Parity-Violating Deep Inelastic Scattering

Electroweak Physics and Nucleon Structure

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"Collective Dynamics in High Energy Collisions"

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Introductory Remarks

- I was very concerned about how basic I should be regarding electron scattering but yesterday's lecture by Jean-Paul saved me time!
- I am an experimentalist: my theory discussion is not going to be very deep; mostly qualitative
- Unfortunately, due to lack of time, my experiment discussions are not going to be very deep either!
- One key point is the continuous interplay between electroweak physics and hadron physics
- I have no idea how long this talk is!

Outline

- Electron Scattering and the Substructure of Matter
- Electroweak Interactions and Parity Violation
- Parity-Violating Deep Inelastic Electron Scattering (PVDIS)
- Modern Electroweak Physics: Search for New High Energy Dynamics
- New PV Results from Jefferson Lab: one in PRL and one in Nature
- The not-so-far Future: The SOLID Experiment
- The Weak Neutral Current as a Complementary Probe of Structure
- The Future: Electroweak Physics at an EIC

Electron Scattering and the Substructure of Matter

Quantum Electrodynamics

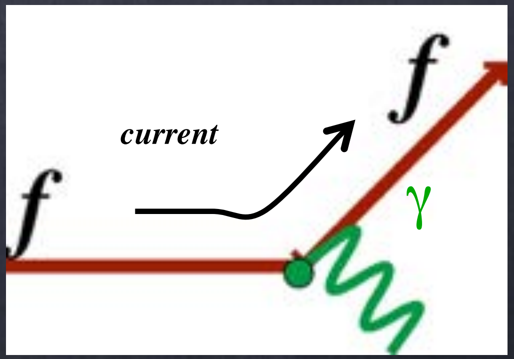
Dirac: relativistic motion of electrons with spin 1/2

$$(i\gamma_\mu \partial^\mu - m)\psi = 0 \qquad \mathcal{L} = \overline{\psi}(\mathrm{i}\gamma_\mu \partial^\mu - \mathrm{m})\psi$$

Local U(1) gauge invariance gives rise to interaction with photon field: $-J_\mu A^\mu$

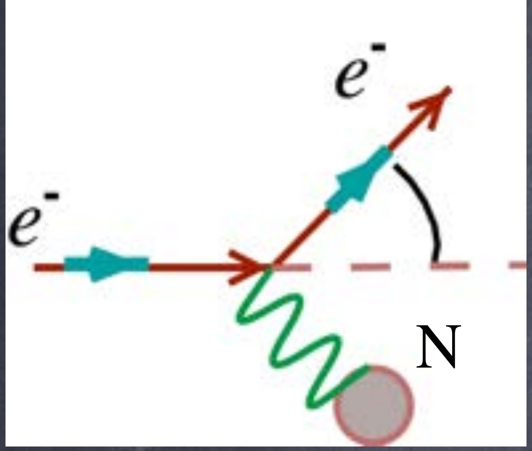
Conserved electromagnetic current $J_\mu = q\overline{\psi}\gamma_\mu\psi$ ***4-vector***

Feynman Rules: emission and absorption of virtual photons by fermion electromagnetic current

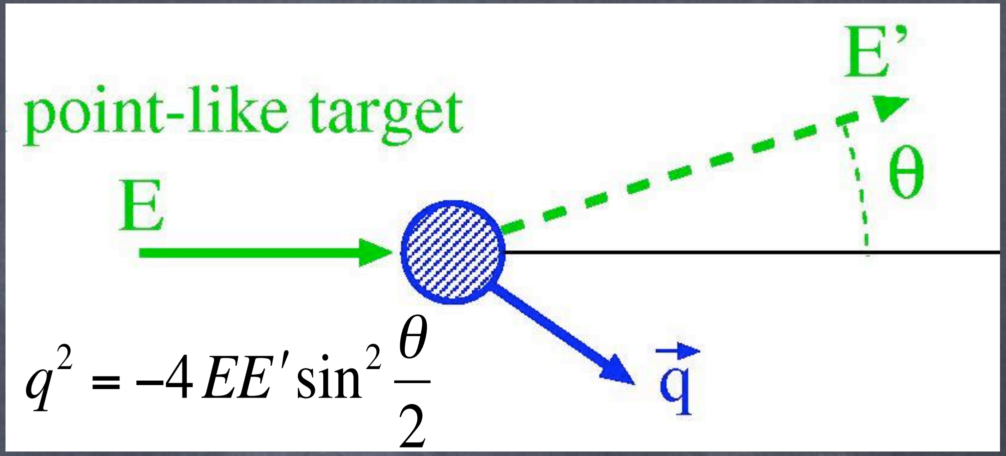


Electron Scattering

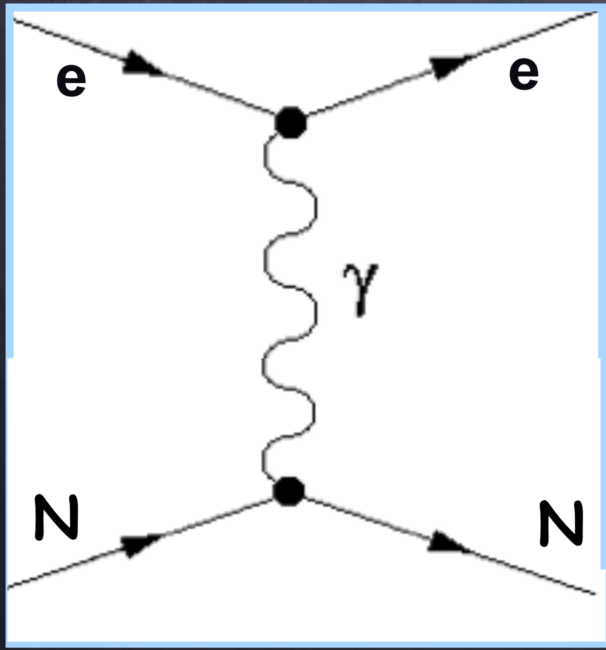
Electromagnetic interaction described as an exchange of a virtual photon.



spin 1/2 electrons scattering off infinitely heavy point nucleus



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



Feynman Rules →

Differential Cross Section

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

The Size of the Nucleus

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

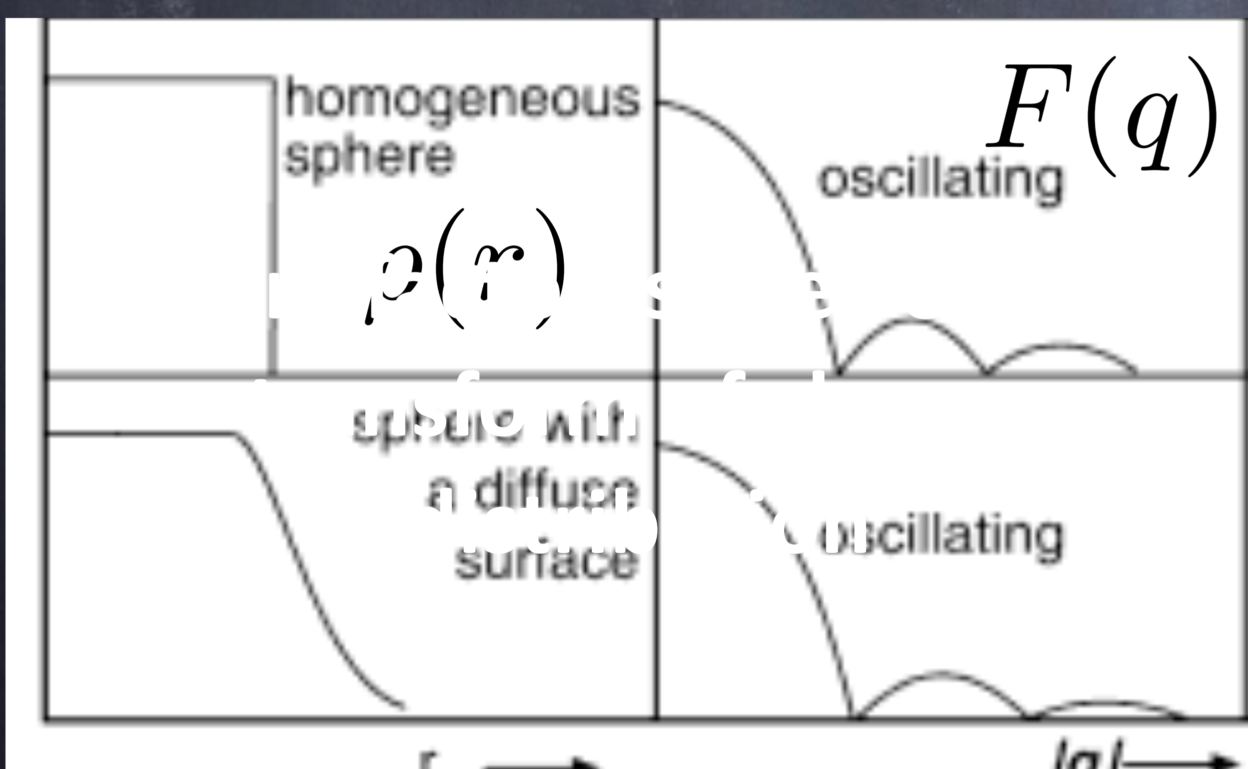
If photon carries low momentum -> long wavelength -> low resolution

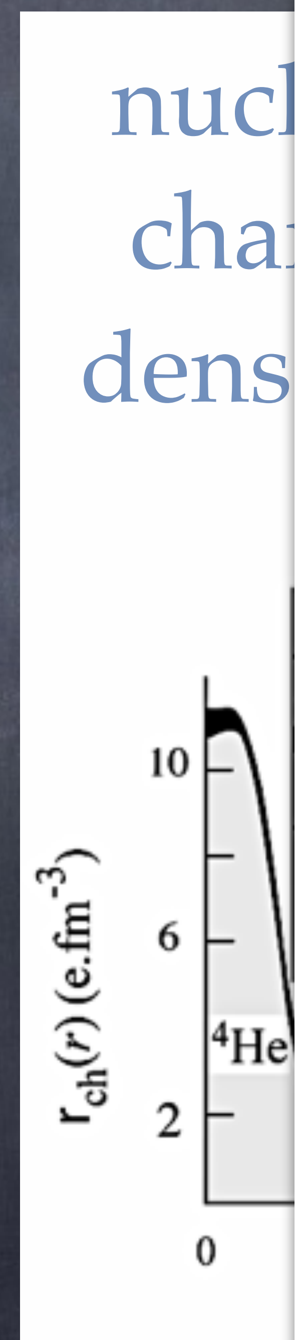
Increasing momentum transfer -> shorter wavelength -> higher resolution to observe smaller structures

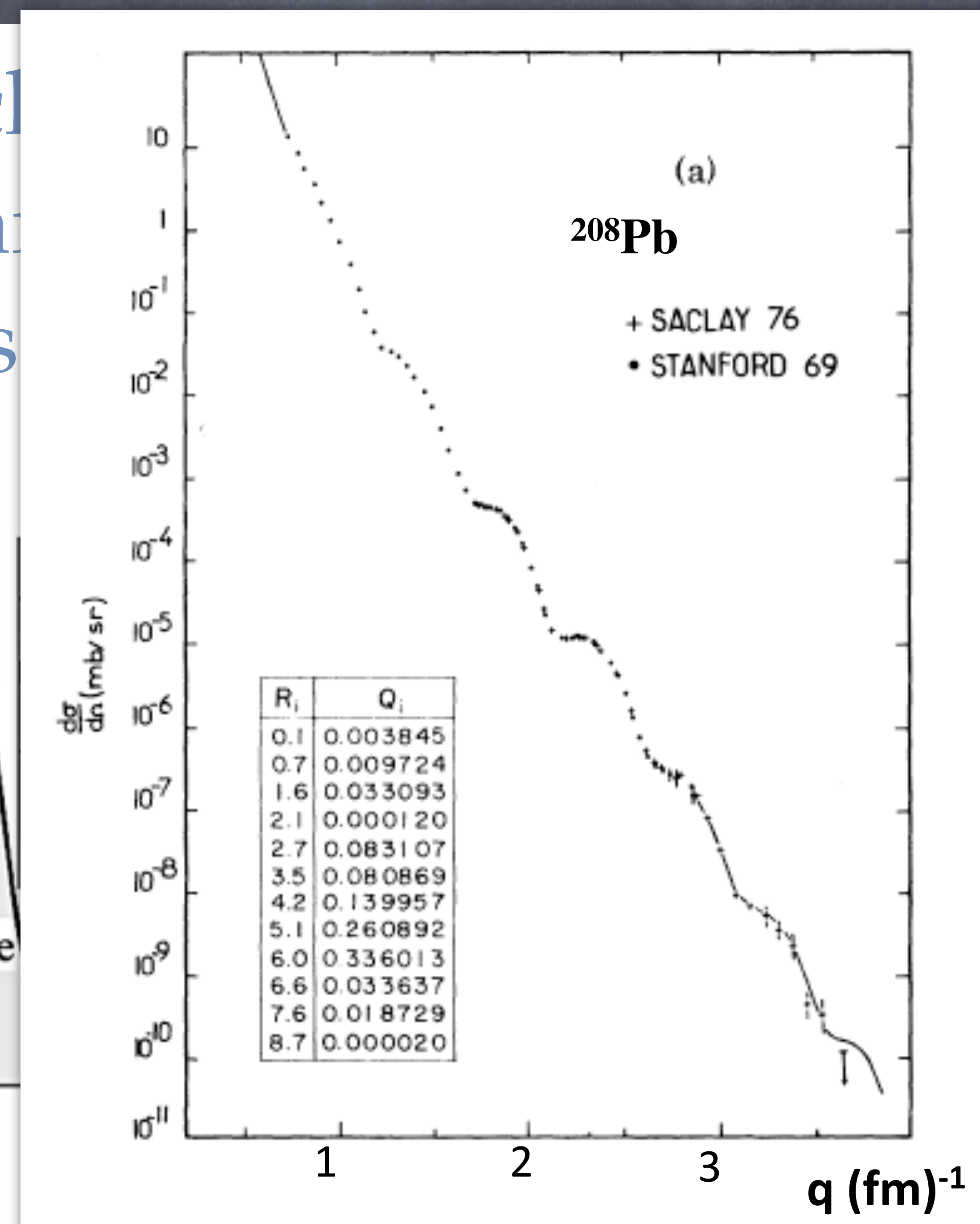
$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{\text{Mott}} |F(q)|^2$$

The point-like scattering probability modified: Introduce a "form factor"

$$F(q) = \int e^{iqr} \rho(r) d^3r$$





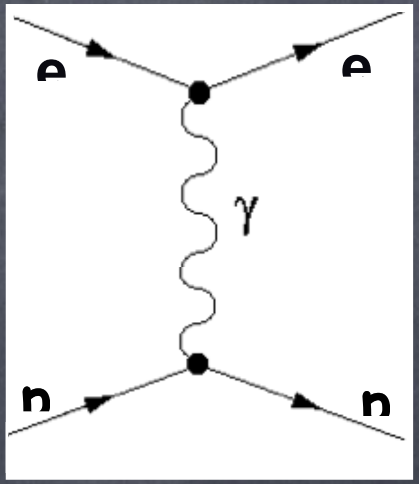


Elastic Electron-Proton Scattering

For a point-like target, accounting for target recoil:

Function of (E,θ). Cross-section for infinitely heavy, fundamental target

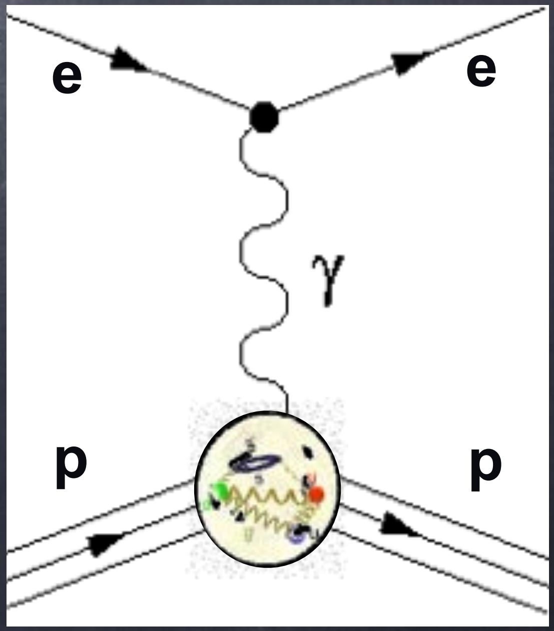
$$\frac{d\sigma}{d\Omega} = \frac{d\sigma}{d\Omega}_{\text{Mott}} \left\{1 + 2\,\tau \tan^2(\theta/2)\right\}$$



$\tau = Q^2/4M^2$ is a convenient kinematic factor

If proton is not point-like: The electric and magnetic form factors G_E and G_M parameterize the effect of proton structure.

$$\frac{d\sigma}{d\Omega} = \frac{d\sigma}{d\Omega}_{\text{Mott}} \frac{E'}{E} \left\{\frac{(G_E^2 + \tau\, G_M^2)}{1+\tau} + 2\,\tau\, G_M^2 \tan^2(\theta/2)\right\}$$



If the proton were like the electron:

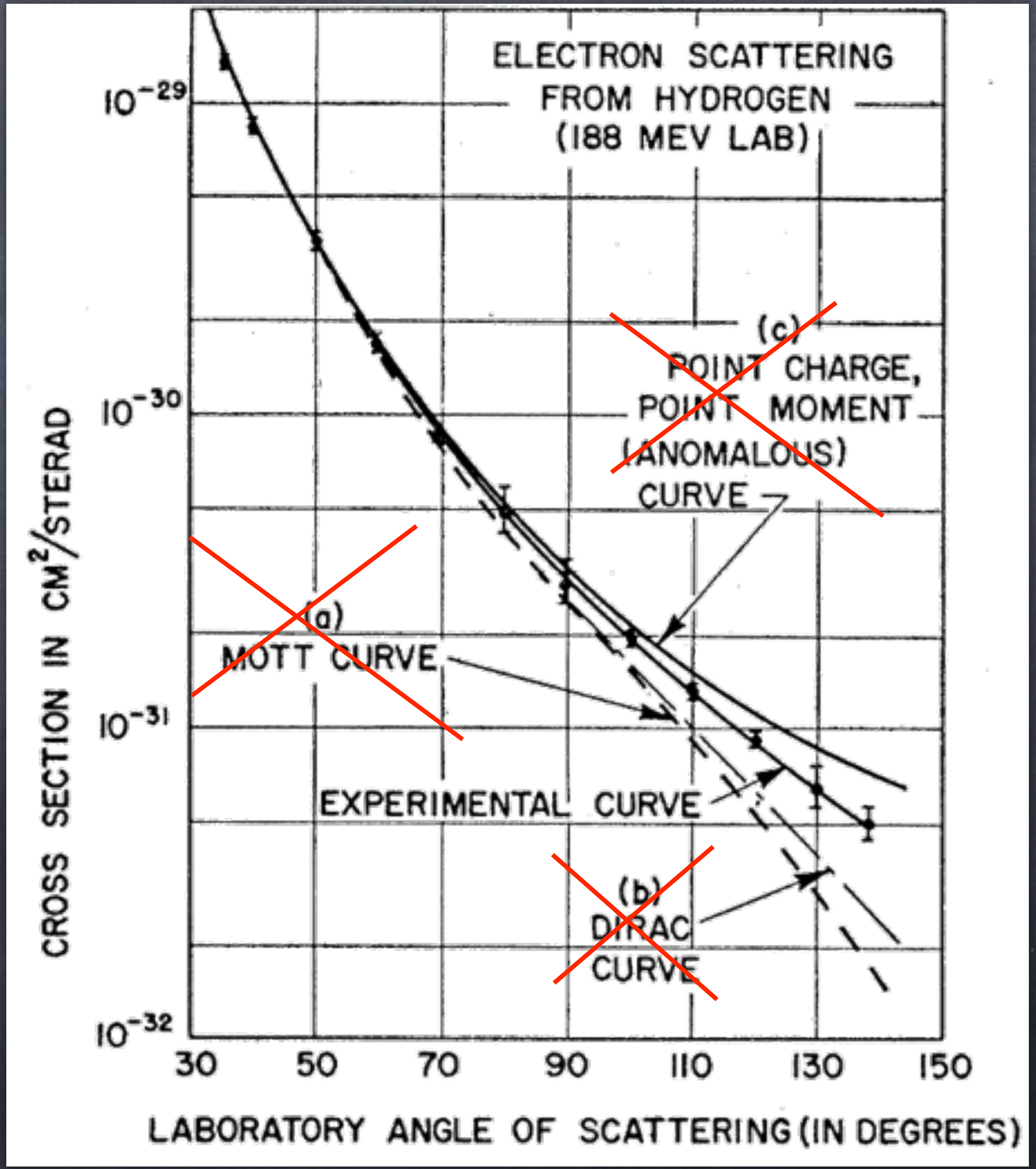
G_E = 1 (proton charge)

G_M = 1 (and the magnetic moment would be 1 Bohr magneton).

Proton Structure

Otto Stern (1932) measured the proton magnetic moment $\mu_p \sim 2.5\ \mu_{Bohr}$ (first indication that the proton was not a point-like particle, Nobel prize 1943)

Cross-section measurements at various scattering angles



Stanford U. Mark III Accelerator McAllister and Hofstadter, Physical Review 102 (1956) 851.

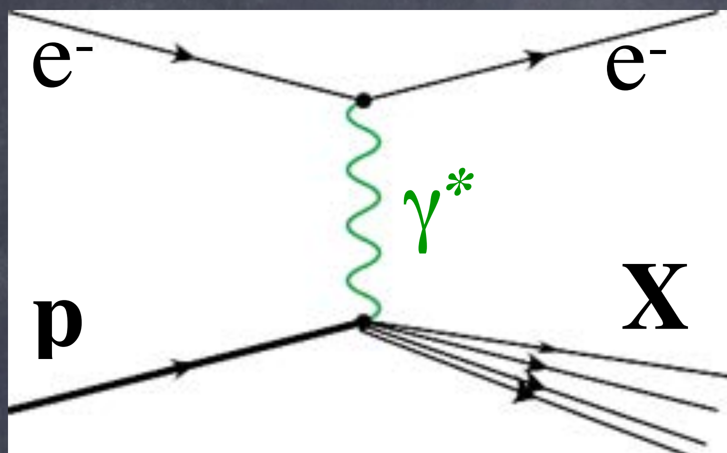
It isn't Mott, nor Dirac, nor Rosenbluth with G_E=1 and G_M=2.79…

the proton has finite size!

Robert Hofstadter – Noble Laureate 1961

Late 1960's

Deep Inelastic Scattering



In the mid-60s, electron accelerators achieved electric field gradients that made 10 Billion Volts of acceleration possible

- *proton absorbs energy and breaks up*
- *total observed energy no longer conserved*
- *need to measure both scattering angle and scattered momentum*

$$\left(\frac{d^2\sigma}{dE'd\Omega}\right) = \left(\frac{d\sigma}{d\Omega}\right)_{Mott} \left\{W_2(Q^2,x) + 2W_1(Q^2,x)\tan^2\left(\frac{\theta}{2}\right)\right\}$$

W_1 and W_2 are structure functions

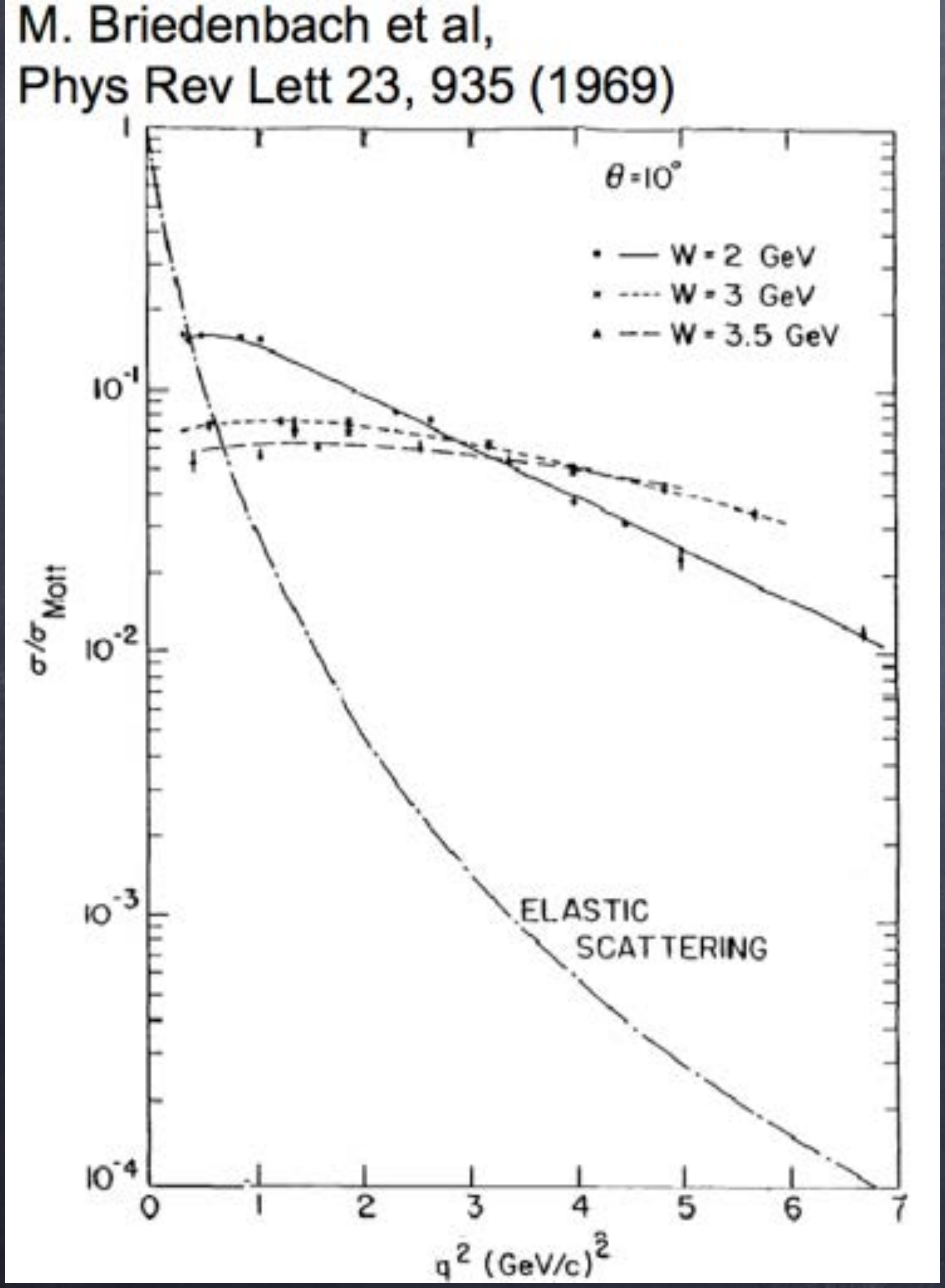
x is fraction of proton momentum carried by struck fragment


SLAC: Stanford Linear Accelerator Center

Friedman, Kendall & Taylor: Nobel Prize 1990, Measurement at SLAC


Electron Spectrometer

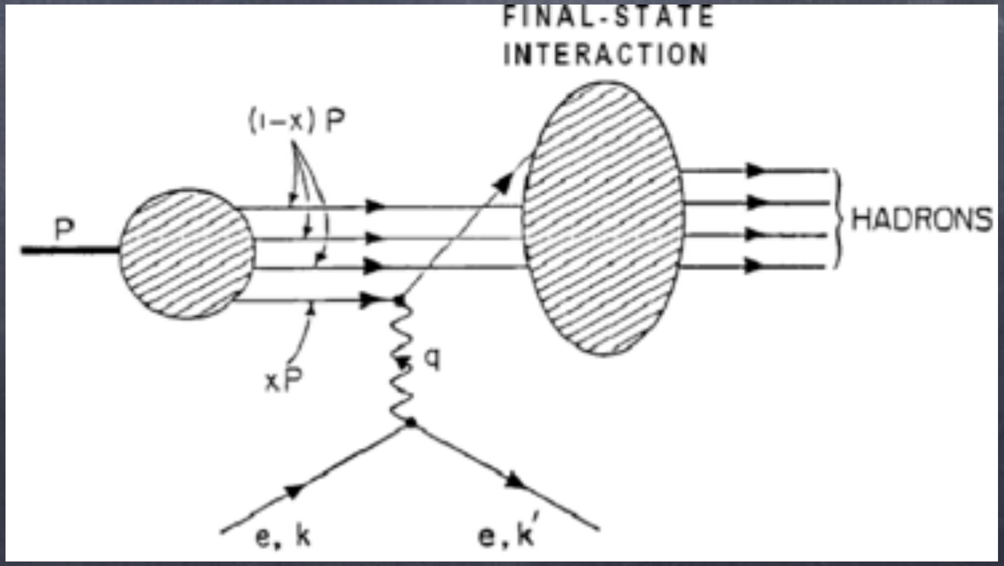
Scaling and Partons



W = Mass of recoiling fragments

As W increased, the structure function became surprisingly independent of Q^2

electrons are hitting structureless objects that have negligible size!

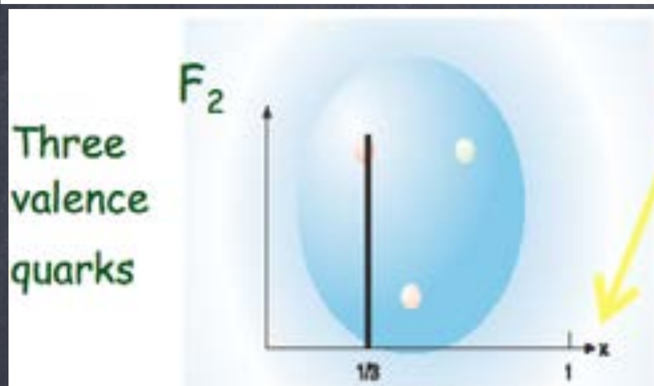


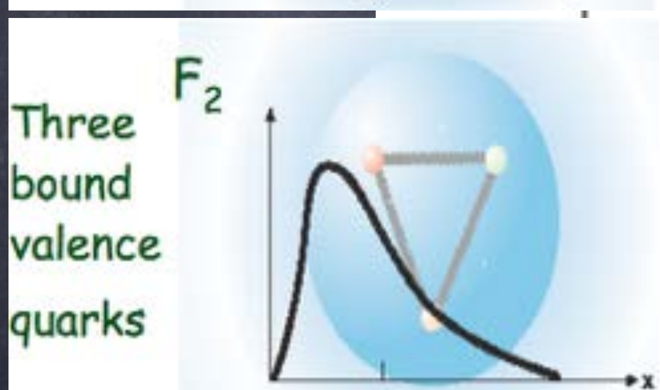
discovery of proton constituents called partons: associate with quarks

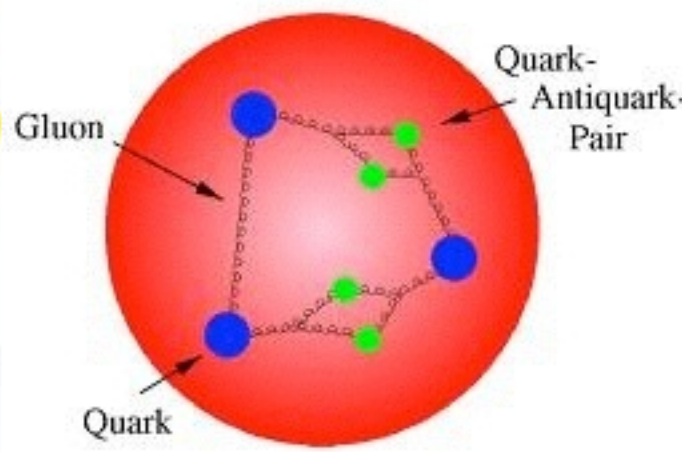
Quantum Chromodynamics and Scaling Violations

Instead of W_1 and W_2, use: F_1 and F_2:

$$F_1 = m_p W_1 \qquad F_2 = \nu W_2$$

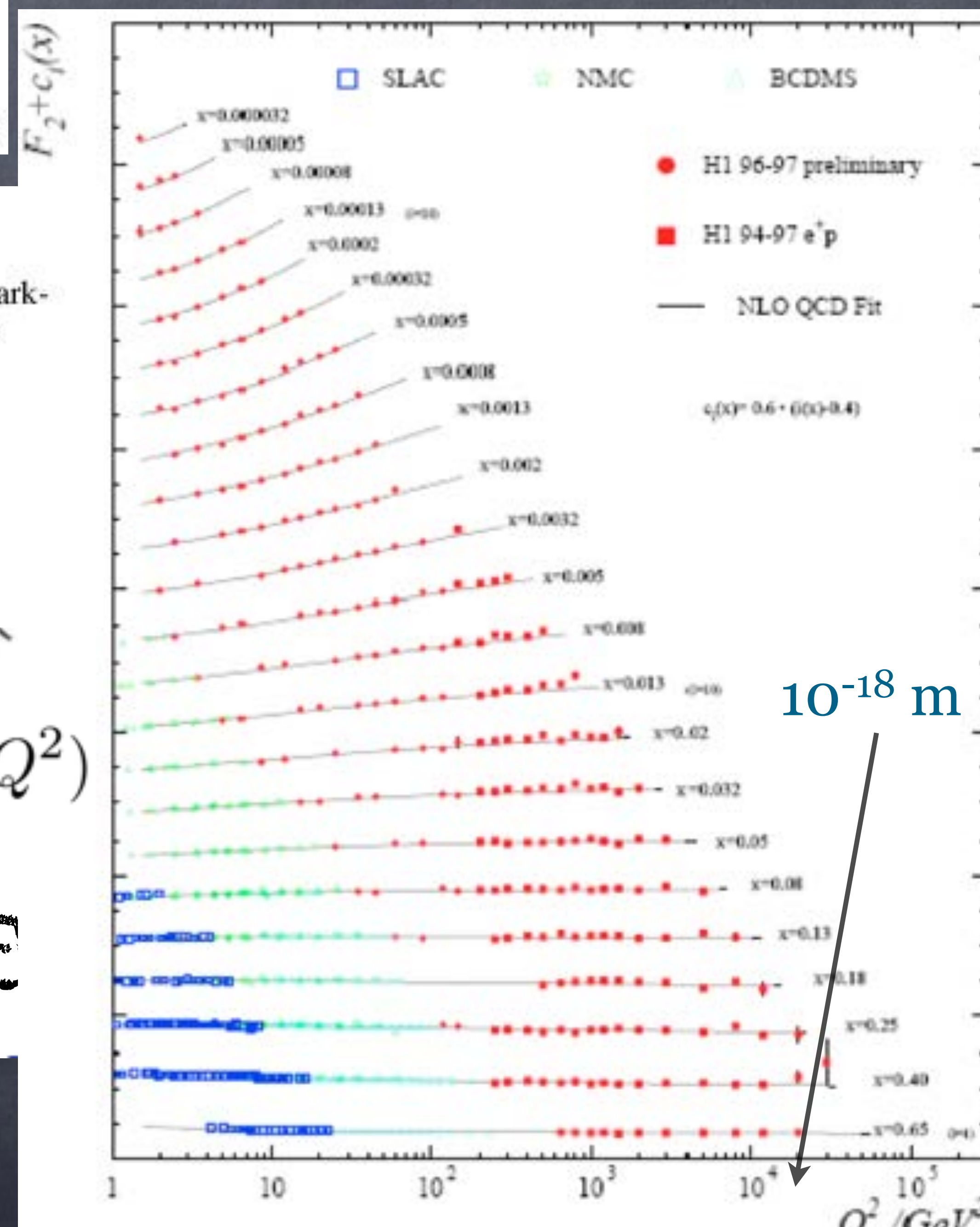






$$\frac{\partial F_2(x,Q^2)}{\partial \ln Q^2} \propto G(x,Q^2)$$

ρ(r)	|F(q²)|	Example
pointlike	constant	Electron
exponential	dipole	Proton
gauss	gauss	^{6}Li
homogeneous sphere	oscillating	—
sphere with a diffuse surface	oscillating	^{40}Ca

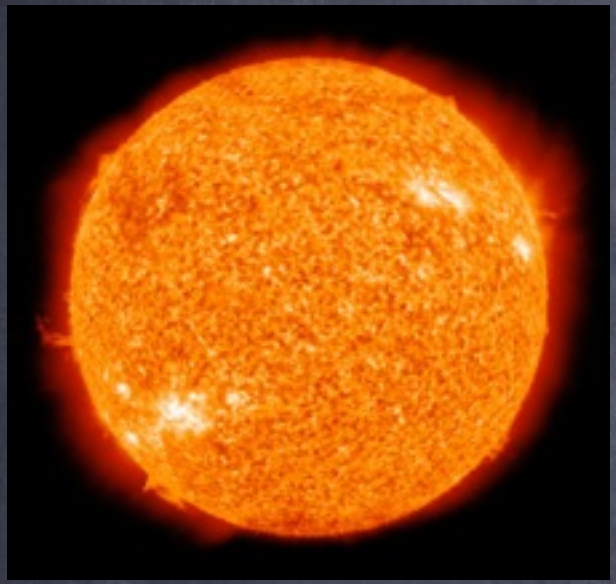


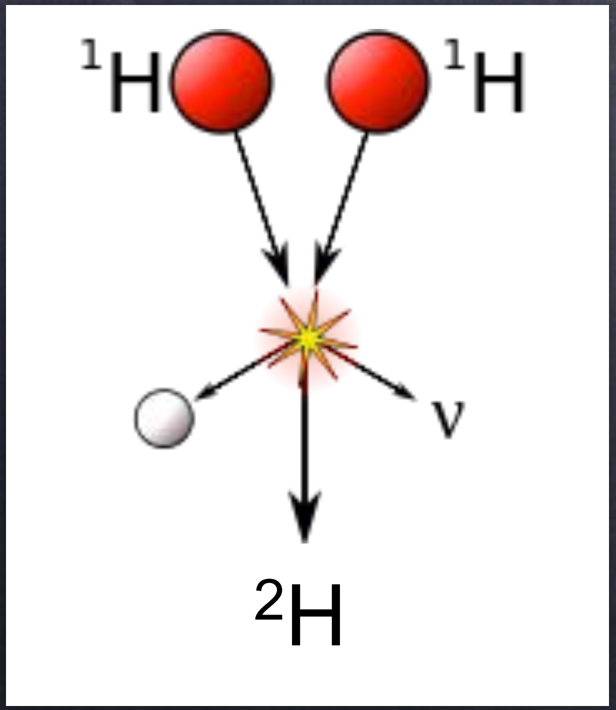
Electroweak Interactions and Parity Violation

Weak Interactions

Solar p-p chain

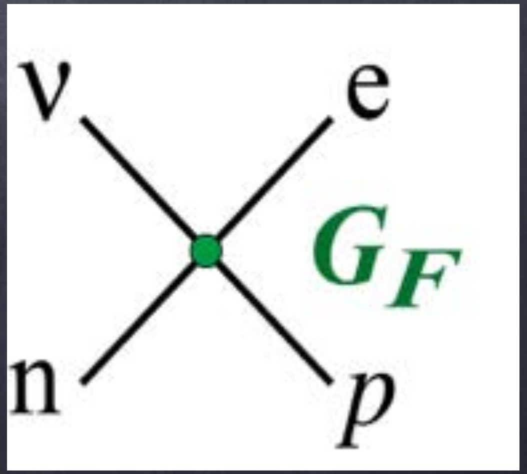
Radioactivity





Fermi Theory for weak interactions

Universal strength:
coupling constant G_F



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

Theory known to breakdown at energy > 100 GeV

Parity Symmetry

Parity P $x, y, z \to -x, -y, -z$ $P\psi(\vec{r}) = \psi(-\vec{r})$

$P^2 = I$ Group has 2 elements, P and I

$[H, P] = 0$ ⇨ $H\psi = E\psi$ & $P\psi = \pi\psi$ ⇨ $\pi = \pm 1$

If hamiltonian is invariant under parity transformations, then π is conserved and observable

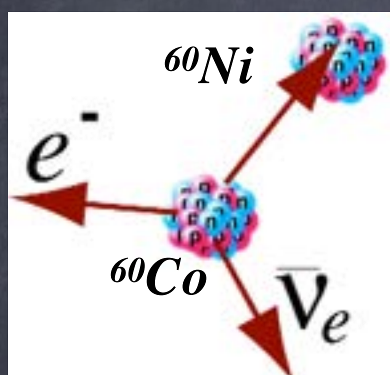
Particle Classification S^π e.g. pions: 0^- pseudoscalar mesons

Tau-theta puzzle (1956) $\theta^+ \to \pi^+\pi^0$ (P=+1) $\tau^+ \to \pi^+\pi^0\pi^0$ (P=-1)

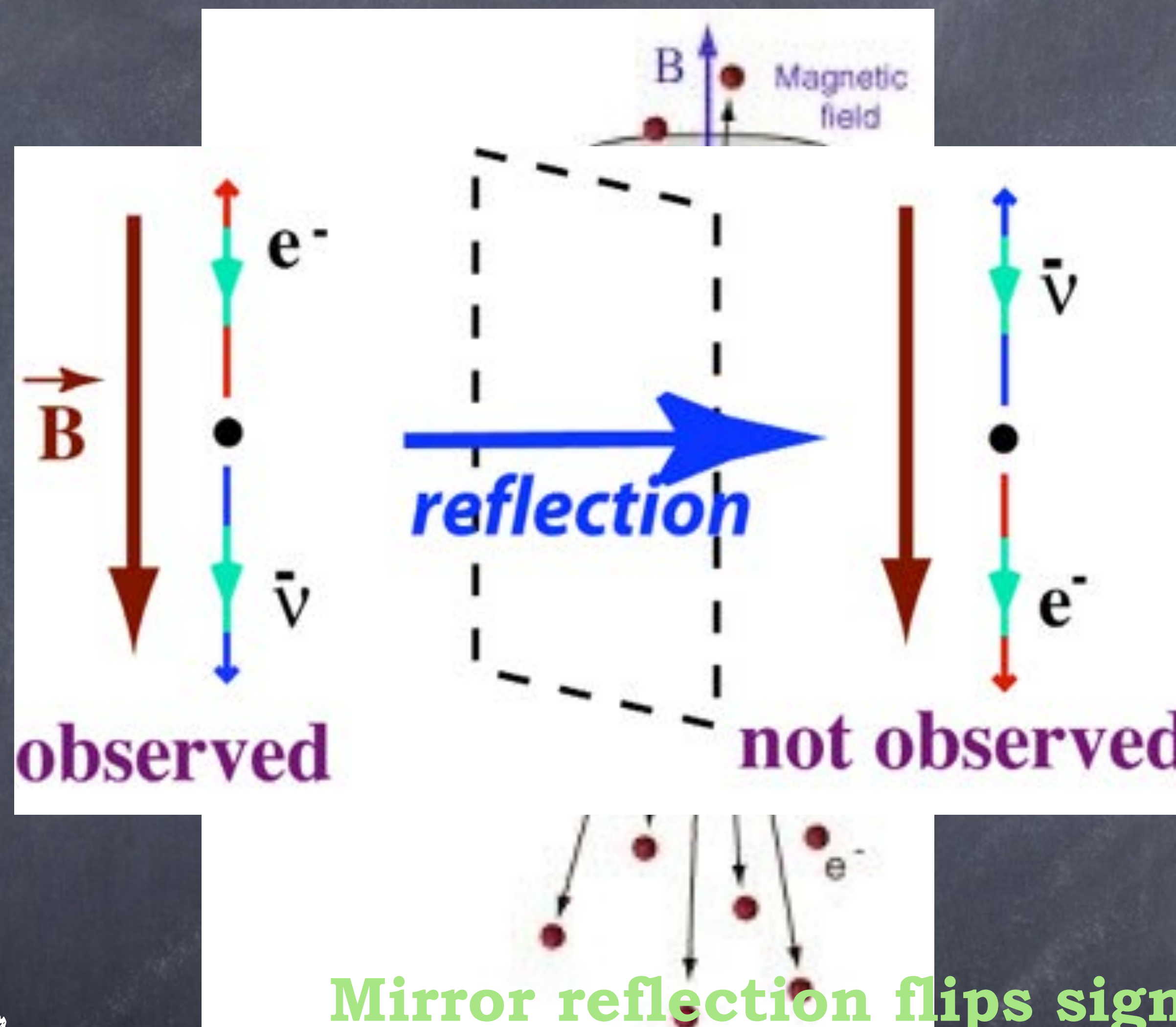
same mass but different parities! Lee and Yang propose:

The SAME particle is produced in strong interactions, but decays via weak interactions;
P conserved in strong interactions, but not in weak interactions

Discovery of Parity Non-Conservation in Weak Interactions



Weak decay of ^{60}Co Nucleus



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

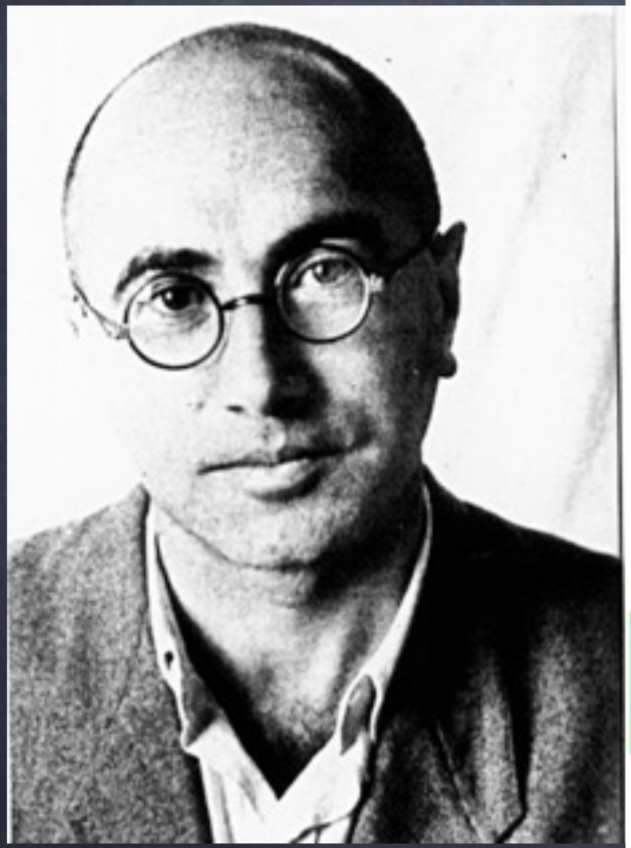
Maximal Parity Violation: V-A Theory

Left-handed ⟷ *right-handed*

ONLY left-handed particles participate in weak interactions

(right-handed anti-particles)

A Classic Paper



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 there a neutral analog of the "charged" weak force?

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

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

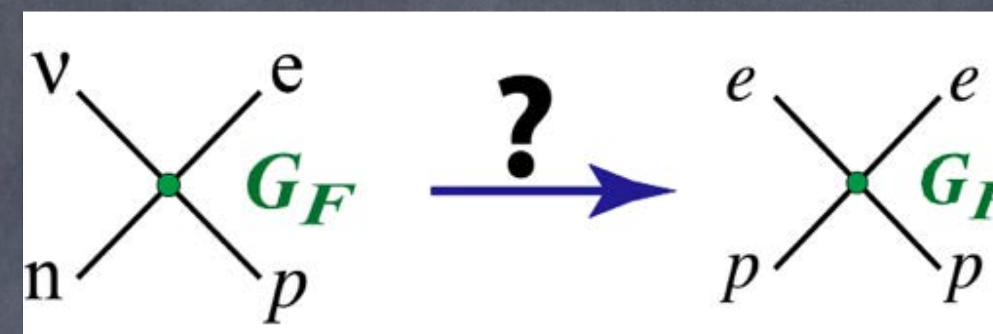
with $g \approx 10^{-49}$ and the operator $O = \gamma_\mu(1 + i\gamma_5)$ characteristic[1] of processes in which parity is not conserved.*

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

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

Neutron β Decay

Electron-proton Weak Scattering

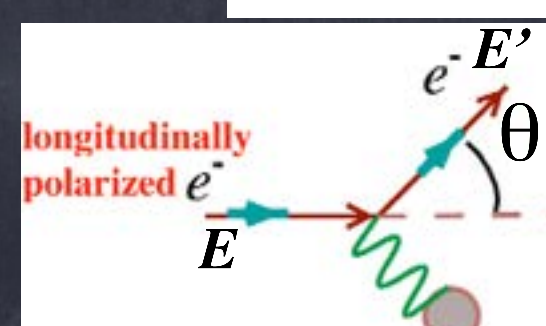


$$\sigma \;\alpha\; |A_{EM} + A_{weak}|^2$$

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

Parity-violating

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

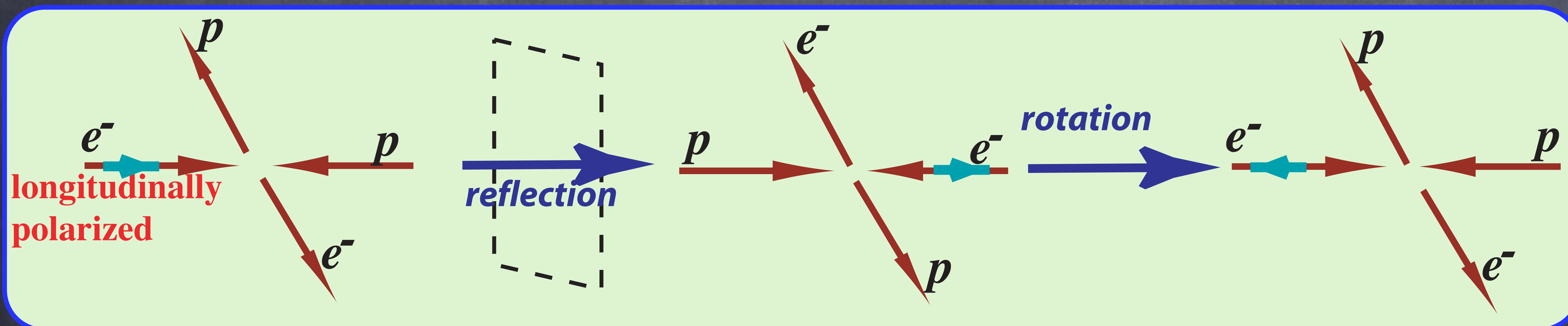


4-momentum transfer

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

Parity-Violating Observable

How to measure parity violation in electron scattering



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

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

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

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

Electroweak Unification

Accept the existence of u & d quarks, electrons, and electron-neutrinos

$SU(2)_L \times U(1)_Y$

2 couplings

4 conserved currents

local gauge invariance yields 4 bosons: W^+, W^-, W^0, B^0

After spontaneous symmetry breaking via Higgs Mechanism:

$$SU(2)_L \times U(1)_Y \rightarrow U(1)_{EM}$$

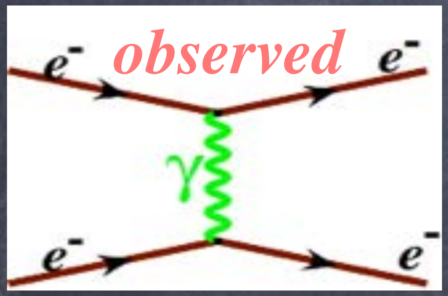
two weak charged currents	electromagnetic current	weak neutral current
$W^\pm$	γ	Z^0

Mass to weak vector bosons and fermions, one Higgs boson, one free parameter: weak mixing angle θ_W

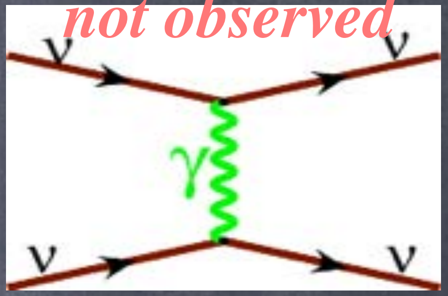
Charge and Handedness

Electric charge determines strength of electric force

Electrons and protons have same charge magnitude: same strength

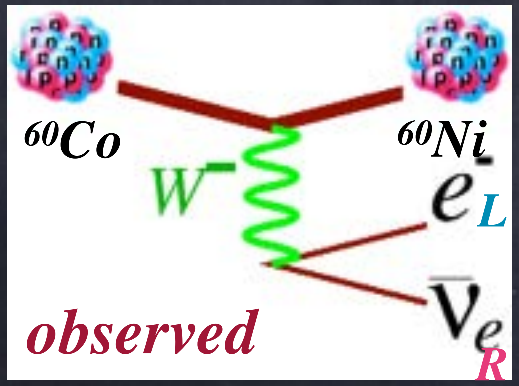


Neutrinos are "charge neutral":
do not feel the electric force



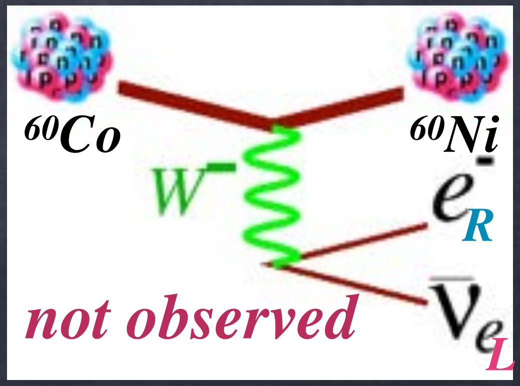
Weak charge determines strength of weak interactions

Left-handed particles (Right-handed antiparticles) have weak charge



right-handed anti-neutrino

Right-handed particles (left-handed antiparticles) are "weak charge neutral"



left-handed anti-neutrino

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

1960's

Electroweak Theory

The correct description of the neutral weak force?

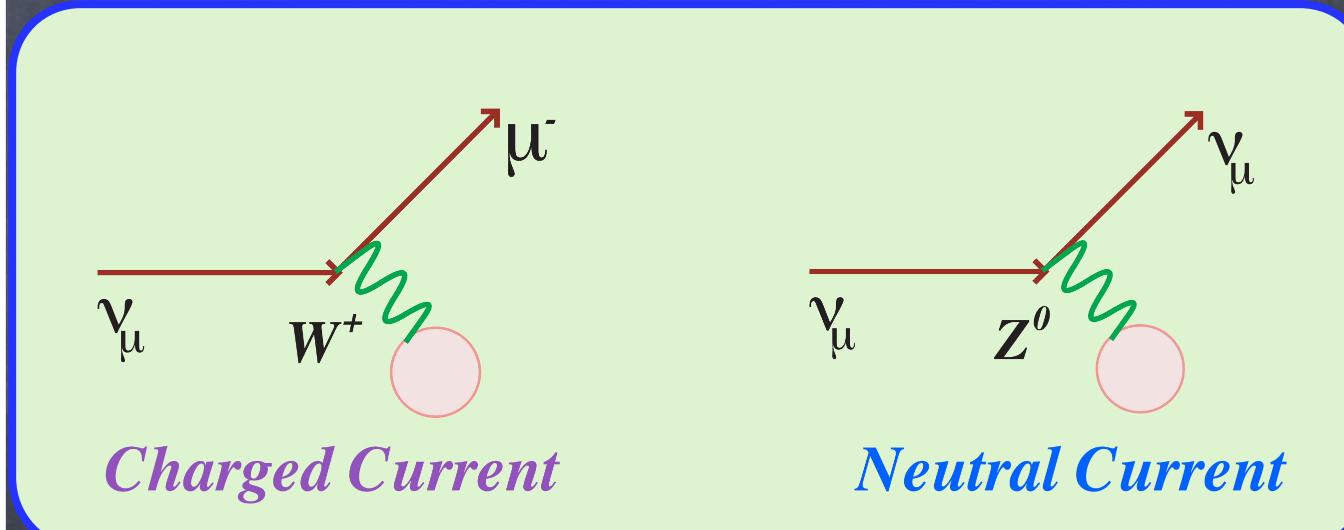
$$\tan\theta_W = \frac{g'}{g} \qquad e = g\sin\theta_W$$

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

The Z boson incorporated

One free parameter: weak mixing angle θ_W

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



Higgs Mechanism + Renormalizability

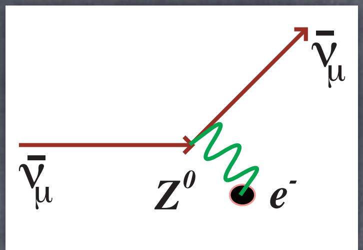
$$\sin^2\theta^0_W = \left(\frac{e^0}{g^0}\right)^2 = 1 - \left(\frac{M^0_W}{M^0_Z}\right)^2$$

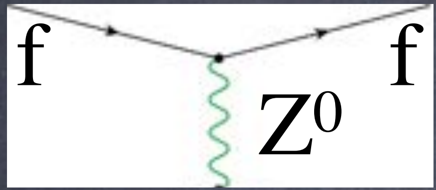
The First Weak Neutral Current Experiments

Remaining Piece

1970's

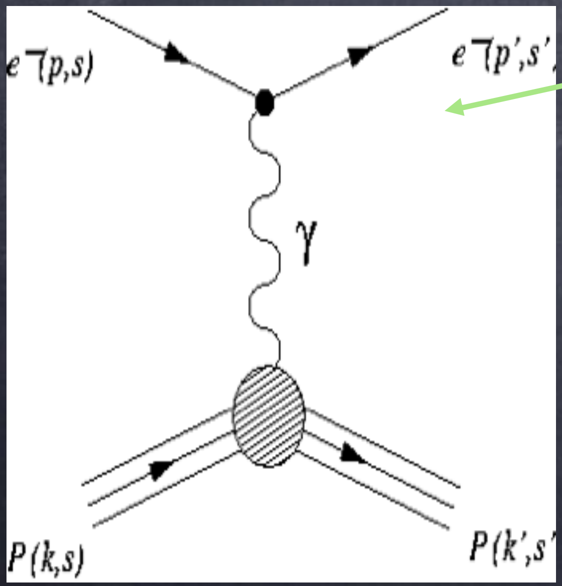
First weak neutral current event: Gargamelle bubble chamber





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

Do lepton-quark neutral current interactions exhibit parity violation?



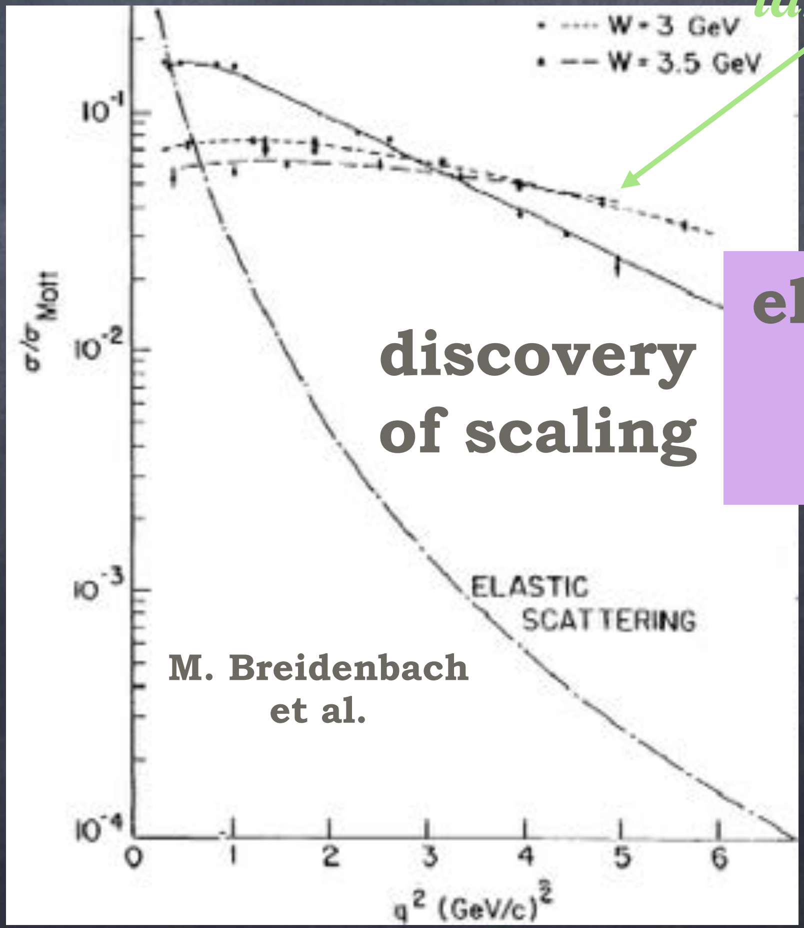
Weinberg model

Parity is violated

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

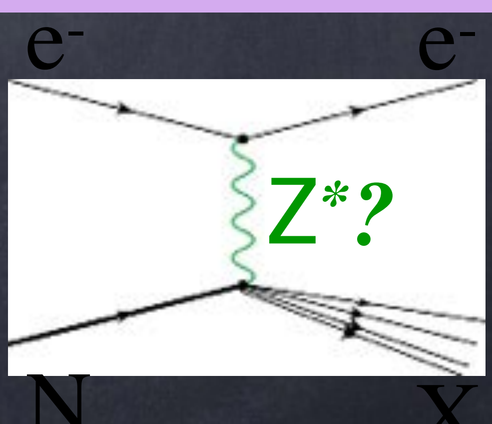
Parity is conserved

First table-top atomic parity violation searches: negative!



large rate at large Q^2

electron-nucleon deep inelastic scattering



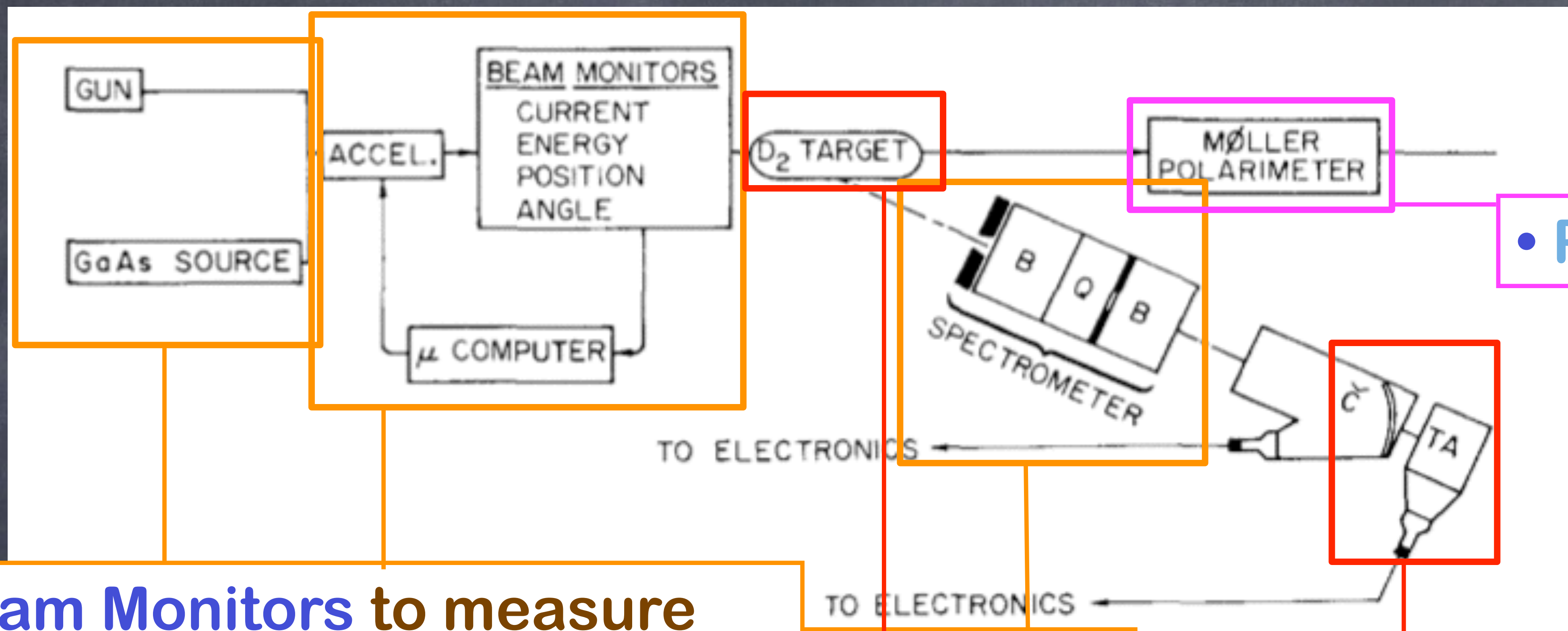
pressing problem in mid-70's

Parity-Violating Deep Inelastic Electron Scattering (PVDIS)

Seminal experiment launched the subfield of PV electron scattering

SLAC E122

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



- Polarimetry

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

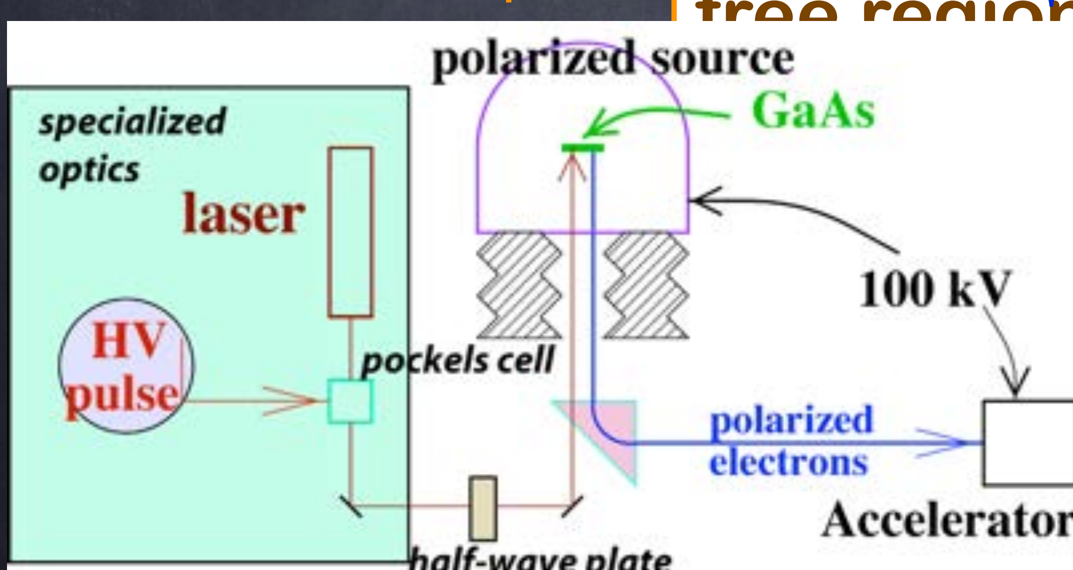
...rometer ...ckground- free region

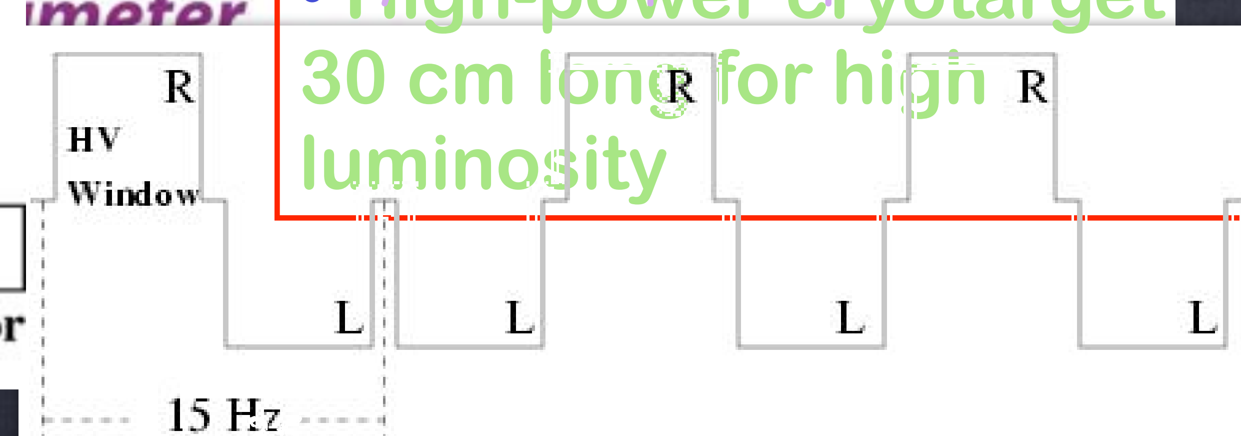
- Flux Integration measures high rate without deadtime

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

- High-power cryotarget 30 cm long for high luminosity

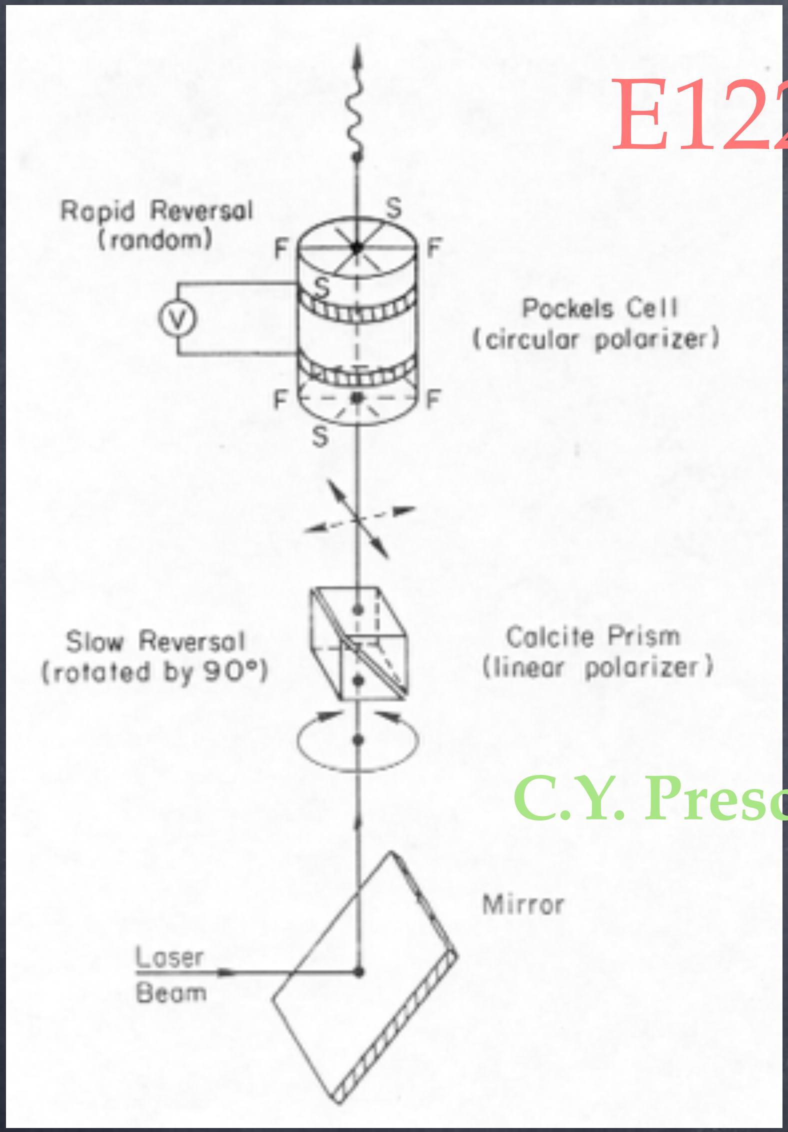
...imeter





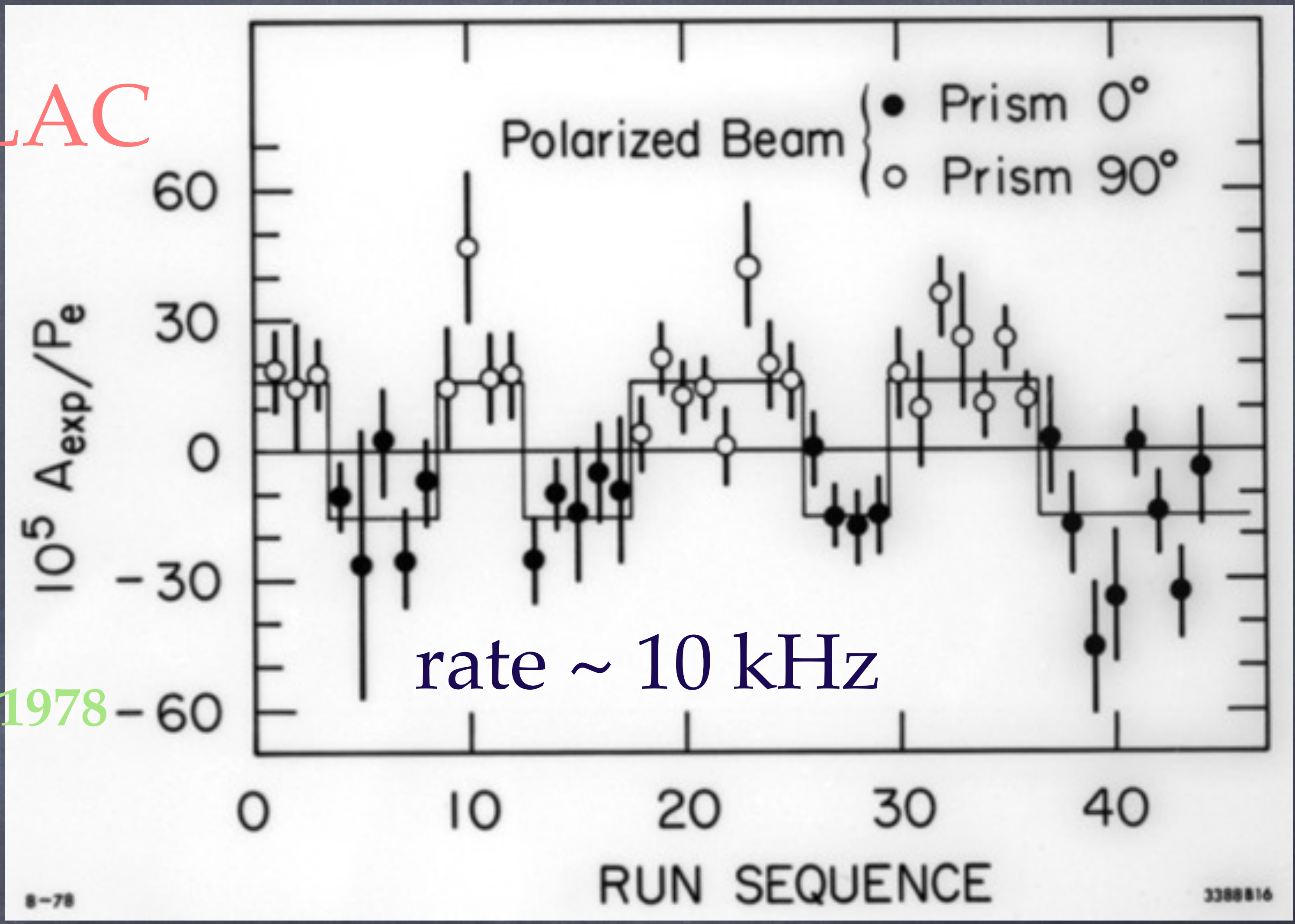
Does the weak neutral current amplitude interfere with the electromagnetic amplitude?

A Landmark Result

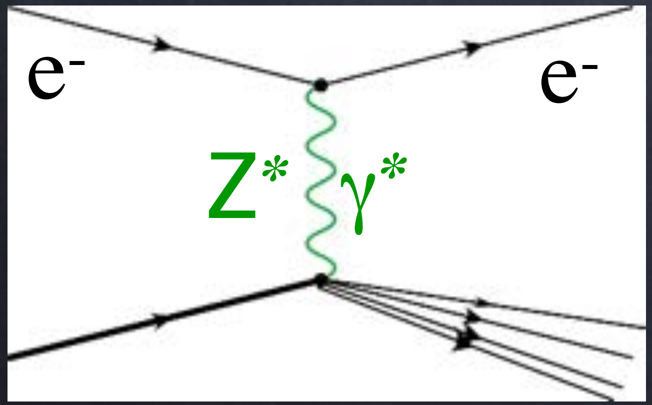


E122 at SLAC

C.Y. Prescott et al, 1978



rate ~ 10 kHz



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

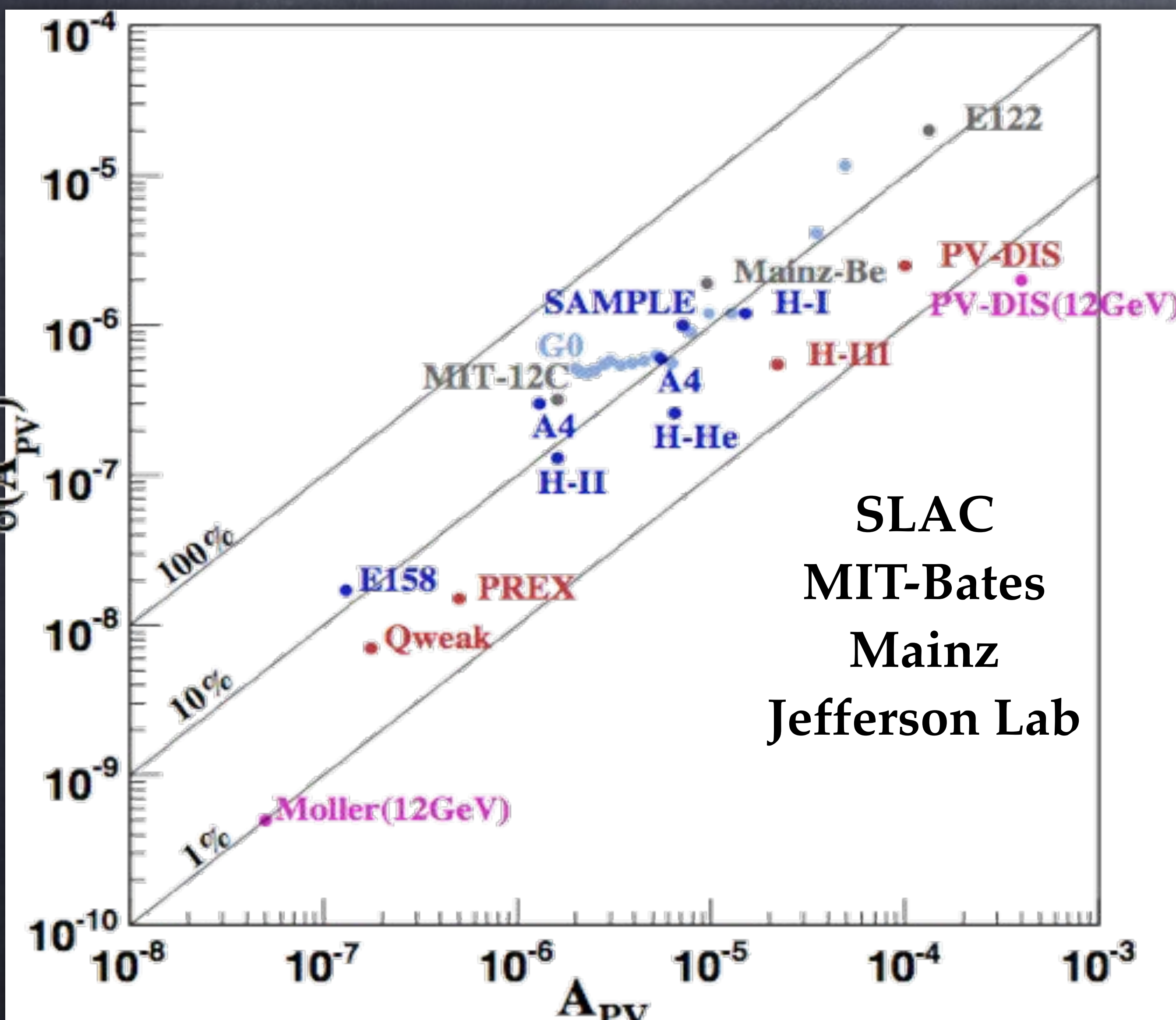
$$A_{PV} \sim 10^{-4}$$
$$\delta(A_{PV}) \sim 10^{-5}$$

Glashow, Weinberg, Salam Nobel Prize awarded in 1979

Continuous interplay between probing hadron structure and electroweak physics

4 Decades of Technical Progress

Parity-violating electron scattering has become a precision tool



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

State-of-the-art:

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

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

Deep Inelastic Scattering Formalism

$$\frac{d^2\sigma_{nc}^{\ell N}}{d\Omega dE'} = \frac{1}{2m_N(4\pi)^2}\frac{|E'|}{E} \times |M_\gamma + M_Z|^2$$

$$\frac{d^3\sigma_{nc}^{\ell N}}{dx\,dy\,d\phi} = \frac{y\alpha^2}{2Q^4} \sum_{i=\gamma,\gamma Z,Z} L^i_{\mu\nu} W_i^{\mu\nu} \eta^i$$

$$\eta^\gamma = 1$$

$$\eta^{\gamma Z} = \left(\frac{GM_Z^2}{2\sqrt{2}\pi\alpha}\right)\left(\frac{Q^2}{Q^2 + M_Z^2}\right)$$

$$\eta^Z = (\eta^{\gamma Z})^2$$

Vector and Axial-Vector Currents

Charged Weak Interactions

Maximal Parity Violation: V-A Theory

$J^\mu \sim \overline{\psi}\gamma^\mu\psi$

vector

$J^\mu \sim \overline{\psi}\gamma^\mu\gamma^5\psi$

axial-vector

$$P_L \equiv \frac{(1-\gamma^5)}{2}$$

left projection operator

$g_V = g_R + g_L$

$g_A = g_R - g_L$

$$g_R = \frac{g_V + g_A}{2} \qquad g_L = \frac{g_V - g_A}{2}$$

Ji, Nucl. Phys. B 402 (1993)
Anselmino, Gambino and Kalinoski, hep-ph/9401264v2
Anselmino, Efremov & Leader, Phys. Rep. **261** (1995)

The Electroweak Current of the Nucleon

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

$$i \equiv \gamma, \gamma Z, Z$$

GSW Model

$$g_V = T^3 - 2q\sin^2\theta_W$$

$$g_A = T^3$$

Not pure V-A

$$F_1^{\gamma Z} = \sum_q e_q (g_V)_q (q + \bar{q}) \qquad F_2^{\gamma Z} = 2xF_1^{\gamma Z}$$

$$F_3^{\gamma Z} = 2\sum_q e_q (g_A)_q (q - \bar{q})$$

$$g_1^{\gamma Z} = \sum_q e_q (g_V)_q (\Delta q + \Delta\bar{q})$$

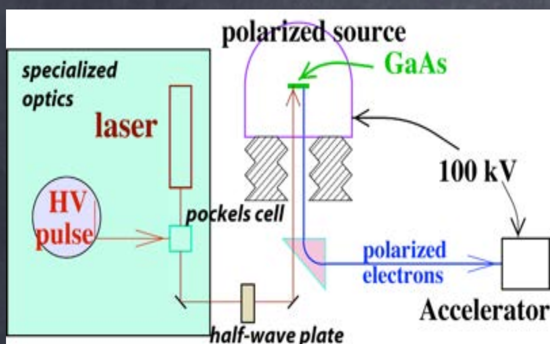
$$g_2^{\gamma Z} = g_4^{\gamma Z} = 0$$

$$g_3^{\gamma Z} = 2x\sum_q e_q (g_A)_q (\Delta q - \Delta\bar{q}) \qquad 2xg_5^{\gamma Z} = g_3^{\gamma Z}$$

Quark-Parton Model

PVDIS Asymmetries

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



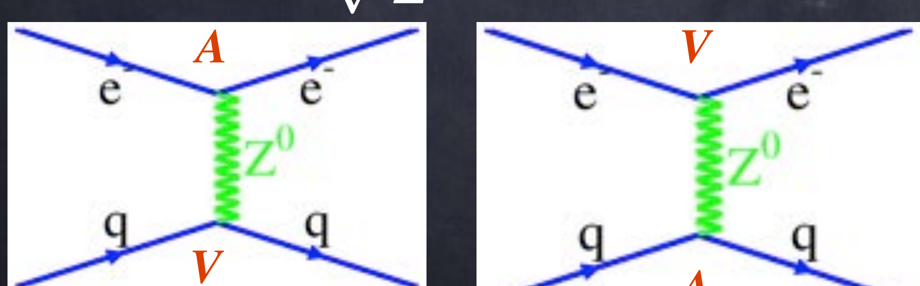
$$-A_{LR} = A_{PV} = \frac{\sigma_\uparrow - \sigma_\downarrow}{\sigma_\uparrow + \sigma_\downarrow} \sim \frac{A_{weak}}{A_\gamma} \sim \frac{G_F Q^2}{4\pi\alpha} (g_A^e g_V^T + \beta\, g_V^e g_A^T)$$

A_{PV} in Electron-Nucleon DIS:

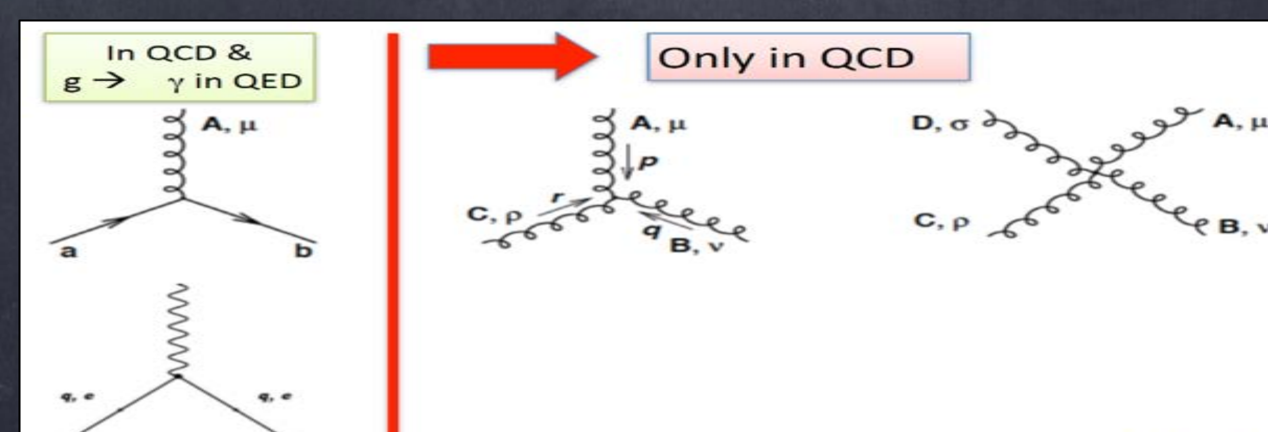
polarized ***electron***, *unpolarized* ***hadron***

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

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



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



Simplifying Assumptions with Deuterium DIS

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

$$A_{PV} = \frac{G_F Q^2}{\sqrt{2}\pi\alpha}\left[a(x) + f(y)b(x)\right] \qquad a(x) = \frac{\sum_i C_{1i} Q_i f_i(x)}{\sum_i Q_i^2 f_i(x)} \qquad b(x) = \frac{\sum_i C_{2i} Q_i f_i(x)}{\sum_i Q_i^2 f_i(x)}$$

For ²H, assuming charge symmetry, structure functions largely cancel in the ratio:

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

Bjorken; Wolfenstein; Cahn & Gilman

E122 measured a; insensitive to b

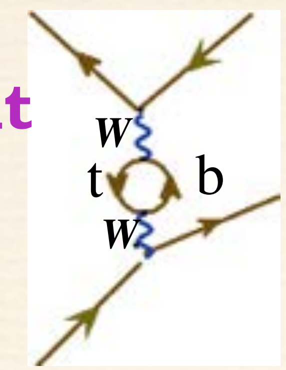
Modern Electroweak Physics

EW Theory at 1-loop

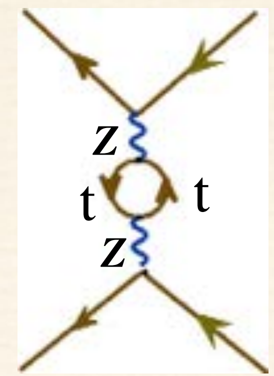
For electroweak interactions, 3 input parameters needed:

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

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

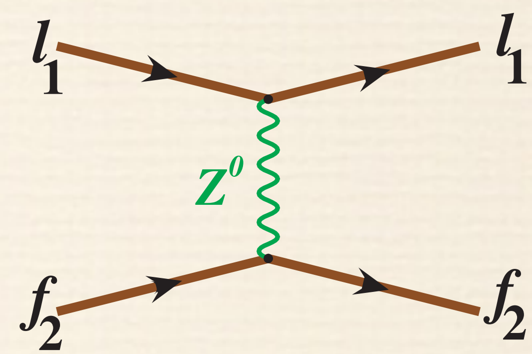


Muon decay



Z production

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



Weak Neutral Current interactions

$\sin^2\theta_W \equiv 1 - m_W^2/m_Z^2$ **simple definition; disfavored due to heavy m_t**

$\sin^2\theta_W^{eff} \equiv (1 - g_{\mu\mu Z})/4$ **good at Z-pole; nasty counterterms at other scales**

$\sin^2\theta_W(M_Z)_{\overline{\text{MS}}} = \sin^2\theta_W^{eff} - 0.00028$

$\sin^2\theta_W(\mu)_{\overline{\text{MS}}} \equiv e^2(\mu)_{\overline{\text{MS}}}/g^2(\mu)_{\overline{\text{MS}}}$ **theoretically motivated; but not physical**

LEP-I, SLC, LEP-II, Tevatron

World Averages

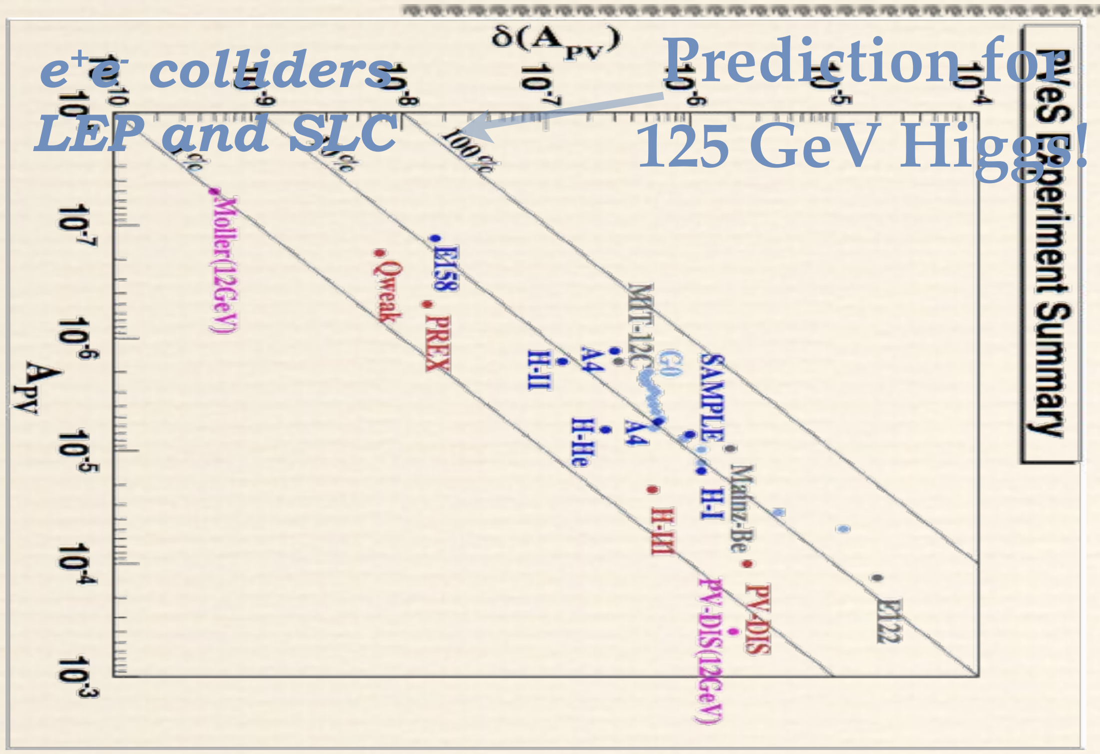
$\sin^2\theta_W(m_Z)_{\overline{\text{MS}}} = 0.23125(16)$

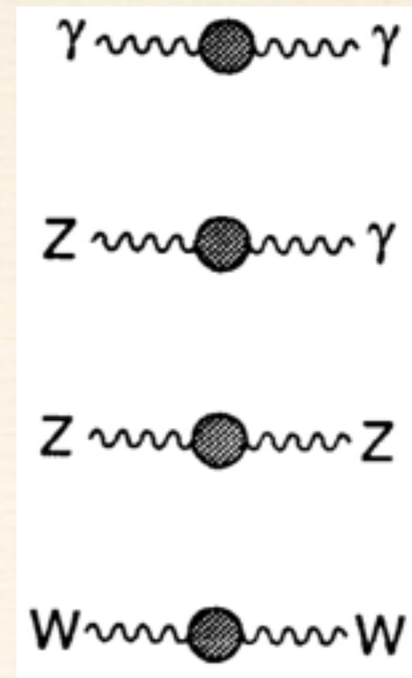
$M_W = 80.385(15)\ \text{GeV}$

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





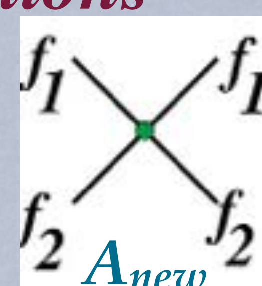
S, T, U parameters

Stringent constraints on large classes of new physics models

Flavor Diagonal Contact Interactions

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

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



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

on resonance: A_Z is imaginary

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

no interference!

New flavor diagonal interactions mediated by a new light boson such as the "dark Z" $Q^2 \ll M_Z^2$

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

A comprehensive search for clues requires, in addition:

The Intensity/Precision Frontier

- ✦ **Violation of Accidental (?) Symmetries**
- ✦ **Direct Detection of Dark Matter**
- ✦ **Measurements of Neutrino Masses and Mixing**
- ✦ **Precise Measurements of SM observables**

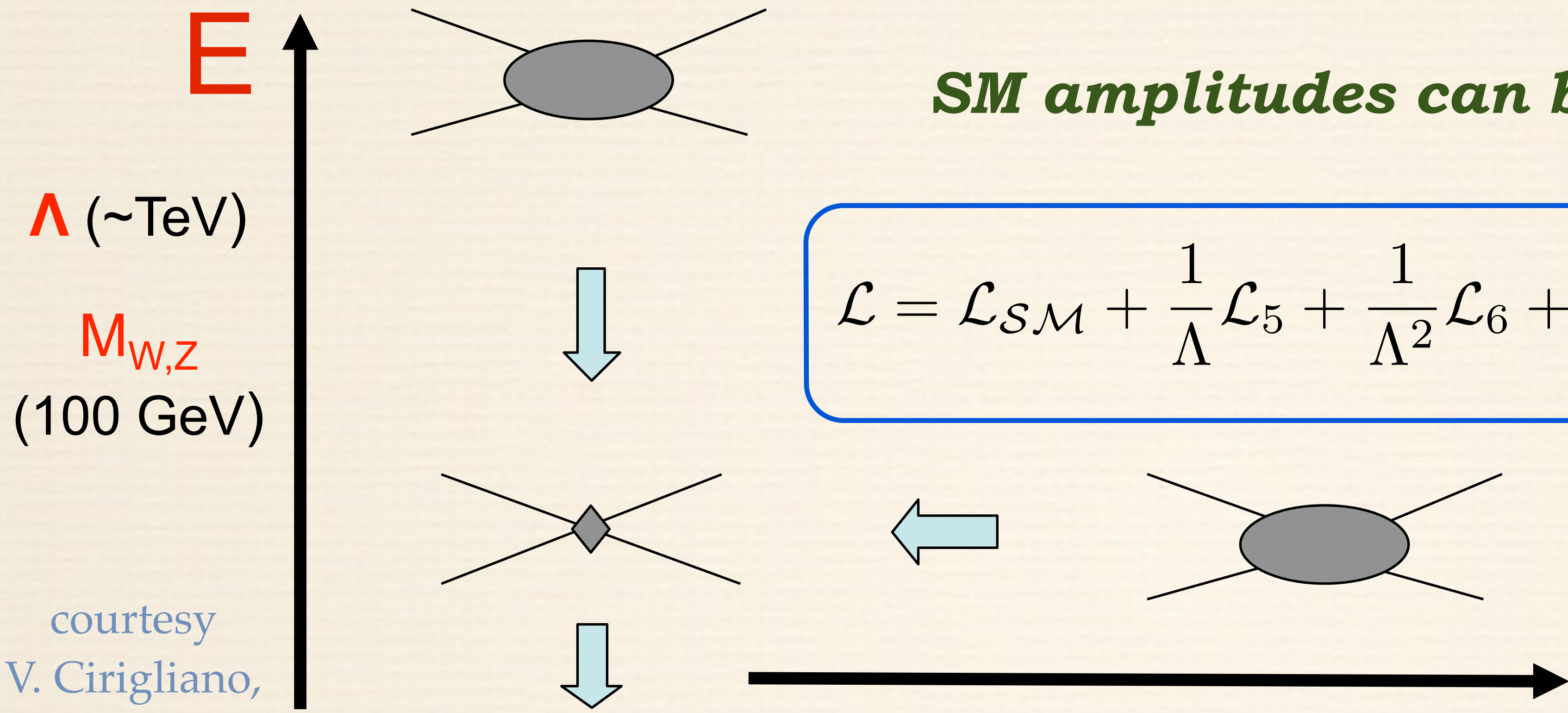
Intense beams, ultra-high precision, exotic nuclei, table-top experiments, rare processes....

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

High Energy Dynamics

Indirect Clues

The Intensity/Precision Frontier



SM amplitudes can be very precisely predicted

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

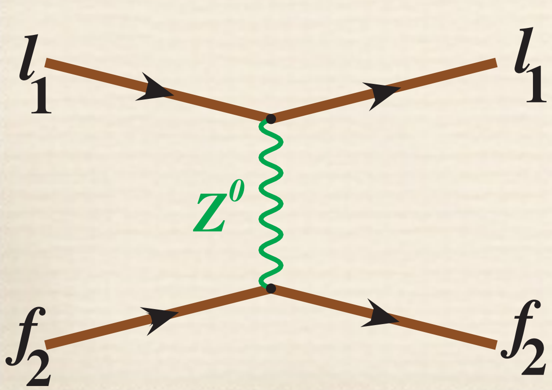
higher dimensional operators can be systematically classified

Dark Sector

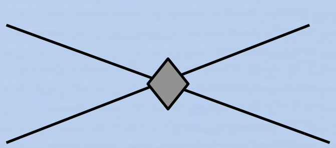
courtesy V. Cirigliano, H. Maruyama, M. Pospelov

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

Search for new neutral superweak forces



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

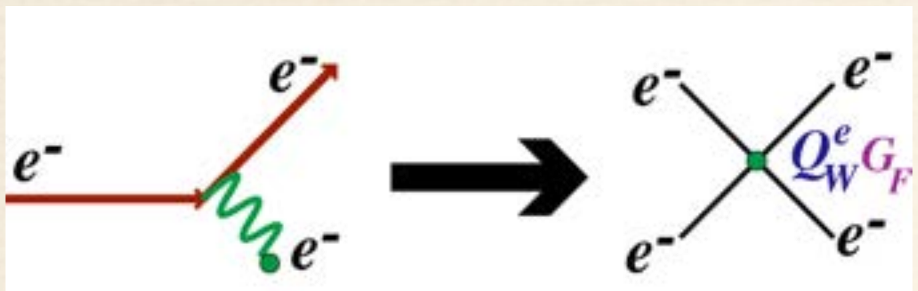


$$\frac{1}{\Lambda^2}\mathcal{L}_6$$

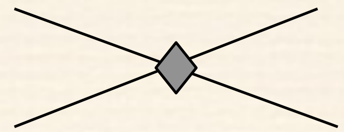
must reach Λ ~ several TeV

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

PV Electron-Electron Scattering



+

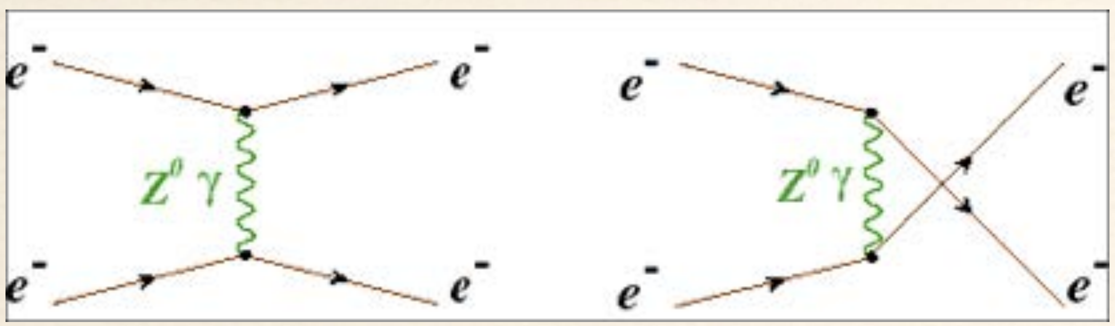


$$\frac{1}{\Lambda^2}\mathcal{L}_6$$

electron target:

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

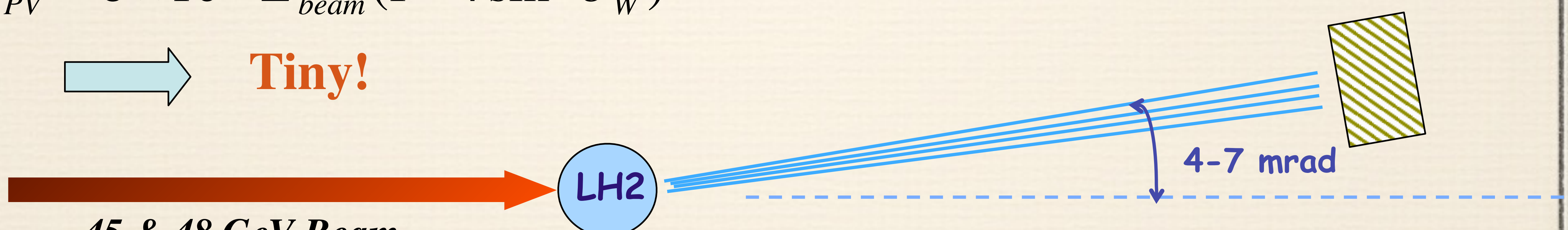
$$\frac{\delta(Q_W)}{Q_W} \sim 10\% \Longrightarrow \frac{\delta(\sin^2\theta_W)}{\sin^2\theta_W} \sim 0.5\%$$



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

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

⇨ **Tiny!**



45 & 48 GeV Beam

85% longitudinal polarization

End Station A at SLAC

SLAC E158: 1997-2004

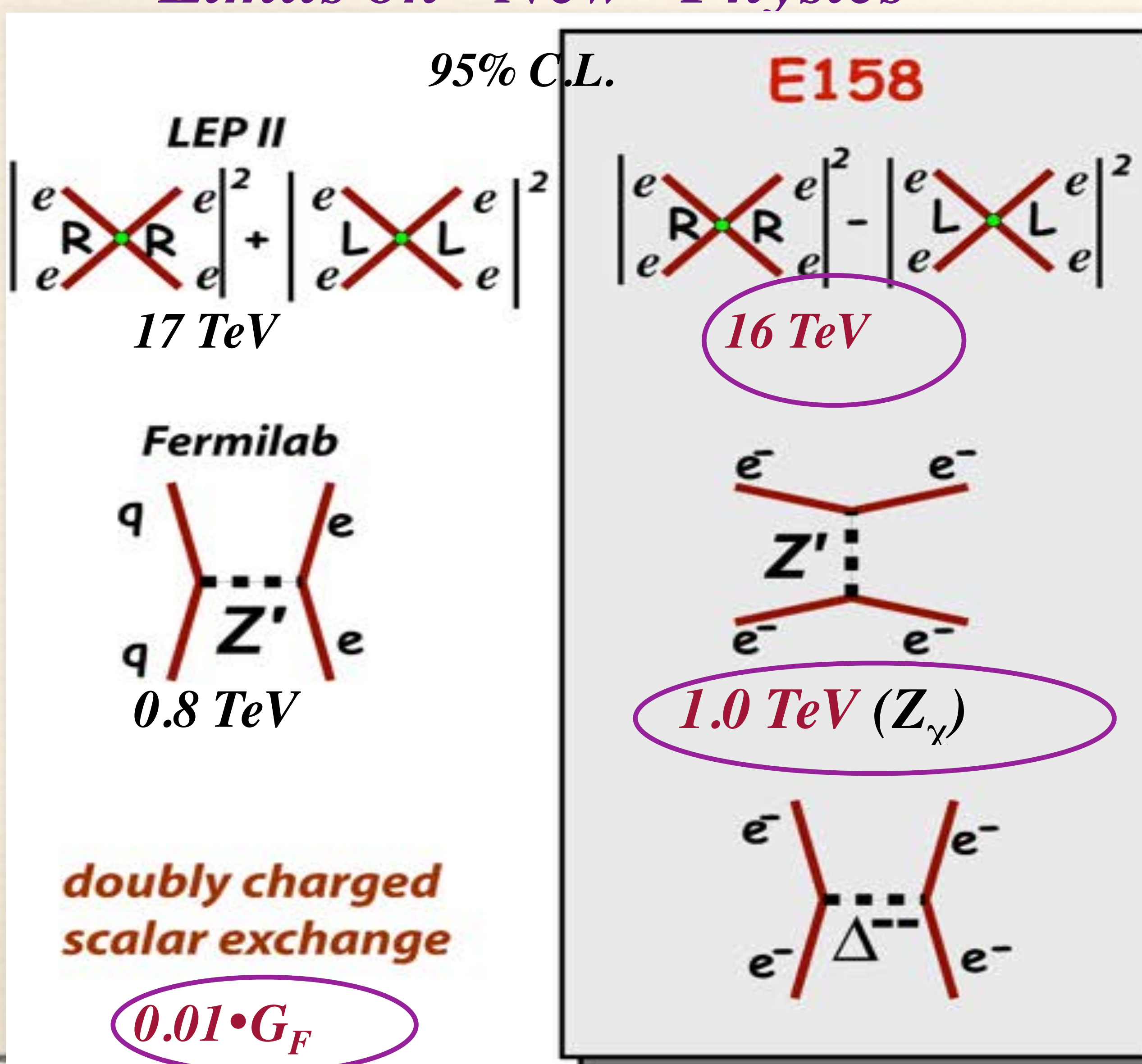
$A_{PV} = (-131 \pm 14 \pm 10) \times 10^{-9}$ Tree-level prediction: ~ -270 ppb

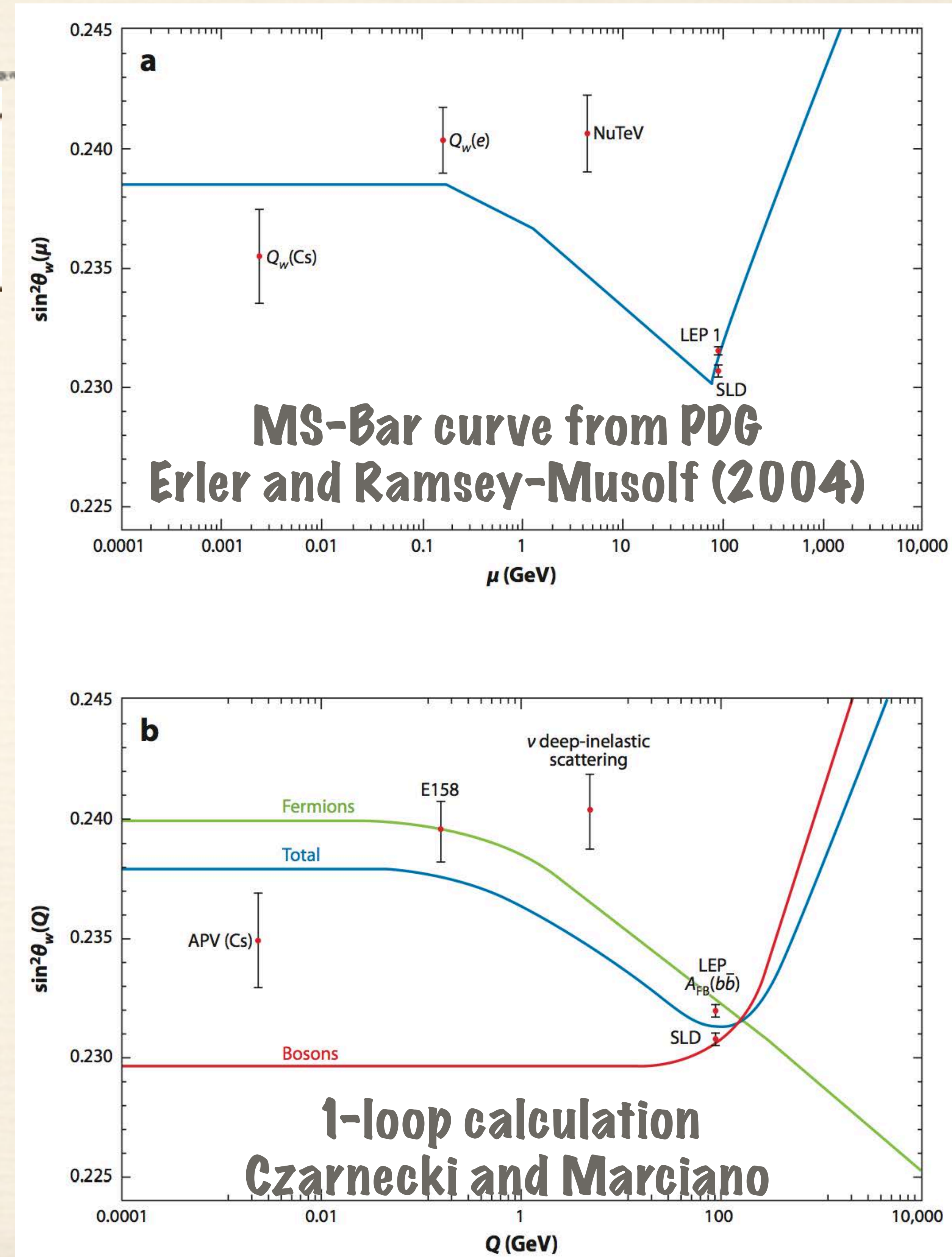
Past Low Q^2 Measurements

Prediction: -154 ppb

Czarnecki and Marciano (1995)

Limits on "New" Physics



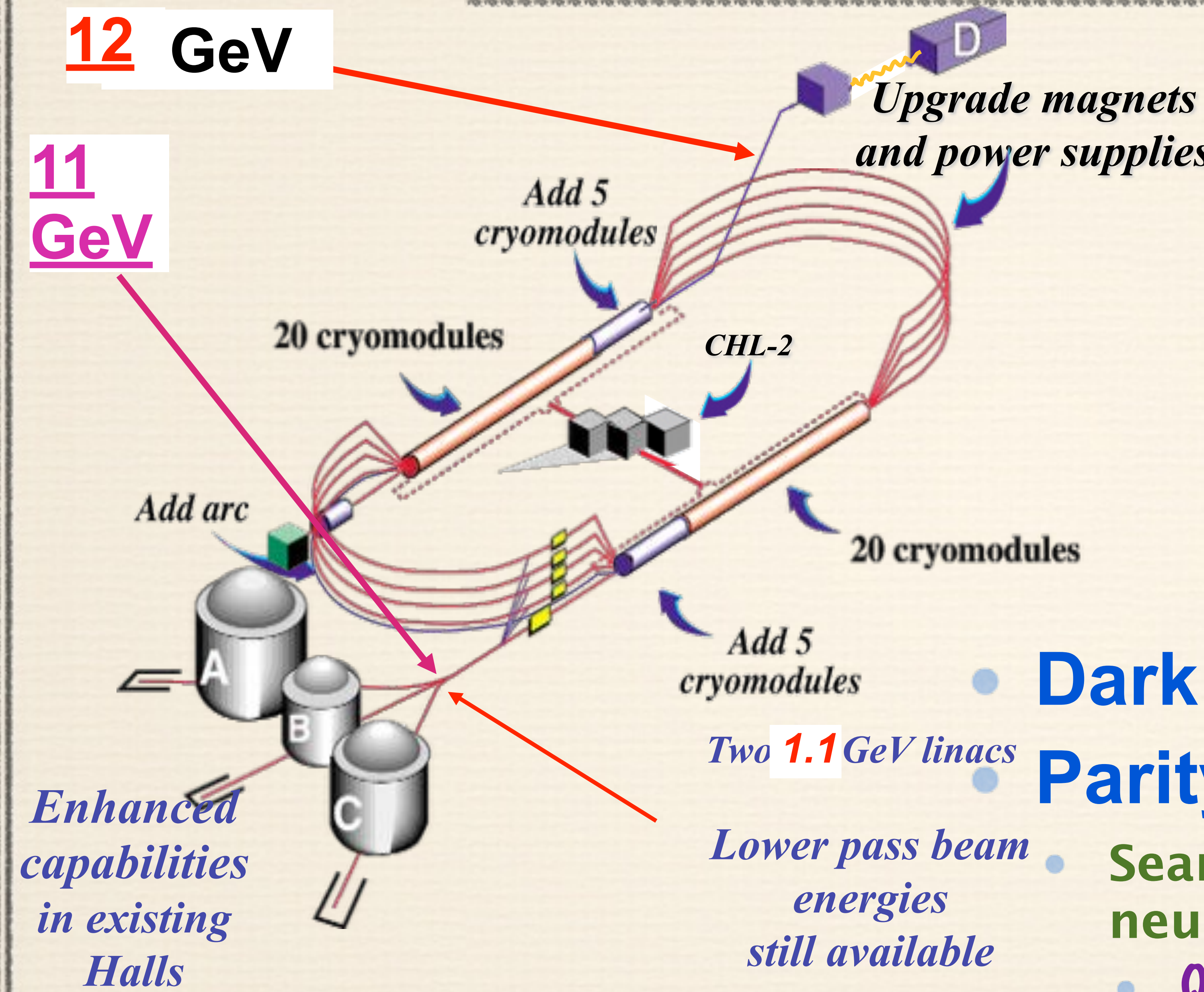


Parity-Violating Electron Scattering at Jefferson Laboratory

Primary Mission: Elucidate QCD Structure of Nucleons and Nuclei

Jefferson Laboratory

First upgraded physics beams to Hall A last month!



2013: Energy Upgrade to 12 GeV

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

Intensity Frontier Topics

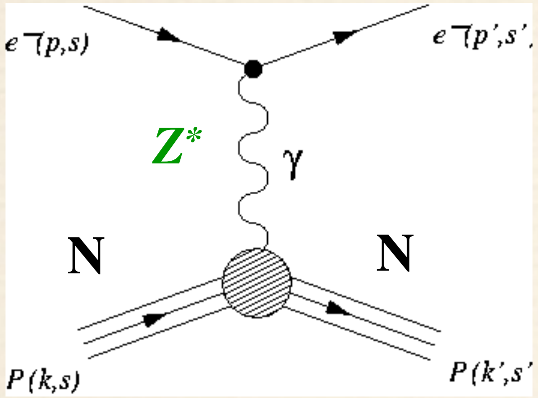
Elastic and deep-inelastic electron-nucleon scattering

Semi-Leptonic Couplings

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

A_{PV} in elastic e-p scattering:

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



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

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

Qweak: First Ever Measurement of Parity Violation in ELASTIC electron-proton scattering

First result:
~4% of data set
A_{PV} = -279 ± 35 ± 31 ppb

PRL 111, 141803 (2013)

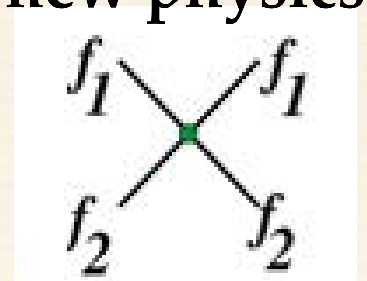
Data-taking done (2010-2012)
After full analysis expect:
$$\delta Q^p_W = \pm 4\% \Rightarrow \delta(\sin^2\theta_W) = \pm 0.3\%$$

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

Back to PVDIS

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

\+ **new physics**

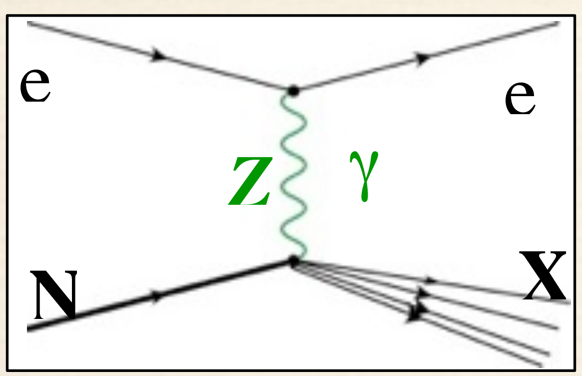


$$\mathcal{L}_{f_1 f_2} = \sum_{i,j=L,R} \frac{(g^{12}_{i\,j})^2}{\Lambda^2_{ij}} \bar{f}_{1i}\gamma_\mu f_{1i}\bar{f}_{2j}\gamma_\mu f_{2j}$$

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

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

PVDIS on a Deuterium Target



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

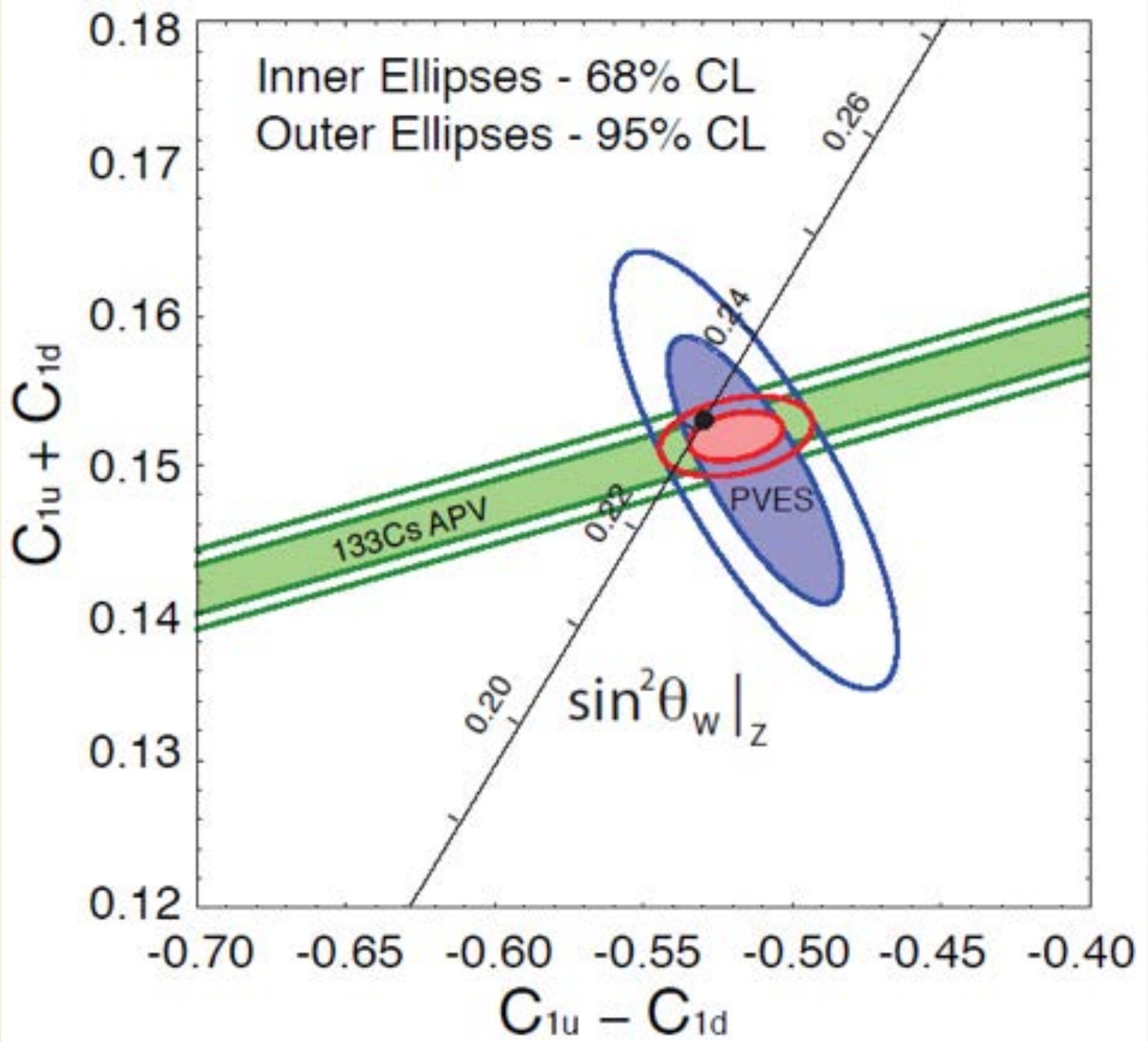
$Q^2 >> 1$ GeV^2 , $W^2 >> 4$ GeV^2

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

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

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

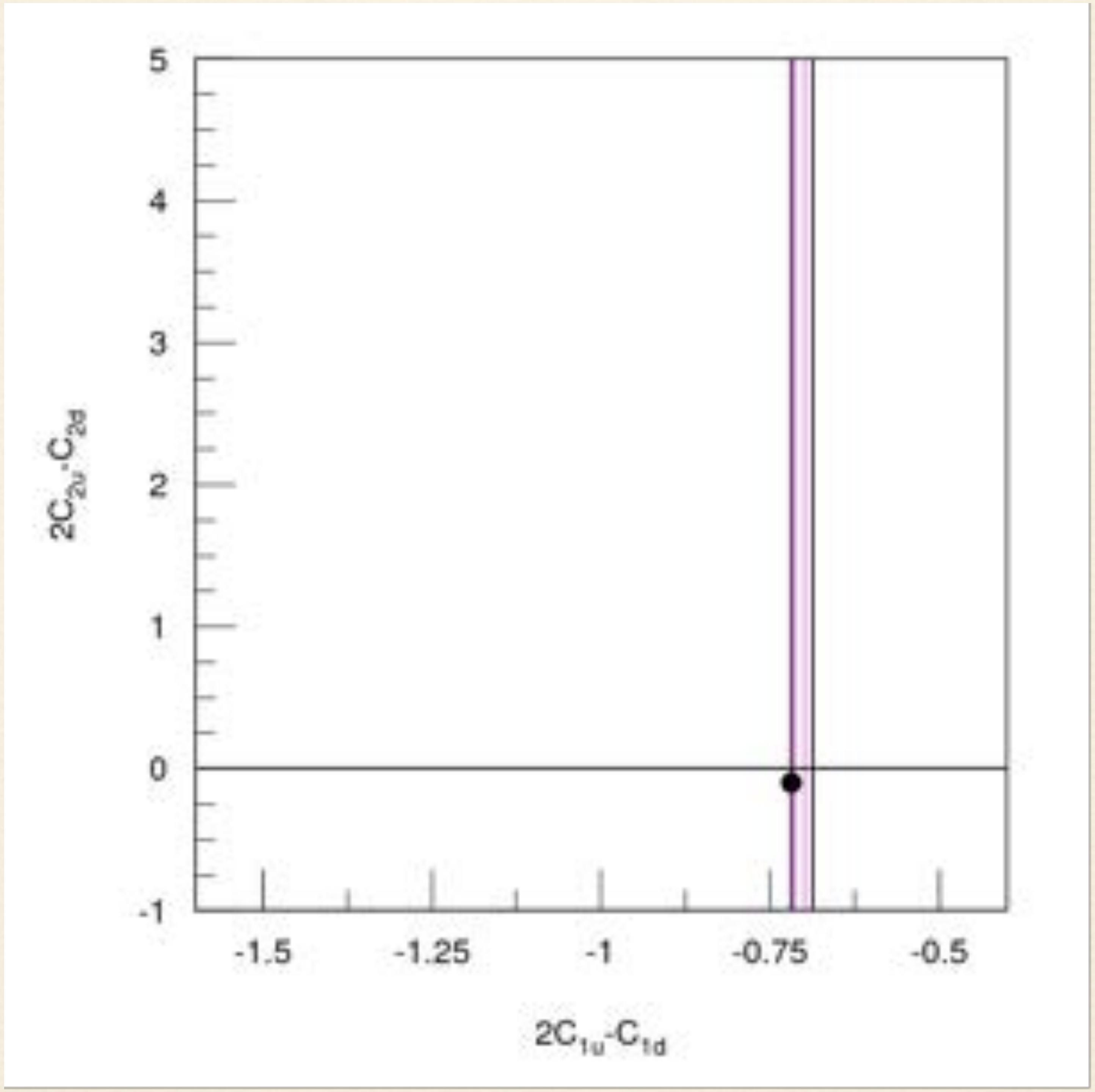
Coupling Constraints



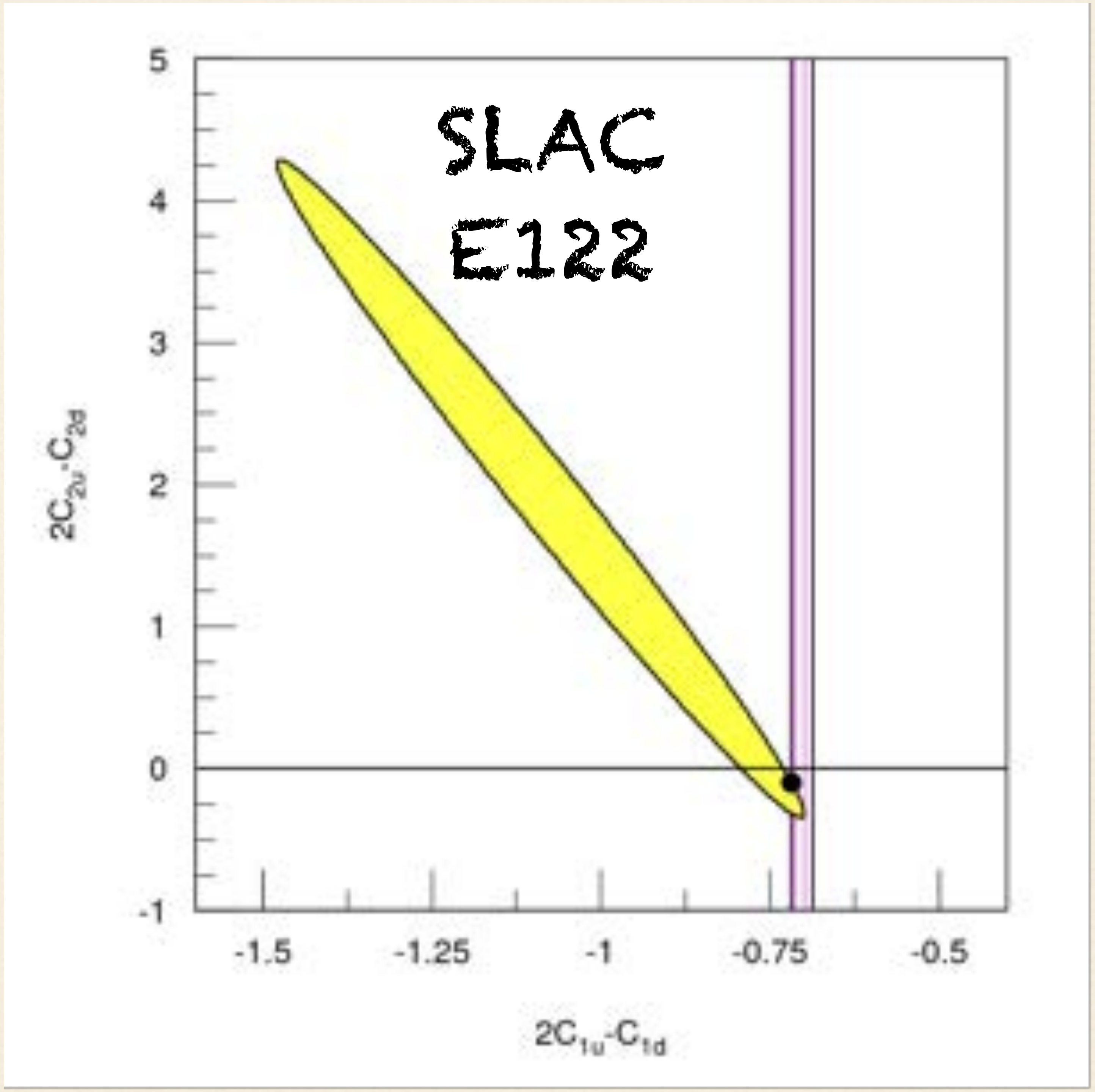
Androic et al., PRL 111, 141803 (2013);

After first Qweak Result

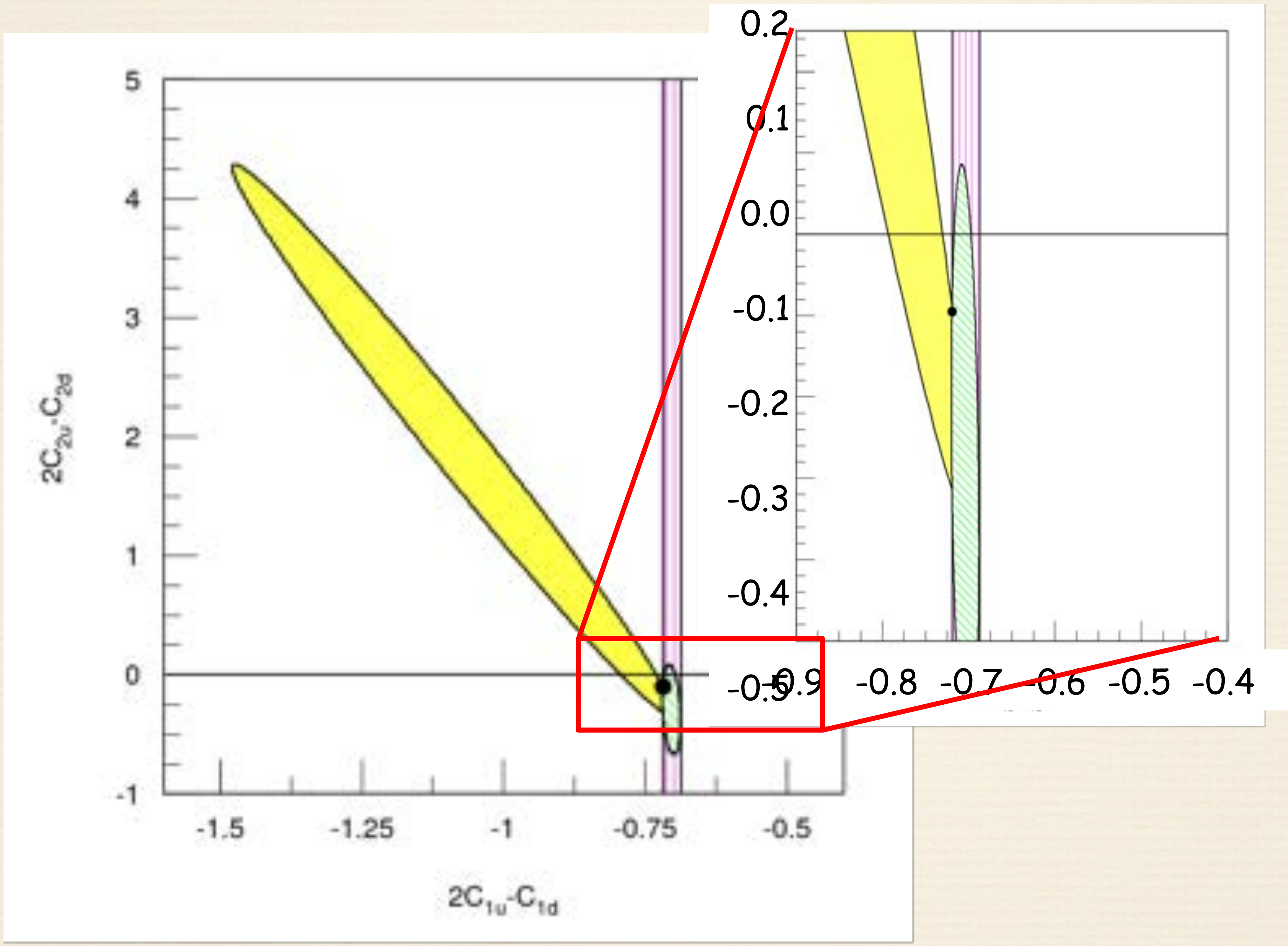
Coupling Constraints



Coupling Constraints

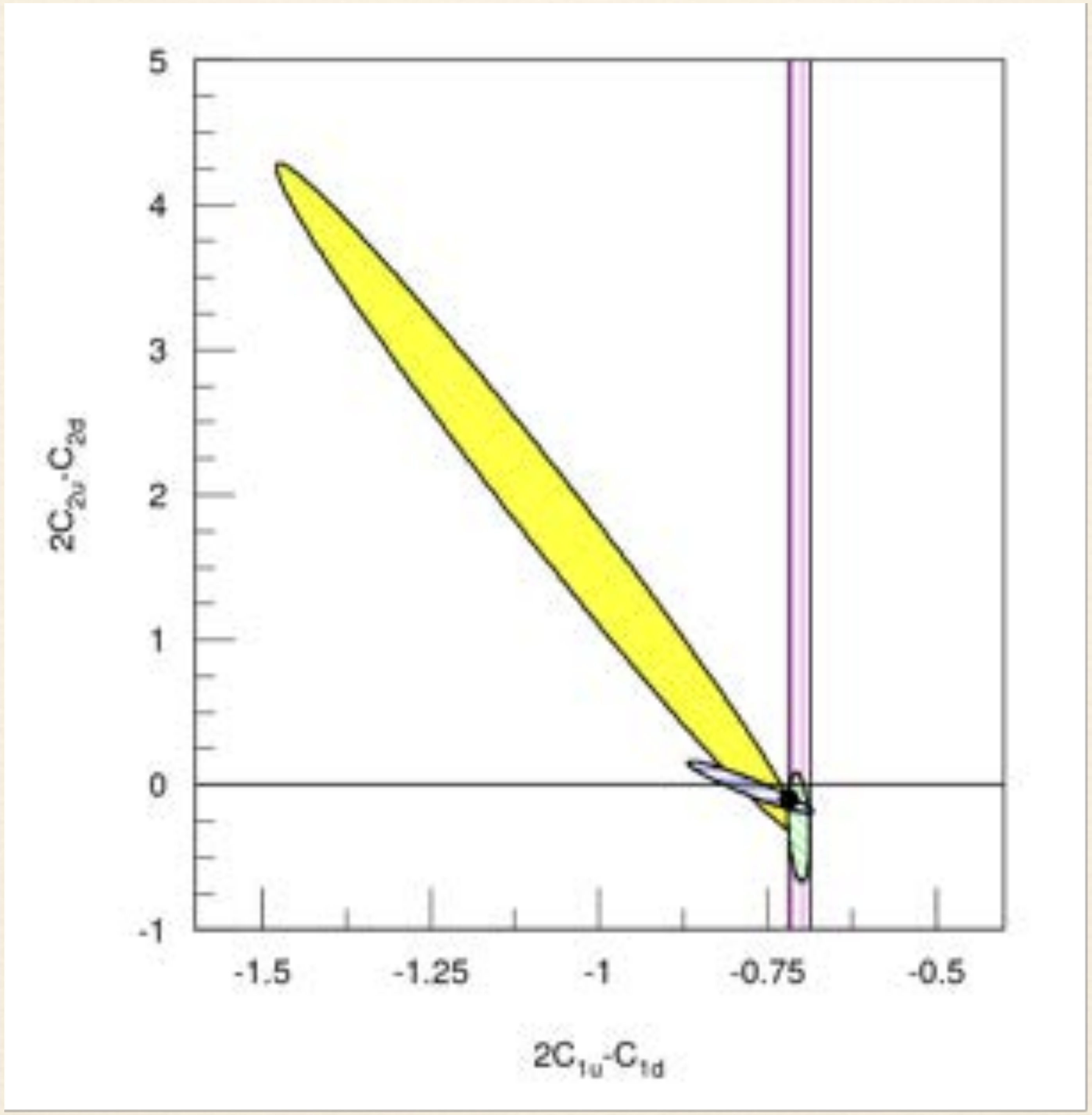


Coupling Constraints



New 6 GeV PVDIS Result

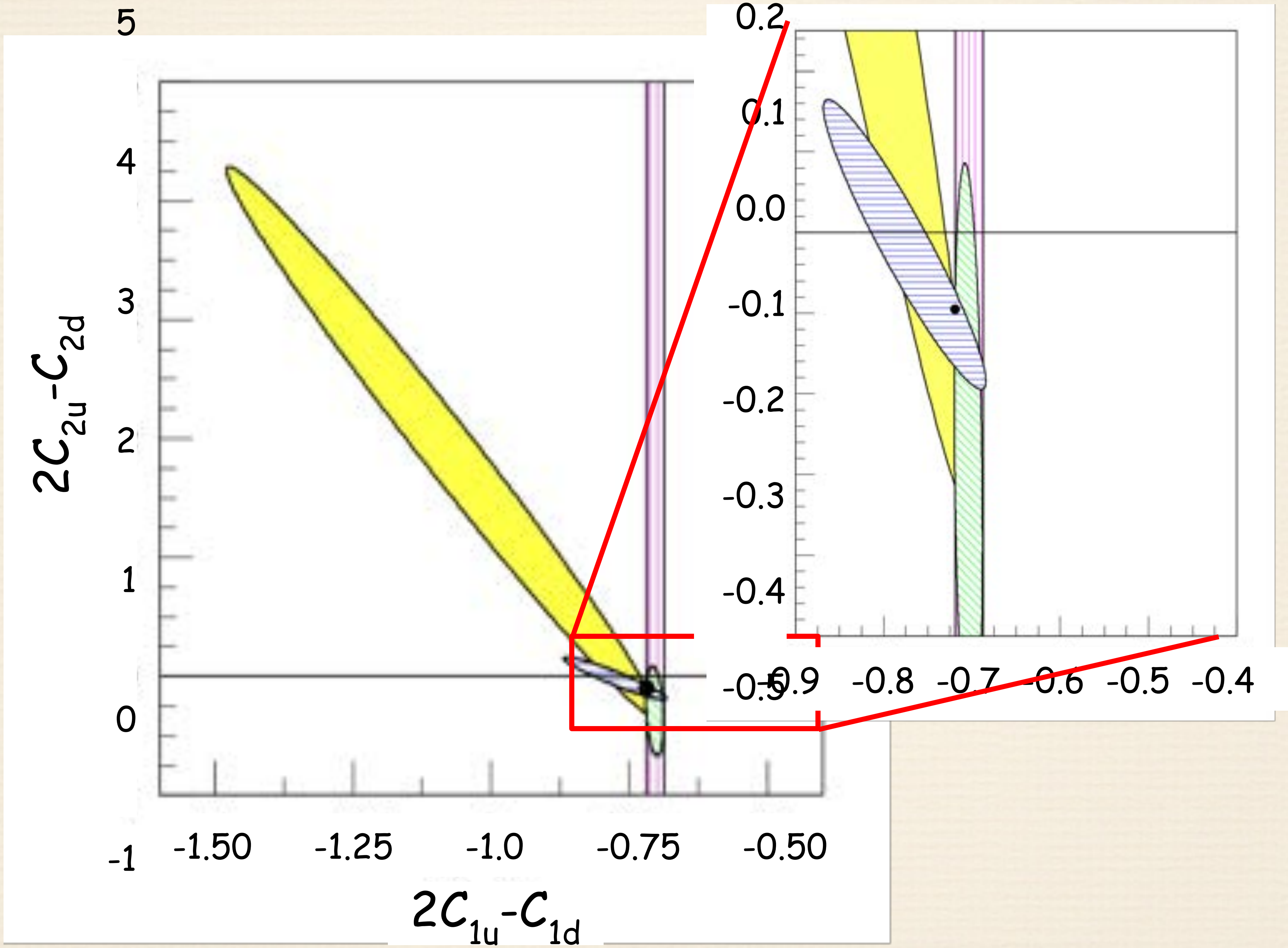
Ran at JLab in 2010



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

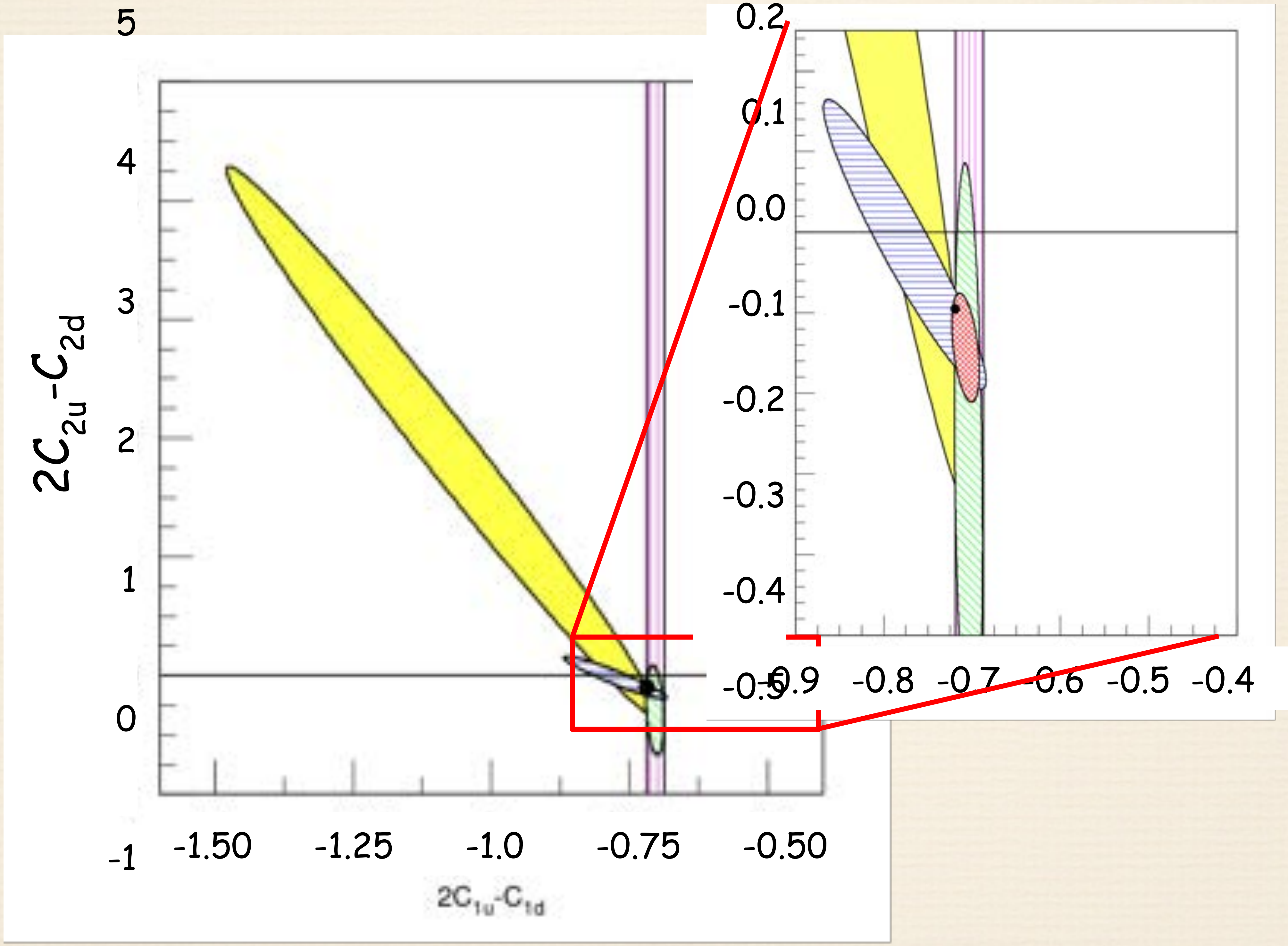
New 6 GeV PVDIS Result

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

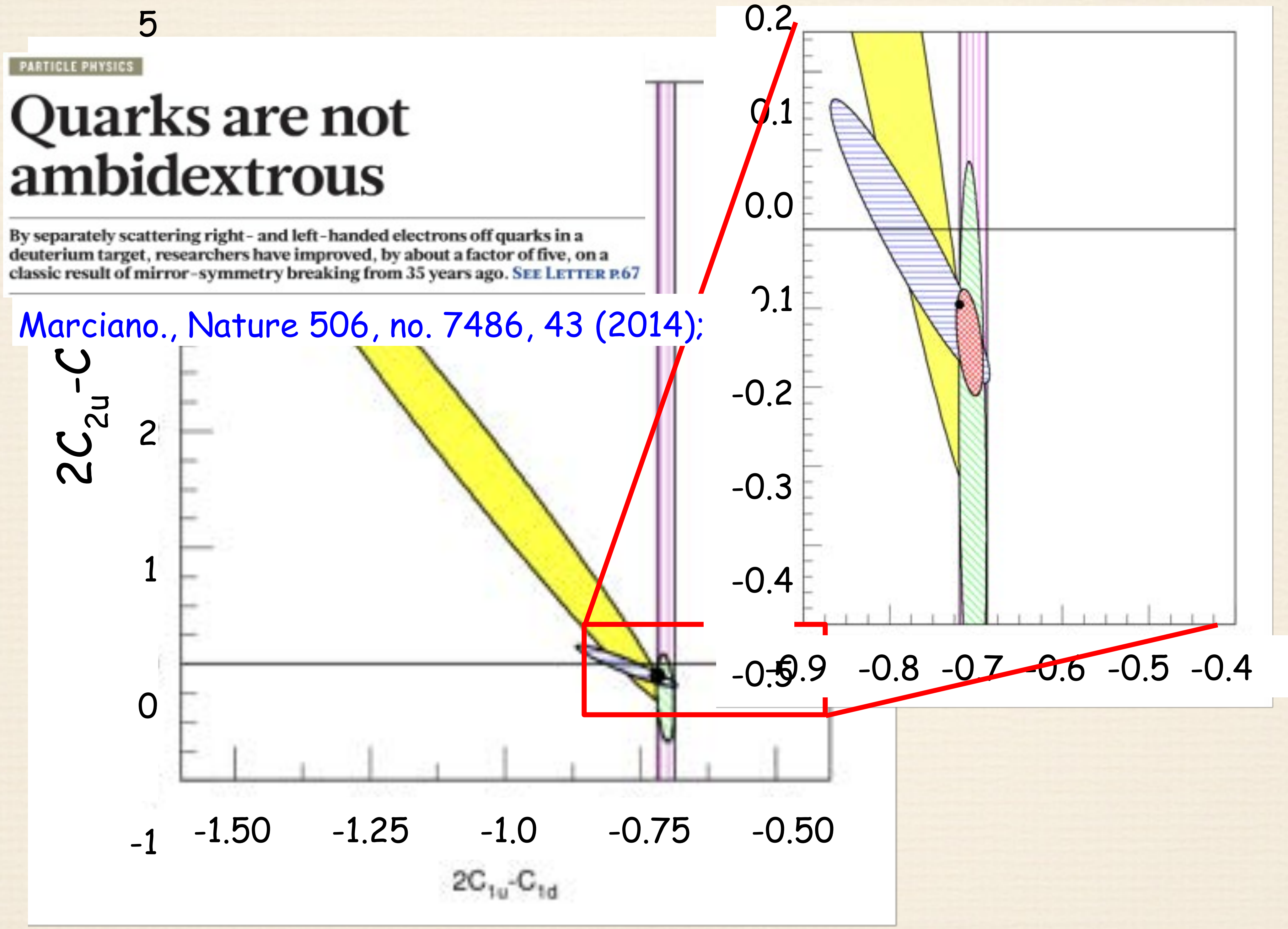


Latest Combined Fit

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

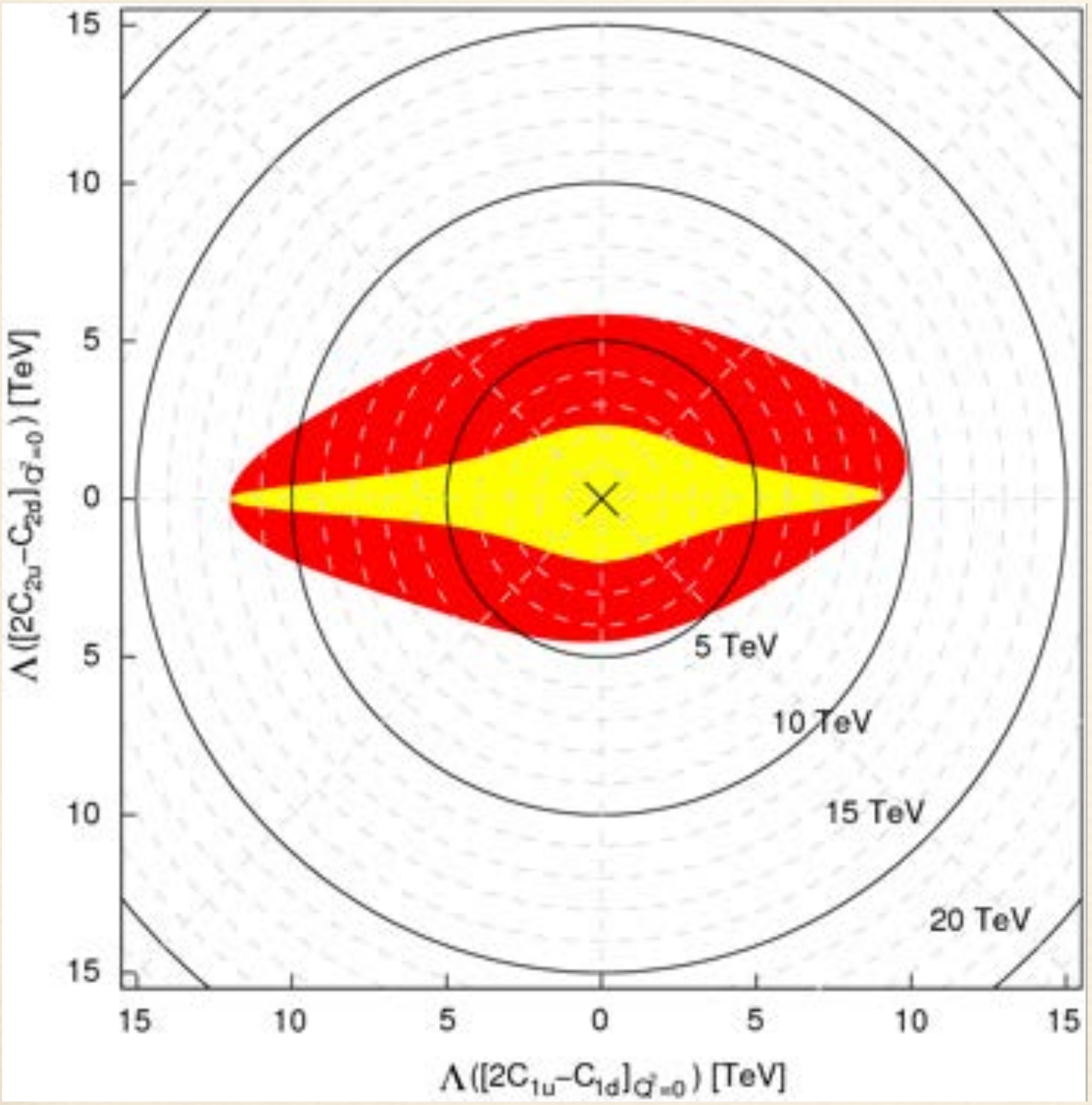


Axial-Quark Couplings are Non-Zero



Limits on New Physics

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



E122: 20%

6 GeV PVDIS: 5%

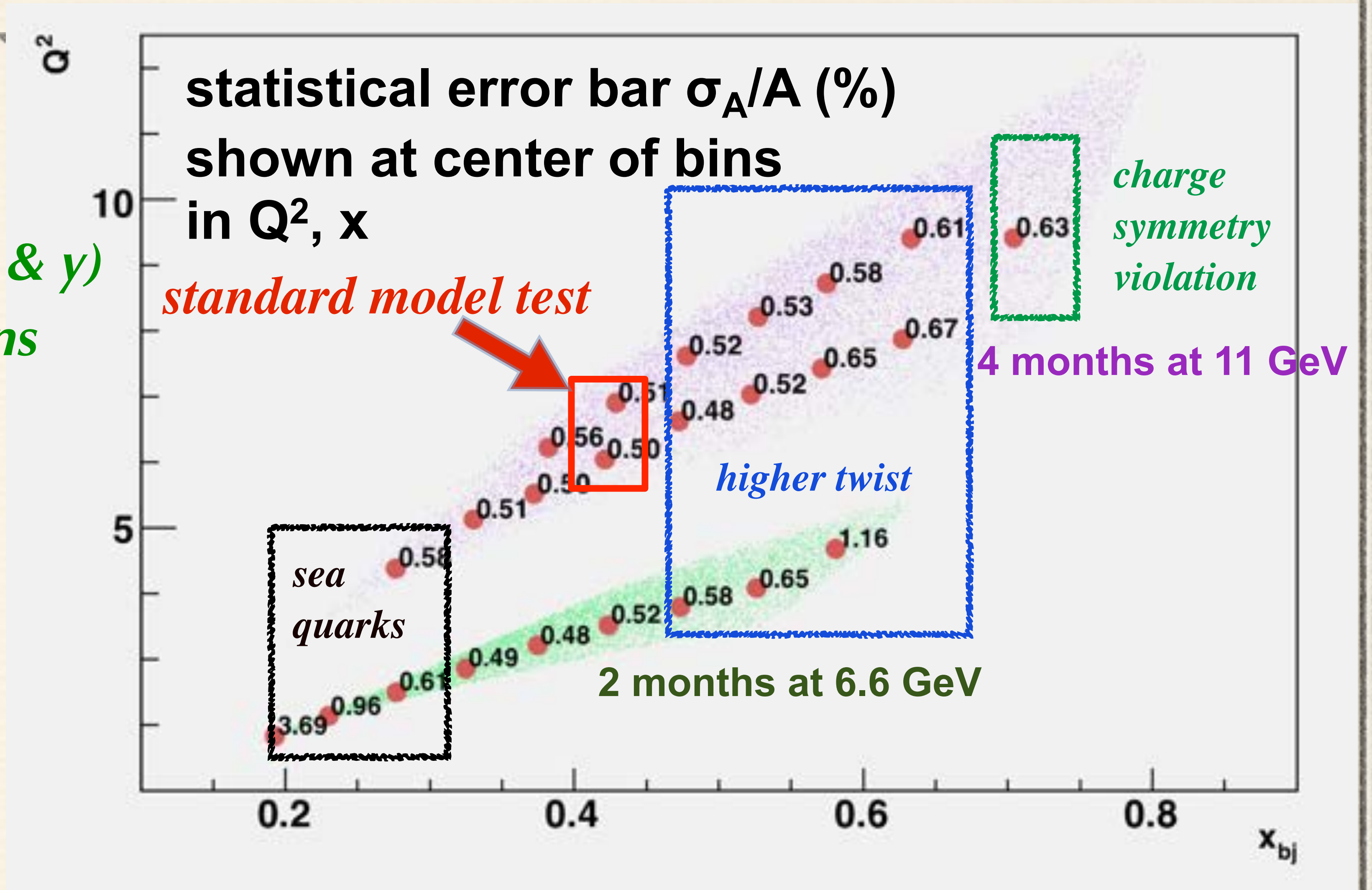
SOLID Goal: 0.6%

Requires 12 GeV upgrade of JLab and a large superconducting solenoid

The SOLID Experiment

Requirements

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

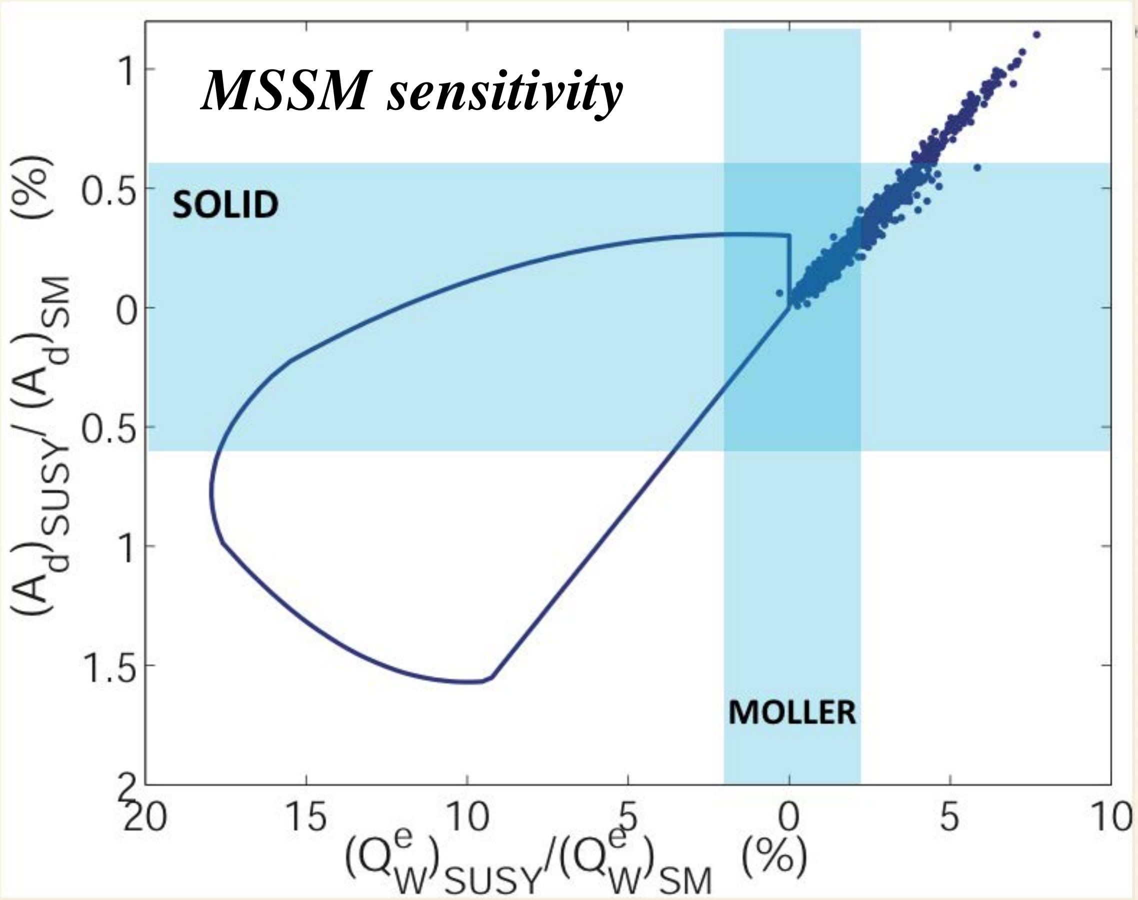


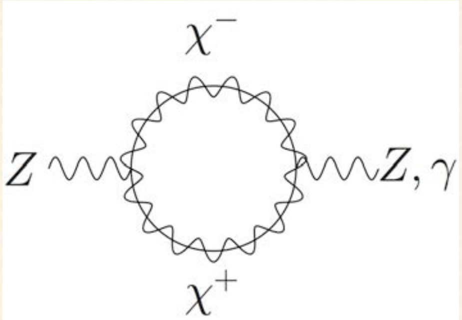
Strategy: sub-1% precision over broad kinematic range: **sensitive Standard Model test** *and* **detailed study of hadronic structure contributions**

$$A = A\left[1 + \beta_{HT}\frac{1}{(1-x)^3 Q^2} + \beta_{CSV}x^2\right]$$

If no CSV, HT, quark sea or nuclear effects, ALL Q^2, x bins should give the same answer within statistics modulo kinematic factors!

SOLID: New Physics Reach





Does Supersymmetry provide a candidate for dark matter?

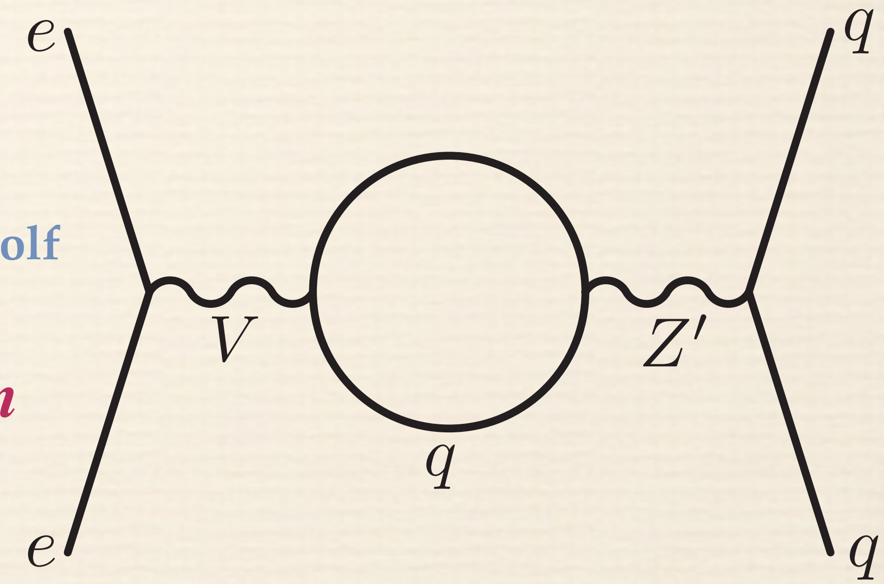
- B and/or L need not be conserved: neutralino decay
- Depending on size and sign of deviation: could lose appeal as a dark matter candidate

Leptophobic Z'

arXiv:1203.1102v1

Buckley and Ramsey-Musolf

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

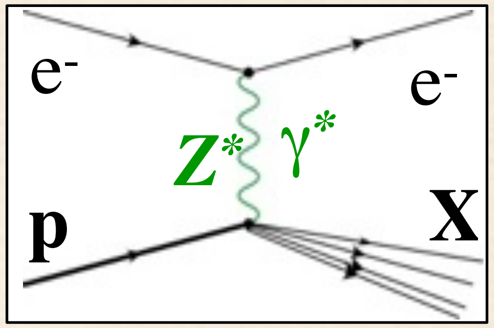


Since electron vertex must be vector, the Z' cannot couple to the C_{1q}'s if there is no electron coupling: can only affect ***C_{2q}'s***

SOLID can improve sensitivity: 100-200 GeV range

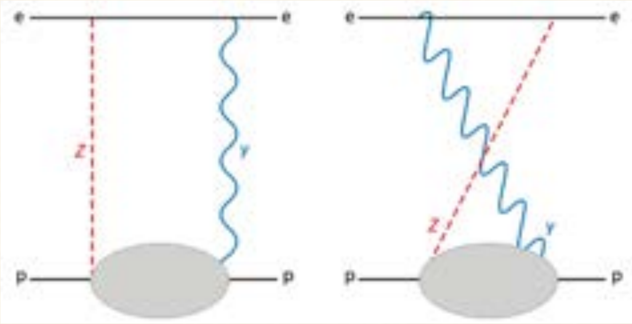
Novel Structure Effects with PVDIS

EW & Hadron Physics Interplay

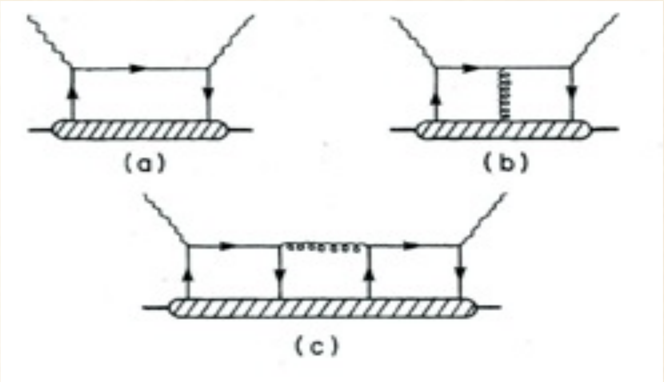


electrons on LH_2

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



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



Charge Symmetry Violation

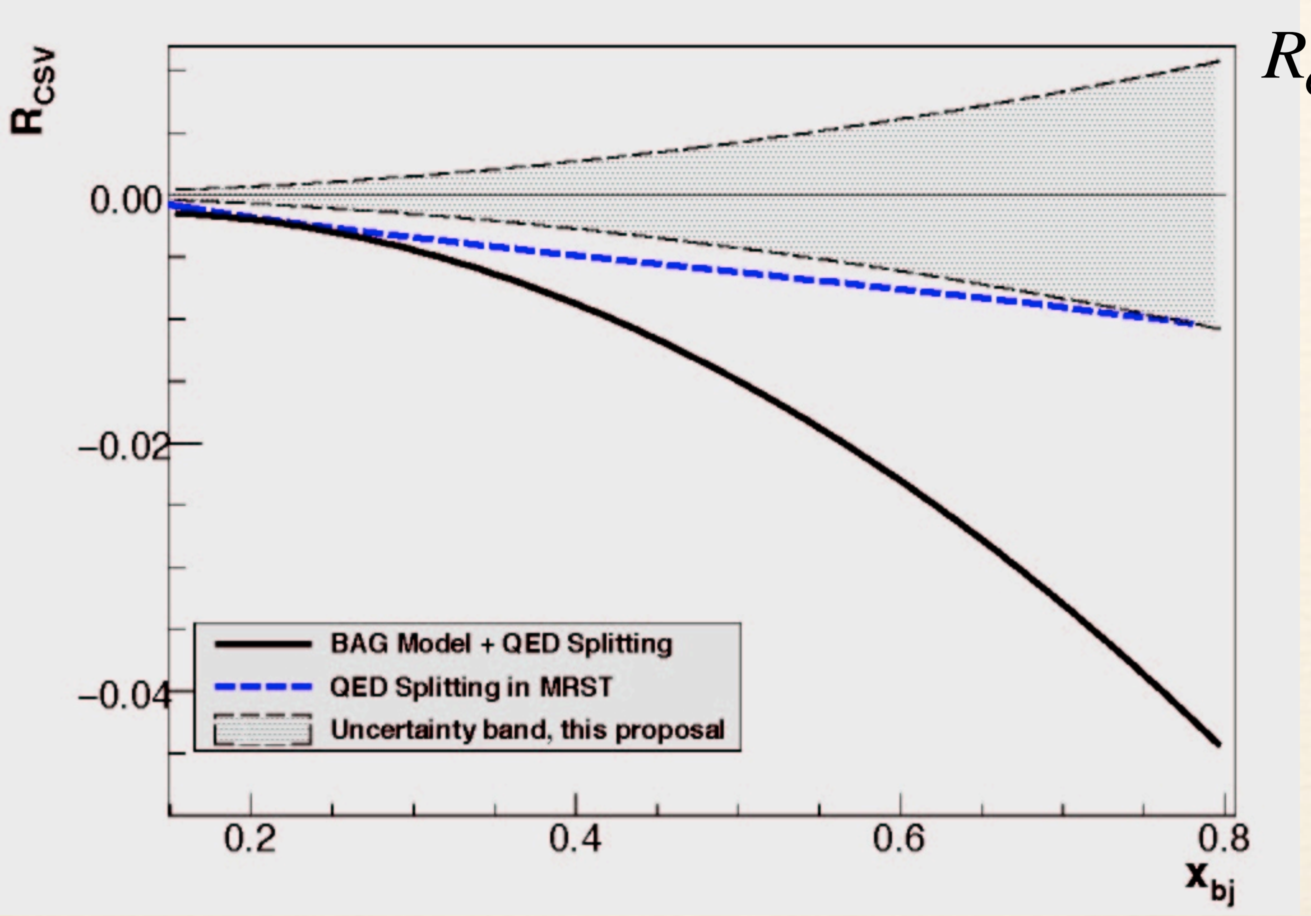
Parton-level charge symmetry assumed in deriving ^2H A_{PV}

Charge Symmetry Violation

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

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

- u,d quark mass difference
- electromagnetic effects



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

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

Special Higher Twist Effect

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

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

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

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

Isospin decomposition before using PDF's

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

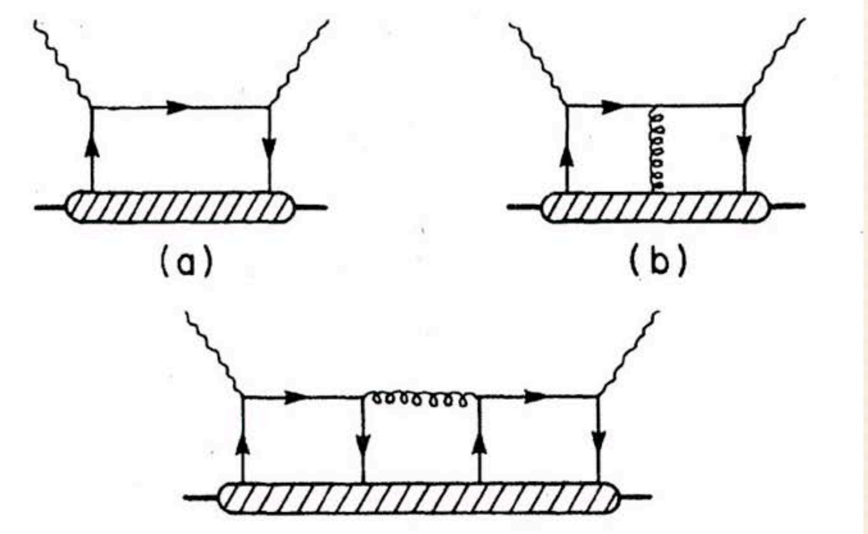
$$\delta = \frac{\langle VV \rangle - \langle SS \rangle}{\langle VV \rangle + \langle SS \rangle}$$

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

Higher-Twist valence quark-quark correlation

Zero in quark-parton model

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



Castorina & Mulders, '84

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

σ_L contributions cancel

Use ν data for small b(x) term.

Longstanding issue in proton structure

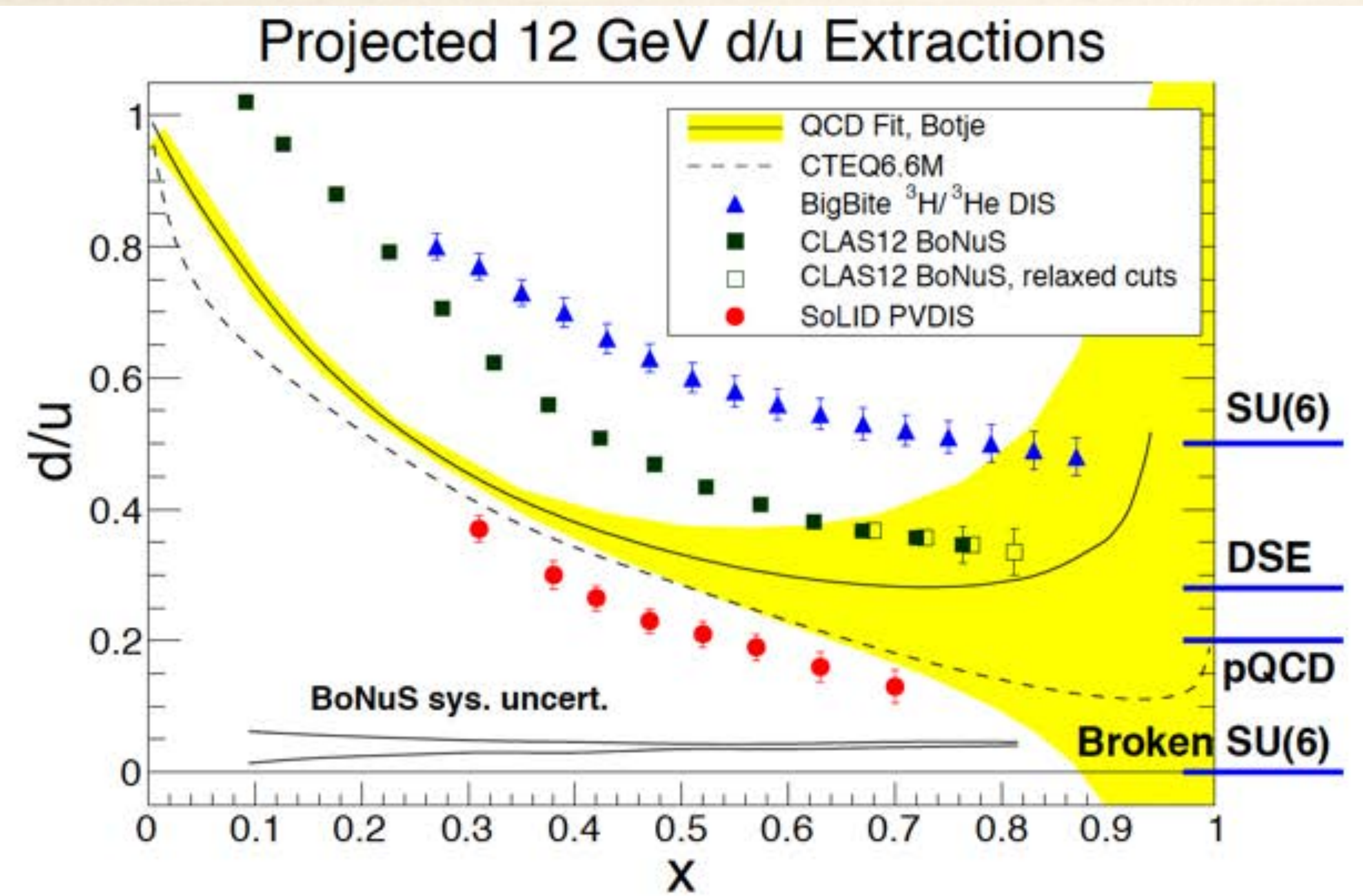
d/u at high-x

PV-DIS off the proton (hydrogen target)

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

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

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



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

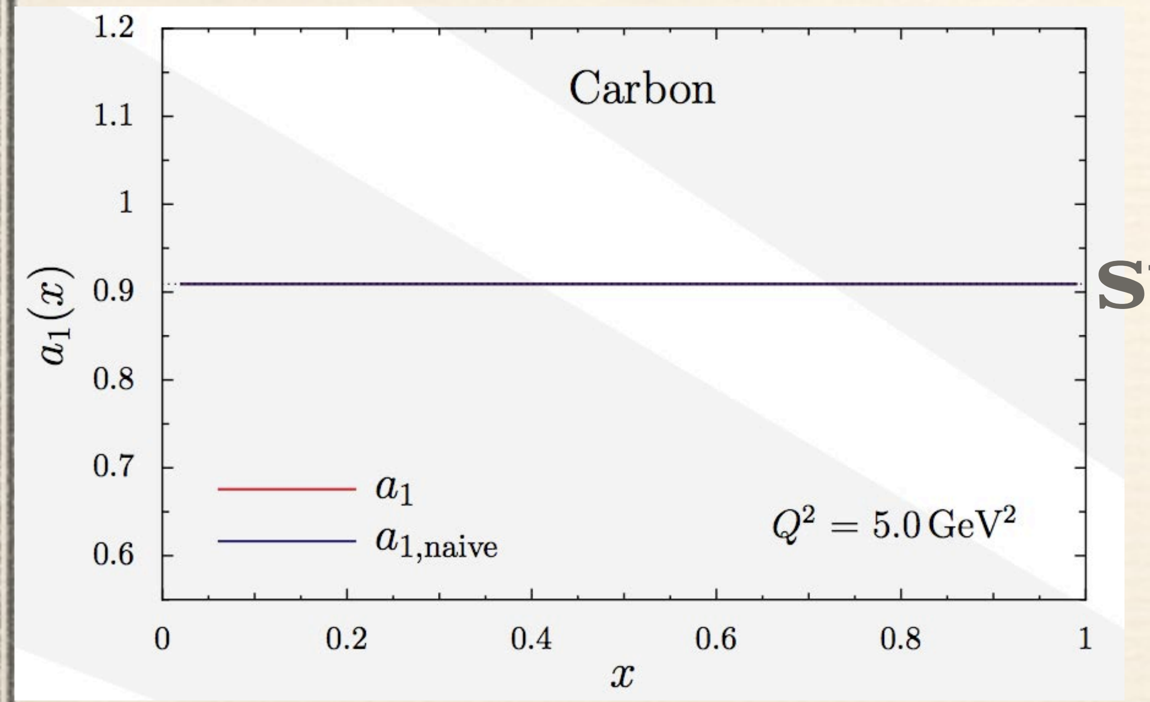
A Novel "EMC" Effect

Consider PVDIS on a heavy nucleus

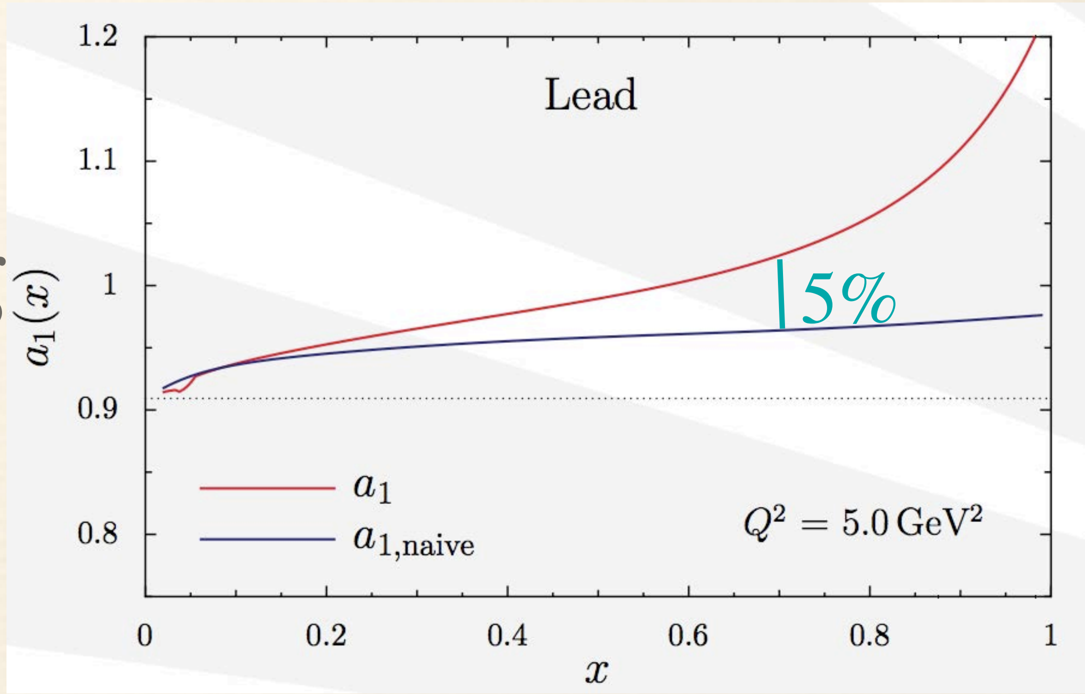
Cloet, Bentz, Thomas, arXiv 0901.3559

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

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

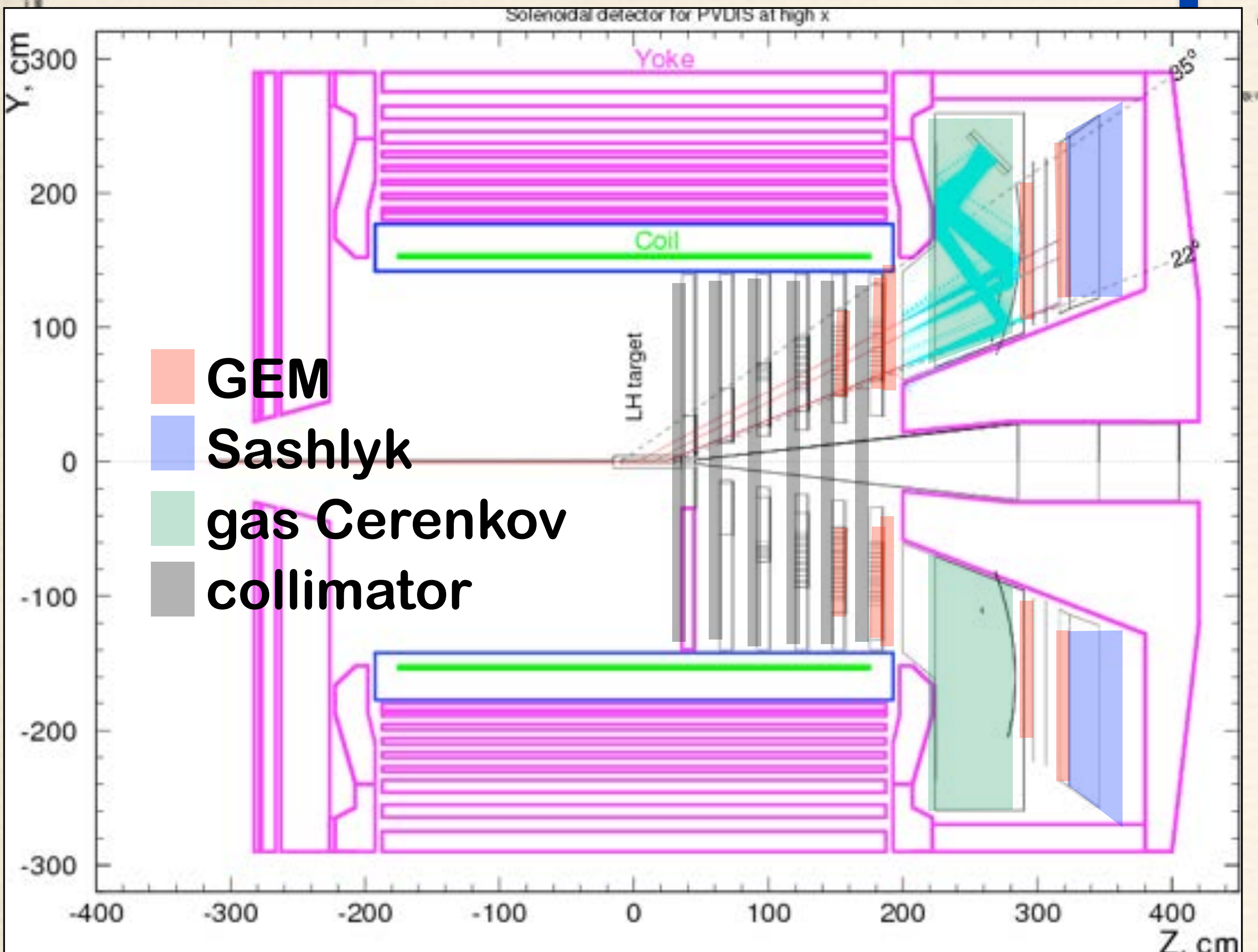


smoking gun!

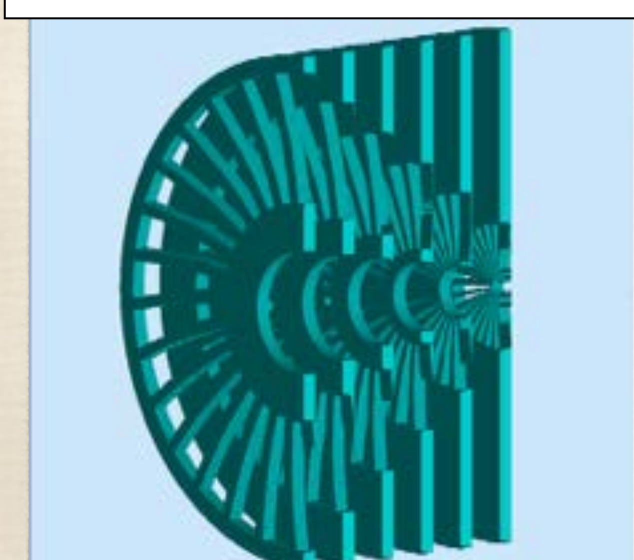


A new proposal using Ca-48 has been submitted to the JLab PAC

SOLID Apparatus



- 20° - 35°, E'~ 1.5 - 5 GeV δp/p ~ 2%
- some regions 10's of kHz/mm², Pion rejection with Cherenkov + segmented calorimeter
- Several large solenoids would work (Zeus, Babar): present design focuses on CLEO-II



- Requirements:
  - Solenoid contains low energy backgrounds (Møller, pions, etc)
  - Baffling to cut backgrounds: **significant engineering**
  - Trajectories measured after baffles
  - **Fast tracking—GEM, particle ID, calorimetry, and pipeline electronics**
  - **Precision polarimetry (0.4%) Compton and atomic hydrogen Moller**

Inclusive and Semi-inclusive deep inelastic scattering

Broad Program

- **^{2}H Parity Violation Experiment**
  - Search for nucleon charge symmetry violation (CSV at the partonic level)
    - Could be partial explanation of NuTeV anomaly
  - Search for a very special category of higher twist dynamics
    - PVDIS off ^{2}H isolates quark-quark correlations
- **PV-DIS with Other Targets**
  - PVDIS off ^{1}H
    - Totally clean (free of nuclear dynamics) measurement of d/u as Bjroken x → 1
  - PVDIS off ^{48}Ca (perhaps even more relevant for NuTeV anomaly)
    - Search for new source of CSV in nuclei (isospin-rotated manifestation of EMC effect)
- **Double-Polarized Semi-Inclusive DIS on ^{3}He & ^{1}H at 11 GeV**

E12-10-006: *Transverse Single Spin Asymmetry ^{3}He (90 days)*

E12-11-007: *Single and Double Spin Asymmetry ^{3}He (35 days)*

PR12-11-108: *Single and Double Spin Asymmetries on Transverse Proton (received full approval last week)*

Electroweak Physics at an EIC

“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

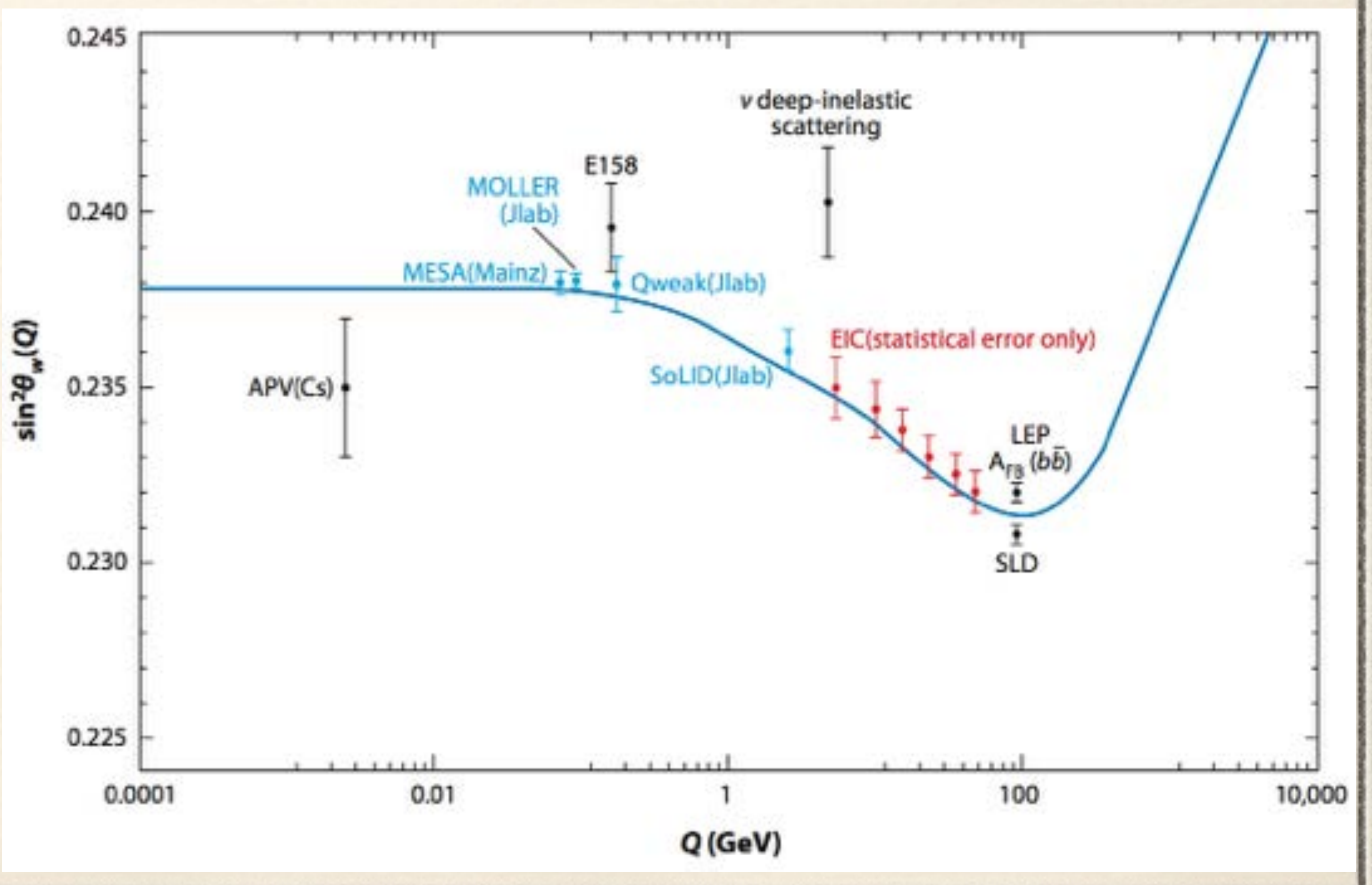
– **Electroweak (spin) structure functions**

– W and Z boson production: different couplings to ***quarks and anti-quarks***

- **Parity violating DIS**: a probe of beyond TeV scale physics

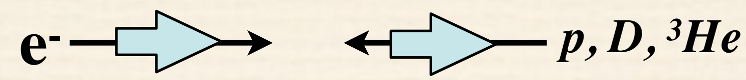
– Measurements at higher Q^2 than the PV DIS 12 GeV at Jlab

– Precision measurement of $Sin^2\Theta_W$



luminosity large: precision measurements of PV observables

EW Structure Functions at EIC



polarized electron, unpolarized hadron

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

unpolarized electron, polarized hadron

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

proton

$$F_1^{\gamma Z} \propto u + d + s$$

$$F_3^{\gamma Z} \propto 2u_v + d_v$$

$$g_1^{\gamma Z} \propto \Delta u + \Delta d + \Delta s$$

$$g_5^{\gamma Z} \propto 2\Delta u_v + \Delta d_v$$

deuteron

$$F_1^{\gamma Z} \propto u + d + 2s$$

$$F_3^{\gamma Z} \propto u_v + d_v$$

$$g_1^{\gamma Z} \propto \Delta u + \Delta d + \Delta s$$

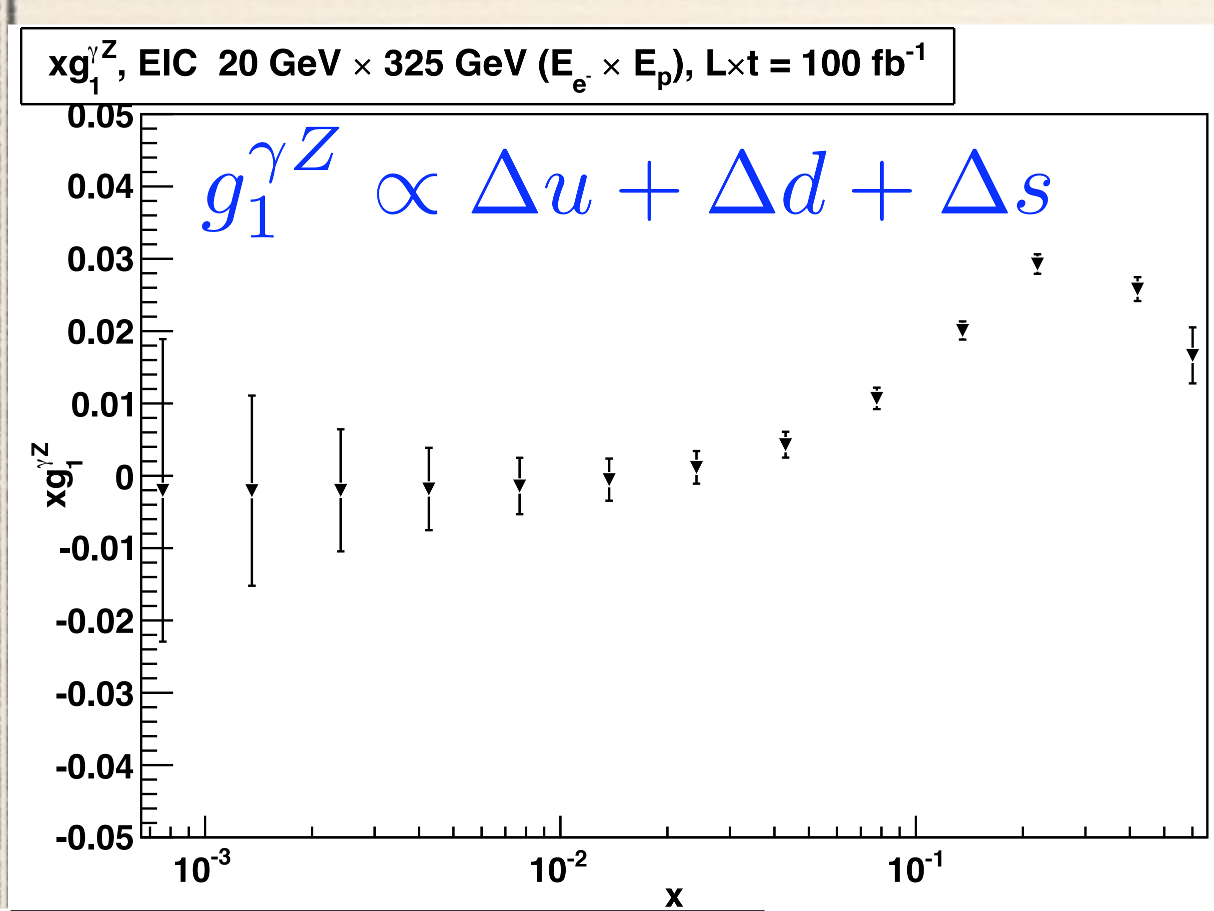
$$g_5^{\gamma Z} \propto \Delta u_v + \Delta d_v$$

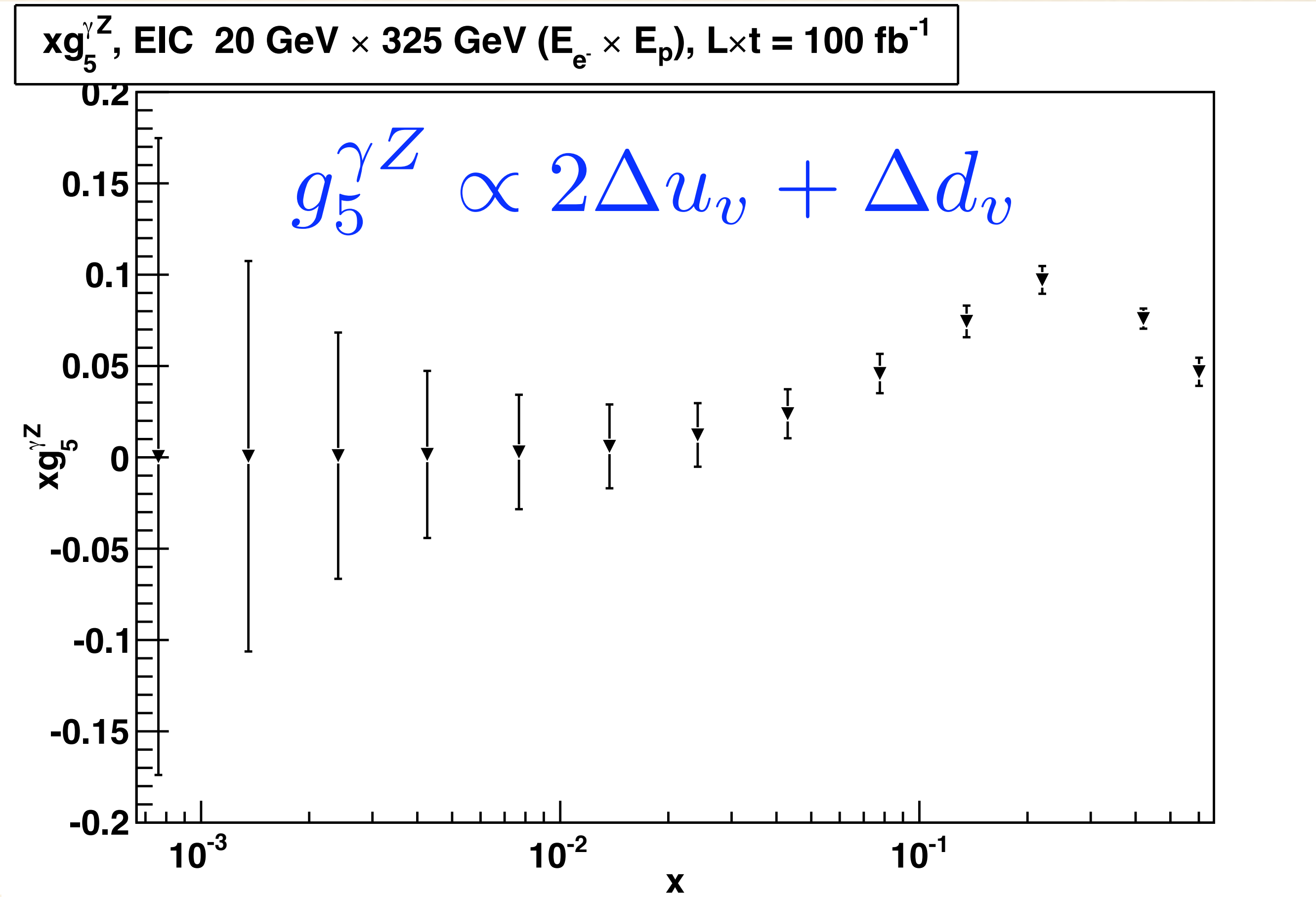
New frontier in precision QCD tests in inclusive DIS:

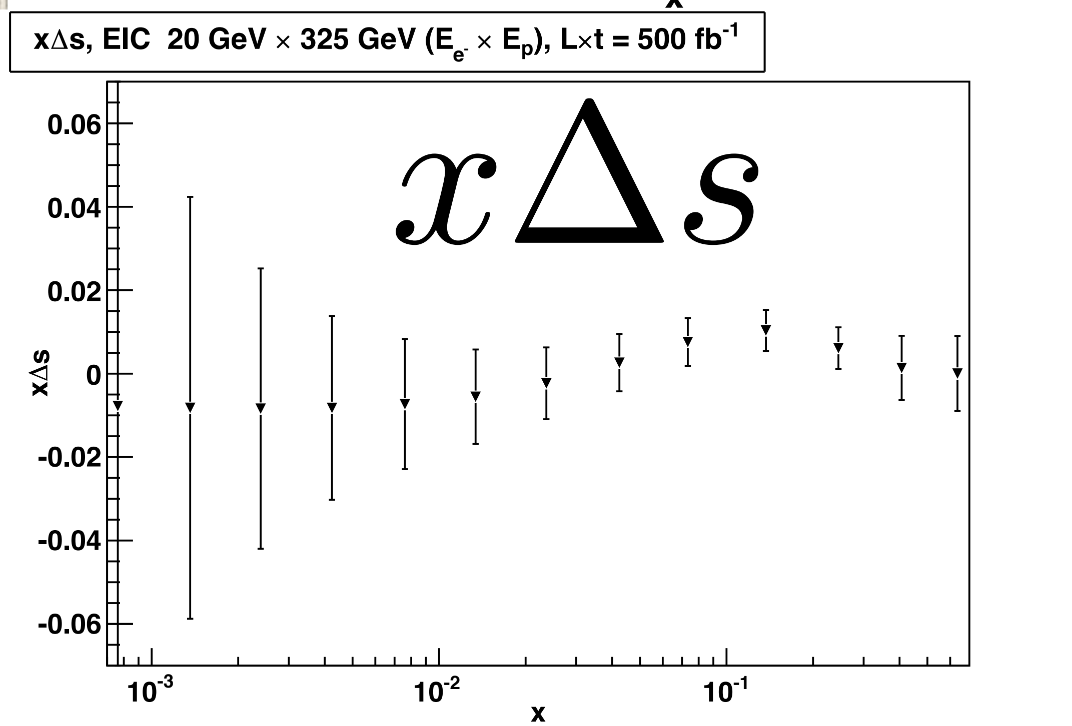
- new "Callan-Gross" relations: above expression has been simplified
- new sum rules: is there new dynamics to be tested or is it a trivial isospin rotation of original Bjorken sum rule?
- Comprehensive exploration of twist-3 terms
- Q^2 evolution carries new dynamics?

Including quark and anti-quark polarizations

Help 6-Flavor Separation







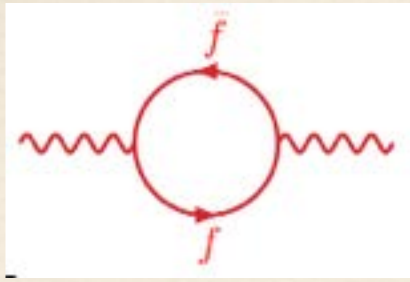
A cross-check showing unambiguously non-zero delta-s in an inclusive measurement?

Semi-inclusive measurements lose statistical power at x ~ 0.1, and have significant theoretical interpretation issues

Summary

- Parity-Violating Electron Scattering played a central role in the development of the Electroweak Theory
- Technical progress over the past several decades have enabled complementary searches for new TeV-scale dynamics as well as novel probes of nuclear and nucleon structure
- Parity-Violating Deep Inelastic Electron Scattering is now being developed as a precision tool at Jefferson Laboratory
- New insights in both electroweak physics beyond the standard model as well as QCD will be enabled
- The physics insights and further technical progress will feed directly into the physics potential of the next QCD frontier machine: The Electron Ion Collider

Heroic efforts of phenomenologists and experimentalists!



Precision Relations

The Electroweak Theory and Measurements at 1-Loop

$$\frac{G_F}{\sqrt{2}} = \frac{g^2}{8M_W^2} \qquad e^2 = 4\pi\alpha \qquad \sin^2\theta_W \approx \left(\frac{e}{g}\right)^2 \approx 1 - \left(\frac{M_W}{M_Z}\right)^2$$

$$(\Delta r)^{\text{expt}} = 1 - \left[\pi\alpha/\{\sqrt{2}G_F m_W^2(1 - m_W^2/m_Z^2)\}\right] = 0.0350(9)$$
$$(\Delta r)^{\text{SM}} = 0.0364(3) + 3.4 \times 10^{-3} \ln\left[m_H/126 \text{ GeV}\right]$$

m_t, α_s **uncertainty**

$$(\Delta\hat{r})^{\text{expt}} = 1 - \left[2\sqrt{2}\pi\alpha/\{G_F m_Z^2 \sin^2 2\theta_W(m_Z)_{\overline{\text{MS}}}\}\right] = 0.0598(5)$$
$$(\Delta\hat{r})^{\text{SM}} = 0.0598(2) + 1.4 \times 10^{-3} \ln\left[m_H/126 \text{ GeV}\right]$$

$$(\Delta r_{\overline{\text{MS}}})^{\text{expt}} = 1 - \left[\pi\alpha/\{\sqrt{2}G_F m_W^2 \sin^2\theta_W(M_Z)_{\overline{\text{MS}}}\}\right] = 0.0699(7)(4)$$
$$(\Delta r_{\overline{\text{MS}}})^{\text{SM}} = 0.0693(2) + 6.5 \times 10^{-4} \ln\left[m_H/126 \text{ GeV}\right]$$

$m_W = 80.362(6)$ GeV **theory**
$m_W = 80.385(15)$ GeV **expt.**

$\sin^2\theta_W(m_Z)_{\overline{\text{MS}}} = 0.23124(6)$
$\sin^2\theta_W(m_Z)_{\overline{\text{MS}}} = 0.23125(16)$

$m_H = 97^{+24}_{-20}$ GeV

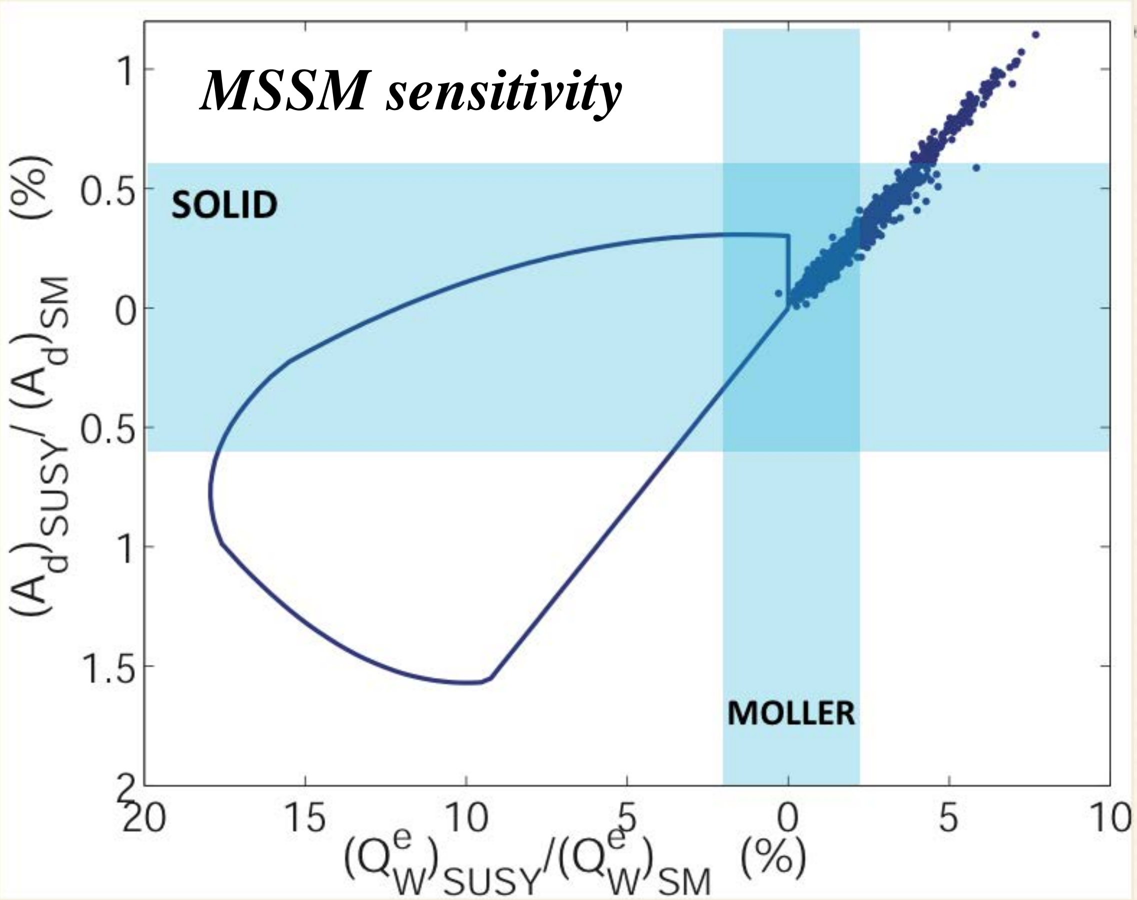
New Physics Sensitivity

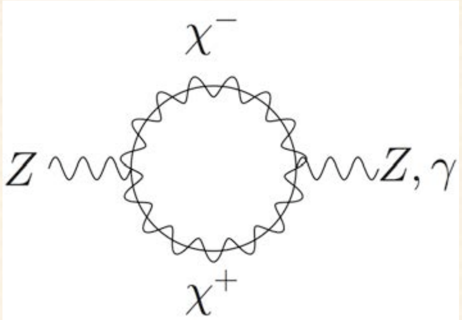
$$
\begin{aligned}
Q_W^e &= \quad -0.0435(9)[1 + 0.25\,T - 0.34\,S + 0.7\,X(Q^2) + 7m_Z^2/m_{Z_\chi}^2] \\
Q_W^p &= \quad 0.0707(9)[1 + 0.15\,T - 0.21\,S + 0.43\,X(Q^2) + 4.3m_Z^2/m_{Z_\chi}^2] \\
Q_W(^{12}C) &= \quad -5.510(5)[1 - 0.003\,T + 0.016\,S - 0.033\,X(Q^2) - m_Z^2/m_{Z_\chi}^2] \\
Q_W(^{133}Cs)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

Kumar, Mantry, Marciano & Souder, arXiv:1302.6263

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

SOLID Sensitivity





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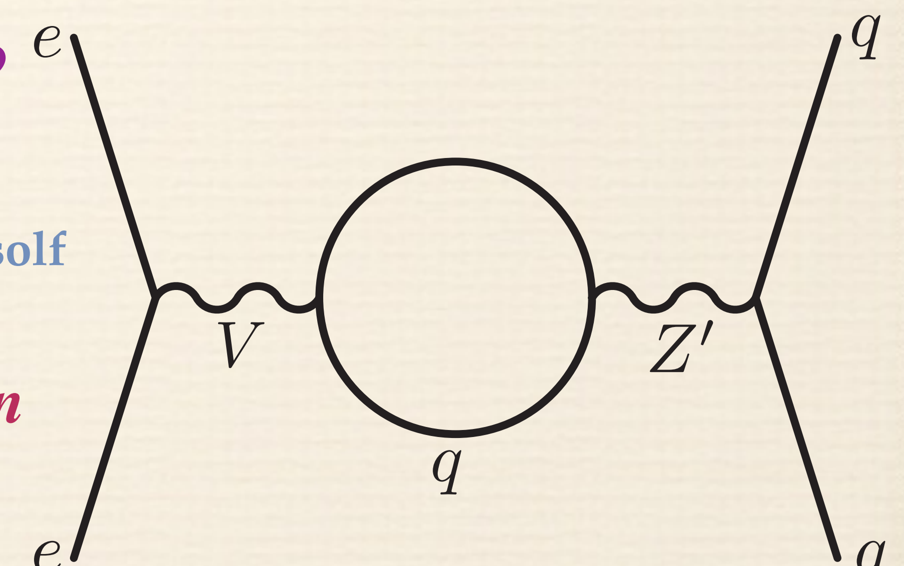


Since electron vertex must be vector, the Z' cannot couple to the C_{1q}'s if there is no electron coupling: can only affect $\mathbf{C_{2q}}$**'s**

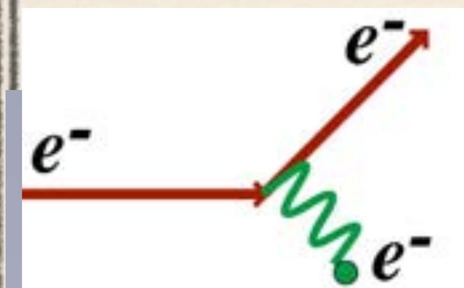
SOLID can improve sensitivity: 100-200 GeV range

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

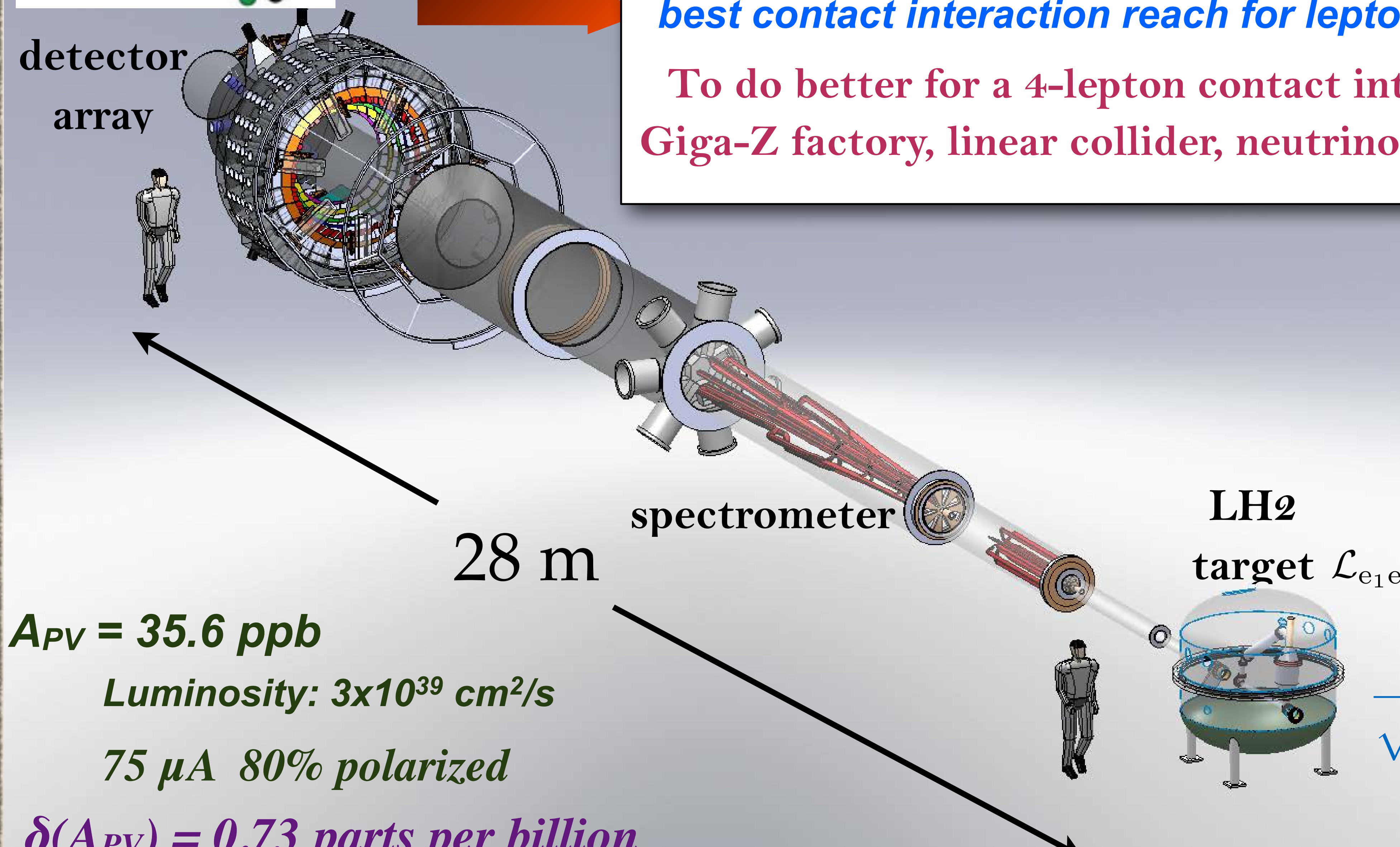


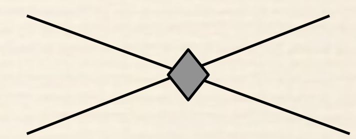
$\delta(\sin^2\theta_W) = \pm\, 0.00026$ (stat.) $\pm\, 0.00012$ (syst.) ⇨ ~ 0.1%

Matches best collider (Z-pole) measurements!

best contact interaction reach for leptons at low OR high energy

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





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

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

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

A_{PV} = 35.6 ppb

Luminosity: $3\text{x}10^{39}$ 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.)

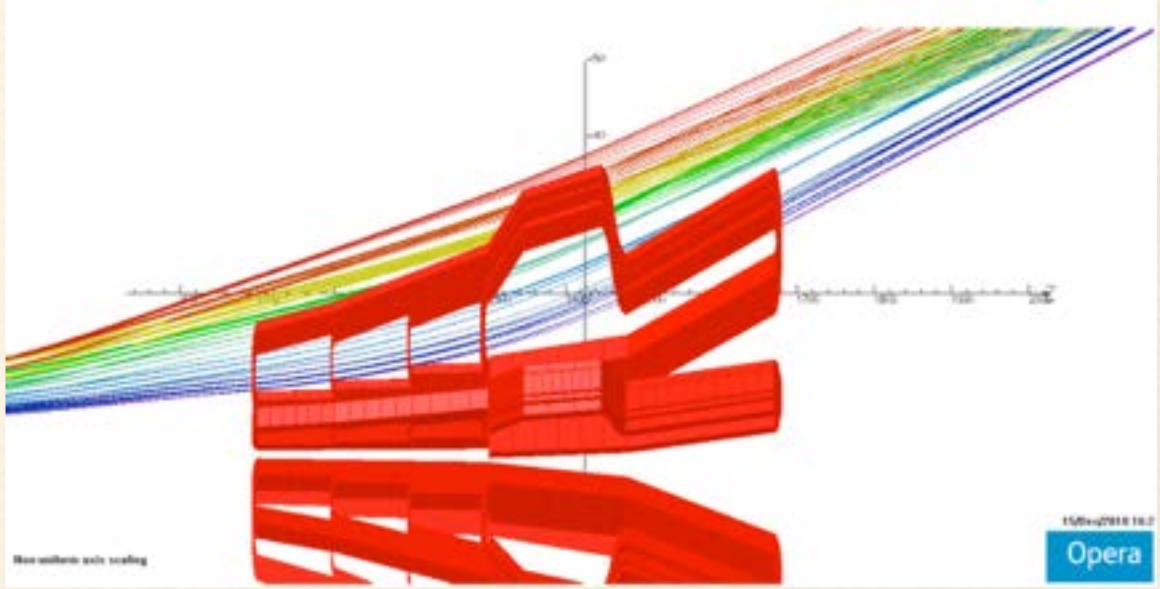
MOLLER Status

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

Technical Challenges

- ~ 150 GHz scattered electron rate
  - Design to flip Pockels cell ~ 2 kHz
  - 80 ppm pulse-to-pulse statistical fluctuations
- 1 nm control of beam centroid on target
  - Improved methods of "slow helicity reversal"
- > 10 gm/cm² liquid hydrogen target
  - 1.5 m: ~ 5 kW @ 85 µA
- Full Azimuthal acceptance with 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

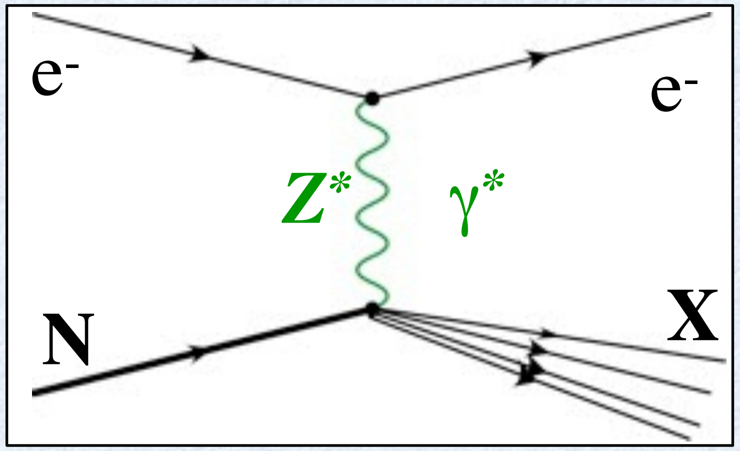
- **MOLLER Collaboration**
  - ~ 100 authors, ~ 30 institutions
  - Expertise from SAMPLE, A4, HAPPEX, G0, PREX, Qweak, E158
  - 4th generation JLab parity experiment



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

PV Deep Inelastic Scattering

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



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

$x \equiv x_{Bjorken}$

$y \equiv 1 - E'/E$

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

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

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

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

$$A_{\rm iso} = \frac{\sigma^l - \sigma^r}{\sigma^l + \sigma^r}$$

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

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

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

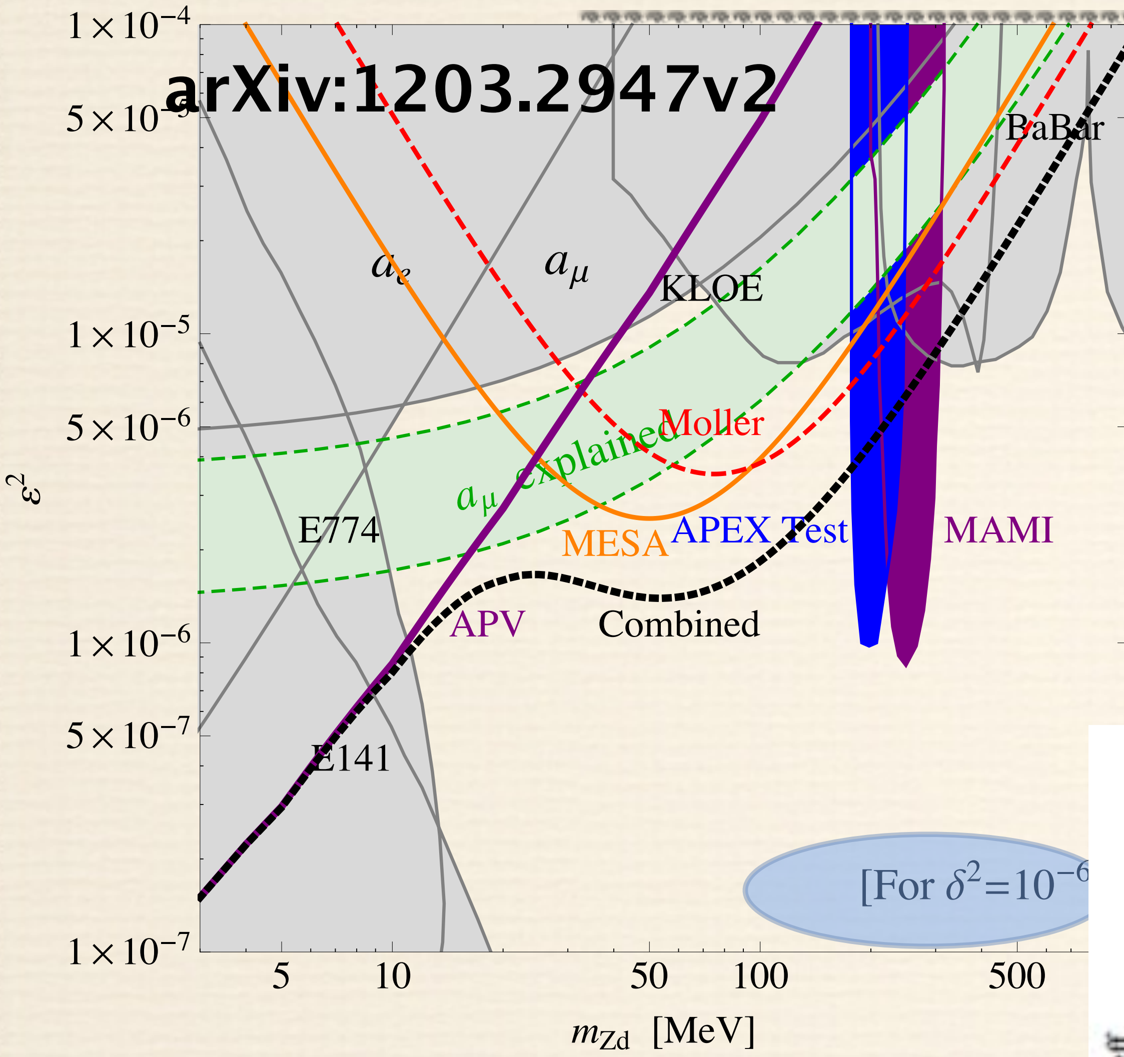
$$R_v(x) = \frac{u_v(x)+d_v(x)}{U(x)+D(x)} \xrightarrow{\text{Large } x} 1$$

Interplay with QCD

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

Dark Z to Invisible Particles

Davoudiasl, Lee, Marciano



Dark Photons:

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

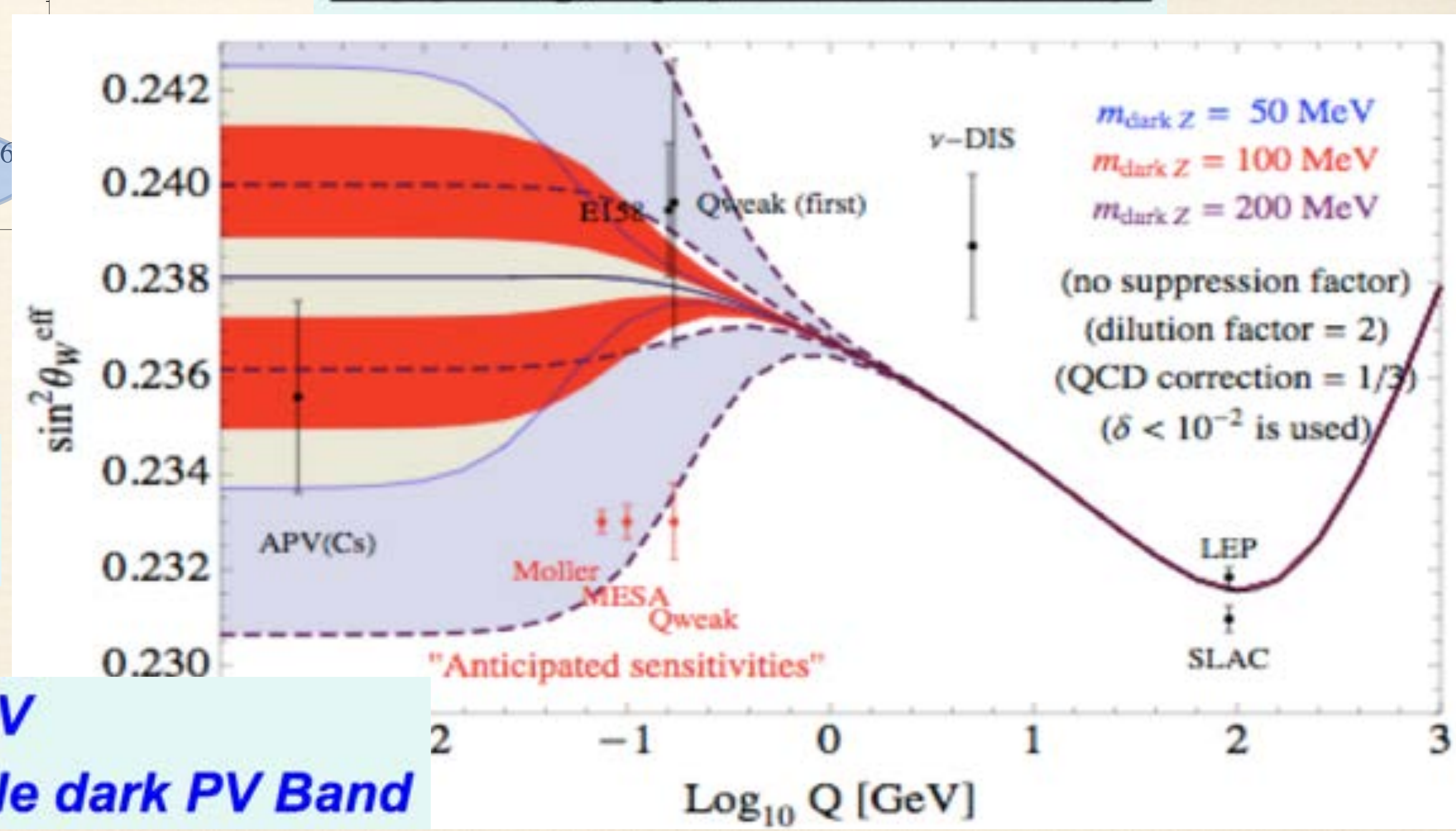
$$\epsilon_Z = \frac{m_{Z_d}}{M_Z}\delta$$

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

  APV & Polarized Electron Scattering at low <Q>

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

δ^2 roughly probed to 10^{-6}



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

ε and δ effects could partially cancel!

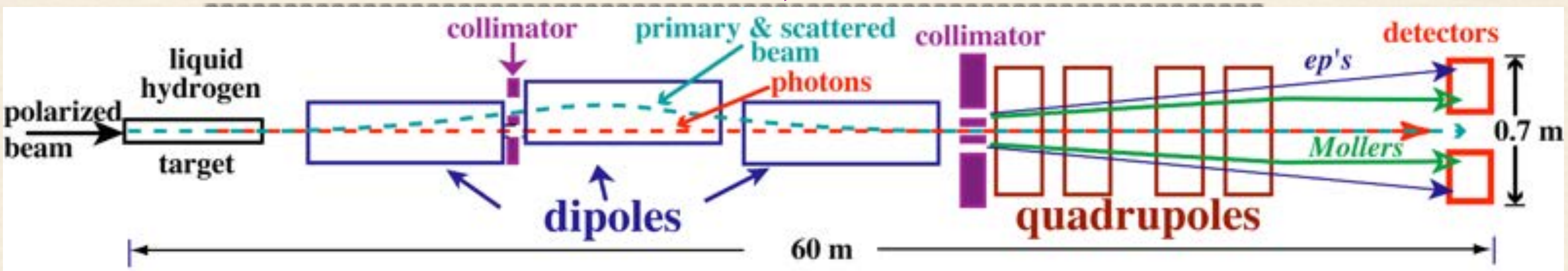
Suppression by ~1/6 allows Z_d~100MeV

Combined with muon g-2 → observable dark PV Band

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

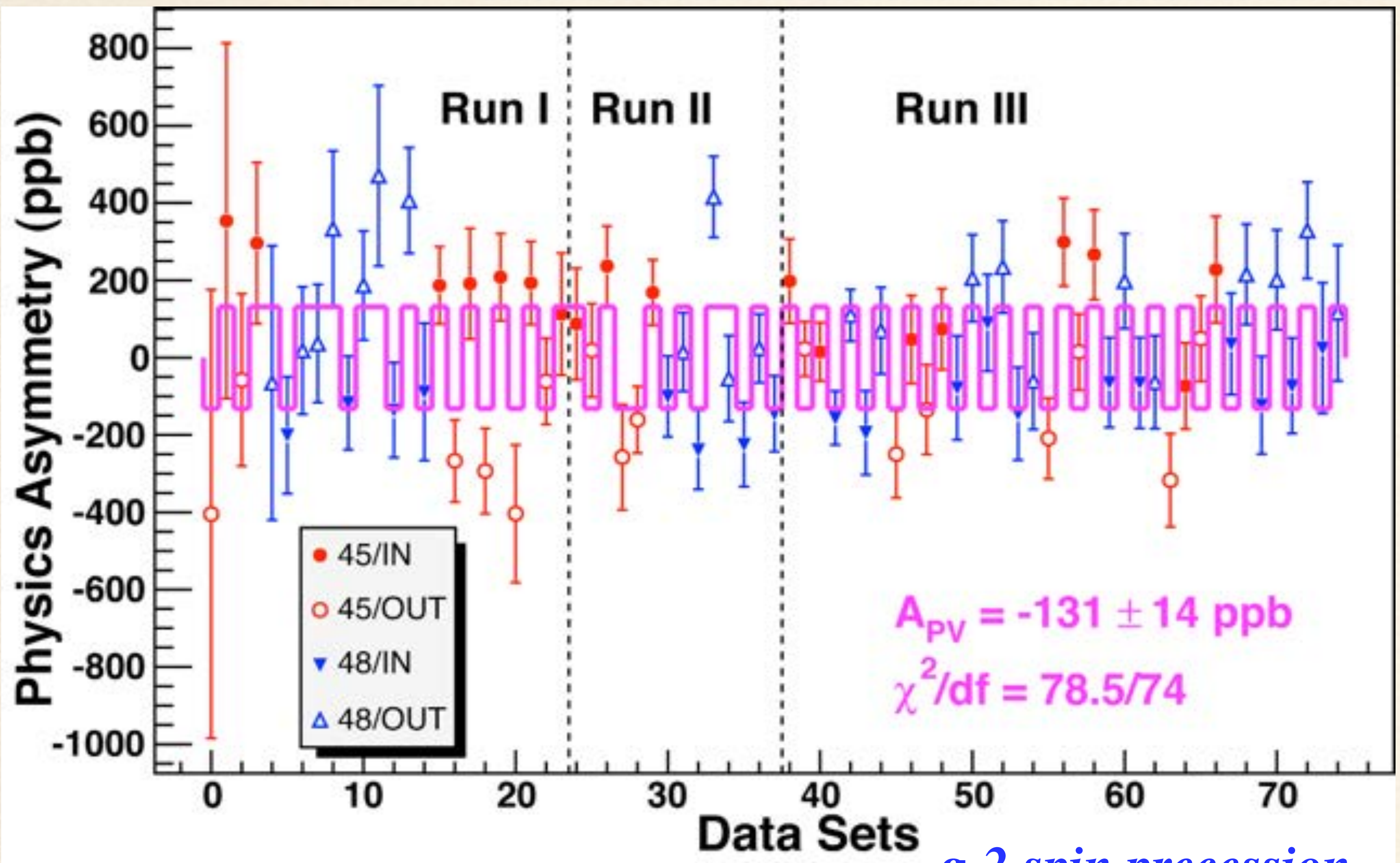


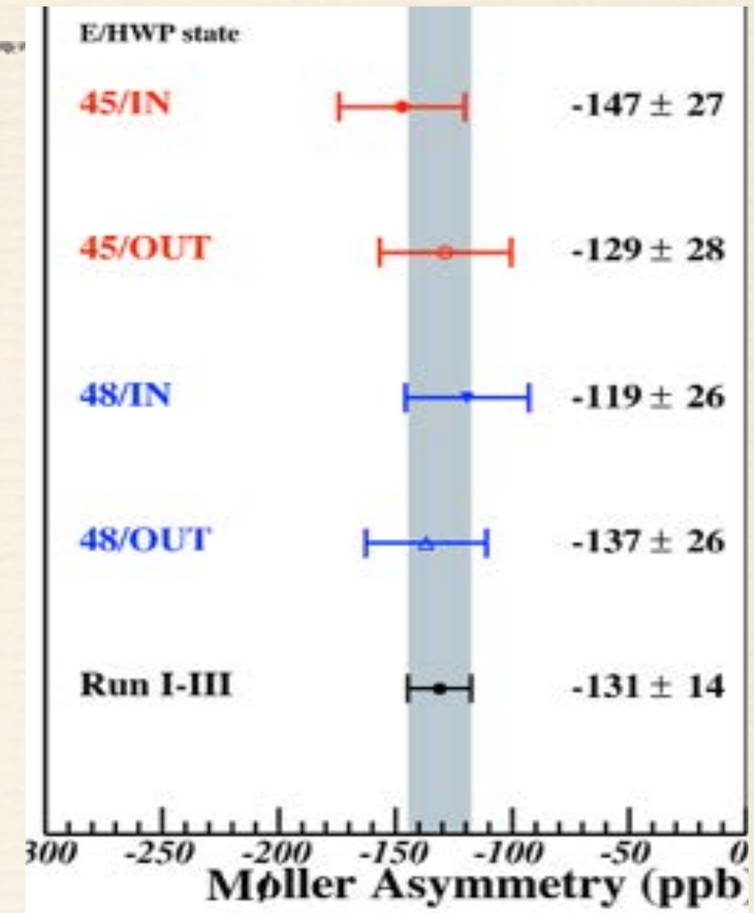
A large number of technical challenges

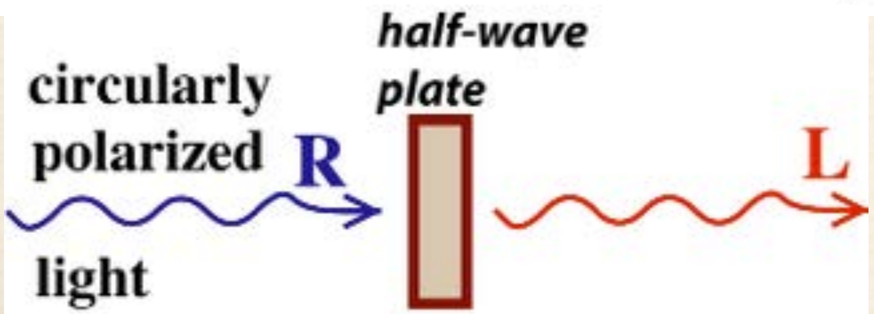
- 10 nm control of beam centroid on target
  - R&D on polarized source laser transport elements
- 12 microamp beam current maximum
  - 1.5 meter Liquid Hydrogen target
- 20 Million electrons per pulse @ 120 Hz
  - 200 ppm pulse-to-pulse statistical fluctuations
    - *Electronic noise and density fluctuations < 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



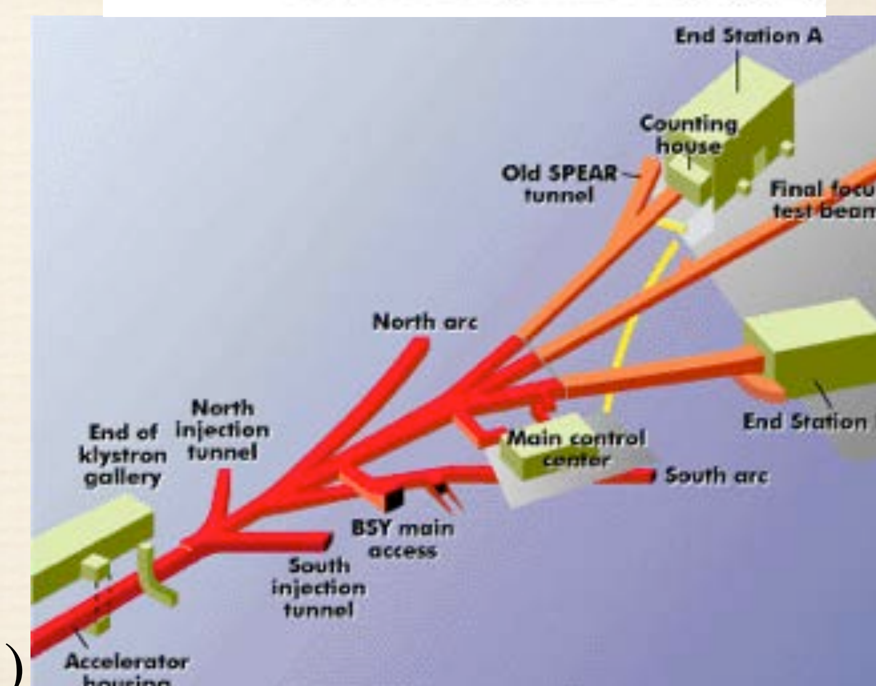




g-2 spin precession

45 GeV: 14.0 revs

48 GeV: 14.5 revs



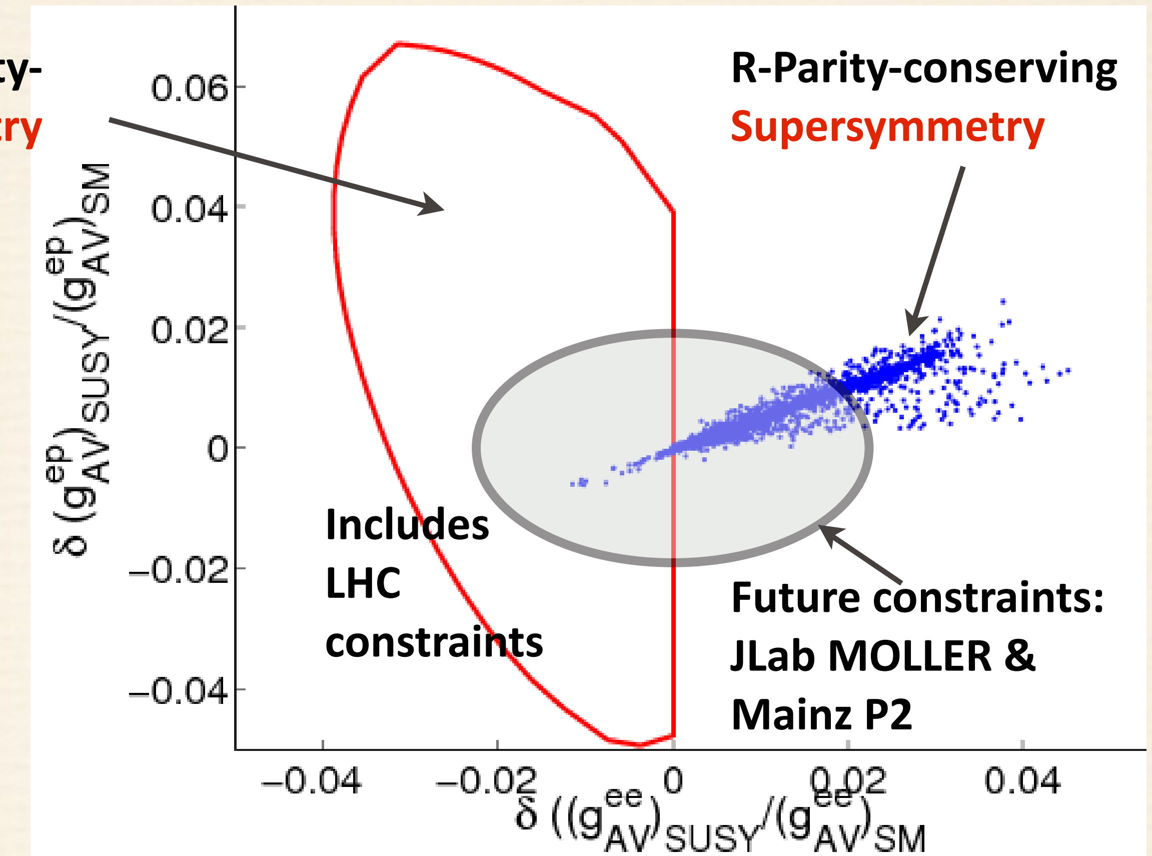
$$A_{PV} = (-131 \pm 14 \pm 10) \times 10^{-9}$$

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

Physics Examples: Beyond LHC

Z resonance measurements: little sensitivity to new contact interactions

Allowed region: R-Parity-violating Supersymmetry



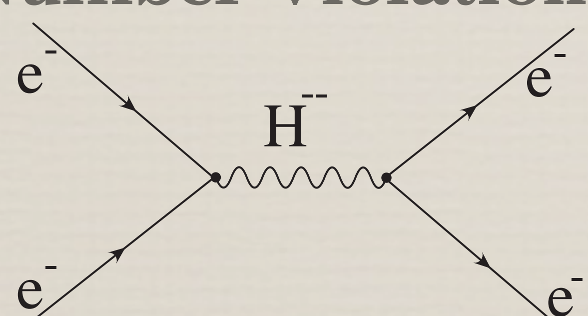
Ramsey-Musolf and Su, Phys. Rep. 456 (2008)

Erler and Su, arXiv:1303.5522

Lepton Number Violation

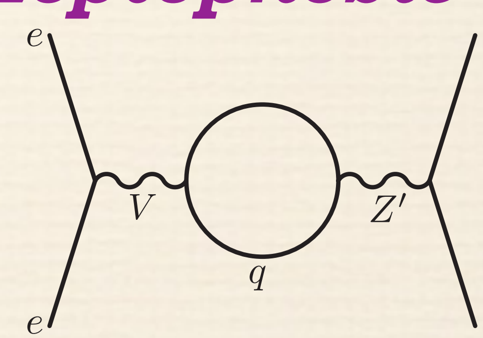
Λ > ***5 TeV***

Doubly-Charged Scalars



Significant reach beyond LEP-200

Leptophobic Z'



PVDIS can improve sensitivity:
100-200 GeV range