Long Range Plan Joint QCD Town Meeting
Temple University
September 13-15, 2014

Parity Violation and Hadron Structure

Recent Results and Future Prospects

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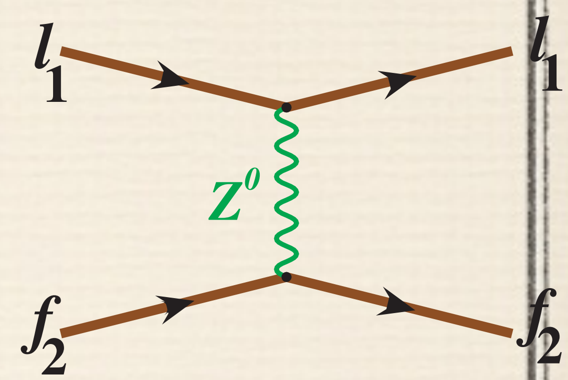
Stony Brook University, SUNY

Acknowledgments: K. Paschke, P. Souder, X. Zheng

Weak Neutral Current Interactions

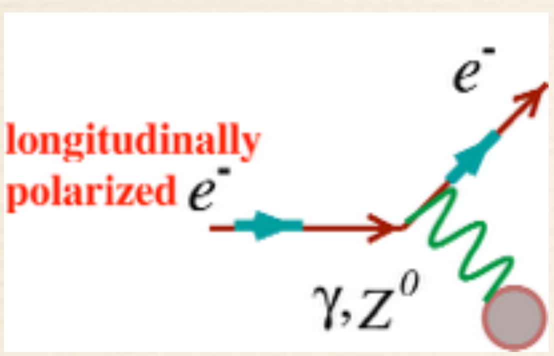


✦ **Precision Neutrino Scattering**

✦ **New Physics/Weak-Electromagnetic Interference**

- *opposite parity transitions in heavy atoms*
- *Spin-dependent electron scattering*

Parity-violating Electron Scattering

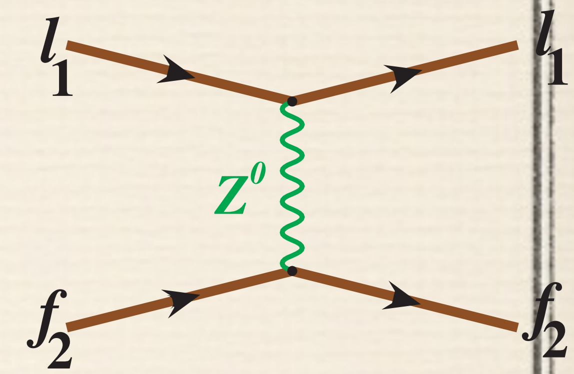


$$-A_{LR} = A_{PV} = \frac{\sigma_\uparrow - \sigma_\downarrow}{\sigma_\uparrow + \sigma_\downarrow} \sim \frac{A_{weak}}{A_\gamma} \sim \frac{G_F Q^2}{4\pi\alpha}(g_A^e g_V^T + \beta g_V^e g_A^T)$$

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

$$A_{PV} \sim 10^{-5} \cdot Q^2 \quad \textit{to} \quad 10^{-4} \cdot Q^2$$

Weak Neutral Current Interactions



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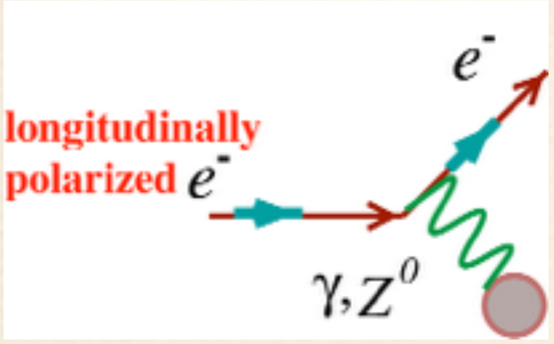

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Specific choices of kinematics and target nuclei probes different physics:

- *In mid 70s, goal was to show $\sin^2\theta_W$ was the same as in neutrino scattering*
- *Since early 90's: target couplings probe novel aspects of hadron structure (strange quark form factors, neutron RMS radius of nuclei)*
- *Future: precision measurements with carefully chosen kinematics can probe physics at the multi-TeV scale, and novel aspects of nucleon structure*

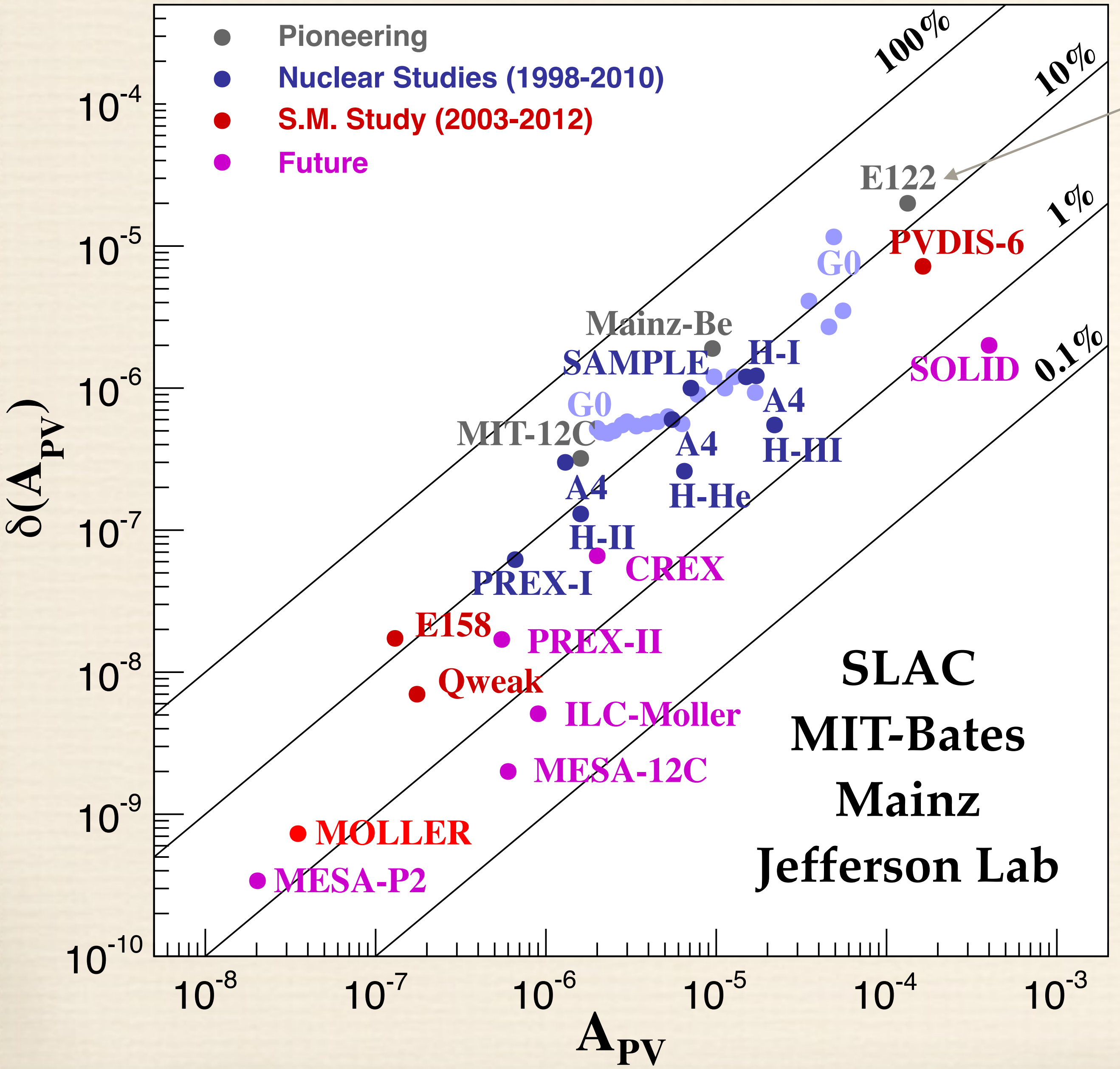
Continuous interplay between probing hadron structure and electroweak physics

Outline

Parity-violating electron scattering has become a precision tool

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

PVeS Experiment Summary



Pioneering electron-quark PV DIS experiment SLAC E122

State-of-the-art:

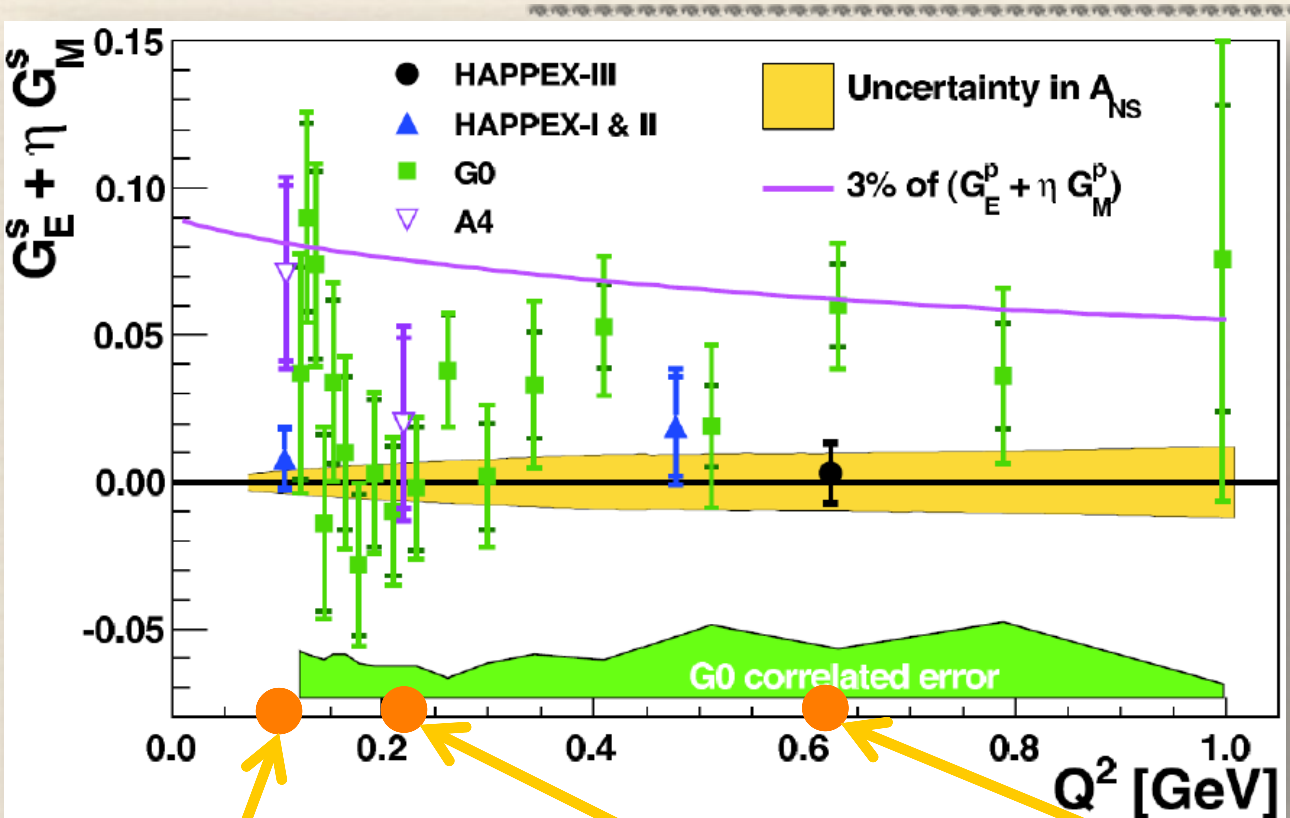
- *sub-part per billion statistical reach and systematic control*
- *sub-1% normalization control*

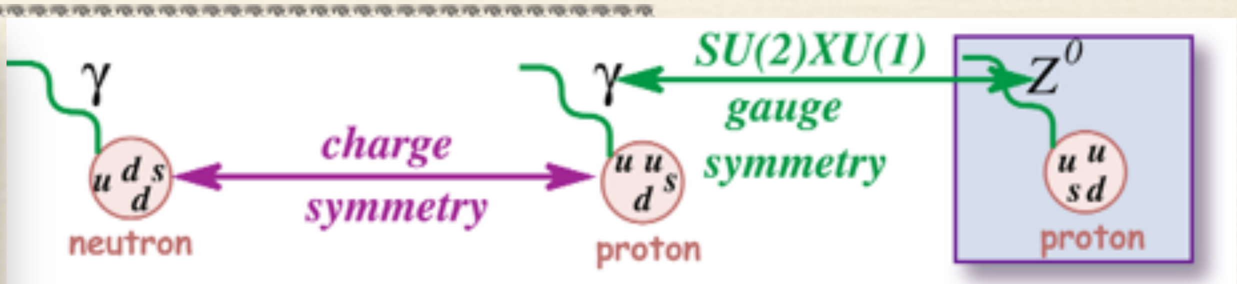
- *Strange Quark Form Factors*
- *Neutron skin of a heavy nucleus*
- *Indirect Searches for New TeV Physics*
- *Novel Probes of Nucleon Structure*
- *Electroweak Structure Functions at an EIC*

2011: Completion of a 2-decade program

Strange Quarks Form Factors

SC Milestone HP4 on Flavor Separated Form Factors at $Q^2 < 1\ GeV^2$

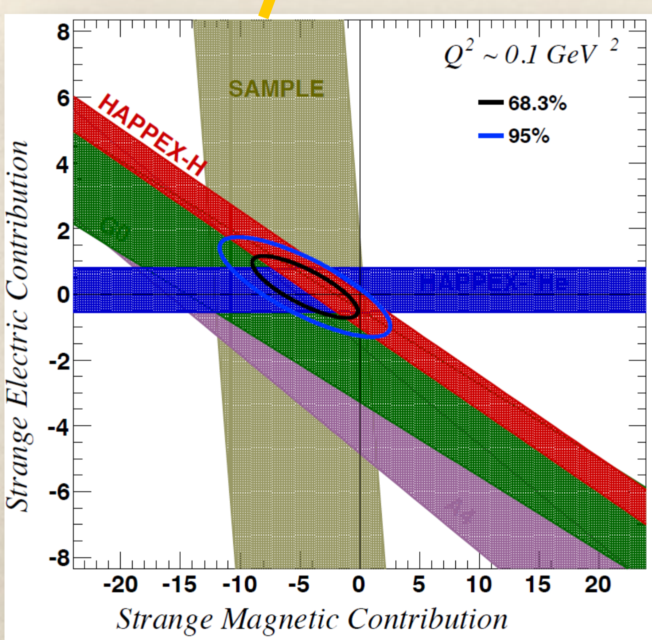


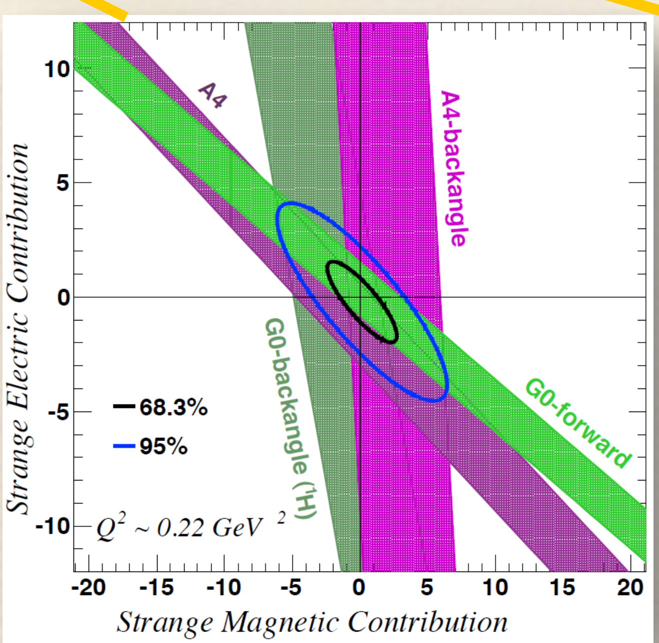


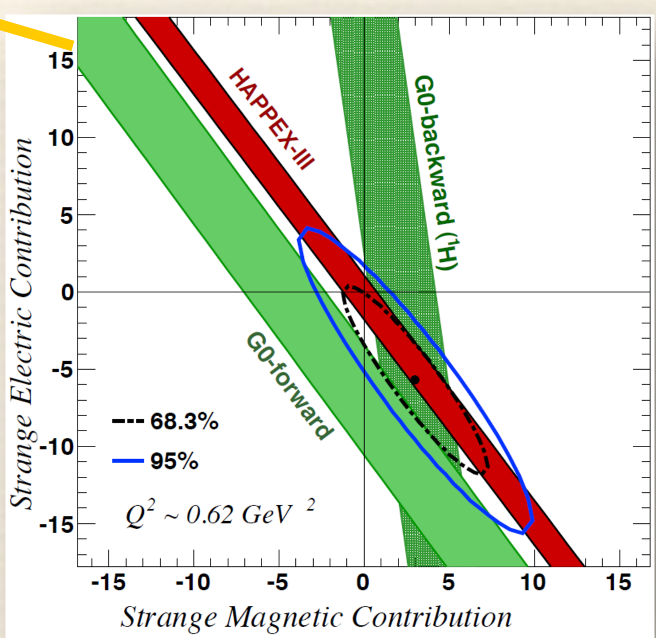
$$G_p^Z \sim (1 - 4\sin^2\theta_W)\, G_p^\gamma - G_n^\gamma - G_s$$

$\Rightarrow$ $G_E^s(Q^2), G_M^s(Q^2)$

- Sensitive Flavor separation at 3 Q^2 values
- No more than few % of EM structure
- Recent lattice results in agreement

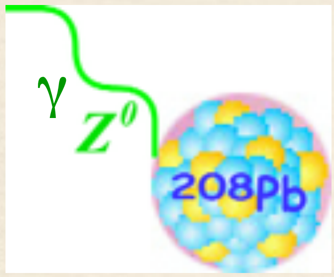






Pb-Radius EXperiment

EW Probe of Neutron Densities



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

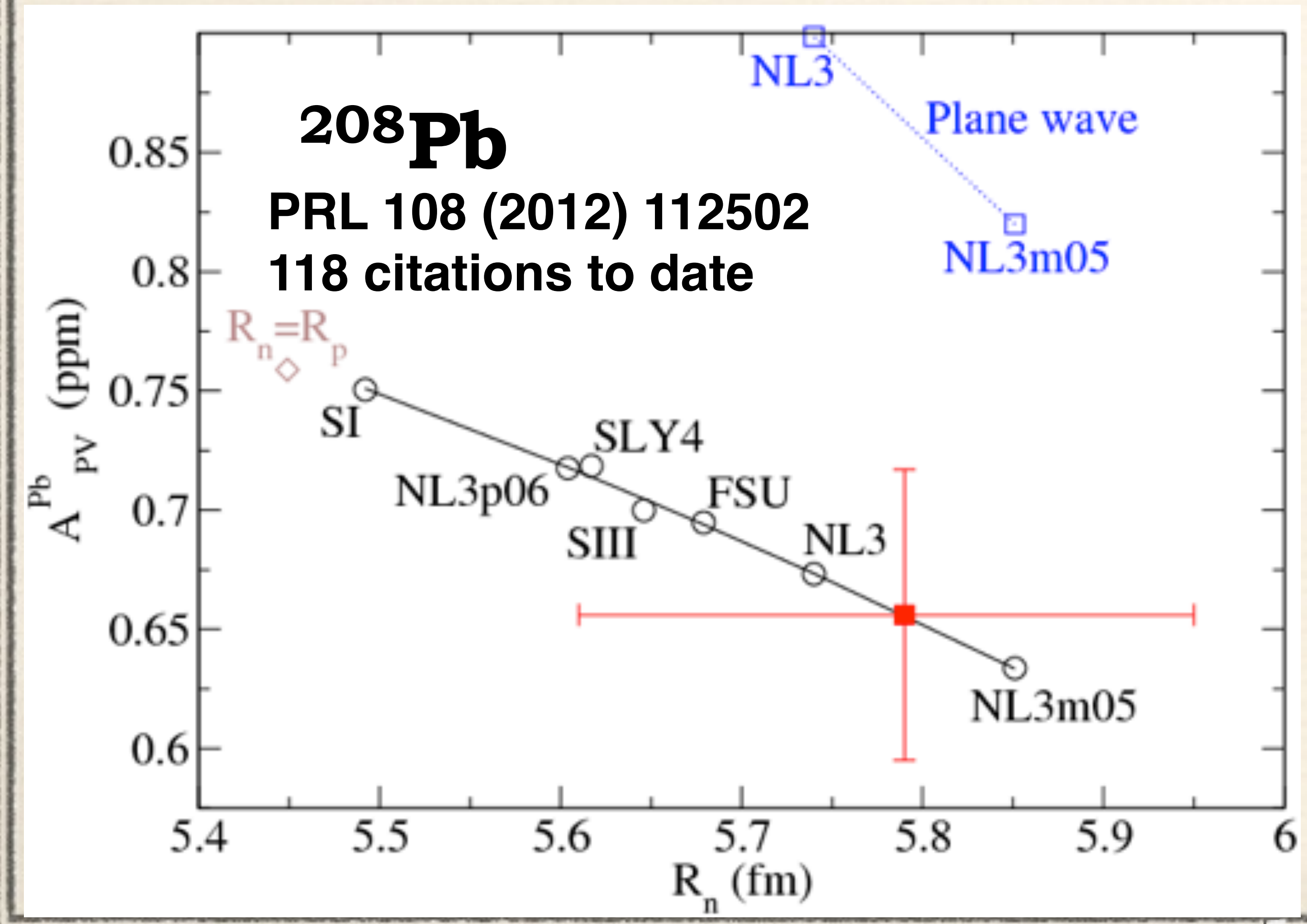
$Q^p_{EM} \sim 1$ $Q^n_{EM} \sim 0$ $Q^n_W \sim -1$ $Q^p_W \sim 1 - 4\sin^2\theta_W$

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

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

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

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



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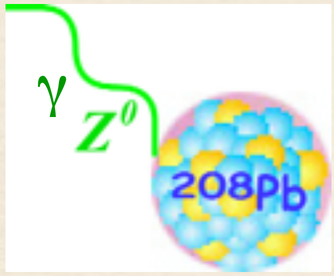

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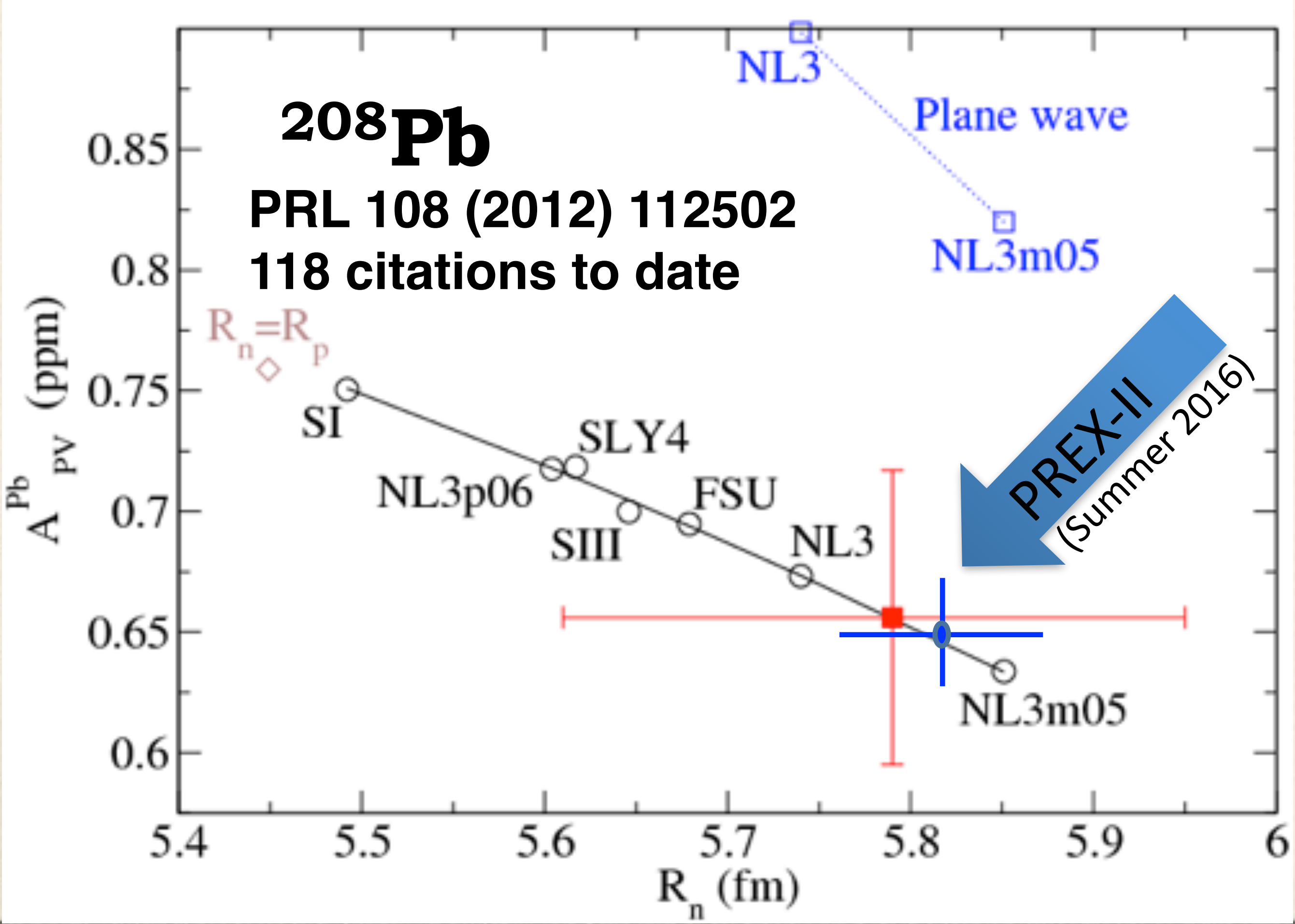

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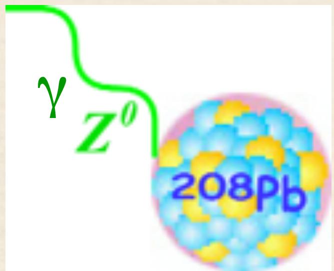

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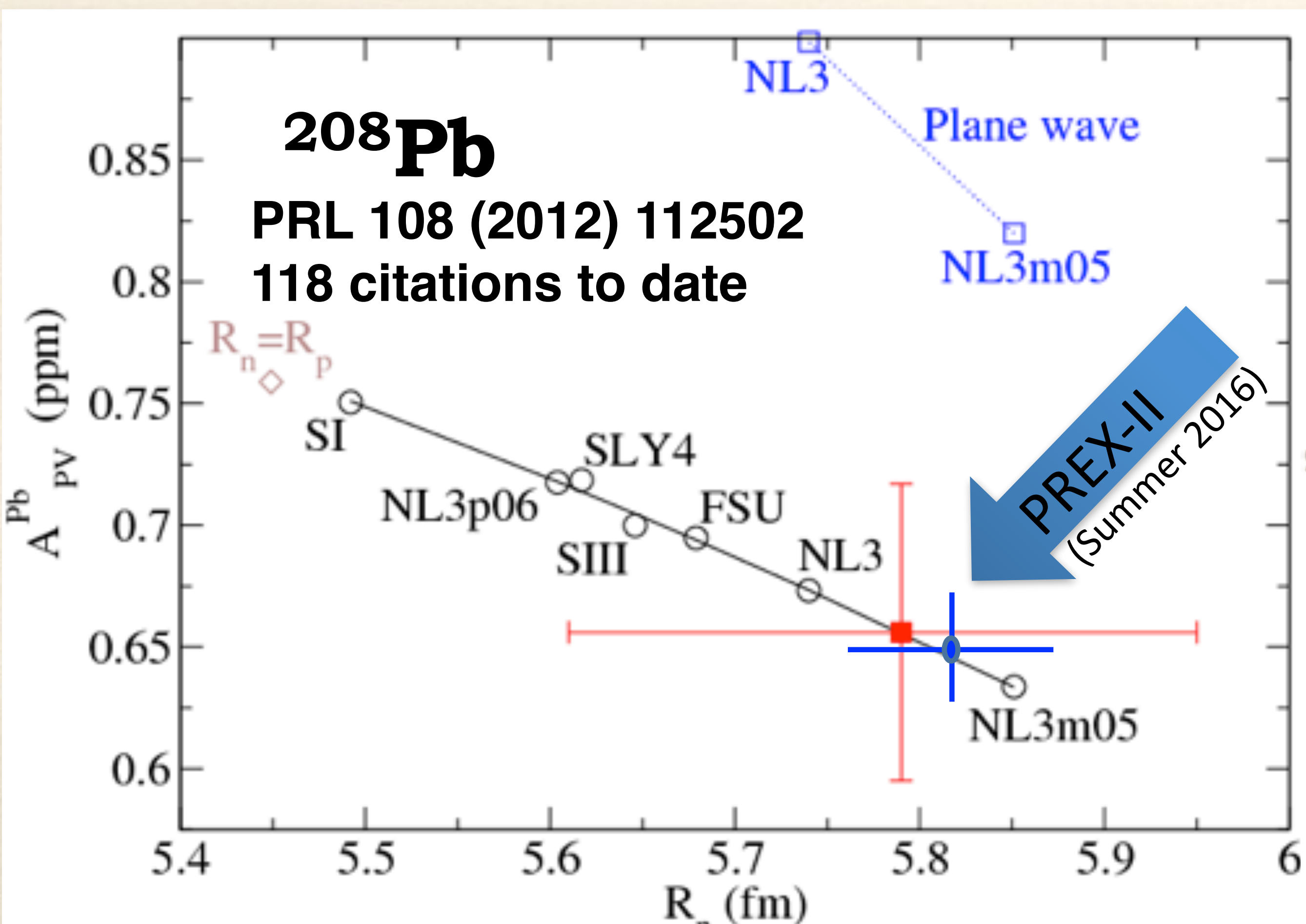
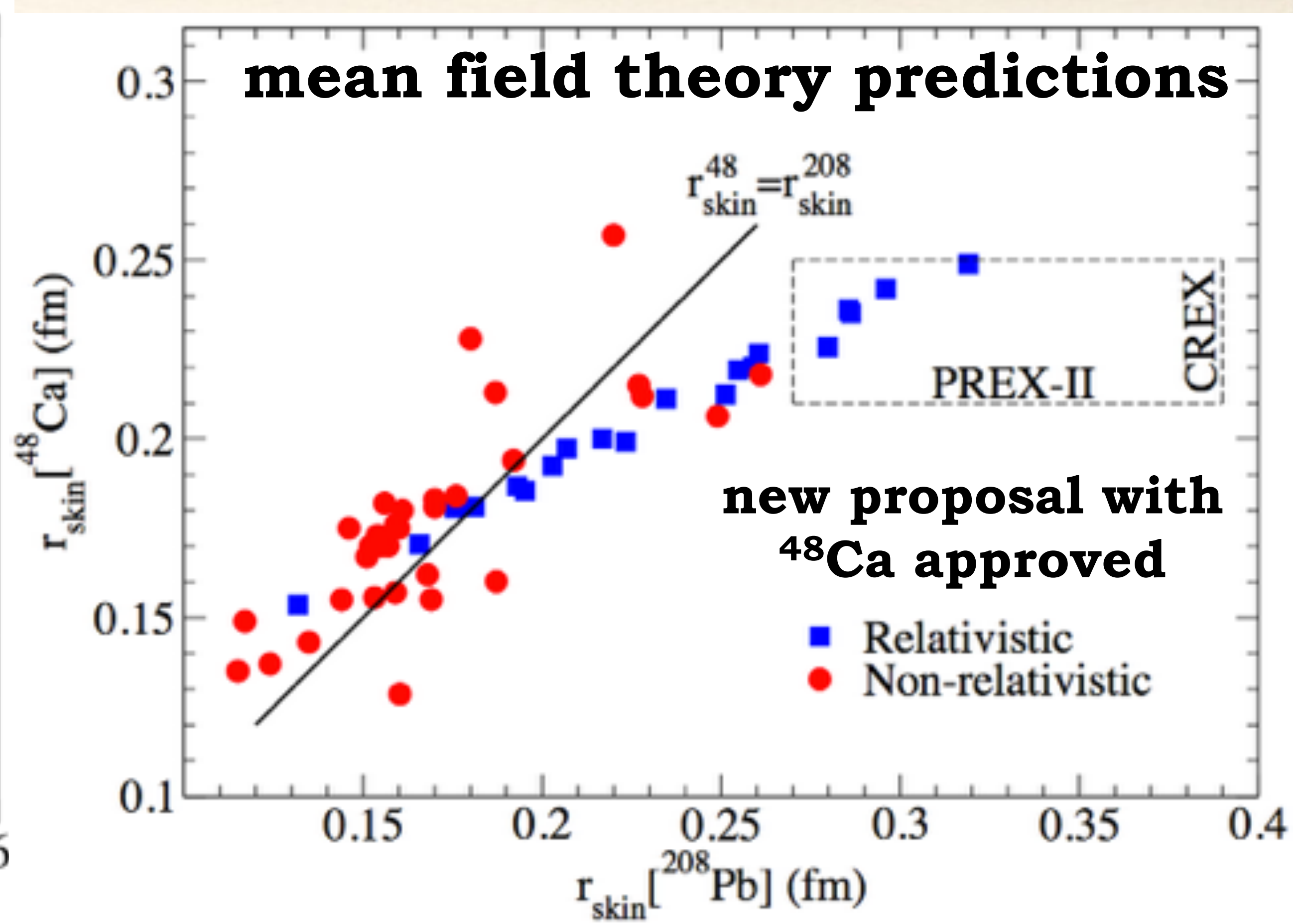


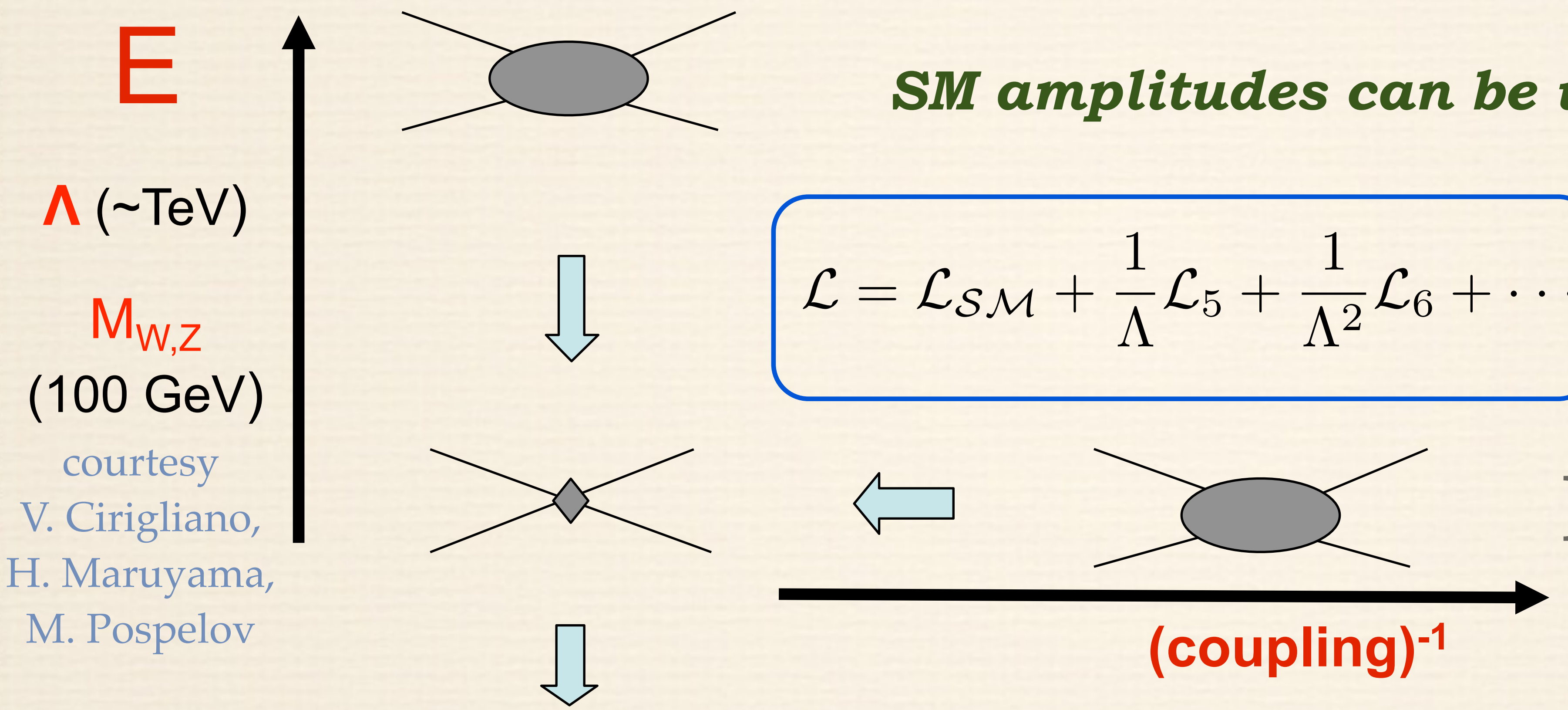


Electroweak Interactions at scales much lower than the W/Z mass

TeV-Scale Probe: Indirect Clues

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

High Energy Dynamics



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

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

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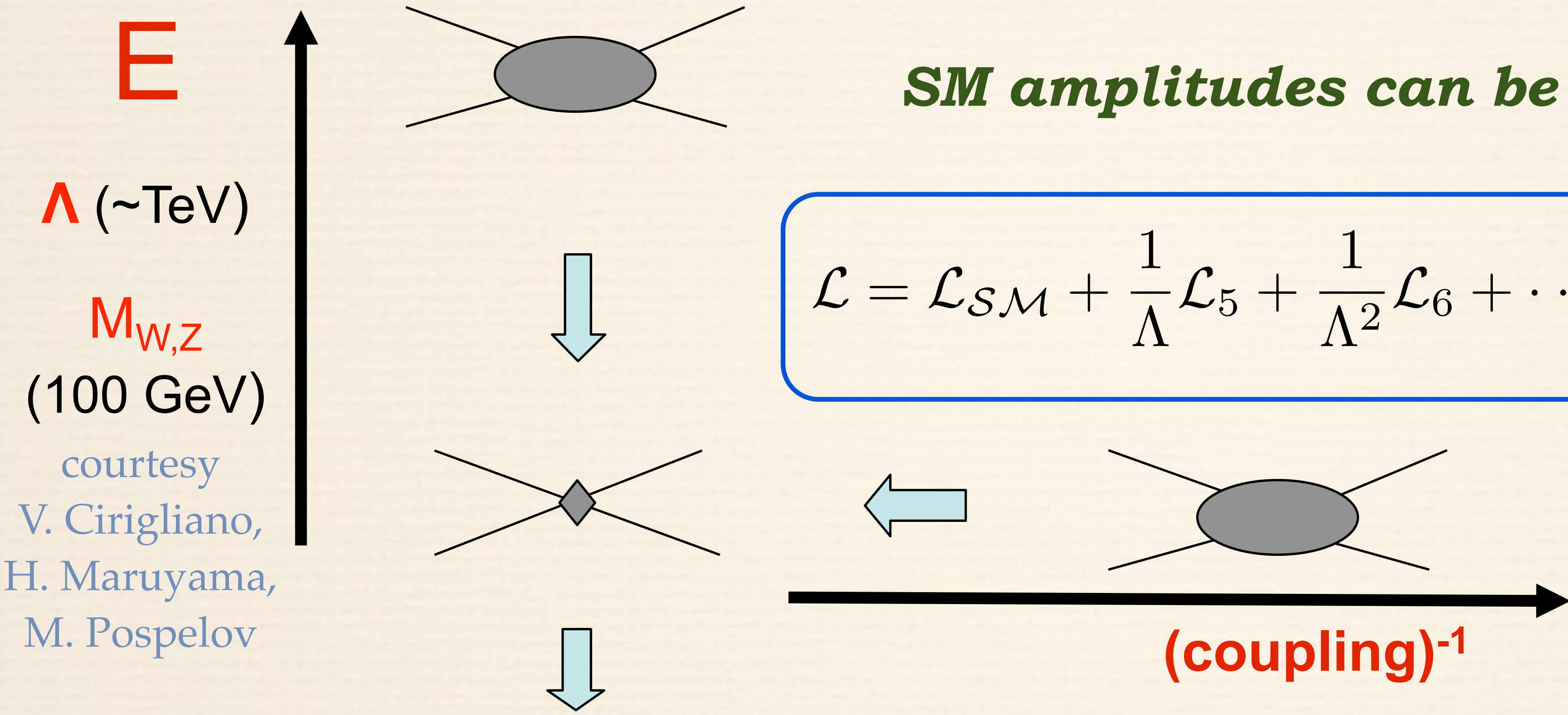

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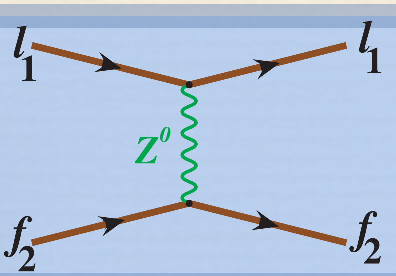
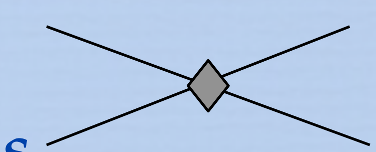
Dark Sector

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



Search for new flavor diagonal neutral currents

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



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

must reach Λ ~ 10 TeV

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Interplay between electroweak and hadron dynamics

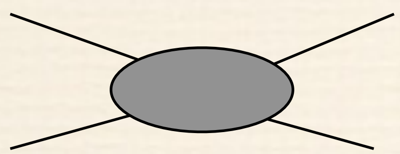
High Energy Dynamics

E

Λ (~TeV)

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

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



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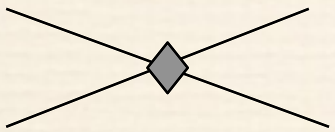

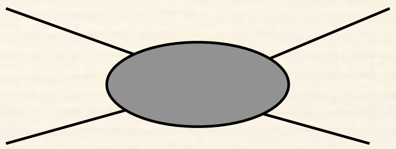

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(coupling)$^{-1}$

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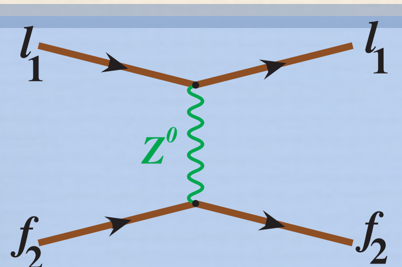

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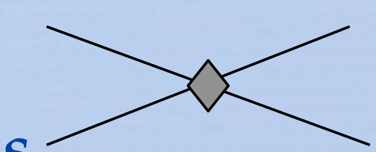

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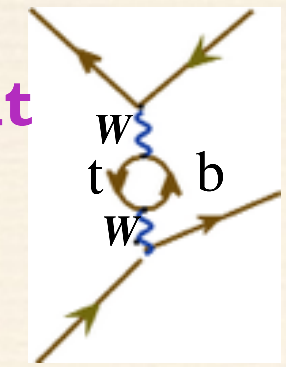
Weak Mixing Angle at 1-Loop

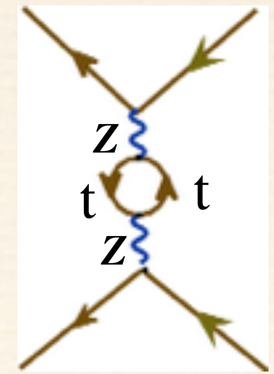
For electroweak interactions, 3 input parameters needed:

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

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

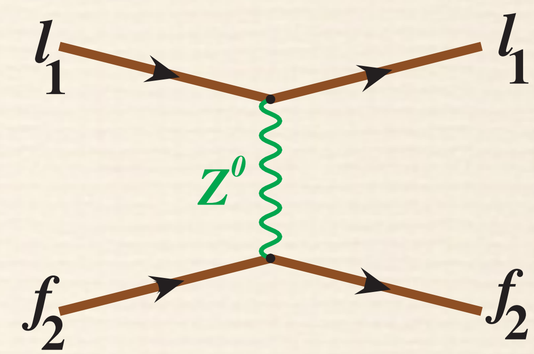


Muon decay



Z production

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



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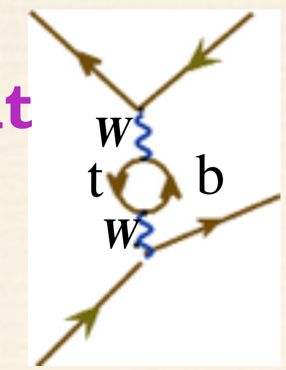

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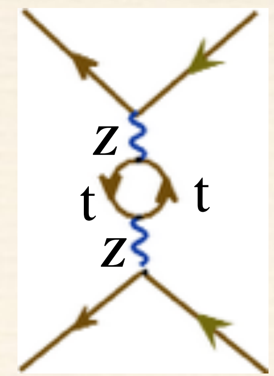

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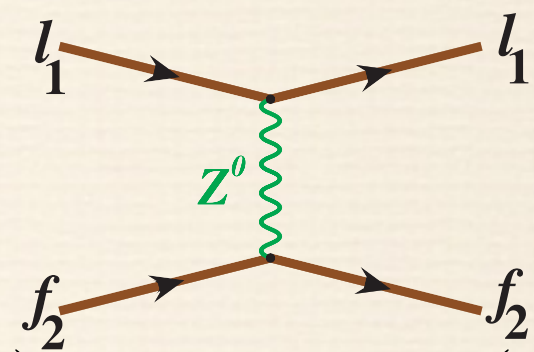

Weak Neutral Current interactions

LEP-I, SLC, LEP-II, Tevatron

World Averages

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

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

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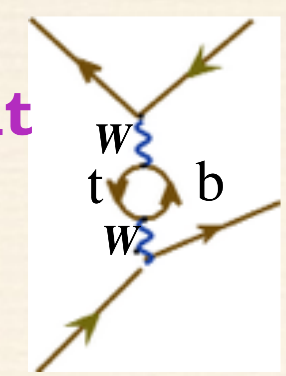

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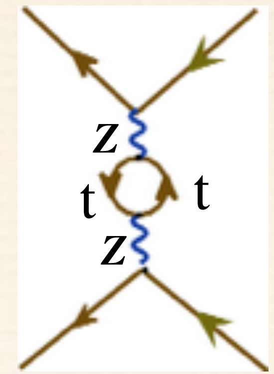

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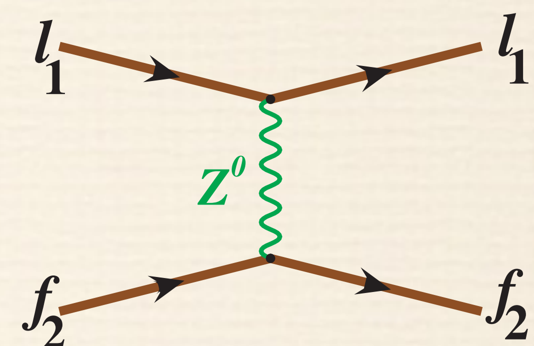

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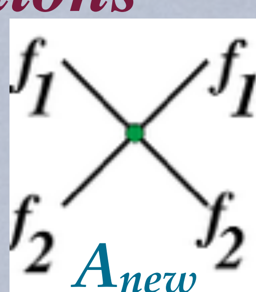
$$L_{f_1 f_2} = \sum_{i,j=L,R} \frac{4\pi}{\Lambda_{ij}^2} \eta_{ij} \bar{f}_{1i}\gamma_\mu f_{1i} \bar{f}_{2j}\gamma^\mu f_{2j}$$



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

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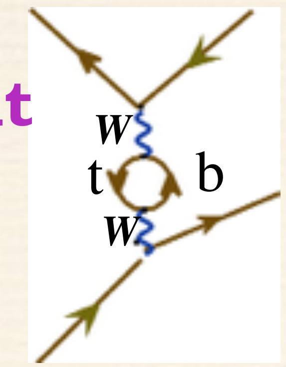

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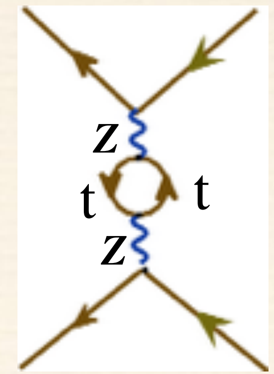

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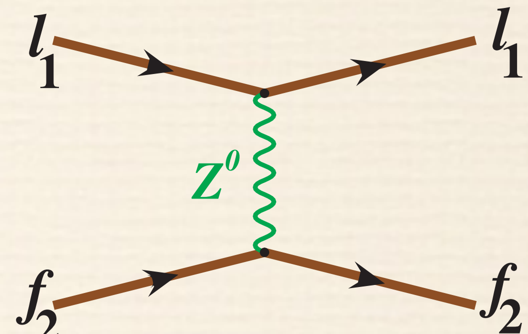

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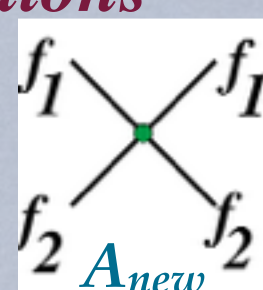


New heavy physics that does not couple directly to SM gauge bosons

on resonance: A_Z is imaginary

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

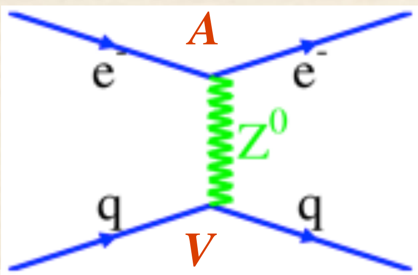
no interference!

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

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

Elastic and deep-inelastic PV scattering

Weak Neutral Current Couplings



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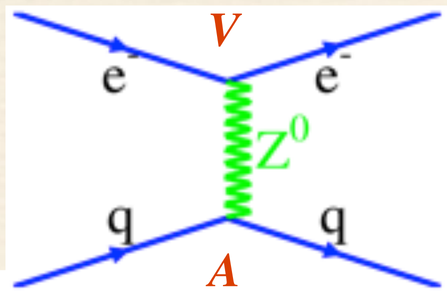

$C_{2i} \equiv 2g_V^e g_A^i$

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

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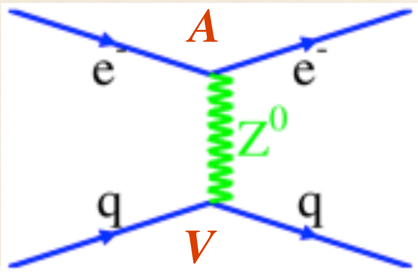

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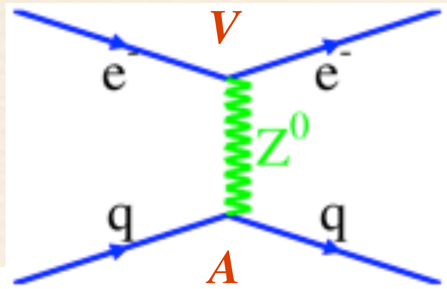

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C_{1u}	$=$	$-\frac{1}{2}+\frac{4}{3}\sin^2\theta_W$	$\approx$	-0.19
C_{1d}	$=$	$\frac{1}{2}-\frac{2}{3}\sin^2\theta_W$	$\approx$	0.35
C_{2u}	$=$	$-\frac{1}{2}+2\sin^2\theta_W$	$\approx$	-0.04
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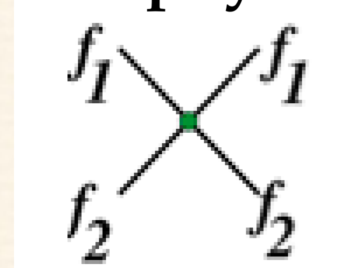
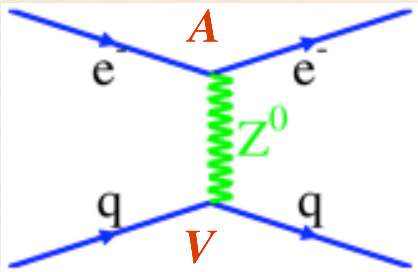
$+$

new physics



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

Weak Neutral Current Couplings



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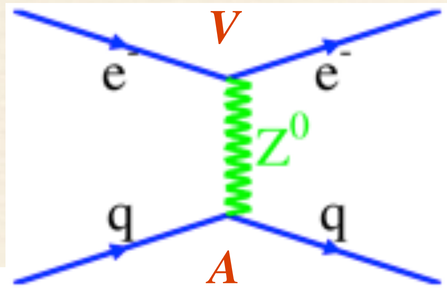

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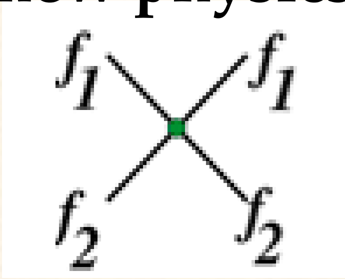

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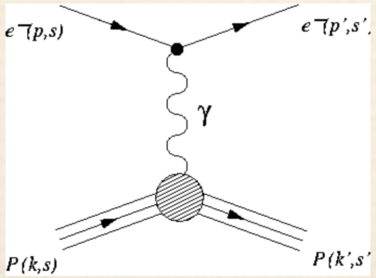
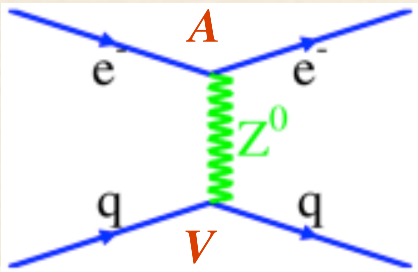
$$C_{1q} \propto (g_{RR}^{eq})^2 + (g_{RL}^{eq})^2 - (g_{LR}^{eq})^2 - (g_{LL}^{eq})^2$$

PV elastic e-p scattering, Atomic parity violation



Elastic and deep-inelastic PV scattering

Weak Neutral Current Couplings



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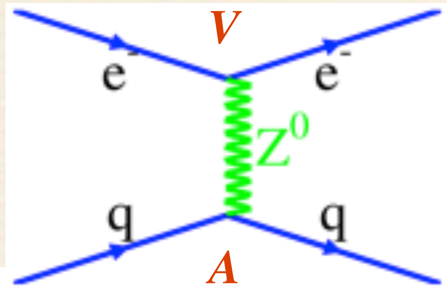

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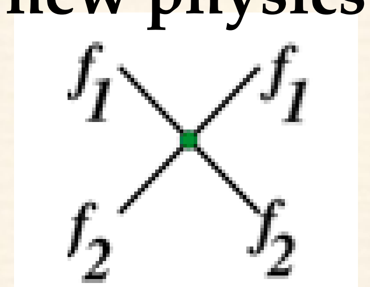
new physics



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PV elastic e-p scattering, Atomic parity violation

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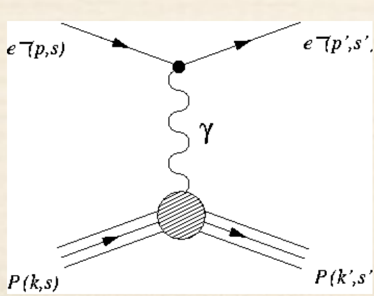
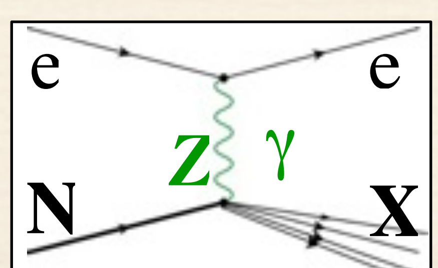
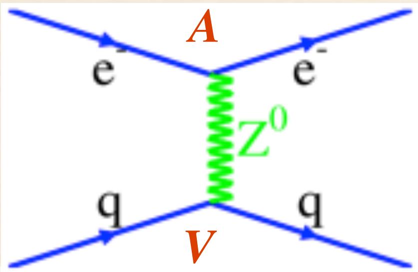
PV deep inelastic scattering





Elastic and deep-inelastic PV scattering

Weak Neutral Current Couplings



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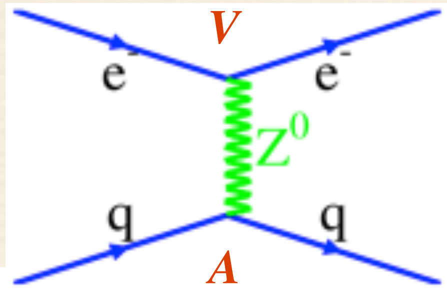

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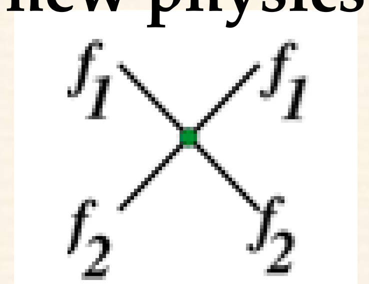
+ **new physics**



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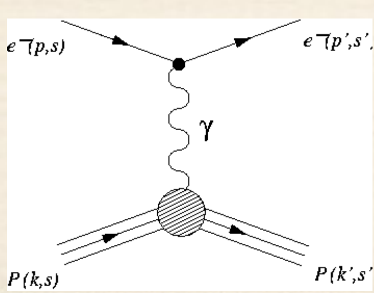
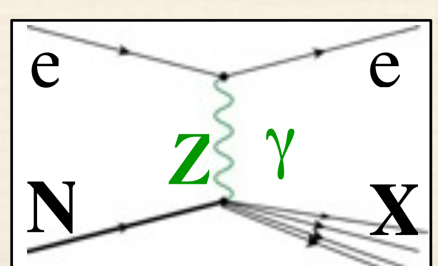
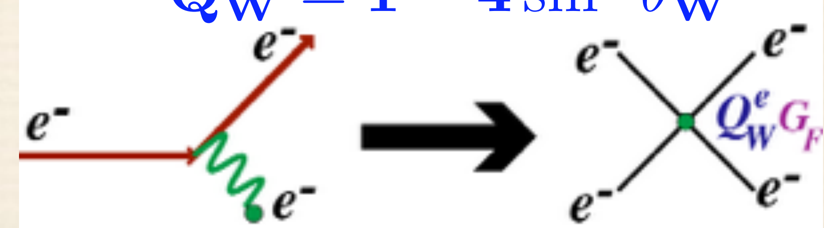


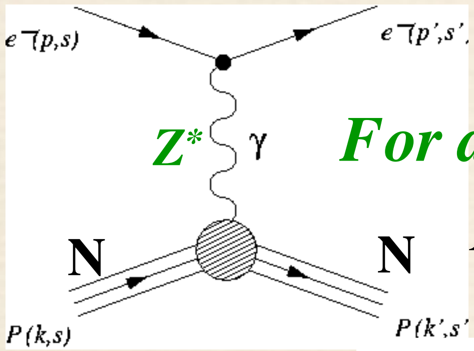


$\mathbf{Q_W = 1 - 4\sin^2\theta_W}$



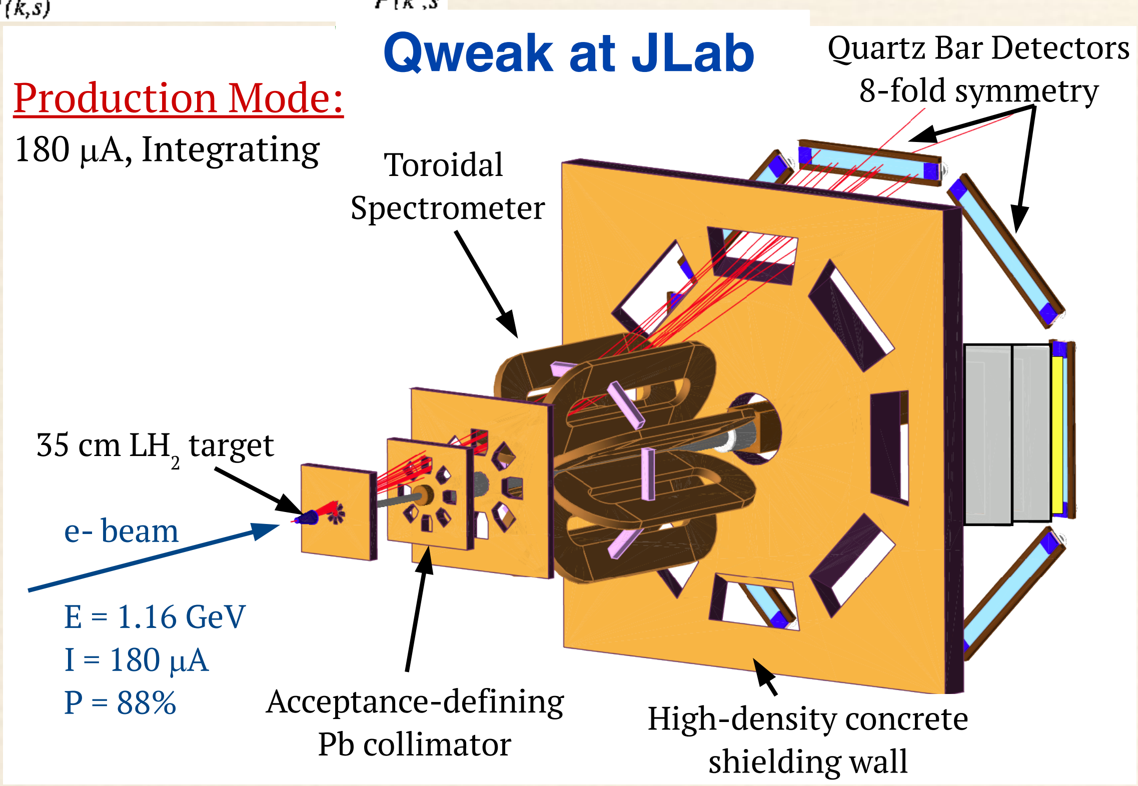
A_{PV} in elastic e-p scattering:

The Weak Charge of the Proton



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

$$A(Q^2 \to 0) = -\frac{G_F}{4\pi\alpha\sqrt{2}}\left[Q^2 \boxed{Q^p_{weak}} + Q^4 B\left(Q^2\right)\right] \quad Q^p_{weak} = 2C_{1u} + C_{1d} \propto 1 - 4\sin^2\vartheta_W$$



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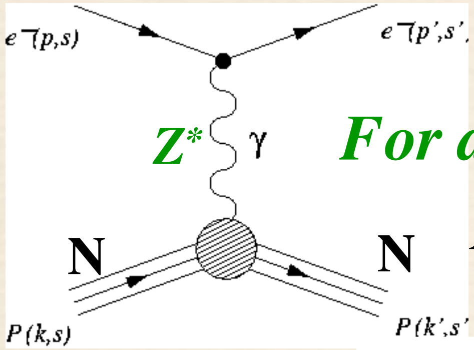

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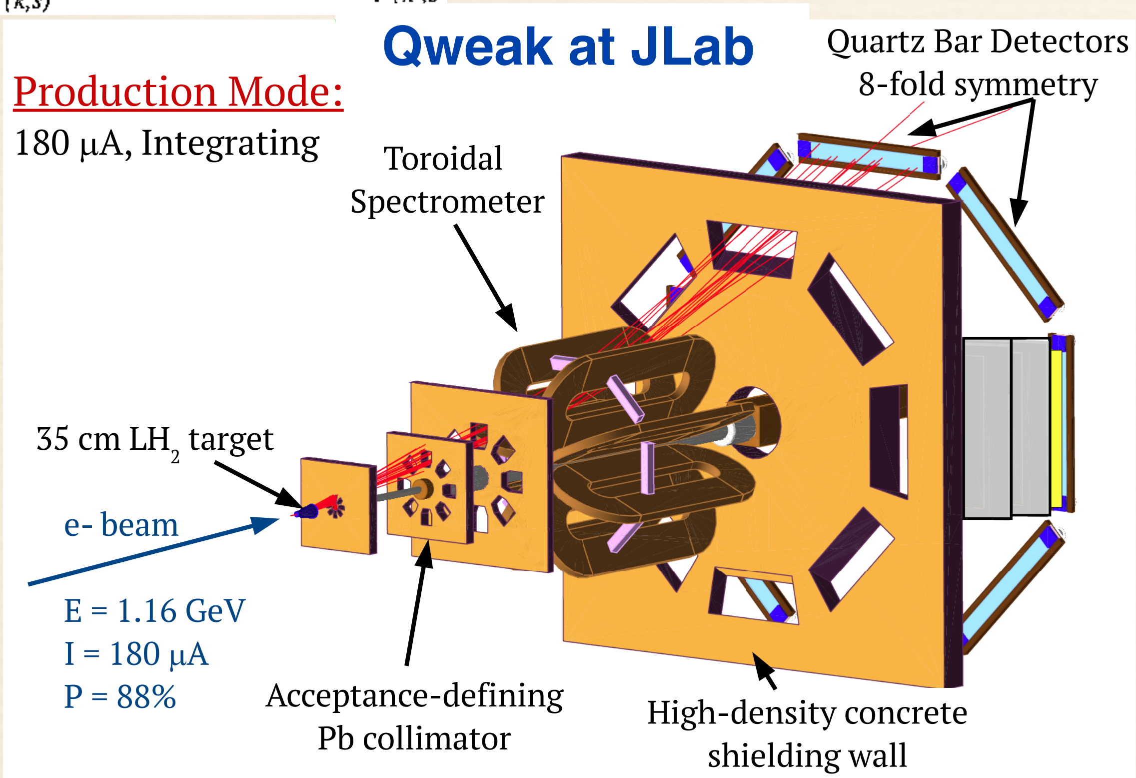

Run 0 Results (1/25th of total dataset) – published in PRL **111**, 141803 (2013)

$$A_{ep} = -279 \pm 35(\text{stat}) \pm 31(\text{syst})\ \text{ppb} \quad \text{at} \quad \left\langle Q^2 \right\rangle = 0.0250\ (\text{GeV}/c)^2$$

$$\boxed{Q^p_W(\text{PVES}) = 0.064 \pm 0.012 \qquad Q^p_W(\text{SM}) = 0.0710 \pm 0.0007}$$

First determination of proton's weak charge in good agreement with Standard Model

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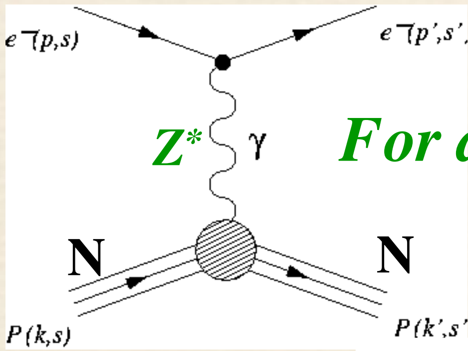

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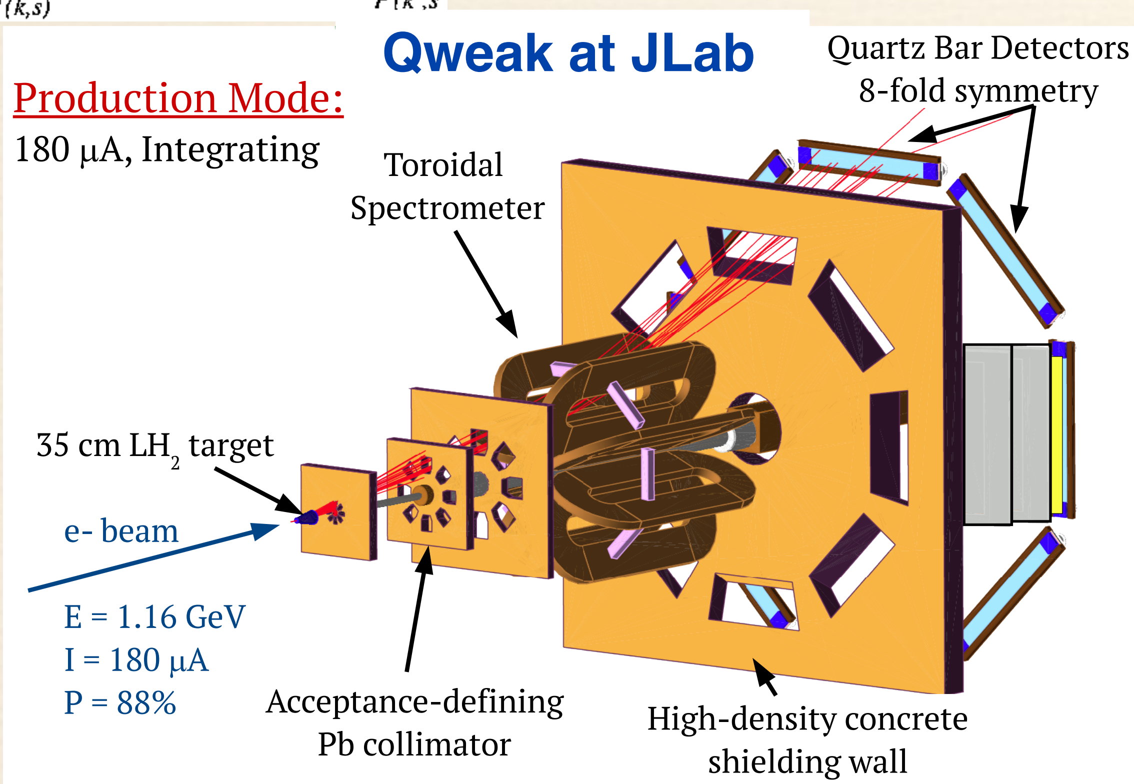

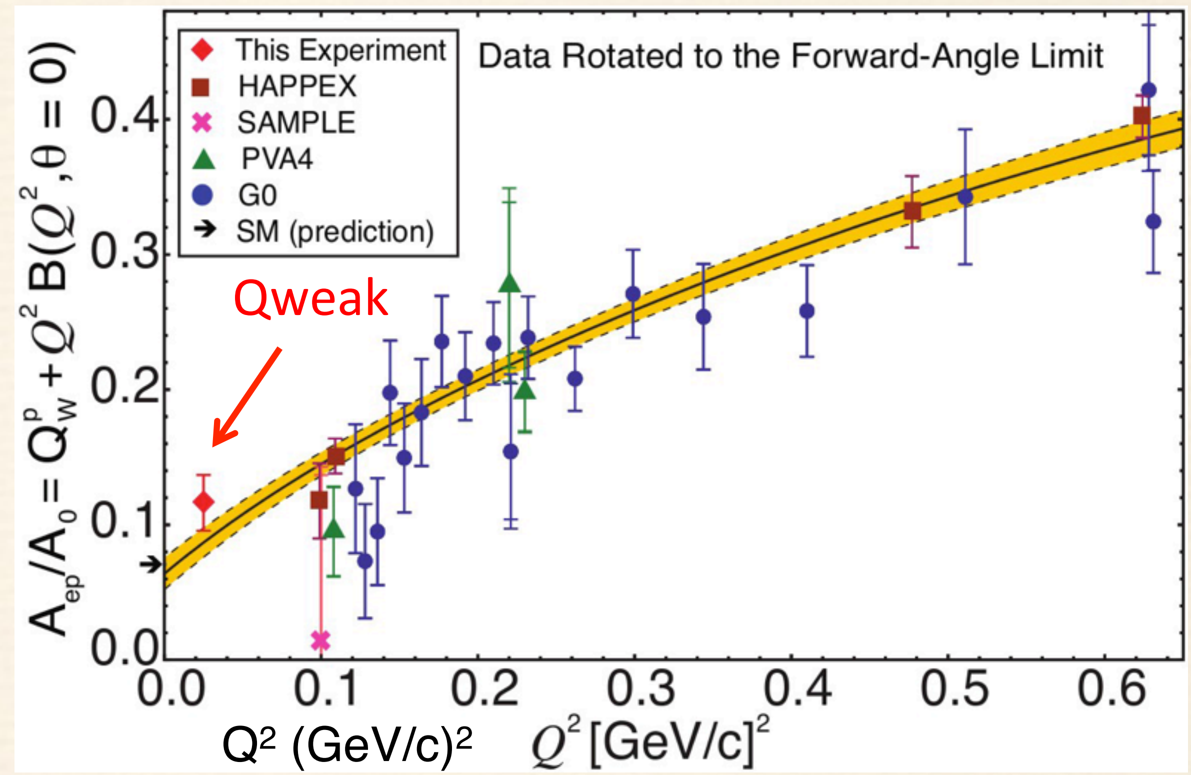

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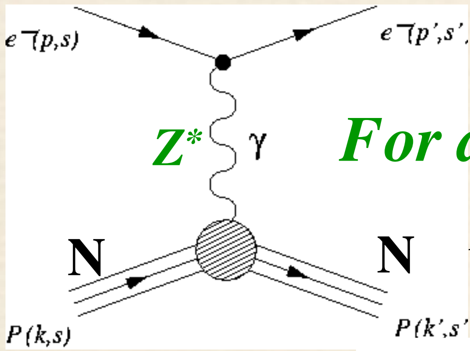

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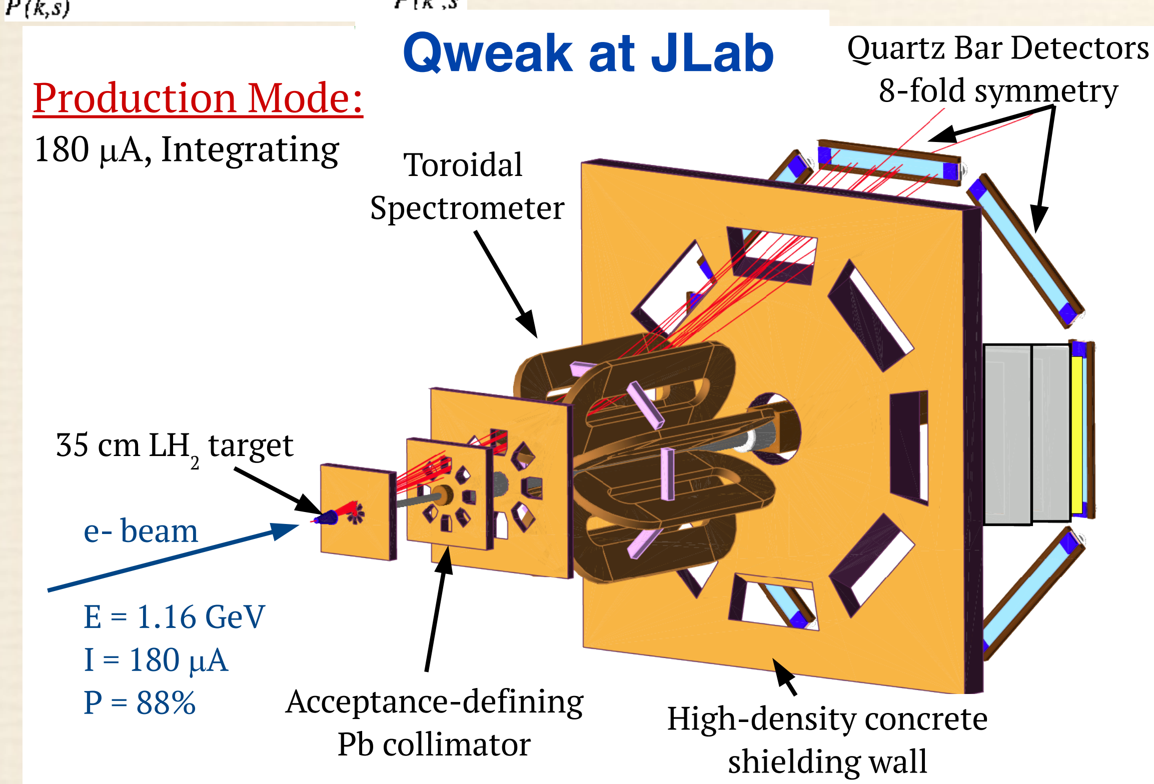

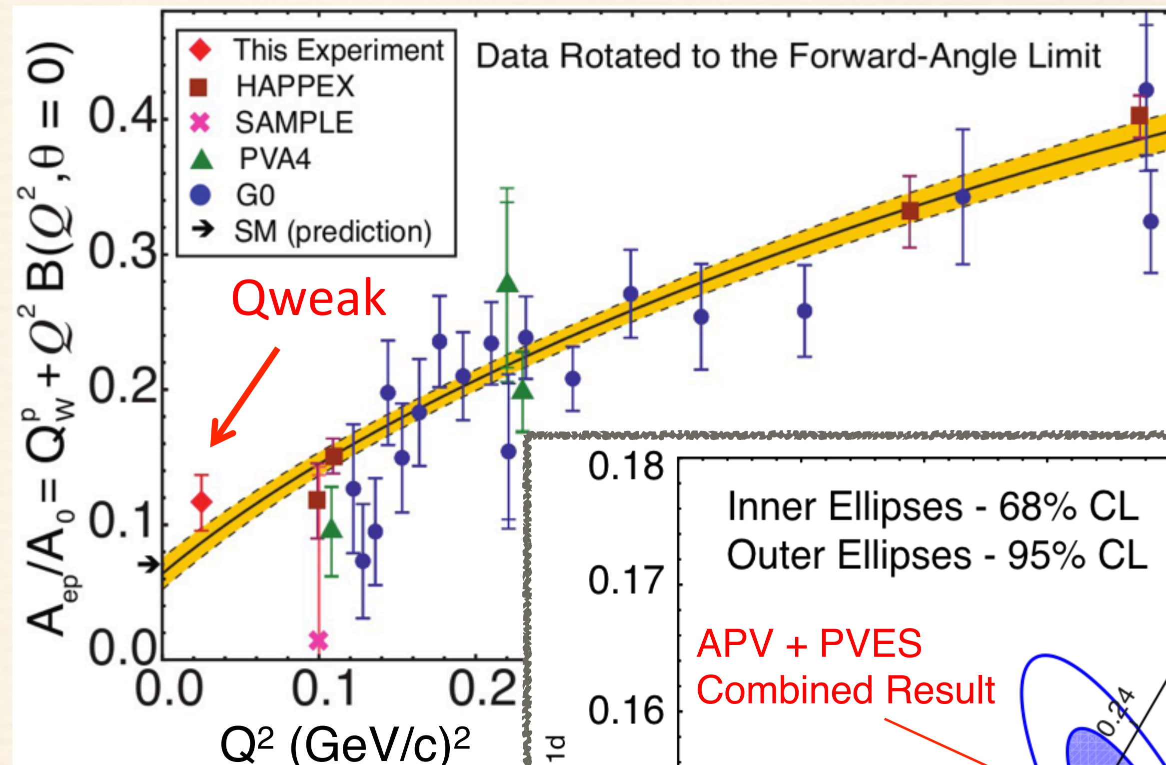

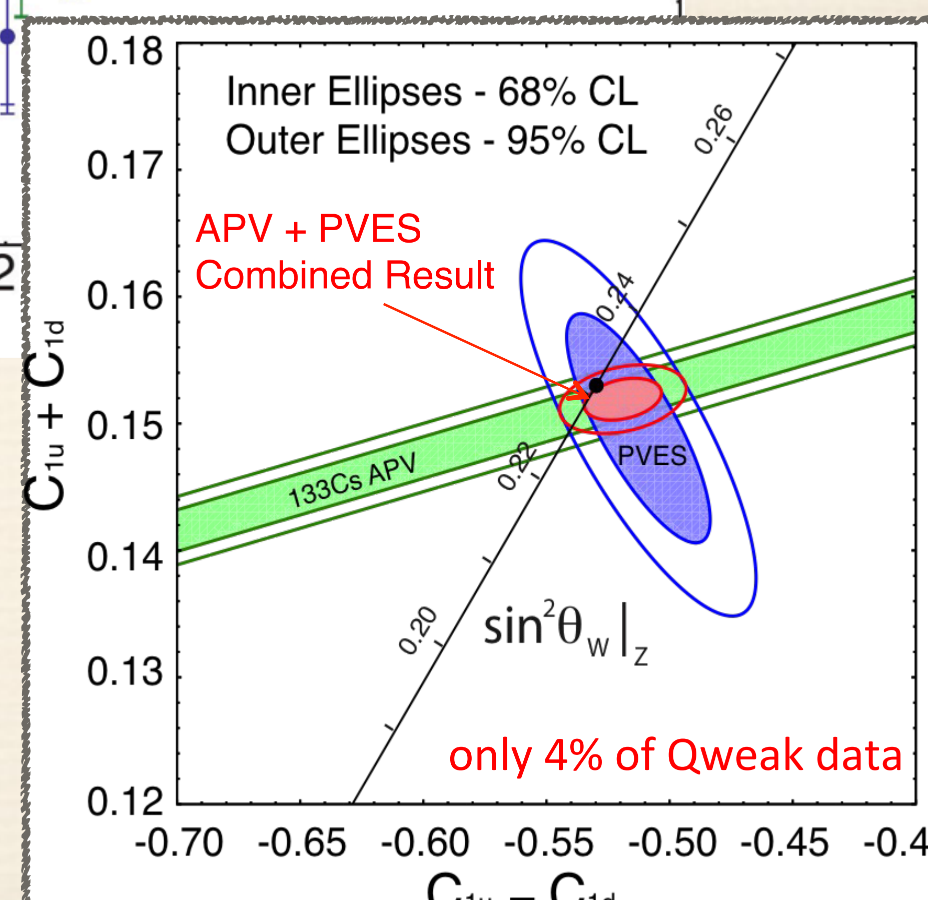

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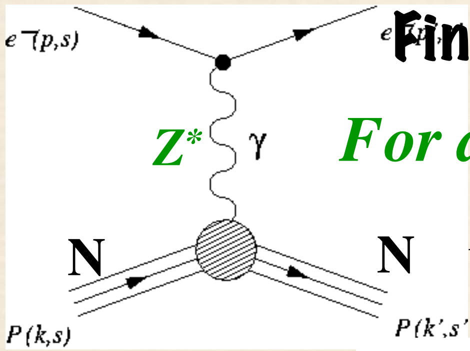

Final result with the full accumulated statistics is anticipated in 2015

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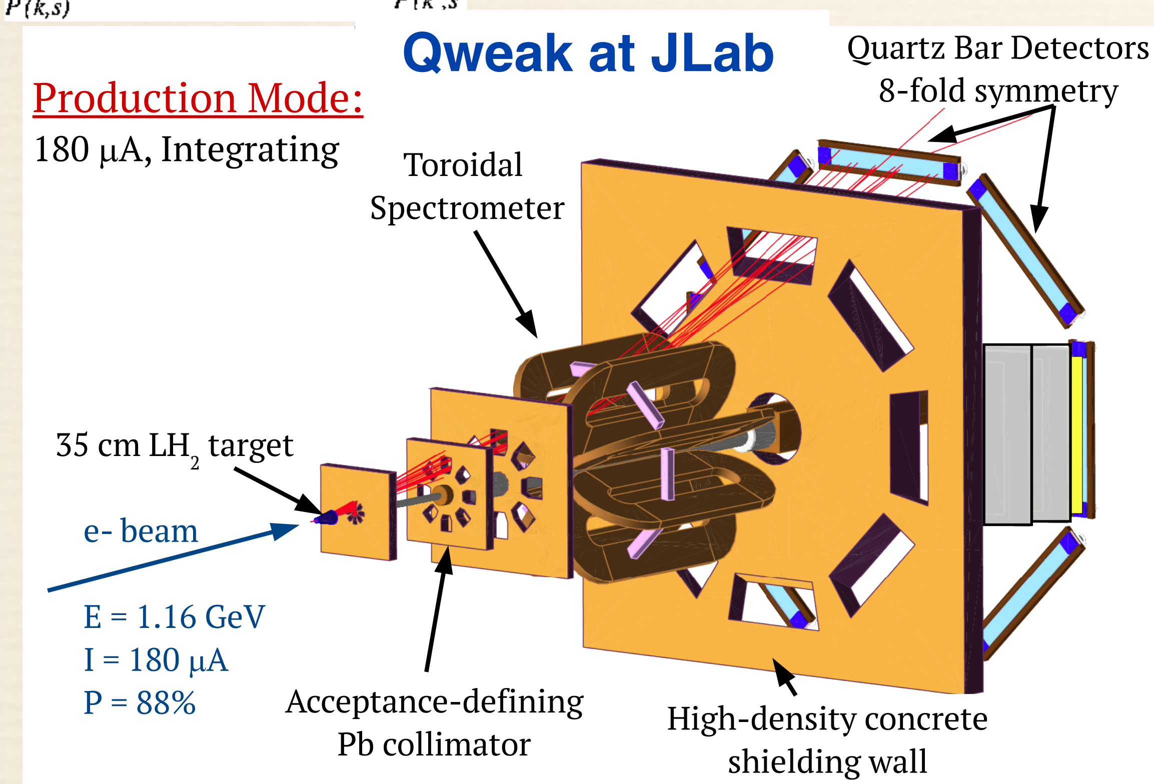

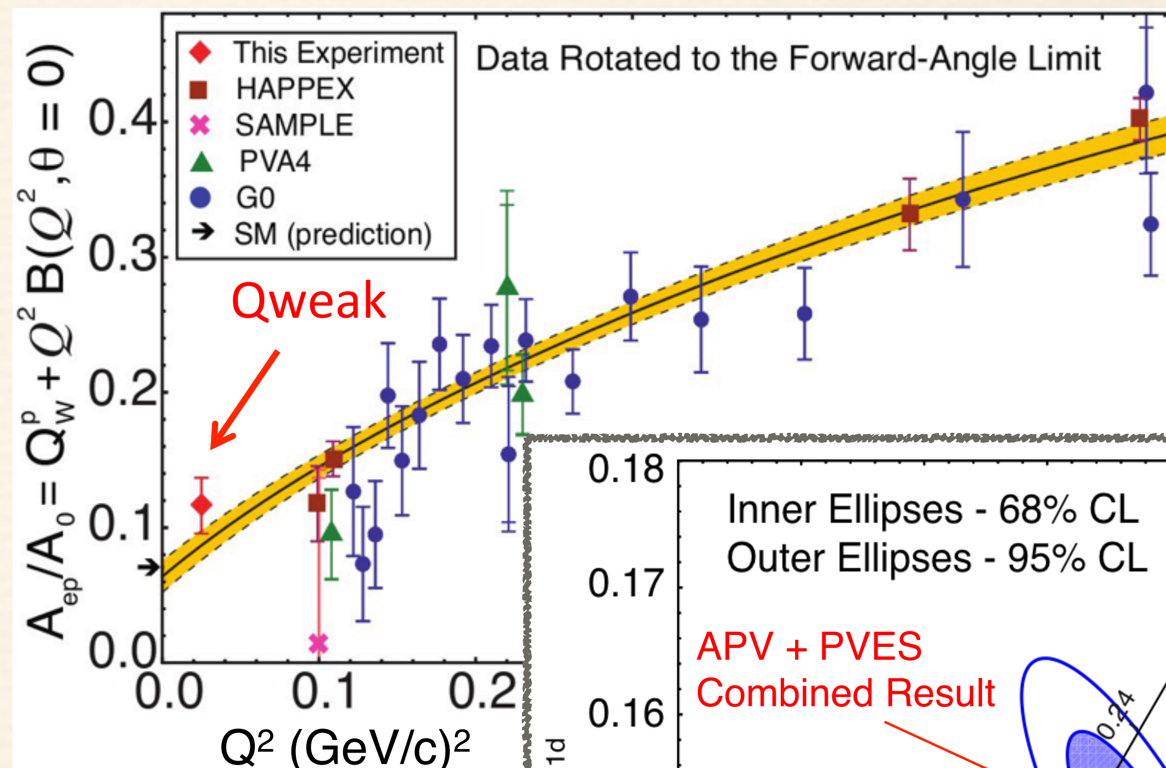

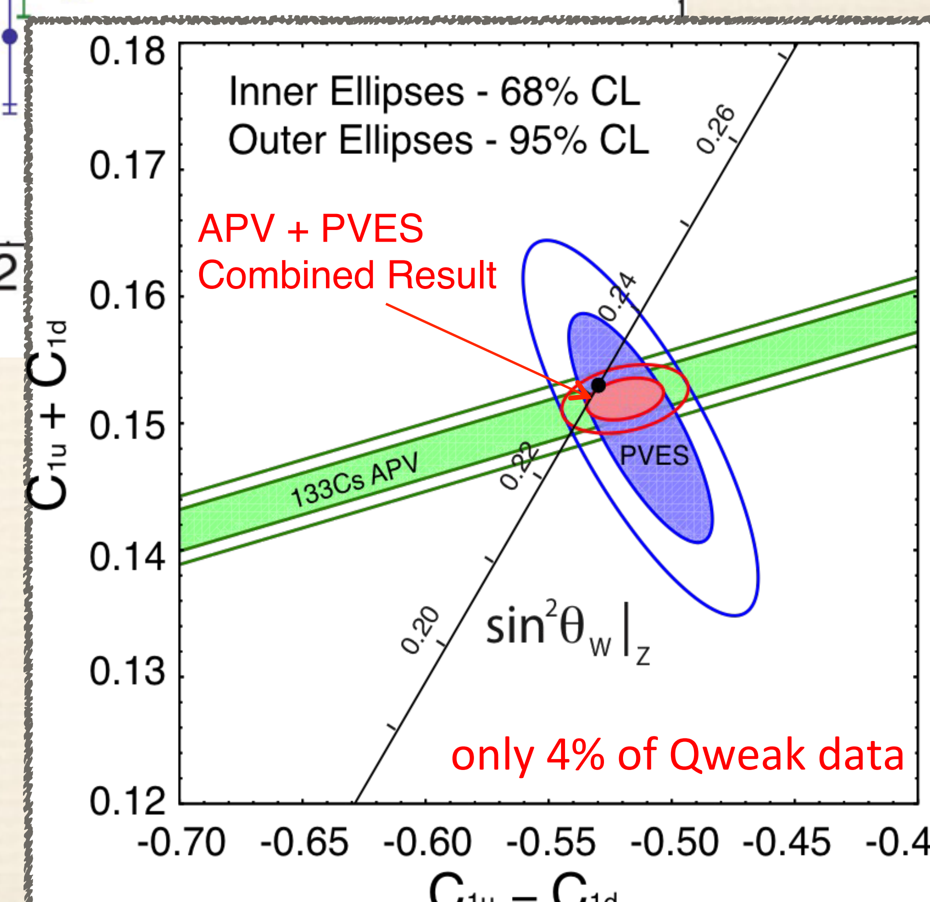

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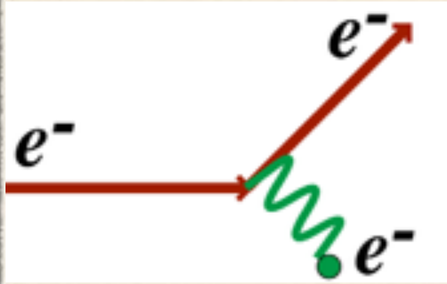
First determination of proton's weak charge in good agreement with Standard Model

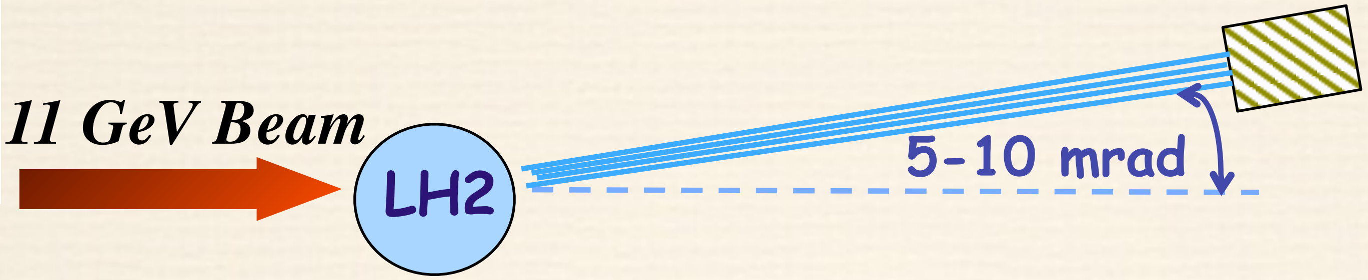
An ultra-precise measurement of the weak mixing angle using Møller scattering

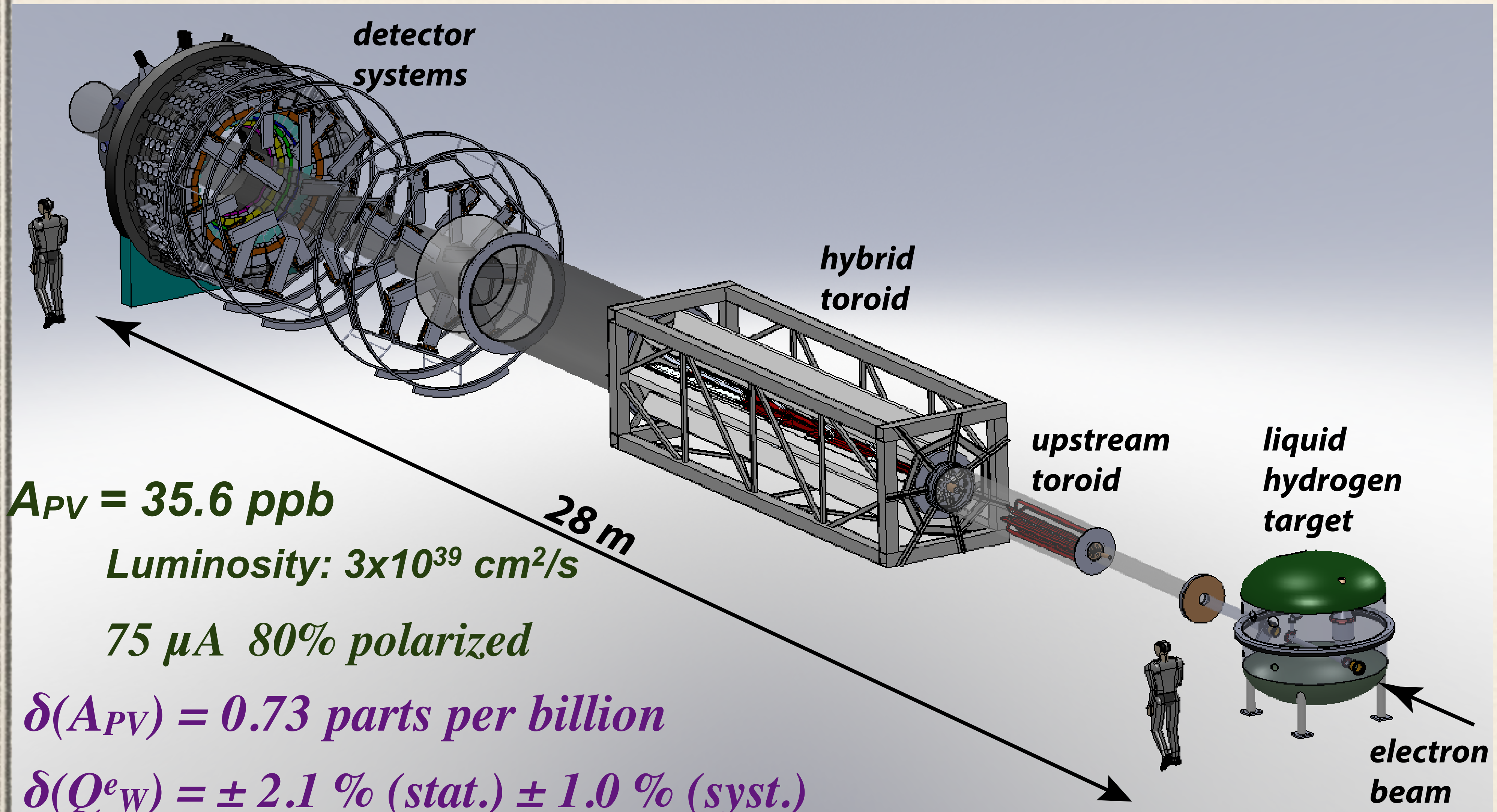
11 GeV Møller scattering

MOLLER at JLab

Measurement Of Lepton Lepton Electroweak Reaction







A_{PV} = 35.6 ppb

Luminosity: 3x10^{39} cm^2/s

75 µA 80% polarized

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

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

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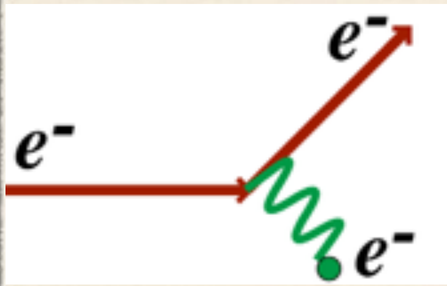

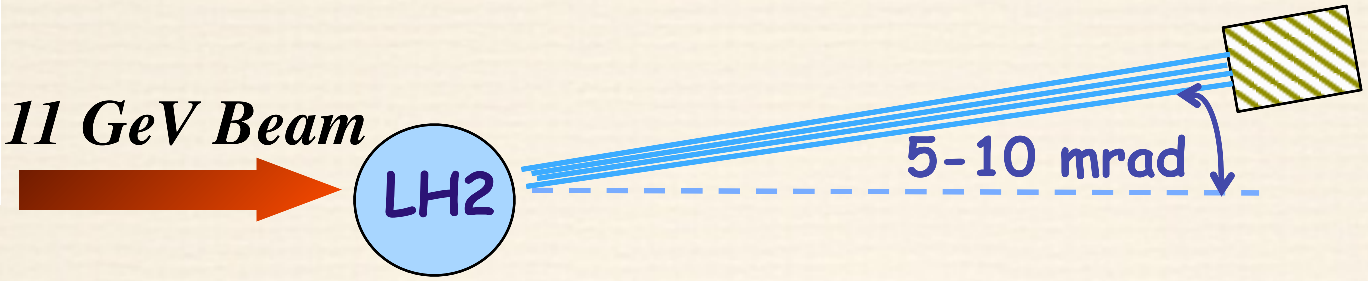

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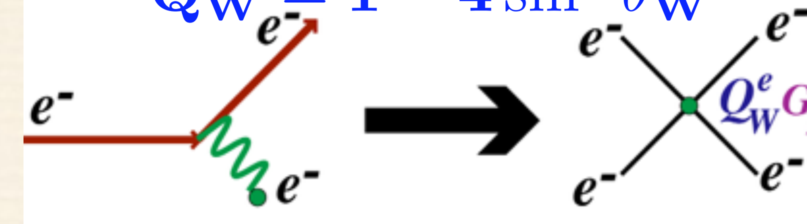
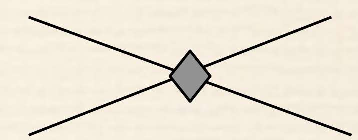


$$+ \quad \frac{1}{\Lambda^2}\mathcal{L}_6$$



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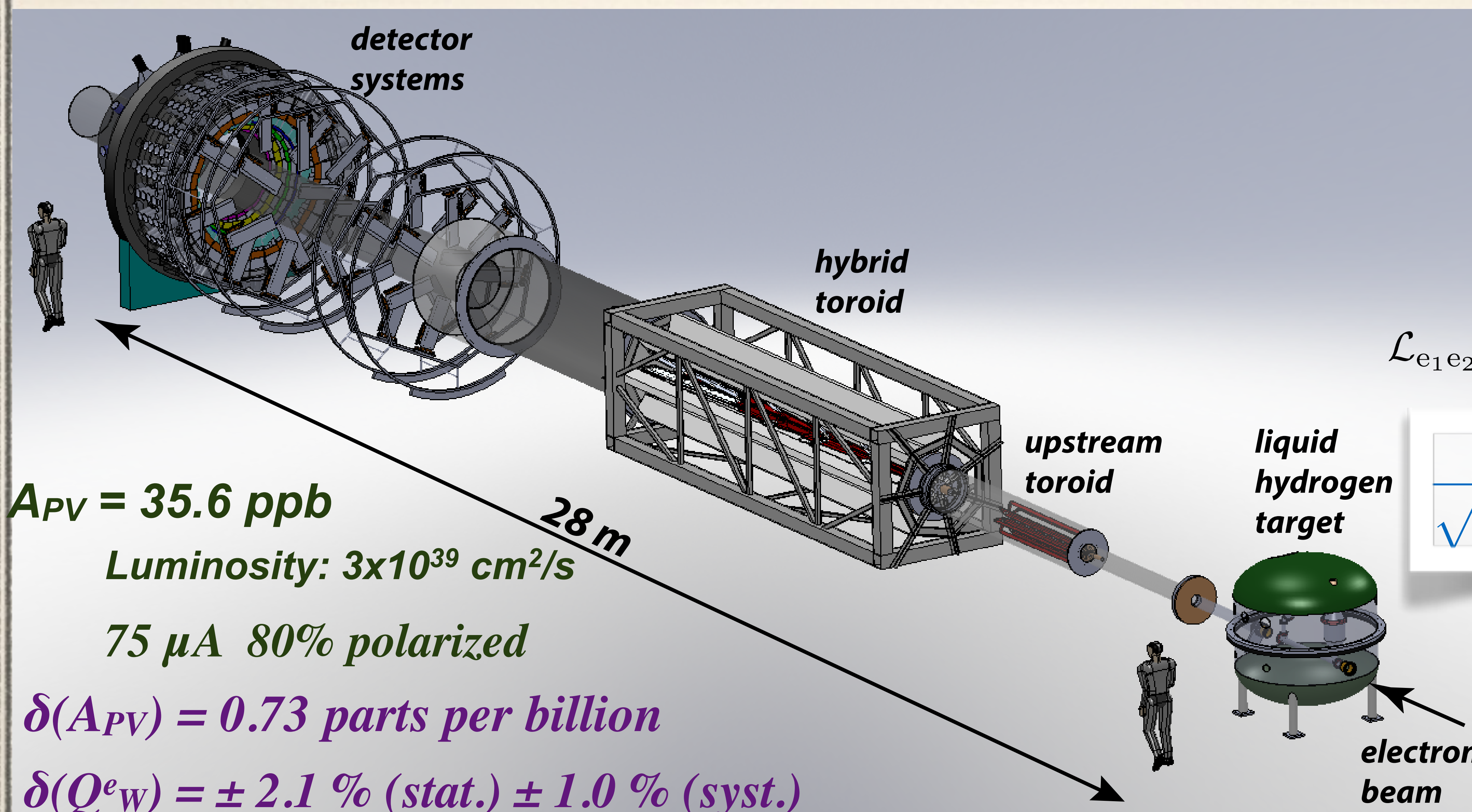
$$\frac{\Lambda}{\sqrt{|g_{RR}^2 - g_{LL}^2|}} = 7.5\ \mathrm{TeV}$$



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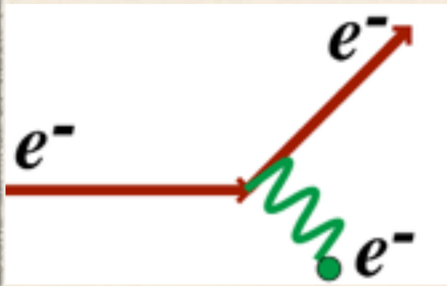
Measurement **O**f **L**epton **L**epton **E**lectroweak **R**eaction



11 GeV Beam

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

Matches best collider (Z-pole) measurements!

best contact interaction reach for leptons at low OR high energy

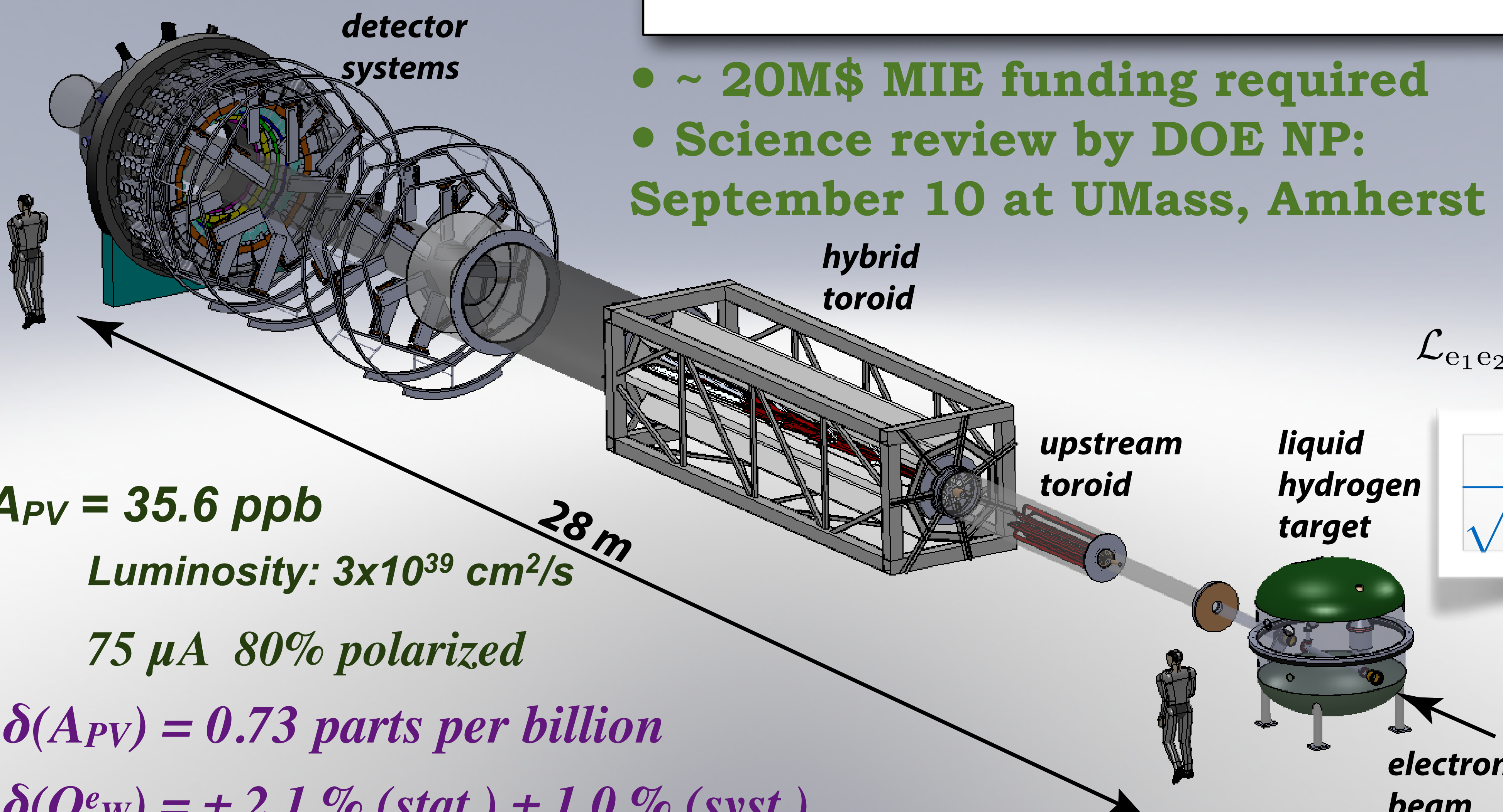
To do better for a 4-lepton contact interaction would require: Giga-Z factory, linear collider, neutrino factory or muon collider

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

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

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

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



A_{PV} = 35.6 ppb

Luminosity: 3x10[39] cm²/s

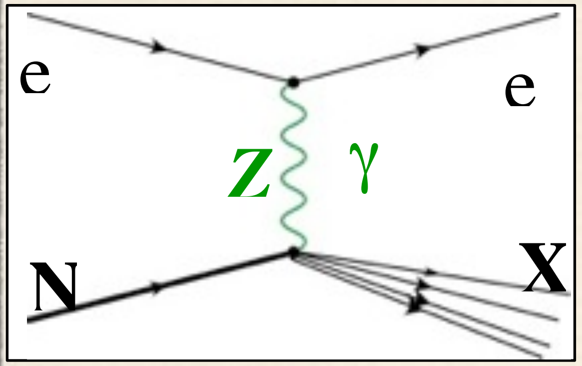
75 μA 80% polarized

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

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

Deep Inelastic Scattering on LD_2

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



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

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

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

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

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

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

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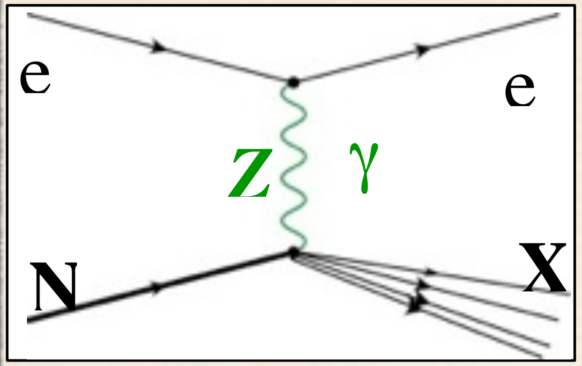

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Wang et al., Nature 506, no. 7486, 67 (2014);

6 GeV run results

$Q^2 \sim 1.1\ GeV^2$

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

$Q^2 \sim 1.9\ GeV^2$

	Asymmetry
A^{phys} (ppm)	-160.80
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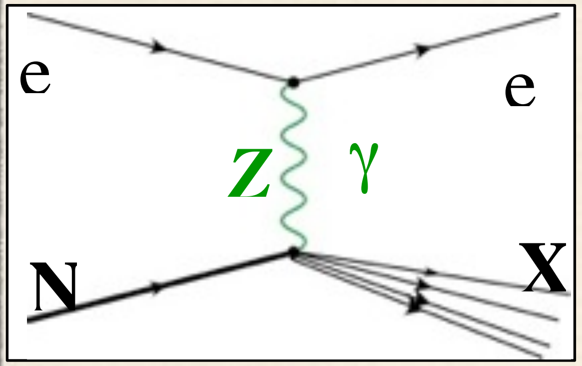

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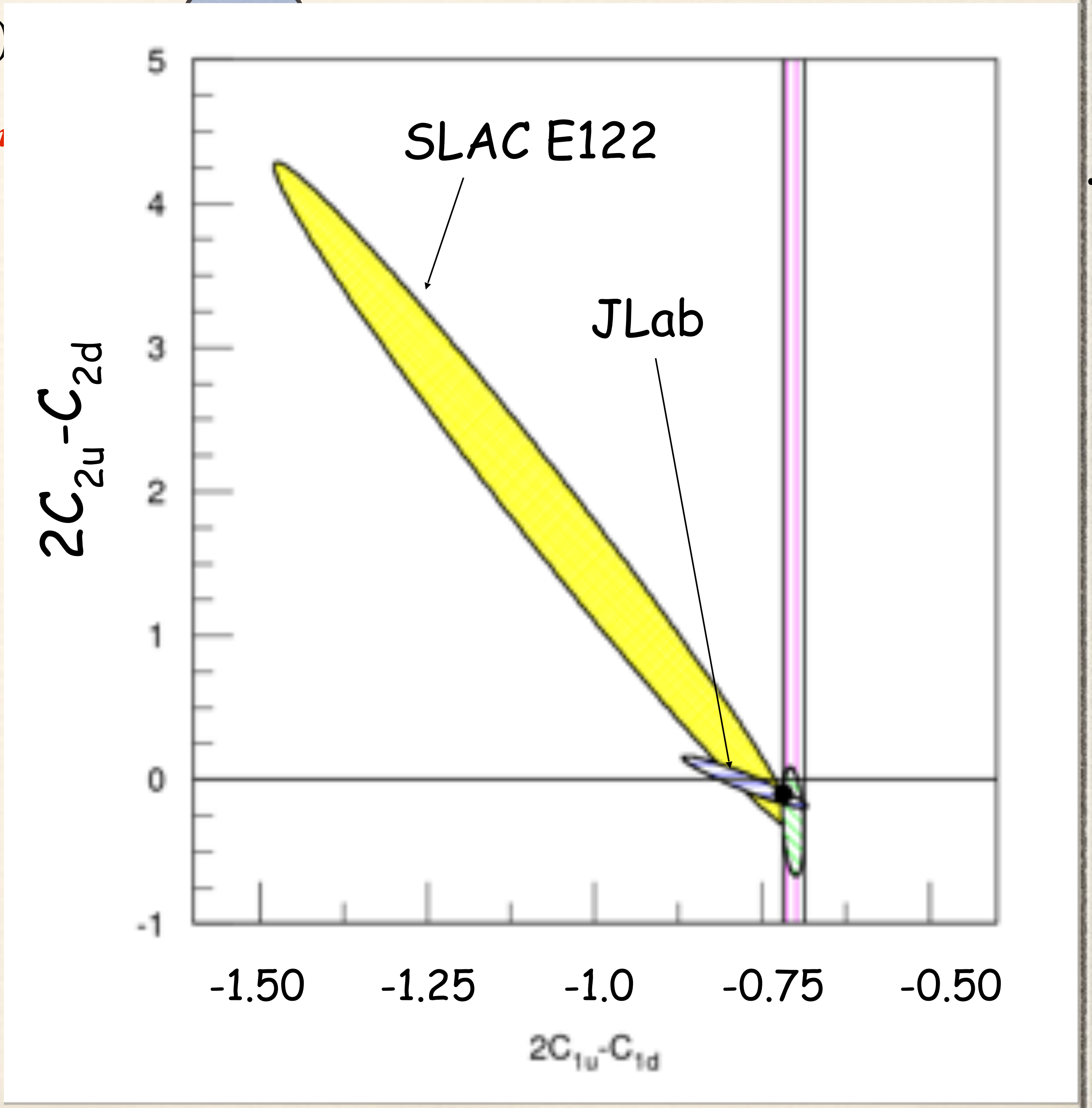

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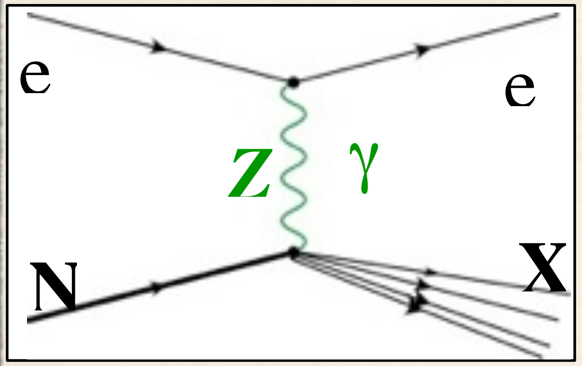

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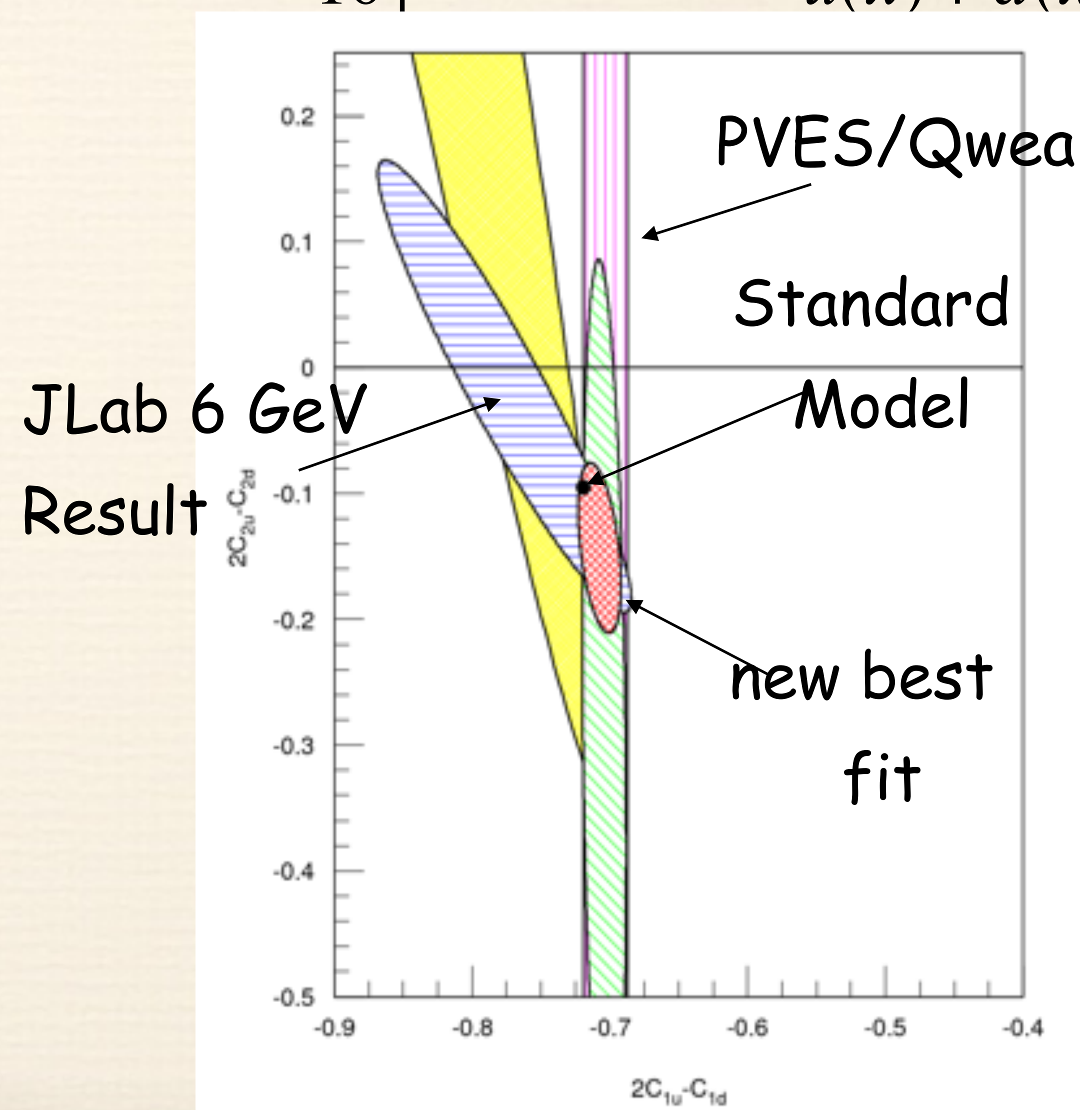

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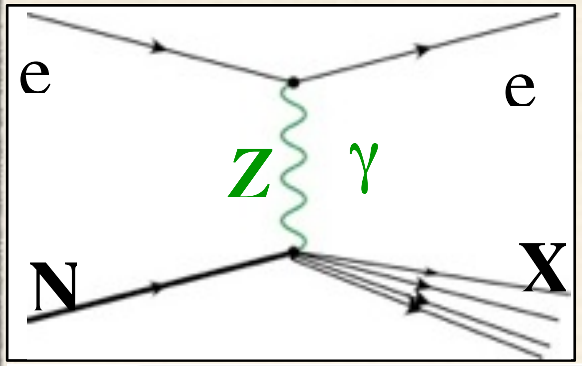


$Q^2 >> 1\ GeV^2$, $W^2 >> 4$

$$A_{PV} = \frac{G_F Q^2}{\sqrt{2}\pi\alpha}\left[a(x) + \ldots\right.$$

For ²H, assuming charge symmetry,

e ratio

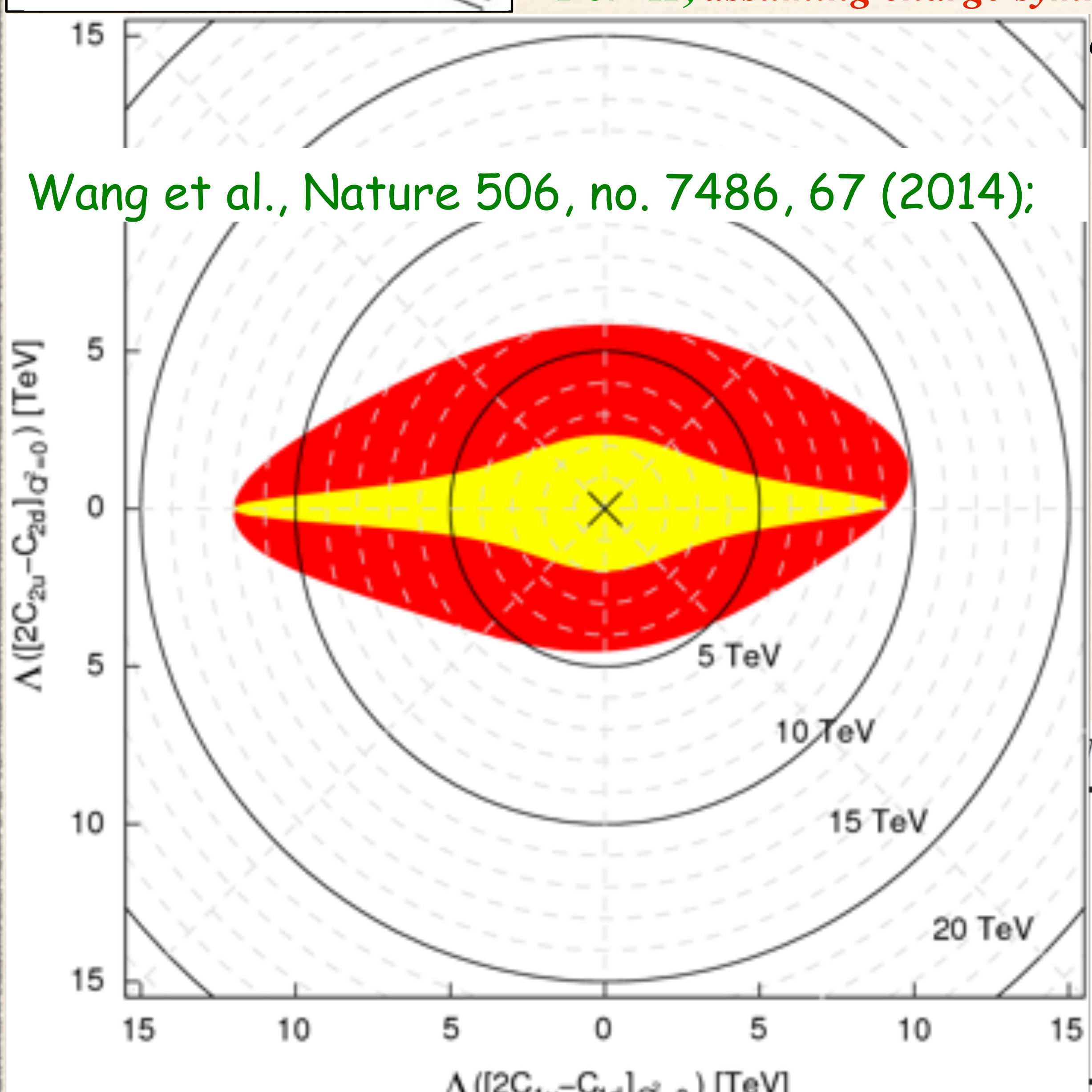
PARTICLE PHYSICS

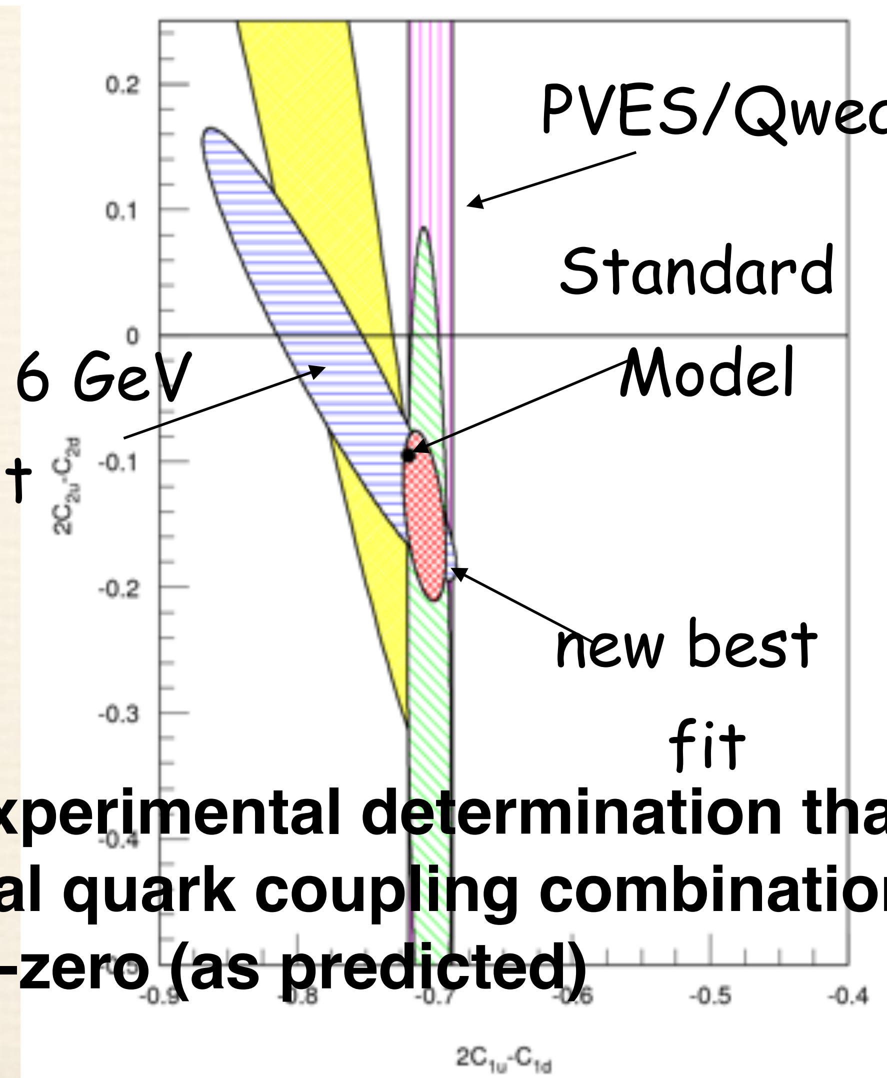
Quarks are not ambidextrous

W. Marciano article in Nature

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

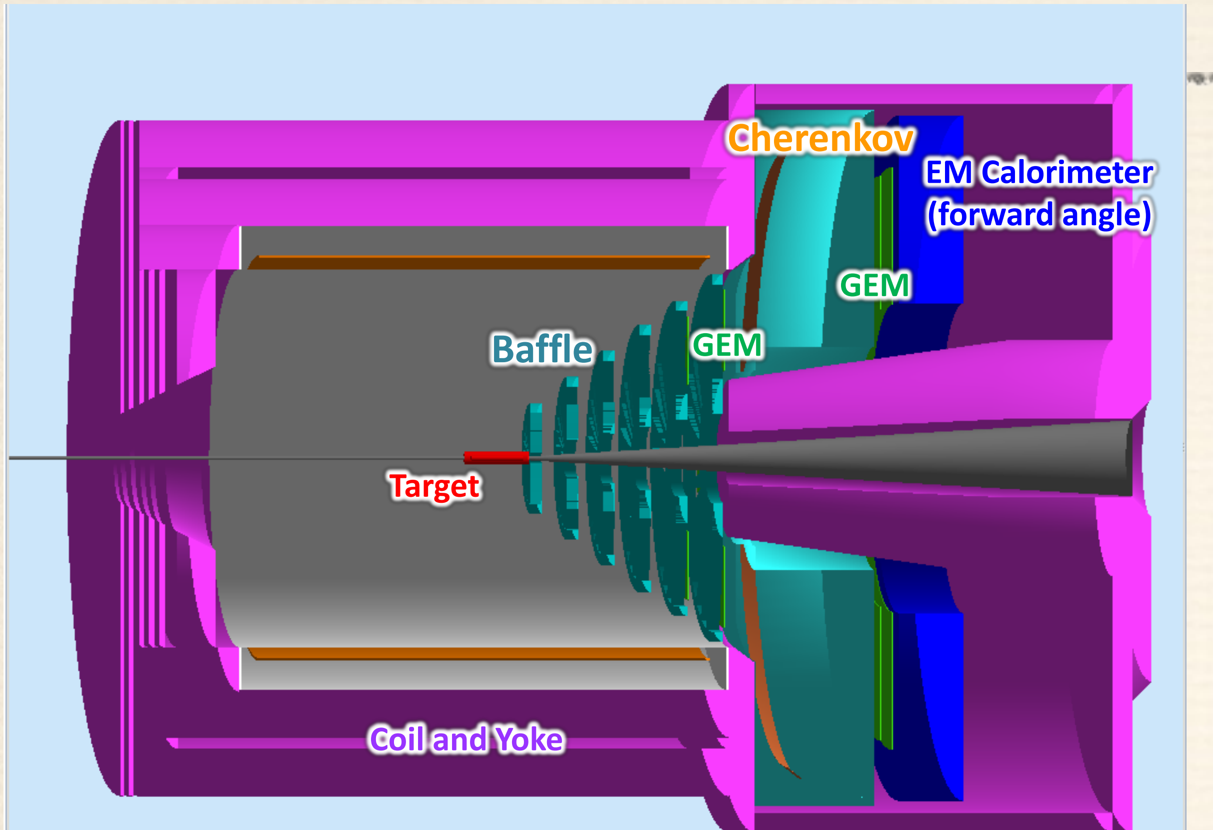
Wang et al., Nature 506, no. 7486, 67 (2014);





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

SOLID with the 12 GeV Upgrade



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

Requirements

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

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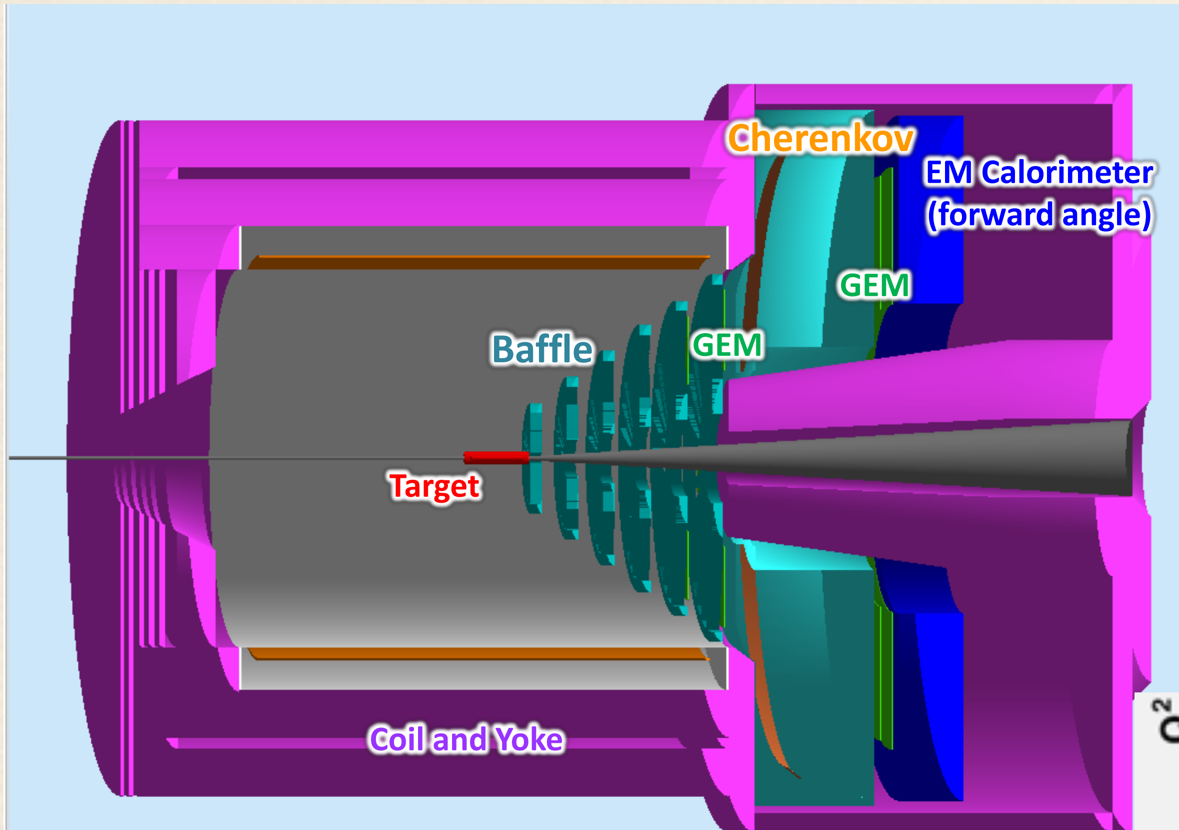

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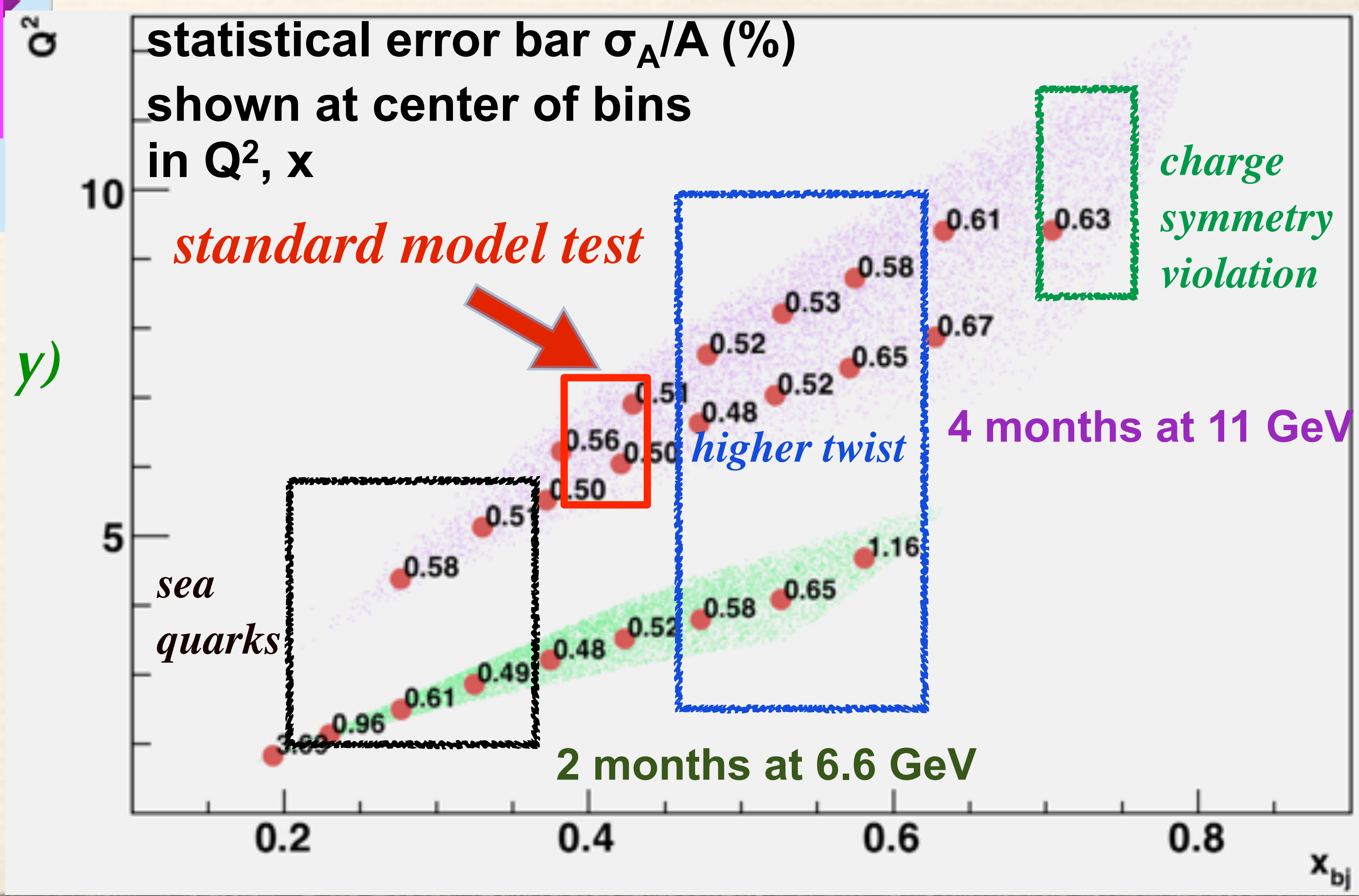
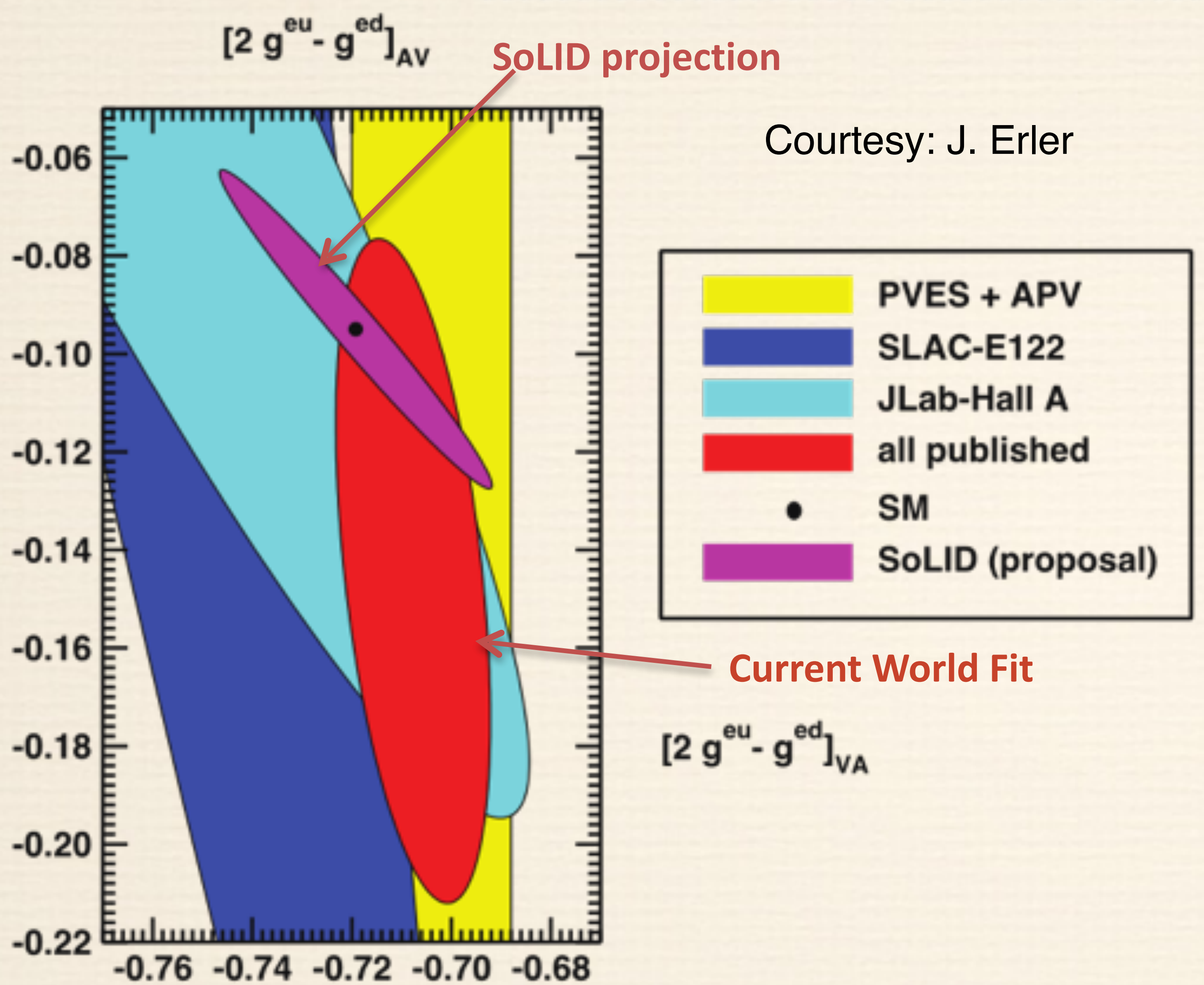
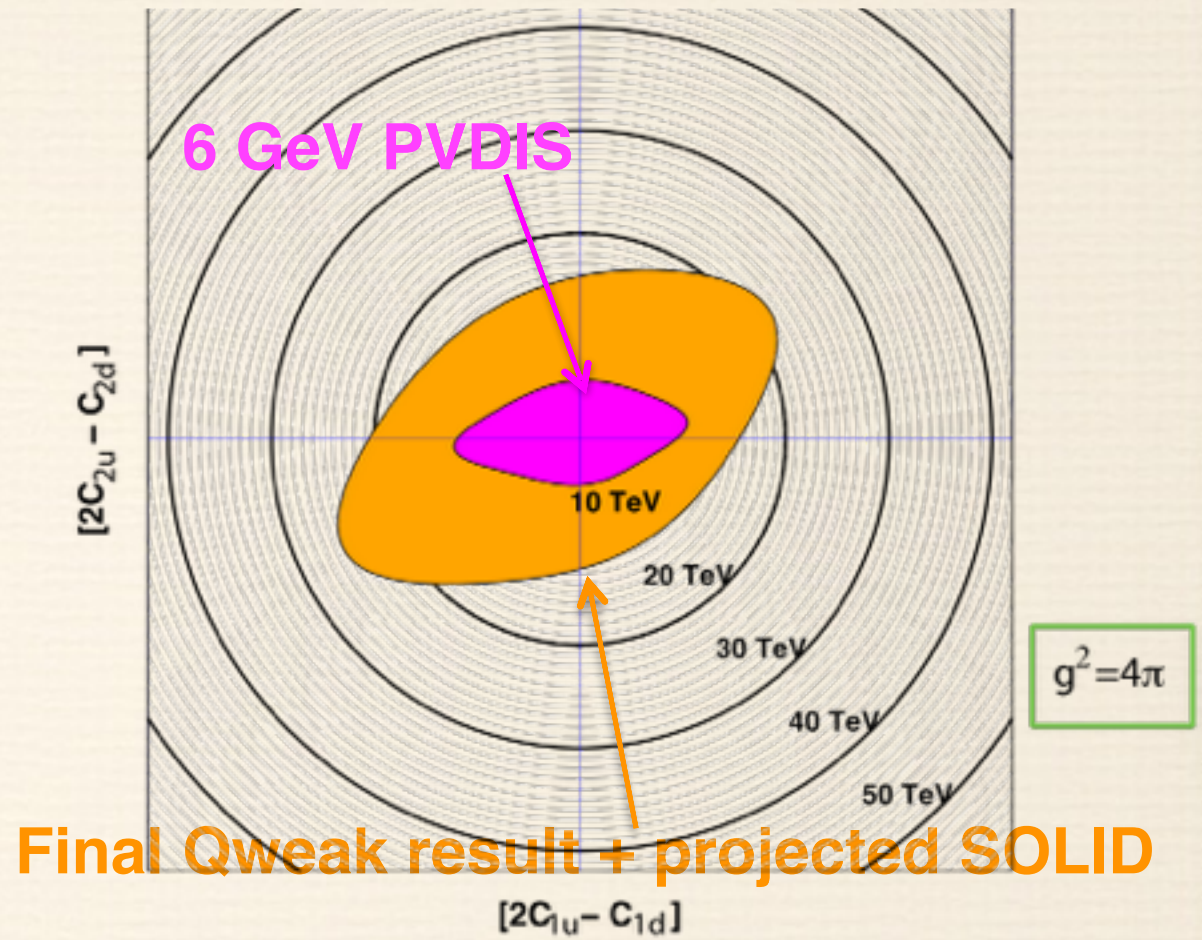


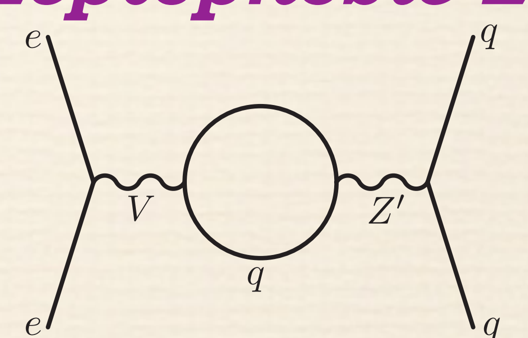
SOLID New Physics Sensitivity





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

Leptophobic Z'



SOLID can improve sensitivity: 100-200 GeV range

QCD Dynamics in Precision D_2 PVDIS

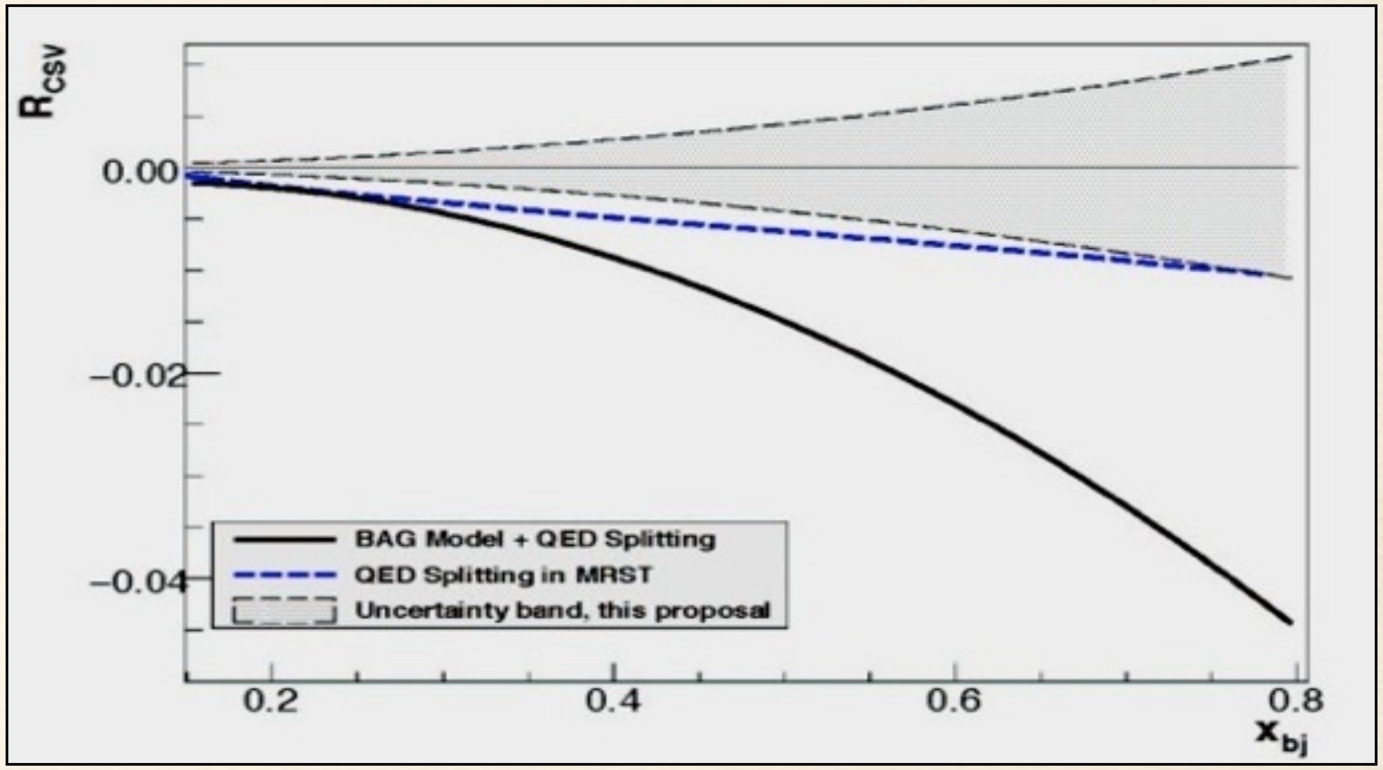
$$u^p(x) \stackrel{?}{=} d^n(x) \quad \Rightarrow \quad \delta u(x) \equiv u^p(x) - d^n(x)$$
$$d^p(x) \stackrel{?}{=} u^n(x) \quad \Rightarrow \quad \delta d(x) \equiv d^p(x) - u^n(x)$$

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

We already know CSV exists:

- u-d mass difference $\delta m = m_d - m_u \approx 4$ MeV
  $\delta M = M_n - M_p \approx 1.3$ MeV
- electromagnetic effects

- **Direct sensitivity to parton-level CSV**
- **Important implications for PDF's**
- ***Could be* partial explanation of the NuTeV anomaly**



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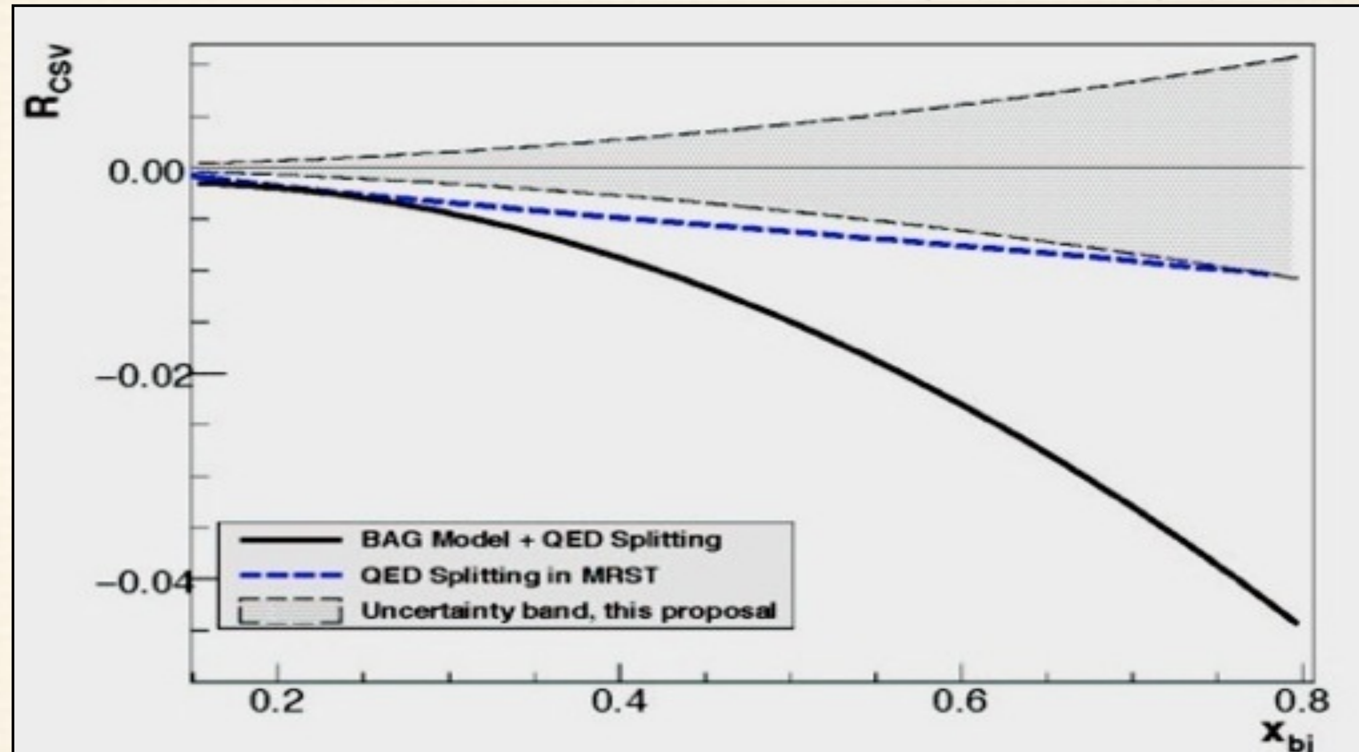
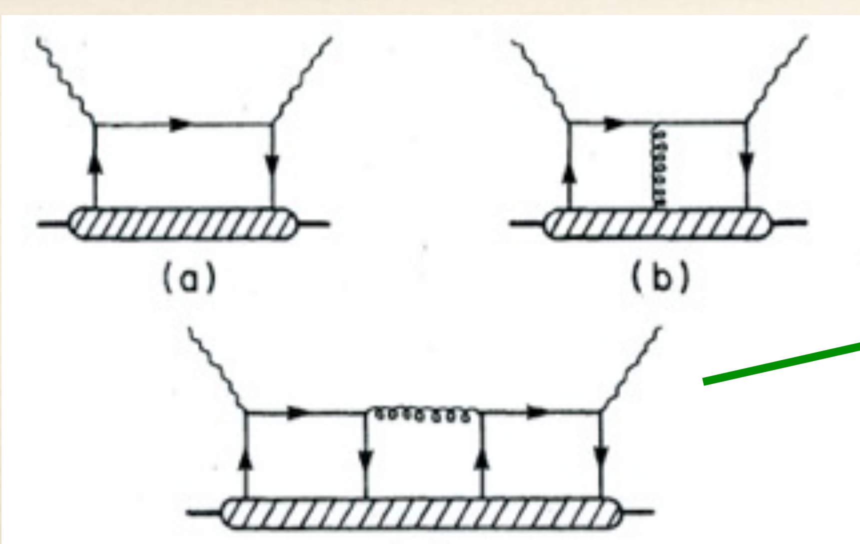




Castorina & Mulders, '84

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

Zero in quark-parton model

Higher-Twist valence quark-quark correlation

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

σ_L contributions cancel

Longstanding issue in proton structure

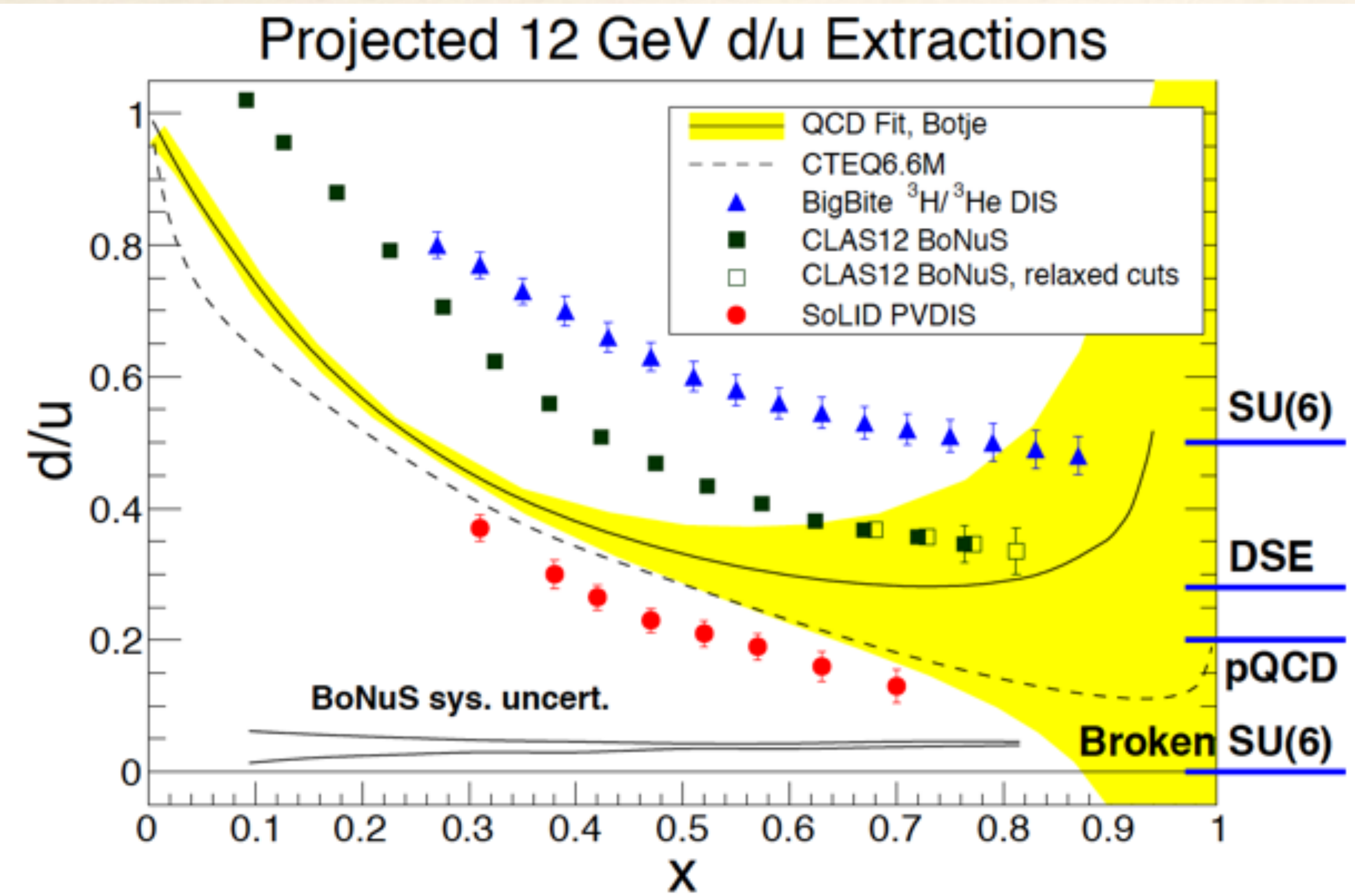
Proton PVDIS: d/u at high x

(high power liquid hydrogen target)

SU(6): d/u~1/2
Broken SU(6): 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 ^{3}H/^{3}He Ratio
  - SoLID - PVDIS *ep*
- The SoLID extraction of *d*/*u* is made directly from *ep* DIS: *no nuclear corrections*

Cloet, Bentz, Thomas, arXiv 0901.3559

^{48}Ca PVDIS

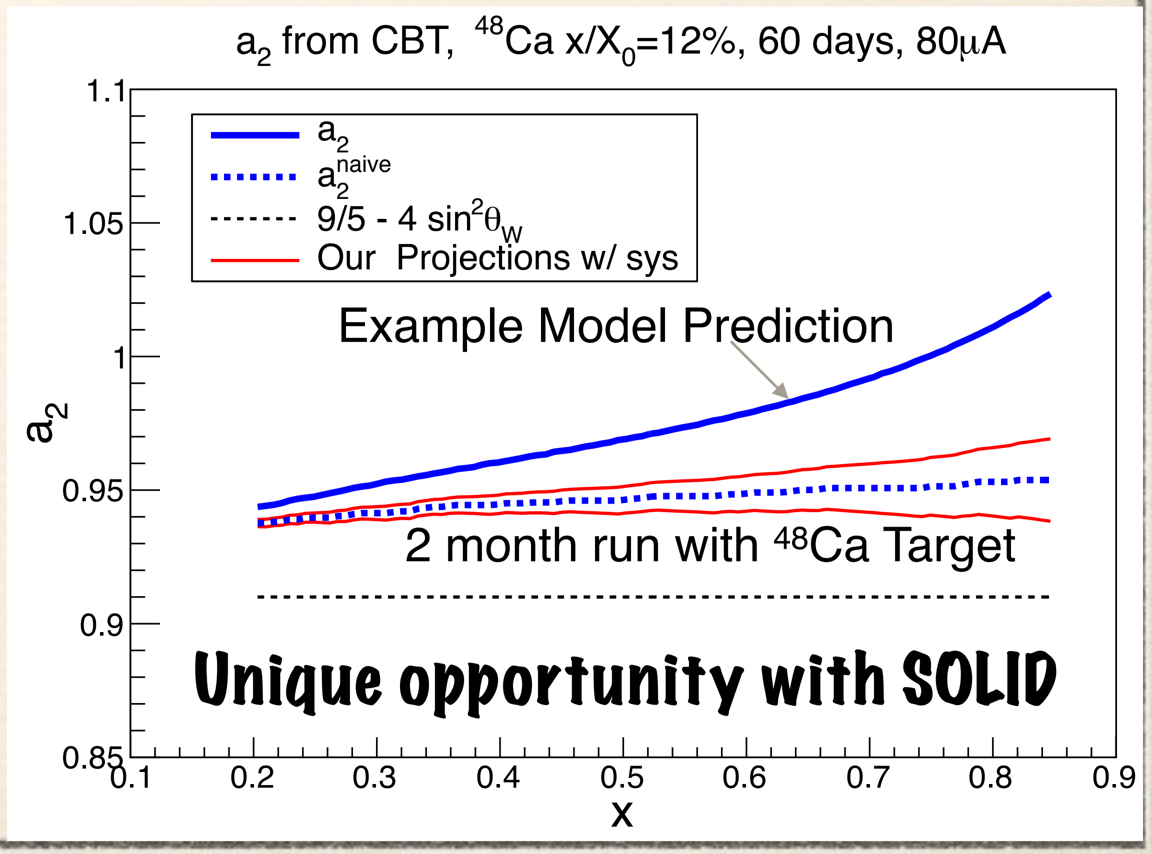
Consider PVDIS on a heavy nucleus

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

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

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

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



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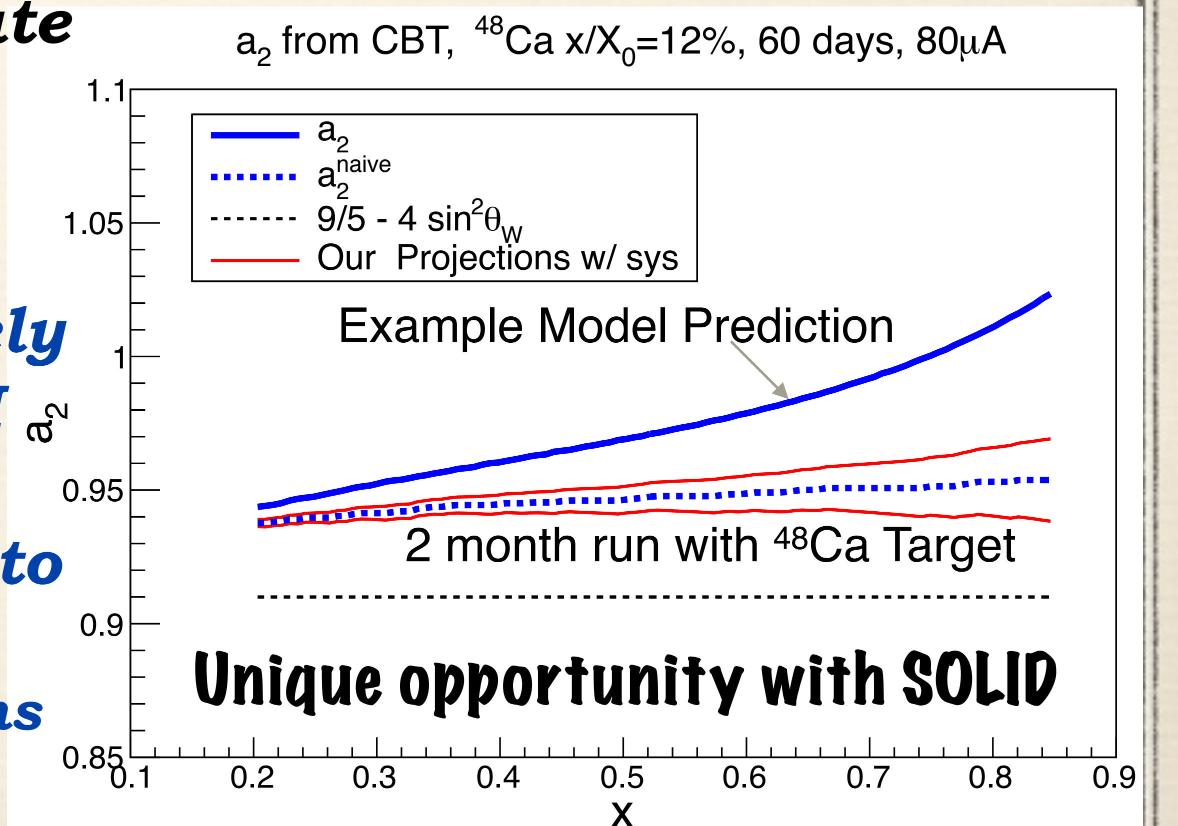
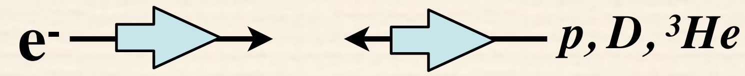
Great leverage for a clean isospin decomposition of the EMC effect in an inclusive measurement

- ***Flavor separation: clean data sparse to date***
- ***With hadrons in the initial or final state, small effects are difficult to disentangle (theoretically and experimentally)***
- ***Precise isotope cross-section ratios in purely electromagnetic electron scattering: MUCH reduced sensitivity to the isovector combination; potentially see small effects to discriminate models***
  - ***a flavor decomposition of medium modifications is extremely challenging***



High luminosity: precision measurements of PV observables

EW Structure Functions at EIC



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

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

***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**

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

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e⁻ → ← ***p, D, ³He***

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proton	**deuteron**
$F_1^{\gamma Z} \propto u + d + s$	$F_1^{\gamma Z} \propto u + d + 2s$
$F_3^{\gamma Z} \propto 2u_v + d_v$	$F_3^{\gamma Z} \propto u_v + d_v$
$g_1^{\gamma Z} \propto \Delta u + \Delta d + \Delta s$	$g_1^{\gamma Z} \propto \Delta u + \Delta d + \Delta s$
$g_5^{\gamma Z} \propto 2\Delta u_v + \Delta d_v$	$g_5^{\gamma Z} \propto \Delta u_v + \Delta d_v$

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proton

similar expressions for the neutron: $u \leftrightarrow d$

$$g_1^{W^-} = (\Delta u + \Delta\bar{d} + \Delta\bar{s} + \Delta c)$$
$$g_1^{W^+} = (\Delta\bar{u} + \Delta d + \Delta s + \Delta\bar{c})$$
$$g_5^{W^+} = (\Delta\bar{u} - \Delta d - \Delta s + \Delta\bar{c})$$
$$g_5^{W^-} = (-\Delta u + \Delta\bar{d} + \Delta\bar{s} - \Delta c)$$

proton

$$F_1^{\gamma Z} \propto u + d + s$$
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$$g_1^{\gamma Z} \propto \Delta u + \Delta d + \Delta s$$
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deuteron

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$$- \frac{p_\mu S_\nu + S_\mu p_\nu}{2(p\cdot q)}g^i_3 + \frac{S\cdot q}{(p\cdot q)^2}p_\mu p_\nu g^i_4 + \frac{S\cdot q}{p\cdot q}g_{\mu\nu}g^i_5$$

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proton

similar expressions for the neutron: $u \leftrightarrow d$

$$g_1^{W^-} = (\Delta u + \Delta\bar{d} + \Delta\bar{s} + \Delta c)$$
$$g_1^{W^+} = (\Delta\bar{u} + \Delta d + \Delta s + \Delta\bar{c})$$
$$g_5^{W^+} = (\Delta\bar{u} - \Delta d - \Delta s + \Delta\bar{c})$$
$$g_5^{W^-} = (-\Delta u + \Delta\bar{d} + \Delta\bar{s} - \Delta c)$$

$$\int_0^1 dx[g_5^{W^-,n} - g_5^{W^-,p}] = g_A\left(1 - \frac{2\alpha_s}{3\pi}\right)$$

new sum rules

proton

$$F_1^{\gamma Z} \propto u + d + s$$
$$F_3^{\gamma Z} \propto 2u_v + d_v$$
$$g_1^{\gamma Z} \propto \Delta u + \Delta d + \Delta s$$
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deuteron

$$F_1^{\gamma Z} \propto u + d + 2s$$
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$$g_5^{\gamma Z} \propto \Delta u_v + \Delta d_v$$

High luminosity: precision measurements of PV observables

EW Structure Functions at EIC

e⁻ → ← p, D, ³He

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

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

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**

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

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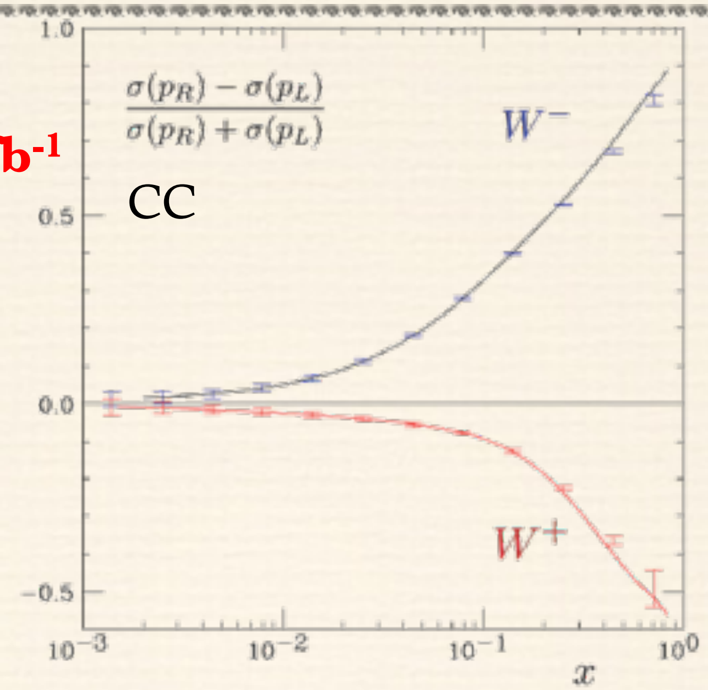
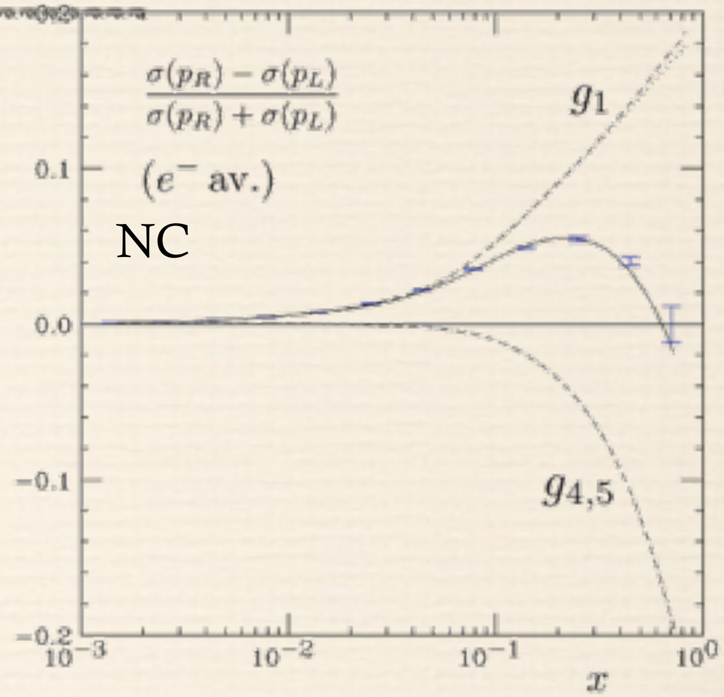
Similar expressions for neutral current structure functions

Examples of Projected Results

20×250 GeV, $Q^2 > 1$ GeV^2, $0.1 < y < 0.9$, **10 fb^{-1}**

(Could begin the program with 5x250 GeV i.e "Stage 1" of the EIC)





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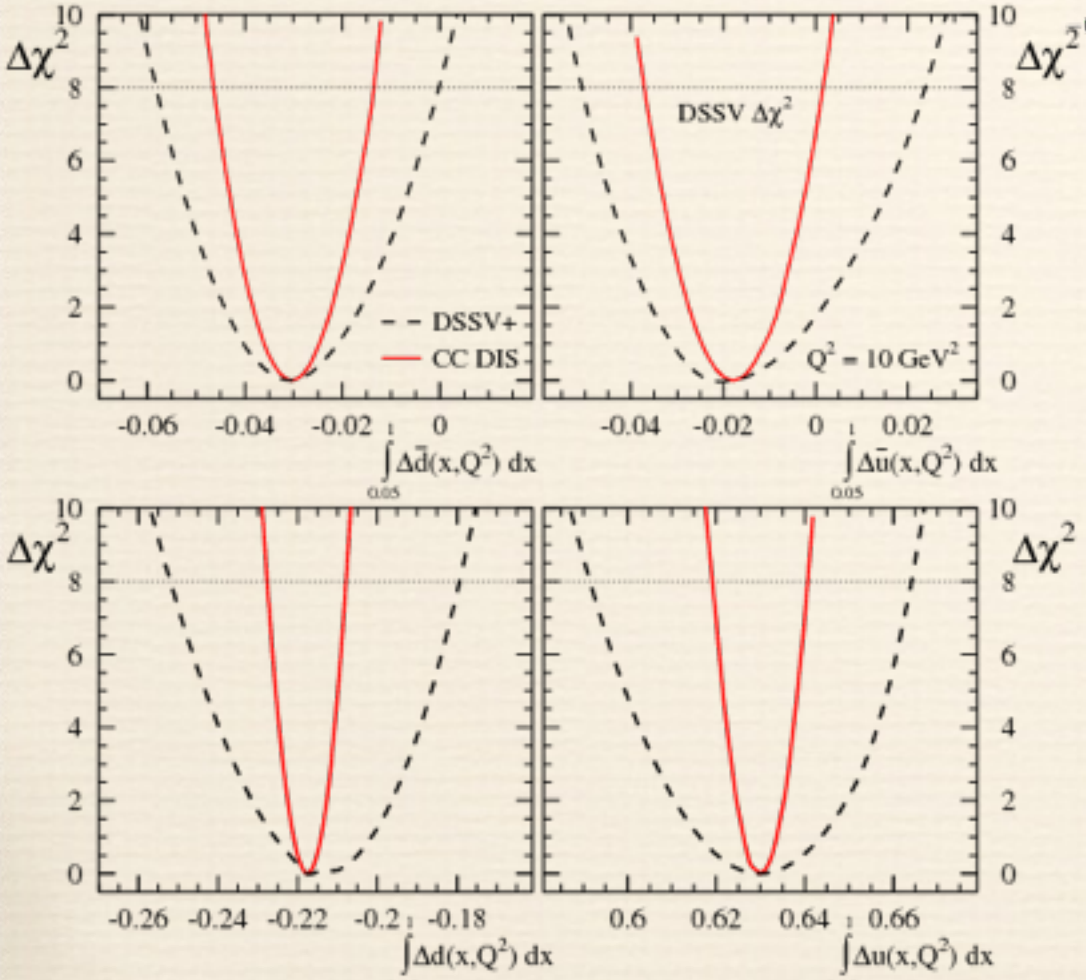
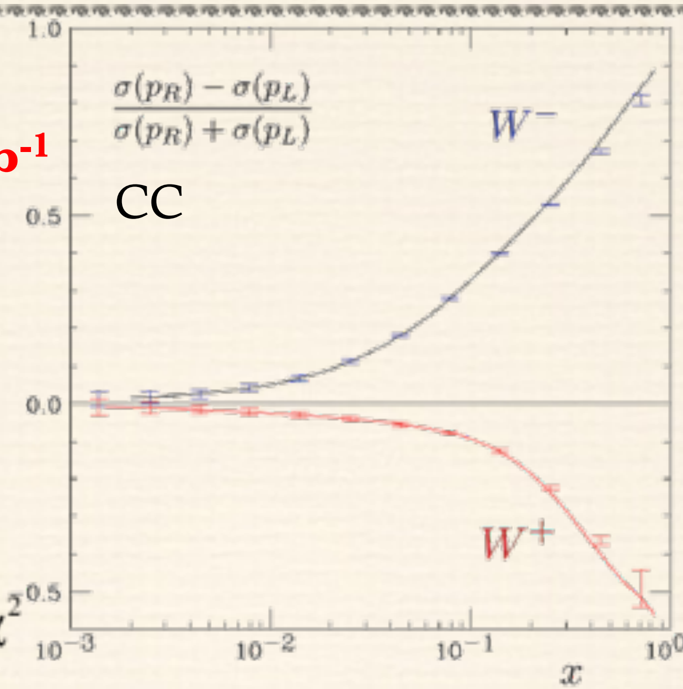
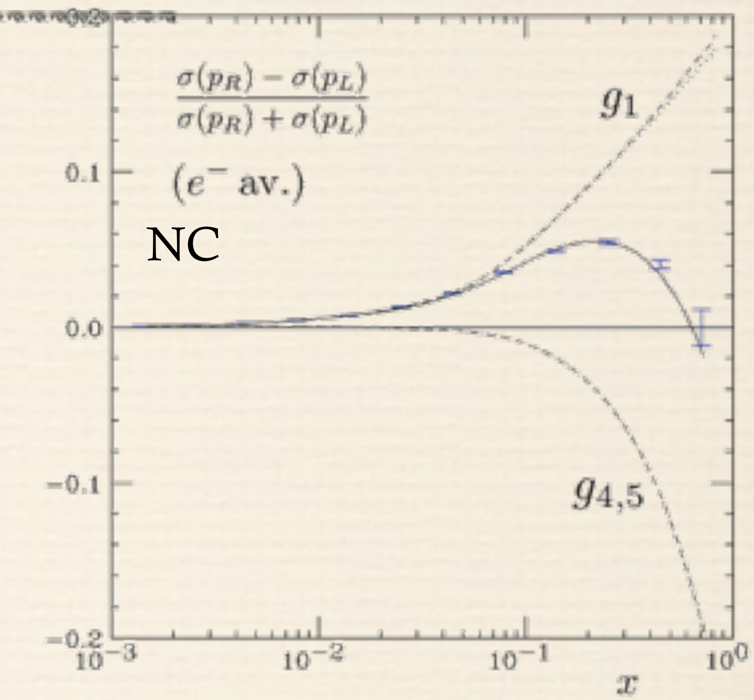
Full analysis of charged current events including radiative corrections

Aschenauer et al, PRD **88**, 114025 (2013)







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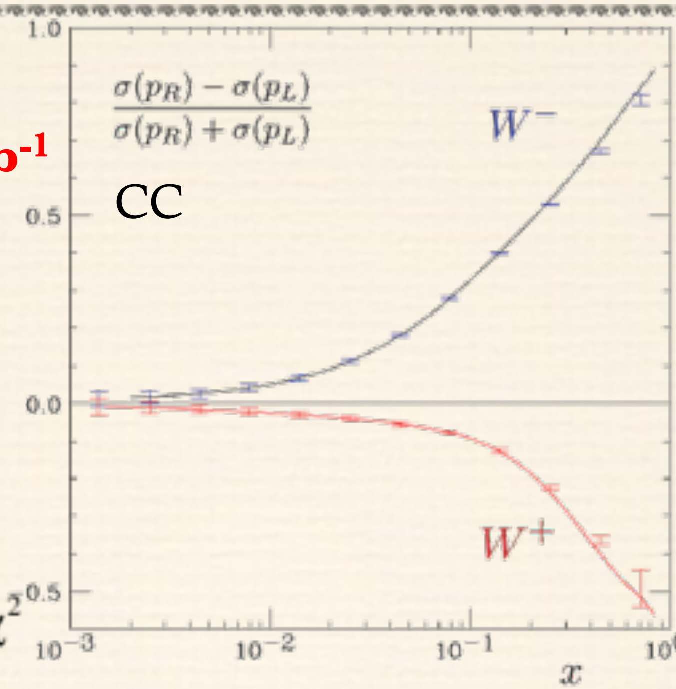

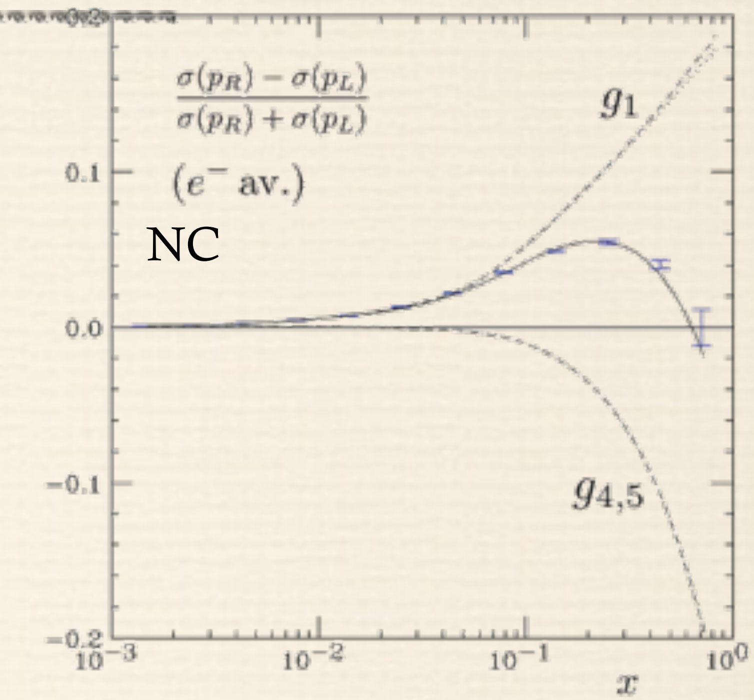

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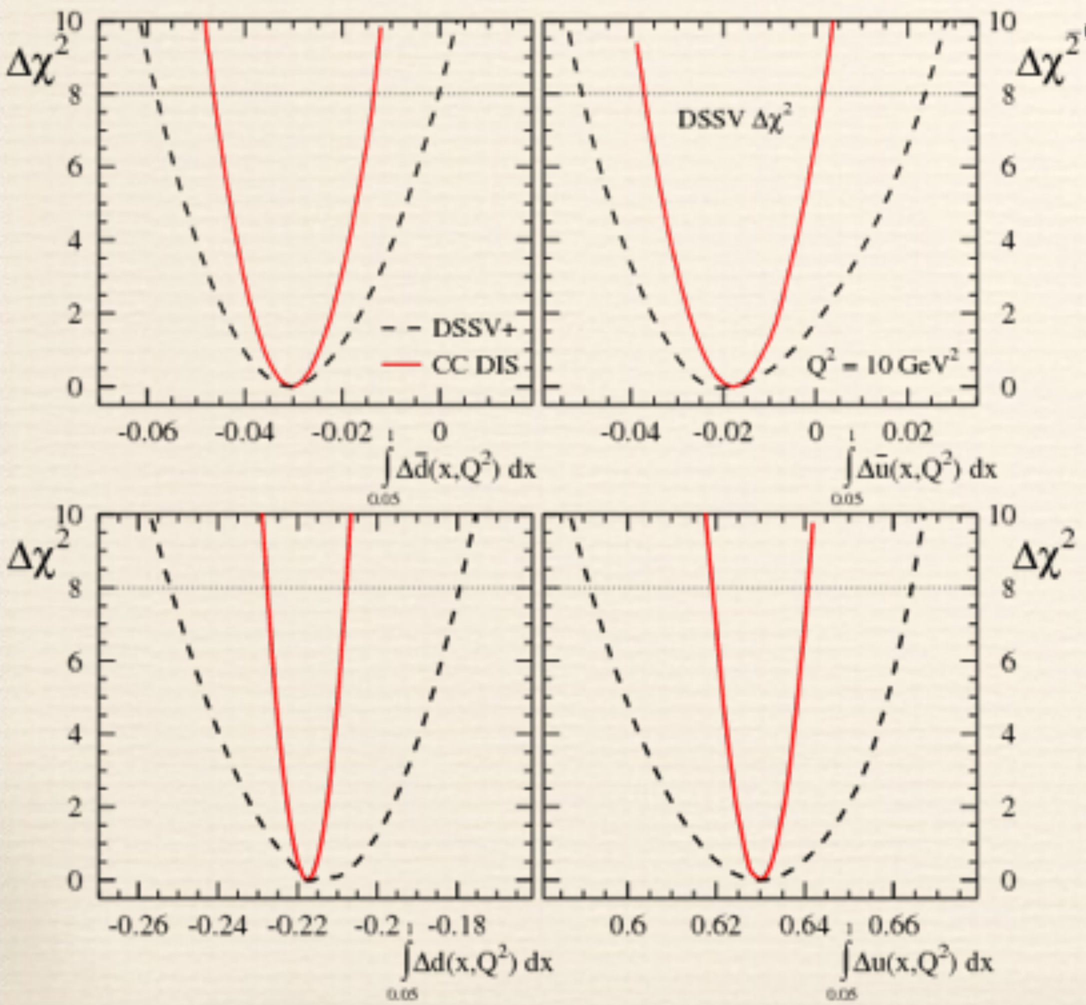
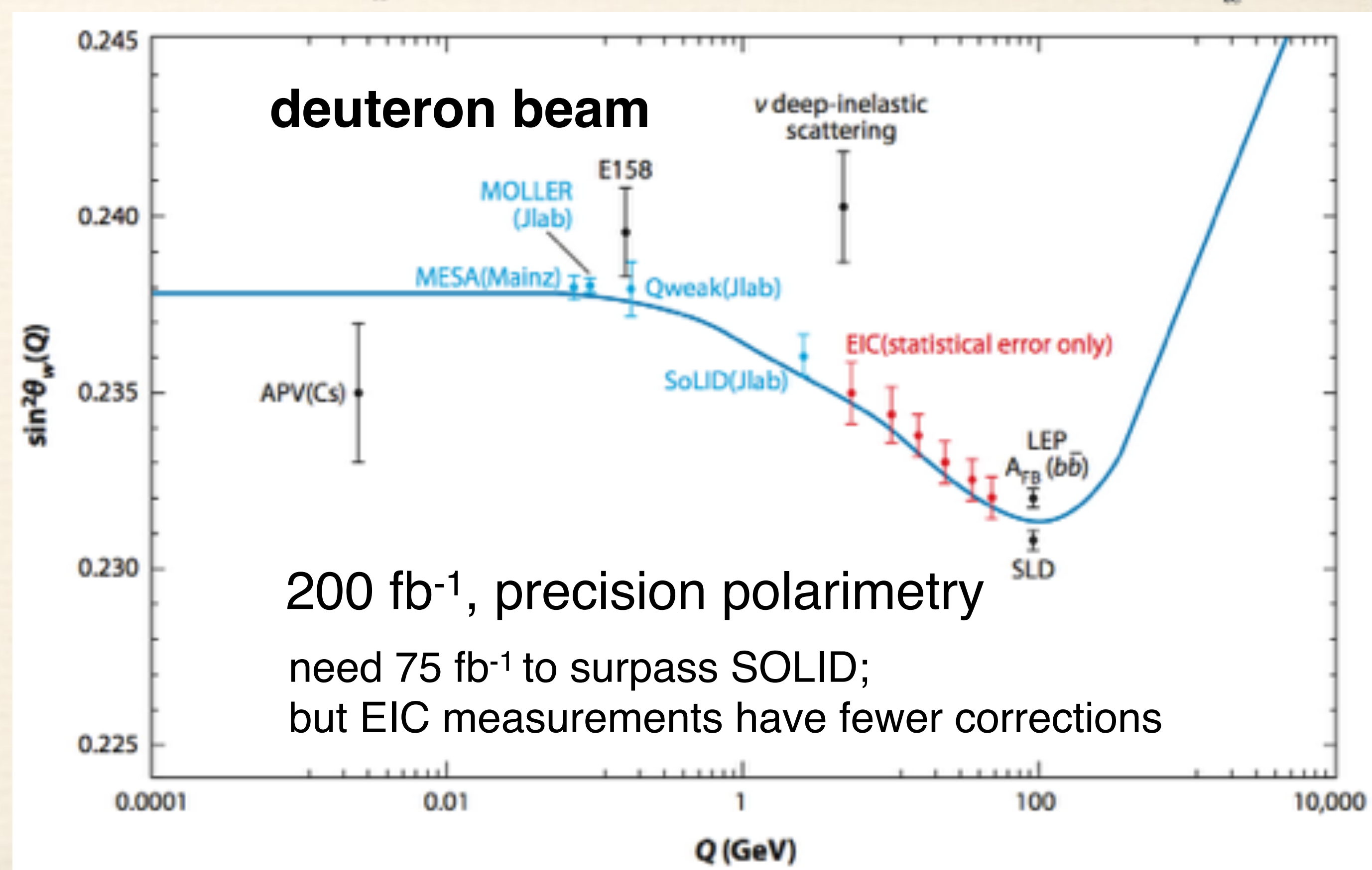




Summary

- **Strange Quark Vector Form Factors**
  - ★ Program complete: strange quarks contribute no more than a few % of EM Form Factors
  - ★ Further accuracy in lattice calculations will validate this important insight into nucleon structure
  - ★ Critical input to precision SM and neutron radius measurements
- **PV Measurements of Neutron Densities**
  - ★ Proof of principle established: precision from new measurements anticipated in next few years
  - ★ Constraint on the density dependence of the Symmetry Energy
- **Search for New TeV-Scale Physics**
  - ★ PV Elastic Scattering: Qweak final results soon, future: MOLLER at JLab & P2 at Mainz
  - ★ PV Deep Inelastic Scattering with Deuterium
    - *first experimental establishment of non-zero axial quark couplings*
    - *12 GeV with SOLID: TeV-scale sensitivity complementary to LHC at 14 TeV*
- **Nucleon Structure Topics Enabled by SOLID**
  - ★ ^{2}H: Access to a dynamically interesting higher-twist effect
  - ★ ^{2}H: Precise constraint of possible parton-level charge symmetry violation at high-x
  - ★ ^{1}H: Precision high-x constraints on d/u with no nuclear corrections
  - ★ ^{48}Ca: Clean, precise inclusive measurement would facilitate flavor decomposition of EMC dynamics
- **New PV Measurements Enabled by the EIC**
  - ★ Natural evolution of the JLab PVDIS Program
  - ★ Novel parity-violating structure functions will provide new insights into nucleon QCD dynamics

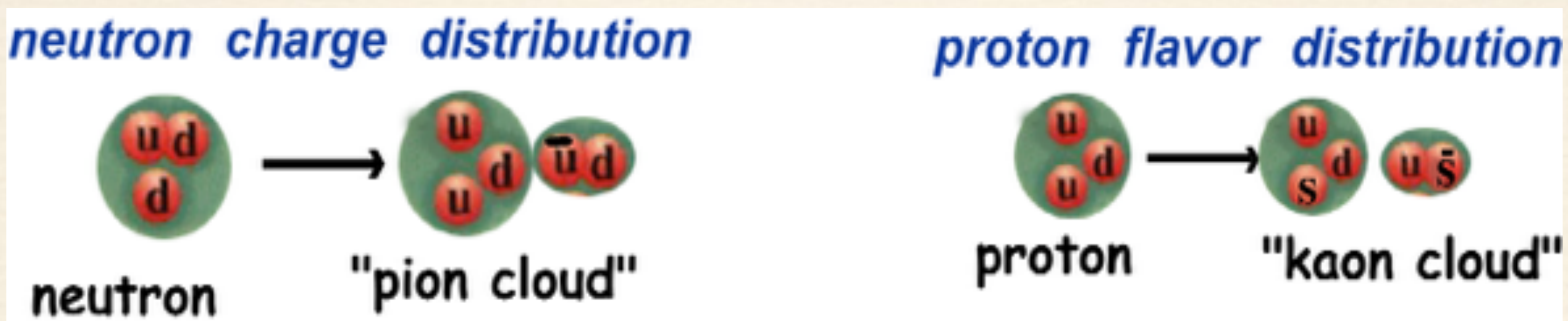
Backup

Strange Quarks in the Nucleon

Quark Model ⟺ ? QCD *Late 1980's*

Strange quarks carry nucleon momentum: Other external properties affected?

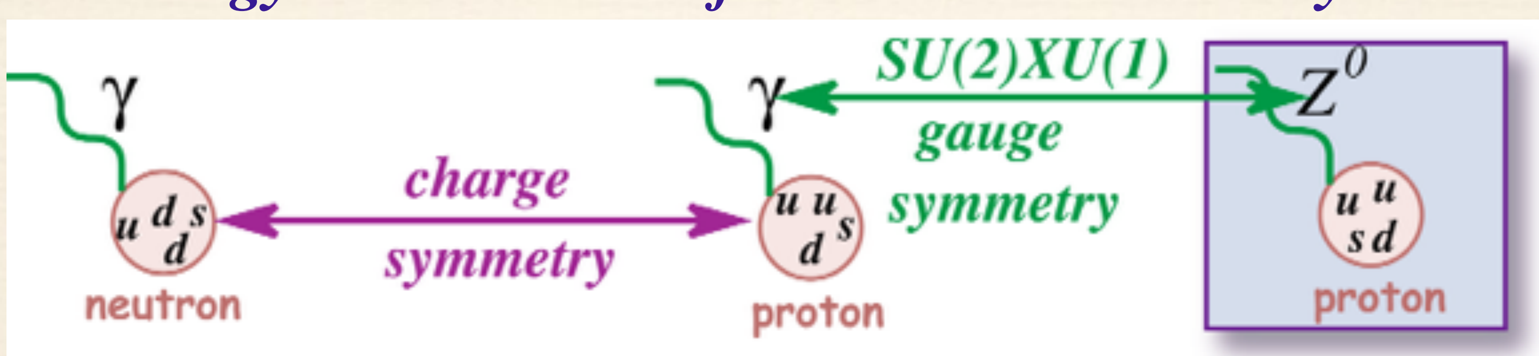
A pressing question after discovery of EMC effect and the spin crisis



?

Even with broken SU(3)$_f$, potentially large effects for vector current predicted

Theorists originally proposed using neutrino scattering; parity-violating electron scattering technology & the success of the electroweak theory led to a new strategy



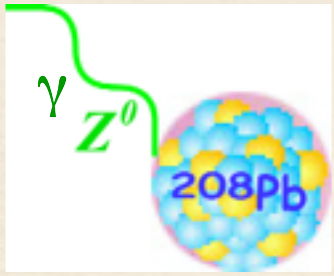
Kaplan & Manohar (1988)
McKeown (1989)
Beck (1990)

$$G_p^Z \sim (1 - 4\sin^2\theta_W)\, G_p^\gamma - G_n^\gamma - G_s \Rightarrow G_E^s(Q^2),\, G_M^s(Q^2)$$

^{4}He target: Unique G_E sensitivity *^{2}H: Enhanced G_A sensitivity*

Pb-Radius EXperiment

EW Probe of Neutron Densities



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

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

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

Pb-Radius EXperiment

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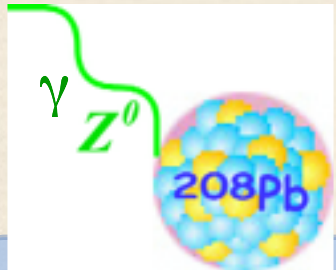

$$A_{PV} \approx \frac{G_F Q^2}{4\pi\alpha\sqrt{2}} \frac{F_n(Q^2)}{F_p(Q^2)}$$

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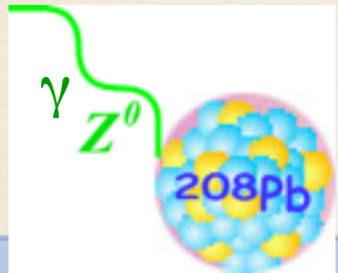

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$Q^2 \sim 0.01$ GeV^2
5^o scattering angle ⇨

$A_{PV} \sim 0.6$ ppm

Rate ~ 1 GHz

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

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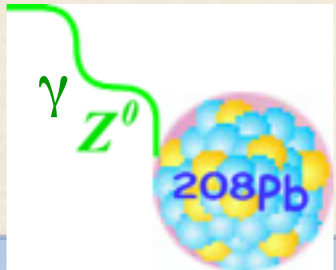

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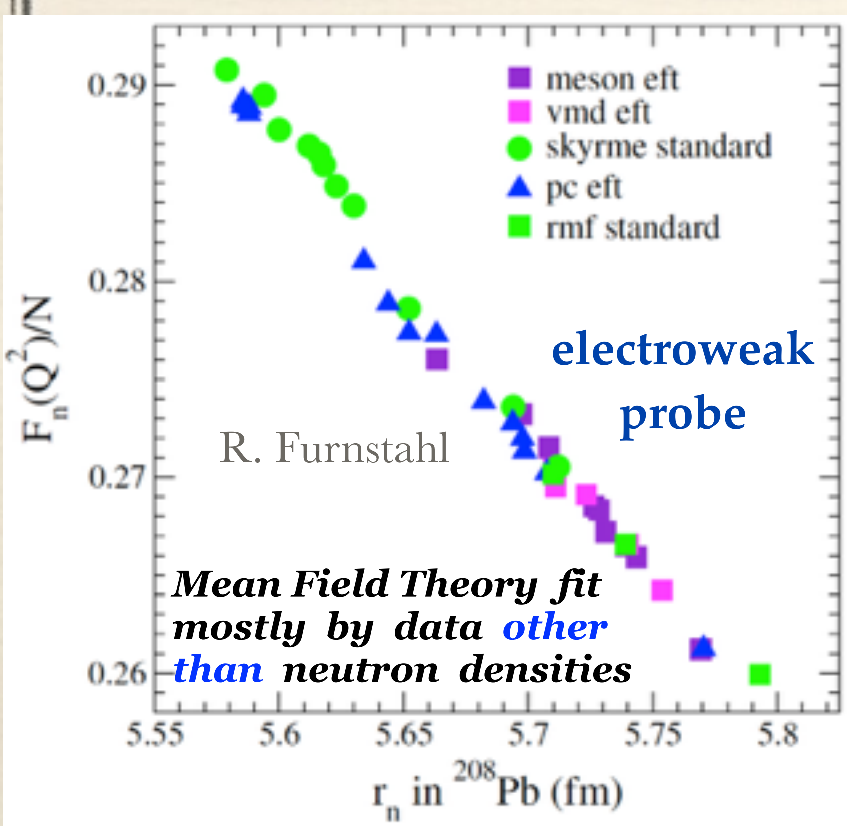

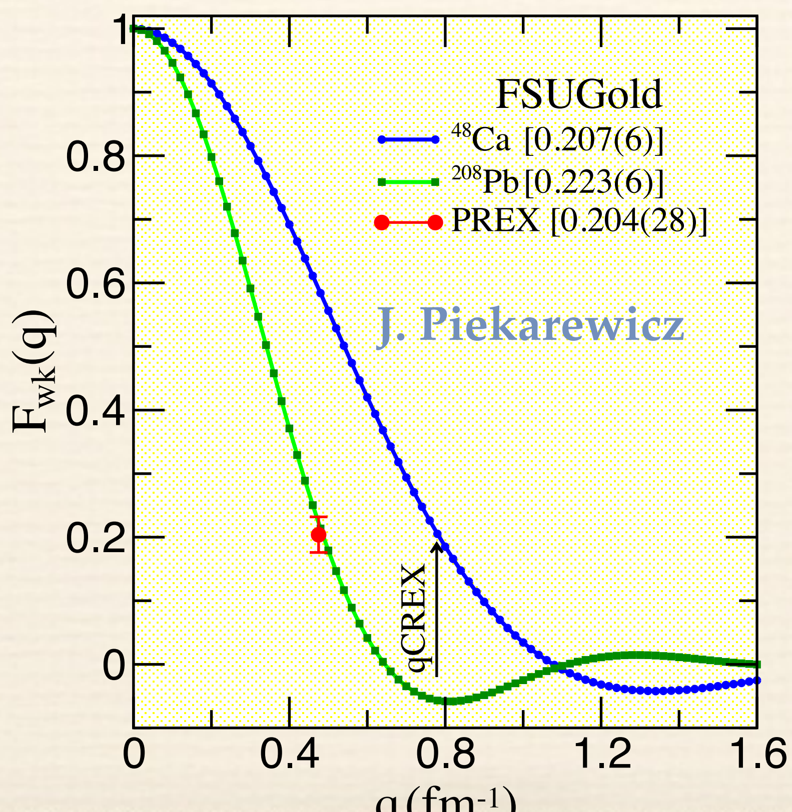

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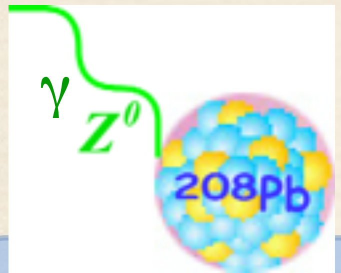

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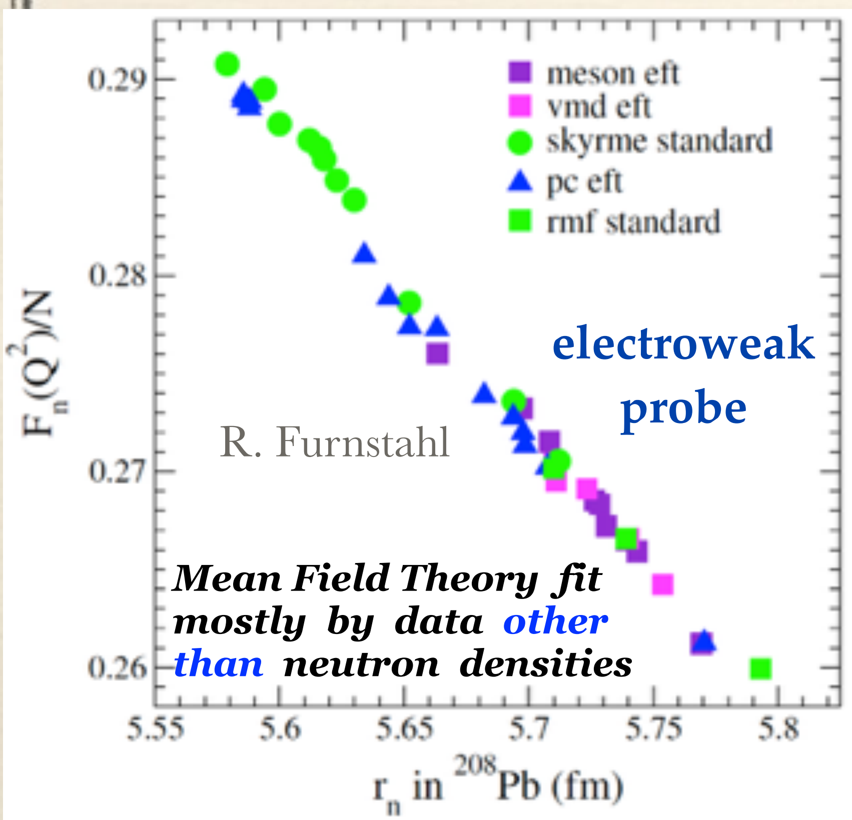

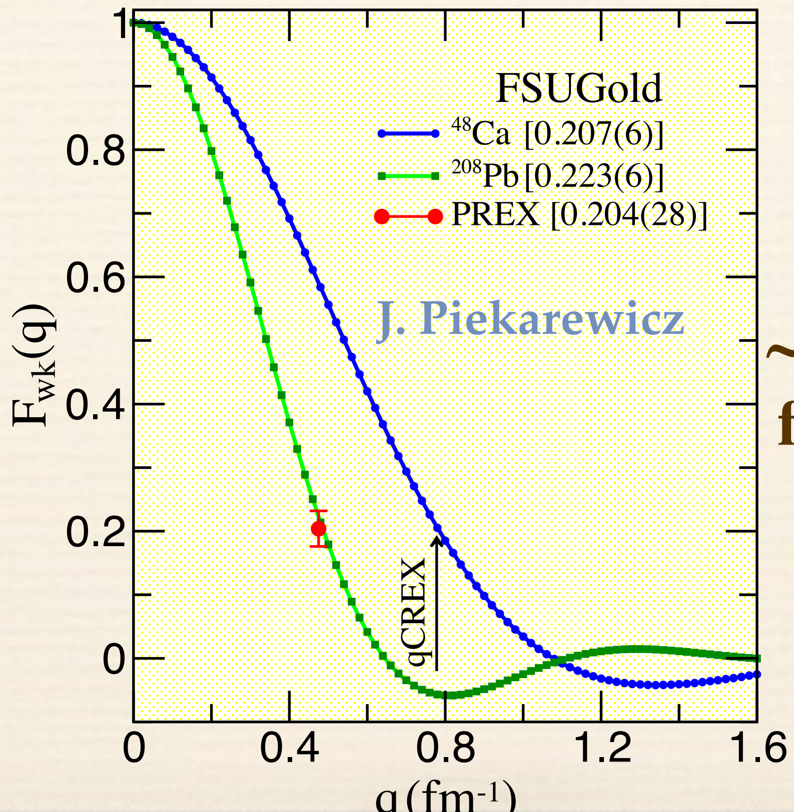

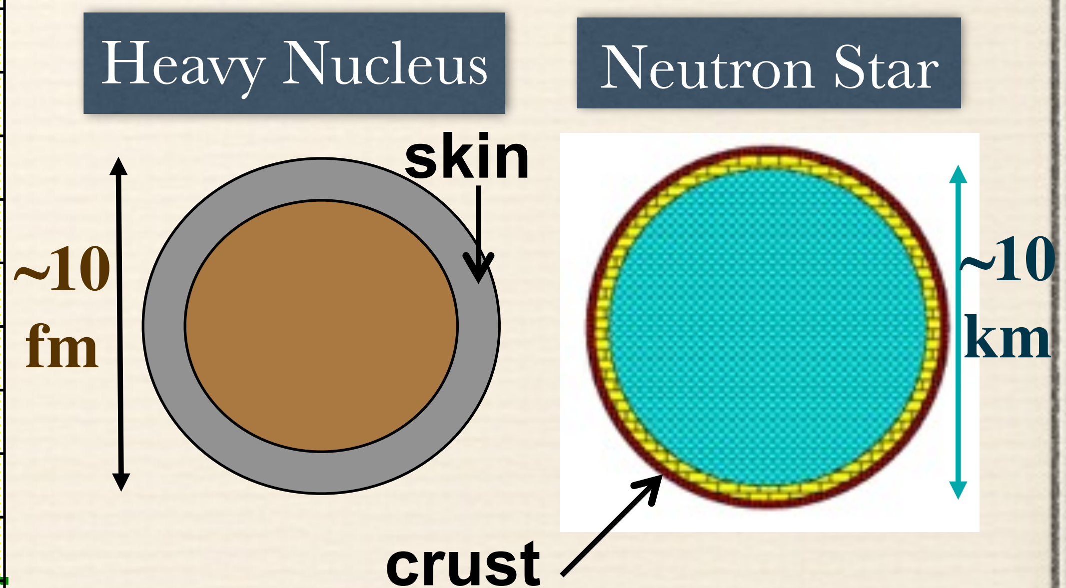

Horowitz and Piekarewicz, PRL 86 (2001)

Fundamental Symmetries & Neutrinos (also HEP Intensity Frontier)

Compelling arguments for "New Dynamics" in the Early Universe

A comprehensive search to understand the origin of matter requires:

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

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

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

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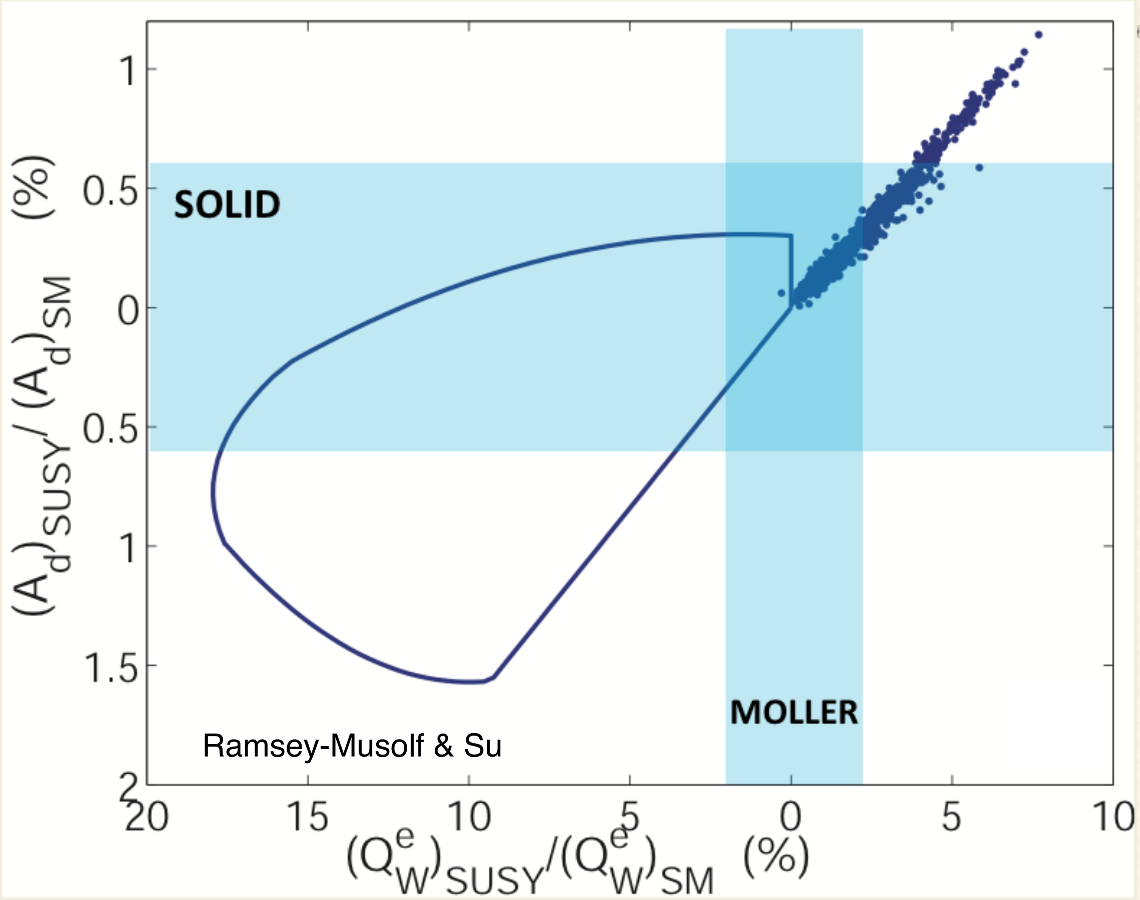
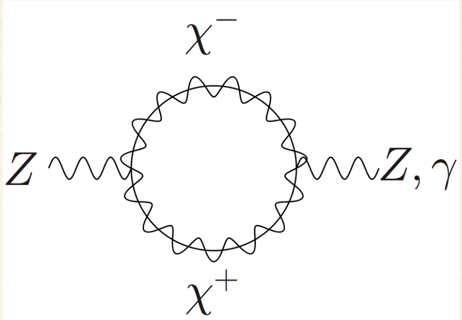
Experimental Facilities/Initiatives/Programs

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

The Role of Low Q^2 Weak Neutral Current Measurements

SOLID Sensitivity

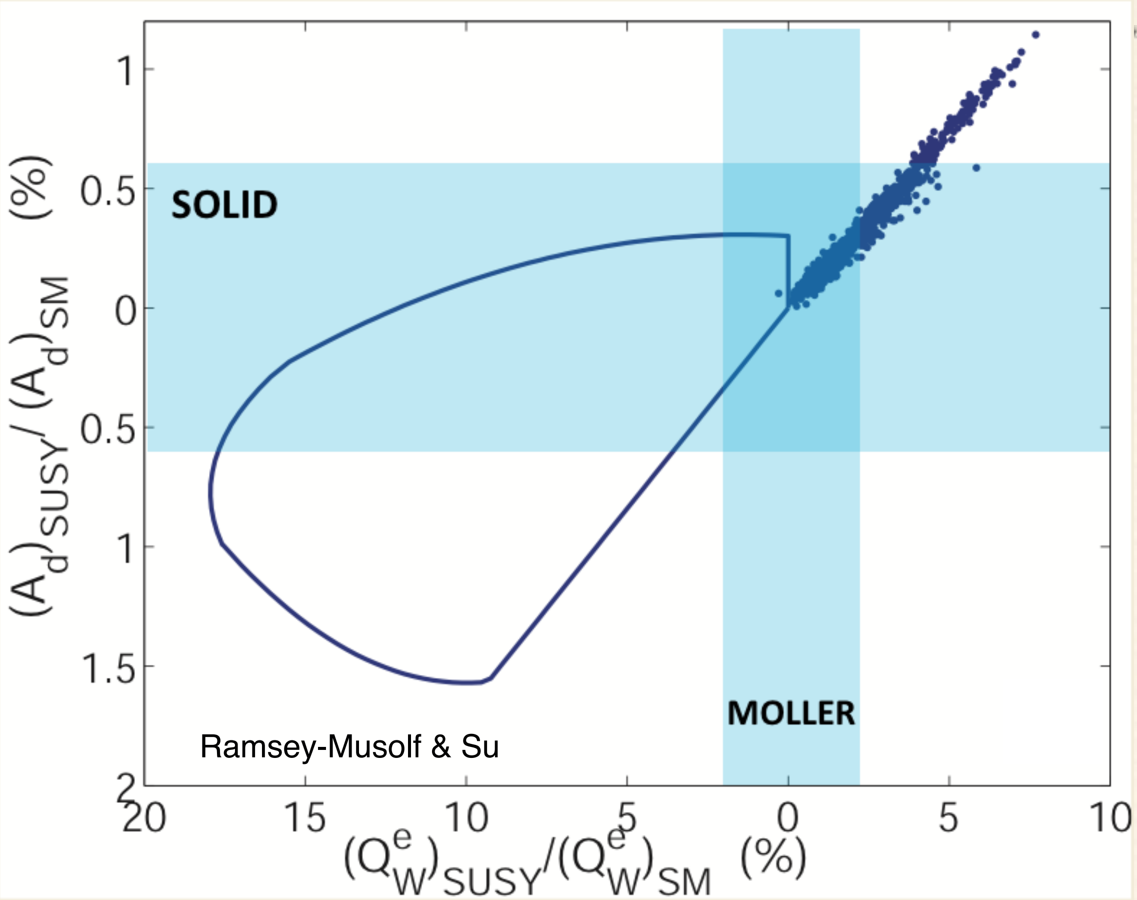


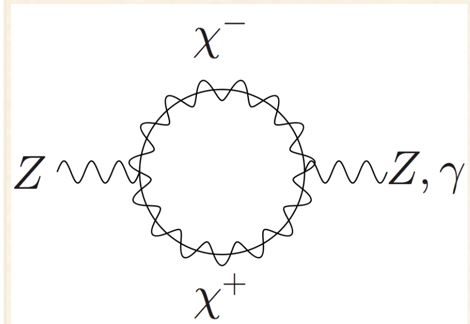


Does Supersymmetry provide a candidate for dark matter?

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

SOLID Sensitivity





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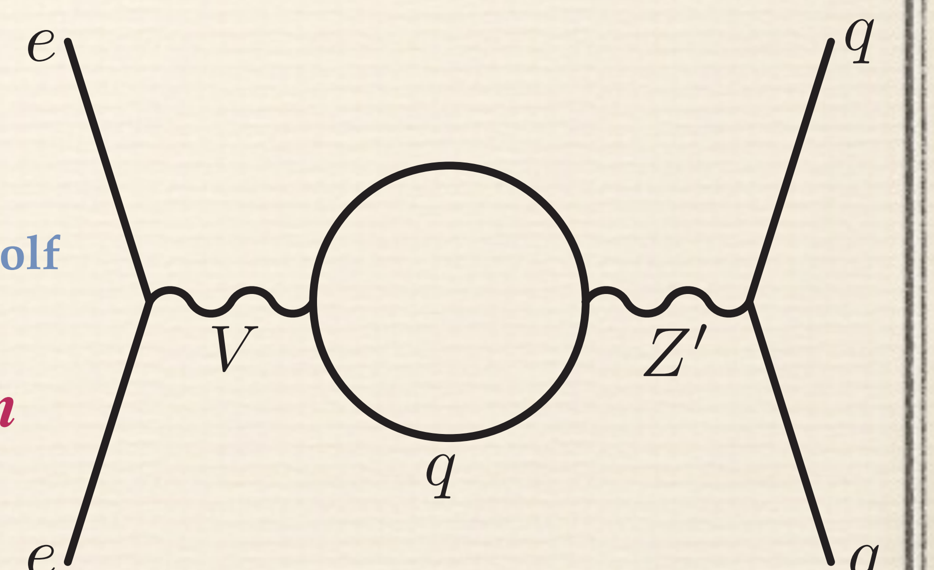
Leptophobic Z'

arXiv:1203.1102v1
Buckley and Ramsey-Musolf

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

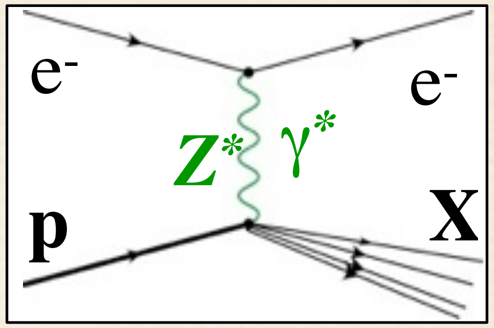


*Since electron vertex must be vector, the Z' cannot couple to the C_{1q}'s if there is no electron coupling: can only affect **C_{2q}'s***

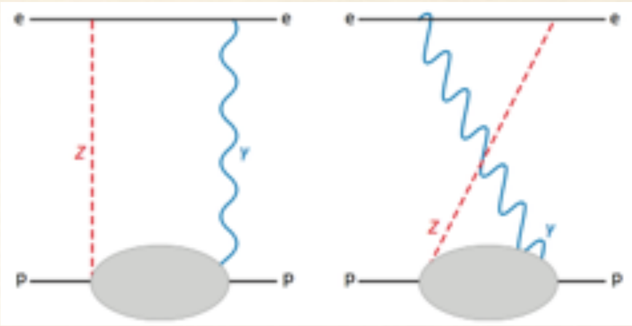
SOLID can improve sensitivity: 100-200 GeV range

EW & Hadron Physics Interplay

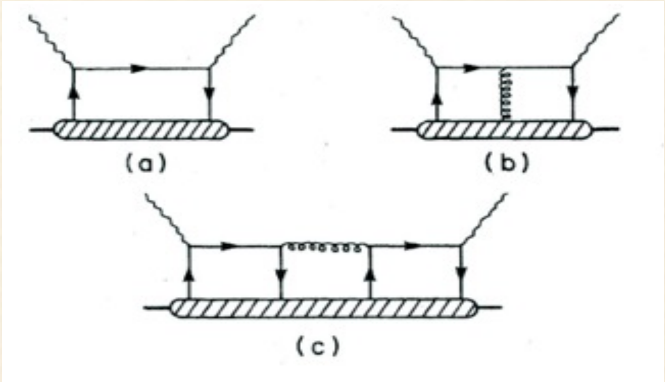
electrons on LH_2



- **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

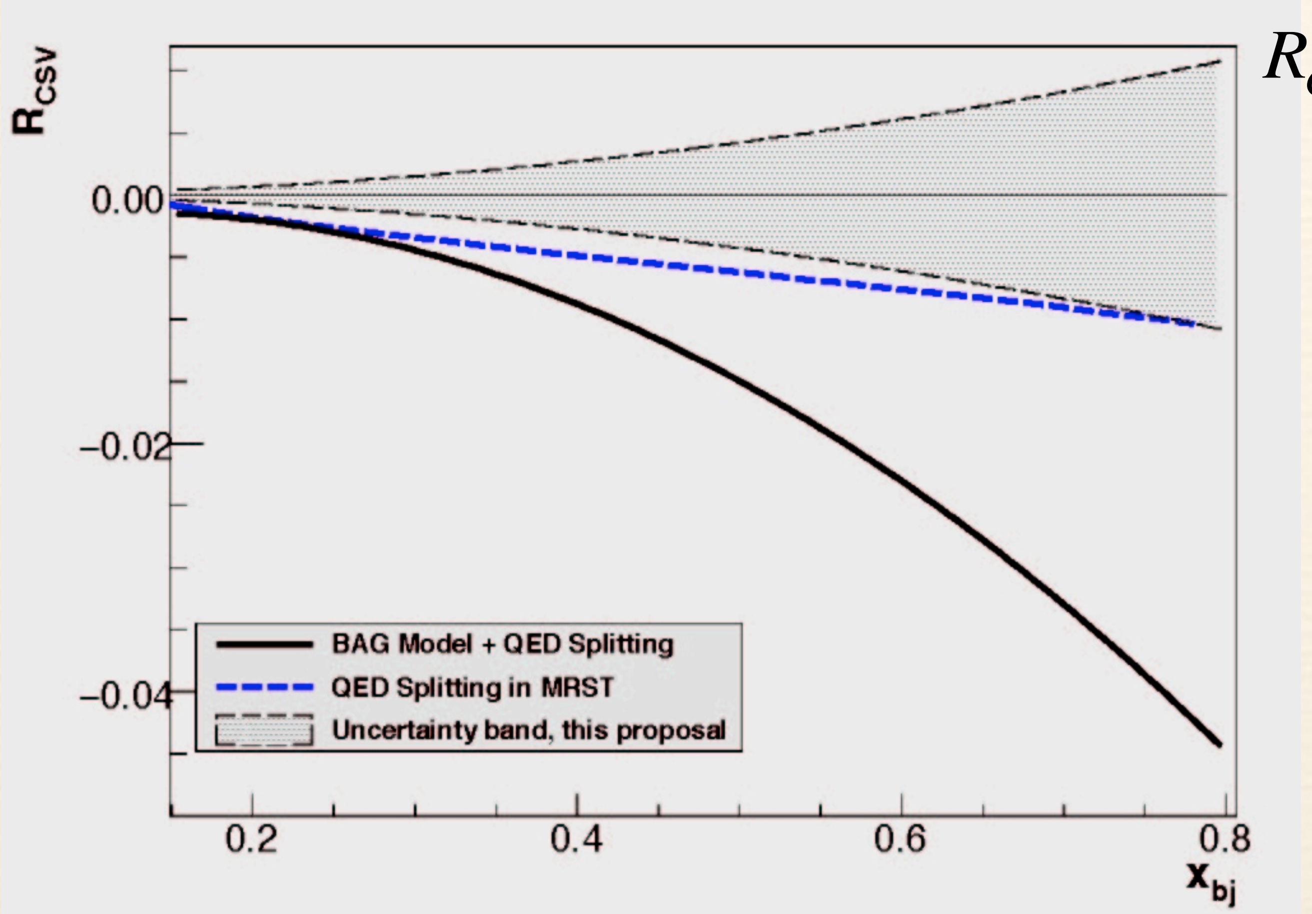
Parton-level charge symmetry assumed in deriving ^2H A_{PV}

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

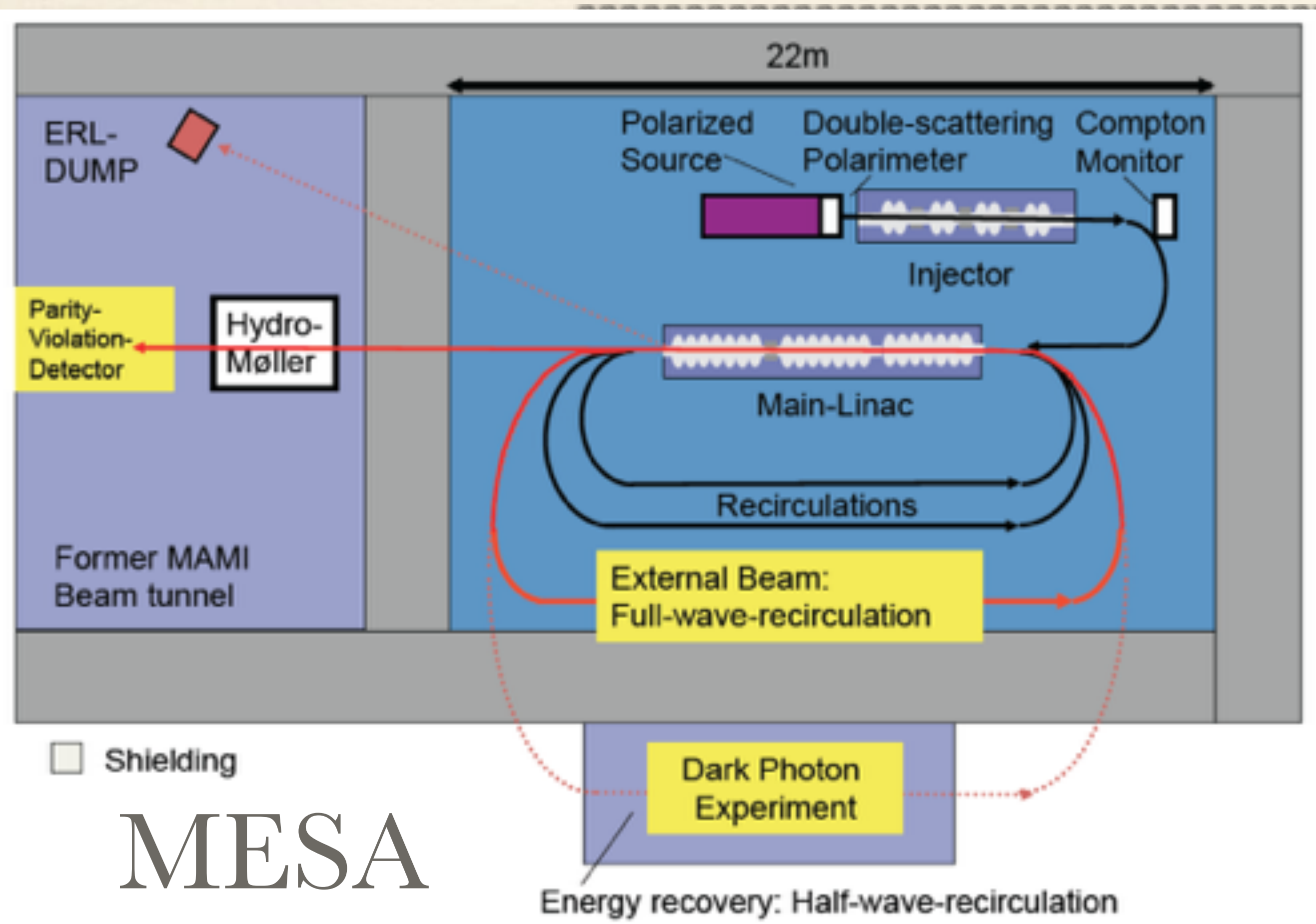


$$R_{CSV} = \frac{\delta A_{PV}(x)}{A_{PV}(x)} = 0.28\frac{\delta u(x) - \delta d(x)}{u(x) + d(x)}$$

- 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

Elastic Electron-Proton Scattering

P2 at Mainz



MESA

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

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

Technically challenging:
great synergy with JLab program

Recent joint beam test of integrating quartz detectors successful

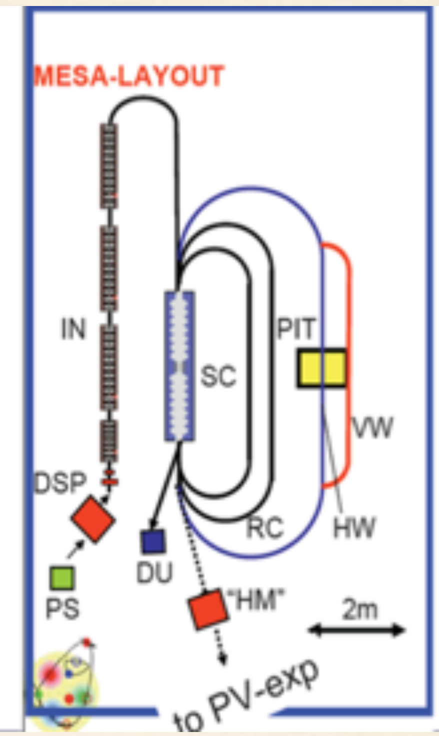
Weak Charge and Neutron Skin at Mainz

Future: MESA/P2 at Mainz

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

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

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



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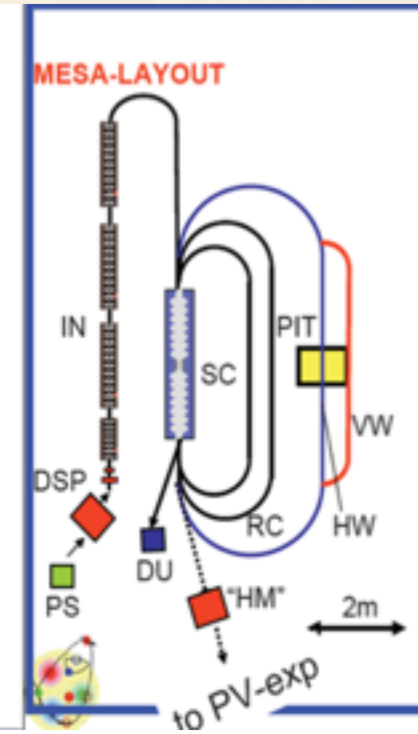
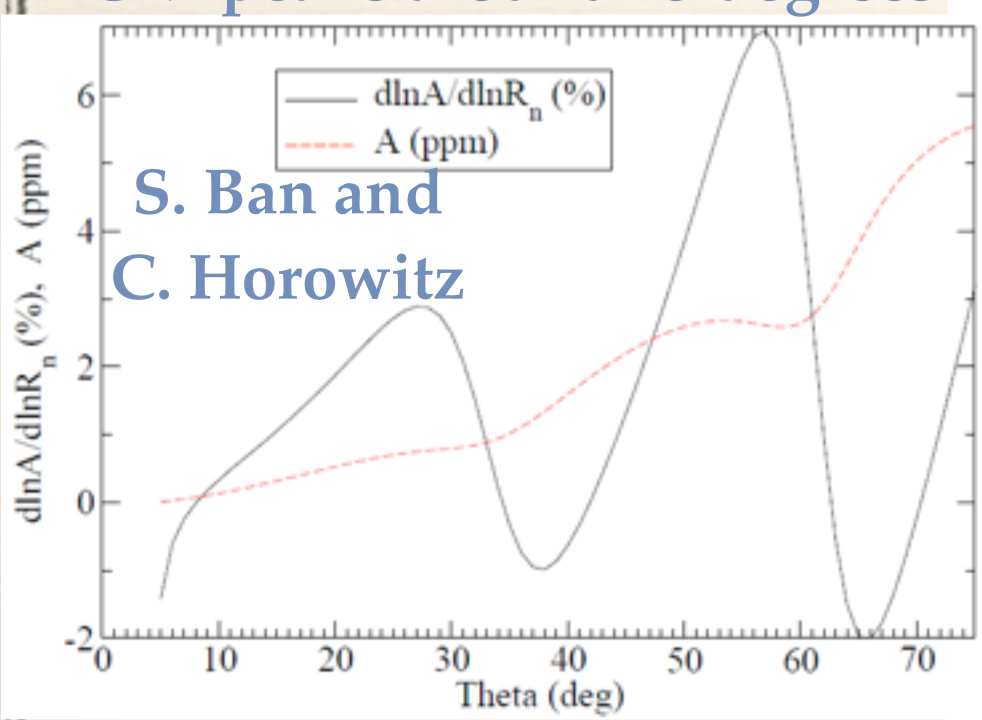


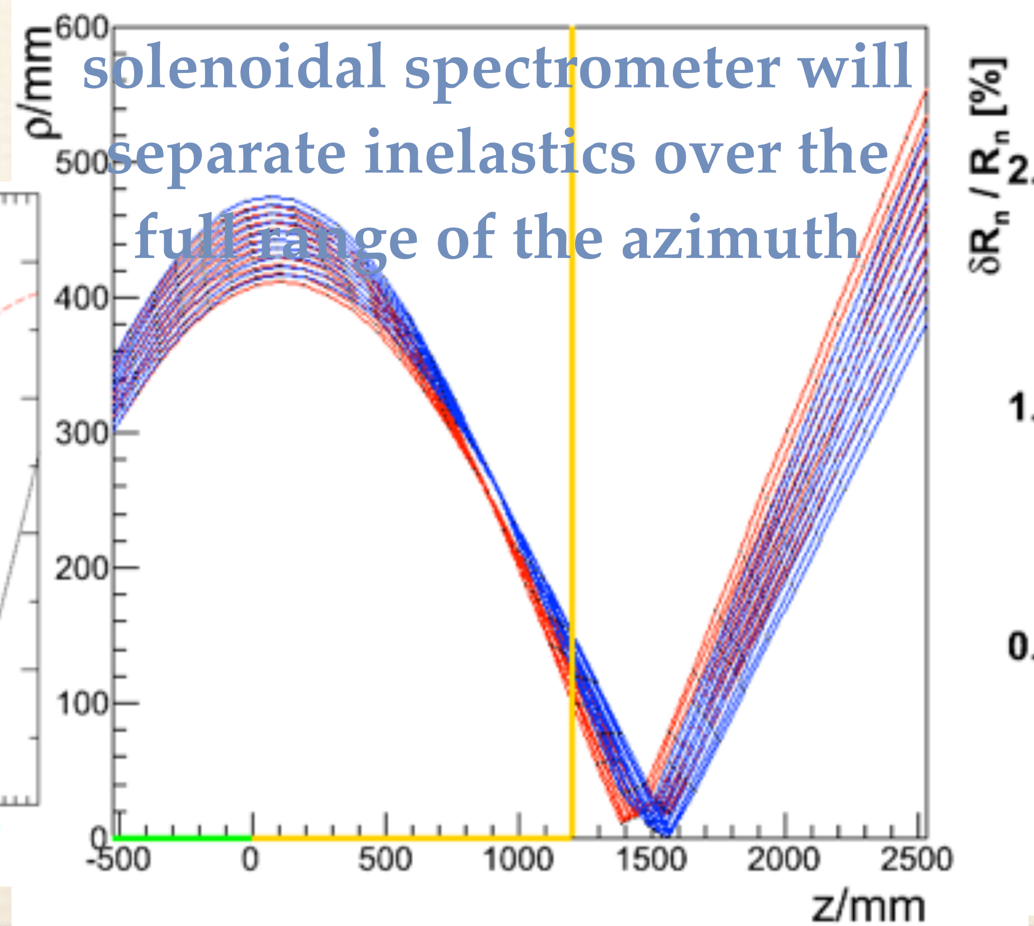
Explore a PREX-style measurement using same solenoidal magnet to be used for P2

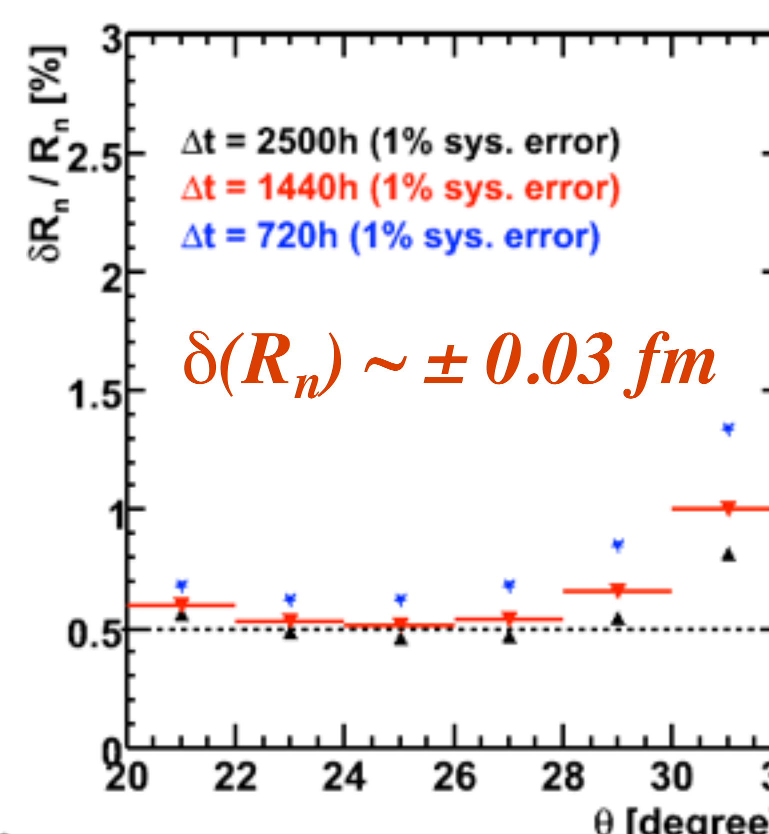
200 MeV
FOM peaks around 25 degrees

S. Ban and C. Horowitz



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

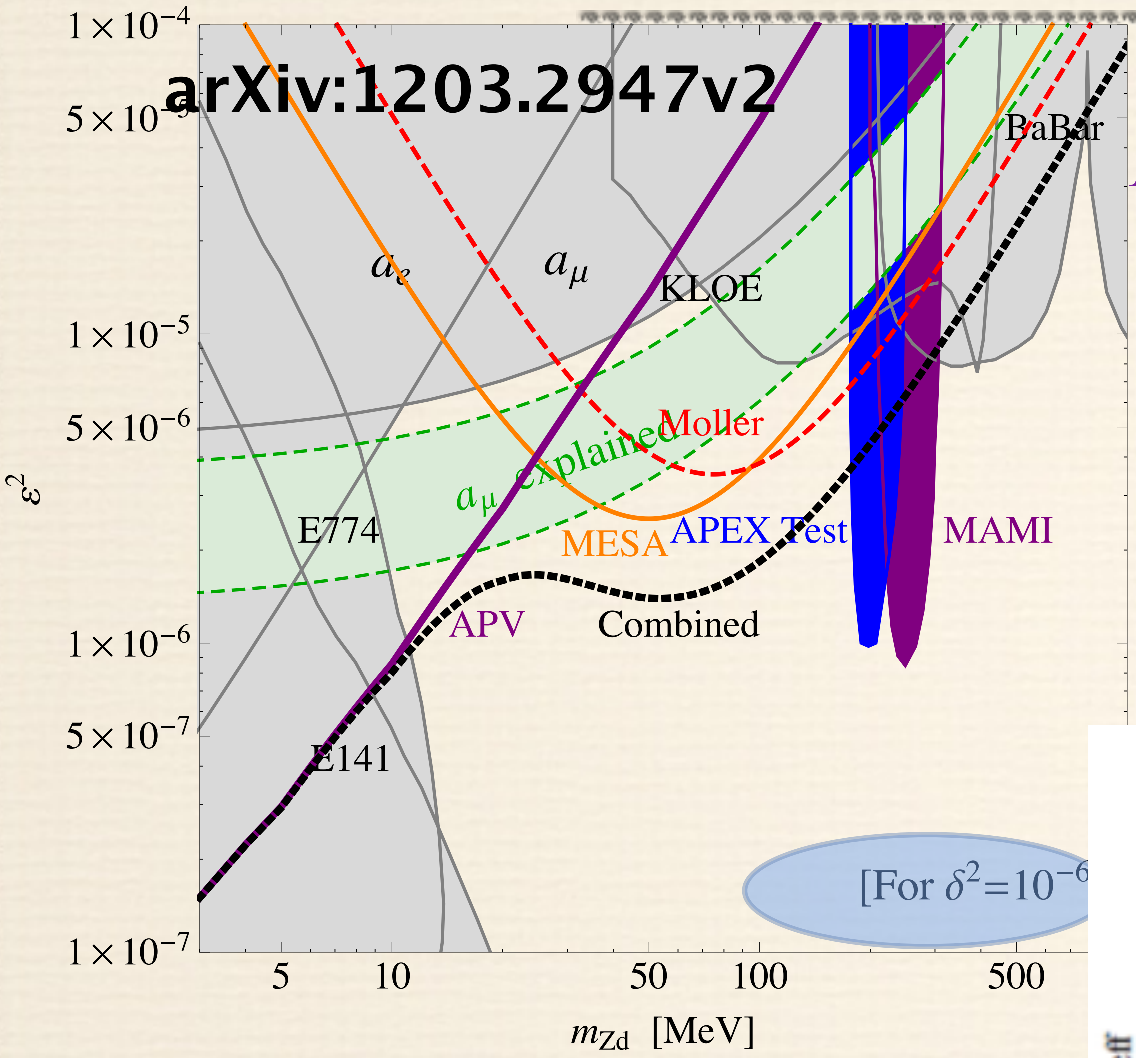




$\delta(R_n) \sim \pm 0.03$ fm

Dark Z to Invisible Particles

Davoudiasl, Lee, Marciano



Dark Photons:

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

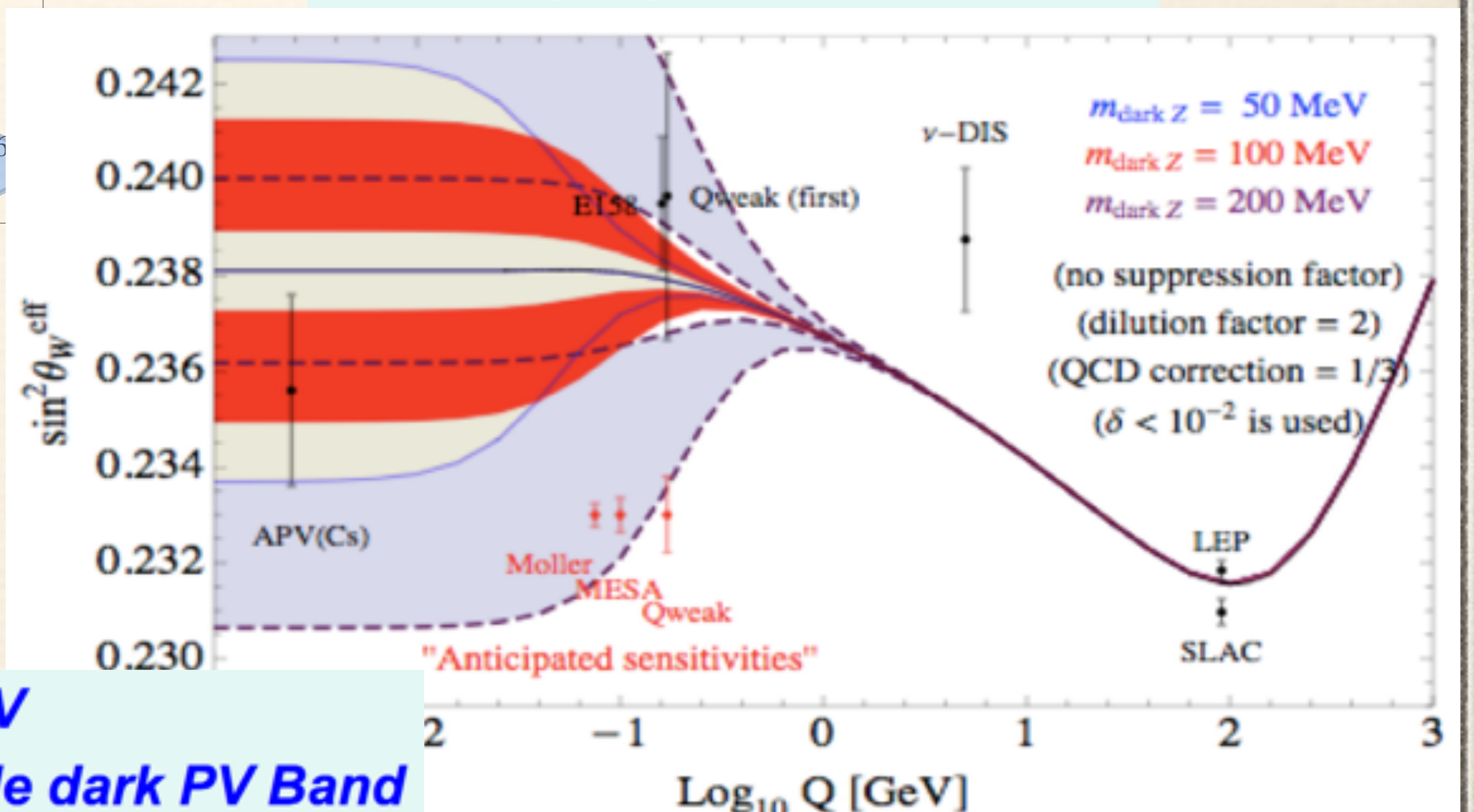
$$\epsilon_Z = \frac{m_{Z_d}}{M_Z}\delta$$

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

  APV & Polarized Electron Scattering at low <Q>

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

δ^2 roughly probed to 10^{-6}



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

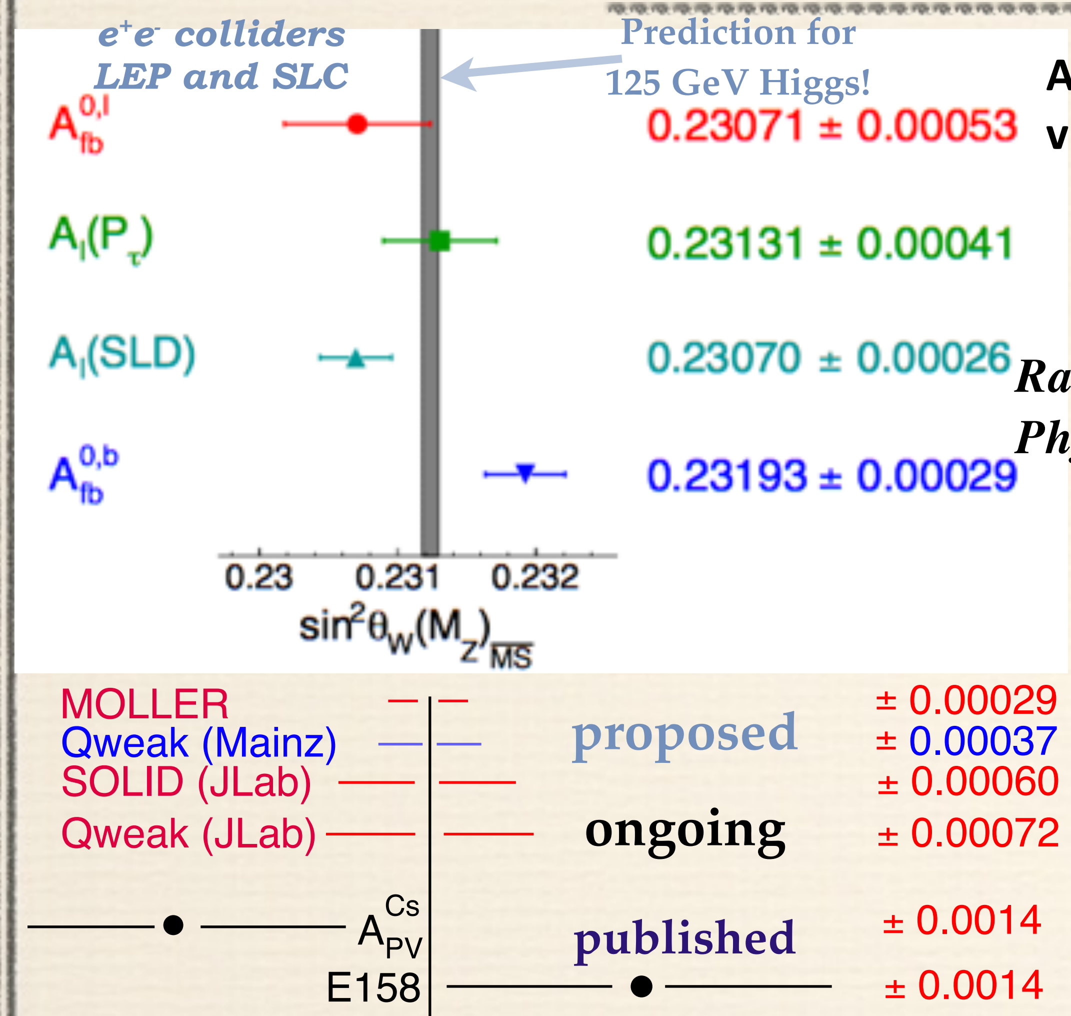
ε and δ effects could partially cancel!

Suppression by ~1/6 allows Z_d~100MeV

Combined with muon g-2 → observable dark PV Band

Physics Examples: Beyond LHC

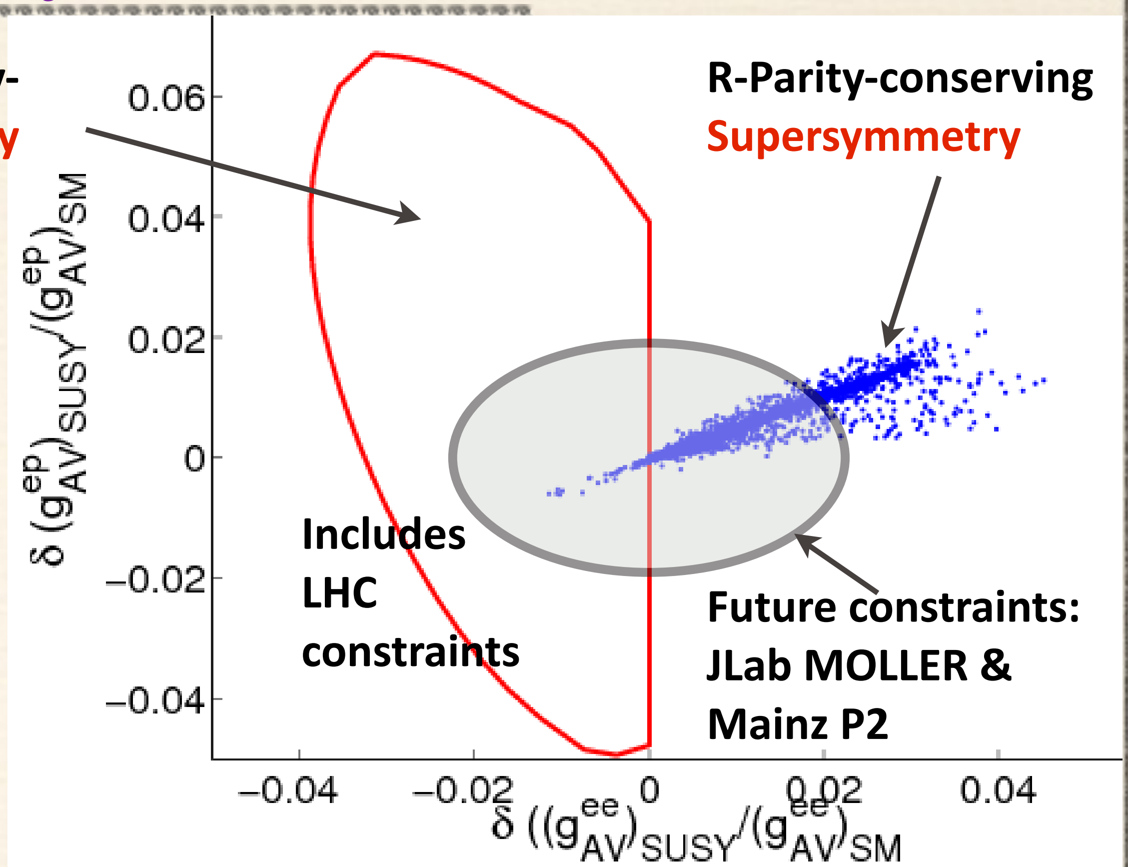
Z resonance measurements: little sensitivity to new contact interactions



Allowed region: R-Parity-violating Supersymmetry

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

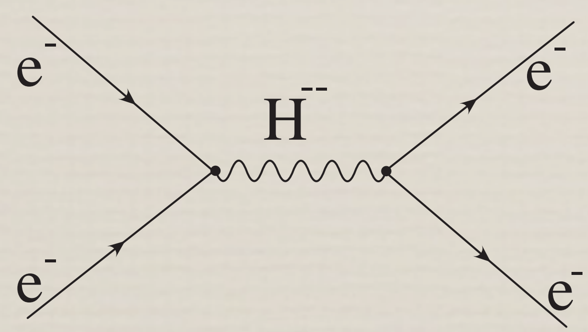
Erler and Su, arXiv:1303.5522



Lepton Number Violation

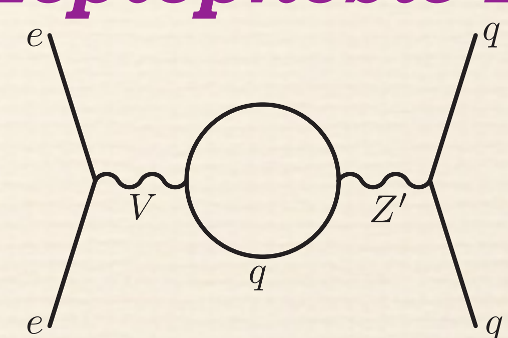
Λ > 5 TeV

Doubly-Charged Scalars



Significant reach beyond LEP-200

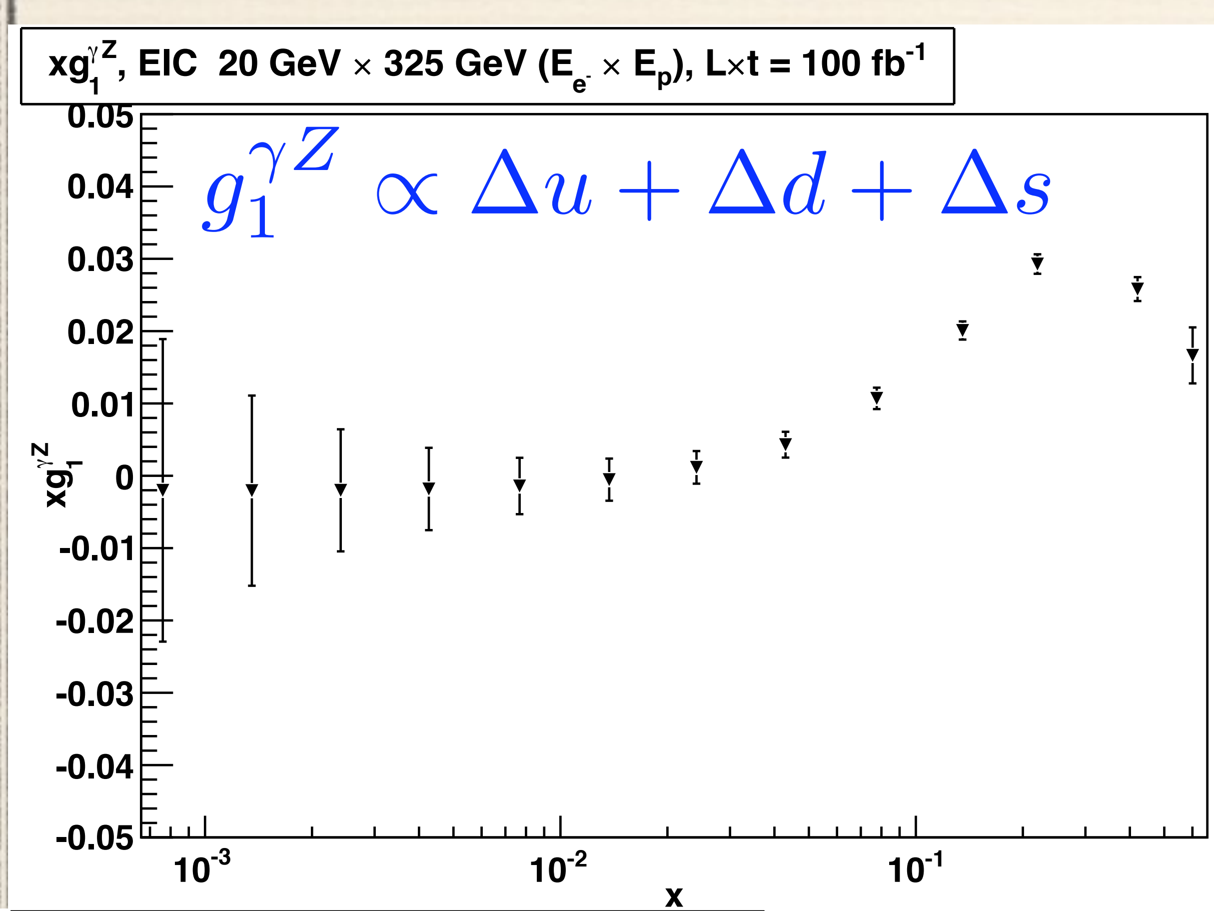
Leptophobic Z'

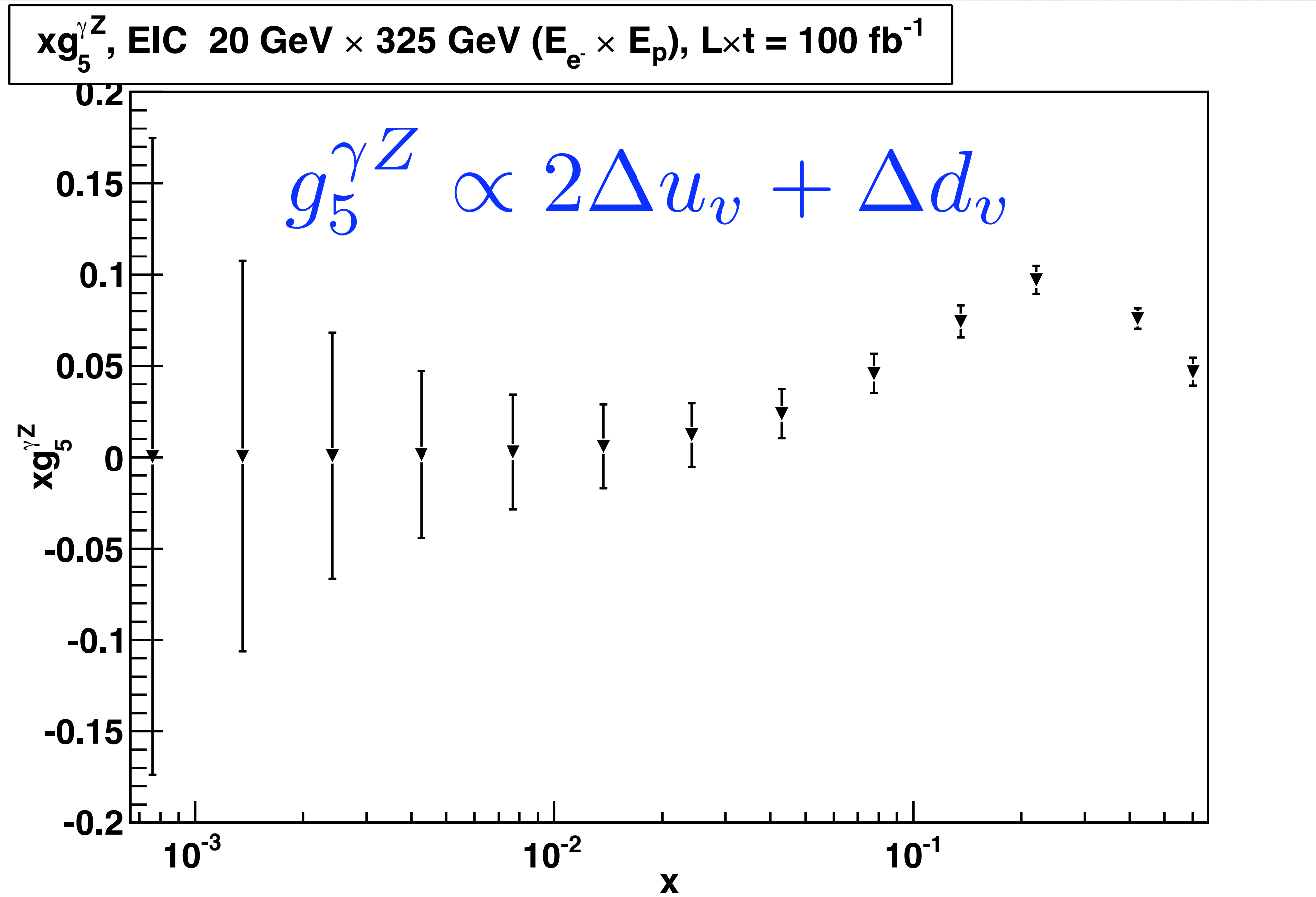


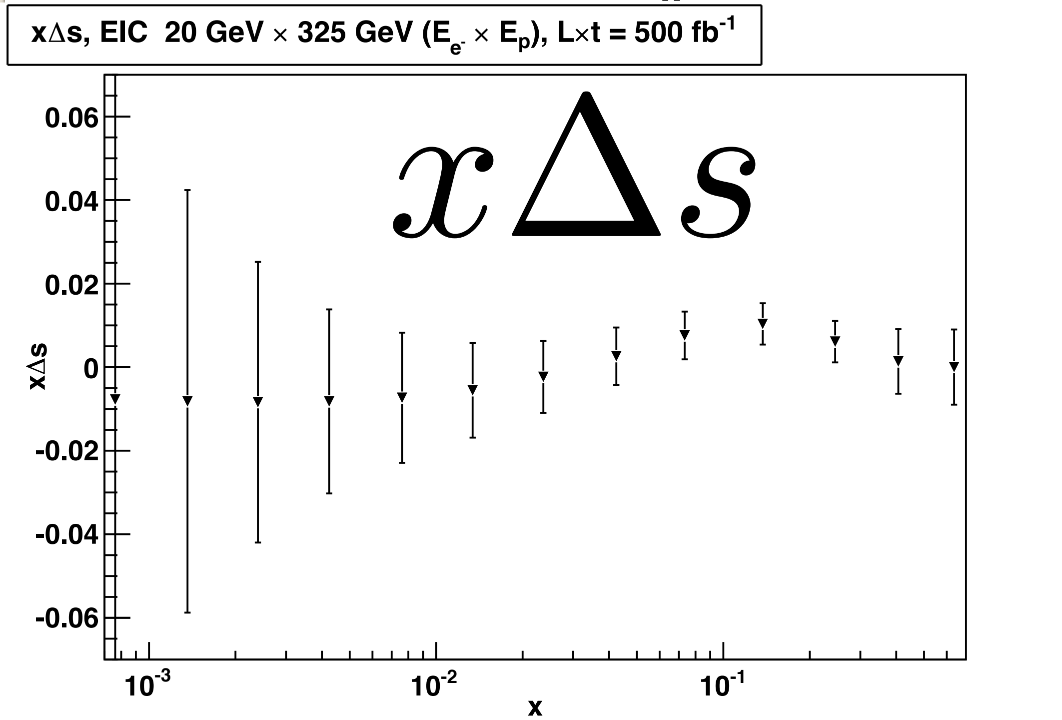
SOLID can improve sensitivity: 100-200 GeV range

Including quark and anti-quark polarizations

Help 6-Flavor Separation





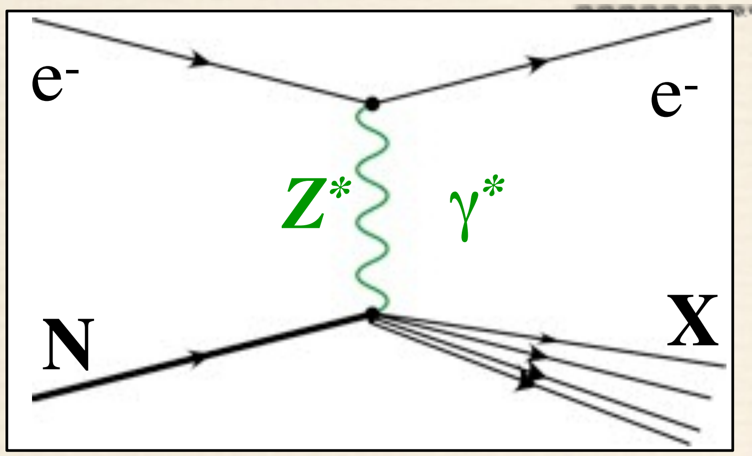


A cross-check showing unambiguously non-zero delta-s in an inclusive measurement?

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

PV Deep Inelastic Scattering

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



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

$x \equiv x_{Bjorken}$

$y \equiv 1 - E'/E$

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

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

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

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

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

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

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

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

Interplay with QCD

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

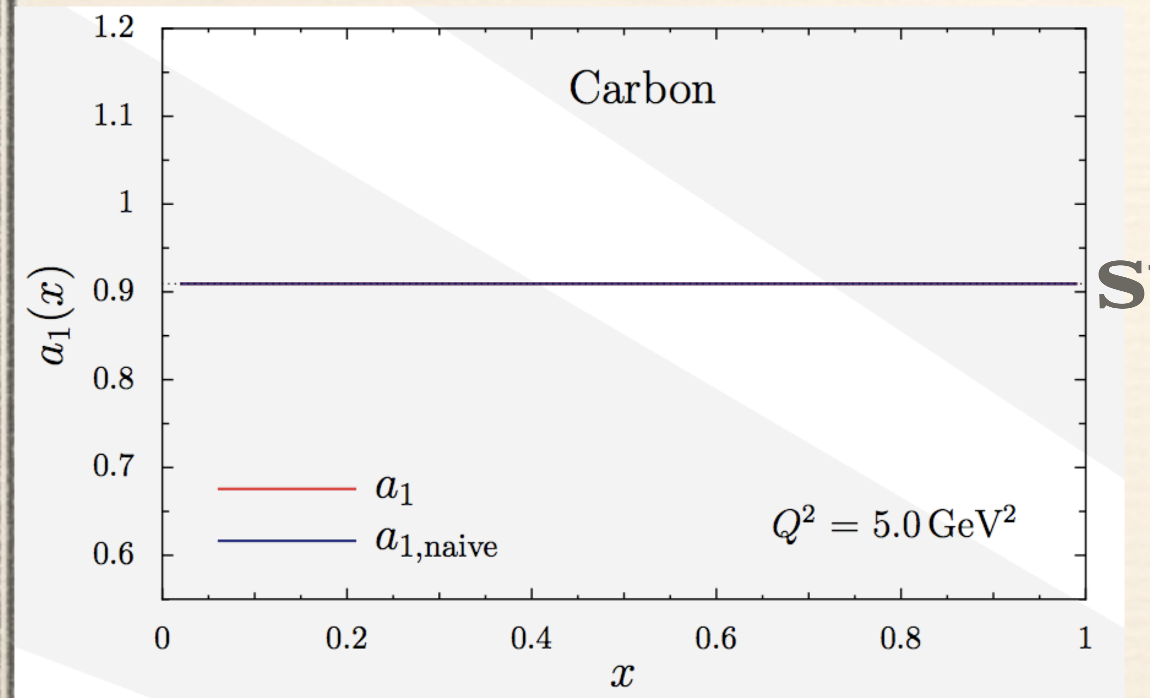
A Novel "EMC" Effect

Consider PVDIS on a heavy nucleus

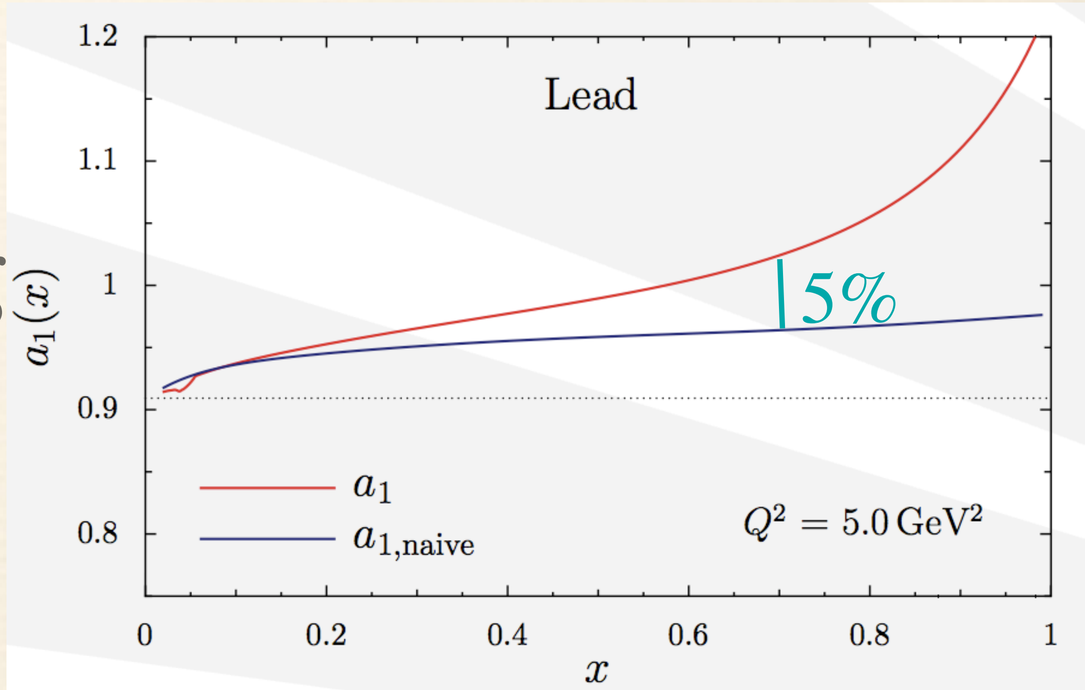
Cloet, Bentz, Thomas, arXiv 0901.3559

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

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



smoking gun!



An improved Ca-48 proposal using Ca-48 being developed for JLab

A Special HT Effect

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

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

Isospin decomposition before using PDF's

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

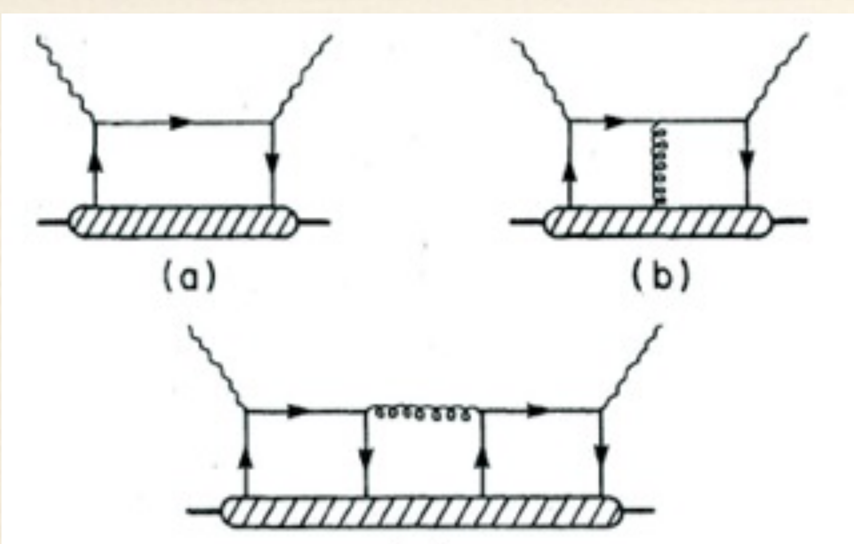
$$\left\langle VV \right\rangle = l_{\mu\nu} \int \left\langle D \,|\, V^\mu(x) V^\nu(0) \,|\, D \right\rangle e^{iq\cdot x} d^4 x$$

$$A_{PV} = \frac{G_F Q^2}{\sqrt{2}\pi\alpha}\left[a(x) + f(y) b(x)\right] \qquad \delta = \frac{\langle VV\rangle - \langle SS\rangle}{\langle VV\rangle + \langle SS\rangle} \qquad a(x) \propto \frac{F_1^{\gamma Z}}{F_1^{\gamma}} \propto 1 - 0.3\delta$$

Higher-Twist valence quark-quark correlation

Zero in quark-parton model

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



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.