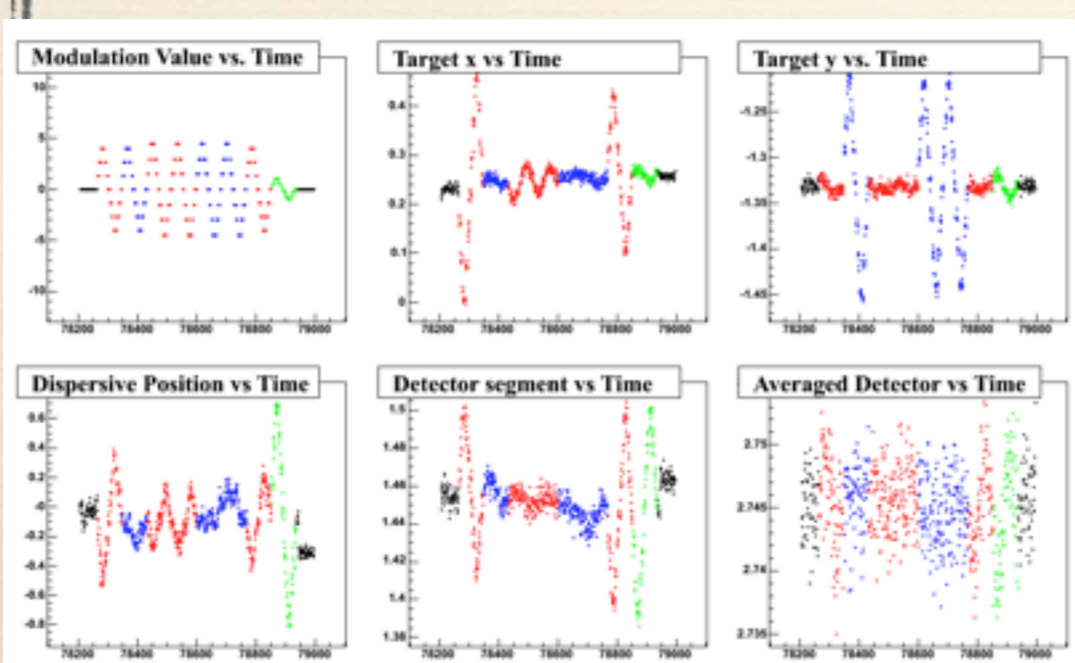
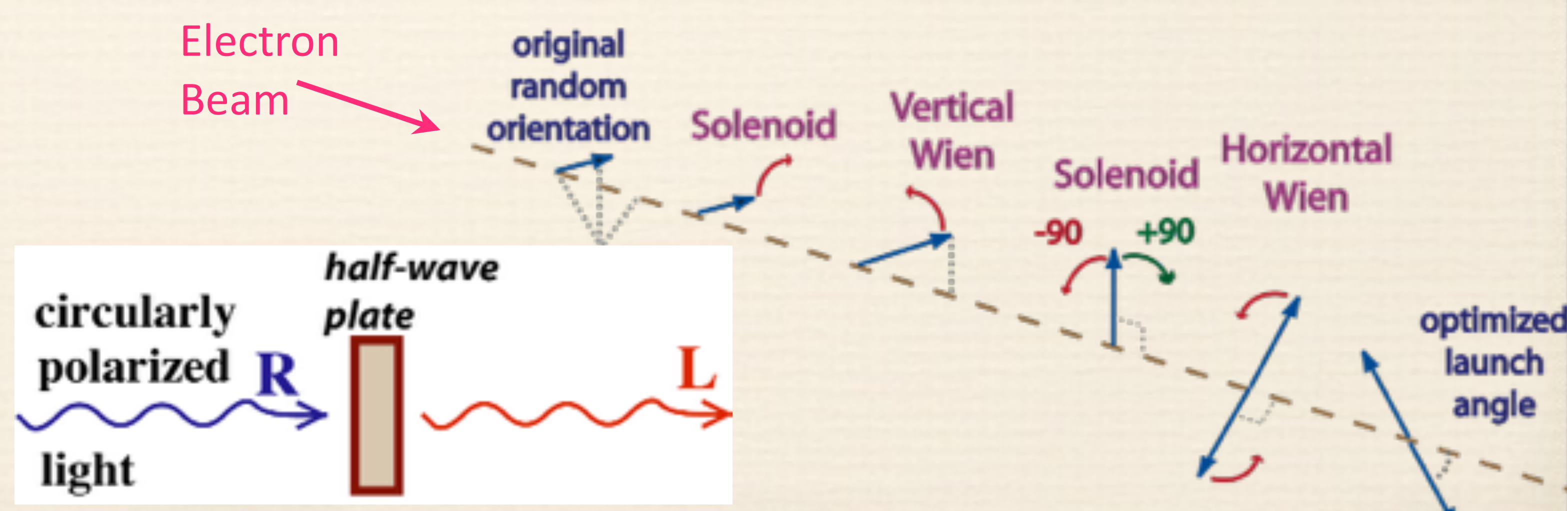
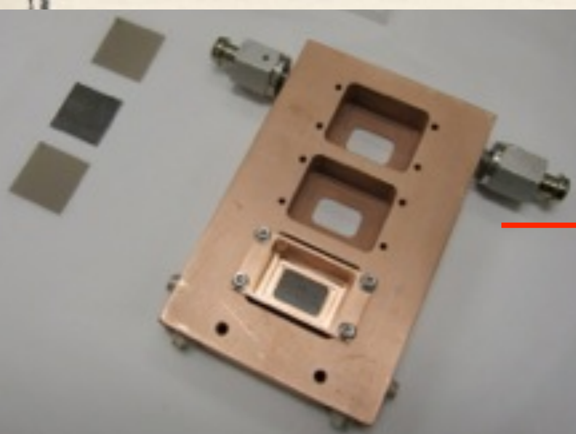
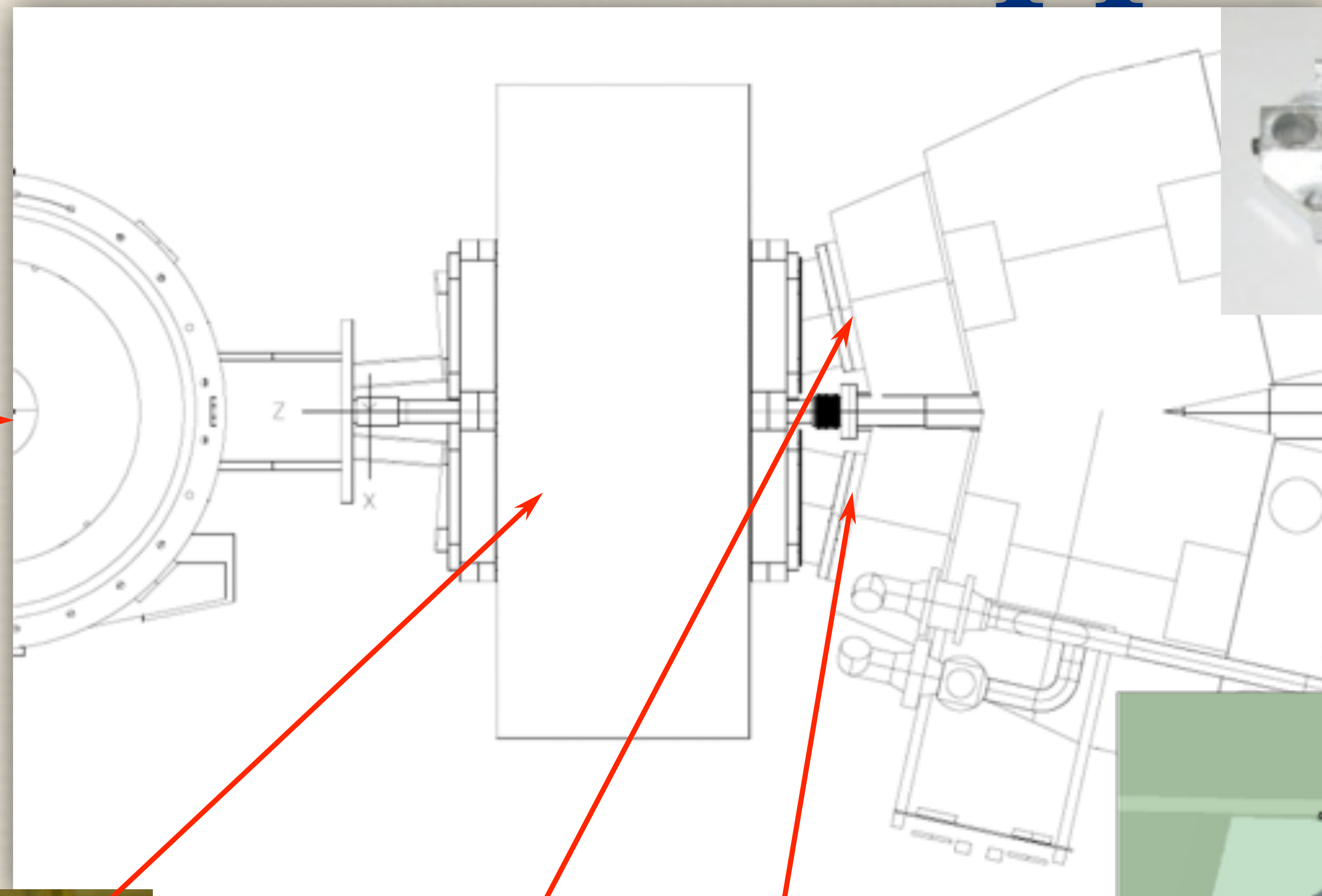


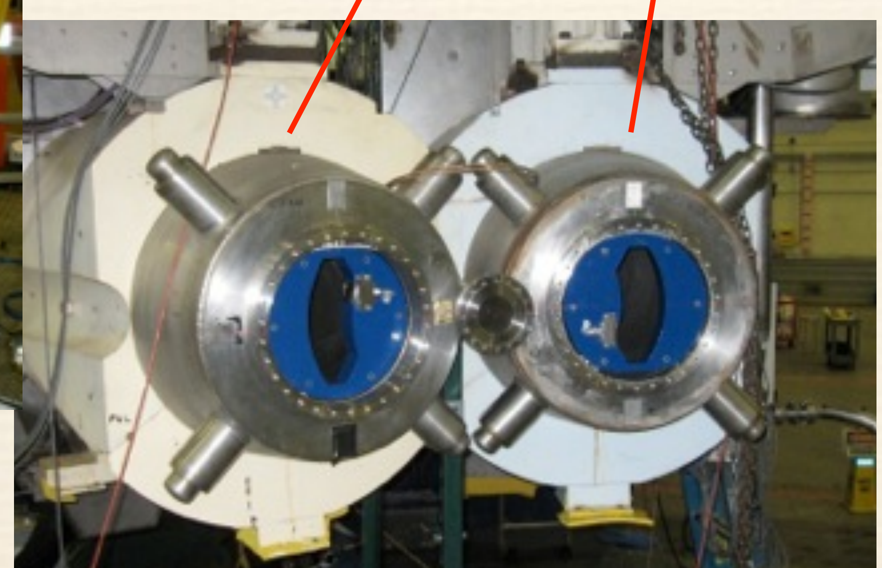

## 2 methods of "slow" reversal

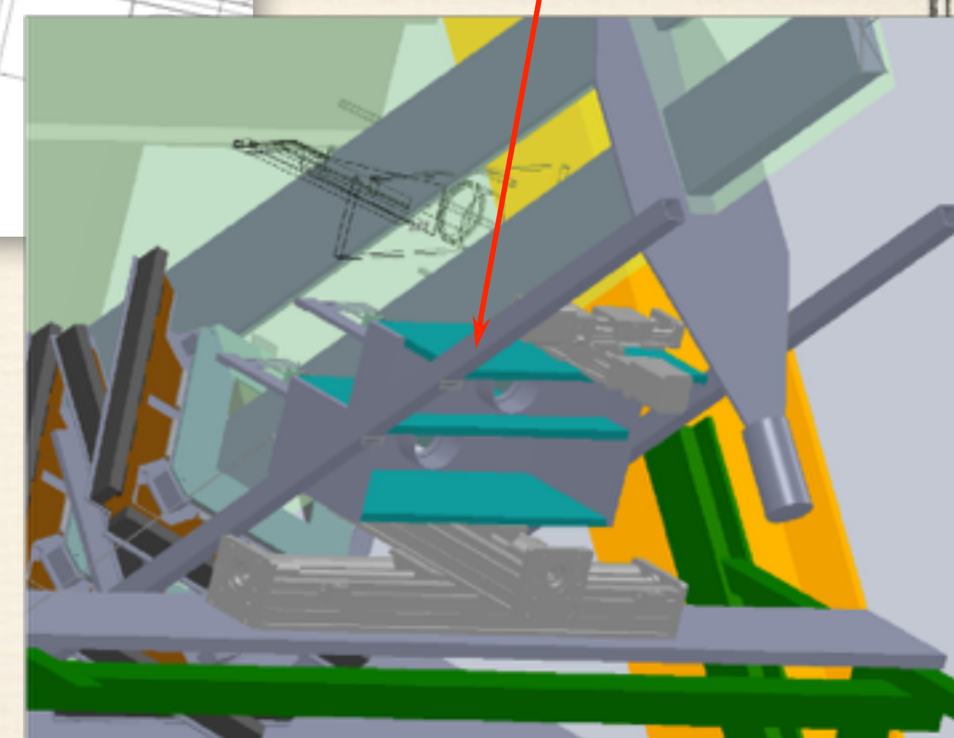


# Aspects of the Apparatus



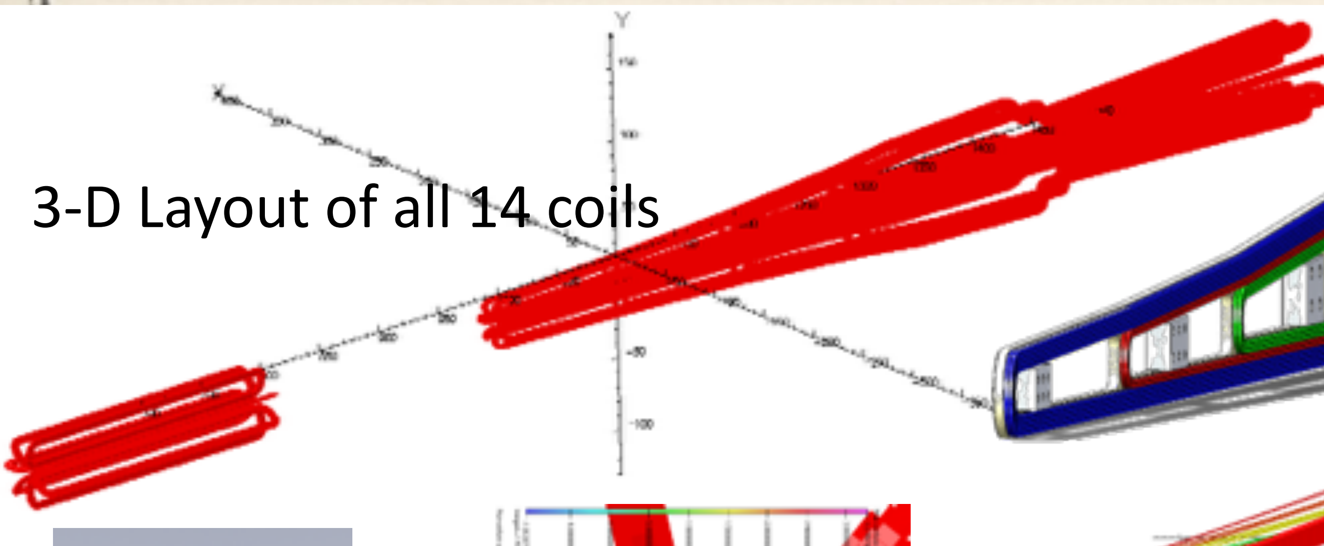


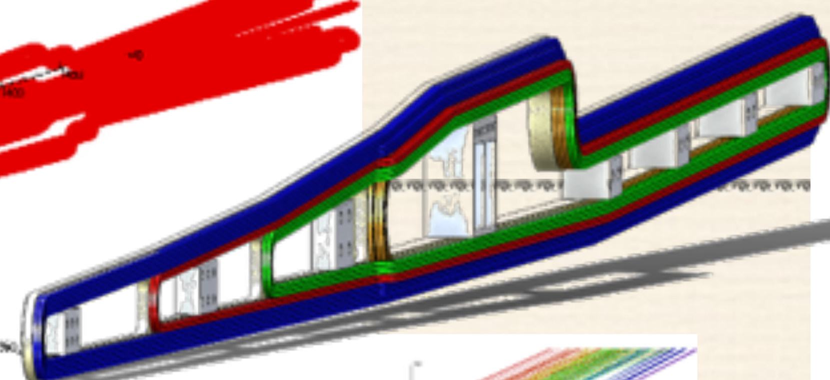




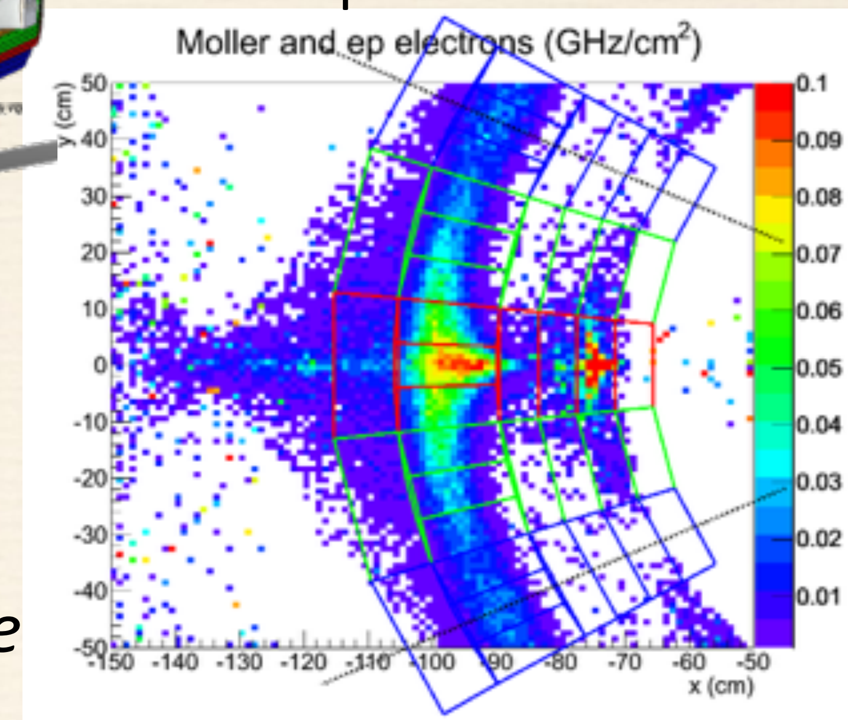
# MOLLER Design

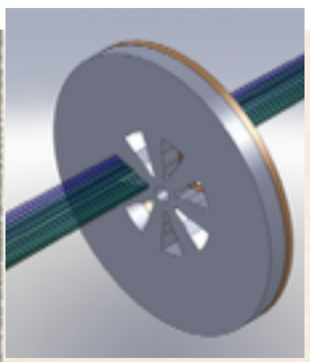
3-D Layout of all 14 coils



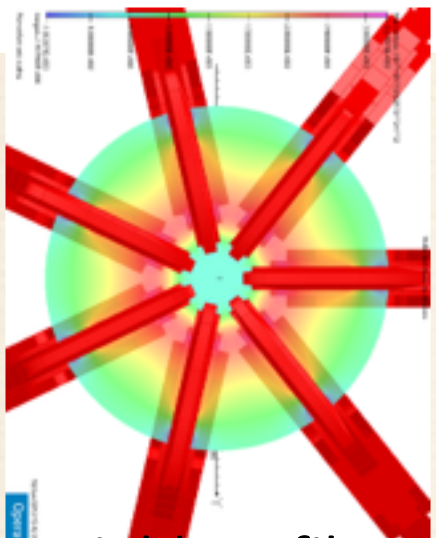


Detector plane distribution

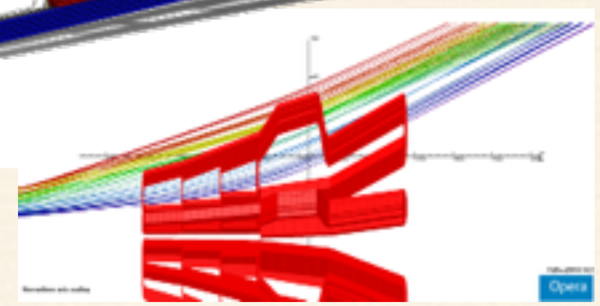


Acceptance collimator



Field Profile

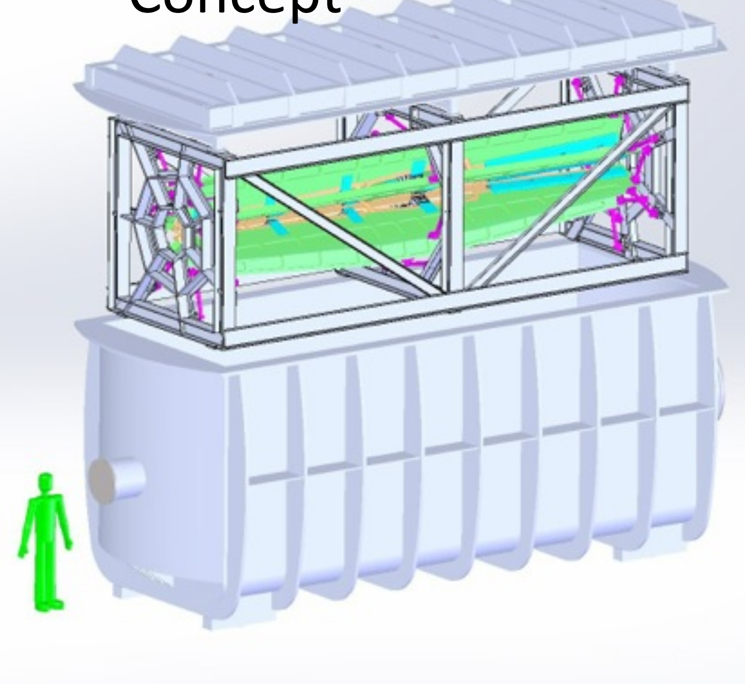


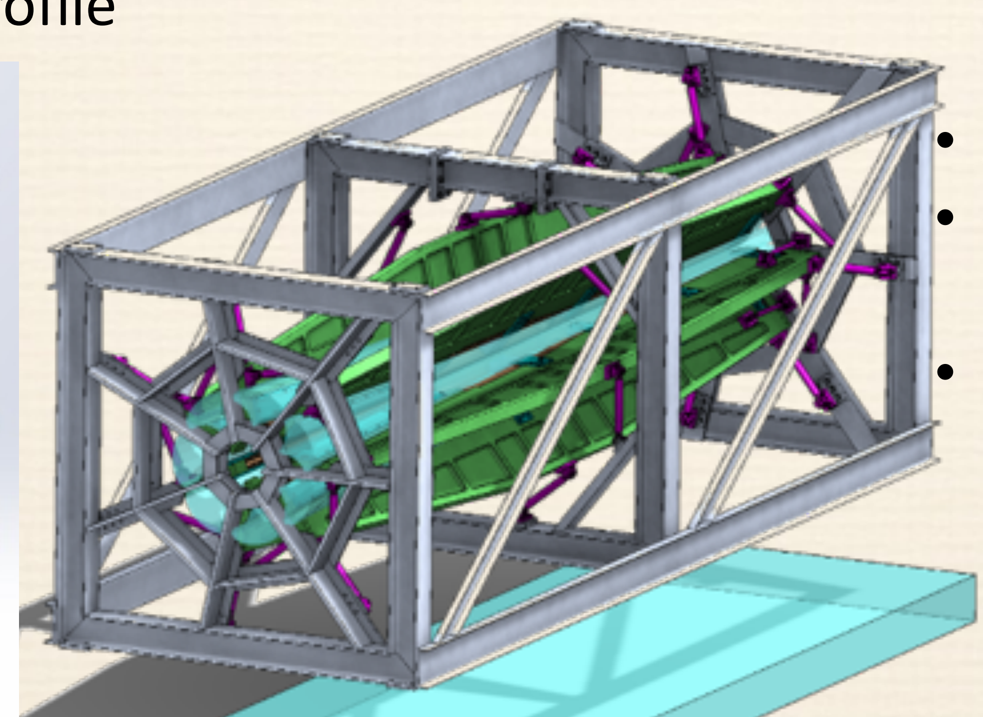
- *Full Azimuthal Acceptance*
- *Warm copper coils*
- *Water cooling*

- Optics are being fine-tuned
  — Reduce backgrounds
  — Optimize asymmetry
  — Symmetric forward/backward
- Collimator optimization
- Position sensitivity study

- Engineering work
  — Native CAD model
  — Water-cooling
  — Support structure
  — Force calculations

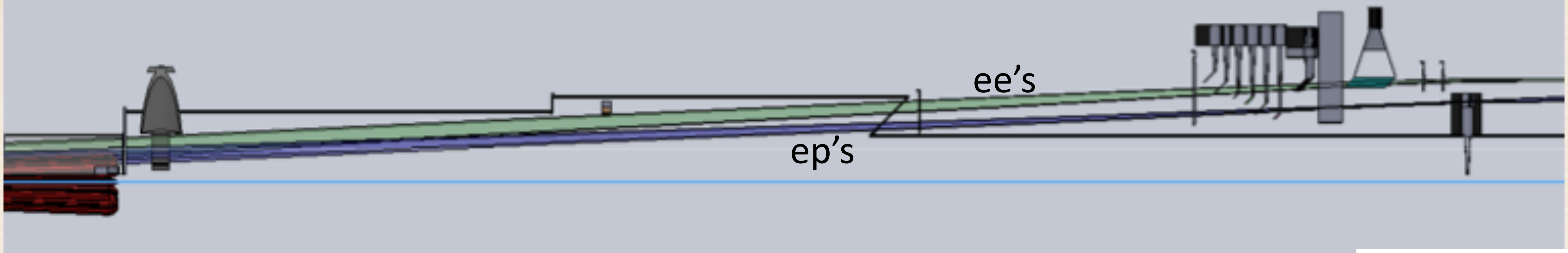
Vacuum Tank Concept



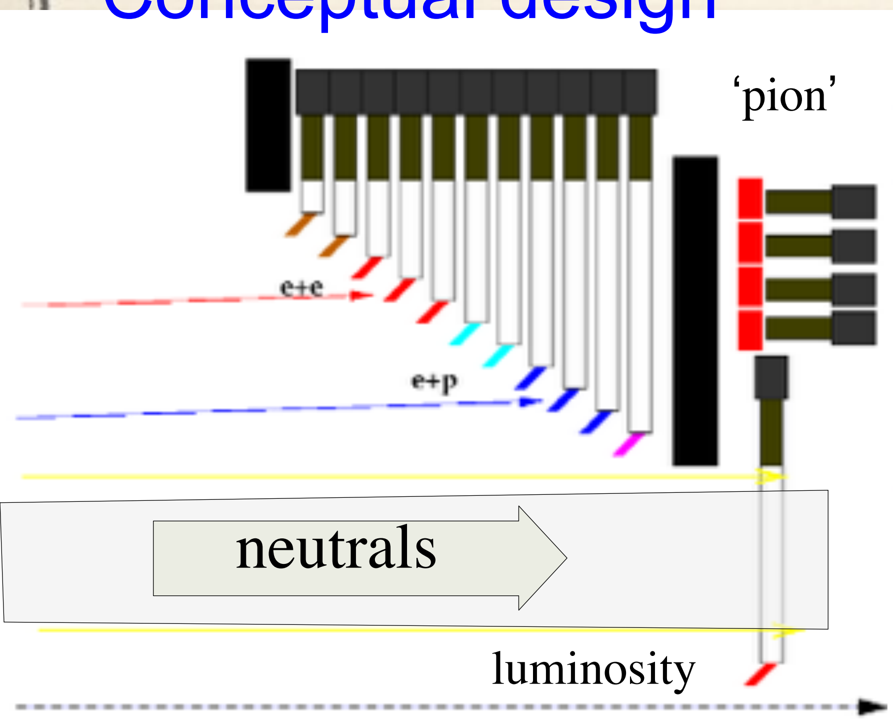


3

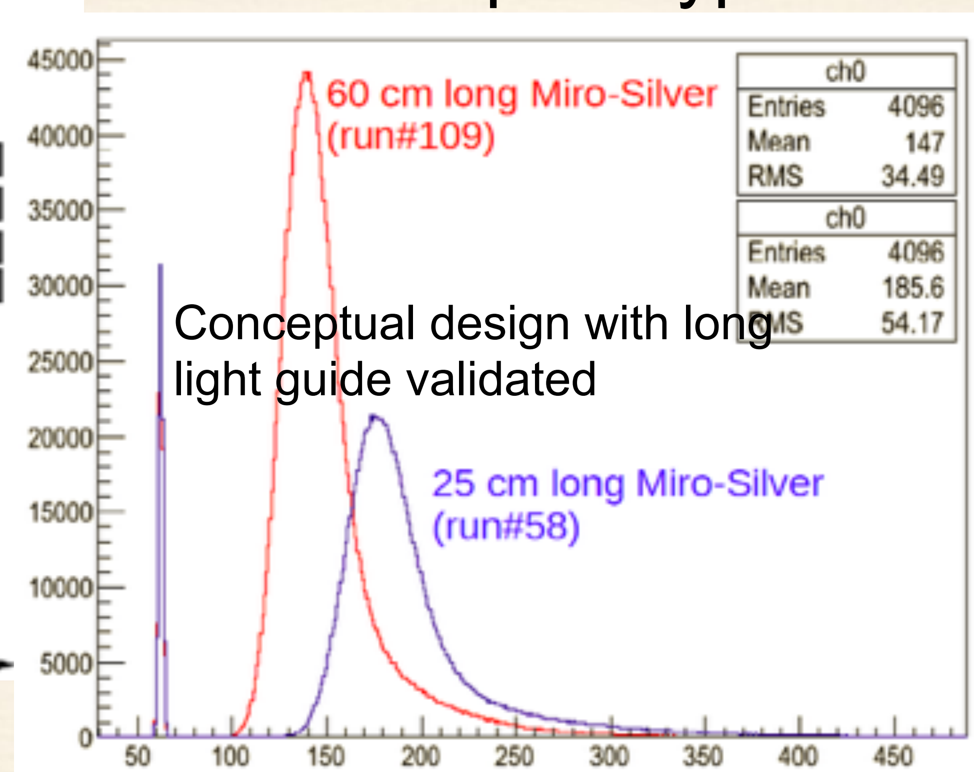
# MOLLER Detectors



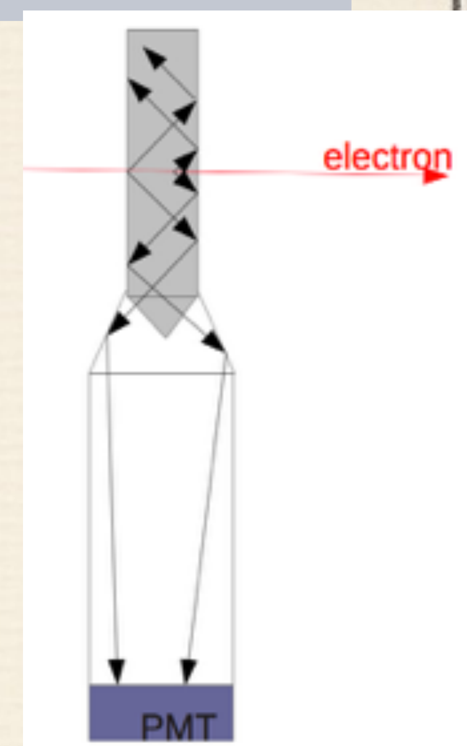

Conceptual design



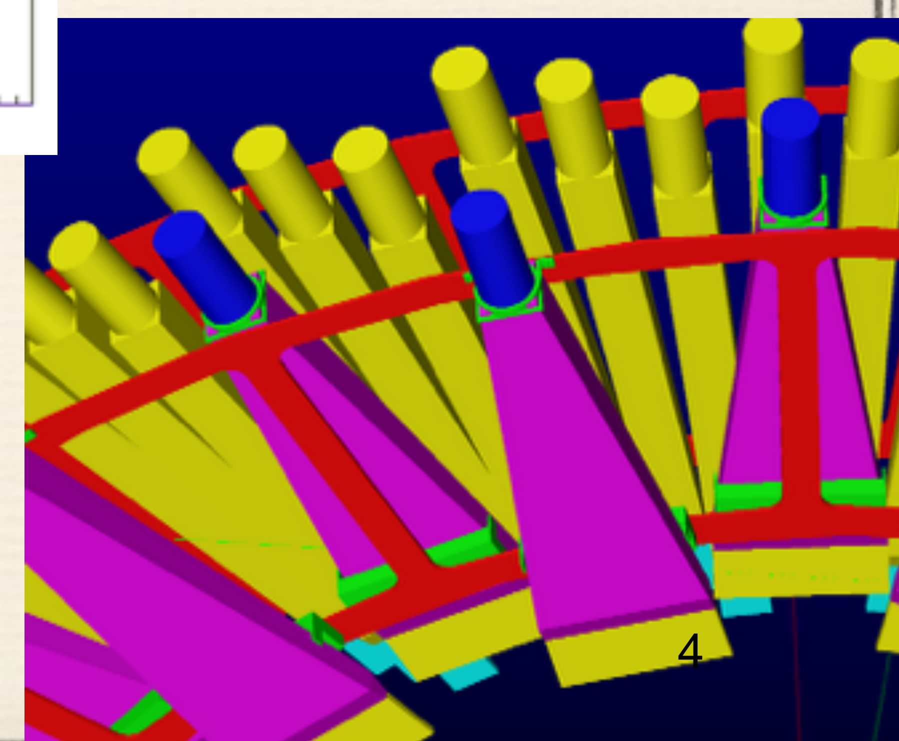

Test beam of prototype at Mainz




Single channel



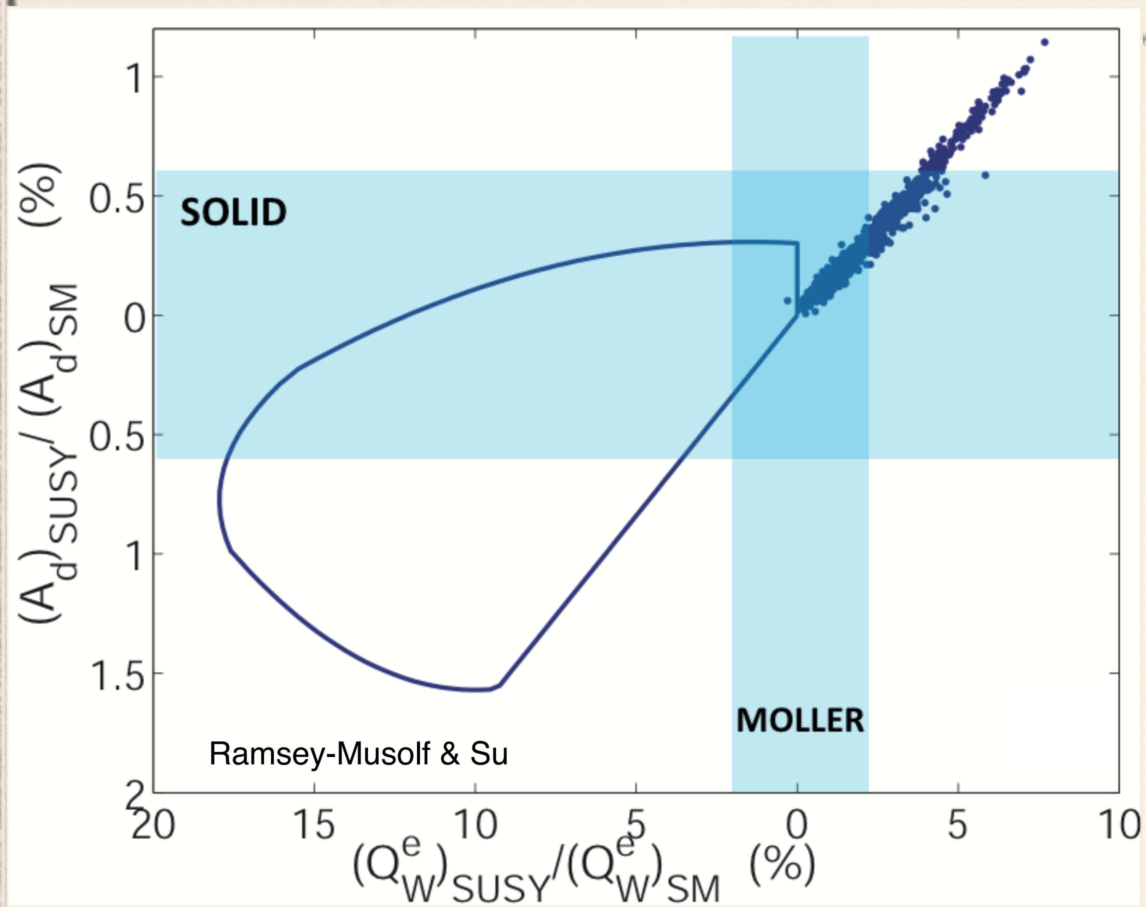

Mounting/ alignment concept

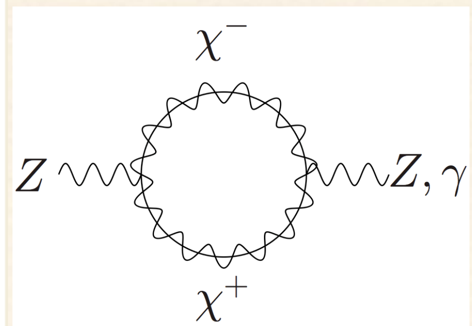


Integrating Detectors

- Moller and e-p electrons:
  - radial and azimuthal segmentation
  - quartz with air lightguides & PMTs
- Pions and muons:
  - quartz sandwich behind shielding
- Luminosity monitors
  - beam & target density fluctuations

# SOLID Sensitivity

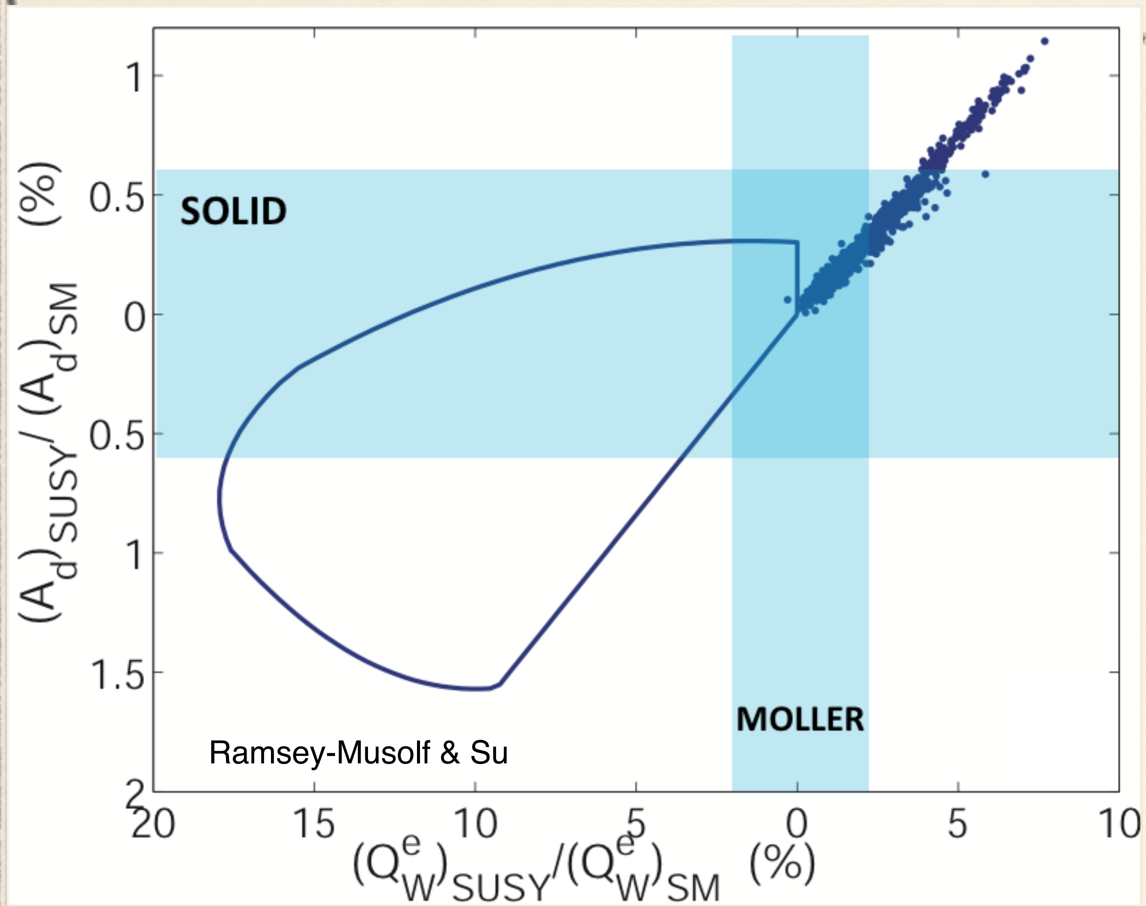


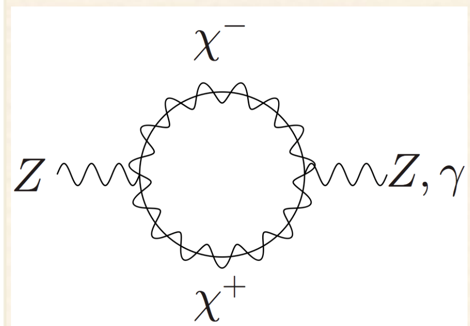




***Does Supersymmetry provide a candidate for dark matter?***

- B and/or L need not be conserved: neutralino decay
- Depending on size and sign of deviation: could lose appeal as a dark matter candidate

# SOLID Sensitivity

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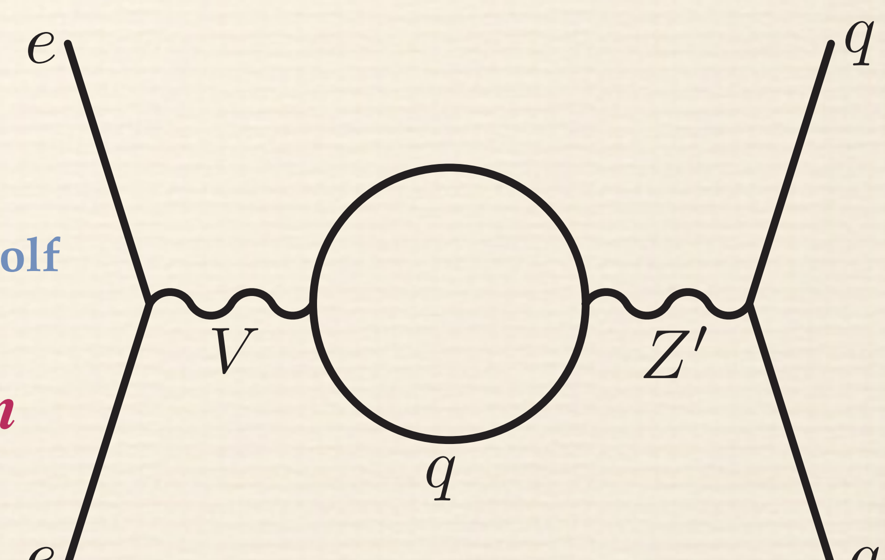
## *Leptophobic Z'*

arXiv:1203.1102v1

Buckley and Ramsey-Musolf

- *Virtually all GUT models predict new Z's*
- *LHC reach ~ 5 TeV, but....*
- *Little sensitivity if Z' doesnt couple to leptons*
- *Leptophobic Z' as light as 120 GeV could have escaped detection*




*Since electron vertex must be vector, the Z' cannot couple to the $C_{1q}$'s if there is no electron coupling: can only affect* **$C_{2q}$'s**

**SOLID can improve sensitivity: 100-200 GeV range**

# The Three Best Measurements

- ✦ **Atomic Parity Violation**
  - ★ The 6S - 7S transition in $^{133}$Cs atom

$$\sin^2\theta_W(m_Z)_{\overline{\rm MS}} = 0.2283(20)$$
$$\langle Q\rangle \simeq 2.4 \text{ MeV}$$

- ✦ **Neutrino Deep Inelastic Scattering**
  - ★ The NuTeV Experiment

$$\sin^2\theta_W(m_Z)_{\overline{\rm MS}} = 0.2356(16)$$
$$\langle Q\rangle \simeq 5 \text{ GeV}$$

- ✦ **Parity-Violating Møller Scattering**
  - ★ The E158 Experiment

$$\sin^2\theta_W(m_Z)_{\overline{\rm MS}} = 0.2329(13)$$
$$\langle Q\rangle \simeq 160 \text{ MeV}$$

# Fundamental Symmetries & Neutrinos (also HEP Intensity Frontier)

**Compelling arguments for "New Dynamics" in the Early Universe**

**A comprehensive search to understand the origin of matter requires:**

**The Large Hadron Collider, astrophysical observations** ***as well as*** **Lower Energy: $Q^2 << M_Z^2$**

***Nuclear/Atomic systems address several topics; unique & complementary:***

- ***Neutrino mass and mixing*** $0\nu\beta\beta$ *decay,* $\theta_{13}$*,* $\beta$ *decay, long baseline neutrino expts…*
- ***Rare or Forbidden Processes*** *EDMs,* ***charged LFV****,* $0\nu\beta\beta$ *decay…*
- ***Dark Matter Searches*** *direct detection, dark photon searches…*
- ***Precision Electroweak Measurements:*** *$(g\text{-}2)_\mu$, charged &* ***neutral current amplitudes***

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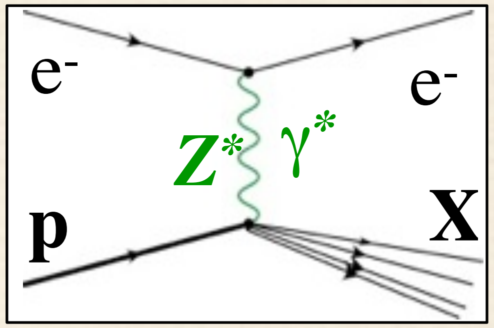
## *Experimental Facilities/Initiatives/Programs*

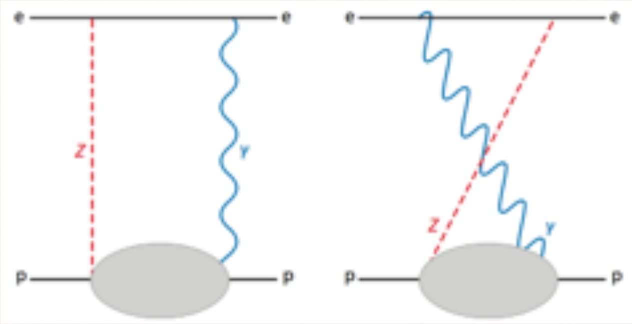
- ***Neutrons:*** *Lifetime, Asymmetries (LANSCE, NIST, SNS…)*
- ***Underground Detectors:*** *Dark Matter, Double-Beta Decay*
- ***Nuclei:*** *Precision Weak Decays, Atomic Parity Violation, EDMs (MSU, ANL, TAMU, Tabletop…)*
- ***Muons, Kaons, Pions:*** *Lifetime, Branching ratios, Michel parameters, g-2 , EDMs (BNL, PSI, TRIUMF, FNAL, J-PARC...)*
- ***Electron Beams:*** *Weak neutral current couplings, precision weak mixing angle, dark photons (JLab, Mainz)*

# EW & Hadron Physics Interplay

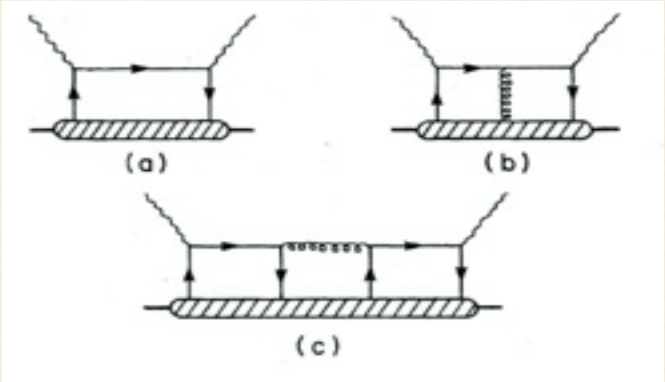
electrons on $LH_2$




- **MOLLER Inelastic backgrounds**
  - Inelastic e-p scattering in diffractive region ($Q^2 << 1$ GeV$^2$, $W^2 > 2$ GeV$^2$) pollutes the Møller peak



- **Box diagram uncertainties**
  - Proton weak charge modified; inelastic intermediate states
- **Parton dynamics in nucleons and nuclei**
  - Higher twist effects
  - charge symmetry violation in the nucleon
  - "EMC" style effects: quark pdfs modified in nuclei



# Charge Symmetry Violation

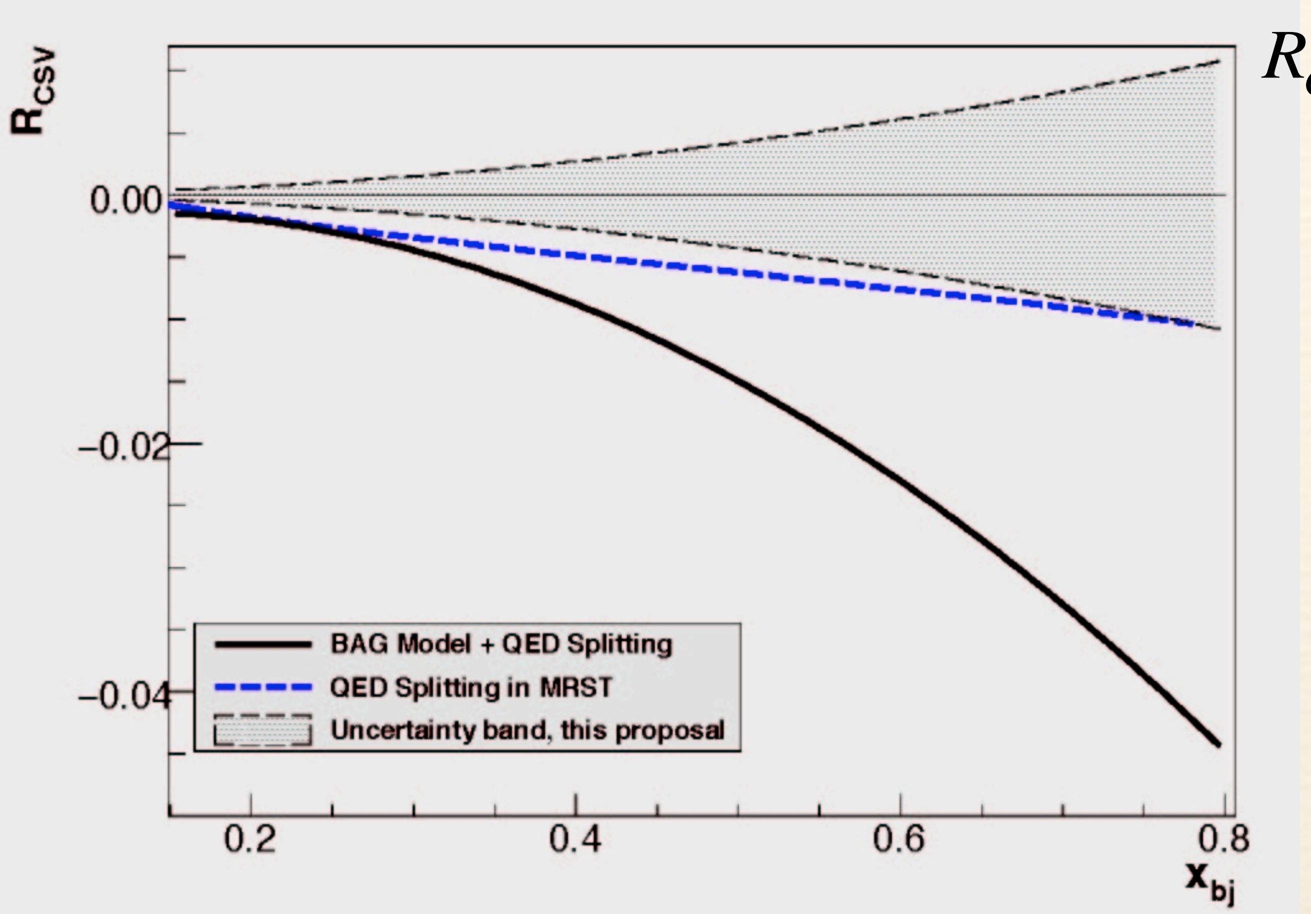
**Parton-level charge symmetry assumed in deriving $^{2}$H $A_{PV}$**

## Charge Symmetry Violation

$$\delta u(x) = u^{p}(x) - d^{n}(x)$$

$$\delta d(x) = d^{p}(x) - u^{n}(x)$$

- u,d quark mass difference
- electromagnetic effects

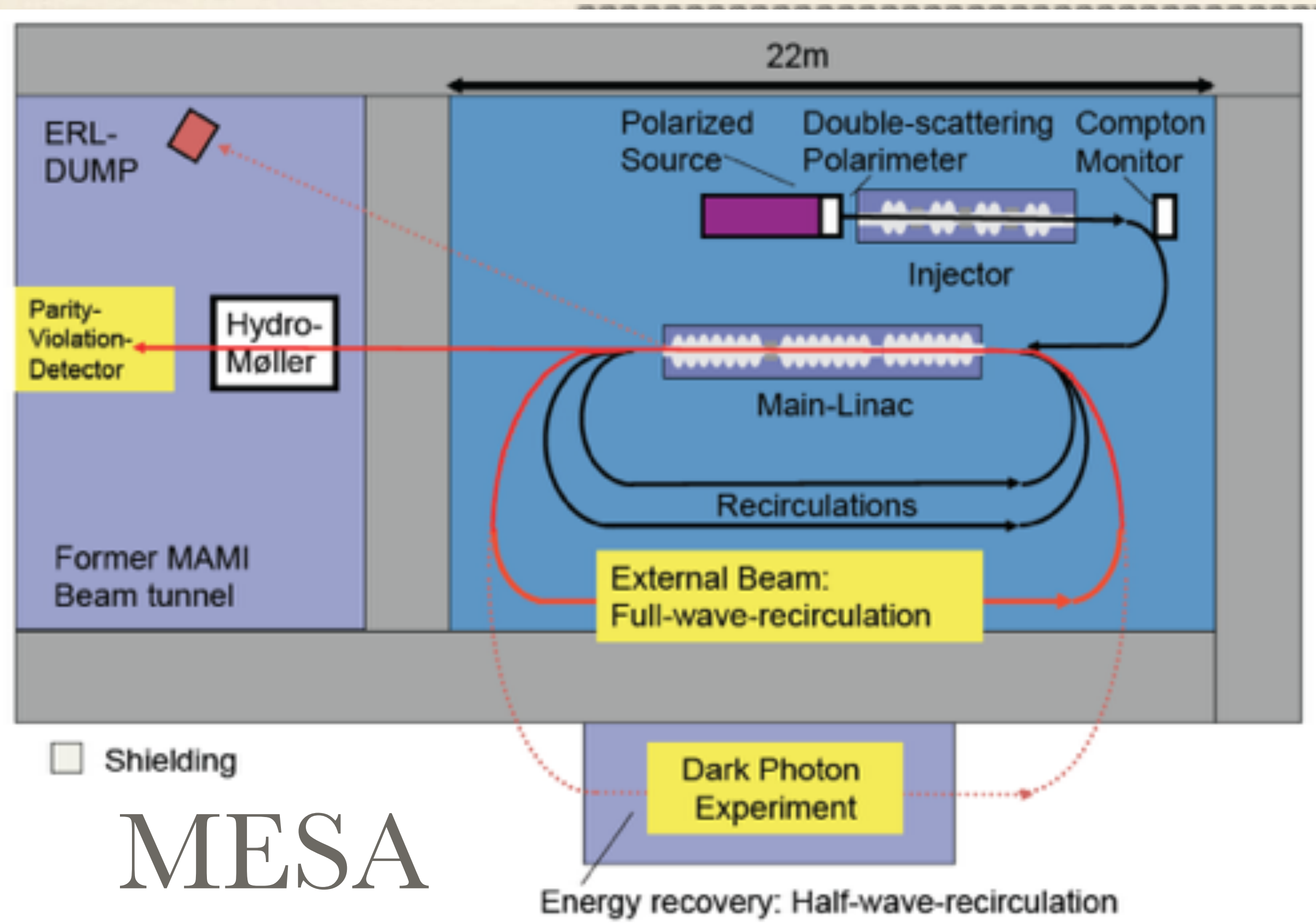



$$R_{CSV} = \frac{\delta A_{PV}(x)}{A_{PV}(x)} = 0.28\,\frac{\delta u(x) - \delta d(x)}{u(x) + d(x)}$$

- Direct observation of parton-level CSV would be very exciting!
- Important implications for high energy collider pdfs
- Could explain significant portion of the NuTeV anomaly

# Elastic Electron-Proton Scattering

## *P2 at Mainz*




| | |
|---|---|
| $E_{Beam}$ | 200 MeV |
| $Q^2/\theta_e$ | 0.0048 GeV$^2$/20° |
| Time/current/target | 10000h/150μA/60cm |
| $A_{phys}$ | -20.25 ppb |
| $\Delta A_{tot}$ | 0.34 ppb (1.7 %) |
| $\Delta A_{stat}$ | 0.25 ppb |
| $\Delta A_{sys}$ | 0.19 ppb (0.9%) |
| Polarization | (85 ± 0.5) % |
| Rate | 0.44 $10^{12}$ Hz |
| $\Delta \sin^2 \theta_{W\ stat}$ | 2.8 $10^{-4}$ |
| $\Delta \sin^2 \theta_{W\ tot}$ | 3.6 $10^{-4}$ (0.15 %) |

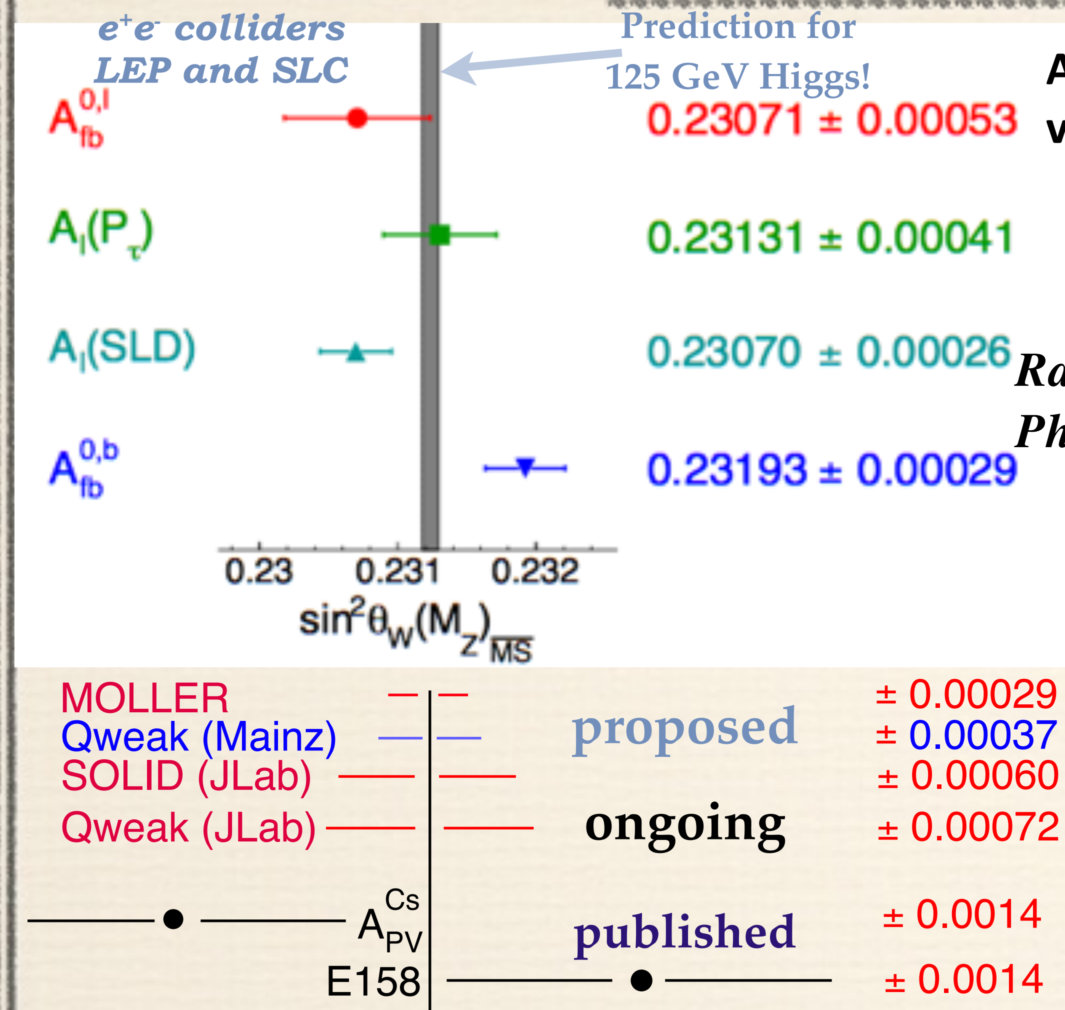
- Funding approval from DFG
- R&D in progress
- Aim to run from 2017-20

**Technically challenging:**
**great synergy with JLab program**

**Recent joint beam test of integrating quartz detectors successful**

# Physics Examples: Beyond LHC

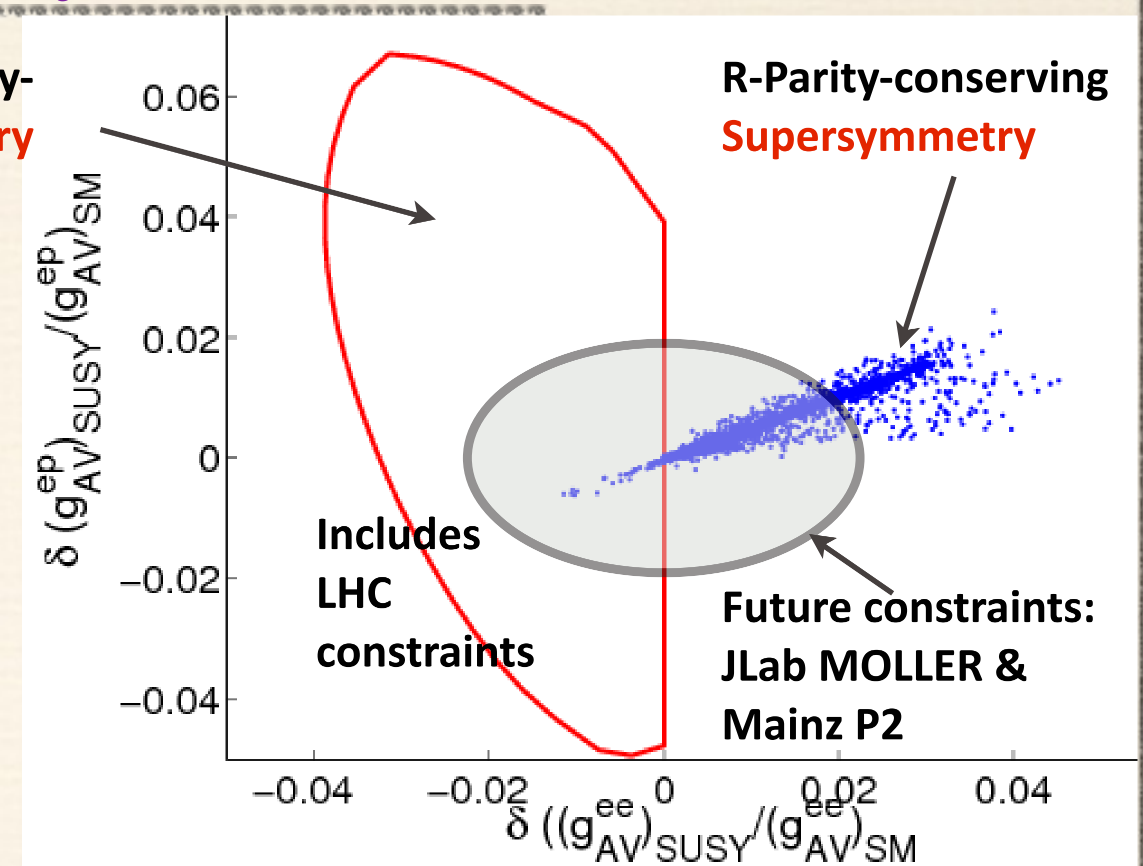
## Z resonance measurements: little sensitivity to new contact interactions




Allowed region: R-Parity-violating Supersymmetry

*Ramsey-Musolf and Su, Phys. Rep. 456 (2008)*

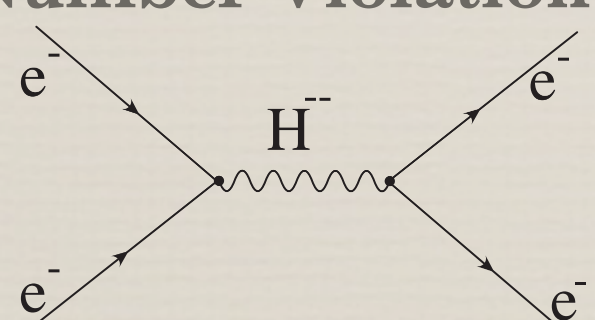
*Erler and Su, arXiv:1303.5522*




### Lepton Number Violation

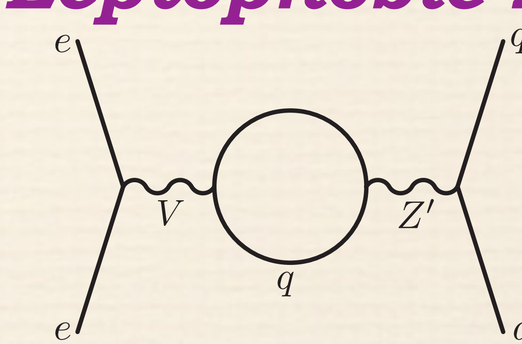
$\Lambda$ > 5 TeV

**Doubly-Charged Scalars**




Significant reach beyond LEP-200

### Leptophobic Z'



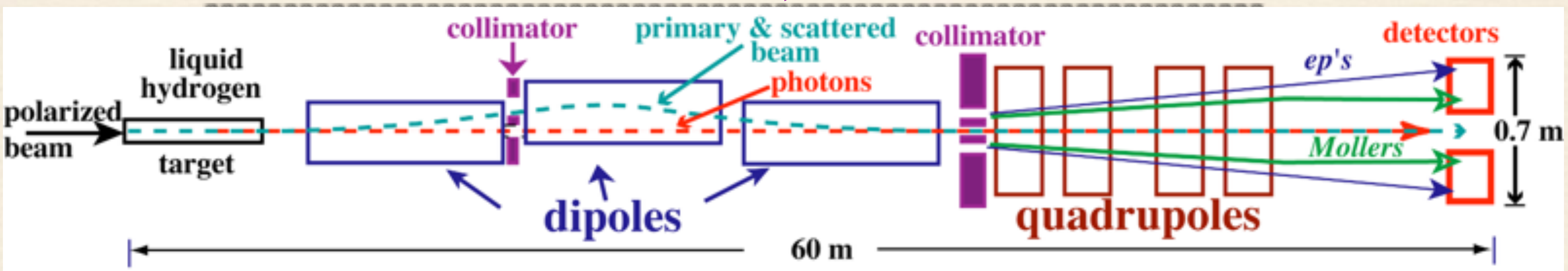

SOLID can improve sensitivity: 100-200 GeV range

*Goal: error small enough to probe TeV scale physics*

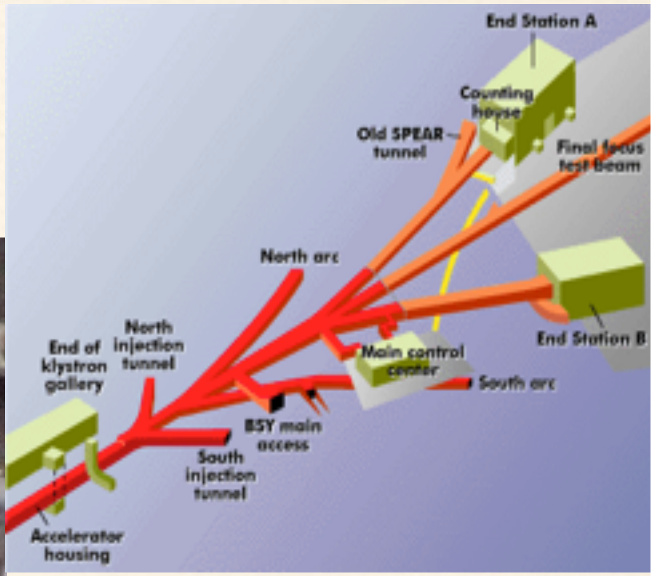
# SLAC E158

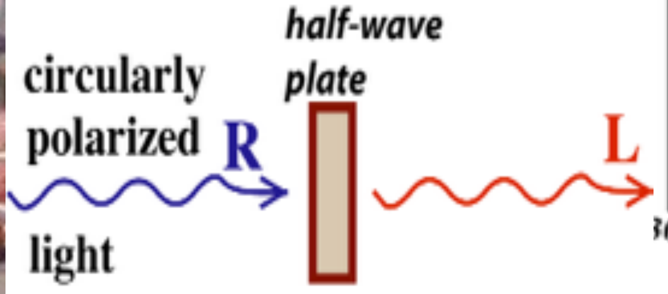
1997-2004

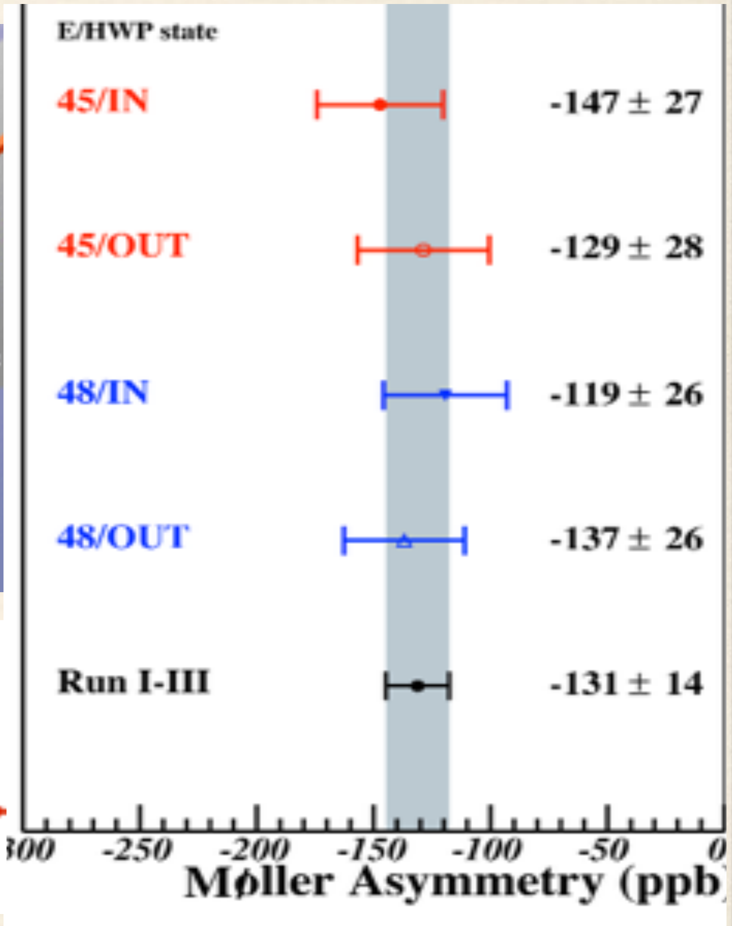
*~ 10 ppb statistical error at highest $E_{beam}$, ~ 0.5% error on weak mixing angle*




## A large number of technical challenges




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

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

# New Physics Sensitivity

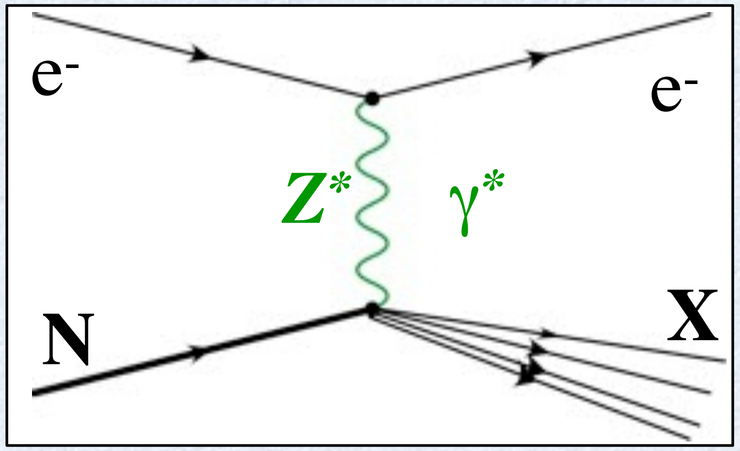
$$
\begin{aligned}
Q_W^e &= -0.0435(9)[1 + 0.25\,T - 0.34\,S + 0.7\,X(Q^2) + 7m_Z^2/m_{Z_x}^2] \\
Q_W^p &= 0.0707(9)[1 + 0.15\,T - 0.21\,S + 0.43\,X(Q^2) + 4.3m_Z^2/m_{Z_x}^2] \\
Q_W(^{12}C) &= -5.510(5)[1 - 0.003\,T + 0.016\,S - 0.033\,X(Q^2) - m_Z^2/m_{Z_x}^2] \\
Q_W(^{133}Cs) &= -73.24(5)[1 + 0.0\,T + 0.011\,S - 0.023\,X(Q^2) - 0.9m_Z^2/m_{Z_x}^2]
\end{aligned}
$$

Kumar, Mantry, Marciano & Souder, arXiv:1302.6263

- **Oblique Corrections (vacuum polarization)**
- **Contact Interactions**
- **Heavy Z's**
- **Light Z's**
- **X Parameter (Q dependence of $\sin^2\theta_W$)**

# PV Deep Inelastic Scattering

## off the simplest isoscalar nucleus and at high Bjorken *x*




$$A_{PV} = \frac{G_F Q^2}{2\sqrt{2}\pi\alpha}\left[g_A \frac{F_1^{\gamma Z}}{F_1^{\gamma}} + g_V \frac{f(y)}{2}\frac{F_3^{\gamma Z}}{F_1^{\gamma}}\right]$$

$$x \equiv x_{Bjorken}$$

$$y \equiv 1 - E'/E$$

$Q^2 >> 1\ \mathrm{GeV}^2$ , $W^2 >> 4\ \mathrm{GeV}^2$

$$A_{PV} = \frac{G_F Q^2}{\sqrt{2}\pi\alpha}\left[a(x) + f(y)b(x)\right]$$

$$Y = \frac{1-(1-y)^2}{1+(1-y)^2 - y^2\frac{R}{R+1}}$$

$$R(x, Q^2) = \sigma^l/\sigma^r \approx 0.2$$

$$A_{\text{iso}} = \frac{\sigma^l - \sigma^r}{\sigma^l + \sigma^r} = -\left(\frac{3G_F Q^2}{\pi\alpha 2\sqrt{2}}\right)\frac{2C_{1u} - C_{1d}(1+R_s) + Y(2C_{2u} - C_{2d})R_v}{5+R_s}$$

**At high x, $A_{iso}$ becomes independent of pdfs, x & W, with well-defined SM prediction for $Q^2$ and y**

$$R_s(x) = \frac{2S(x)}{U(x)+D(x)} \xrightarrow{\text{Large } x} 0$$

$$R_v(x) = \frac{u_v(x)+d_v(x)}{U(x)+D(x)} \xrightarrow{\text{Large } x} 1$$

### Interplay with QCD

- Parton distributions (u, d, s, c)
- Charge Symmetry Violation (CSV)
- Higher Twist (HT)
- Nuclear Effects (EMC)

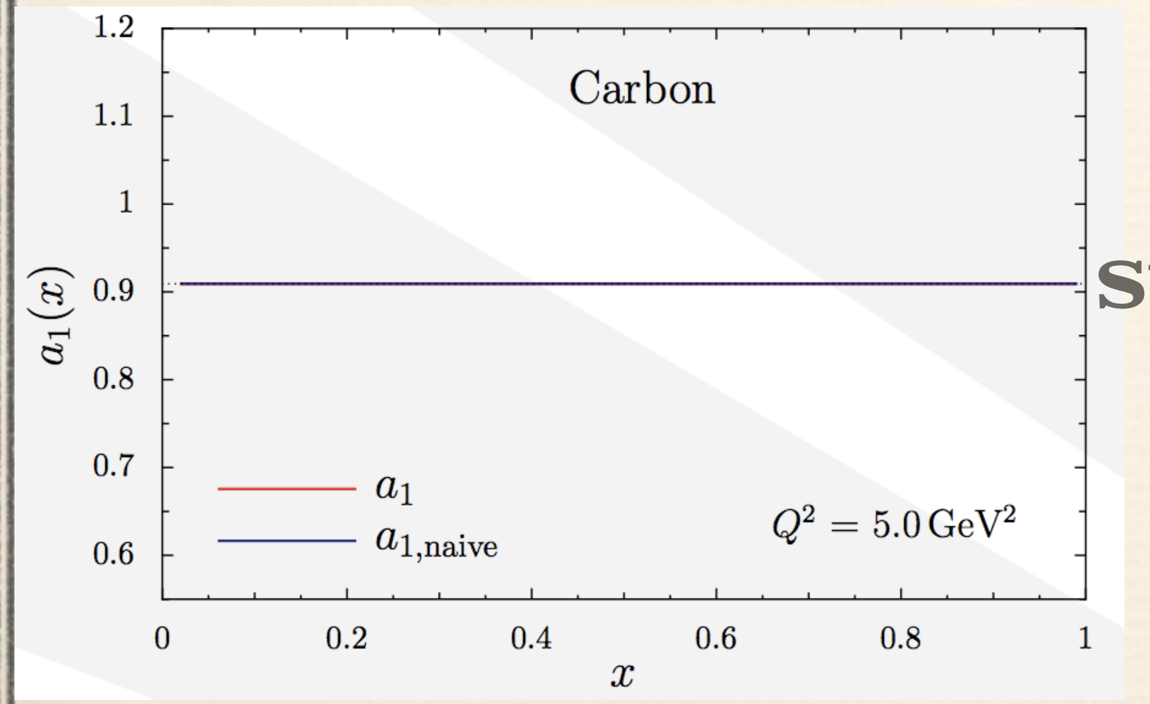
# A Novel "EMC" Effect

*Consider PVDIS on a heavy nucleus*

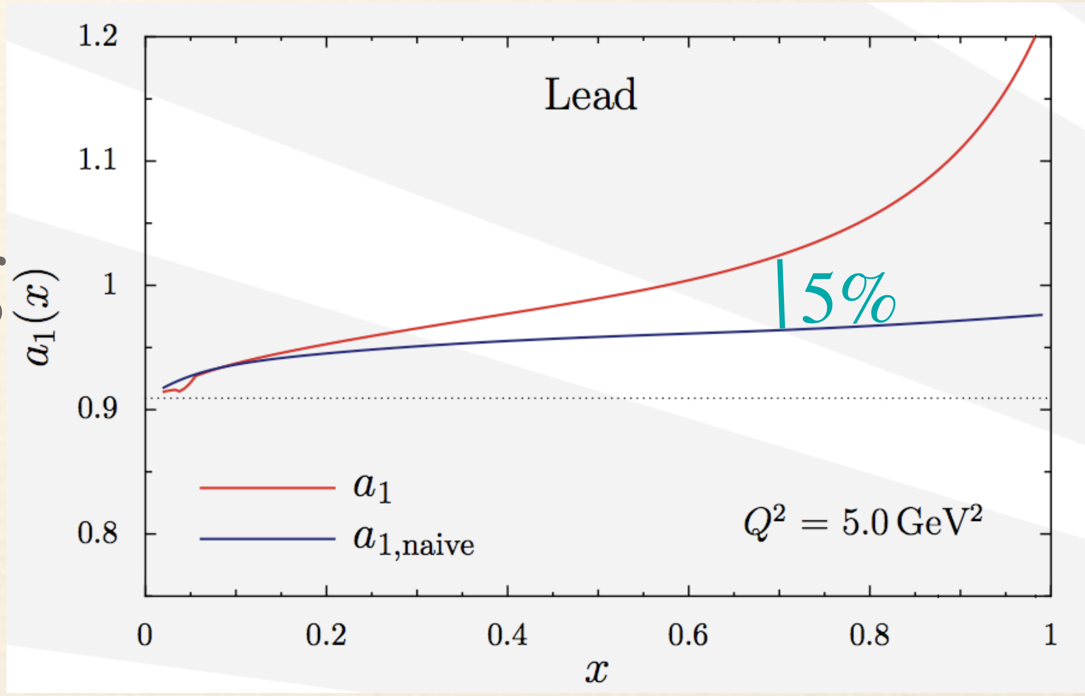
*Cloet, Bentz, Thomas, arXiv 0901.3559*

- **Neutron or proton excess in nuclei leads to a isovector-vector mean field (ρ exchange)**
- **shifts quark distributions: "apparent" CSV**
- **Isovector EMC effect: explain additional 2/3 of NuTeV anomaly**

- **new insight into medium modification of quark distributions**




**smoking gun!**




**A new proposal using Ca-48 has been submitted to the JLab PAC**

# A Special HT Effect

**The observation of Higher Twist in PV-DIS would be exciting direct evidence for diquarks**

following the approach of
Bjorken, PRD 18, 3239 (78),
Wolfenstein, NPB146, 477 (78)

$$V_\mu = \left(\bar{u}\gamma_\mu u - \bar{d}\gamma_\mu d\right) \Leftrightarrow S_\mu = \left(\bar{u}\gamma_\mu u + \bar{d}\gamma_\mu d\right)$$

$$\langle VV \rangle = l_{\mu\nu} \int \langle D \,|\, V^\mu(x) V^\nu(0) \,|\, D \rangle e^{iqx} d^4 x$$

**Isospin decomposition before using PDF's**

$$A_{PV} = \frac{G_F Q^2}{\sqrt{2}\pi\alpha}\left[a(x) + f(y) b(x)\right]$$

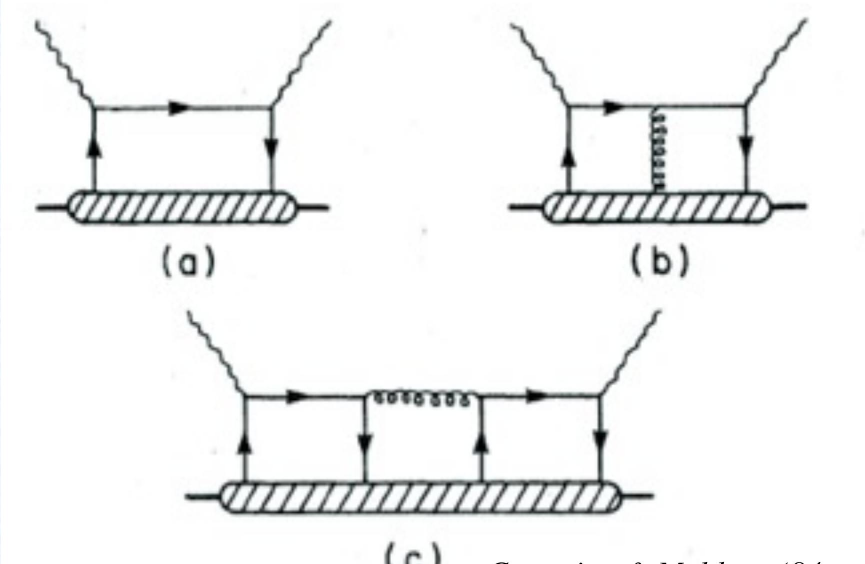
$$\delta = \frac{\langle VV \rangle - \langle SS \rangle}{\langle VV \rangle + \langle SS \rangle}$$

$$a(x) \propto \frac{F_1^{\gamma Z}}{F_1^{\gamma}} \propto 1 - 0.3\delta$$

**Higher-Twist valence quark-quark correlation**

**Zero in quark-parton model**

$$\langle VV \rangle - \langle SS \rangle = \langle (V-S)(V+S) \rangle \propto l_{\mu\nu} \int \langle D \,|\, \bar{u}(x)\gamma^\mu u(x) \bar{d}(0)\gamma^\nu d(0) \rangle e^{iqx} d^4 x$$




*Castorina & Mulders, '84*

**(c) type diagram is the only operator that can contribute to a(x) higher twist: theoretically very interesting!**

**$\sigma_L$ contributions cancel**

Use ν data for small b(x) term.