Low Energy Measurements of the Weak Mixing Angle

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Beyond the Standard Model with Weak Neutral Current Interactions at $Q^2 << M_Z^2$

Krishna Kumar
Stony Brook University

COFI Workshop on BSM Physics with Charged Leptons,
Puerto Rico, May 23, 2018

Outline

- Historical Perspective on Weak Neutral Currents
- Motivation for Modern Low Q^2 Measurements
- Review of Past Measurements
- Overview of Future Initiatives
- Brief Comments on Neutrino Scattering
- Conclusion and Outlook

Historical Perspective

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

Electroweak Interactions

$$\tan\theta_W = \frac{g'}{g} \qquad e = g\sin\theta_W$$

$$A_\mu = B^0_\mu \cos\theta_W + W^0_\mu \sin\theta_W$$
$$Z_\mu = W^0_\mu \cos\theta_W - B^0_\mu \sin\theta_W\,.$$

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

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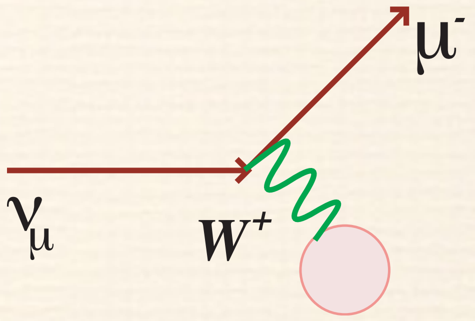

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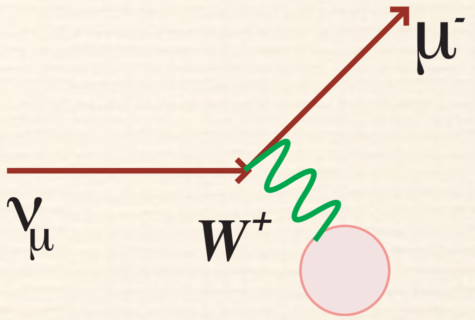

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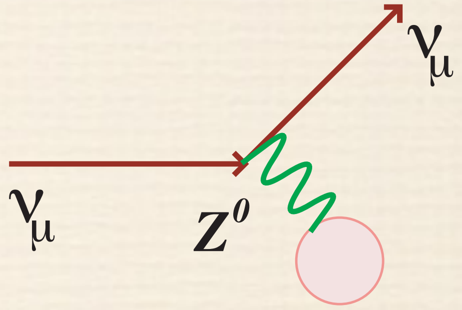

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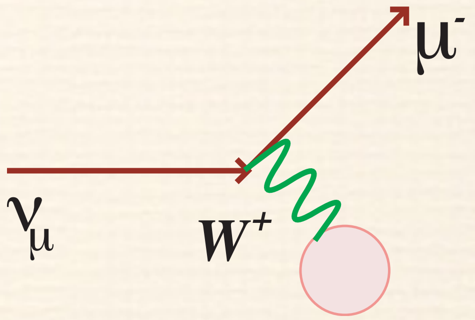

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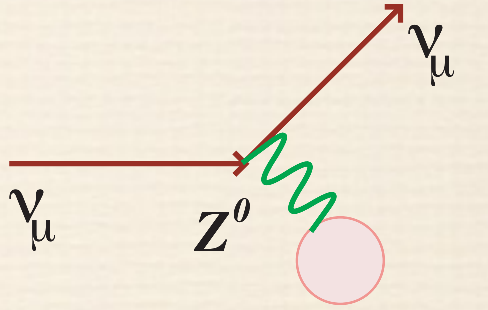


Neutral Current

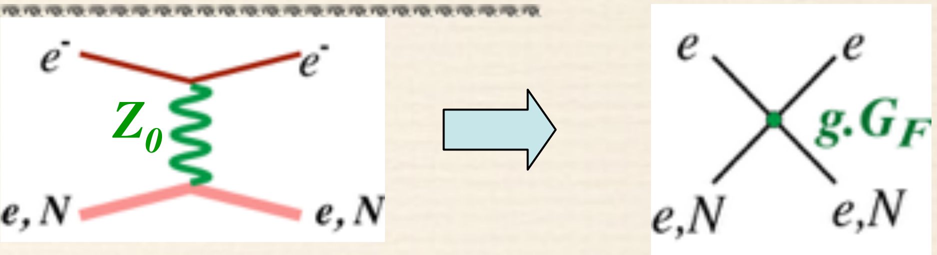
Higgs Mechanism + Renormalizability

$$\sin^2\theta_W^0 = \left(\frac{e^0}{g^0}\right)^2 = 1 - \left(\frac{M_W^0}{M_Z^0}\right)^2$$

Ancient history provides useful perspective

The Weak Neutral Current

Low energy WNC interactions ($Q^2 << M_Z^2$)



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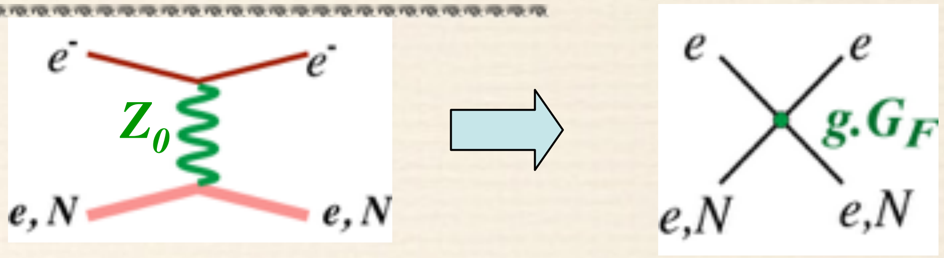

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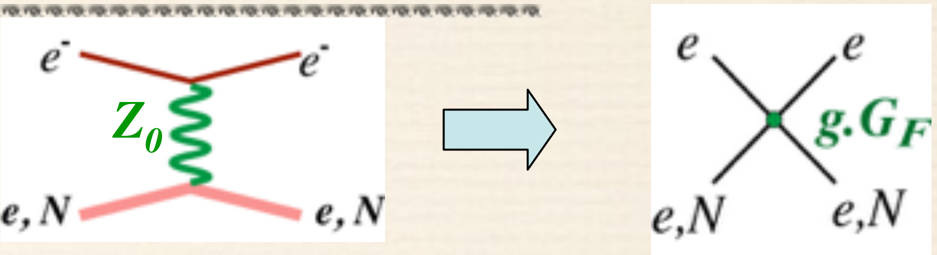

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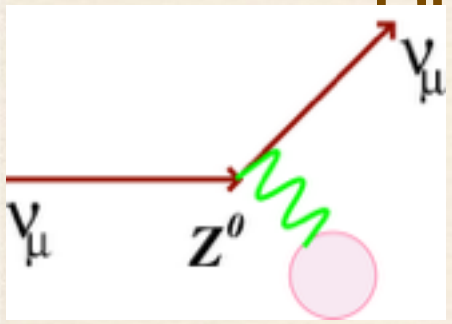

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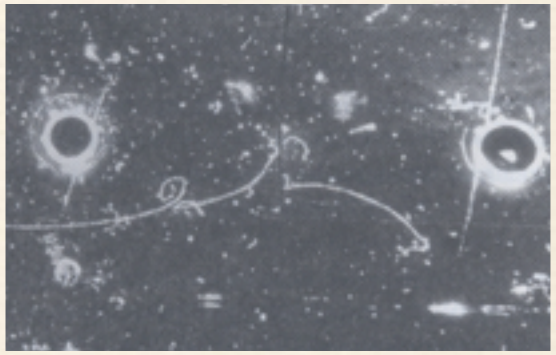

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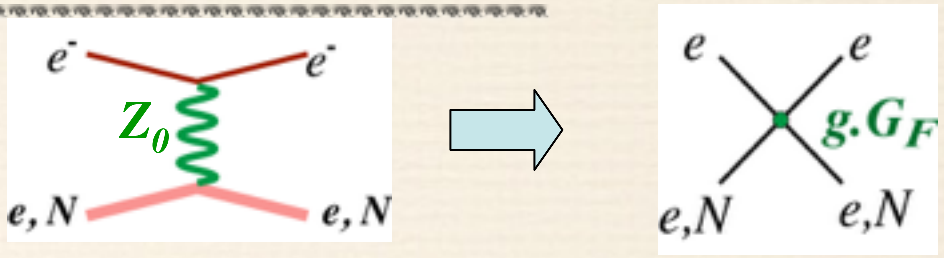

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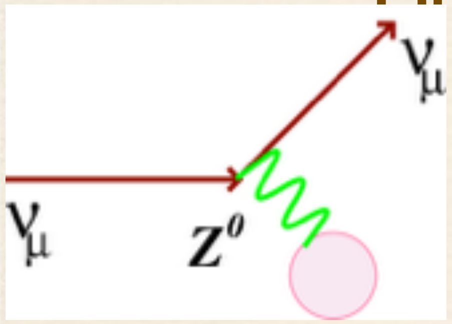

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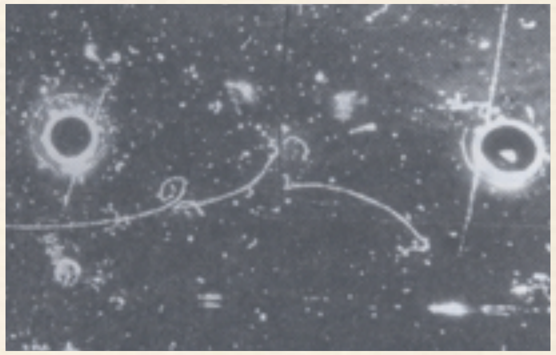

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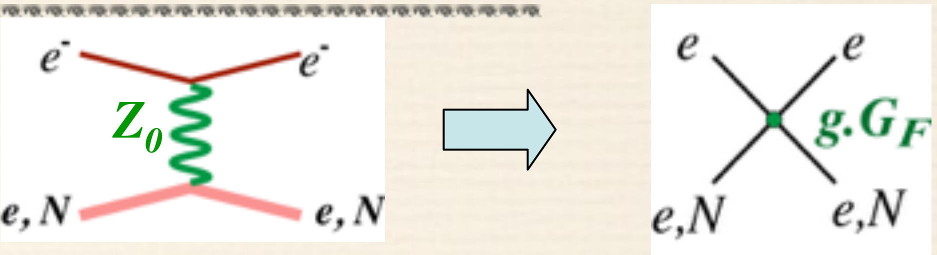

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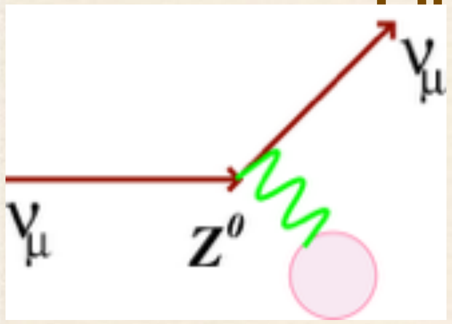

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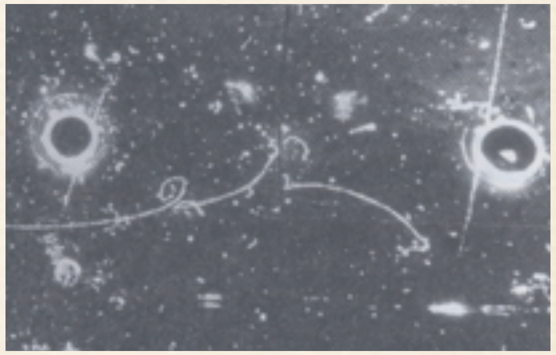

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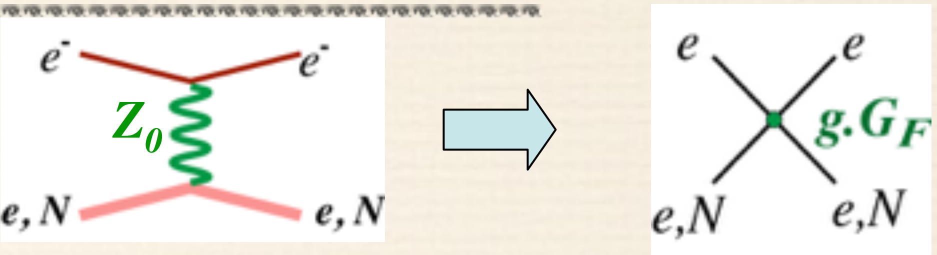

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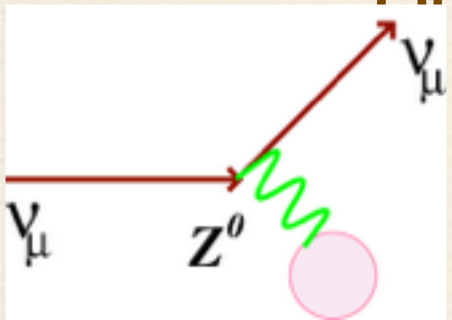

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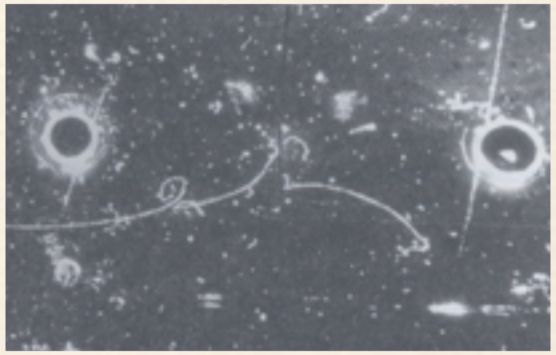

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$$\begin{pmatrix}\nu\\ e\end{pmatrix}_l \quad \begin{pmatrix}E^0\\ e\end{pmatrix}_r$$

Parity is conserved

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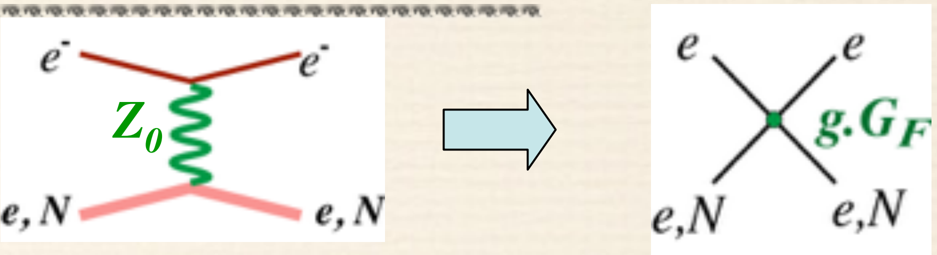

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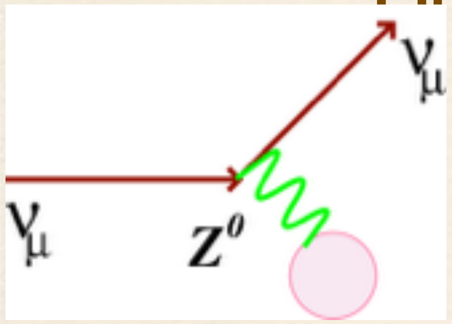

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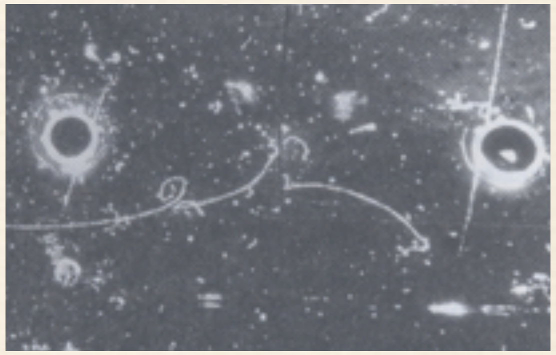

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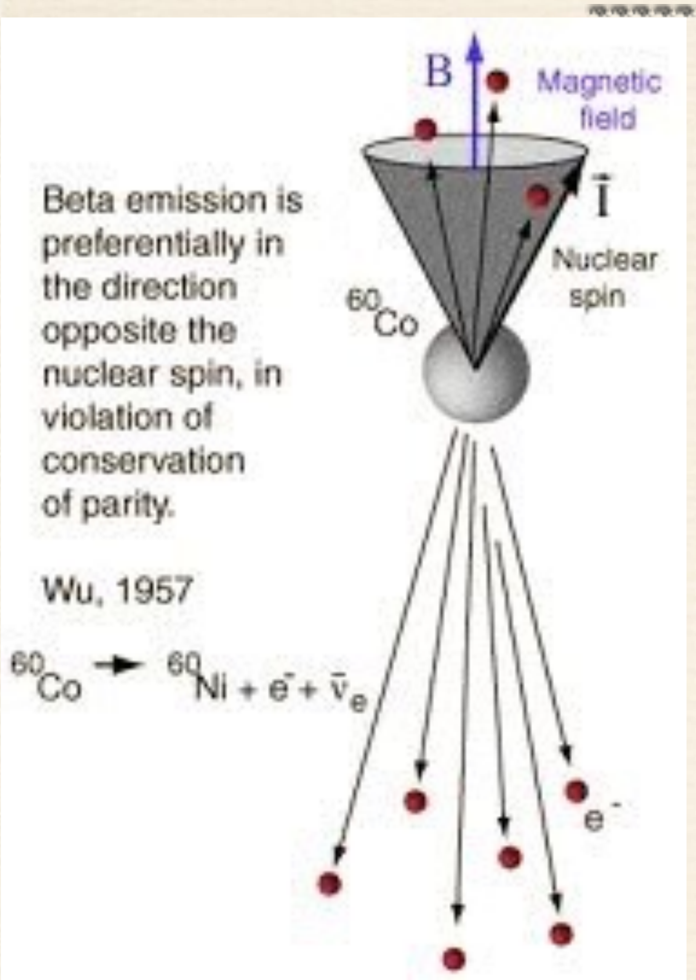
$$\begin{pmatrix}\nu\\ e\end{pmatrix}_l \quad (e)_r$$

Parity is violated

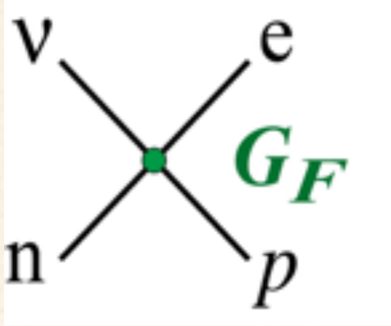
Zel'dovich speculation: Is Electron Scattering Parity-Violating?

Electroweak Scattering

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



Nuclear β Decay



charge and flavor-changing

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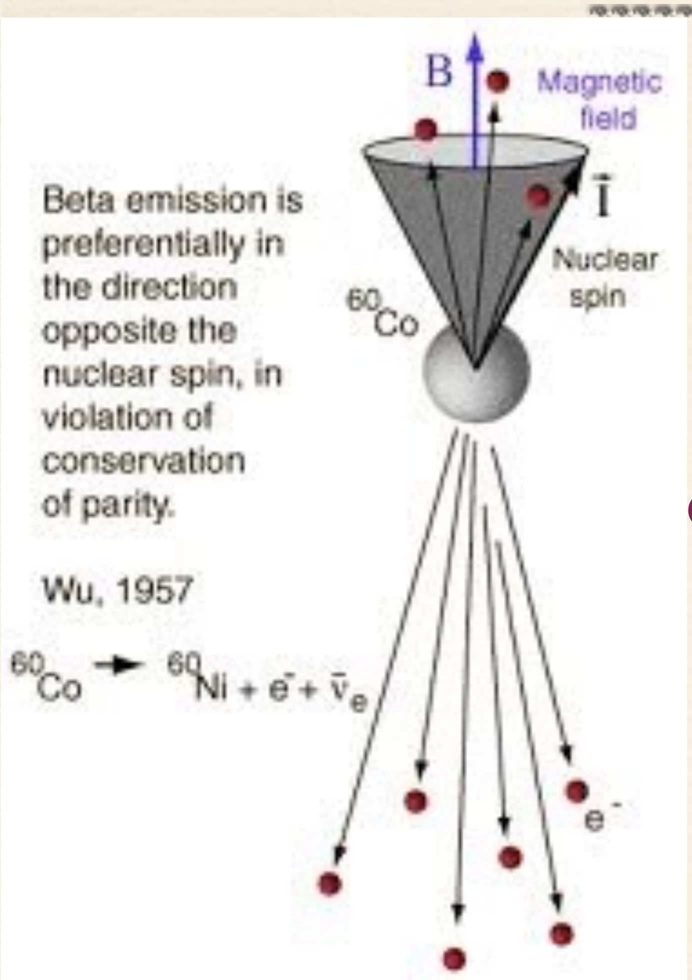

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Wu, 1957

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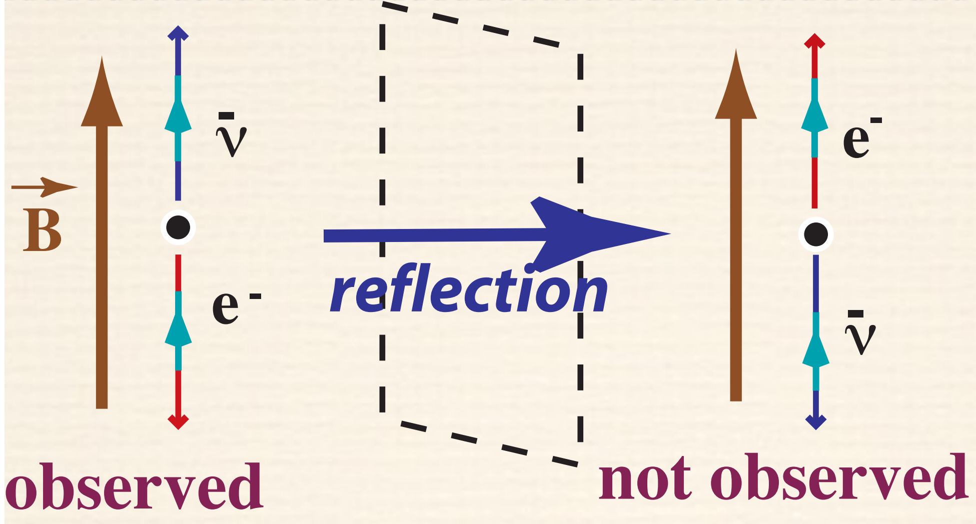

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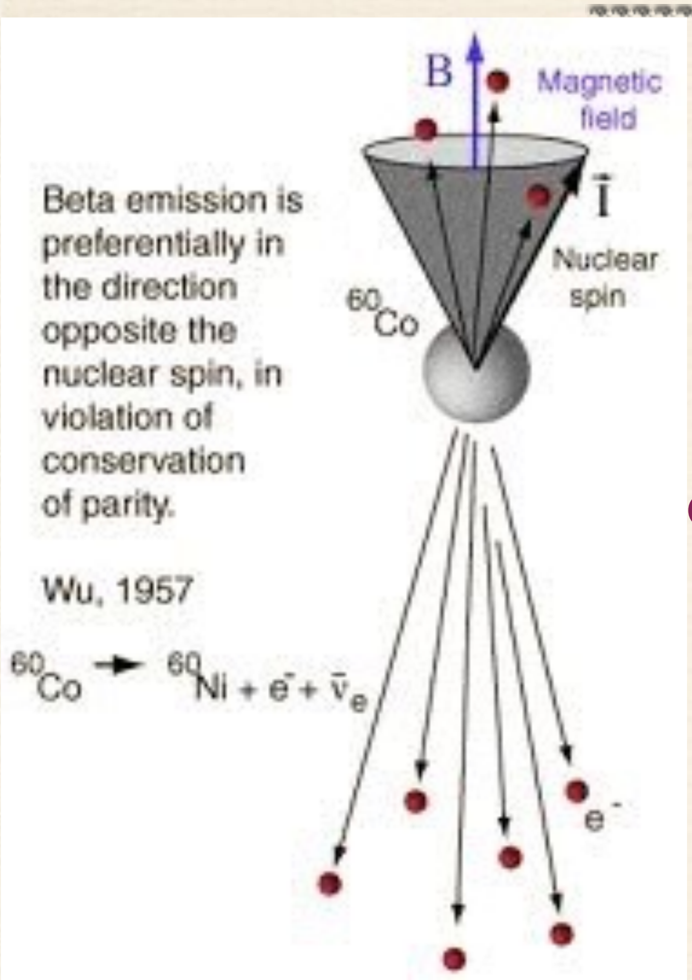

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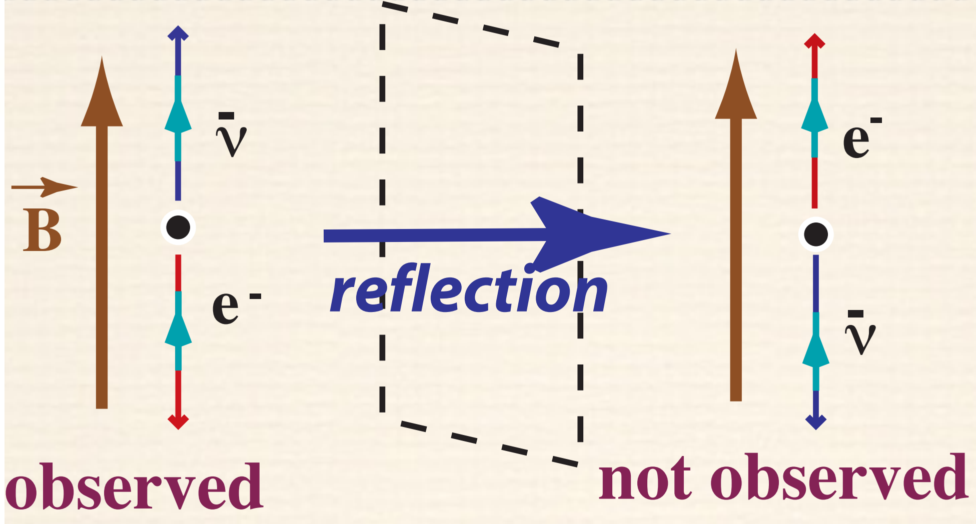
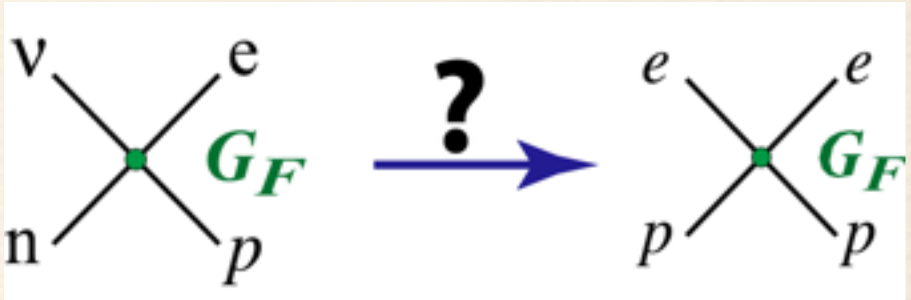


Neutron β Decay

Electron-proton Weak Scattering



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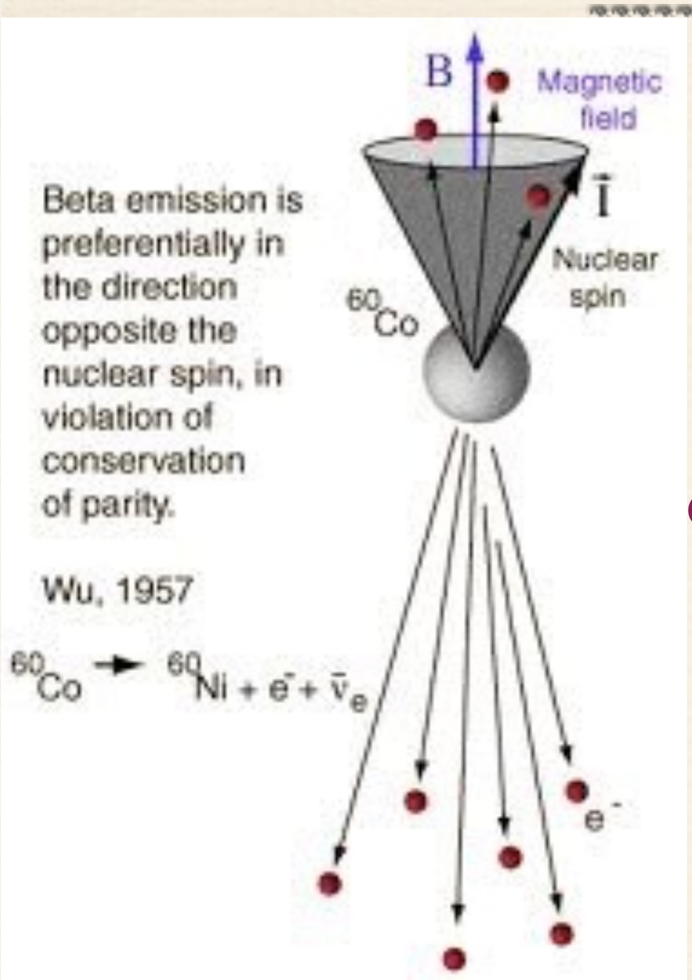

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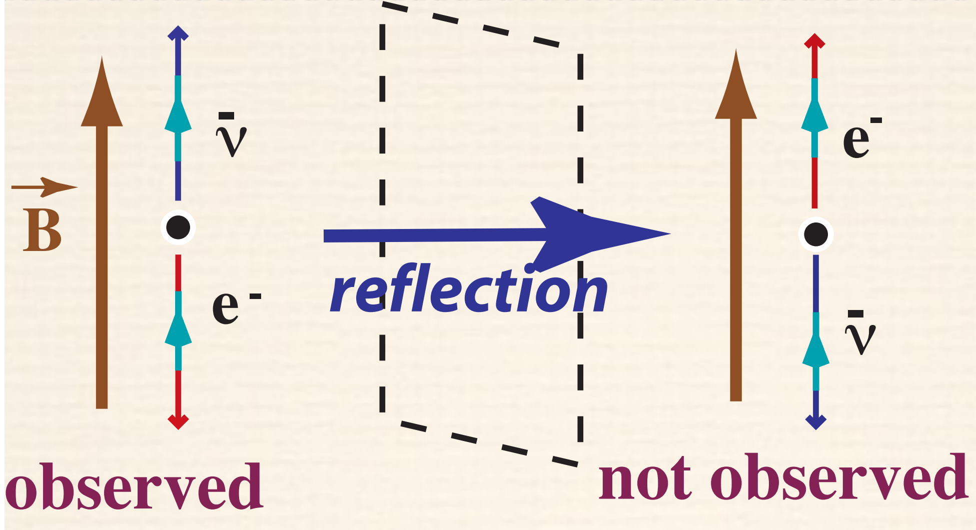

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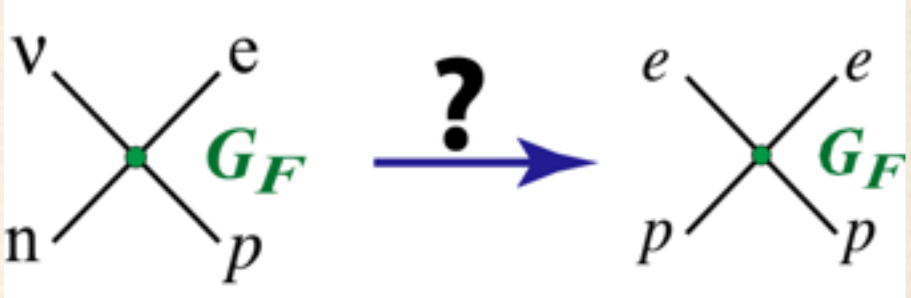

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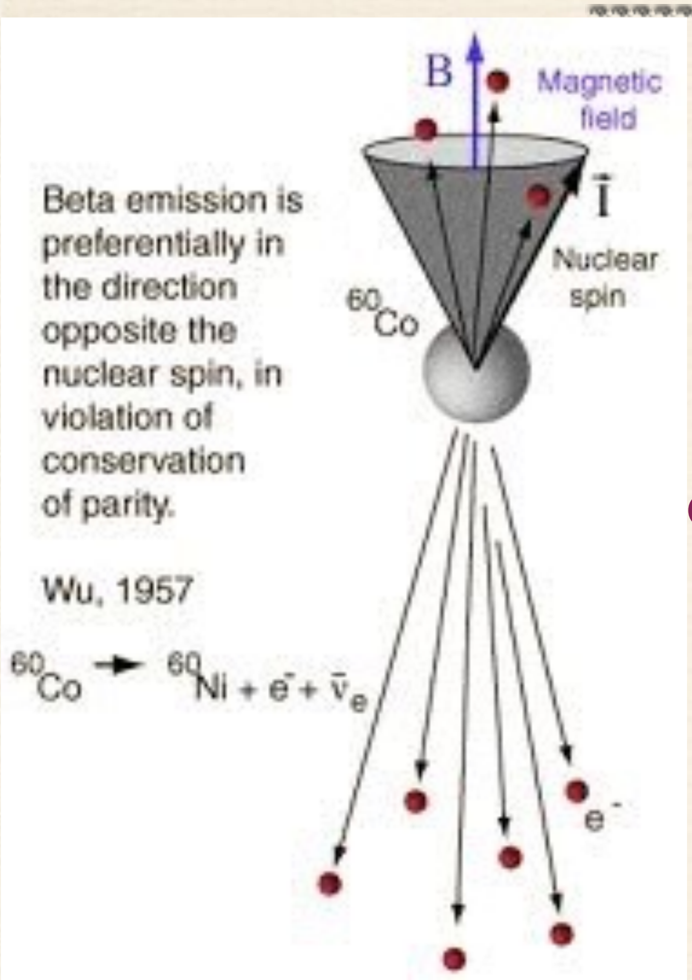
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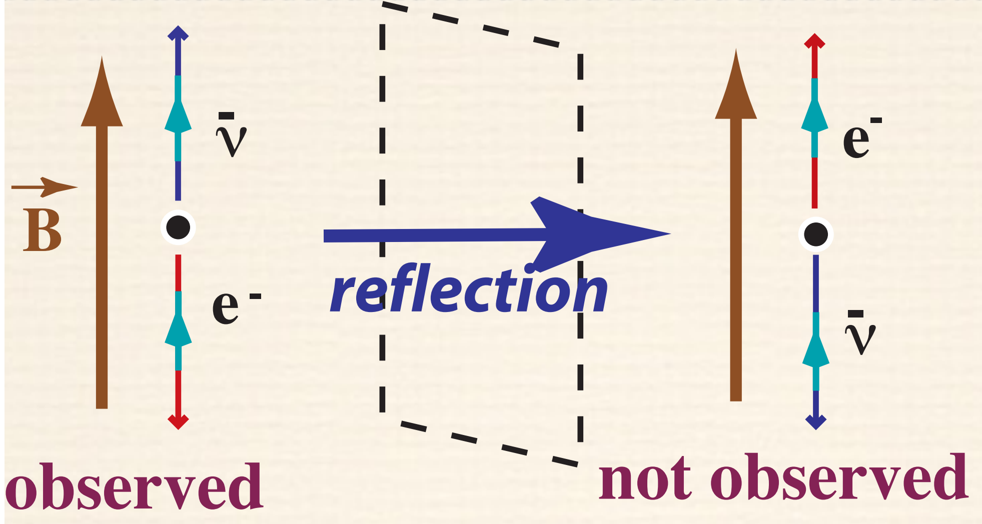

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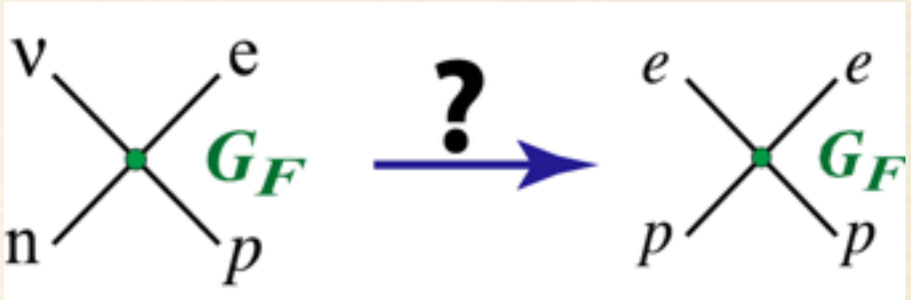

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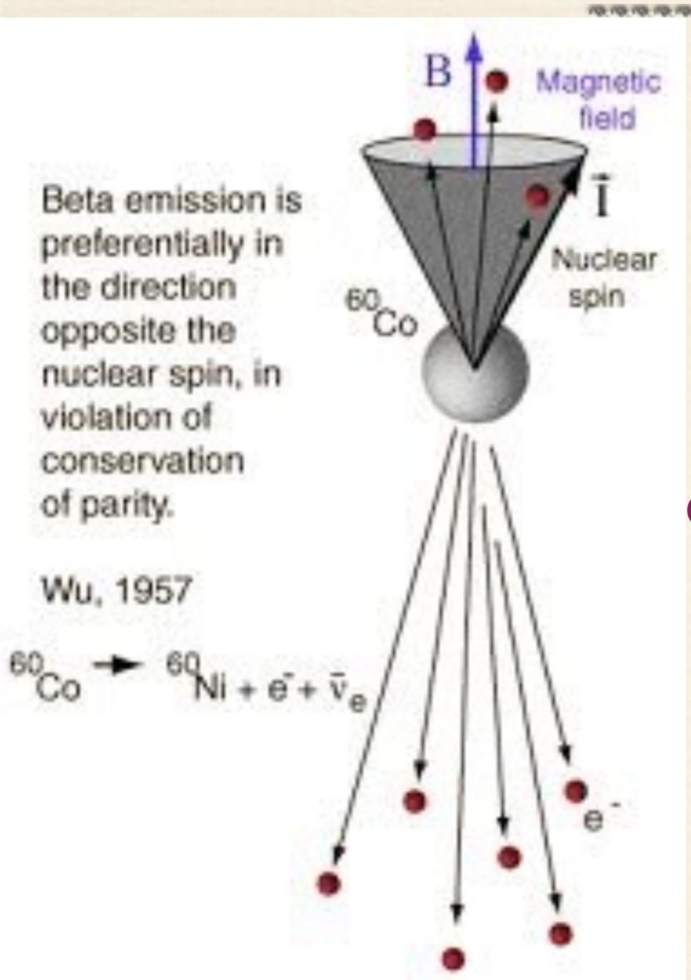

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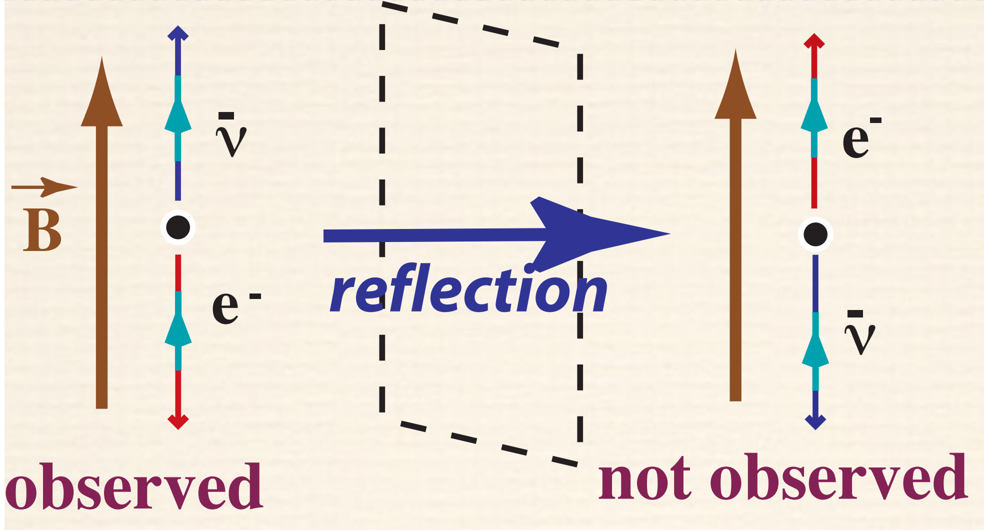

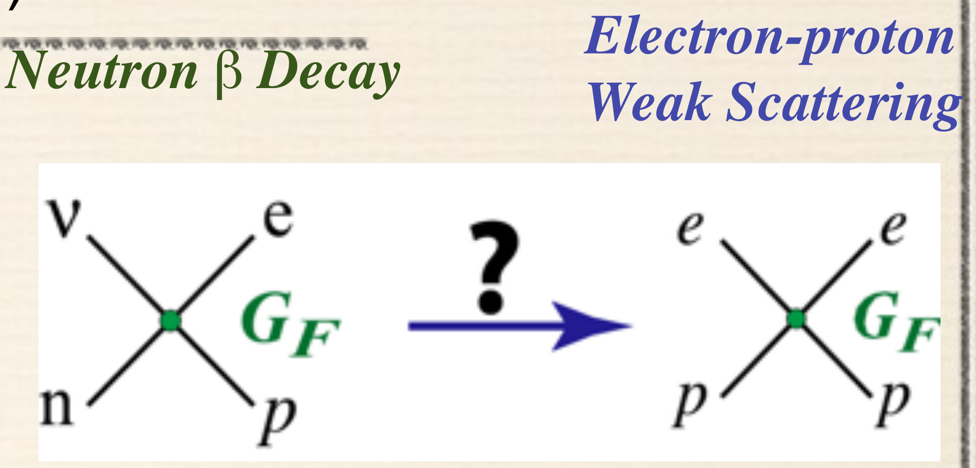

$$A_{PV} = \frac{\sigma_\uparrow - \sigma_\downarrow}{\sigma_\uparrow + \sigma_\downarrow} = -A$$

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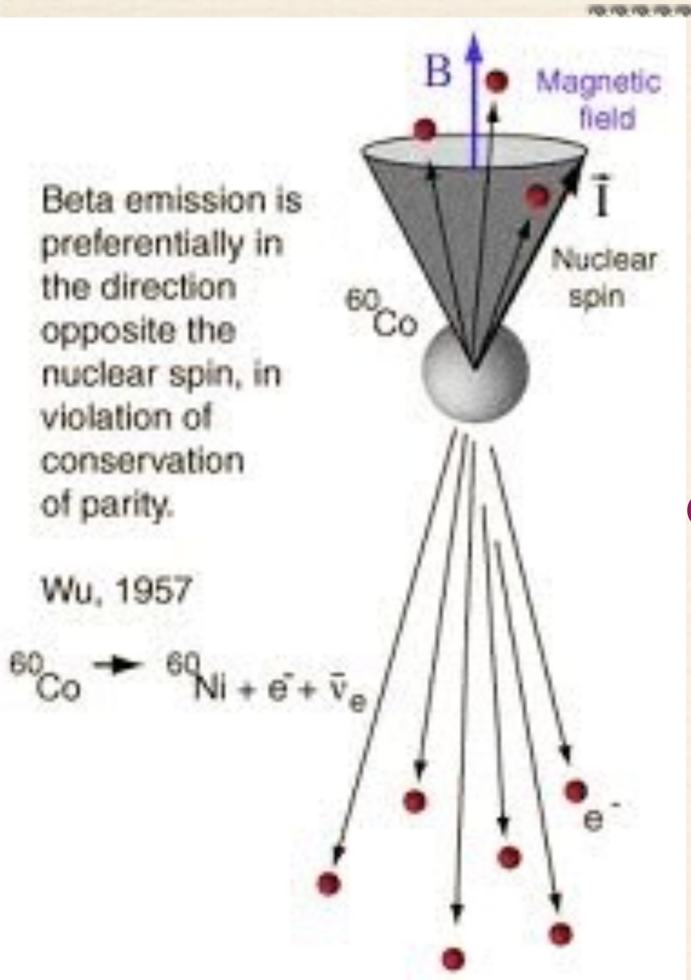

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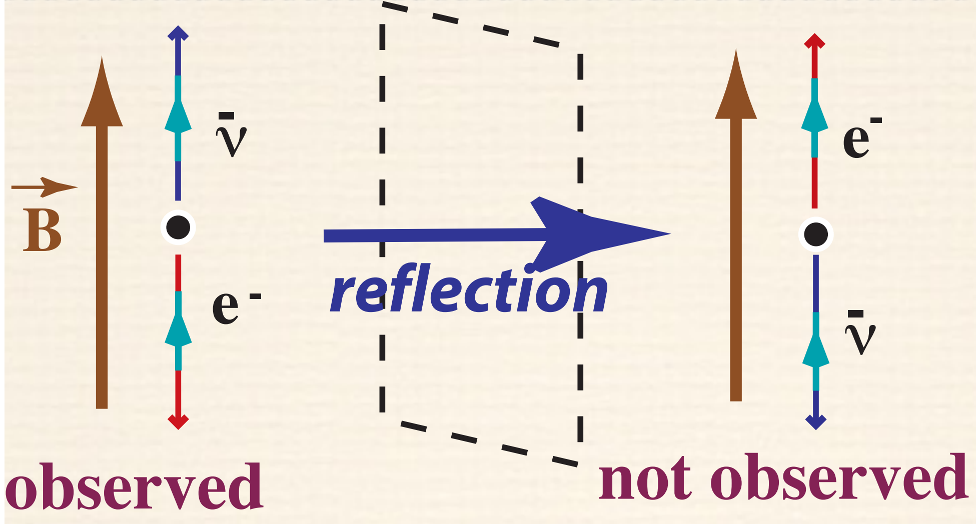

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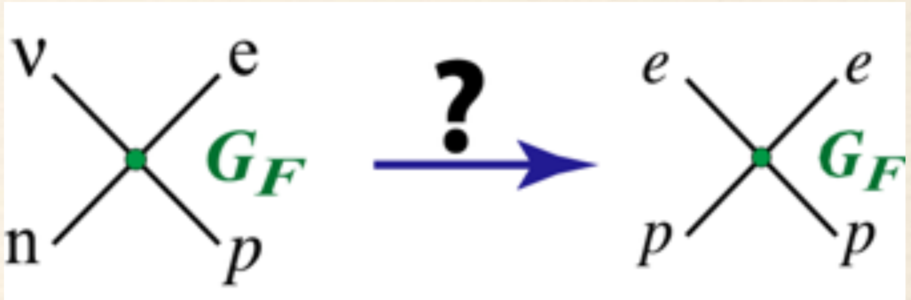

$$A_{PV} = \frac{\sigma_\uparrow - \sigma_\downarrow}{\sigma_\uparrow + \sigma_\downarrow} = -A$$

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

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

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

Parity-violating

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

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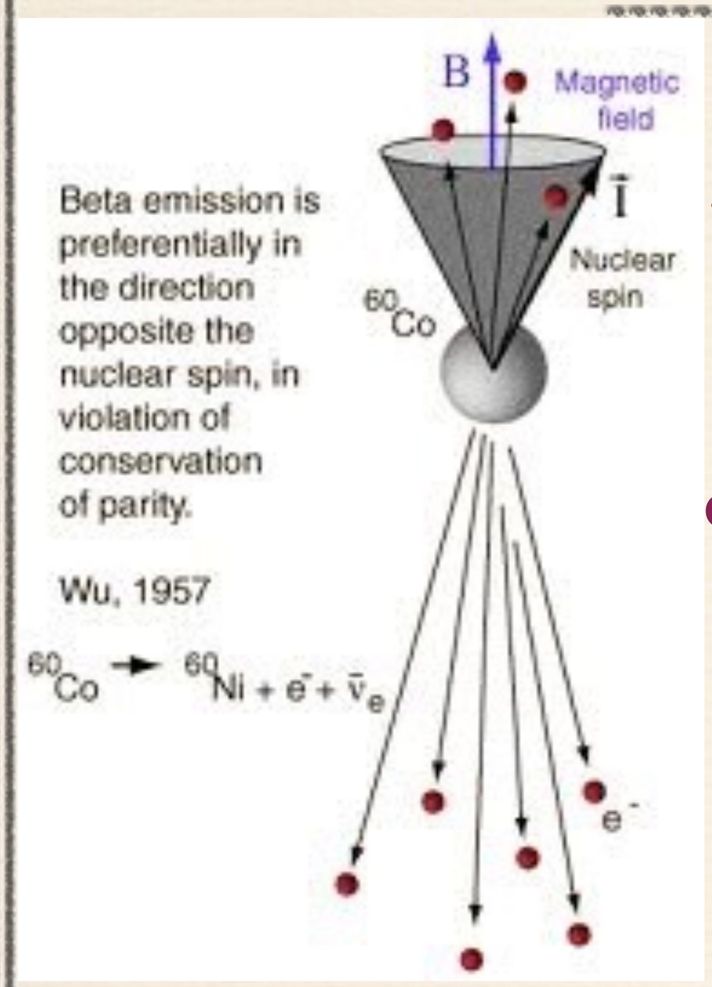

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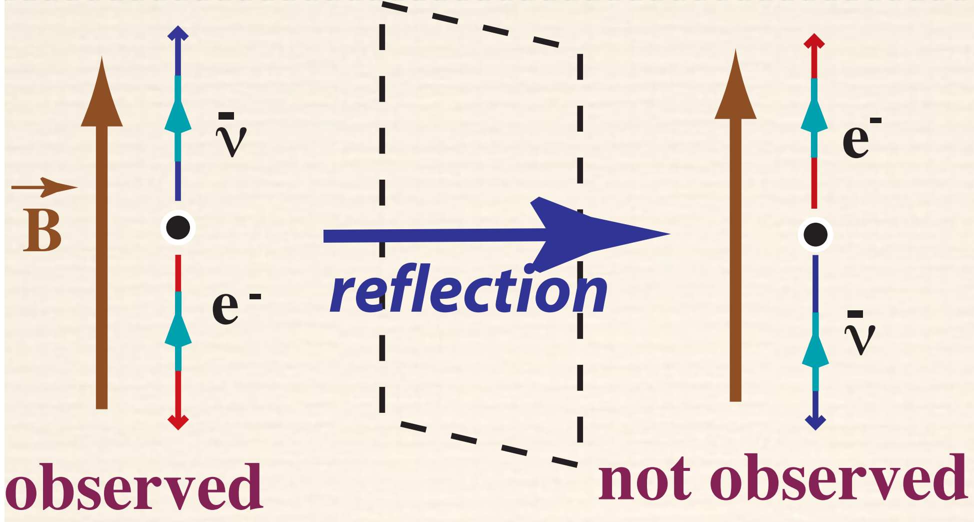

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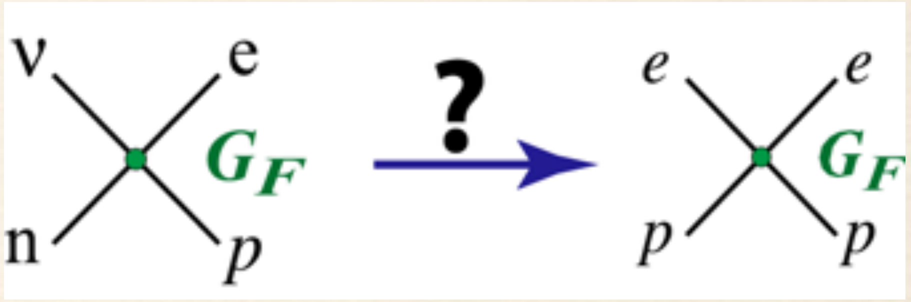


$$A_{PV} = \frac{\sigma_\uparrow - \sigma_\downarrow}{\sigma_\uparrow + \sigma_\downarrow} = -A$$

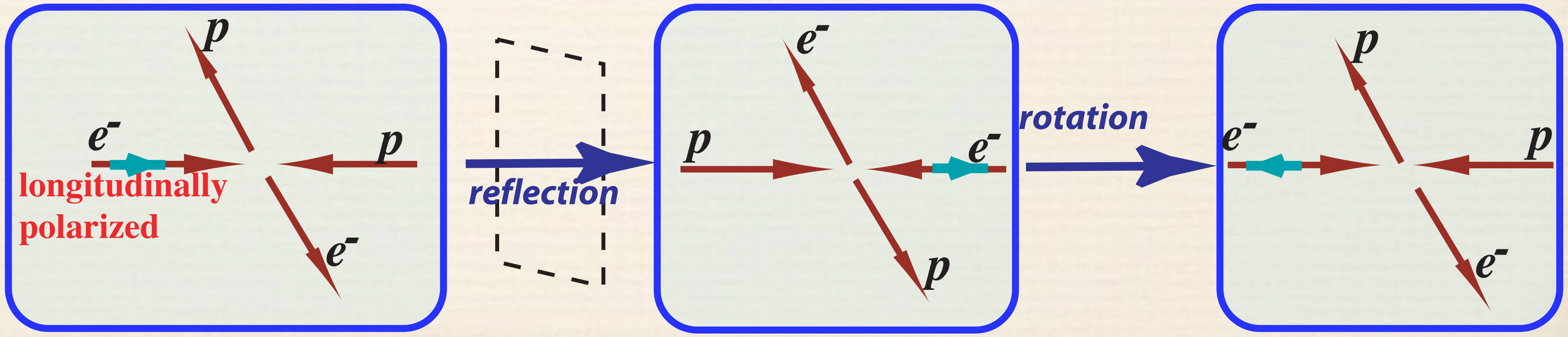
$$\sim \frac{A_{weak}}{A_{EM}} \sim \frac{G_F Q^2}{4\pi\alpha}$$

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

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

Parity-violating

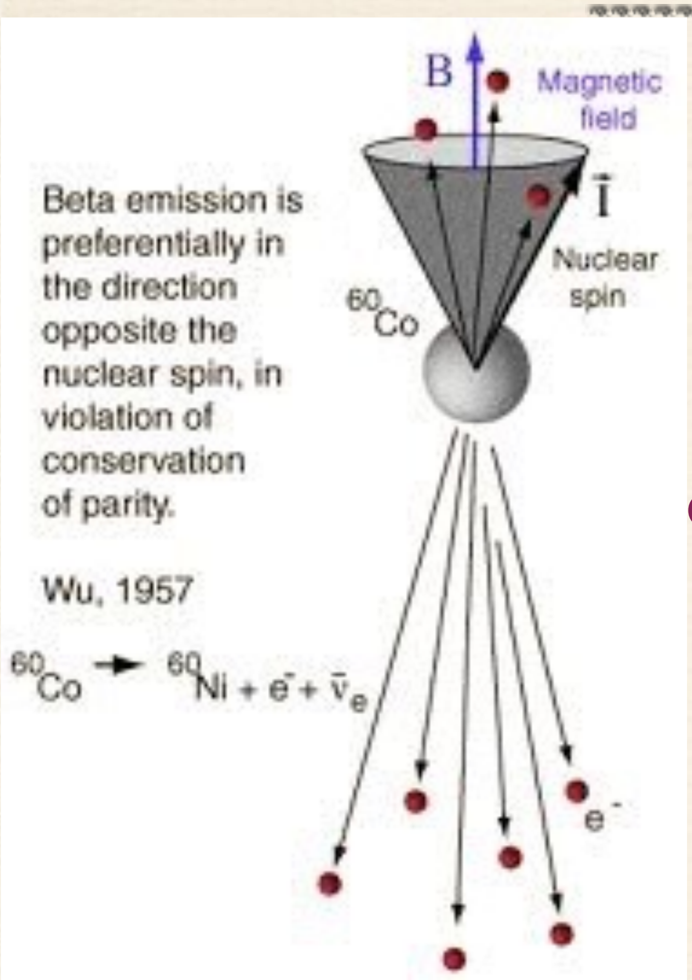
$$A_{PV} \sim 10^{-4} \cdot Q^2\ (\mathrm{GeV}^2)$$



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

Electroweak Scattering

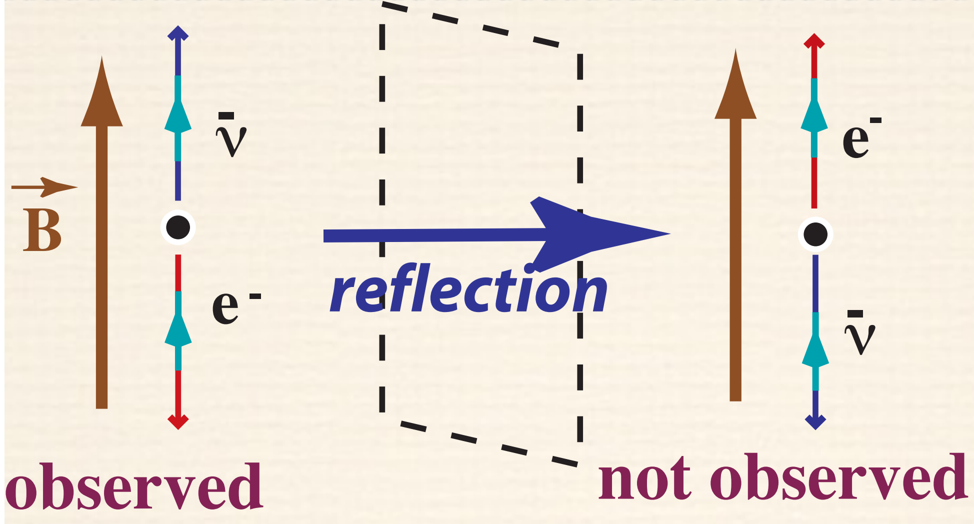
JETP **36**, pp 964-66 (1959)



Beta emission is preferentially in the direction opposite the nuclear spin, in violation of conservation of parity.

Wu, 1957

$^{60}\mathrm{Co} \rightarrow {}^{60}\mathrm{Ni} + e^- + \bar{\nu}_e$



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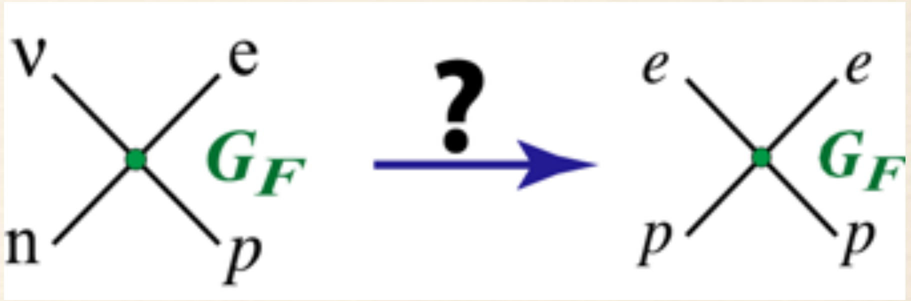

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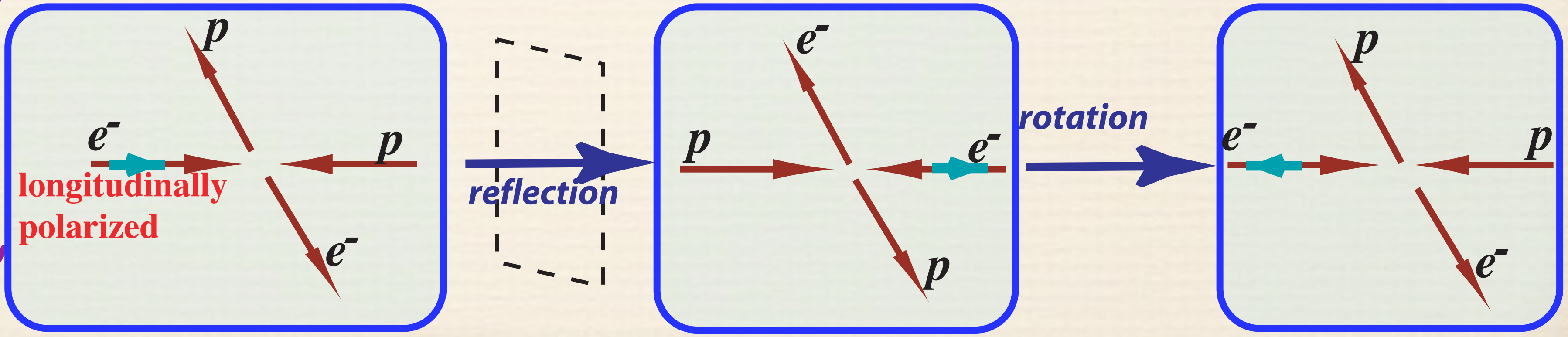
Parity-violating

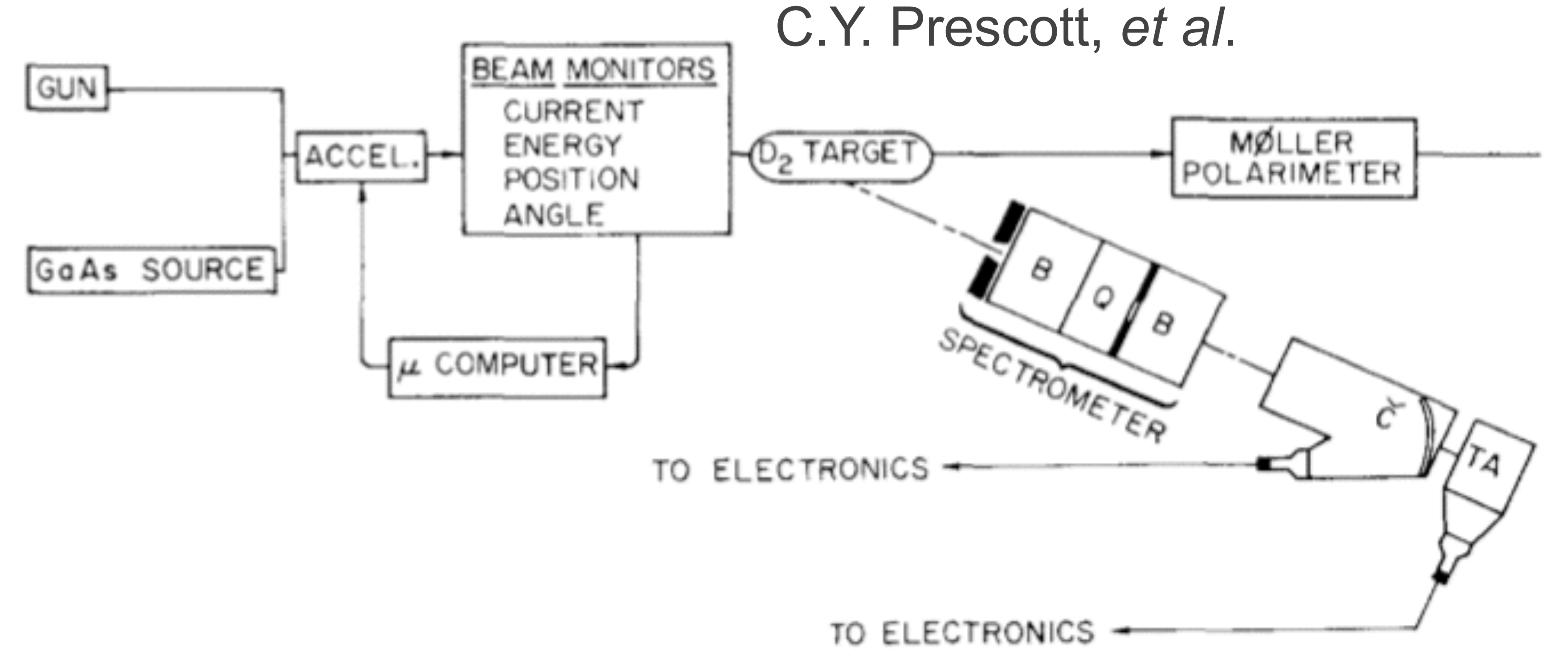
$$A_{PV} \sim 10^{-4} \cdot Q^2 \text{ (GeV}^2\text{)}$$

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



The first Parity-Violating Electron Scattering (PVES) Experiment

Anatomy of E122 at SLAC



C.Y. Prescott, *et al.*

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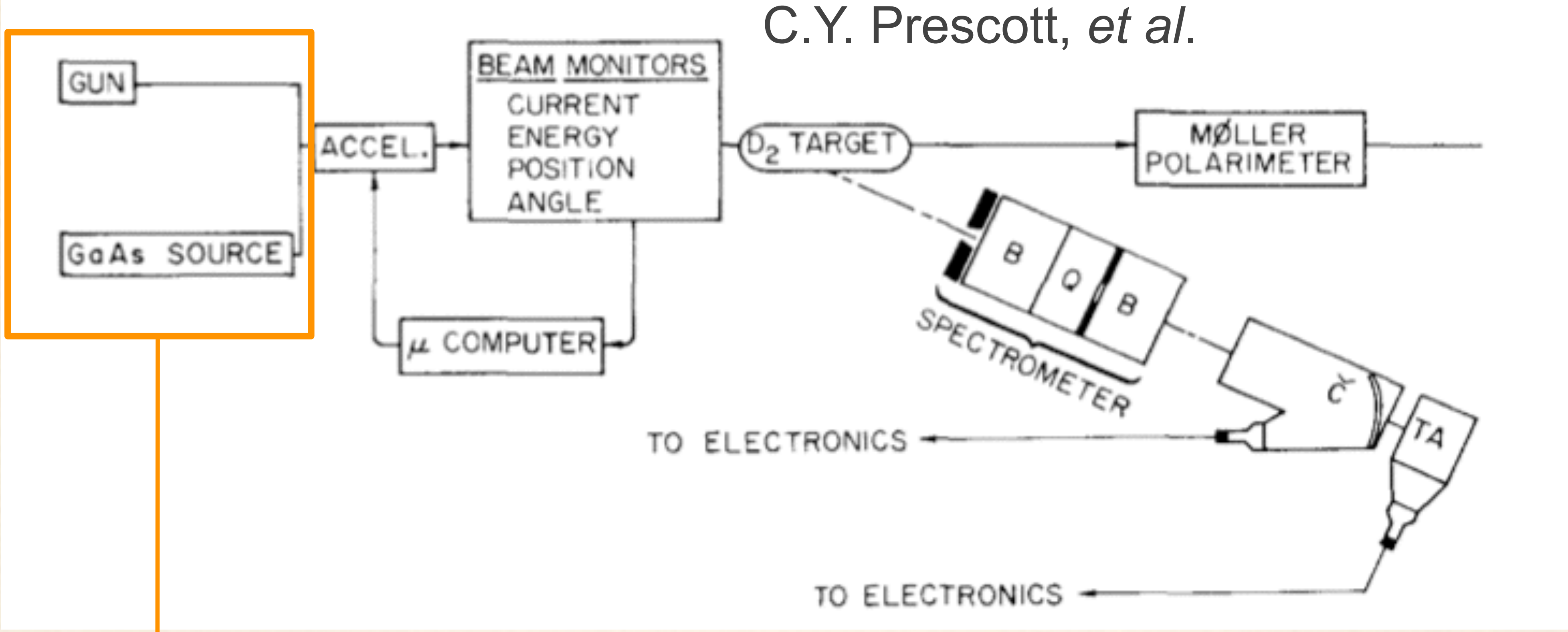
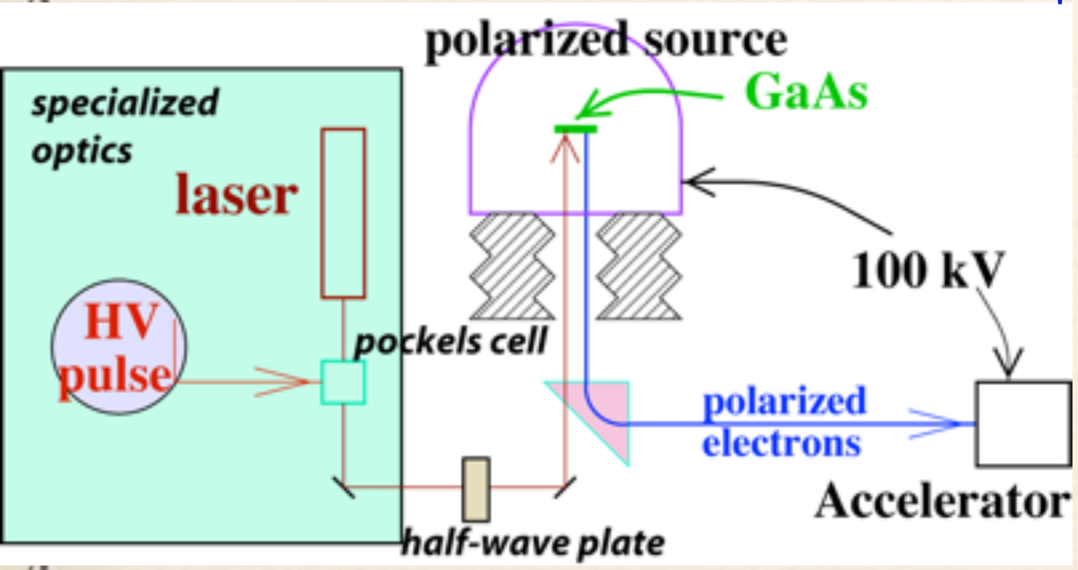
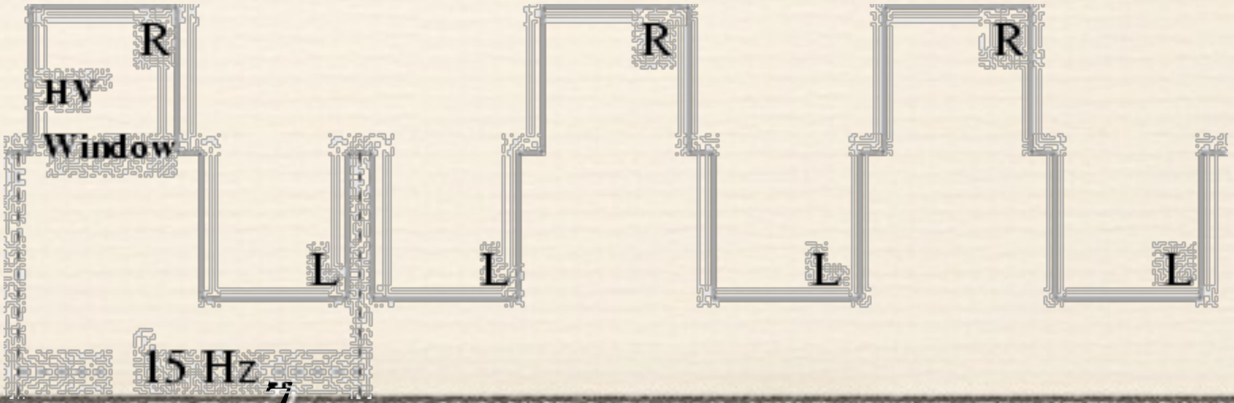

C.Y. Prescott, *et al.*



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

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



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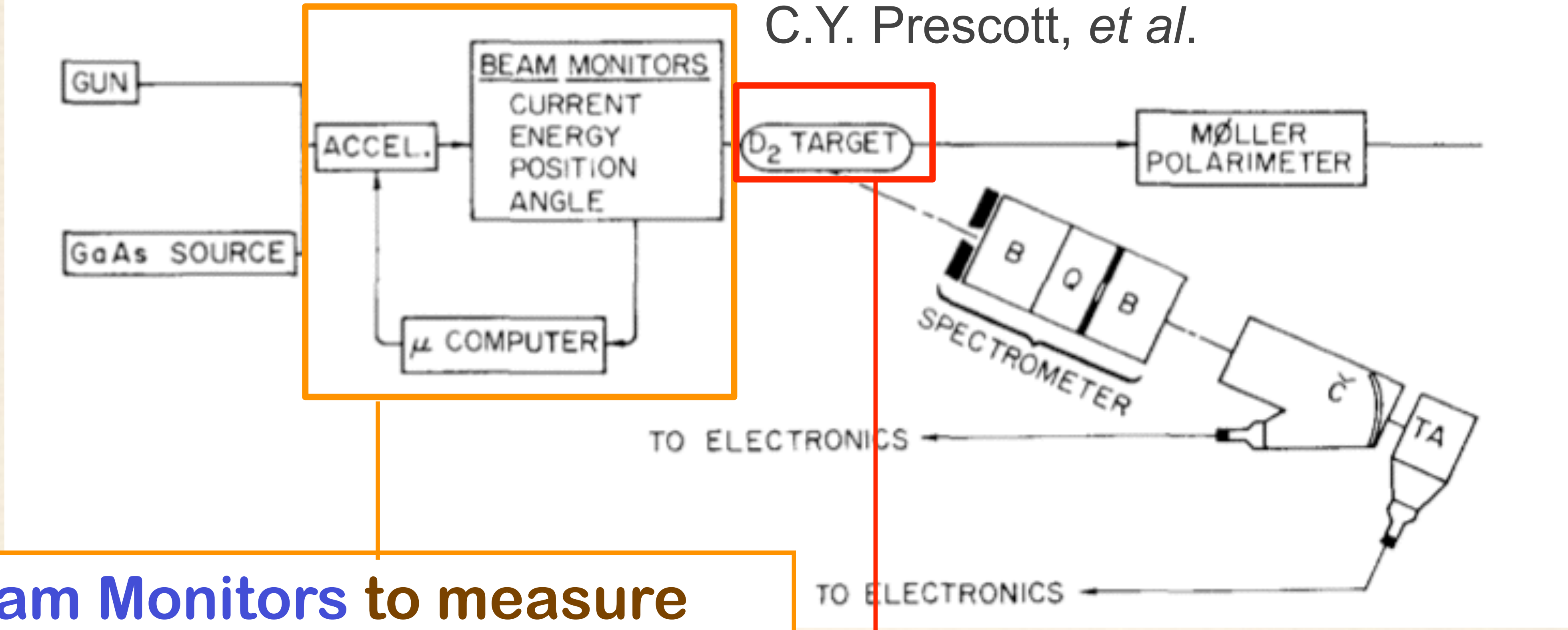


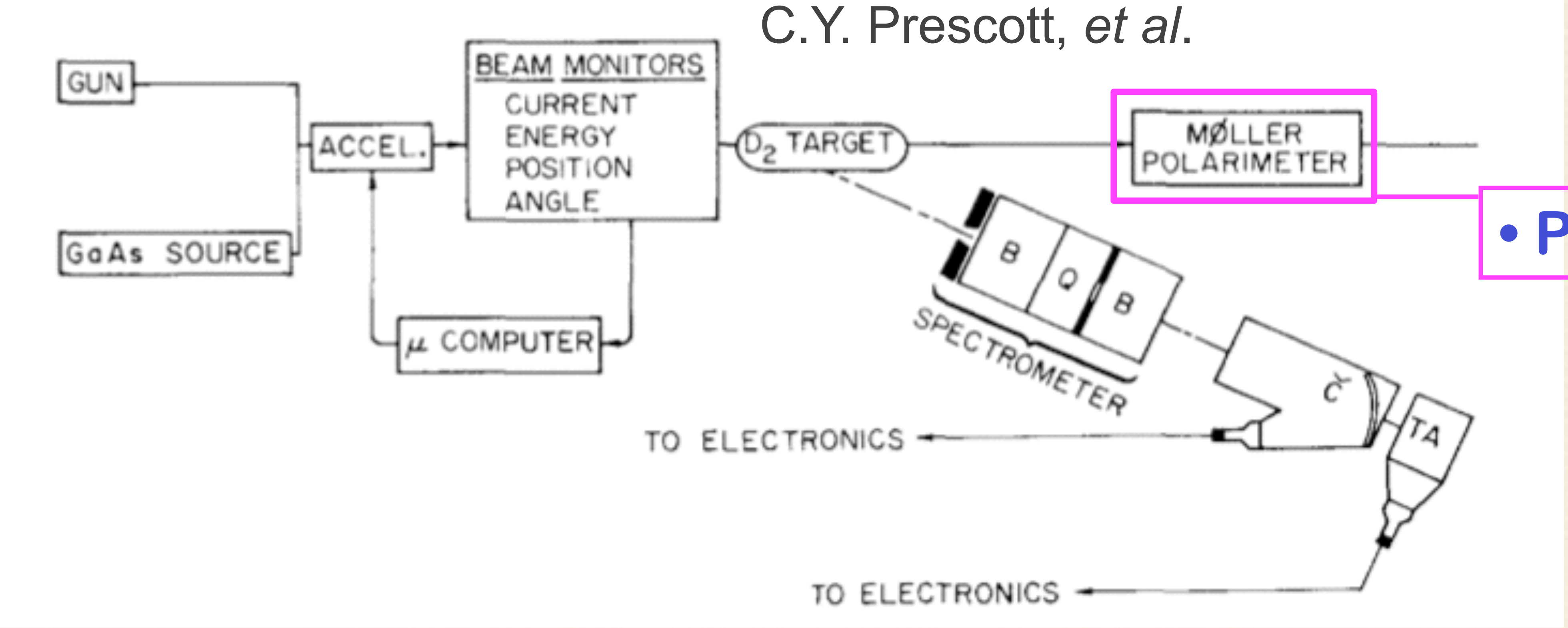
C.Y. Prescott, *et al.*

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

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

The first Parity-Violating Electron Scattering (PVES) Experiment

Anatomy of E122 at SLAC

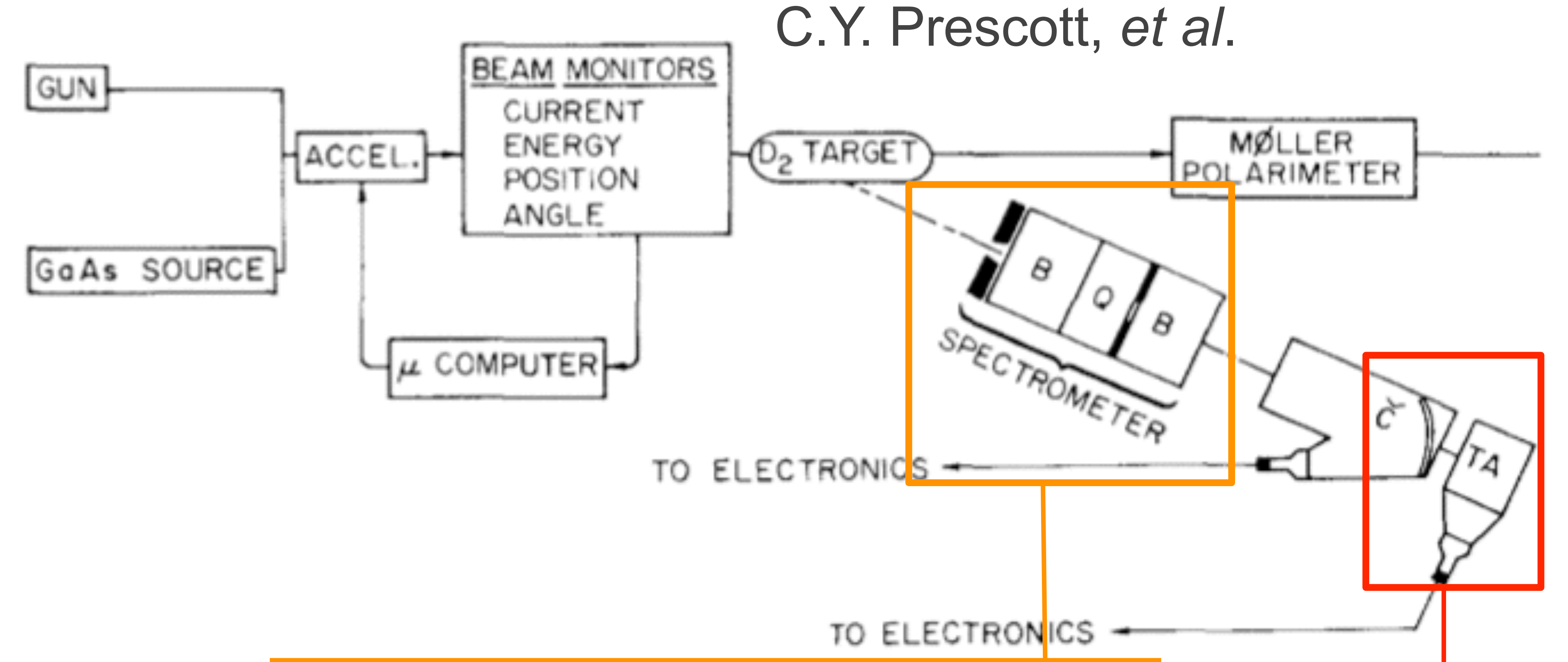


C.Y. Prescott, *et al.*

- Polarimetry

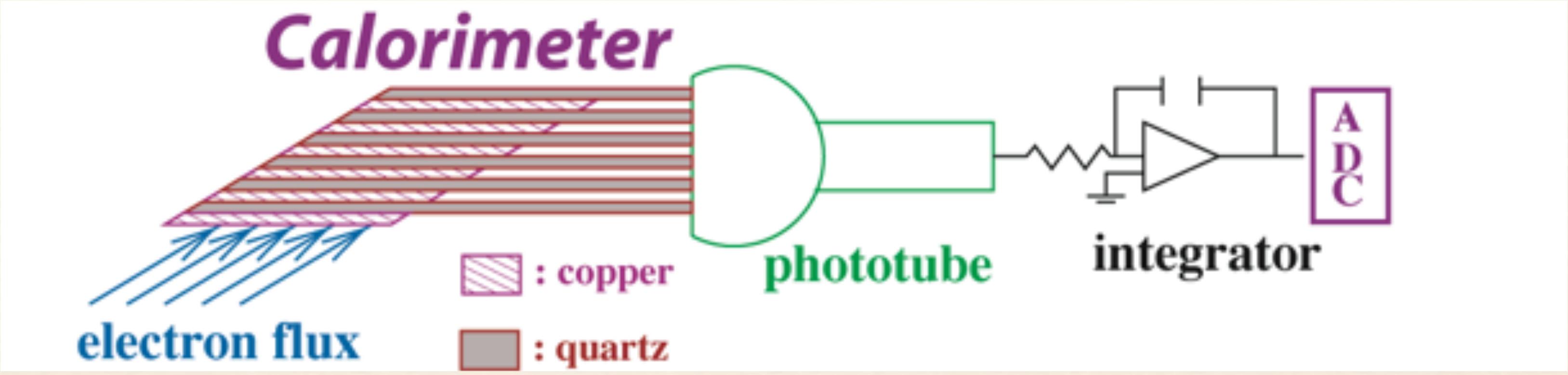
The first Parity-Violating Electron Scattering (PVES) Experiment

Anatomy of E122 at SLAC


C.Y. Prescott, *et al.*

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

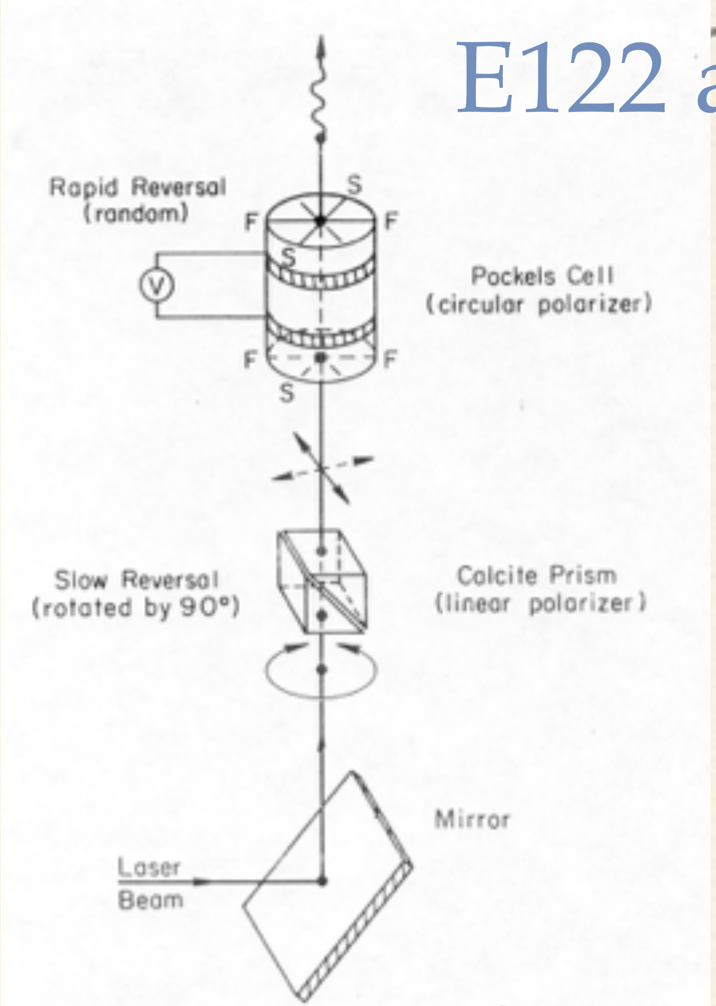
- **Flux Integration** measures high rate without deadtime

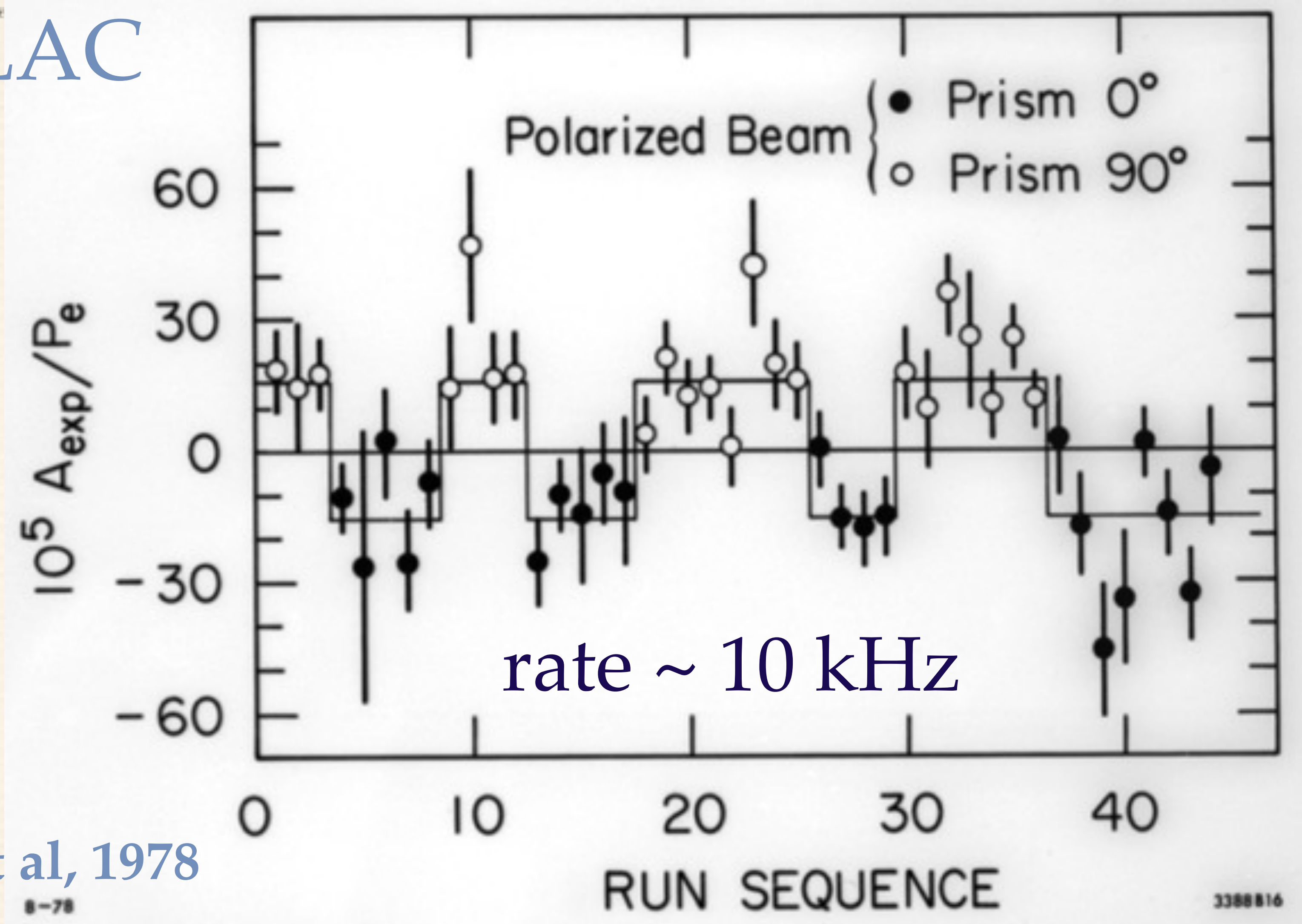


Does the weak neutral current amplitude interfere with the electromagnetic amplitude?

SLAC E122 Result

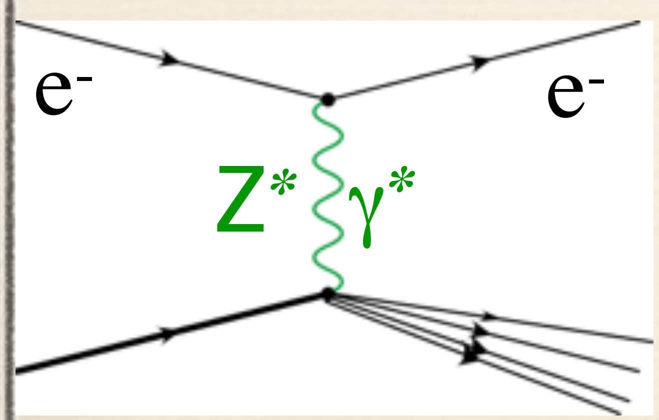
E122 at SLAC





rate ~ 10 kHz

C.Y. Prescott et al, 1978



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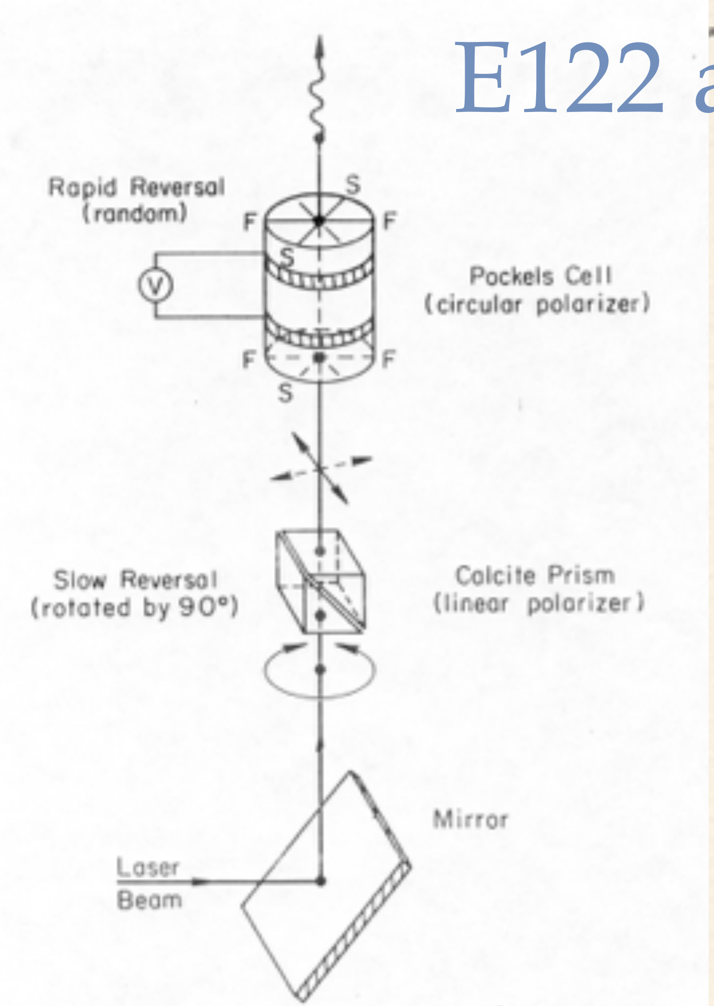

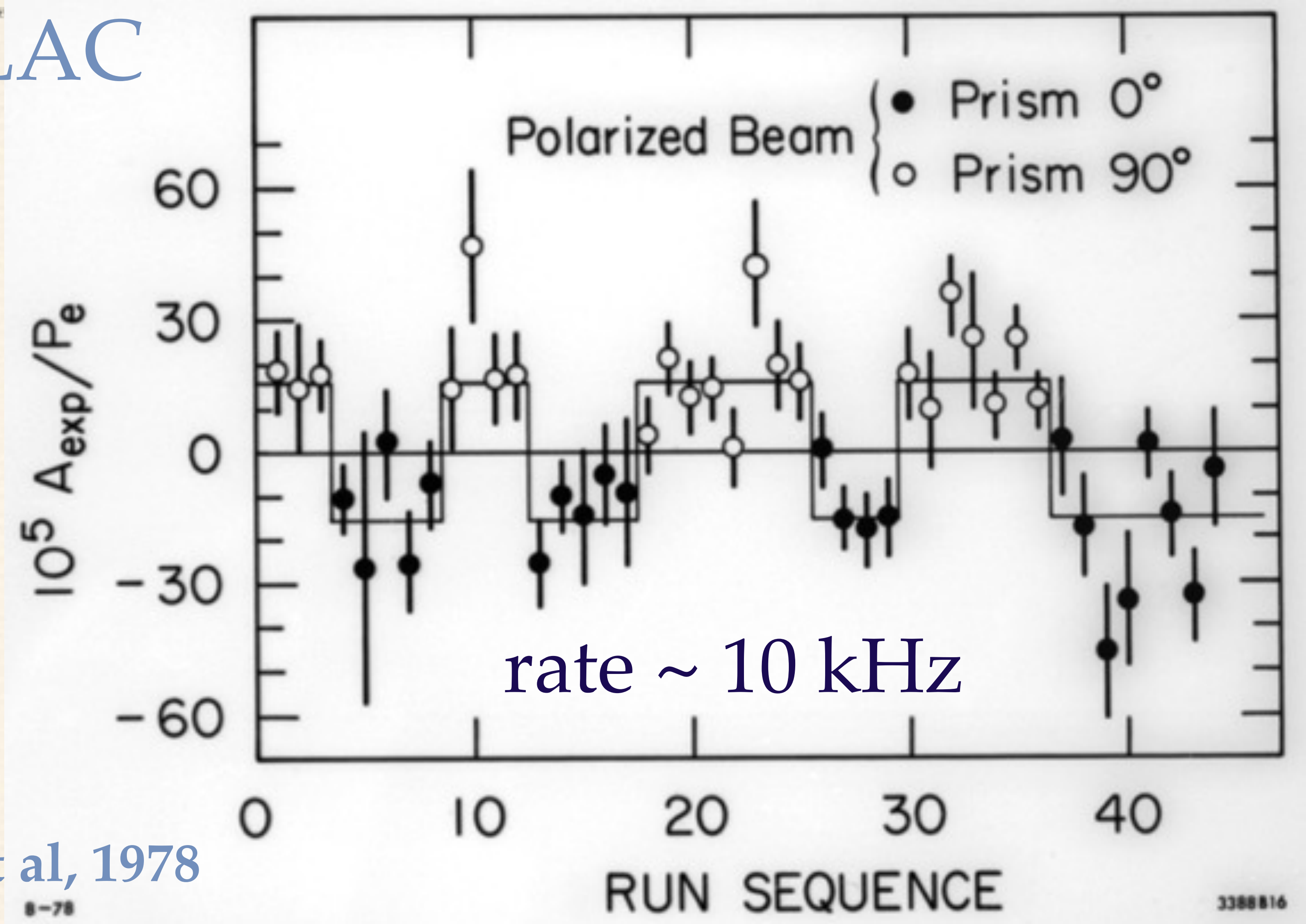

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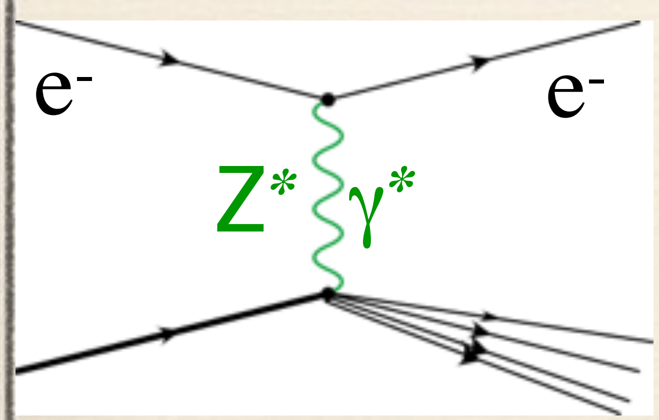

- ***Parity Violation in Weak Neutral Current Interactions***
- ***$\sin^2\theta_W$ = 0.224 ± 0.020: same as in neutrino scattering***

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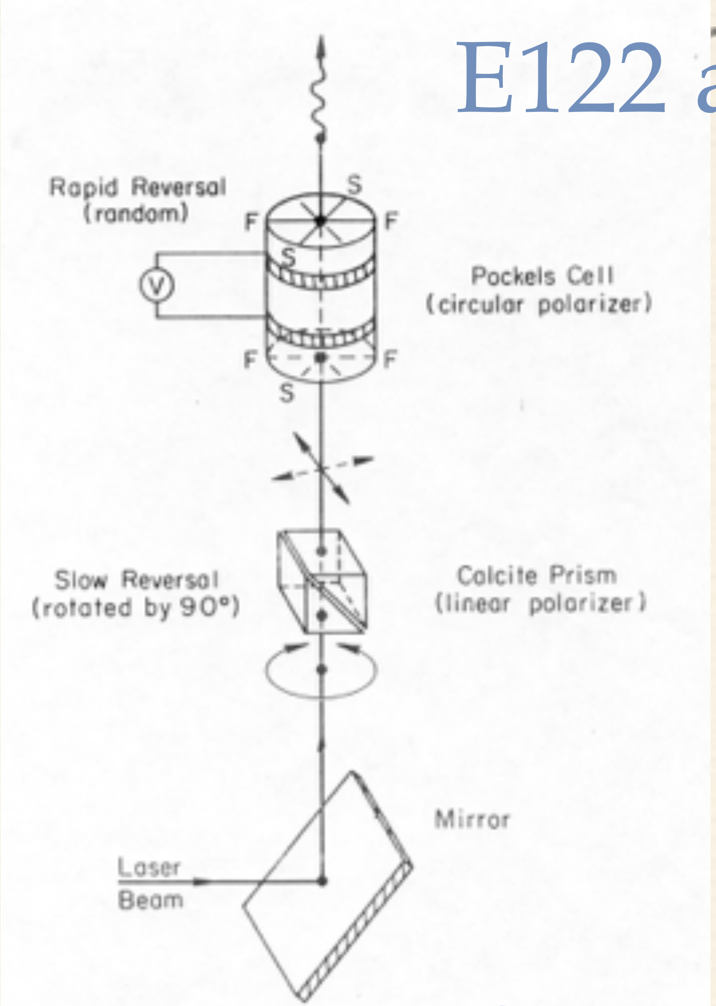

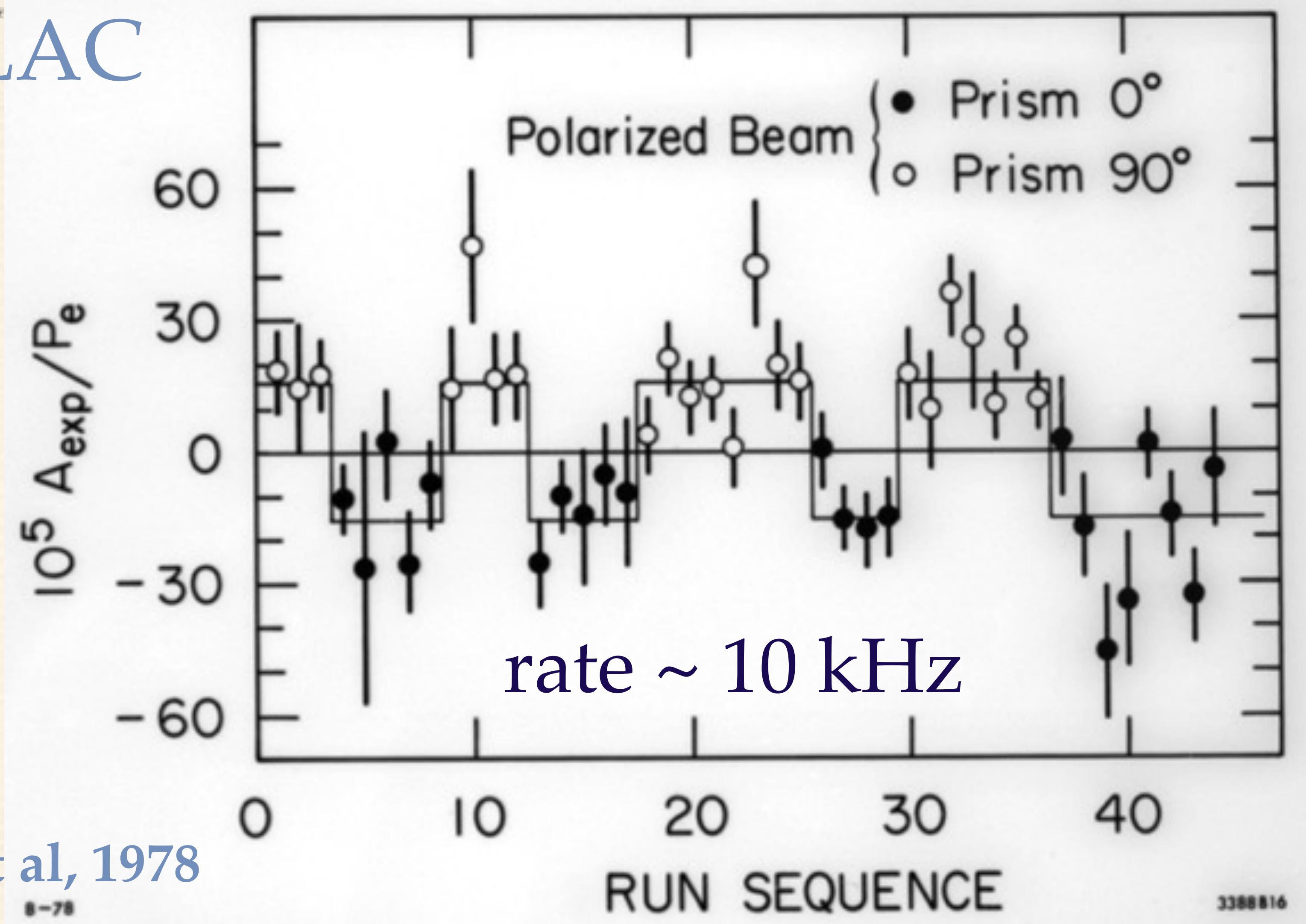

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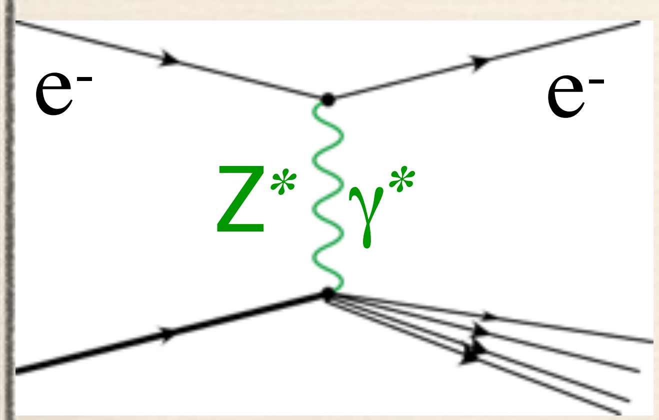

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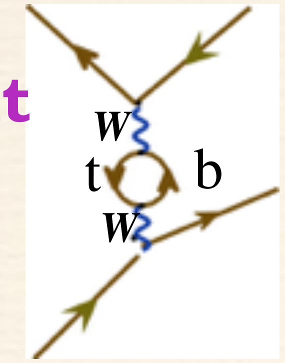
Glashow, Weinberg, Salam Nobel Prize awarded in 1979

Electroweak Theory at 1-Loop

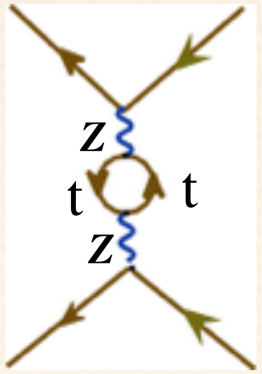
For electroweak interactions, 3 input parameters needed:

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

α_{QED} G_F M_Z



Muon decay



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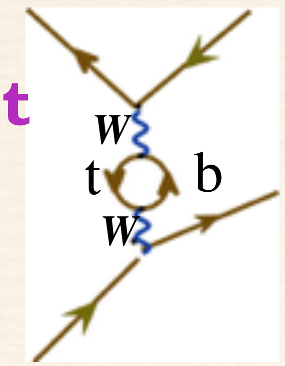

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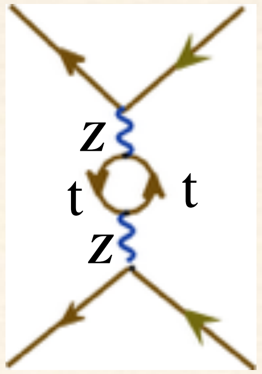
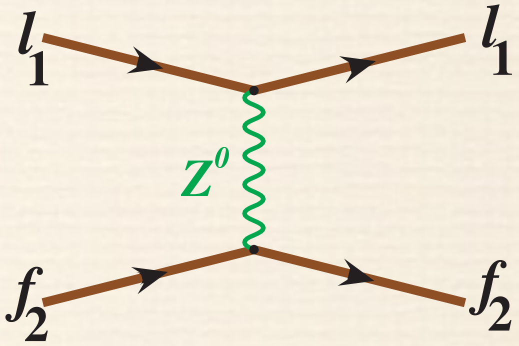


Z production

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



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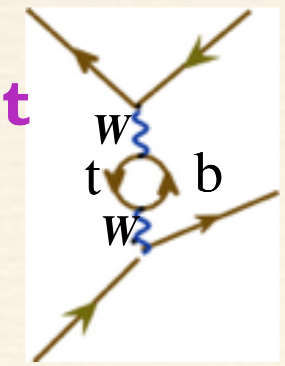

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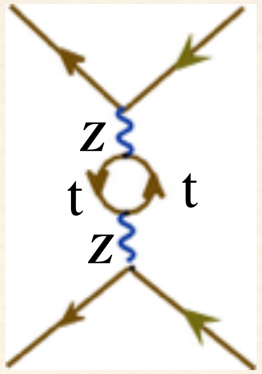

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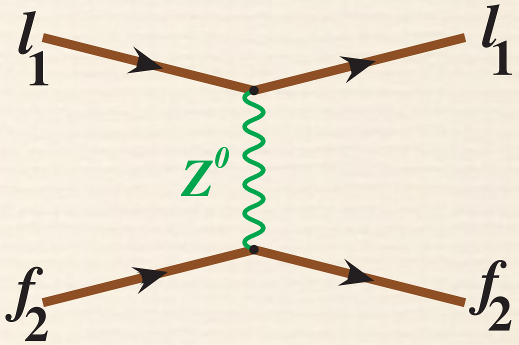

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$$\sin^2\theta_W \equiv 1 - m_W^2/m_Z^2$$

simple definition; disfavored due to heavy m_t

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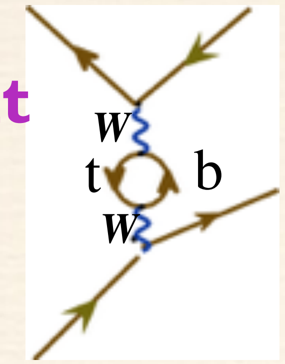

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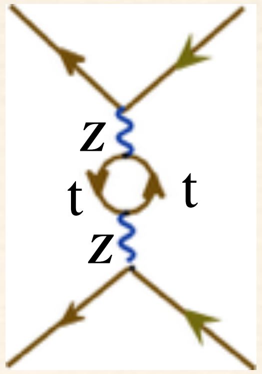

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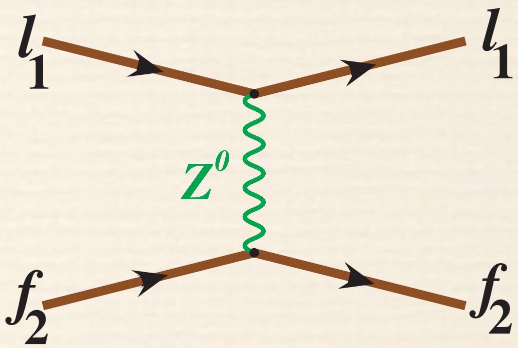

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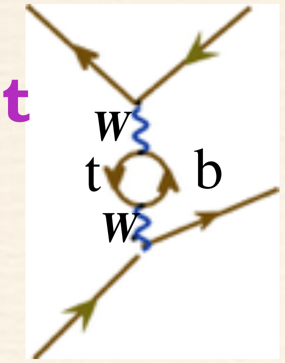

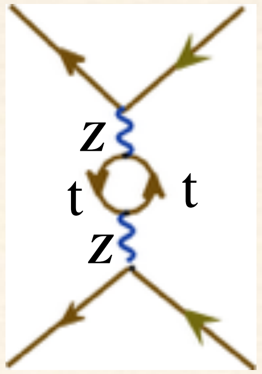

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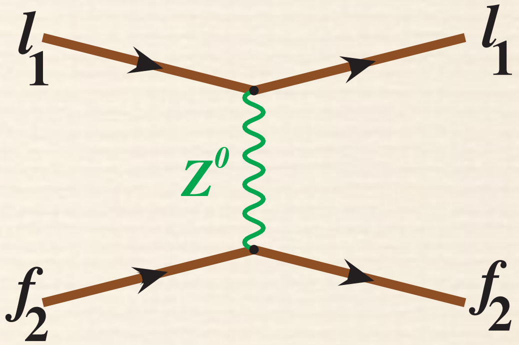

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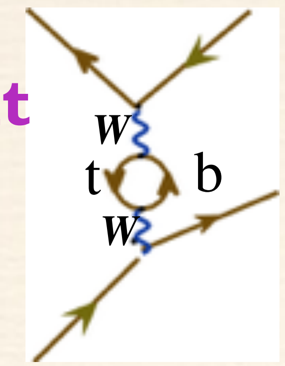

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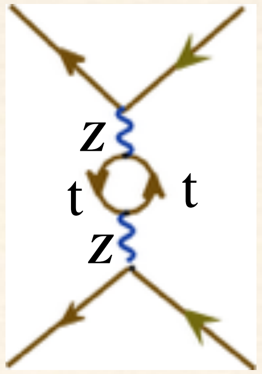

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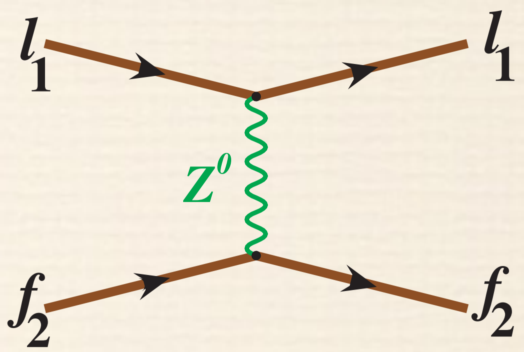

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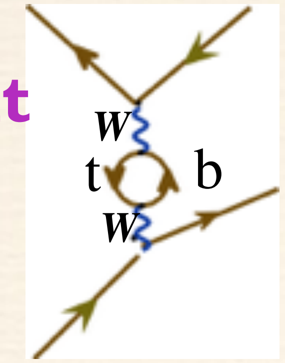

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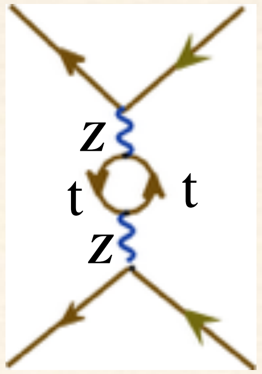

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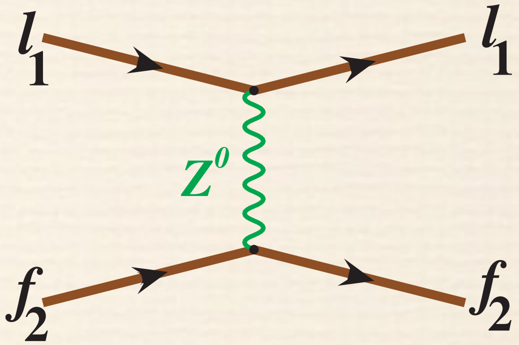

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World Averages

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

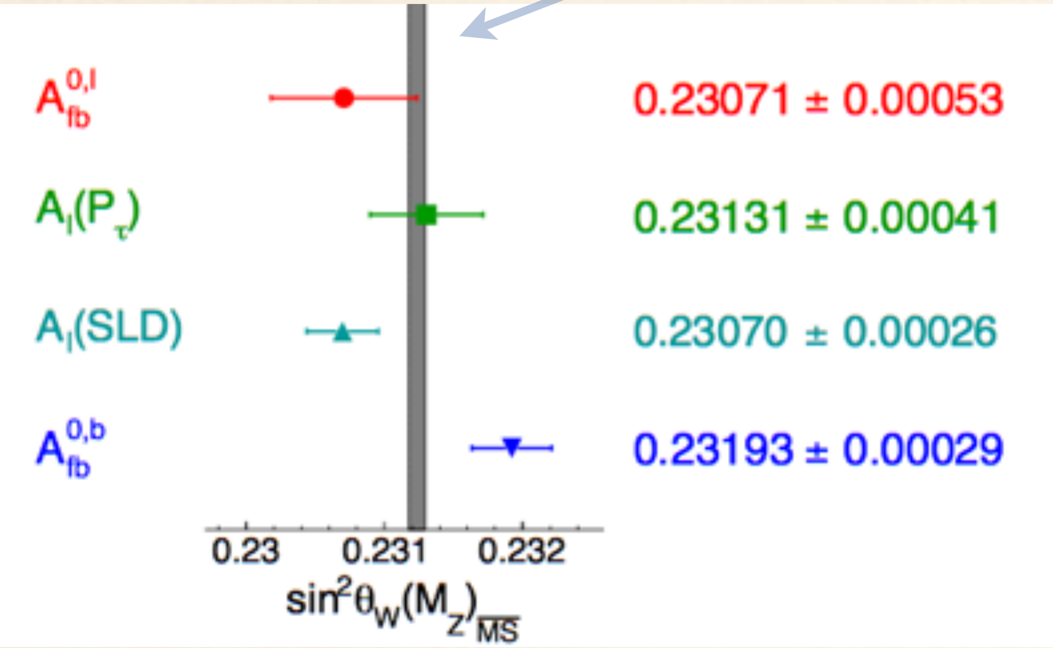
$$M_W = 80.385(15)\ \mathrm{GeV}$$

Theory vs Experiment

The most precise measurements at LEP/SLC

colliders: LEP, SLC

Prediction for 125 GeV Higgs



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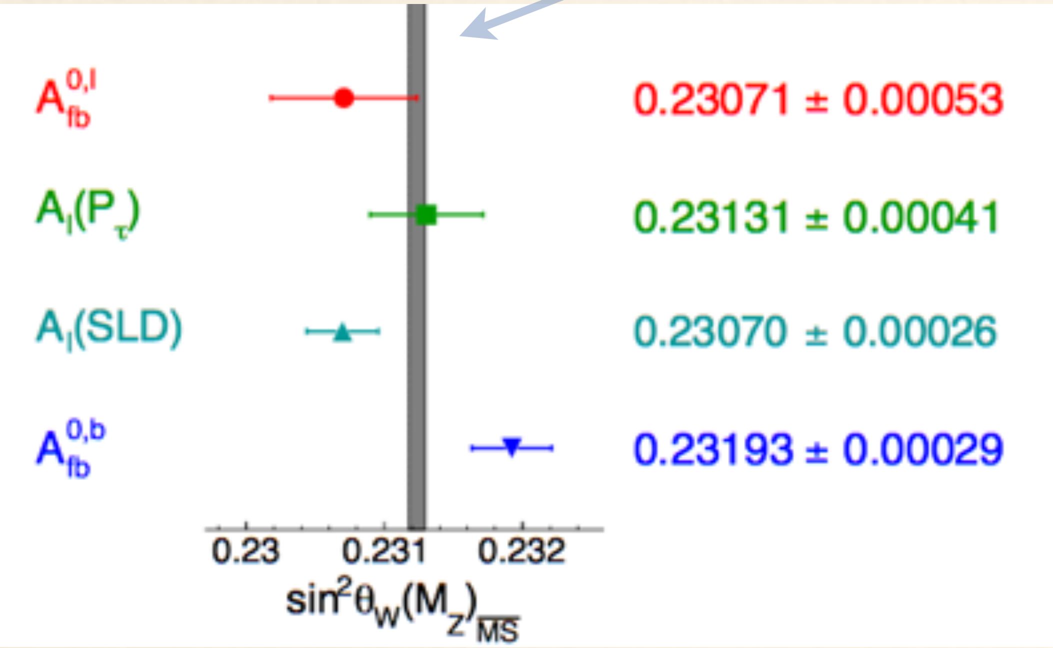

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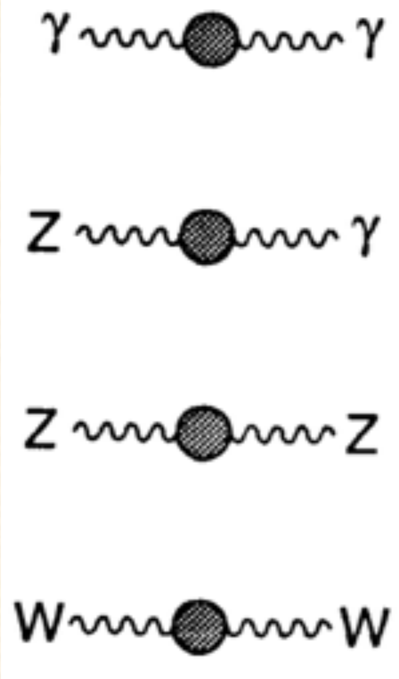

S,T, U parameters

Stringent constraints on large classes of new physics models

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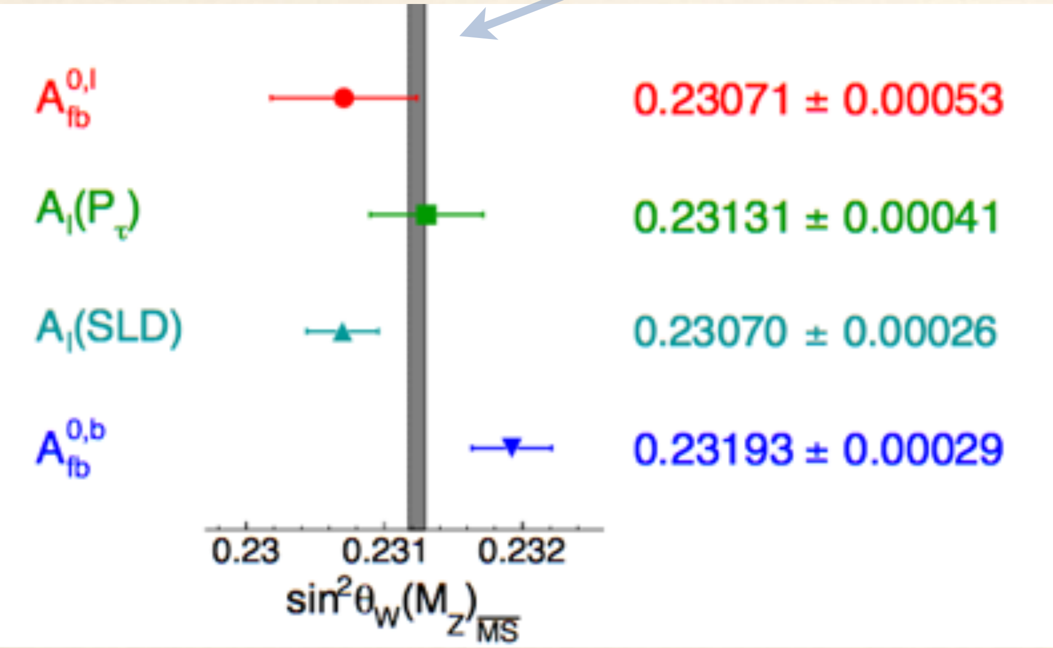
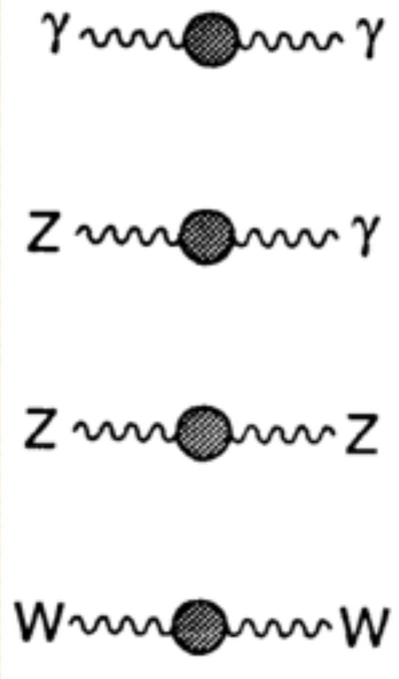


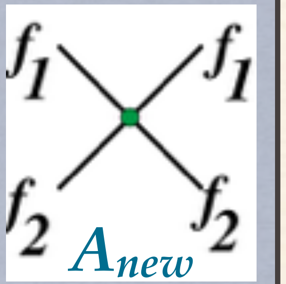


S,T, U parameters

Stringent constraints on large classes of new physics models

Flavor Diagonal Contact Interactions

Consider $f_1\bar{f}_1 \to f_2\bar{f}_2$ or $f_1 f_2 \to f_1 f_2$



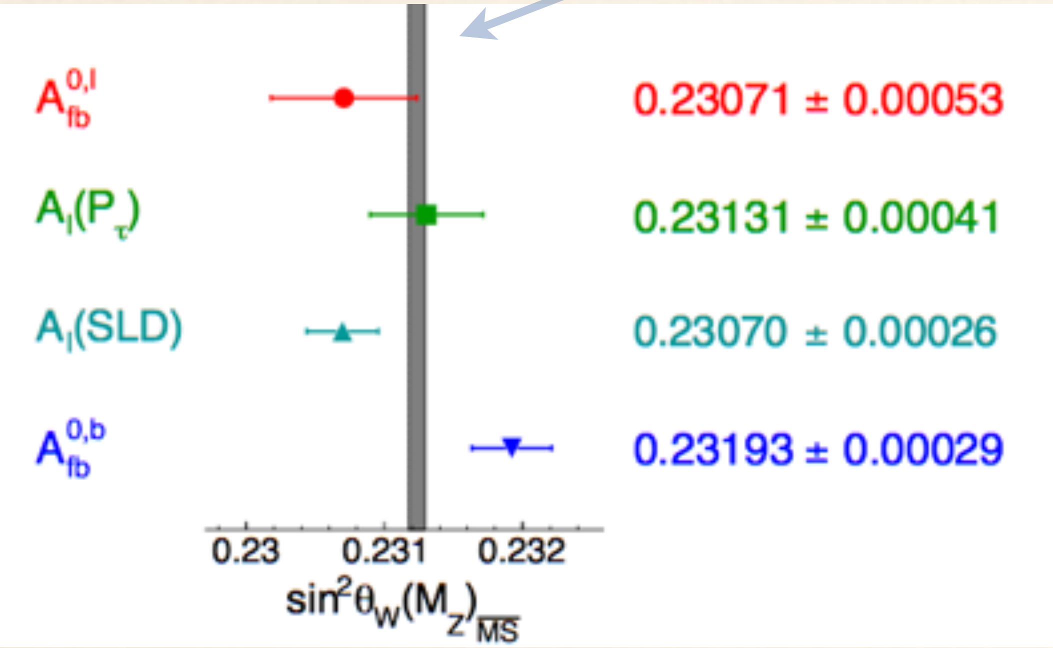
$$L_{f_1 f_2} = \sum_{i,j=L,R} \frac{4\pi}{\Lambda_{ij}^2} \eta_{ij} \bar{f}_{1i}\gamma_\mu f_{1i} \bar{f}_{2j}\gamma^\mu f_{2j}$$

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

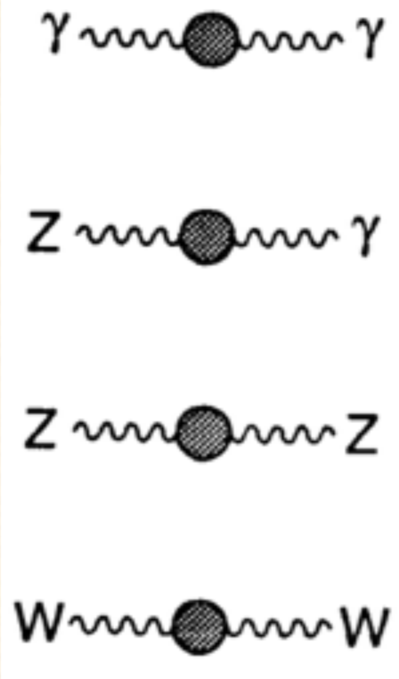
Theory vs Experiment

The most precise measurements at LEP/SLC

colliders: LEP, SLC



Prediction for 125 GeV Higgs



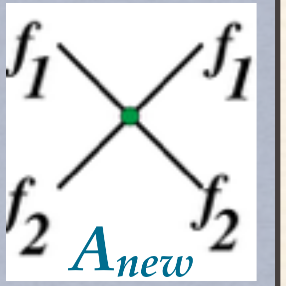
S,T, U parameters

Stringent constraints on large classes of new physics models

Flavor Diagonal Contact Interactions

Consider $f_1\bar{f}_1 \to f_2\bar{f}_2$ or $f_1 f_2 \to f_1 f_2$

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



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

on resonance: A_Z is imaginary

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

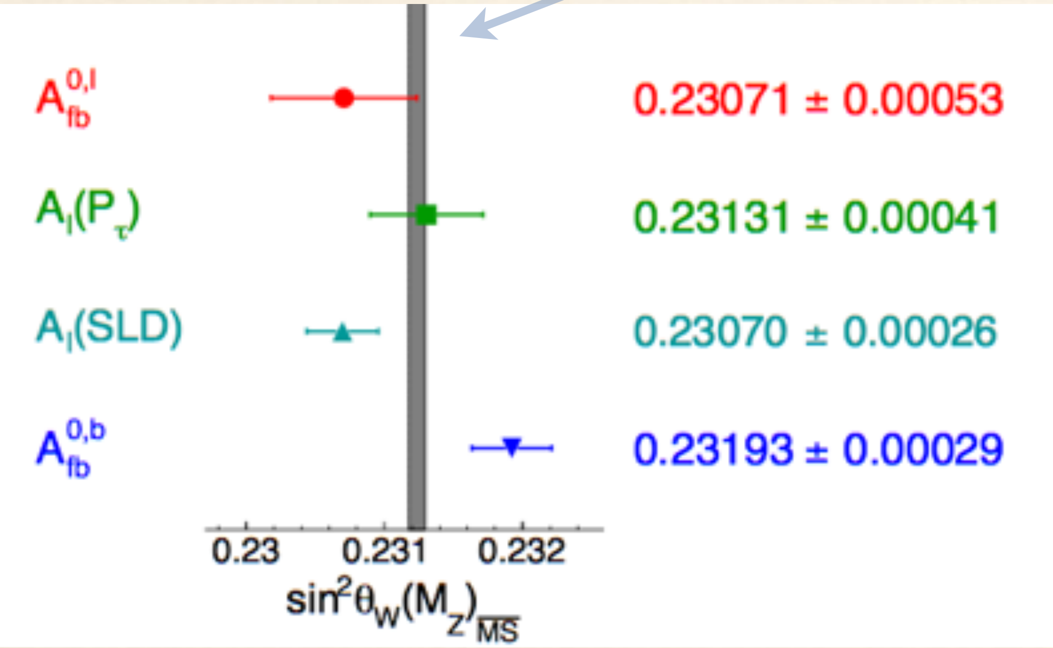
no interference!

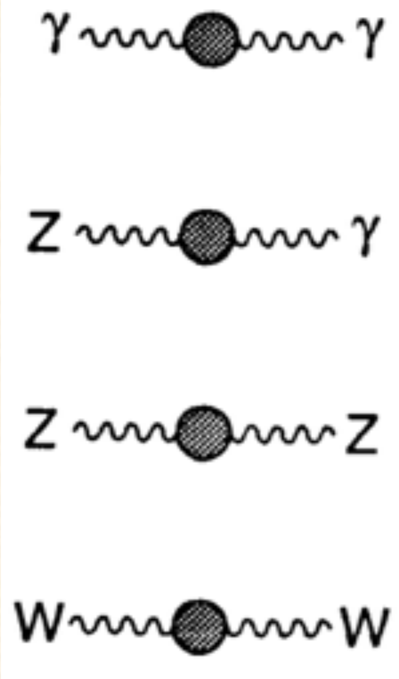
Theory vs Experiment

The most precise measurements at LEP/SLC

colliders: LEP, SLC

Prediction for 125 GeV Higgs





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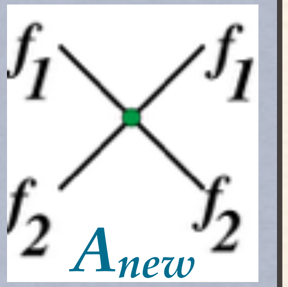

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no interference!

Unique role for $\sin^2\theta_W$ measurements at $Q^2 \ll M_Z^2$

Motivation for Low Q^2 Measurements

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

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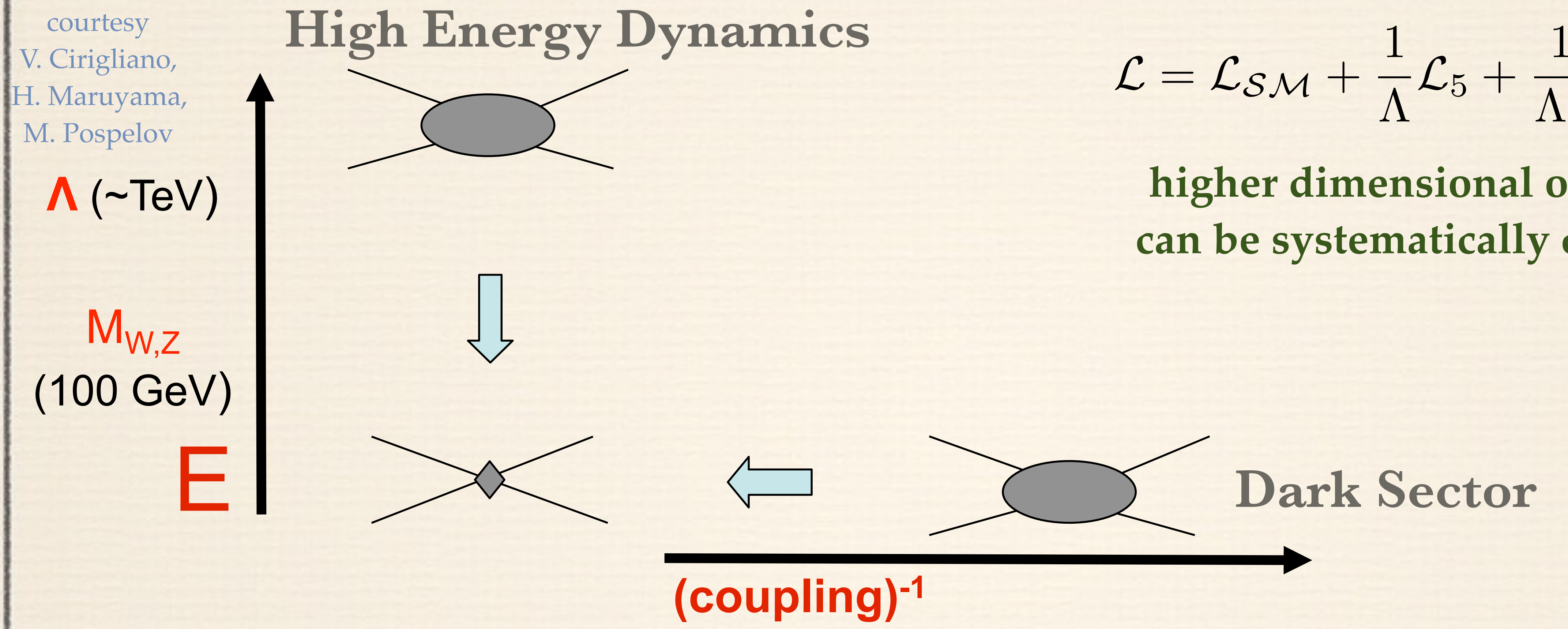
The Intensity/Precision Frontier

- **Violation of Approximate (?) Symmetries**
  - Neutrinoless Double-Beta Decay, EDMs, CLFV,...
- **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....

BSM Indirect Searches

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



High Energy Dynamics

Λ (~TeV)

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

E

Dark Sector

(coupling)$^{-1}$

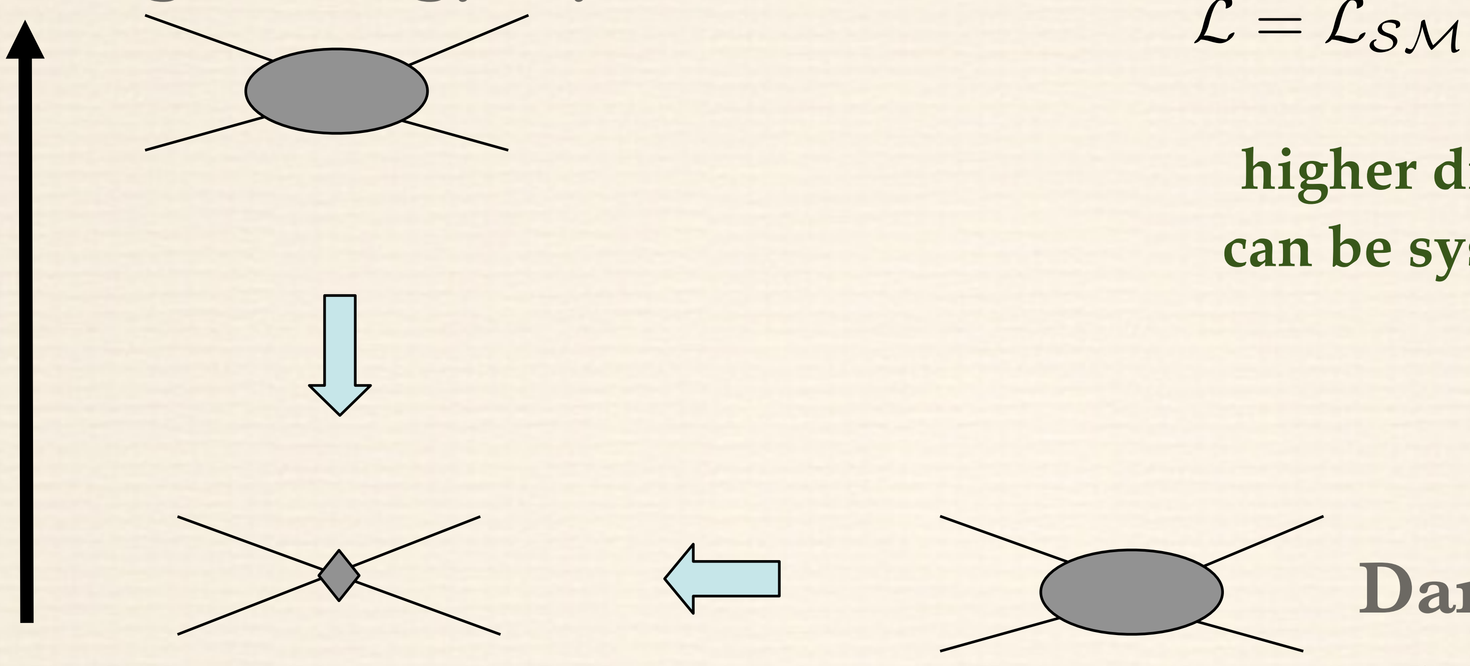
$$\mathcal{L} = \mathcal{L}_{\mathcal{SM}} + \frac{1}{\Lambda}\mathcal{L}_5 + \frac{1}{\Lambda^2}\mathcal{L}_6 + \cdots$$

**higher dimensional operators
can be systematically classified**

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

Weak Neutral Current Interactions (WNC) at $Q^2 \ll M_Z^2$

BSM Indirect Searches



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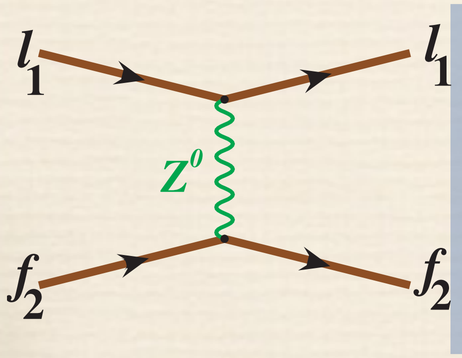
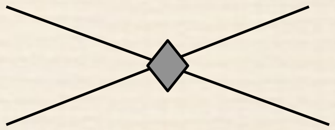


Search for new flavor diagonal CP-conserving neutral currents

Tiny yet measurable deviations from
SM processes with precise predictions



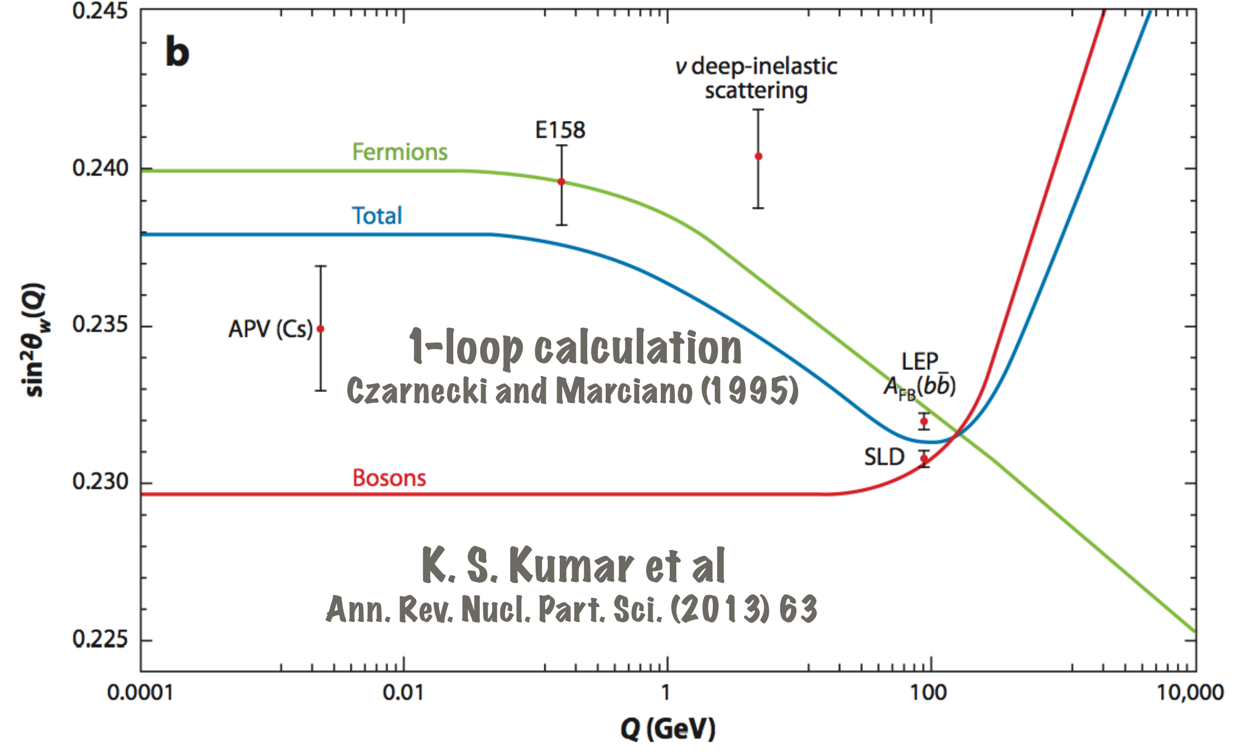
$$\frac{1}{\Lambda^2}\mathcal{L}_6$$

must reach Λ ~ 10 TeV

Thumb Rule: Weak mixing angle must be measured to sub-1% precision

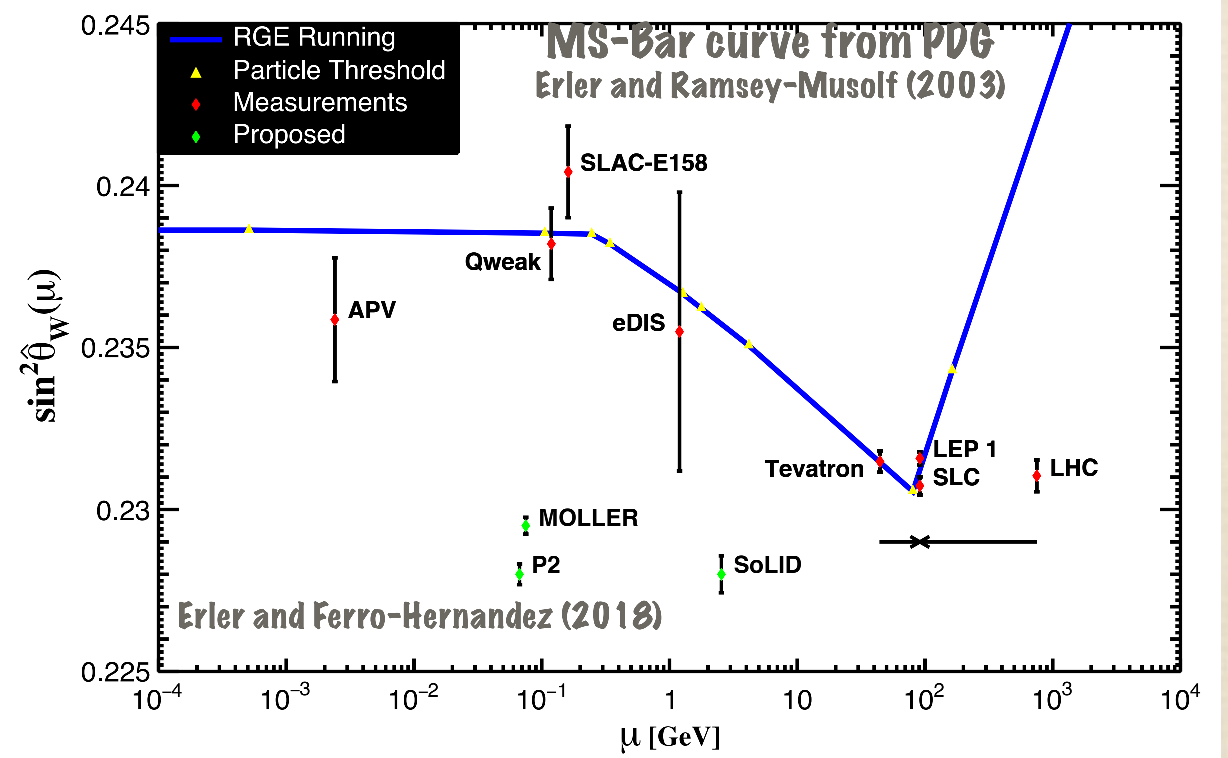
WNC "Bookkeeping"

- **Atomic Parity Violation: Cs-133**
  - future measurements and theory challenging
- **Neutrino Deep Inelastic Scattering: NuTeV**
  - future measurements and theory challenging
- **PV Møller Scattering: E158 at SLAC**
  - statistics limited, theory robust
  - next generation: MOLLER (factor of 5 better)
- **PV elastic e-p scattering: Qweak**
  - theory robust at low beam energy
  - next generation: P2 (factor of 3 better)
- **PV Deep Inelastic Scattering: PVDIS**
  - theory robust for ^{2}H in valence quark region
  - factor of 5 to 8 improvement possible: SOLID



1-loop calculation
Czarnecki and Marciano (1995)

K. S. Kumar et al
Ann. Rev. Nucl. Part. Sci. (2013) 63



MS-Bar curve from PDG
Erler and Ramsey-Musolf (2003)

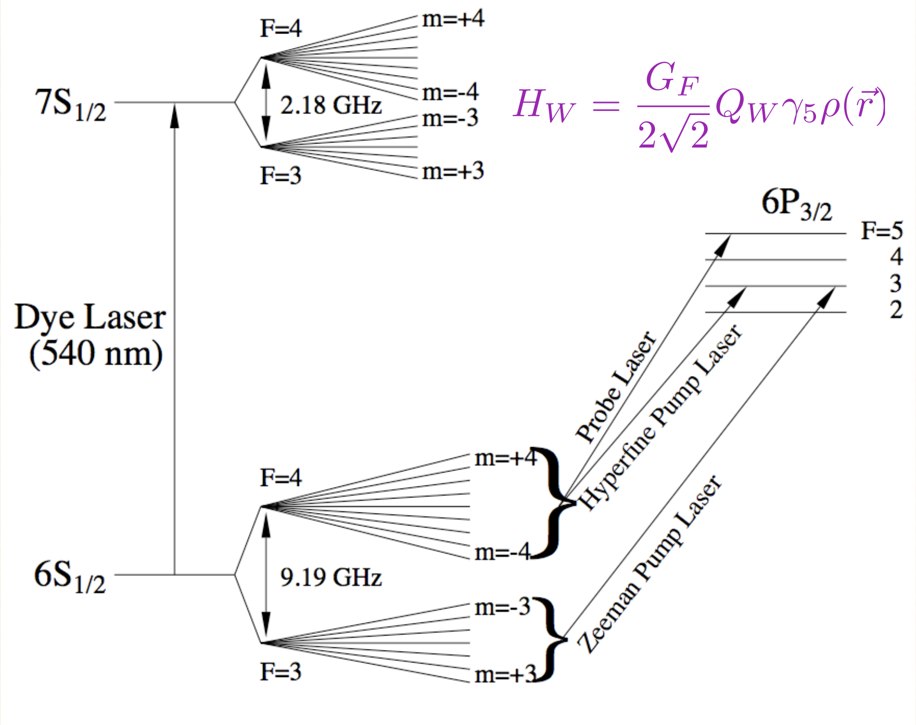
Erler and Ferro-Hernandez (2018)

Review of Charged Lepton Measurements

Cs APV

Carl Wieman and collaborators at U. Colorado (Boulder)

Partial Level Structure of Cesium



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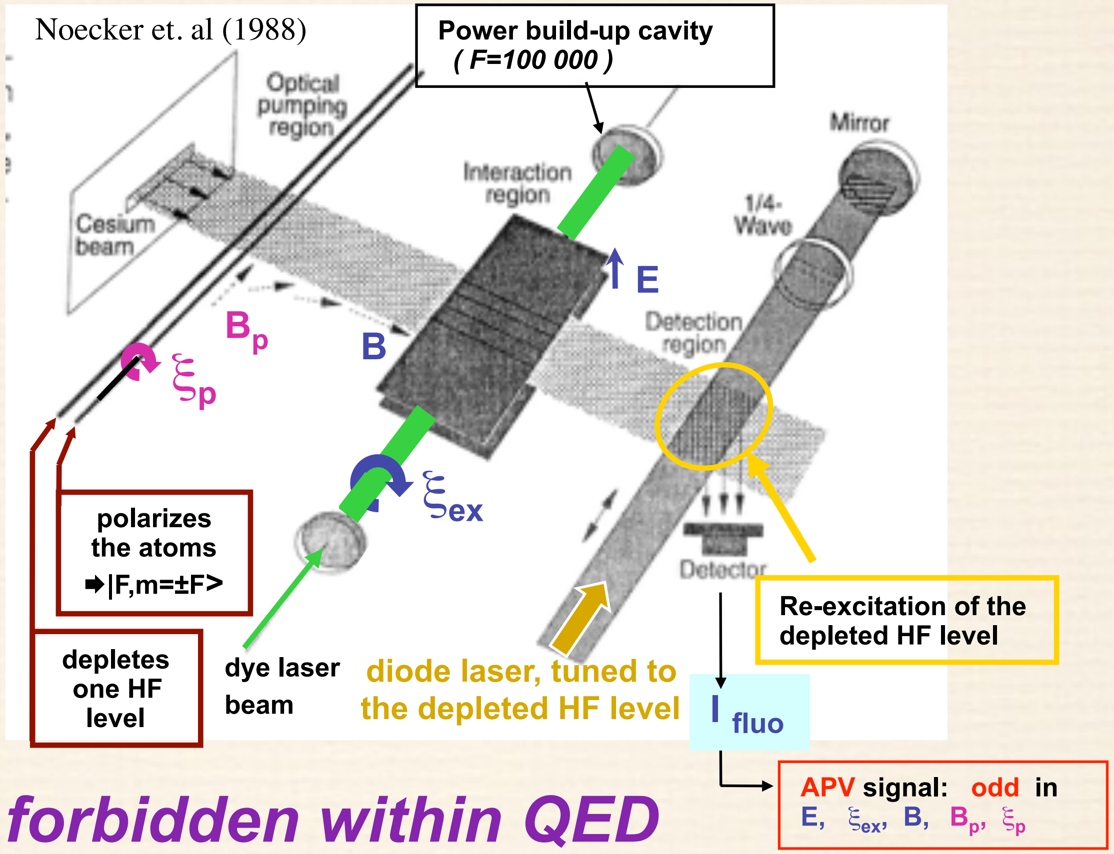
Boulder Experiment



Power build-up cavity
(*F=100 000*)

polarizes the atoms
➡|F,m=±F>

depletes one HF level

dye laser beam

diode laser, tuned to the depleted HF level

Re-excitation of the depleted HF level

APV signal: odd in
E, ξ_{ex}, B, B$_p$, ξ_p

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- ***Parity Violation introduces small opposite parity admixtures***
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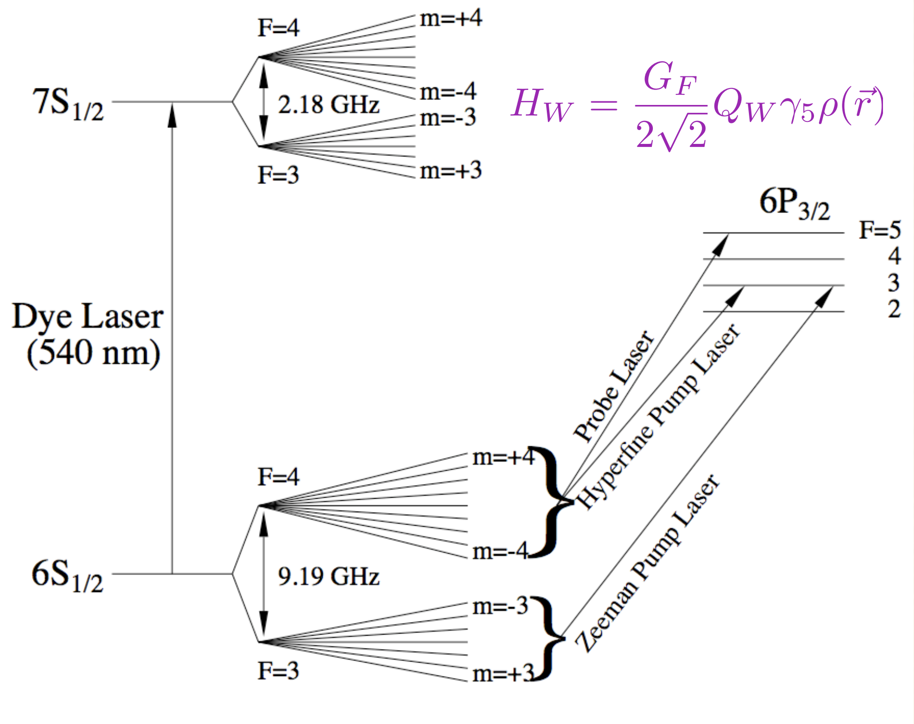

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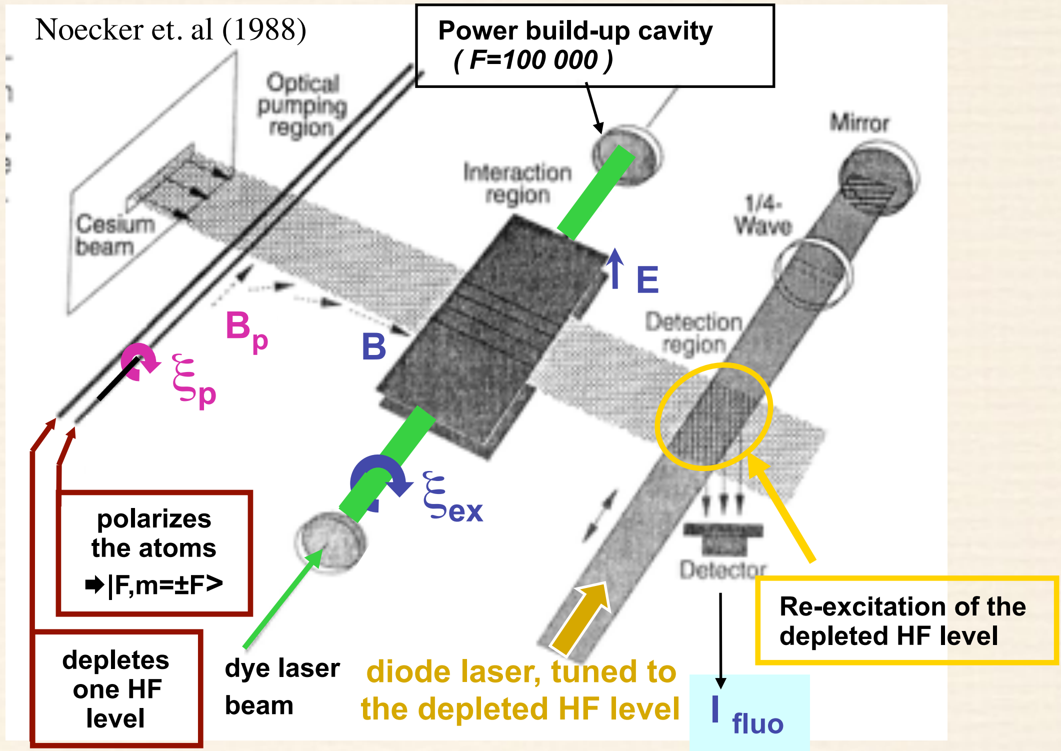

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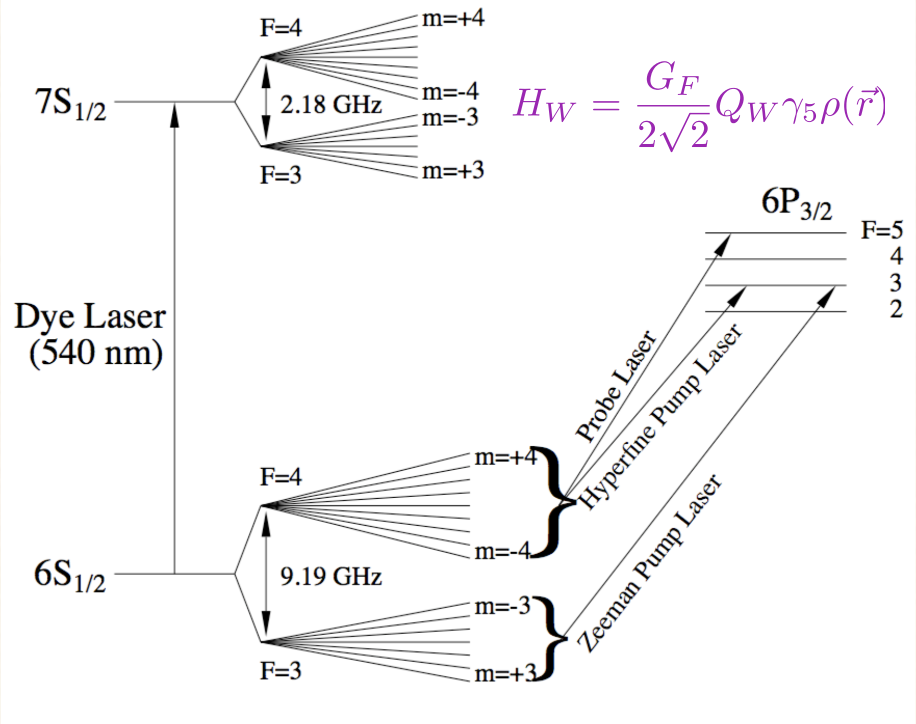

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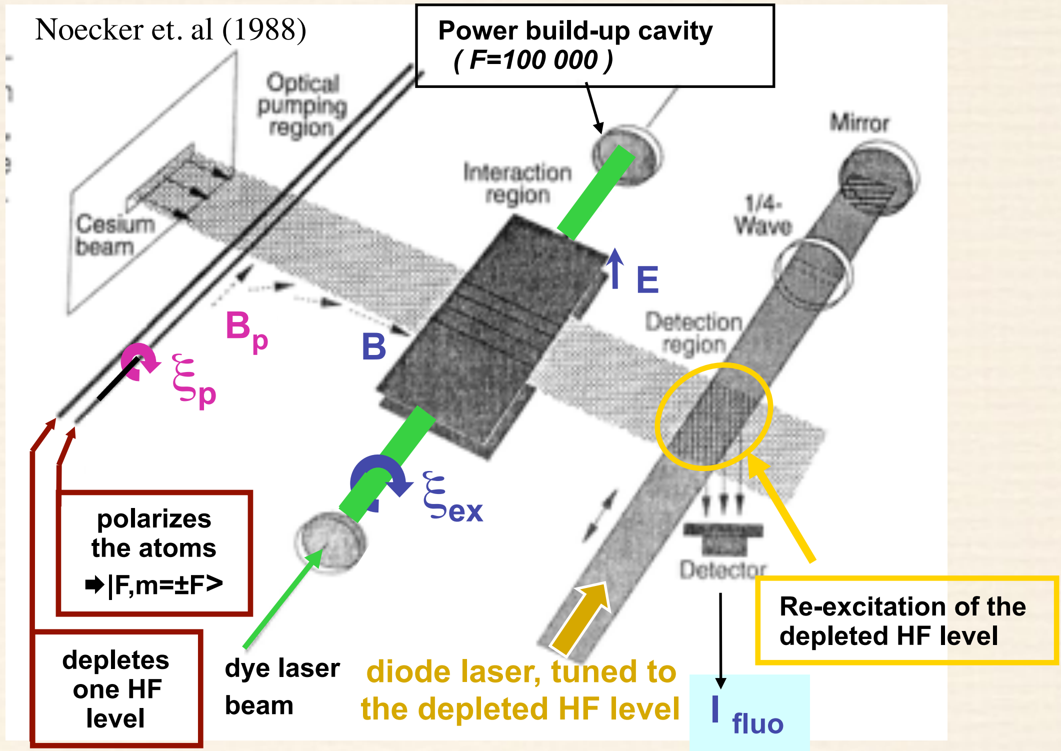

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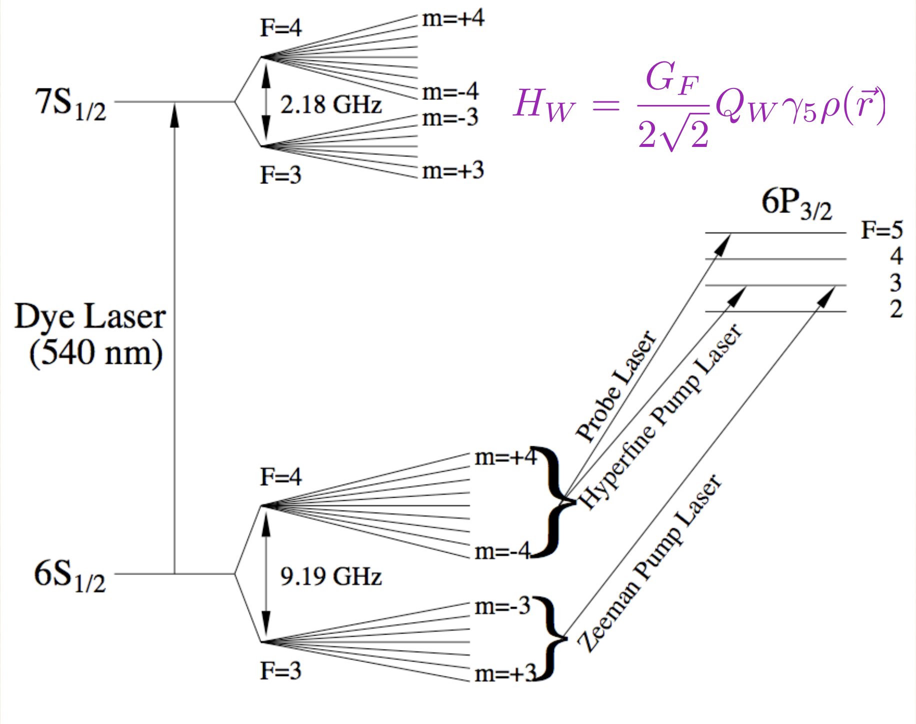

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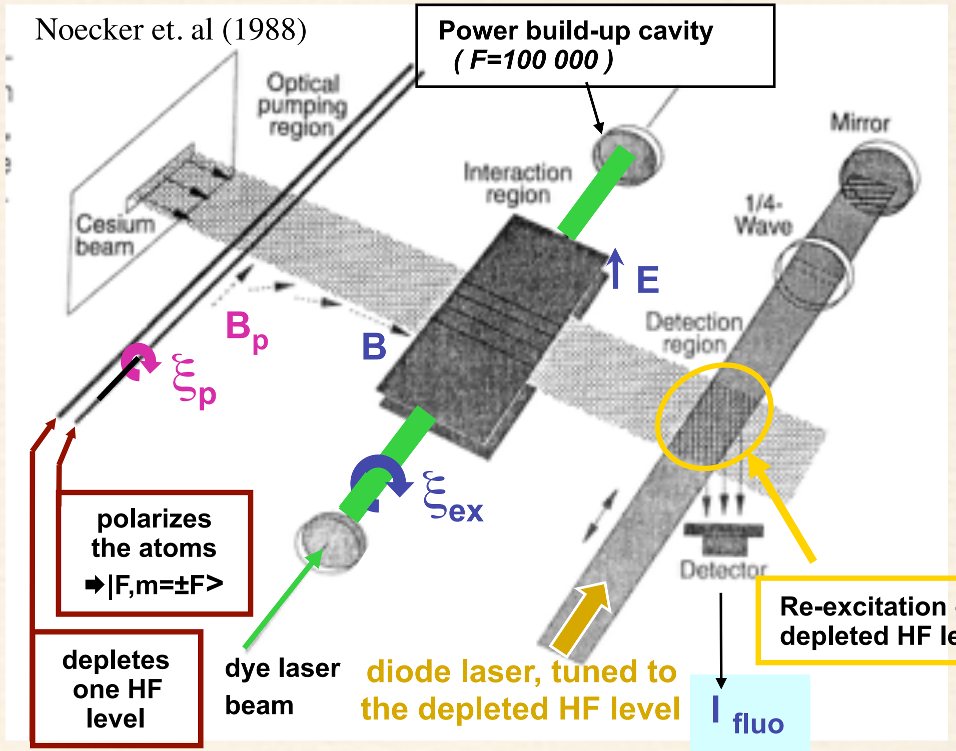

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I_{fluo}

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$$k_{PNC}$$

Atomic Theory

$$0.9065(36) \times 10^{-11} ea_0$$

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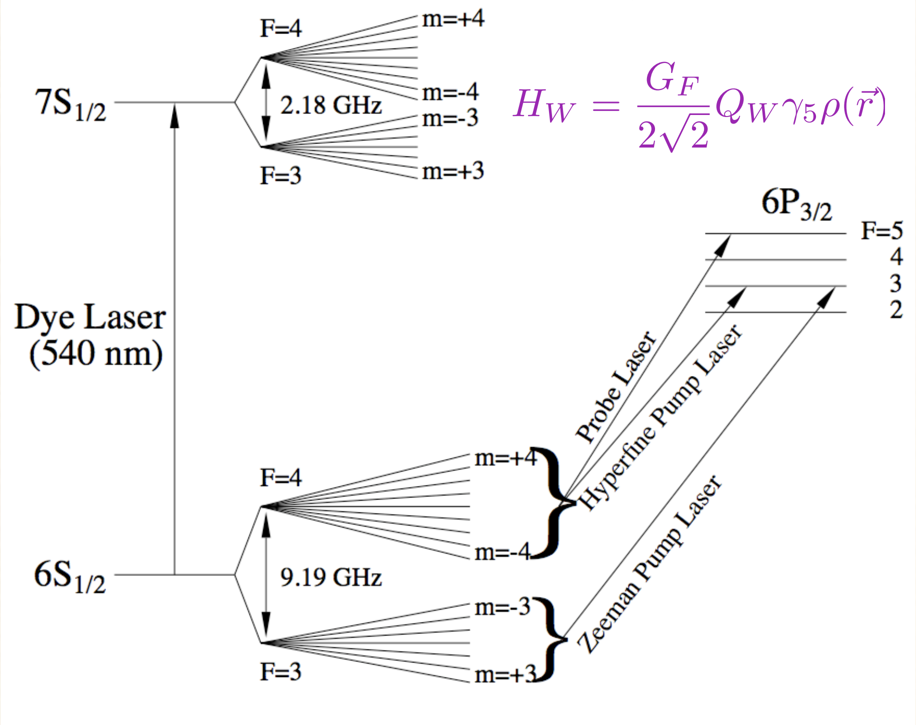

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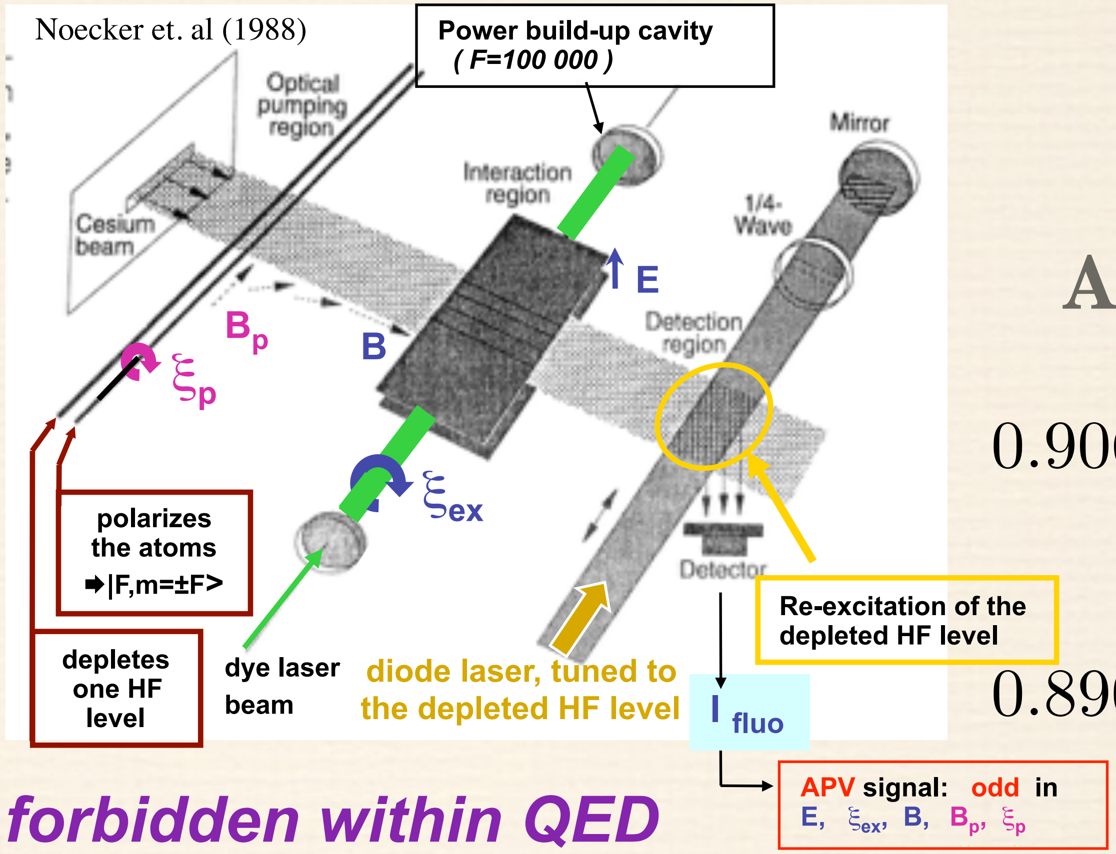

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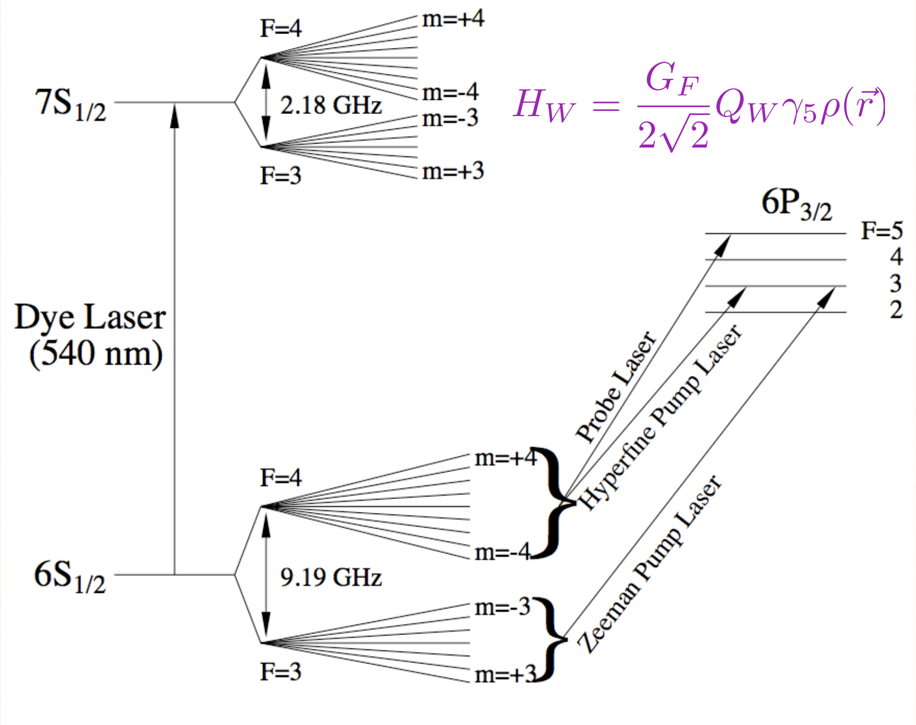

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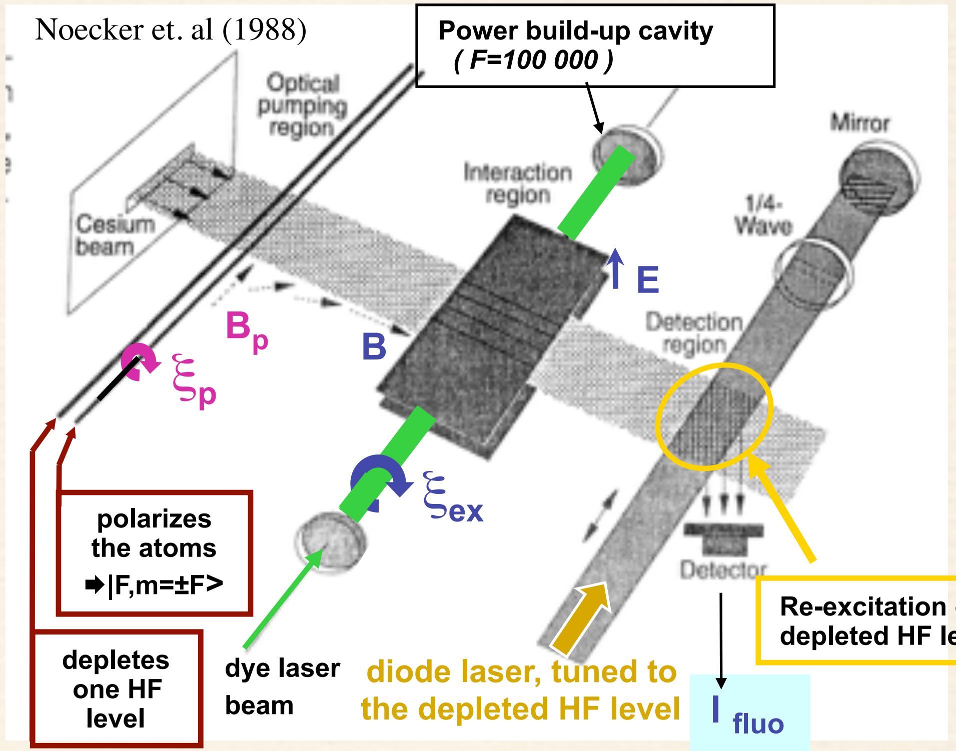

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Cs APV

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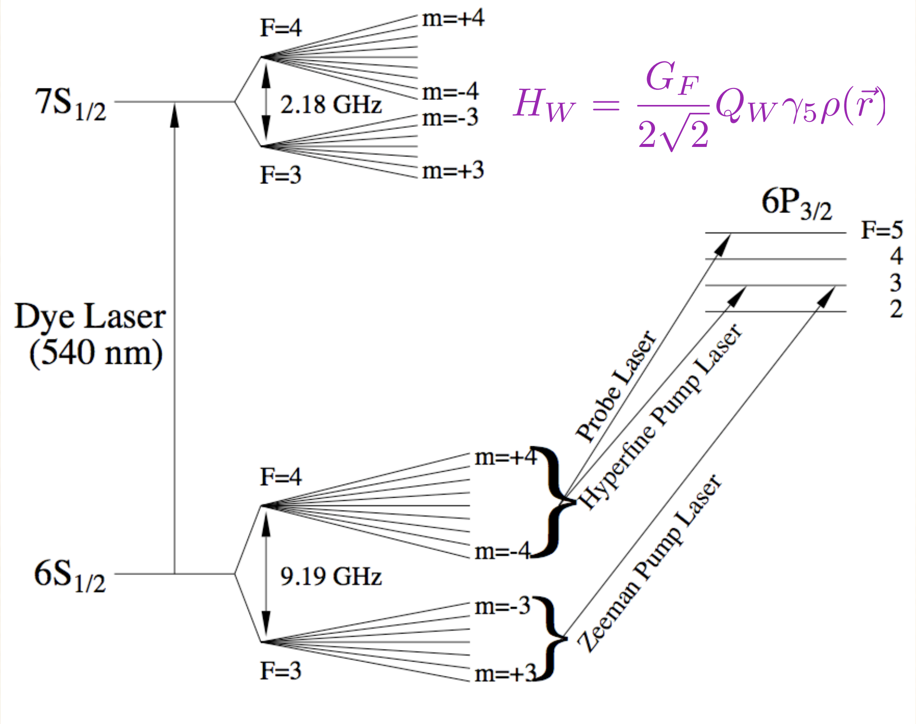

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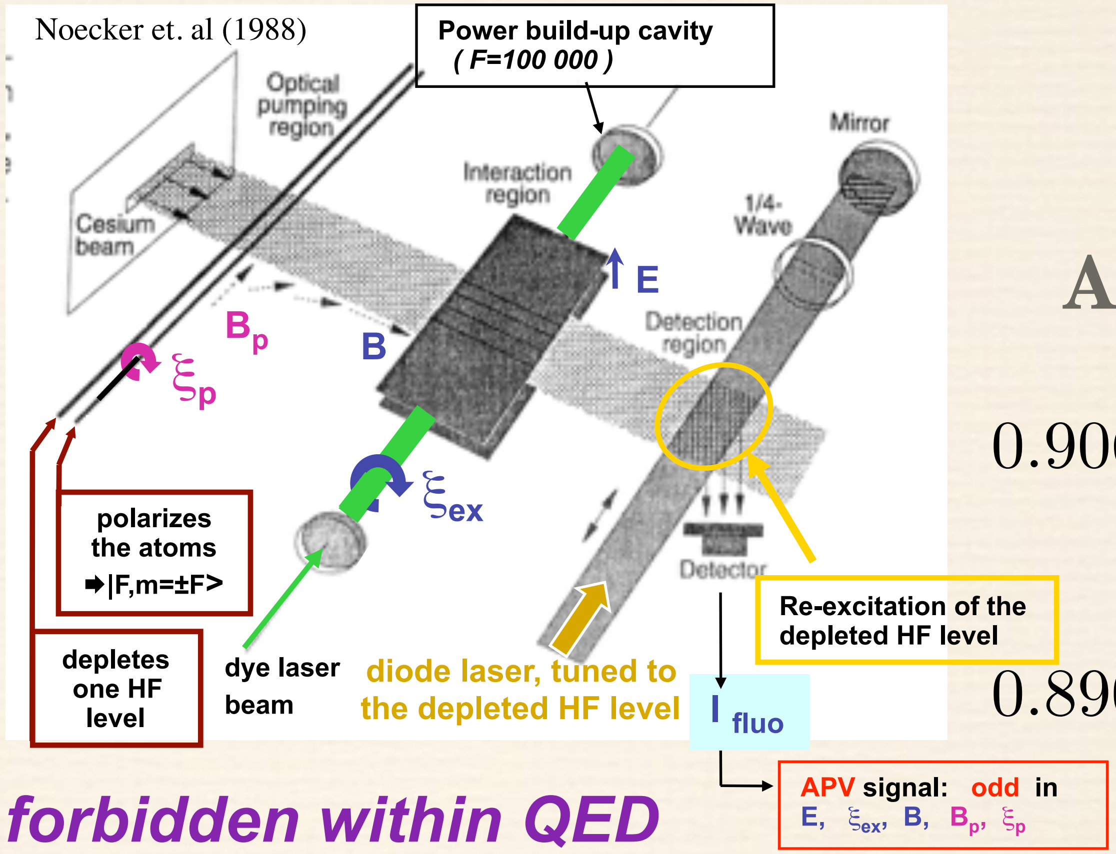

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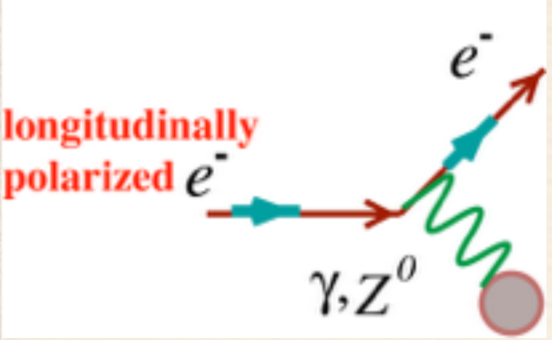
$$\sin^2\theta_W(m_Z)_{\overline{\text{MS}}} = 0.2283(20)$$

1.5 σ low

4 decades of measurements: emergence as a precision tool

Parity-Violating Electron Scattering (PVES)



g_V is a function of $\sin^2\theta_W$

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

Weak Charge Q_W

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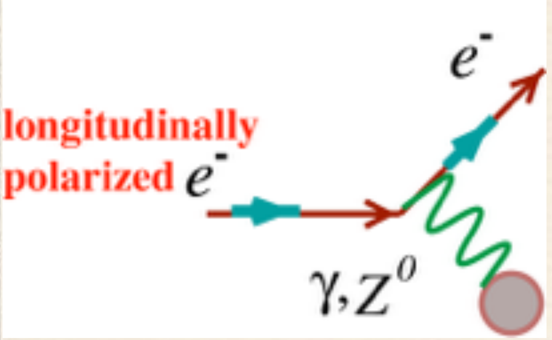

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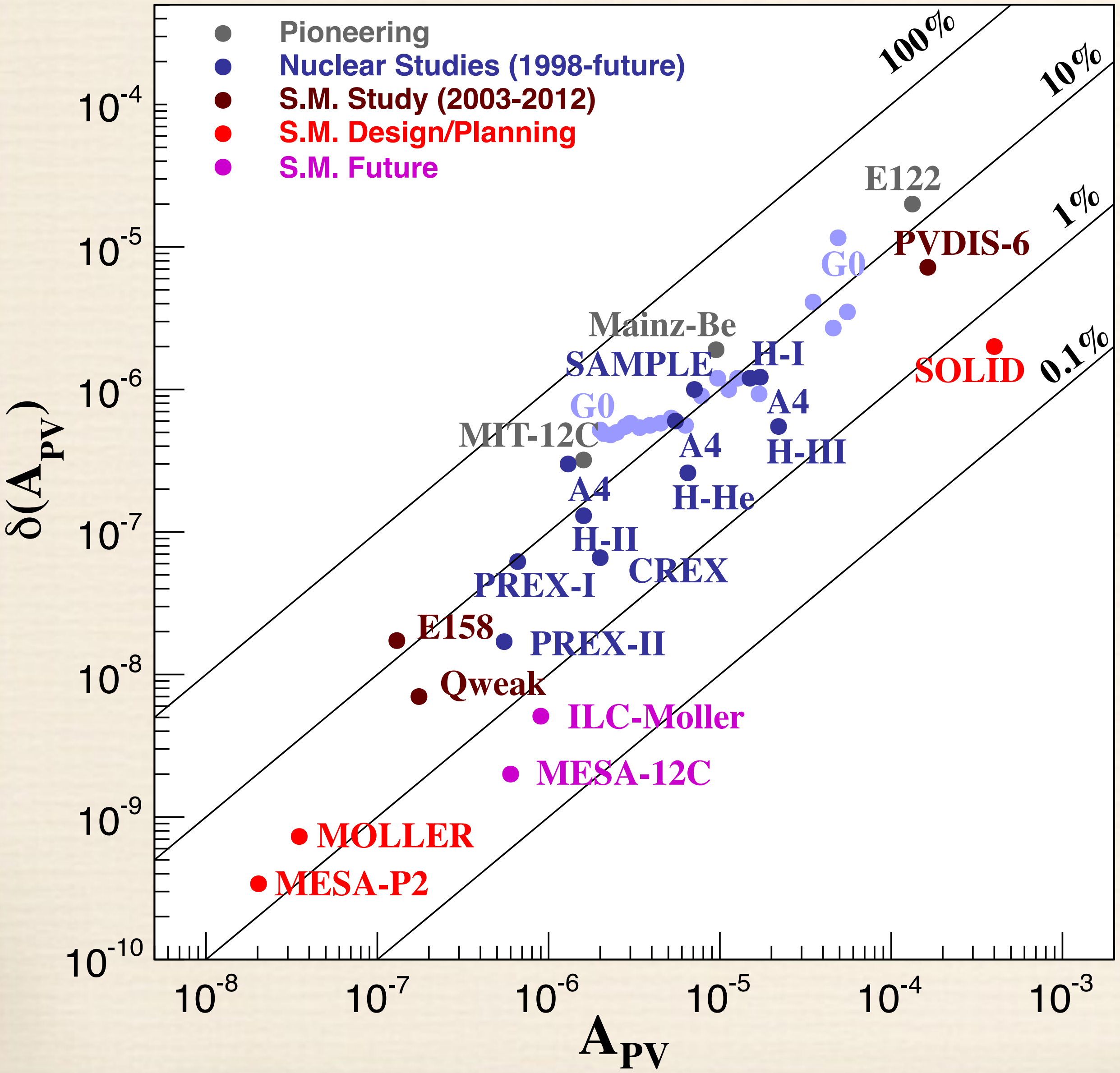


Variety of Physics Topics:

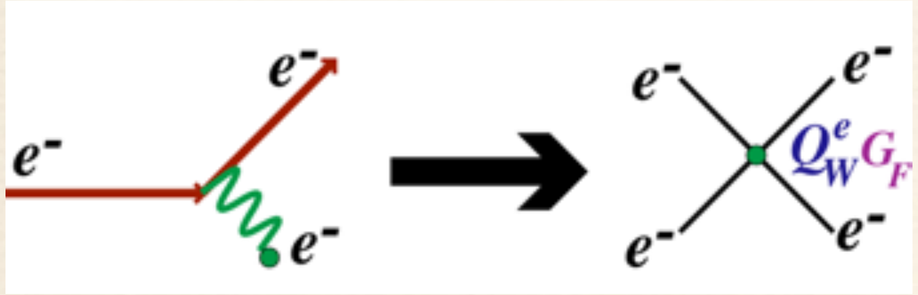
continuous interplay between hadron physics and electroweak physics

Steady improvements in accelerator and detector technology

State of the Art

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

PV Electron-Electron Scattering



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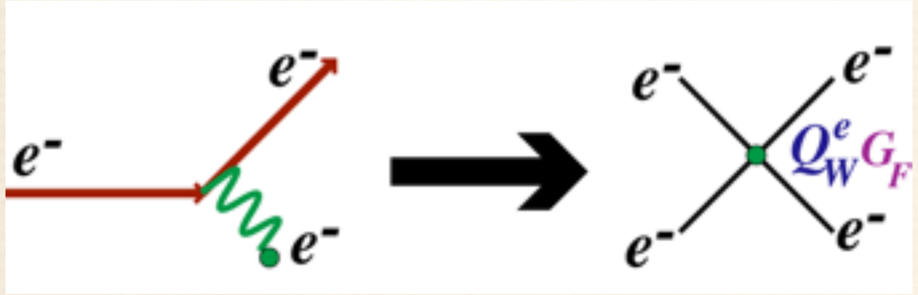
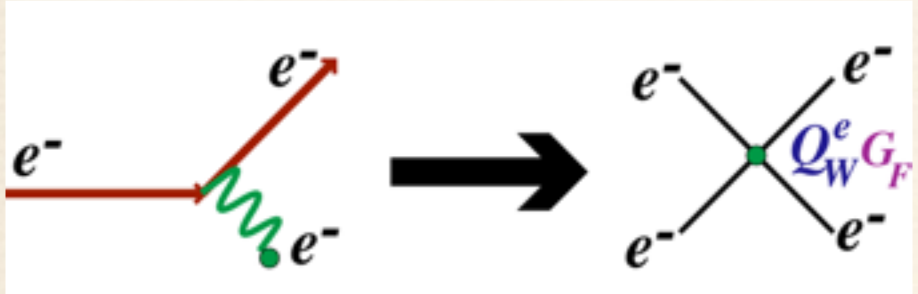


electron target:

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

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

PV Electron-Electron Scattering



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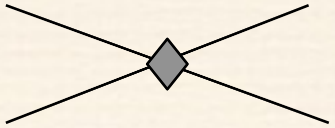

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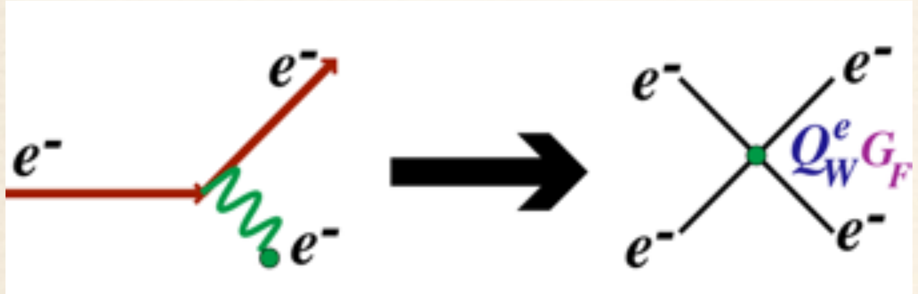

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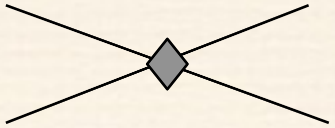
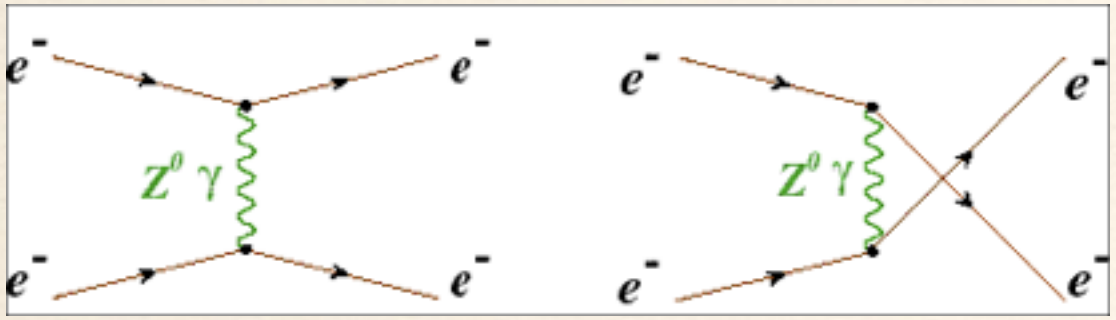


$$\frac{1}{\Lambda^2}\mathcal{L}_6$$

electron target:

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

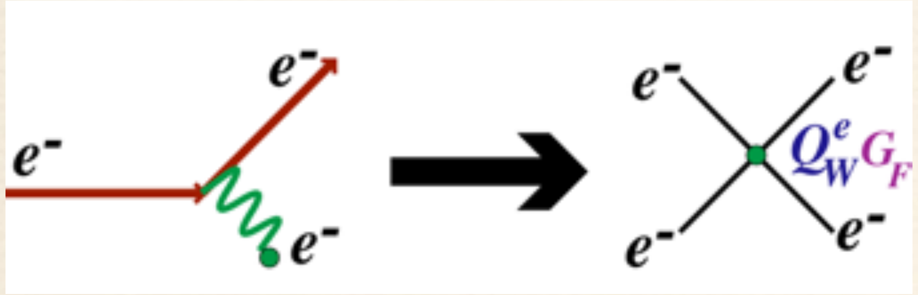
$$\frac{\delta(Q_W)}{Q_W} \sim 10\% \Longrightarrow \frac{\delta(\sin^2\theta_W)}{\sin^2\theta_W} \sim 0.5\%$$



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

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

PV Electron-Electron Scattering



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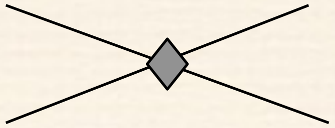

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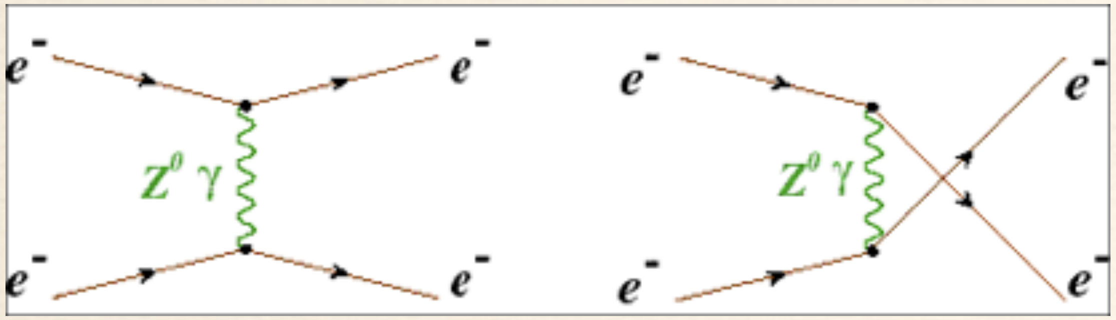

$$\left|\mathbf{A}_\gamma + \mathbf{A_Z} + \mathbf{A}_{\text{new}}\right|^2 \to \mathbf{A}_\gamma^2\left[\mathbf{1} + \mathbf{2}\left(\frac{\mathbf{A_Z}}{\mathbf{A}_\gamma}\right) + \mathbf{2}\left(\frac{\mathbf{A}_{\text{new}}}{\mathbf{A}_\gamma}\right)\right]$$

$$A_{PV} \approx 8\times10^{-8} E_{beam}(1 - 4\sin^2\vartheta_W)$$

⇒ **Tiny!**

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

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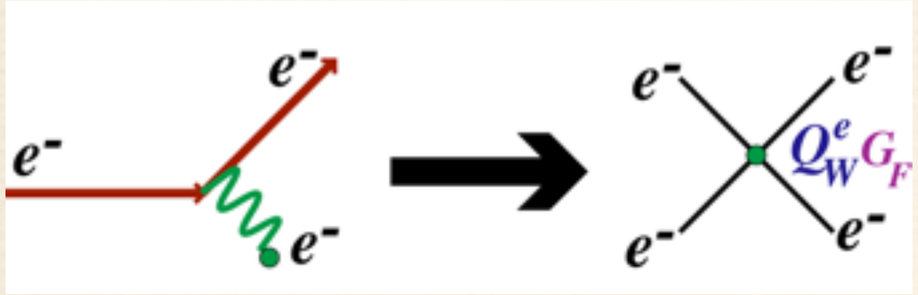

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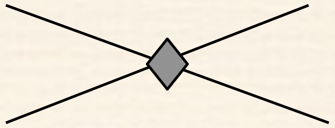

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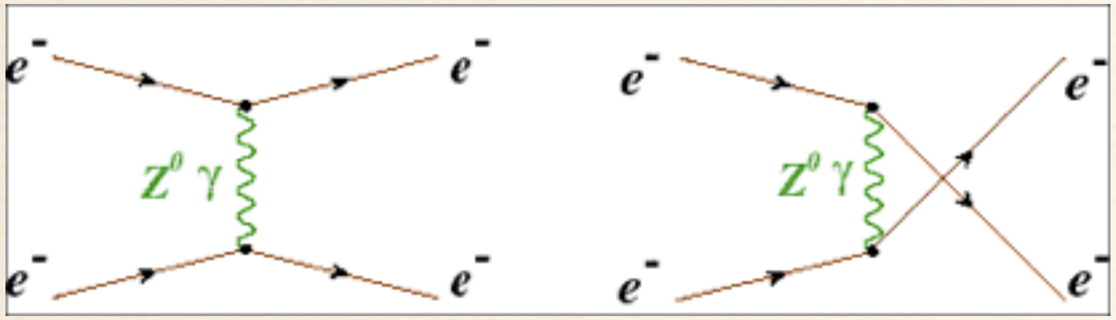

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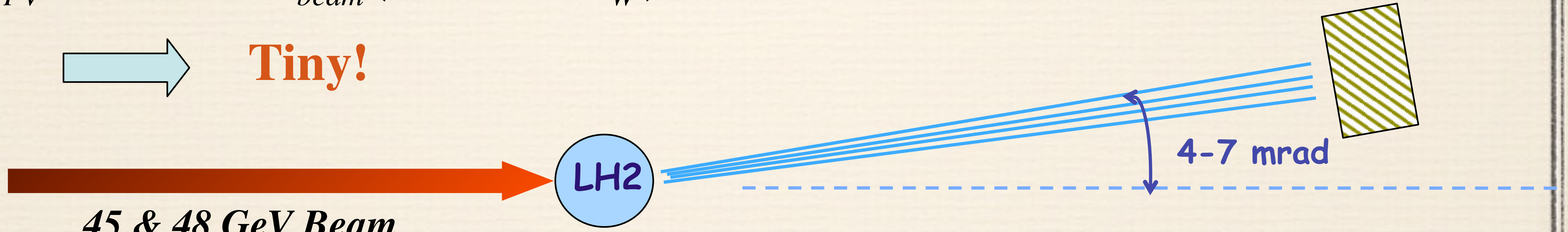


45 & 48 GeV Beam

85% longitudinal polarization

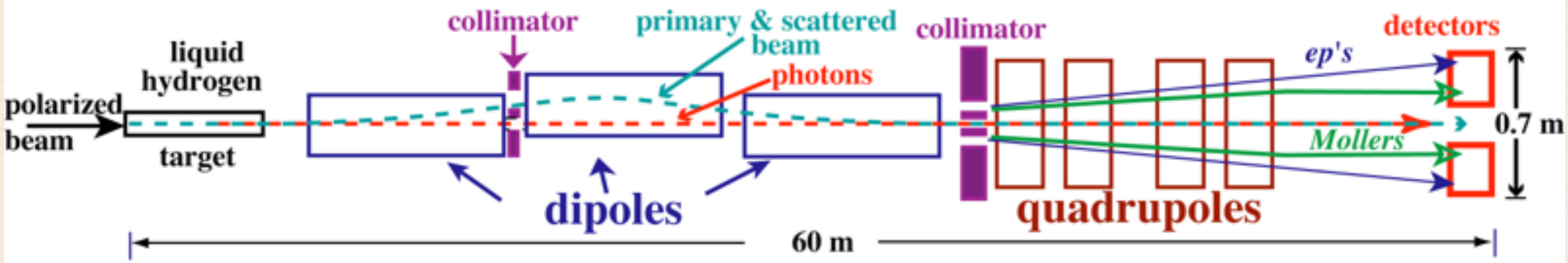
SLAC E158: 1997-2004

End Station A at SLAC

Goal: error small enough to probe TeV scale physics

E158

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



A large number of technical challenges

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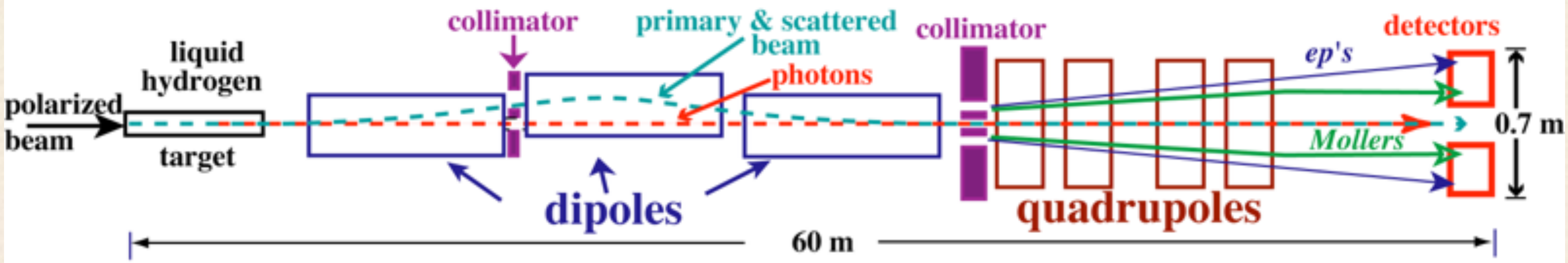
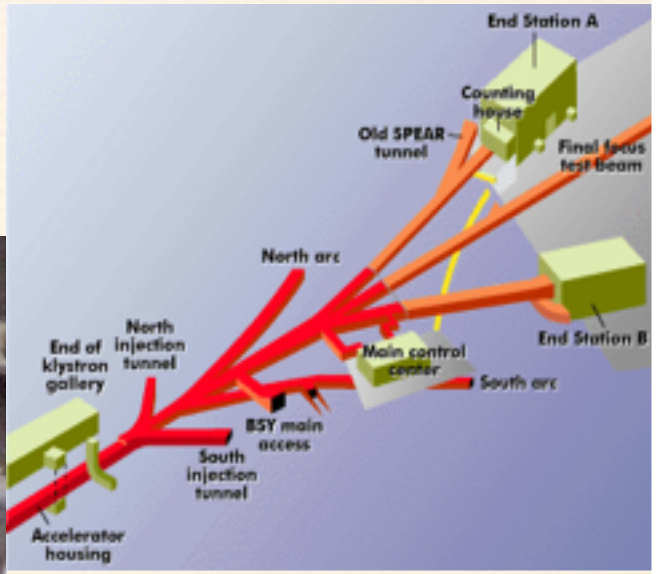
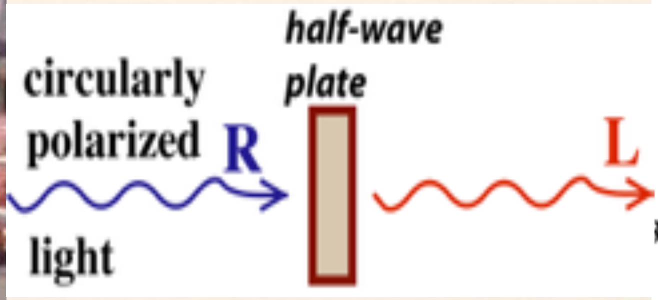
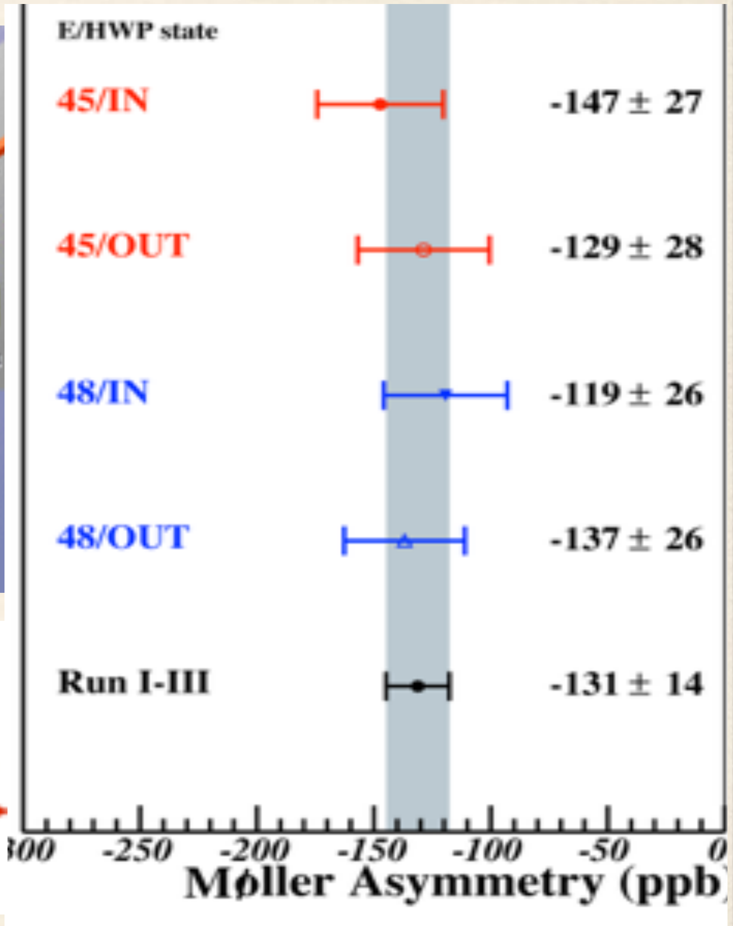


A large number of technical challenges







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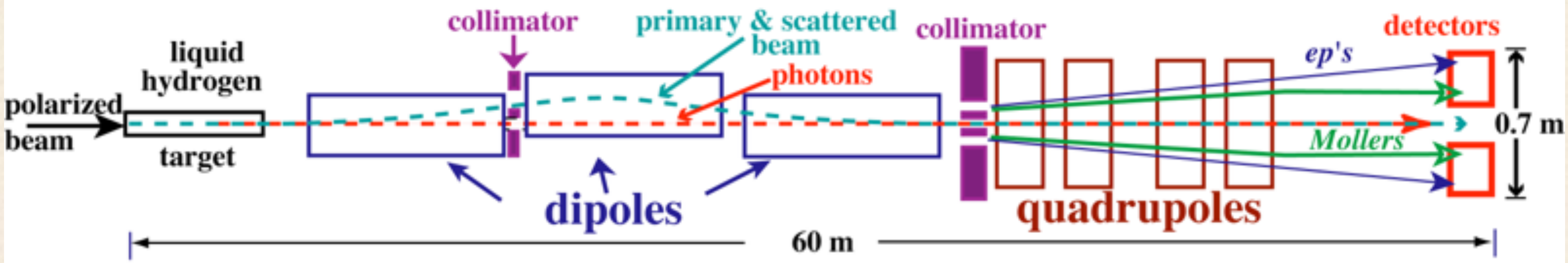

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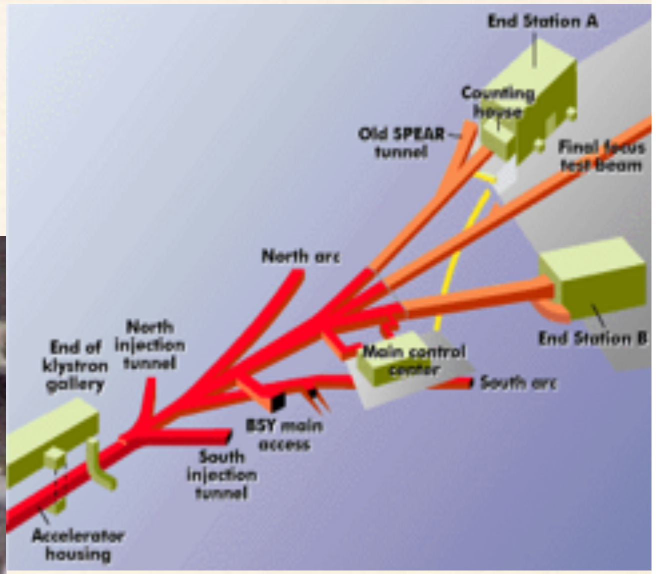

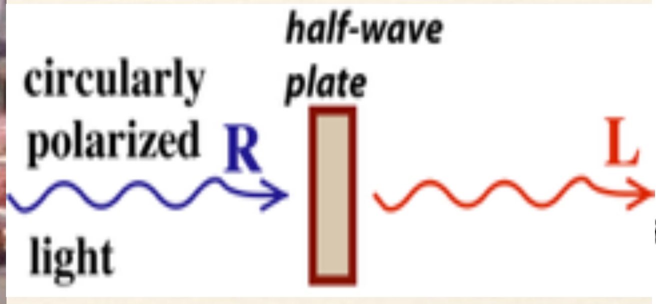

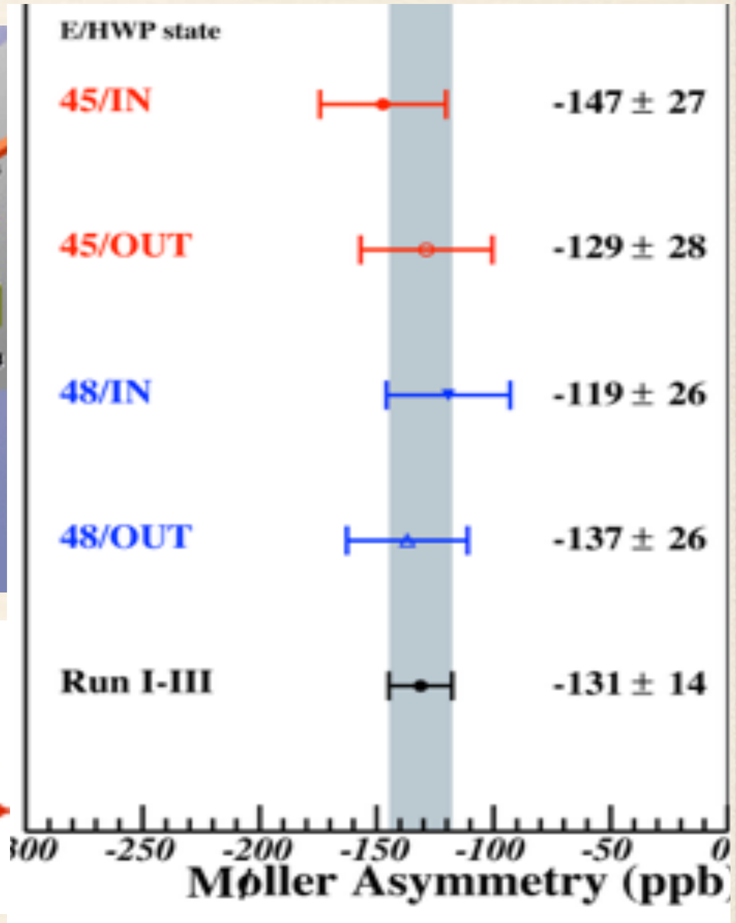

$$A_{PV} = (-131 \pm 14 \pm 10) \times 10^{-9}$$

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

Tree-level prediction: ~ 250 ppb

E158 Implications

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Final E158 Result

E158 Implications

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

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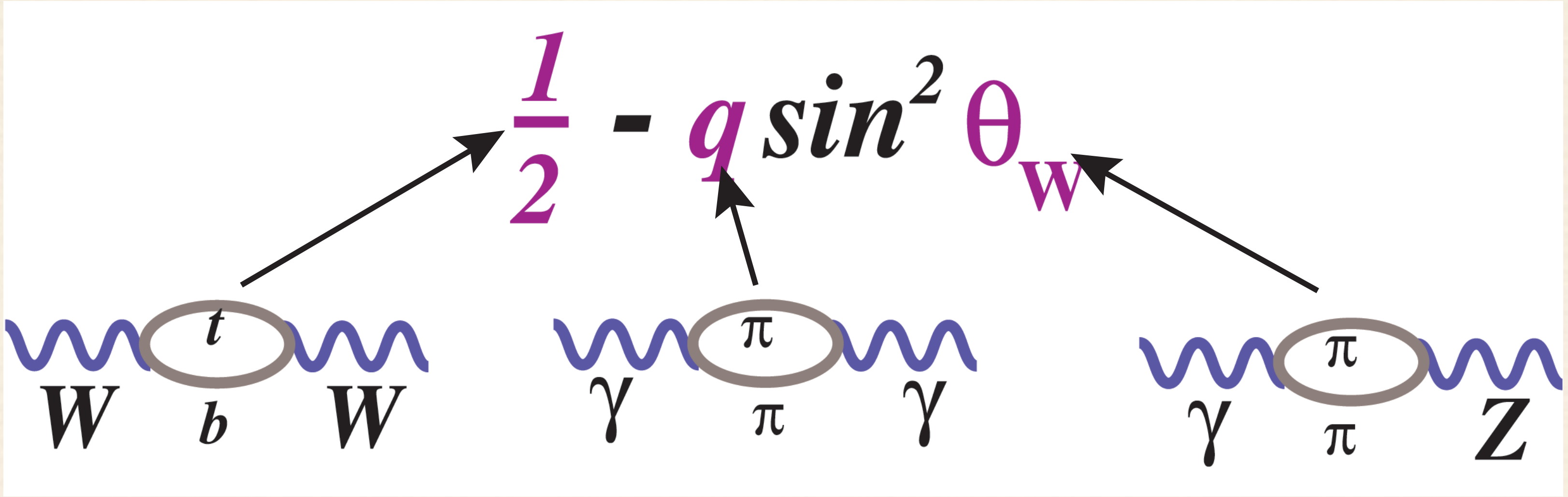
Phys. *Rev*. *Lett*. **95** 081601 (2005)



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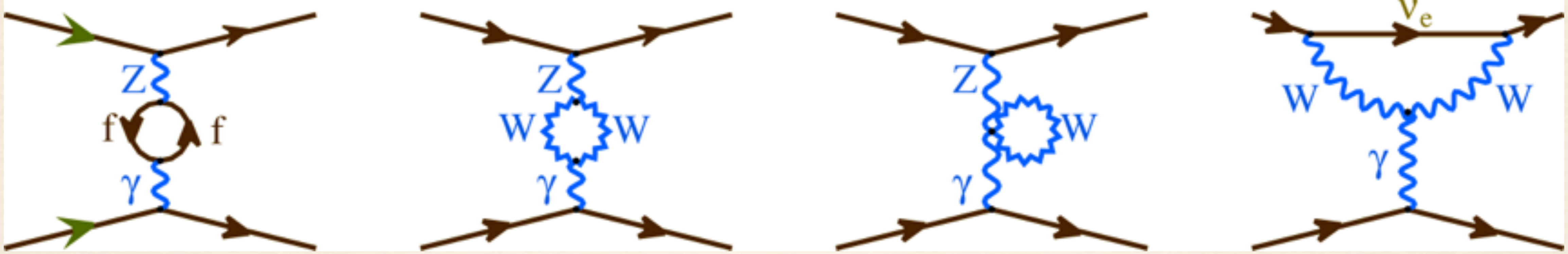
Czarnecki and Marciano (1995)



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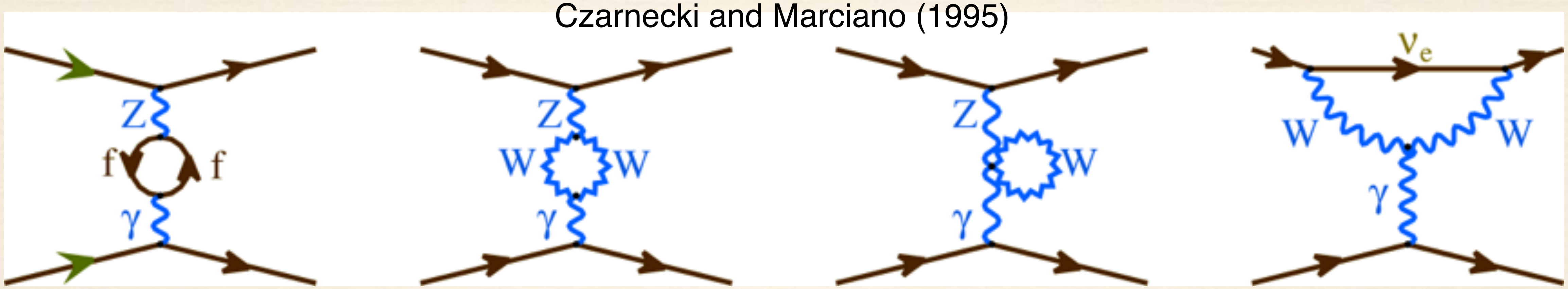

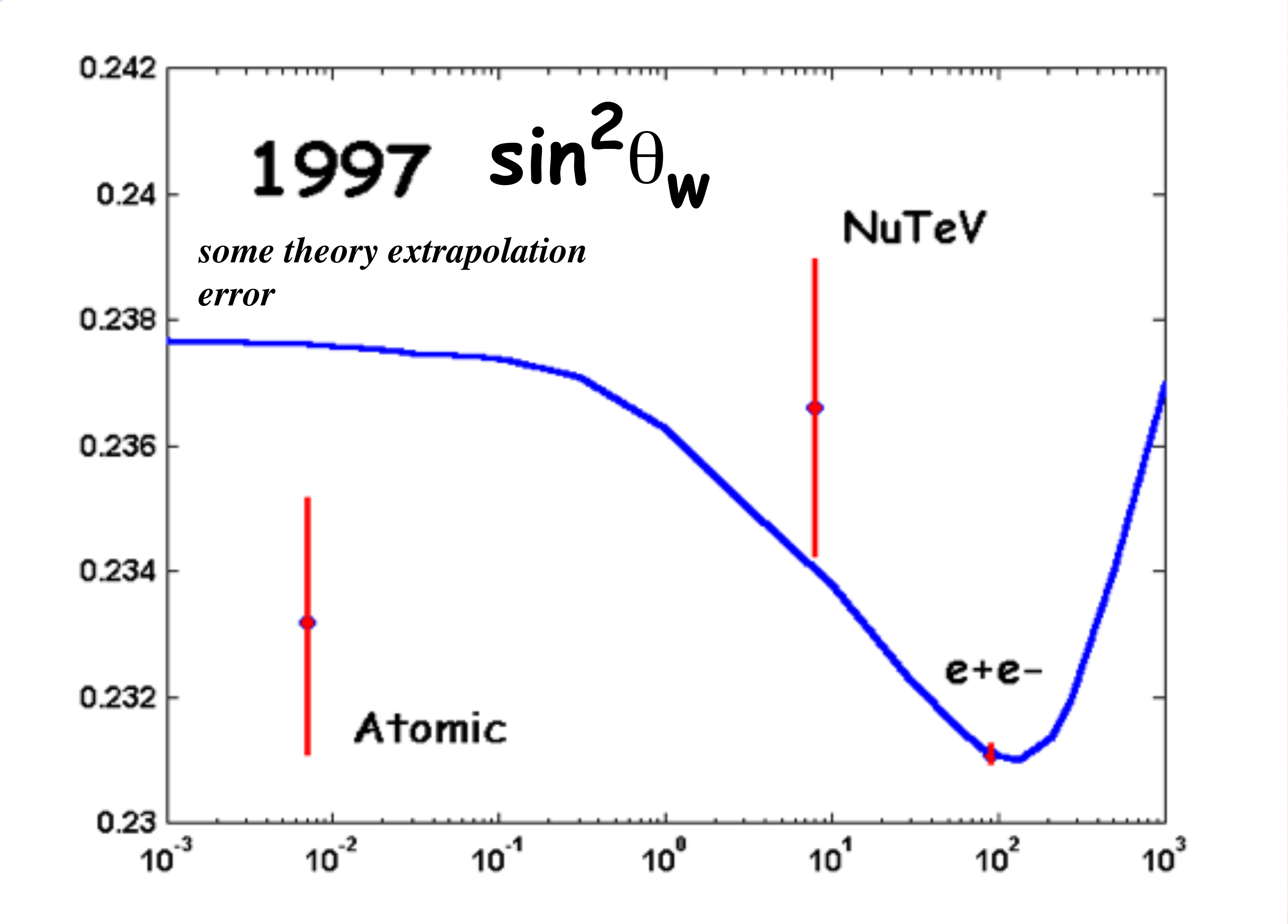

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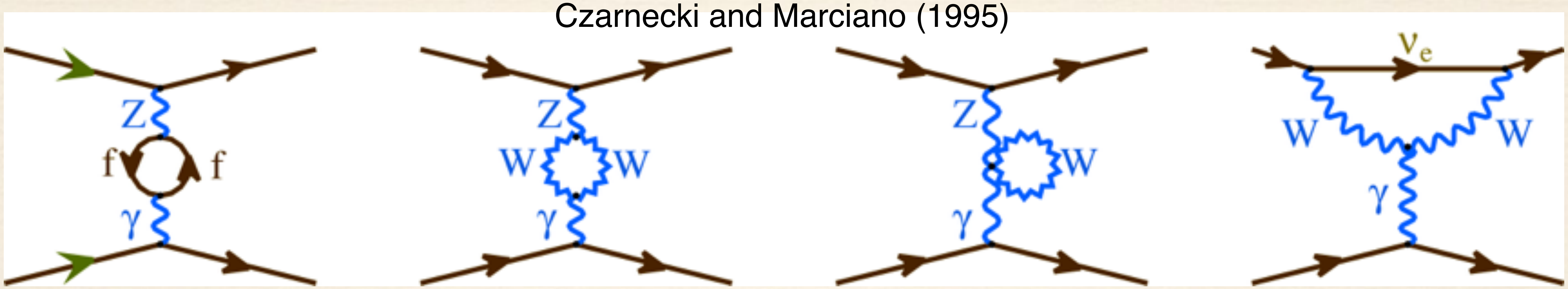
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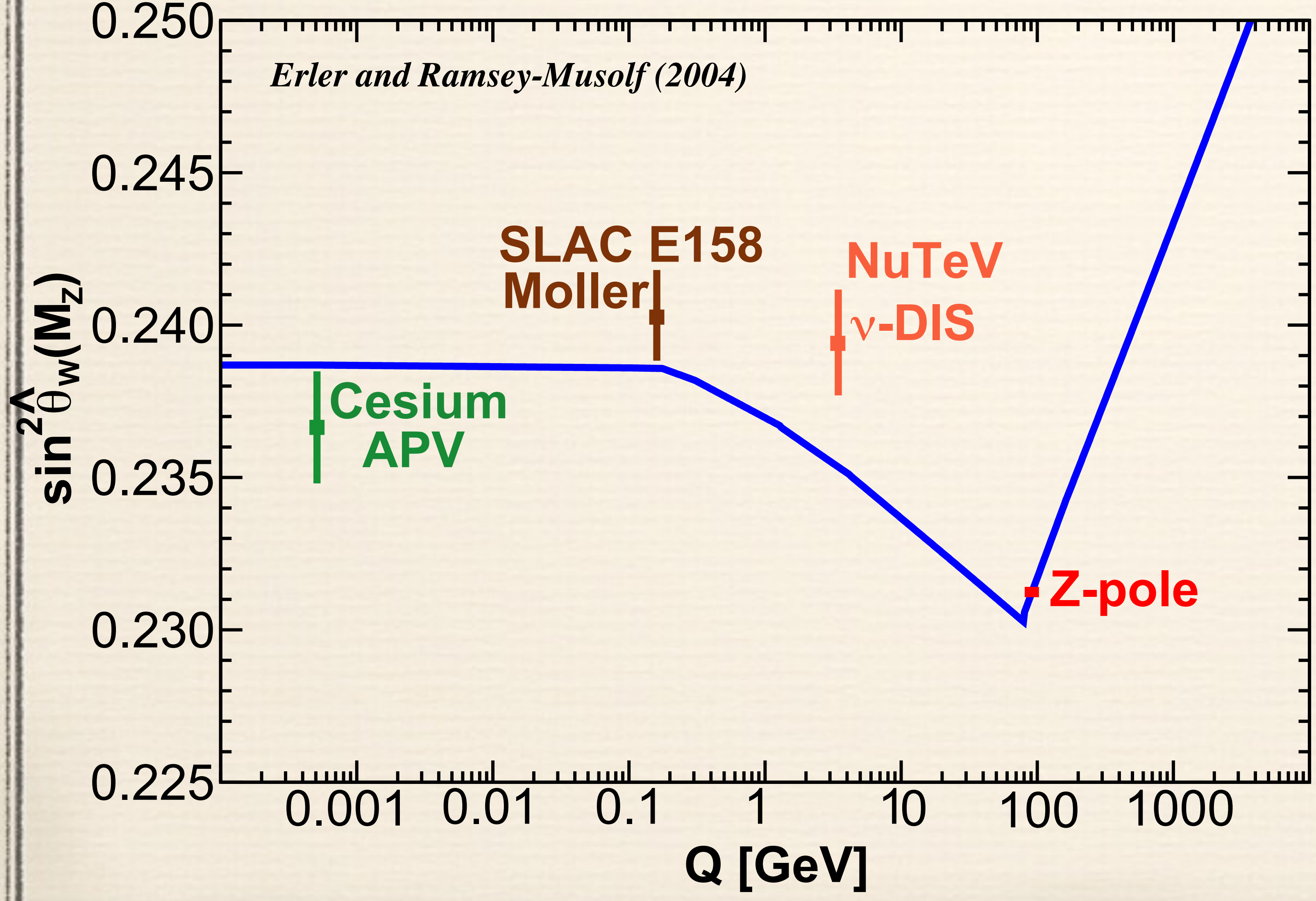

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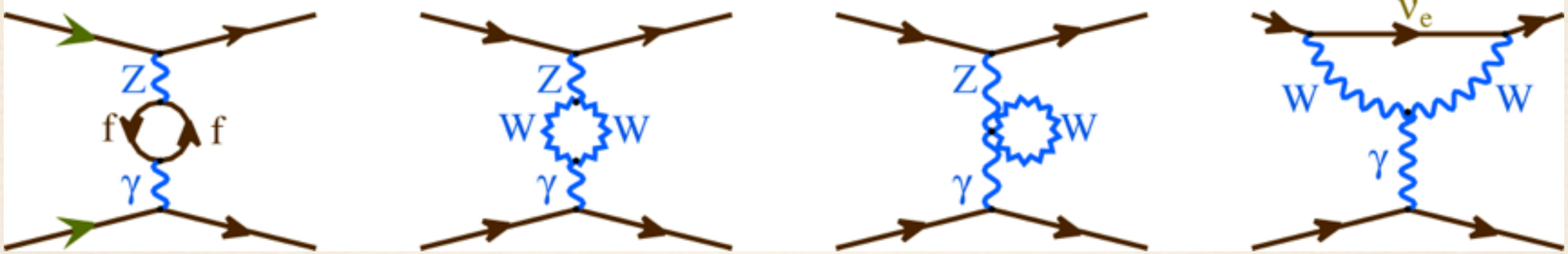

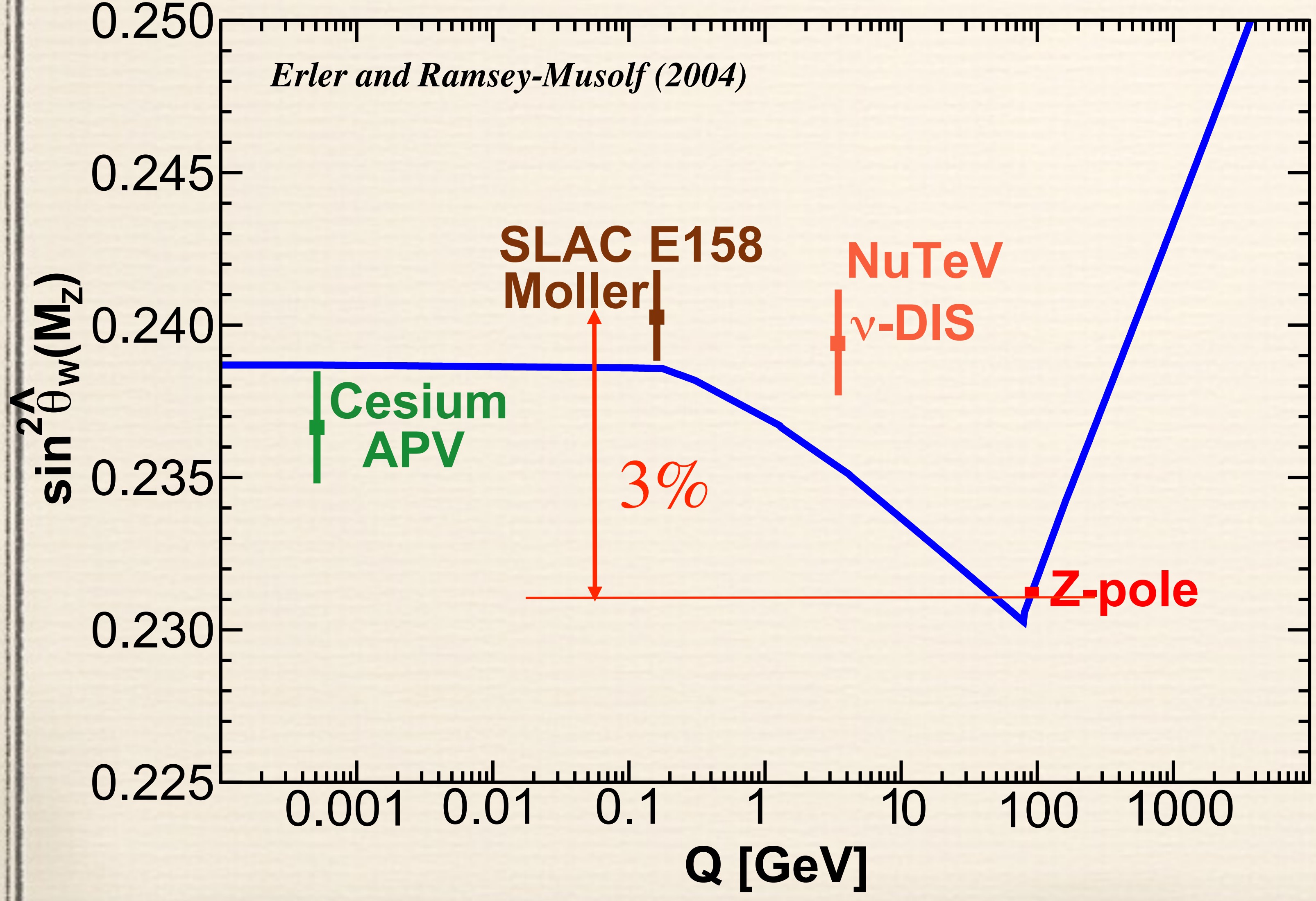

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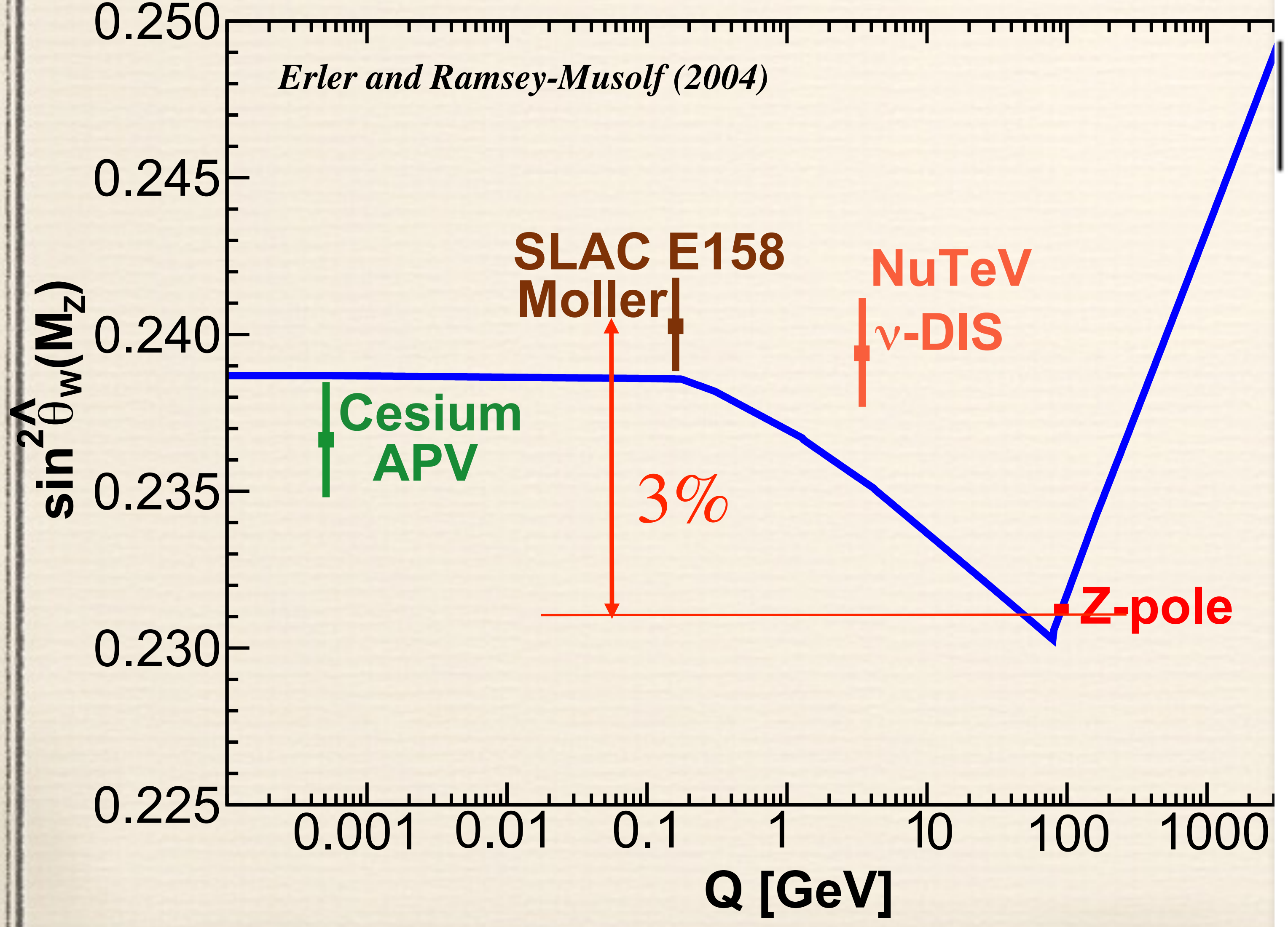
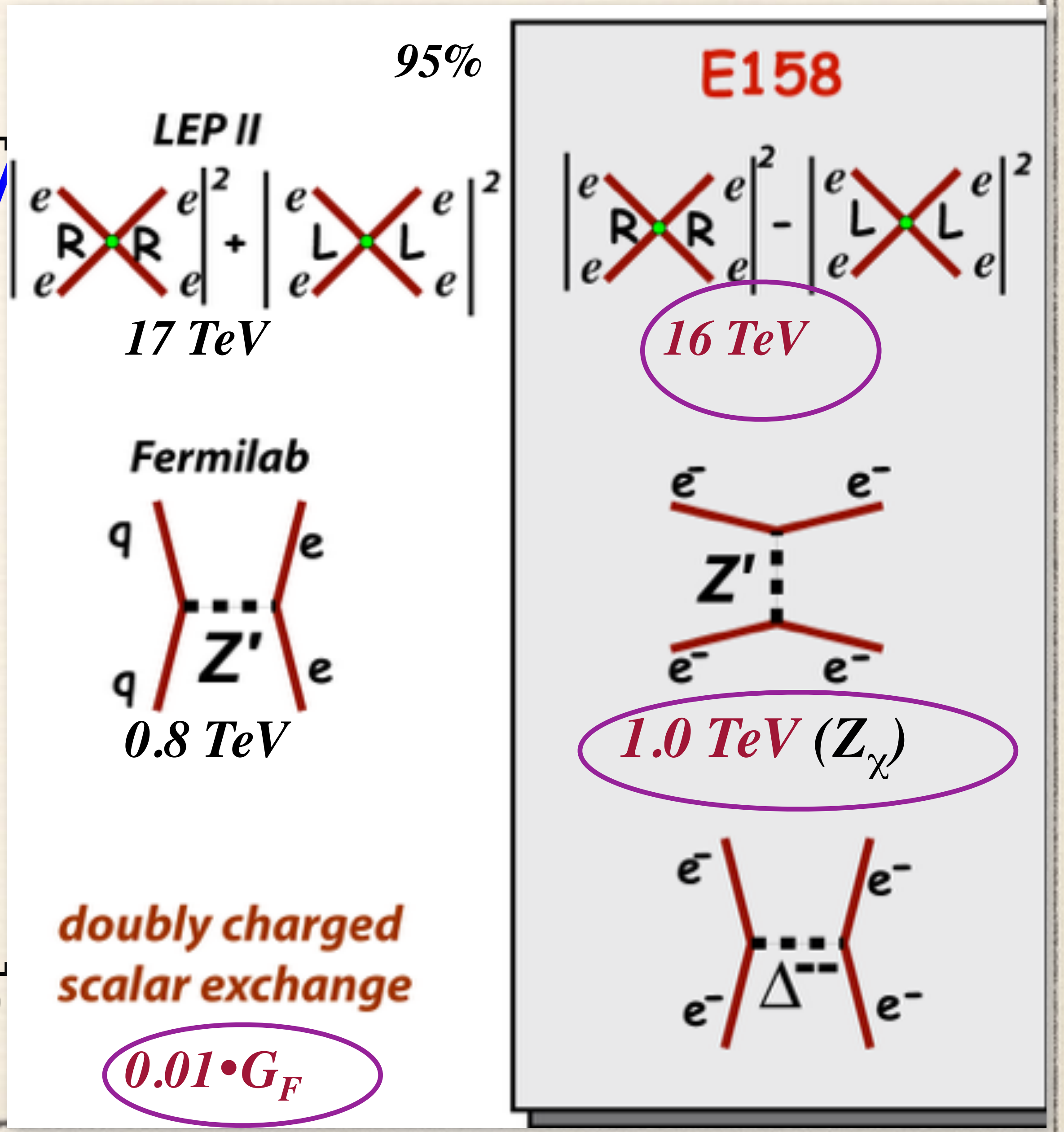
Phys. Rev. Lett. **95** 081601 (2005)

Limits on "New" Physics





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Final E158 Result

Nature

Vol 435 26 May 2005

NEWS AND VIEWS

E158 Implications

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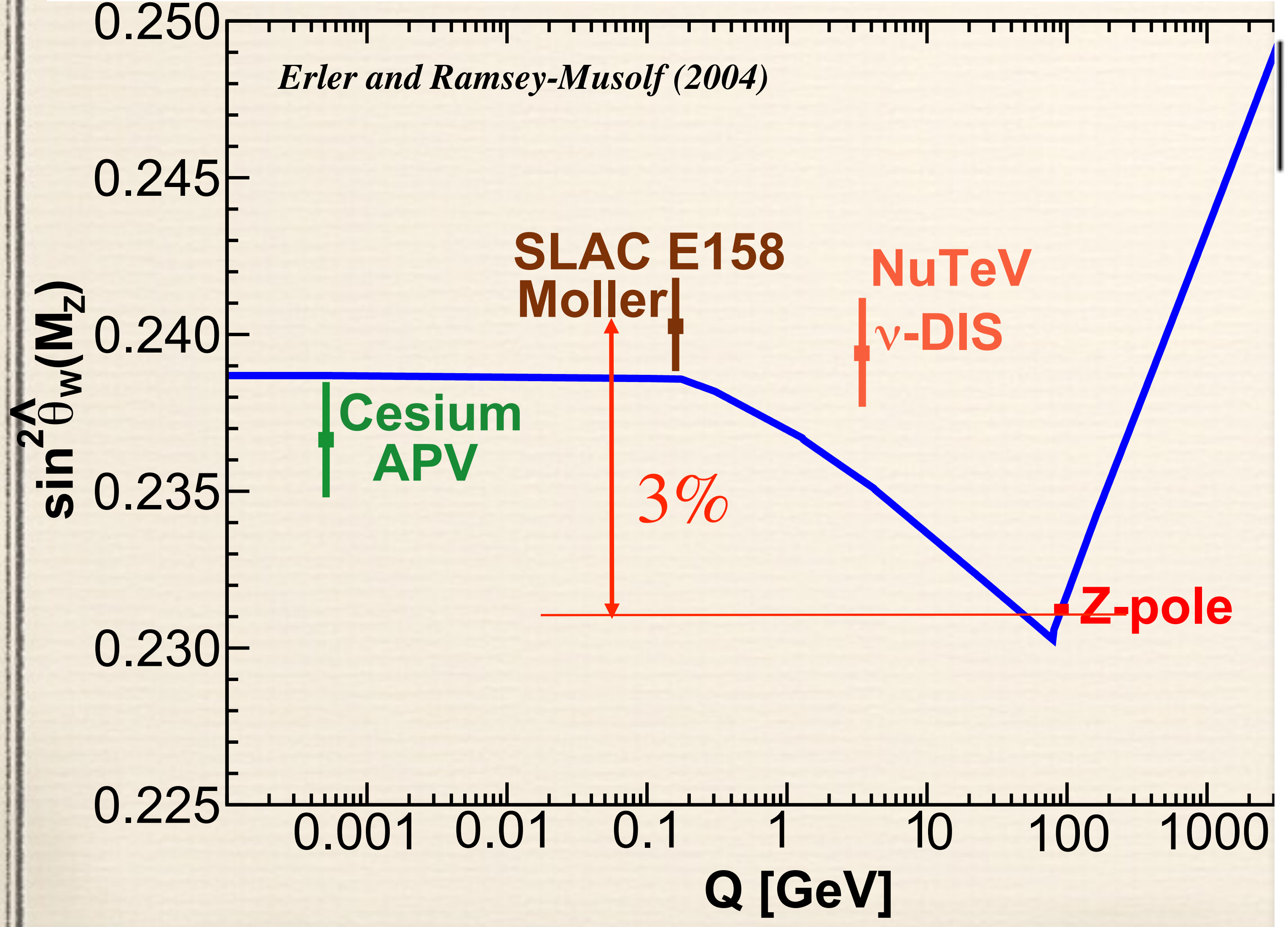
PARTICLE PHYSICS

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.



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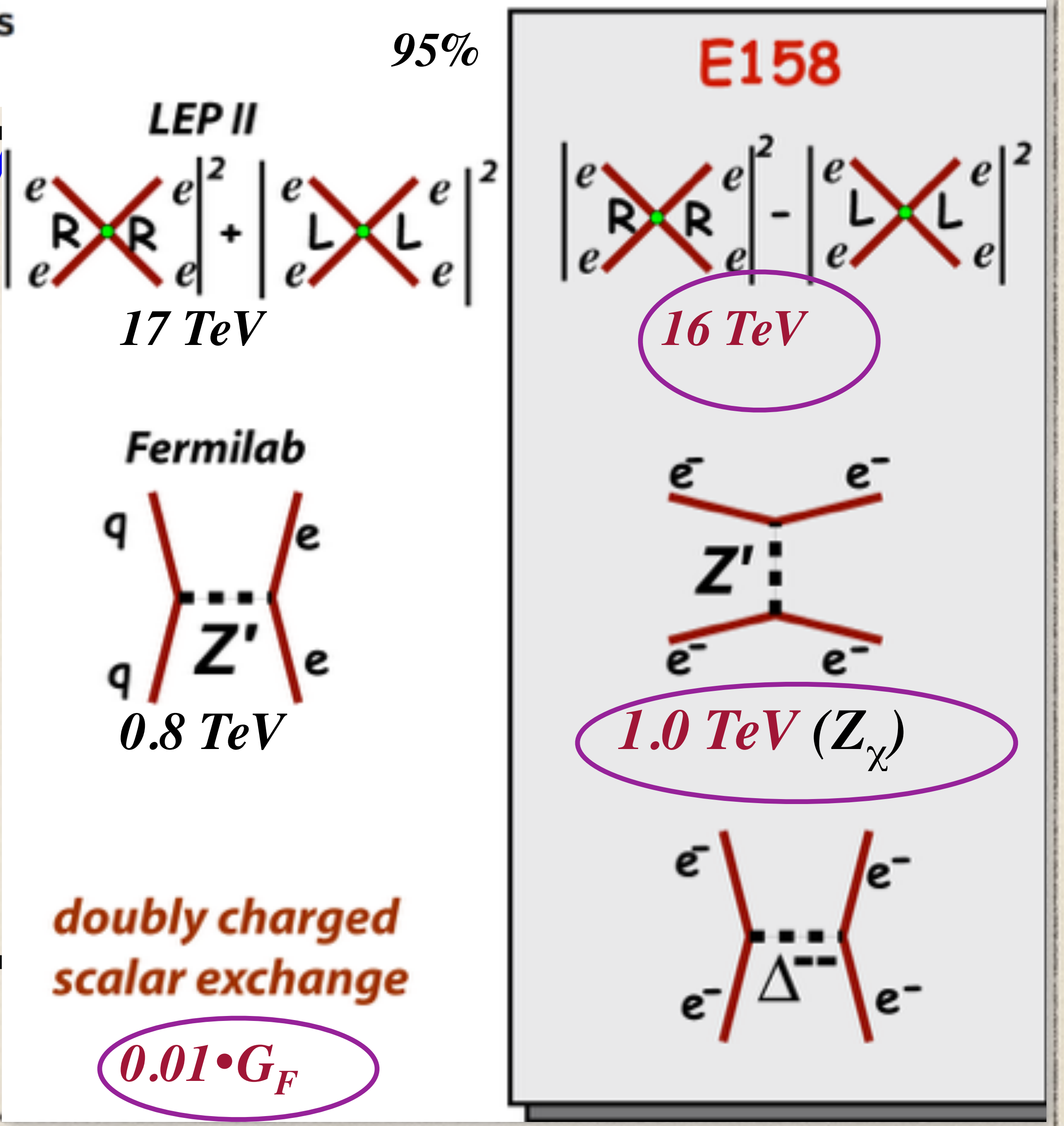

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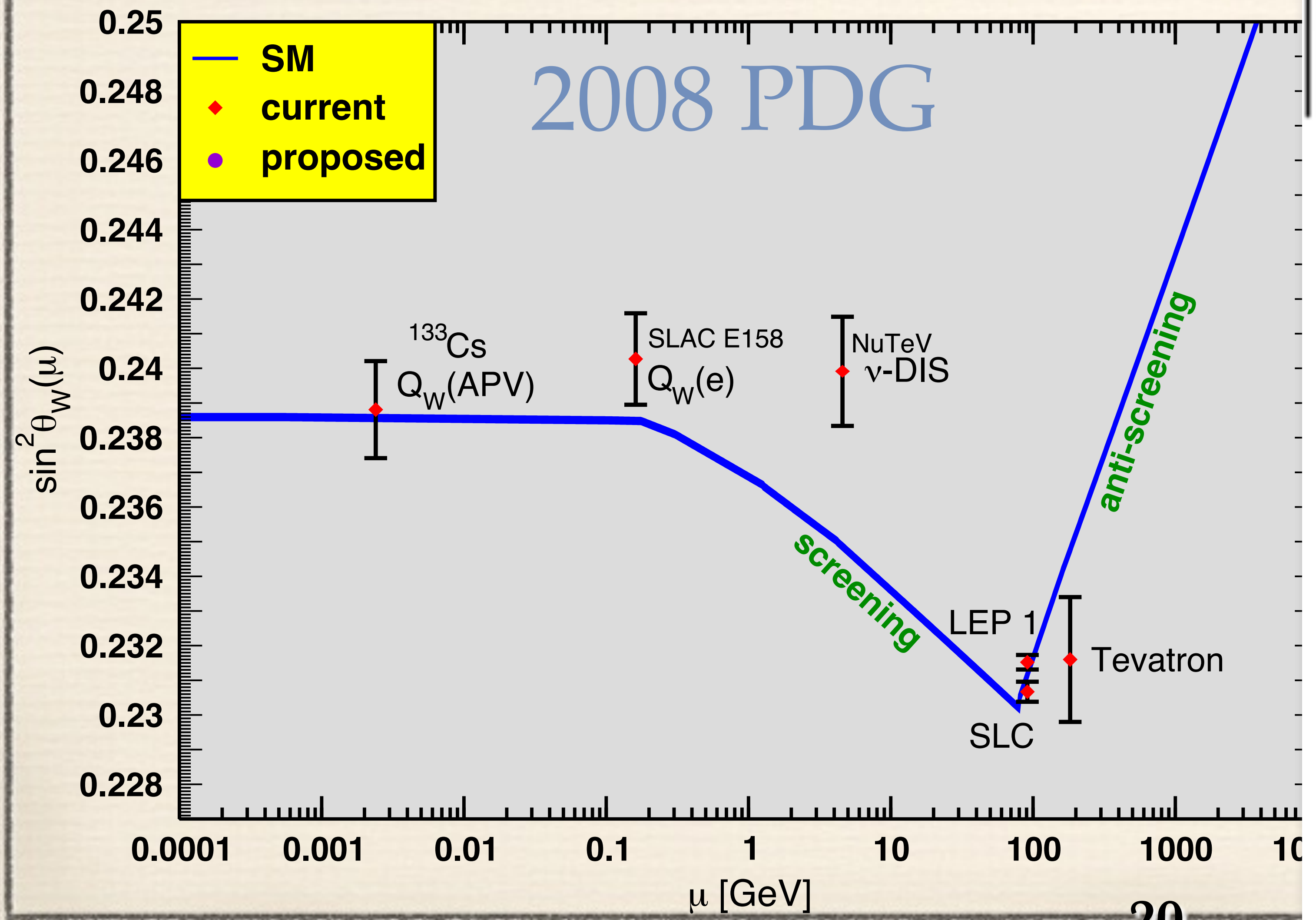

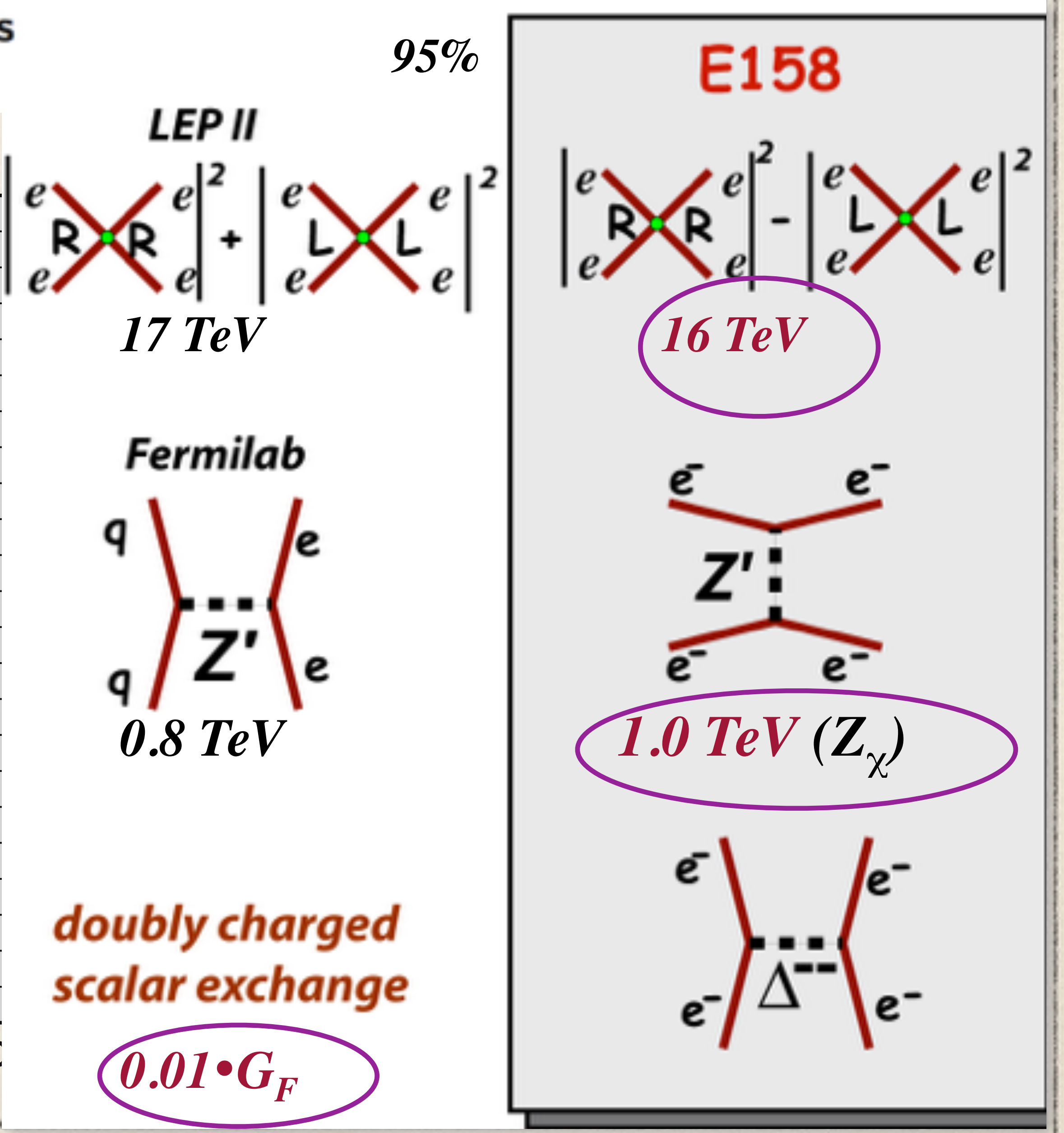

LEP II: 17 TeV

Fermilab: 0.8 TeV

doubly charged scalar exchange: $0.01 \cdot G_F$

E158: 16 TeV; 1.0 TeV (Z_χ)

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Nature

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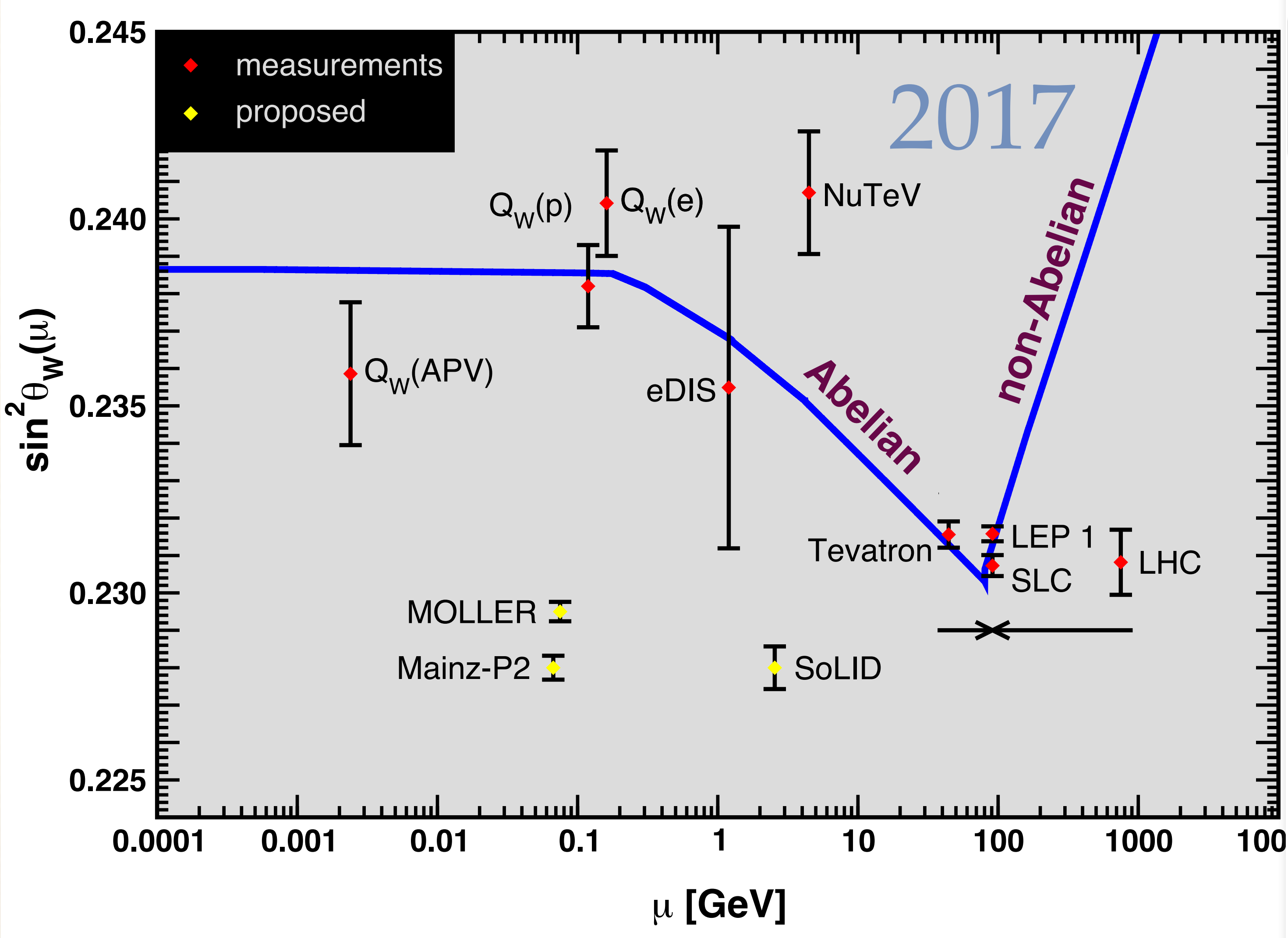
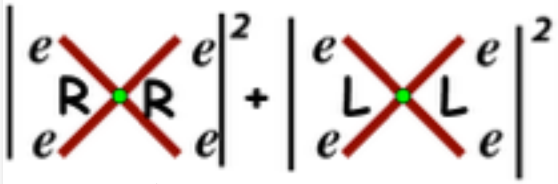


Limits on “New” Physics

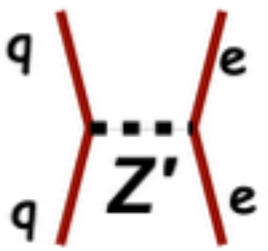
95%

LEP II



17 TeV

Fermilab



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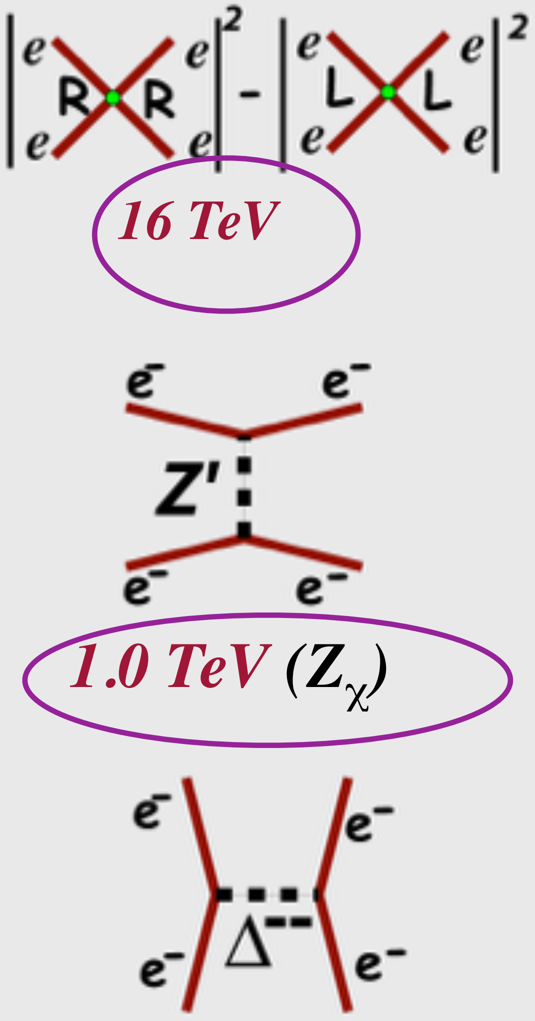
E158



16 TeV

1.0 TeV (Z_χ)

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Final E158 Result

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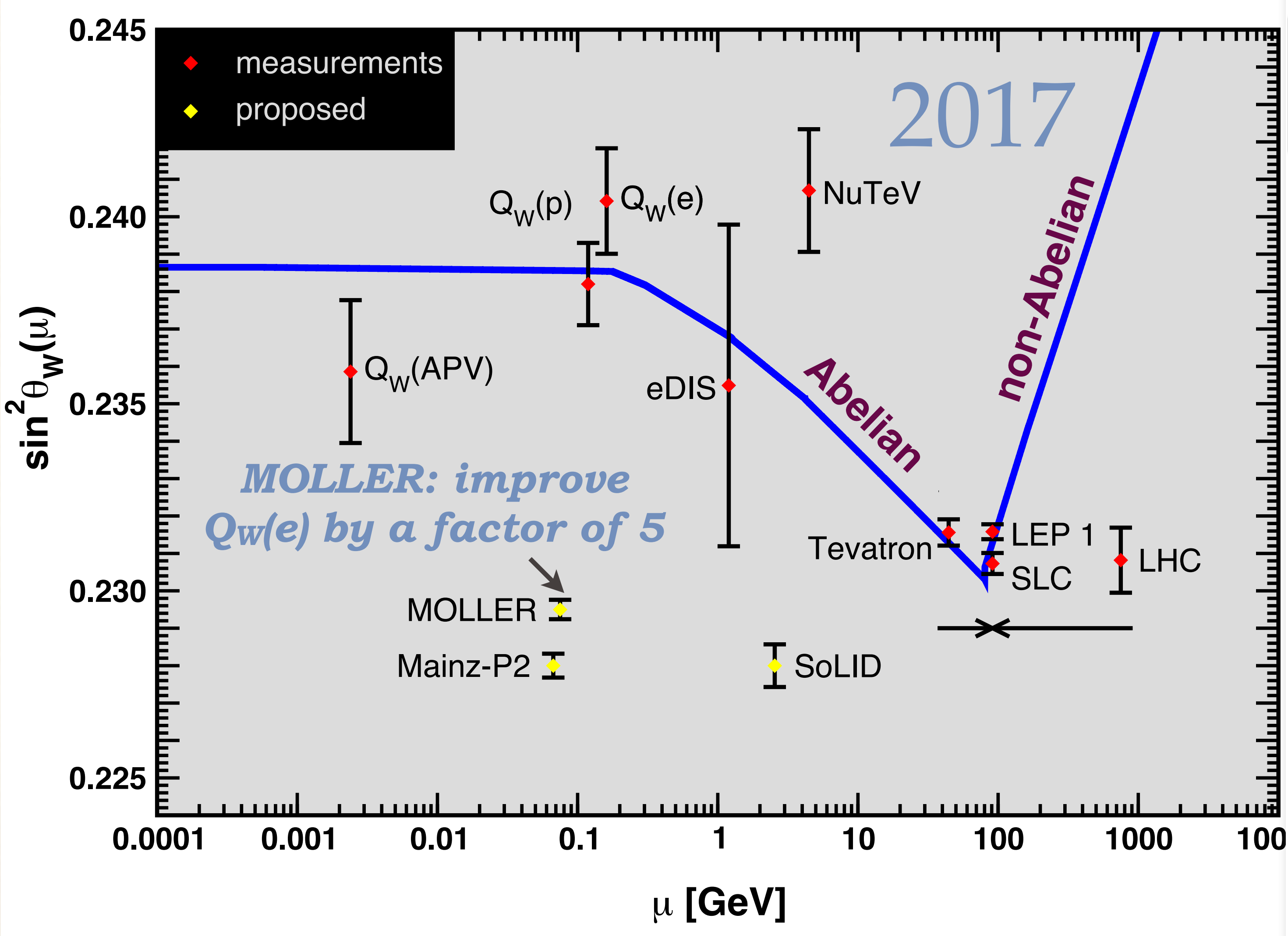
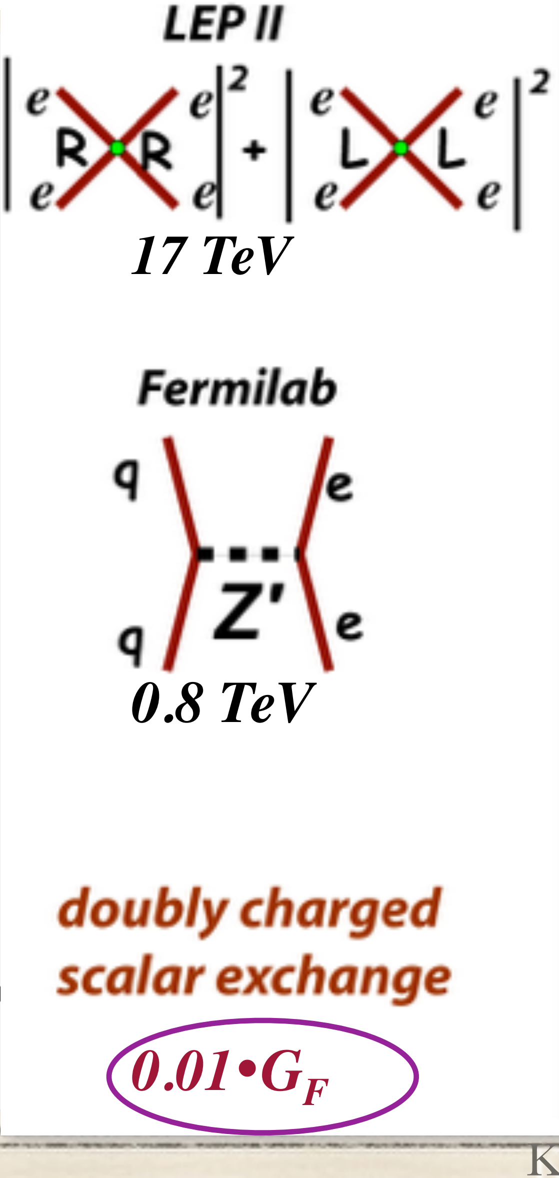


MOLLER: improve Qw(e) by a factor of 5

Limits on "New" Physics

95%



doubly charged scalar exchange

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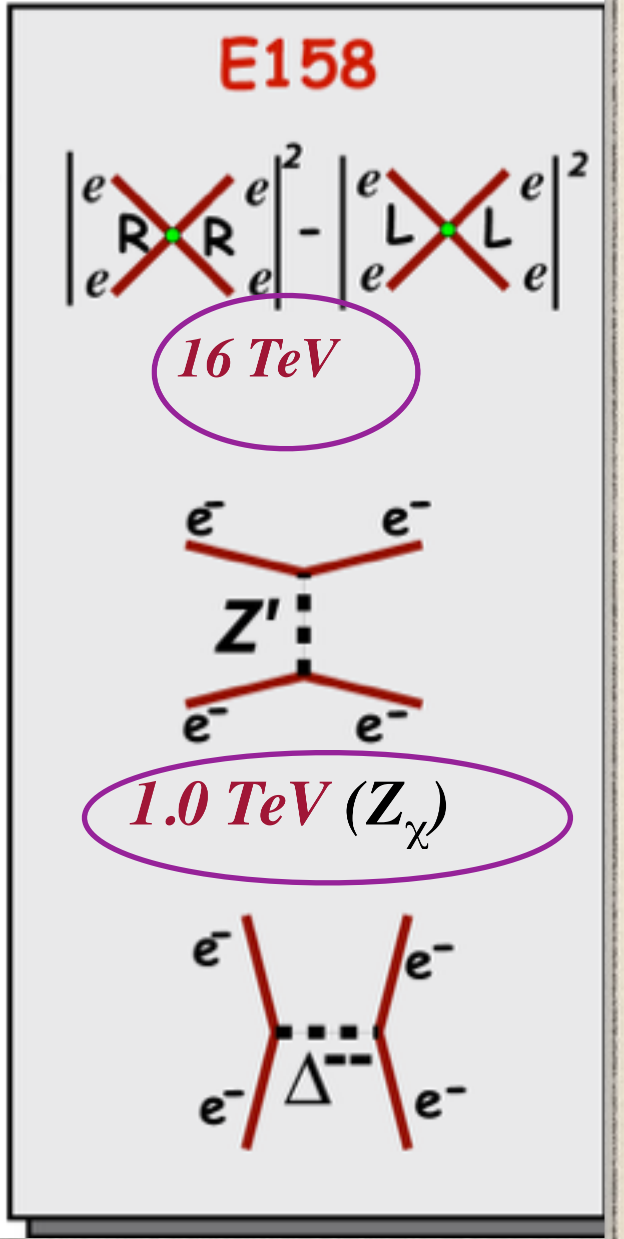
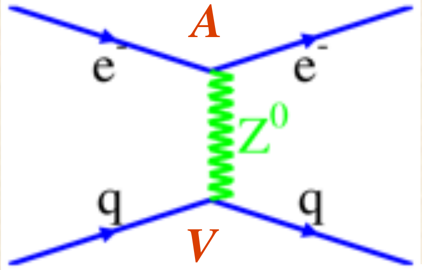
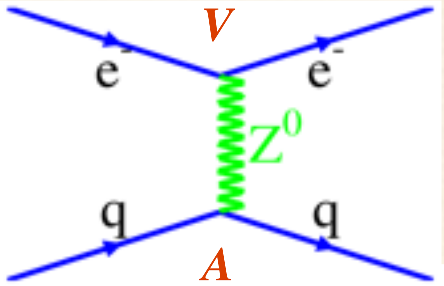


Semi-leptonic WNC Interactions

PVES on Hadron Targets



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

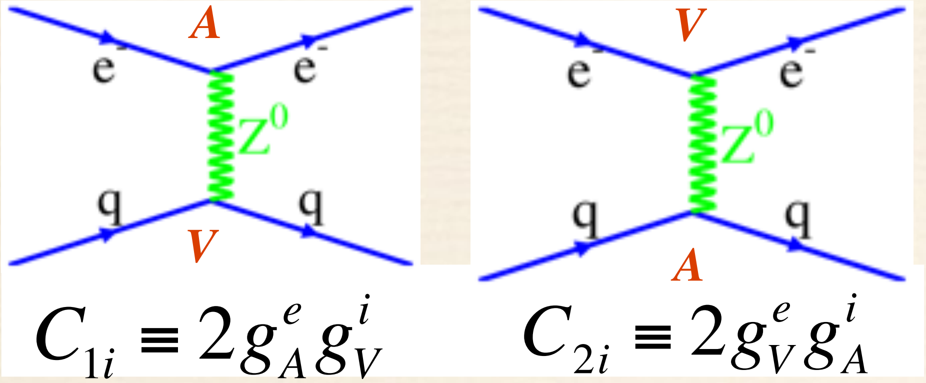


$C_{2i} \equiv 2g_V^e g_A^i$

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

Semi-leptonic WNC Interactions

PVES on Hadron Targets

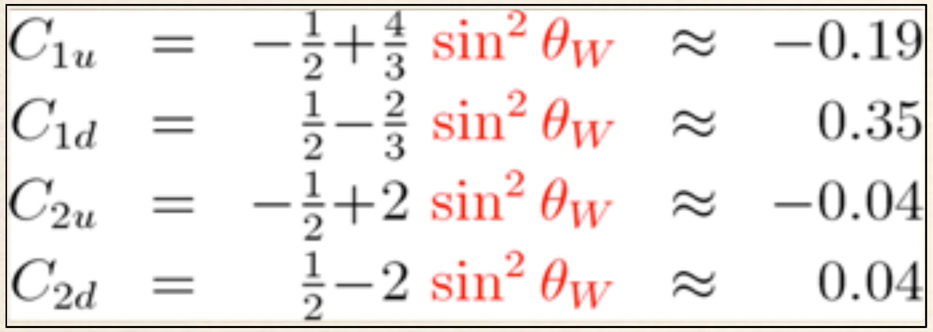


$C_{1i} \equiv 2g_A^e g_V^i$ $\quad$ $C_{2i} \equiv 2g_V^e g_A^i$

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

$$+\bar{e}\gamma^\mu e(C_{2u}\bar{u}\gamma_\mu\gamma_5 u + C_{2d}\bar{d}\gamma_\mu\gamma_5 d)]$$

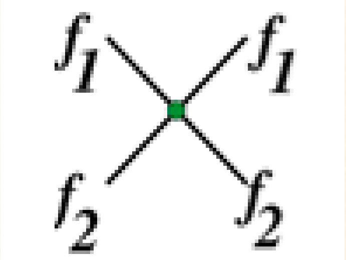
$$+C_{ee}(e\gamma^\mu\gamma_5 e\bar{e}\gamma_\mu e)$$



$$\begin{aligned} C_{1u} &= -\tfrac{1}{2}+\tfrac{4}{3}\sin^2\theta_W \approx -0.19 \\ C_{1d} &= \tfrac{1}{2}-\tfrac{2}{3}\sin^2\theta_W \approx 0.35 \\ C_{2u} &= -\tfrac{1}{2}+2\sin^2\theta_W \approx -0.04 \\ C_{2d} &= \tfrac{1}{2}-2\sin^2\theta_W \approx 0.04 \end{aligned}$$

+

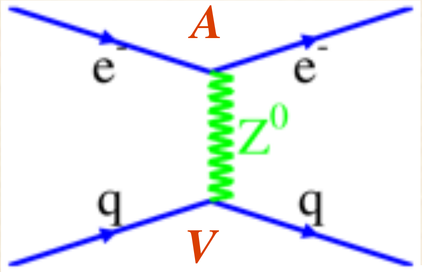
new physics



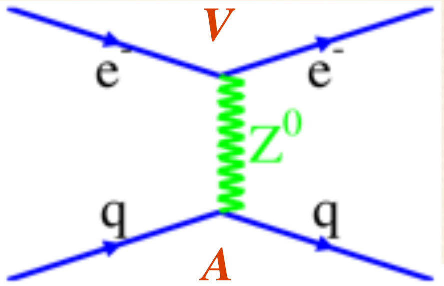
$$\mathcal{L}_{f_1 f_2} = \sum_{i,j=L,R} \frac{(g_{ij}^{12})^2}{\Lambda_{ij}^2} \bar{f}_{1i}\gamma_\mu f_{1i}\bar{f}_{2j}\gamma_\mu f_{2j}$$

Semi-leptonic WNC Interactions

PVES on Hadron Targets



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



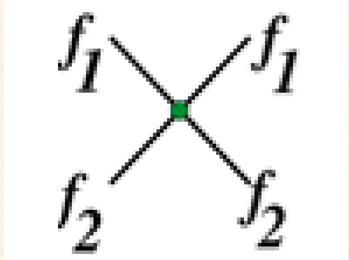
$C_{2i} \equiv 2g_V^e g_A^i$

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

$$\begin{array}{lclcl}
C_{1u} & = & -\frac{1}{2}+\frac{4}{3}\sin^2\theta_W & \approx & -0.19 \\
C_{1d} & = & \frac{1}{2}-\frac{2}{3}\sin^2\theta_W & \approx & 0.35 \\
C_{2u} & = & -\frac{1}{2}+2\sin^2\theta_W & \approx & -0.04 \\
C_{2d} & = & \frac{1}{2}-2\sin^2\theta_W & \approx & 0.04
\end{array}$$

\+

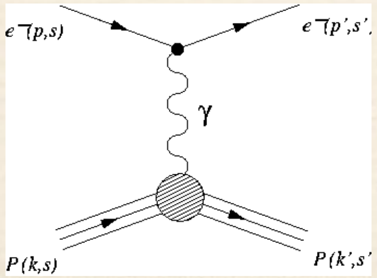
new physics



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

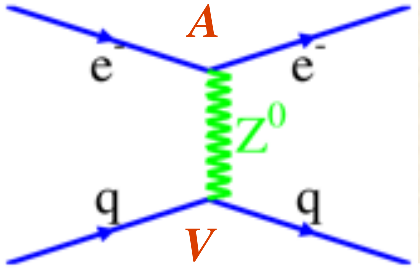
$$C_{1q} \propto (g^{eq}_{RR})^2 + (g^{eq}_{RL})^2 - (g^{eq}_{LR})^2 - (g^{eq}_{LL})^2 \Rightarrow$$

PV elastic e-N scattering, Atomic parity violation

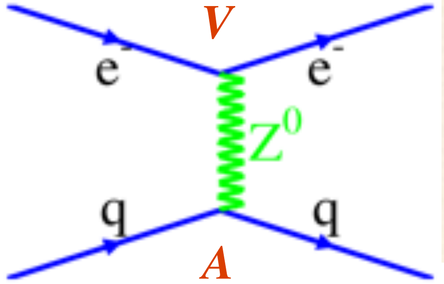


Semi-leptonic WNC Interactions

PVES on Hadron Targets

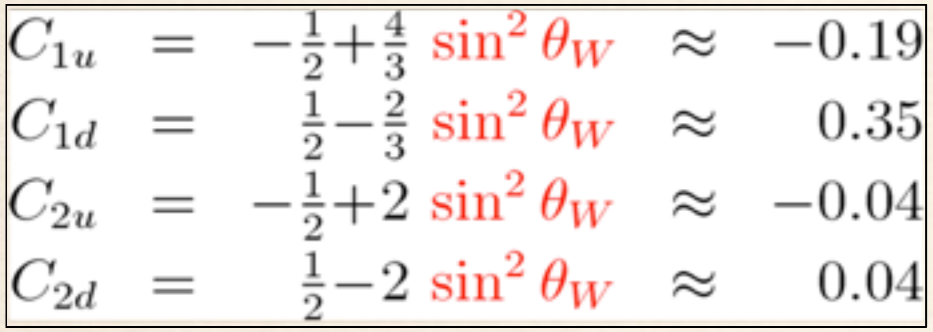


$$C_{1i} \equiv 2g^e_A g^i_V$$



$$C_{2i} \equiv 2g^e_V g^i_A$$

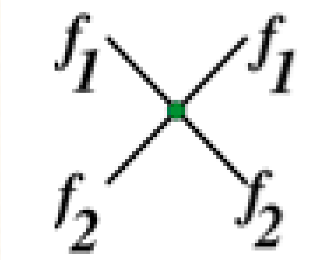
$$\mathcal{L}^{PV} = \frac{G_F}{\sqrt{2}}[\bar{e}\gamma^\mu\gamma_5 e(C_{1u}\bar{u}\gamma_\mu u + C_{1d}\bar{d}\gamma_\mu d)$$
$$+\bar{e}\gamma^\mu e(C_{2u}\bar{u}\gamma_\mu\gamma_5 u + C_{2d}\bar{d}\gamma_\mu\gamma_5 d)]$$
$$+C_{ee}(e\gamma^\mu\gamma_5 e\bar{e}\gamma_\mu e)$$



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

+

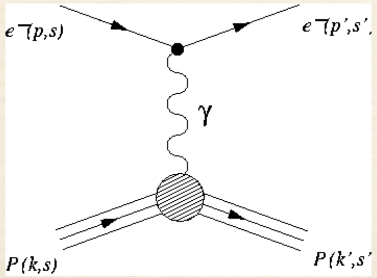
new physics

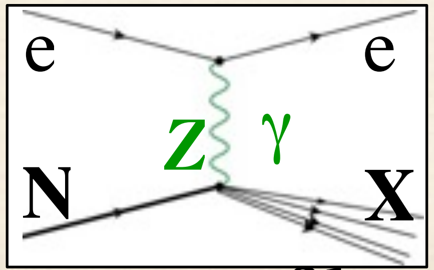


$$\mathcal{L}_{f_1 f_2} = \sum_{i,j=L,R} \frac{(g^{12}_{i\,j})^2}{\Lambda^2_{ij}} \bar{f}_{1i}\gamma_\mu f_{1i}\bar{f}_{2j}\gamma_\mu f_{2j}$$

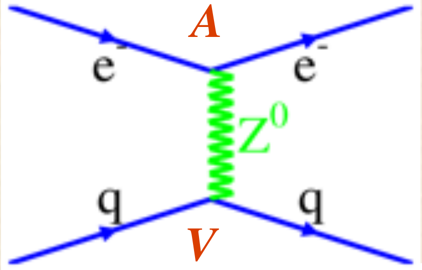
$$C_{1q} \propto (g^{eq}_{RR})^2 + (g^{eq}_{RL})^2 - (g^{eq}_{LR})^2 - (g^{eq}_{LL})^2 \Rightarrow$$ ***PV elastic e-N scattering, Atomic parity violation***

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

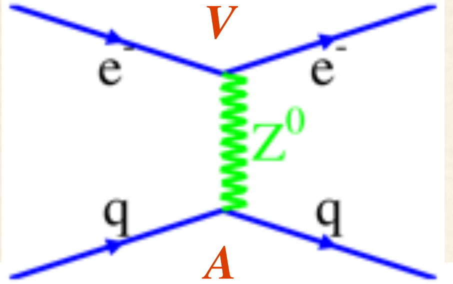




PVES on Hadron Targets



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



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

$$\begin{aligned}
C_{1u} &= -\tfrac{1}{2}+\tfrac{4}{3}\sin^2\theta_W \approx -0.19\\
C_{1d} &= \tfrac{1}{2}-\tfrac{2}{3}\sin^2\theta_W \approx 0.35\\
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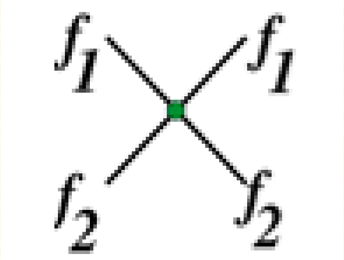
\end{aligned}$$

+

new physics



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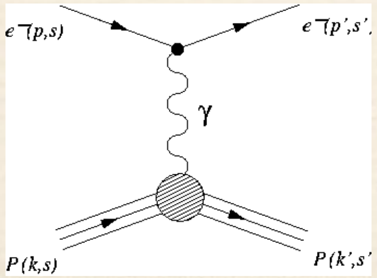
⇨ *PV elastic e-N scattering, Atomic parity violation*

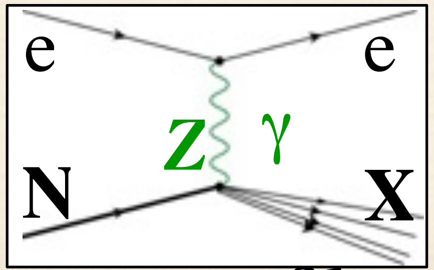
$$C_{2q} \propto (g_{RR}^{eq})^2 - (g_{RL}^{eq})^2 + (g_{LR}^{eq})^2 - (g_{LL}^{eq})^2$$

⇨ *PV deep inelastic scattering*

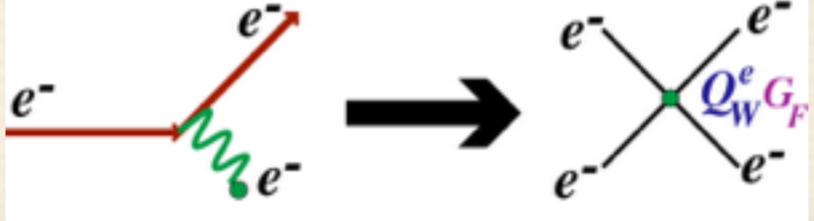
$$C_{ee} \propto (g_{RR}^{ee})^2 - (g_{LL}^{ee})^2$$

⇨ *PV Møller scattering*



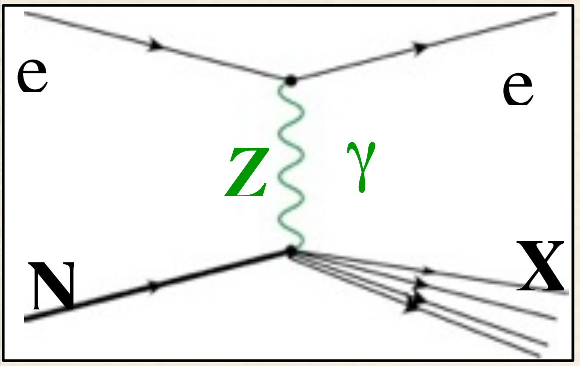


$\mathbf{Q_W = 1 - 4\sin^2\theta_W}$



PVDIS

A_{PV} in deep inelastic e-D scattering:



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

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

a(x): function of C_{1i}'s

b(x): function of C_{2i}'s

For ^{2}H, assuming charge symmetry, structure functions cancel in the ratio:

$$b(x) = \frac{3}{10}\left[(2C_{2u} - C_{2d})\frac{u_v(x) + d_v(x)}{u(x) + d(x)}\right] + \cdots$$

PVDIS

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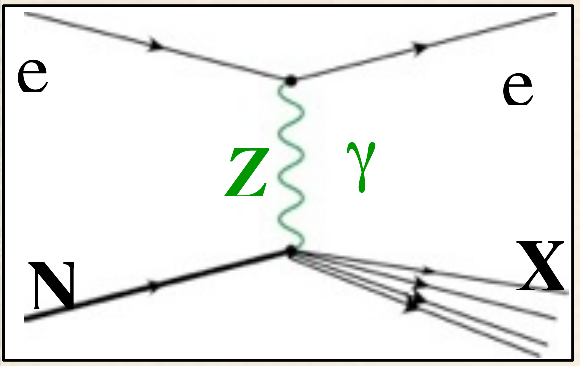

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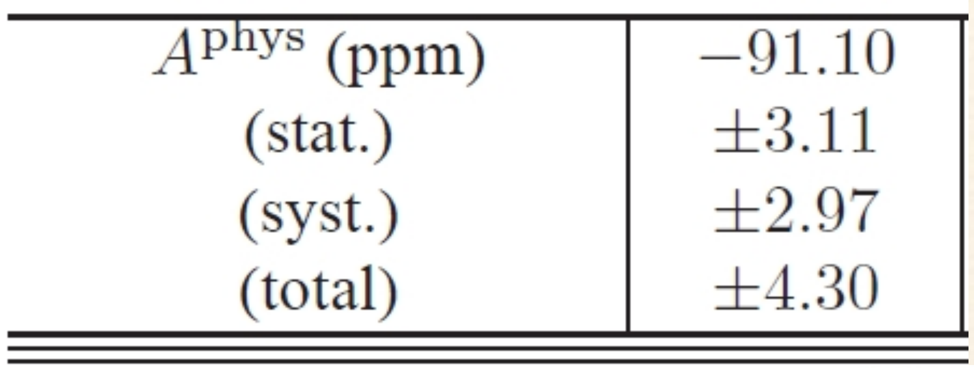
Wang et al., Nature 506, no. 7486, 67 (2014);

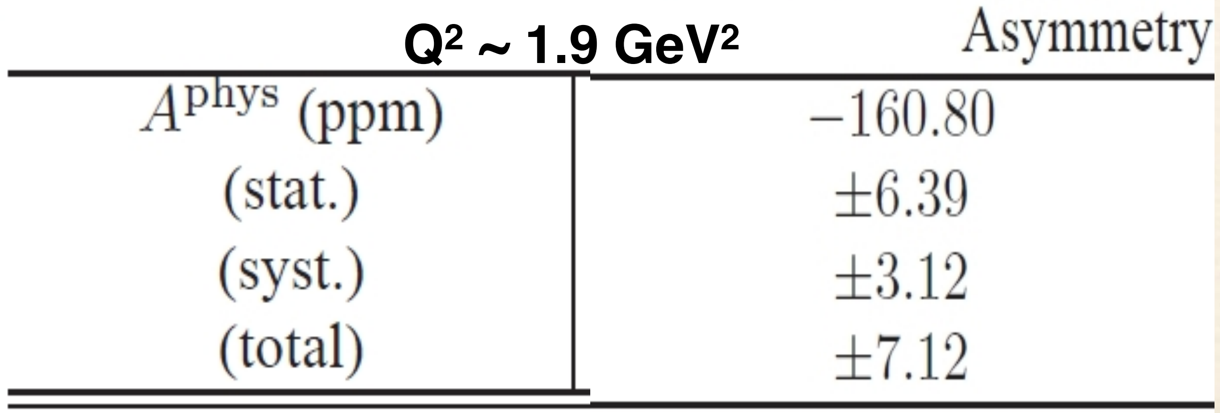
6 GeV run results

$Q^2 \sim 1.1$ GeV^2



A^{phys} (ppm)	−91.10
(stat.)	±3.11
(syst.)	±2.97
(total)	±4.30

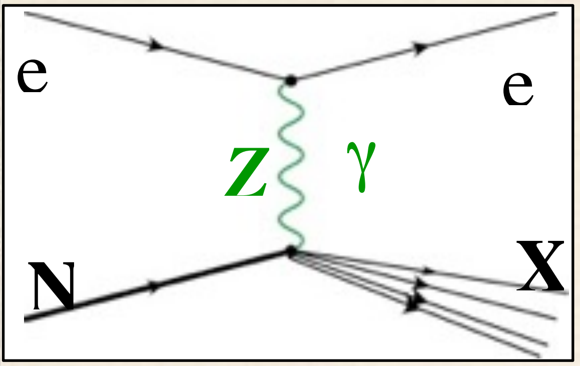
$Q^2 \sim 1.9$ GeV^2



	Asymmetry
A^{phys} (ppm)	−160.80
(stat.)	±6.39
(syst.)	±3.12
(total)	±7.12

PVDIS

A_{PV} in deep inelastic e-D scattering:



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Wang et al., Nature 506, no. 7486, 67 (2014);

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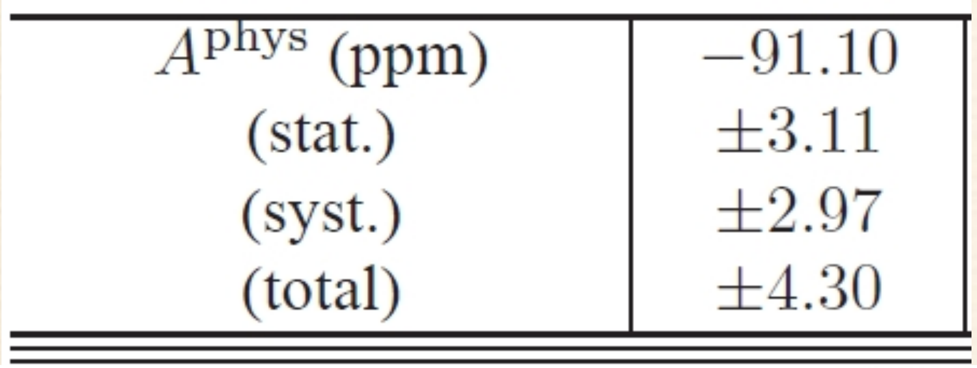

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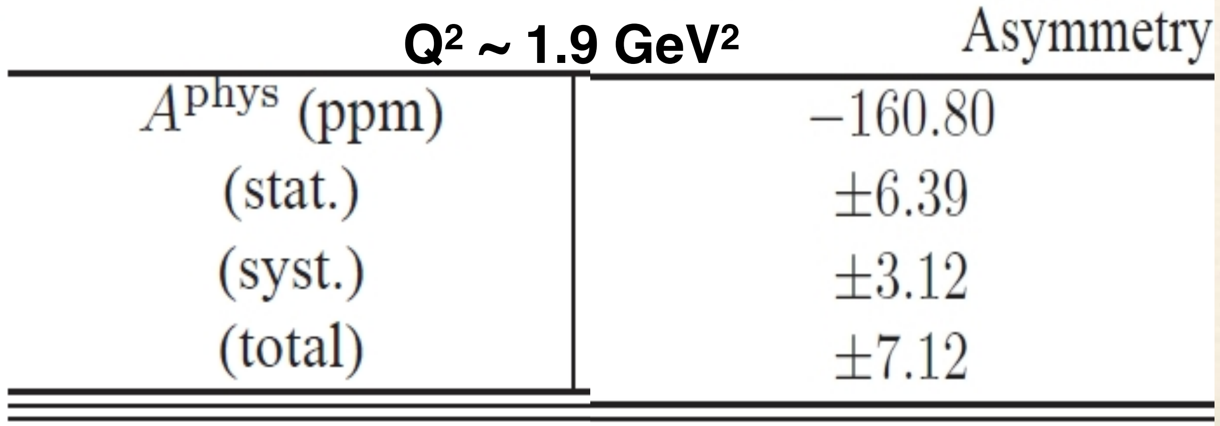

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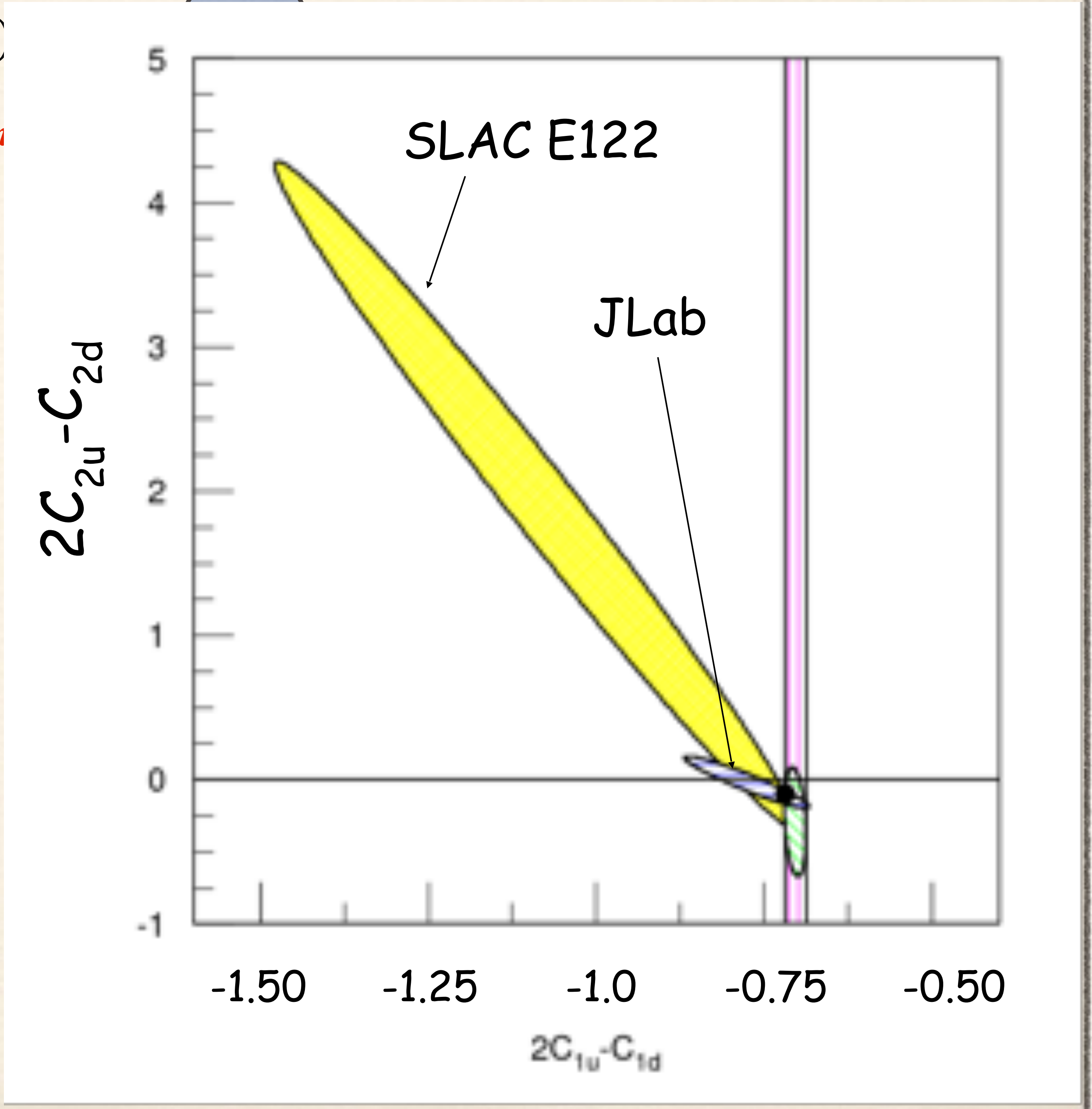
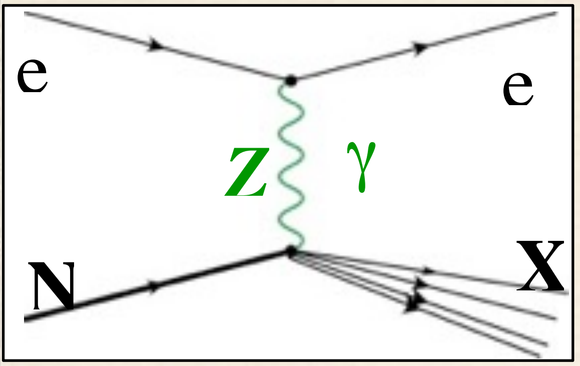


PVDIS

A_{PV} in deep inelastic e-D scattering:



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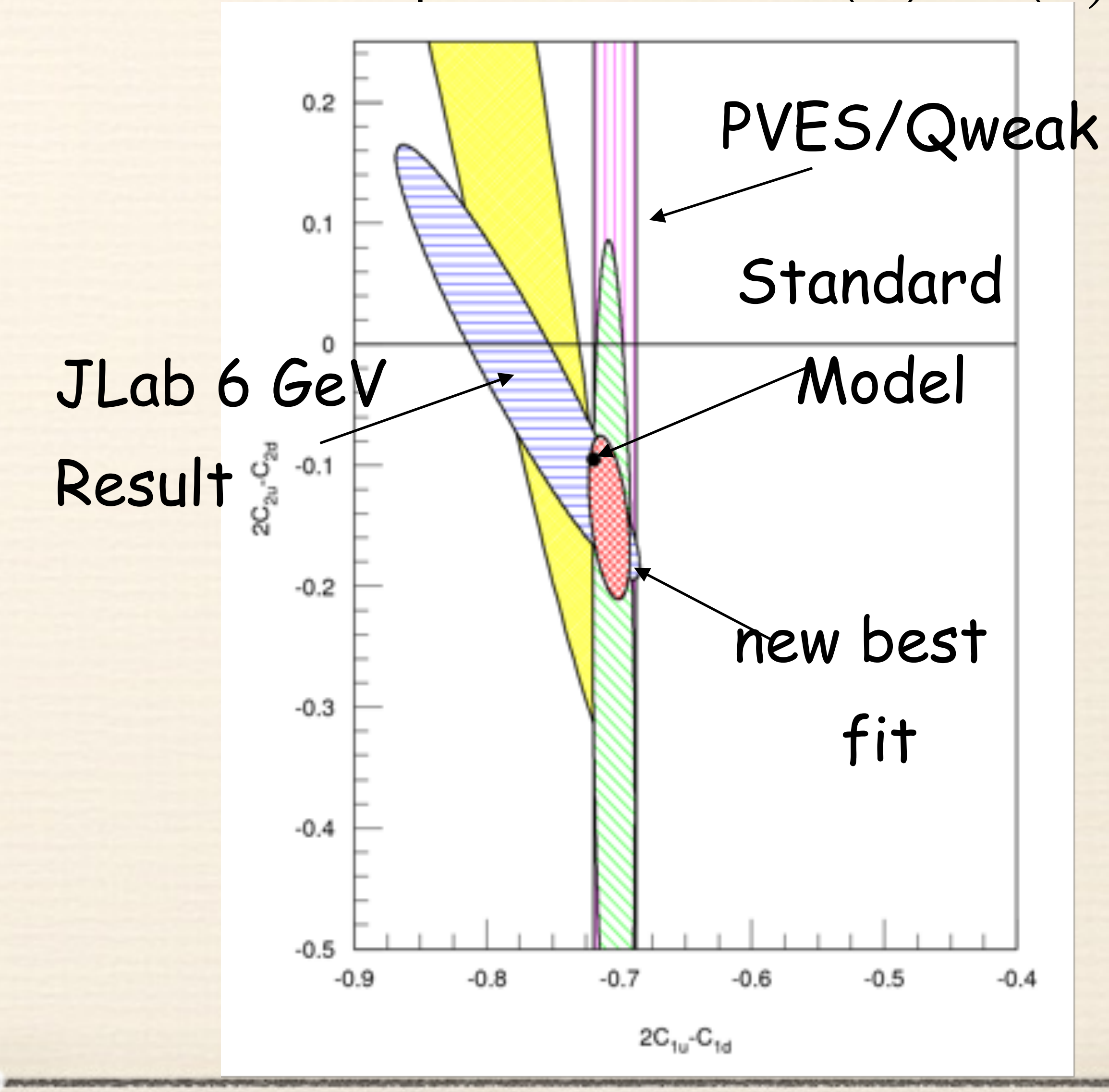
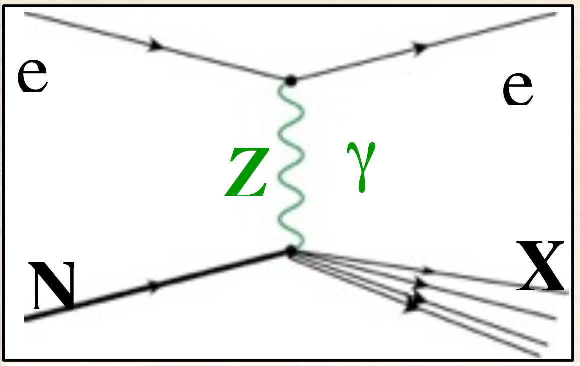


PVDIS

A_{PV} in deep inelastic e-D scattering:



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

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For ^2H, assuming charge symmetry,

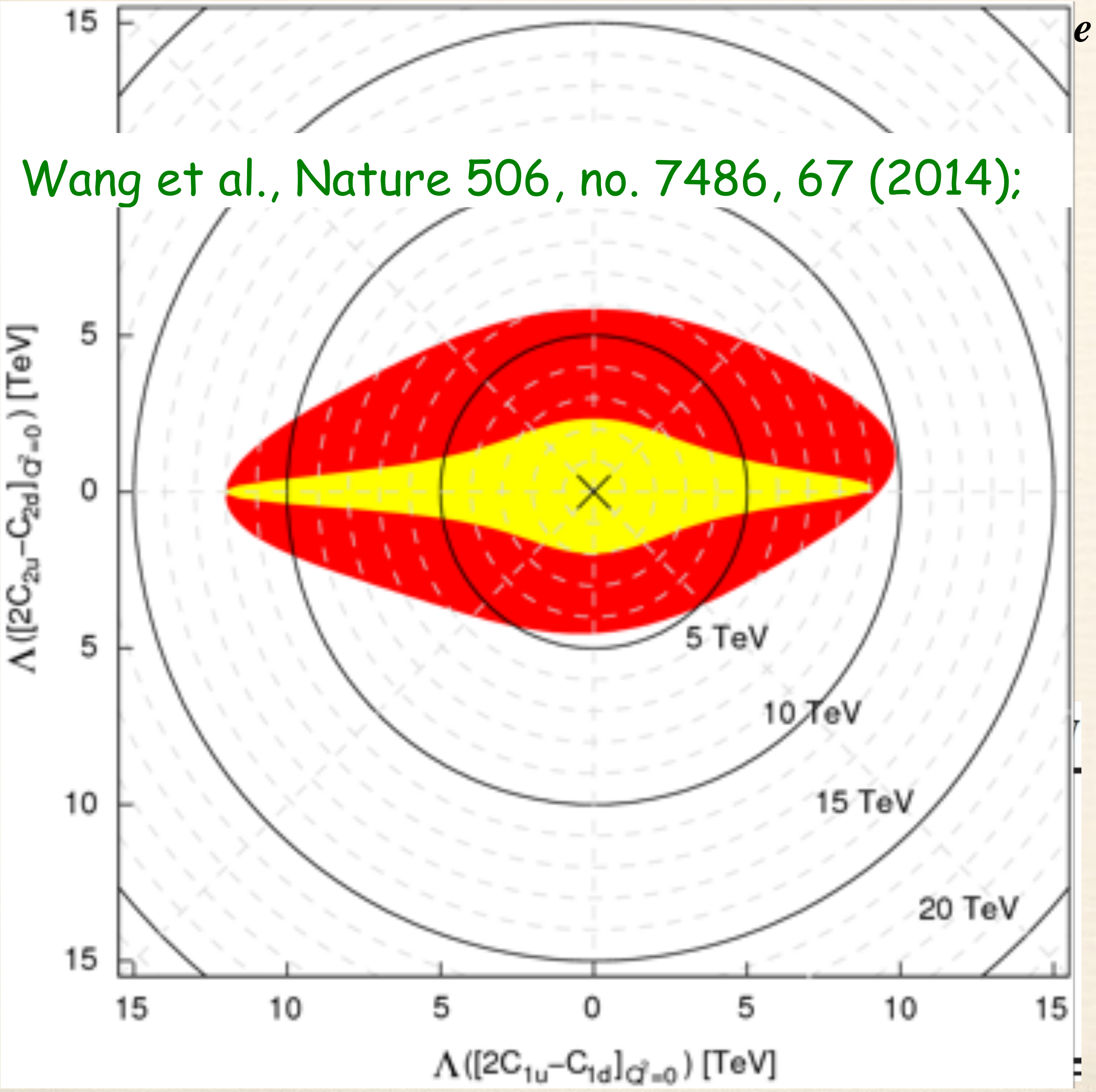
e ratio

PARTICLE PHYSICS

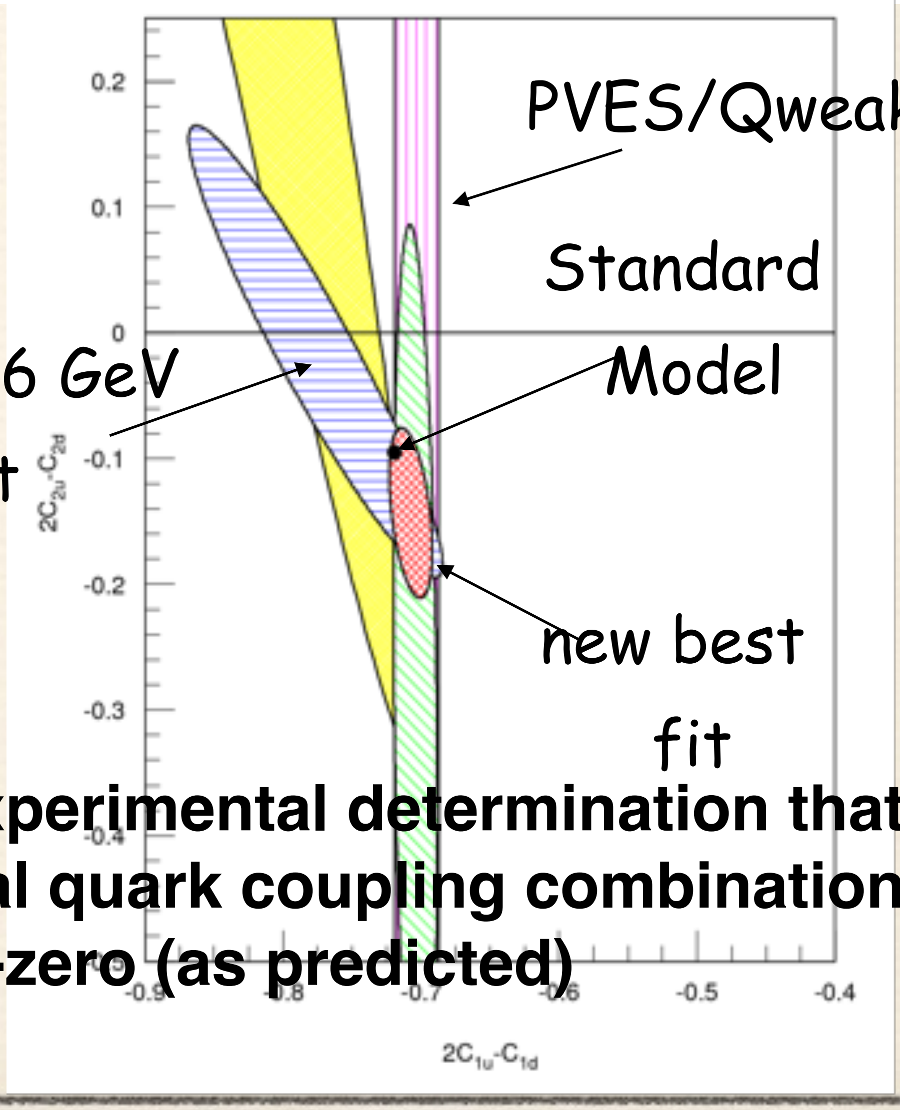
Quarks are not ambidextrous

By separately scattering right- and left-handed electrons off quarks in a deuterium target, researchers have improved, by about a factor of five, on a classic result of mirror-symmetry breaking from 35 years ago. SEE LETTER P.67

W. Marciano article in Nature



Wang et al., Nature 506, no. 7486, 67 (2014);



PVES/Qweak

Standard Model

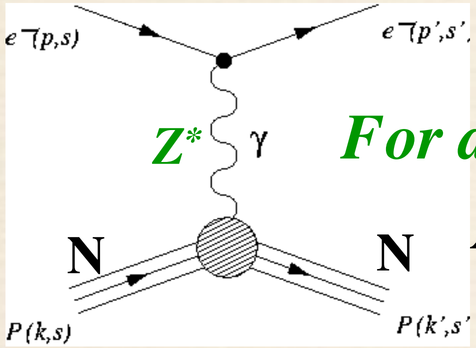
JLab 6 GeV Result

new best fit

first experimental determination that an axial quark coupling combination is non-zero (as predicted)

A_{PV} in elastic e-p scattering: **Qweak at JLab**

The Weak Charge of the Proton



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

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

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

A_{PV} *in elastic e-p scattering:* Qweak at JLab

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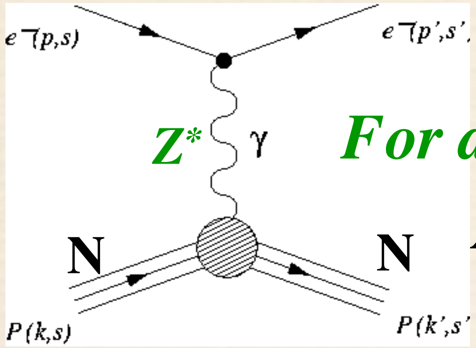

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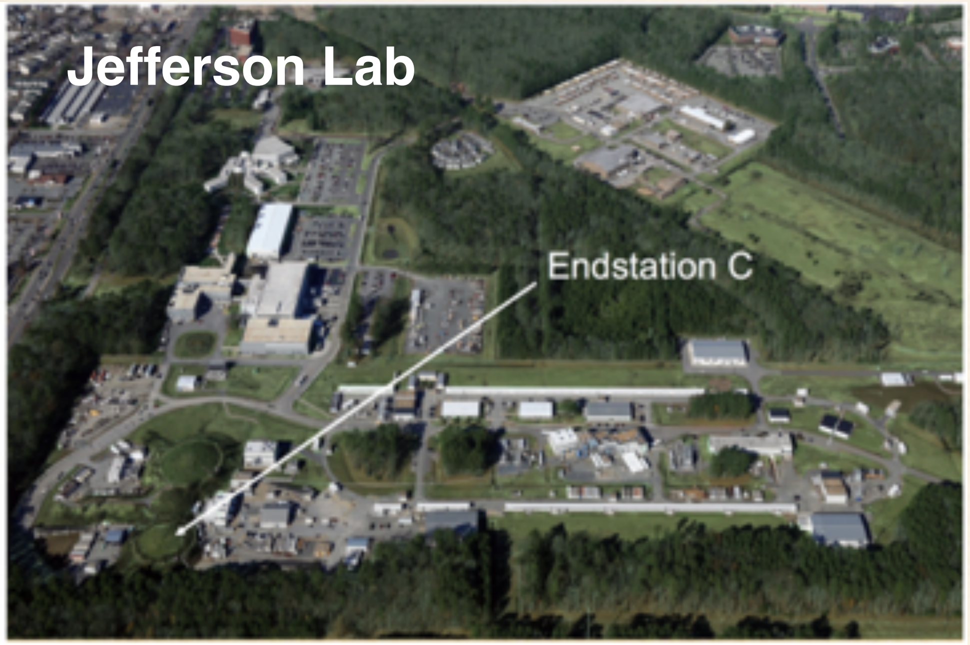
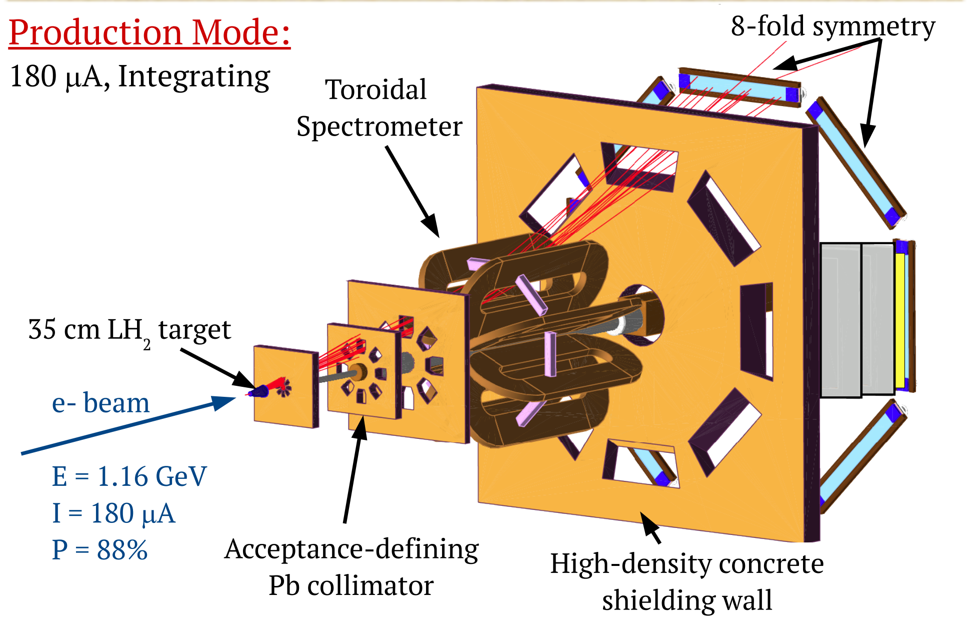
Two Production Runs: Feb-May '11, Nov '11-May '12





A_{PV} *in elastic e-p scattering:* Qweak at JLab

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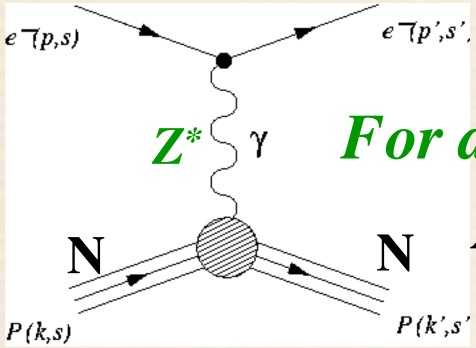

Final result recently published: Nature 557 (2018) no.7704, 207-211

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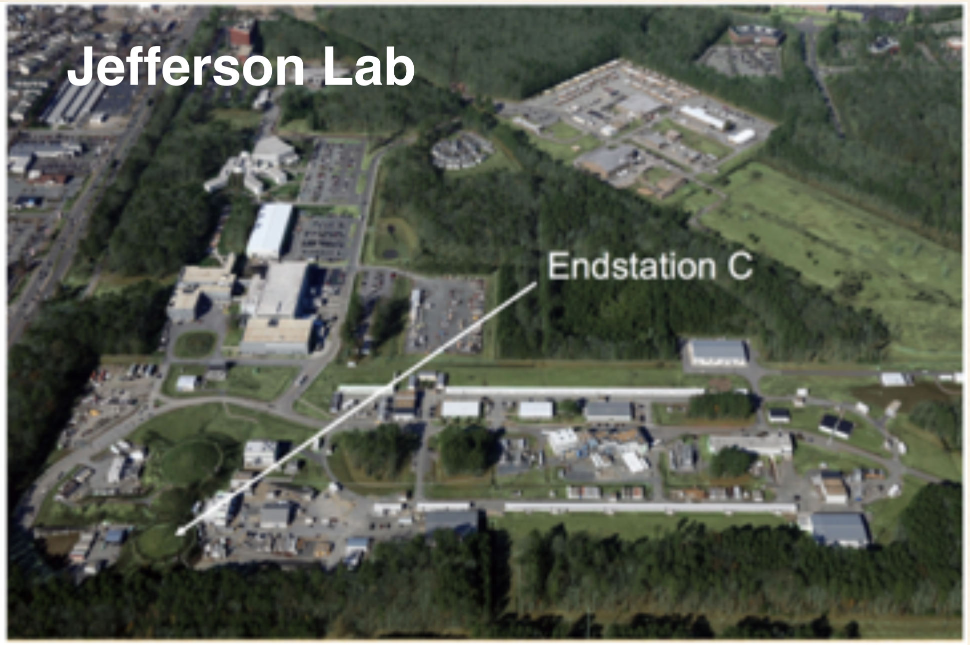
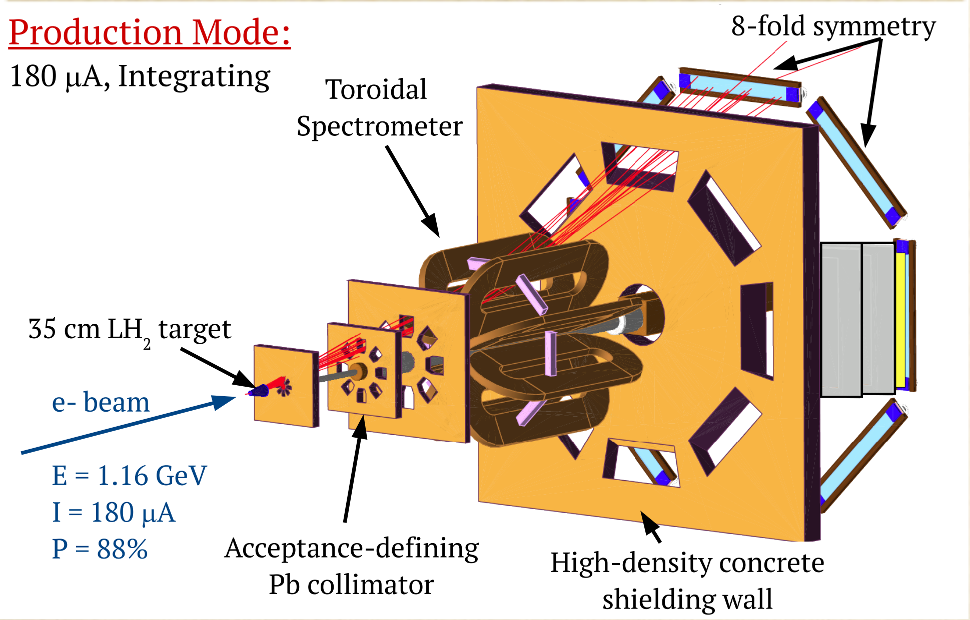
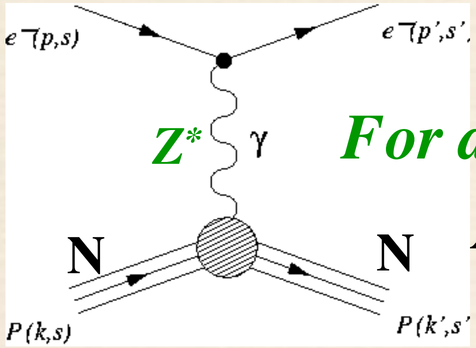




Production Mode:
180 µA, Integrating

A_{PV} in elastic e-p scattering: Qweak at JLab

The Weak Charge of the Proton



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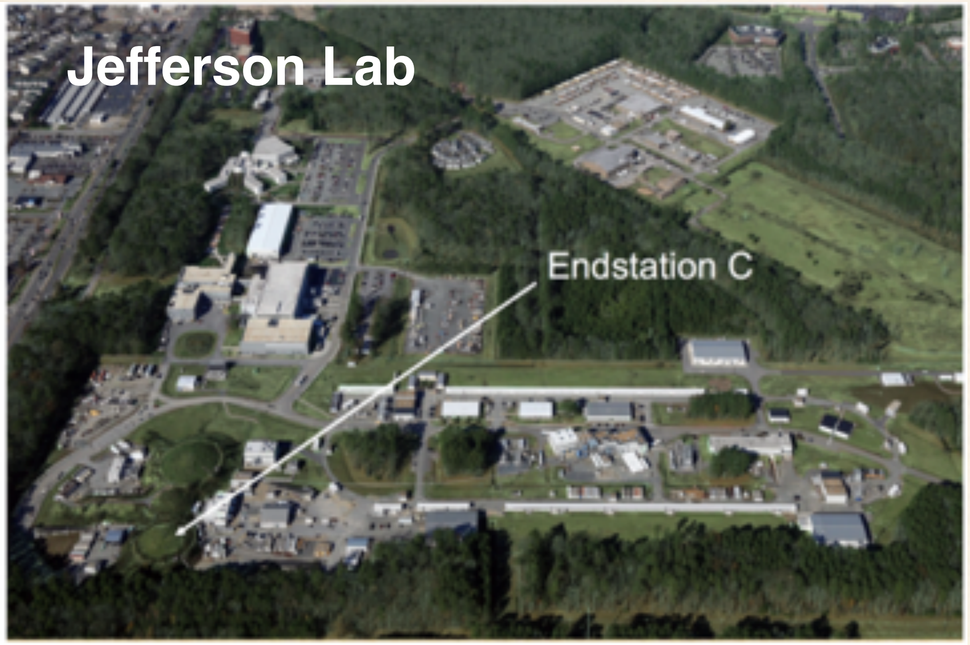
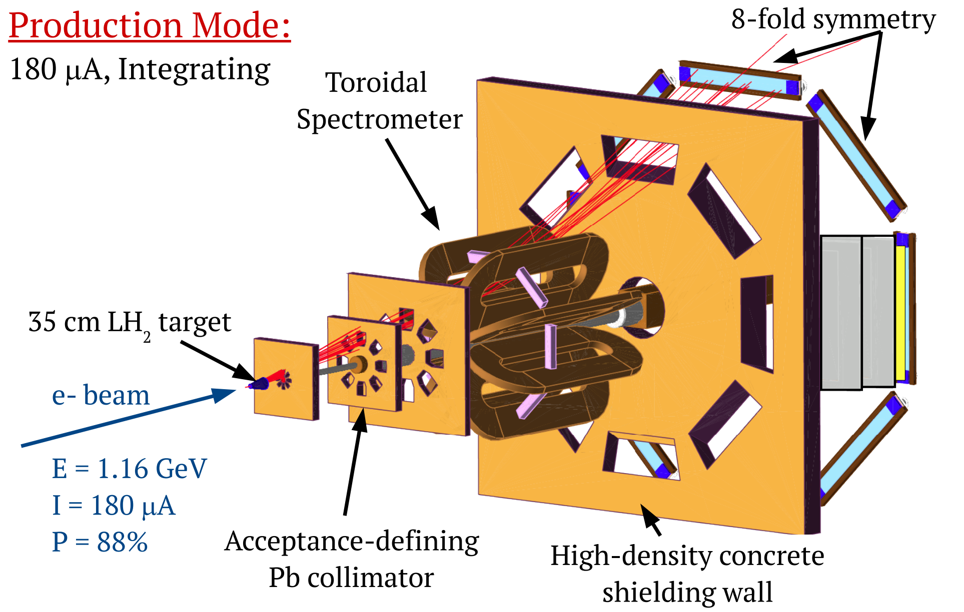
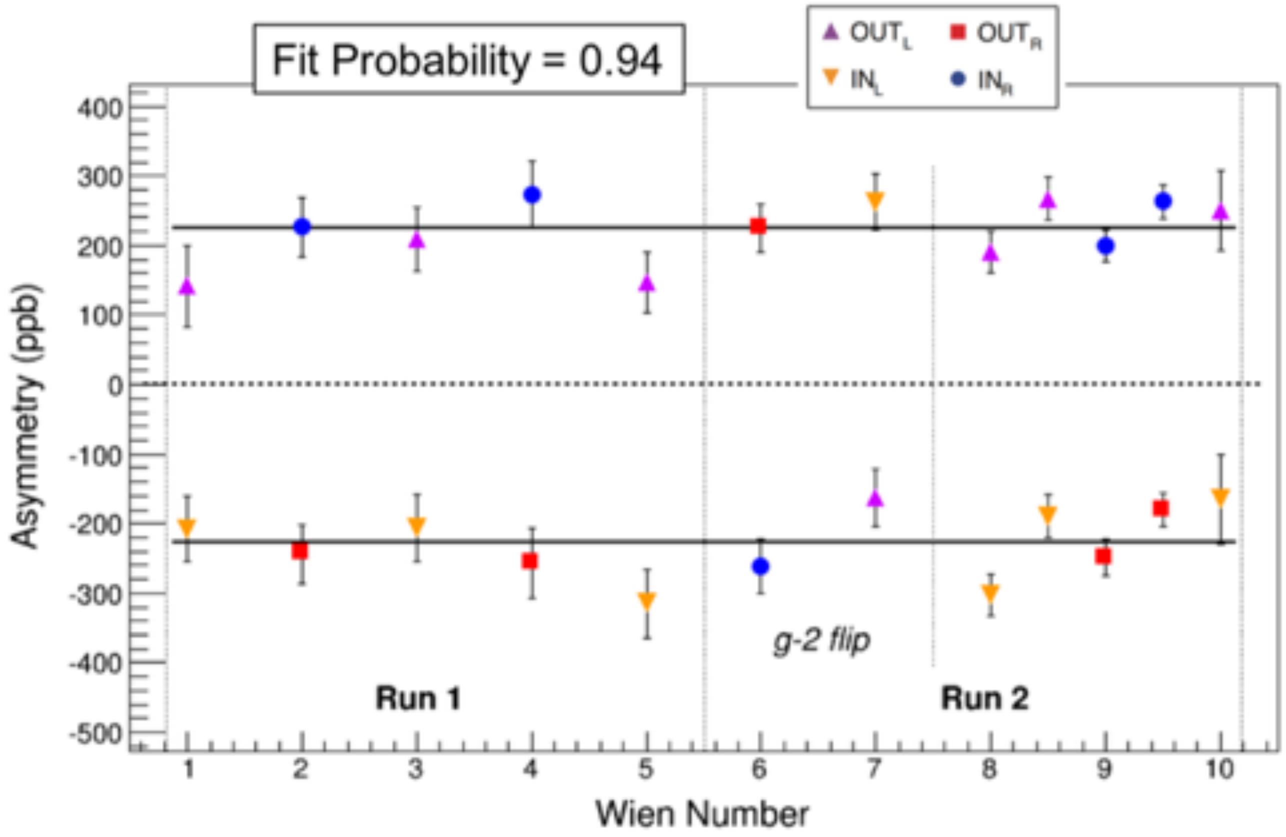






Behavior of Asymmetry under Slow Reversals

Three slow reversal types:

IN/OUT: reversal of laser helicity (IWHP)

L/R: reversal of electron beam via Wien filter

g-2 flip: reversal of electron via spin precession in accelerator

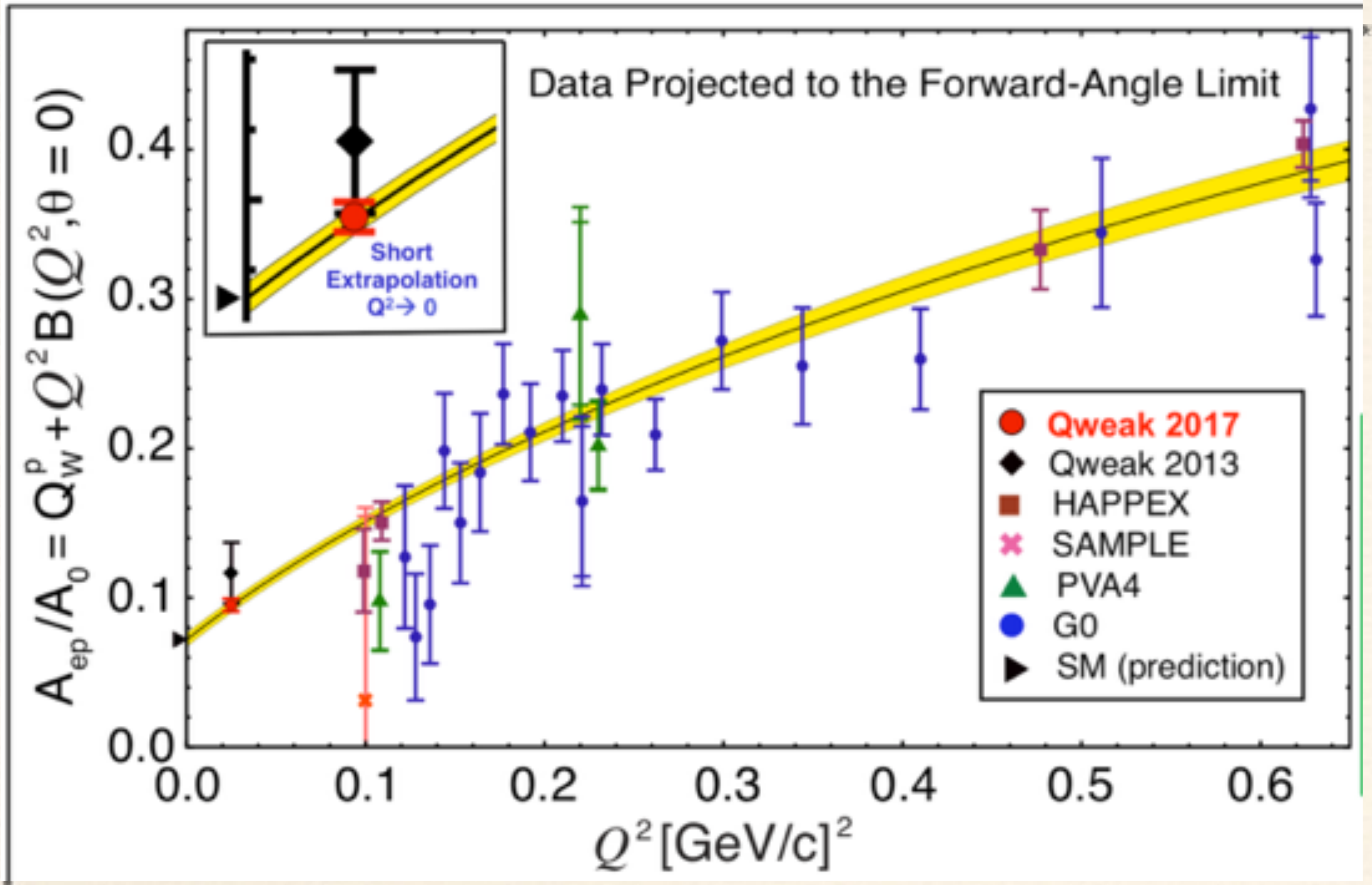
Combining the data without sign corrections gives
NULL average = -1.75 ± 6.51 ppb
- consistent with zero, as expected

$$A_{ep} = -226.5 \pm 7.3(\text{stat}) \pm 5.8(\text{syst})\ \text{ppb at } \langle Q^2 \rangle = 0.0249\ (\text{GeV}/c)^2$$

Nature 557 (2018) no.7704, 207-211

QWeak Result

SM: 0.0708 ± 0.0003



Quantity	Value	Error
Q_W^p	0.0719	0.0045
$\sin^2\theta_W$	0.2382	0.0011
ρ_s	0.19	0.11
μ_s	-0.18	0.15
$G_A^{Z(T=1)}$	-0.67	0.33

$$A_{ep} = -226.5 \pm 7.3(\text{stat}) \pm 5.8(\text{syst})\ \text{ppb at}\ \langle Q^2 \rangle = 0.0249\ (\text{GeV}/c)^2$$

Nature 557 (2018) no.7704, 207-211

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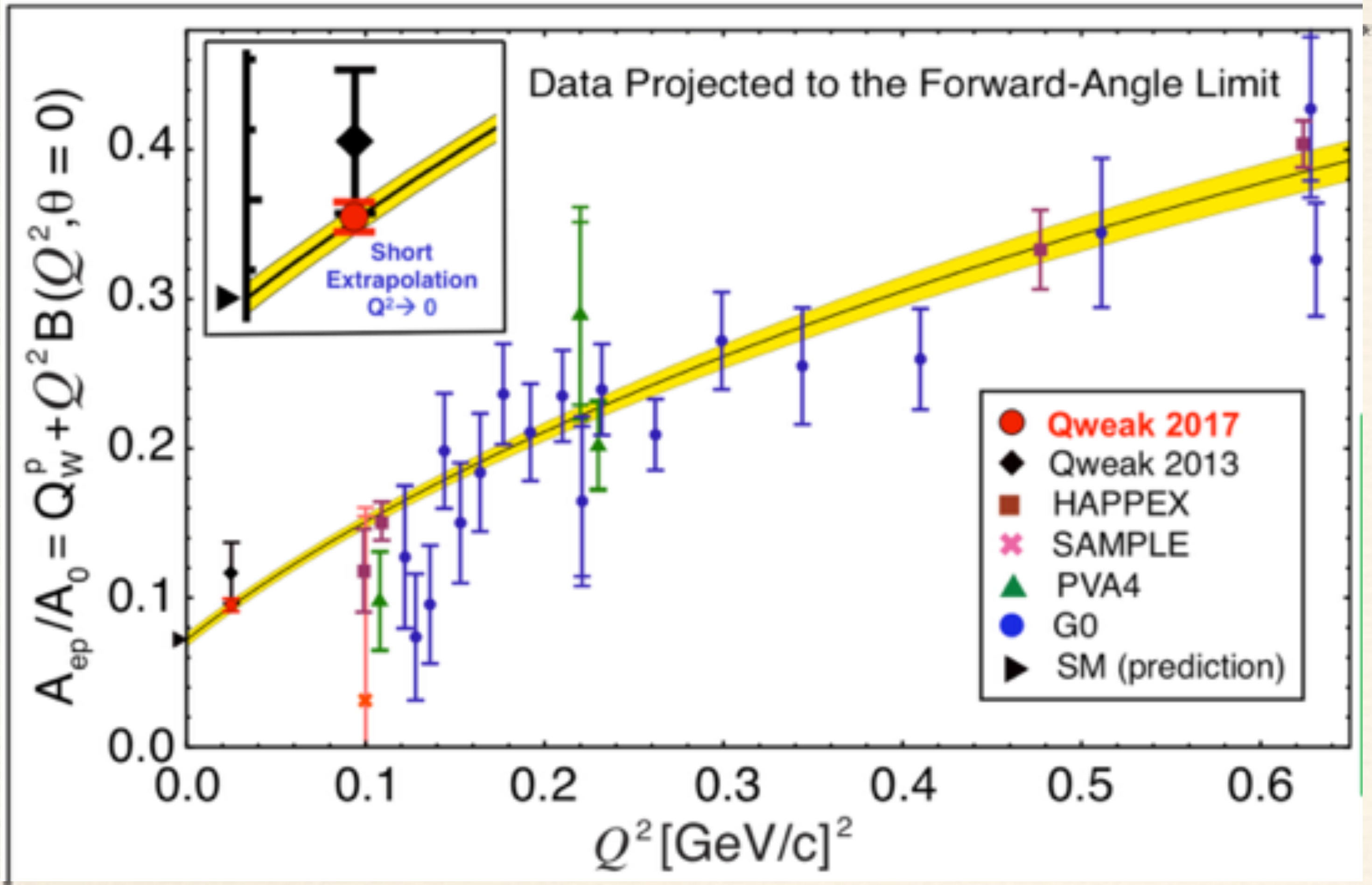

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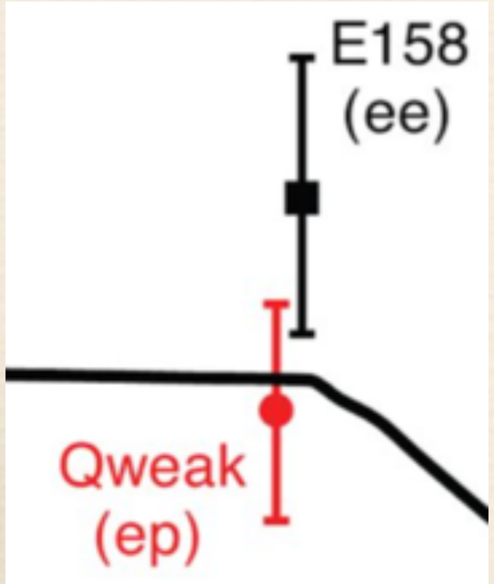
ρ_s	0.19	0.11
μ_s	-0.18	0.15
$G_A^{Z(T=1)}$	-0.67	0.33

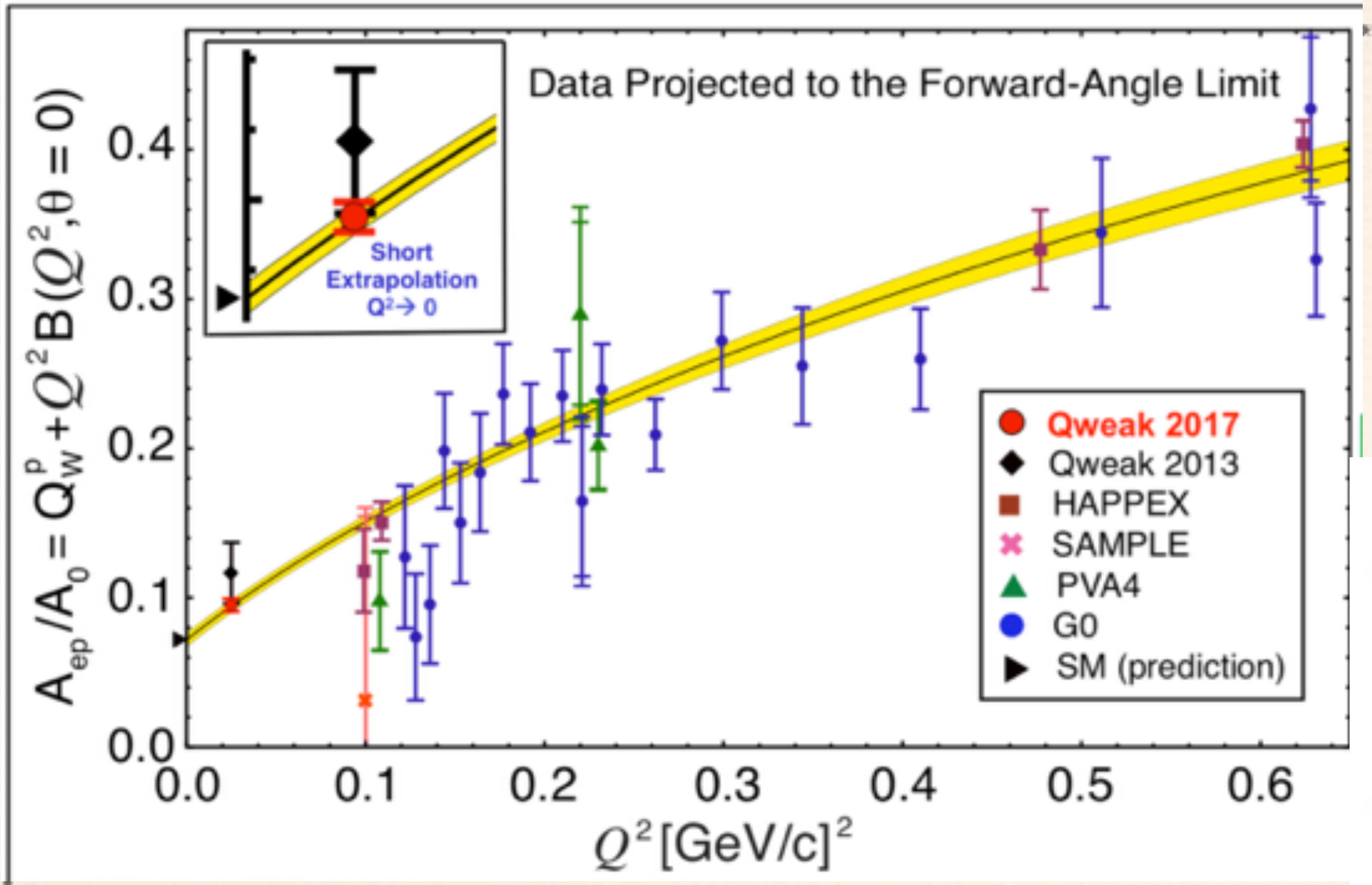


$$A_{ep} = -226.5 \pm 7.3(\text{stat}) \pm 5.8(\text{syst})\ \text{ppb at}\ \left\langle Q^2 \right\rangle = 0.0249\ (\text{GeV}/c)^2$$

Nature 557 (2018) no.7704, 207-211

QWeak Result

SM: 0.0708 ± 0.0003



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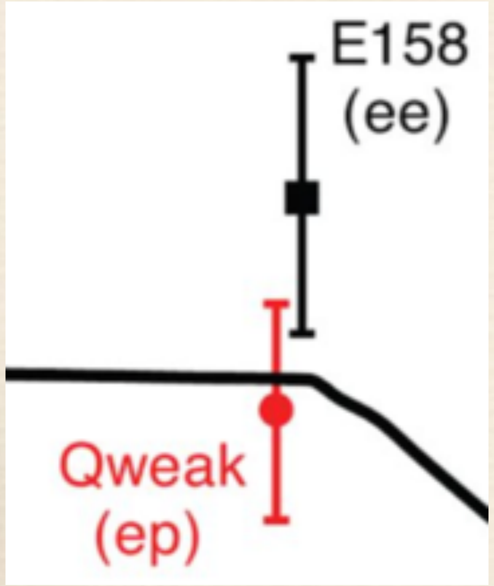

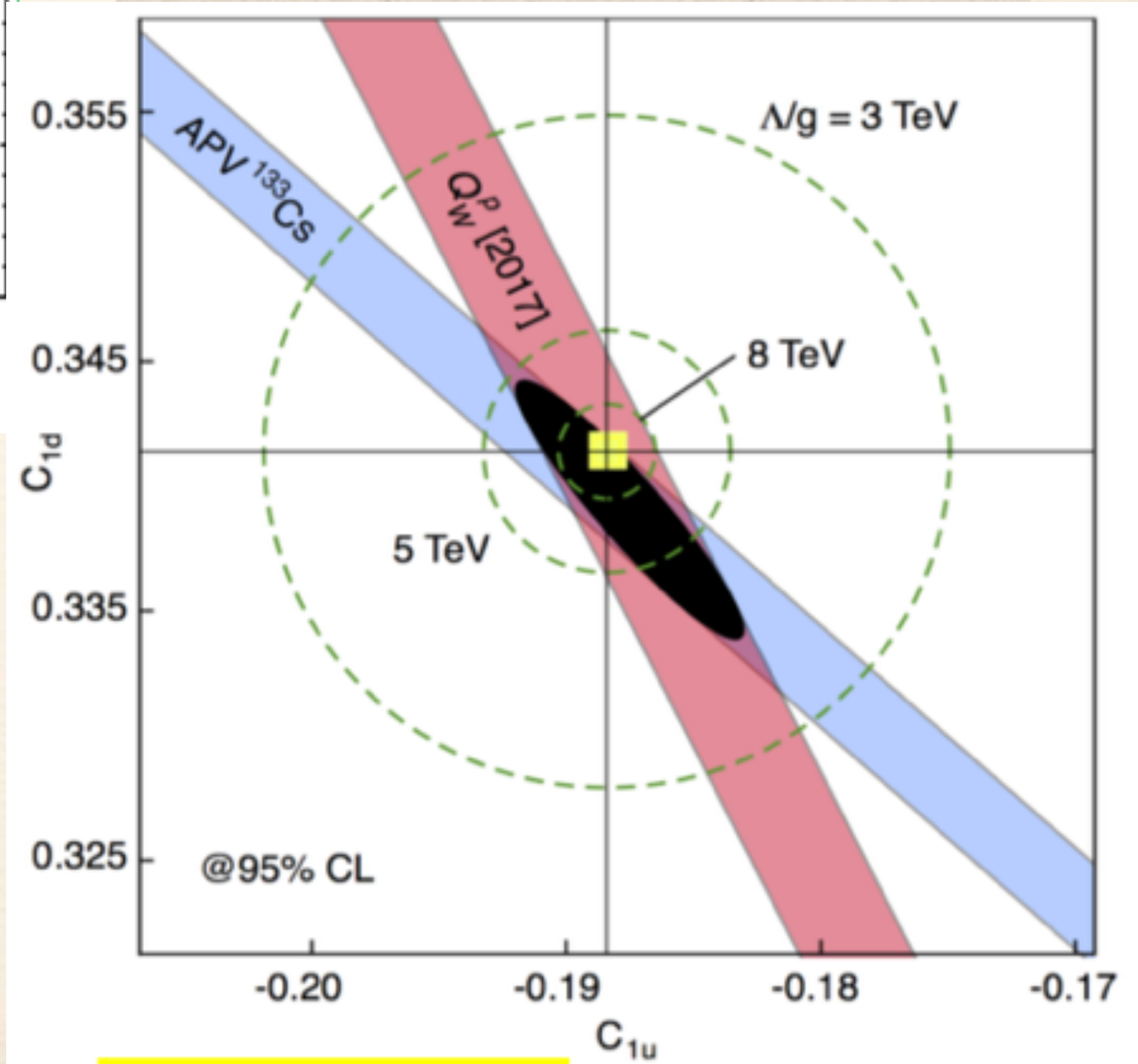

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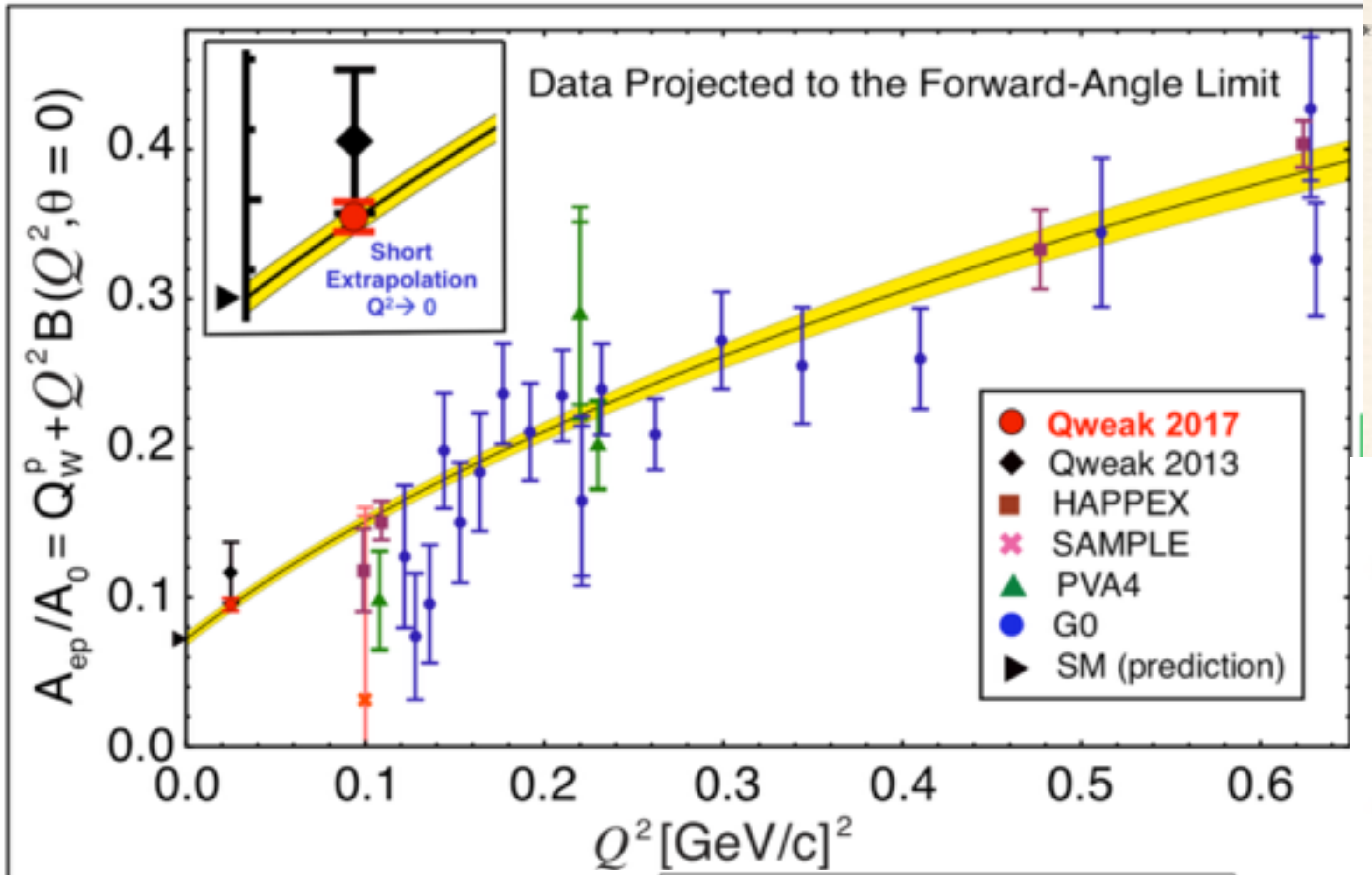

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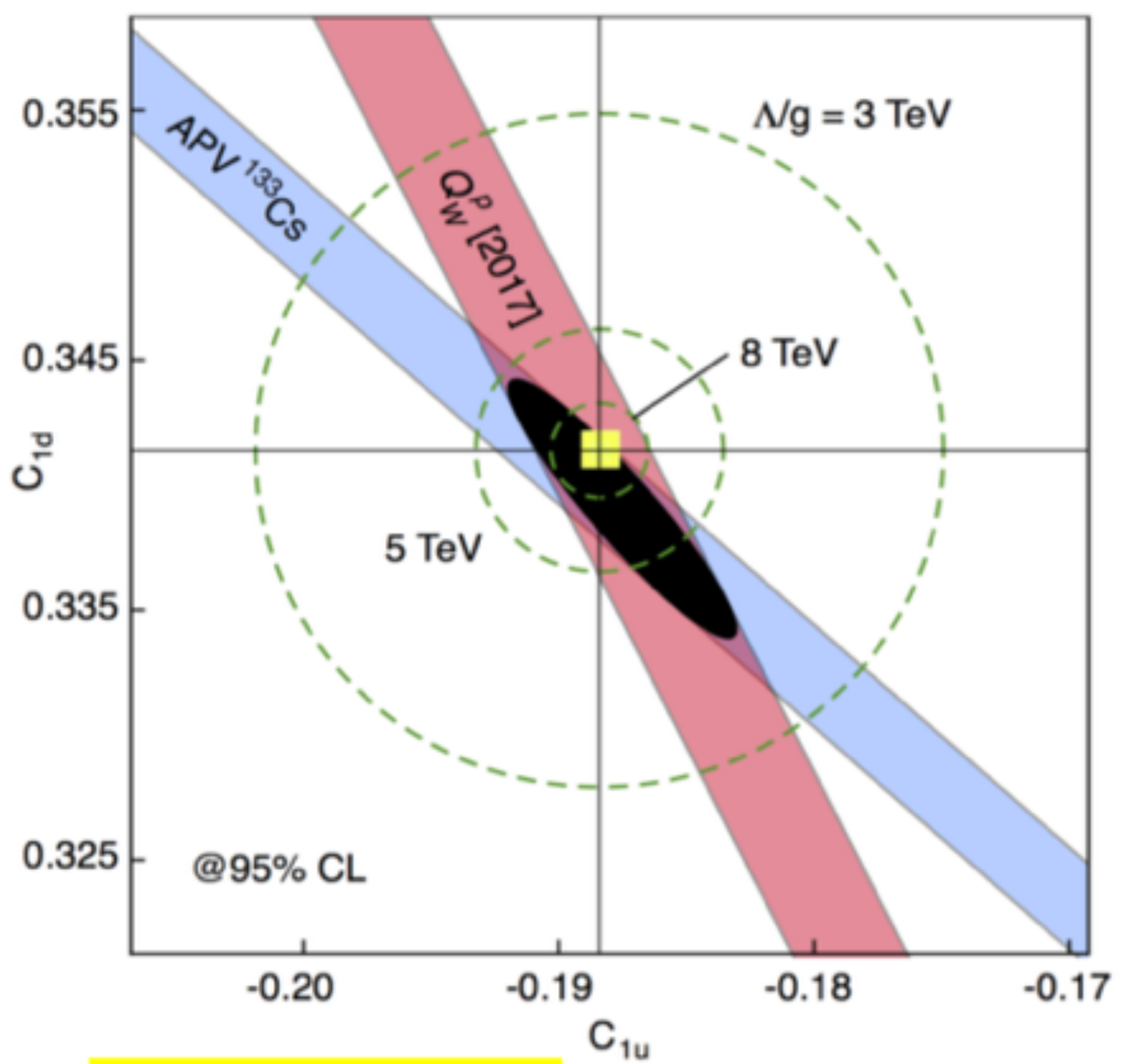
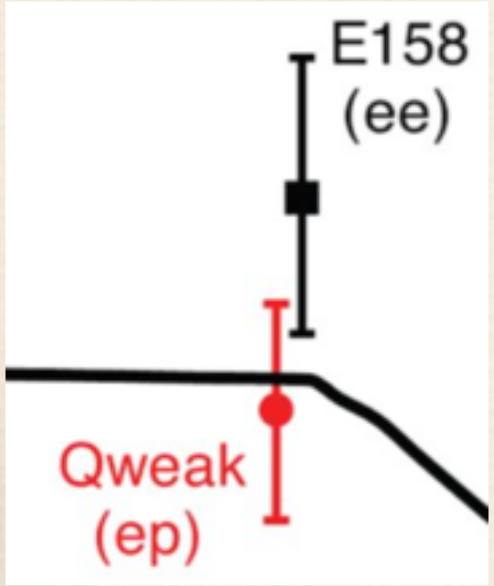
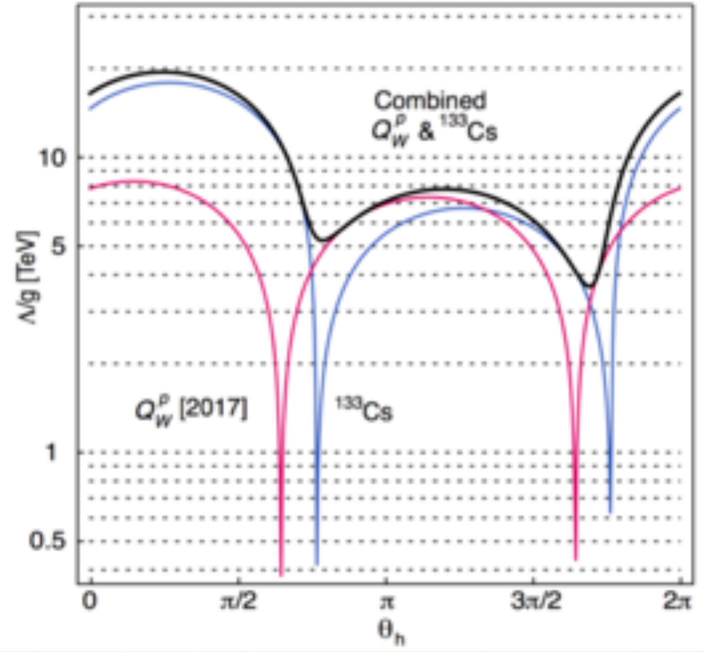


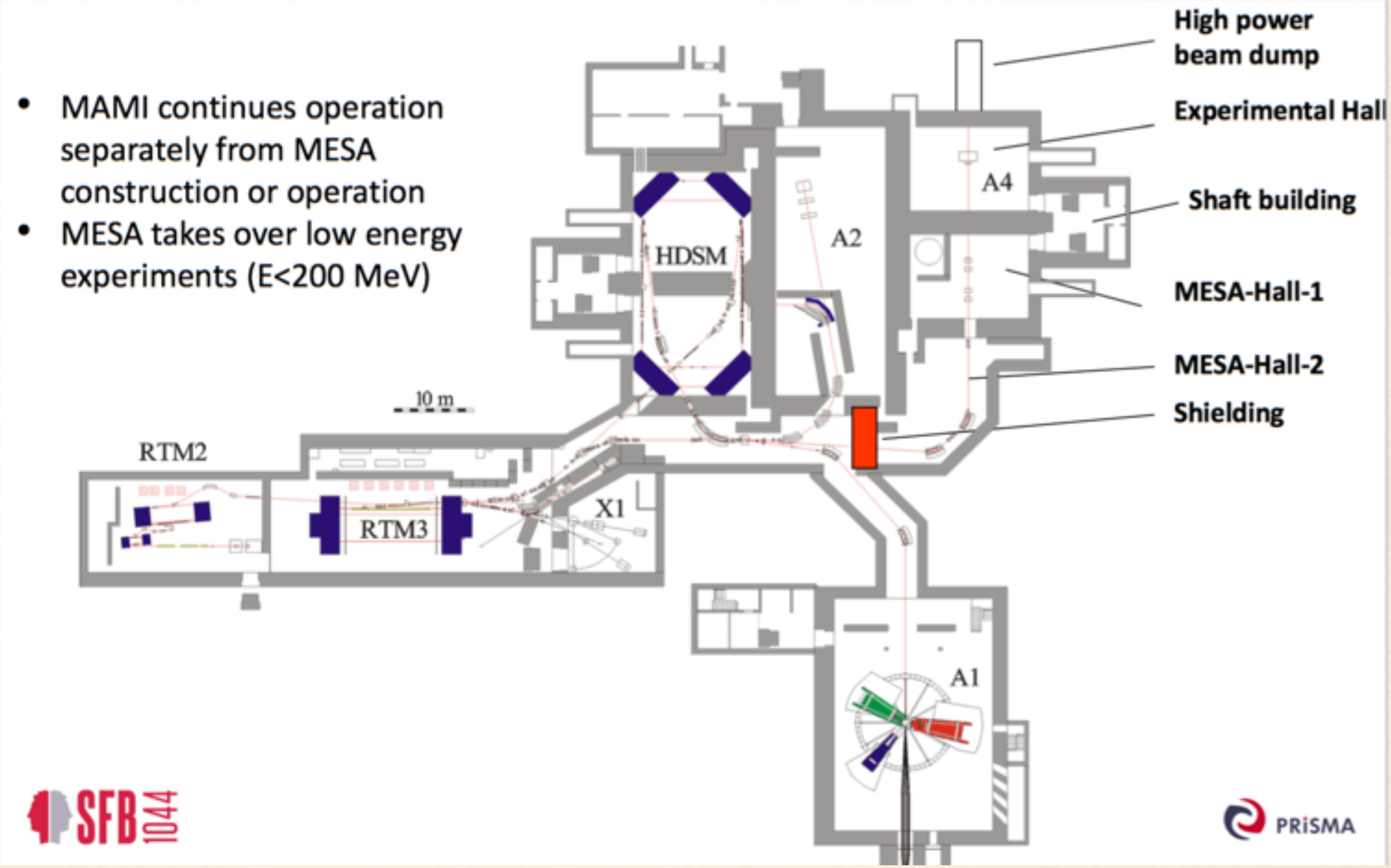




Future Prospects

Johannes Gutenberg University (JGU), Mainz, Germany

New MESA Accelerator



- MAMI continues operation separately from MESA construction or operation
- MESA takes over low energy experiments (E<200 MeV)

Johannes Gutenberg University (JGU), Mainz, Germany

New MESA Accelerator

- MAMI continues operation separately from MESA construction or operation
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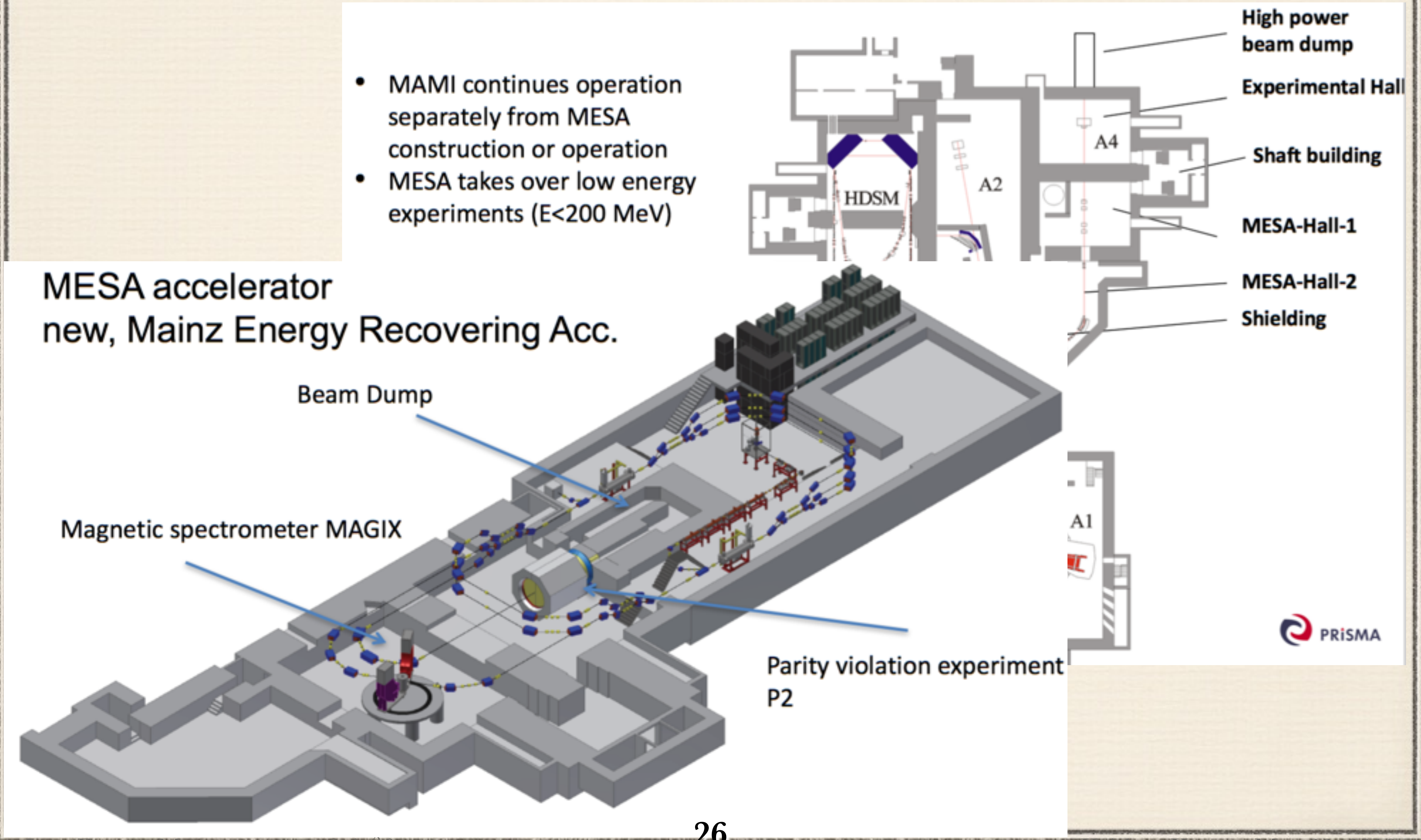
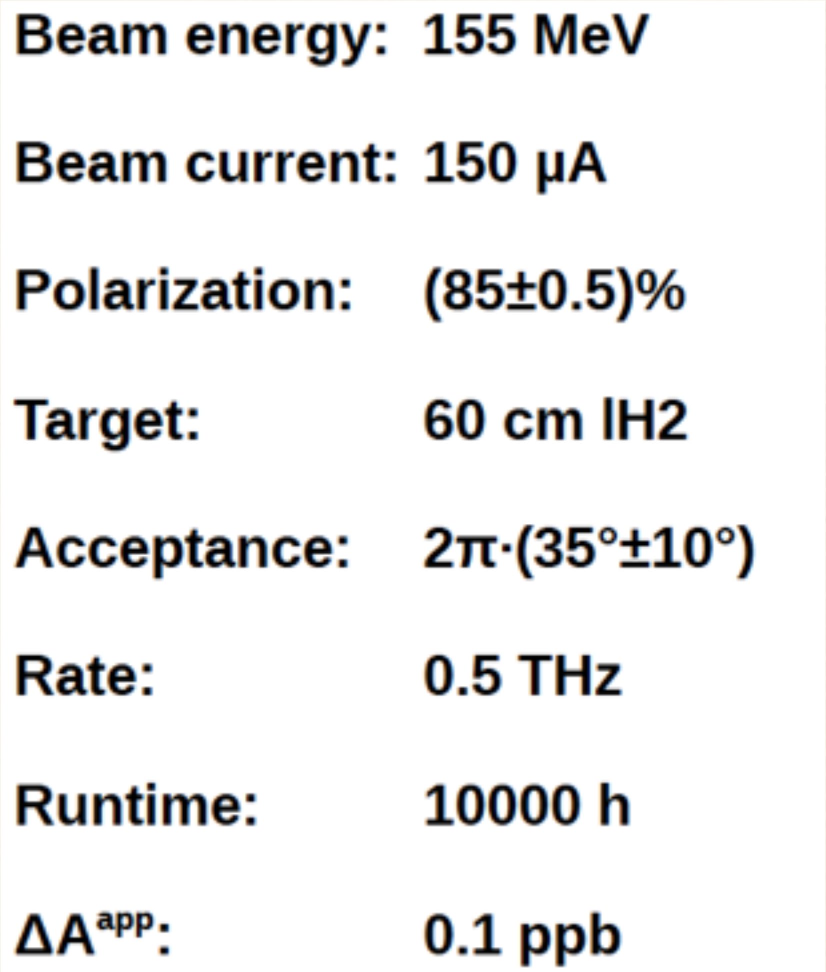
MESA accelerator
new, Mainz Energy Recovering Acc.

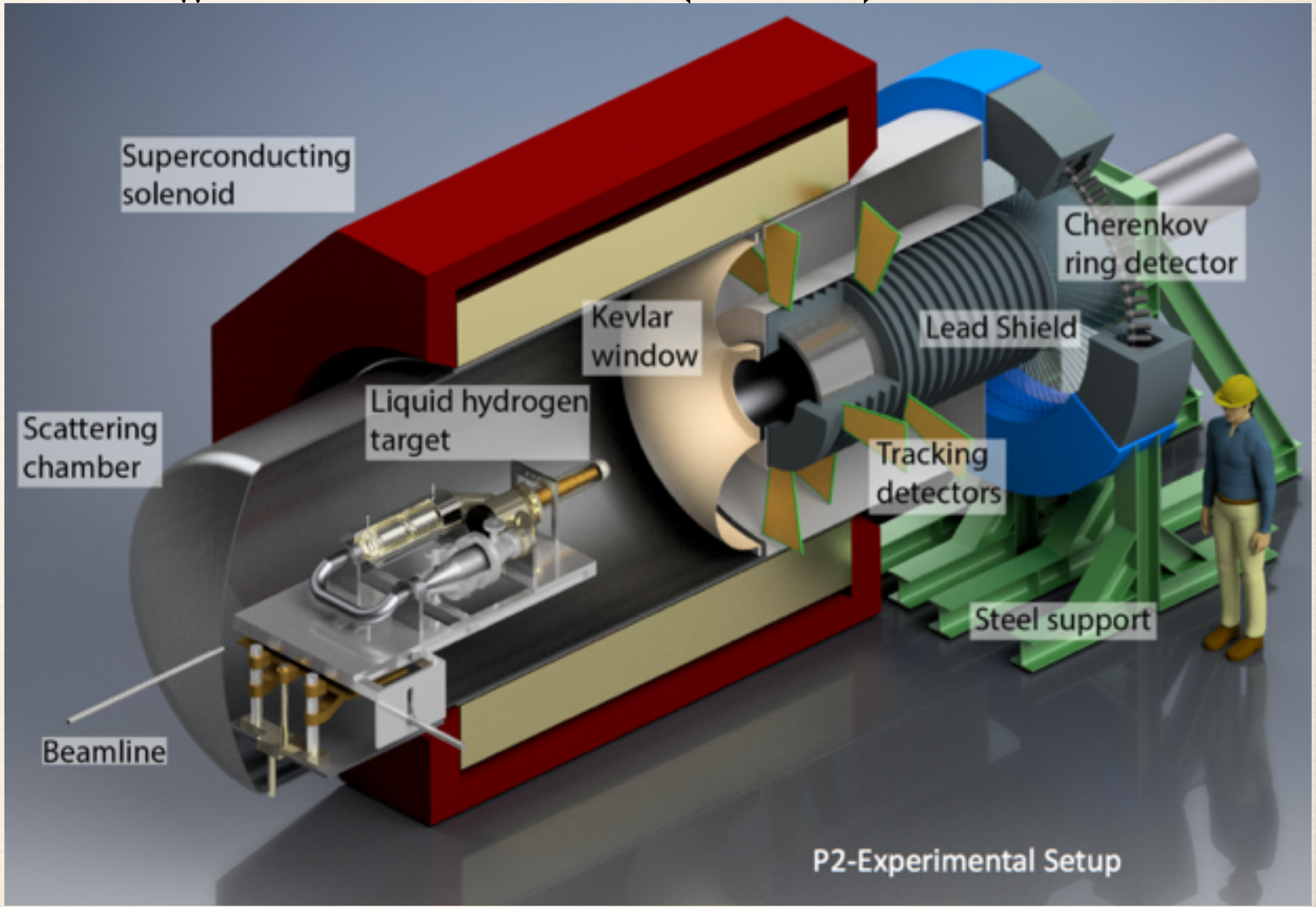


P2 at MESA, JGU Mainz



Beam energy:	**155 MeV**
Beam current:	**150 µA**
Polarization:	**(85±0.5)%**
Target:	**60 cm lH2**
Acceptance:	**2π·(35°±10°)**
Rate:	**0.5 THz**
Runtime:	**10000 h**
ΔA^{app}:	**0.1 ppb**

$\langle A^{exp} \rangle$	-39.94	ppb	
ΔA^{exp}	0.56	ppb	(1.4%)
$\langle Q^2 \rangle$	0.006	GeV^2	
$\Delta \sin^2 \theta_W$	0.00033		(0.14%)



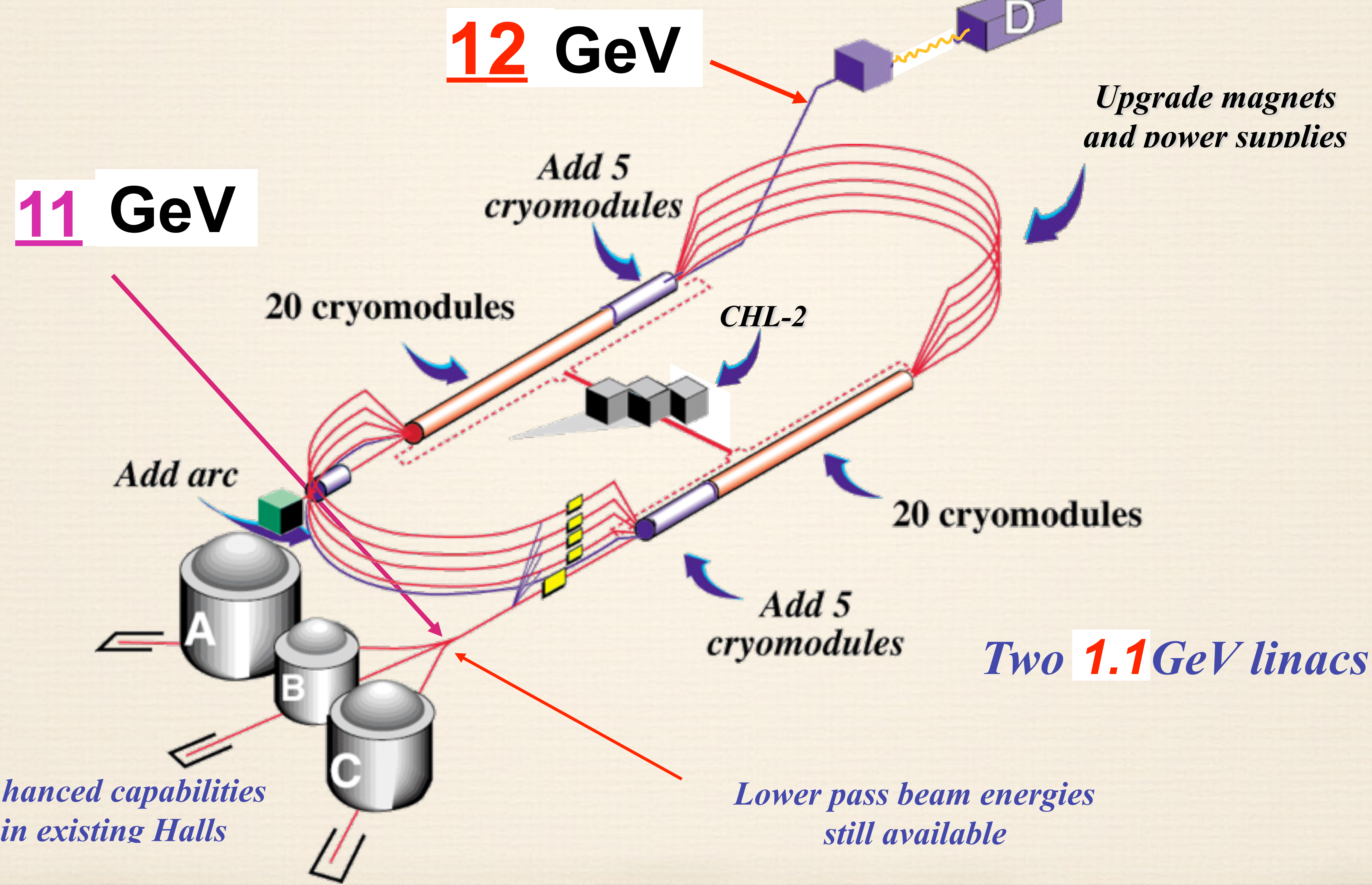
P2-Experimental Setup

My Guess!

- New MESA hall: end of 2019
- Installation: 2020
- Commissioning: 2021
- Physics in 2021/22

The 12 GeV Upgrade of JLab

4-Hall Operation fully commissioned



12 GeV

11 GeV

Upgrade magnets and power supplies

Add 5 cryomodules

20 cryomodules

CHL-2

Add arc

20 cryomodules

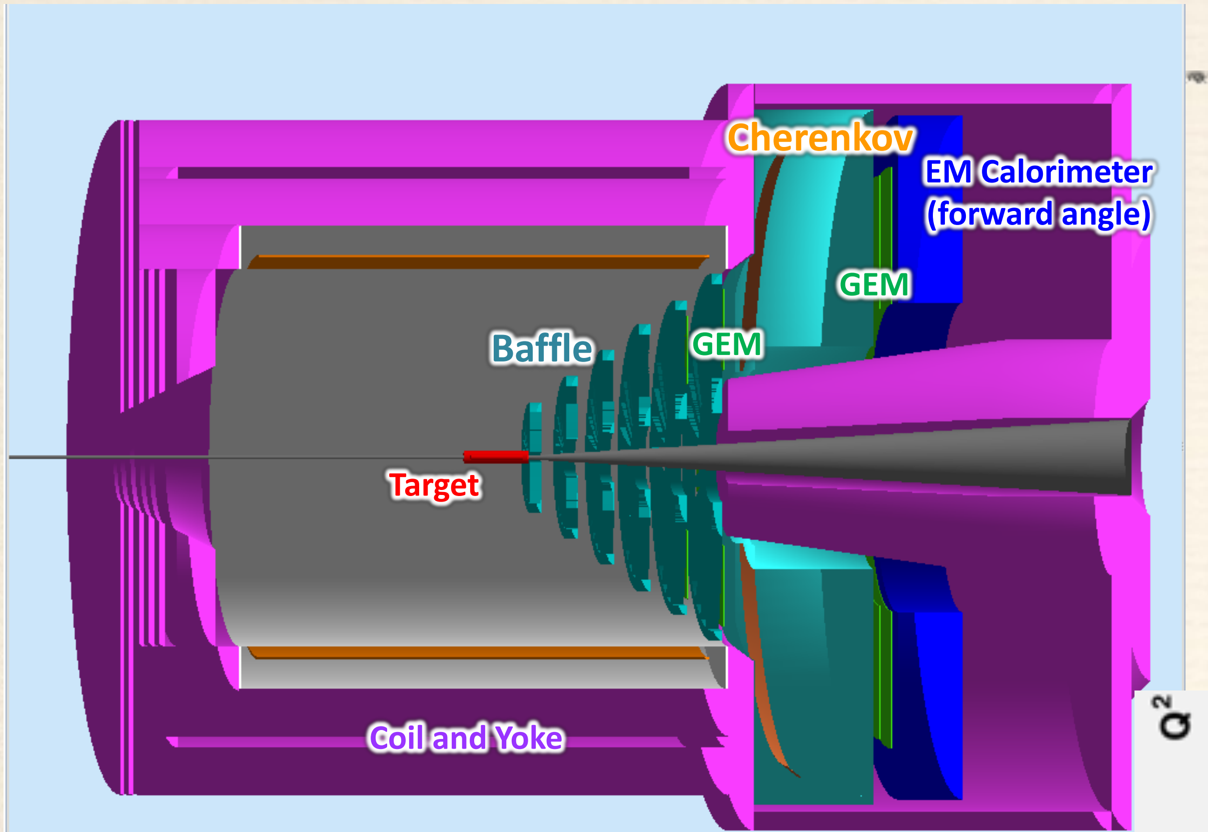
Add 5 cryomodules

Two 1.1GeV linacs

Enhanced capabilities in existing Halls

Lower pass beam energies still available

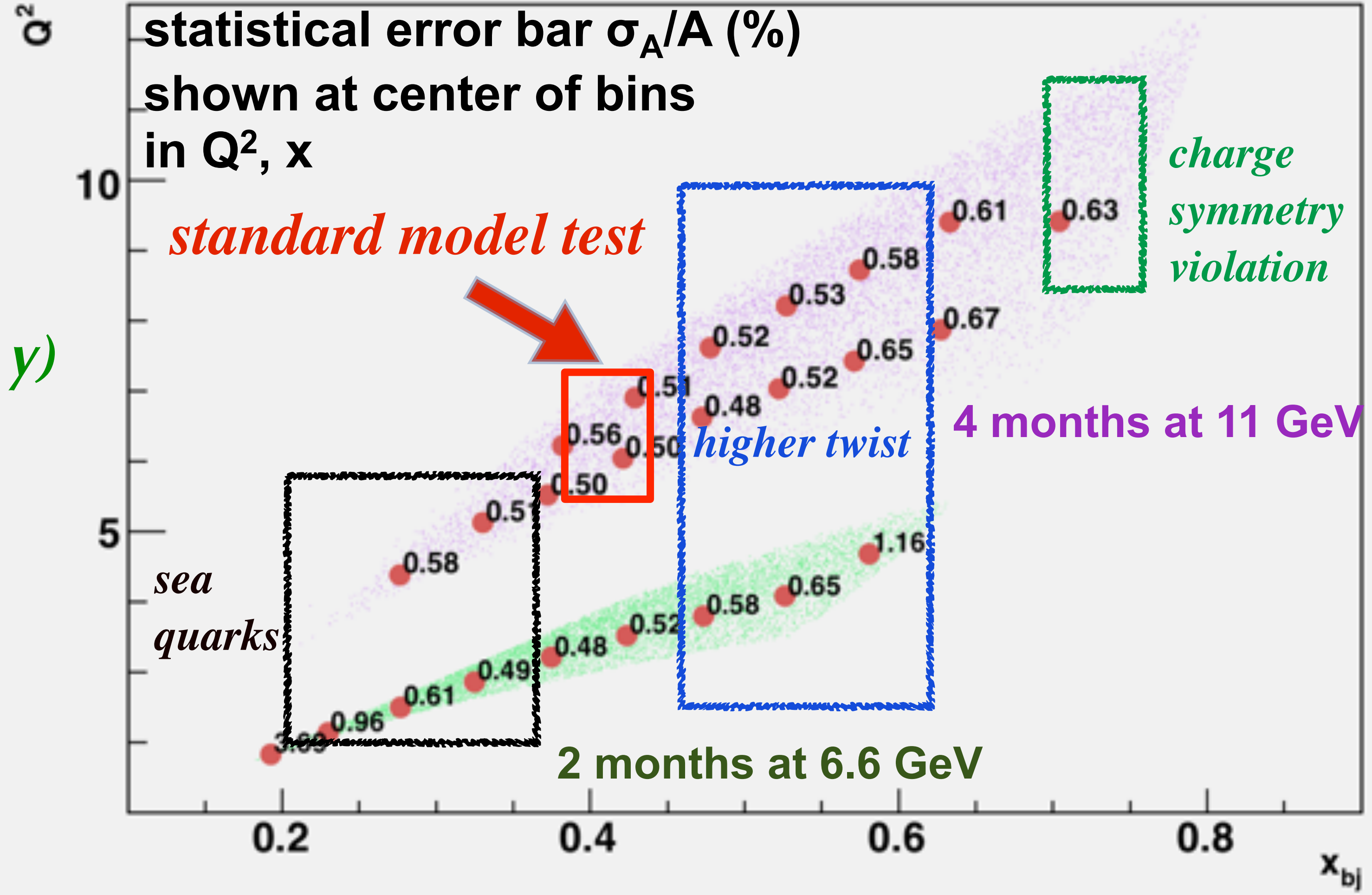
PVDIS at 12 GeV: SOLID



<u>Strategy:</u> sub-1% precision over broad kinematic range: **sensitive Standard Model test** *and* **detailed study of hadronic structure contributions**

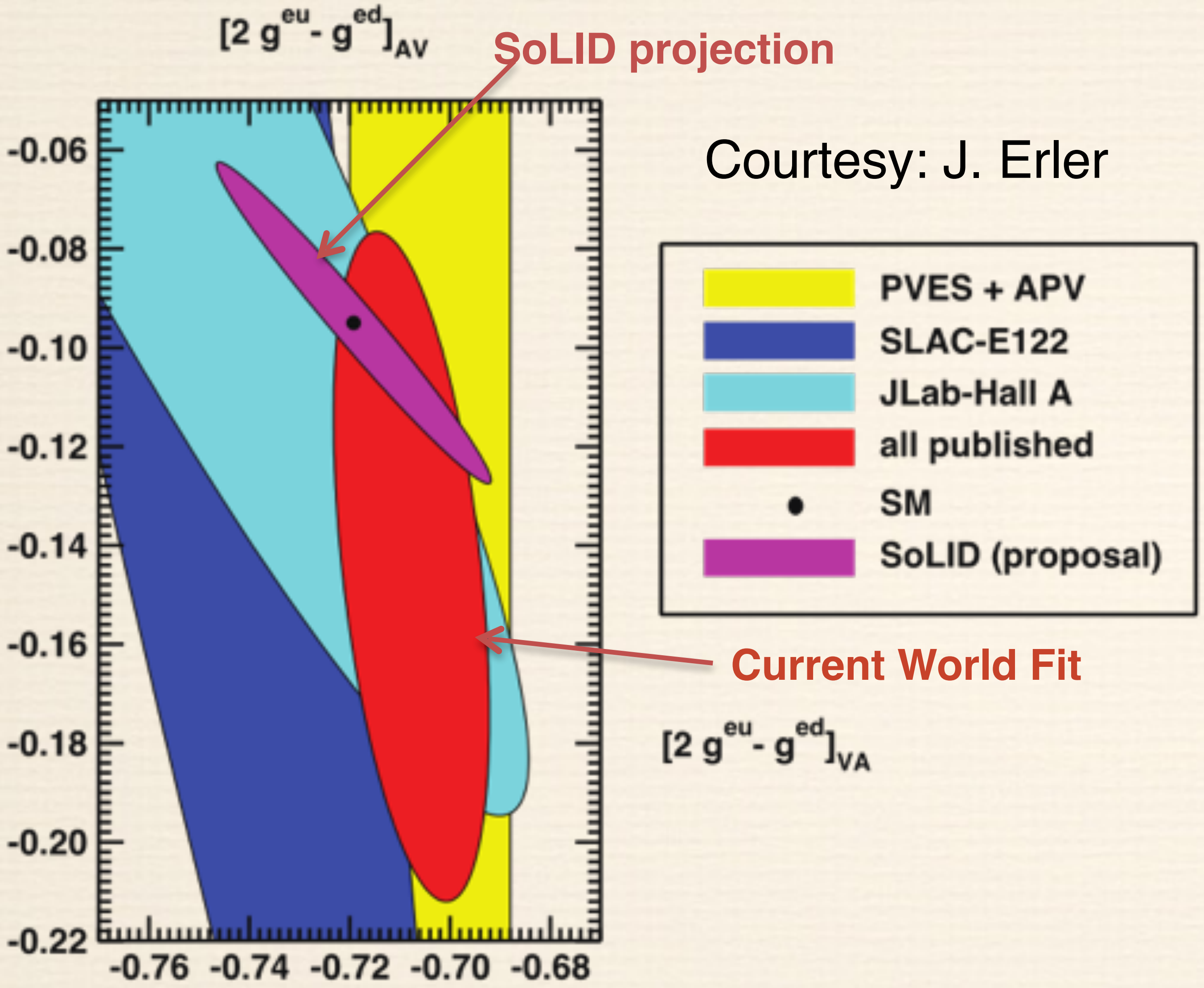
Requirements

- ***High Luminosity with E > 10 GeV***
- ***Large scattering angles (for high x & y)***
- ***Better than 1% errors for small bins***
- ***x-range 0.25-0.75***
- ***W^2 > 4 GeV^2***
- ***Q^2 range a factor of 2 for each x***
  - (Except at very high x)
- ***Moderate running times***



statistical error bar σ_A/A (%) shown at center of bins in Q^2, x

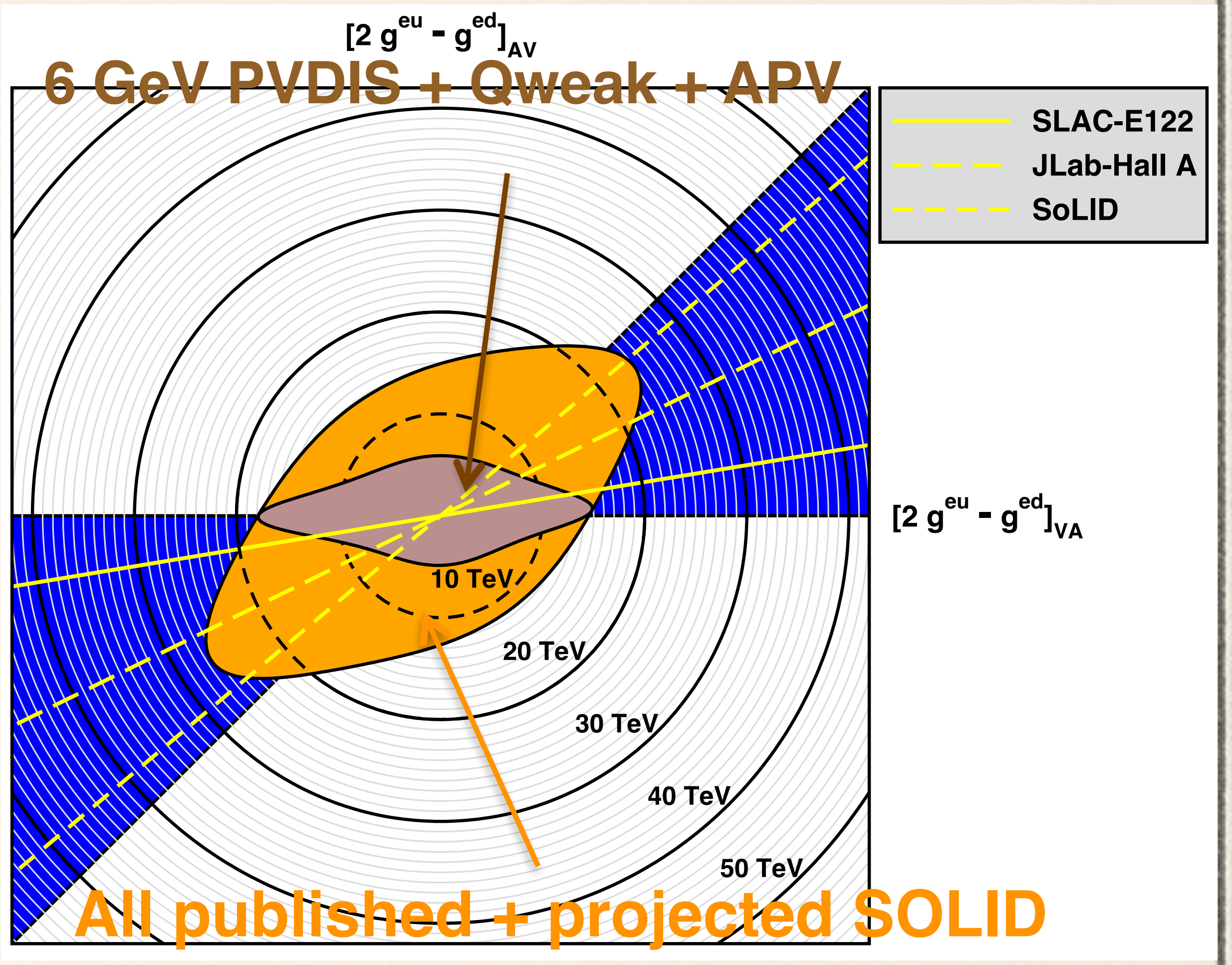
SoLID New Physics Sensitivity



SoLID projection

Current World Fit

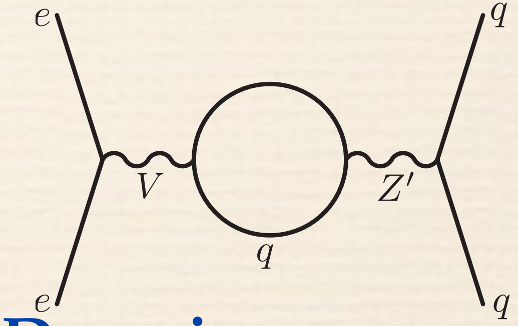
Courtesy: J. Erler



6 GeV PVDIS + Qweak + APV

All published + projected SOLID

Leptophobic Z'



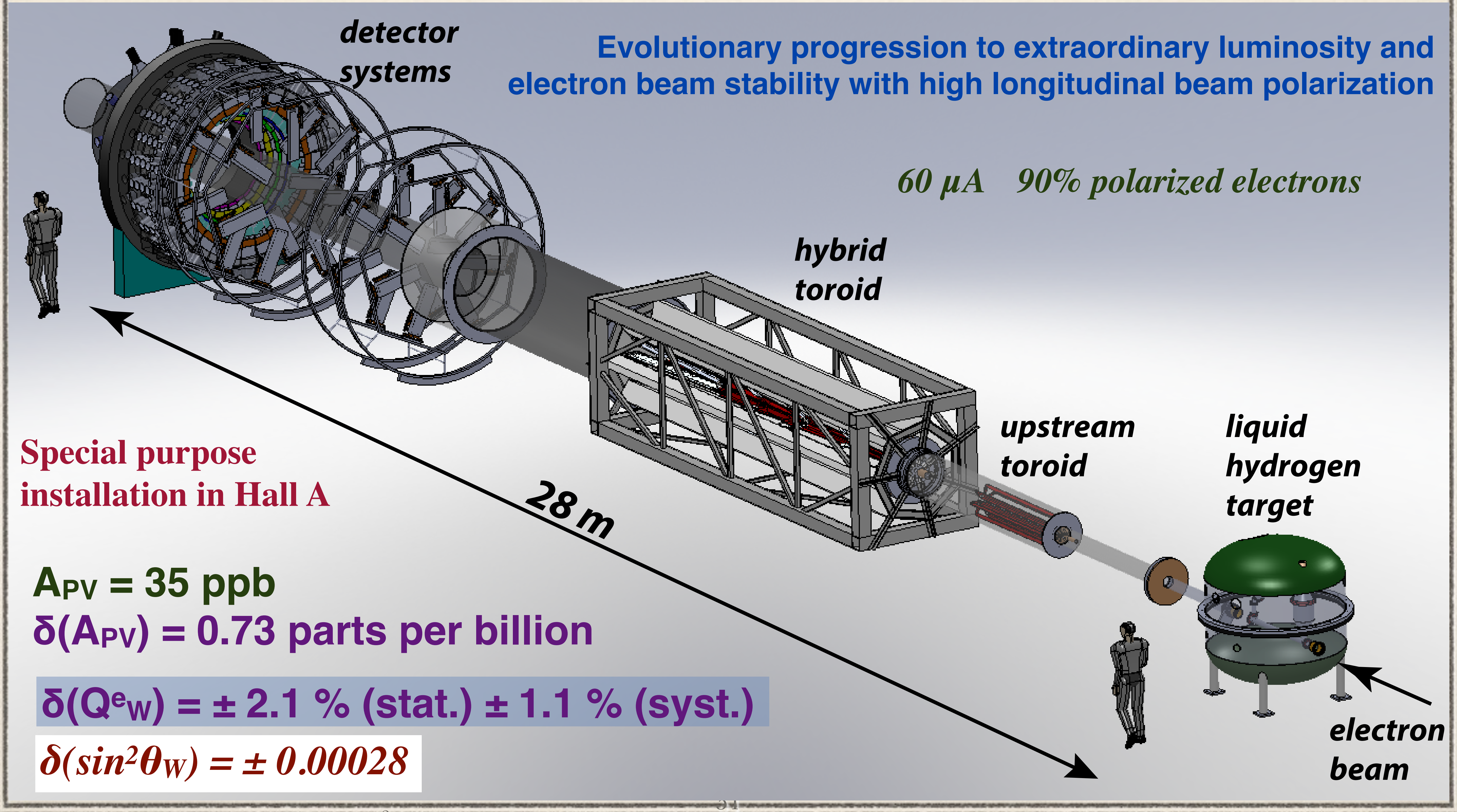
Qweak, P2 and SOLID will expand sensitivity that will match high luminosity LHC reach with complementary chiral and flavor combinations

SOLID can improve sensitivity: 100-200 GeV range

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

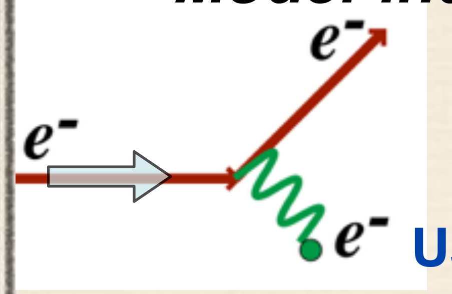
A_{PV} = 35 ppb

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

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

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

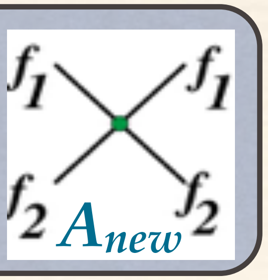
Model-independent Picture of 4-Fermion Flavor Diagonal Contact Interactions



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

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

no interference term!

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

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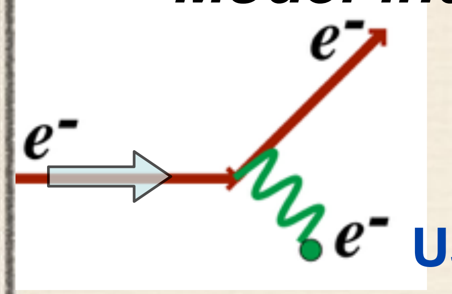

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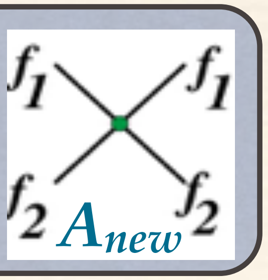

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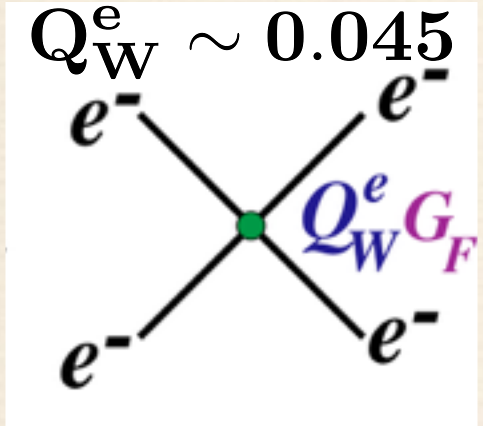
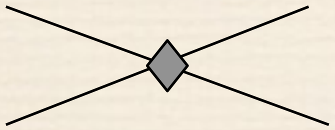


$$\frac{\delta Q_W^e}{Q_W^e} = 2.4\%$$

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

unprecedented sensitivity!

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

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

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

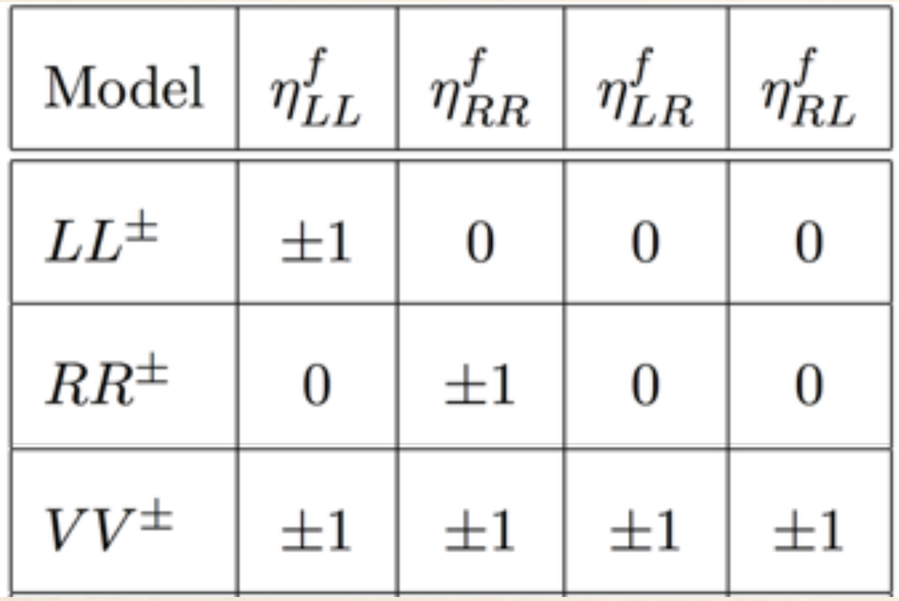
95% C. L. Reach

Comparison with e^+e^- Collisions

Best reach on purely leptonic contact interaction amplitudes: LEP200

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

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



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

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

MOLLER Reach $\Lambda^{\mathrm{ee}}_{\mathrm{LL}} \sim \mathbf{27}$ 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 $Q^2 << M_Z^2$

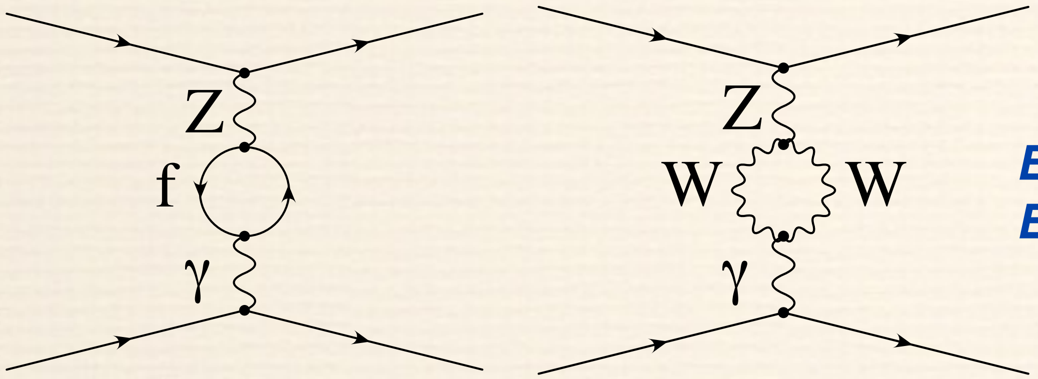
Electroweak Theory

EW Theory Prediction Uncertainty Well Below Projected Experimental Uncertainty

Czarnecki and Marciano (1995)

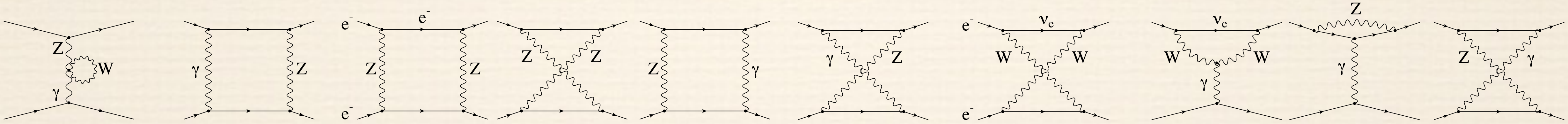
$$A_{PV}(ee) \propto \rho G_F \left[1 - 4\kappa(0)\sin^2\theta_W(m_Z)_{\overline{\mathrm{MS}}}\right] + \cdots$$

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**

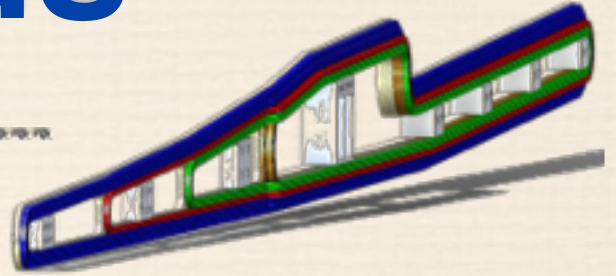
MOLLER **$\delta(Q^e_W)$ goal = ± 2.1 % (stat.) ± 1.1 % (syst.)**

MOLLER Apparatus

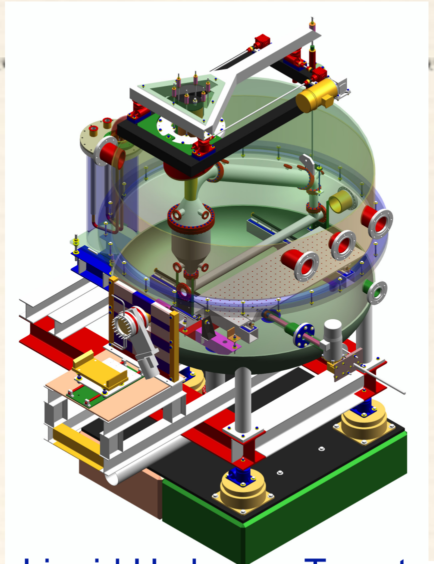
Technical Challenges

Evolutionary Improvements from Technology of Third Generation Experiments

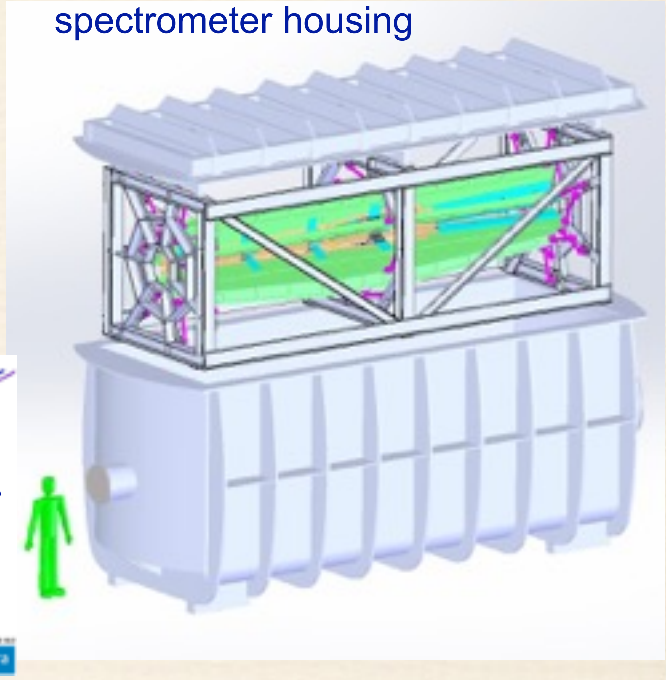
- **~ 150 GHz scattered electron rate**
- **1 nm control of beam centroid on target**
- **> 10 gm/cm² liquid hydrogen target**
  - **1.5 m: ~ 5 kW @ 85 μA**
- **Full Azimuthal acceptance w/ θ_{lab} ~ 5 mrad**
  - **novel toroidal spectrometer pair**
  - **radiation hard, highly segmented integrating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



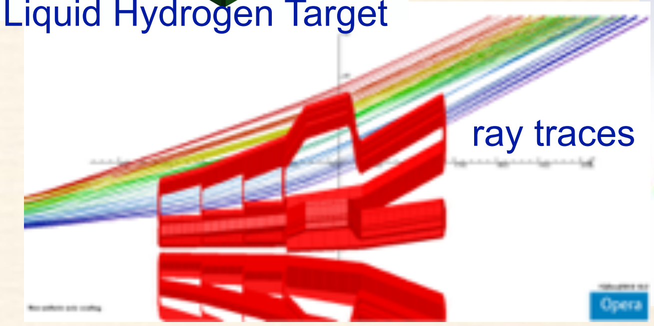
hybrid spectrometer coil



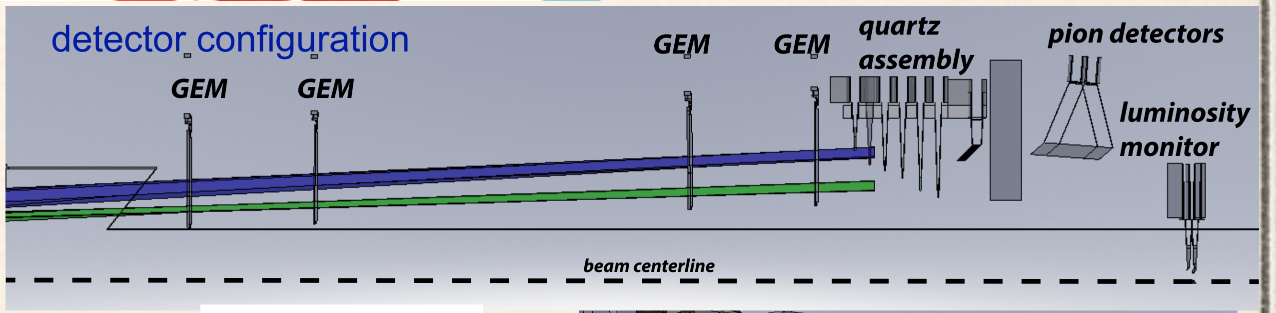
Liquid Hydrogen Target



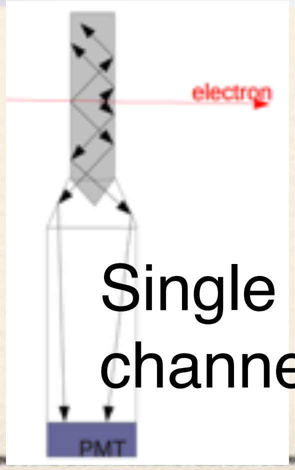
spectrometer housing



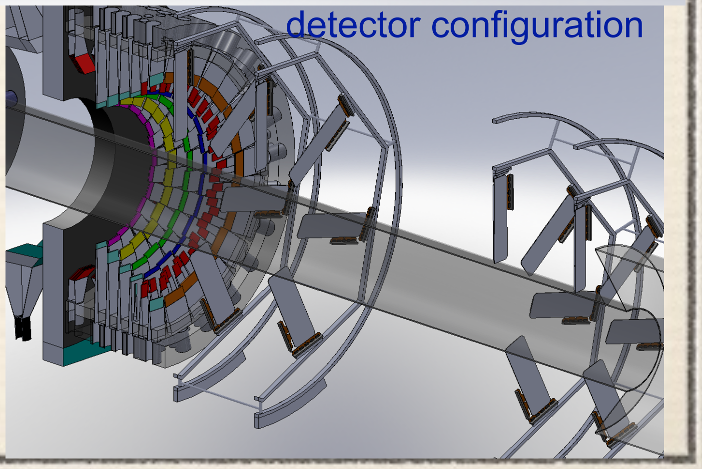
ray traces



detector configuration



Single channel



detector configuration

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

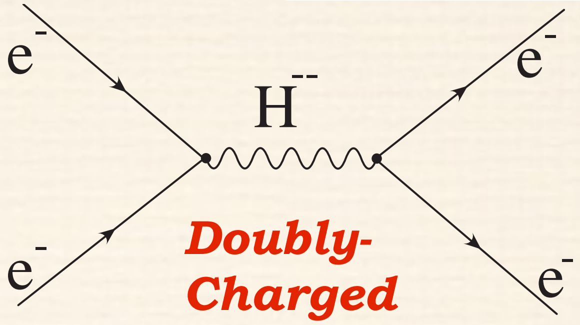
Unique Opportunity: Purely Leptonic Reaction at $Q^2 << M_Z^2$

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

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

5 σ for h_{ee} ~ 1 and M_Δ ~ 1 TeV

V. Cirigliano et al, PRD **70** (2004) 075007

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

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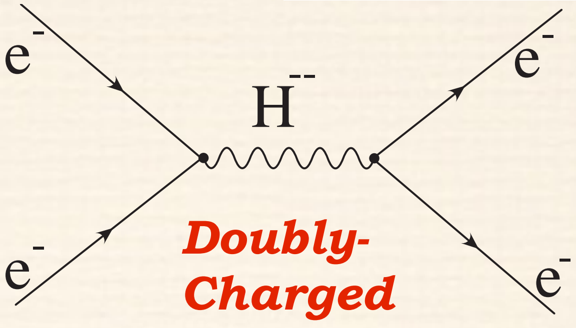

Doubly-Charged Scalar

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

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

V. Cirigliano et al, PRD **70** (2004) 075007

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 $Q^2 \ll M_Z^2$

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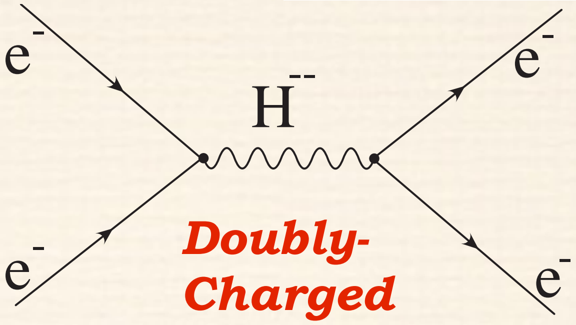

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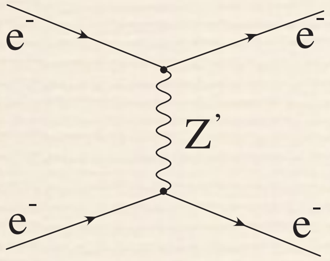
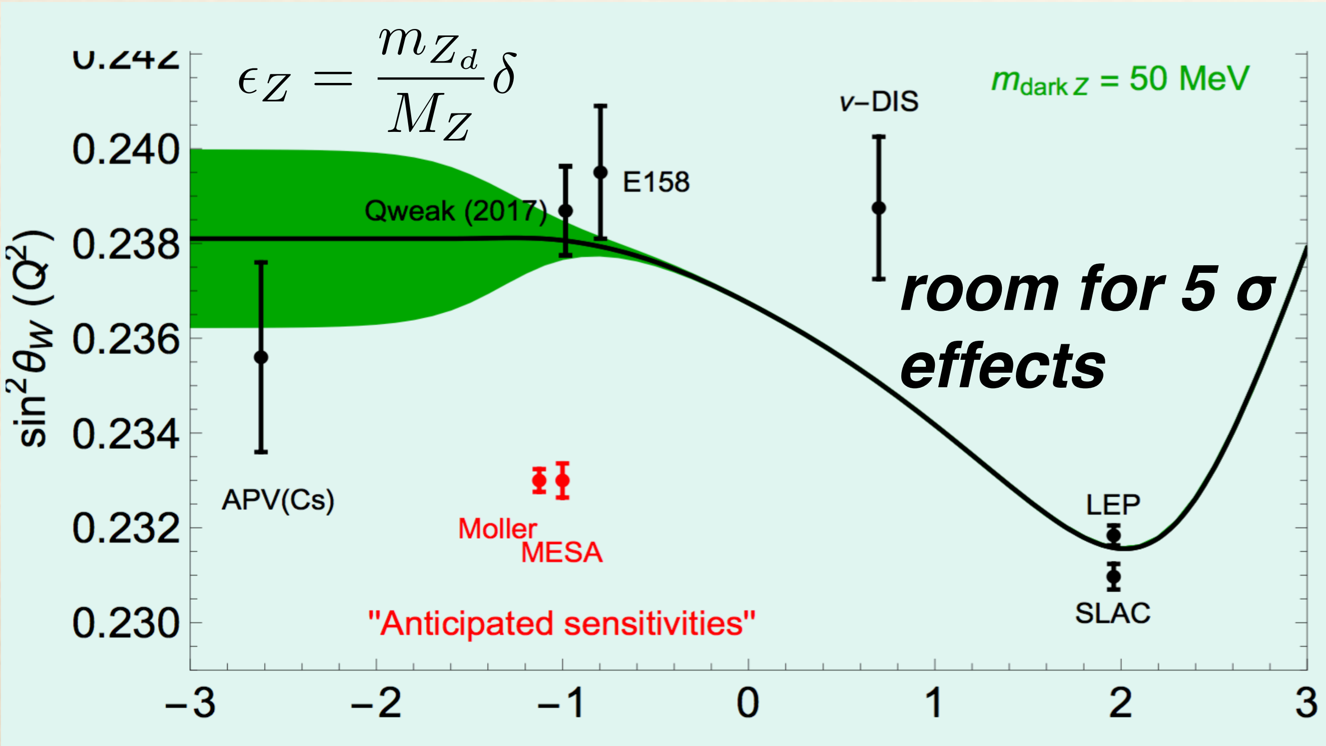


Heavy Photons (A' mixed with Z_0): The Dark Z

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

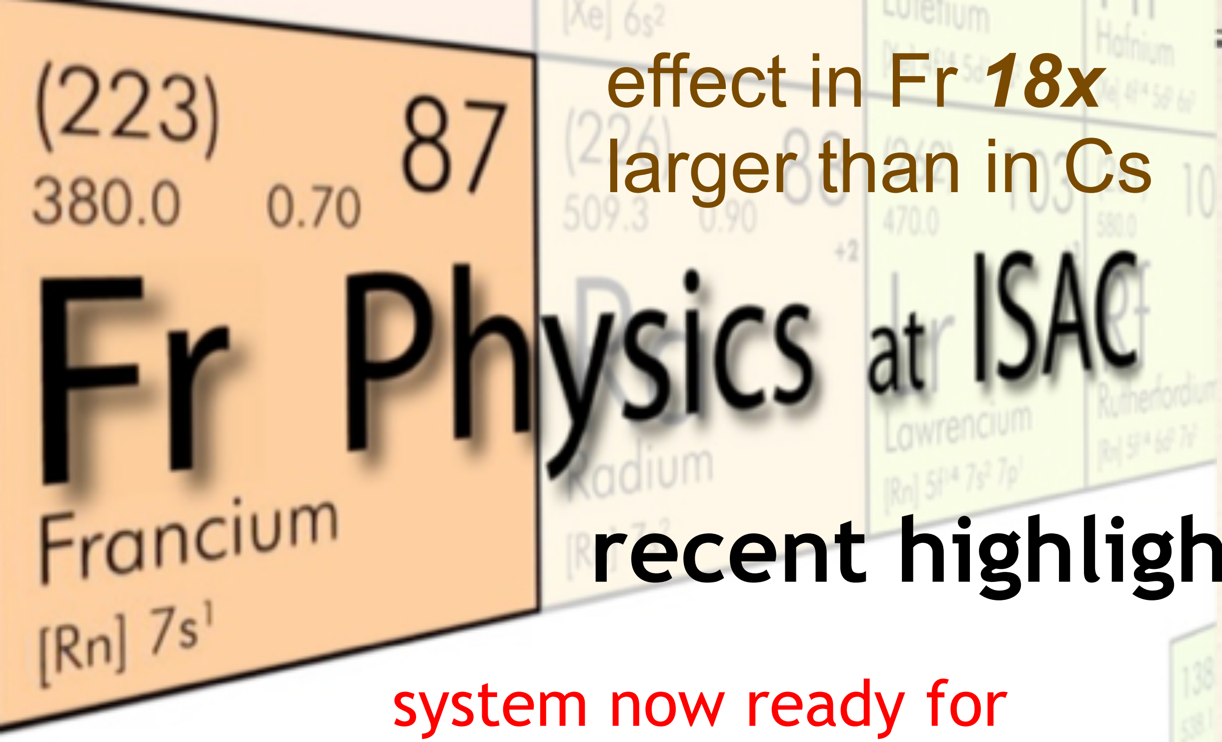


room for 5 σ effects

Constraining Lorentz Invariance

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

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

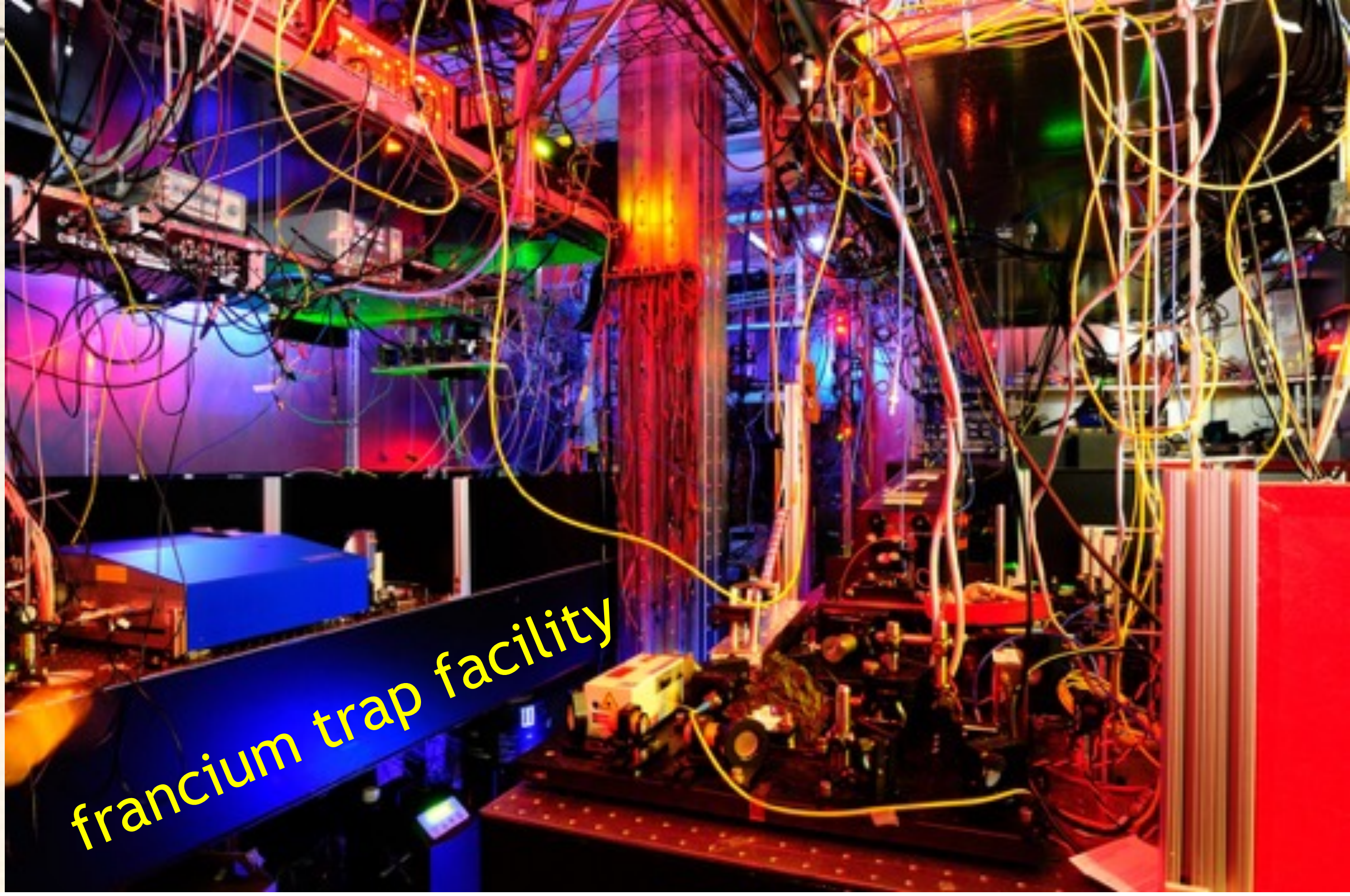


Fr Physics at ISAC

effect in Fr ***18x*** larger than in Cs

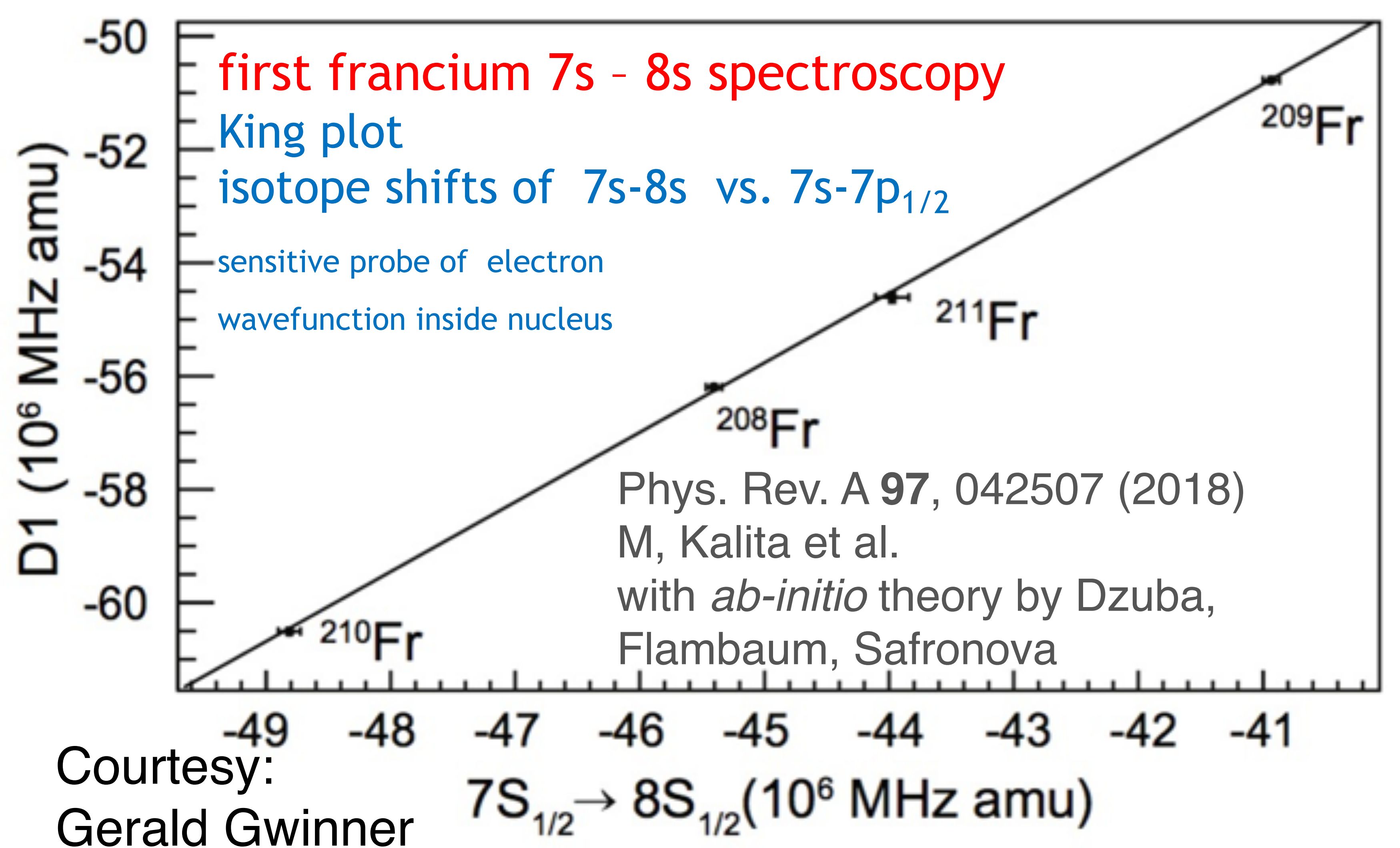
recent highlights

system now ready for
7s-8s spectroscopy campaign
towards APNC



francium trap facility

built ultra-stable (10^{-10} level)
reference cavity for 7s-8s spectr.



first francium 7s – 8s spectroscopy

King plot

isotope shifts of 7s-8s vs. 7s-$7p_{1/2}$

sensitive probe of electron
wavefunction inside nucleus

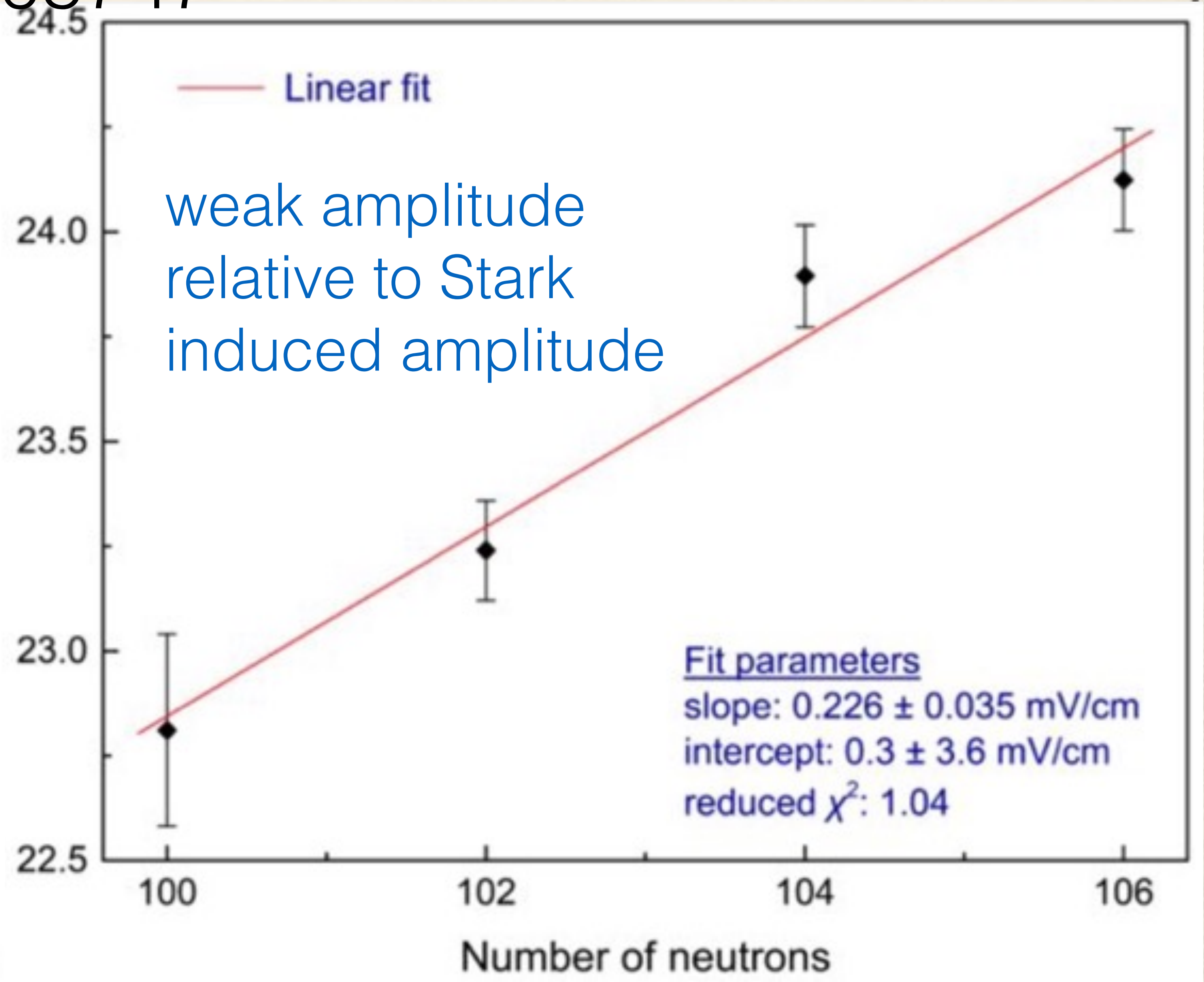
Phys. Rev. A **97**, 042507 (2018)
M, Kalita et al.
with *ab-initio* theory by Dzuba, Flambaum, Safronova

Courtesy:
Gerald Gwinner

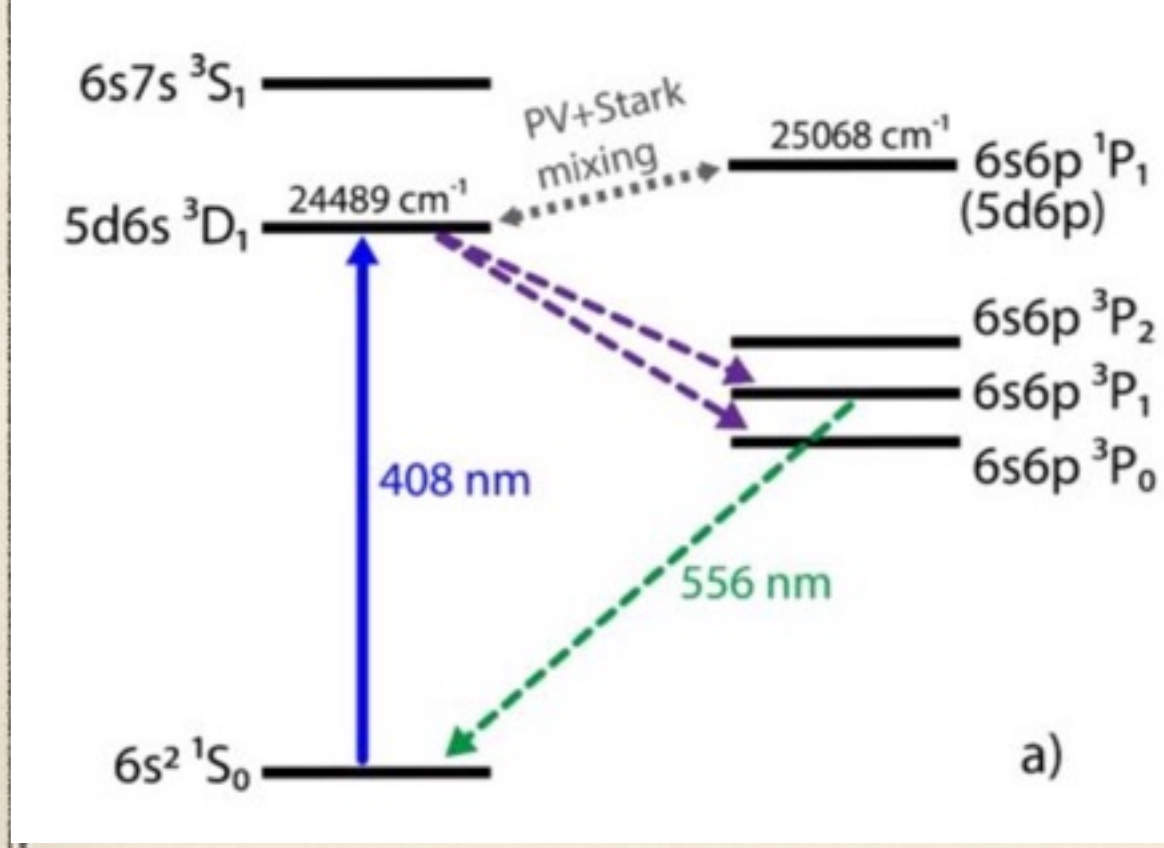
Mainz/Berkeley Ytterbium APV

Antypas et al. arXiv:1804.05747

First demonstration of dependence of nuclear weak charge on # of neutrons.



weak amplitude relative to Stark induced amplitude



Experimental accuracy ≈ 0.5% in each isotope! Boulder Cs: 0.35%

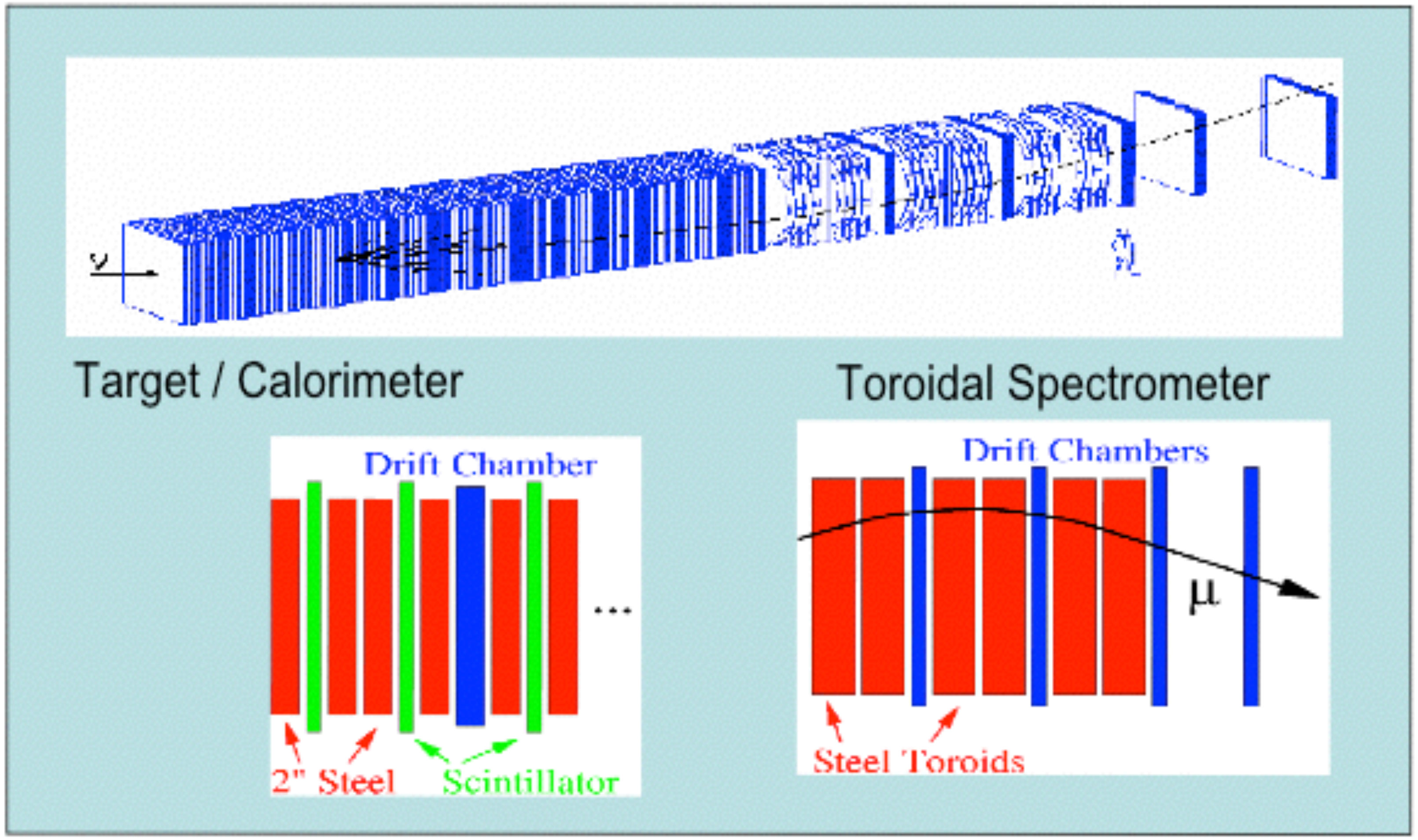
But at this point, atomic theory not established at this level

Isotope shifts to 0.05%?? Neutron skins…

Neutrino Scattering

DIS neutrino and anti-neutrino charged and neutral current cross-sections

NuTeV



$$R^- = \frac{\sigma^{NC}_{\nu N} - \sigma^{NC}_{\bar{\nu} N}}{\sigma^{CC}_{\nu N} - \sigma^{CC}_{\bar{\nu} N}} \approx \rho^2\left(\frac{1}{2} - \sin^2\theta_W\right)$$

$$\boxed{\begin{aligned}\sin^2\theta_W^{(on-shell)} &= 0.2277 \pm 0.0013(stat.)\\ &\pm 0.0009(syst.)\end{aligned}}$$

Standard Model prediction is 0.2227
(3σ deviation)

Most precise measurement of neutrino-quark coupling

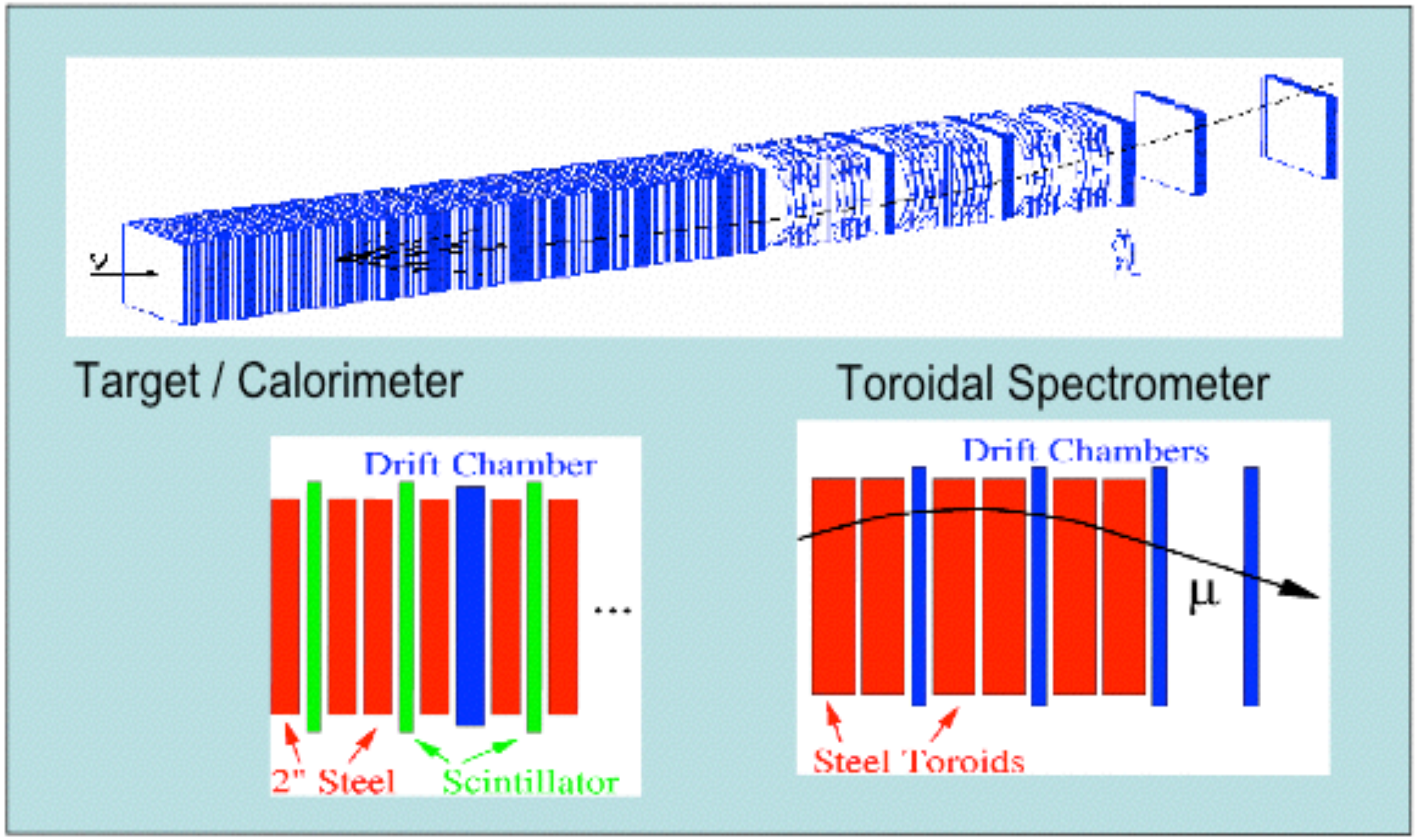
Subtle parton physics effects can affect the result

generated great interest in both nuclear and particle phenomenology

DIS neutrino and anti-neutrino charged and neutral current cross-sections

NuTeV

Significant discovery: but EW or QCD Physics?



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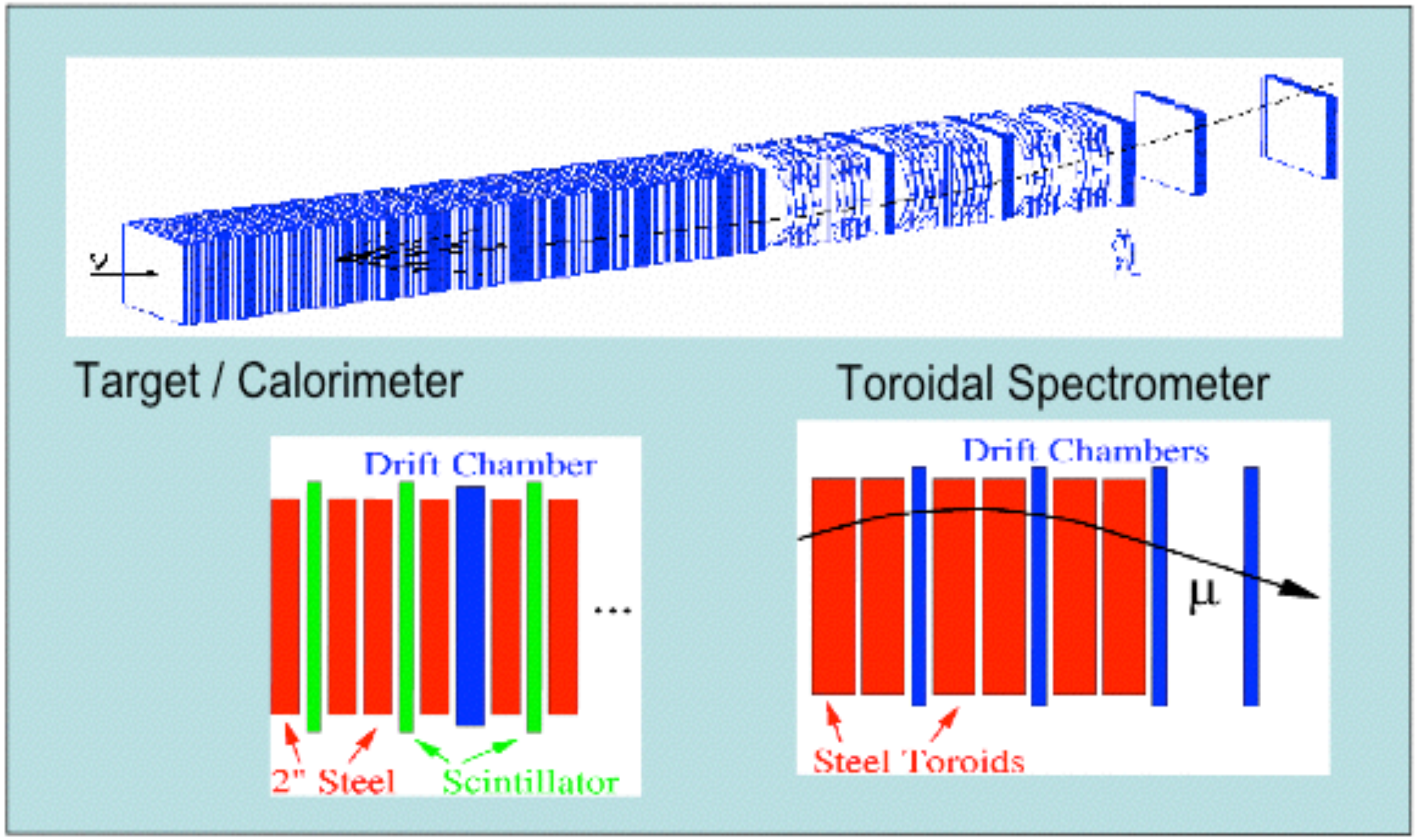

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Cloet, Bentz, Thomas, arXiv 0901.3559

^{48}Ca PVDIS with SoLID

Consider PVDIS on a heavy nucleus

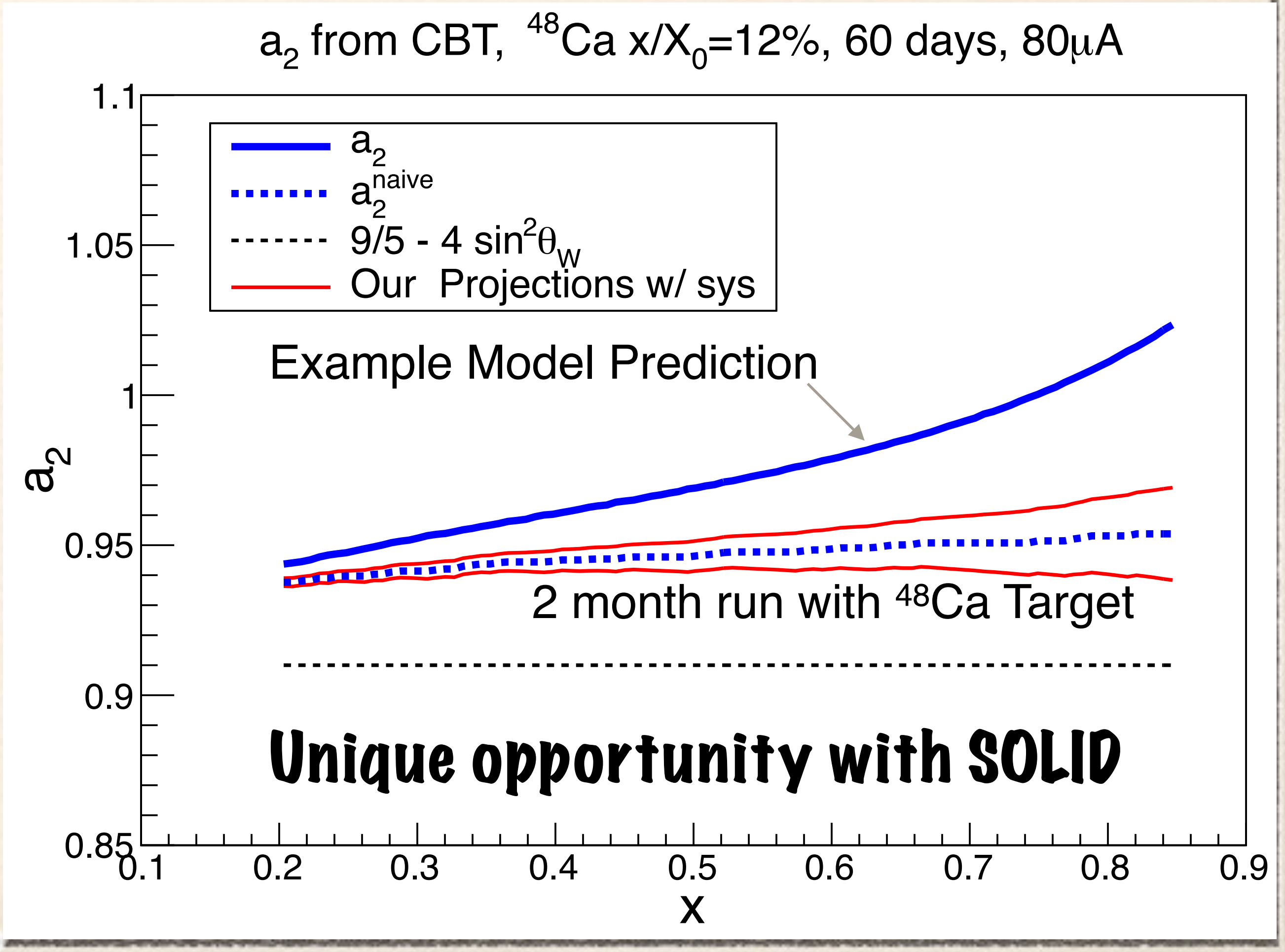
- **Neutron or proton excess in nuclei leads to a isovector-vector mean field (ρ exchange)**
- **shifts quark distributions: “apparent” charge symmetry violation**
- **Isovector EMC effect: explain at least 2/3 of the NuTeV anomaly**

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

$$a_2 \simeq \frac{9}{5} - 4\sin^2\theta_W - \frac{12}{25}\frac{u_A^+ - d_A^+}{u_A^+ + d_A^+} + \cdots$$

Great leverage for a clean isospin decomposition of the EMC effect in an inclusive measurement

Flavor separation of EMC effect extremely challenging!



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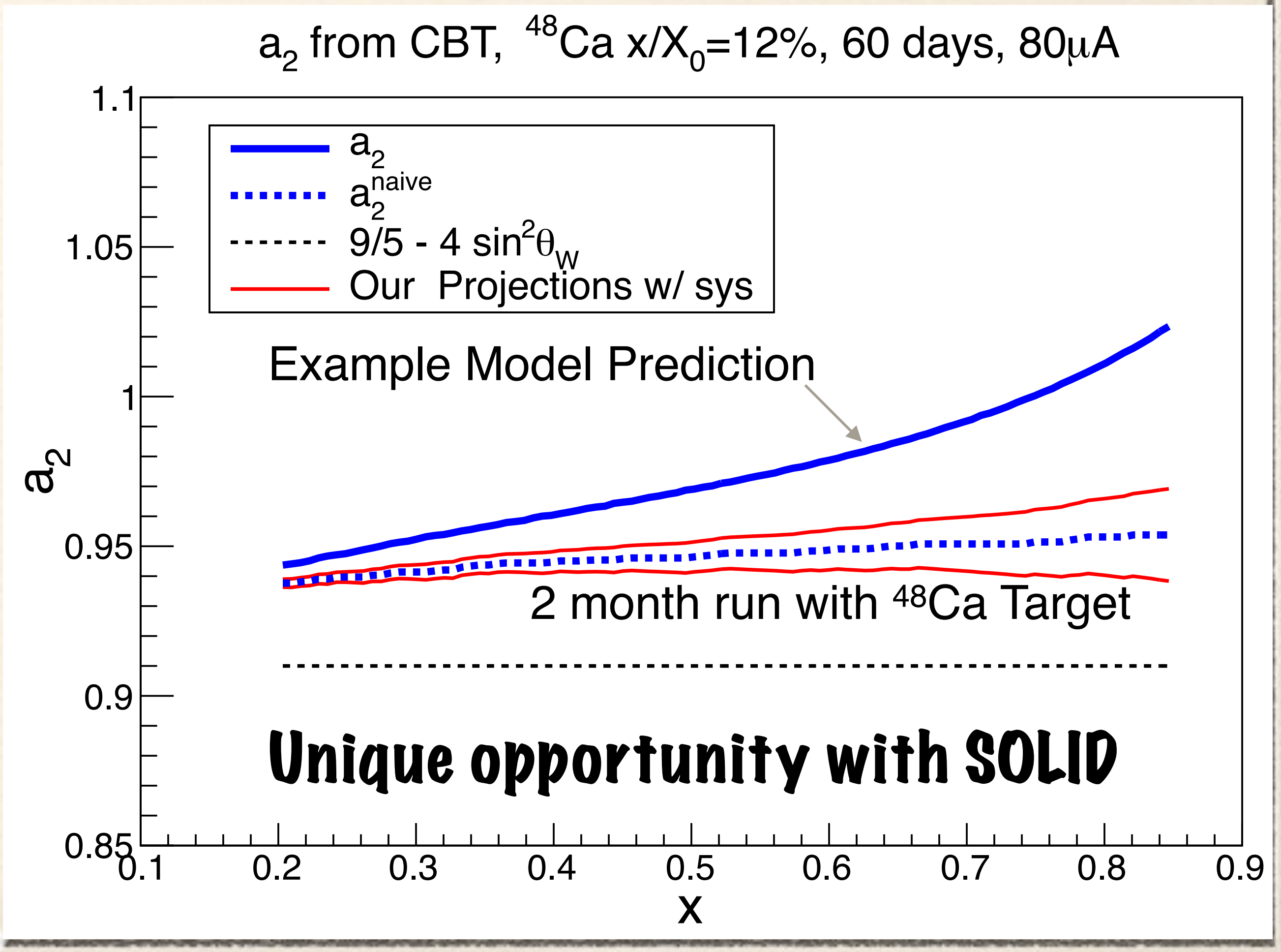
Great leverage for a clean isospin decomposition of the EMC effect in an inclusive measurement

Flavor separation of EMC effect extremely challenging!

- ***With hadrons in the initial or final state, small effects are difficult to disentangle (theoretically and experimentally)***
- ***Precise isotope cross-section ratios in purely electromagnetic electron scattering: MUCH reduced sensitivity to the isovector combination***



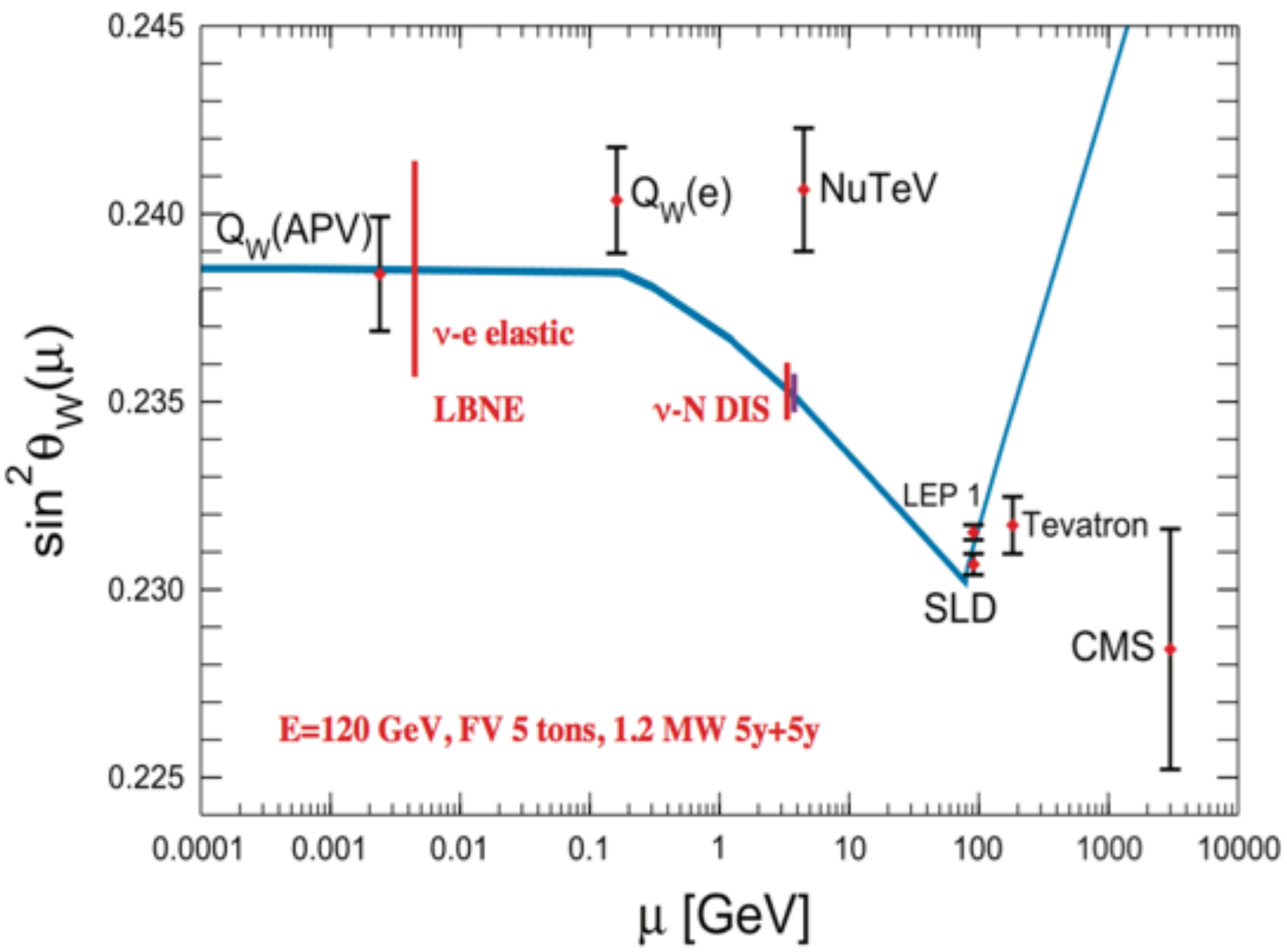
Courtesy : Roberto Petti

Potential of LBNF (if…)

✦ *Sensitivity expected from ν scattering in DUNE comparable to the Collider precision:*

- *FIRST single experiment to directly check the running of* $\sin^2\theta_W$*:*
  elastic ν-e scattering and νN DIS have different scales
- *Different scale of momentum transfer with respect to LEP/SLD (off Z^0 pole)*
- *Direct measurement of neutrino couplings to Z^0*
  $\Longrightarrow$ *Only other measurement LEP* $\Gamma_{\nu\nu}$
- *Independent cross-check of the NuTeV* $\sin^2\theta_W$ *anomaly* ($\sim 3\sigma$ *in* ν *data) in a similar* Q^2 *range*

Deep synergy
with the LBL
oscillation program:
same requirements
and
mutual feedback



✦ *Different independent channels:*

- $\mathcal{R}^{\nu} = \frac{\sigma^{\nu}_{\rm NC}}{\sigma^{\nu}_{\rm CC}}$ *in ν-N DIS (~0.35%)*
- $\mathcal{R}_{\nu e} = \frac{\sigma^{\bar\nu}_{\rm NC}}{\sigma^{\nu}_{\rm NC}}$ *in ν-e^- NC elastic (~1%)*
- *NC/CC ratio* $(\nu p \to \nu p)/(\nu n \to \mu^- p)$
  in (quasi)-elastic interactions
- *NC/CC ratio* ρ^0/ρ^+ *in coherent processes*

$\Longrightarrow$ *Combined EW fits like LEP*

✦ *Reduction of uncertainties to* $\sim 0.2\%$ *with 1-2 yr run in high energy mode*

$\nu + A \rightarrow \nu + A$

Courtesy: Kate Scholberg

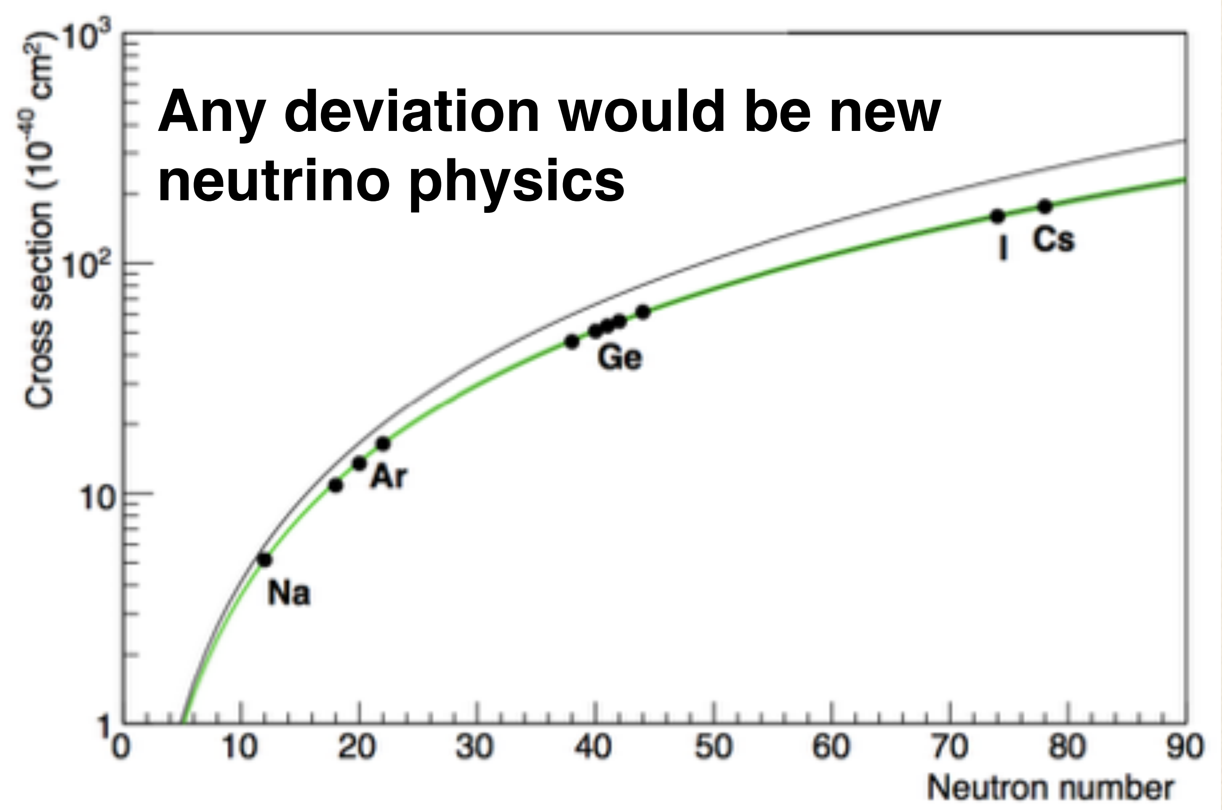
Coherent Neutrino Scattering

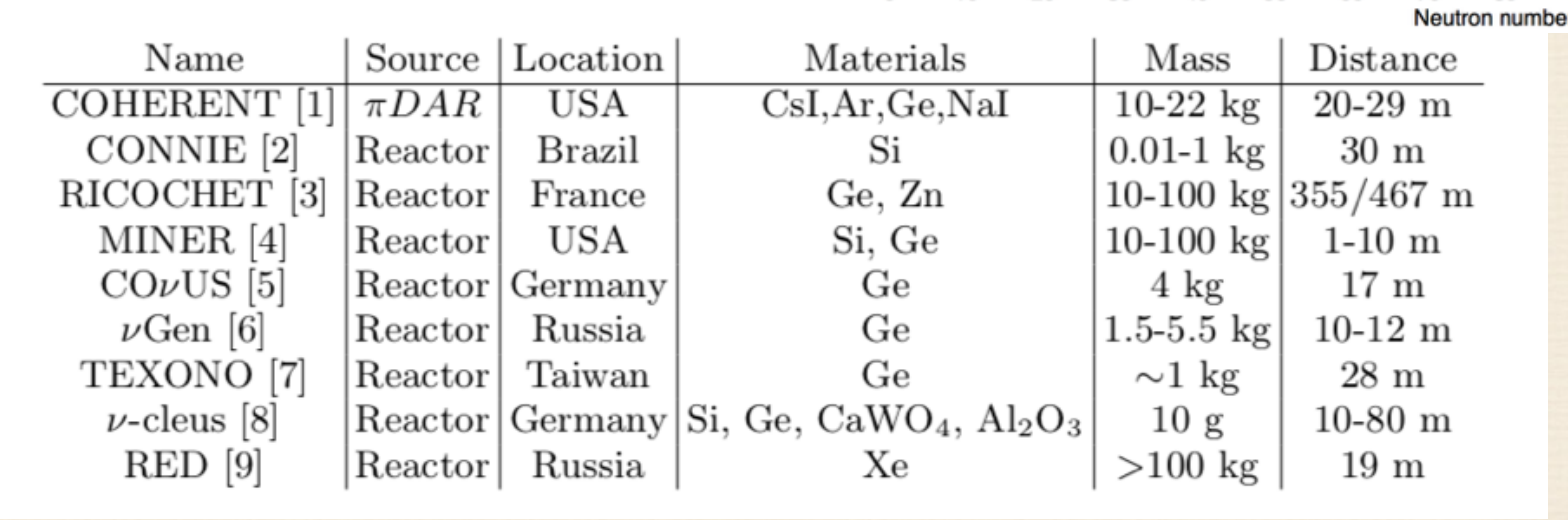
For $QR << 1$,

[total xscn] ~ A^2 * [single constituent xscn]

The so-called "neutrino floor" (**signal!**) for Dark Matter experiments

$$\frac{d\sigma}{dT} = \frac{G_F^2 M}{2\pi}\frac{Q_W^2}{4}F^2(Q)\left(2 - \frac{MT}{E_\nu^2}\right)$$


Any deviation would be new neutrino physics



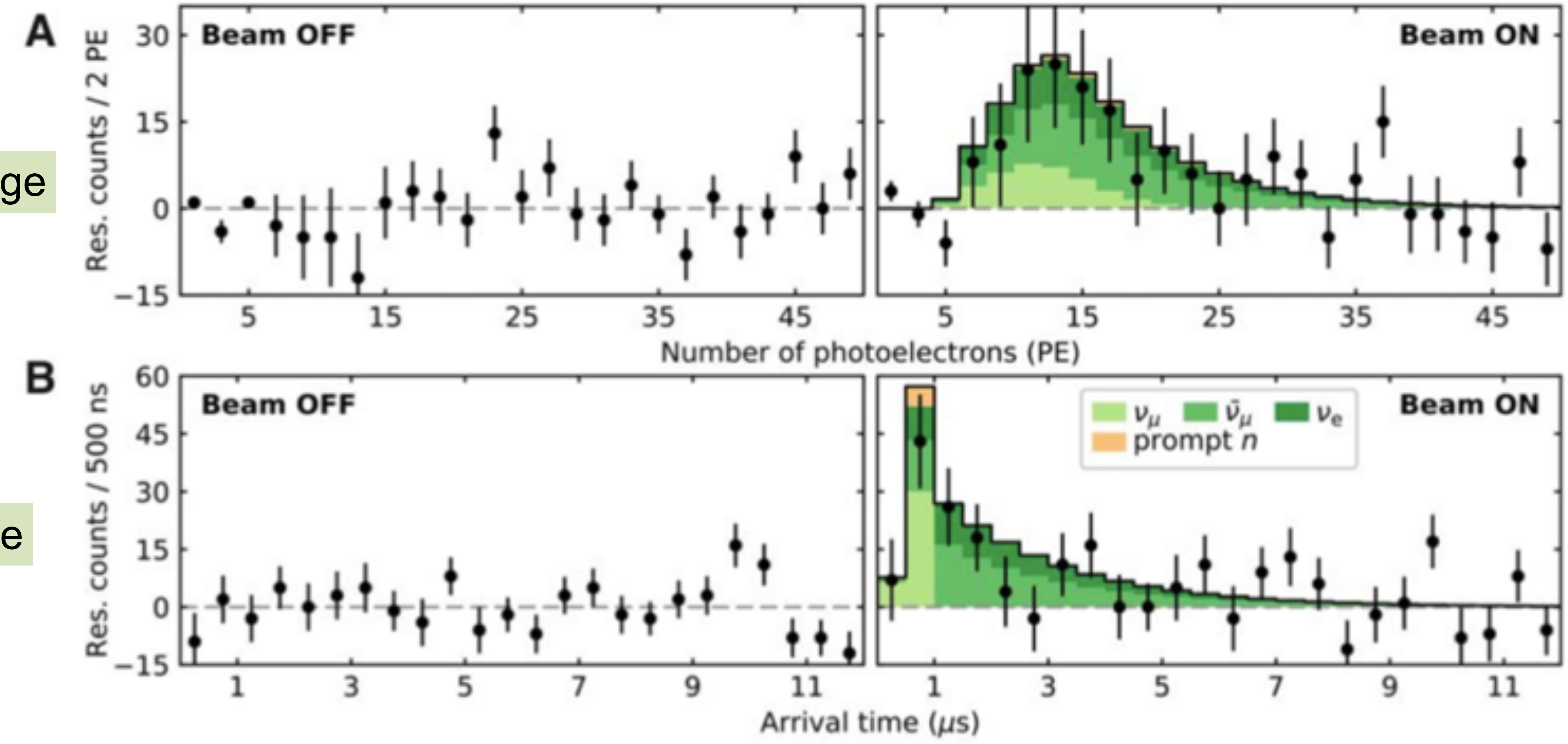
Name	Source	Location	Materials	Mass	Distance
COHERENT [1]	πDAR	USA	CsI,Ar,Ge,NaI	10-22 kg	20-29 m
CONNIE [2]	Reactor	Brazil	Si	0.01-1 kg	30 m
RICOCHET [3]	Reactor	France	Ge, Zn	10-100 kg	355/467 m
MINER [4]	Reactor	USA	Si, Ge	10-100 kg	1-10 m
COνUS [5]	Reactor	Germany	Ge	4 kg	17 m
νGen [6]	Reactor	Russia	Ge	1.5-5.5 kg	10-12 m
TEXONO [7]	Reactor	Taiwan	Ge	~1 kg	28 m
ν-cleus [8]	Reactor	Germany	Si, Ge, CaWO$_4$, Al$_2$O$_3$	10 g	10-80 m
RED [9]	Reactor	Russia	Xe	>100 kg	19 m

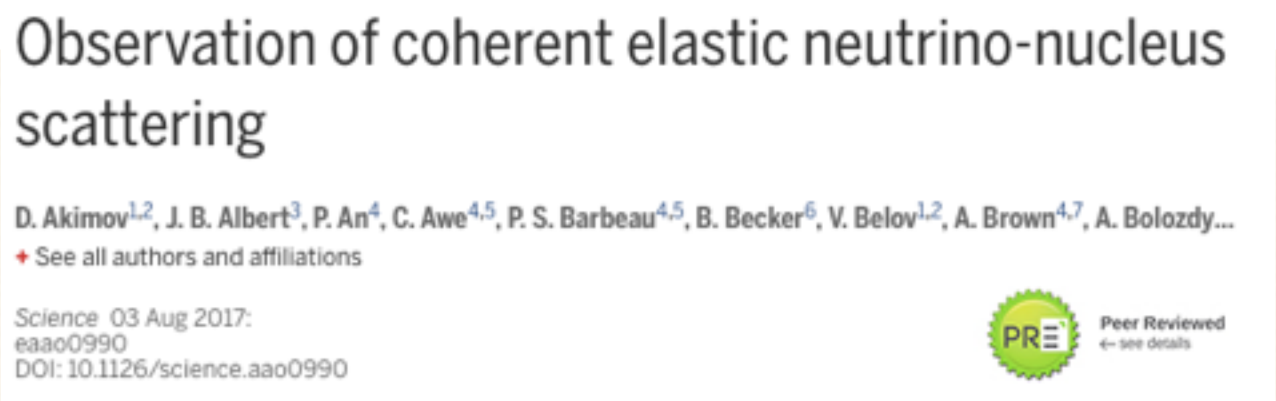
COHERENT Result

First light at the SNS with 14.6-kg CsI[Na] detector

Charge

Time





Observation of coherent elastic neutrino-nucleus scattering

D. Akimov[1,2], J. B. Albert[3], P. An[4], C. Awe[4,5], P. S. Barbeau[4,5], B. Becker[6], V. Belov[1,2], A. Brown[4,7], A. Bolozdy...

+ See all authors and affiliations

Science 03 Aug 2017:
eaao0990
DOI: 10.1126/science.aao0990

D. Akimov et al., *Science*, 2017
http://science.sciencemag.org/content/early/2017/08/02/science.aao0990

Summary and Outlook

- **Measurements of the Weak Mixing Angle**
  - Central to our understanding of the Standard Model
  - Remains relevant for BSM searches, especially flavor-diagonal
- **Parity-Violating Electron Scattering in the next decade**
  - Technical progress has enabled unprecedented precision
  - flagship experiments at electron accelerators
  - Fundamental Nuclear/Nucleon Physics
    - *Neutron RMS radii of heavy nuclei*
    - *valence quark structure of protons and neutrons*
  - Fundamental Electroweak Physics and BSM Searches
    - *Search for new dynamics at the multi-TeV scale*
    - *precision measurement of the weak mixing angle*
- **Atomic Parity Violation and Neutrino Scattering**
  - The low Q region might become important in the future!
  - Neutrino scattering should be investigated in any case…

Backups

Fundamental Symmetries & Neutrinos:

The 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: $Q^2 << M_Z^2$

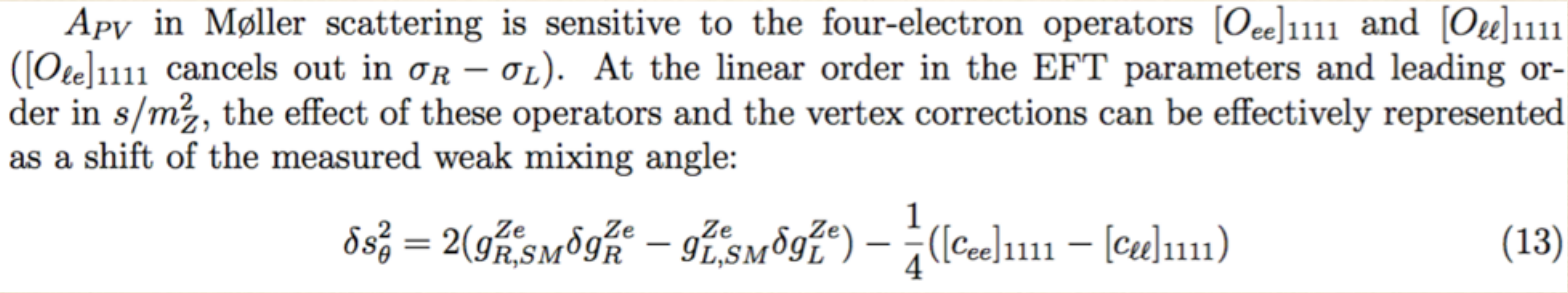
***Nuclear/Atomic* systems address several topics; unique & complementary:**

- ***Neutrino mass and mixing*** $0\nu\beta\beta$ *decay,* θ_{13}*,* β *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:*** *$(g-2)_\mu$, charged &* ***neutral current amplitudes***

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)*

4-Electron Operator Reach

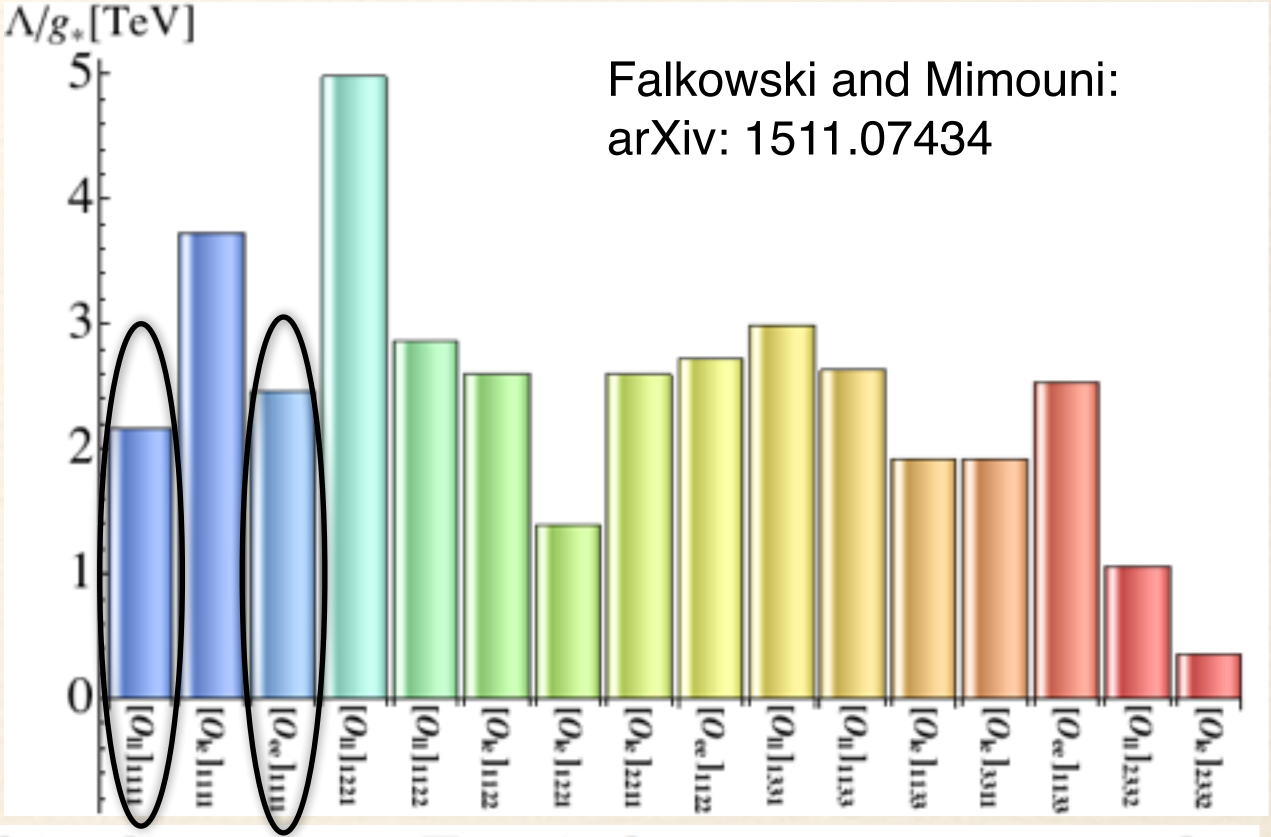


A_{PV} in Møller scattering is sensitive to the four-electron operators $[O_{ee}]_{1111}$ and $[O_{\ell\ell}]_{1111}$ ($[O_{\ell e}]_{1111}$ cancels out in $\sigma_R - \sigma_L$). At the linear order in the EFT parameters and leading order in s/m_Z^2, the effect of these operators and the vertex corrections can be effectively represented as a shift of the measured weak mixing angle:

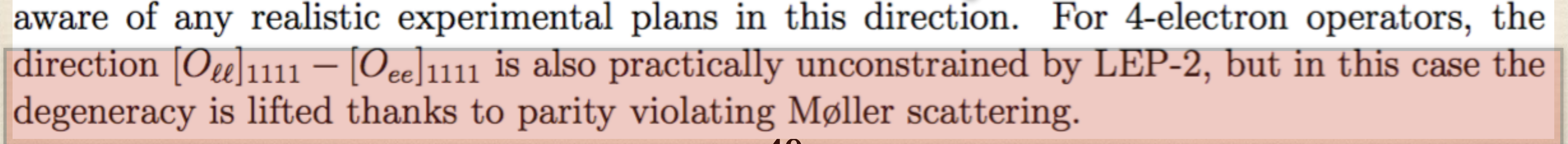
$$\delta s_\theta^2 = 2(g_{R,SM}^{Ze}\delta g_R^{Ze} - g_{L,SM}^{Ze}\delta g_L^{Ze}) - \frac{1}{4}([c_{ee}]_{1111} - [c_{\ell\ell}]_{1111}) \qquad (13)$$

MOLLER reach is 7.5 TeV

Current LHC reach including recent 13 TeV running is 5 to 6 TeV for llqq operators



Falkowski and Mimouni:
arXiv: 1511.07434



aware of any realistic experimental plans in this direction. For 4-electron operators, the direction $[O_{\ell\ell}]_{1111} - [O_{ee}]_{1111}$ is also practically unconstrained by LEP-2, but in this case the degeneracy is lifted thanks to parity violating Møller scattering.

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

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

Best projected uncertainty among projects being considered over next 10 years:
worldwide and at any energy scale

- **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**
  - **Hidden weak scale scenarios**
  - **Lepton Number Violating Amplitudes**
  - **Light Dark Matter Mediators**
  - **…**

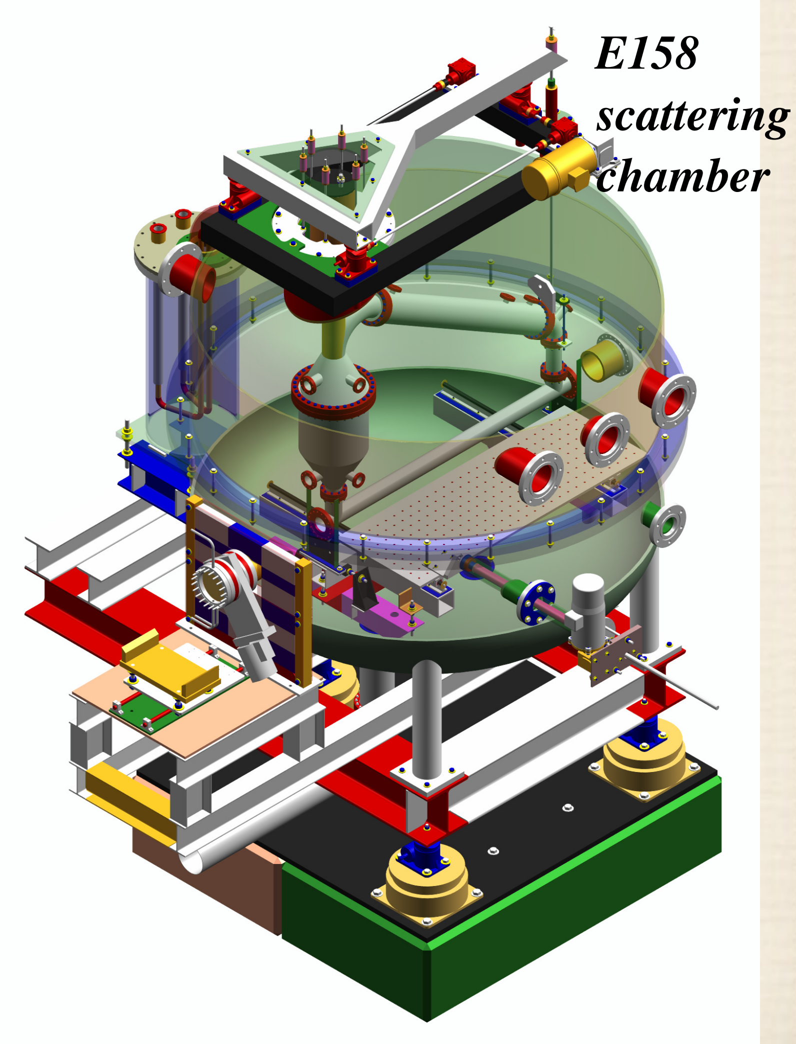
Liquid Hydrogen Target

- **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***

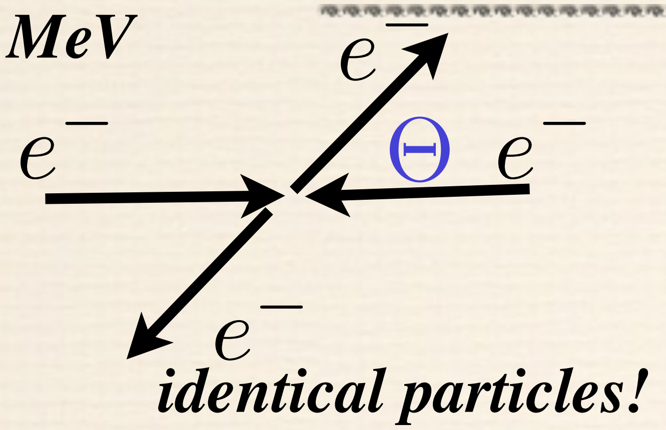
parameter	value
length	*150 cm*
thickness	*10.7 gm/cm^2*
X_0	*17.5%*
p,T	*35 psia, 20K*
power	*5000 W*

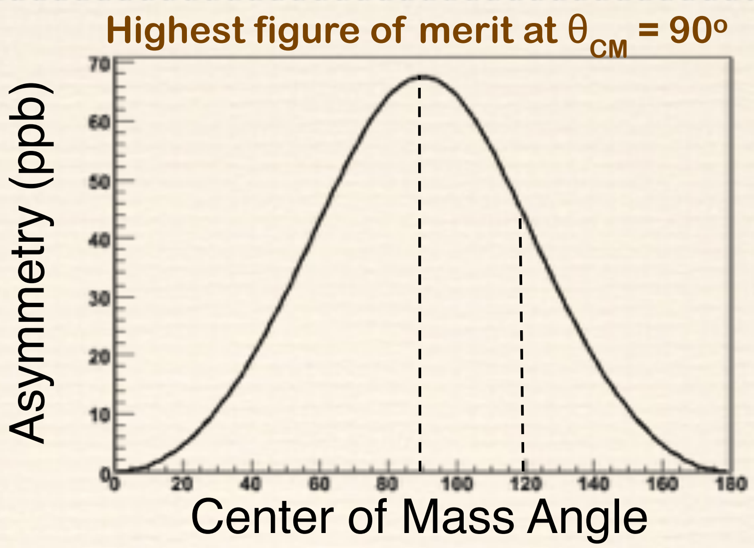
Progressive evolution of sophistication over generations of PVES experiments; most recently, Qweak

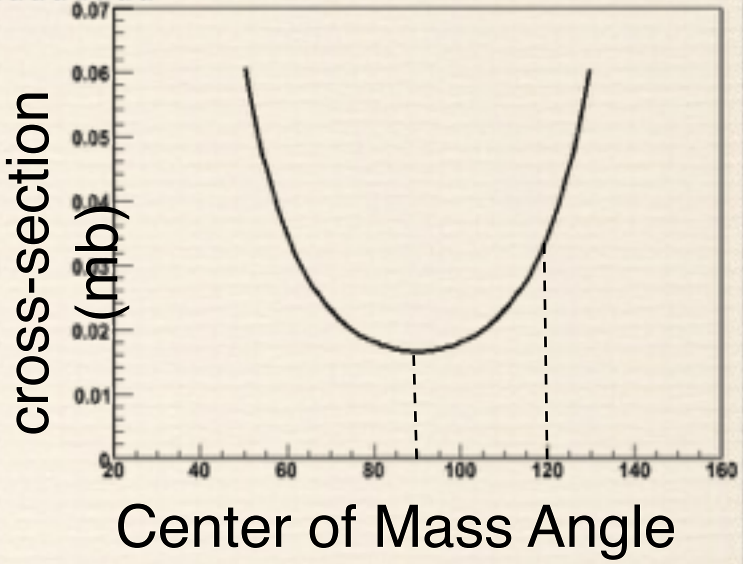

E158 scattering chamber

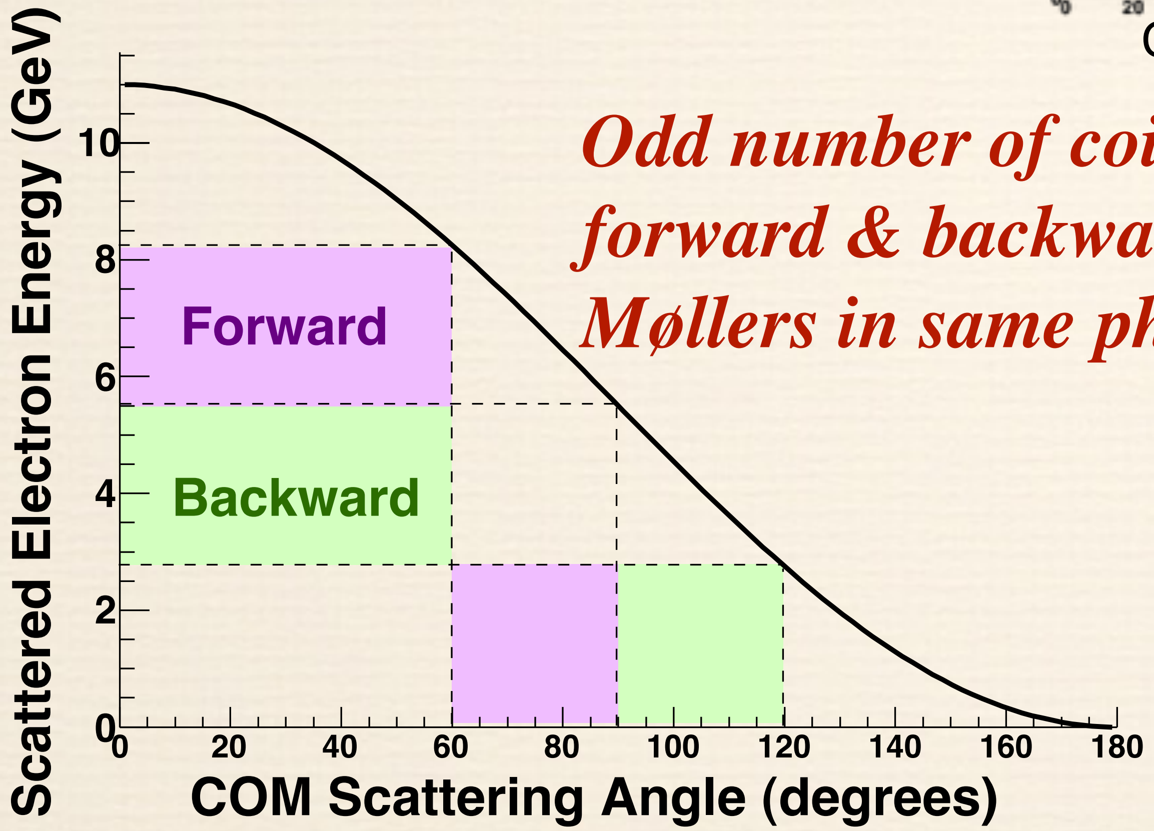
Møller Kinematics

$E_{COM} = 53\ MeV$



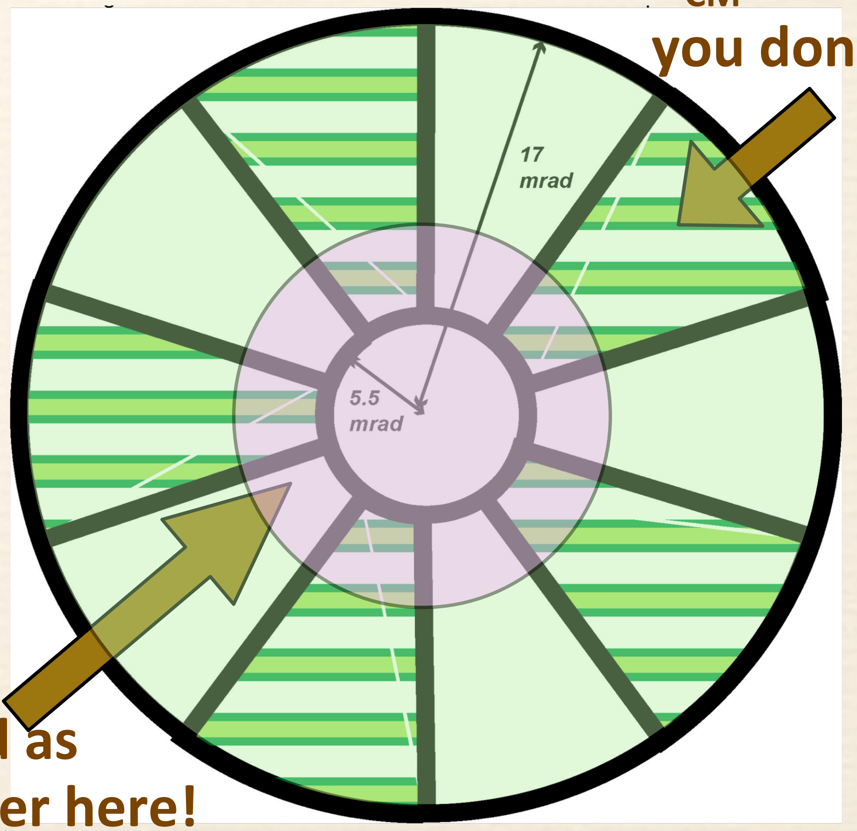






Odd number of coils: both forward & backward Møllers in same phi-bite

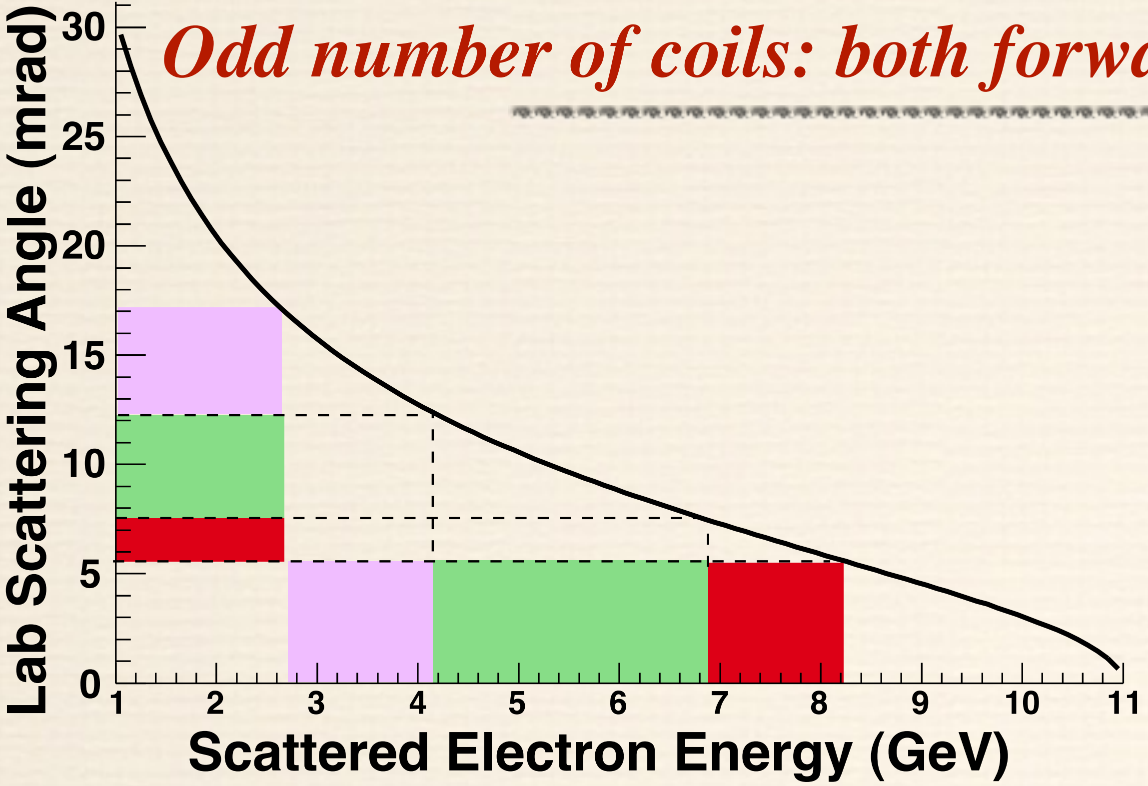
All of those rays of θ_{CM}=[90,120] that you don't get here...

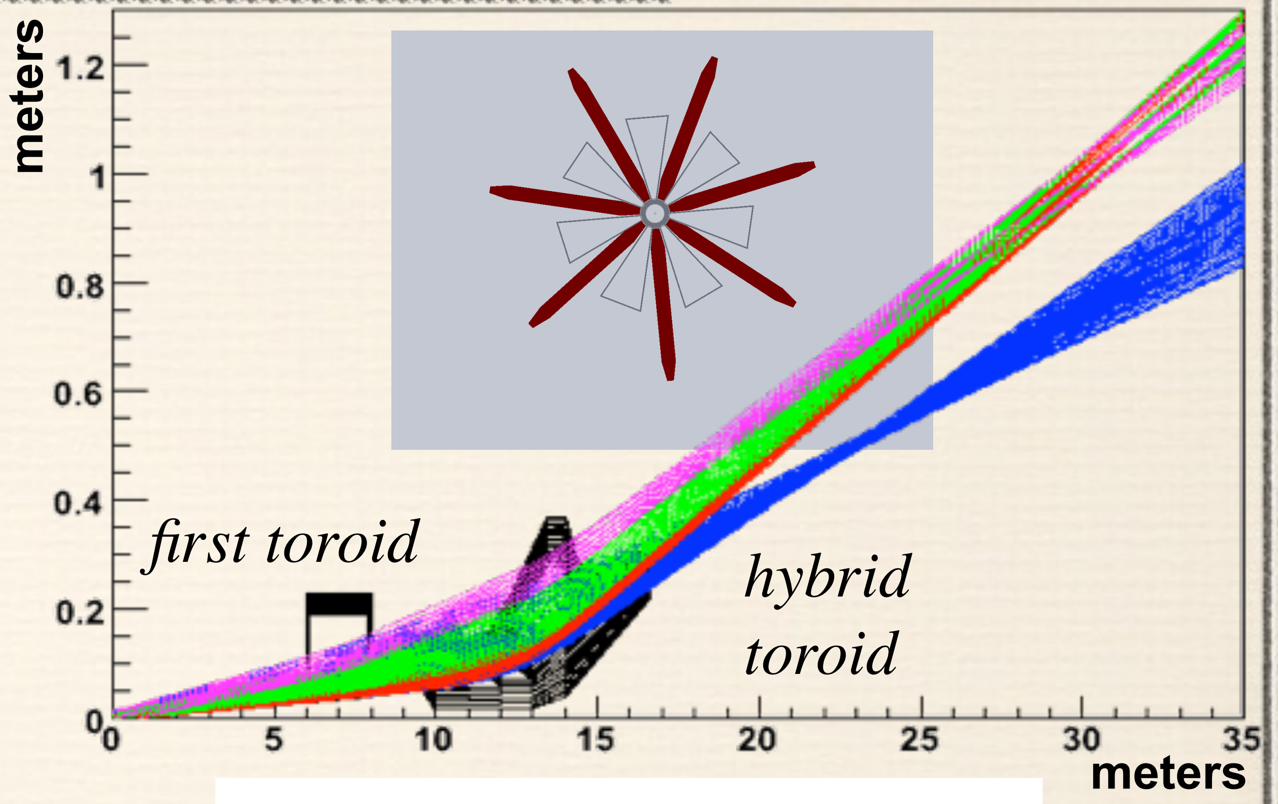


... are collected as θ_{CM}=[60,90] over here!

100% Azimuthal Acceptance

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





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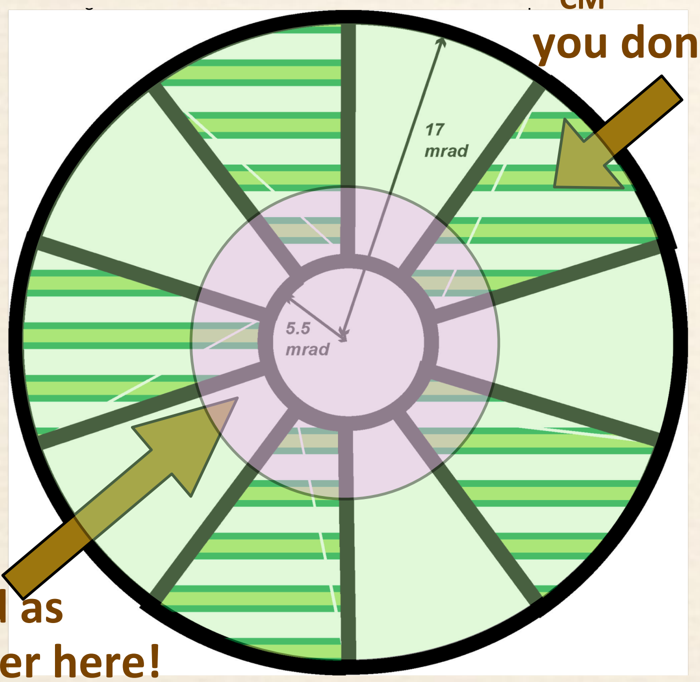

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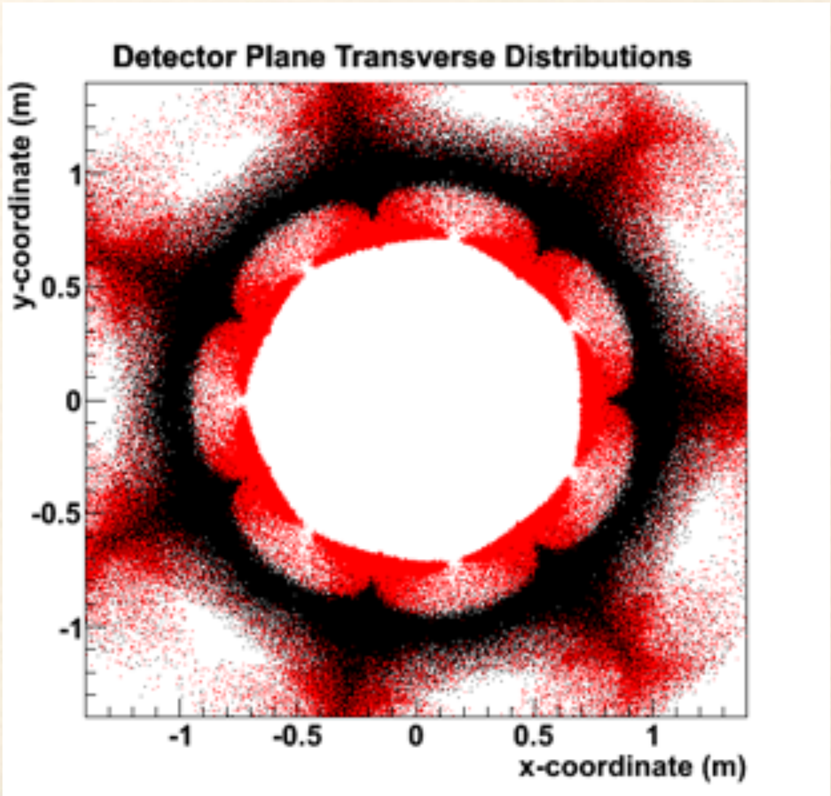
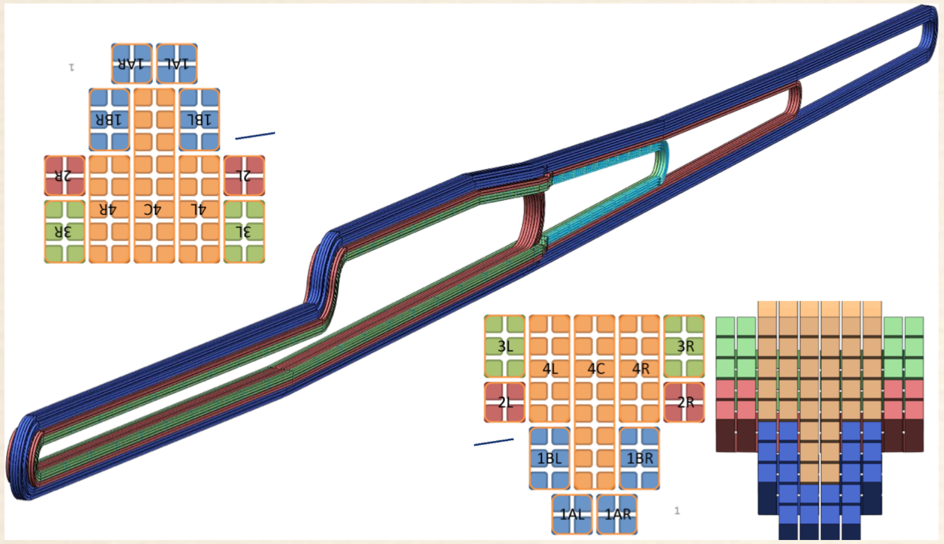
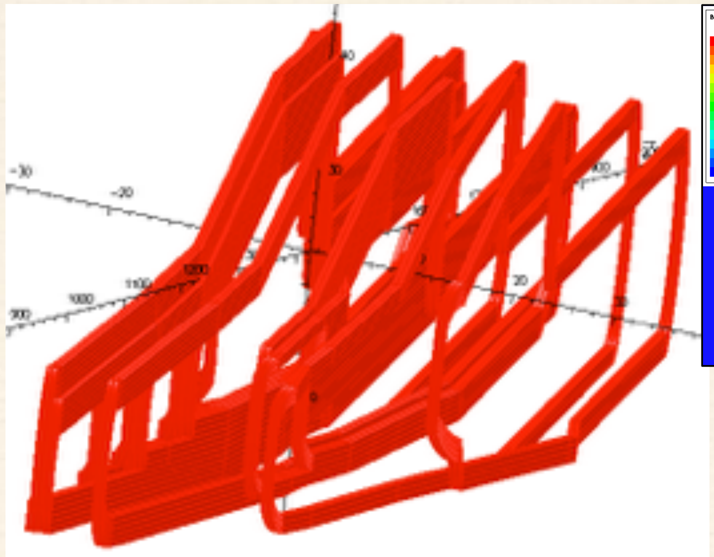
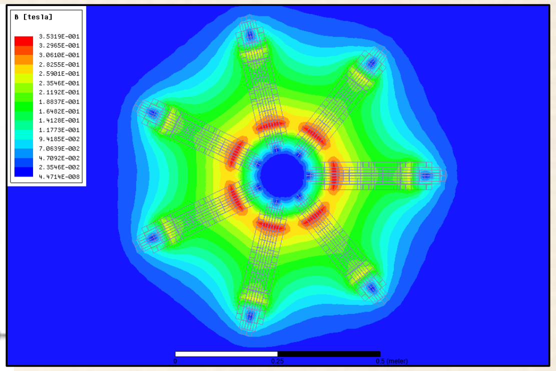
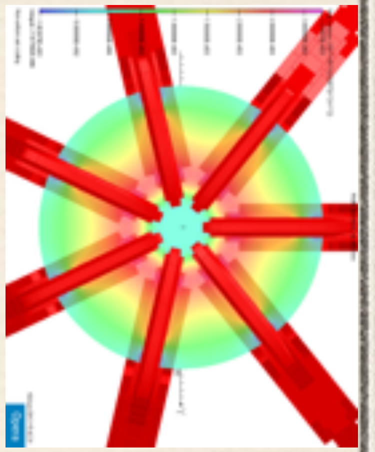


Spectrometer Engineering



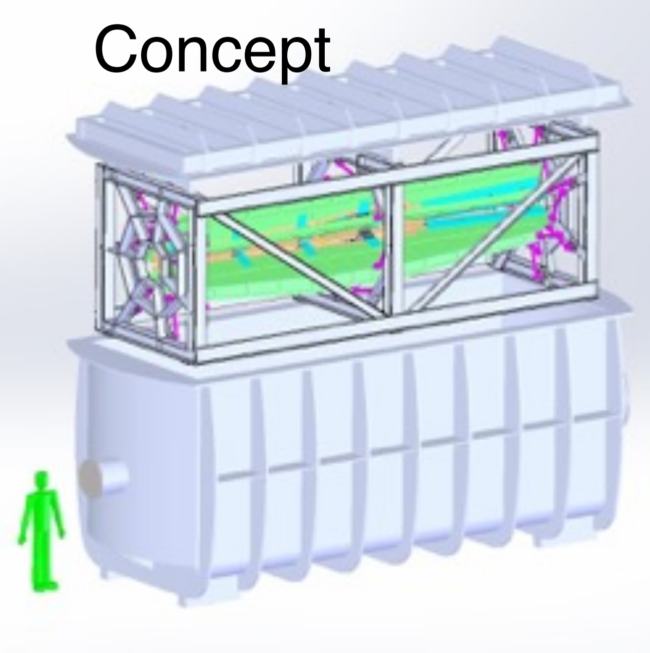


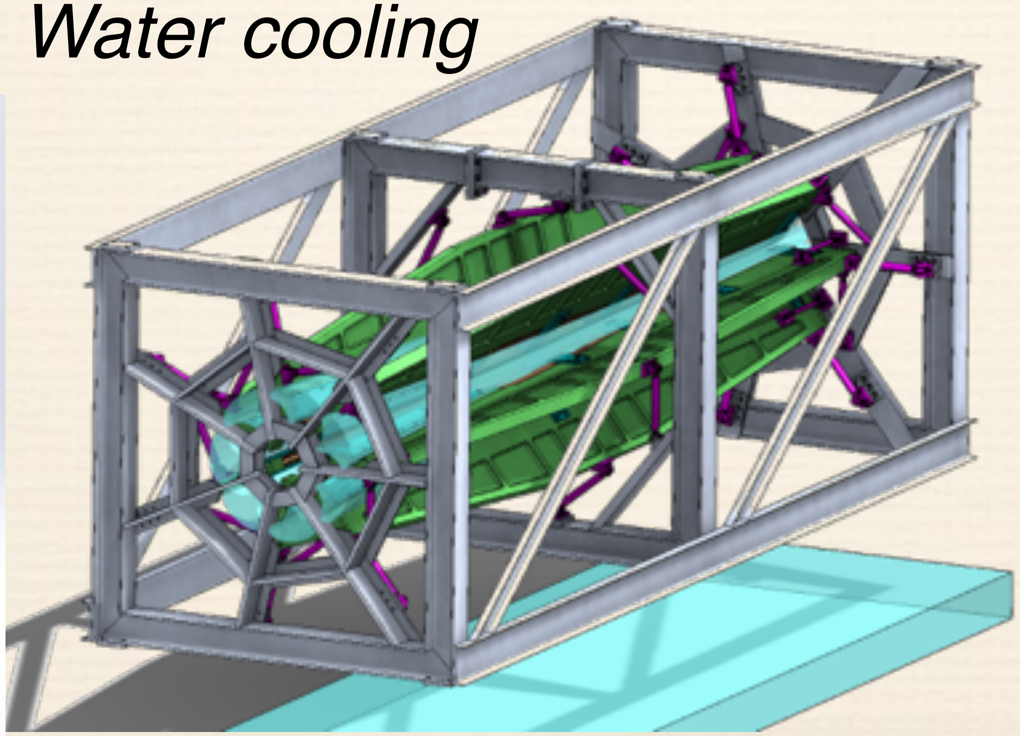




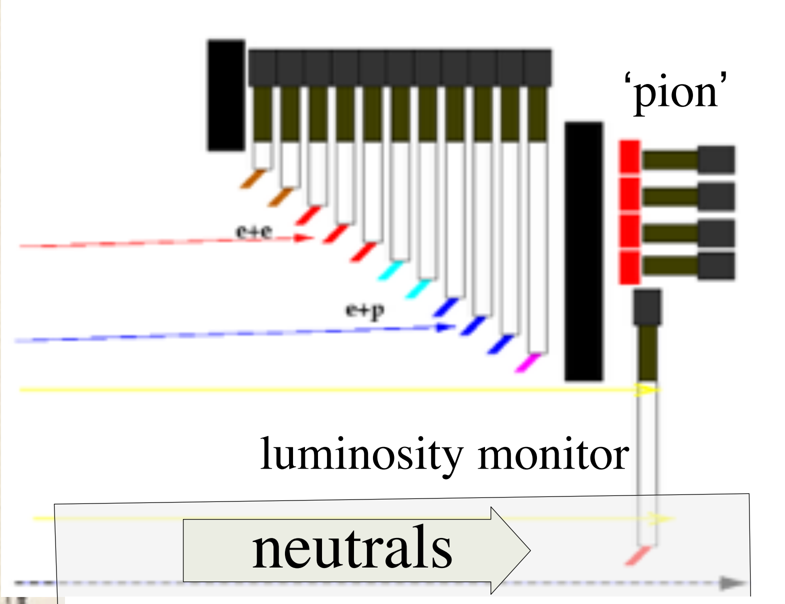
- *Full Azimuthal Acceptance*
- *Warm copper coils*
- *Water cooling*

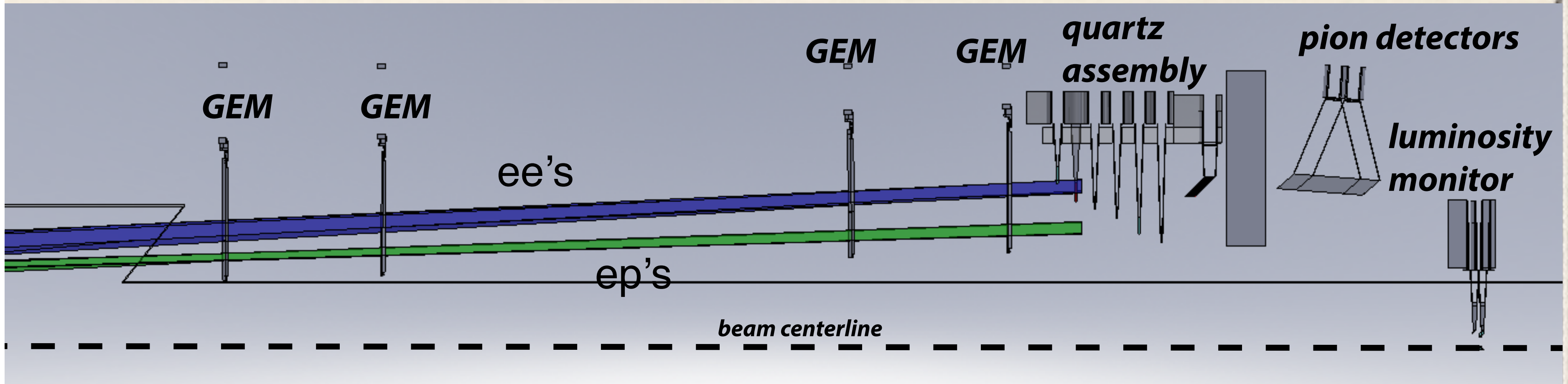
Vacuum Tank
Concept



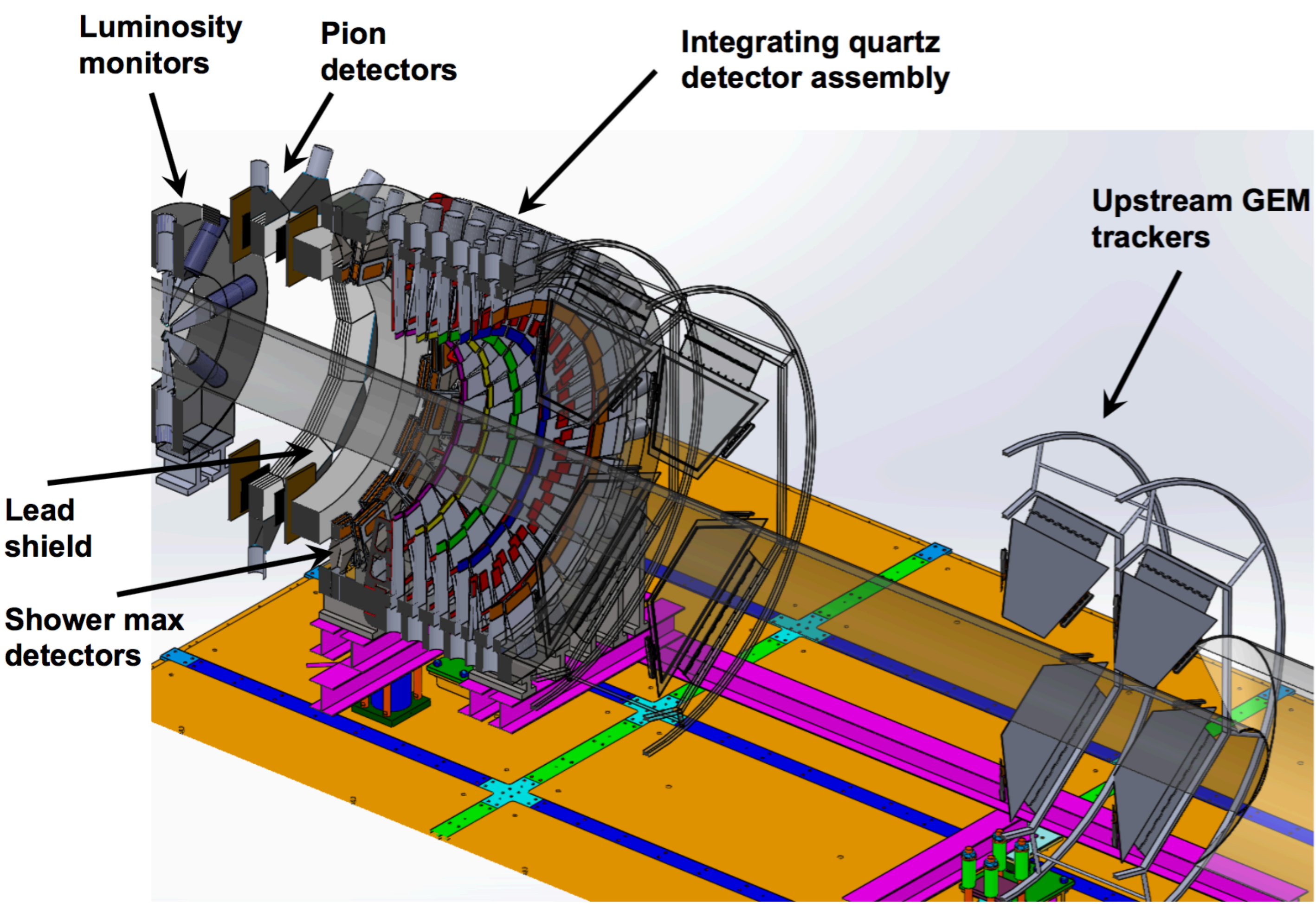


Integrating Detector Concept



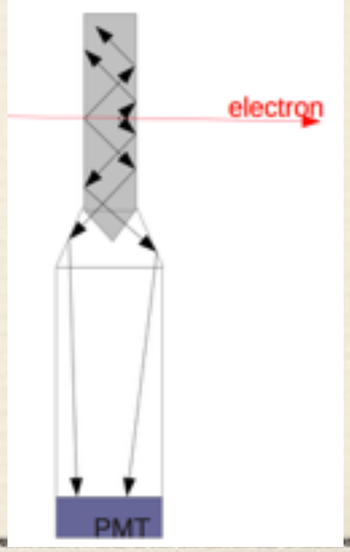


Perspective View of Detector Assembly



- **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

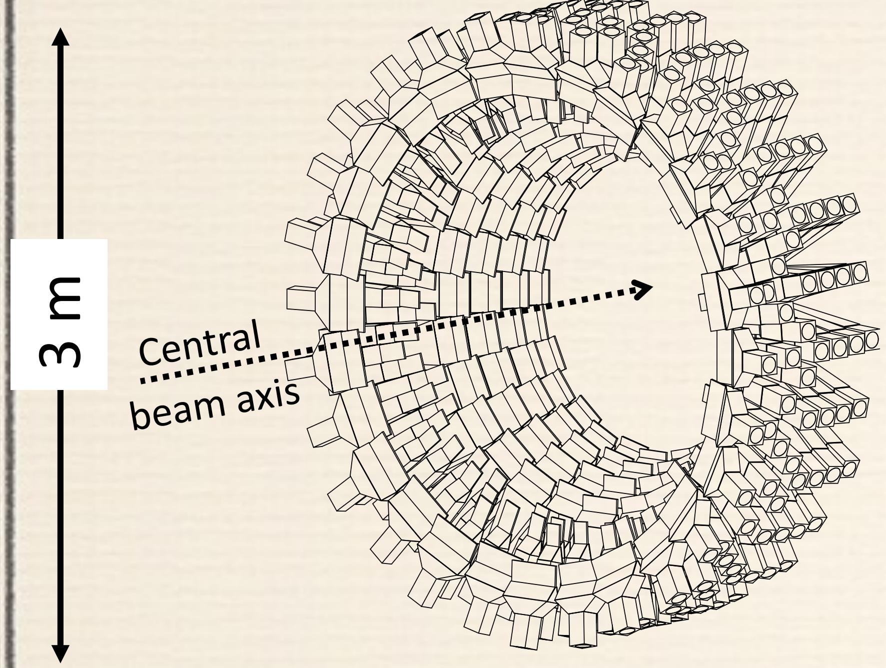


First MOLLER publication: investigation of air lightguide backgrounds

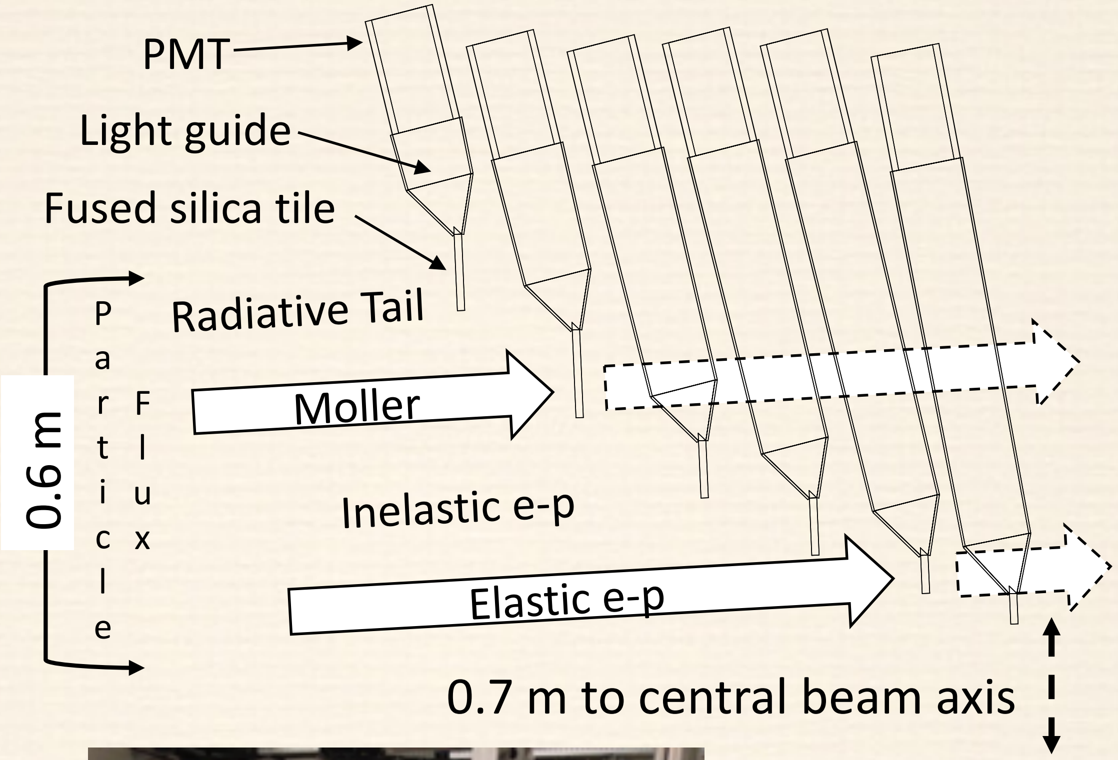
NIM A 896 (2018) 96–102

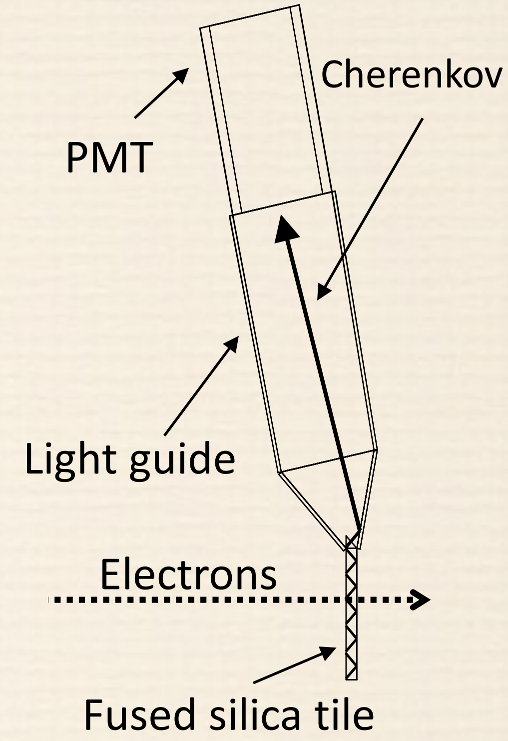
Detector R&D

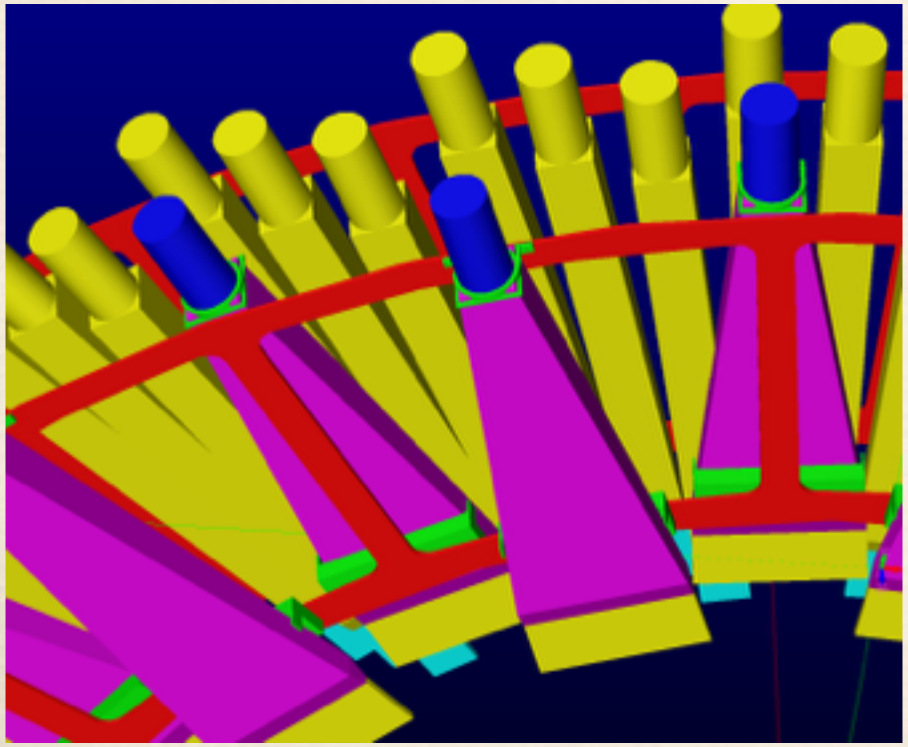
Collaboration with Mainz group and availability of test beams has been critical

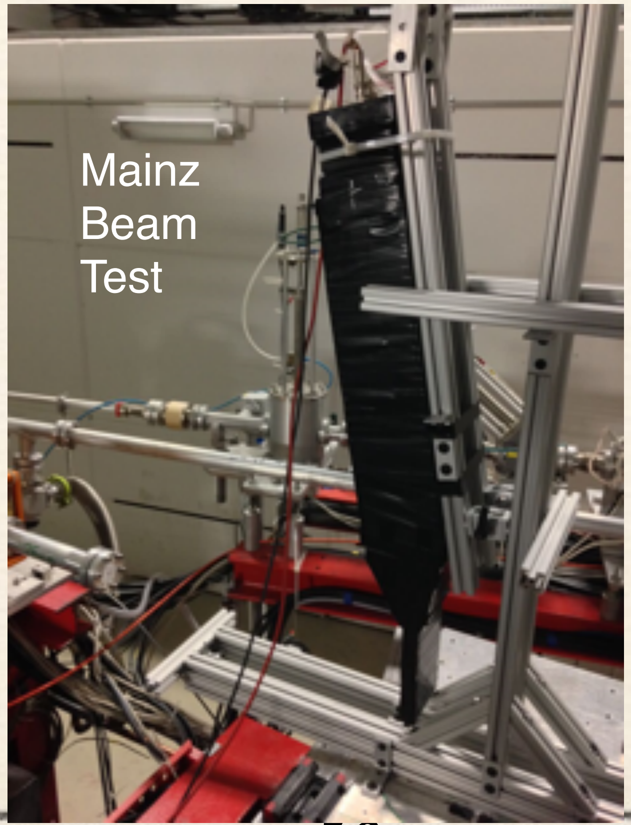


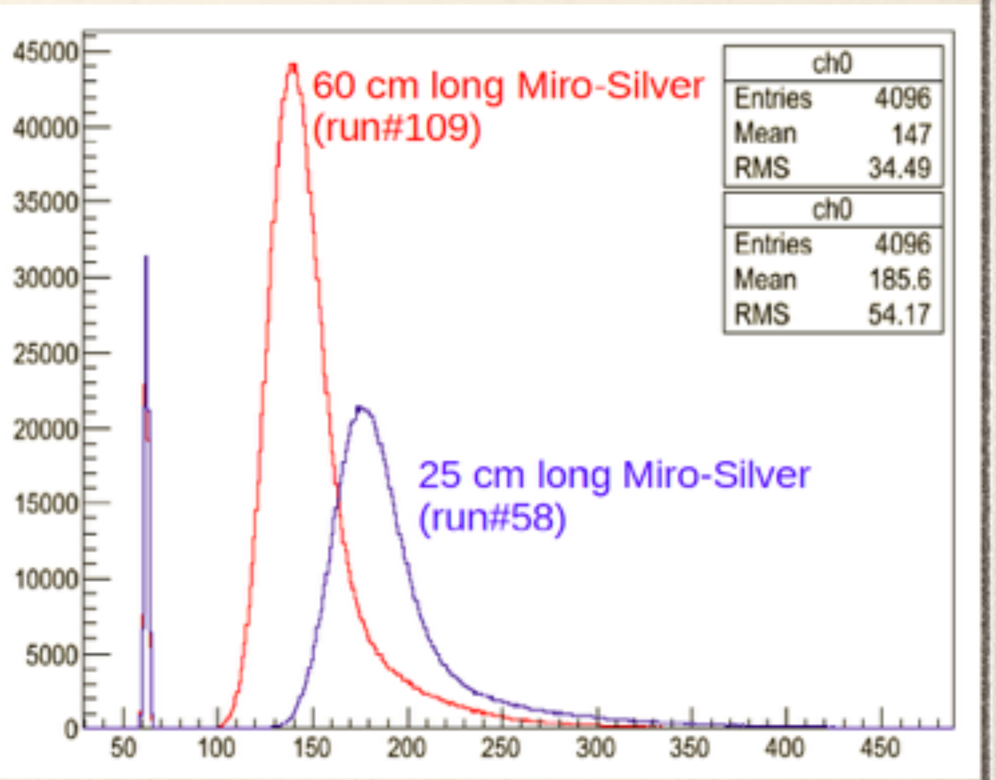
Detector assembly



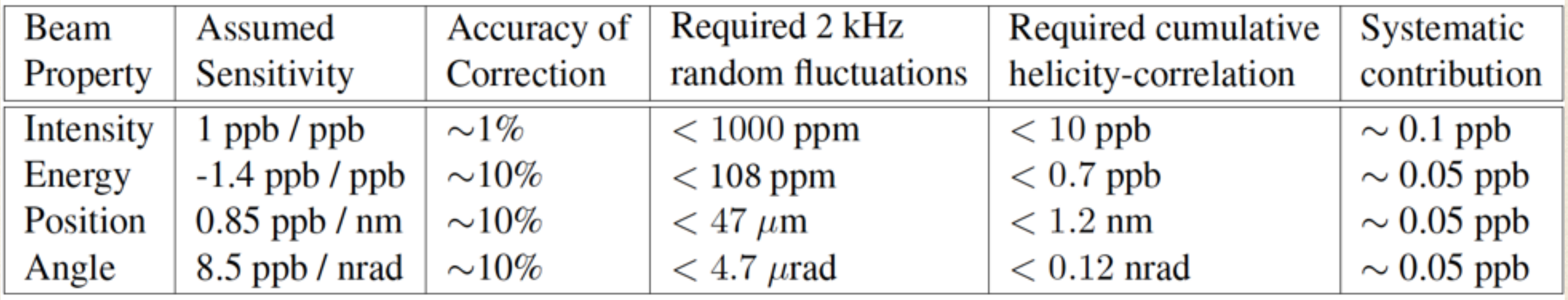




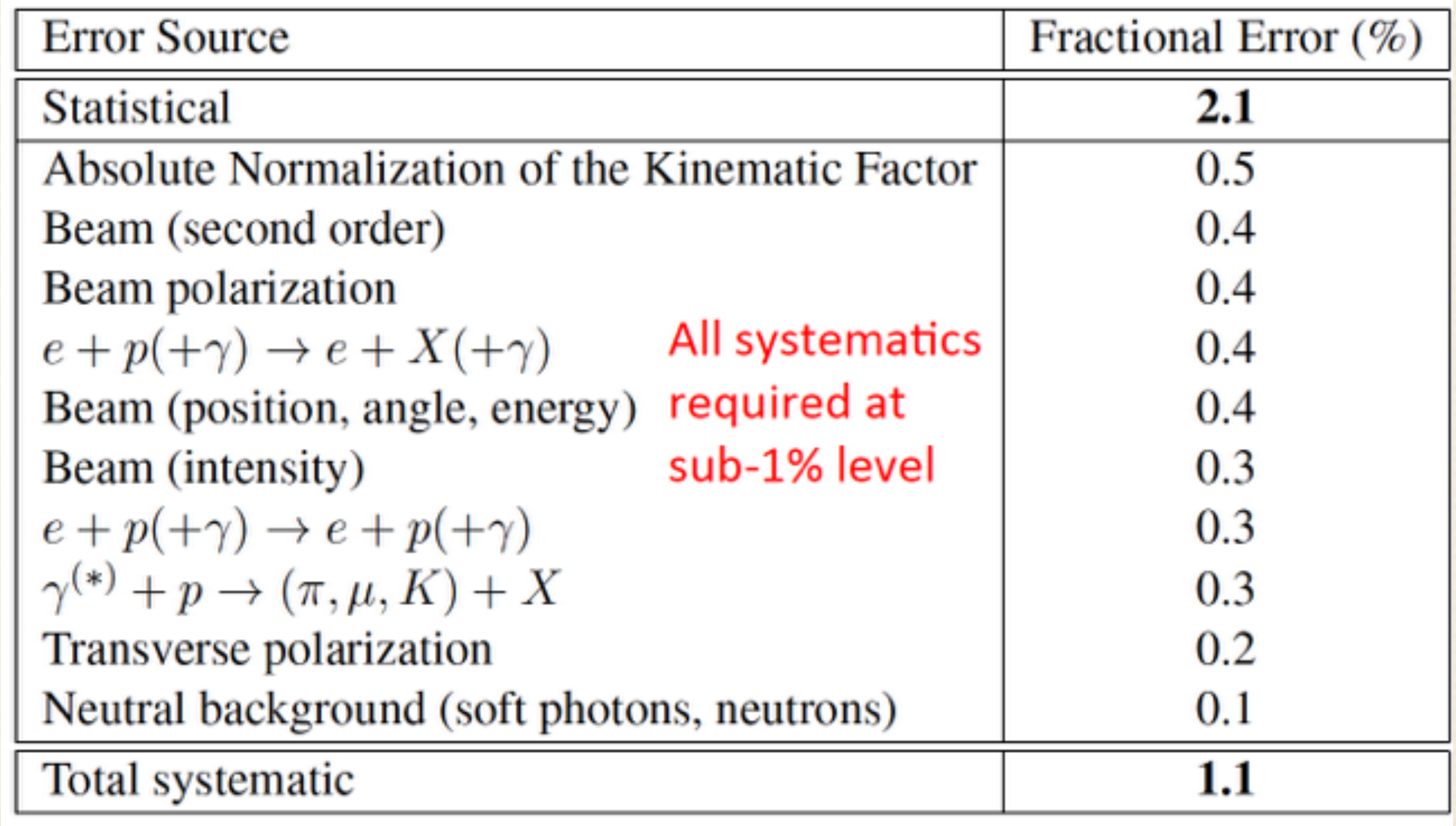




MOLLER Uncertainty Table



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

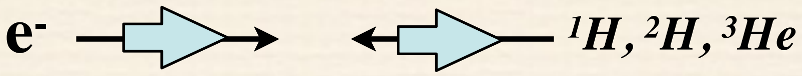


Error Source	Fractional Error (%)
Statistical	**2.1**
Absolute Normalization of the Kinematic Factor	0.5
Beam (second order)	0.4
Beam polarization	0.4
$e + p(+\gamma) \rightarrow e + X(+\gamma)$	0.4
Beam (position, angle, energy)	0.4
Beam (intensity)	0.3
$e + p(+\gamma) \rightarrow e + p(+\gamma)$	0.3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

All systematics required at sub-1% level

High luminosity: precision measurements of PV observables

EW Structure Functions at the EIC



The core physics topics of the EIC have driven designs that reach a new regime of extraordinarily high polarized luminosity, state-of-the-art collider detector technology and precision polarimetry

$$\frac{1}{2m_N} W^i_{\mu\nu} = -\frac{g_{\mu\nu}}{m_N} F^i_1 + \frac{p_\mu p_\nu}{m_N (p\cdot q)} F^i_2 + i\frac{\epsilon_{\mu\nu\alpha\beta}}{2(p\cdot q)}\left[\frac{p^\alpha q^\beta}{m_N} F^i_3 + 2q^\alpha S^\beta g^i_1 - 4x p^\alpha S^\beta g^i_2\right] - \frac{p_\mu S_\nu + S_\mu p_\nu}{2(p\cdot q)} g^i_3 + \frac{S\cdot q}{(p\cdot q)^2} p_\mu p_\nu g^i_4 + \frac{S\cdot q}{p\cdot q} g_{\mu\nu} g^i_5$$

Ji, Vogelsang, Blümlein, ...
Anselmino, Efremov & Leader,
Phys. Rep. **261** (1995)

High luminosity: precision measurements of PV observables

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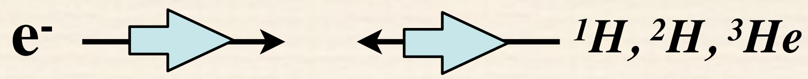

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polarized ***electron, unpolarized hadron***

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

unpolarized ***electron, polarized hadron***

$$A_{TPV} = \frac{G_F Q^2}{2\sqrt{2}\pi\alpha}\left[g_V\frac{g_5^{\gamma Z}}{F_1^\gamma} + g_A f(y)\frac{g_1^{\gamma Z}}{F_1^\gamma}\right]$$

proton	**deuteron**
$F_1^{\gamma Z} \propto u + d + s$	$F_1^{\gamma Z} \propto u + d + 2s$
$F_3^{\gamma Z} \propto 2u_v + d_v$	$F_3^{\gamma Z} \propto u_v + d_v$
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High luminosity: precision measurements of PV observables

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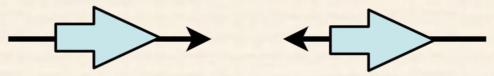

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$$a(x) = \frac{3}{10}\left[(2C_{1u} - C_{1d})\right] + \cdots \quad b(x) = \frac{3}{10}\left[(2C_{2u} - C_{2d})\frac{u_v(x) + d_v(x)}{u(x) + d(x)}\right] + \cdots$$

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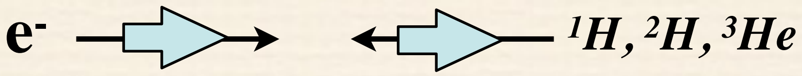

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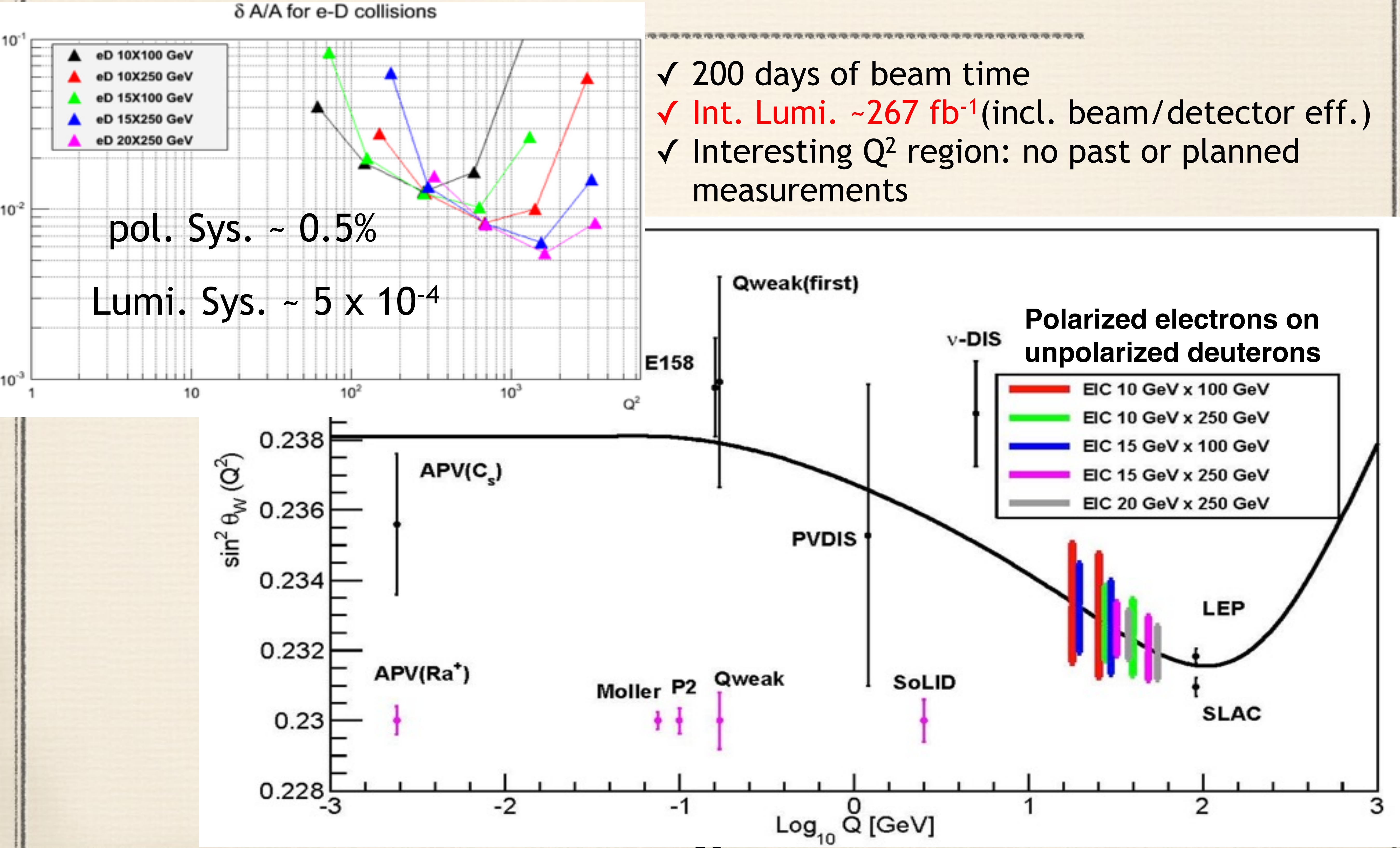
Propose a dedicated deuteron run: this observable will average over the deuteron polarization

Y.X. Zhao, A. Deshpande, KK, S. Riordan (SBU), J. Huang (BNL)

EIC Weak Mixing Angle

- ✓ 200 days of beam time
- ✓ Int. Lumi. ~267 fb^{-1}(incl. beam/detector eff.)
- ✓ Interesting Q^2 region: no past or planned measurements



pol. Sys. ~ 0.5%

Lumi. Sys. ~ 5 x 10^{-4}

Lepton Flavor Conservation

Is it exact? No! Neutrino Oscillations!

- ν's have mass! *individual lepton flavors are not conserved*
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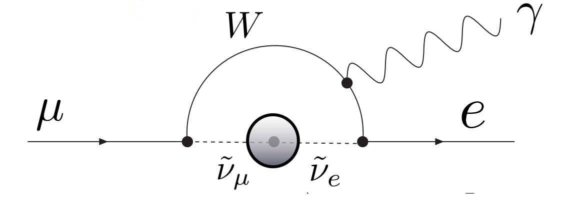

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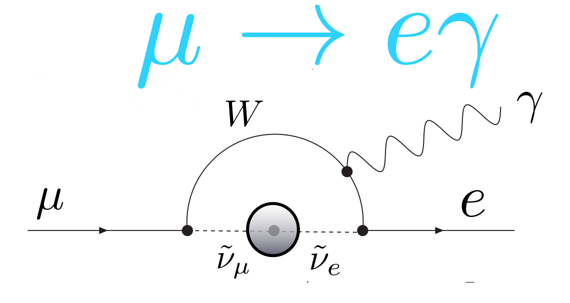

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tiny standard model branching fraction

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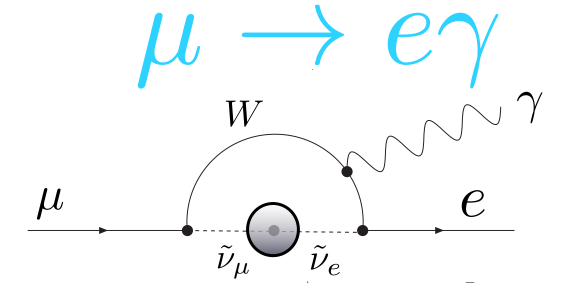

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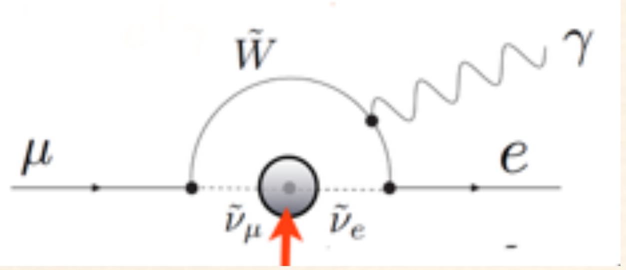
Slepton mixing
in SUSY



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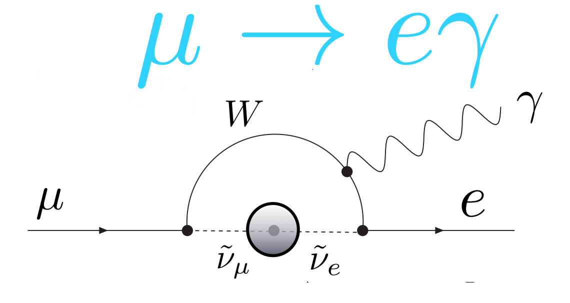

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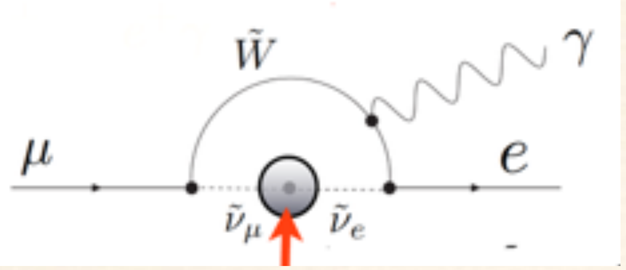

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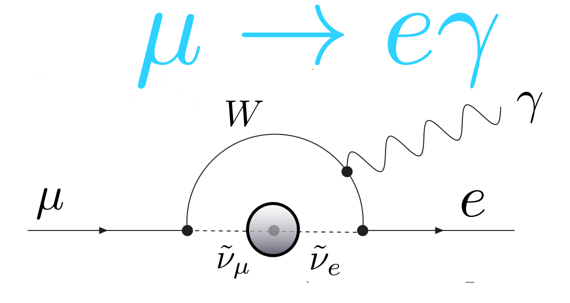

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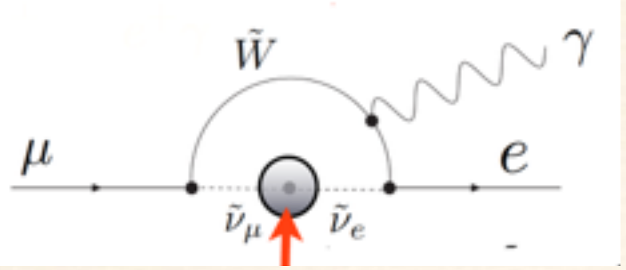

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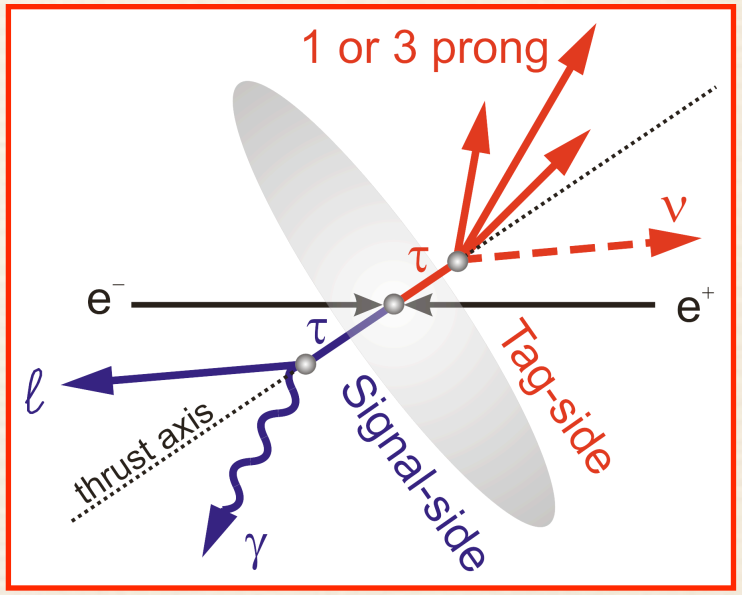
μ or τ ⟶ eγ, e^+e^-e, K_L→μe, ...

Need very high fluxes for required statistical reach

New high intensity kaon & muon beams and high luminosity e+e- colliders all over the world



Tau Decays at e+e- colliders

Even a decade from now, the EIC can compete in the first-to-third generation searches

e-τ Conversion Search

$$e^- + p \rightarrow \tau^- + X$$

Topology: neutral current DIS event; except that the electron is replaced by tau lepton

- If mixed in with hadron remnants, the tau would be boosted
- If forward in the incident electron direction, the tau would be isolated
- Potential for clean identification with high efficiency:
  - look for single pion, three pions in a narrow cone, single muon: should be able to devise several good triggers
  - tau vertex displaced 200 to 3000 microns: would greatly help background rejection and maintain high efficiency if vertex detector is included in EIC detector design

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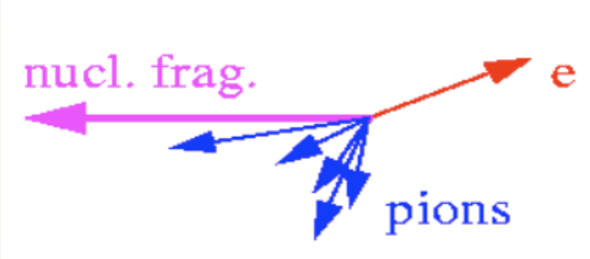
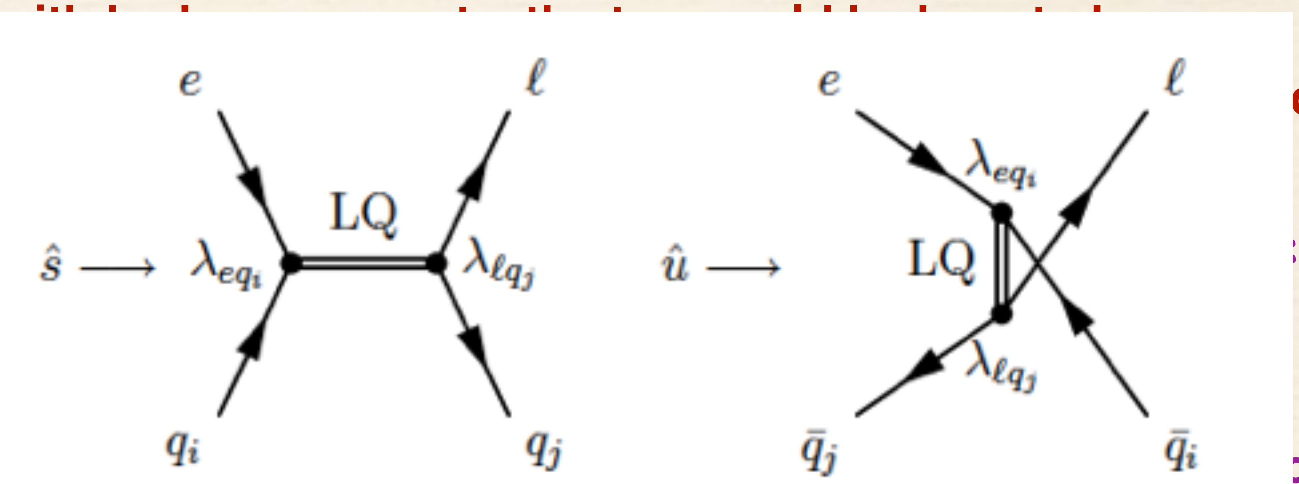


- If mixed in
- If forward i … d
- Potential fo
  - look for … should be able to
  - tau ver … background rejectio … cluded in EIC de … design



Gonderinger and Ramsey-Musolf, arXiv: 1006.5063

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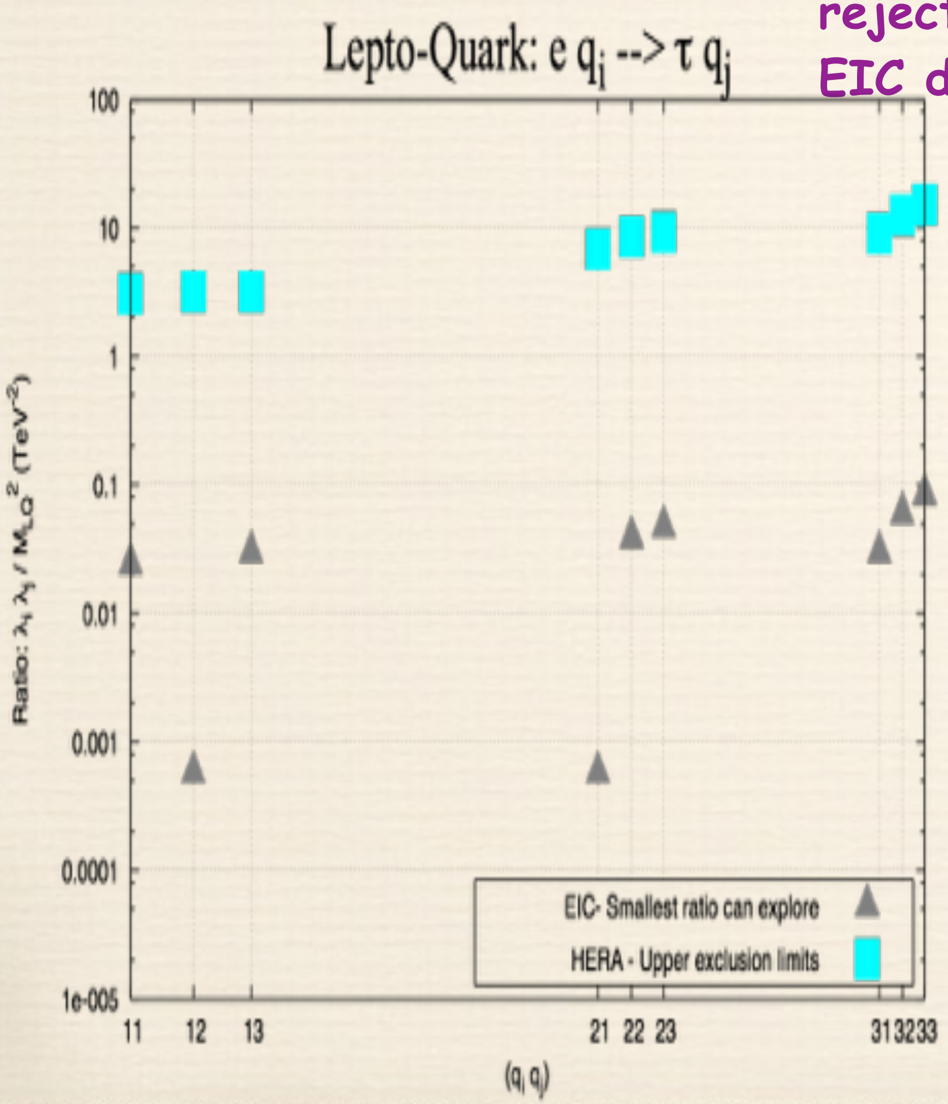
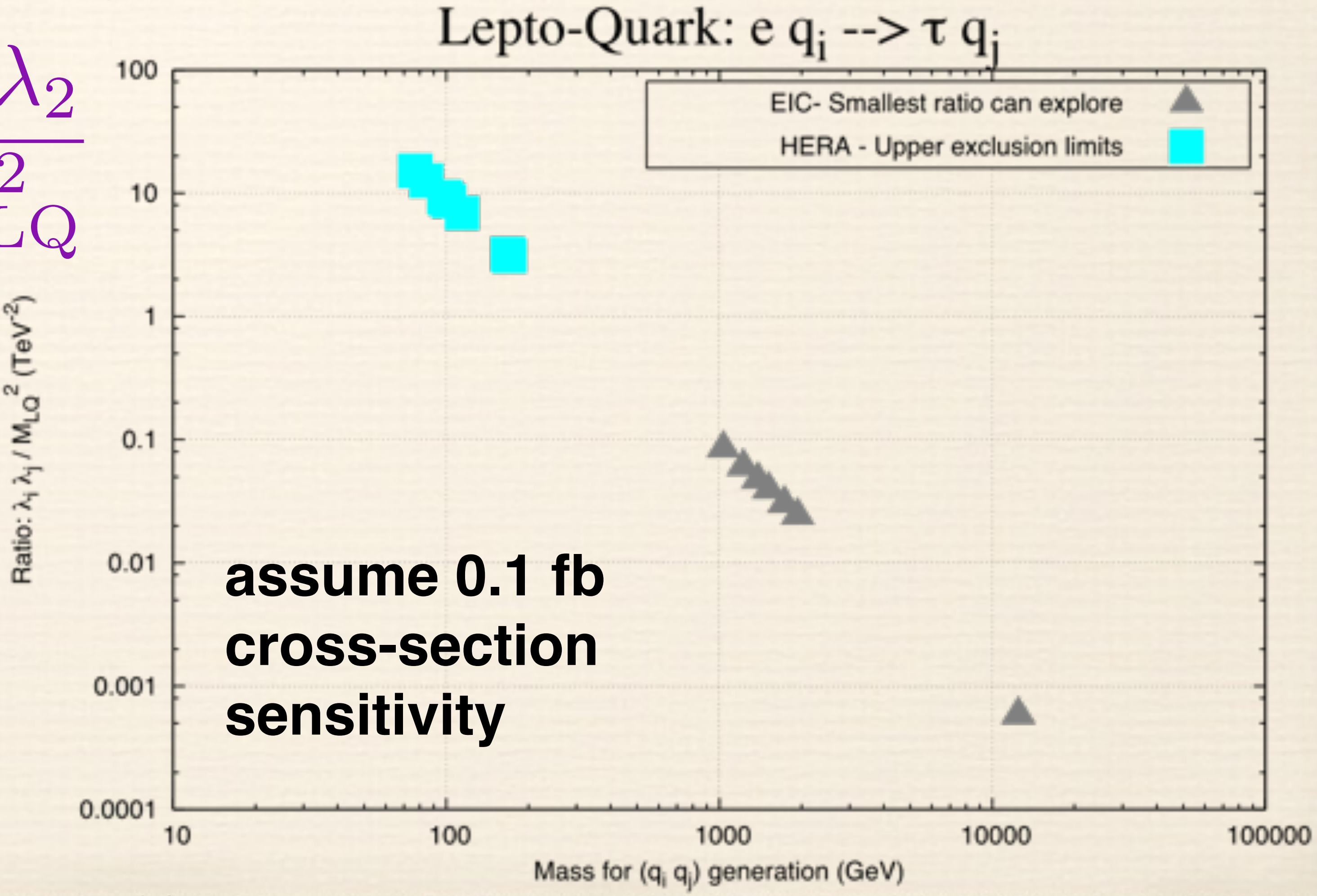


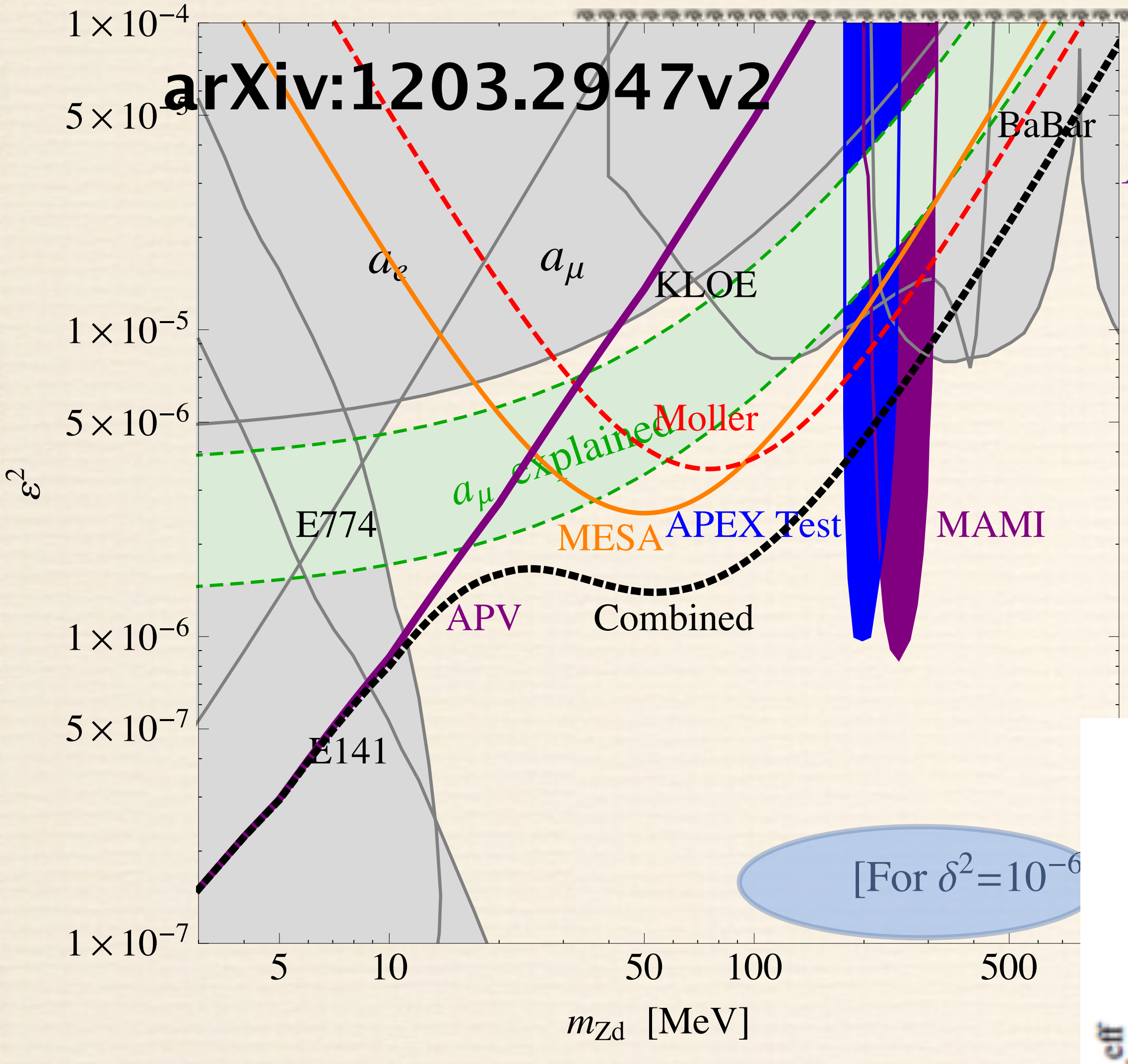
$$\frac{\lambda_1 \lambda_2}{M_{\rm LQ}^2}$$



assume 0.1 fb cross-section sensitivity

Dark Z to Invisible Particles

Davoudiasl, Lee, Marciano



Dark Photons:

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

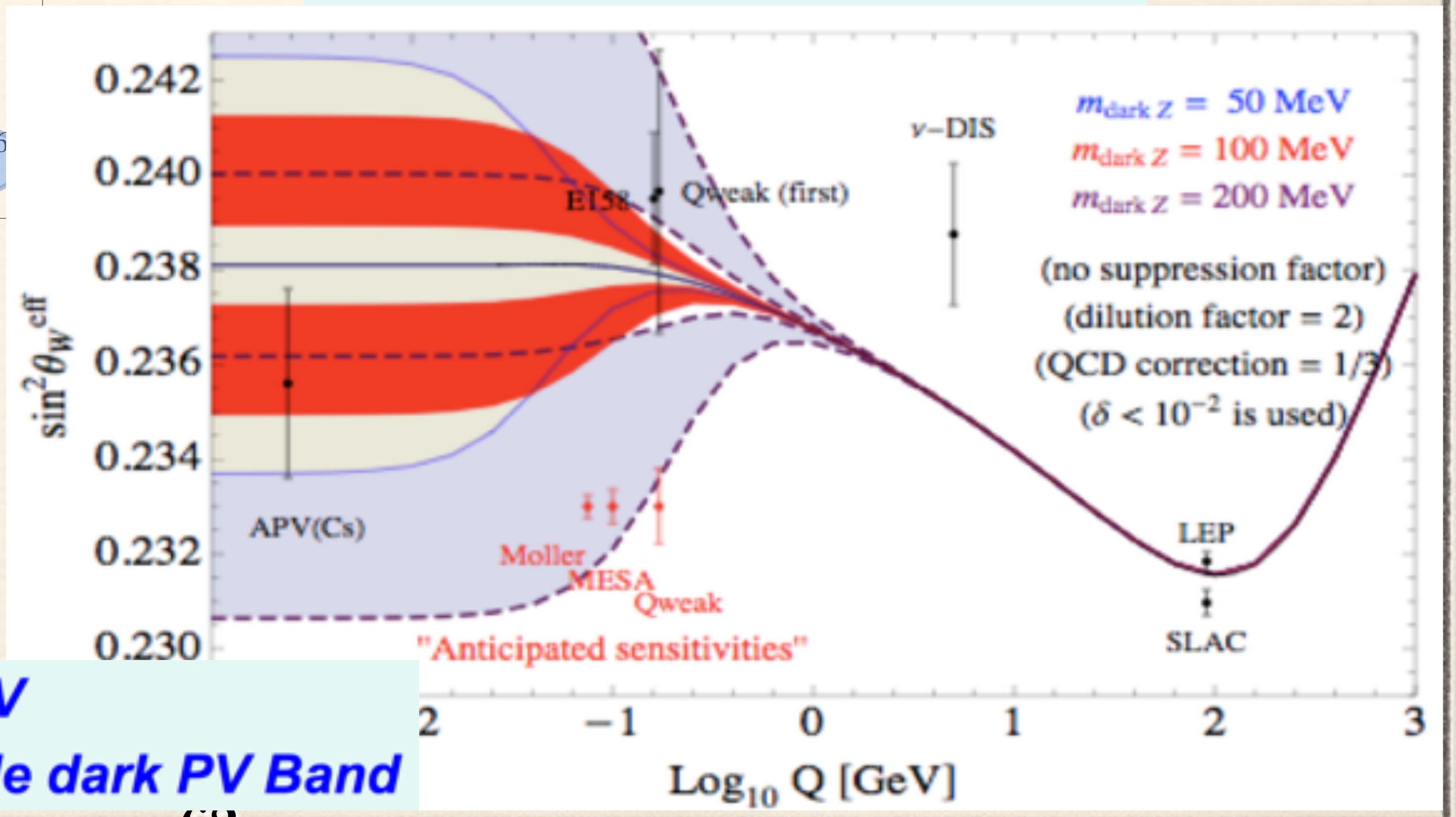
$$\epsilon_Z = \frac{m_{Z_d}}{M_Z}\delta$$

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

  APV & Polarized Electron Scattering at low <Q>

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

δ^2 roughly probed to 10^{-6}



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

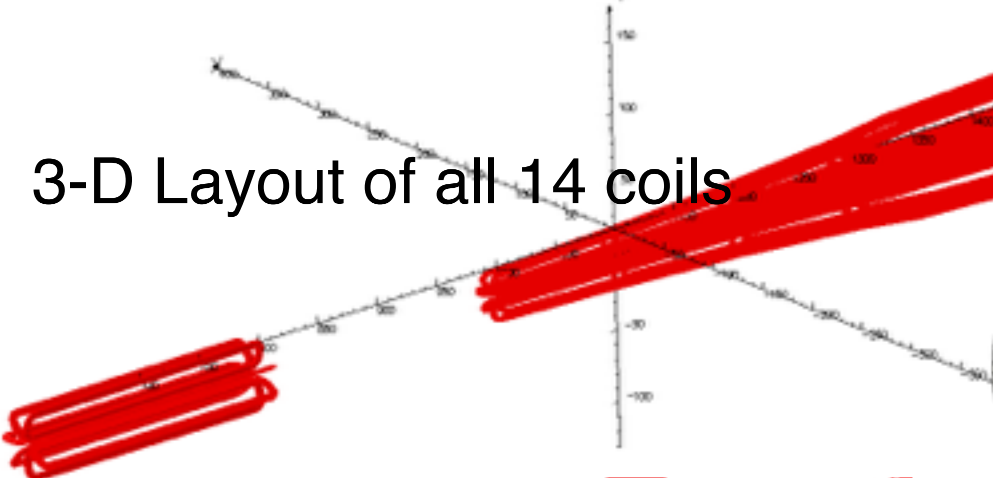
ε and δ effects could partially cancel!

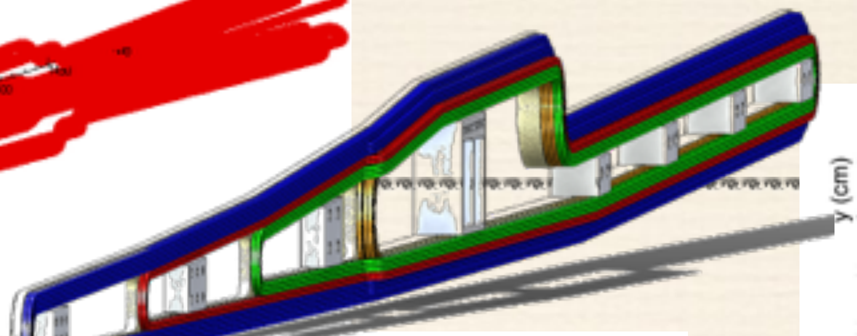
Suppression by ~1/6 allows Z_d~100MeV

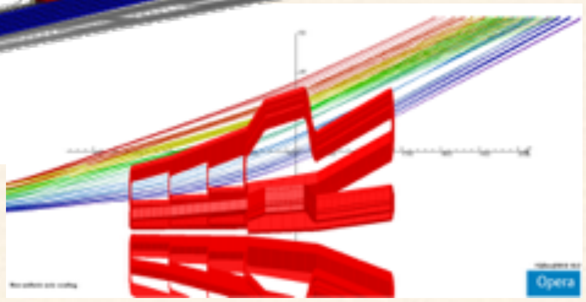
Combined with muon g-2 → observable dark PV Band

Spectrometer Engineering

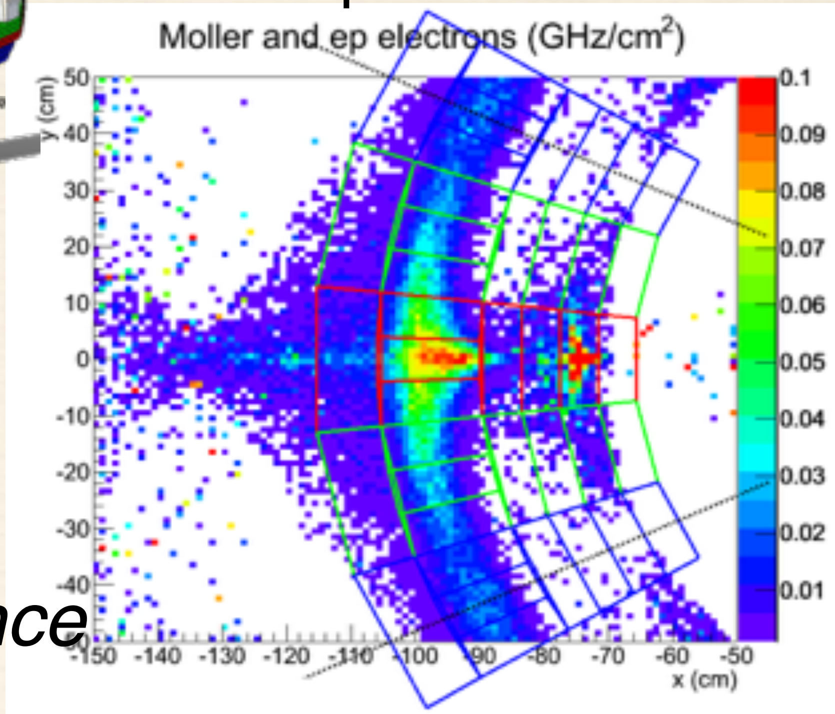
3-D Layout of all 14 coils

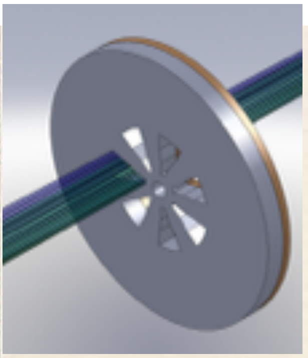




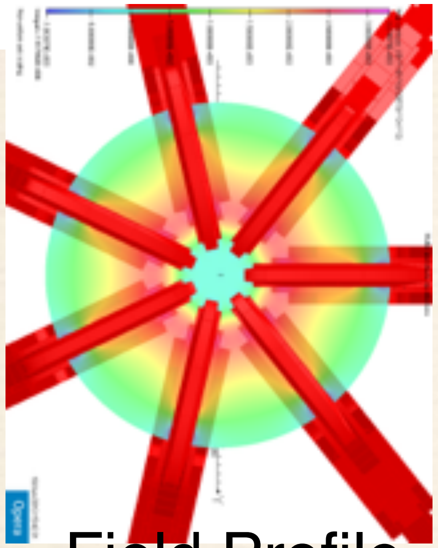


Detector plane distribution





Acceptance collimator



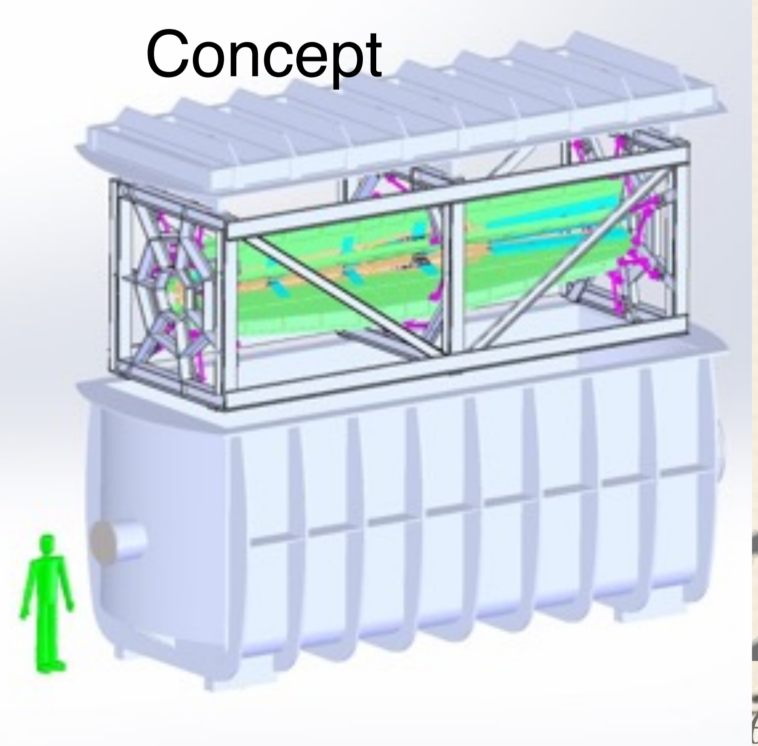
Field Profile

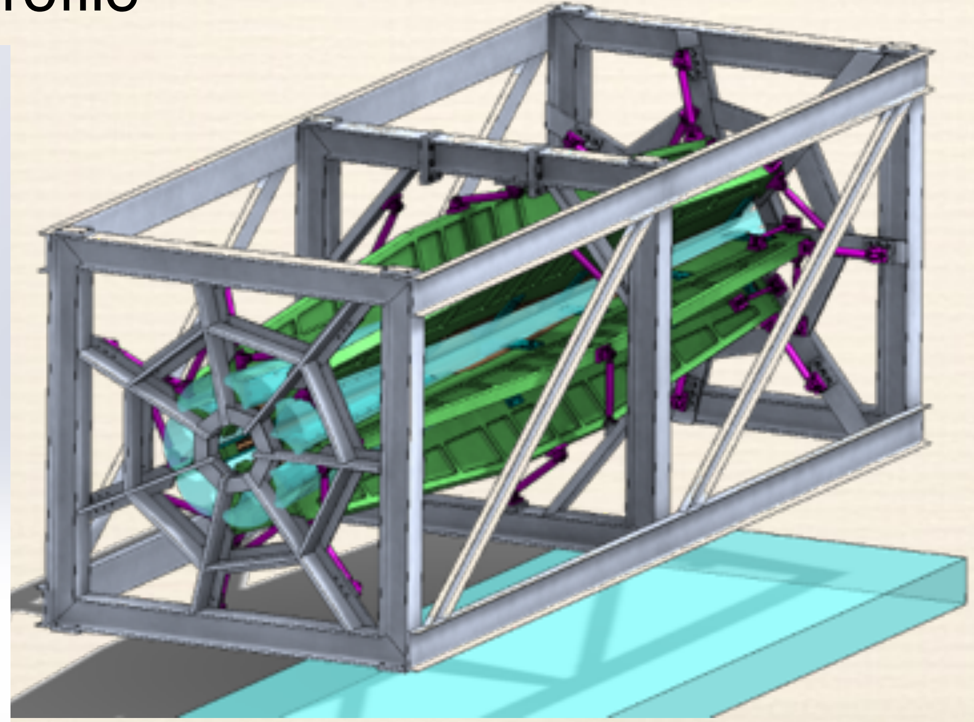
- *Full Azimuthal Acceptance*
- *Warm copper coils*
- *Water cooling*

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

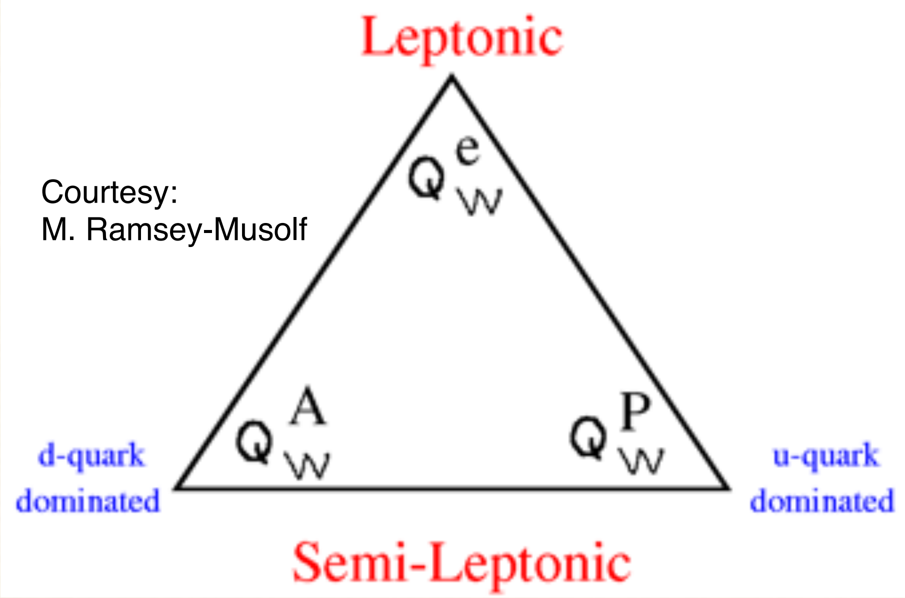
- Engineering work
  - — Native CAD model
  - — Water-cooling
  - — Support structure
  - — Force calculations

Vacuum Tank Concept





PVES Initiatives: Complementarity



Courtesy:
M. Ramsey-Musolf

$$[2C_{2u} - C_{2d}]$$

axial-quark couplings

vector-quark couplings

SUSY Loops → Q_W^e and Q_W^p:same absolute shift, smaller for others

GUT Z’ → High for Q_W(Cs), Q_W^e(relative), smaller for others

Leptophobic Z’ → axial-quark couplings (C_2’s) only

RPV SUSY → Different for all four in sign and magnitude

Leptoquarks → semi-leptonic only; different sensitivities

Lepton Number Violation → Q_W^e only

Generic Model Reach

$$X(Q^2) \equiv \alpha^{-1}(\sin^2\theta_W(Q^2) - \sin^2\theta_W(M_Z^2))$$

$$\begin{aligned} Q_W^e &= -0.0435[1 + 0.7\,X(Q^2) + 7m_Z^2/m_{Z_\chi}^2] \\ Q_W^p &= 0.0707[1 + 0.43\,X(Q^2) + 4.3m_Z^2/m_{Z_\chi}^2] \\ Q_W(^{12}C) &= -5.510[1 - 0.033\,X(Q^2) - m_Z^2/m_{Z_\chi}^2] \\ Q_W(^{133}Cs) &= -73.24[1 - 0.023\,X(Q^2) - 0.9m_Z^2/m_{Z_\chi}^2] \end{aligned}$$

$$\mathbf{2.4\%\ Q_W^e \Longrightarrow 1.4\%\ Q_W^p,\ 0.34\%\ Q_W(^{12}C),\ 0.3\%\ Q_W(^{133}Cs)}$$

12% 6% 25% 0.6%

published uncertainties

The projected equivalent uncertainties in competing axial-electron, vector-electron/quark neutral current amplitudes remain challenging to reach.

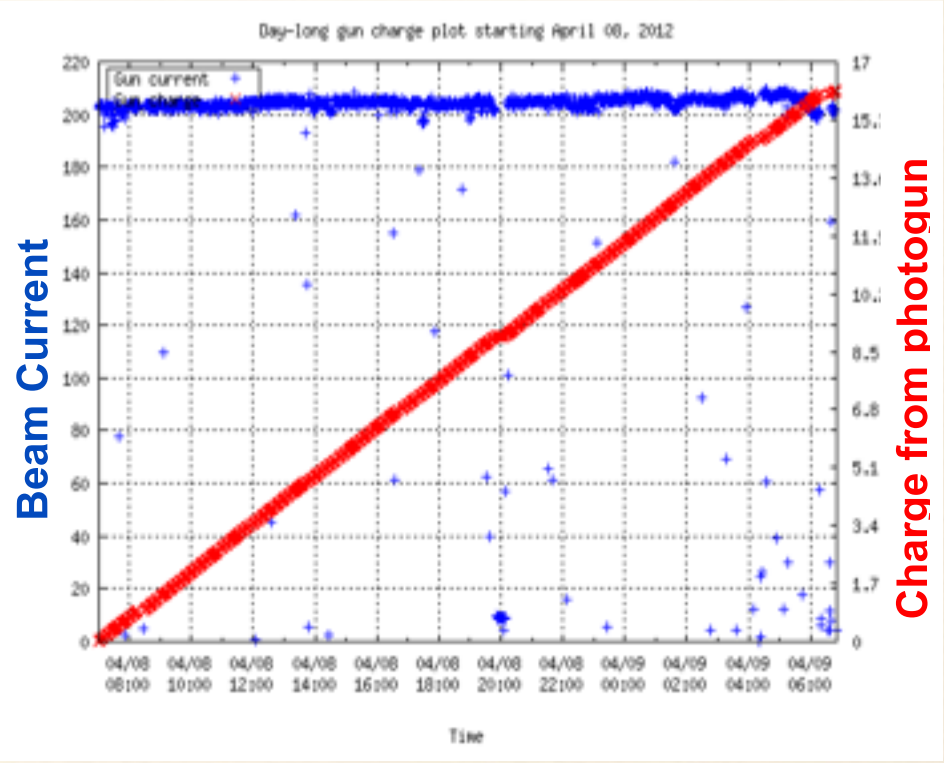
Polarized Source at JLab

B. Matthew Poelker
2011 E. O. Lawrence Award

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

Electron Gun Requirements

- **Ultrahigh vacuum**
- **No field emission**
- **Maintenance-free**



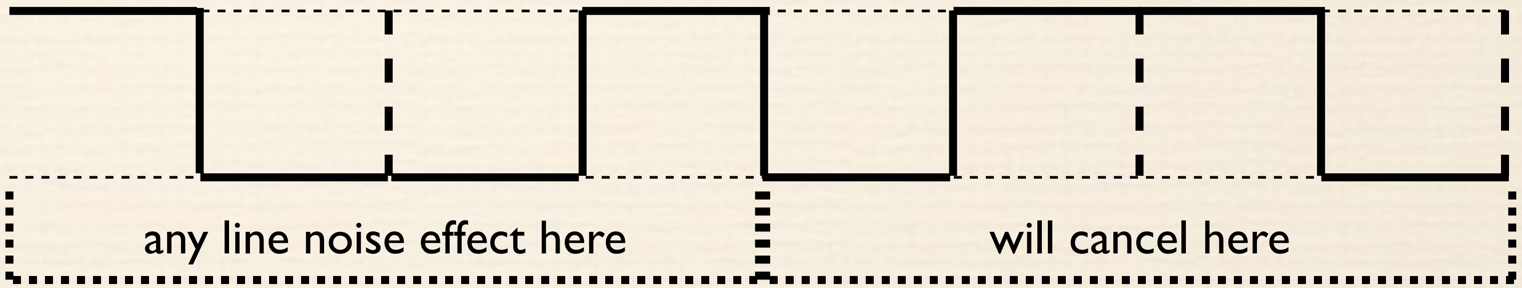
← **24 Hours** →

✧ **Beam helicity is chosen pseudo-randomly at multiple of 60 Hz**

- ***sequence of "window multiplets"***

Example: at 240 Hz reversal

Choose 2 pairs pseudo-randomly, force complementary two pairs to follow



Analyze each "macropulse" of 8

MOLLER will plan to use 1.96 kHz reversal; subtleties in details of timing (e.g. 64-plet)

Noise characteristics have been unimportant in past JLab experiments: Not so for PREX, Qweak and MOLLER....

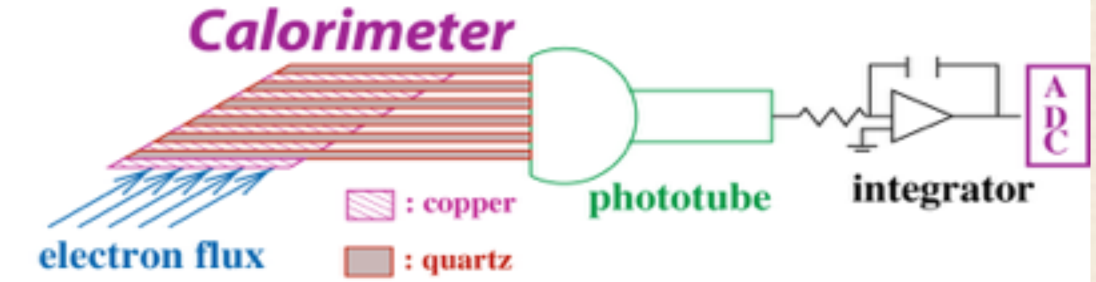
Instantaneous Signal Rate ~ 100 GHz

Flux Integration

1 kHz Pulse Pair Width: ~100 ppm → 10 Billion Pairs: 1 ppb (average 10^7 s)

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

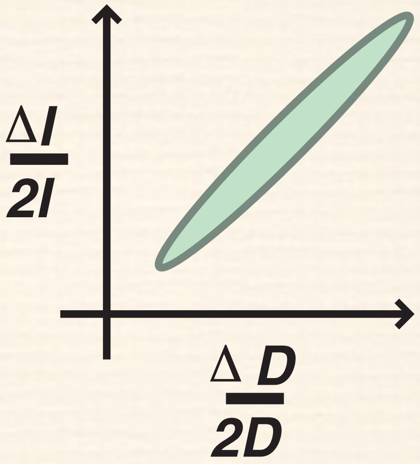
$$A_{pair} = \frac{\Delta F}{2F} + \Delta A$$

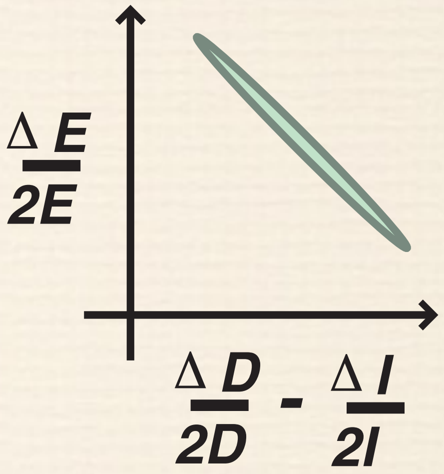


Detector D, Current I: F = D/I

I order: x, y, θ_x, θ_y, E

II order: e.g. spot-size



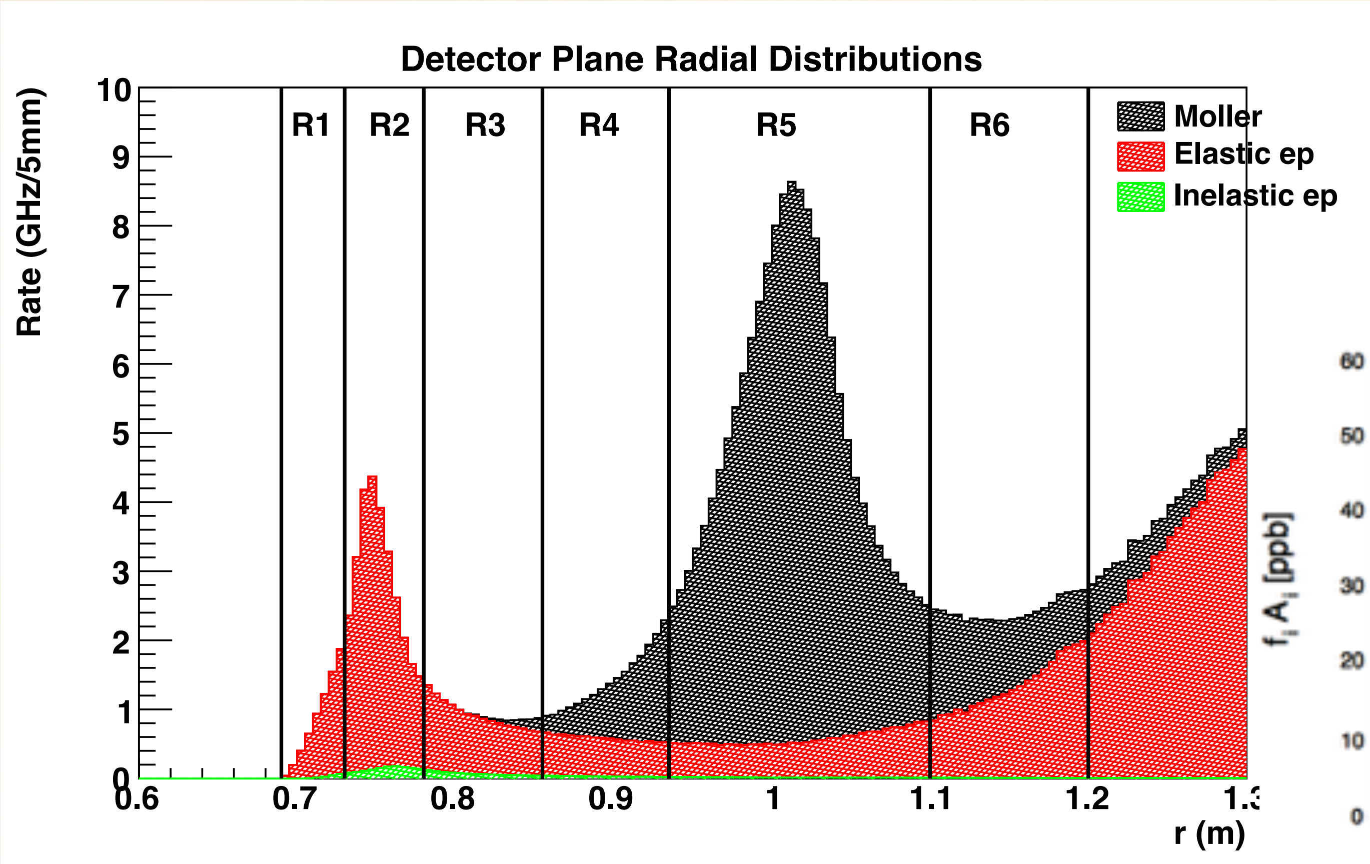


After corrections, variance of A_{pair} must get as close to counting statistics as possible: ~ 100 ppm (1kHz pairs); central value then reflects A_{phys}

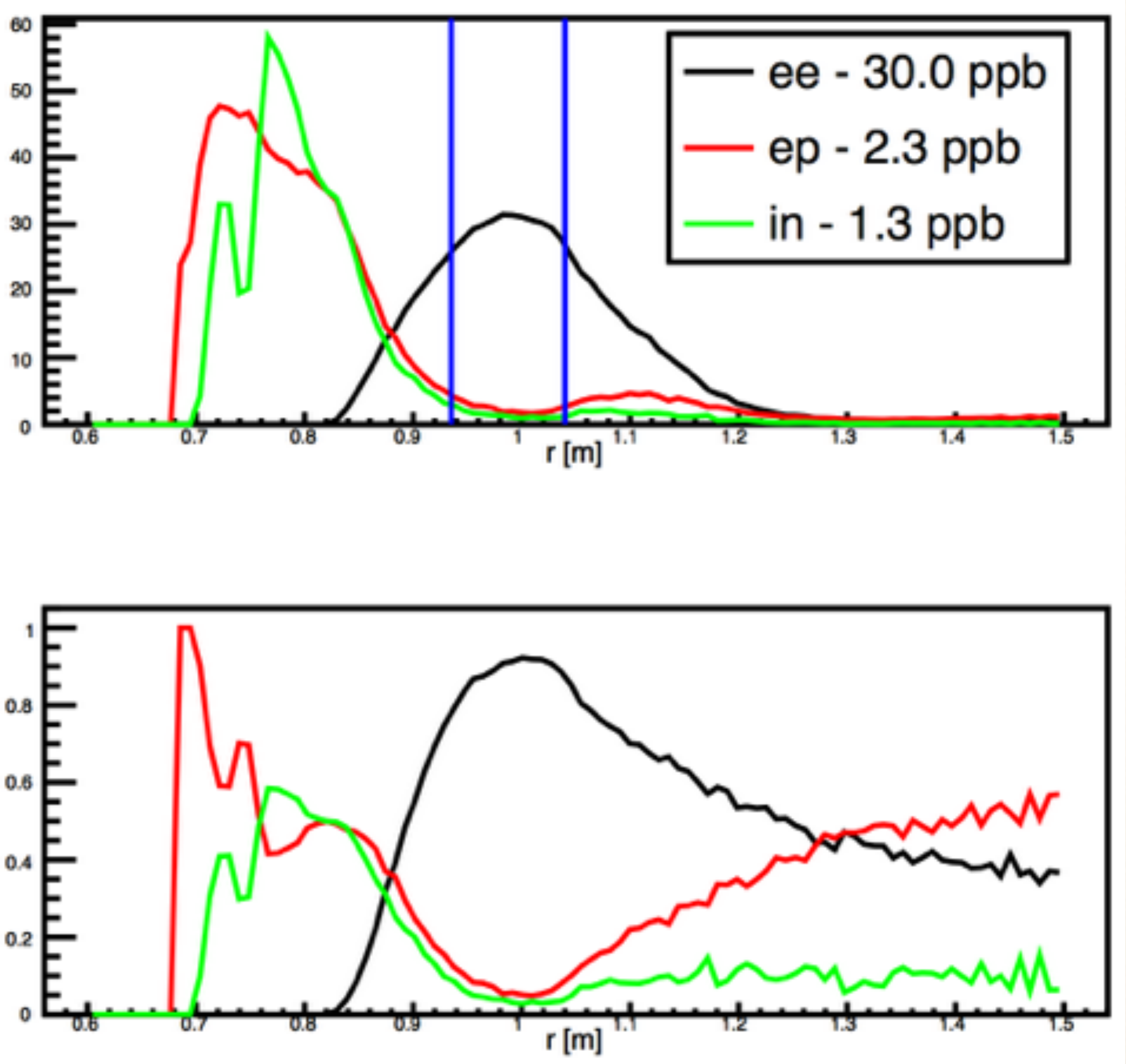
Must minimize (both) random and helicity-correlated fluctuations in average window-pair response of electron beam trajectory, energy and spot-size.

The characteristics of the JLab beam, both at the 2 kHz time scale (~ppm, microns), to grand averages over several days (~ppb, nm), are critical to extracting a measurement which is dominated by statistical fluctuations.

MOLLER Backgrounds



The primary irreducible backgrounds are from electrons scattering elastically and inelastically off target protons

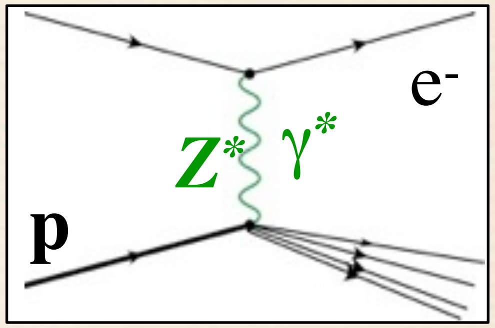


- photons and neutrons
  - 2-bounce collimation system
- pions and muons
  - real and virtual photo-production and DIS
  - continuous parasitic measurement: guards against potential hyperon background

EW Physics and QCD Interplay

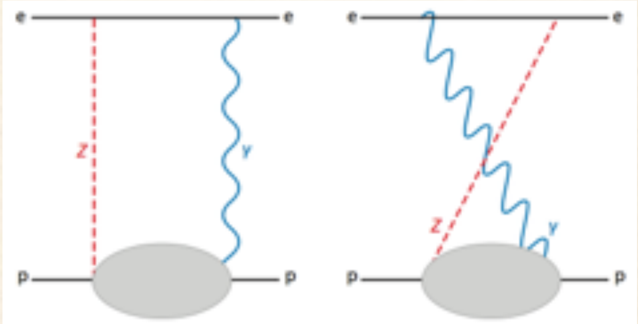
- **Strange Quark Form Factors**

electrons
on LH_2



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

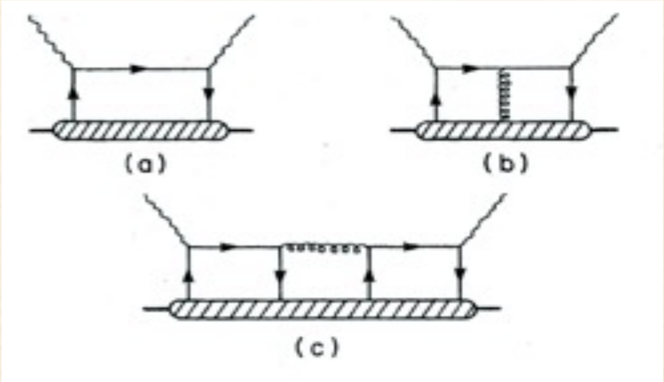
- **Box diagram uncertainties**



  - Proton weak charge modified; inelastic intermediate states

- **Parton dynamics in nucleons and nuclei**

Physics of SOLID



  - Higher twist effects
  - charge symmetry violation in the nucleon
  - "EMC" style effects: quark pdfs modified in nuclei

MOLLER Auxiliary Measurements

✦ A_{PV} in Inelastic Electron Proton Scattering

- ★ The intermediate rings will directly constrain the weak neutral current proton coupling in diffractive kinematics
- ★ New input to improved constraints on the box diagram uncertainties for calculation of the proton weak charge
- ★ Interesting QCD dynamics: related to quark-hadron duality

✦ Transverse Asymmetry Measurements

- ★ Dedicated Møller vector analyzing power measurements with transversely polarized beams: exquisite check of our understanding of the apparatus
- ★ Parasitic measurements of the vector analyzing power in elastic and inelastic electron-proton scattering in an entirely new kinematic regime
  - If the physics evolves such that heavier nuclei measurements become interesting: apparatus can be used for new measurements that would be feasible with just a few hours of beam!