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Low Energy Determinations of the

Weak Mixing Angle

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UMass, Amherst

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Low-Energy Measurements of the Weak Mixing Angle

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The E158, MOLLER and SOLID Collaborations

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Special thanks to Bill Marciano for numbers and education!

Outline

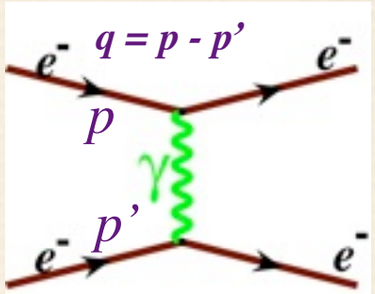
- **Early History**
  - Electroweak Unification
  - Parity-Violating Electron Scattering
- **Precision Electroweak Physics**
  - The Weak Mixing Angle at 1-Loop
    - *The Most Precise Measurements*
  - The Weak Mixing Angle at Low Energy
    - *The Three Best Measurements*
- **New Generation of Experiments**
  - Global Search for Physics Beyond the Standard Model
  - Ideas for the Far Future
- **Summary and Outlook**

Early History

EM and Weak Forces

By the late 1940s: A consistent relativistic quantum theory of Electromagnetic Interactions

Electromagnetic interactions mediated by "off-shell" or virtual photons: Quantum Electrodynamics (QED)



Charged particle scattering

Length scale of interaction $\lambda \sim \frac{\hbar c}{q}$

10^{-15} m: 200 MeV **10^{-18} m: 200 GeV**

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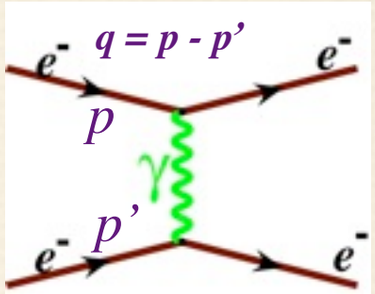

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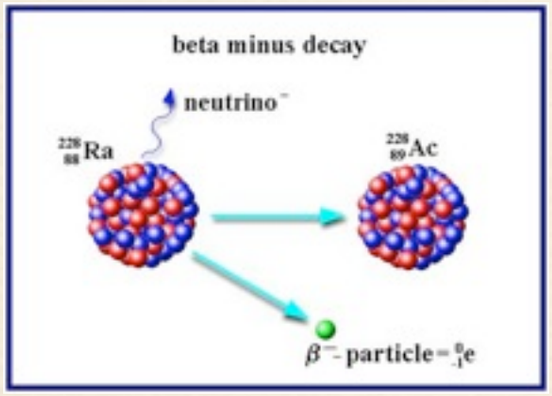
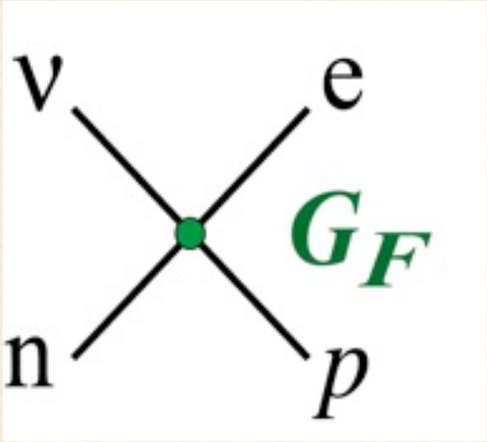
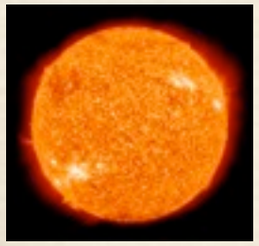
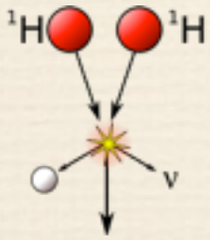


Fermi Theory for weak interactions

Universal strength: coupling constant G_F $\frac{G_F}{\sqrt{2}} \simeq \frac{1}{(350\ \mathrm{GeV})^2}$







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

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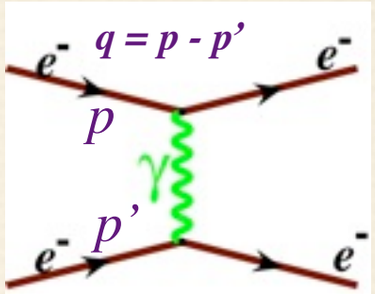

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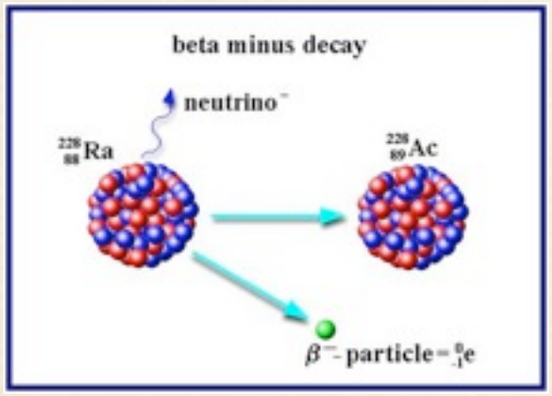

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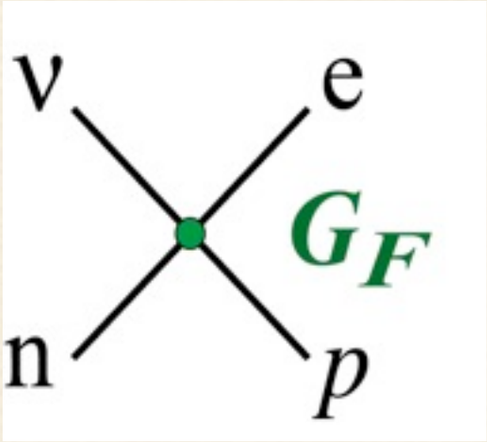

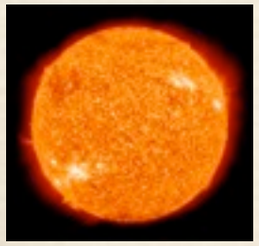

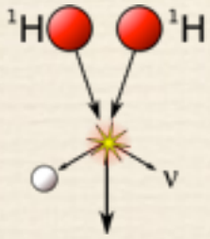

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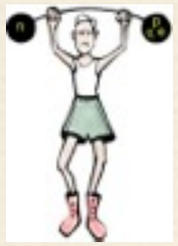
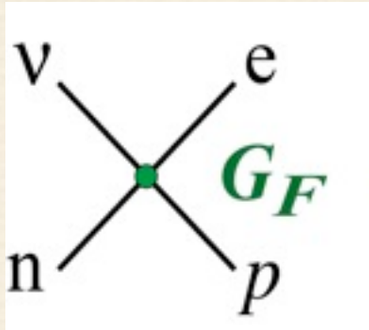
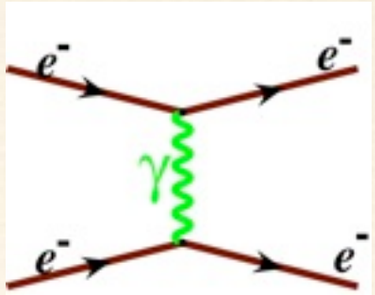
Theory expected to breakdown below 1 TeV

Electroweak Unification







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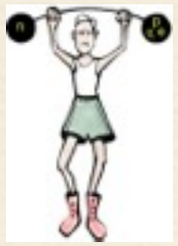

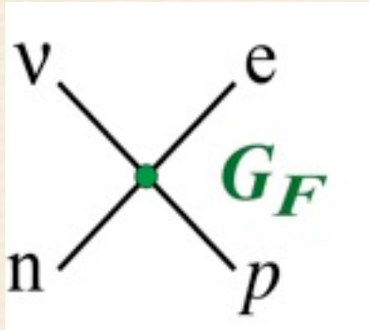

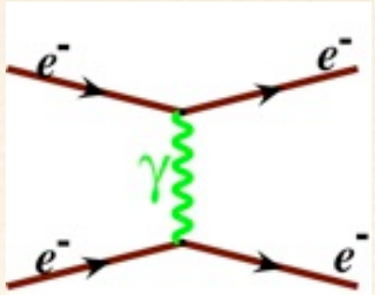

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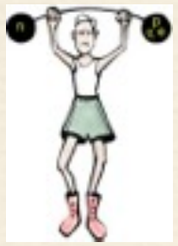

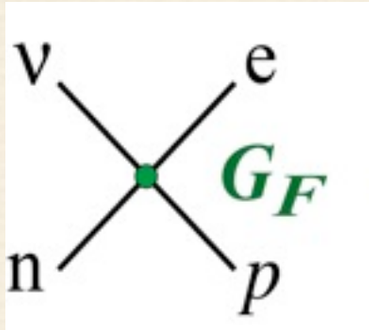

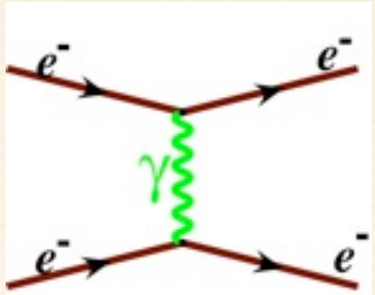

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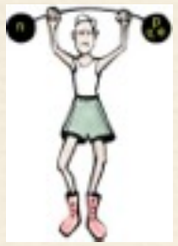

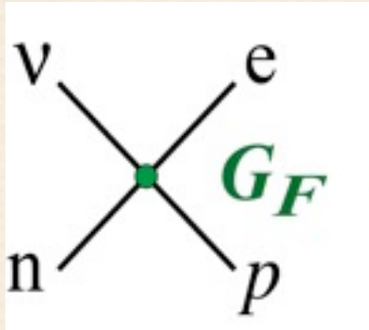

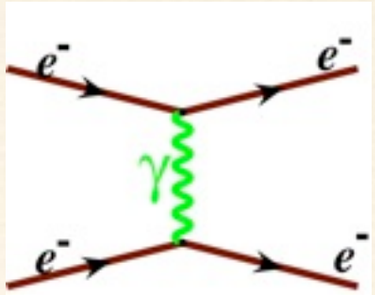

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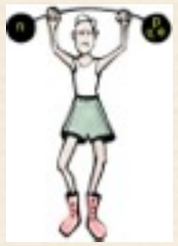

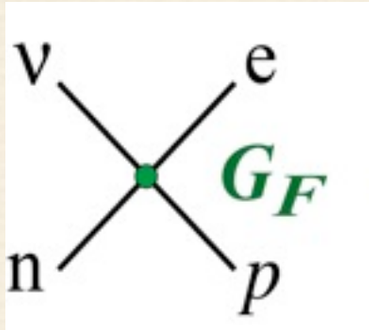

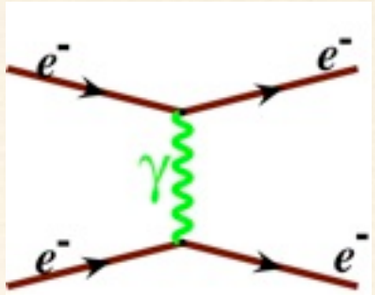

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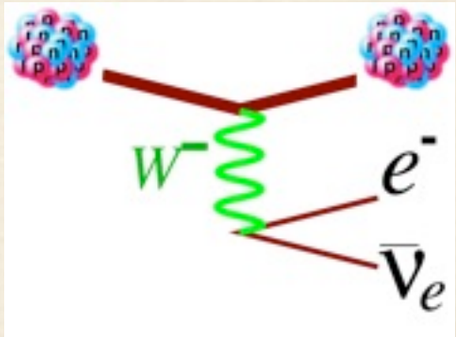
massive force carriers are W bosons ~ 80 GeV

^{60}Co ^{60}Ni



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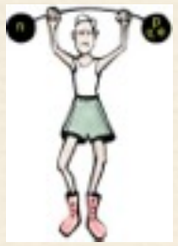

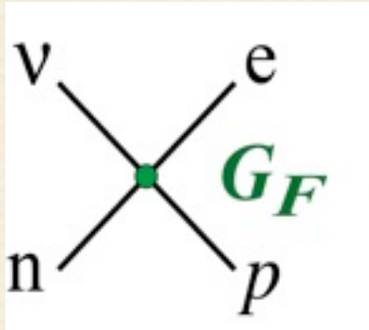

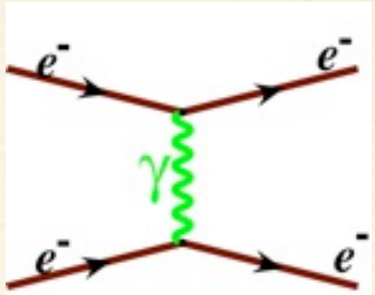

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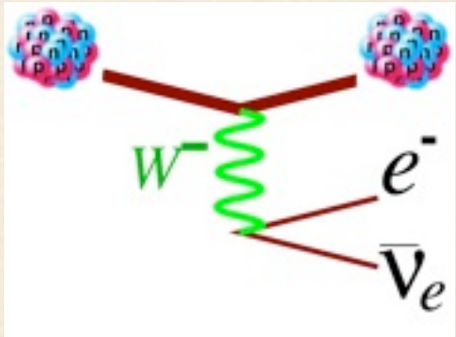


*Weak interactions do **not** obey mirror symmetry*

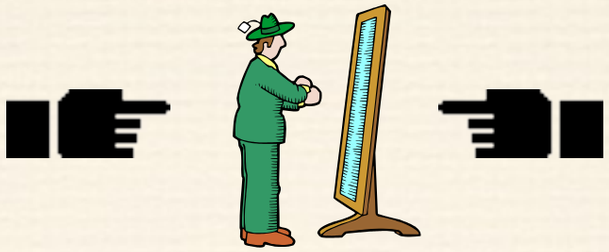
"handedness" plays a role

Theoretical speculation motivated by the τ-θ puzzle

Parity Violation Discovery 1957

parity transformation (reflection)

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



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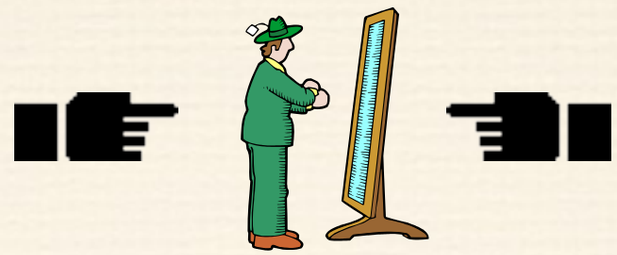

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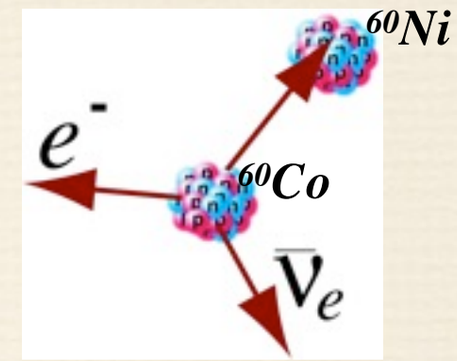
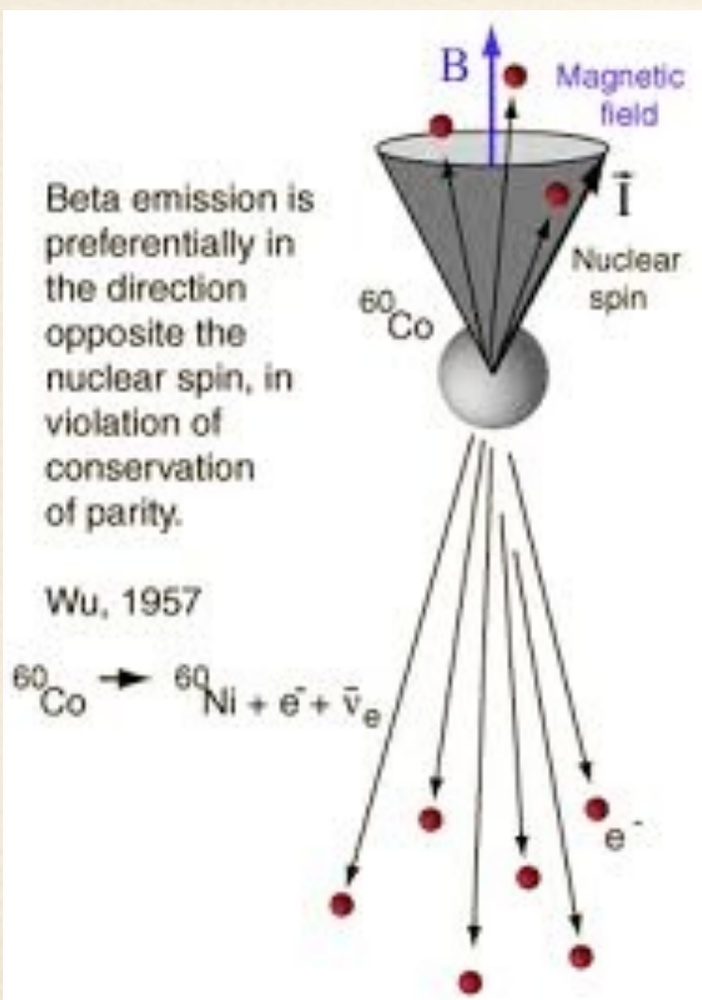


Weak decay of ^{60}Co Nucleus



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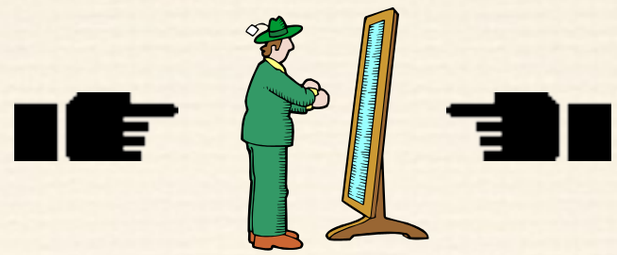

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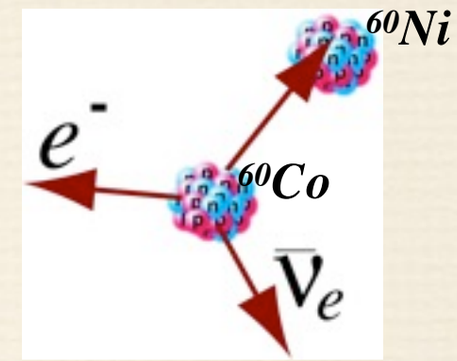

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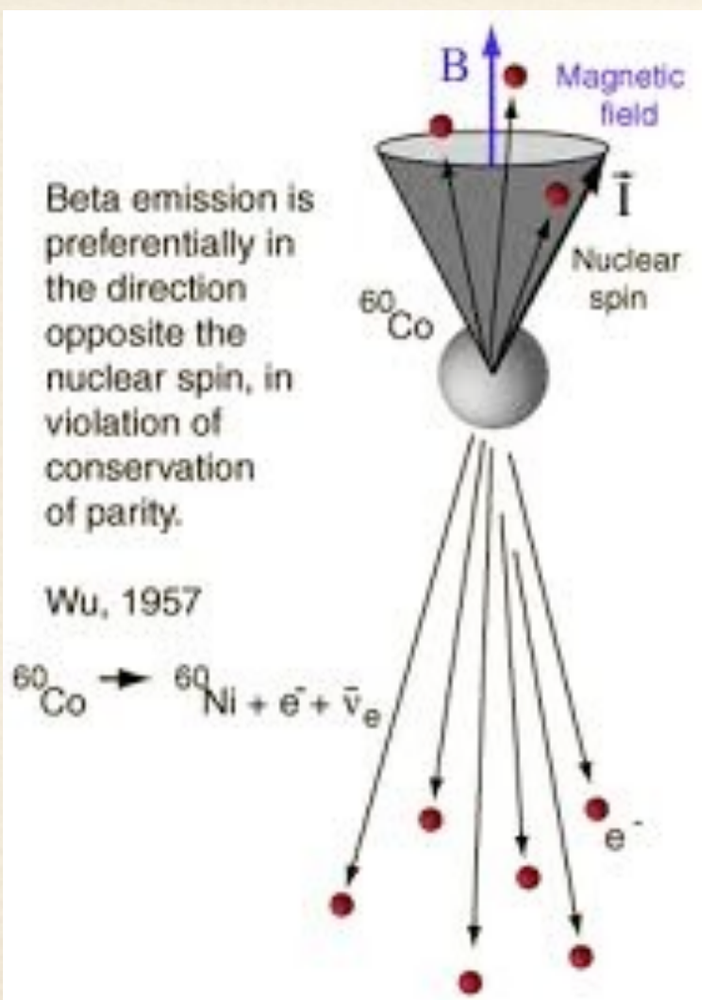

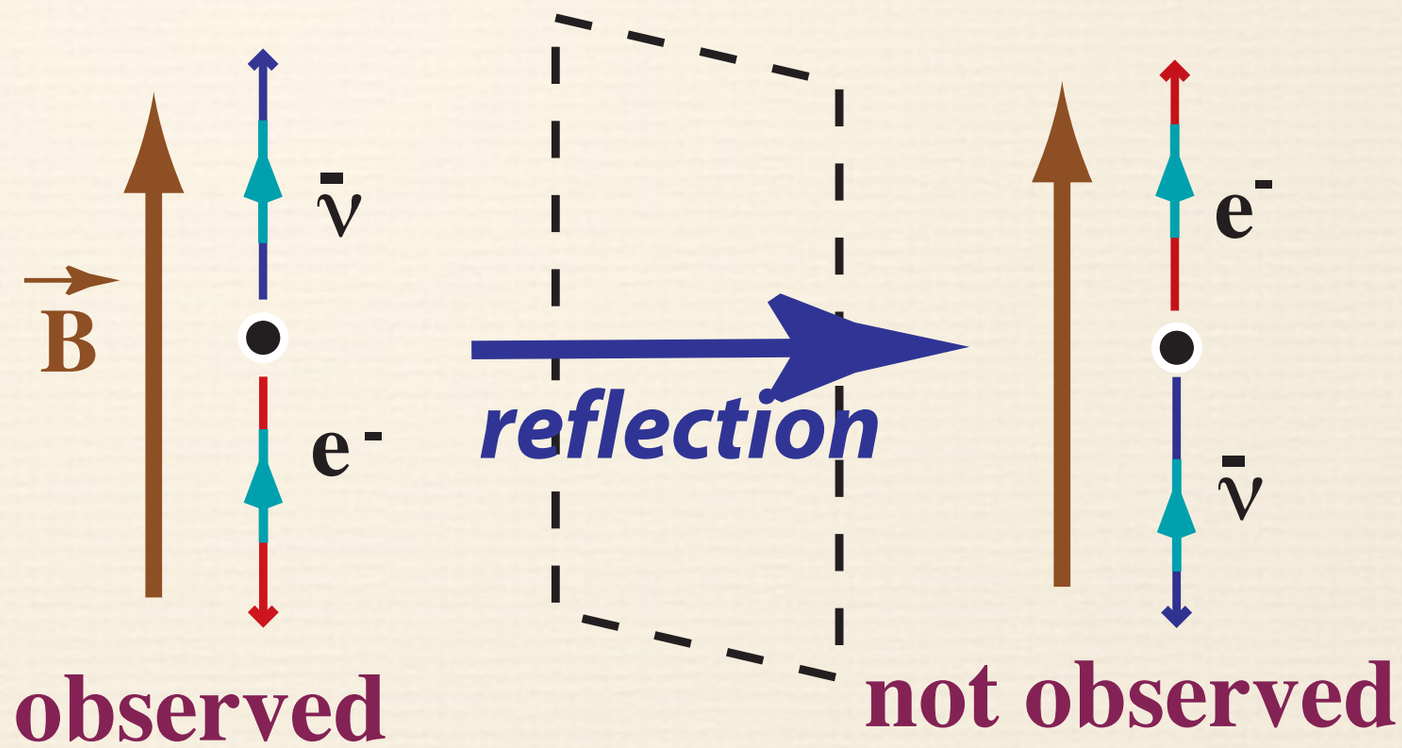

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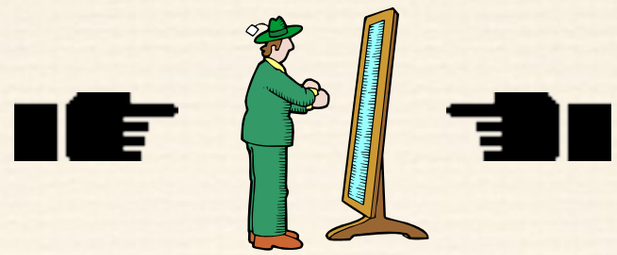

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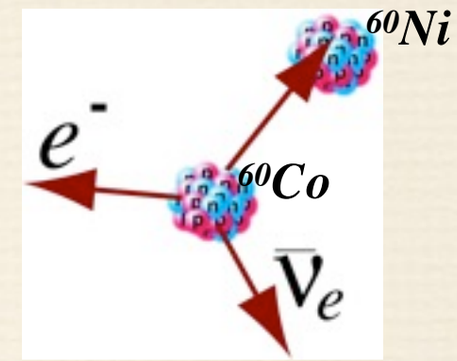

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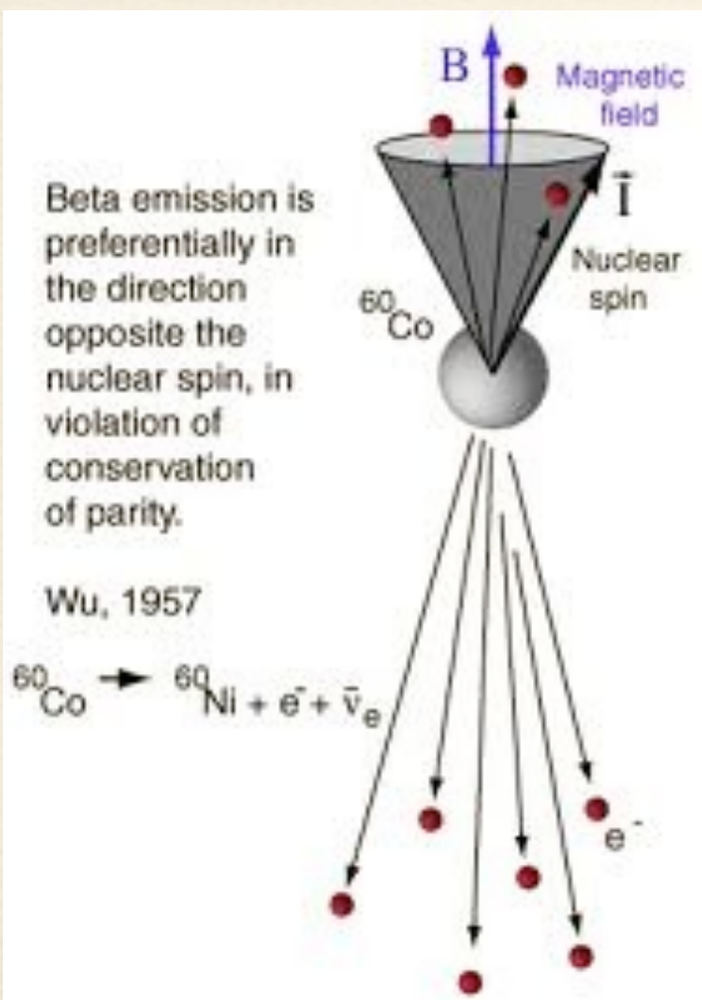

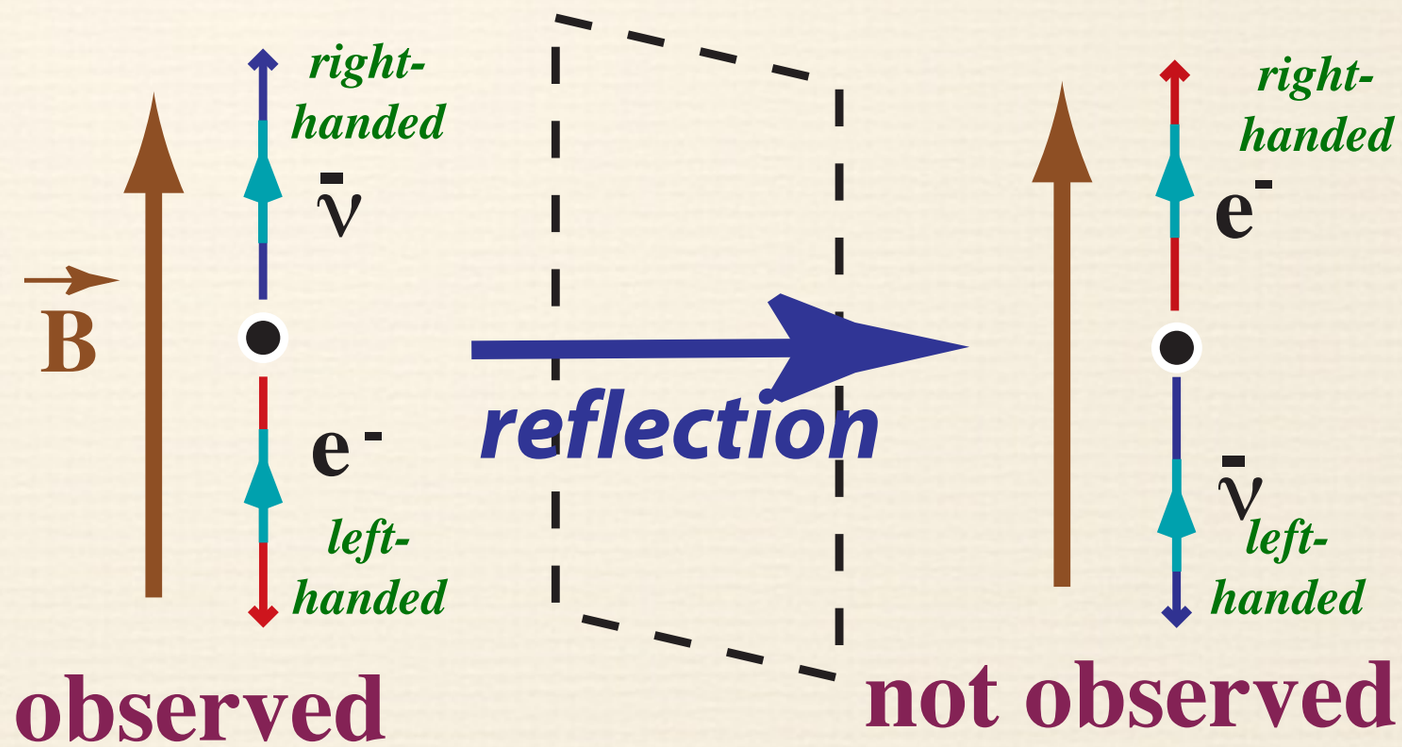

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Nature is not "mirror-symmetric"

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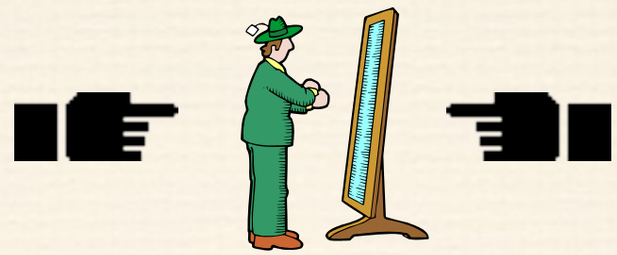

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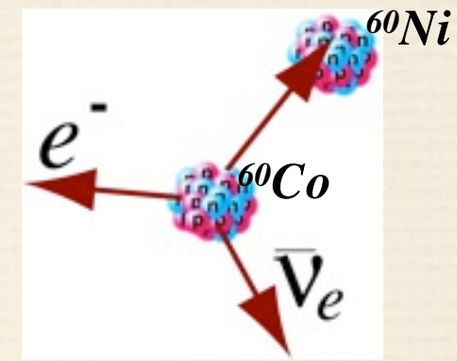

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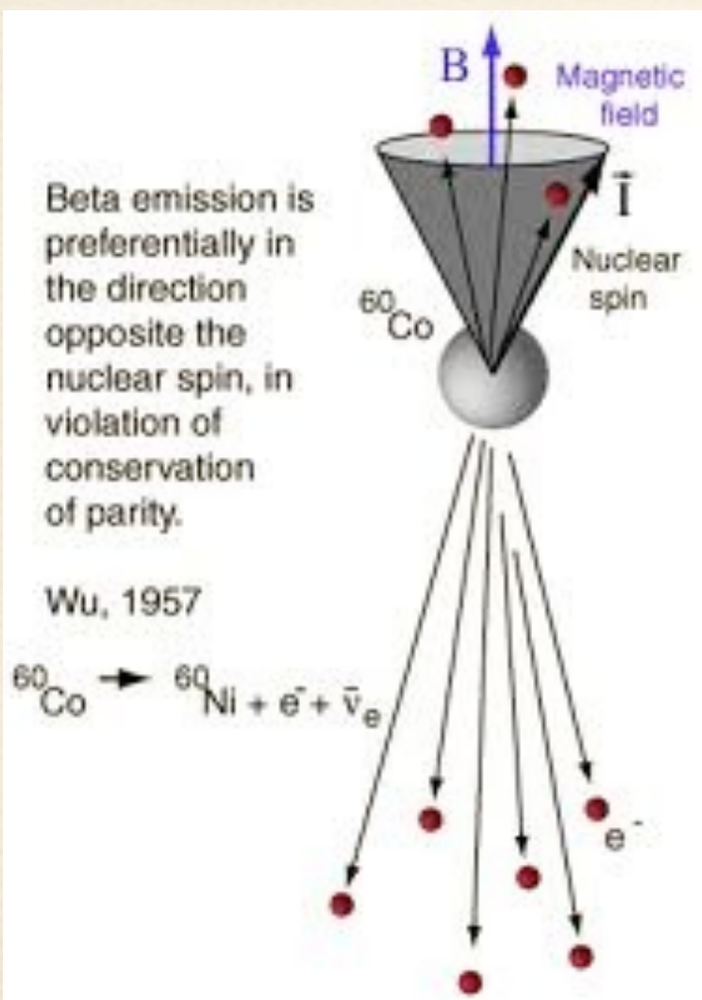
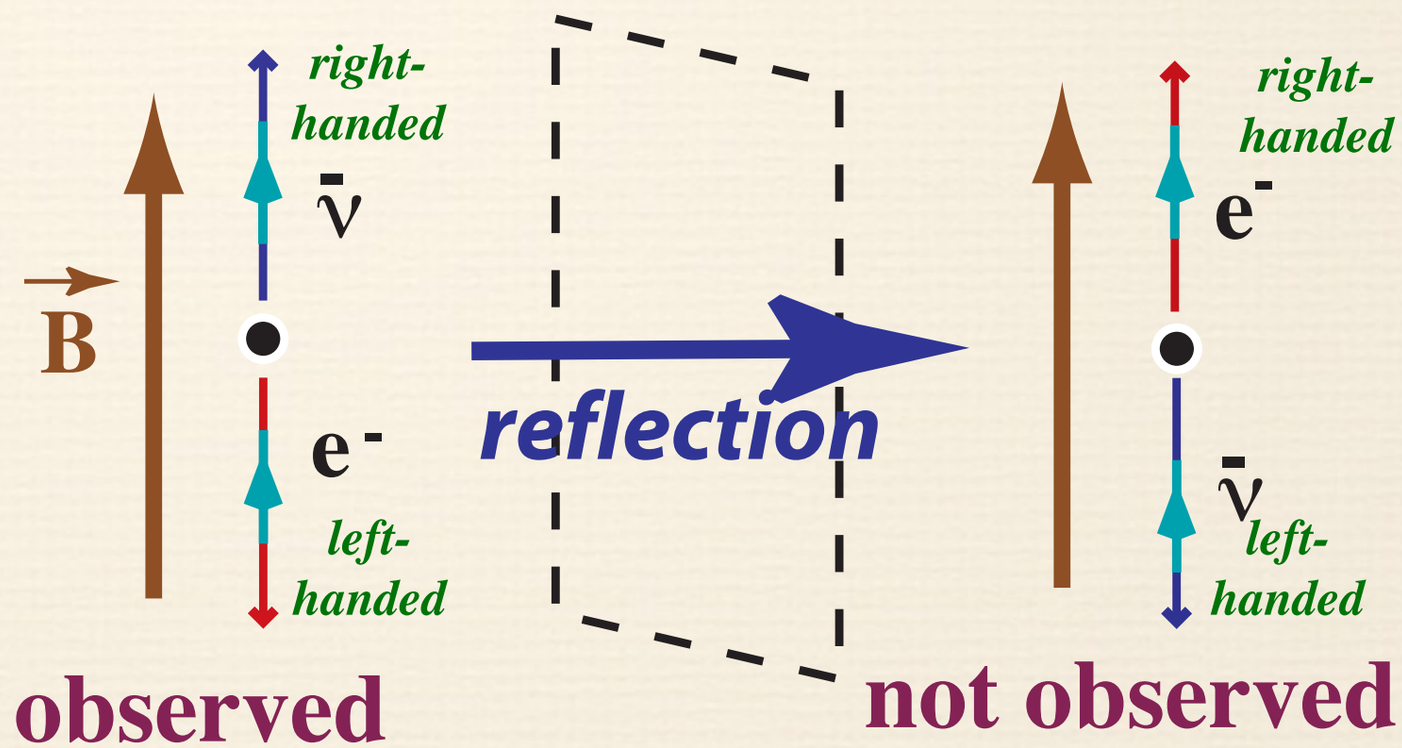




matter particles have spin = 1/2

$$h = \frac{\vec{s} \bullet \vec{p}}{|\vec{s}||\vec{p}|} = \pm 1$$

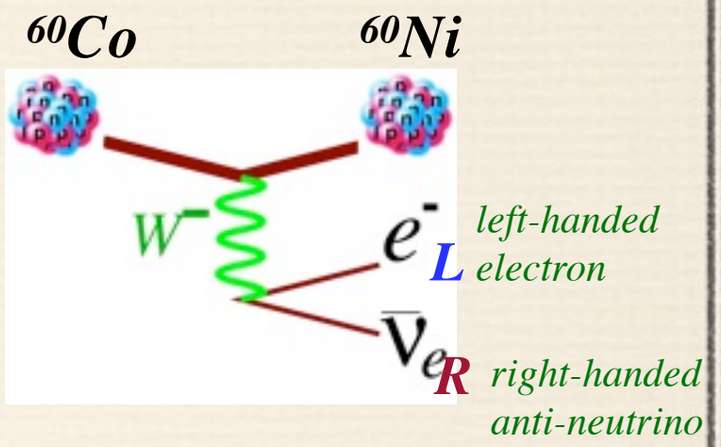
handedness or
helicity/chirality

Mirror reflection flips sign of helicity

Left-handed ⟺ ***right-handed***

Only left-handed particles can exchange W bosons

(right-handed anti-particles)



Building on the concept of "V-A"

A Classic Paper

1958

matter particles have spin = 1/2

$$h = \frac{\vec{s} \bullet \vec{p}}{|\vec{s}||\vec{p}|} = \pm 1$$

handedness or *helicity/chirality*

Mirror reflection flips sign of helicity

Left-handed ⟺ *right-handed*

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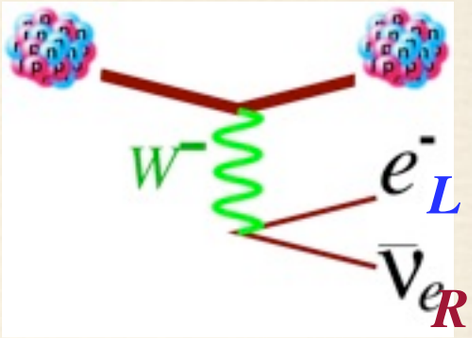
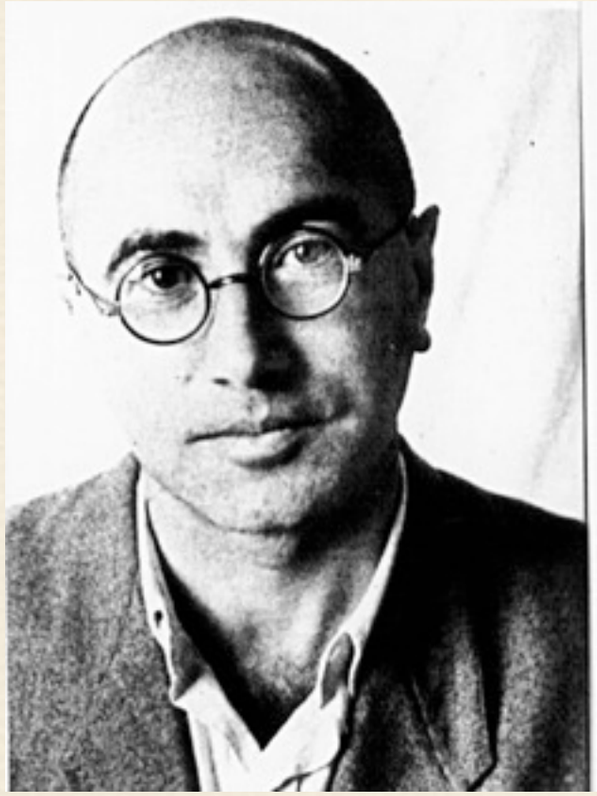


left-handed electron

right-handed anti-neutrino



LETTERS TO THE EDITOR

PARITY NONCONSERVATION IN THE FIRST ORDER IN THE WEAK-INTERACTION CONSTANT IN ELECTRON SCATTERING AND OTHER EFFECTS

Ya. B. ZEL'DOVICH

Submitted to JETP editor December 25, 1958

J. Exptl. Theoret. Phys. (U.S.S.R.) **36**, 964–966 (March, 1959)

Is Electron Scattering Mirror-Symmetric?

Brilliant Speculation

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

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

there exists an interaction

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

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

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

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

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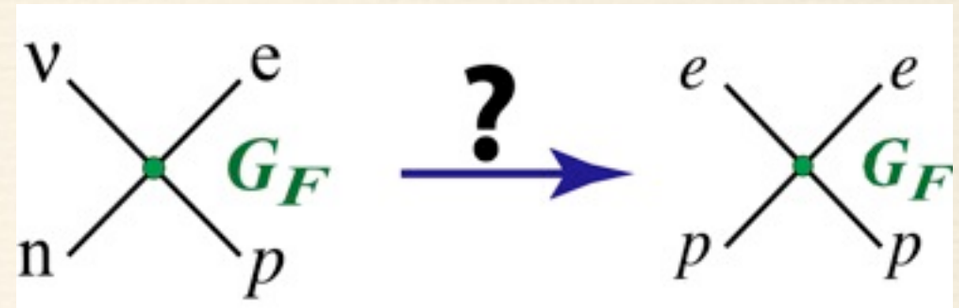
Neutron β Decay

Electron-proton Weak Scattering



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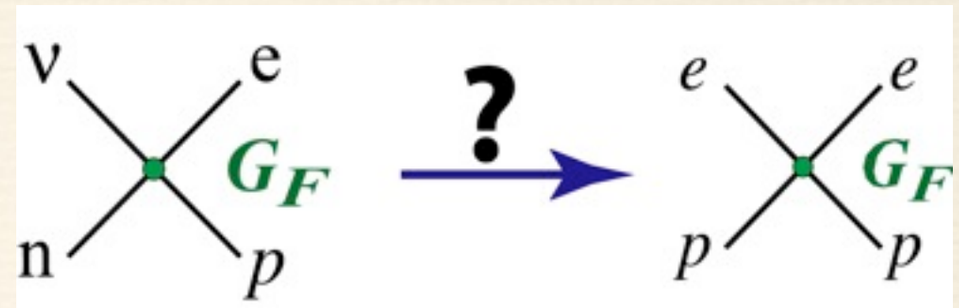

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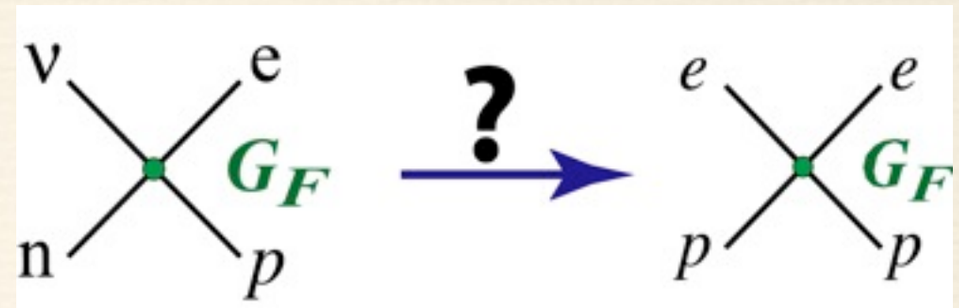

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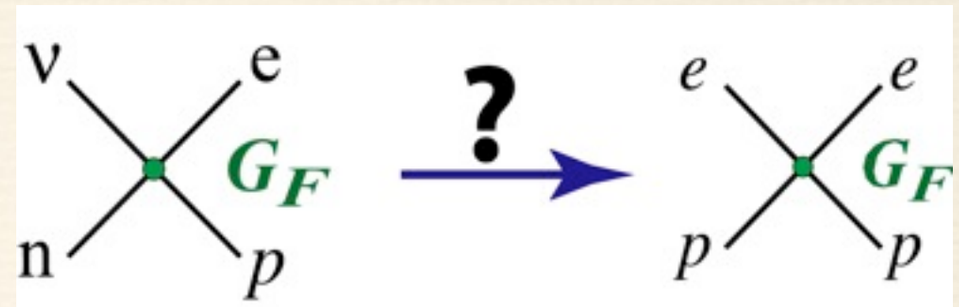

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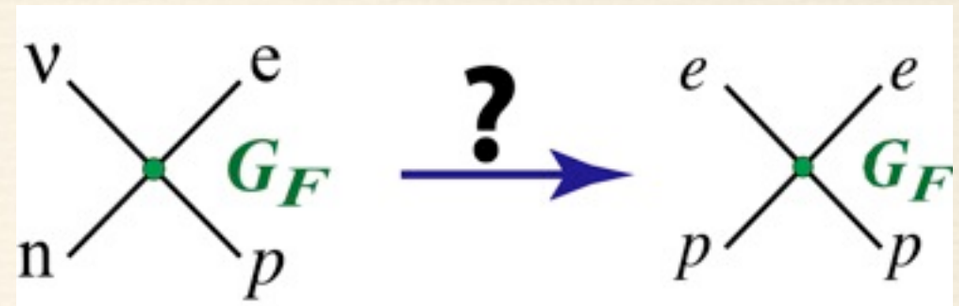

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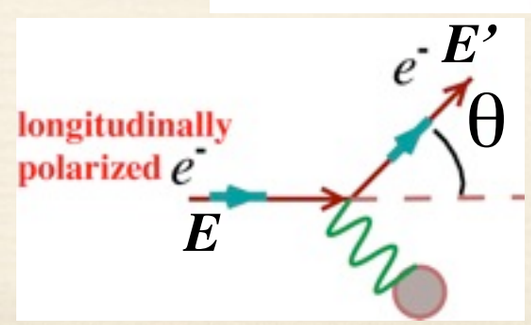
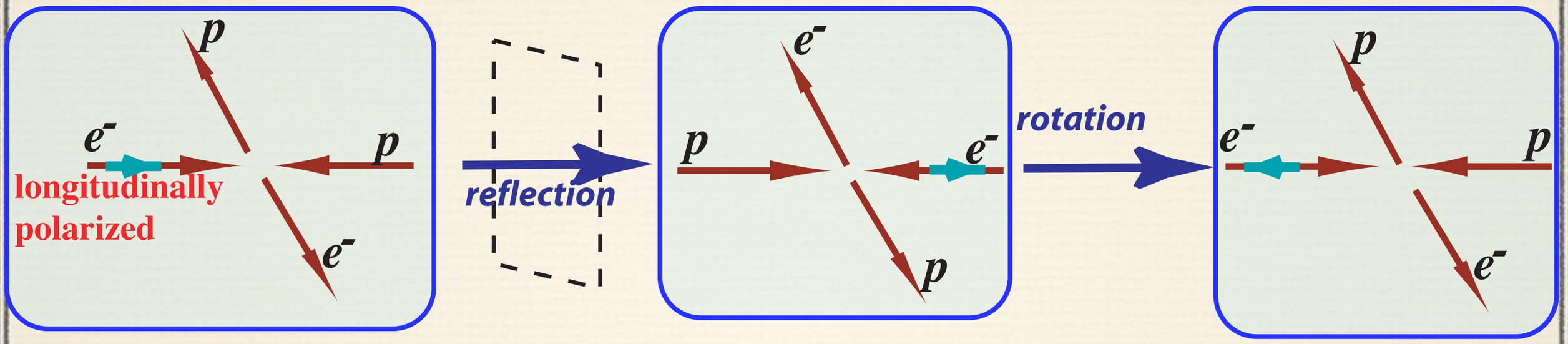


4-momentum transfer

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

How to observe parity violation in electron scattering

PV Asymmetry Signature



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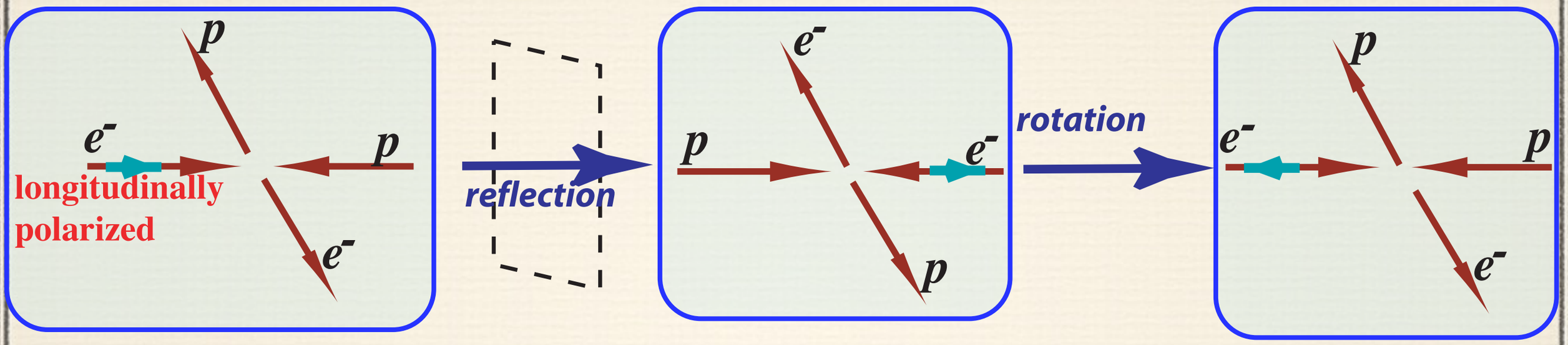

- *One of the incident beams longitudinally polarized*
- *Change sign of longitudinal polarization*
- *Measure fractional rate difference*

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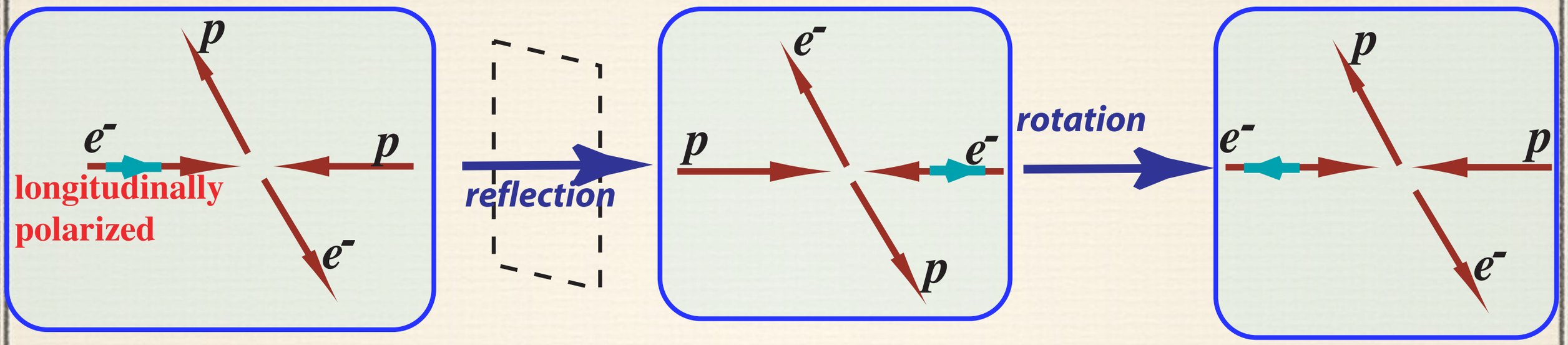

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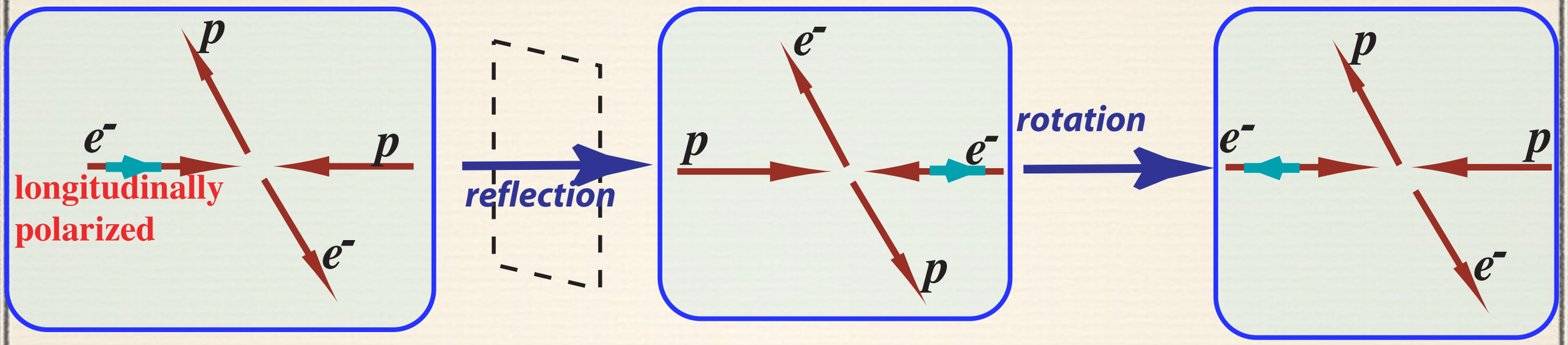

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$$A_{PV} \sim 10^{-4} \cdot Q^{2(\mathrm{GeV}^2)}$$

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

Electroweak Theory

1960's

The correct description of the neutral weak force?

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

$$A_\mu = B^0_\mu \cos\theta_W + W^0_\mu \sin\theta_W$$
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The Z boson incorporated

	Left-	Right-
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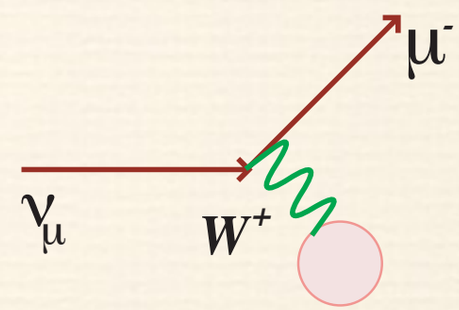

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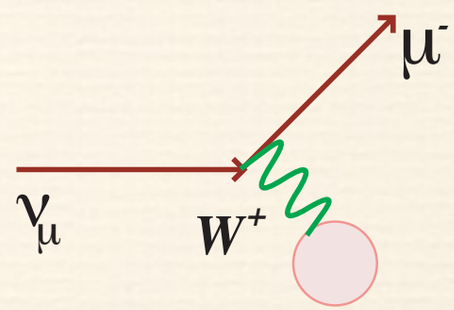

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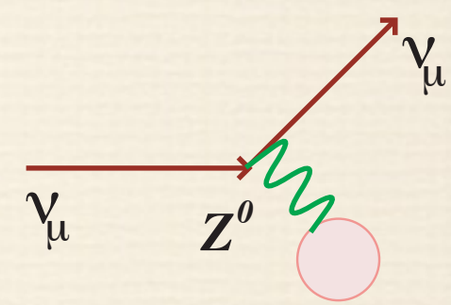

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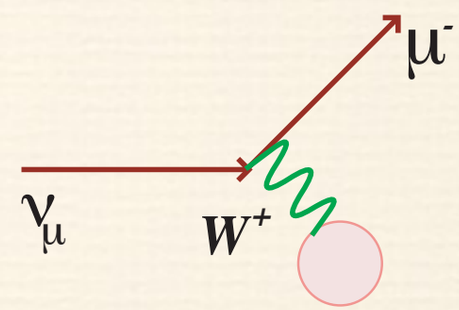

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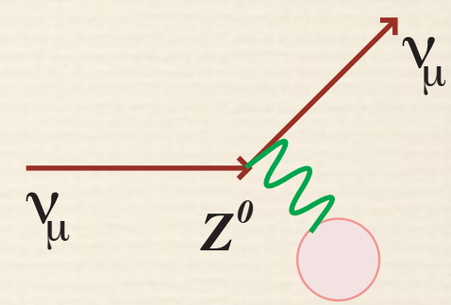


Neutral Current

Higgs Mechanism + Renormalizability

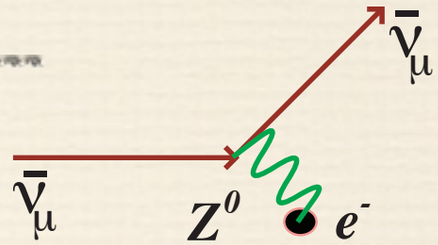
$$\sin^2\theta_W^0 = \left(\frac{e^0}{g^0}\right)^2 = 1 - \left(\frac{M_W^0}{M_Z^0}\right)^2$$

The First Weak Neutral Current Experiments

Experimental Aspects

1970's

First weak neutral current event: Gargamelle bubble chamber



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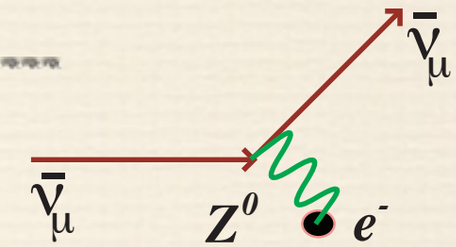

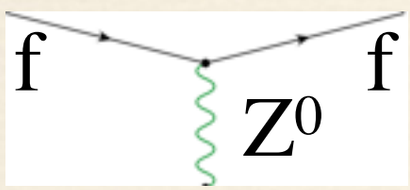

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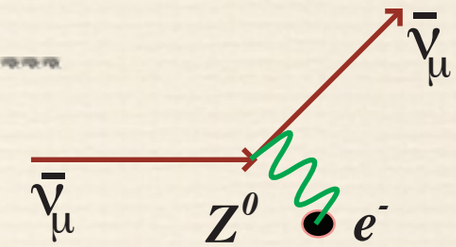

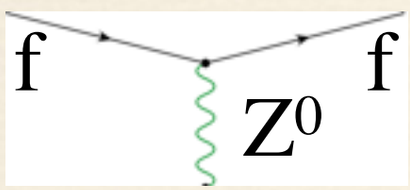

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Do lepton-quark neutral current interactions exhibit parity violation?

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

or

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Weinberg model

Parity is violated

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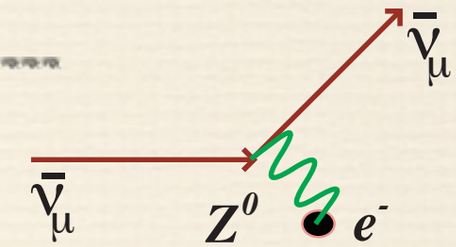

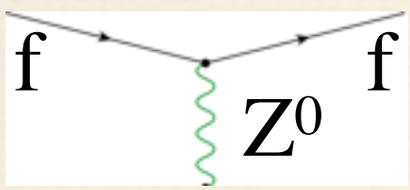

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First table-top atomic parity violation searches: negative!

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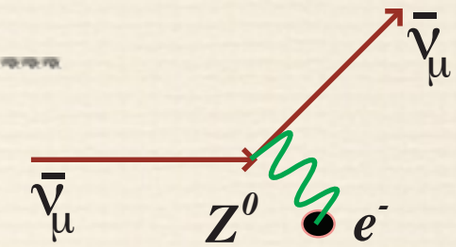
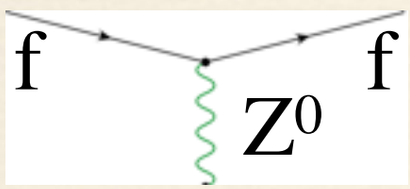




$$\frac{g}{\cos\theta_W} Z_\mu \bar{f}\gamma^\mu (T_{3f} - 2Q_f \sin^2\theta_W - T_{3f}\gamma_5) f, \quad T_{3f} = \pm 1/2$$

Do lepton-quark neutral current interactions exhibit parity violation?

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

or

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

Weinberg model

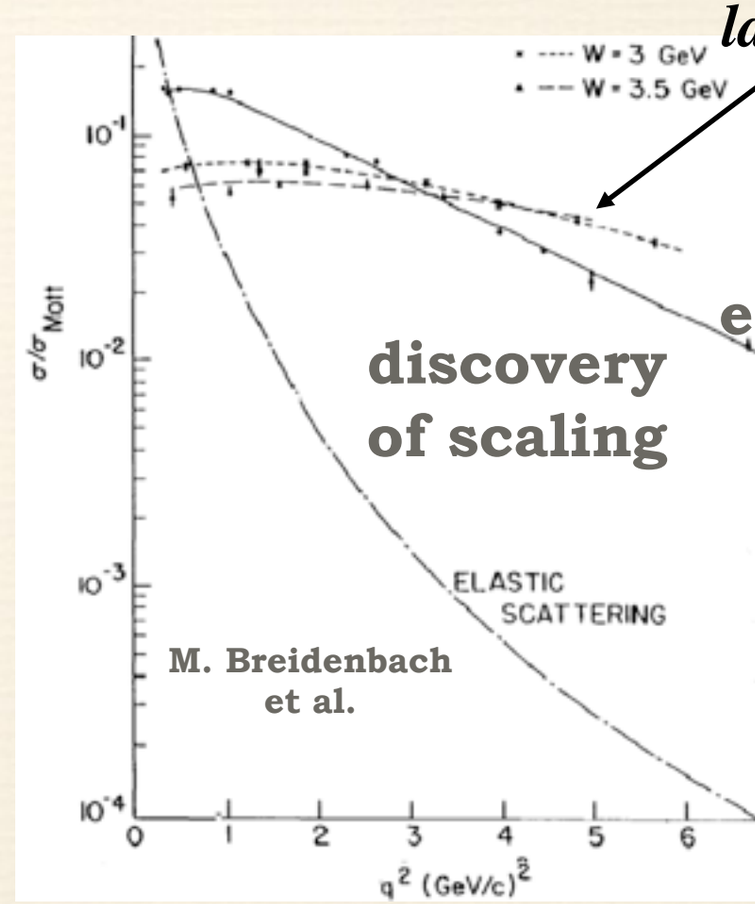
Parity is violated

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

Parity is conserved

First table-top atomic parity violation searches: negative!

large rate at large Q^2



discovery of scaling

electron-nucleon deep inelastic scattering

The First Weak Neutral Current Experiments

Experimental Aspects

1970's

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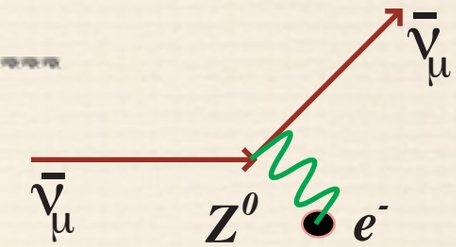

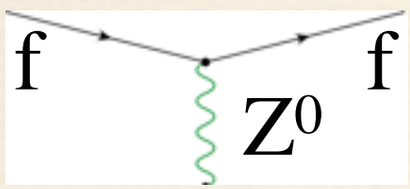

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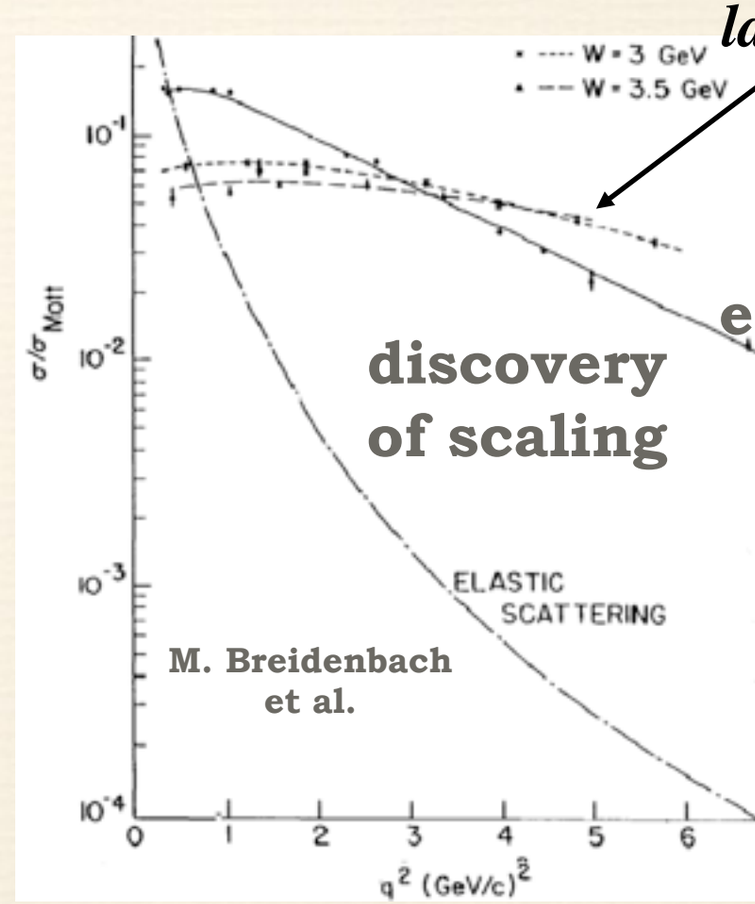

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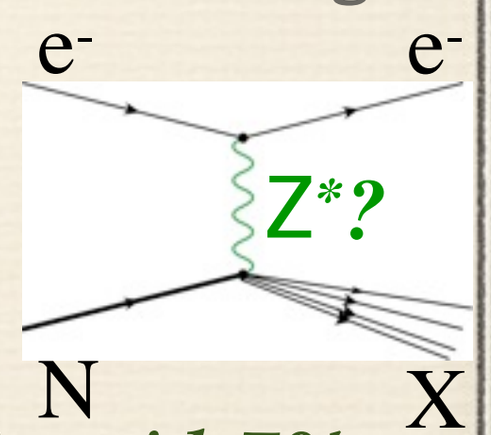
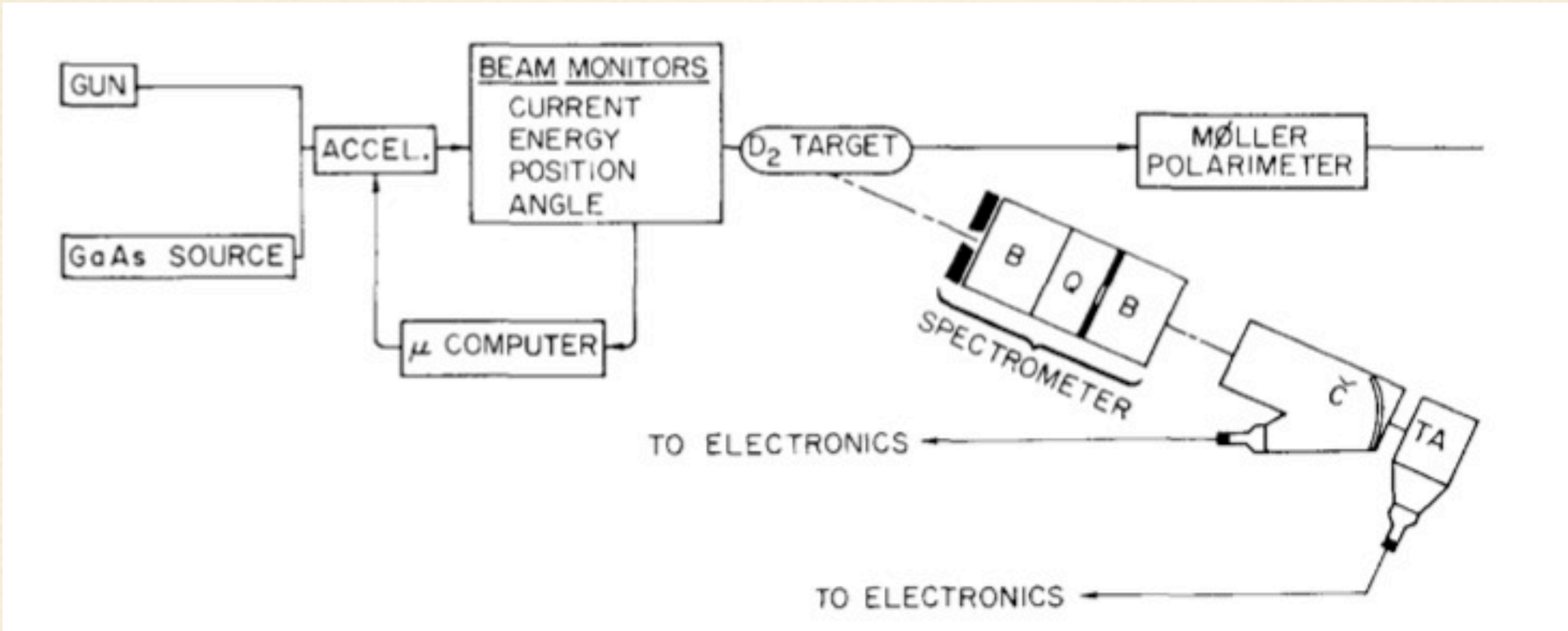


pressing problem in mid-70's

Seminal experiment launched the subfield of PV electron scattering

SLAC E122

C.Y. Prescott, *et al.*
1978



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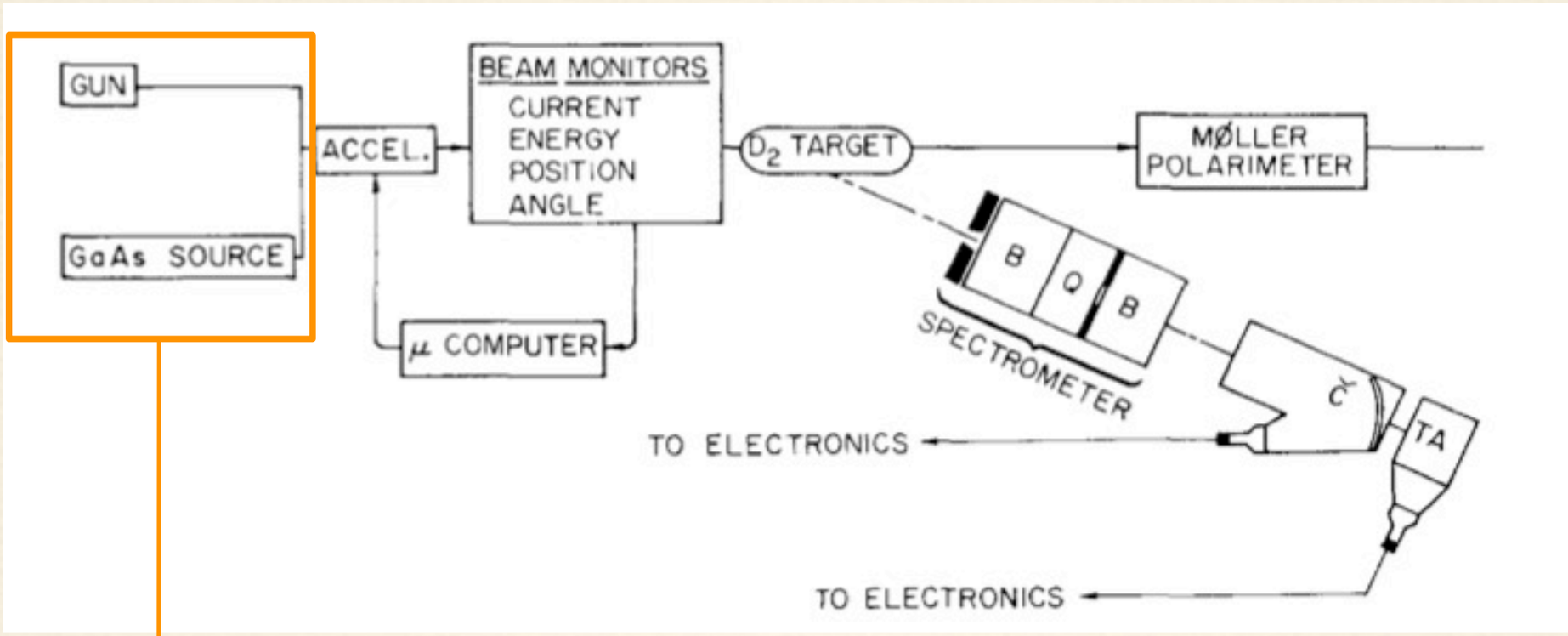
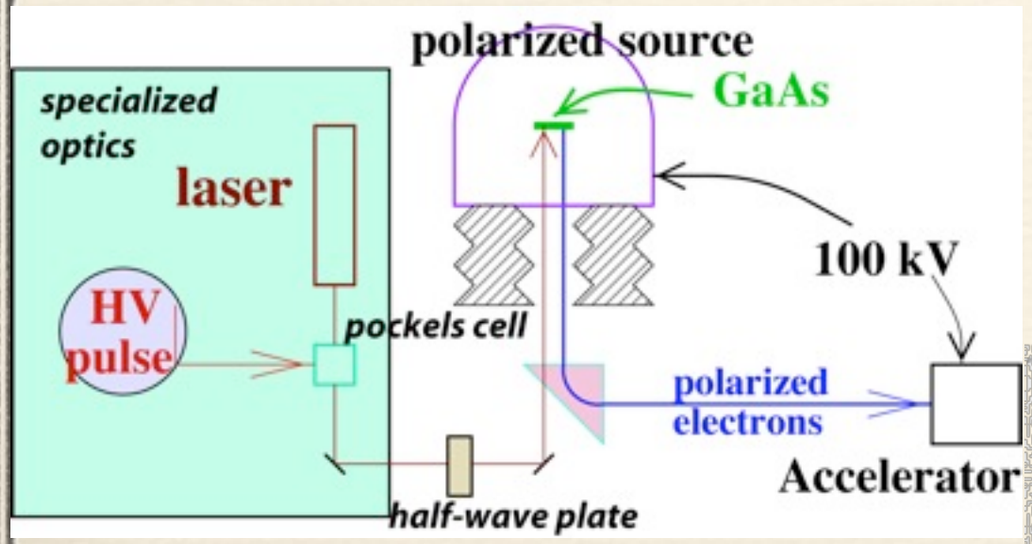
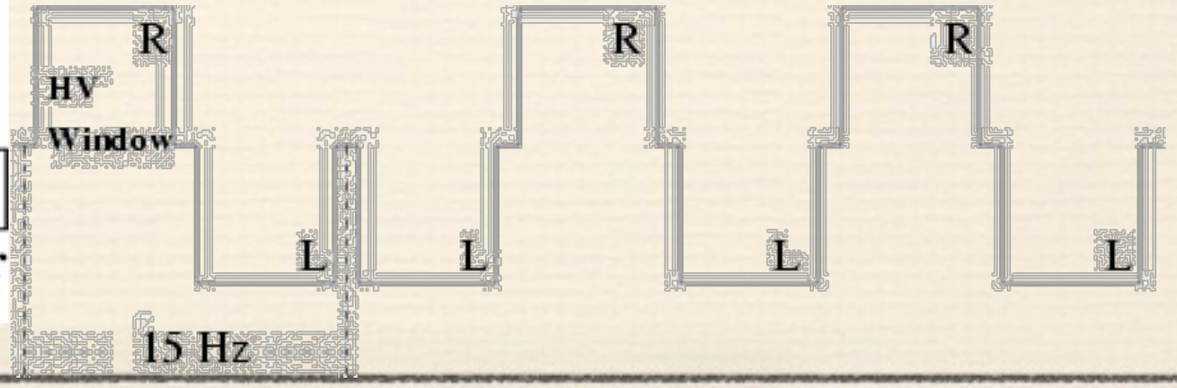




✧ **Beam helicity sequence is chosen pseudo-randomly**

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



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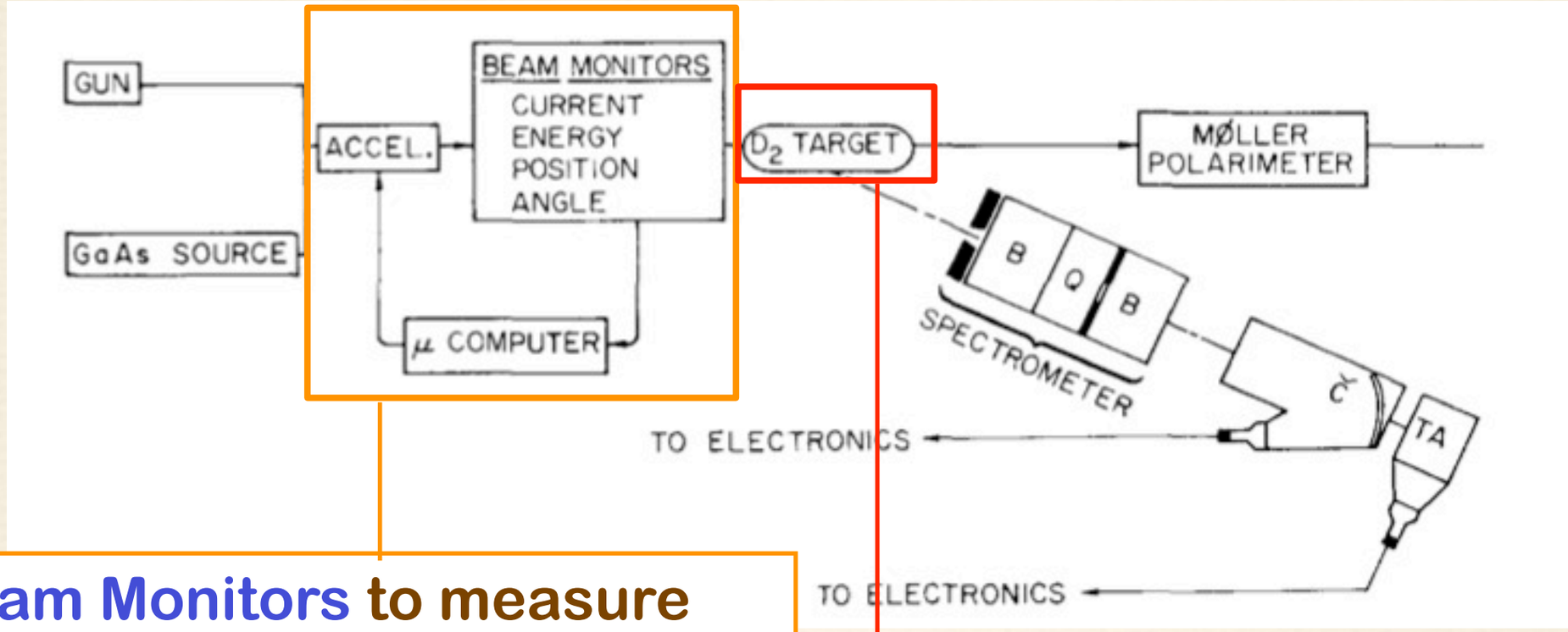

- **Beam Monitors** to measure helicity-correlated changes in beam parameters

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

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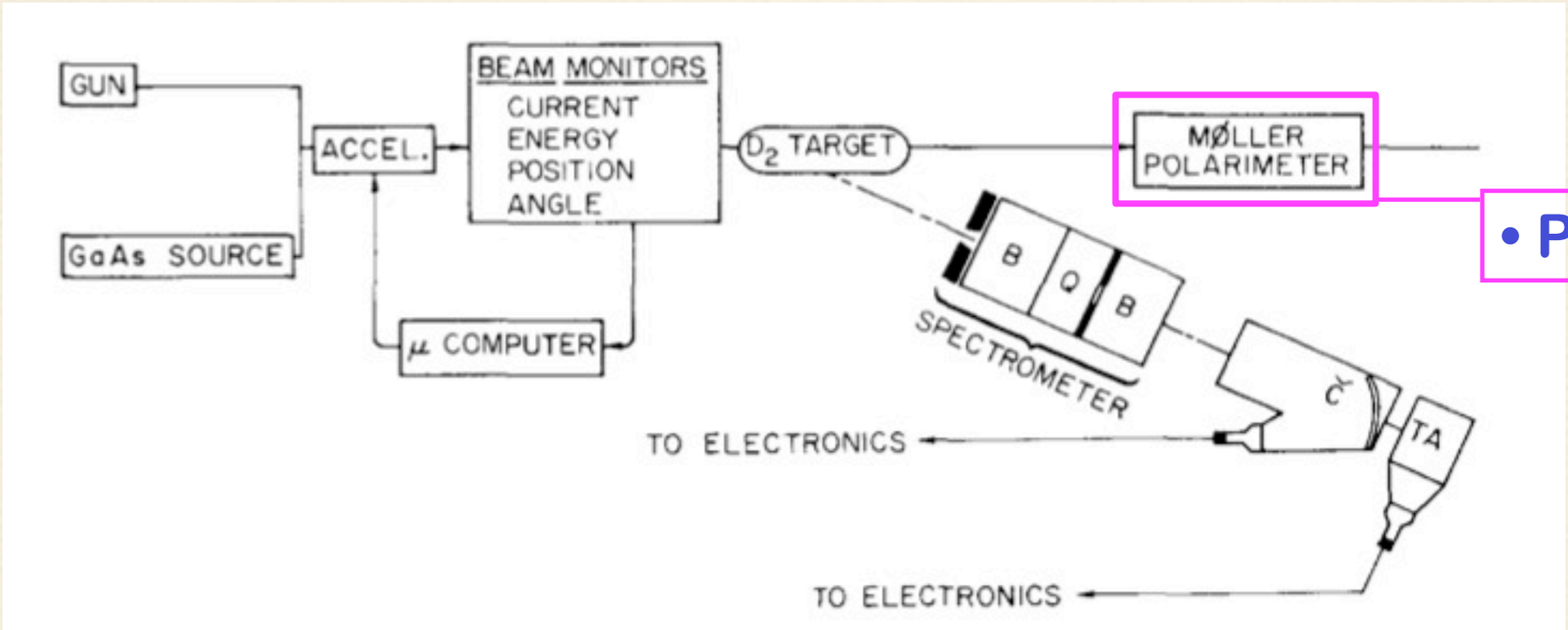

• **Polarimetry**

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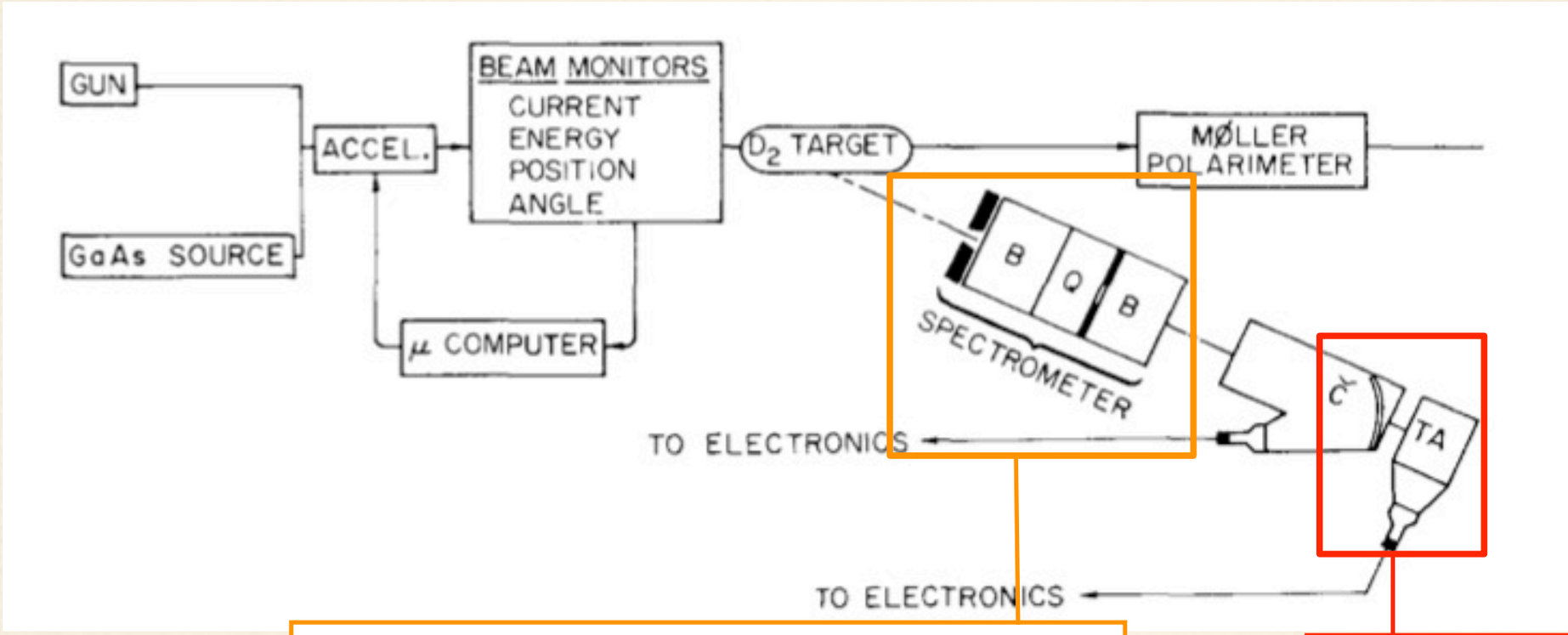
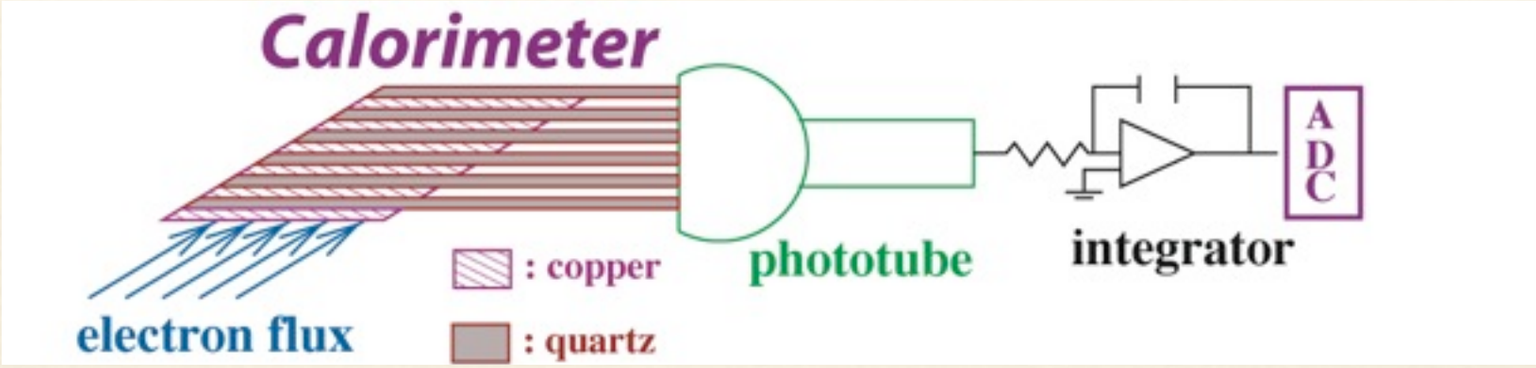


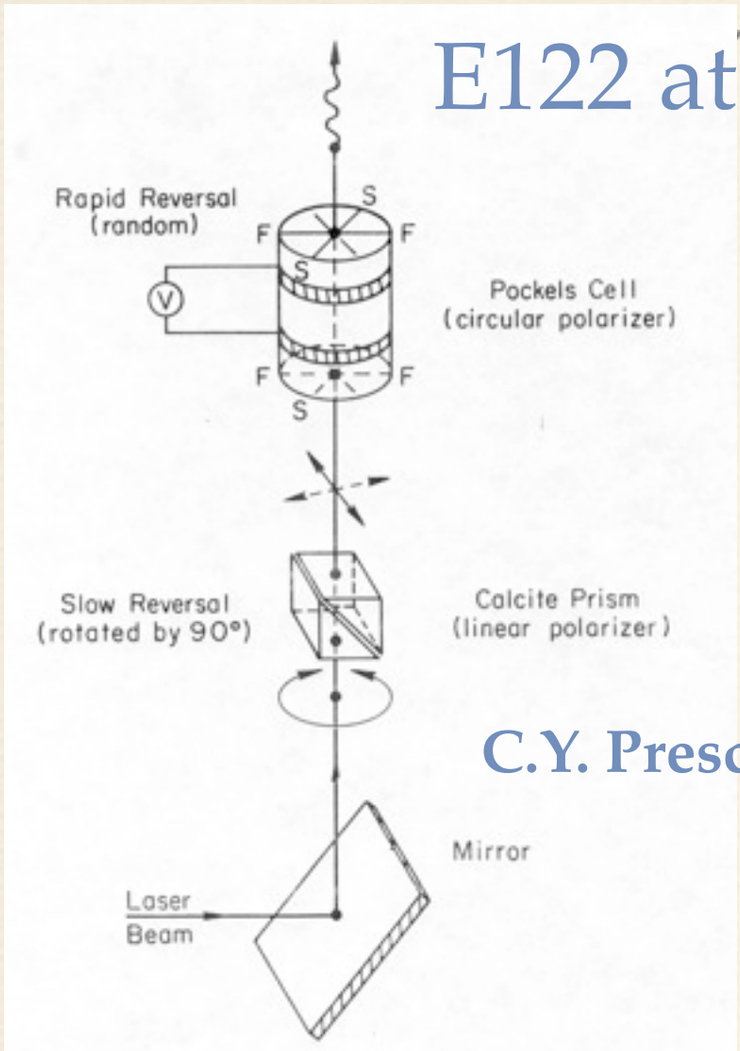
- **Magnetic spectrometer directs flux to background-free region**

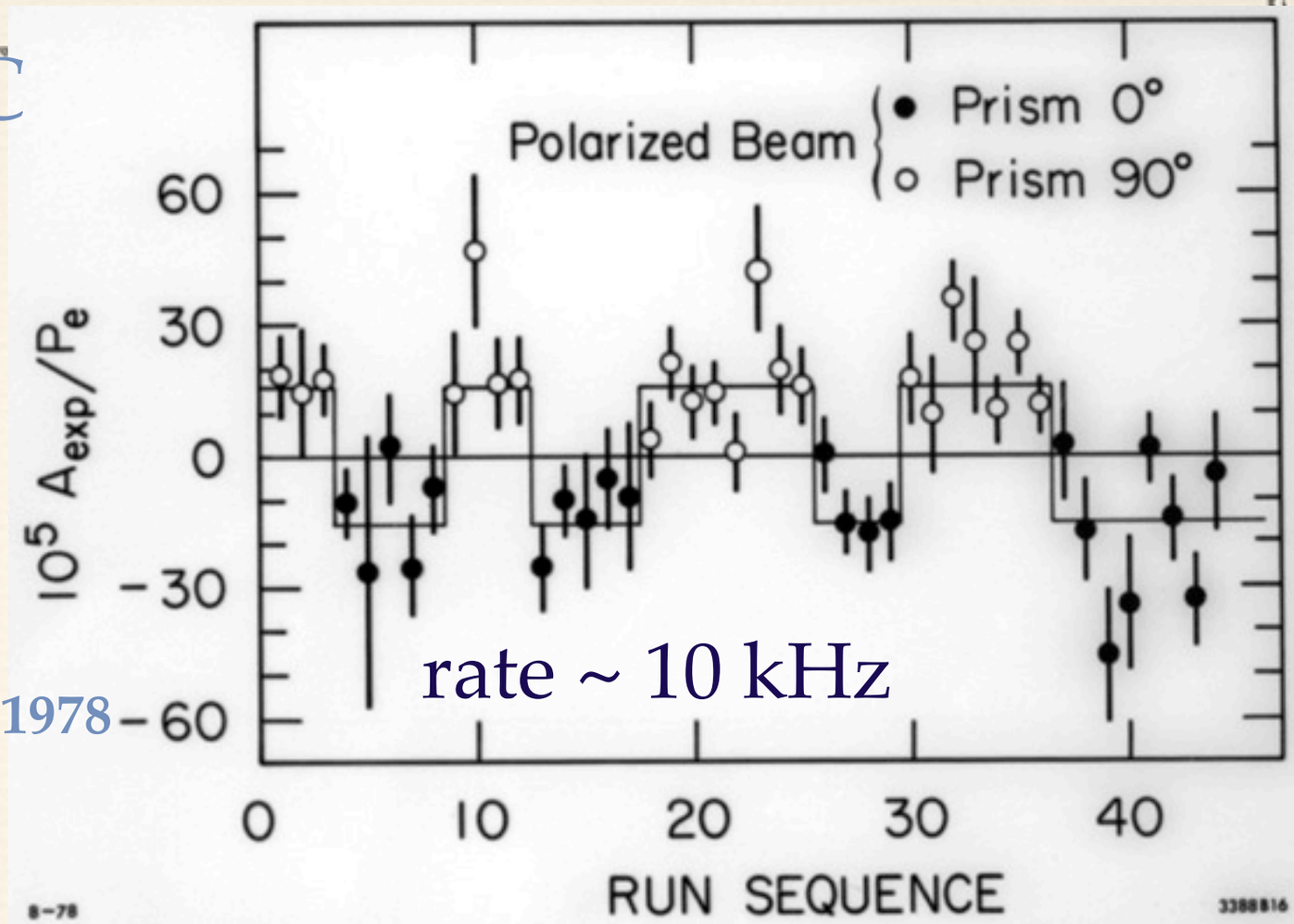
- **Flux Integration measures high rate without deadtime**

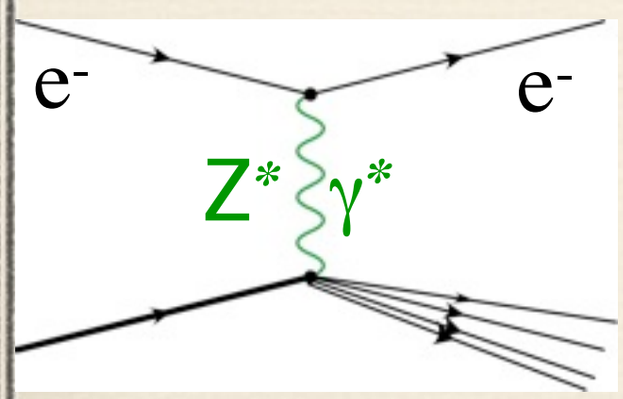


Does the weak neutral current amplitude interfere with the electromagnetic amplitude?

A Landmark Result







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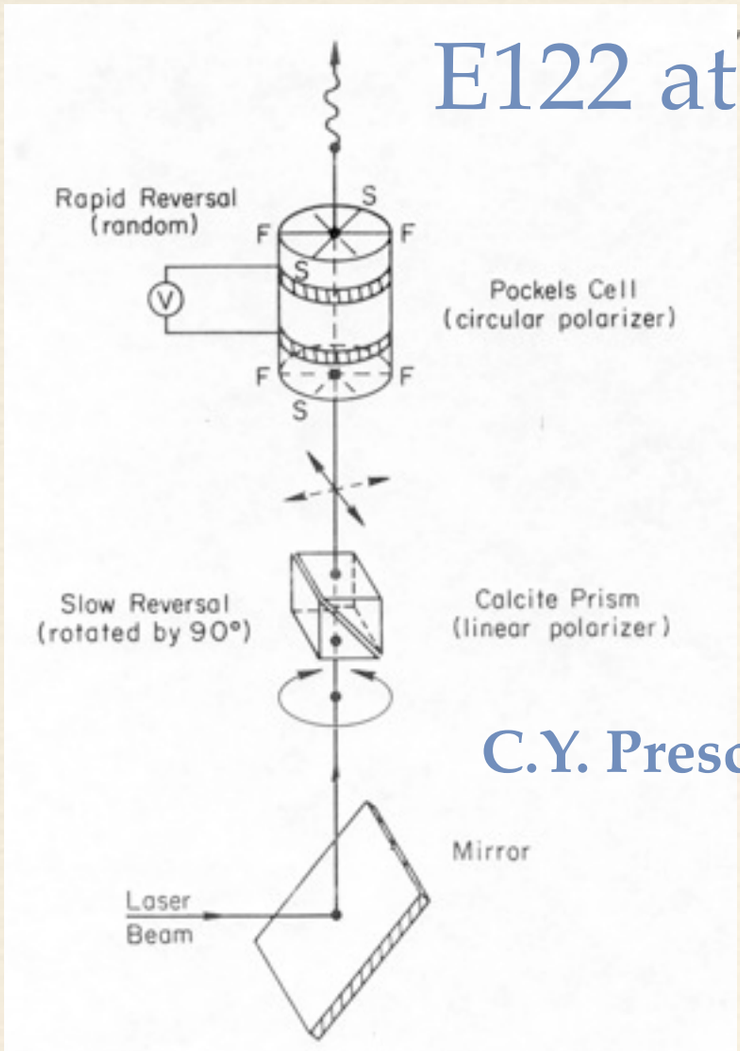

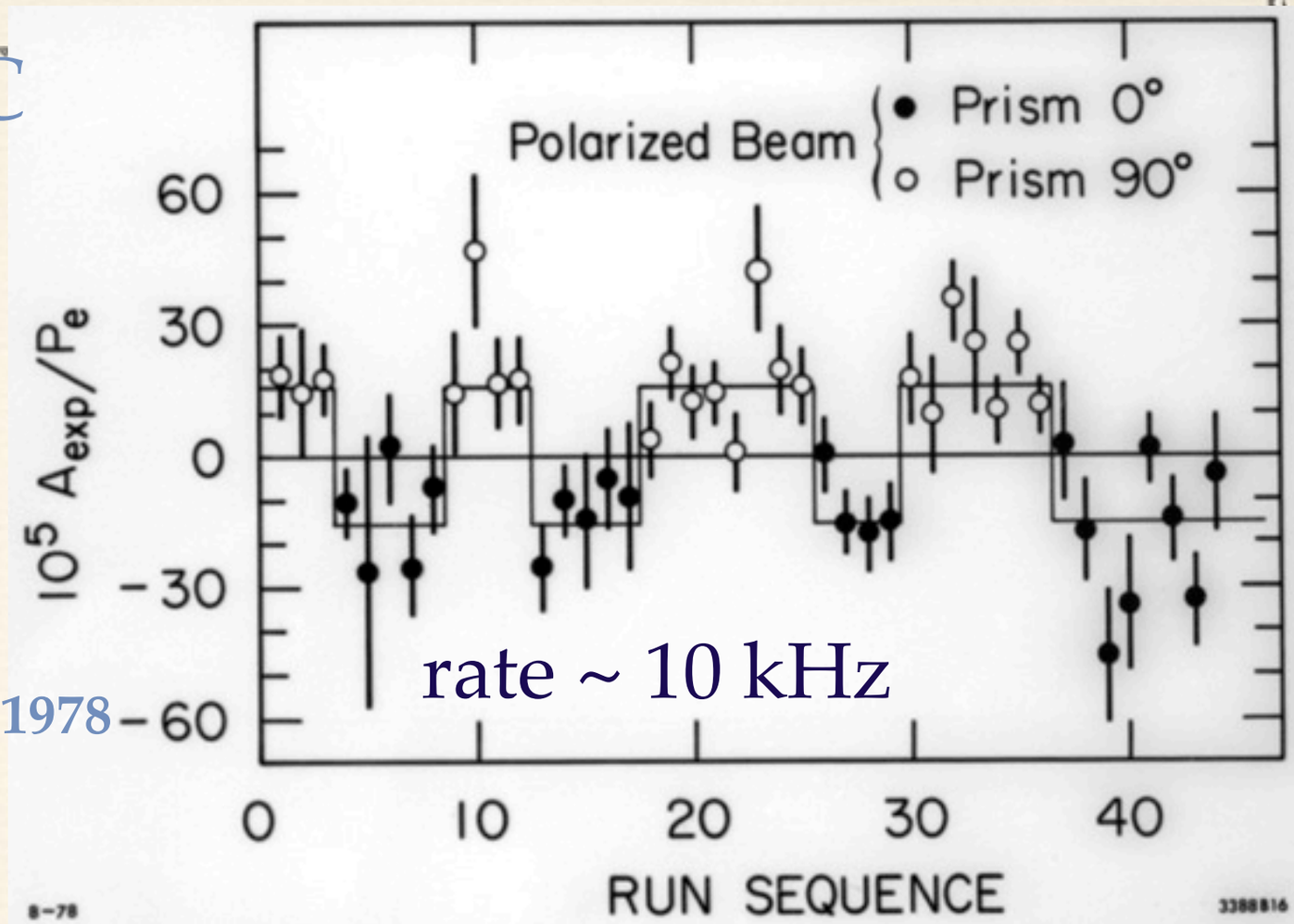

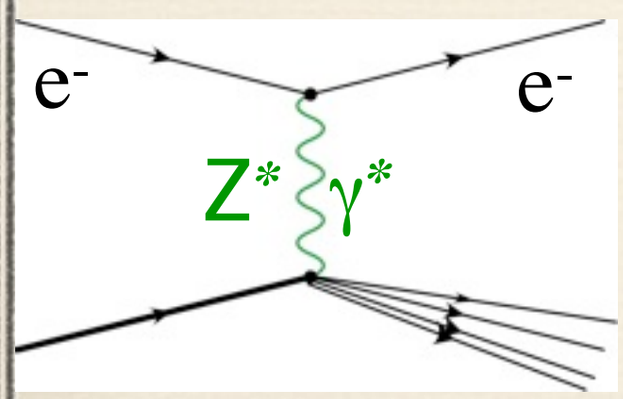

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- ***$\sin^2\theta_W$ = 0.224 ± 0.020: same as in neutrino scattering***

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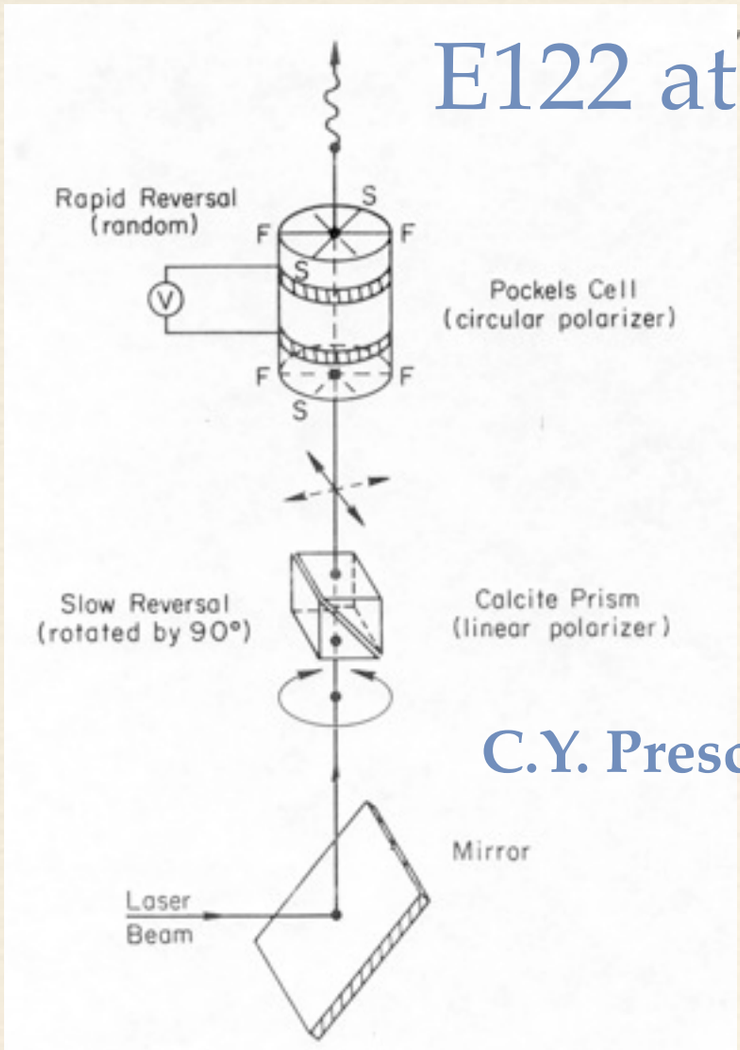

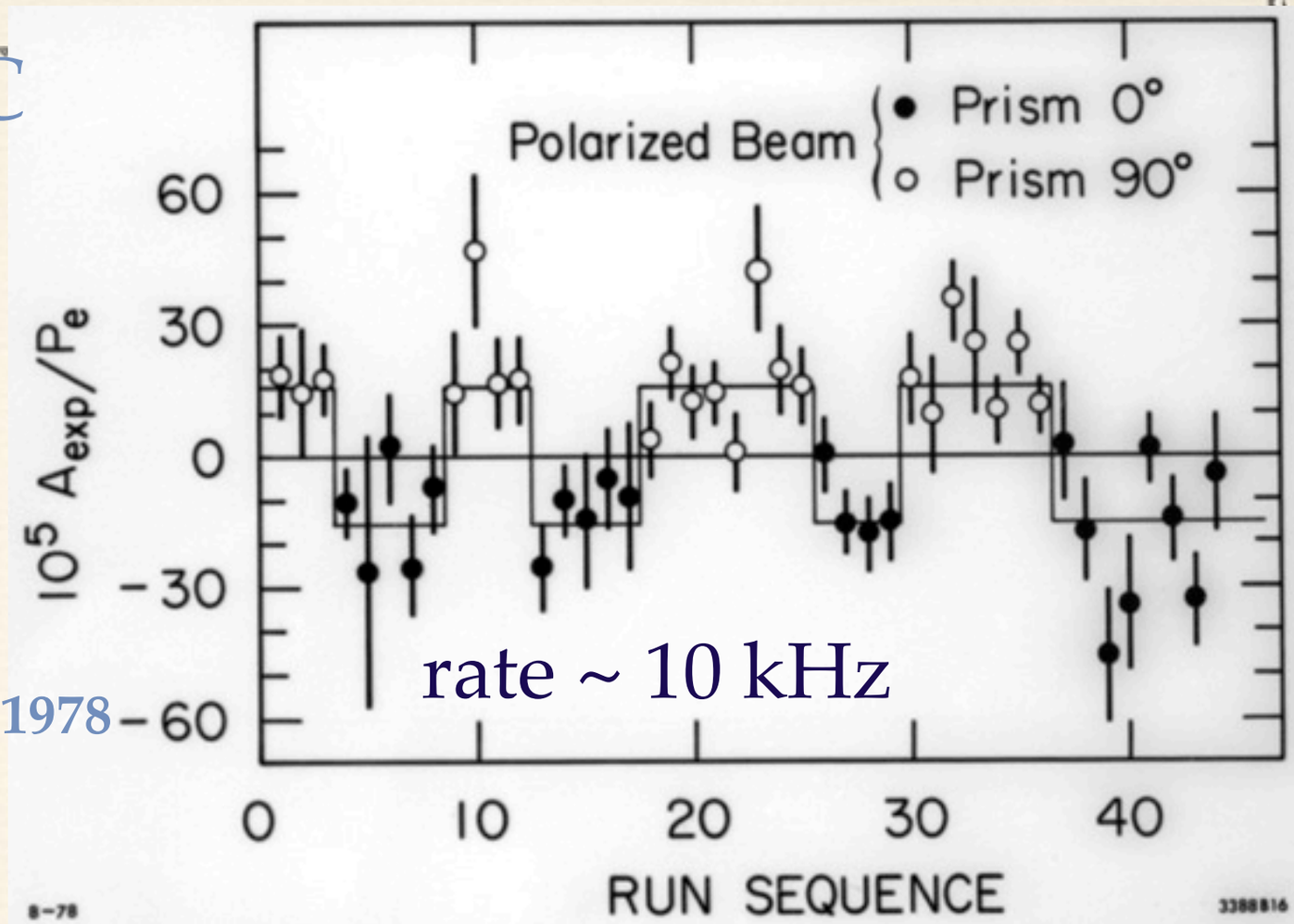

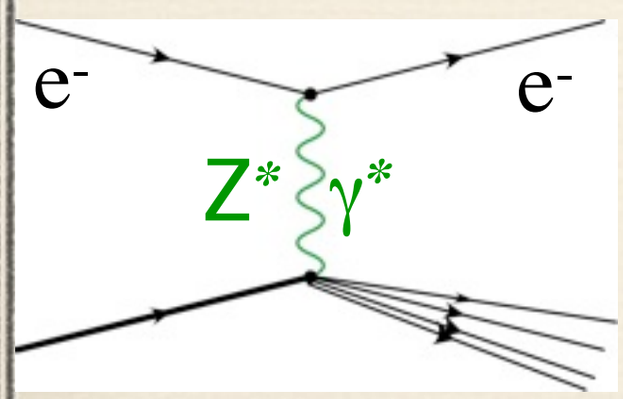

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Glashow, Weinberg, Salam Nobel Prize awarded in 1979

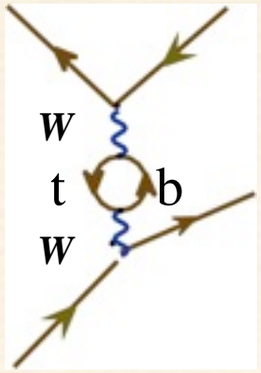
Precision EW Physics

Quantum Corrections

For electroweak interactions, 3 input parameters needed:

1. **electron g-2 anomaly**
2. **The muon lifetime**
3. **The Z line shape**

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



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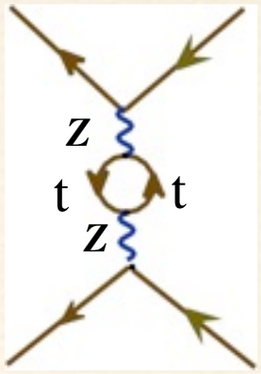

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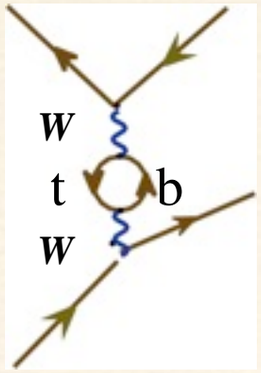

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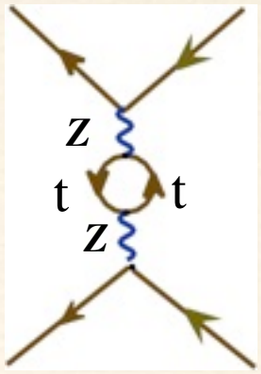

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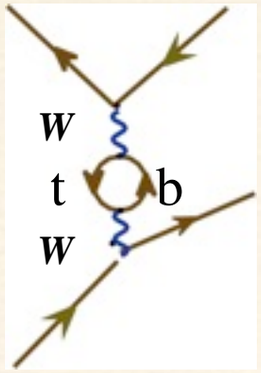

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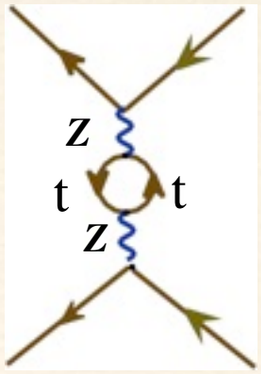

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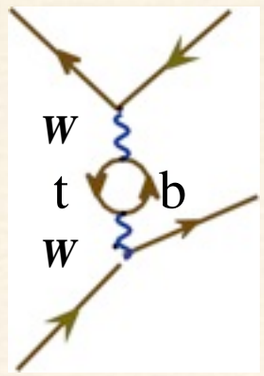

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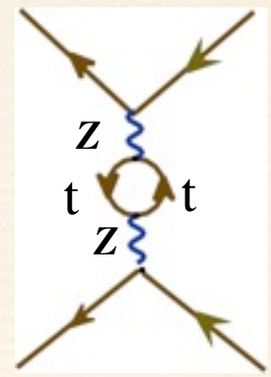

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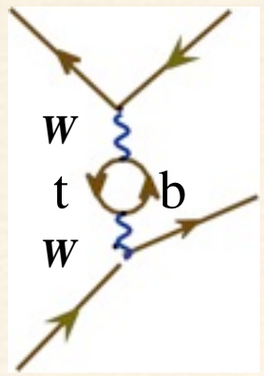

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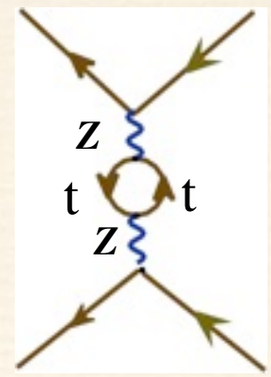

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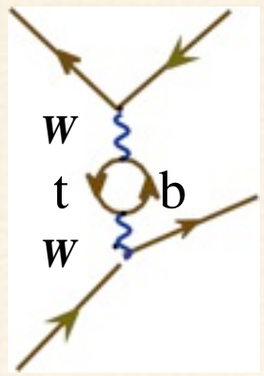

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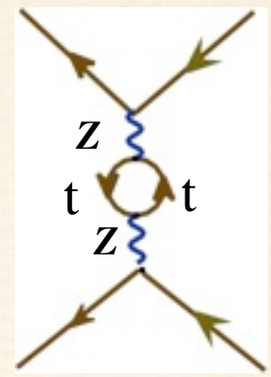

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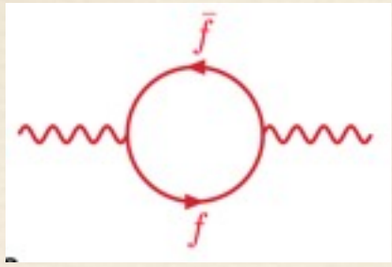
LEP-I, SLC, LEP-II, Tevatron

World Averages

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

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

Heroic efforts of phenomenologists and experimentalists!



Precision Relations

The Electroweak Theory and Measurements at 1-Loop

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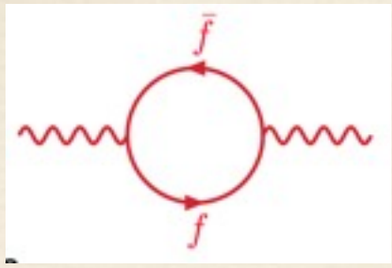

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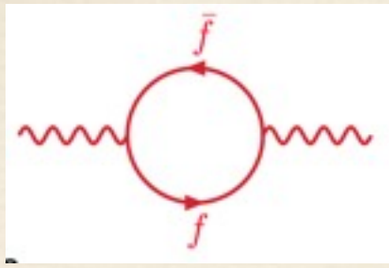

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m_t, α_s uncertainty

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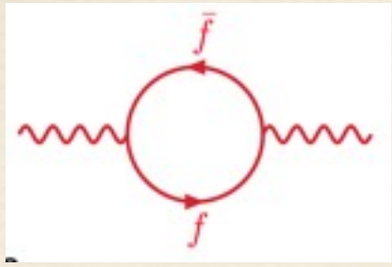

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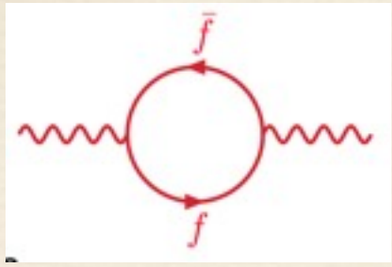

Precision Relations

The Electroweak Theory and Measurements at 1-Loop

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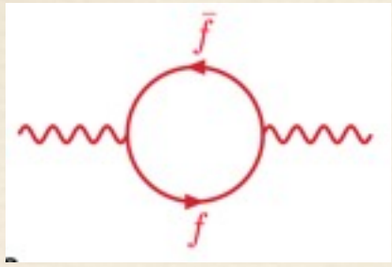

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$m_W = 80.385(15)$ GeV **expt.**

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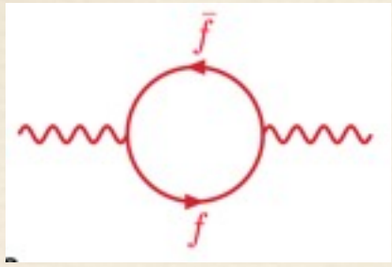

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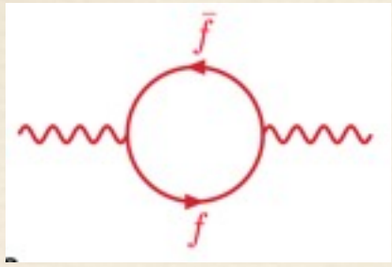

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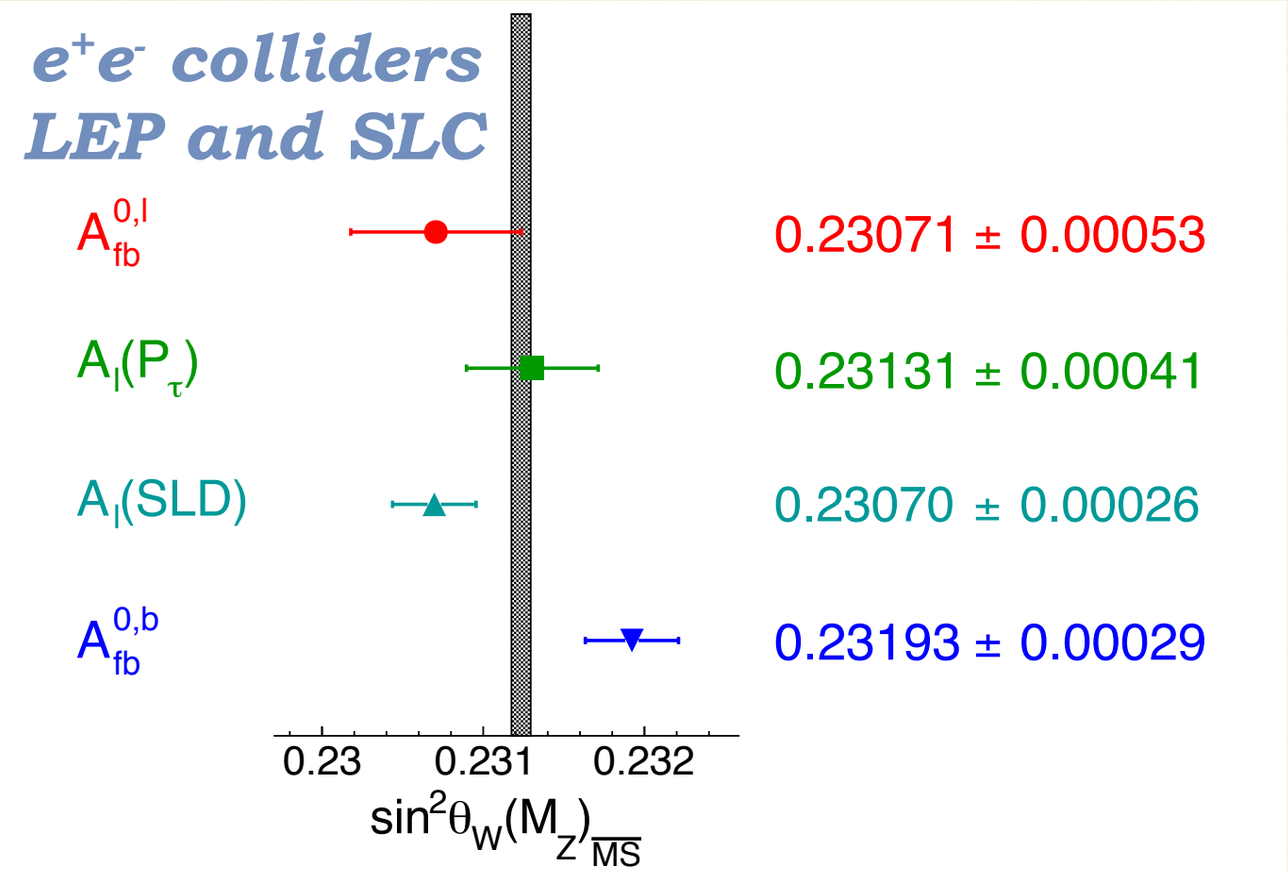
The Weak Mixing Angle

The most precise measurements at LEP/SLC



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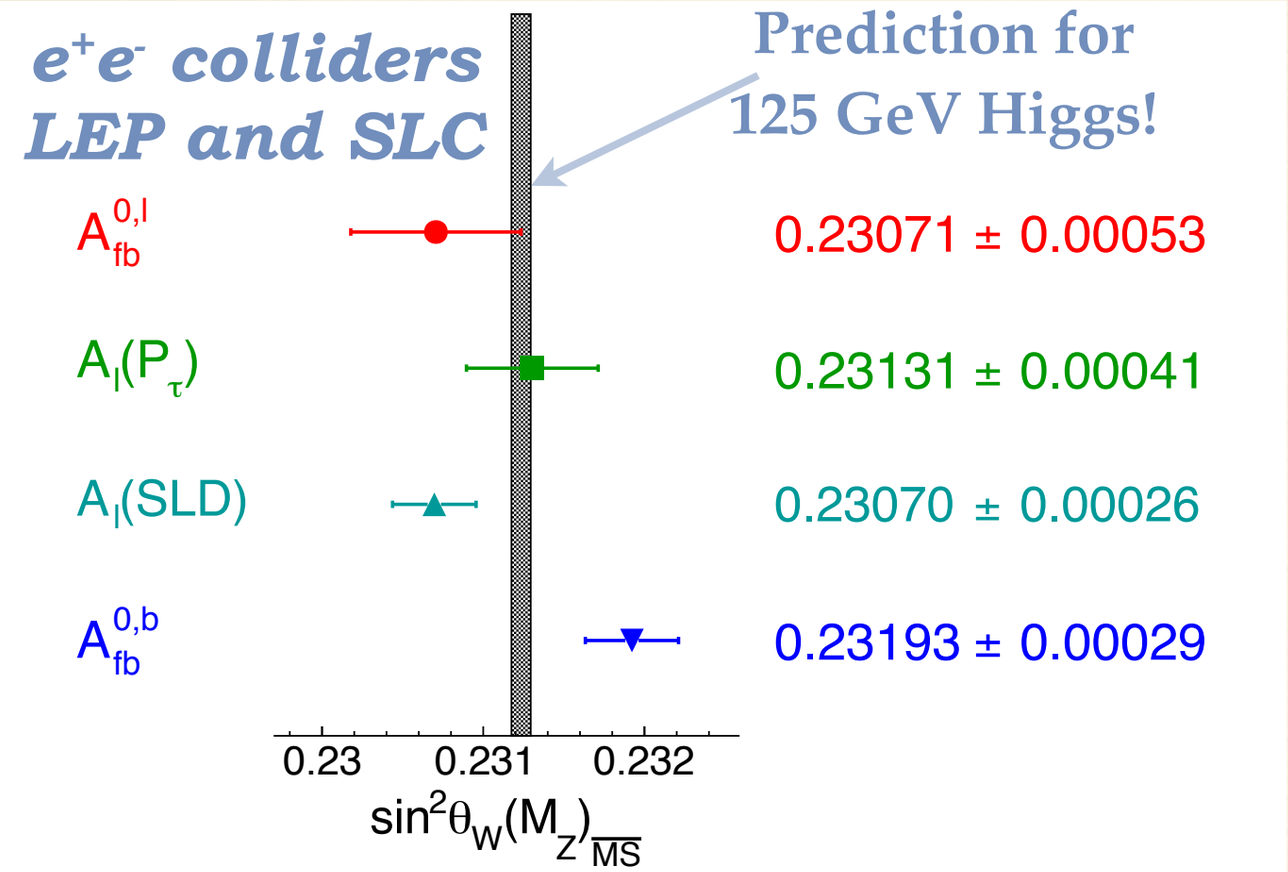

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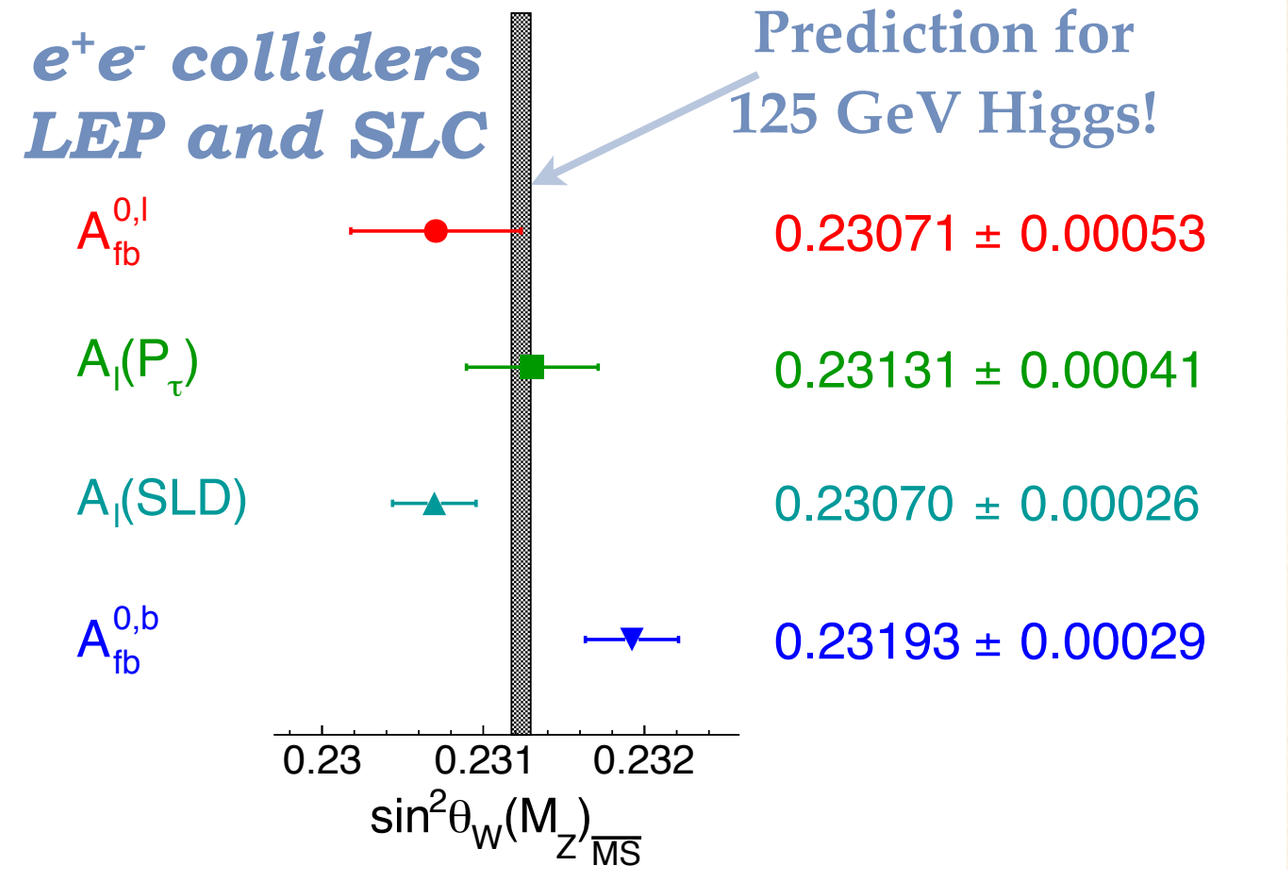

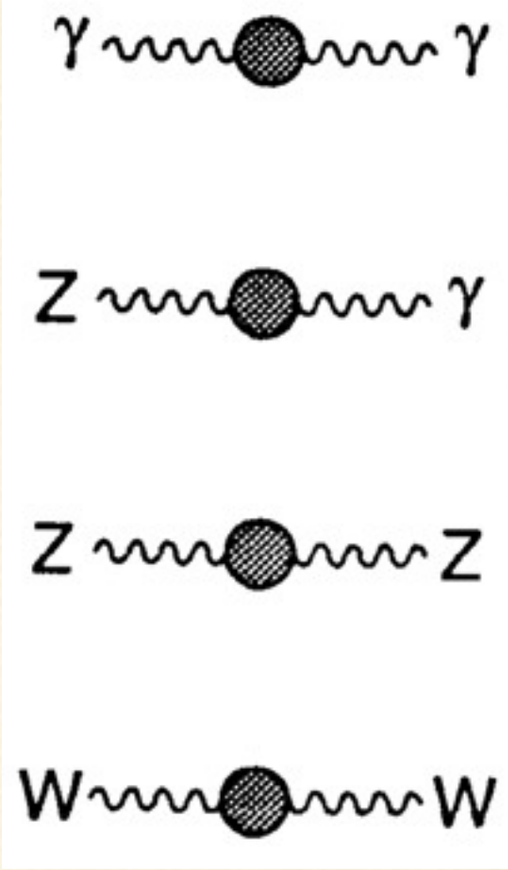

S,T, U parameters

Stringent constraints on large classes of new physics models

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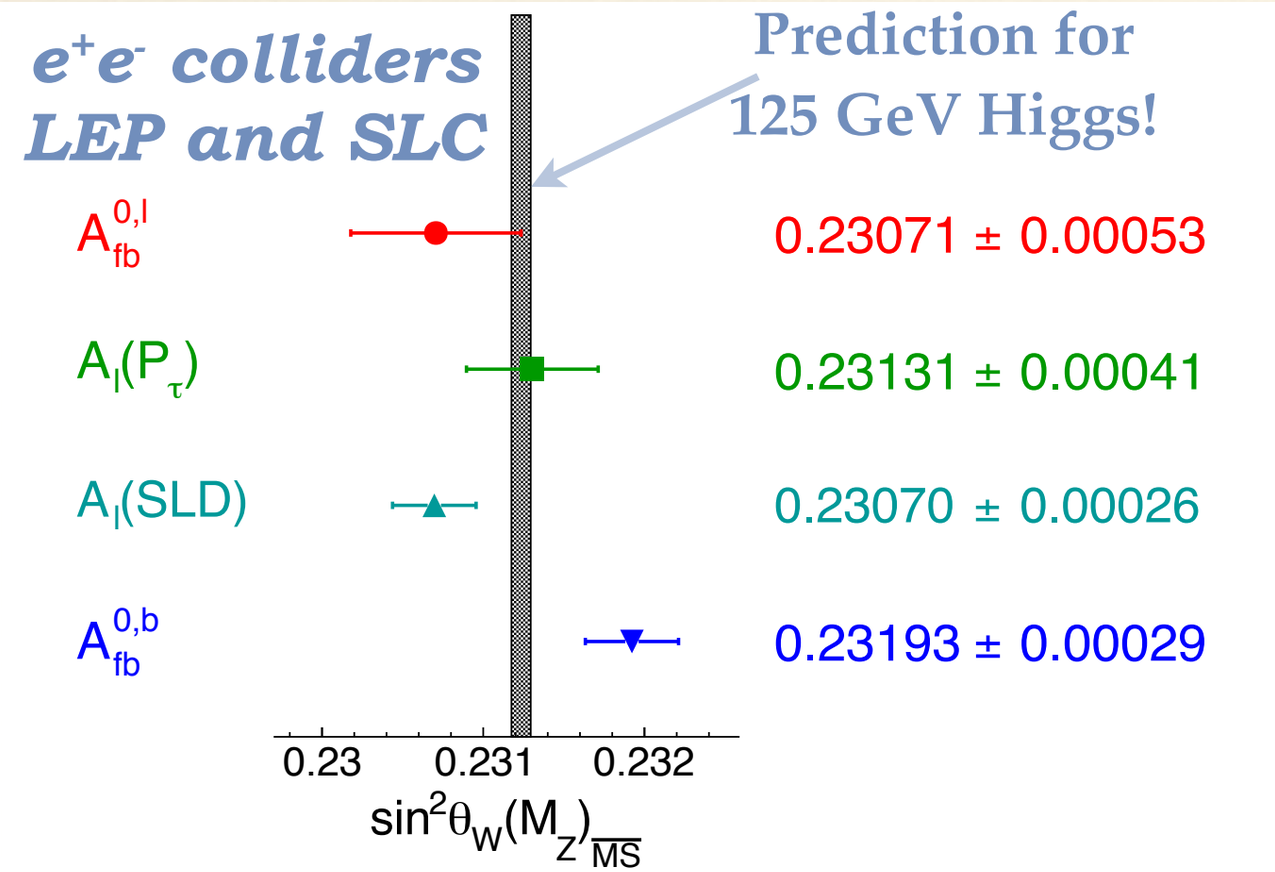

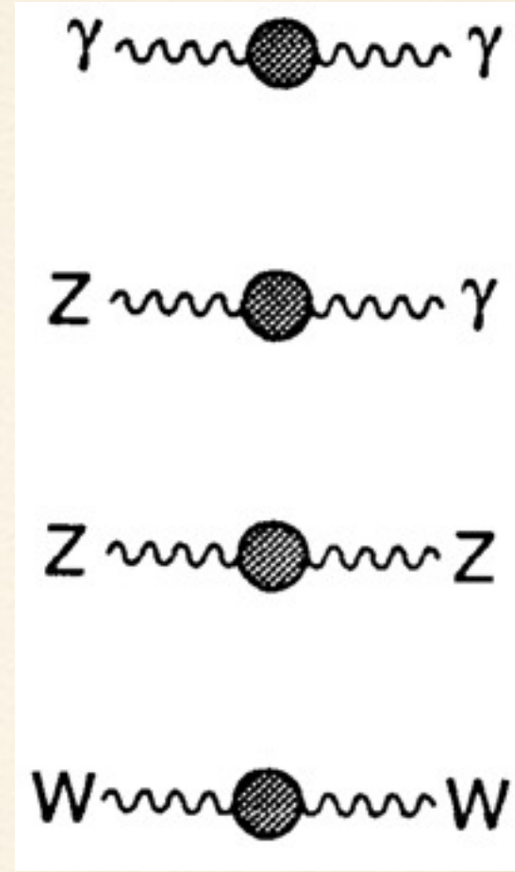

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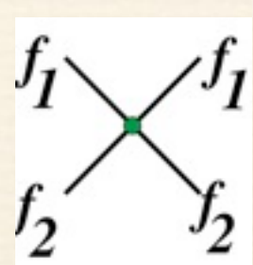
Flavor Diagonal Interactions

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

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

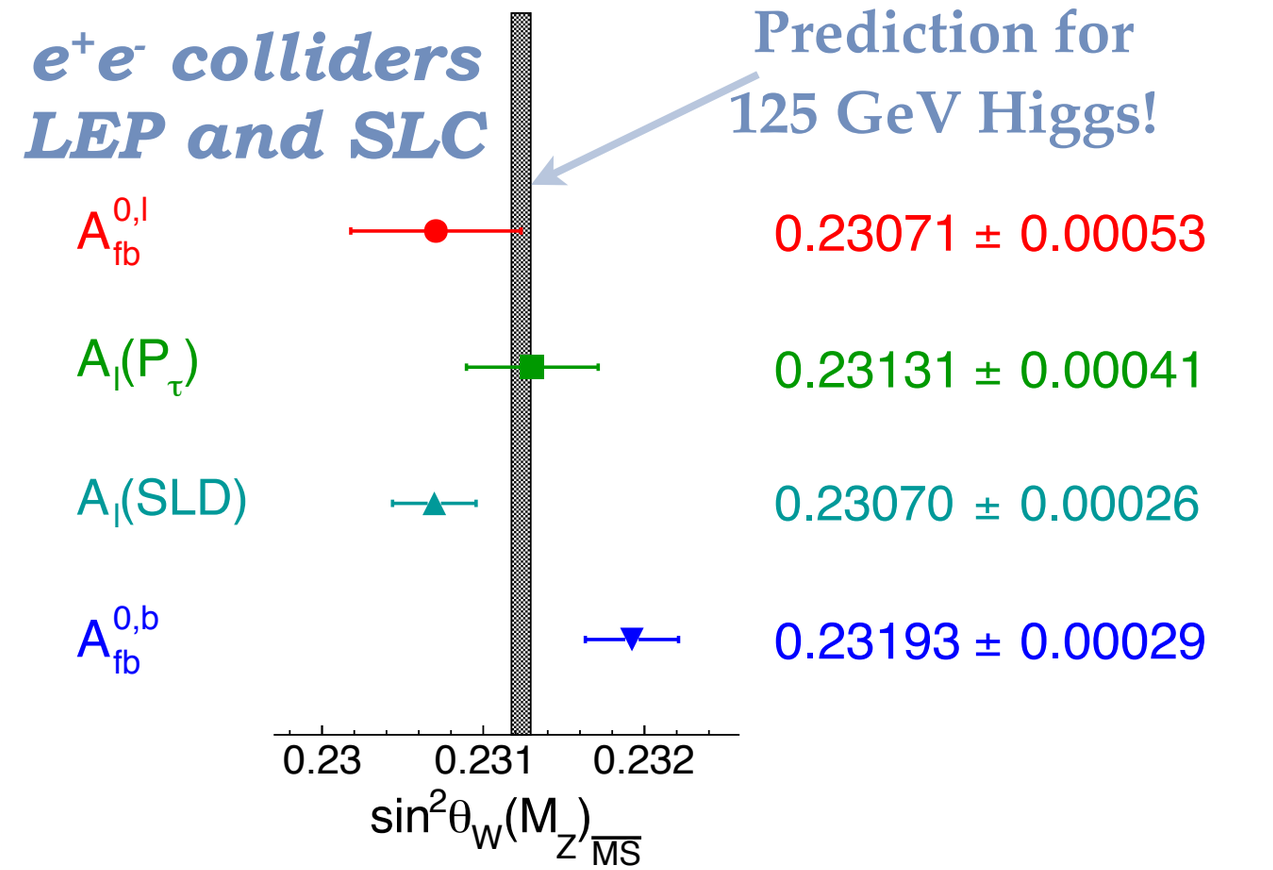
A_{new}

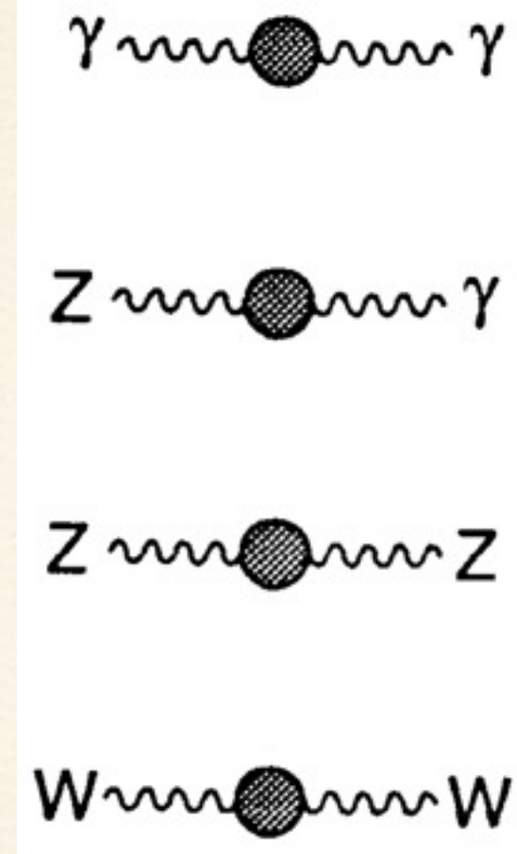


New heavy physics that does not couple directly to SM gauge bosons

The Weak Mixing Angle

The most precise measurements at LEP/SLC





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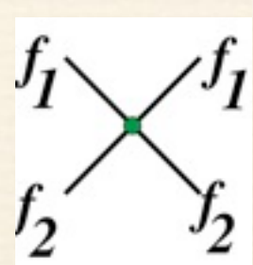

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on resonance: A_Z is imaginary

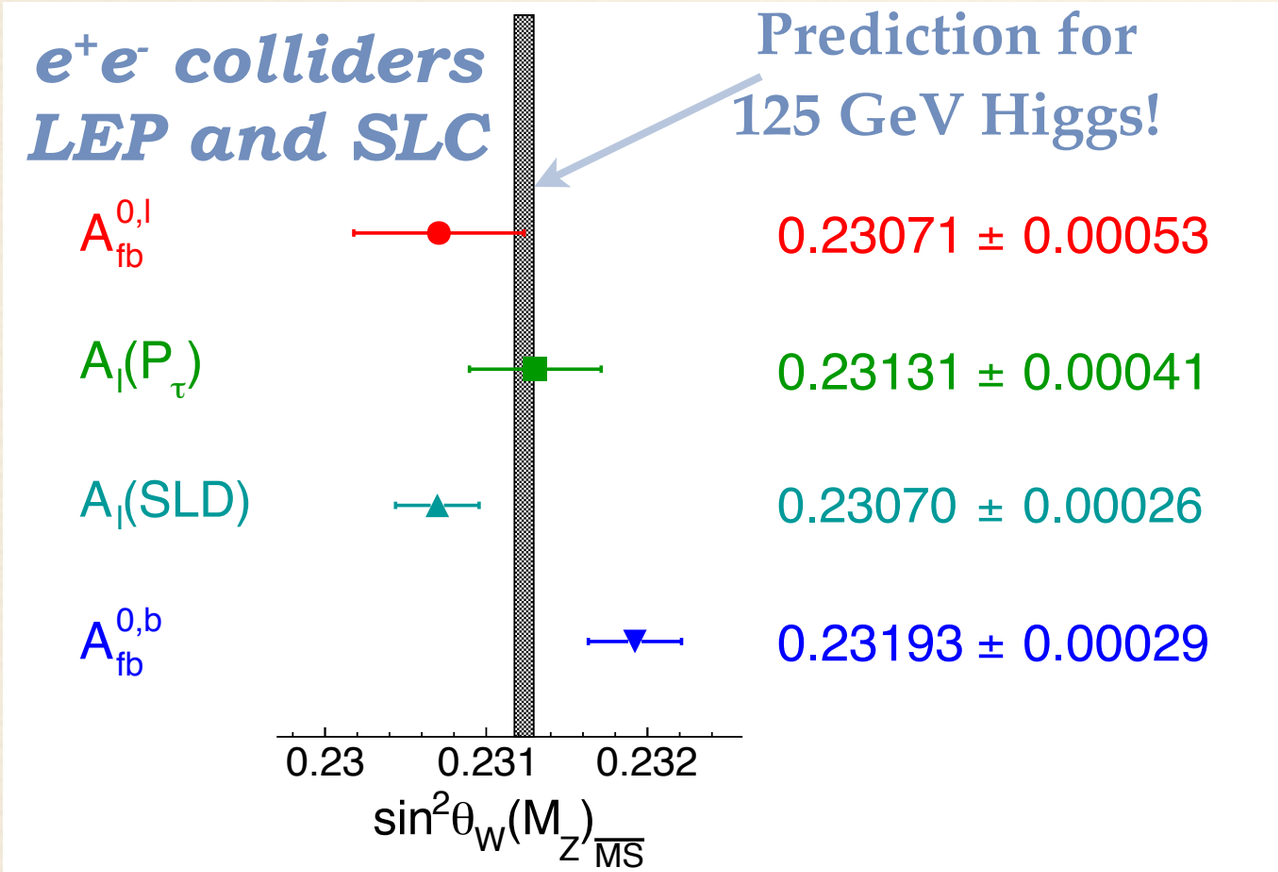
$$\left|A_Z + A_{new}\right|^2 \to A_Z^2\left[1 + \left(\frac{A_{new}}{A_Z}\right)^2\right]$$

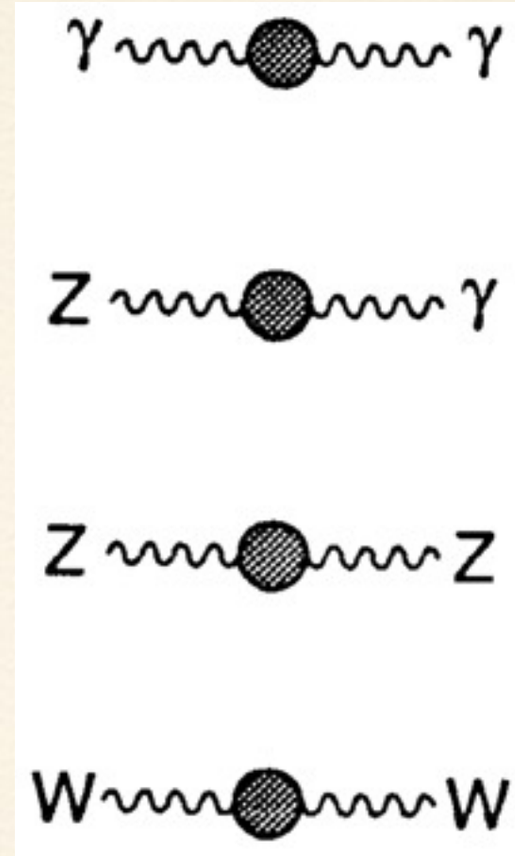
no interference!

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

The Weak Mixing Angle

The most precise measurements at LEP/SLC





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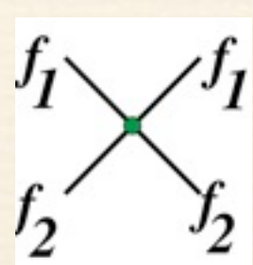

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Physics down to a length scale of 10^{-19} m well understood but.....

EW Physics after LEP/SLC

Many questions still unanswered….

The High Energy Frontier: Collider Physics

The Cosmic Frontier: Particle, Nuclear and Gravitational Astrophysics

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- ✦ **Violation of Accidental (?) Symmetries**
- ✦ **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....

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

Indirect Clues

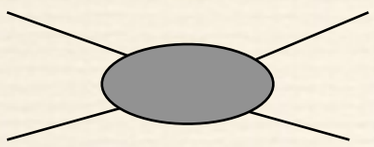
The Intensity/Precision Frontier

High Energy Dynamics

E

Λ (~TeV)

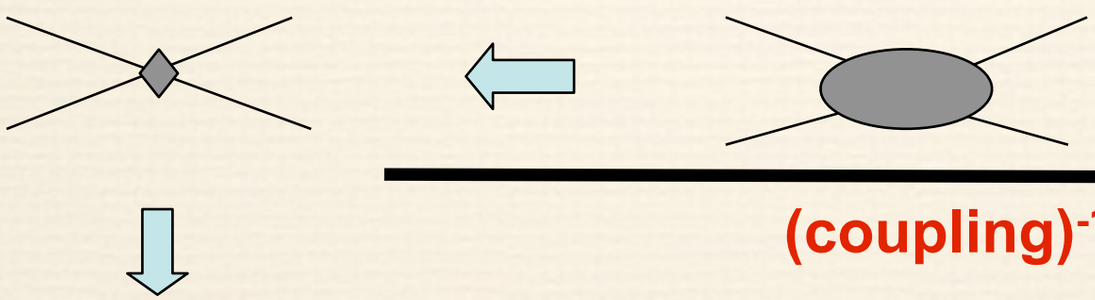
$M_{W,Z}$ (100 GeV)



SM amplitudes can be very precisely predicted

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

higher dimensional operators can be systematically classified



Dark Sector

(coupling)$^{-1}$

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

Heavy Z's, Light Z's (dark forces), technicolor, compositeness, extra dimensions, SUSY…

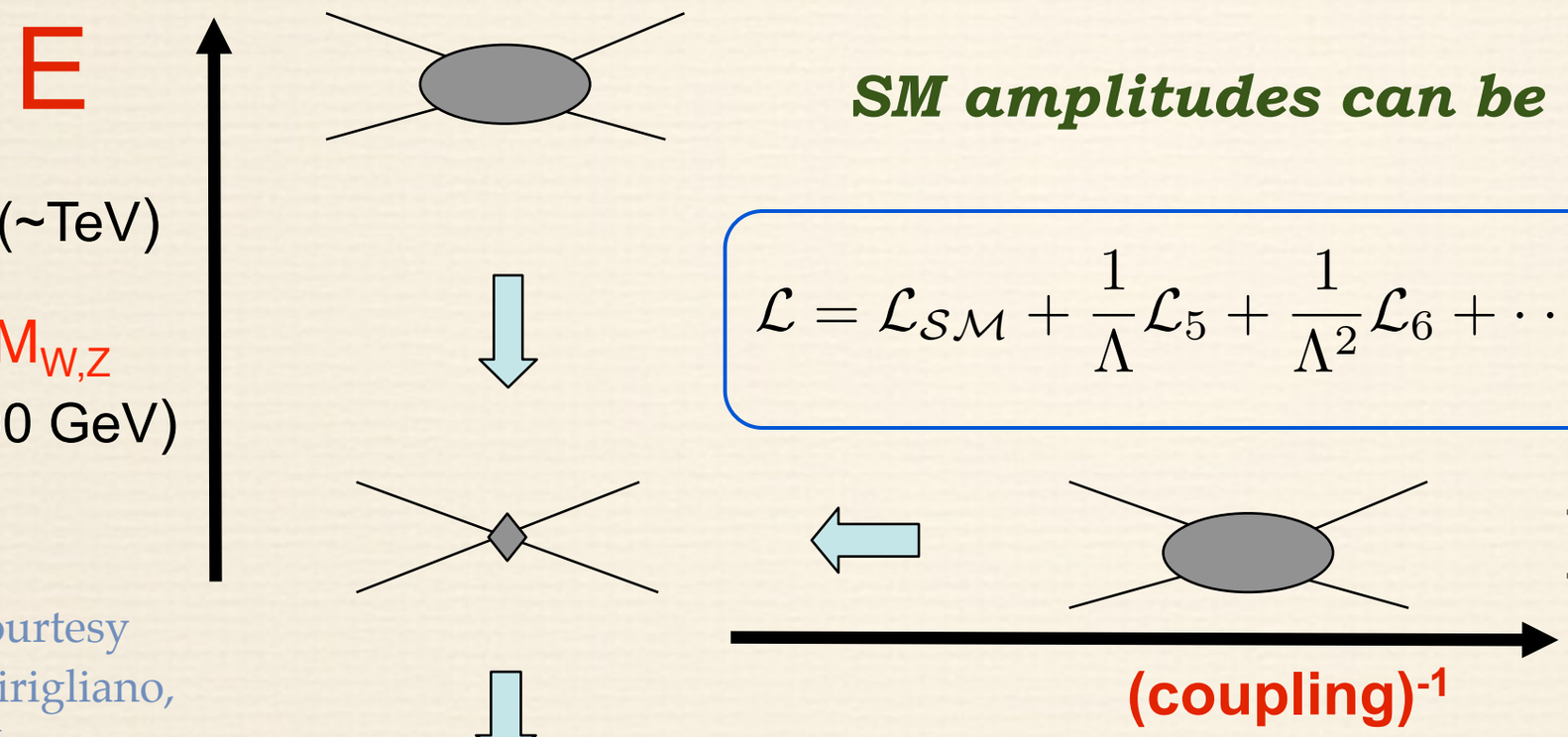
Electroweak Interactions at scales much lower than the W/Z mass

Indirect Clues

The Intensity/Precision Frontier

Interplay between electroweak and hadron dynamics

High Energy Dynamics



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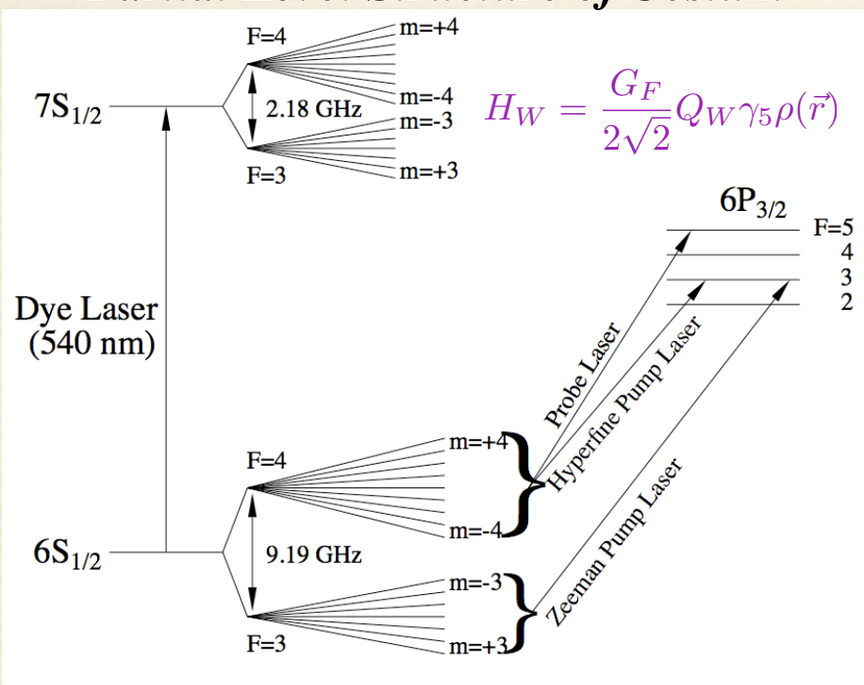
Low Energy Measurements

Atomic Parity Violation

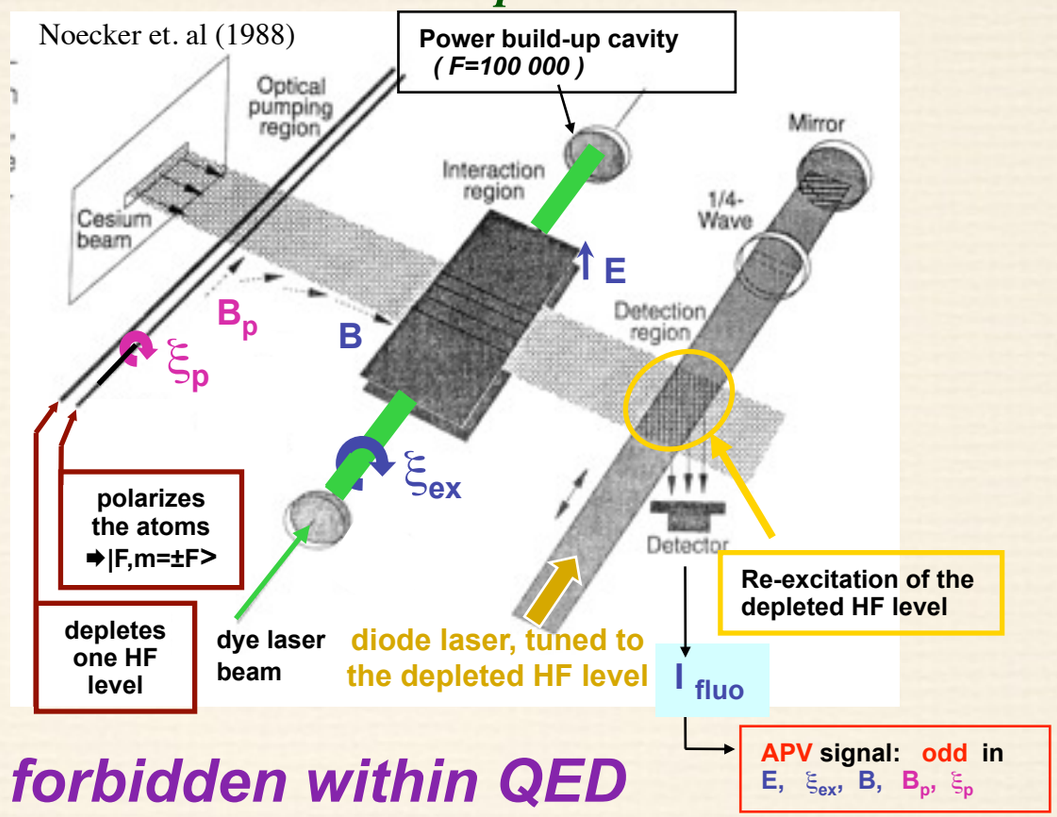
Carl Wieman and collaborators at U. Colorado (Boulder)

Partial Level Structure of Cesium



$$H_W = \frac{G_F}{2\sqrt{2}} Q_W \gamma_5 \rho(\vec{r})$$

Boulder Experiment



- ***6S → 7S transition in ^{133}Cs is forbidden within QED***
- ***Parity Violation introduces small opposite parity admixtures***
- ***Induce an E1 Stark transition, measure E1-PV interference***
- ***5 sign reversals to isolate APV signal and suppress systematics***
- ***Signal is ~ 6 ppm, measured to ~ 20 ppb***

$$Q_W(Z,N) = Z(1-4\sin^2\theta_W) - N$$

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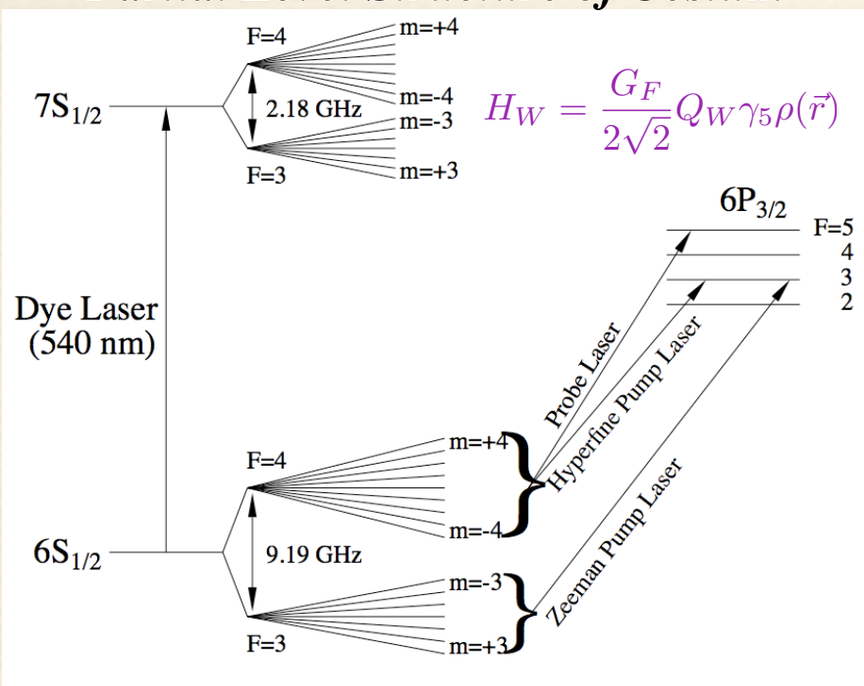

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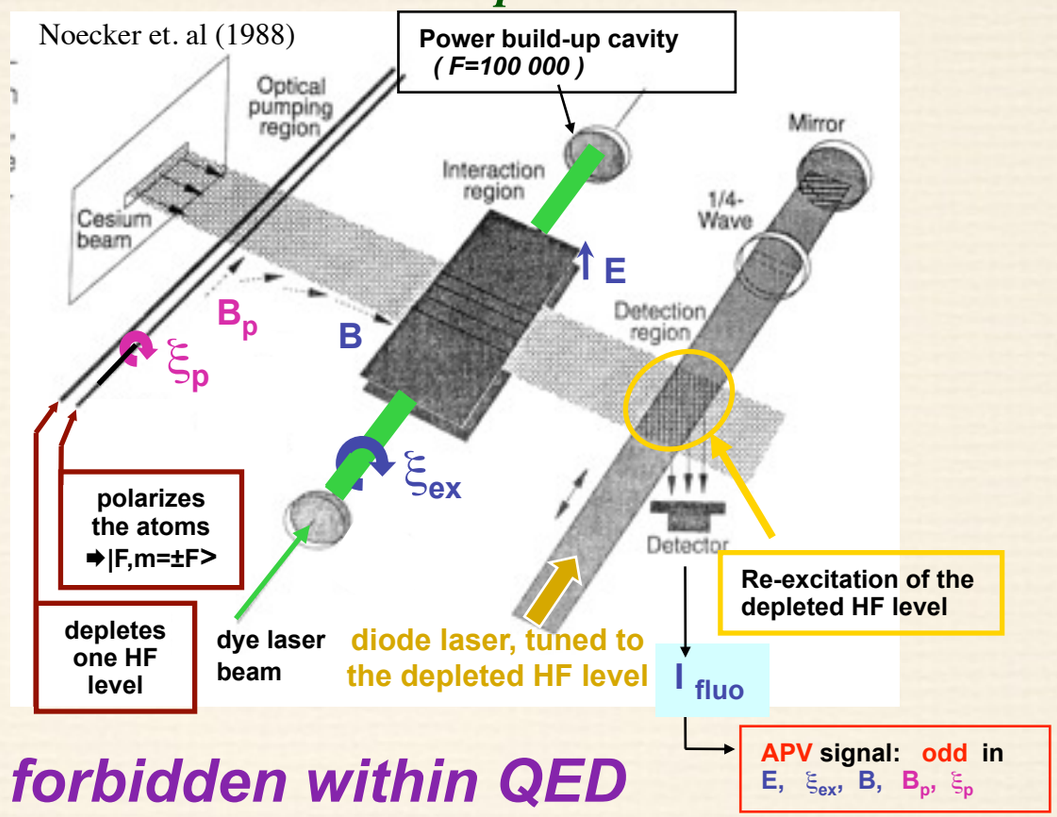

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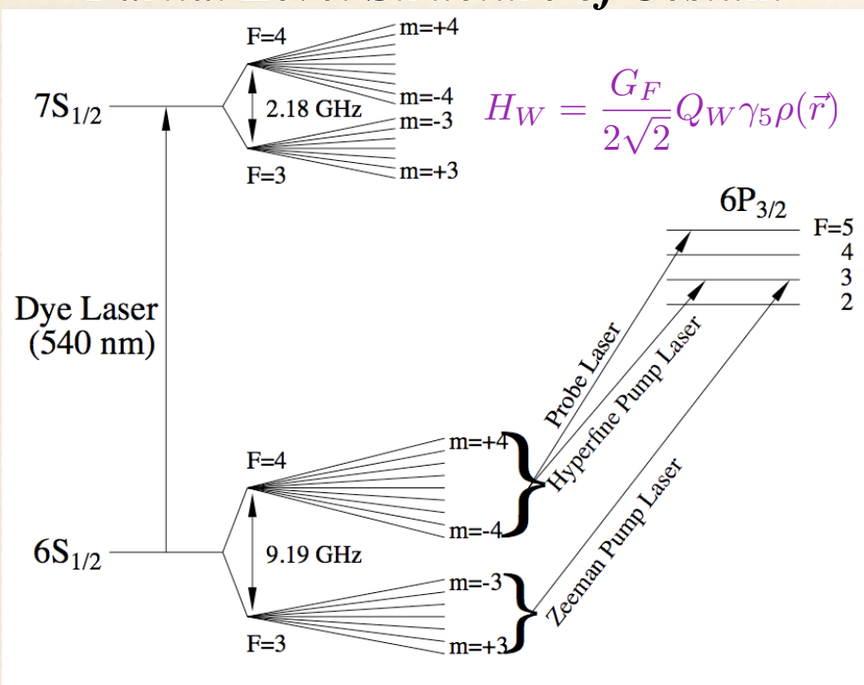

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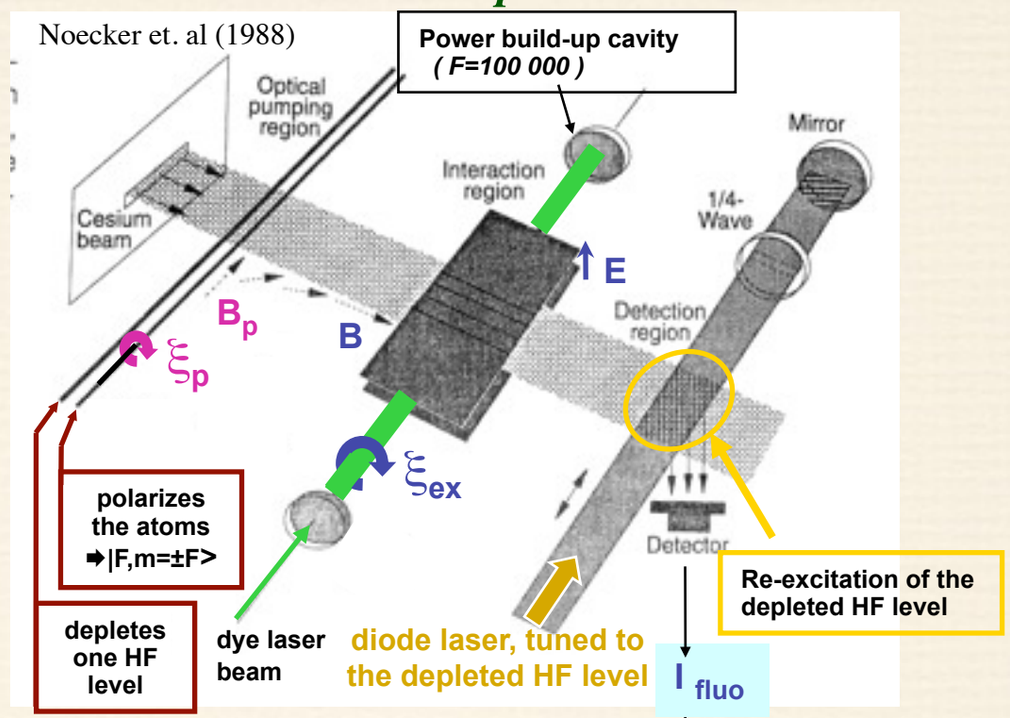

APV signal: odd in E, ξ_{ex}, B, B_p, ξ_p

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$$Im(E1_{PNC})/\beta = 1.5935(56)\ \mathrm{mV/cm}$$

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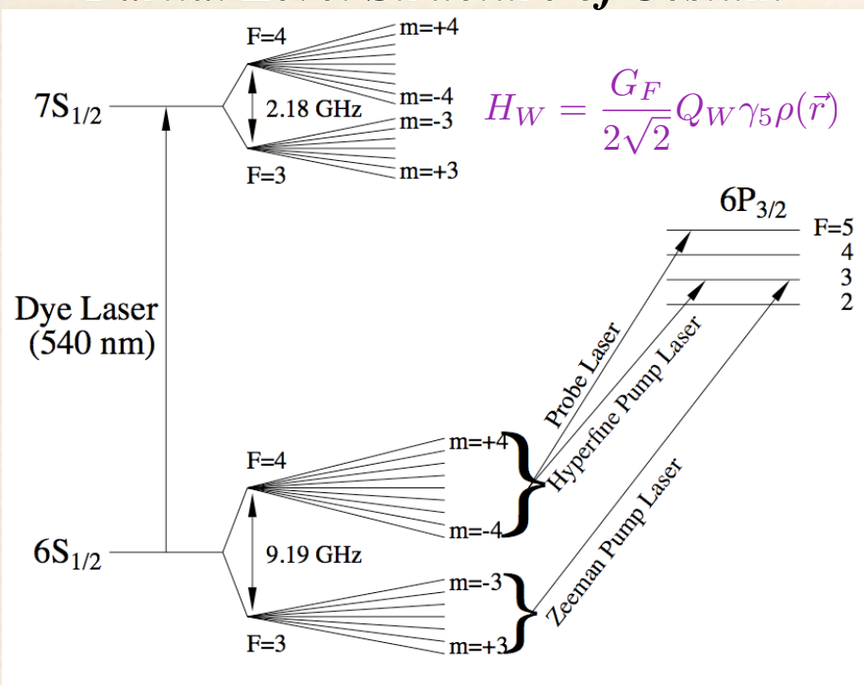
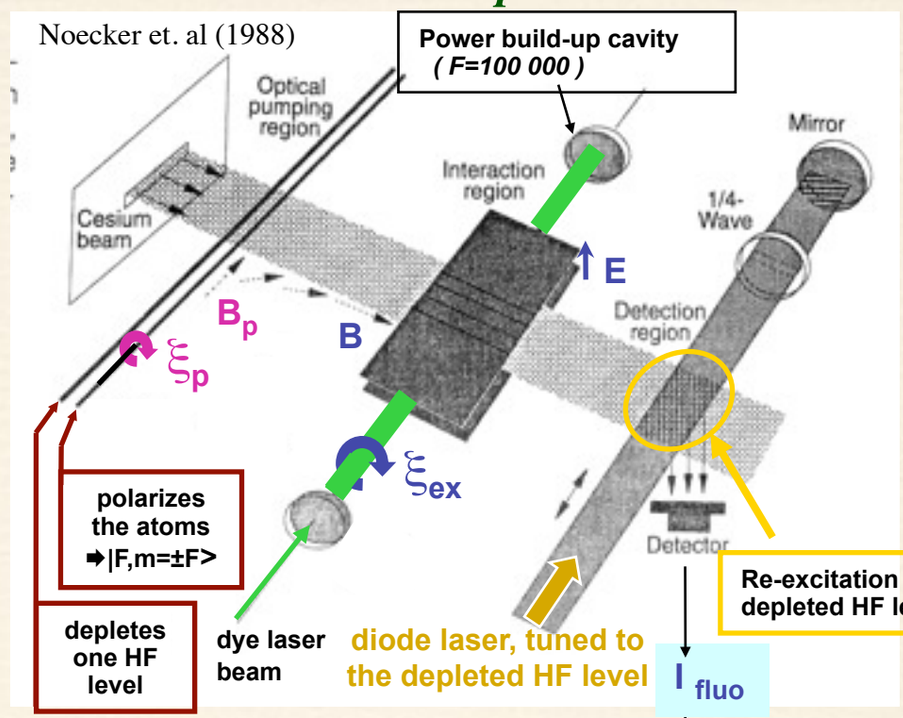


$$H_W = \frac{G_F}{2\sqrt{2}} Q_W \gamma_5 \rho(\vec{r})$$

Boulder Experiment



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

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$$Im(E1_{PNC})/\beta = 1.5935(56)\ \mathrm{mV/cm}$$

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Atomic Parity Violation

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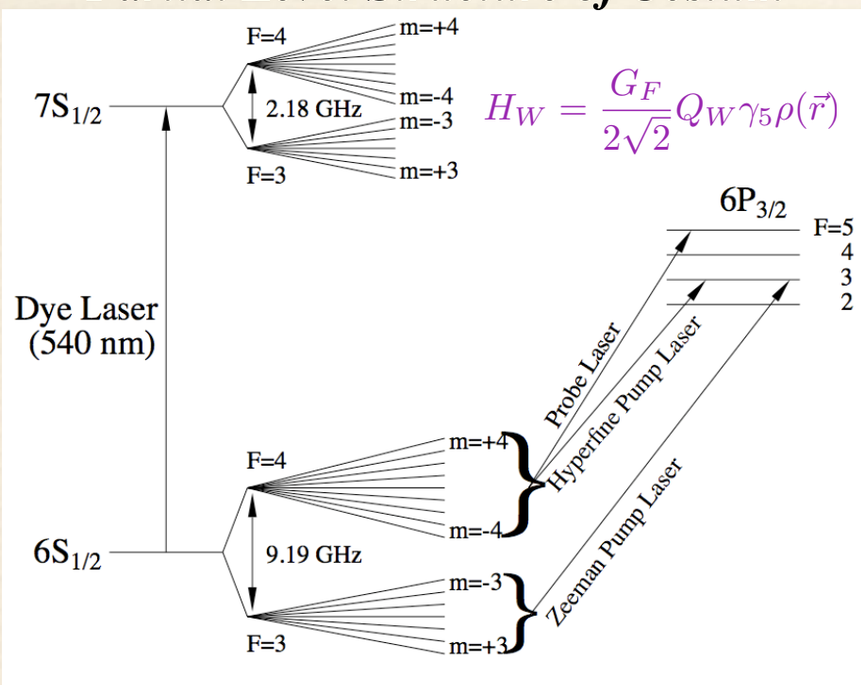

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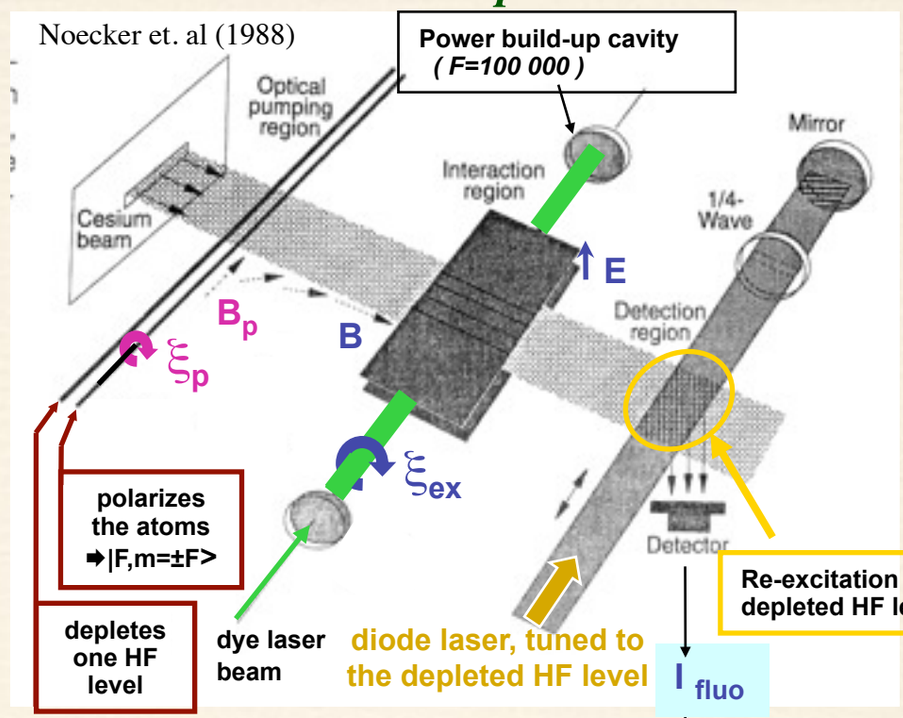

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k_{PNC}

Atomic Theory

$0.9065(36) \times 10^{-11} e a_0$

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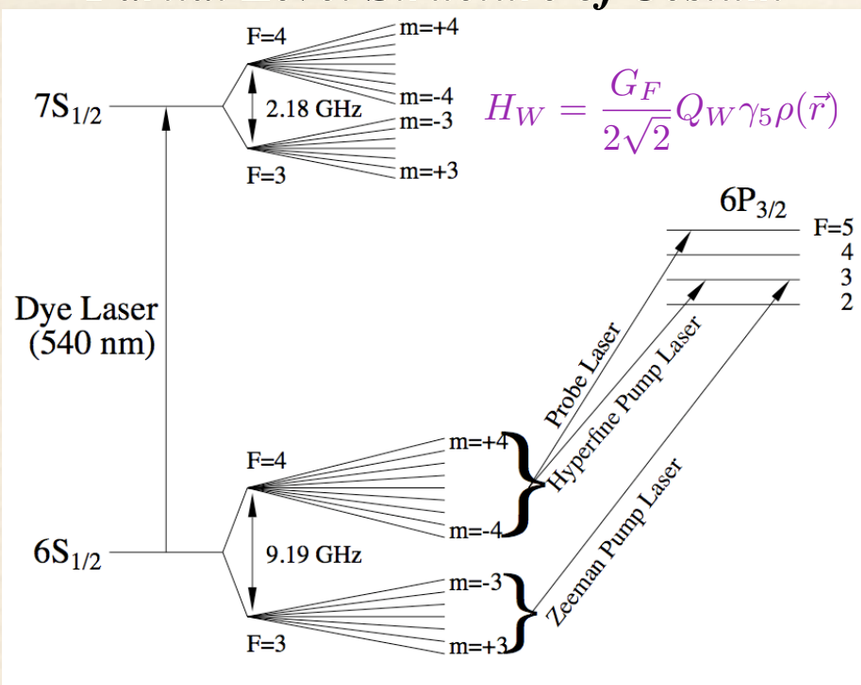

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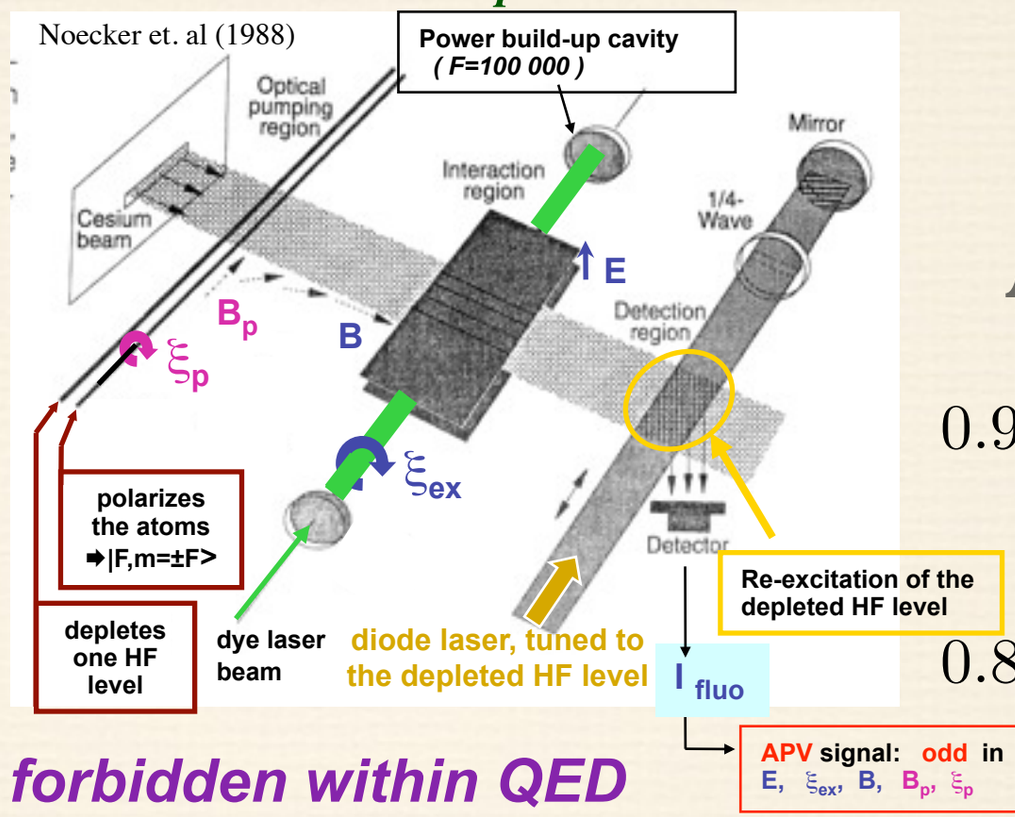

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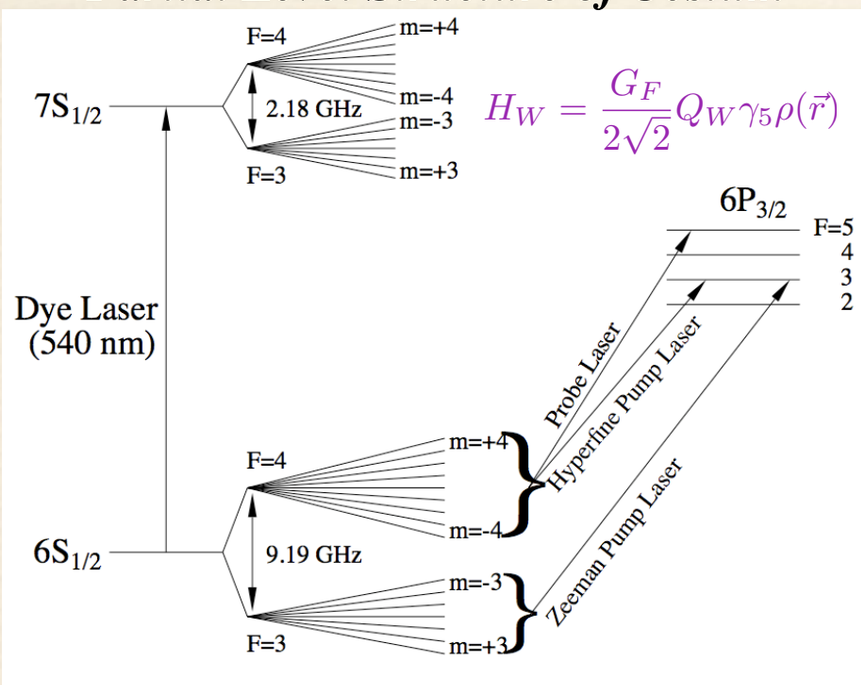

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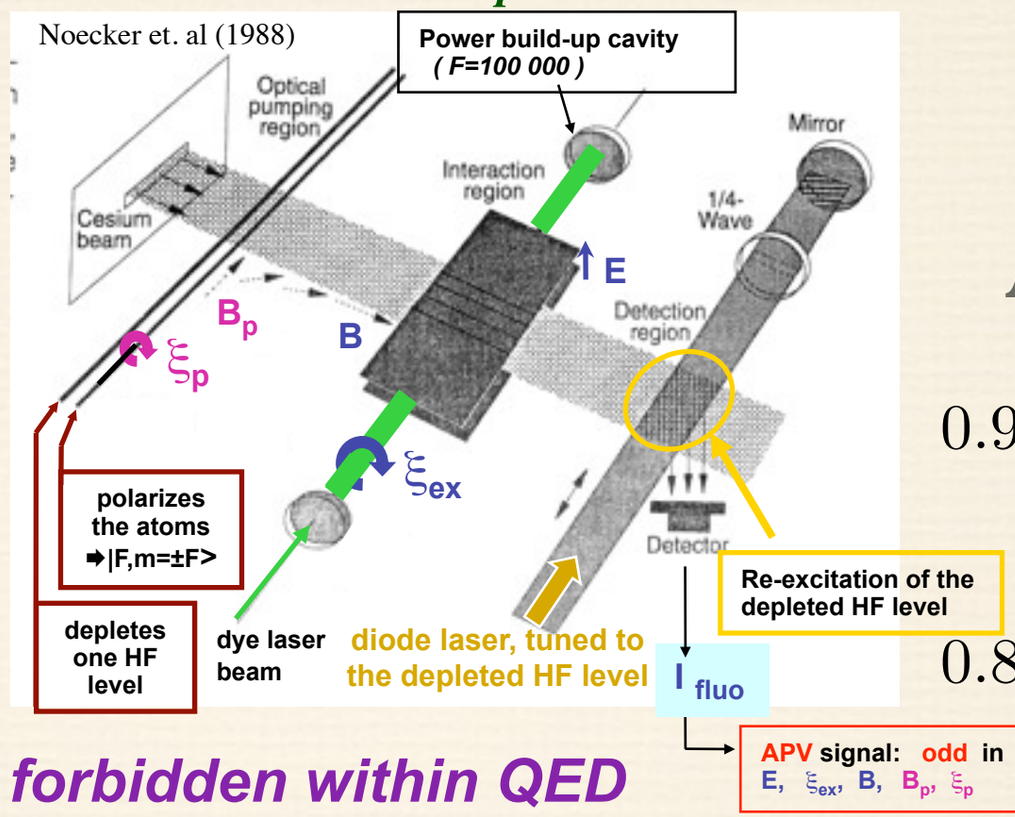

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Atomic Parity Violation

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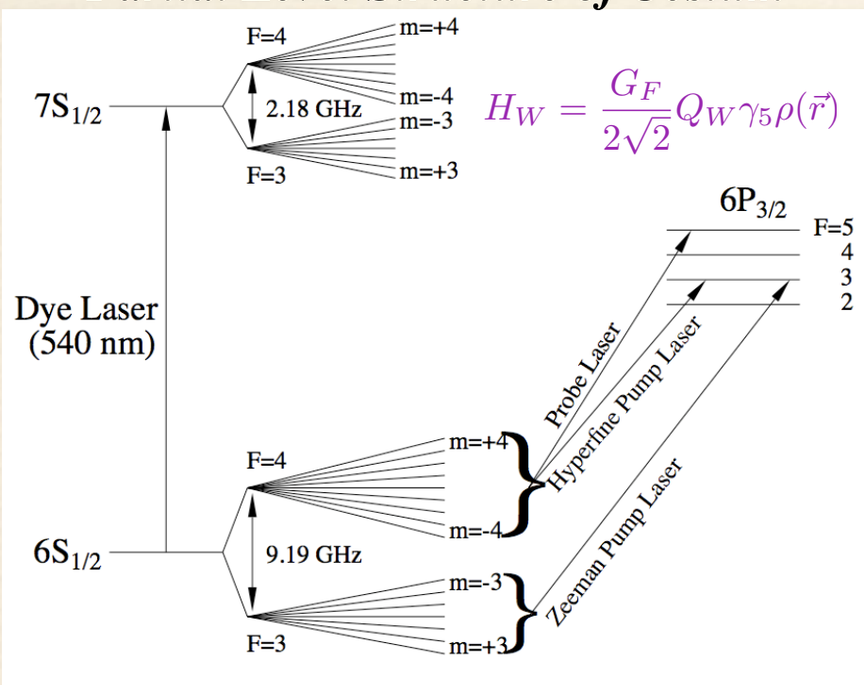

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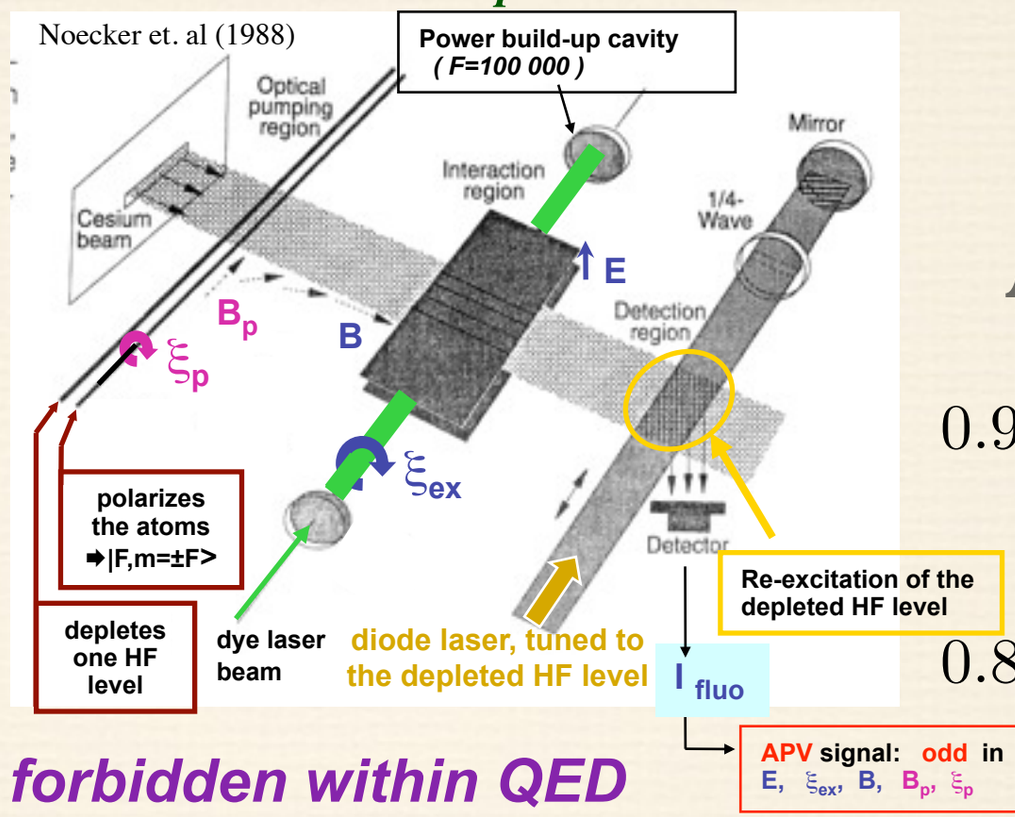

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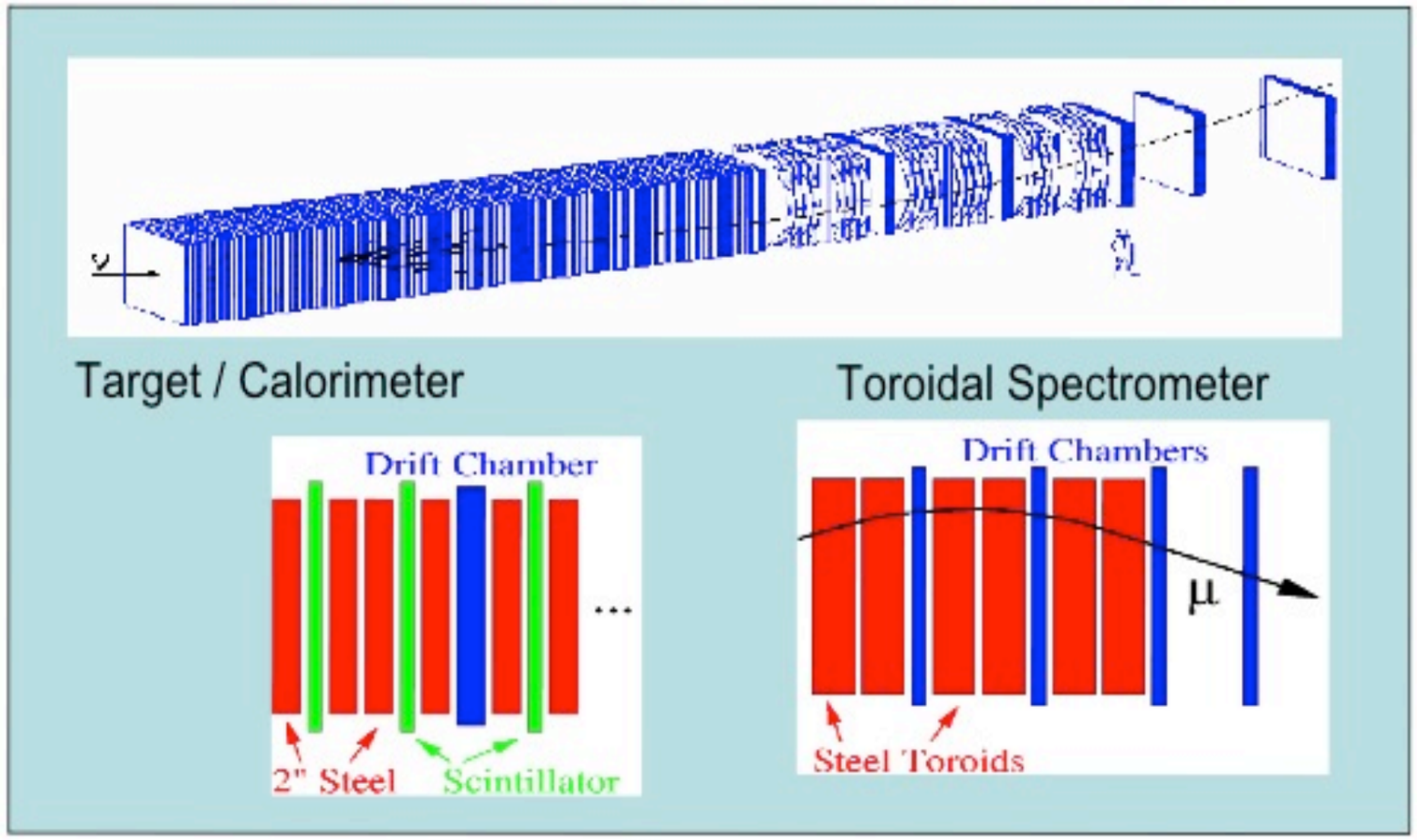
1.5 σ low

NuTeV



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

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

Standard Model prediction is 0.2227 (3σ deviation)

Most precise measurement of neutrino-quark coupling

Subtle parton physics effects can affect the result

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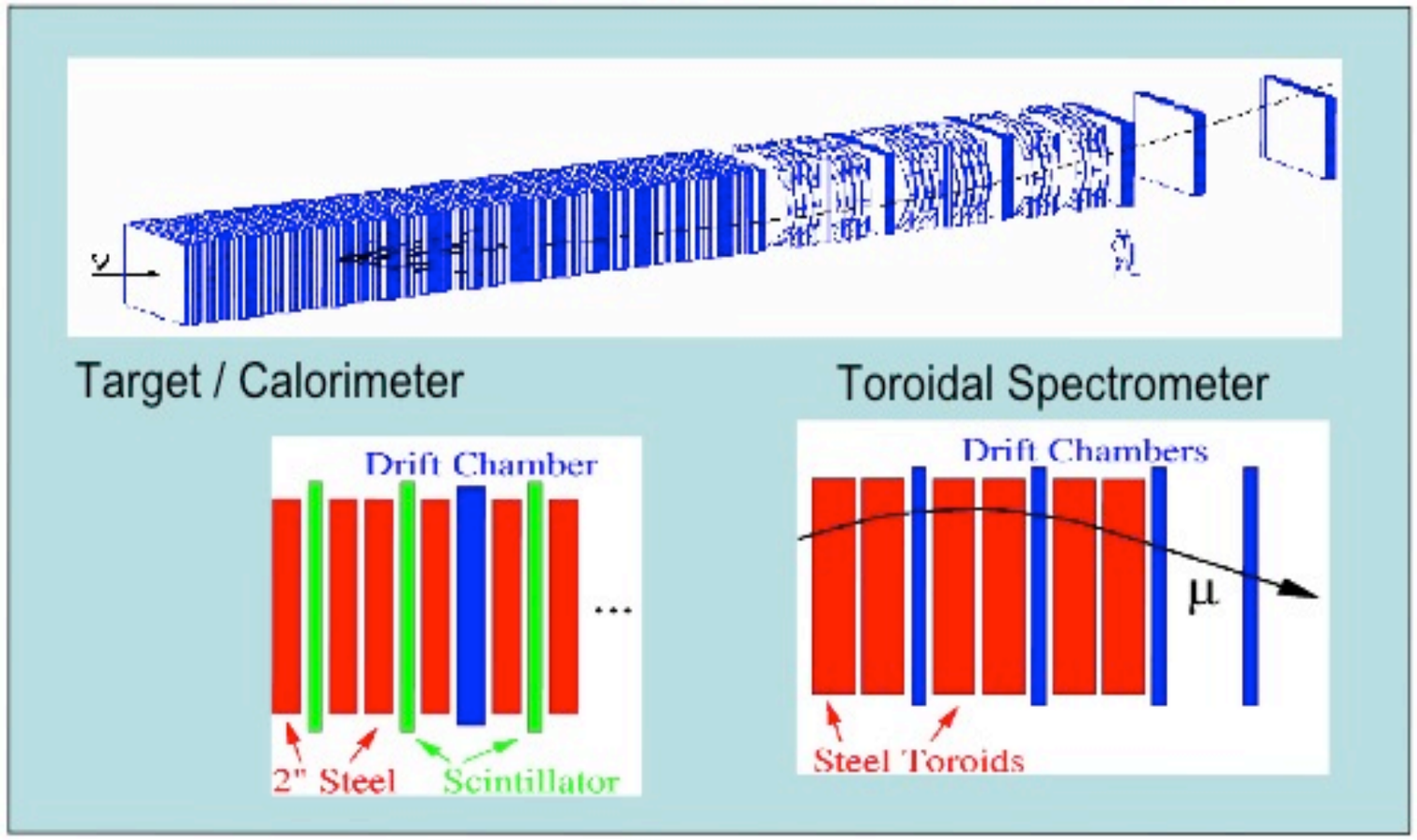
NuTeV

Significant discovery: but EW or QCD Physics?



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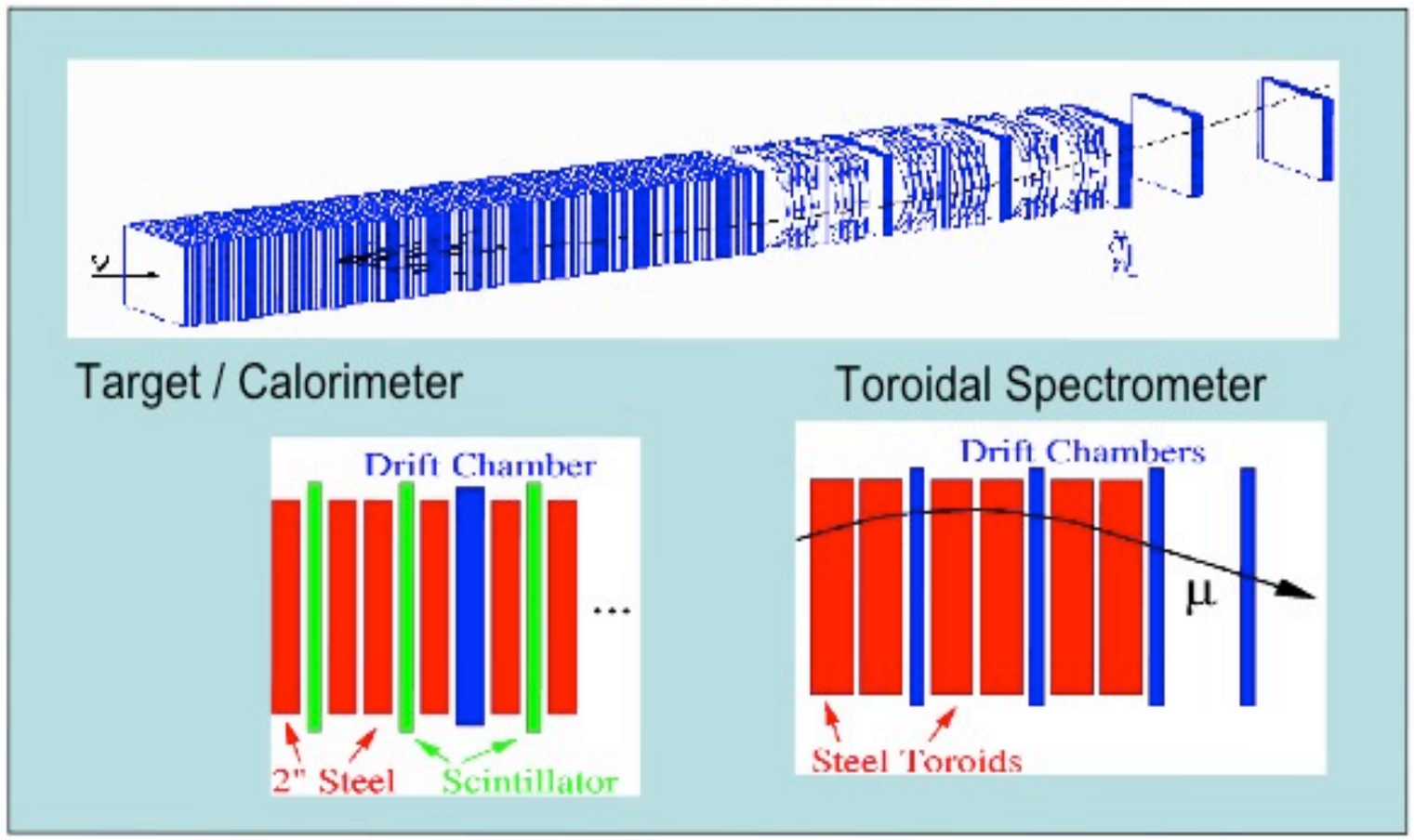

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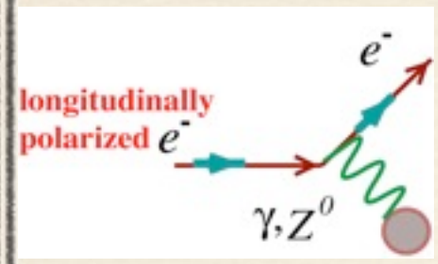

$$-A_{LR} = A_{PV} = \frac{\sigma_{\uparrow} - \sigma_{\downarrow}}{\sigma_{\uparrow} + \sigma_{\downarrow}} \sim \frac{A_{weak}}{A_{\gamma}} \sim \frac{G_F Q^2}{4\pi\alpha} \left(g_A^e g_V^T + \beta\, g_V^e g_A^T\right)$$

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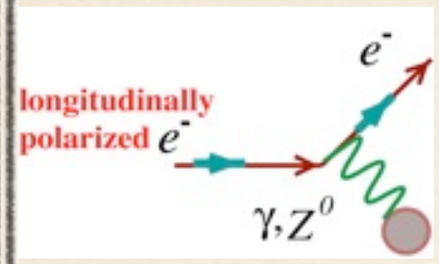

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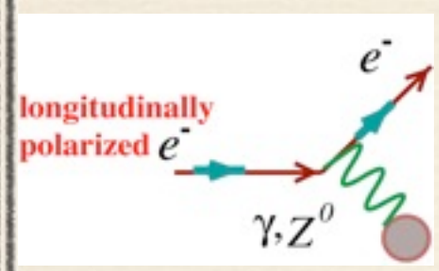

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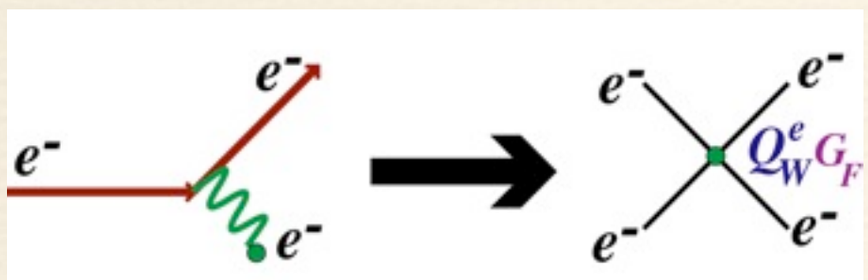

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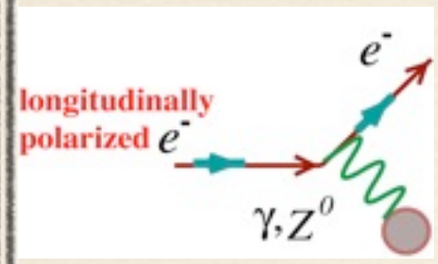

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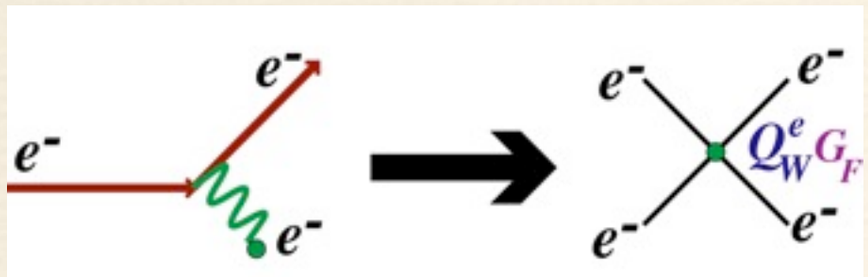

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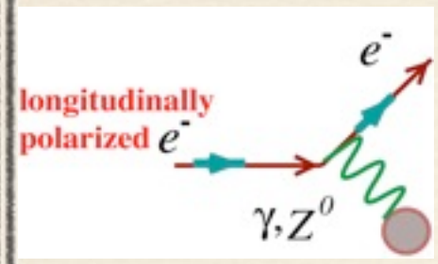

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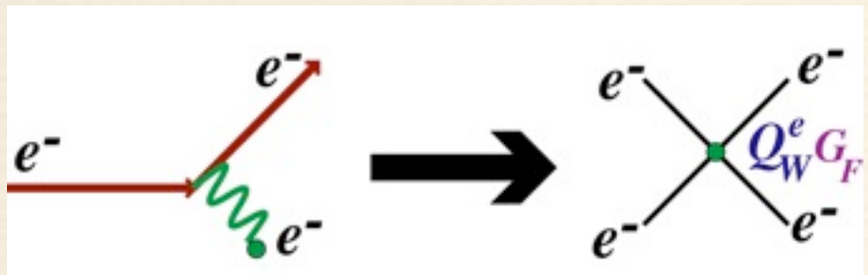

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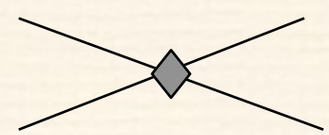

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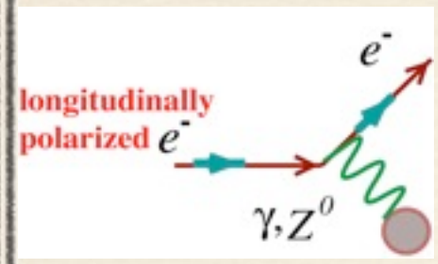

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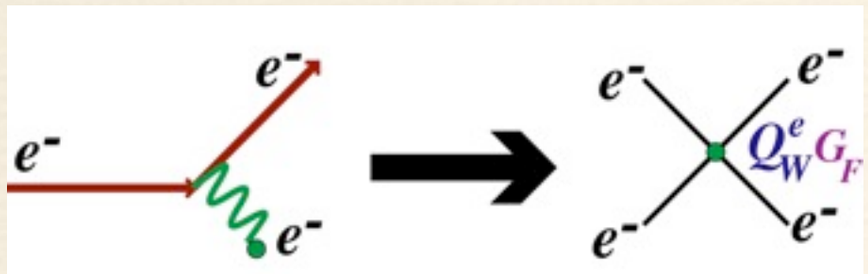

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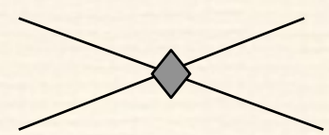

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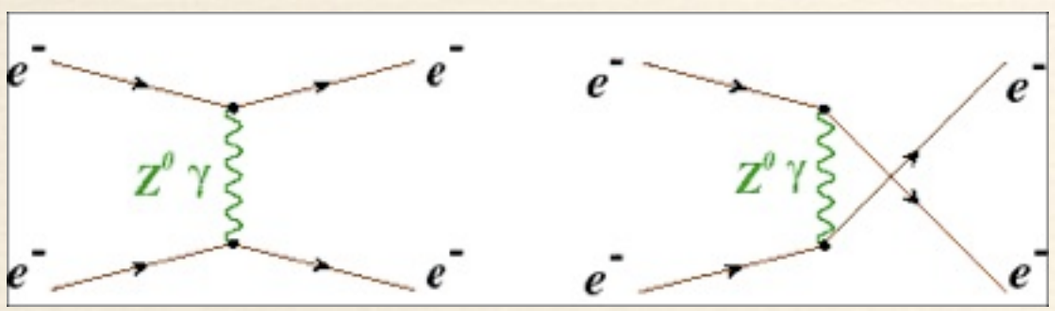

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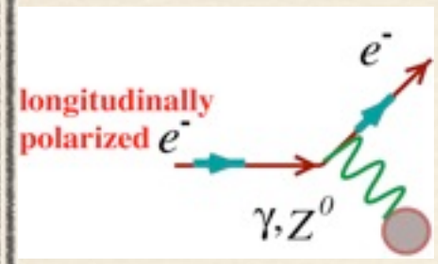

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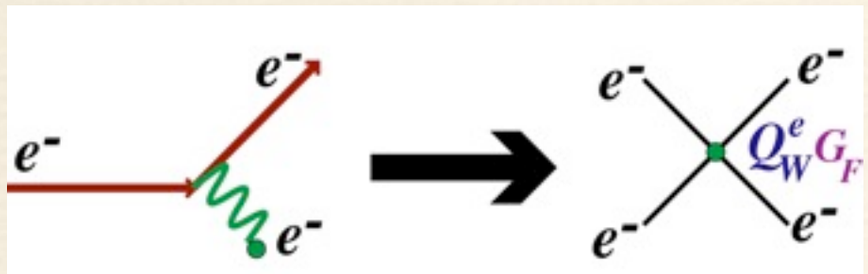

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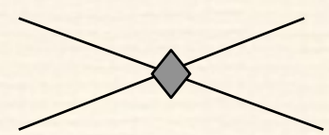

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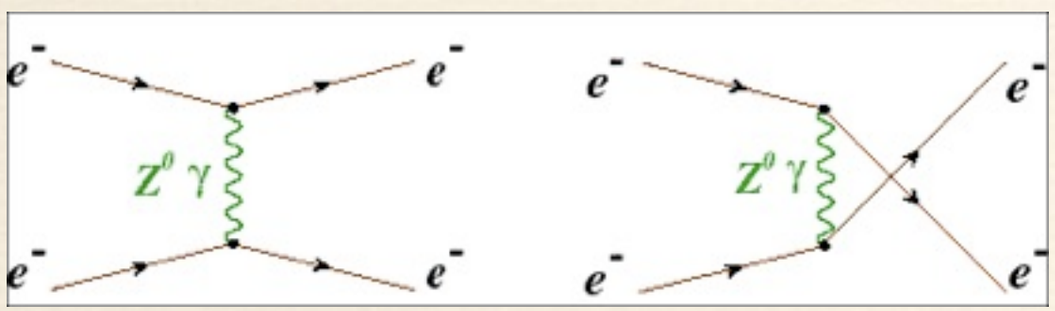

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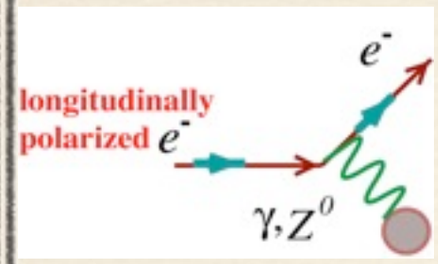
$$A_{PV} \approx 8\times10^{-8} E_{beam}(1 - 4\sin^2\vartheta_W)$$

$\Rightarrow$ **Tiny!**

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

PV Electron-Electron Scattering

Weak Charge Q_W



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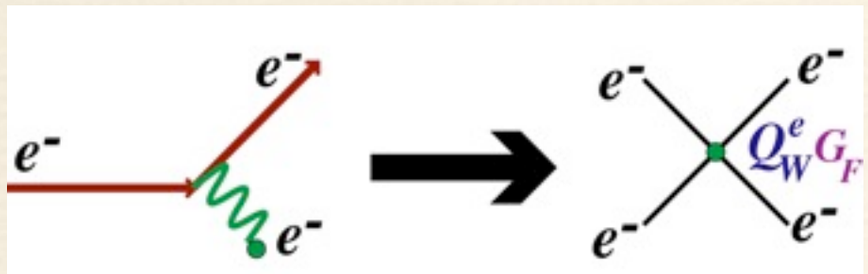

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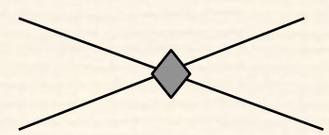

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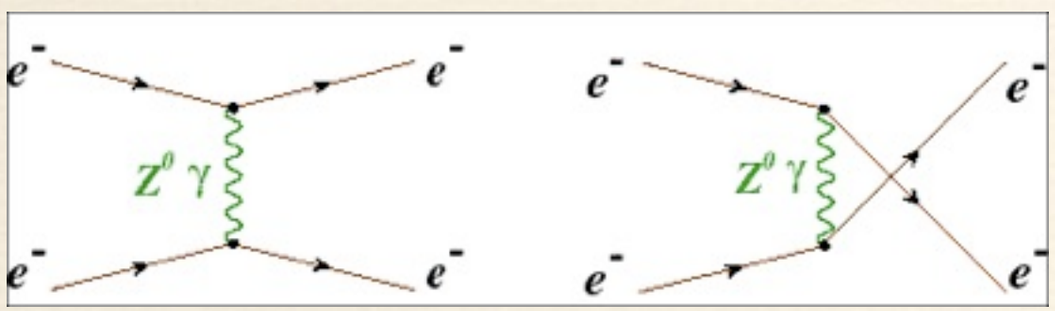


$$\left|A_\gamma + A_Z + A_{new}\right|^2 \rightarrow A_\gamma^2\left[1 + 2\left(\frac{A_Z}{A_\gamma}\right) + 2\left(\frac{A_{new}}{A_\gamma}\right)\right]$$

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

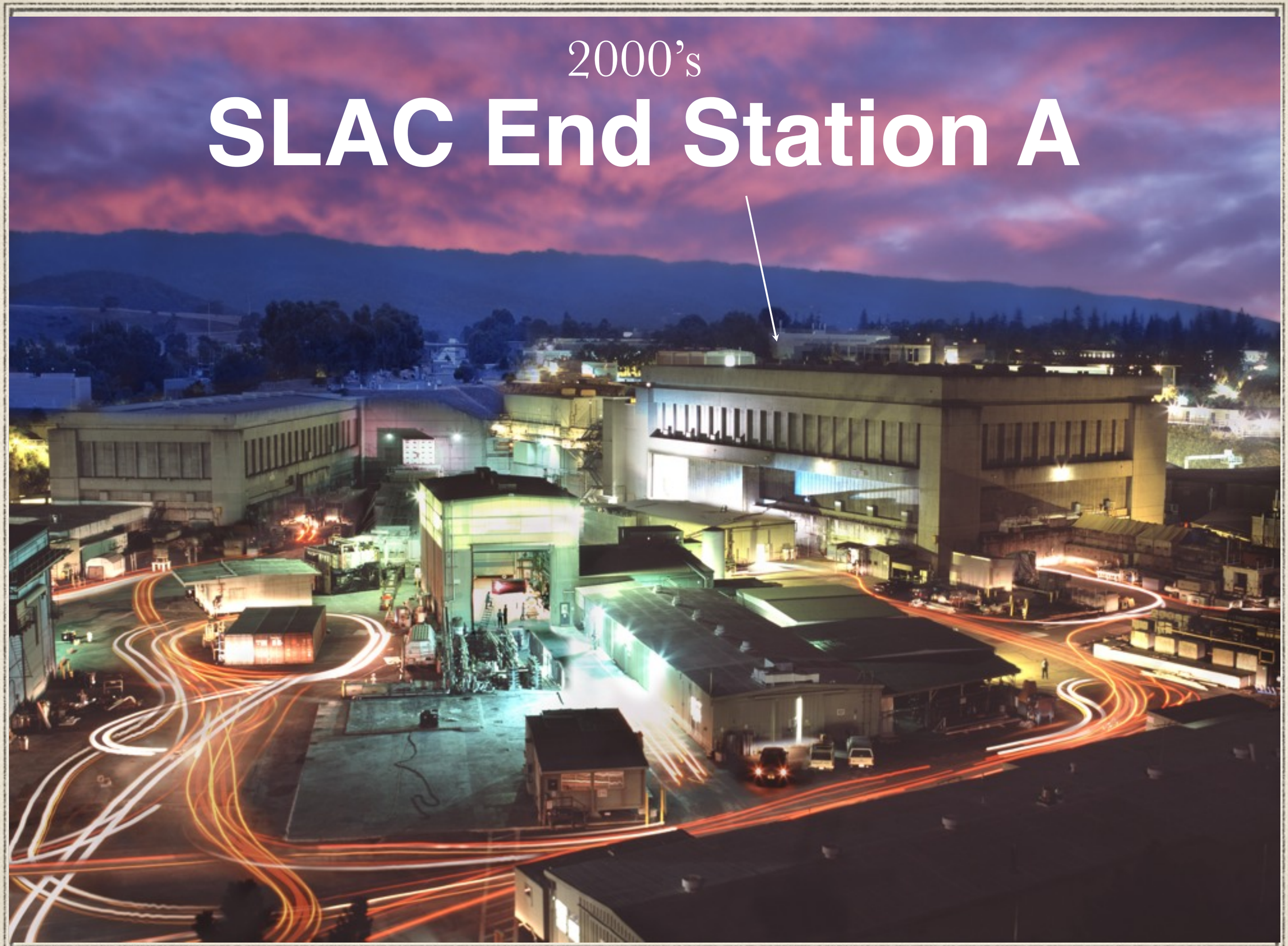
Tiny!

SLAC E158: 1999-2004

45 & 48 GeV Beam

85% longitudinal polarization

End Station A at SLAC

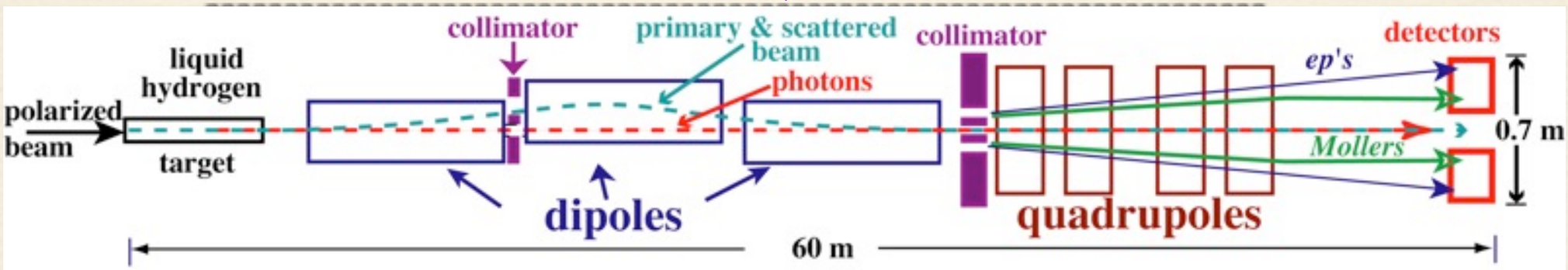

2000's
SLAC End Station A

Goal: error small enough to probe TeV scale physics

SLAC E158 Proposal

1997

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



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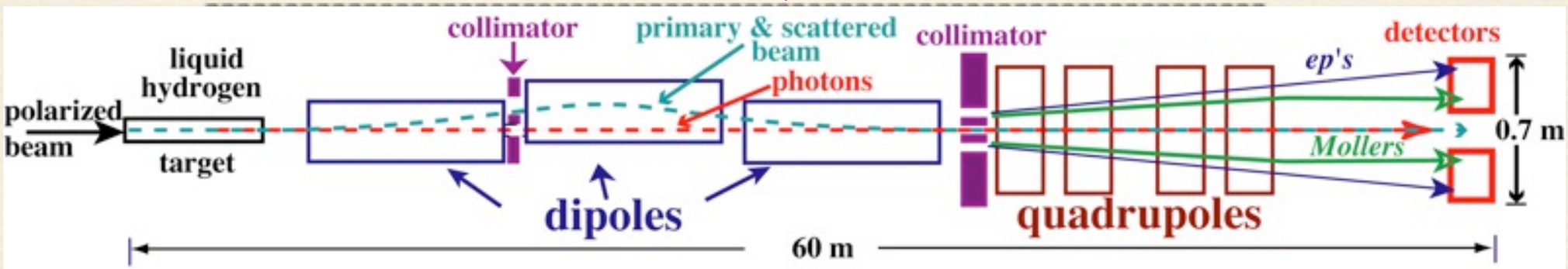
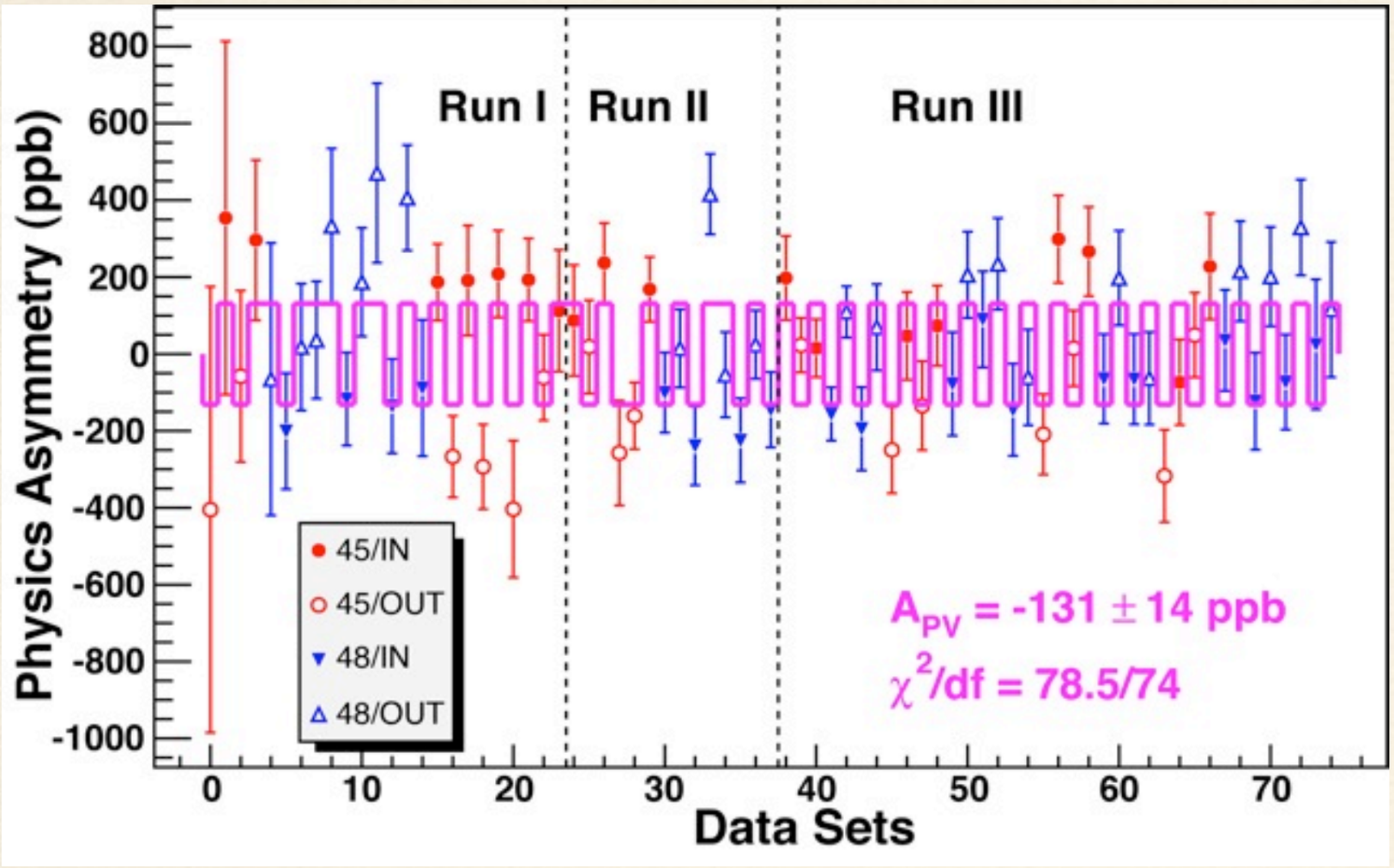


A large number of technical challenges

- 10 nm control of beam centroid on target
  - R&D on polarized source laser transport elements
- 12 microamp beam current maximum
  - 1.5 meter Liquid Hydrogen target
- 20 Million electrons per pulse @ 120 Hz
  - 200 ppm pulse-to-pulse statistical fluctuations
    - *Electronic noise and density fluctuations < 10^{-4}*
    - *Pulse-to-pulse monitoring resolution ~ 1 micron*
    - *Pulse-to-pulse beam fluctuations < 100 microns*
  - 100 Mrad radiation dose from scattered flux
    - *State-of-the-art radiation-hard integrating calorimeter*
- Full Azimuthal acceptance with θ_{lab} ~ 5 mrad
  - Quadrupole spectrometer
  - Complex collimation and radiation shielding issues

~60 physicists, 8 Ph.D. Students

E158 Physics Data 2002-3



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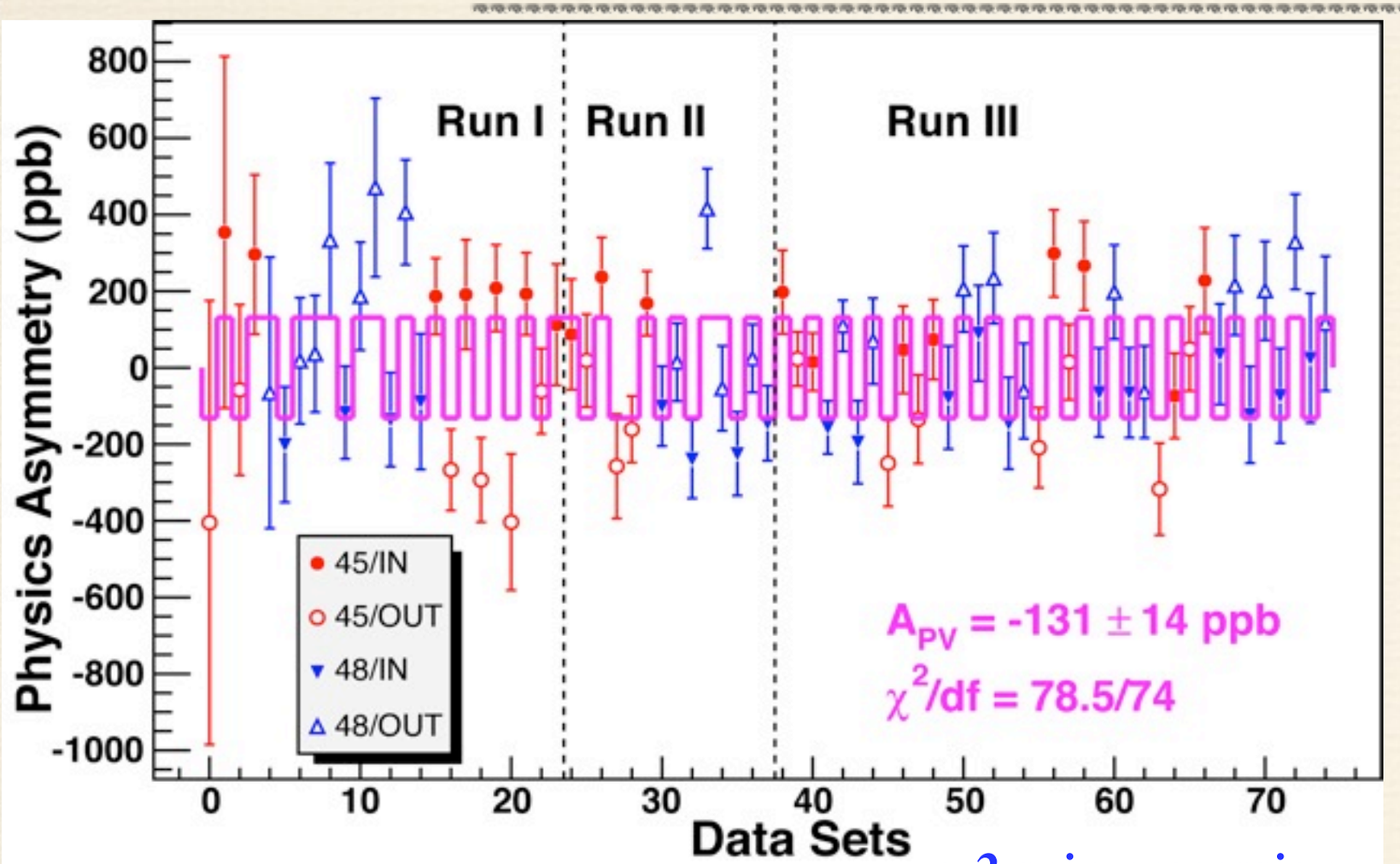
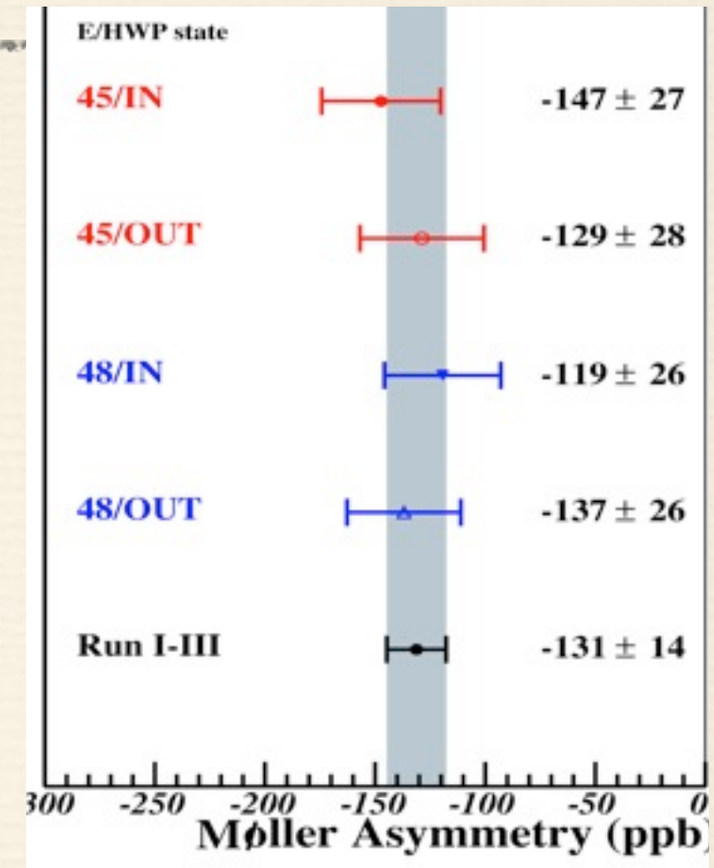
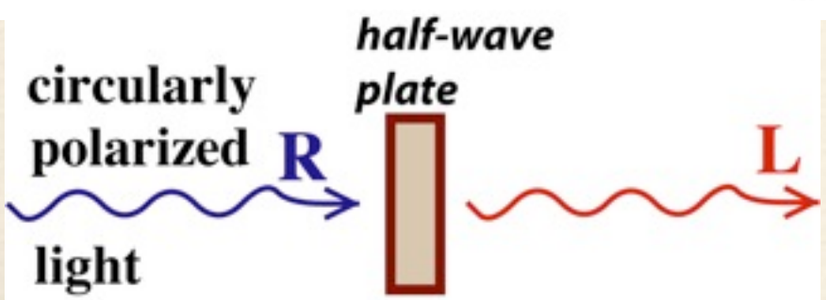


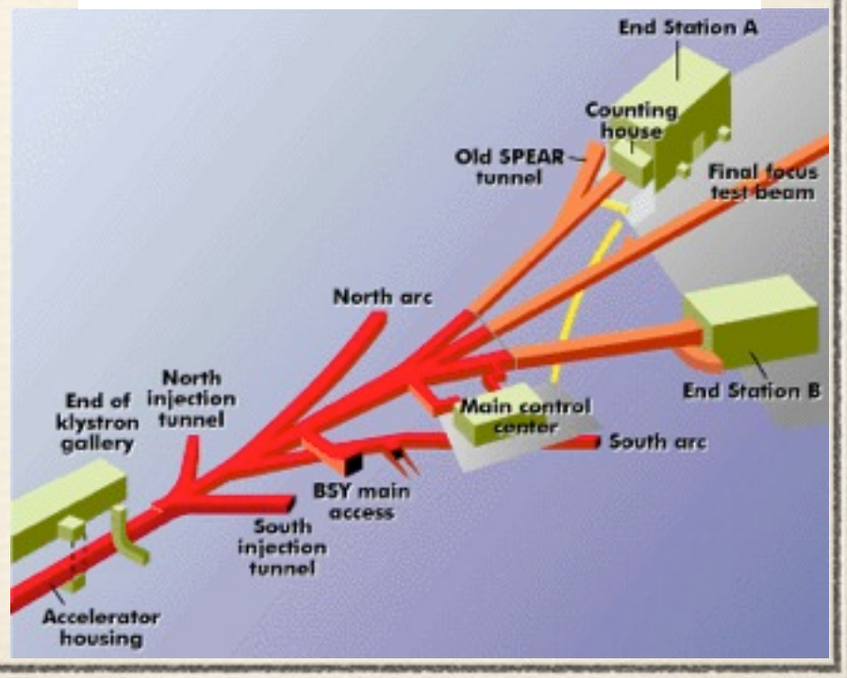




g-2 spin precession

45 GeV: 14.0 revs

48 GeV: 14.5 revs



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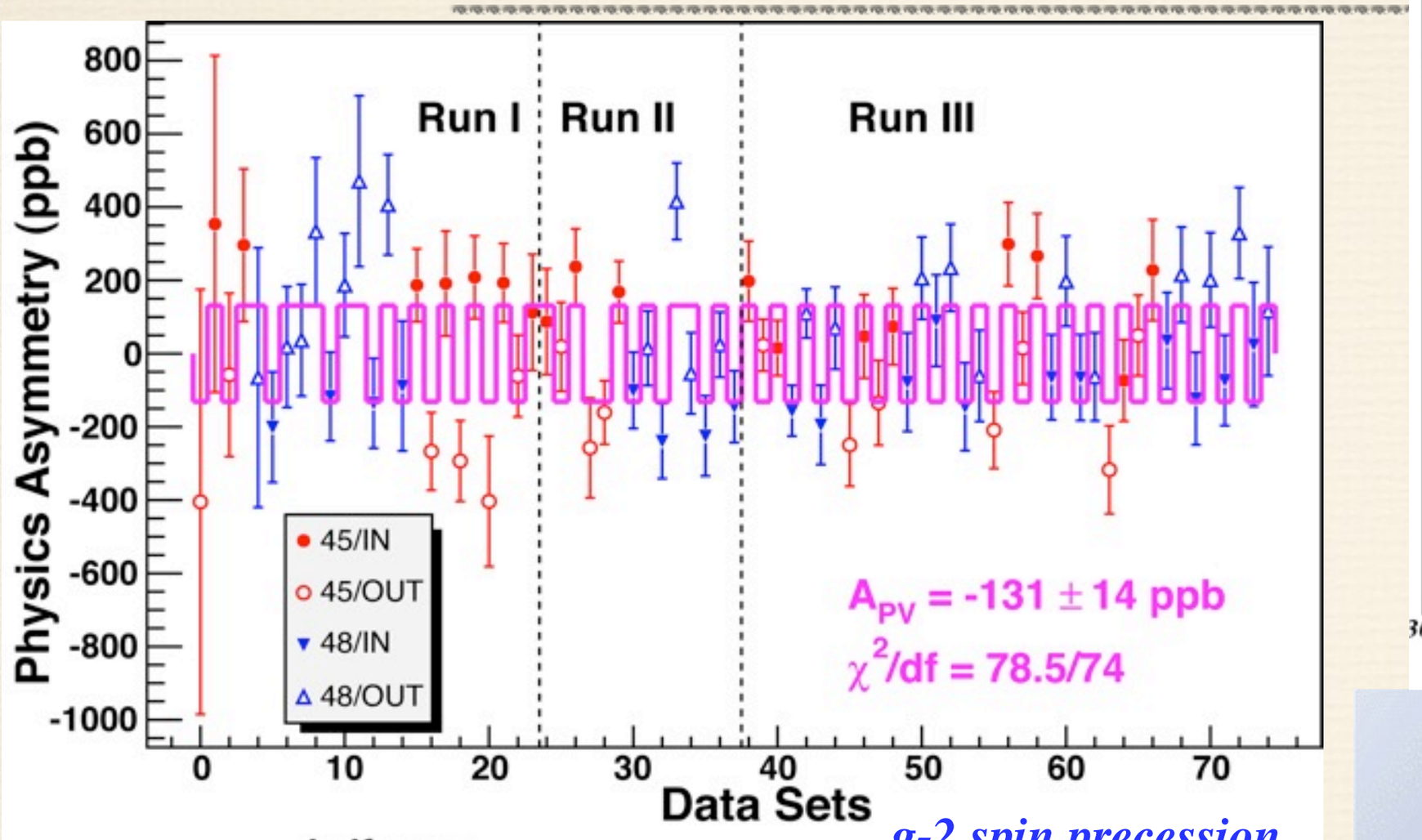

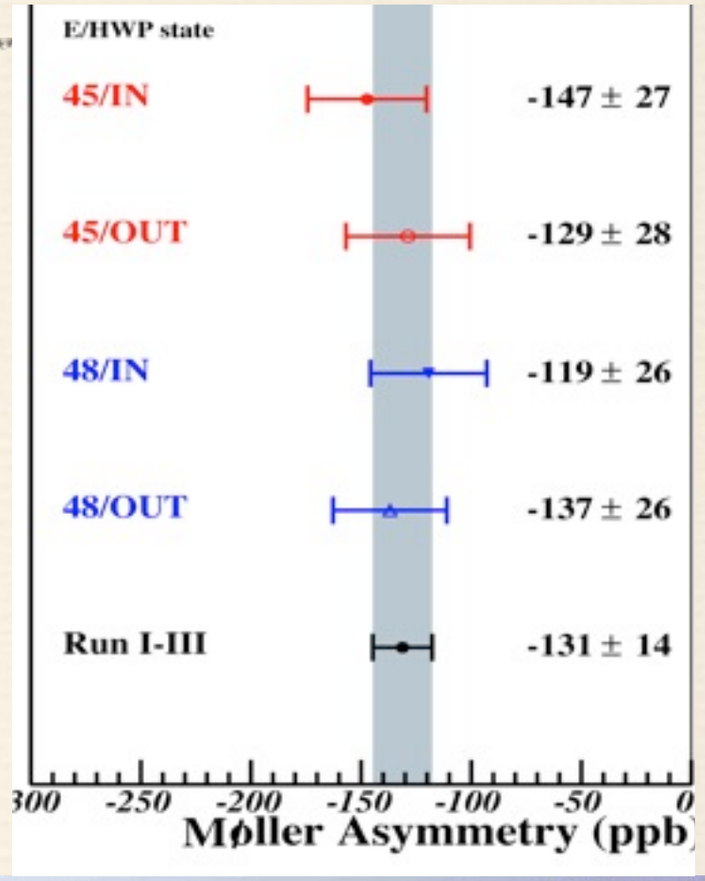

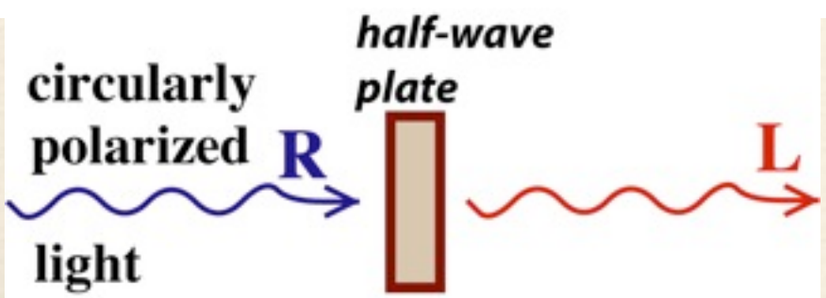

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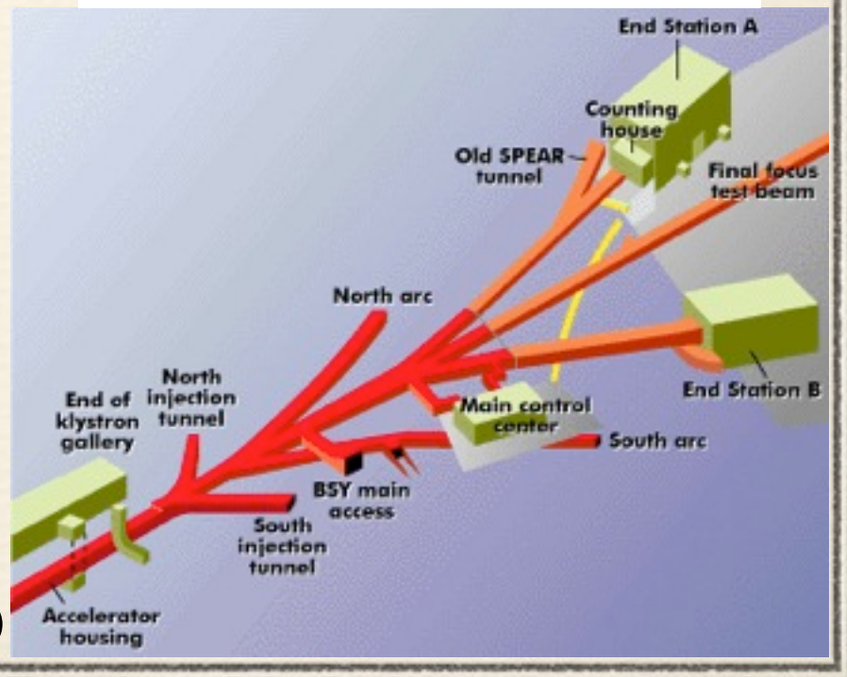

$$A_{PV} = (-131 \pm 14 \pm 10) \times 10^{-9}$$

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

Tree-level prediction: ~ 250 ppb

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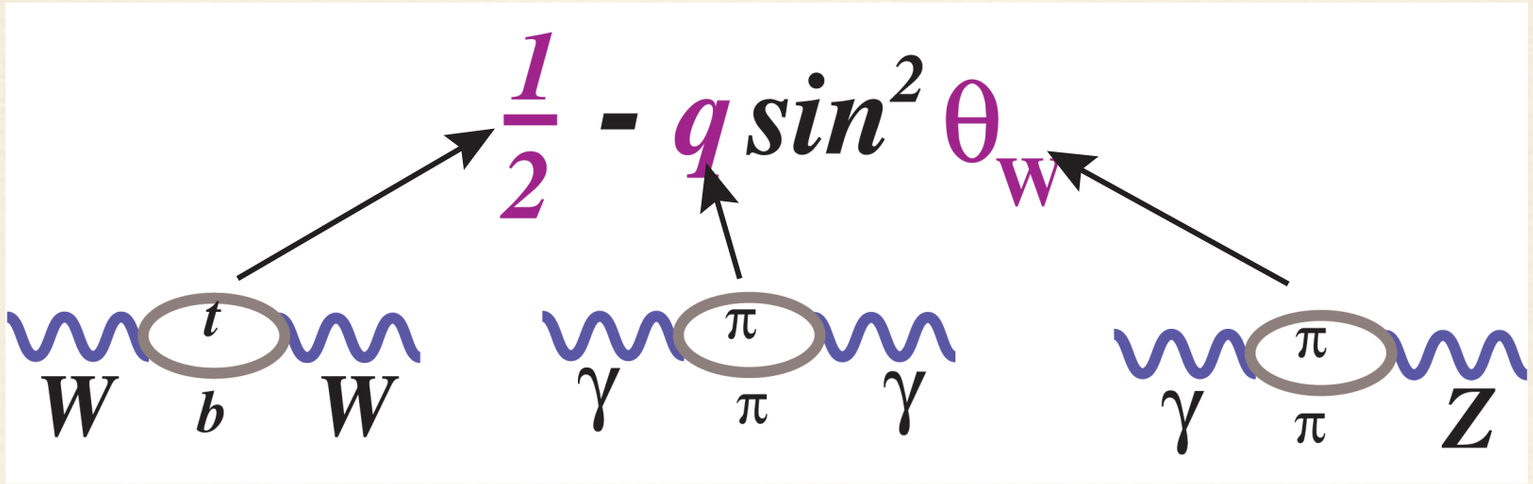

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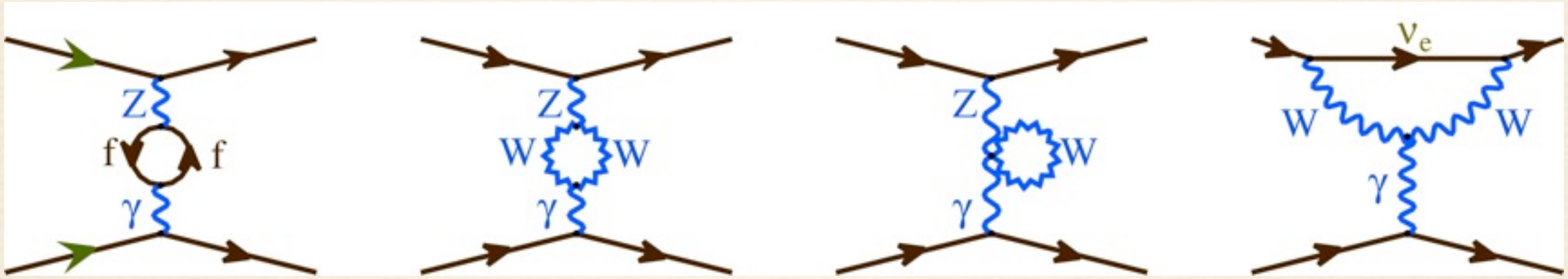

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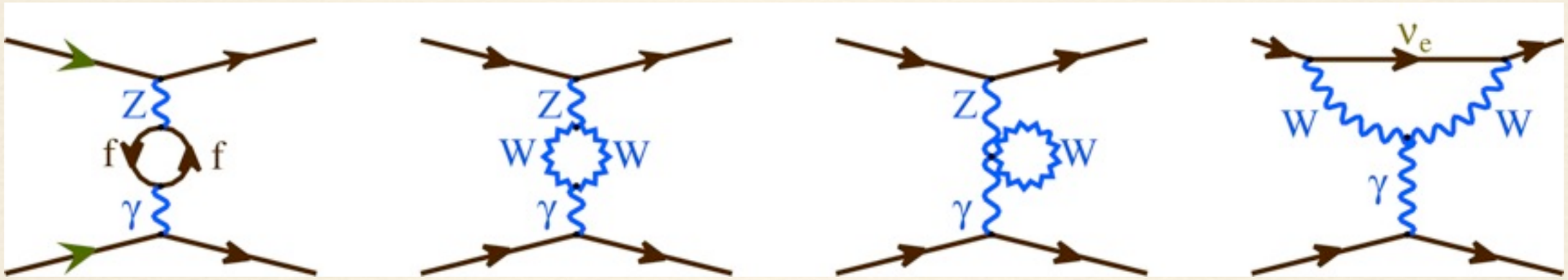

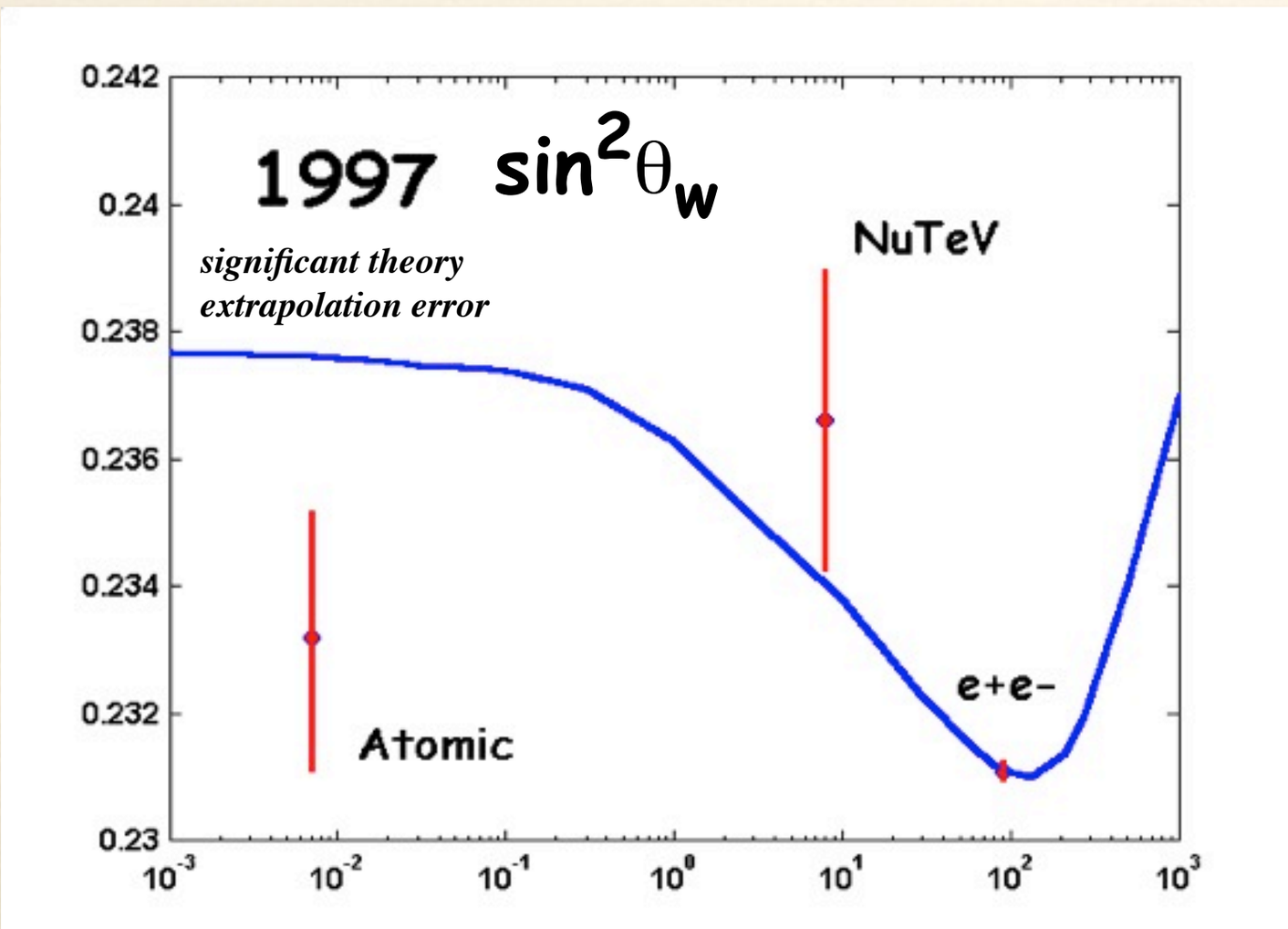

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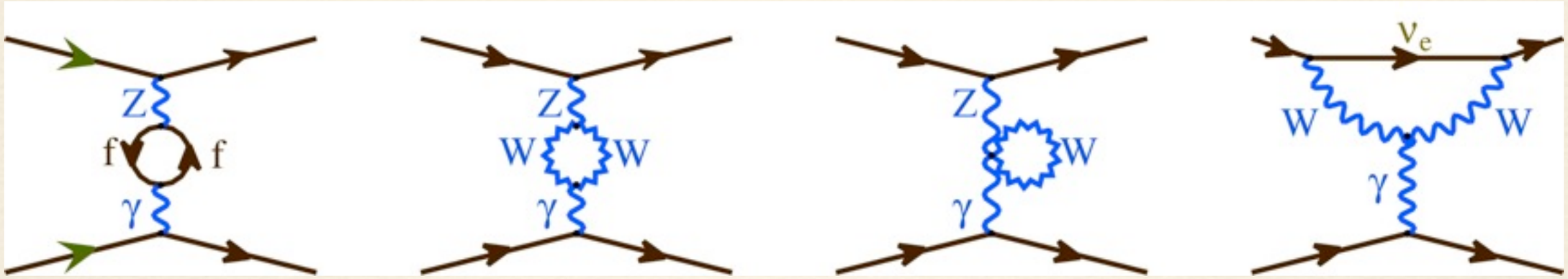

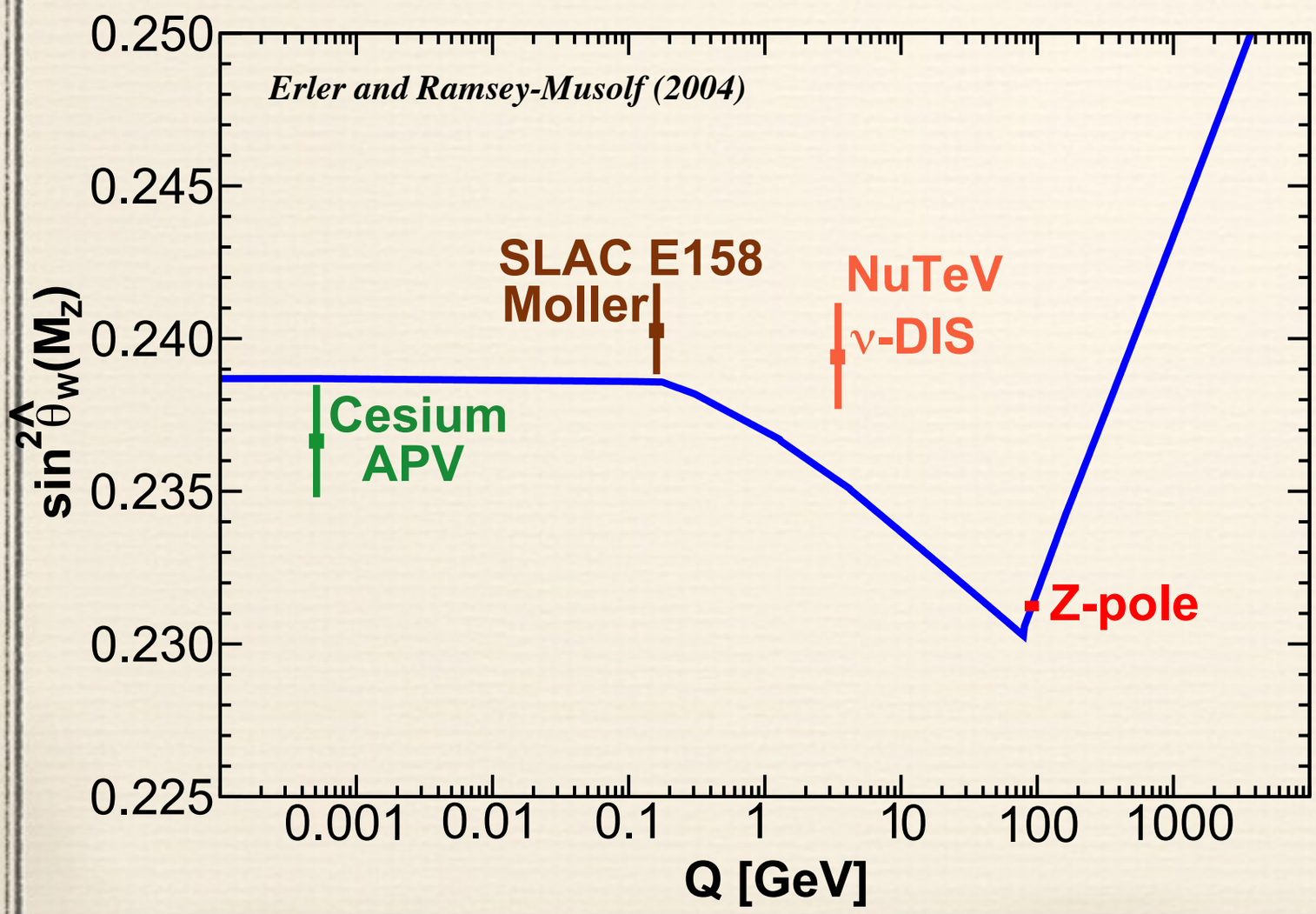

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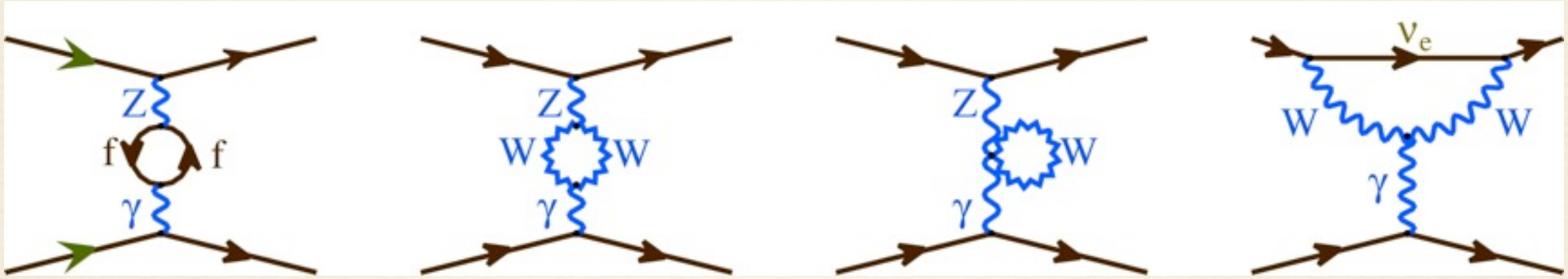

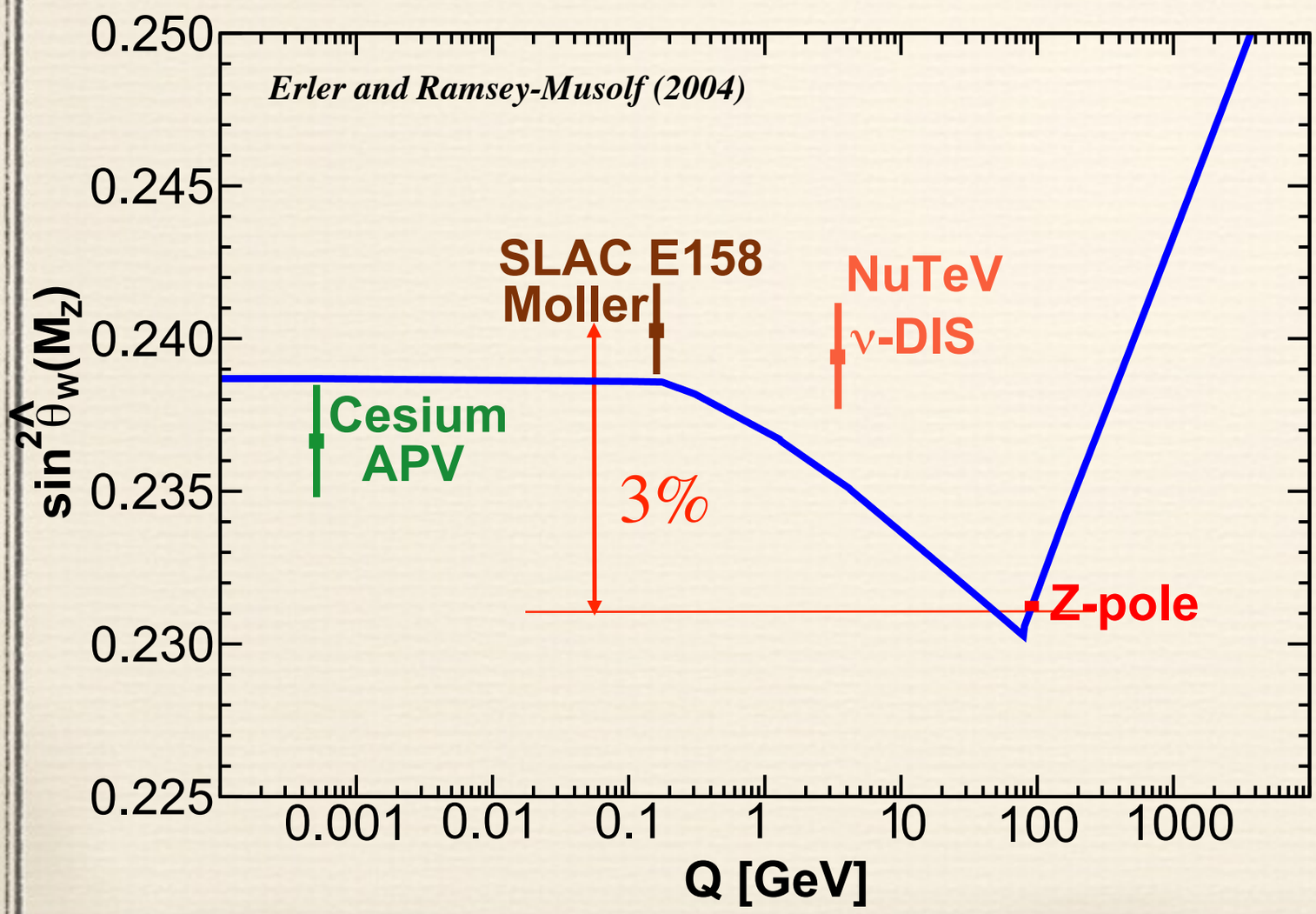

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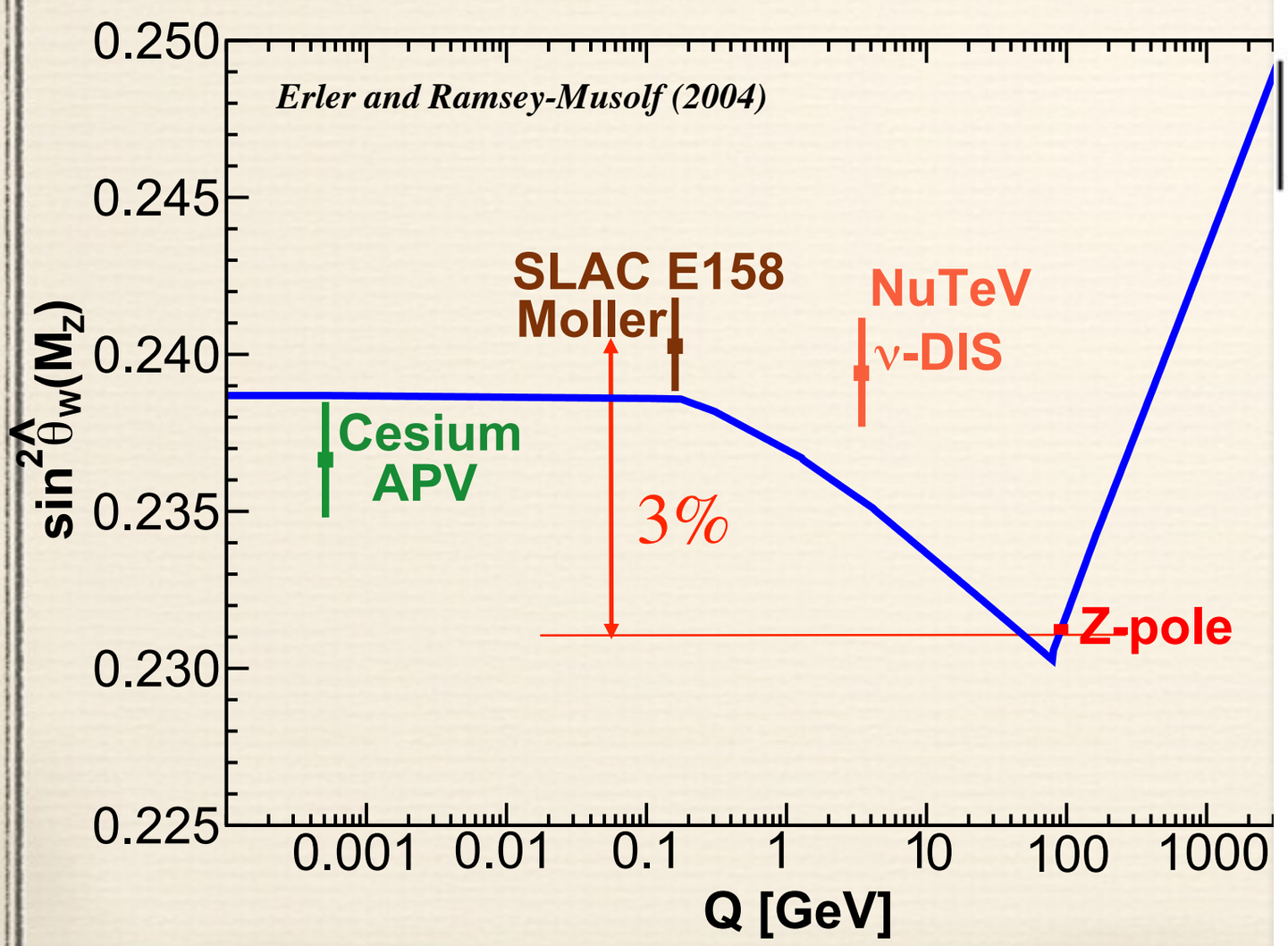
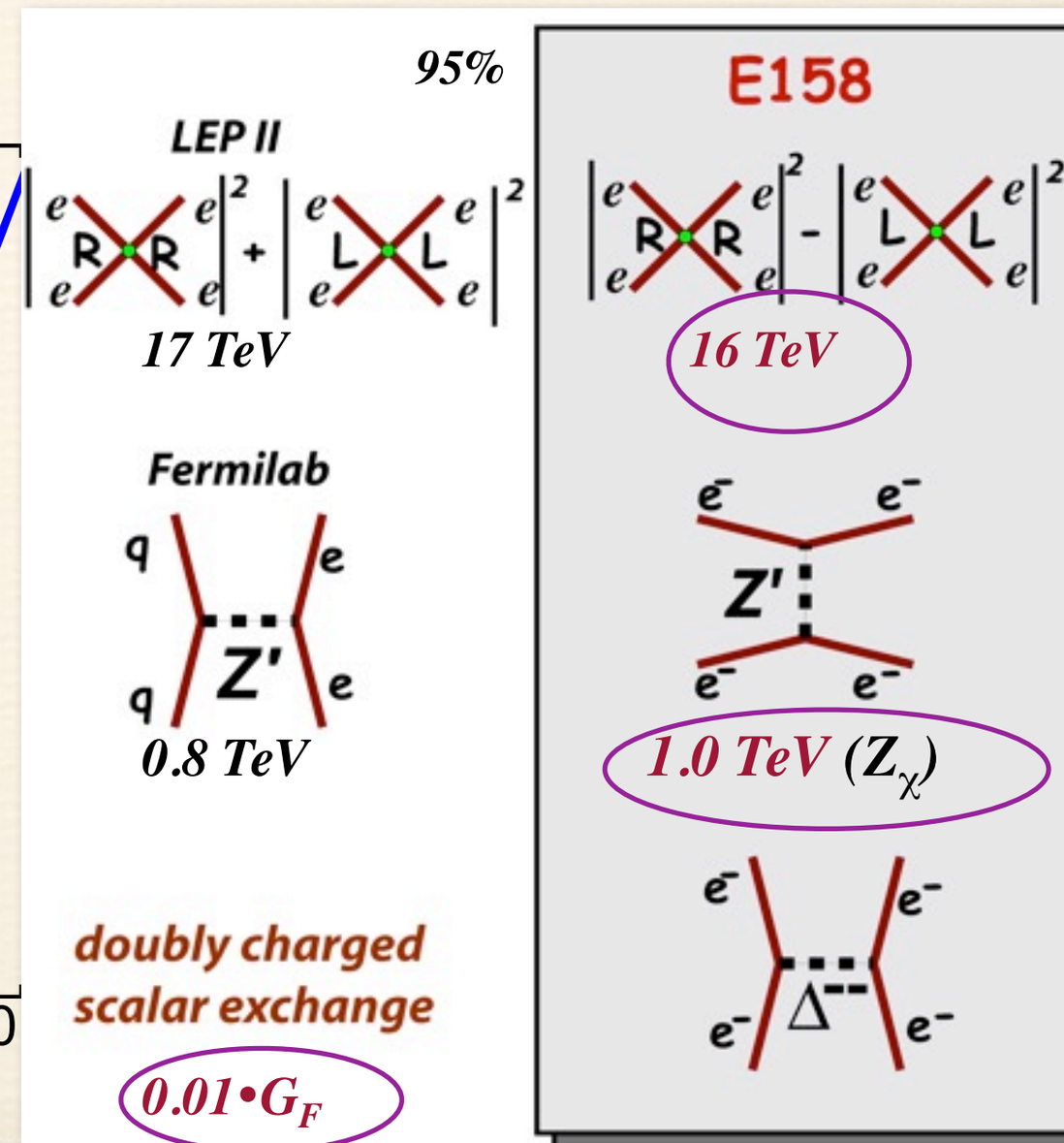


Limits on "New" Physics



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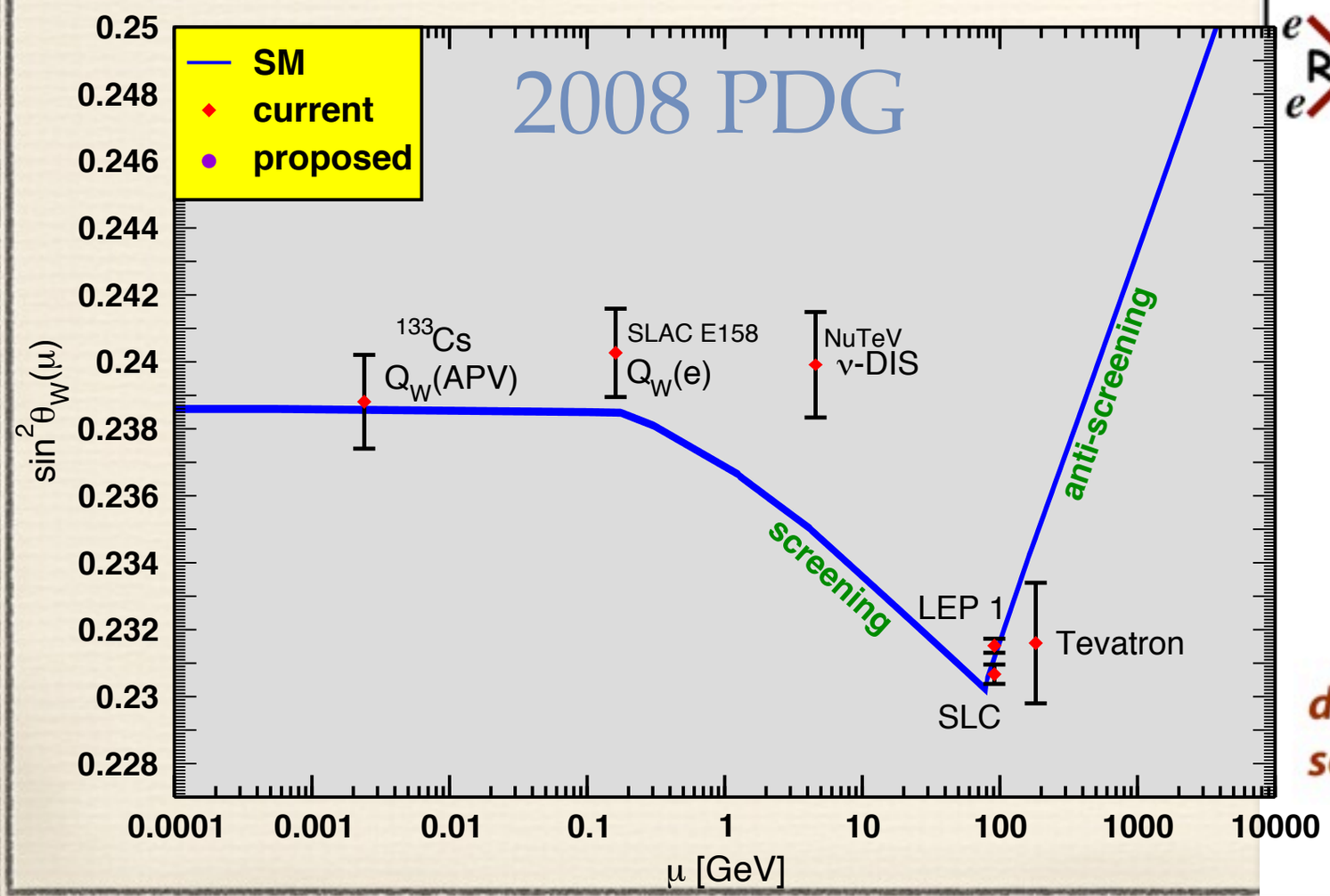

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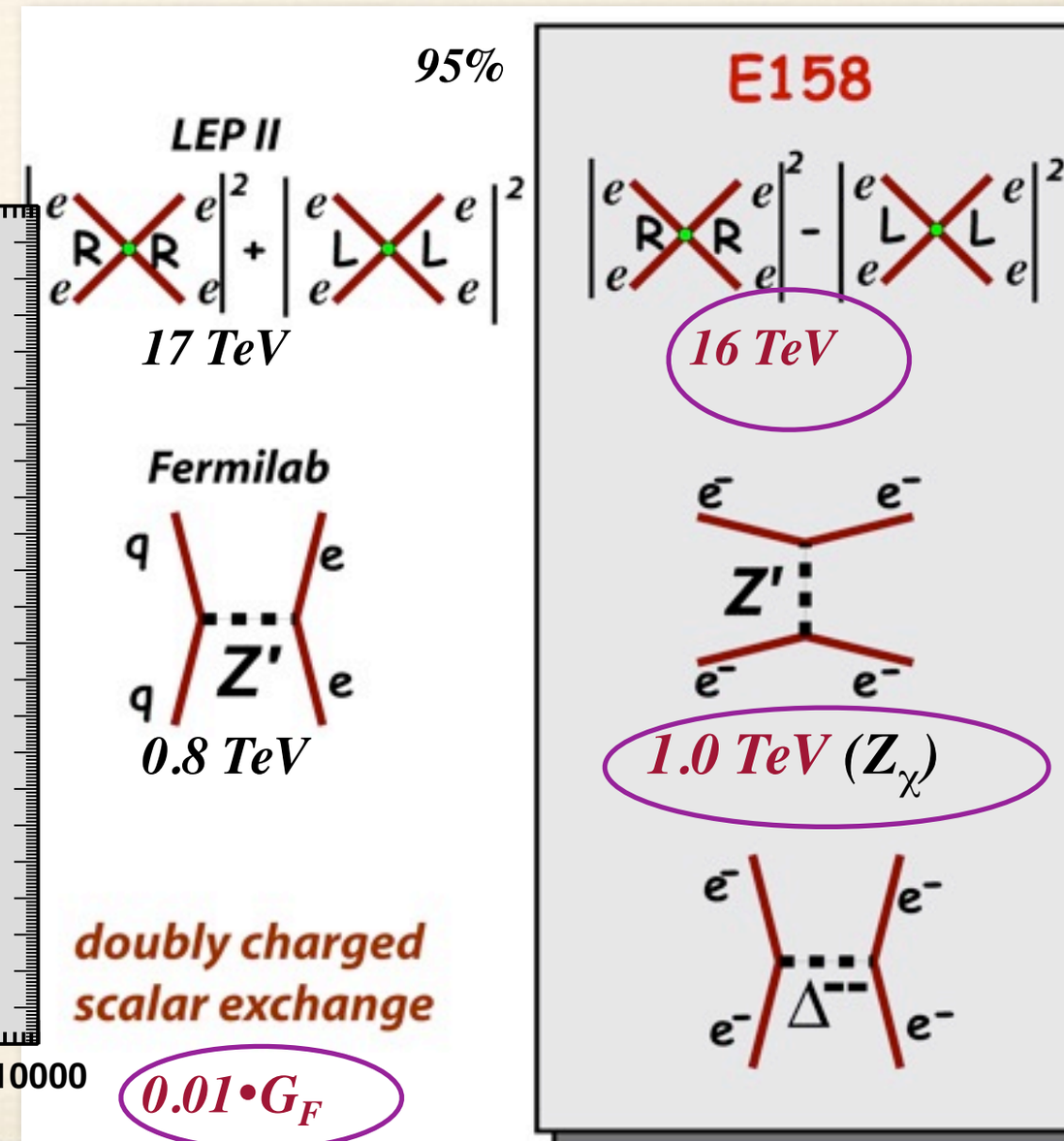

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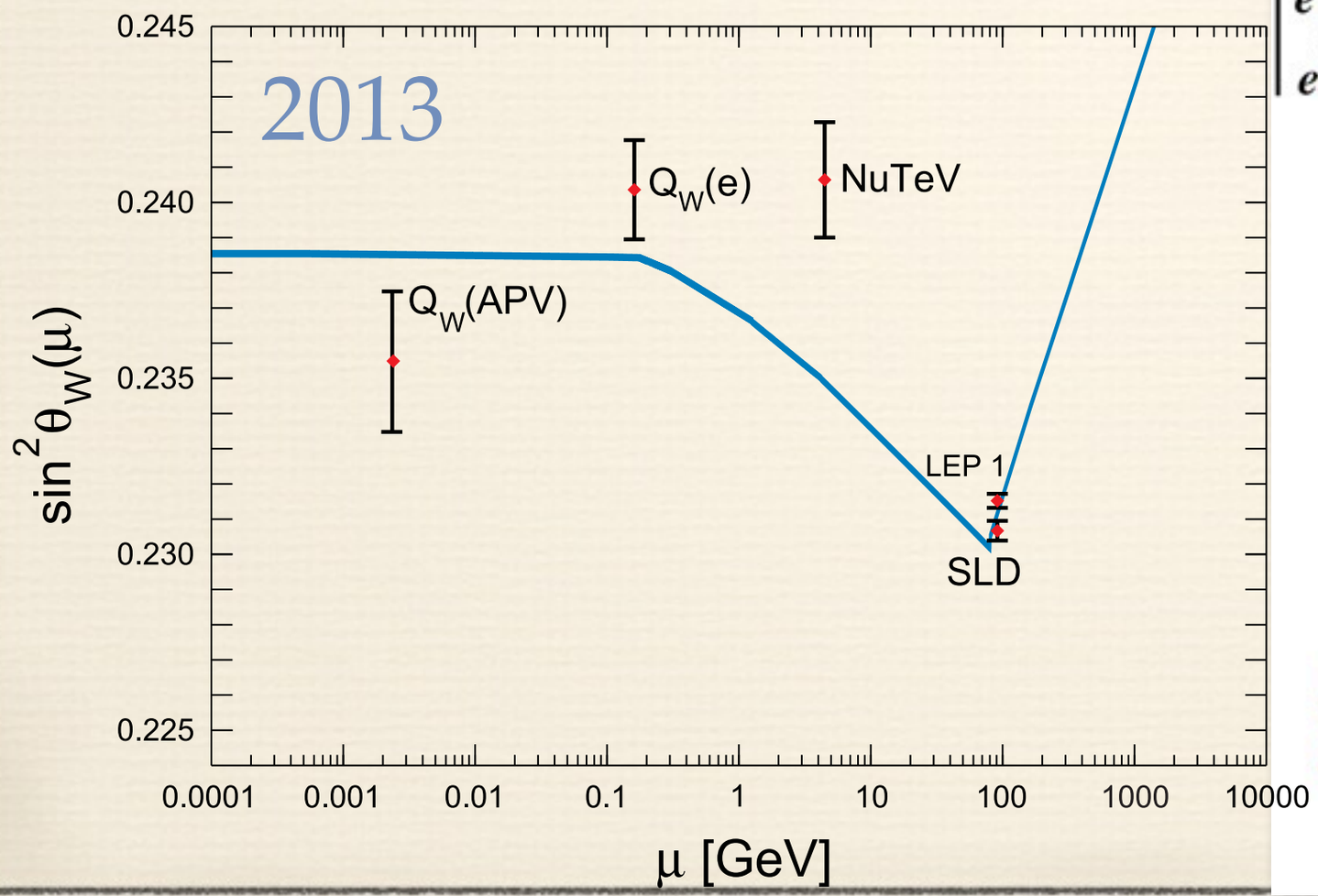

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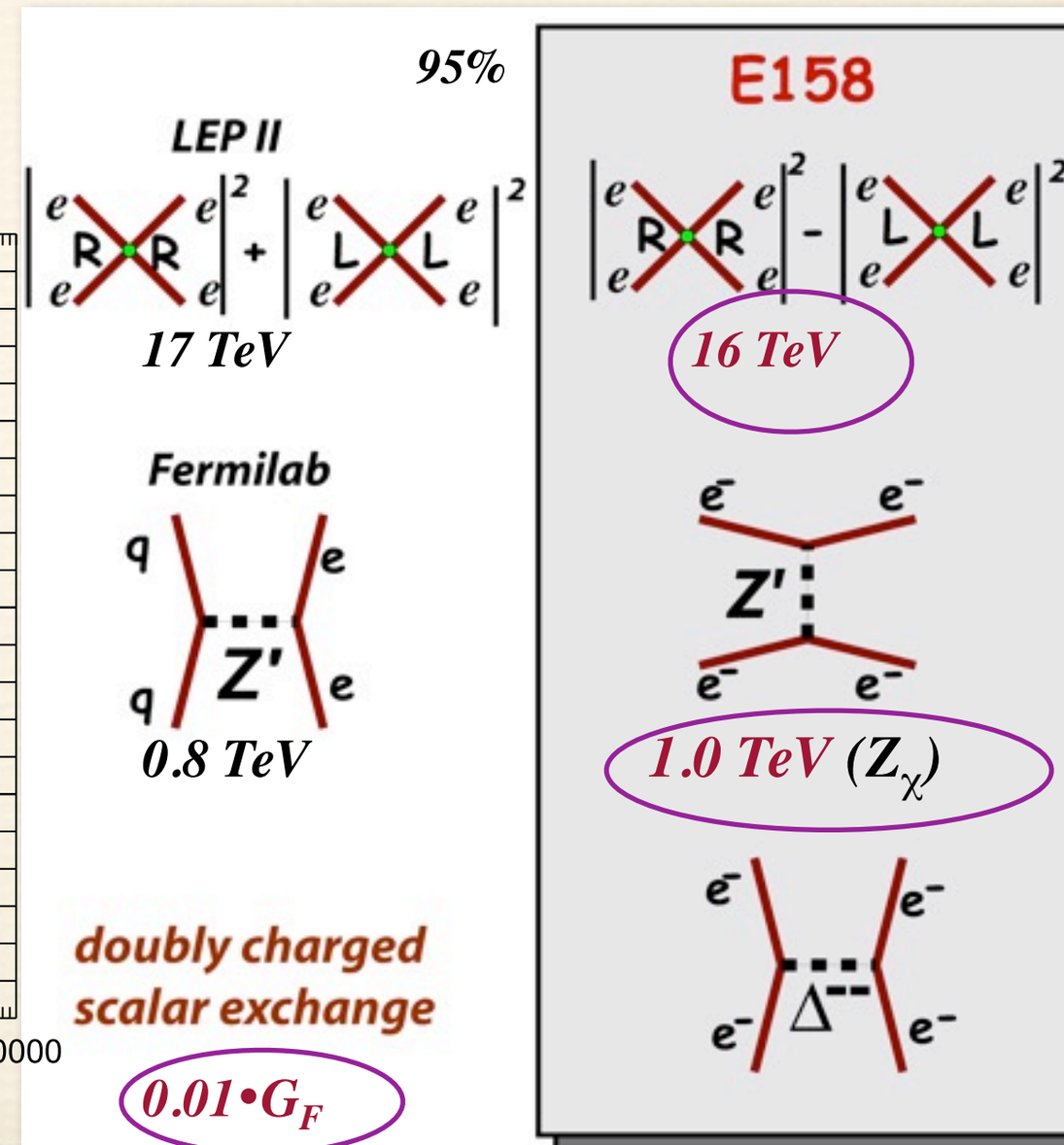

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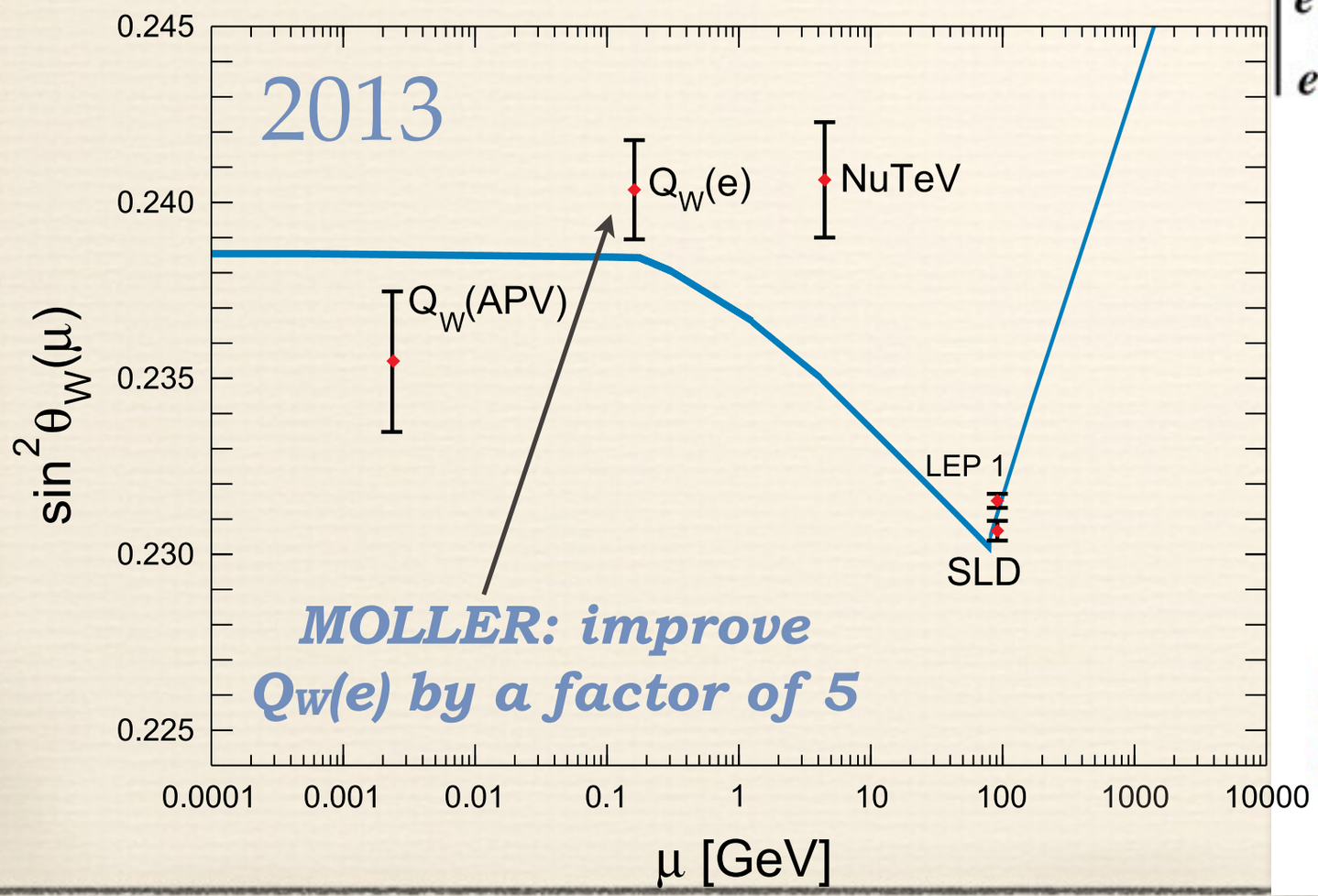

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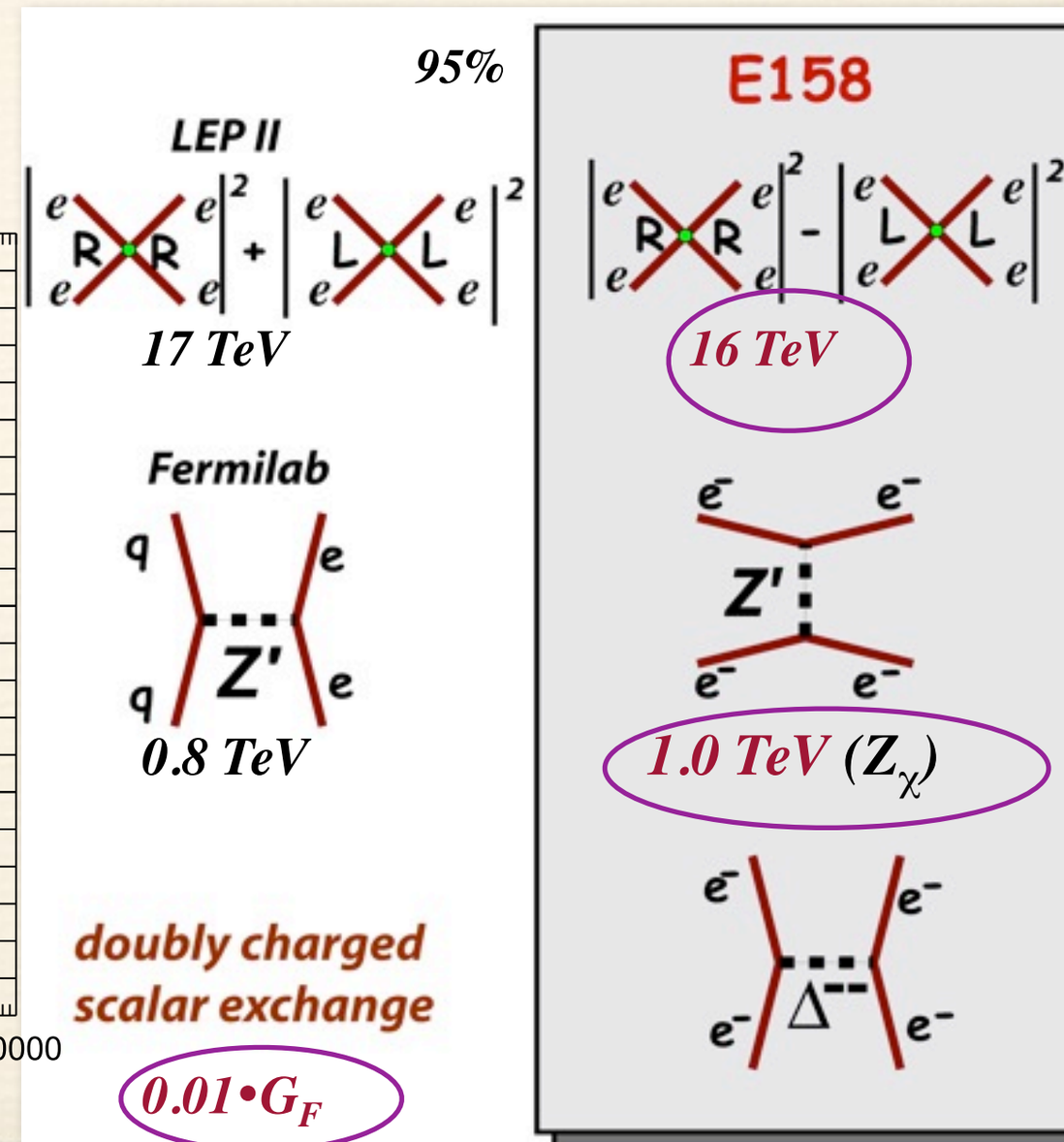
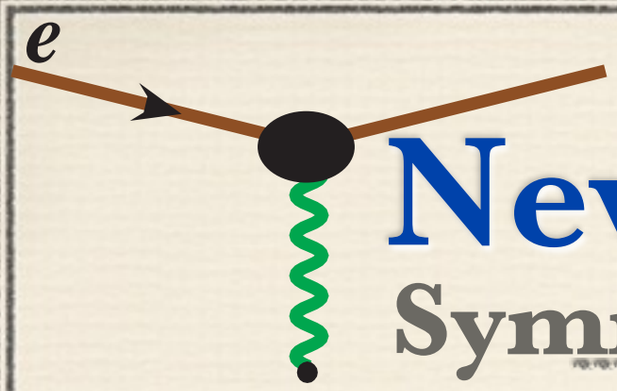
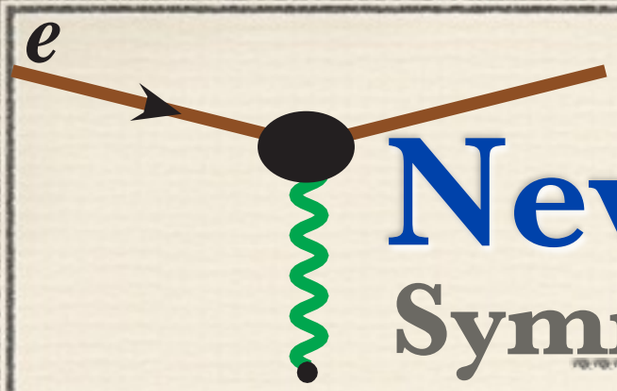


New Generation of Experiments



New Electron Operators

Symmetry Violation with Electrons



New Electron Operators

Symmetry Violation with Electrons

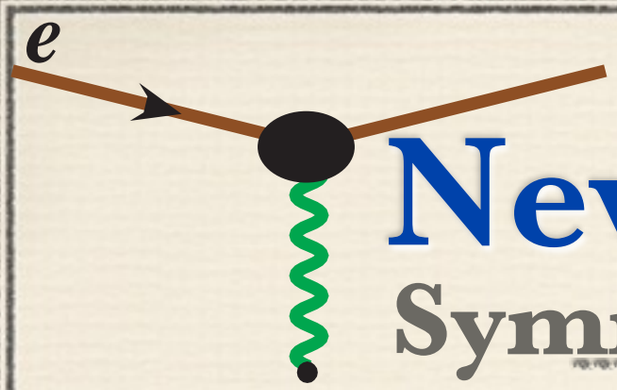
- **Violation of Lepton Number**
  - Neutrinoless Double-Beta Decay?

$$\frac{1}{\Lambda}\mathcal{L}_5$$

10^{15} GeV

$$\frac{1}{\Lambda^5}\mathcal{L}_9$$

multi-TeV



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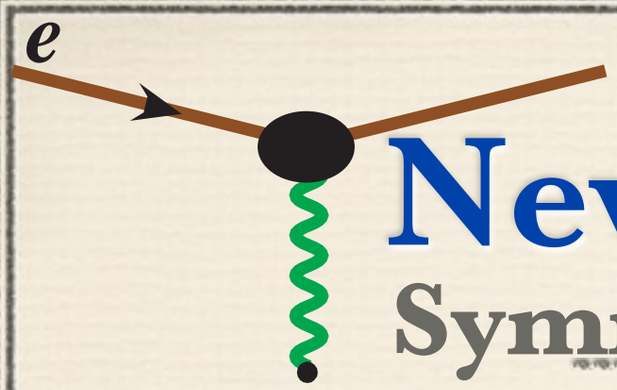
- **Violation of Time Reversal Symmetry**
  - Non-zero Electric Dipole Moment of the Electron?

100s of TeV

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



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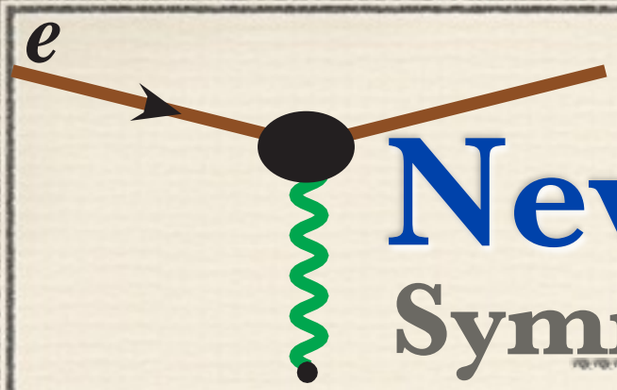

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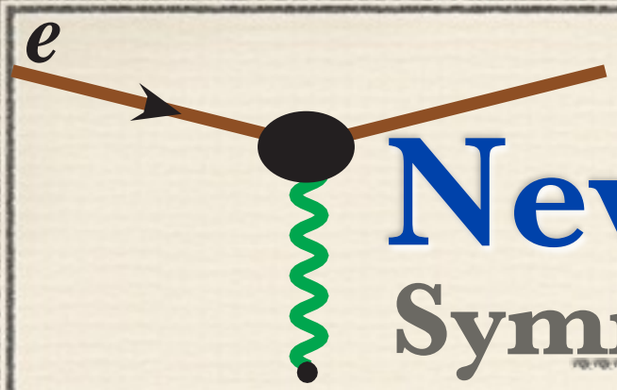
  - ★ new contributions to parity-violating electron scattering?



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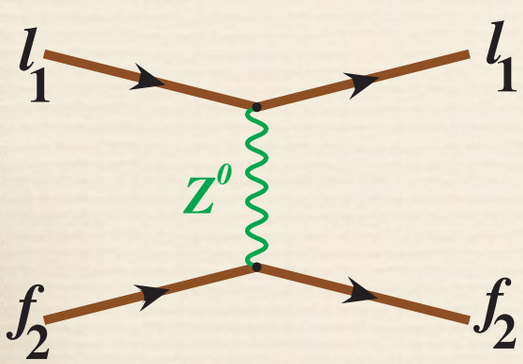
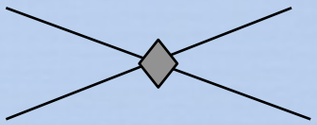
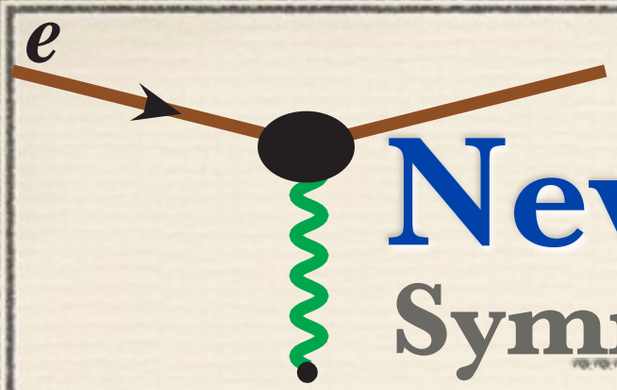
Search for new neutral superweak forces



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



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



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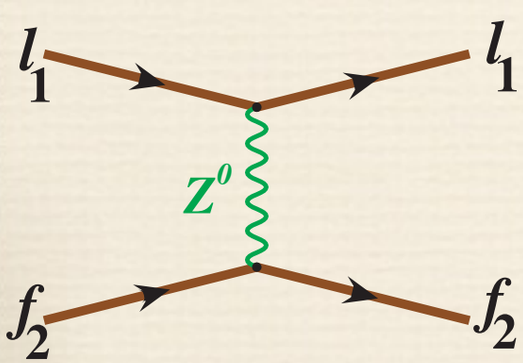

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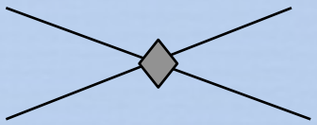
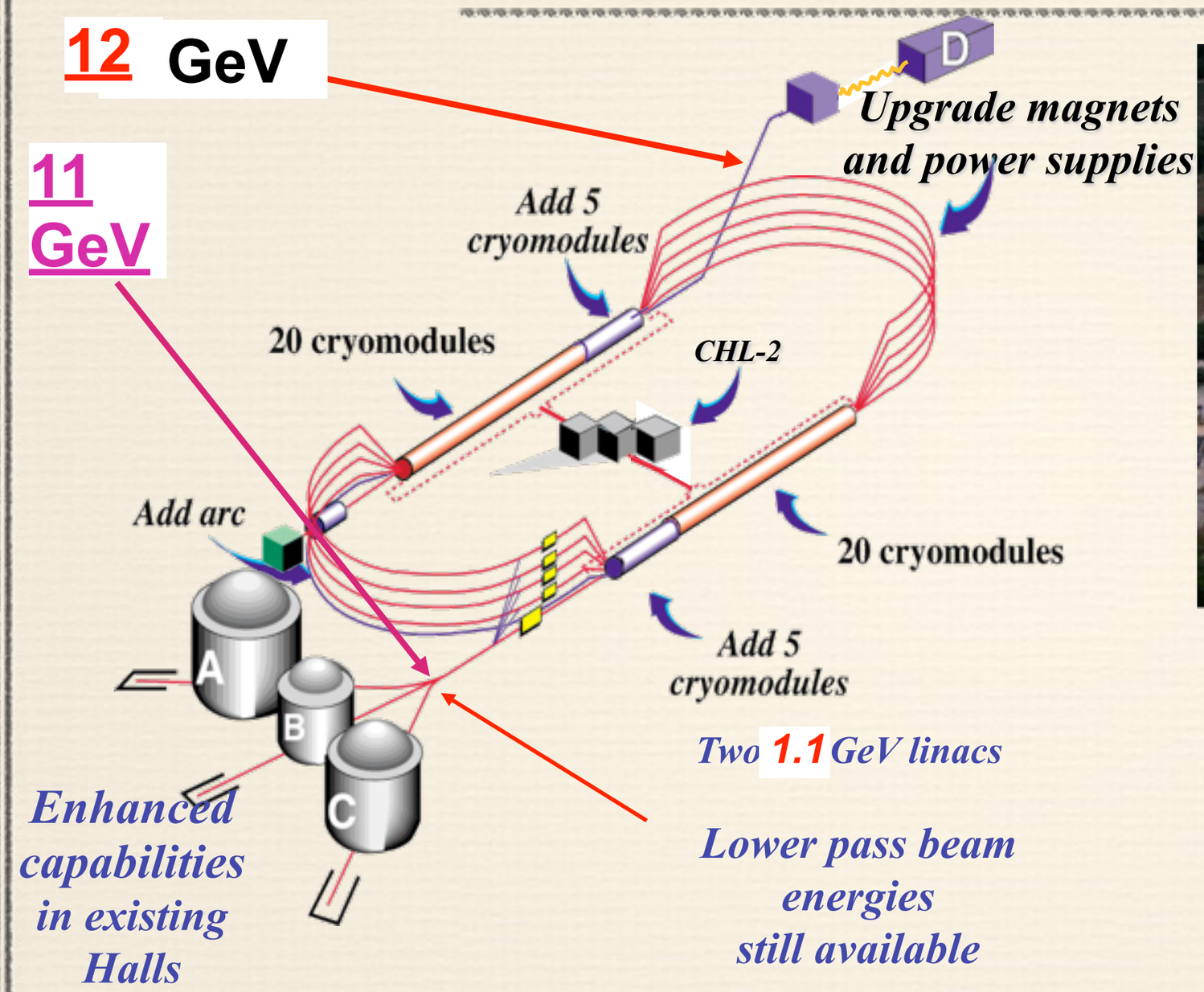


$\frac{1}{\Lambda^2}\mathcal{L}_6$

must reach Λ ~ 10 TeV:
colliders and fixed target are complementary

Primary Mission: Elucidate QCD Structure of Nucleons and Nuclei

Jefferson Laboratory



2013: Energy Upgrade to 12 GeV

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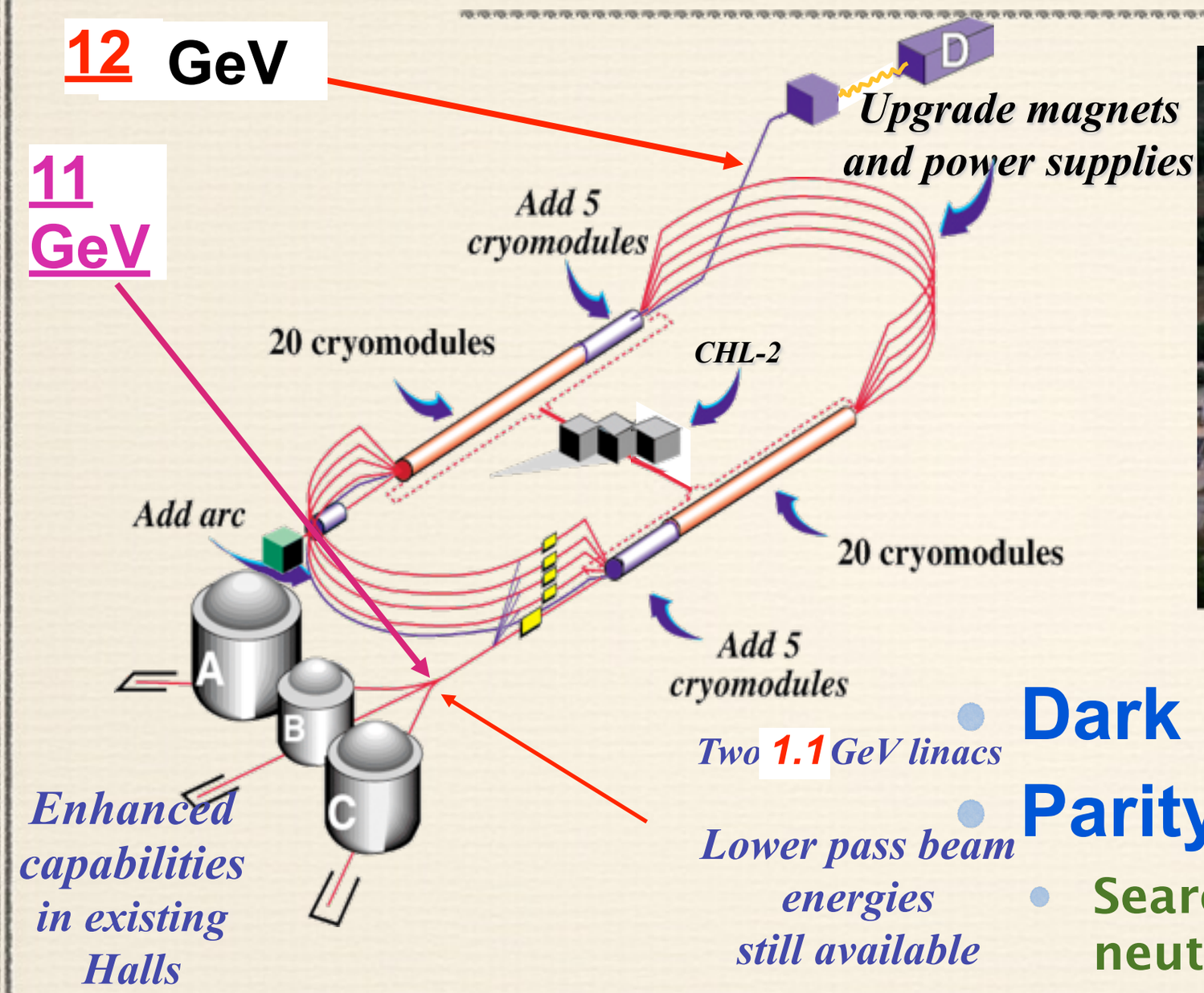


2013: Energy Upgrade to 12 GeV

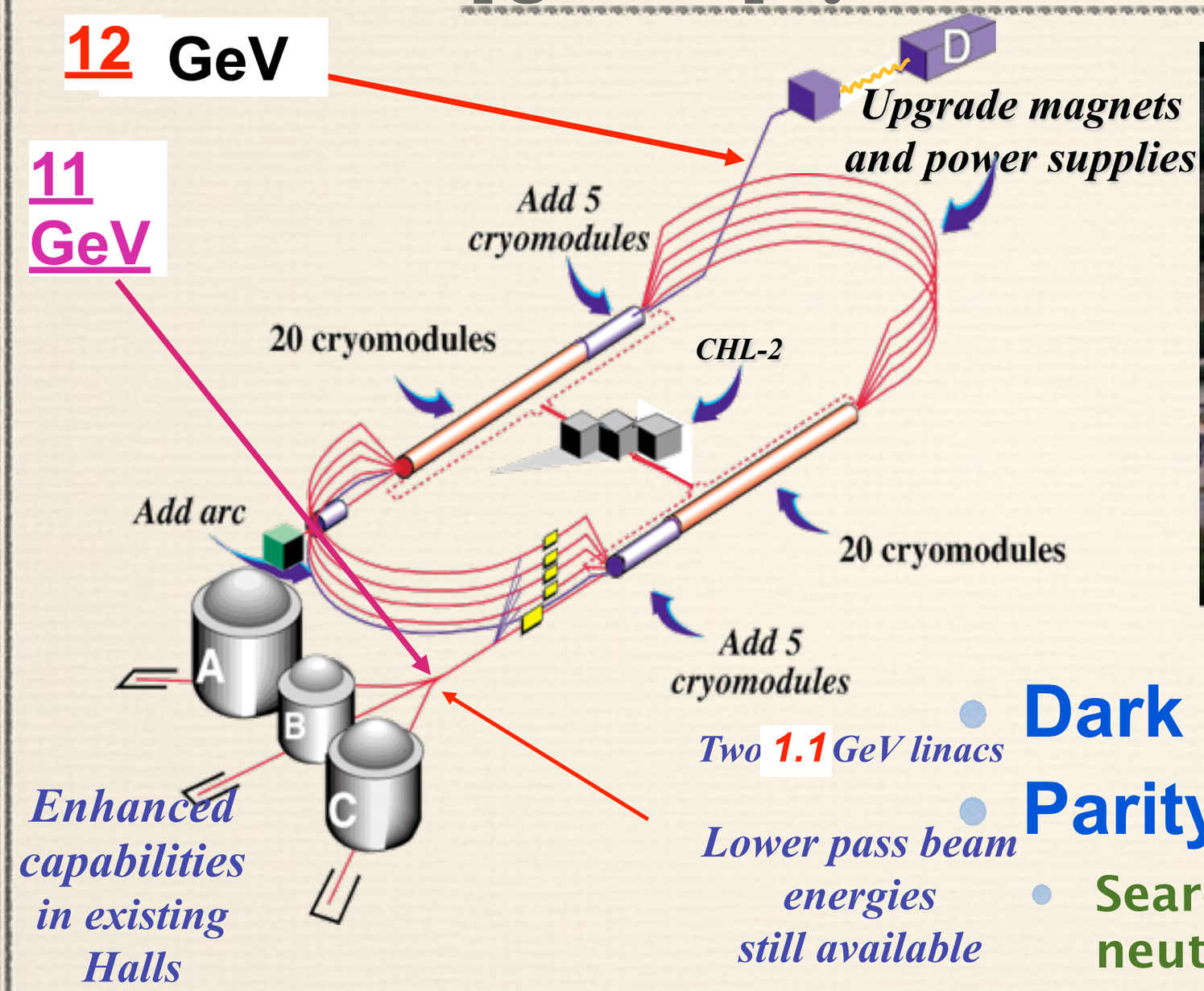
- **Dark Photon Searches**
- **Parity Violation**
  - Search for new flavor-conserving neutral current interactions
    - Qweak: elastic electron-proton scattering
    - MOLLER: electron-electron scattering
    - SOLID: electron deep-inelastic scattering

Intensity Frontier Topics

Primary Mission: Elucidate QCD Structure of Nucleons and Nuclei

Jefferson Laboratory

First upgraded physics beams to Hall A in 2014



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    - Qweak: elastic electron-proton scattering
    - MOLLER: electron-electron scattering
    - SOLID: electron deep-inelastic scattering

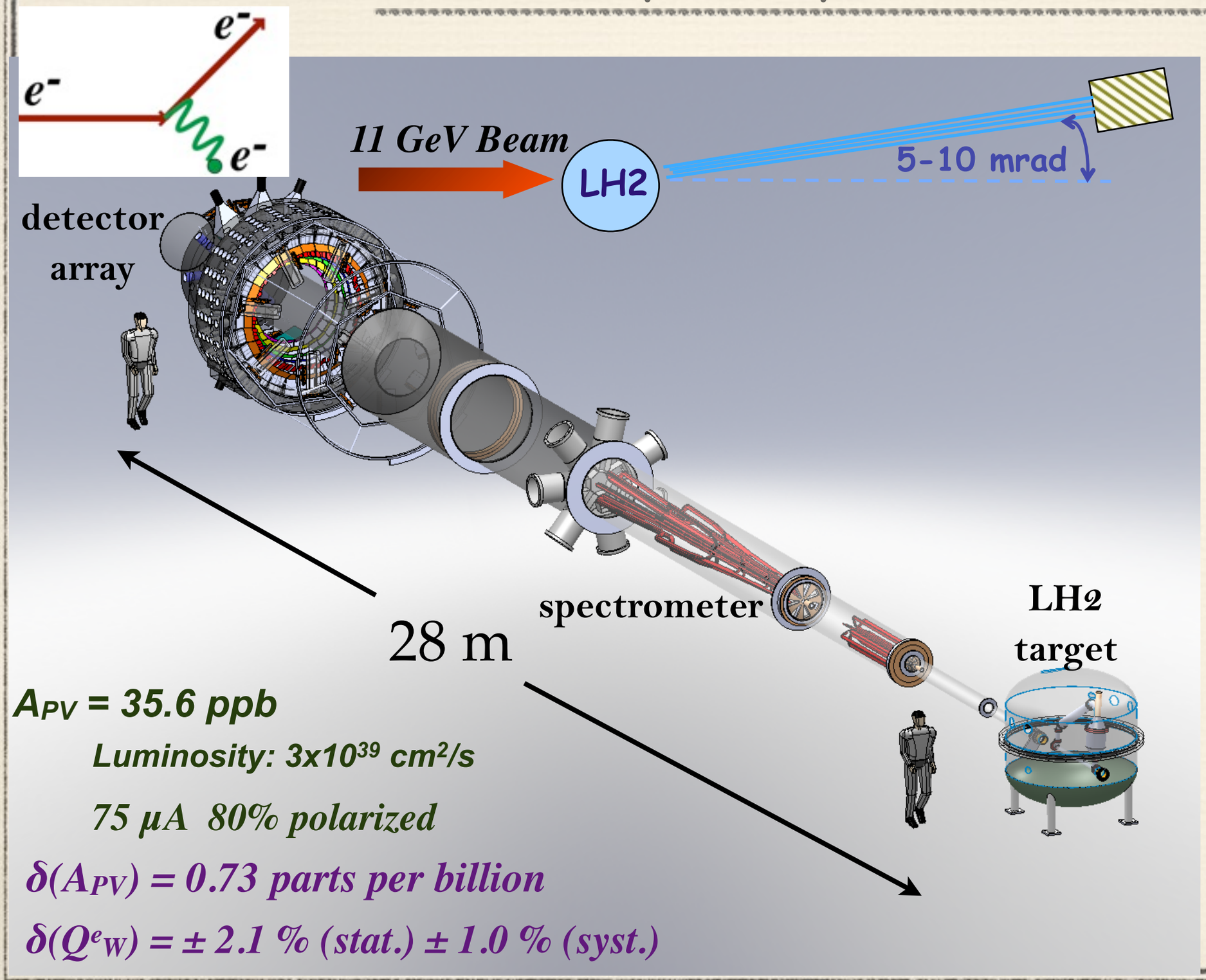
Intensity Frontier Topics

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

11 GeV Møller scattering

MOLLER at JLab

Measurement Of Lepton Lepton Electroweak Reaction



A_{PV} = 35.6 ppb

Luminosity: 3×10^{39} cm^2/s

75 μA 80% polarized

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

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

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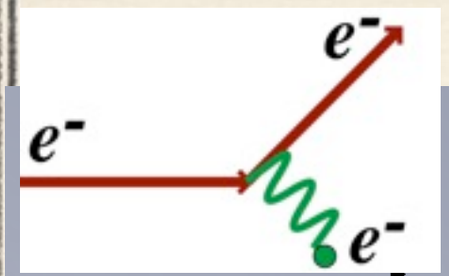
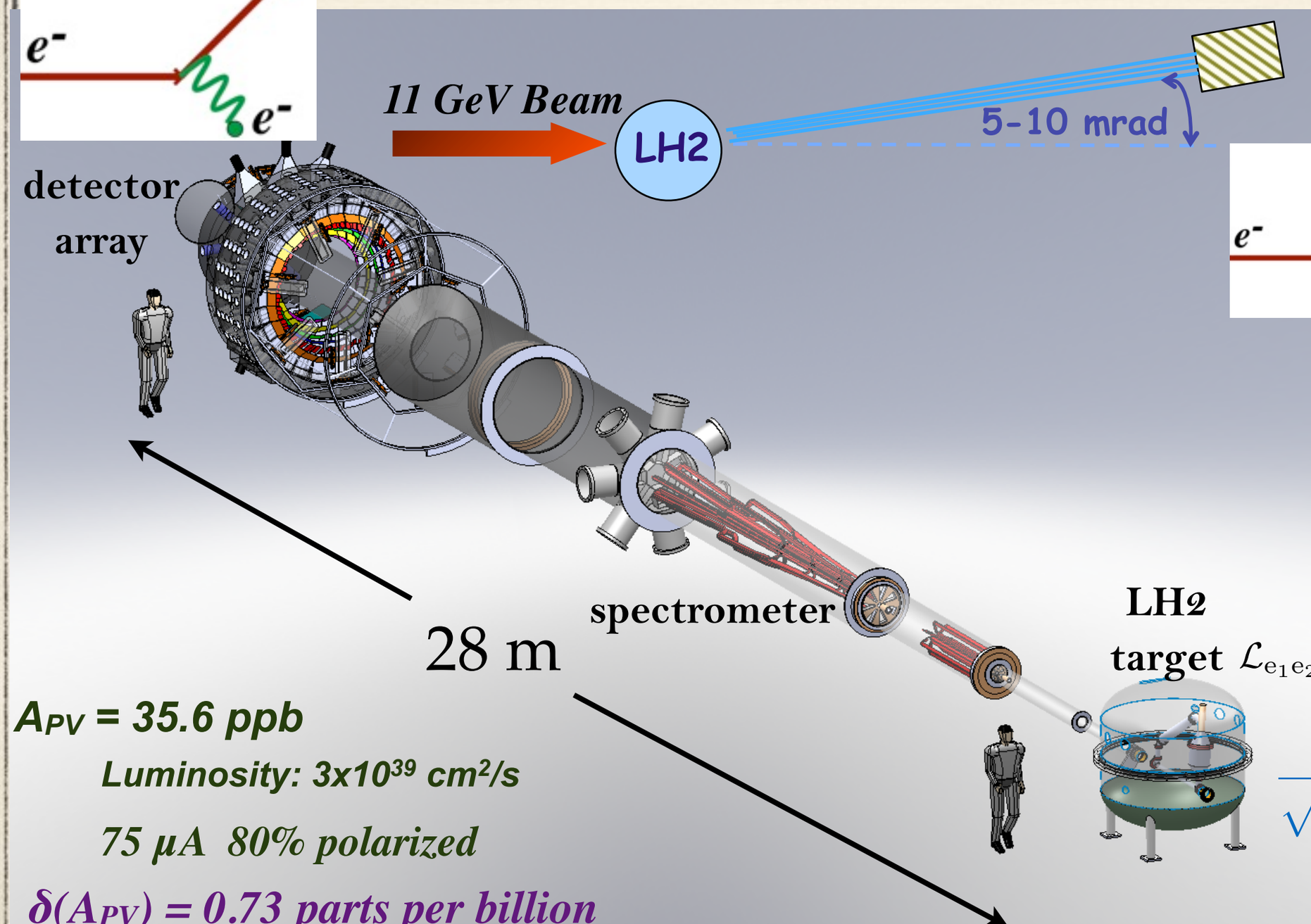
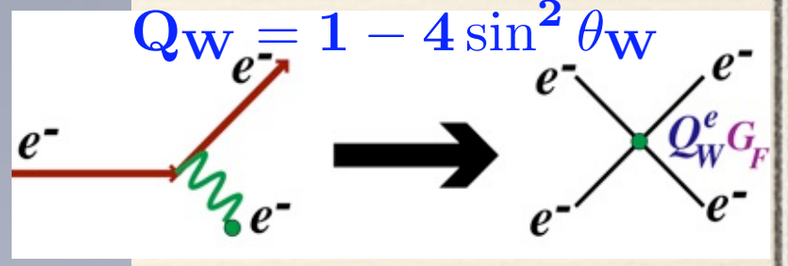
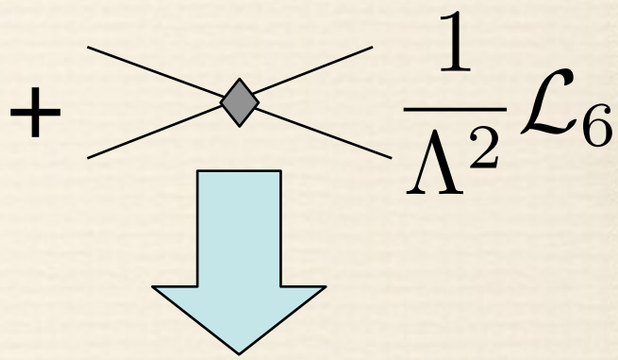




$$Q_W = 1 - 4\sin^2\theta_W$$





$$\mathcal{L}_{e_1e_2} = \sum_{i,j=L,R} \frac{g_{ij}^2}{2\Lambda^2}\bar{e}_i\gamma_\mu e_i \bar{e}_j \gamma^\mu e_j$$

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

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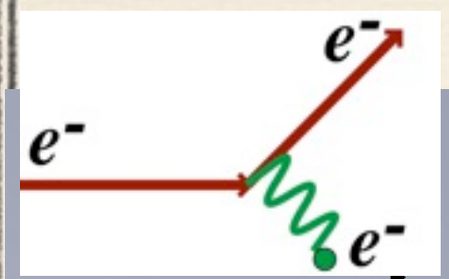
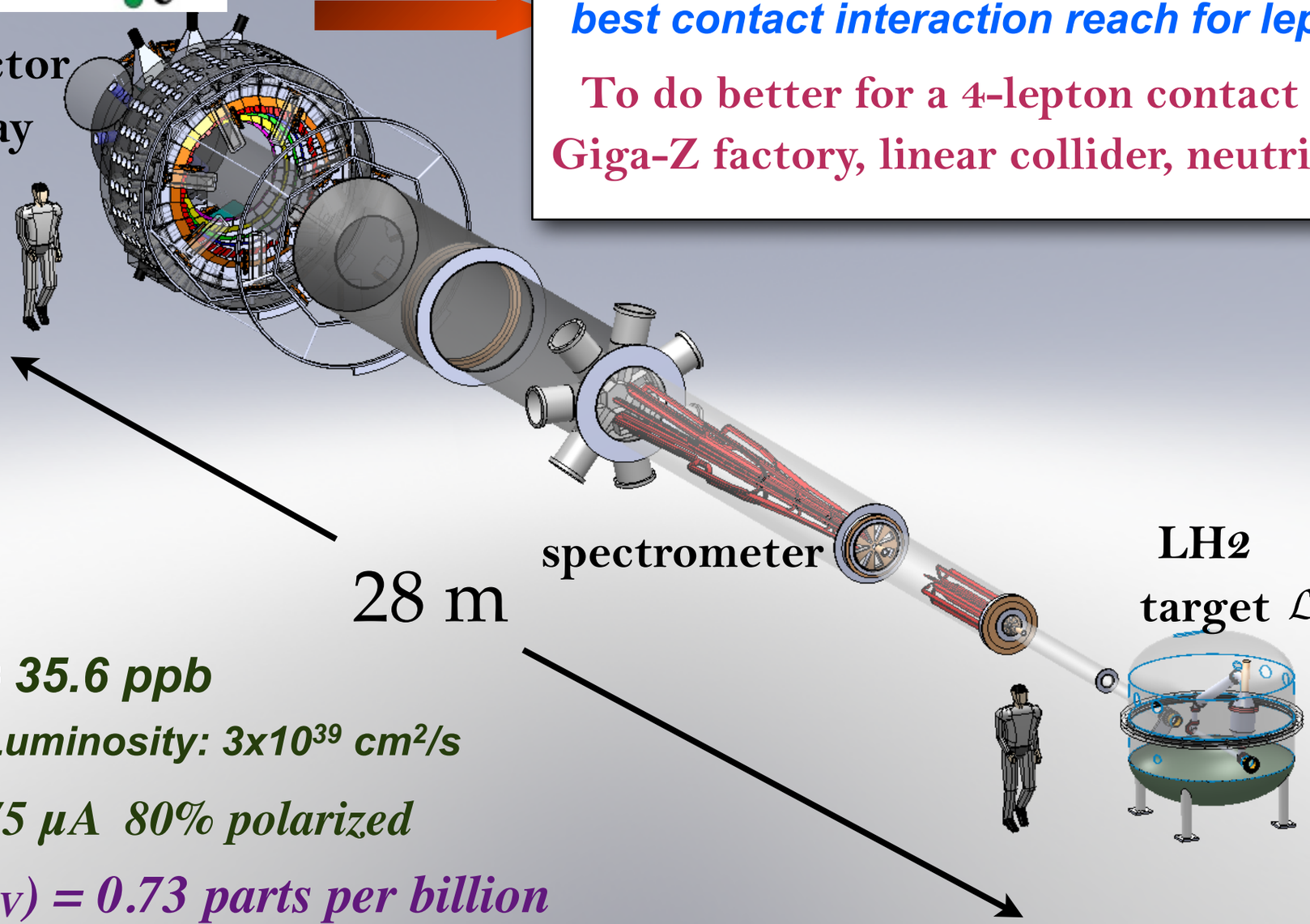


$\delta(\sin^2\theta_W) = \pm\, 0.00026\ (stat.) \pm 0.00012\ (syst.)$ ⇨ $\sim 0.1\%$

Matches best collider (Z-pole) measurements!

best contact interaction reach for leptons at low OR high energy

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



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

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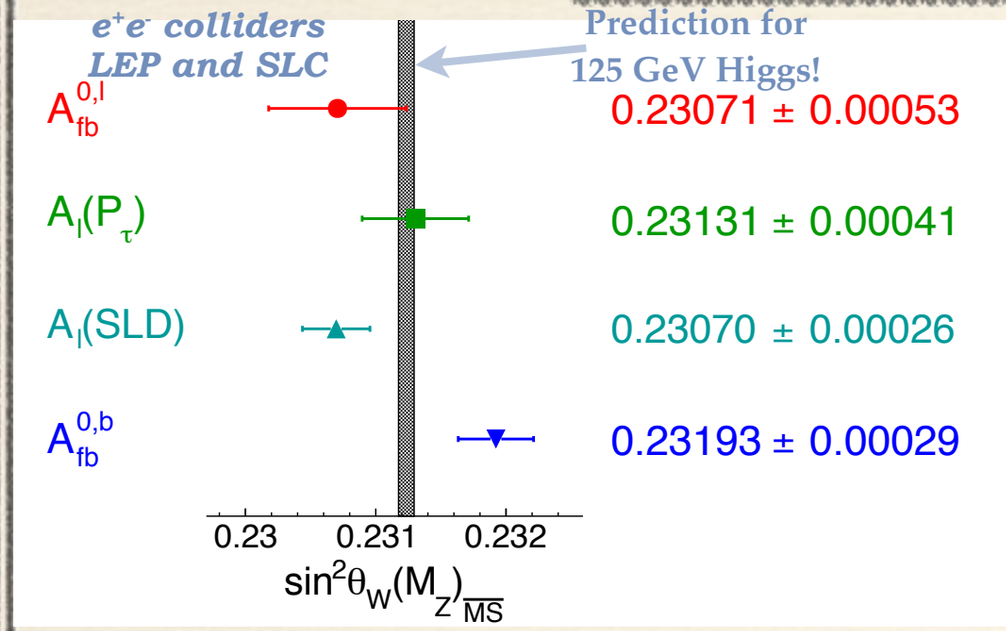
Physics Examples: Beyond LHC

Z resonance measurements: little sensitivity to new contact interactions



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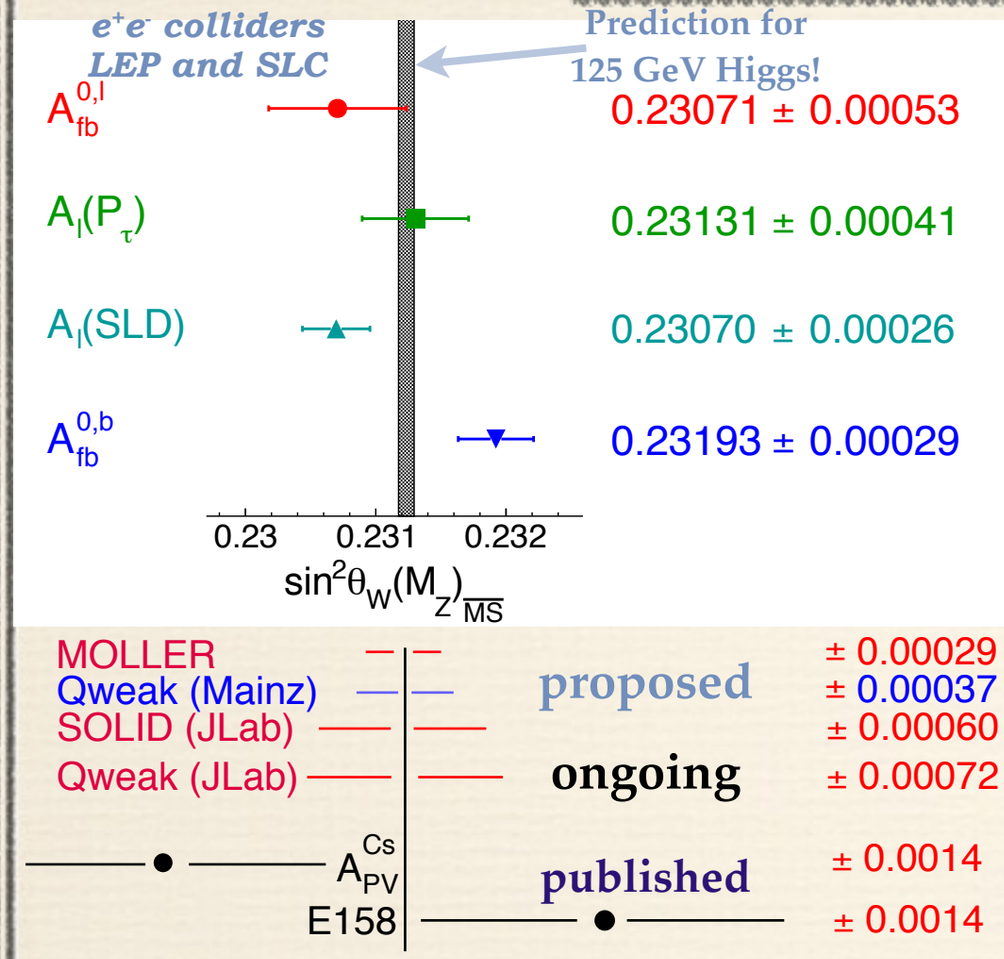

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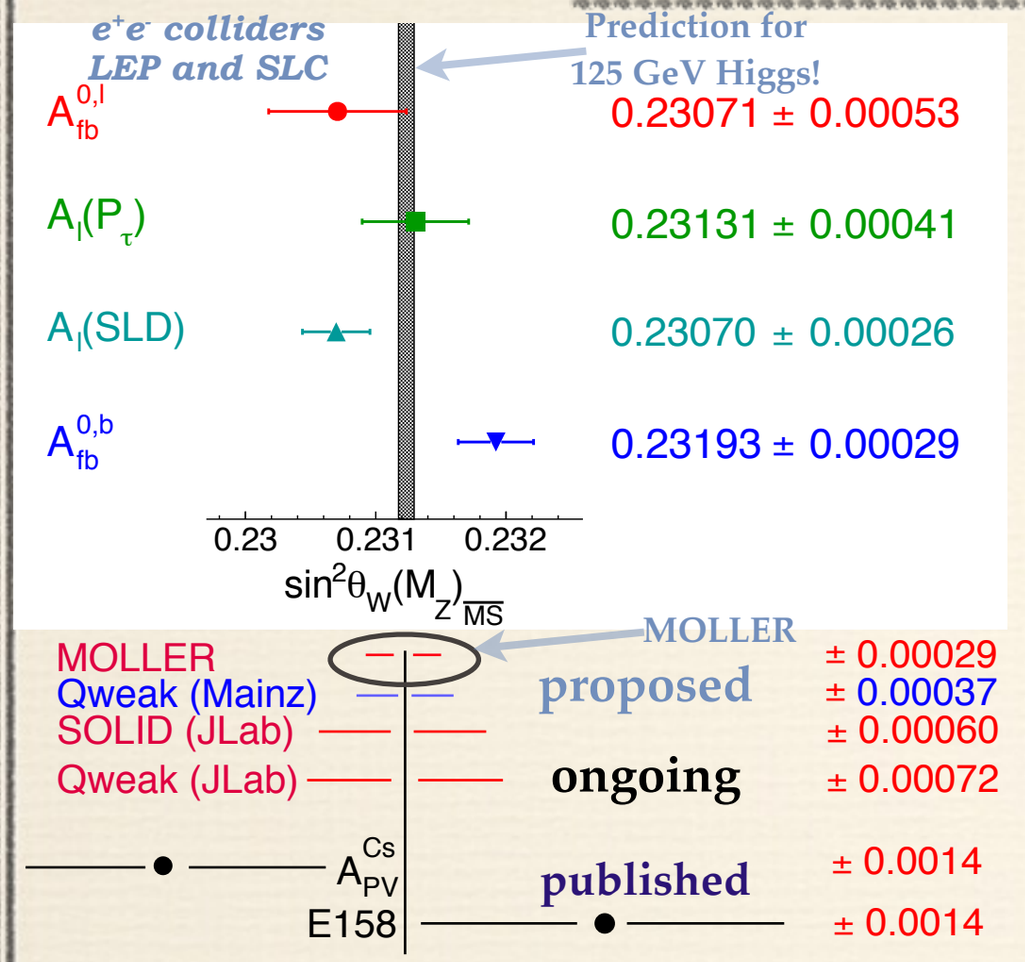

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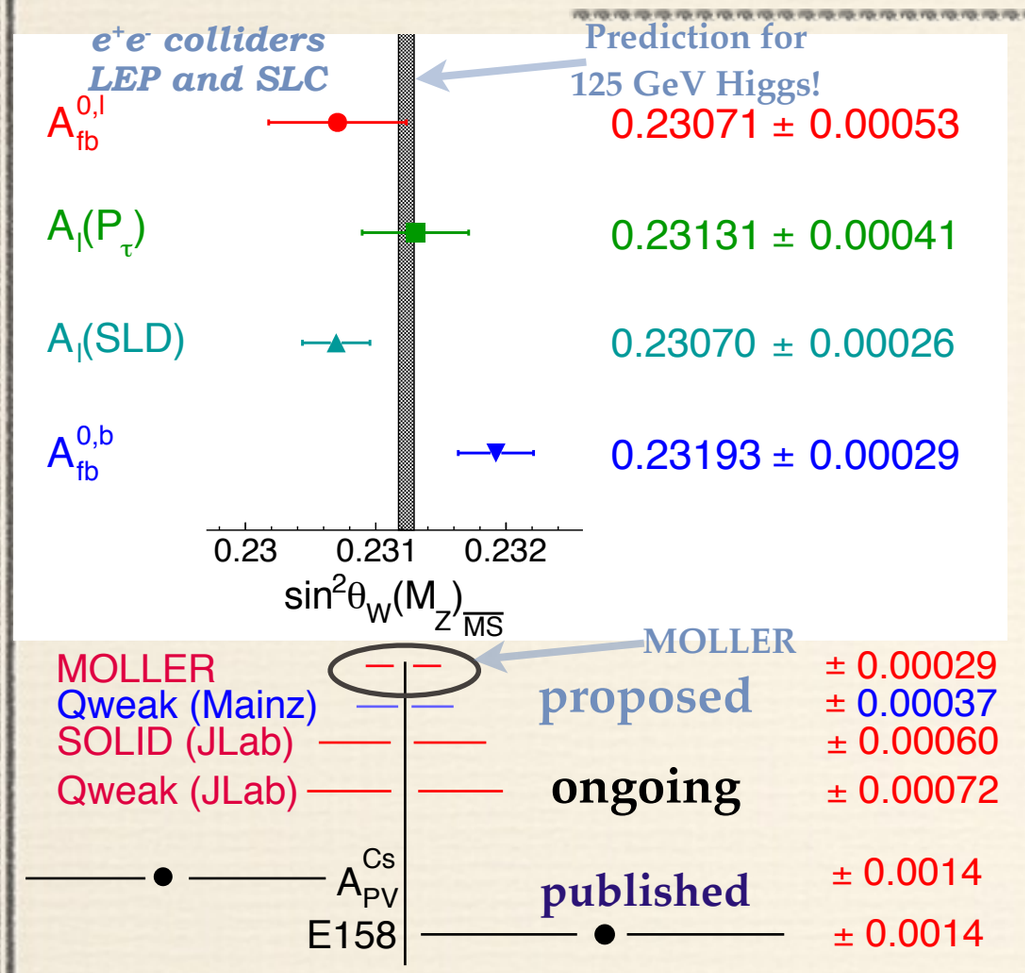
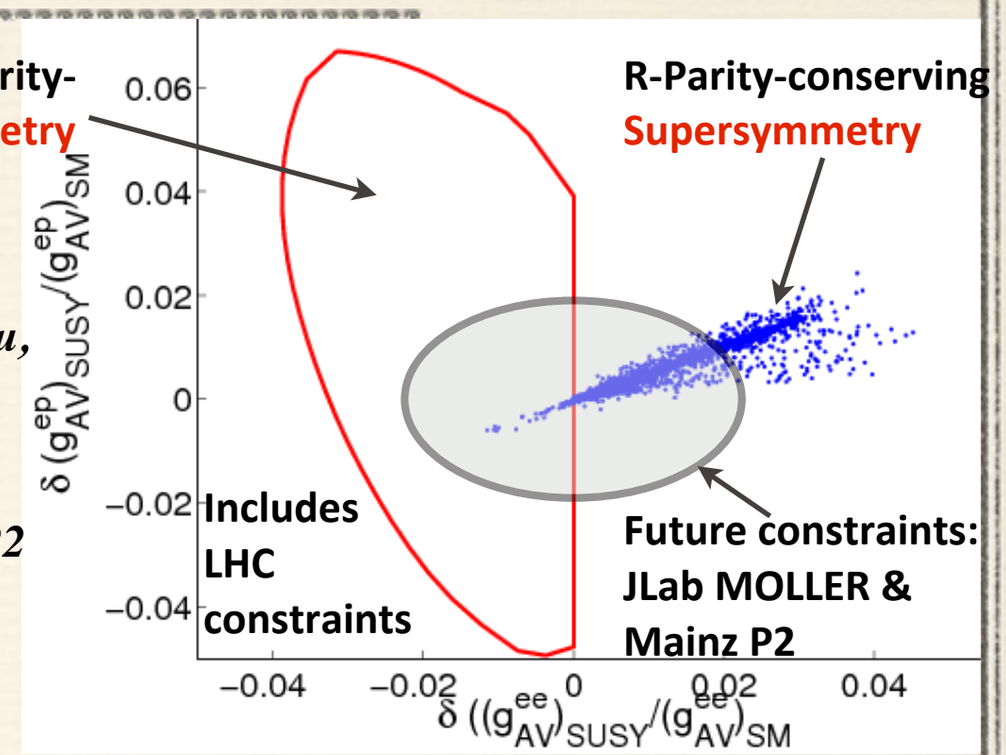


Ramsey-Musolf and Su, Phys. Rep. 456 (2008)

Erler and Su, arXiv:1303.5522



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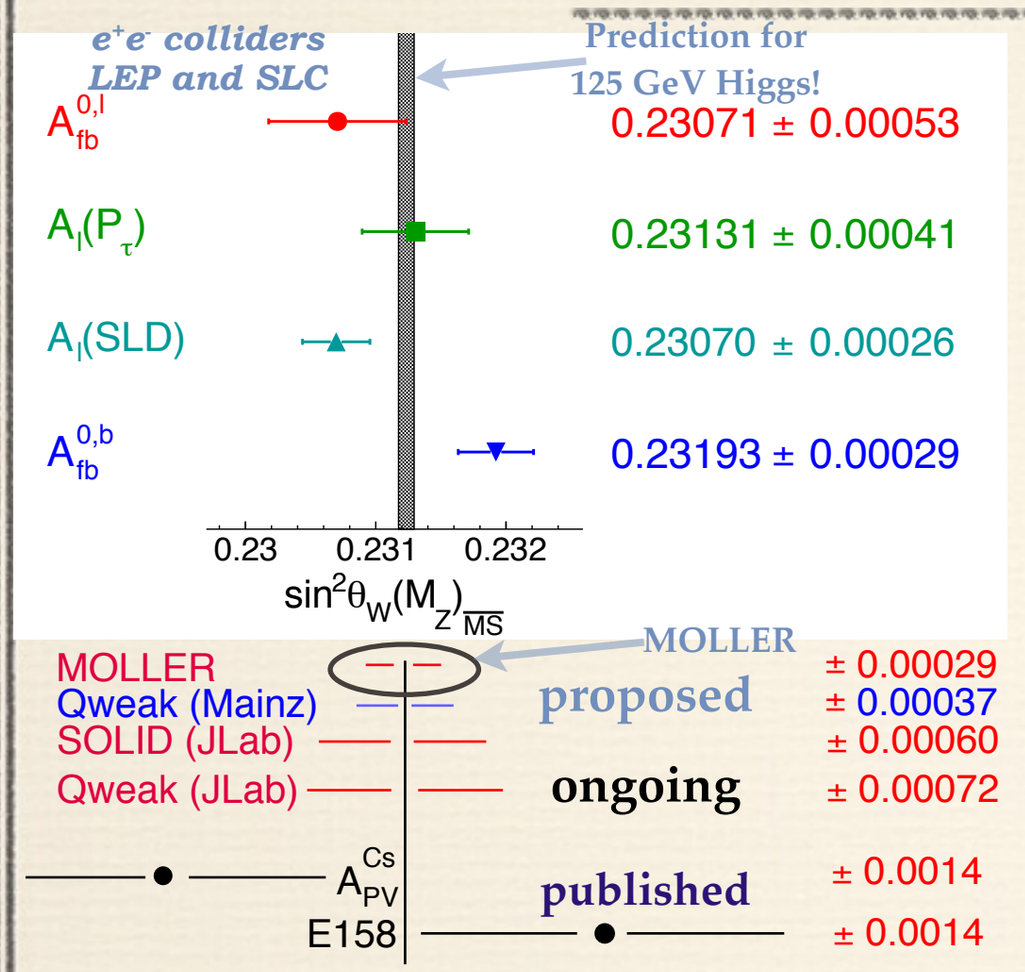

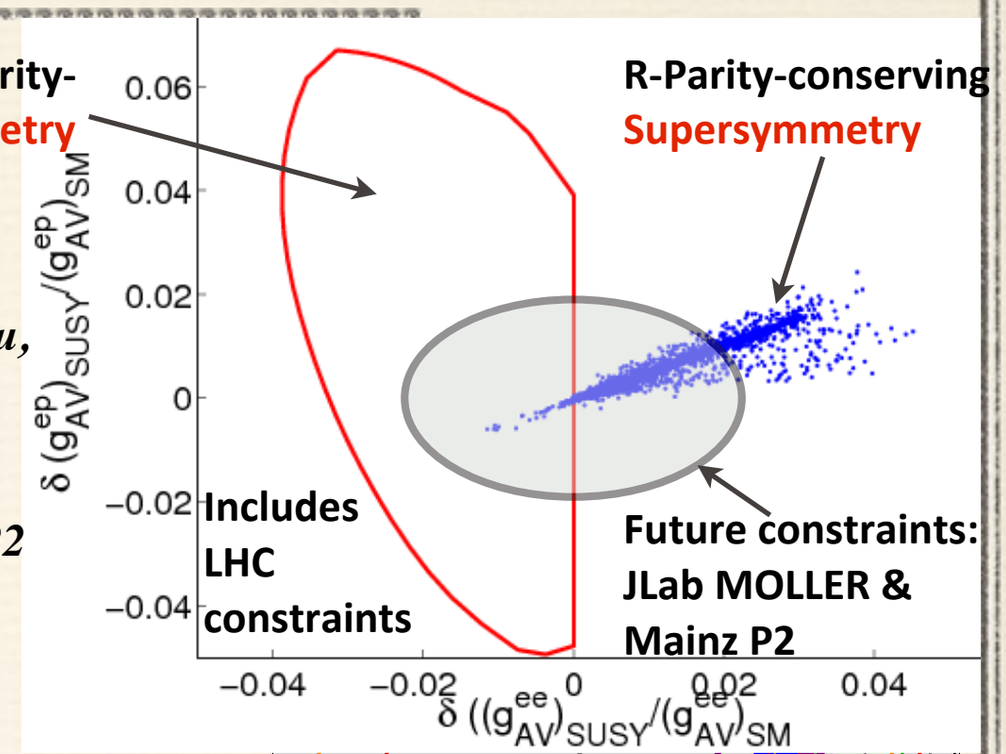

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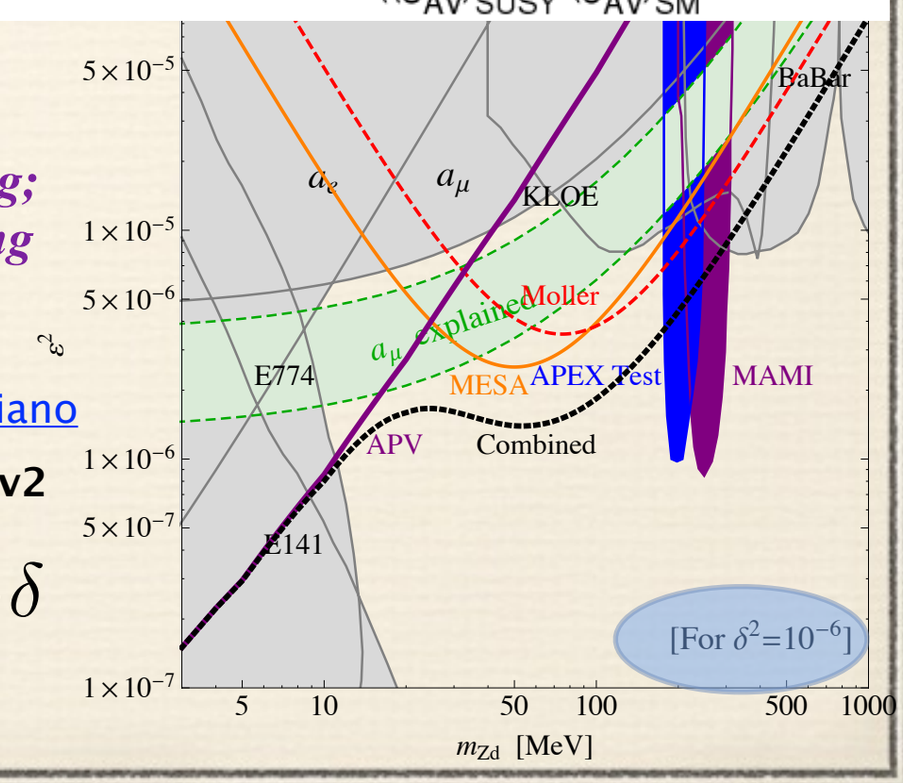
Dark Photons:

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

Davoudiasl, Lee, Marciano

arXiv:1203.2947v2

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



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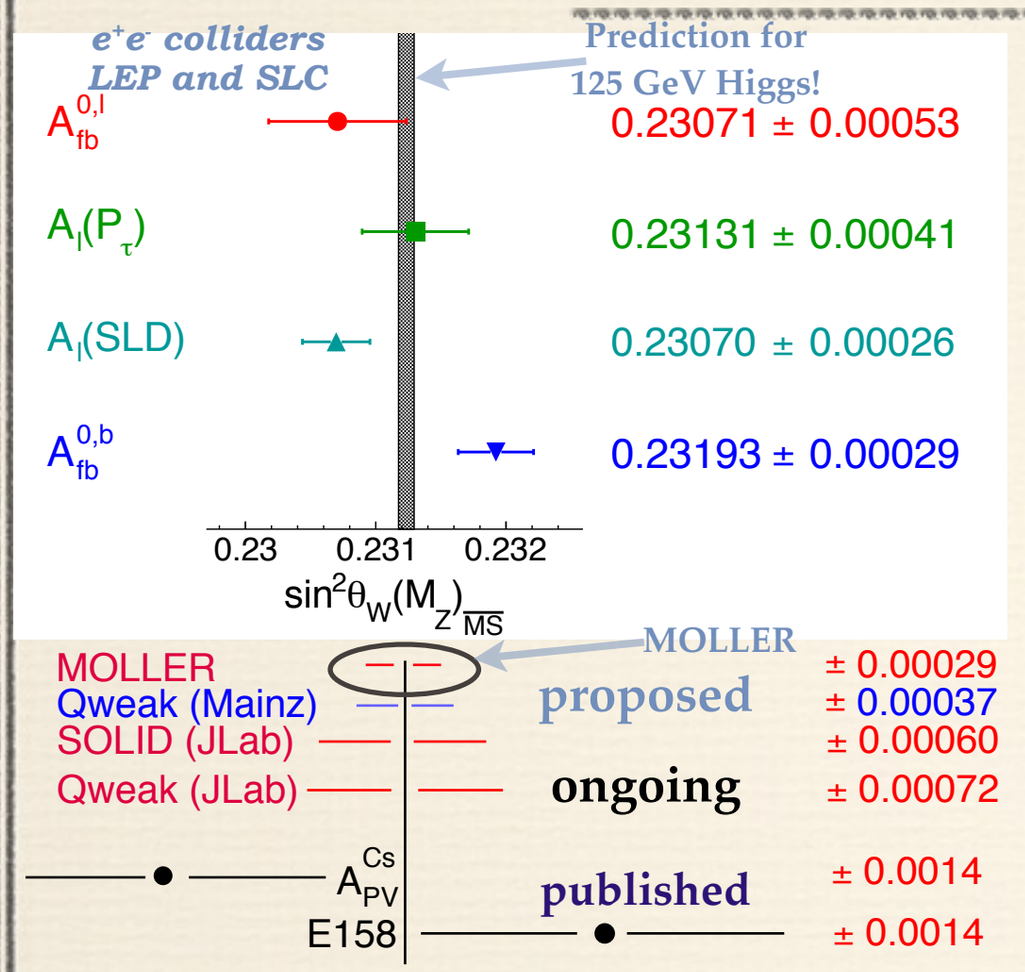

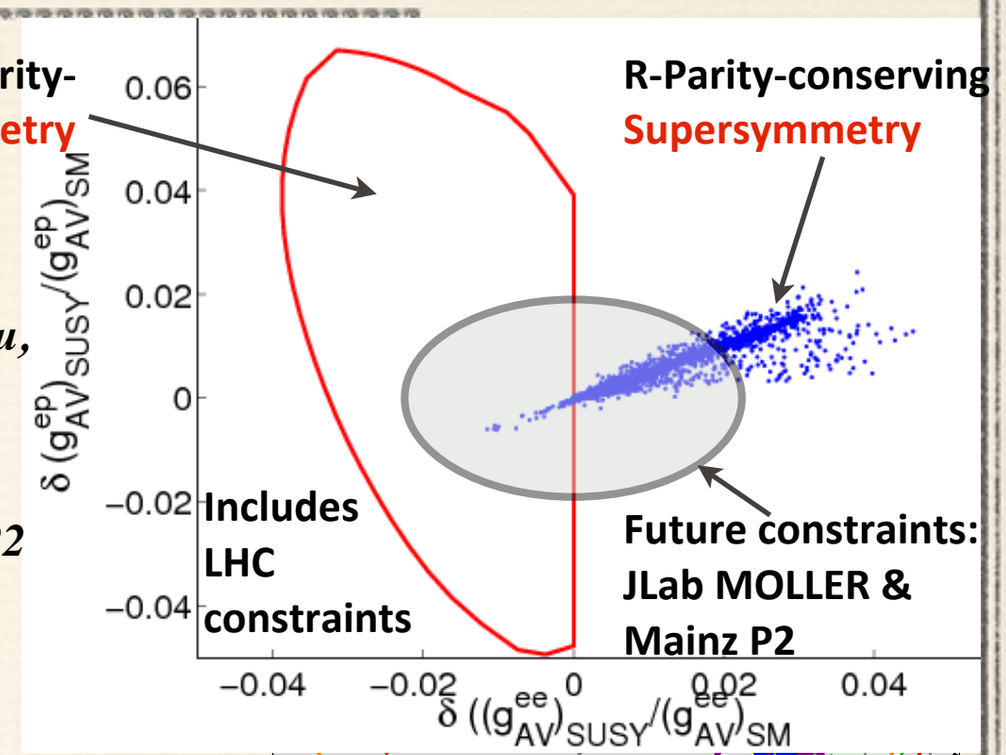

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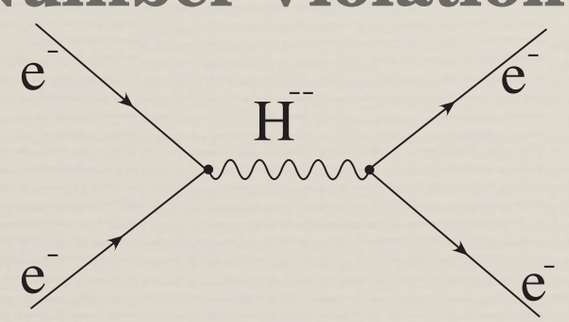
Lepton Number Violation

Λ > 5 TeV

Doubly-Charged Scalars



Significant reach beyond LEP-200

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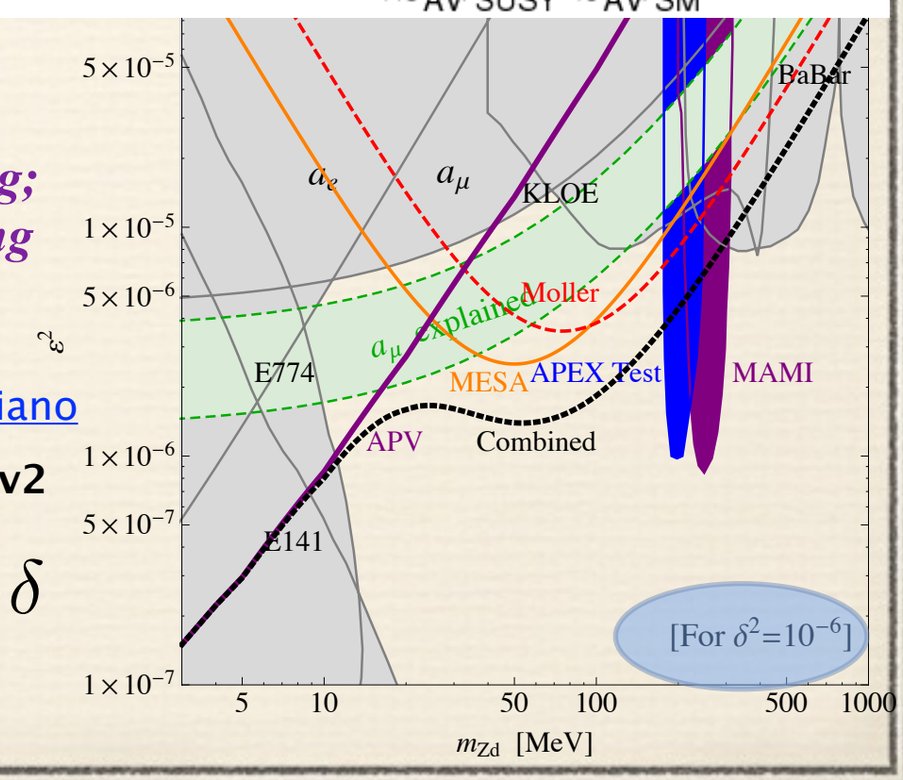
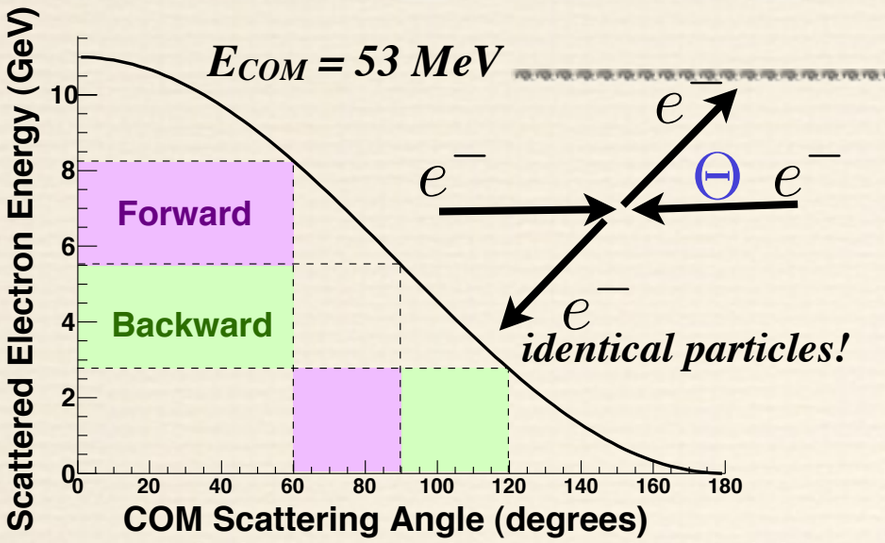
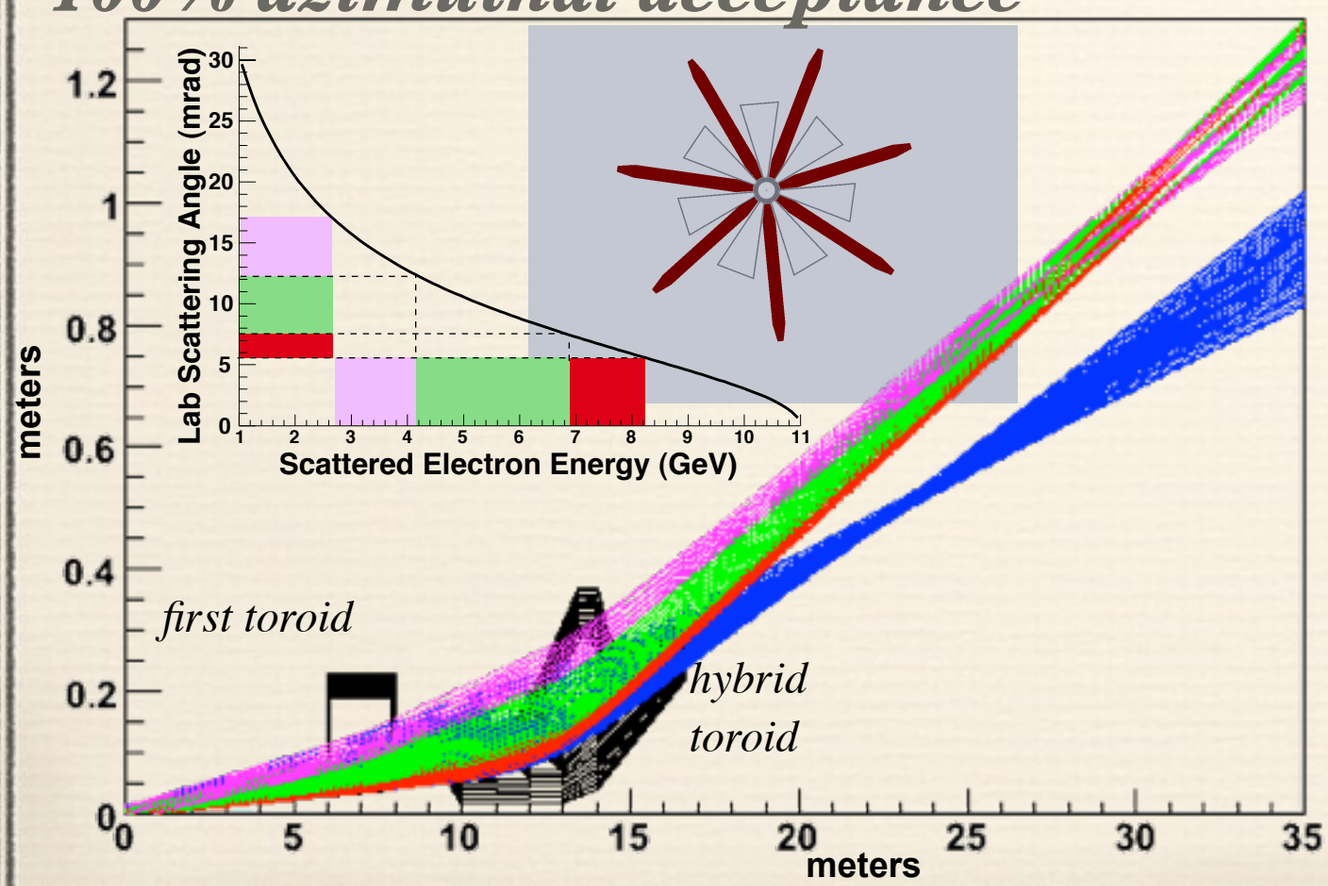


Unique Spectrometer Concept



odd number of coils:
100% azimuthal acceptance



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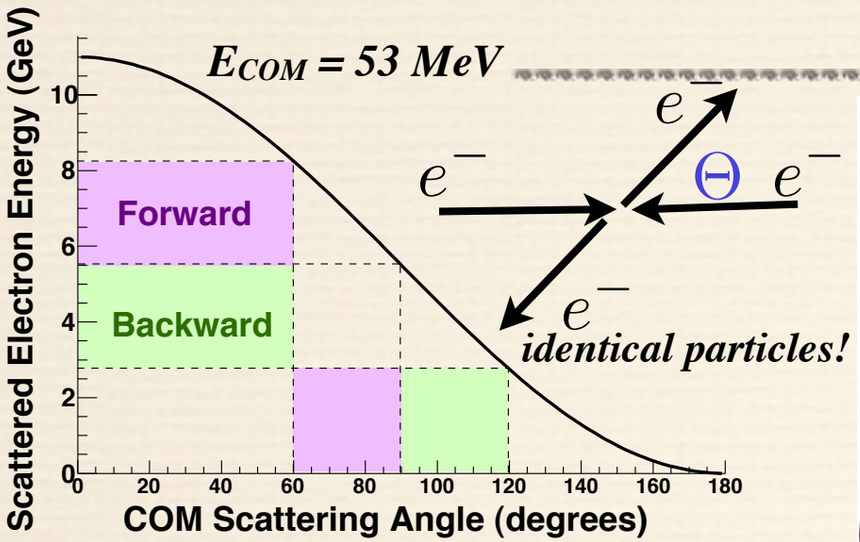

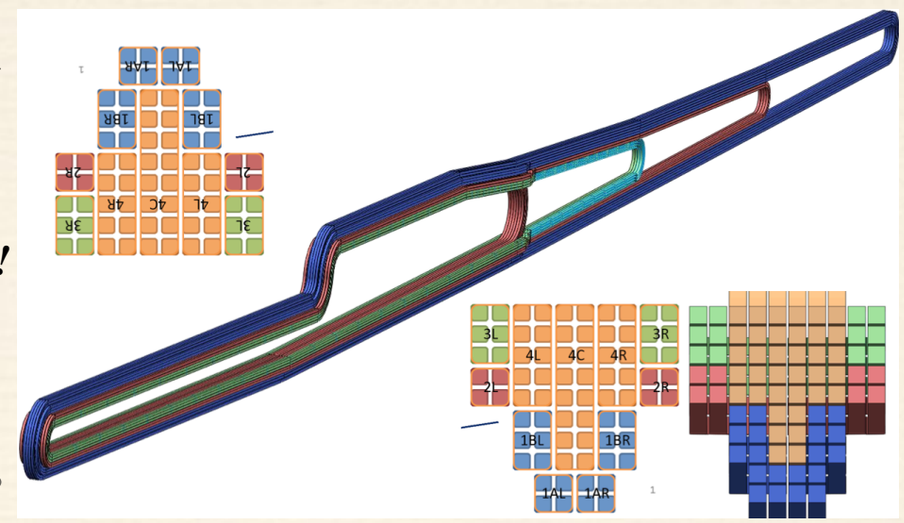

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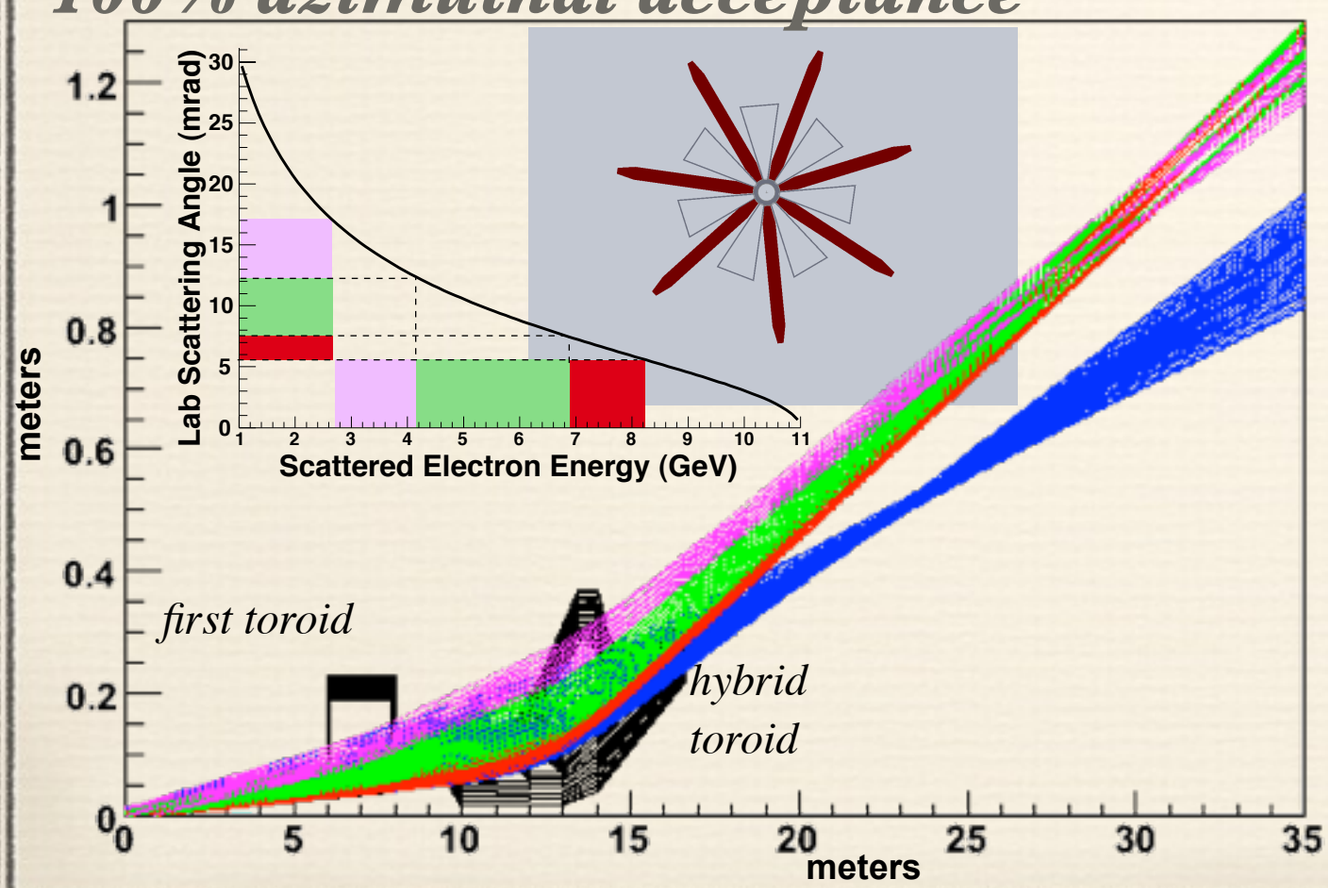

conceptual engineering design:
MIT-Bates, UMass, Manitoba

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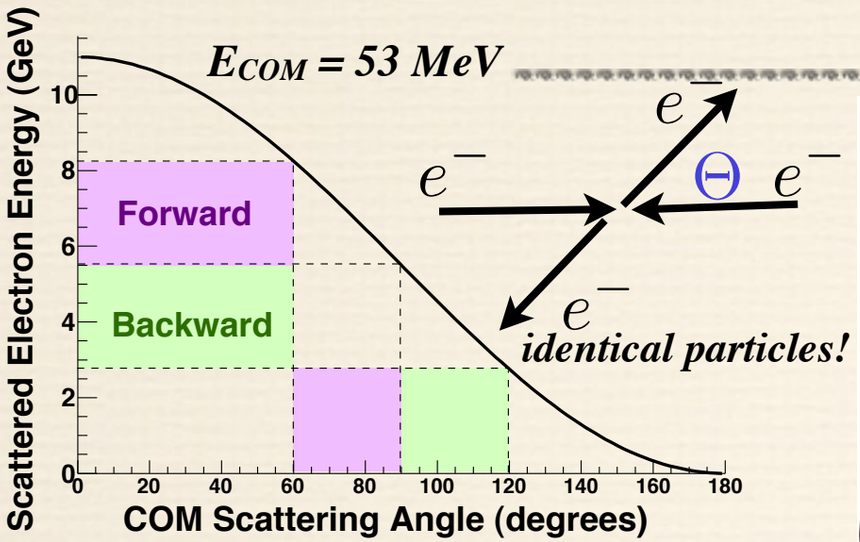

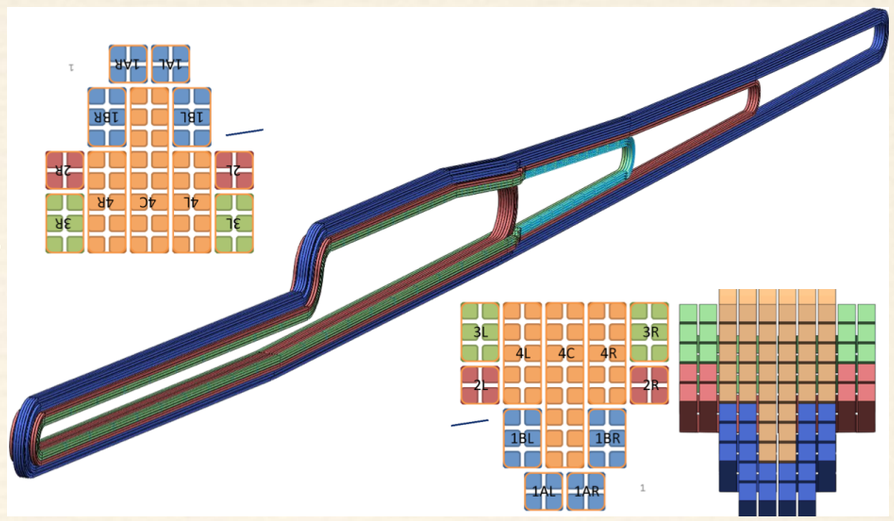

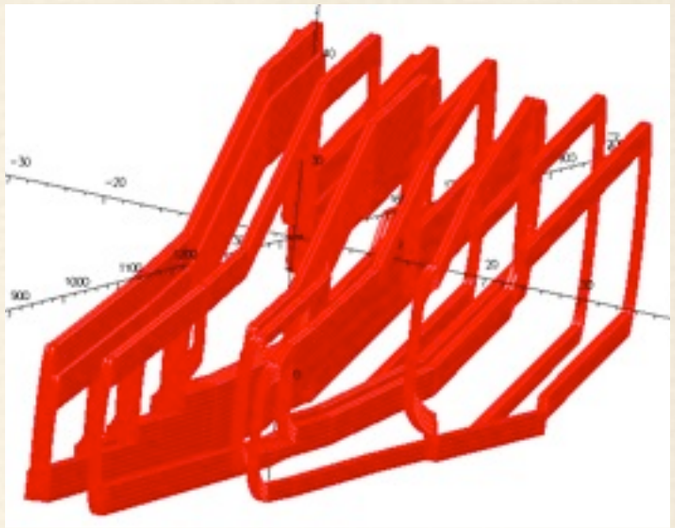

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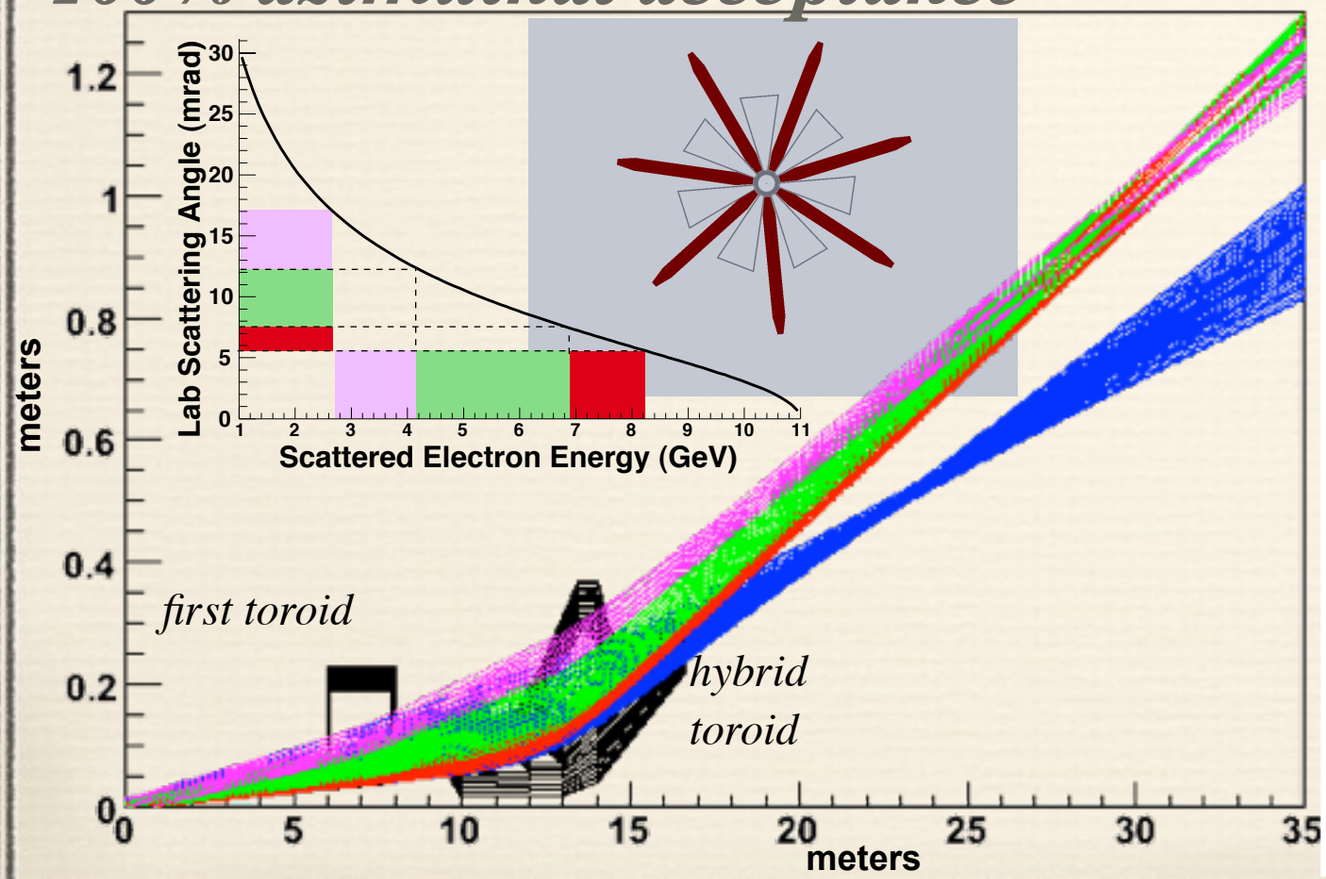

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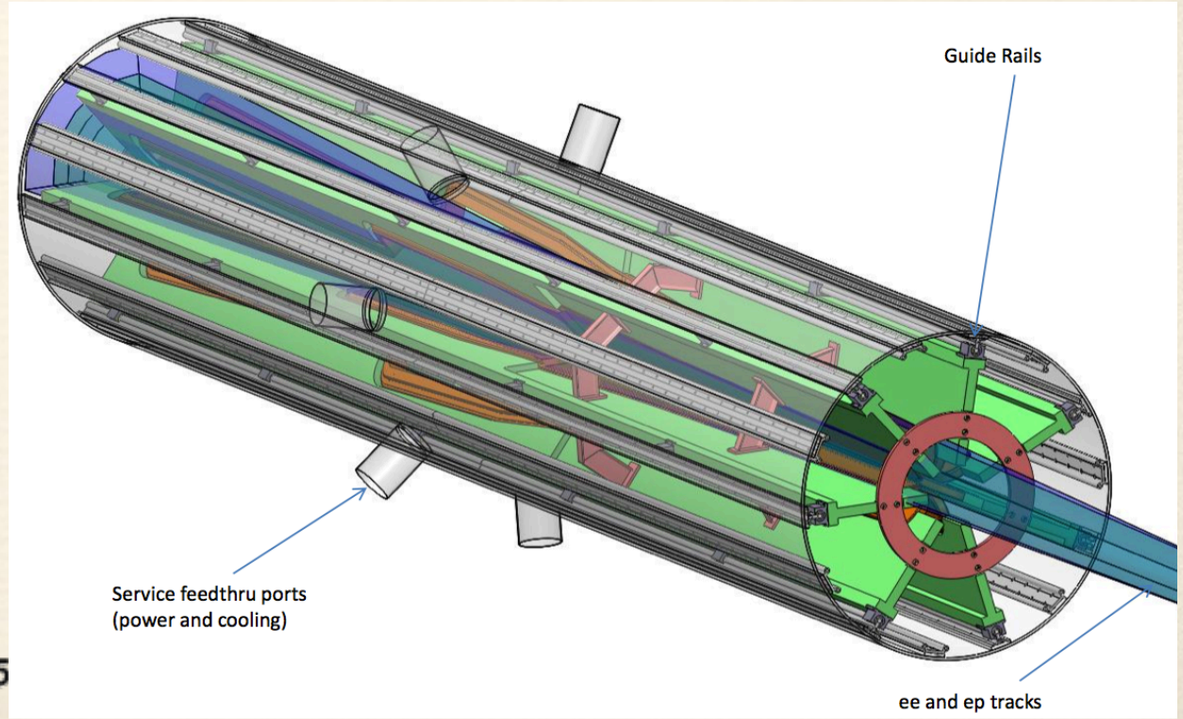


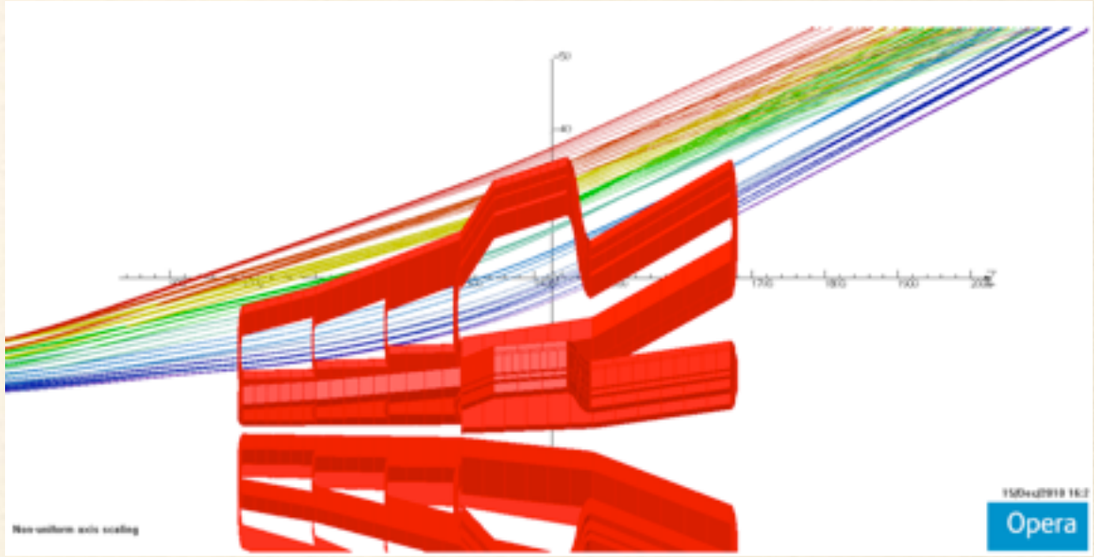
MOLLER Status

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

Technical Challenges

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

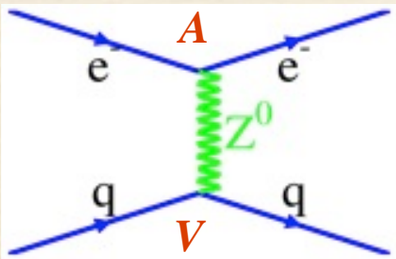
- **MOLLER Collaboration**
  - ~ 100 authors, ~ 30 institutions
  - Expertise from SAMPLE, A4, HAPPEX, G0, PREX, Qweak, E158
  - 4th generation JLab parity experiment



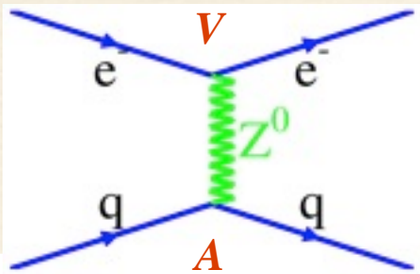
- **20M$ proposal to DoE NP**
- **2-3 years construction**
- **2-3 years running**

Elastic and deep-inelastic electron-nucleon scattering

Semi-Leptonic Couplings



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



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

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

Elastic and deep-inelastic electron-nucleon scattering

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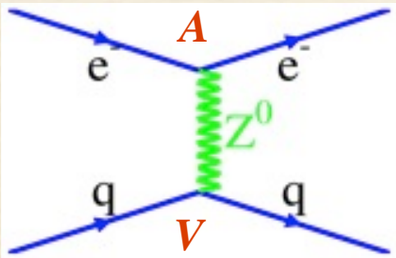

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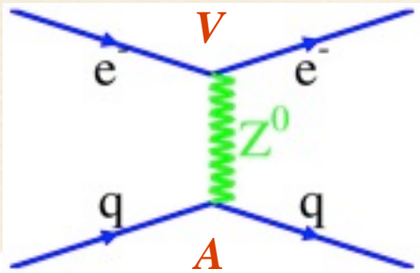

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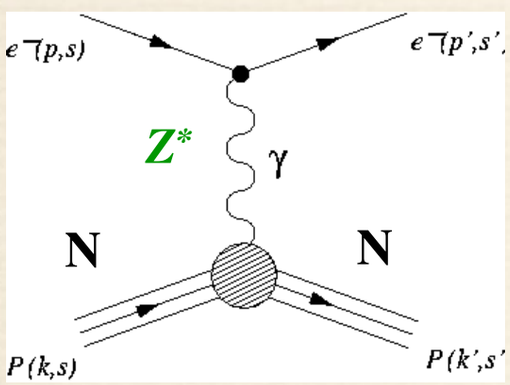
A_{PV} in elastic e-p scattering:



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

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

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

Elastic and deep-inelastic electron-nucleon scattering

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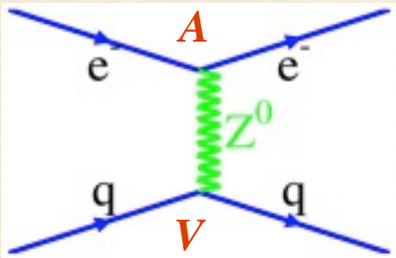

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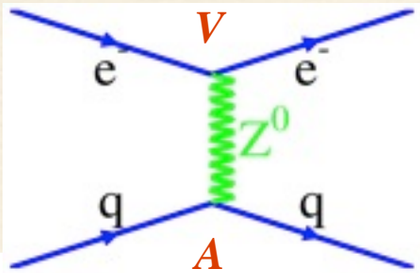

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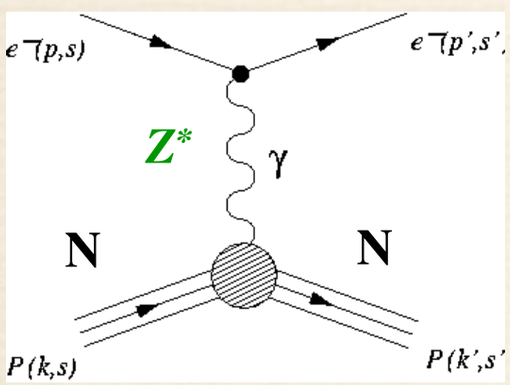

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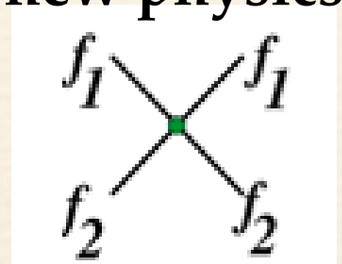
C_{1u}	$=$	$-\frac{1}{2}+\frac{4}{3}\sin^2\theta_W$	$\approx$	-0.19
C_{1d}	$=$	$\frac{1}{2}-\frac{2}{3}\sin^2\theta_W$	$\approx$	0.35
C_{2u}	$=$	$-\frac{1}{2}+2\sin^2\theta_W$	$\approx$	-0.04
C_{2d}	$=$	$\frac{1}{2}-2\sin^2\theta_W$	$\approx$	0.04

+

new physics



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

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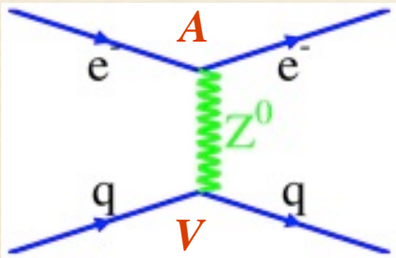

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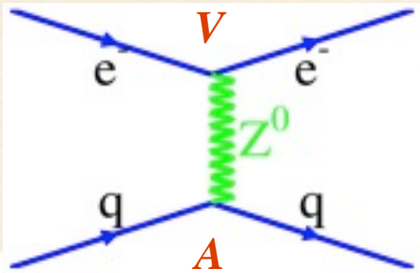

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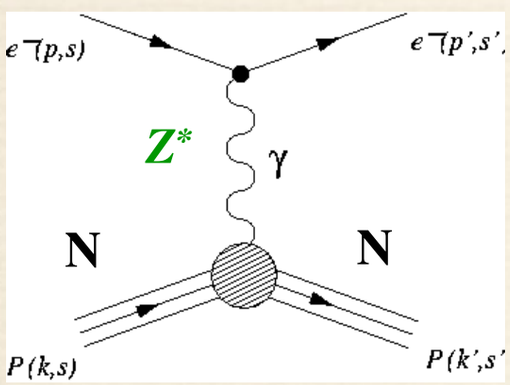
$$\mathcal{L}^{PV} = \frac{G_F}{\sqrt{2}} [\bar{e}\gamma^\mu\gamma_5 e(C_{1u}\bar{u}\gamma_\mu u + C_{1d}\bar{d}\gamma_\mu d) + \bar{e}\gamma^\mu e(C_{2u}\bar{u}\gamma_\mu\gamma_5 u + C_{2d}\bar{d}\gamma_\mu\gamma_5 d)]$$

A_{PV} in elastic e-p scattering:



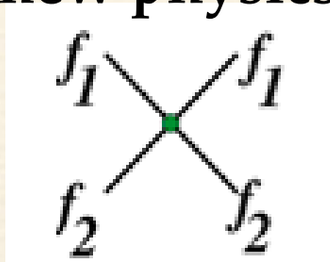
For a ^{1}H target, nucleon structure contribution well-constrained from measurements

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

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

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

new physics



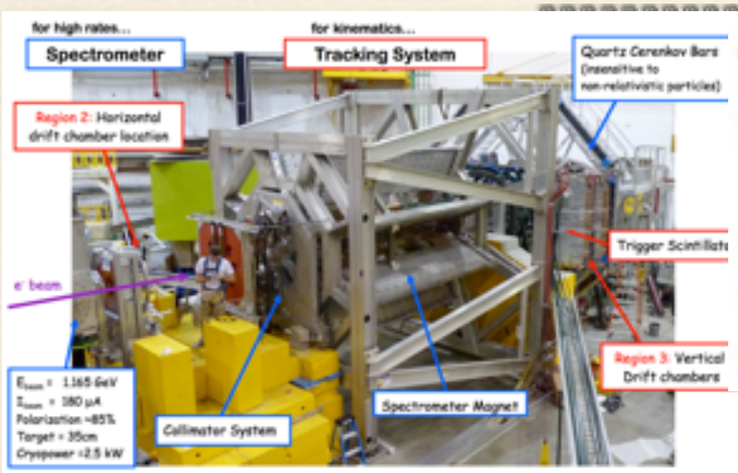
$$\mathcal{L}_{f_1 f_2} = \sum_{i,j=L,R} \frac{(g^{12}_{ij})^2}{\Lambda^2_{ij}} \bar{f}_{1i}\gamma_\mu f_{1i} \bar{f}_{2j}\gamma_\mu f_{2j}$$

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

PV elastic e-p scattering, Atomic parity violation

Elastic Electron-Proton Scattering

Qweak at JLab and P2 at Mainz



Technical highlights:

- World's highest power cryotarget (2.3 kW) (< 40 ppm "boiling" at 180 μA)
- 180 μA , 86% polarized beam
- Compton and Moller polarimetry
- Low noise, high precision electronics

first result with 4% of data; analysis of full data set ongoing

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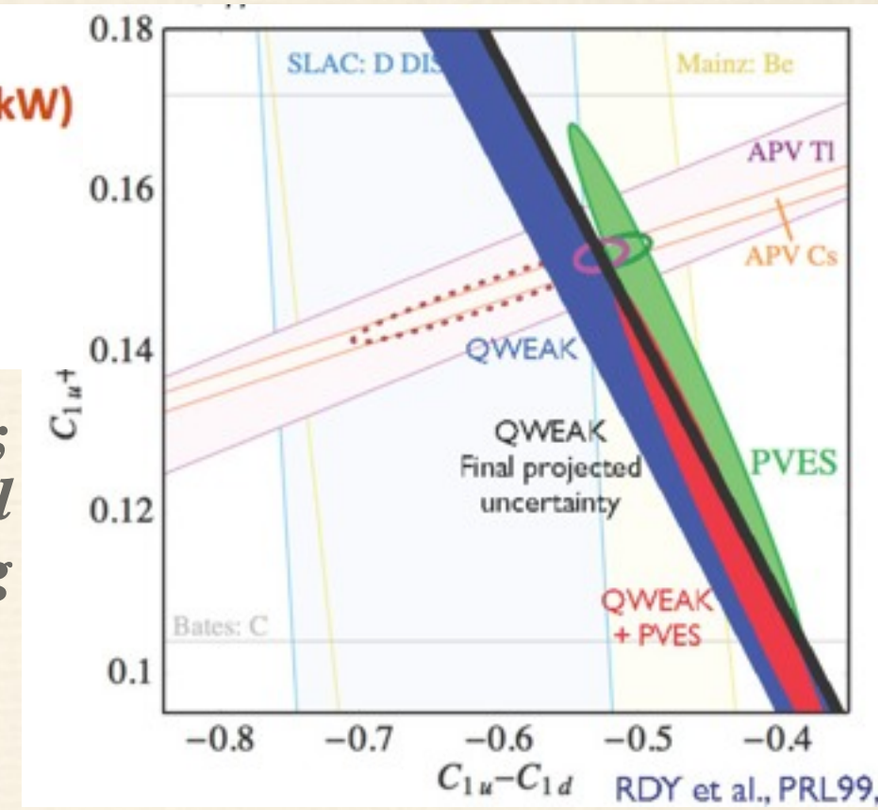
Data-taking done (2010-2012)

After full analysis expect:

$$\delta Q_W^p = \pm 4\% \Rightarrow \delta(\sin^2\theta_W) = \pm 0.3\%$$



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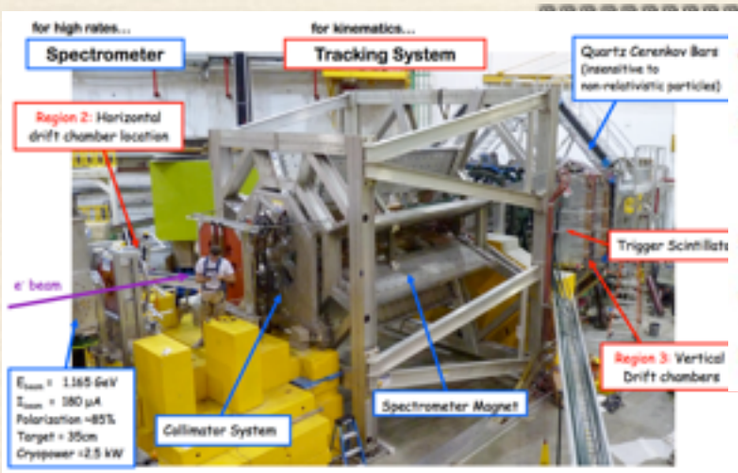

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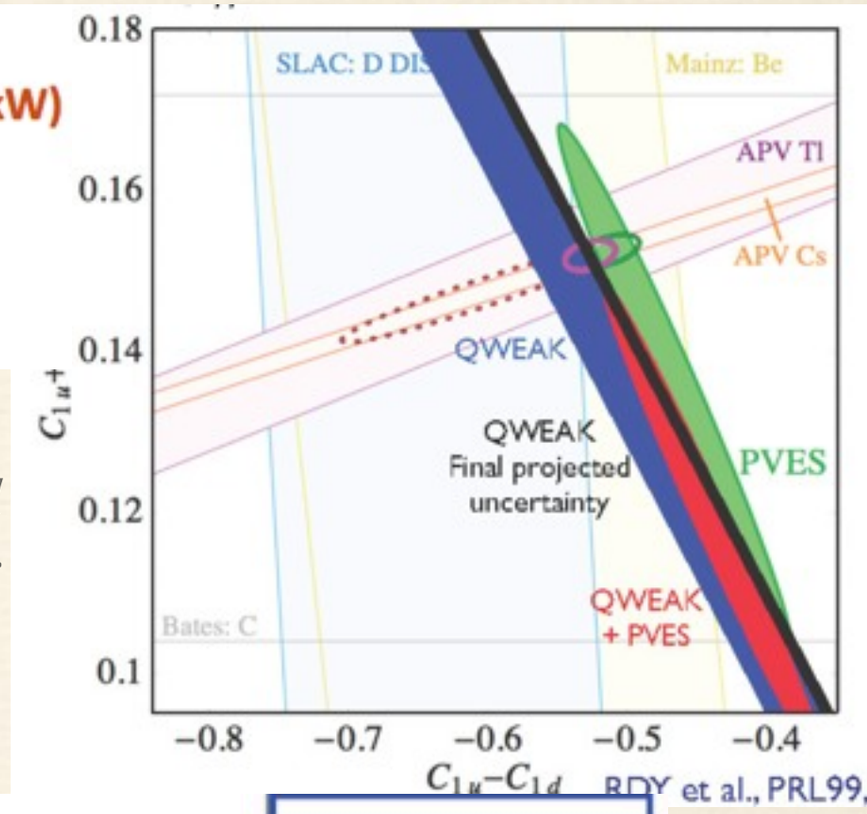

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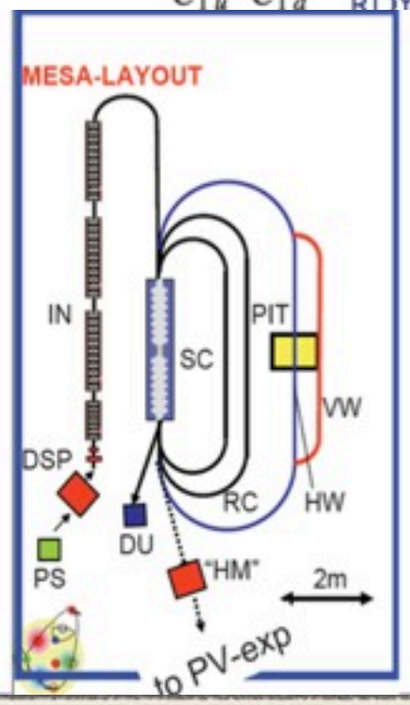
Future: MESA/P2 at Mainz

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

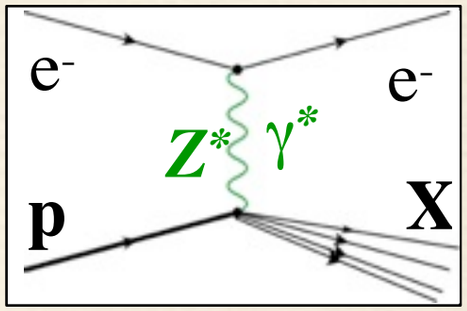
- A_{PV} = -20 ppb to 2.1% (0.4ppb)
- $\delta(\sin^2\theta_W)$ = 0.2%

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



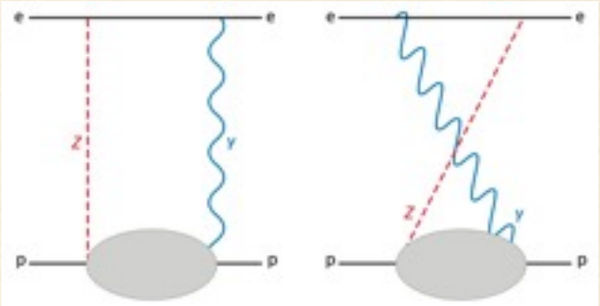
EW Physics & QCD Interplay

electrons on LH_2



✦ Inelastic backgrounds

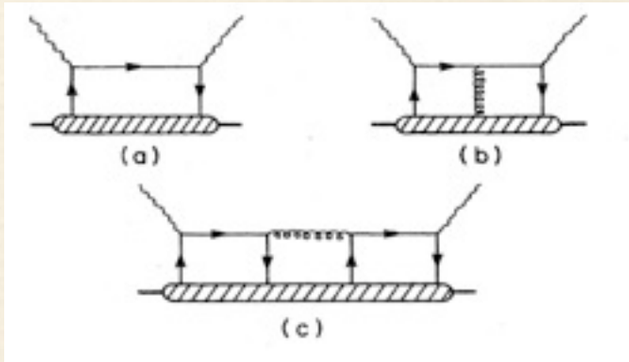
★ Inelastic e-p scattering in diffractive region ($Q^2 << 1$ GeV^2, $W^2 > 2$ GeV^2) pollutes the Møller peak



✦ Box diagram uncertainties

★ Proton weak charge modified; inelastic intermediate states

✦ Parton dynamics in nucleons and nuclei



★ Higher twist effects

★ charge symmetry violation in the nucleon

★ "EMC" style effects: quark pdfs modified in nuclei

Each "interest group" must buy into the other group's goals!

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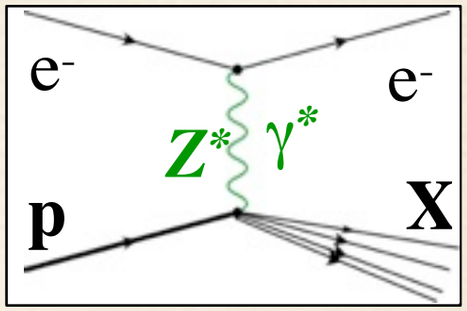

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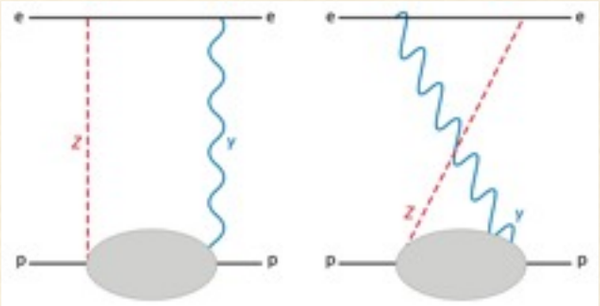

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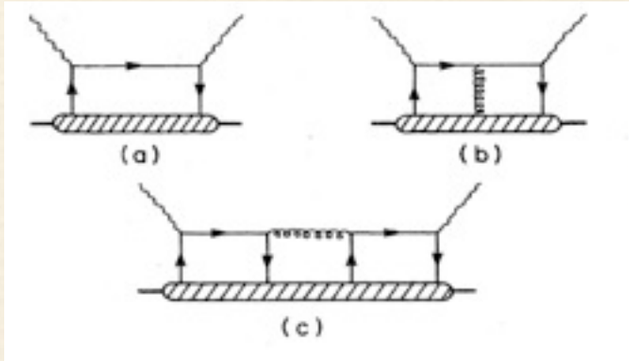

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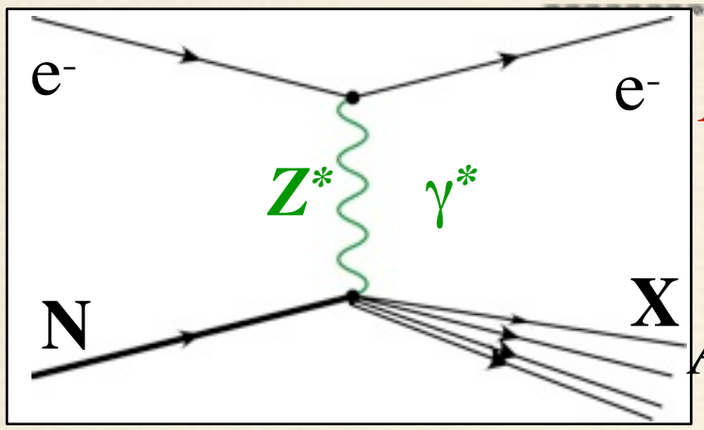
SOLID at JLab

Deuterium Target



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

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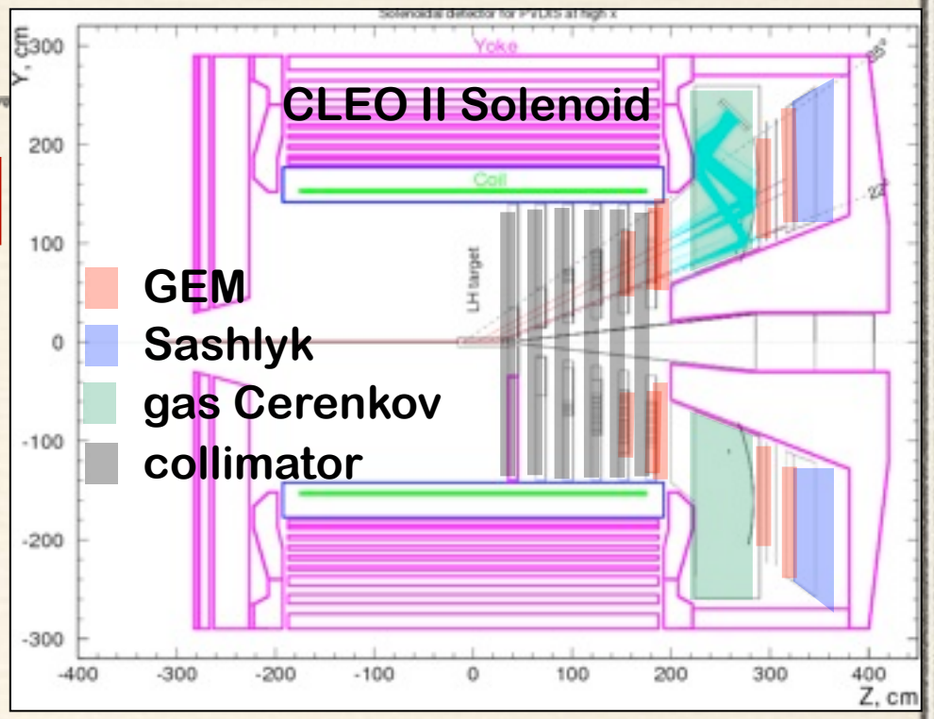
$$A_{PV} = \frac{G_F Q^2}{\sqrt{2}\pi\alpha}\left[a(x) + f(y)b(x)\right]$$

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



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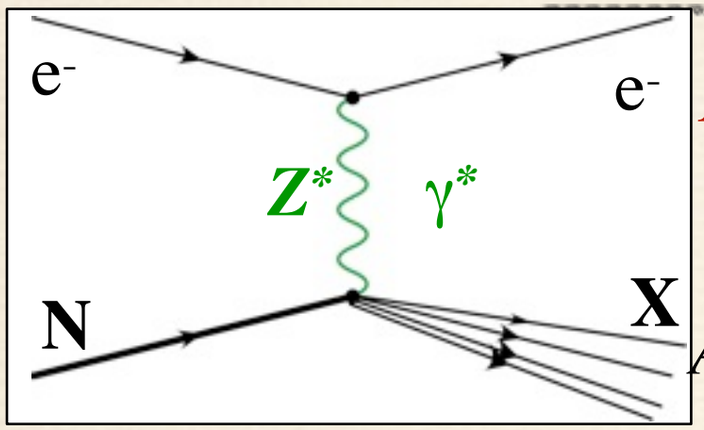

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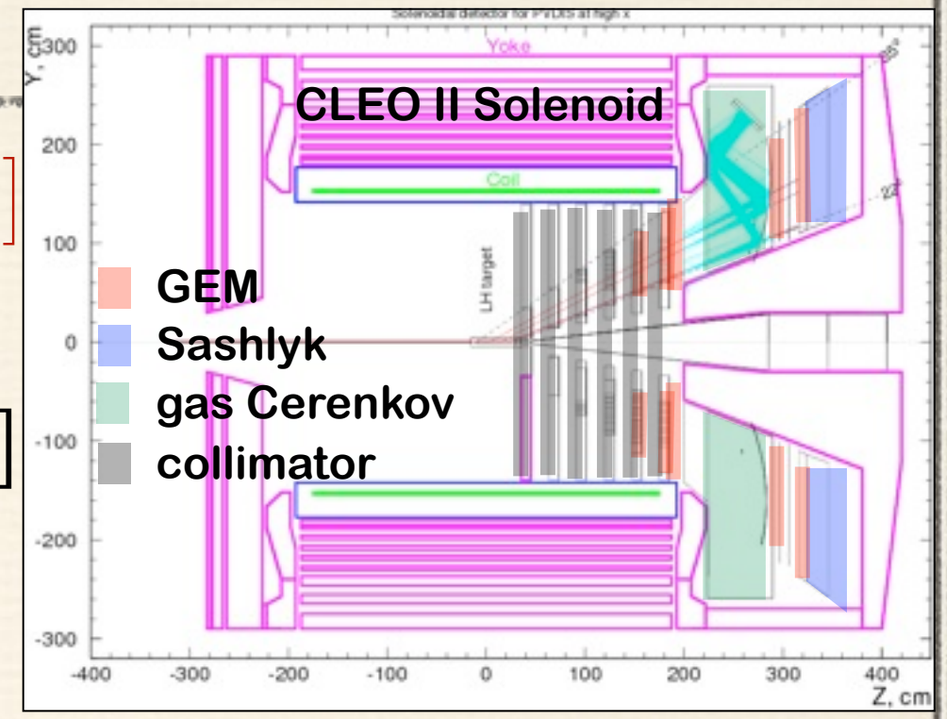

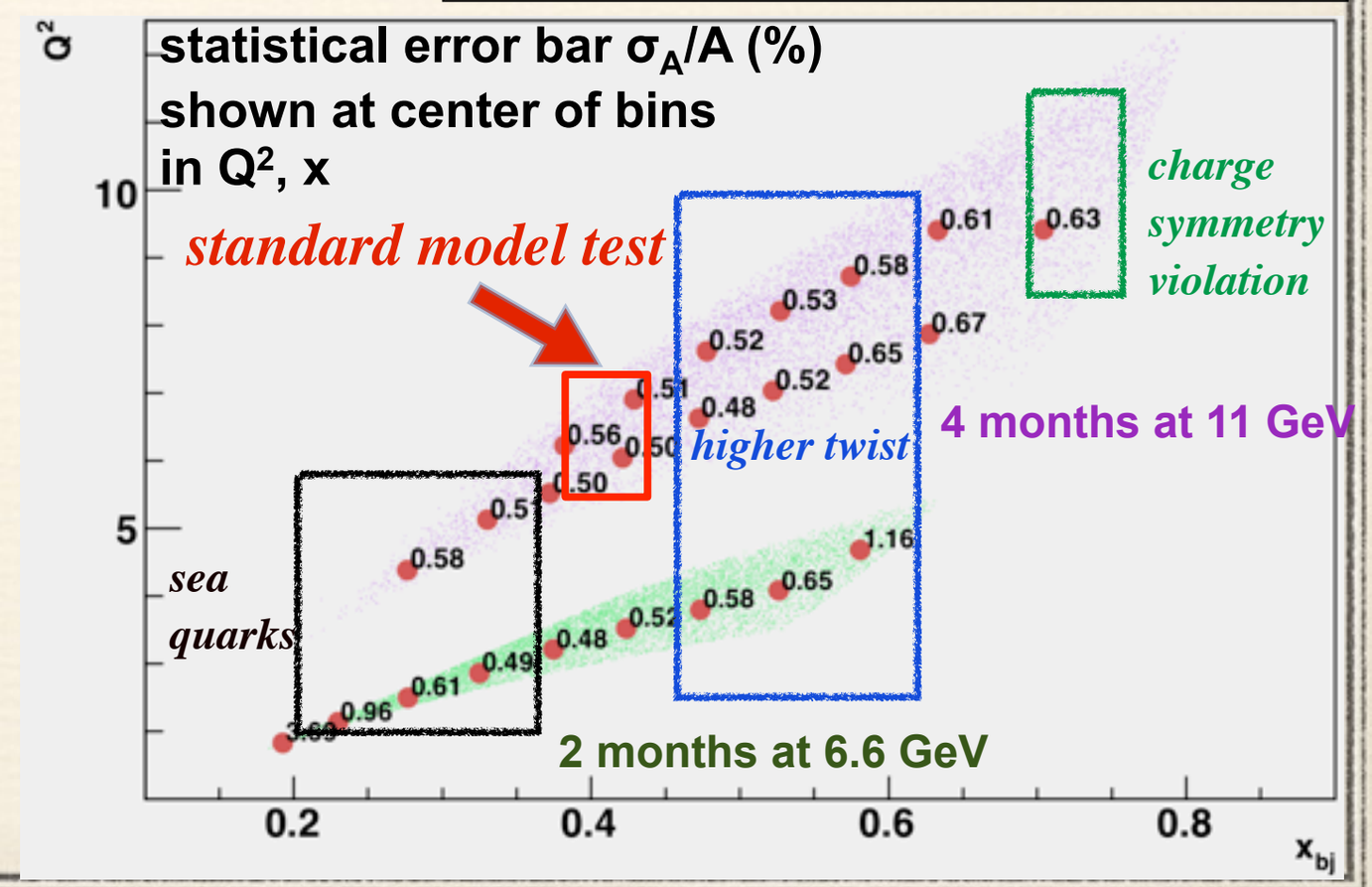

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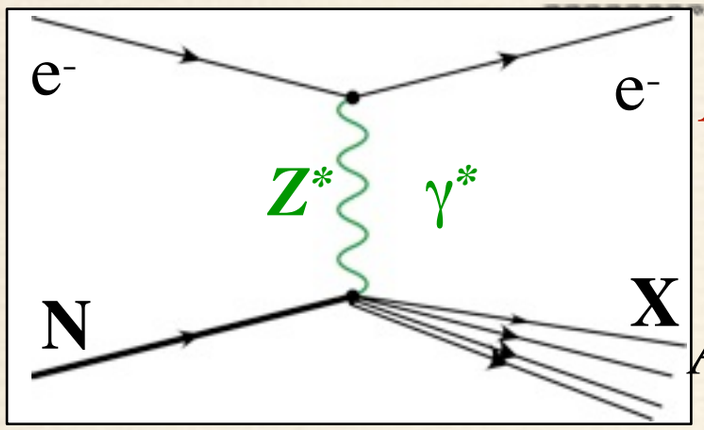

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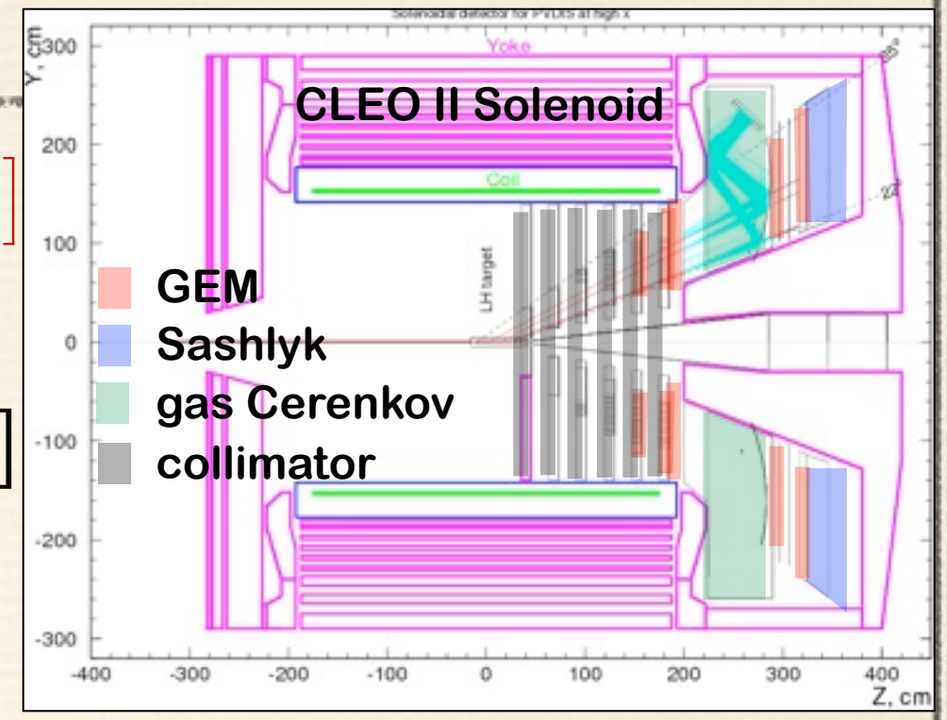
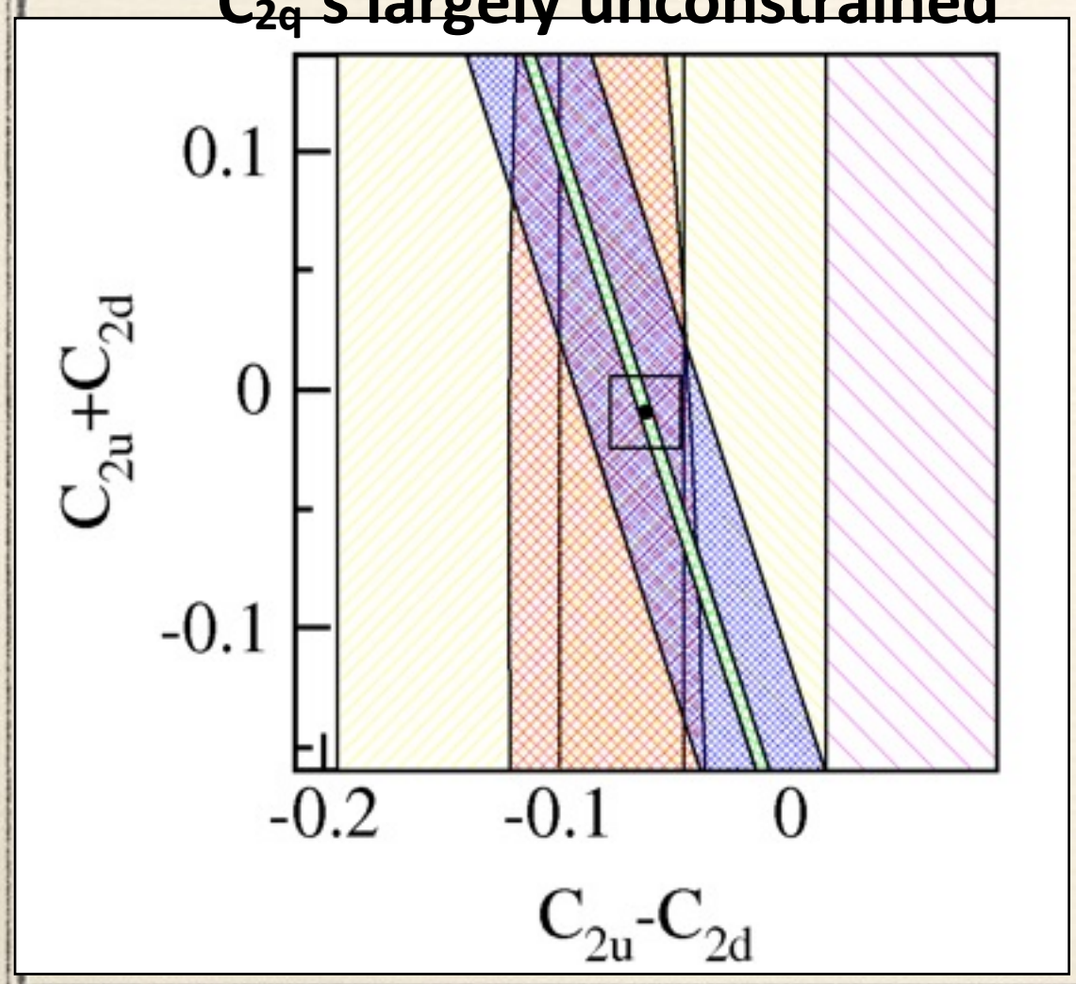
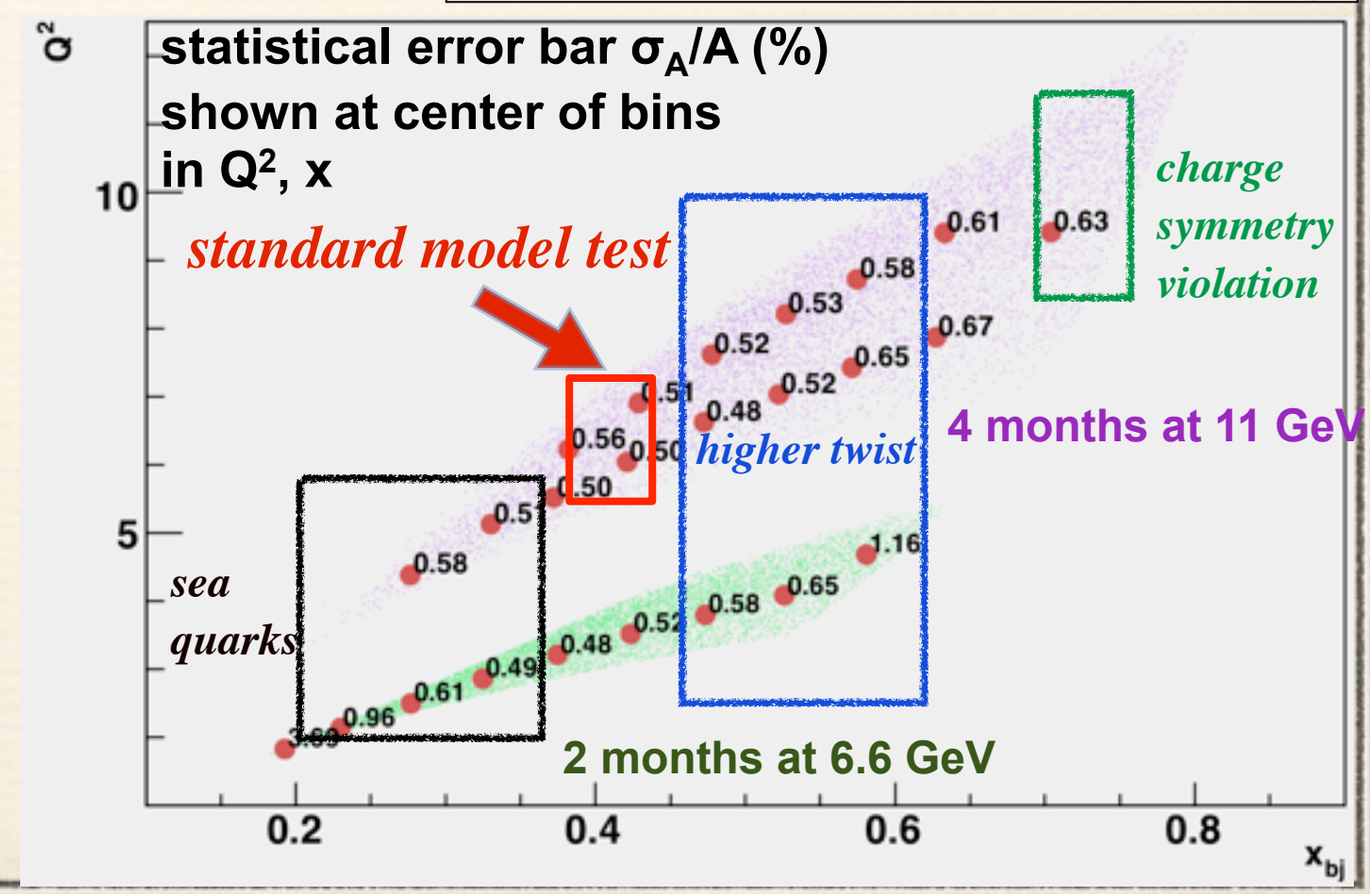
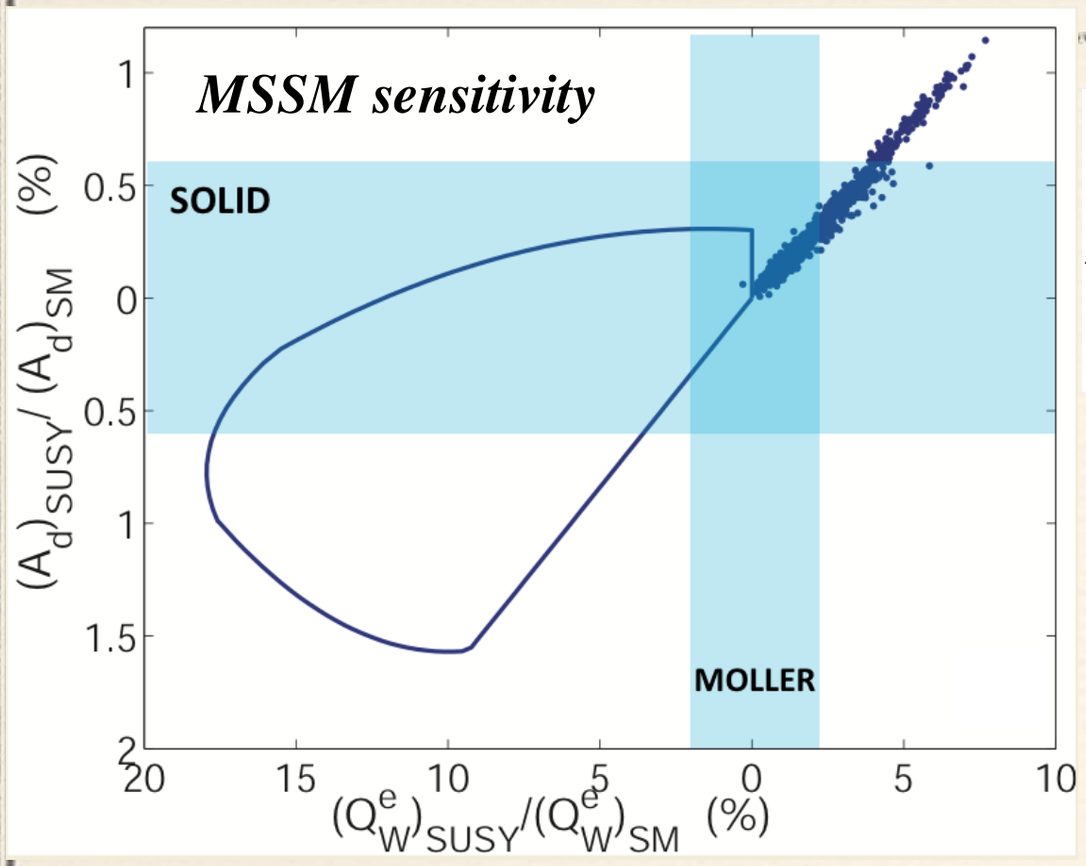


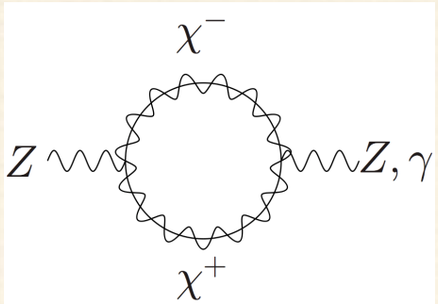
C_{2q}'s largely unconstrained





SOLID Sensitivity





Does Supersymmetry provide a candidate for dark matter?

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

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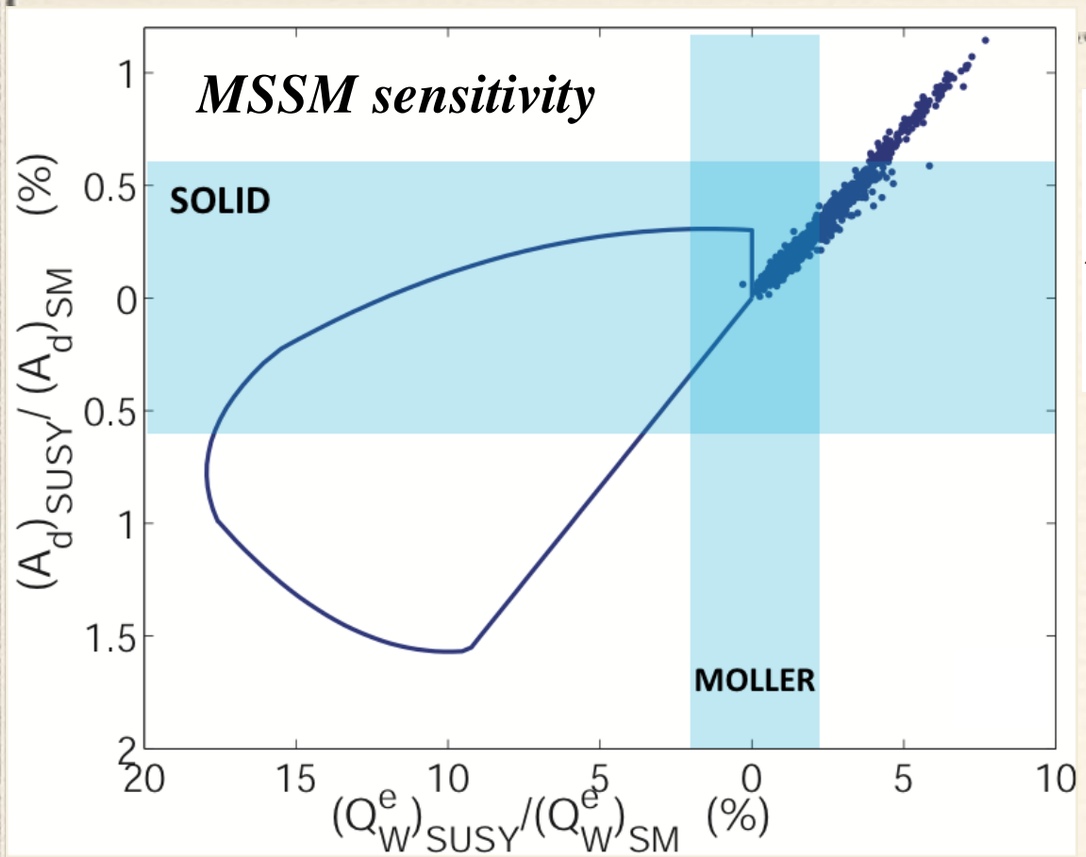

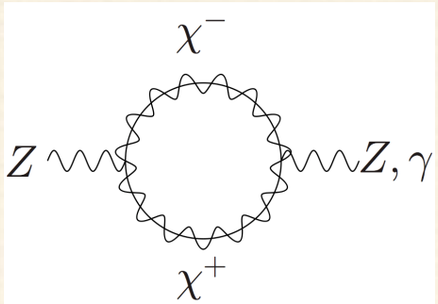

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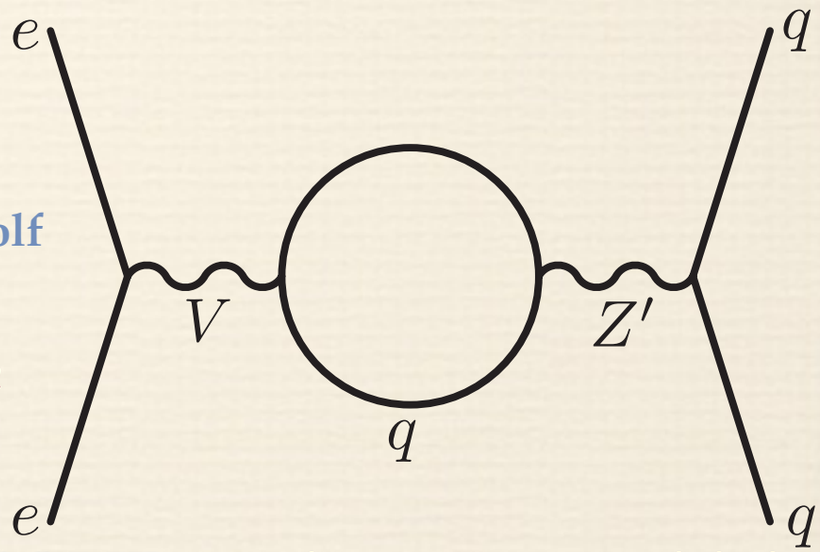
Leptophobic Z'

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

arXiv:1203.1102v1
Buckley and Ramsey-Musolf



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

SOLID can improve sensitivity: 100-200 GeV range

Nuclei: Collection of Nucleons?

Charge symmetry violation (CSV)

$$u^p(x) \stackrel{?}{=} d^n(x) \quad \Rightarrow \quad \delta u(x) \equiv u^p(x) - d^n(x)$$

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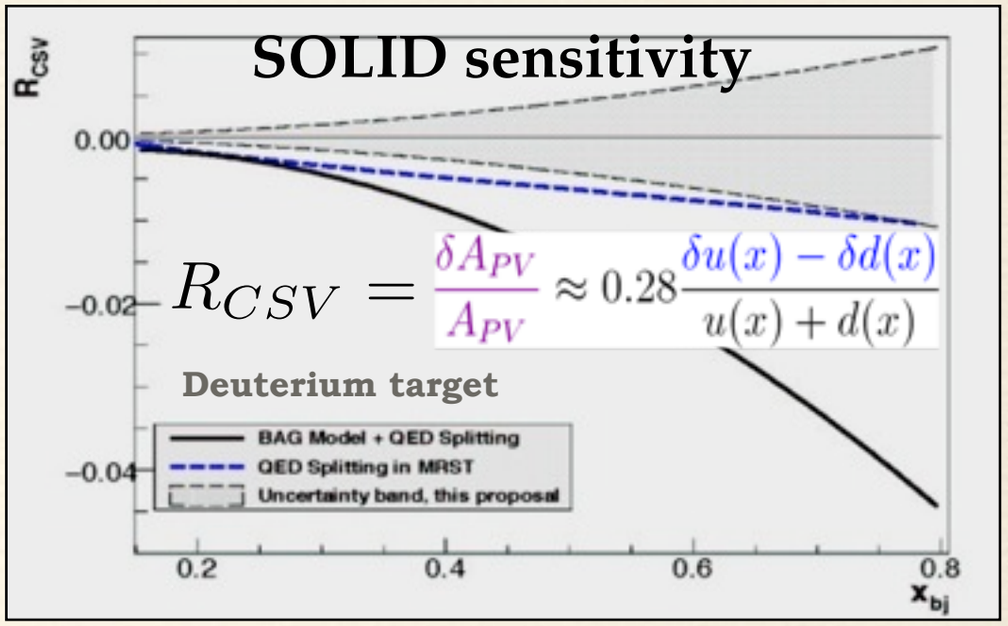

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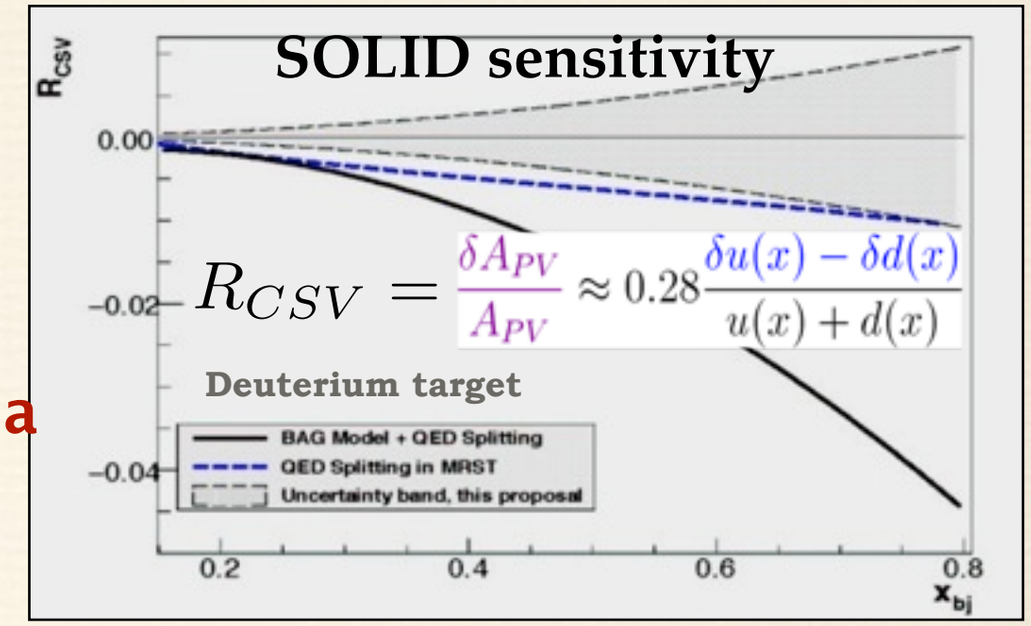

From Nucleons to Nuclei

- Neutron or proton excess in nuclei leads to a isovector-vector mean field (ρ exchange)
- shifts quark distributions: "apparent" CSV
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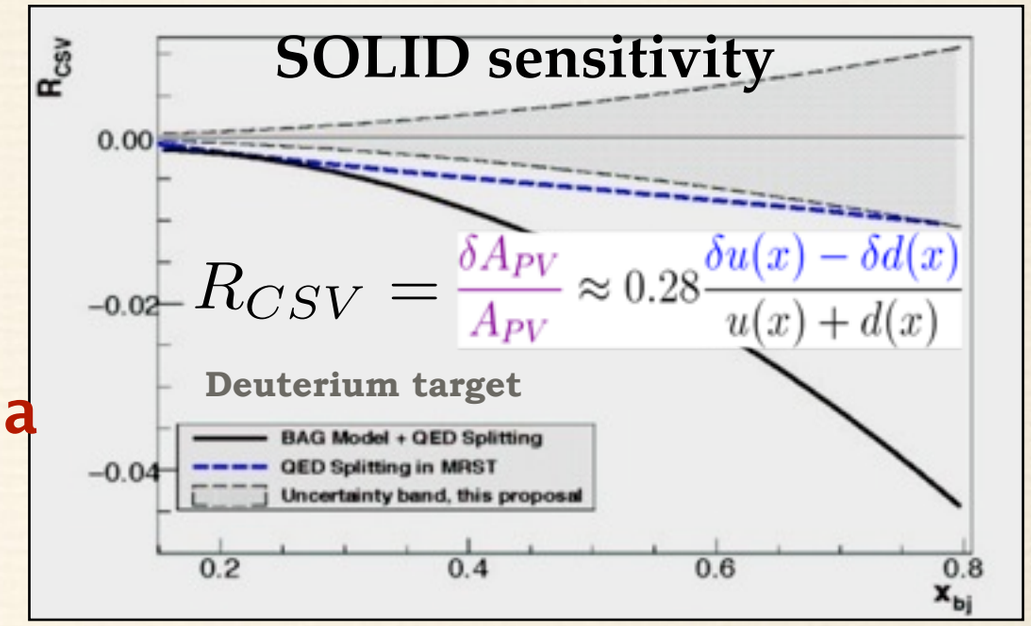

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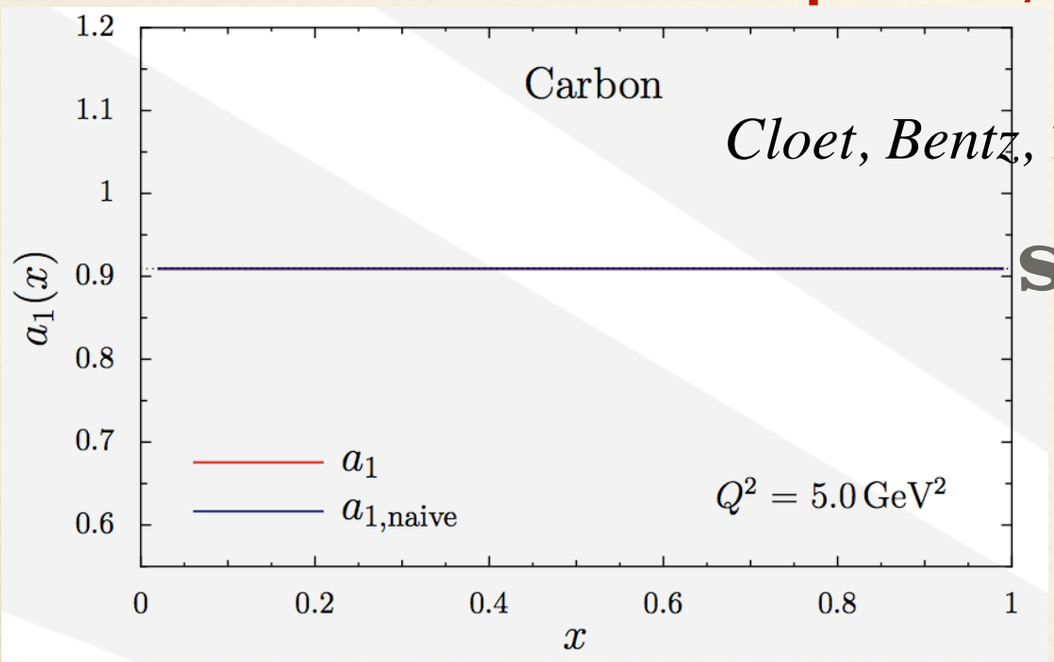
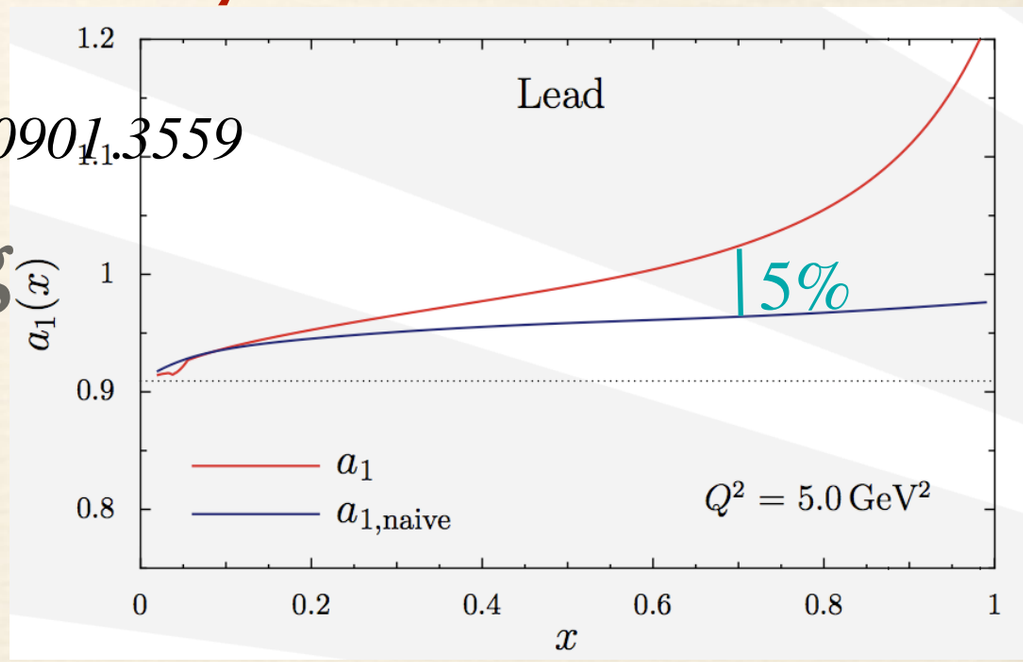


Cloet, Bentz, Thomas, arXiv 0901.3559

smoking gun!



- **nuclear medium modification of quark distributions?**

The Far Future?

"Parasitic" Opportunity: Electroweak & BSM Physics

EW Physics at an EIC

An Electron-Ion Collider is the next big machine envisioned in US Nuclear Physics

A high energy, high luminosity (polarized) *ep* and eA collider and a suitably designed detector

eRHIC at Brookhaven National Laboratory using the existing RHIC complex

ELIC at Jefferson Laboratory using the Upgraded 12GeV CEBAF

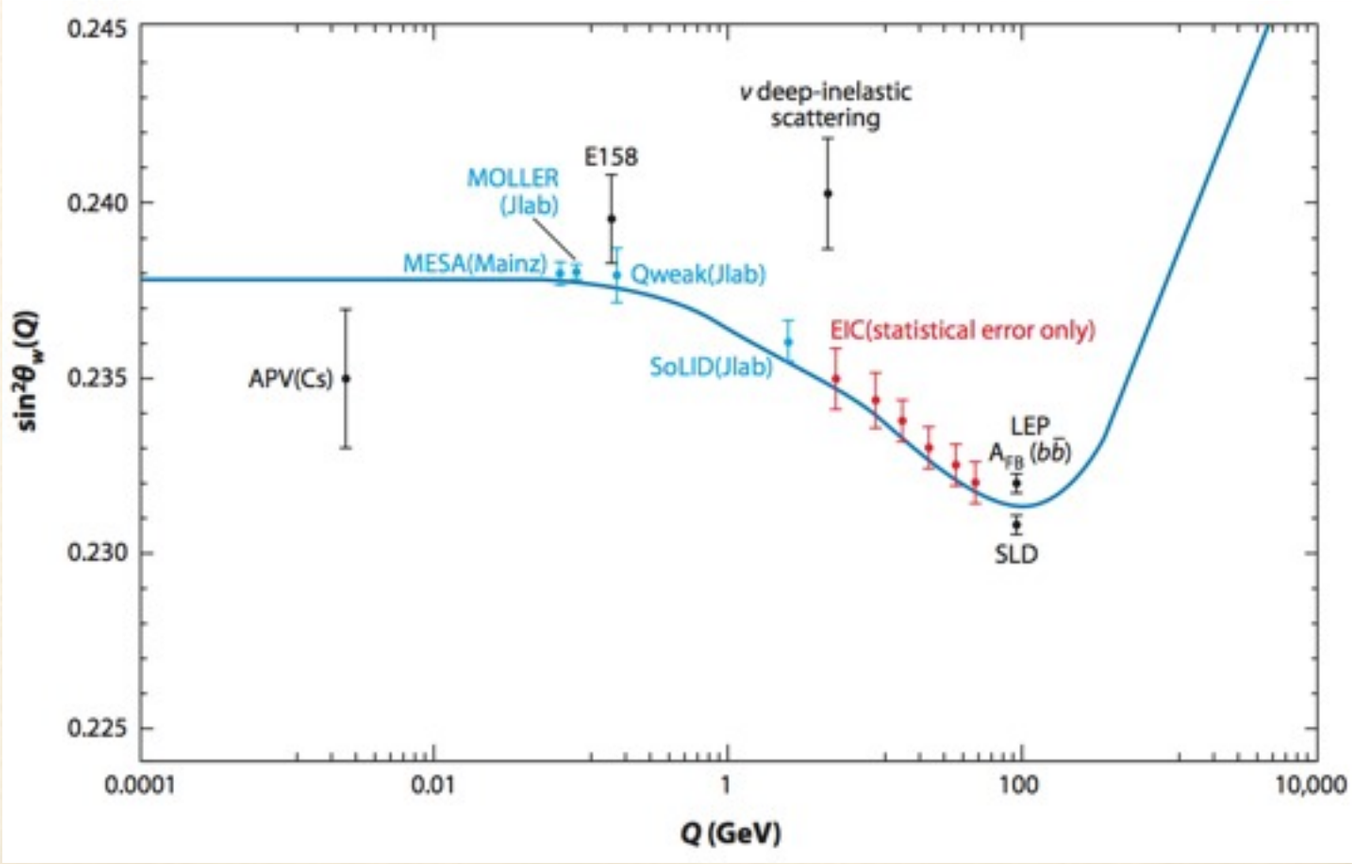
Two Machine Designs

Both planned to be STAGED

- E_e=10 GeV (5-30 GeV variable)
- E_p=250 GeV (50-325 GeV Variable)
- Sqrt(S_{ep}) = 100 (30-200) GeV

- **Electroweak (spin) structure functions**
- W and Z boson production: different couplings to ***quarks and anti-quarks***

- **Parity violating DIS**: a probe of beyond TeV scale physics
- Measurements at higher Q^2 than the PV DIS 12 GeV at Jlab
- Precision measurement of $Sin^2\Theta_W$



Can one get below ± 0.0001 without a Giga-Z?

Møller Scattering at an ILC

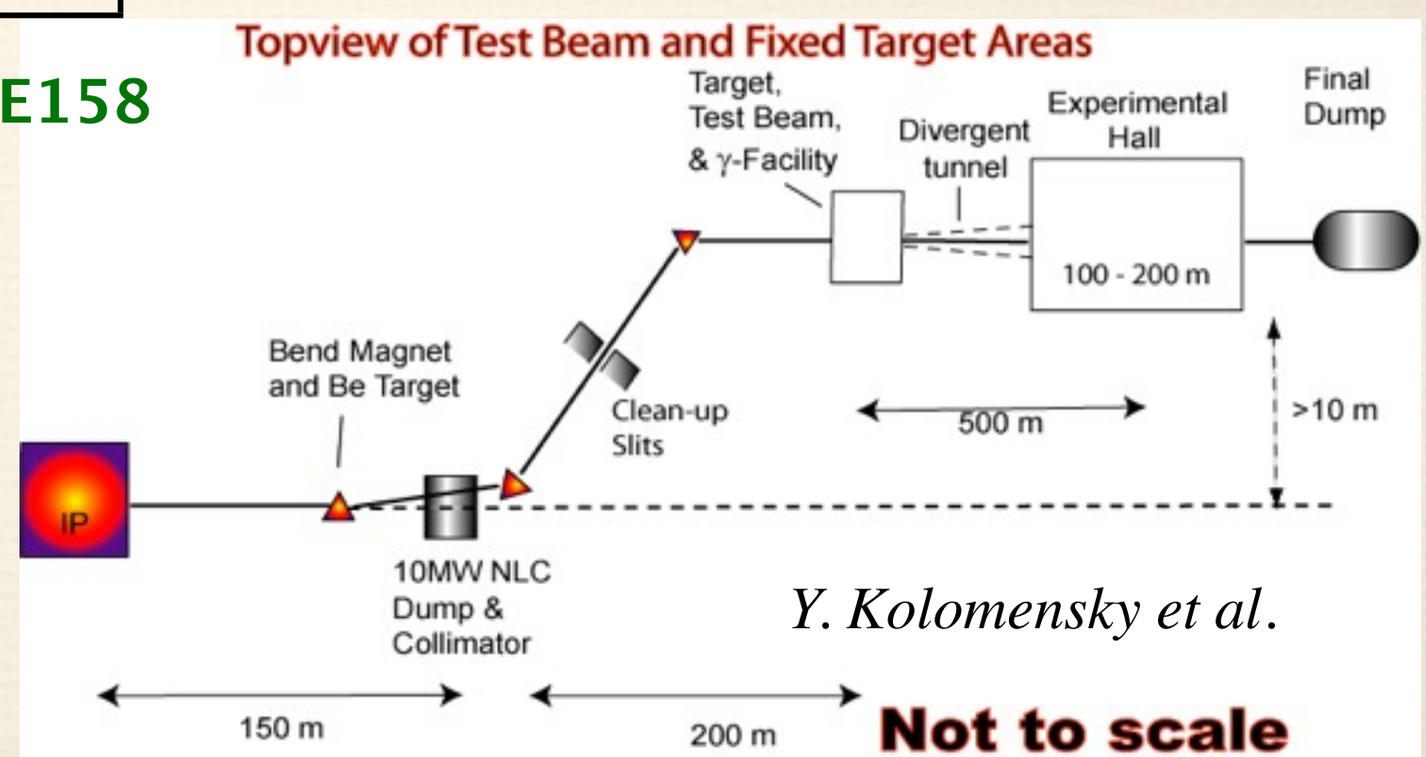
K.K, Snowmass 96	E158	LC
Energy (GeV)	48	250-500
Intensity/pulse	4.5×10^{11}	14×10^{11}
Pulse Rate (Hz)	120	120
P_e	85%	90%
Time (s)	5×10^6	2×10^7
A_{LR} (ppm)	0.15	1-2
δA_{LR} (ppm)	0.015	0.008
$\delta \sin^2(\theta_W)$	0.001	0.00006-8

Compton Polarimetry

$$\delta P_e(\text{syst}) \approx 0.25\% \quad \text{(projected)}$$
$$\approx 0.50\% \quad \text{(SLD)}$$

$$\frac{\delta \sin^2\theta_W}{\sin^2\theta_W} \approx \frac{1}{20}\frac{\delta P_e}{P_e} \Rightarrow \delta \sin^2\theta_W \approx 0.00003$$

- Order of magnitude better than E158
- Parasitic "exhaust" beam ?
- Approaching Giga-Z territory
- Need 3 or 4 such independent measurements



Y. Kolomensky et al.

Møller scattering could be the centerpiece of a compelling fixed-target program at the ILC

Beyond Electron Scattering

✦ Atomic Parity Violation

- ★ New facilities being designed
  - *Trapped Francium at TRIUMF, Canada*
  - *Trapped Radium+ ions at KVI, Netherlands*
- ★ Systematic and statistical reach
  - *chains of isotopes would alleviate atomic theory issues*
  - *luminosity increases feasible with new FRIB facility*

✦ Neutrino Scattering

- ★ Fine-grained near-detector measurement at LBNE?
- ★ Reactor experiments have so far not demonstrated the capability to achieve the needed statistics
- ★ Neutrino factory?

Summary

- **Measurements of the Weak Mixing Angle**
  - ★ Central to our understanding of the Standard Model
  - ★ Likely remain central in our search for new physics
- **Parity-Violating Electron Scattering**
  - ★ 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 Particle Physics
    - *Search for new dynamics at the multi-TeV scale*
    - *complementary to colliders; would help interpret potential anomalies*
    - *precision measurement of the weak mixing angle*

A remarkably productive research program that will continue to flourish over the next decade