Acknowledgments: W. Marciano, M. Ramsey-Musolf, M. Stratmann, W. Vogelsang

POETIC VI
Ecole Polytechnique
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Electroweak and Beyond Standard Model Physics

at an
Electron Ion Collider

Krishna Kumar
Stony Brook U. & ACFI

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

Fundamental Symmetries & Neutrinos:

The Intensity Frontier

Compelling arguments for "New Dynamics" in the Early Universe

A comprehensive search to understand the origin of matter requires:

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

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

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

Experimental Facilities/Initiatives/Programs

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

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What about the EIC?

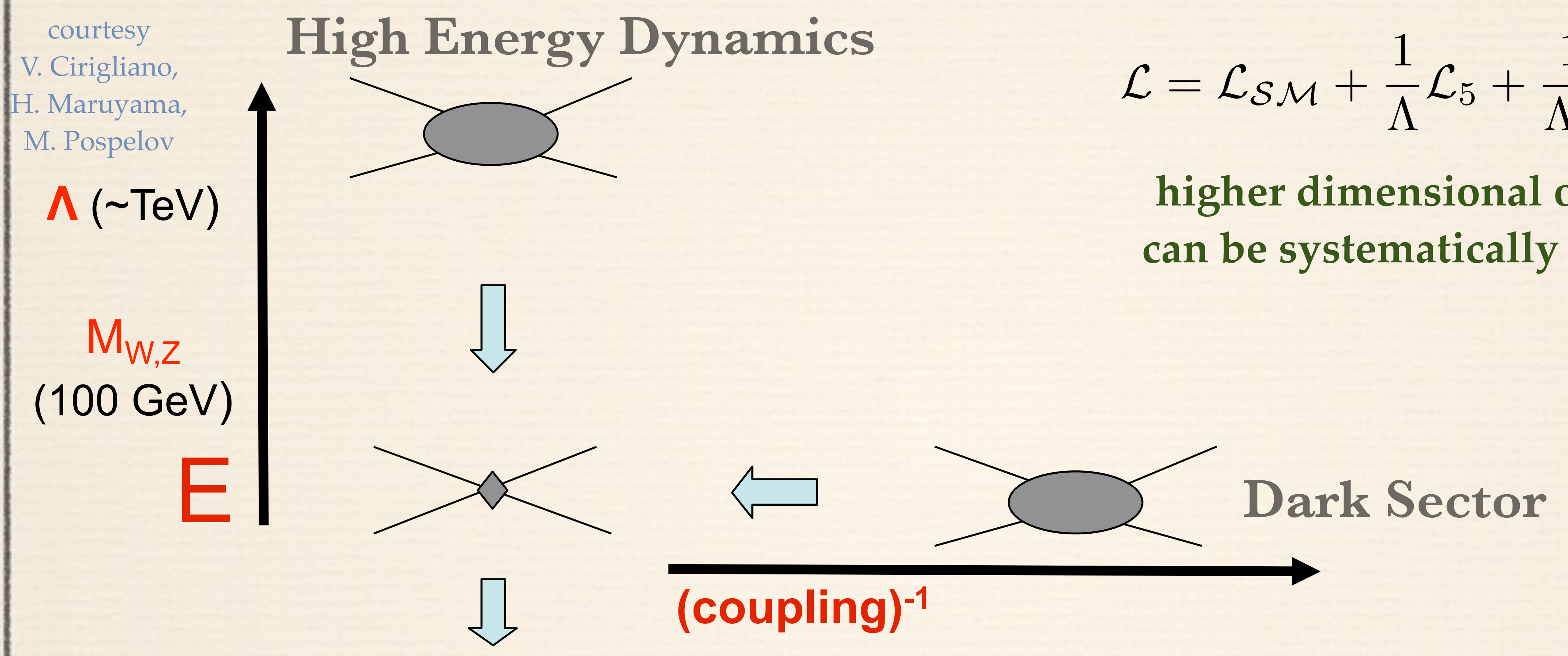
Outline

- **Low Q^2 Weak Neutral Currents**
  - Global Search for Physics Beyond the Standard Model
  - The Weak Mixing Angle at 1-Loop
    - *The Three Best Measurements at $Q^2 << M_Z^2$*
    - *The ongoing program and initiatives in the next decade*
- **Electroweak Physics at the EIC**
  - Neutral Current Structure Functions
  - The Weak Mixing Angle
  - Polarized Quark Distributions
- **Charged Lepton Flavor Violation**
  - Tau to Electron Conversion at the EIC
- **Summary and Outlook**

The Role of Low Q^2 Weak Neutral Current Measurements

Low Energy Frontier of the Standard Model

Indirect Clues for New Physics



High Energy Dynamics

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

Λ (~TeV)

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

E

Dark Sector

(coupling)$^{-1}$

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

higher dimensional operators
can be systematically classified

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

Indirect Clues for New Physics

Interplay between electroweak and hadron dynamics

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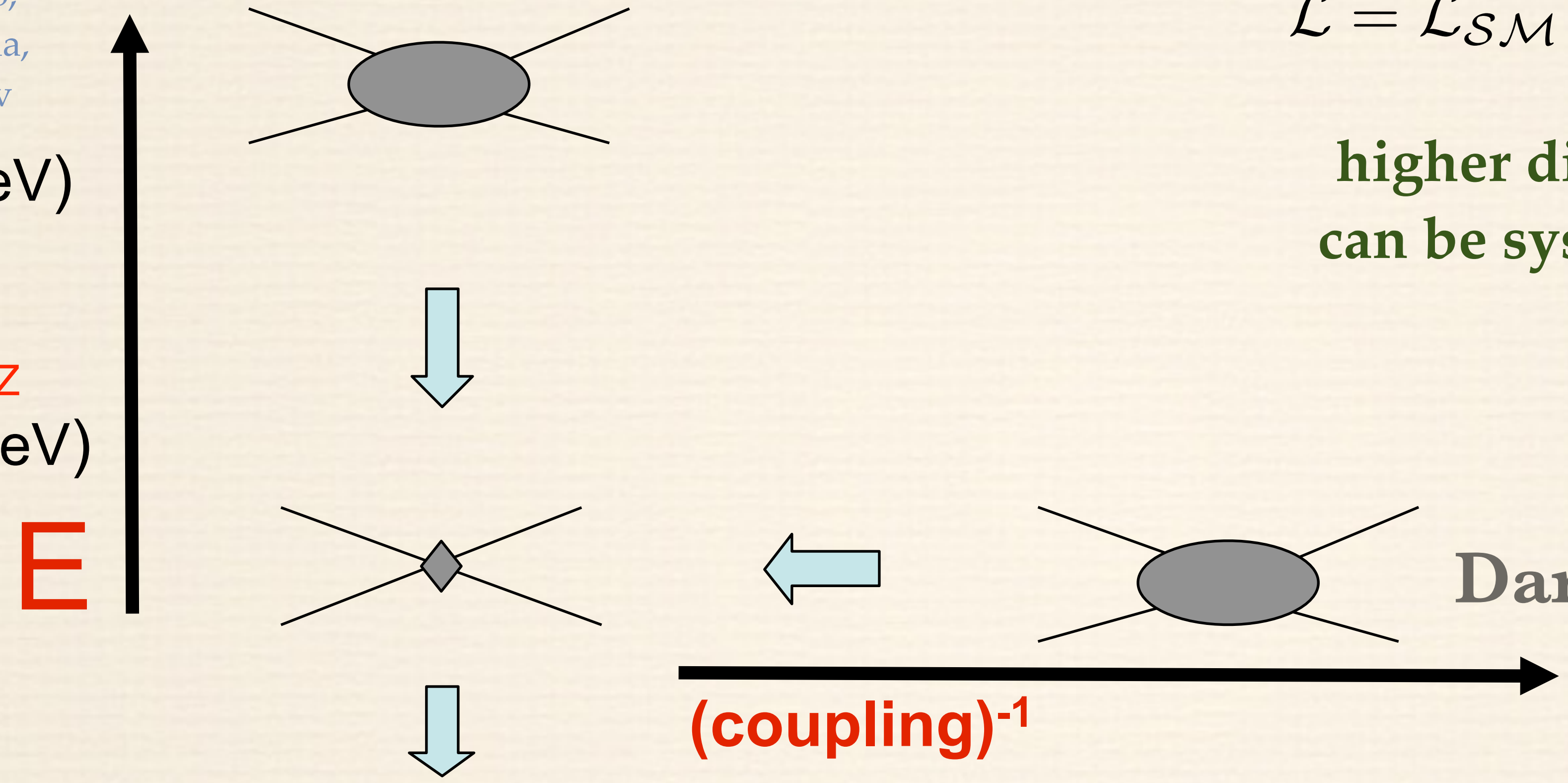

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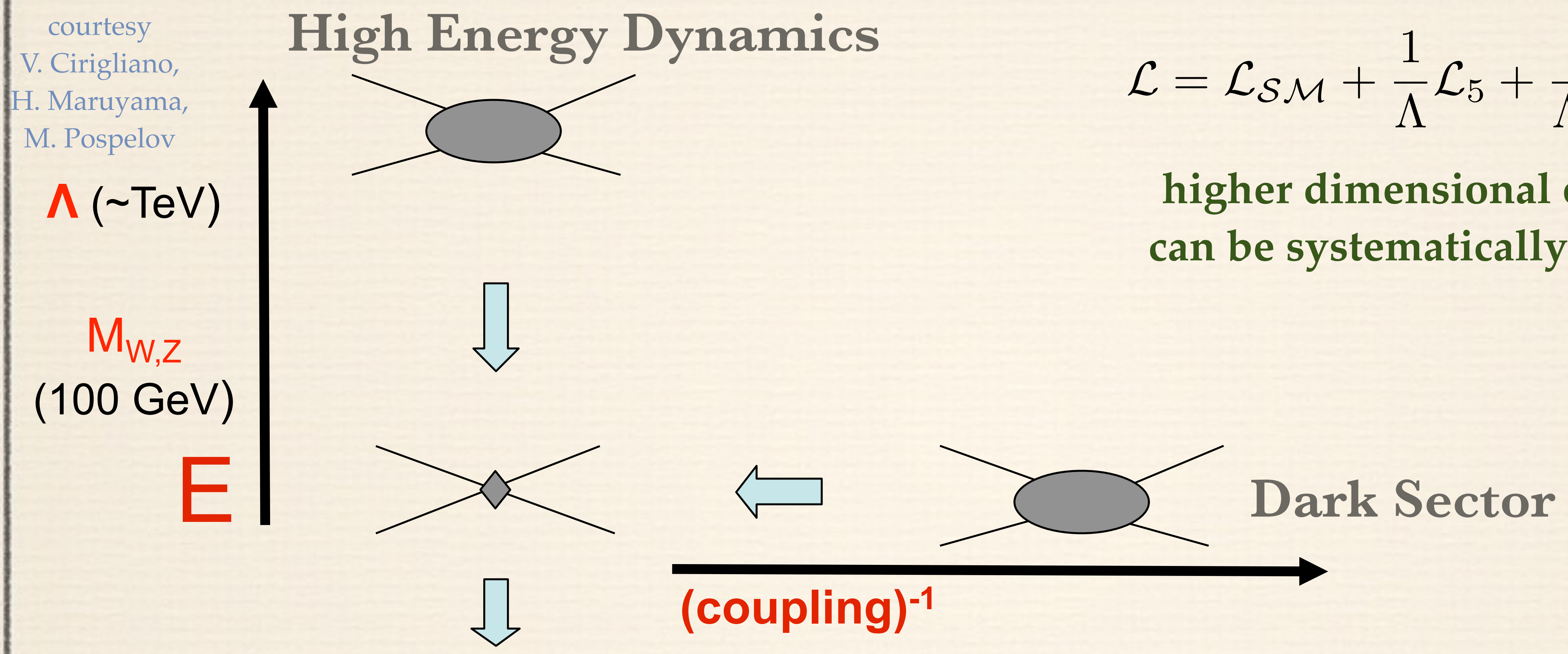

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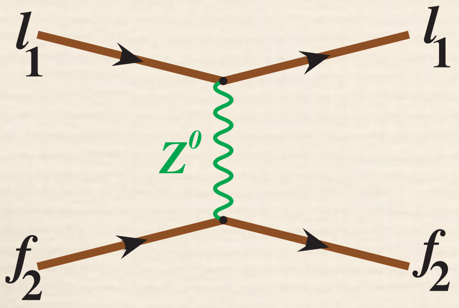
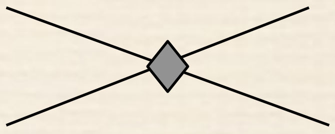


Search for new flavor diagonal neutral currents

Tiny yet measurable deviations from
SM processes with precise predictions

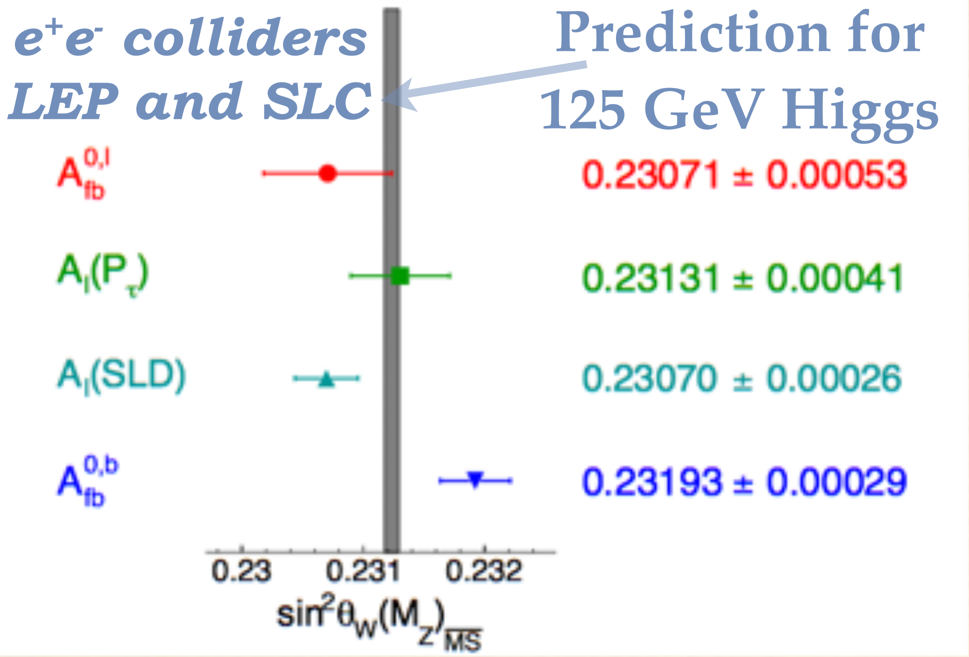


$$\frac{1}{\Lambda^2}\mathcal{L}_6$$

must reach beyond Λ ~ 10 TeV

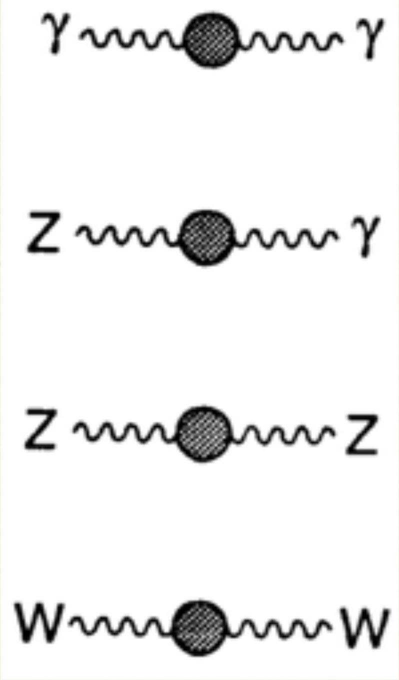
Measurements of $\sin^2\theta_W$

All Neutral Current Amplitudes are functions of the weak mixing angle



e^+e^- colliders LEP and SLC

Prediction for 125 GeV Higgs



S,T, U parameters

Stringent constraints on large classes of new physics models

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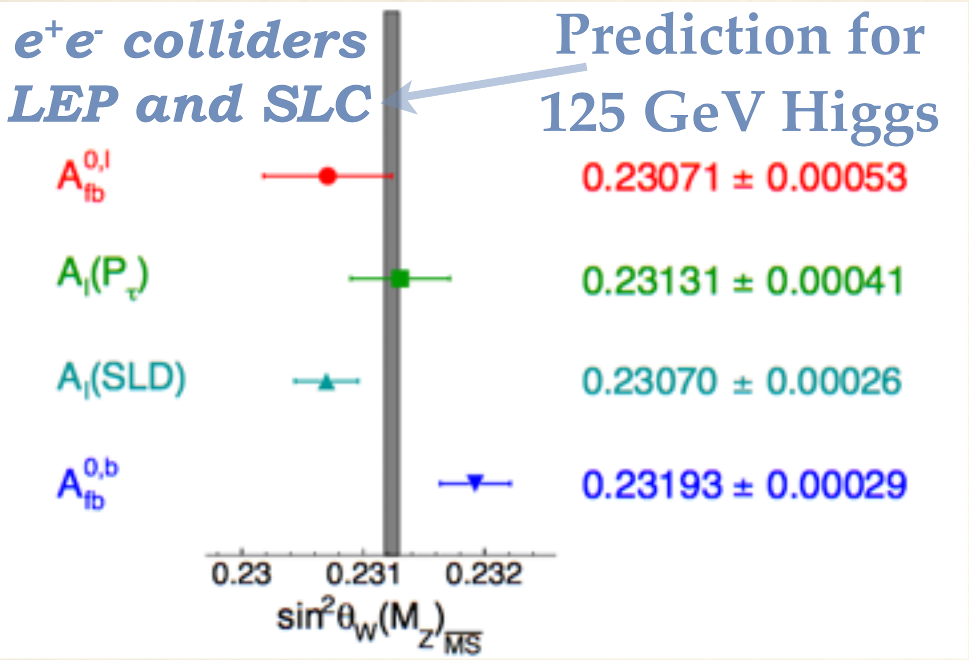
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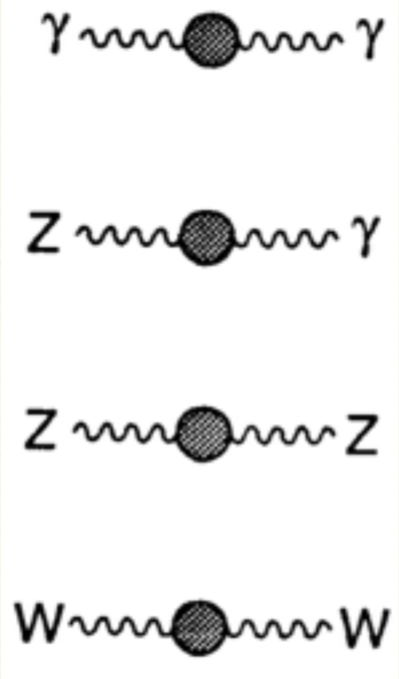

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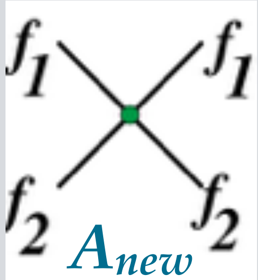
Flavor Diagonal Contact Interactions

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

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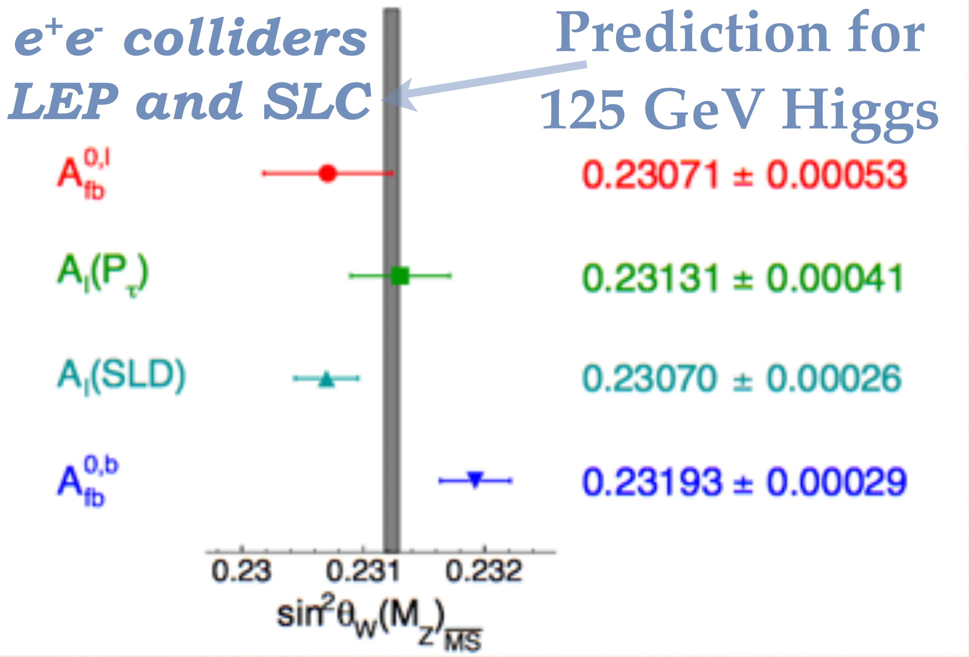
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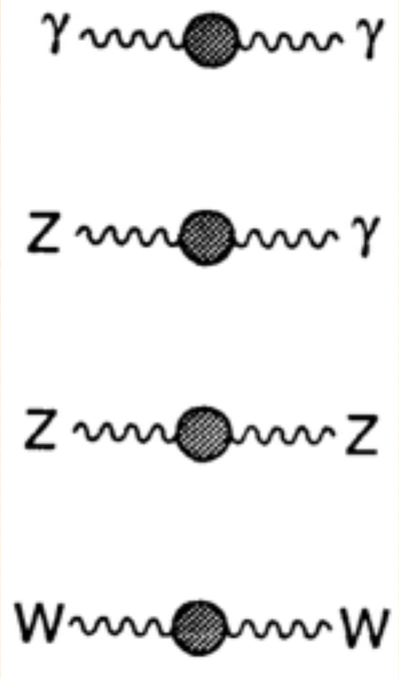

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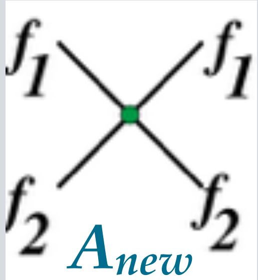


New heavy physics that does not couple directly to SM gauge bosons

on resonance: A_Z is imaginary

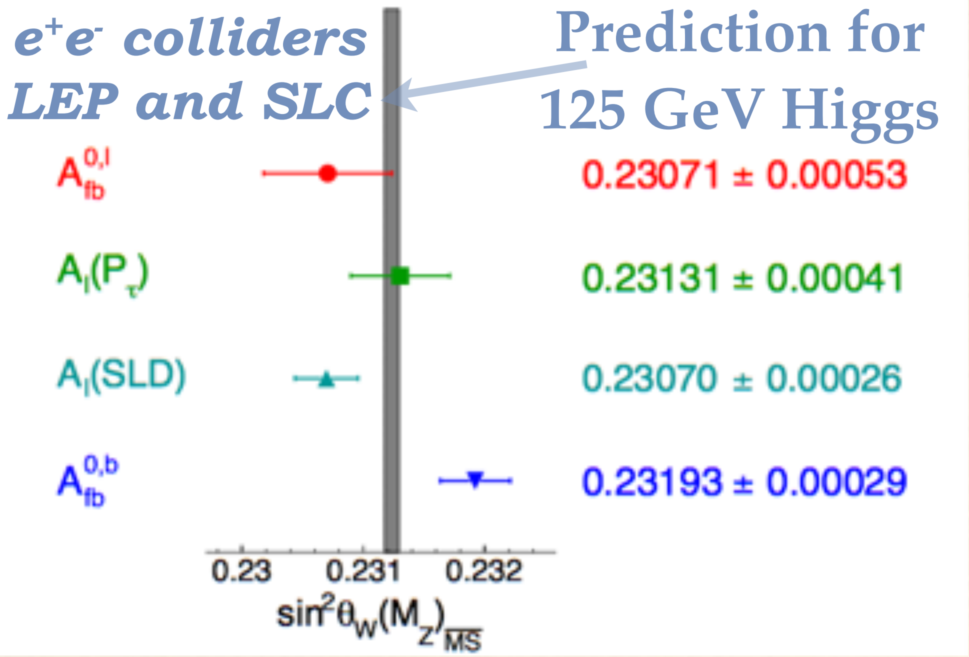
$$\left|A_Z + A_{\text{new}}\right|^2 \to A_Z^2\left[1+\left(\frac{A_{\text{new}}}{A_Z}\right)^2\right]$$

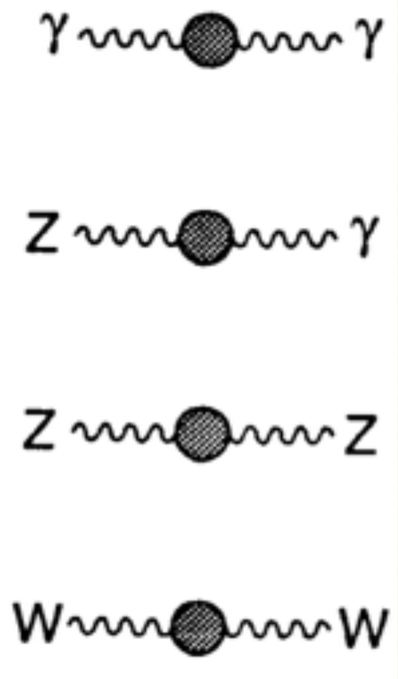
no interference!

Unique role for Low Energy Weak Neutral Current Measurements

Measurements of $\sin^2\theta_W$

All Neutral Current Amplitudes are functions of the weak mixing angle





S,T, U

parameters

Stringent constraints on large classes of new physics models

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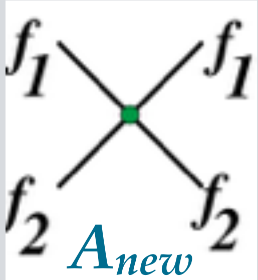

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no interference!

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

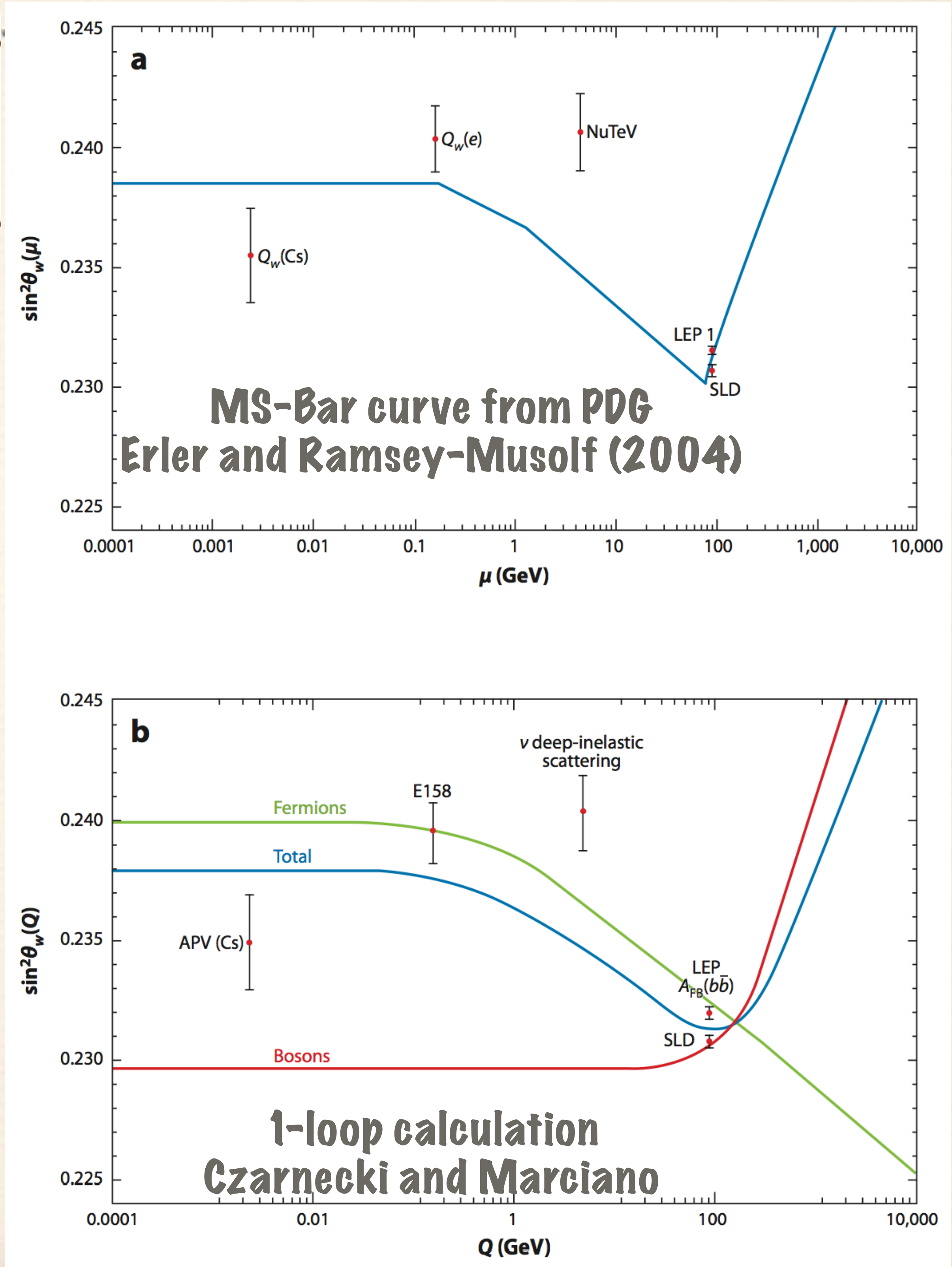
$$Q^2 \ll M_Z^2$$

Comparing with theory requires full treatment of 1-loop electroweak corrections

Status of low Q^2 Experiments

Czarnecki and Marciano (1995)

- **Atomic Parity Violation**
  - future measurements and theory challenging
- **Neutrino Deep Inelastic Scattering**
  - future measurements and theory challenging
- **PV Møller Scattering**
  - E158 at SLAC (total uncertainty 17 ppb)
    - *statistics limited, theory robust*



MS-Bar curve from PDG
Erler and Ramsey-Musolf (2004)

1-loop calculation
Czarnecki and Marciano

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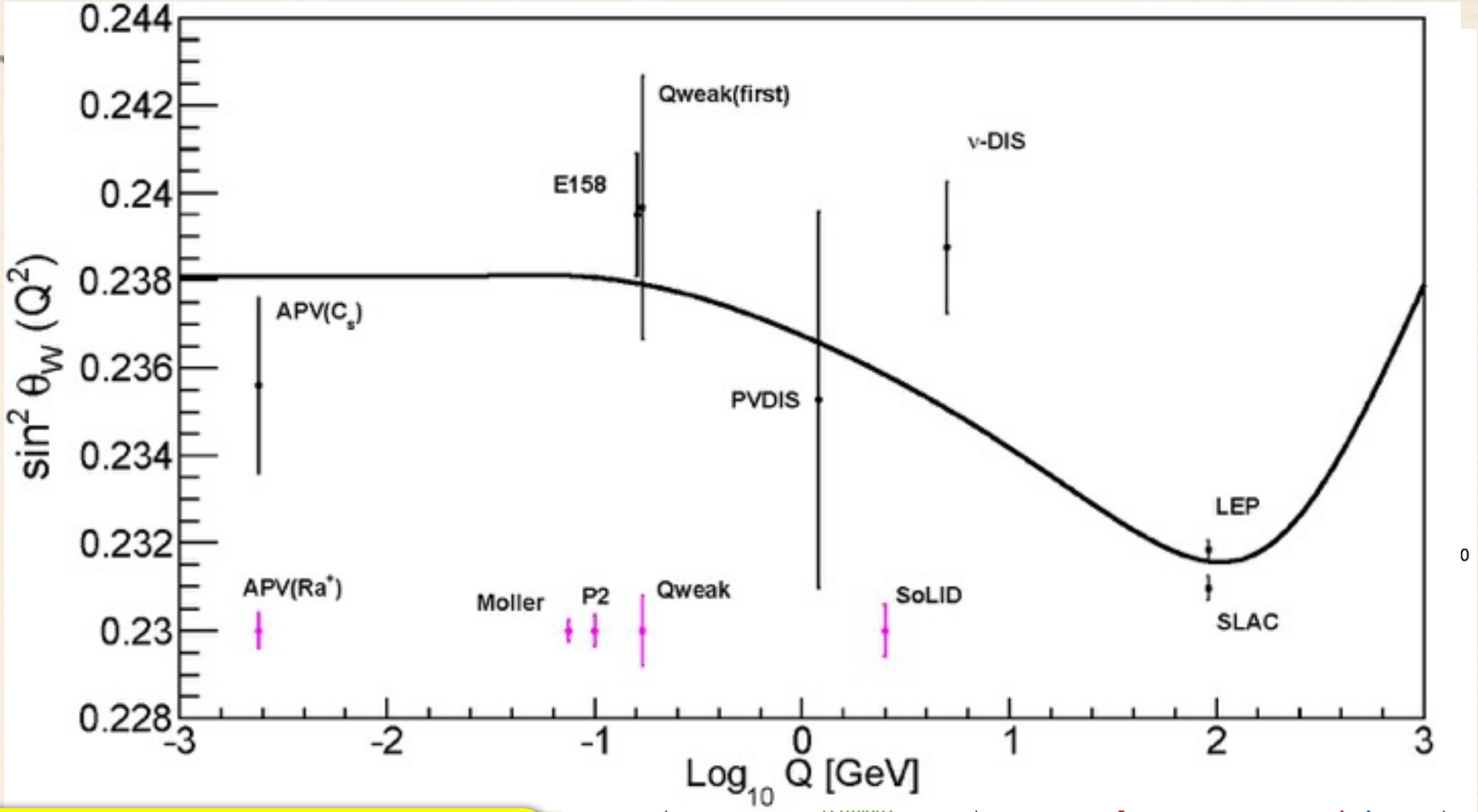
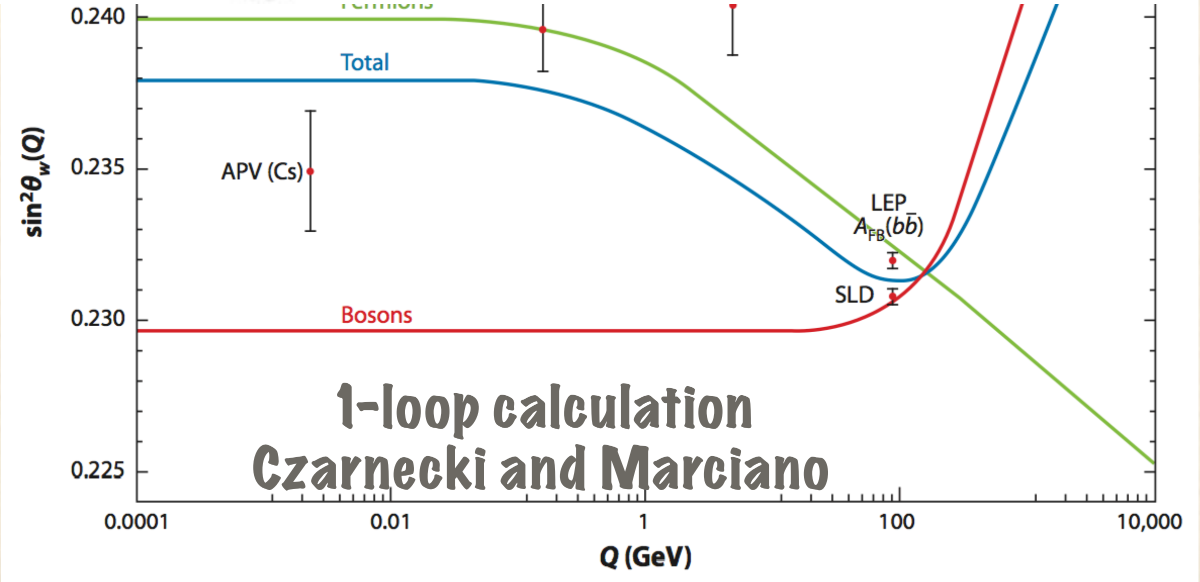


Ongoing and Future Measurements

6 GeV PVDIS at JLab: first non-zero determination of axial-vector quark couplings

Qweak at JLab: should produce precision measurement soon

Under Design: MOLLER and SoLID at JLab and P2 at Mainz MESA



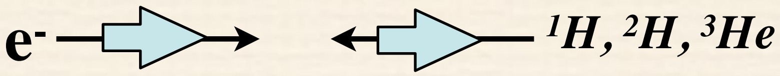
1-loop calculation
Czarnecki and Marciano

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

Electroweak and BSM Physics at the EIC

High luminosity: precision measurements of PV observables

Electroweak Structure Functions



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

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

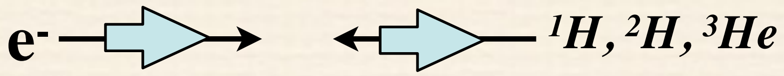
proton

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

similar expressions for neutron: $u \leftrightarrow d$

High luminosity: precision measurements of PV observables

Electroweak Structure Functions



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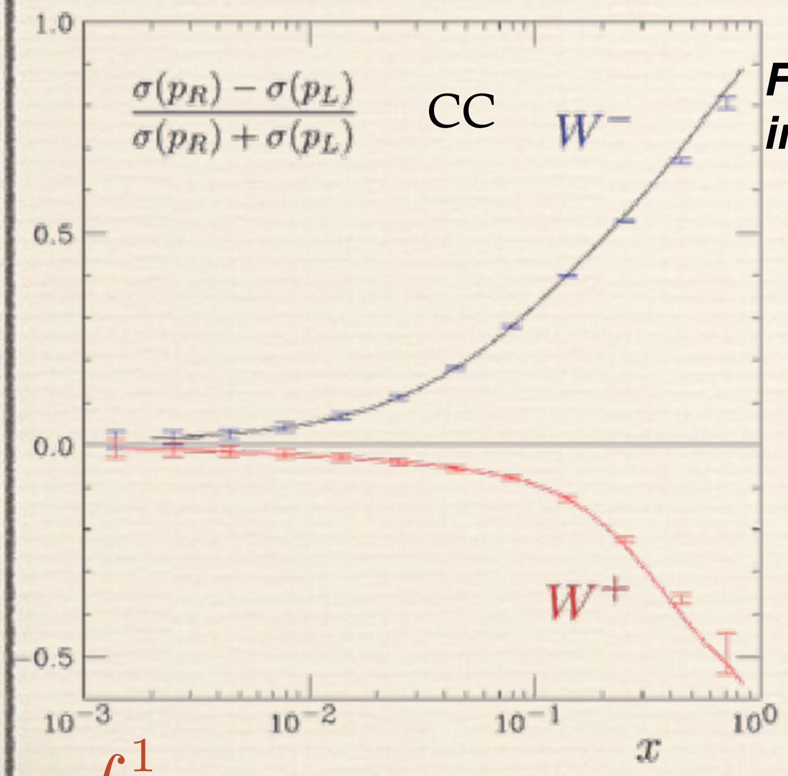
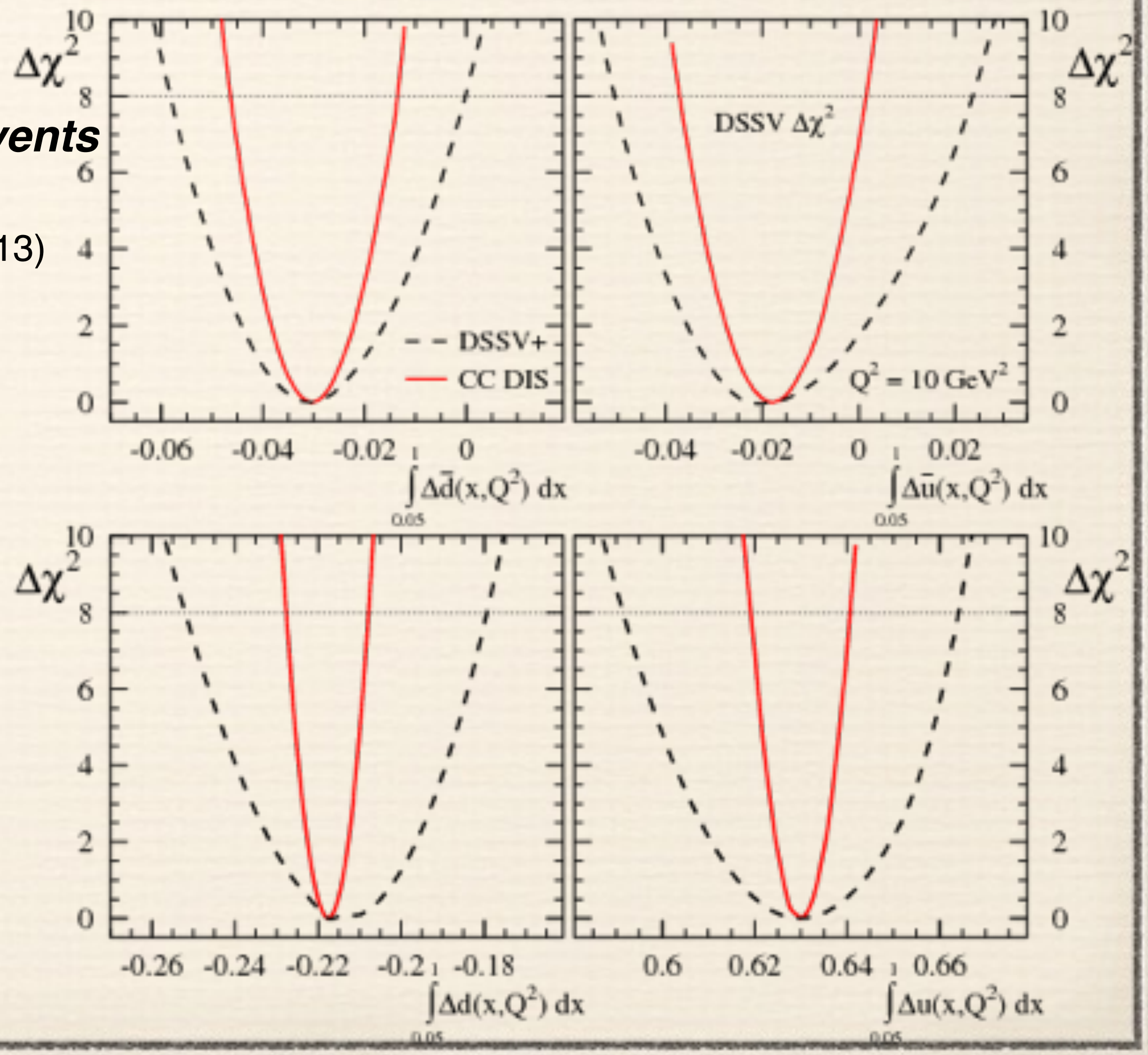


Full analysis of charged current events including radiative corrections

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

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**)

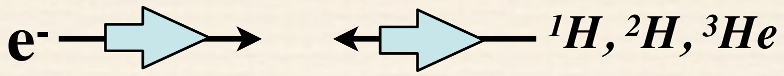


$$\int_0^1 dx[g_5^{W^-,n} - g_5^{W^-,p}] = g_A\left(1 - \frac{2\alpha_s}{3\pi}\right)$$

new sum rules

focus for the moment on Q² range where γZ interference dominates

Neutral Current Analysis



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

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

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

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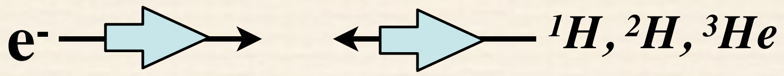
Neutral Current Analysis



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

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

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

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

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

- **DJANGOH generator simulates DIS processes including QED and QCD effects at NLO**
  - ✓ Developed by Hubert Spiesberger and used at BNL for the EIC Charged Current study
- **Electron Beam asymmetry A_{PV} (R-L) and Hadron Beam asymmetry A_{TPV} (R-L):**
  - ✓ Doing y dependent fit to the asymmetry in order to extract projections on $F_1^{\gamma Z}$ and $F_3^{\gamma Z}$ ($G_1^{\gamma Z}$ and $G_5^{\gamma Z}$)
- **$\sin^2\theta_W$ projections are from electron beam asymmetries in e-D collisions**
- *Highlights of the projections:*
  - ✓ Include radiative corrections
  - ✓ Unfolding of kinematical migration due to radiation
  - ✓ Cuts:
    - ☐ $Q^2 > 1$ GeV^2, $W_h > 2$ GeV, $y > 0.1$ for structure function studies
    - ☐ $Q^2 < 6400$ GeV^2 and $x > 0.2$ in addition for $\sin^2\theta_W$ projections
  - ✓ Lumi: 100 fb^{-1} (per nucleon for e-D collisions) nominal
  - ✓ Beam or target polarization: 80%

Y. Zhao (SBU)
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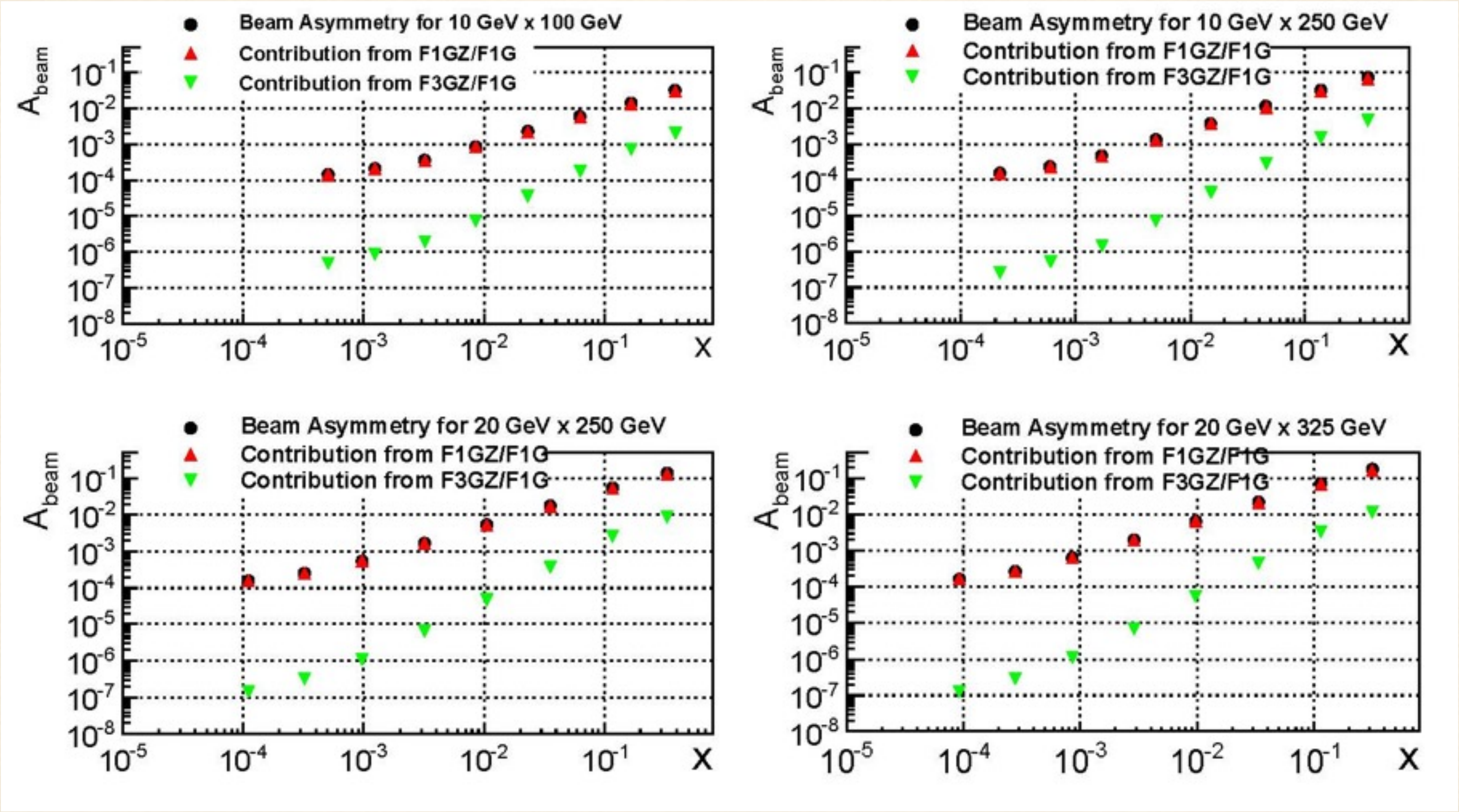
Electron Asymmetry A$_{PV}$

polarized electron; unpolarized proton

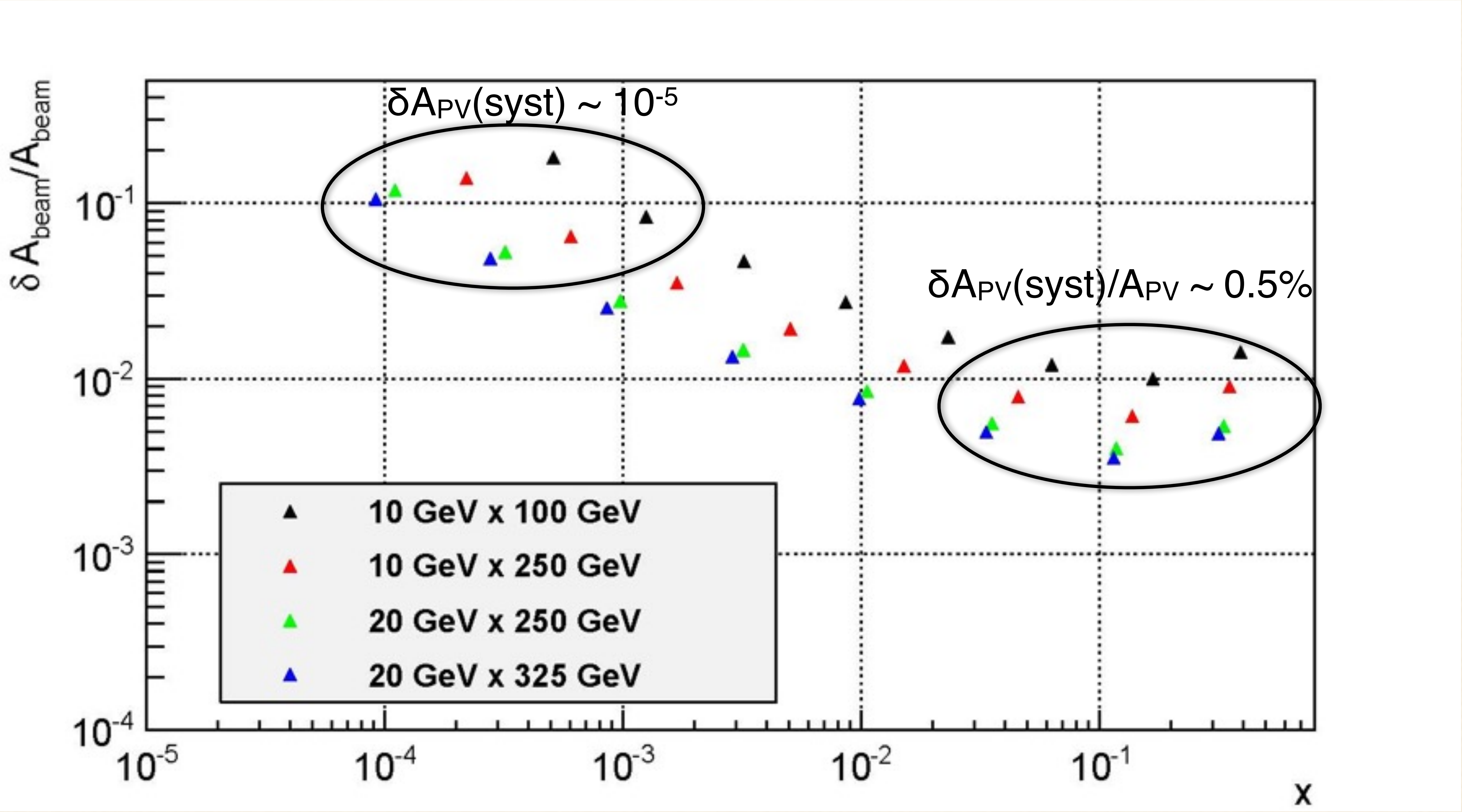
$$A_{PV} = \frac{G_F Q^2}{2\sqrt{2}\pi\alpha}\left[g_A \frac{F_1^{\gamma Z}}{F_1^{\gamma}} + g_V \frac{f(y)}{2}\frac{F_3^{\gamma Z}}{F_1^{\gamma}}\right]$$



A_{PV} Fractional Error

100 fb^{-1}

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



Fraction Statistical Errors on Structure Functions

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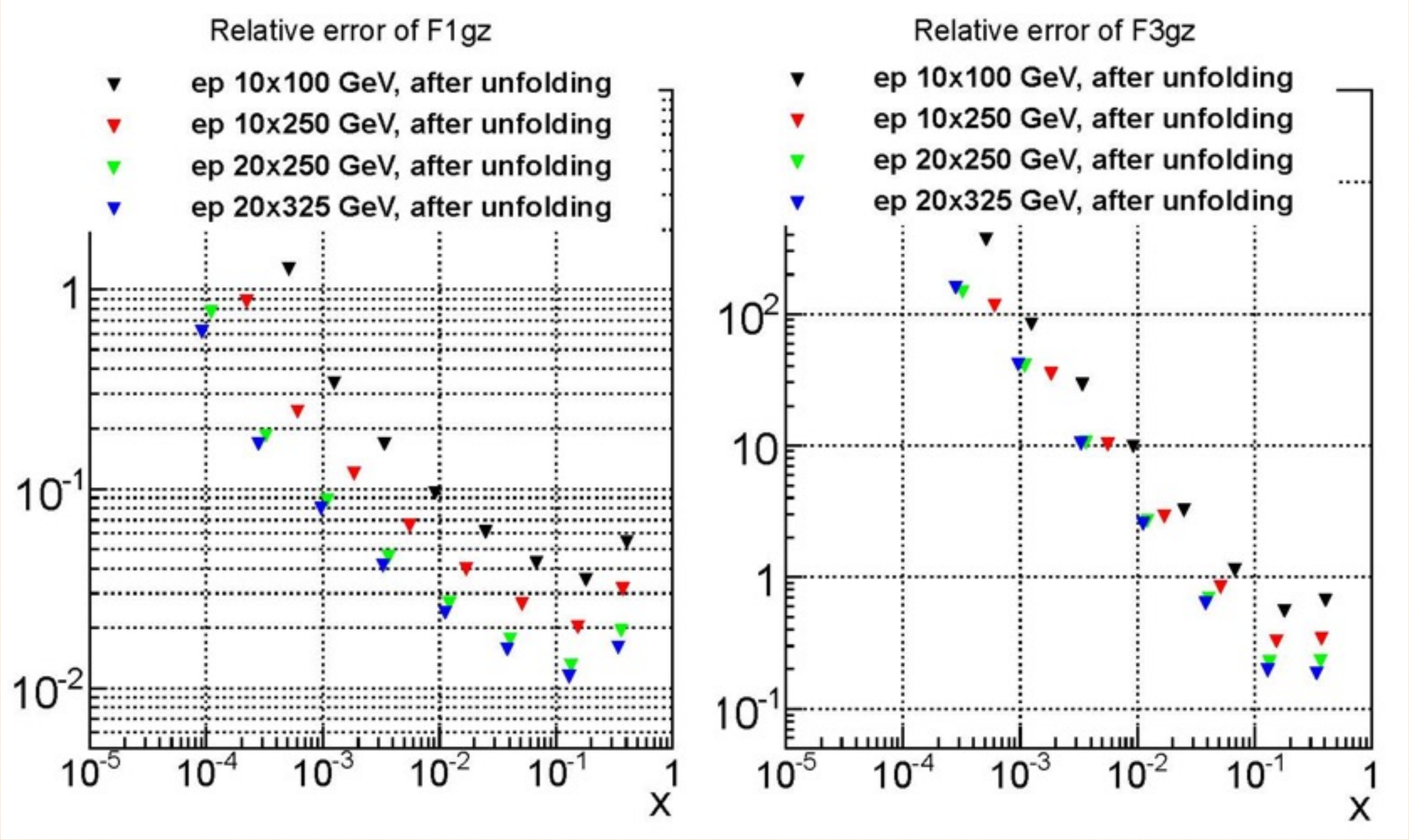
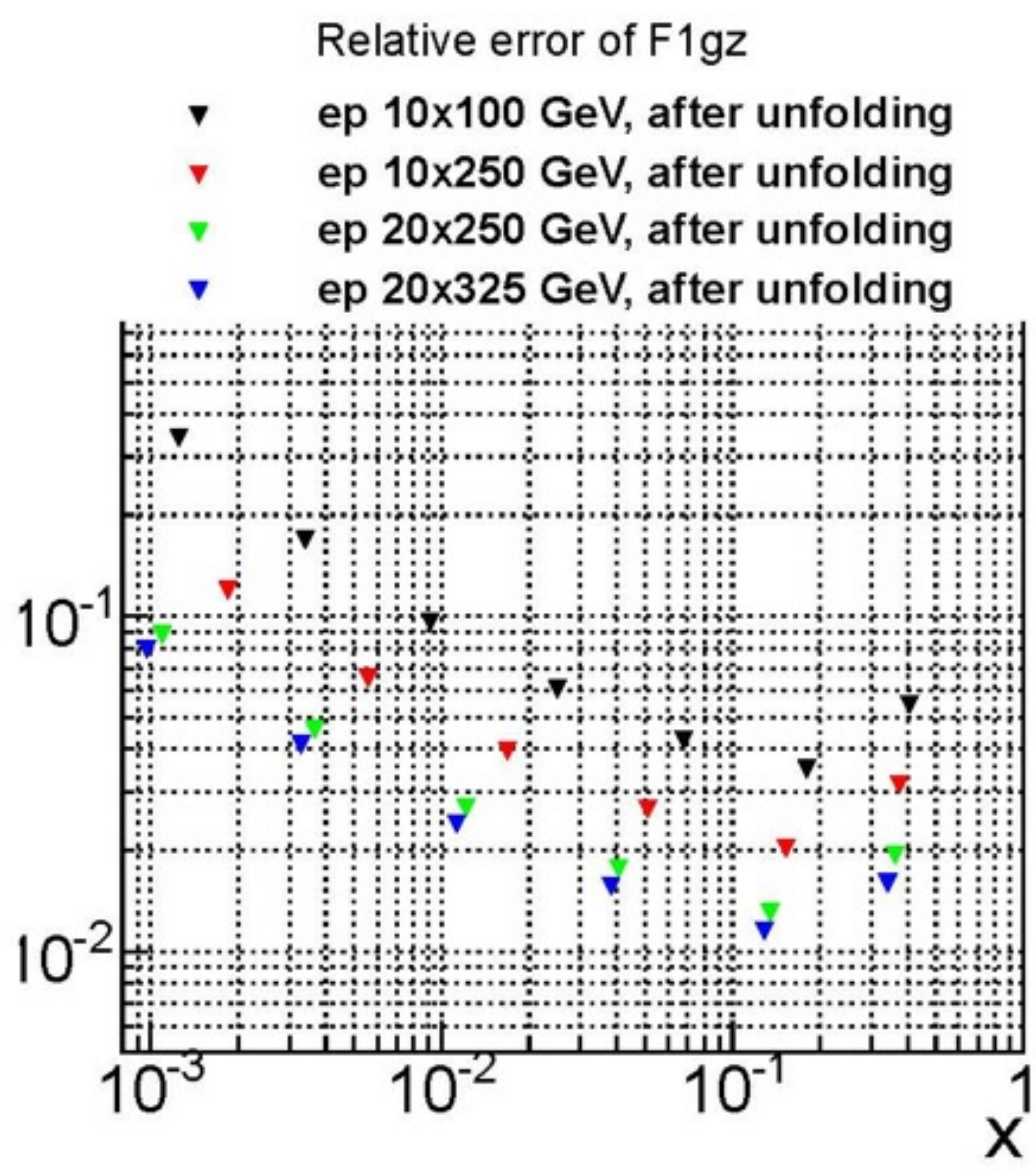


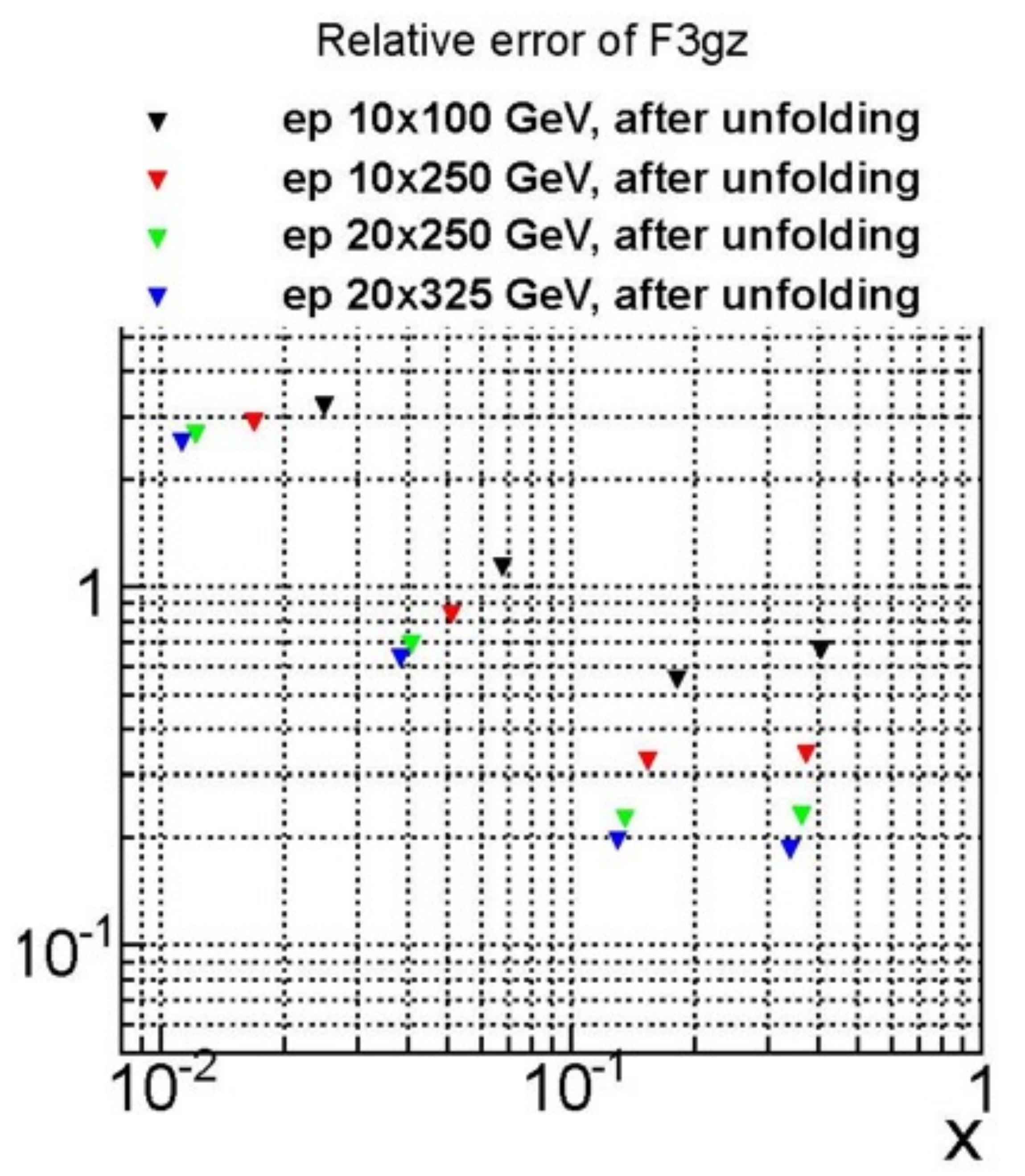
Fraction Statistical Errors on Structure Functions

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



Relative error of F1gz

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

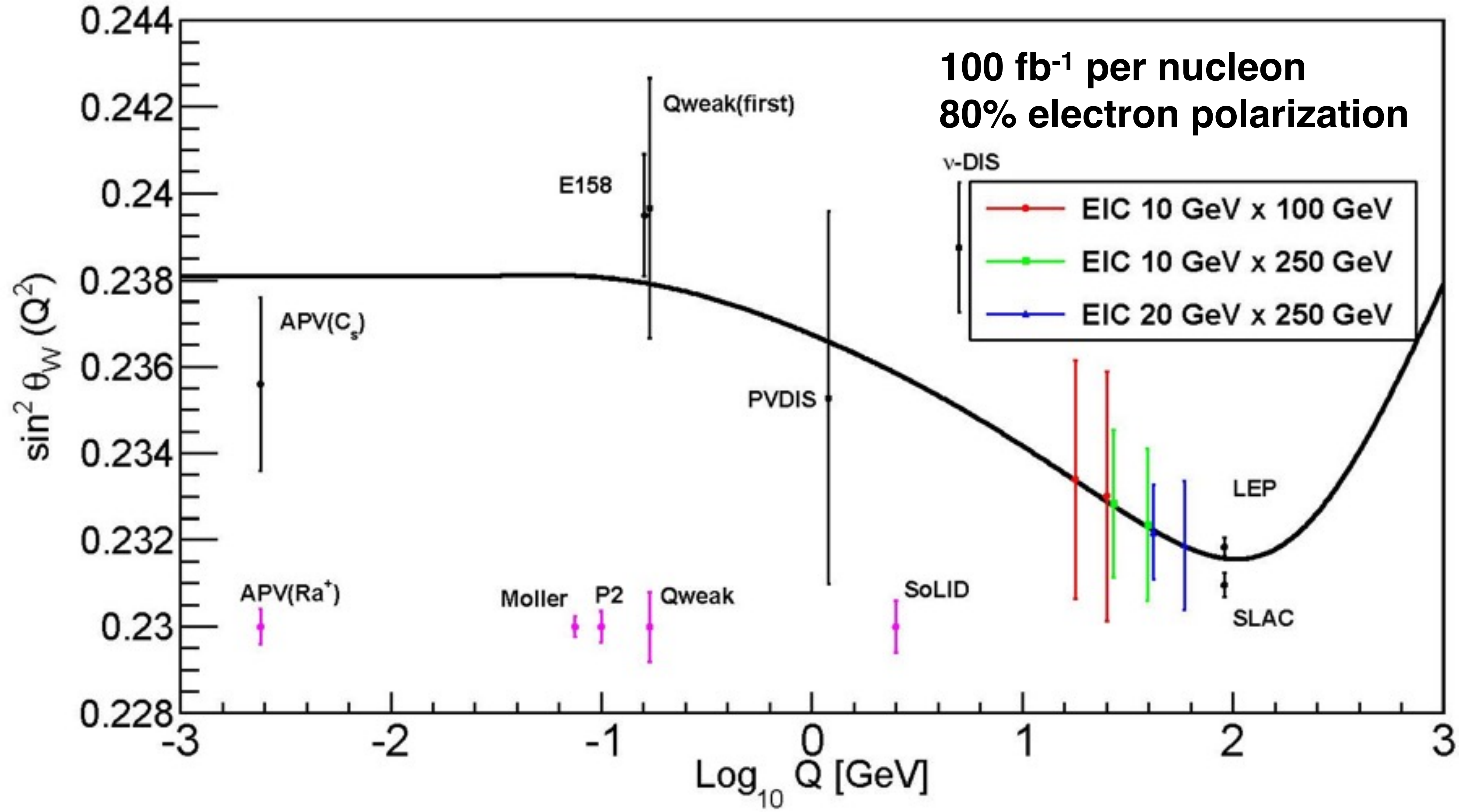


Relative error of F3gz

for a deuteron, structure functions cancel:
assuming charge symmetry and neglecting strange quarks

Weak Mixing Angle

$$g_A^e \frac{F_1^{\gamma Z}}{F_1^{\gamma}} \to g_A^e(2g_V^u - g_V^d) \propto \left(\frac{20}{3}\sin^2\theta_W - 1\right)$$


100 fb^{-1} per nucleon
80% electron polarization

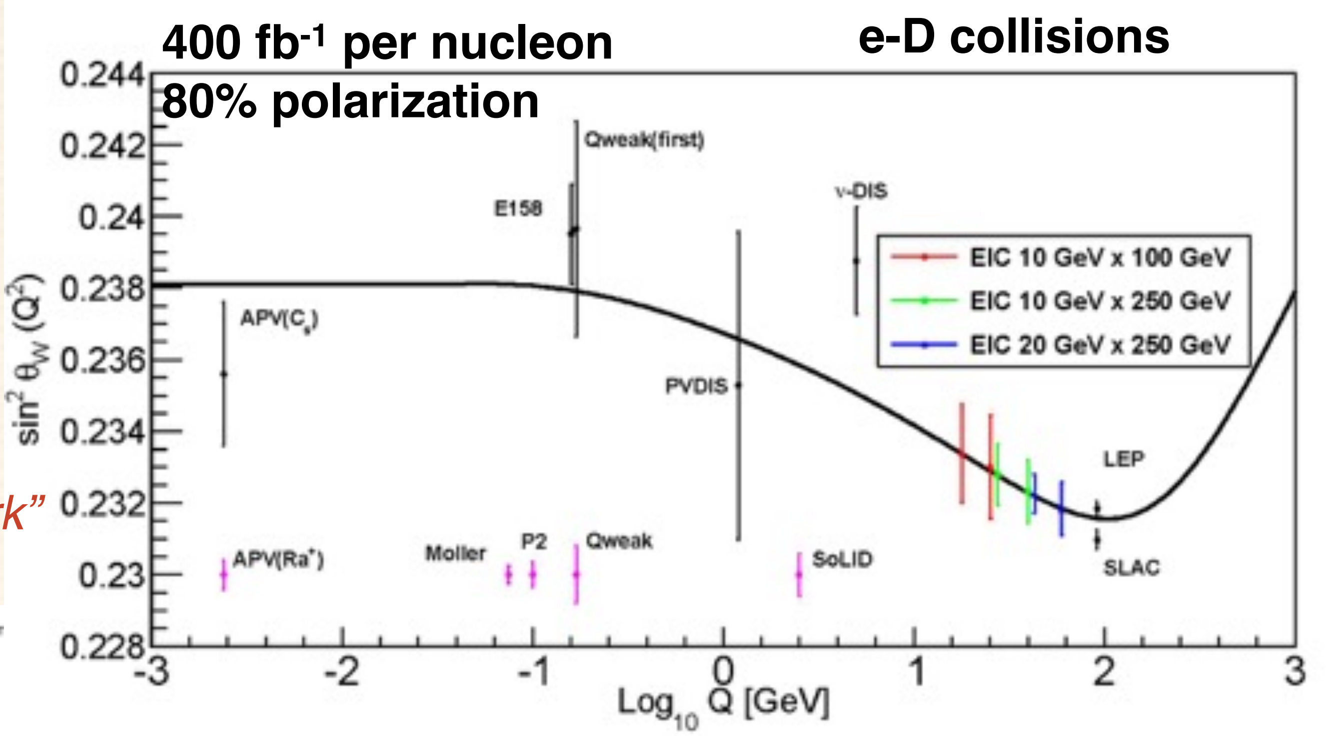
Next Steps for $F_1^{\gamma Z}$, $F_3^{\gamma Z}$ analysis

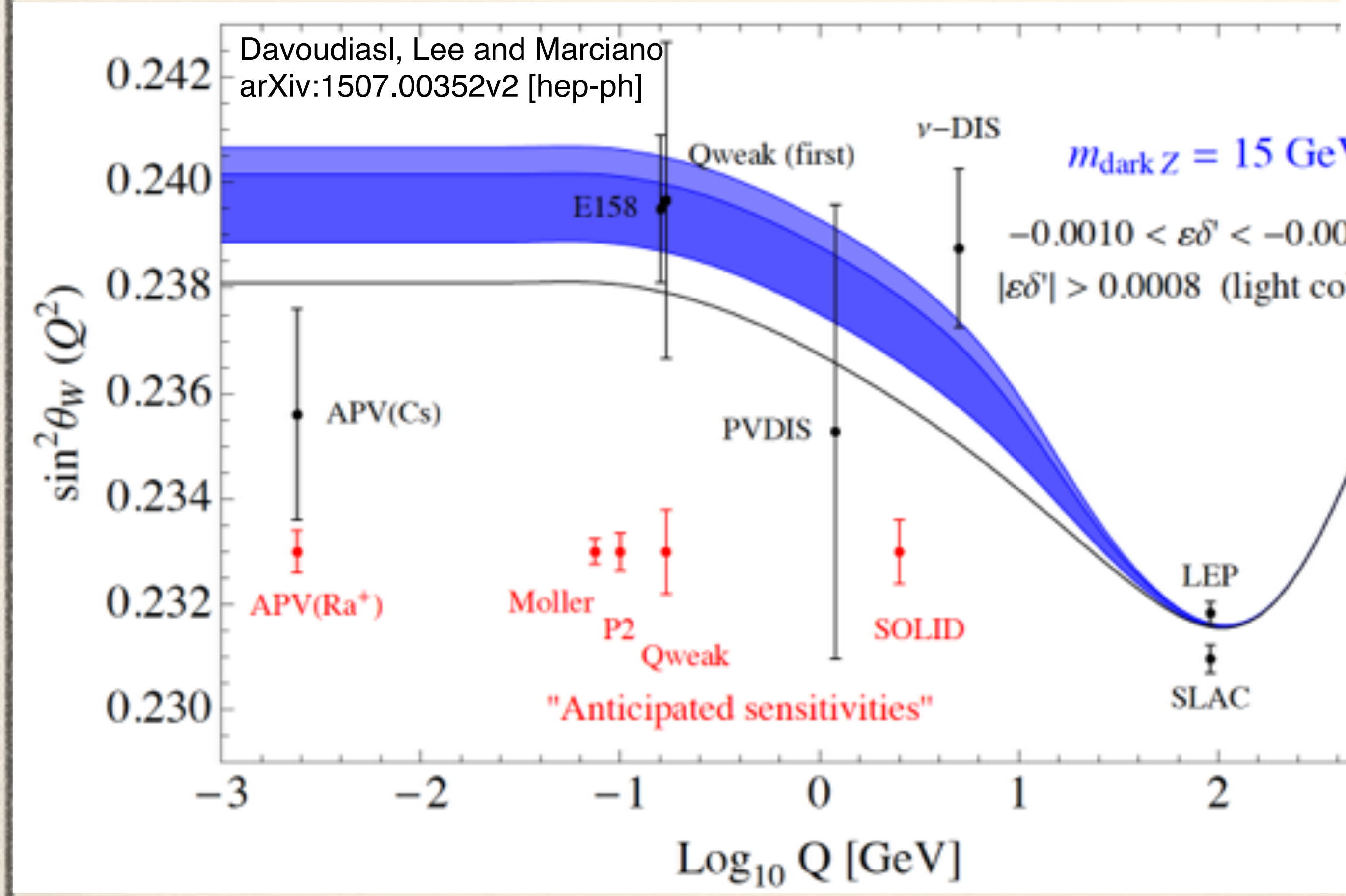
What will be the electroweak landscape in 2025?

Has LHC discovered new physics?

Presumably, the red projections below have been successful…

It has been pointed out that there are rather weak limits on "dark" Z bosons (dark photons with small mixing with the Z^0 boson)



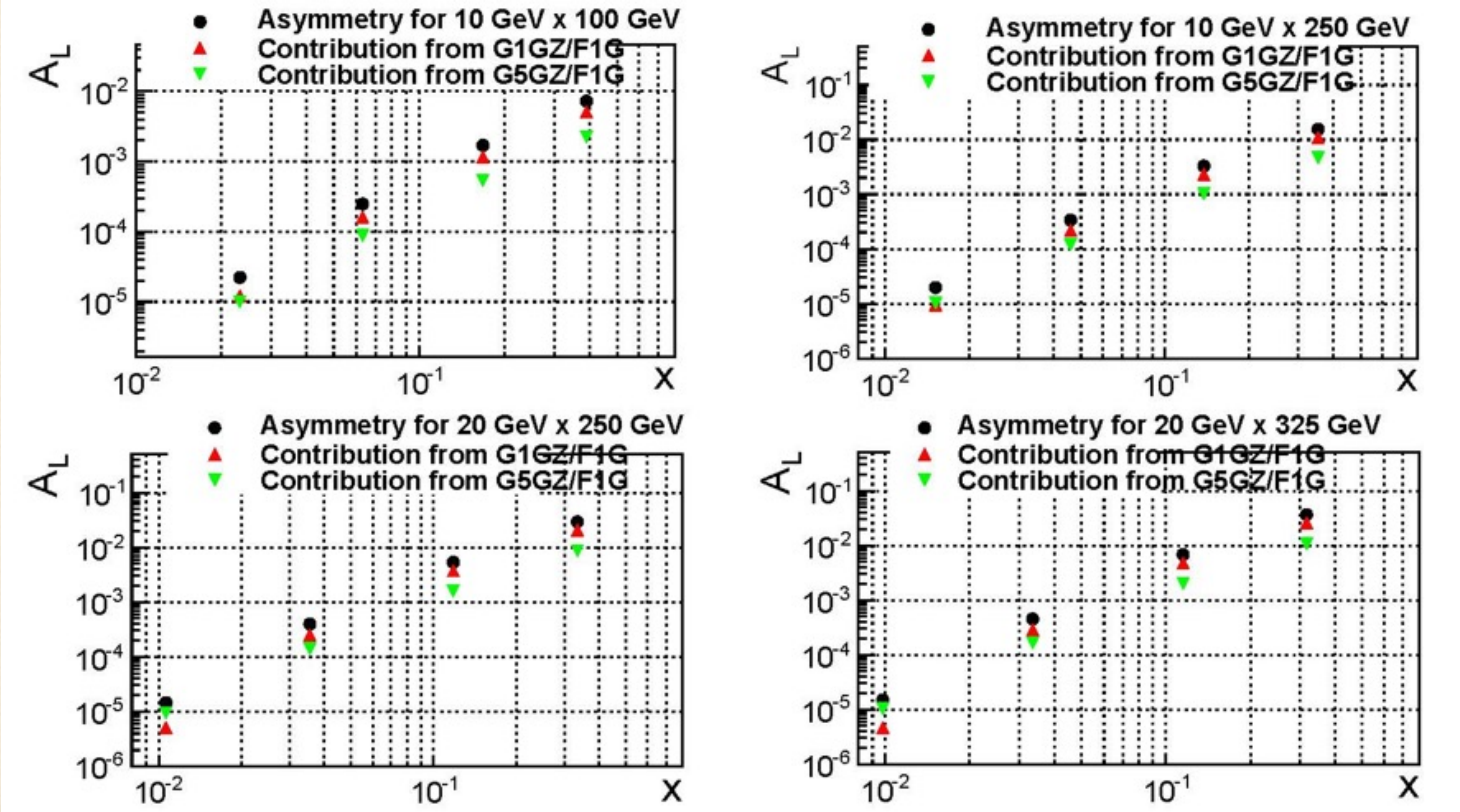


- **Do measurements help constrain *u, d, s* pdfs?**
- **Conversely, are *u*, *d, s* pdfs known well enough from other measurements so one can use electron-proton data at EIC to better constrain $\sin^2\theta_W$?**

Hadron Asymmetry A_{TPV}

unpolarized electron; polarized proton

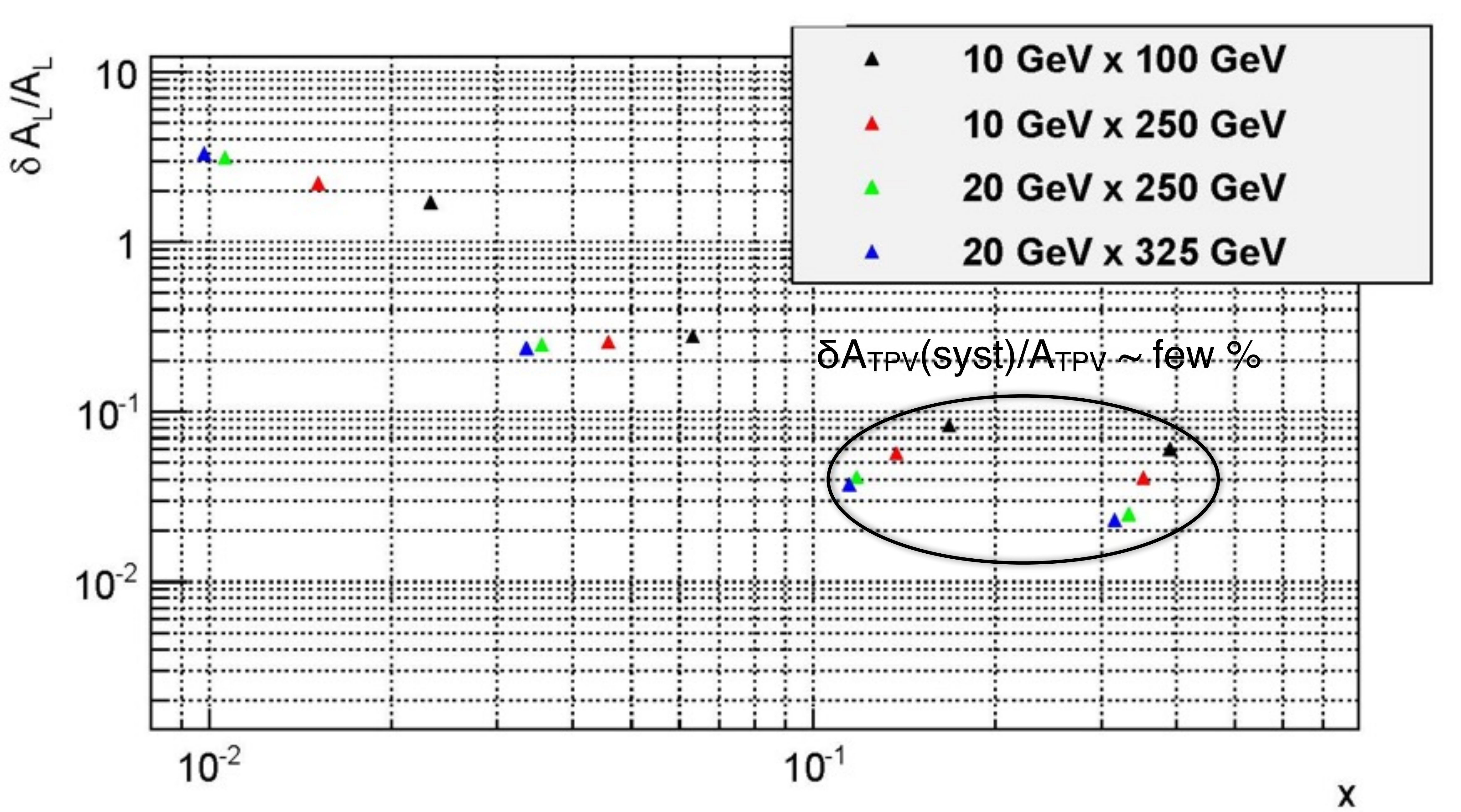
$$A_{TPV} = \frac{G_F Q^2}{2\sqrt{2}\pi\alpha}\left[g_V \frac{g_5^{\gamma Z}}{F_1^\gamma} + g_A f(y) \frac{g_1^{\gamma Z}}{F_1^\gamma}\right]$$



A_{TPV} Fractional Error

100 fb^{-1}

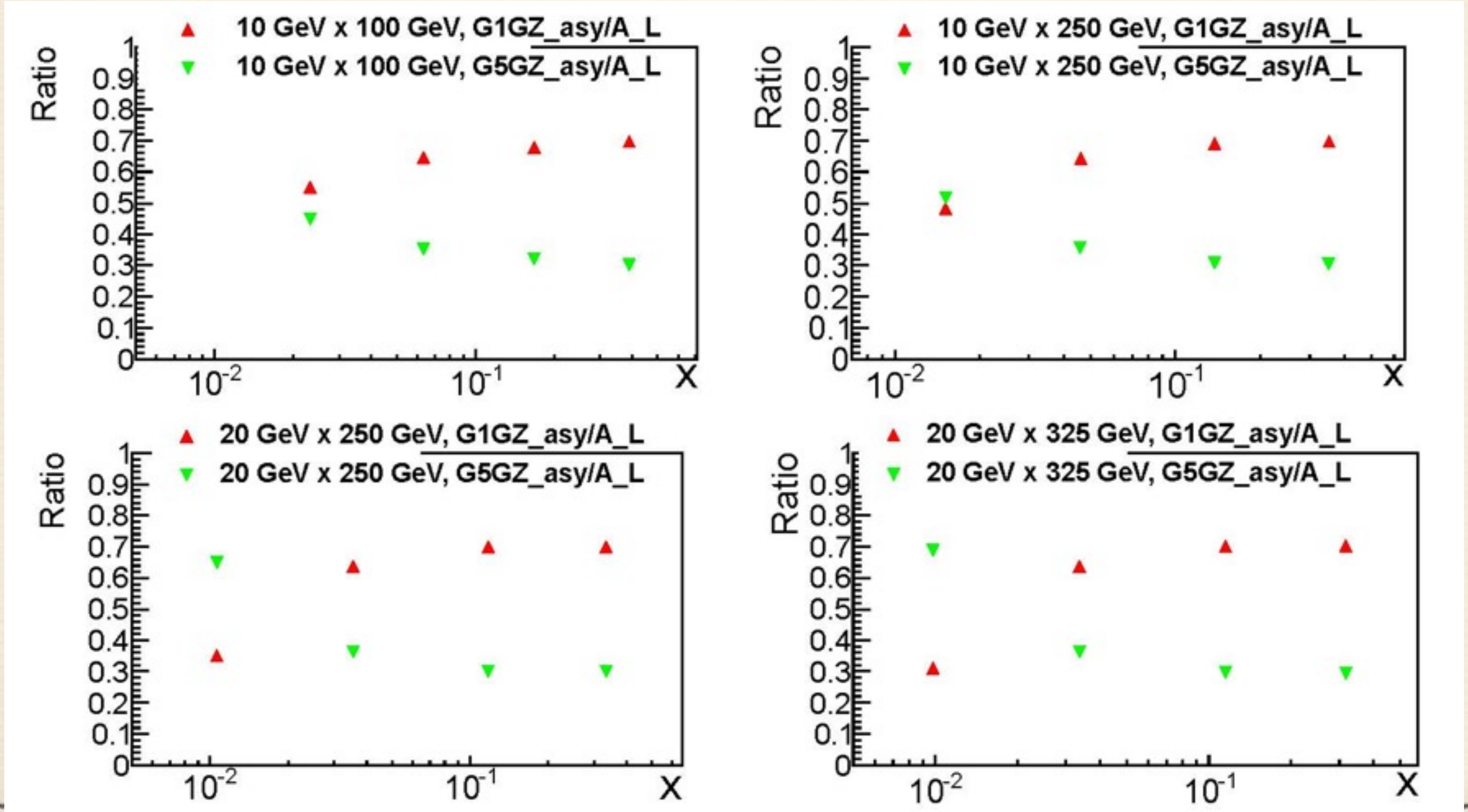
$$A_{TPV} = \frac{G_F Q^2}{2\sqrt{2}\pi\alpha}\left[g_V \frac{g_5^{\gamma Z}}{F_1^{\gamma}} + g_A f(y) \frac{g_1^{\gamma Z}}{F_1^{\gamma}}\right]$$



$\delta A_{TPV}(\text{syst})/A_{TPV} \sim$ few %

y-dependence separates g_1 and g_5

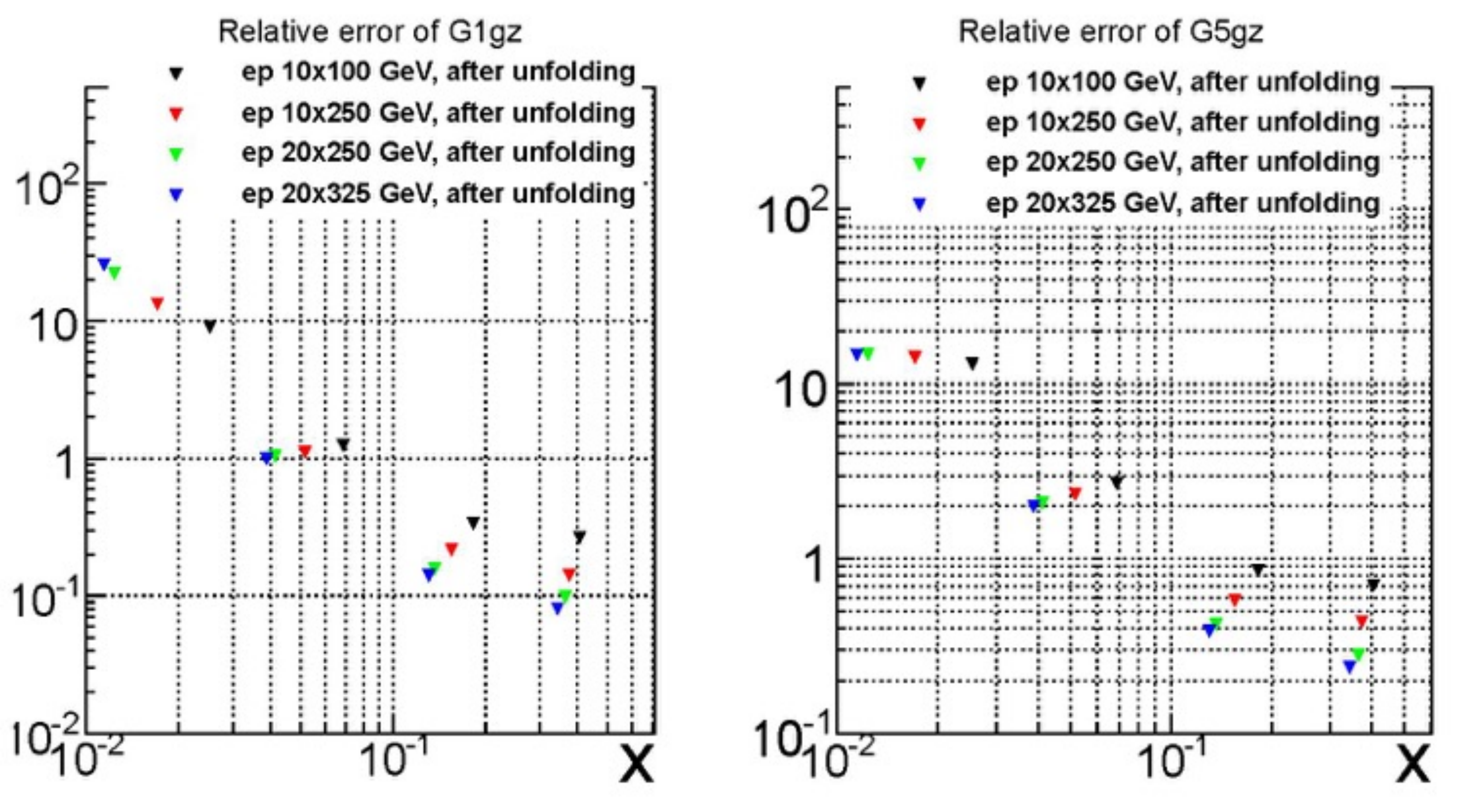
$$A_{TPV} = \frac{G_F Q^2}{2\sqrt{2}\pi\alpha}\left[g_V \frac{g_5^{\gamma Z}}{F_1^{\gamma}} + g_A f(y) \frac{g_1^{\gamma Z}}{F_1^{\gamma}}\right]$$



Fraction Statistical Errors on Structure Functions

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

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



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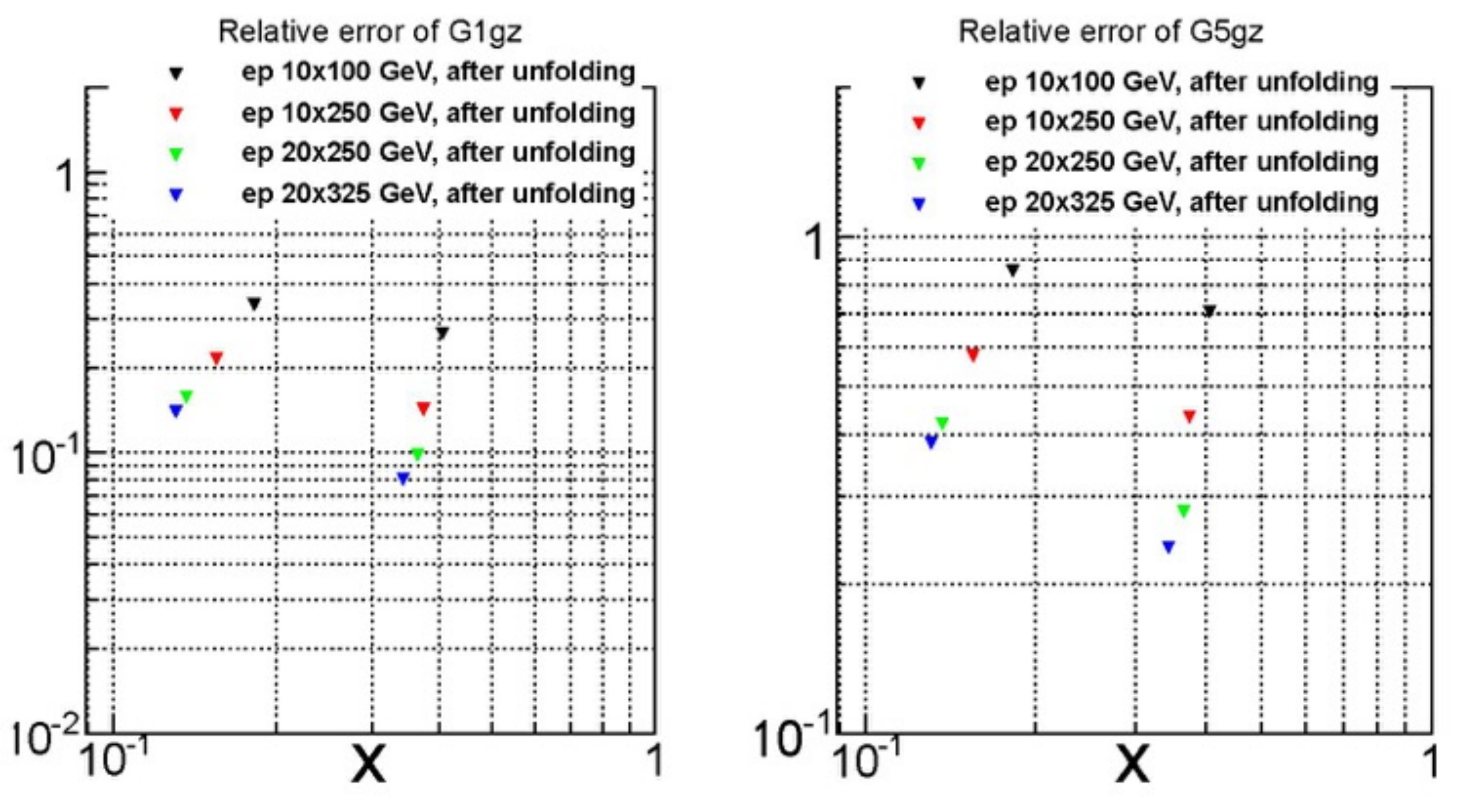

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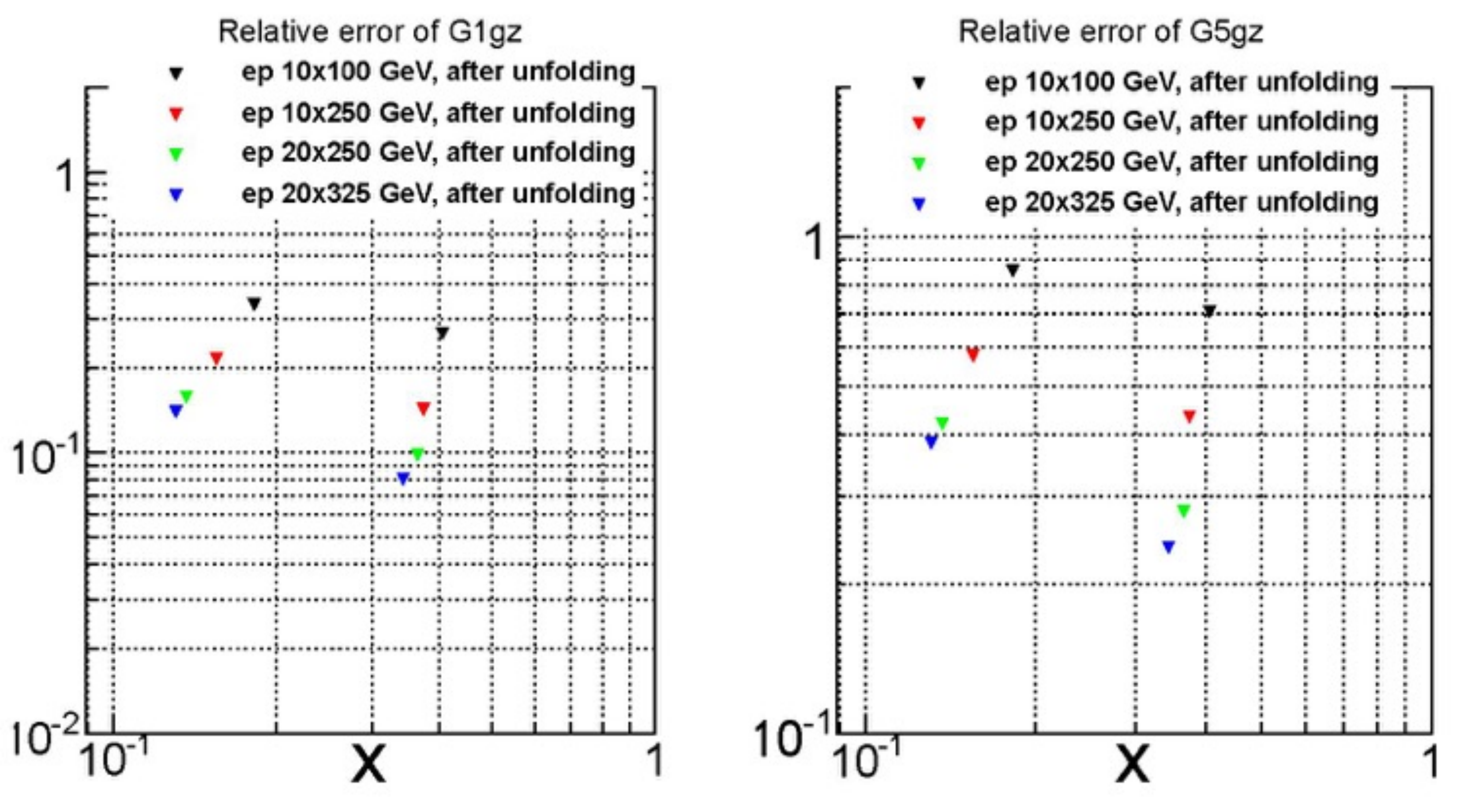

Next Steps

- Generate pseudo data for polarized pdf constraints at various integrated luminosities
- Look at complementarity of proton, deuteron, helium-3 and charged current data

Charged Lepton Flavor Violation at the EIC

Lepton Flavor Conservation

Is it exact? No!   Neutrino Oscillations!

- ν's have mass! *individual lepton flavors are not conserved*
- Therefore Lepton Flavor Violation occurs in Charged Leptons too

Lepton Flavor Conservation

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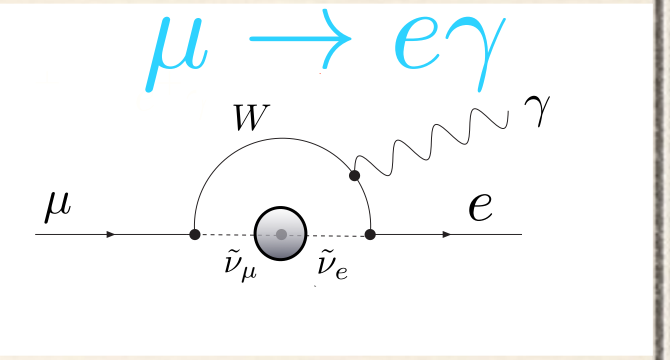

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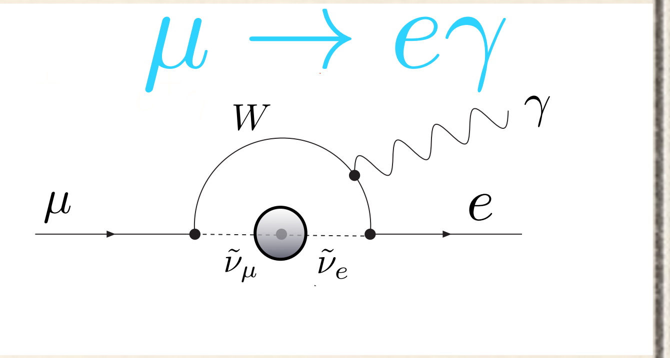

- **ν's have mass!** ***individual lepton flavors are not conserved***
- **Therefore Lepton Flavor Violation occurs in Charged Leptons too**

$$\mathrm{BR}(\mu \to e\gamma) = \frac{3\alpha}{32\pi}\left|\sum_{i=2,3} U^*_{\mu i} U_{ei} \frac{\Delta m^2_{1i}}{M_W^2}\right|^2 < 10^{-54}$$

tiny standard model branching fraction

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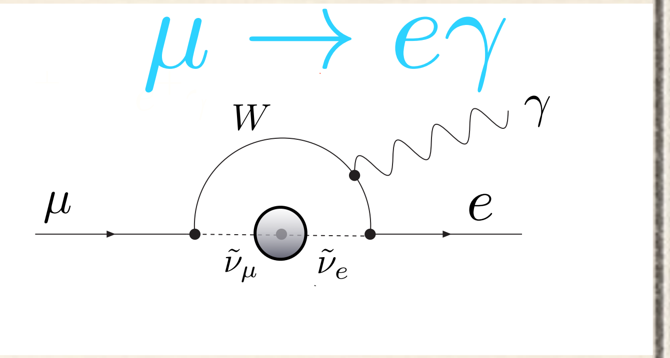
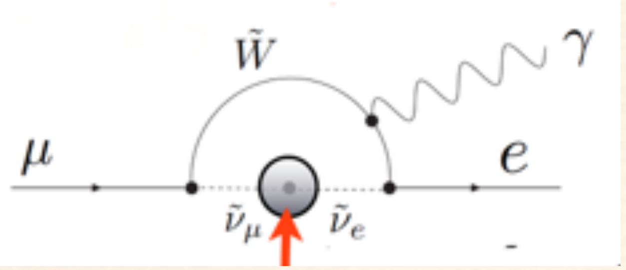
$\mu \rightarrow e\gamma$



Slepton mixing
in SUSY



$\mathrm{BR}(\mu \rightarrow e\gamma) \sim 10^{-15}$

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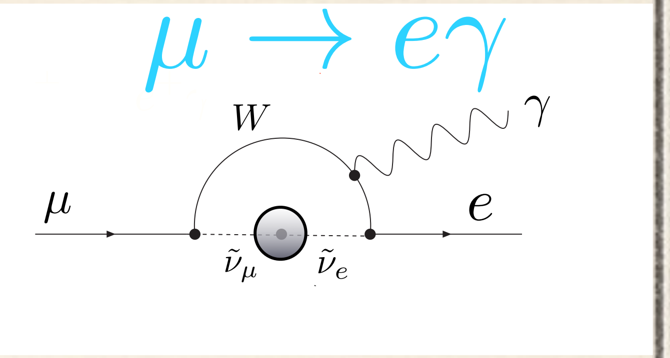

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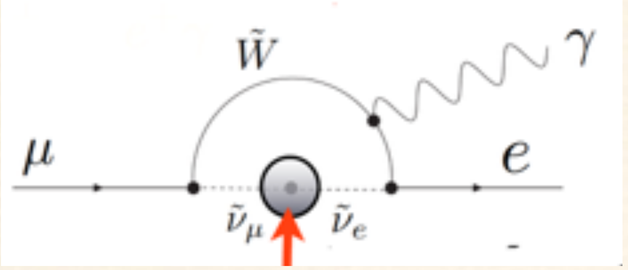

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$$\mathrm{BR}(\mu \to e\gamma) \quad = \quad \frac{3\alpha}{32\pi} \left| \sum_{i=2,3} U^*_{\mu i} U_{ei} \frac{\Delta m^2_{1i}}{M^2_W} \right|^2 < 10^{-54}$$

tiny standard model branching fraction

Major experimental searches are ongoing; mass reach depends on flux and sensitivity of technique

$$\mathcal{L}_{\mathrm{eff}} = \mathcal{L}_{\mathrm{SM}} + \frac{C_{\mu e}}{\Lambda^2} \bar{e}_L \sigma^{\alpha\beta} \mu_R \Phi F_{\alpha\beta}$$

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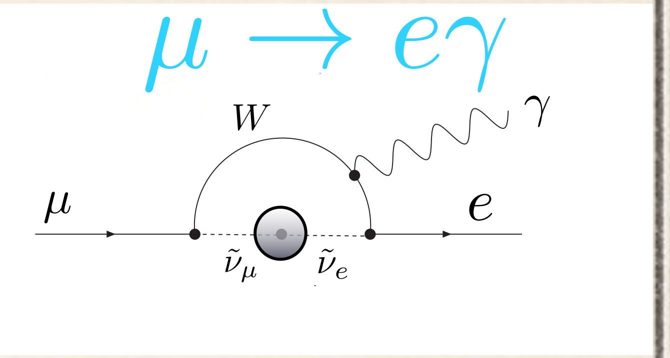

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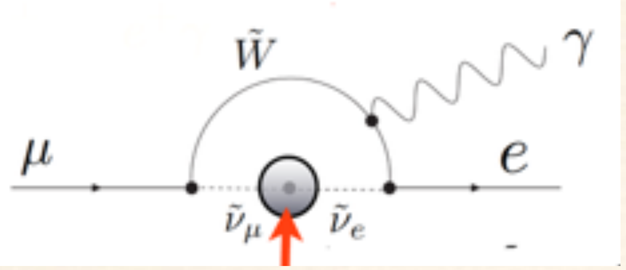

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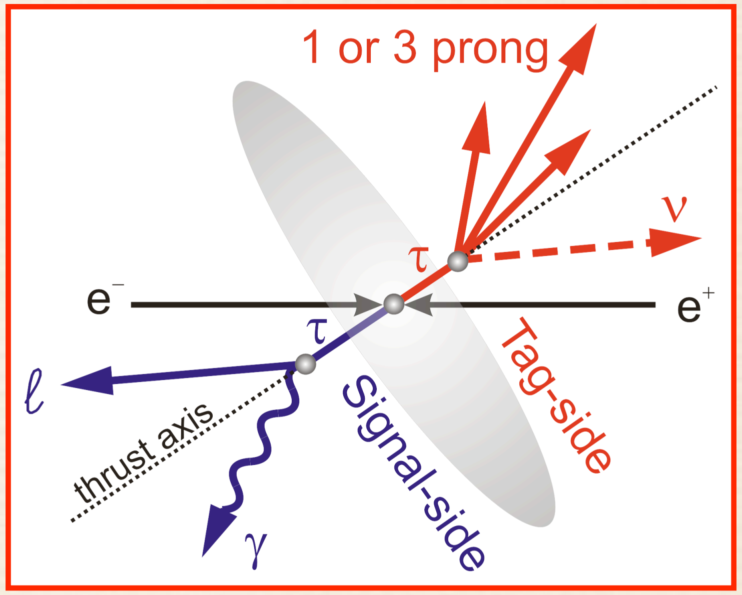
$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \frac{C_{\mu e}}{\Lambda^2}\bar{e}_L \sigma^{\alpha\beta}\mu_R \Phi F_{\alpha\beta}$$

μ or $\tau \longrightarrow e\gamma$, e^+e^-e, $K_L \rightarrow \mu e$, ...

Need very high fluxes for required statistical reach

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

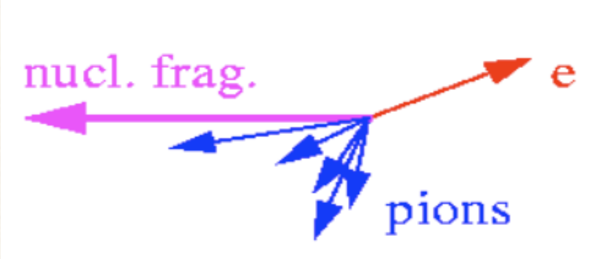


Tau Decays at e+e- colliders

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

e-τ Conversion Search

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



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

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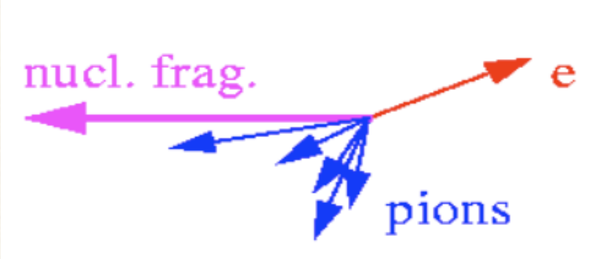

Topology: neutral current DIS event; except that the electron is replaced by tau lepton

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

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

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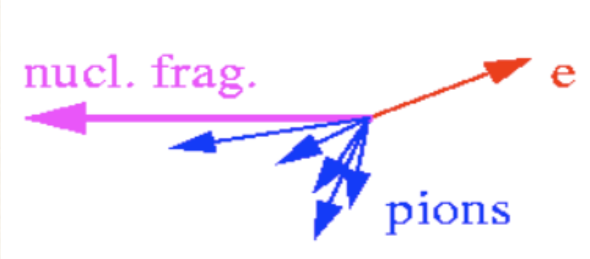
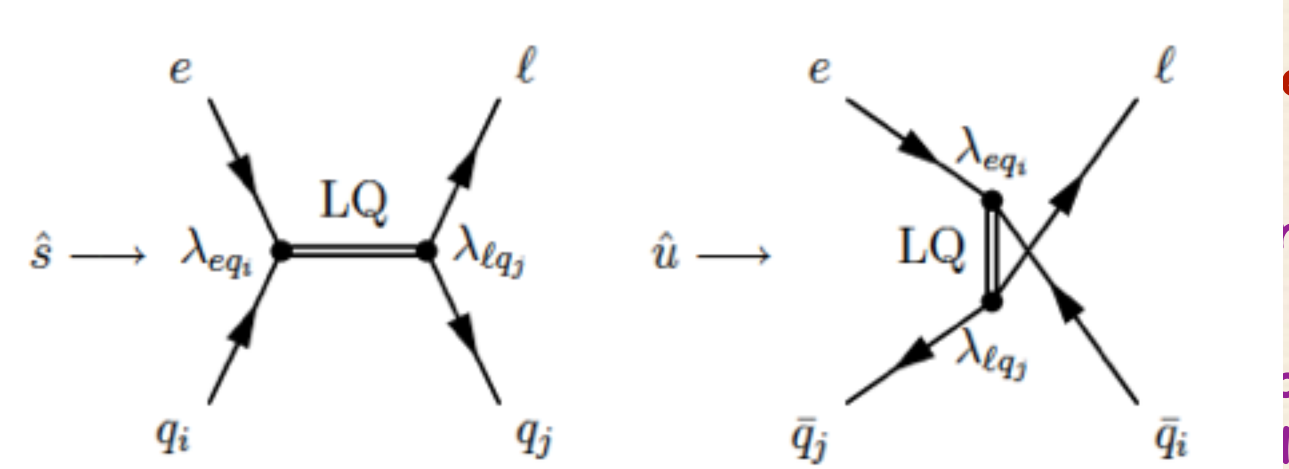
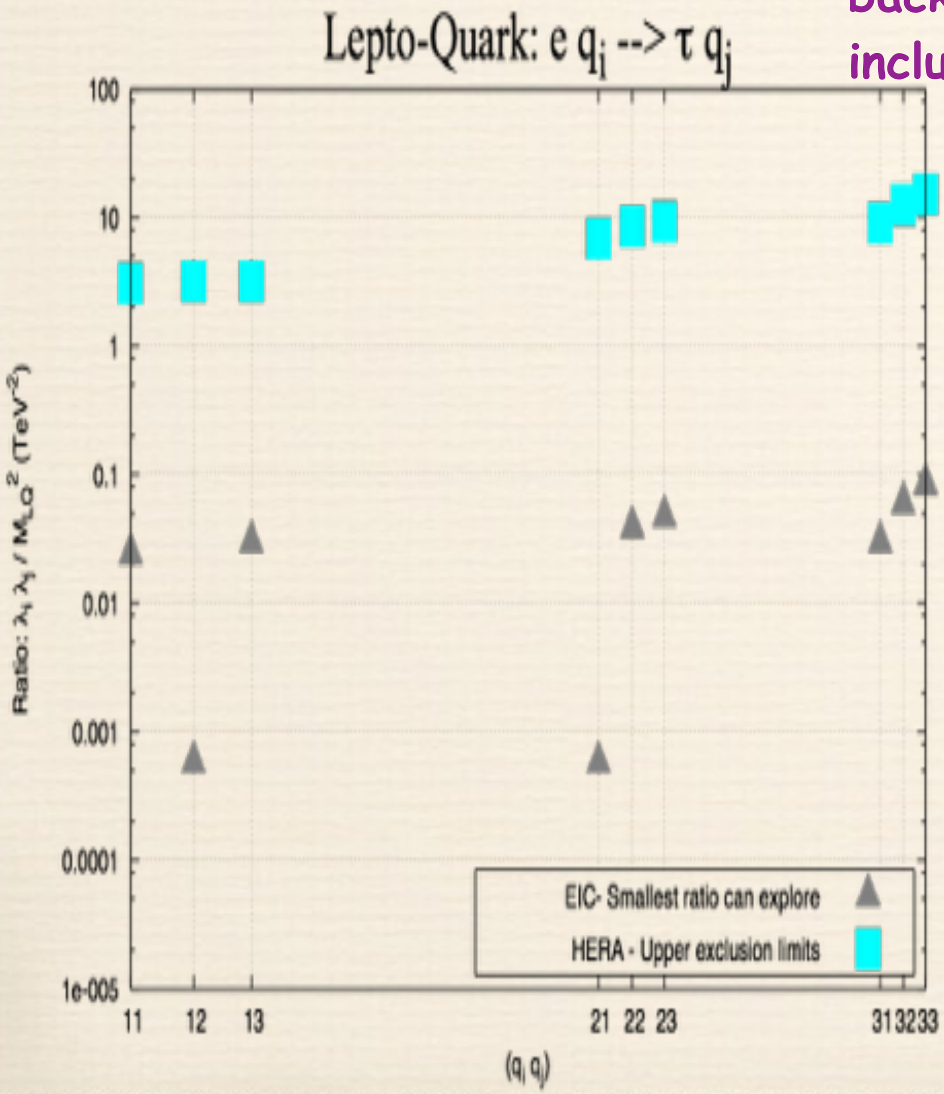


Topology: neutral current DIS event; except that the electron is replaced by tau lepton

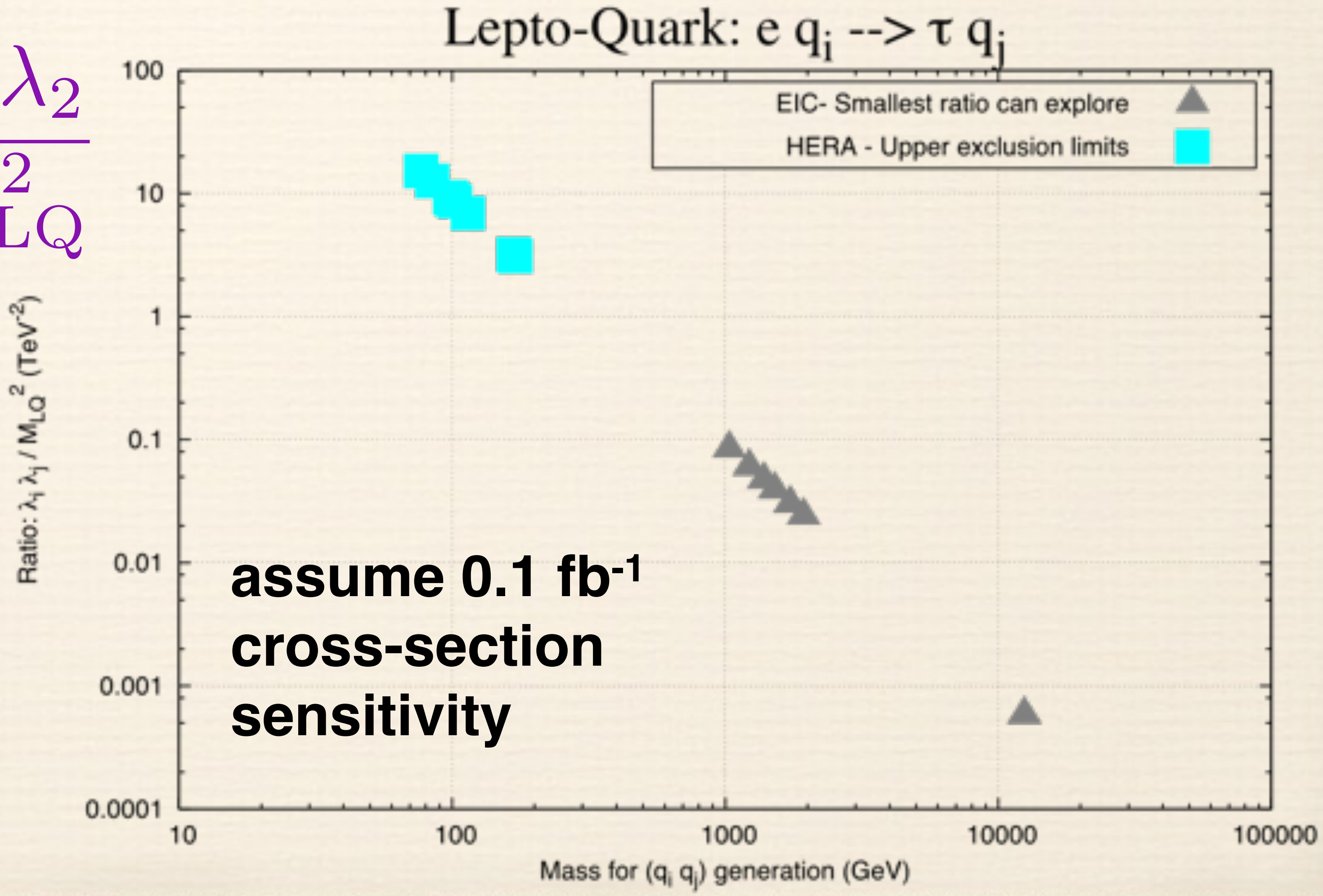
- If mixed in with hadron remnants, the tau would be boosted
- If forward … ed
- Potential f
  - look f… n: should be abl
  - tau ve… b backgr… letector is include… in EIC detector design



Gonderinger and Ramsey-Musolf, arXiv: 1006.5063



$$\frac{\lambda_1 \lambda_2}{M^2_{\rm LQ}}$$



assume 0.1 fb^{-1} cross-section sensitivity

challenge for measurement: 10 to 30% efficiency with zero background

MC Generator Studies

C. Faroughy (UG Researcher now at U. Maryland),
+S.Teneja (post doc, now a research faculty in Canada)
A. Deshpande (SBU)

- **Standard model backgrounds generated**: Neutral & Charged current DIS, photo-production, lepton-pair production & W production…. *Compare event topologies* with the LQ events

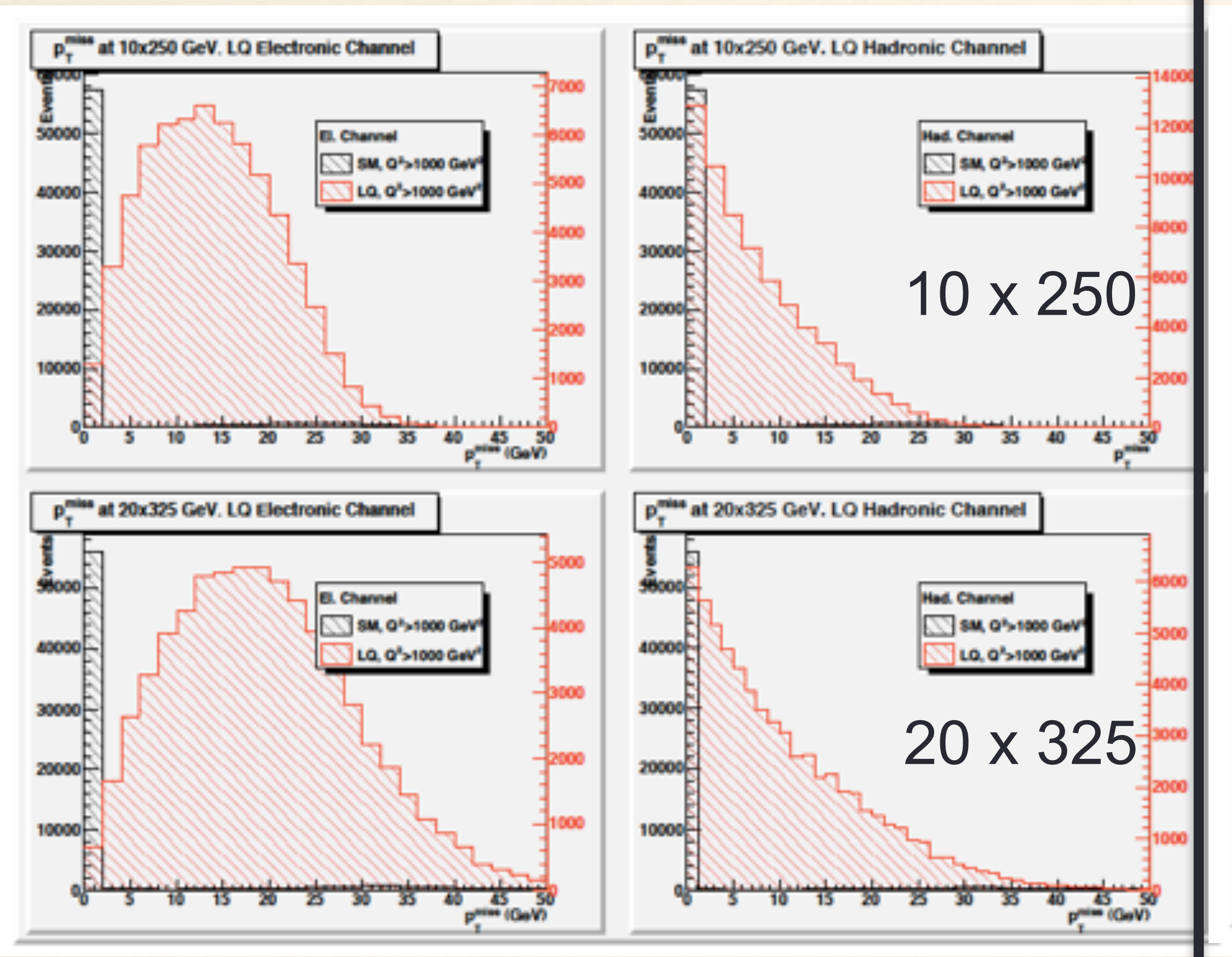
- τ has a clean signature: Analyses similar to those performed for such analyses in H1 and ZEUS analyses at HERA: **Indicates that reliable identification of Tau is certainly possible both for**
  - Leptonic Decays of τ
  - Hadronic Decays: Narrow “pencil” like jets with 1-3 pions

- Very clear differences in topologies of SM and LQ events established. GEANT detector simulations now underway.

Event Topology: LQ vs SM

C. Faroughy (UG Researcher now at U. Maryland),
+S.Teneja (post doc, now a research faculty in Canada)
A. Deshpande (SBU)

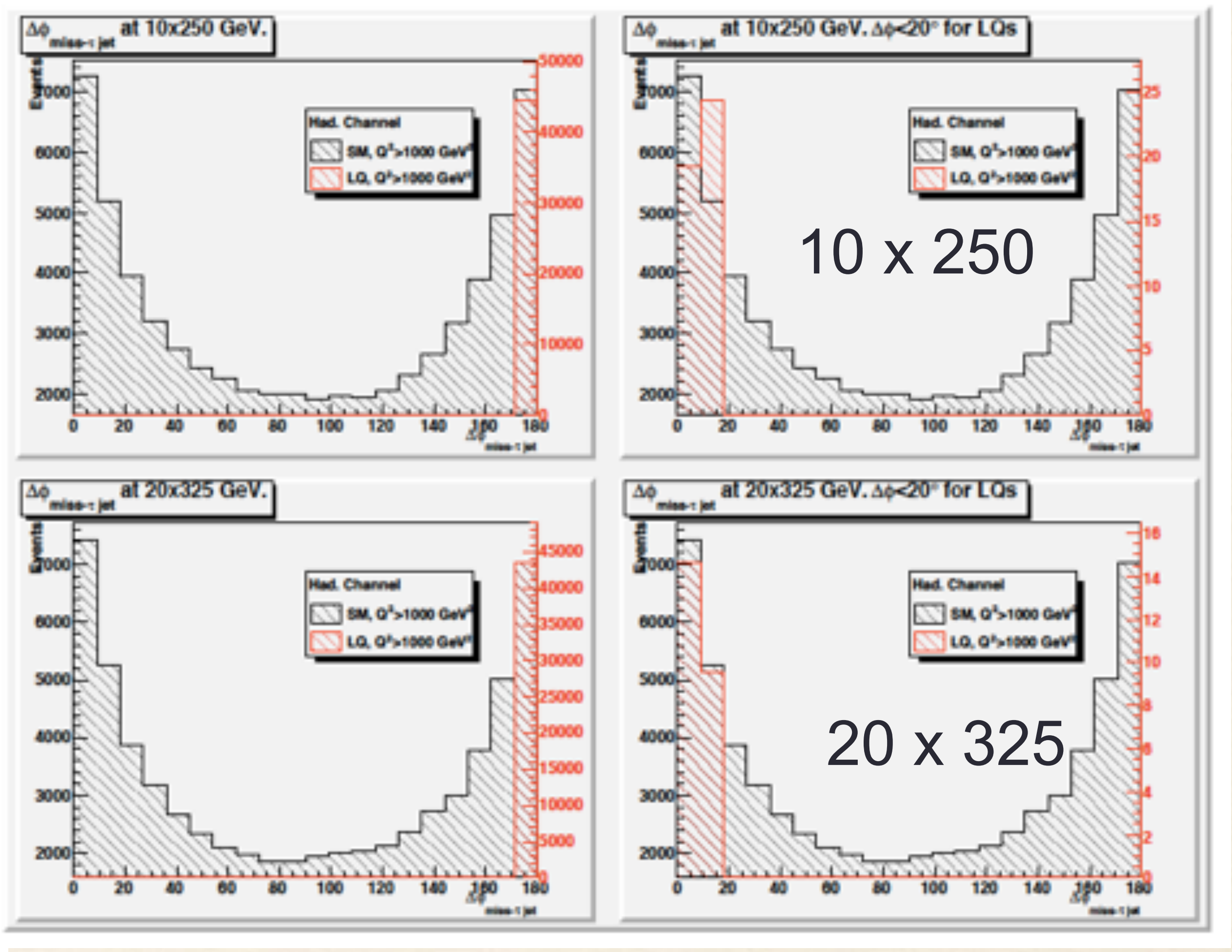
$$p_T^{miss} = \sqrt{(\sum P_{x,i})^2 + (\sum P_{y,i})^2}$$



10 x 250

20 x 325

Acoplanarity: $\Delta\phi_{miss}$-τ_{jet}



10 x 250

20 x 325

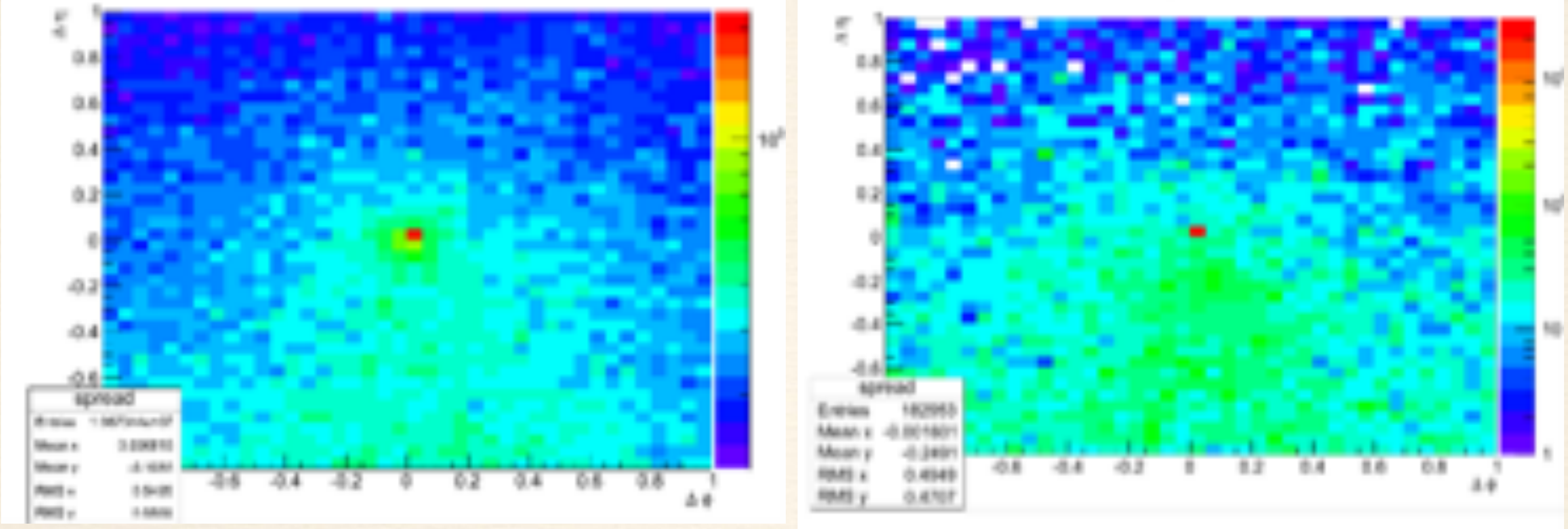
Based on similar studies at HERA:
H1 Collaboration, F. D. Aaron et al., Phys. Lett. B 701 20 (2011)
ZEUS Collaboration, S. Chekanov et al., Eur. Phys. J. C44 463 (2005)

achieve 10% efficiency with very good signal-to-background ratio

Next Steps in e-Tau Study

The previous studies ended with first G4 Calorimeter Results

Jet width seems narrower in “pencil-like” jets, compared to “hadronic jets”



τ decay jet

Normal hadronic jet in DIS

Jets width studies to “re-begin”

- Collider CM Energy variation
- Need of PID/Tracking on hadronic final states and hence jets
- Study Vertex Detector Discrimination
- Carry out a likelihood analysis to maximize discrimination
- …

Summary

- **Fundamental Symmetries and Neutrinos**
  - Central to our quest to understand the origin of matter
- **Parity-Violating Electron Scattering in the next decade**
  - Technical progress has enabled unprecedented precision
  - flagship experiments at electron accelerators
  - Fundamental Nuclear/Nucleon Physics
    - *Neutron RMS radii of heavy nuclei*
    - *valence quark structure of protons and neutrons*
  - Fundamental Electroweak Physics
    - *Search for new dynamics at the multi-TeV scale*
    - *precision measurement of the weak mixing angle*
- **EIC enables access to novel EW observables**
  - Novel spin-independent and spin-dependent structure functions
  - Precision Weak Mixing Angle at an interesting Q^2 range
  - Highly complementary sensitivity to charged lepton flavor violation

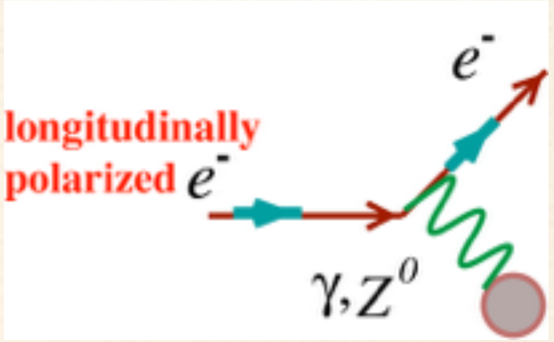
Serious detector-level studies of these latter topics are now beginning….

Backup

Parity-Violating Electron Scattering

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

Longitudinally Polarized Electron Scattering off Unpolarized Targets



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

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

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

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

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*

The Three Best Measurements

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

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

$$\langle Q\rangle \simeq 2.4\ \mathrm{MeV}$$

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

$$\sin^2\theta_W(m_Z)_{\bar{\mathrm{M}}\mathrm{S}} = 0.2356(16)$$

$$\langle Q\rangle \simeq 5\ \mathrm{GeV}$$

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

$$\sin^2\theta_W(m_Z)_{\bar{\mathrm{M}}\mathrm{S}} = 0.2329(13)$$

$$\langle Q\rangle \simeq 160\ \mathrm{MeV}$$

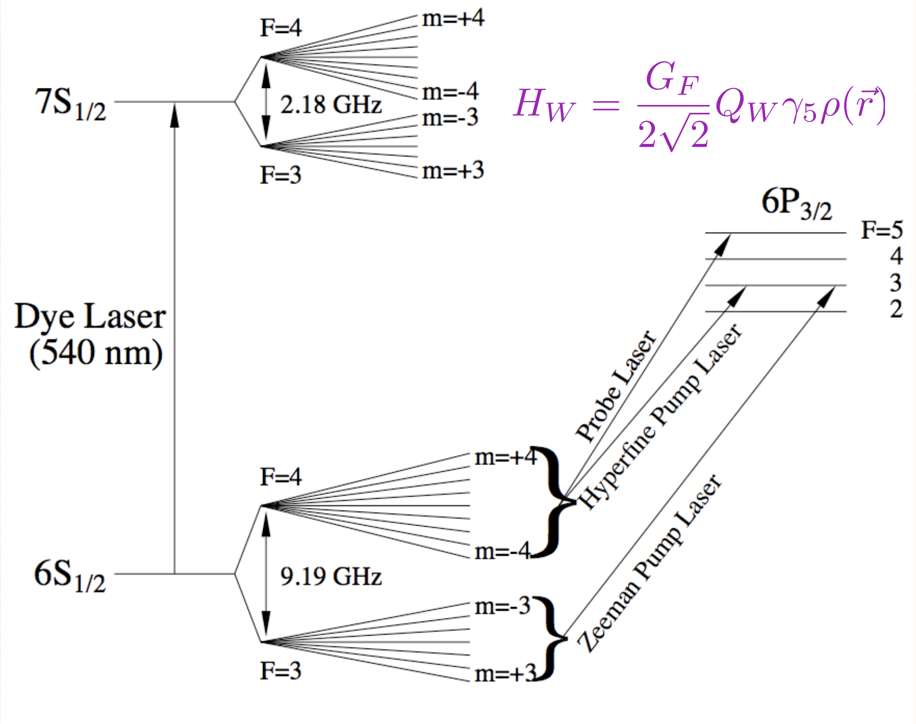
$$Q_W(Z,N) = Z(1-4\sin^2\theta_W) - N$$

$$\frac{\delta(Q_W)}{Q_W} \sim 0.6\% \Longrightarrow \frac{\delta(\sin^2\theta_W)}{\sin^2\theta_W} \sim 0.9\%$$

Atomic Parity Violation

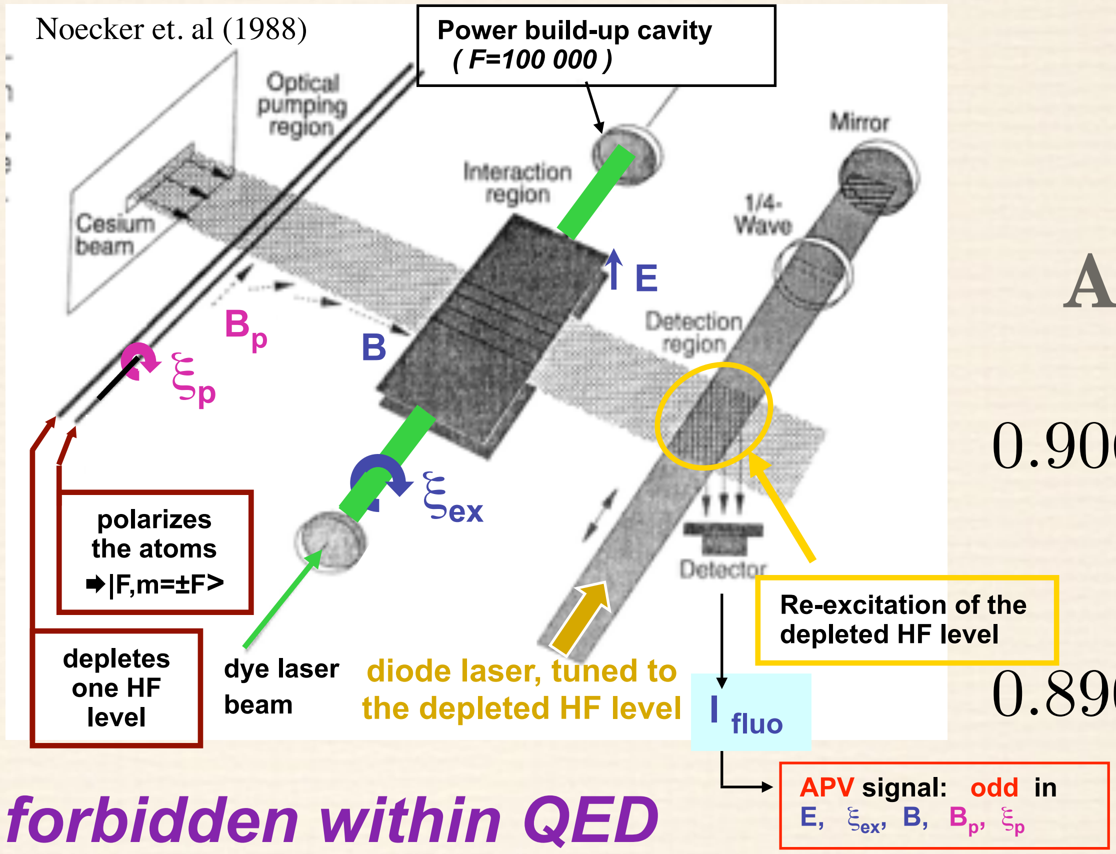
Carl Wieman and collaborators at U. Colorado (Boulder)

Partial Level Structure of Cesium



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

Boulder Experiment


Noecker et. al (1988)

$$k_{PNC}$$

Atomic Theory

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

1999

$$0.8906(26) \times 10^{-11} e a_0$$

2010

$$0.8977(40) \times 10^{-11} e a_0$$

2012

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

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

$$Q_W = \left(\frac{E1_{PNC}/\beta}{M_{hf}/\beta}\right)\left(\frac{N M_{hf}}{k_{PNC}}\right)$$

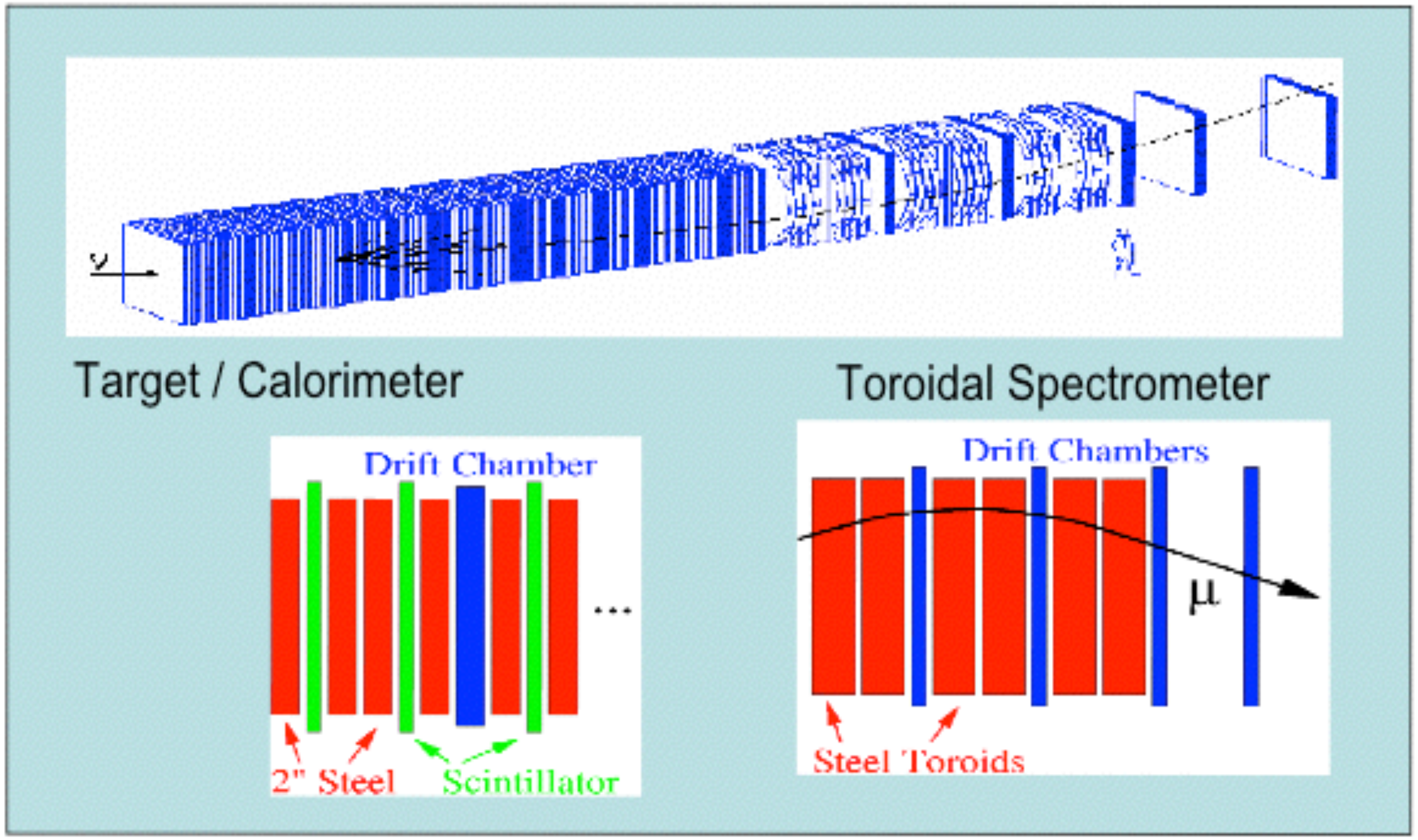
$$\sin^2\theta_W(m_Z)_{\overline{\mathrm{MS}}} = 0.2283(20)$$

1.5 σ low

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

NuTeV

Significant discovery: but EW or QCD Physics?



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

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

Standard Model prediction is 0.2227
(3σ deviation)

Most precise measurement of neutrino-quark coupling

Subtle parton physics effects can affect the result

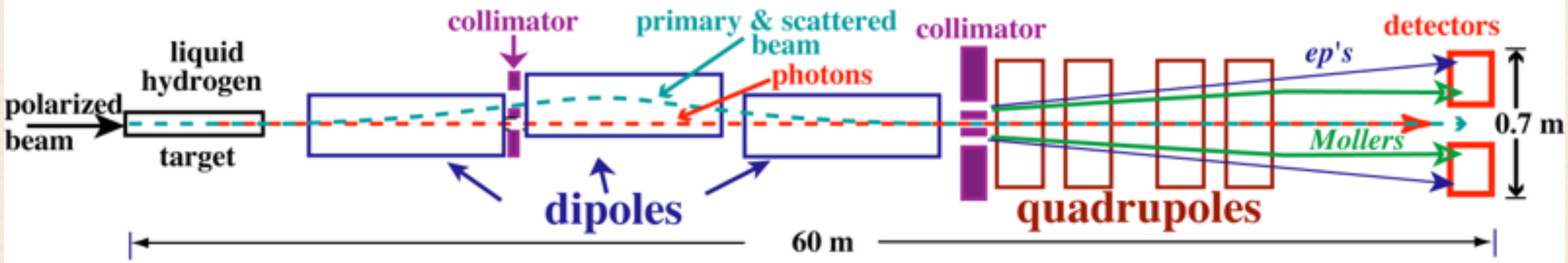
generated great interest in both nuclear and particle phenomenology

Goal: error small enough to probe TeV scale physics

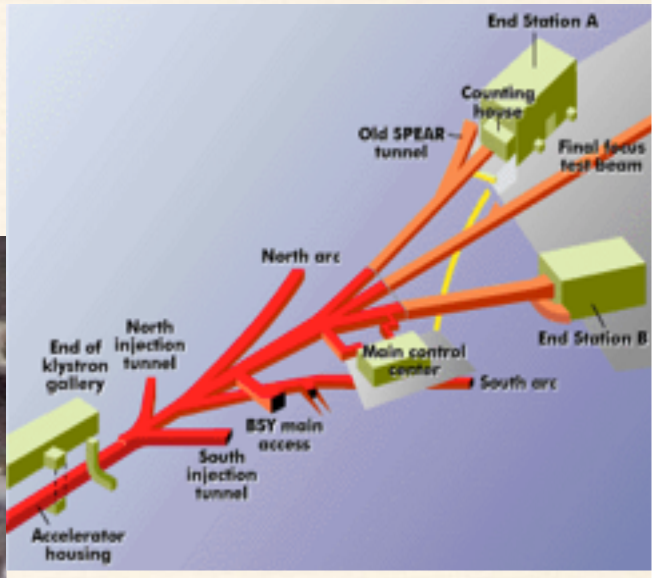
SLAC E158

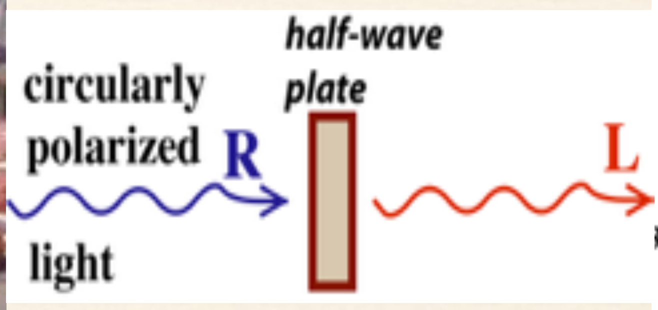
1997-2004

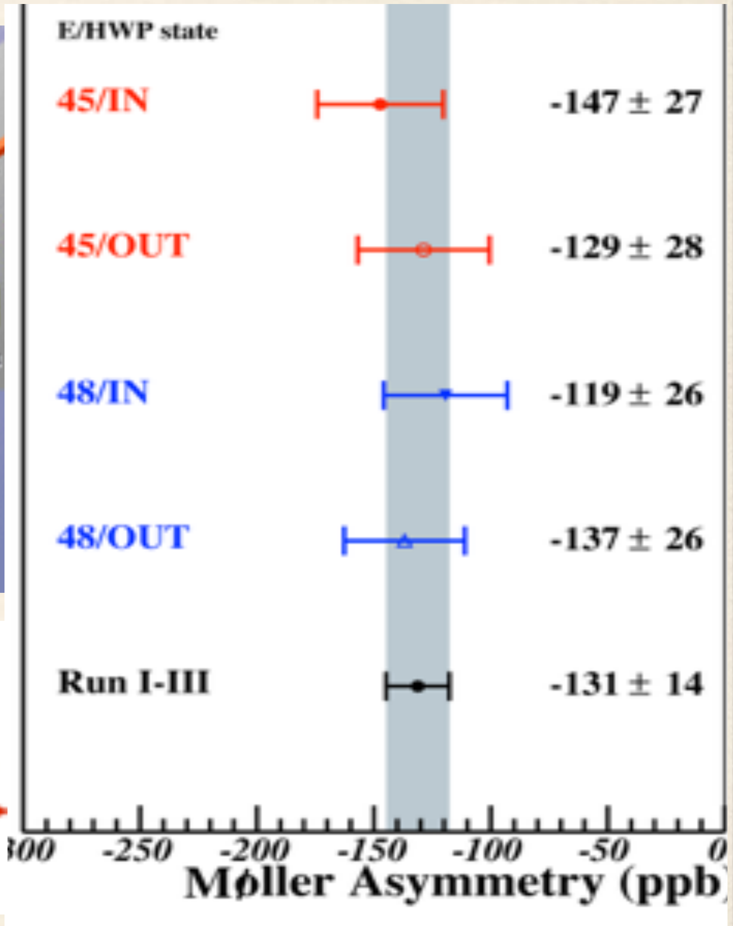
~ 10 ppb statistical error at highest E_{beam}, ~ 0.5% error on weak mixing angle



A large number of technical challenges





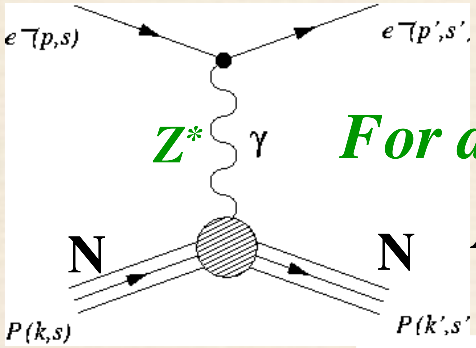


$$A_{PV} = (-131 \pm 14 \pm 10) \times 10^{-9}$$

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

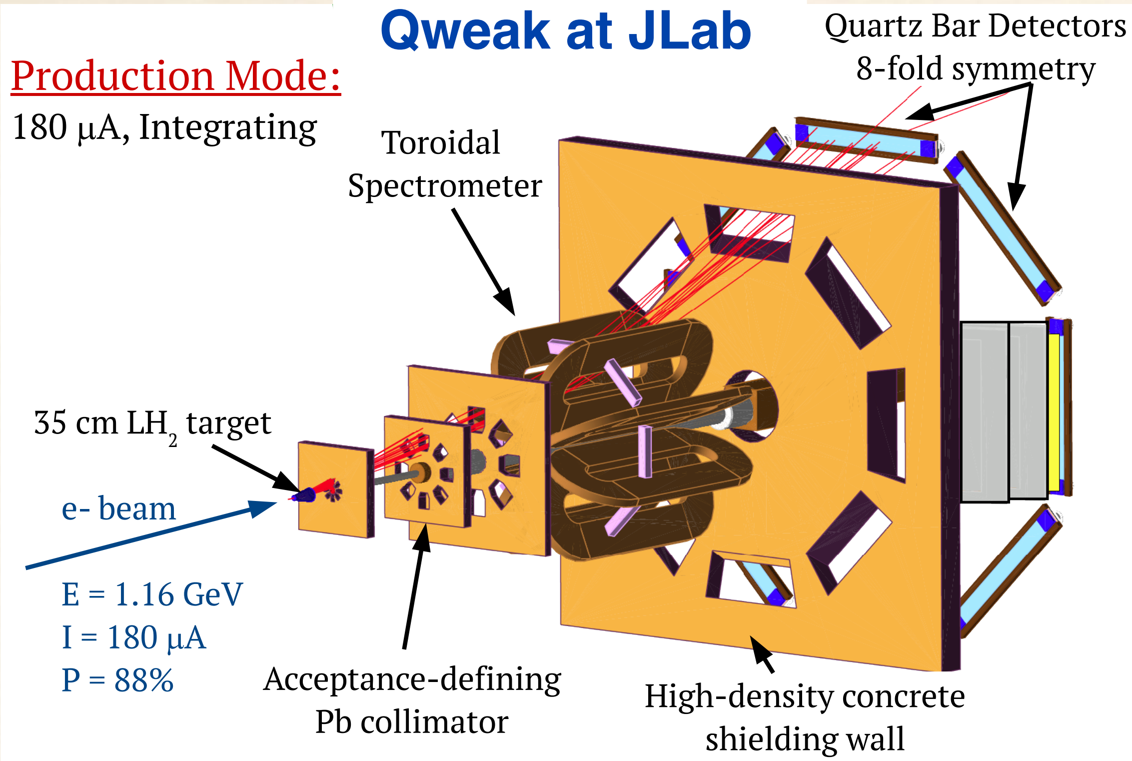
A_{PV} in elastic e-p scattering:

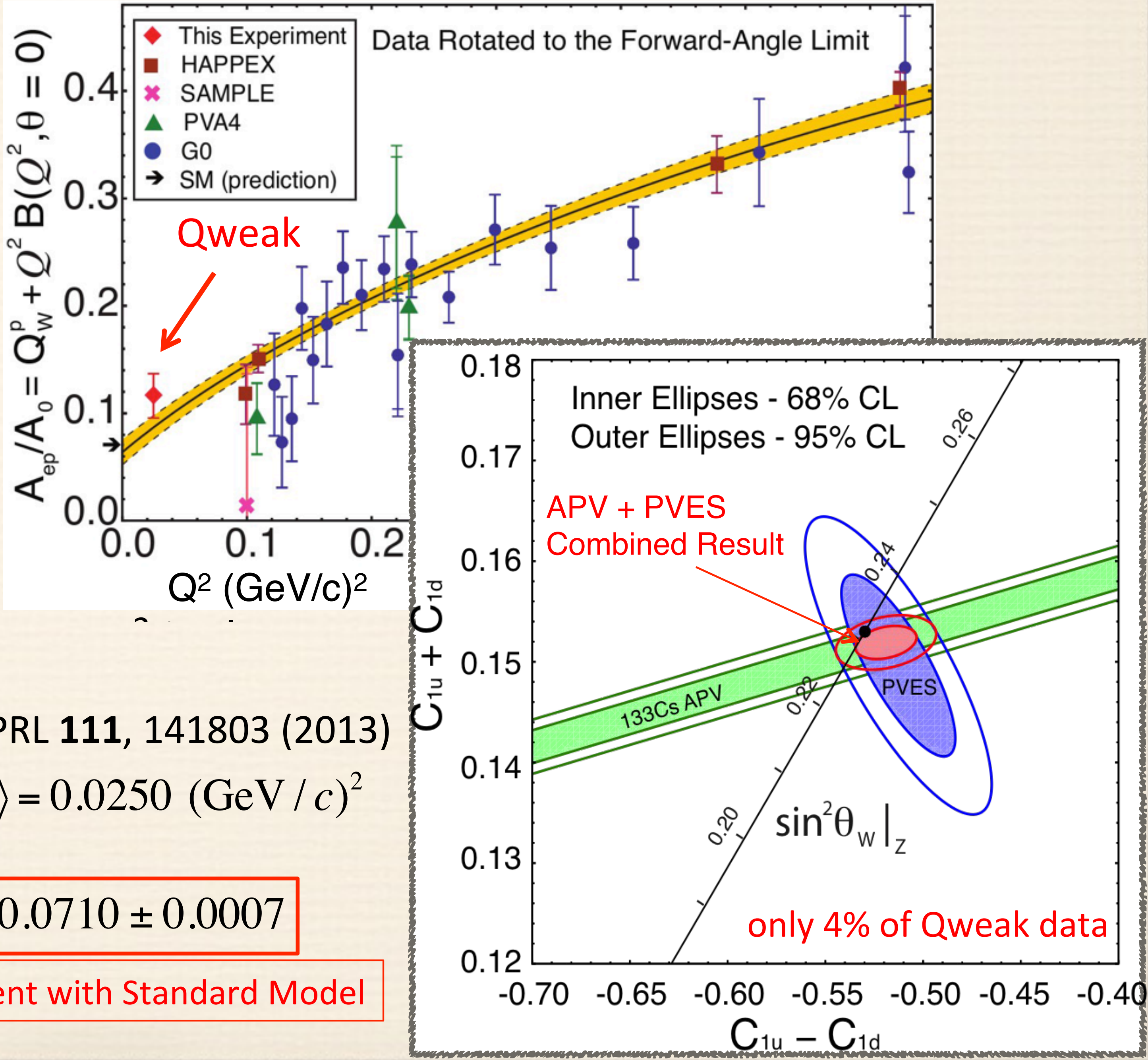
The Weak Charge of the Proton



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

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





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

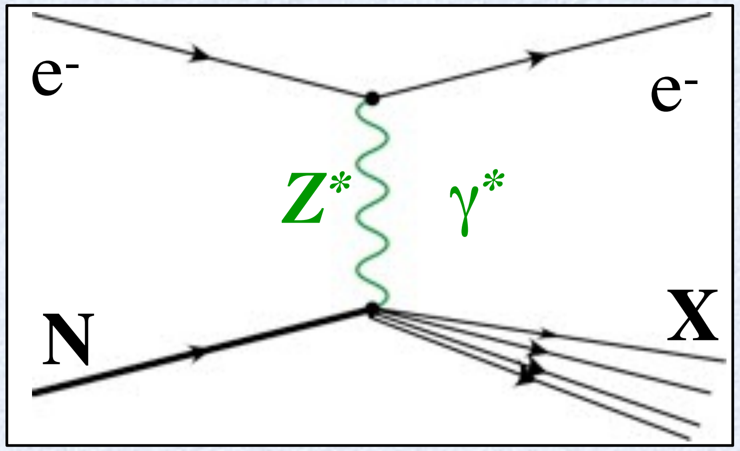
$$A_{ep} = -279 \pm 35(\text{stat}) \pm 31(\text{syst})\ \text{ppb} \quad \text{at} \quad \left\langle Q^2 \right\rangle = 0.0250\ (\text{GeV}/c)^2$$

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

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

PV Deep Inelastic Scattering

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



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

$$x \equiv x_{Bjorken}$$

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

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

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

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

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

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

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

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

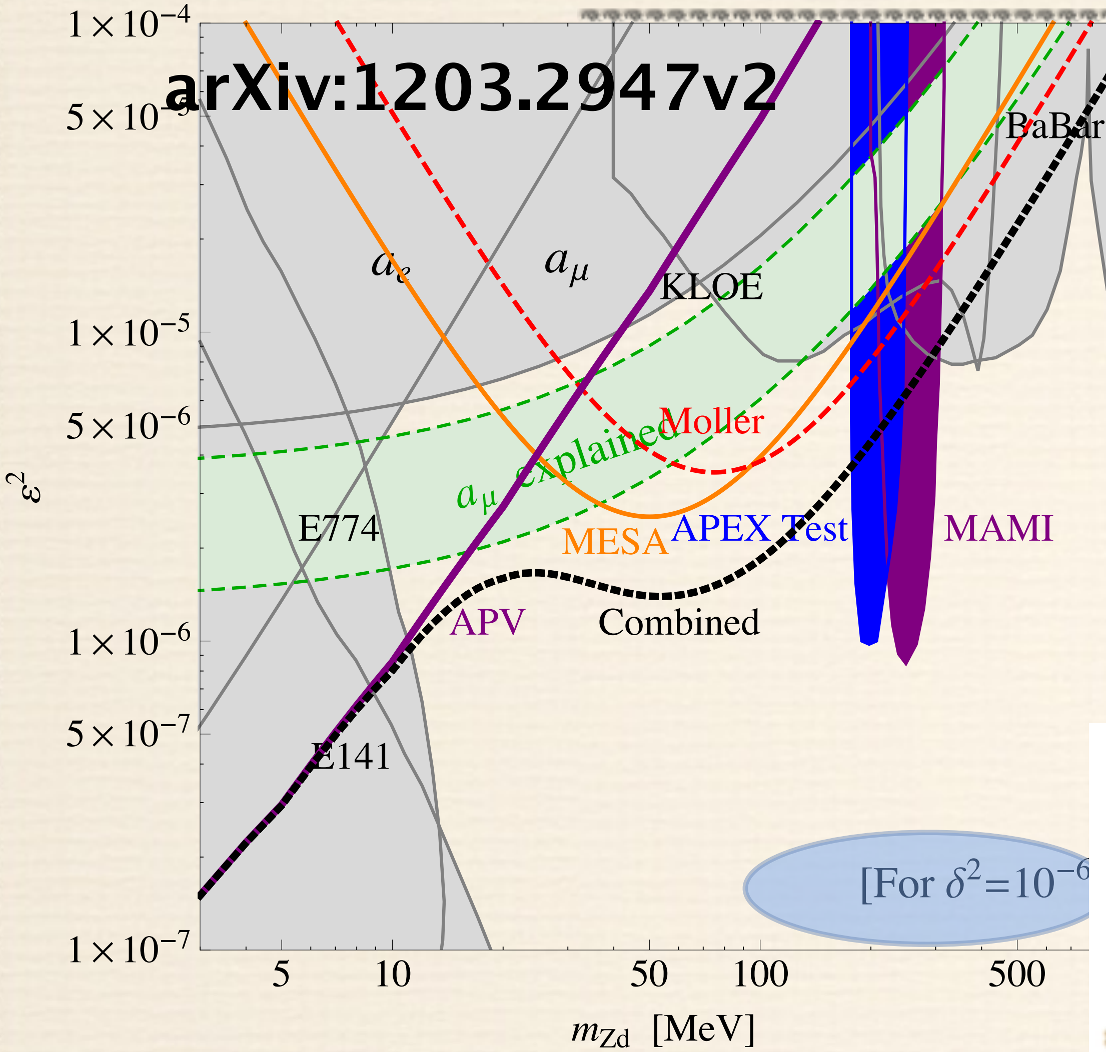
$$R_v(x) = \frac{u_v(x)+d_v(x)}{U(x)+D(x)} \xrightarrow{\text{Large } x} 1$$

Interplay with QCD

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

Dark Z to Invisible Particles

Davoudiasl, Lee, Marciano



Dark Photons:

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

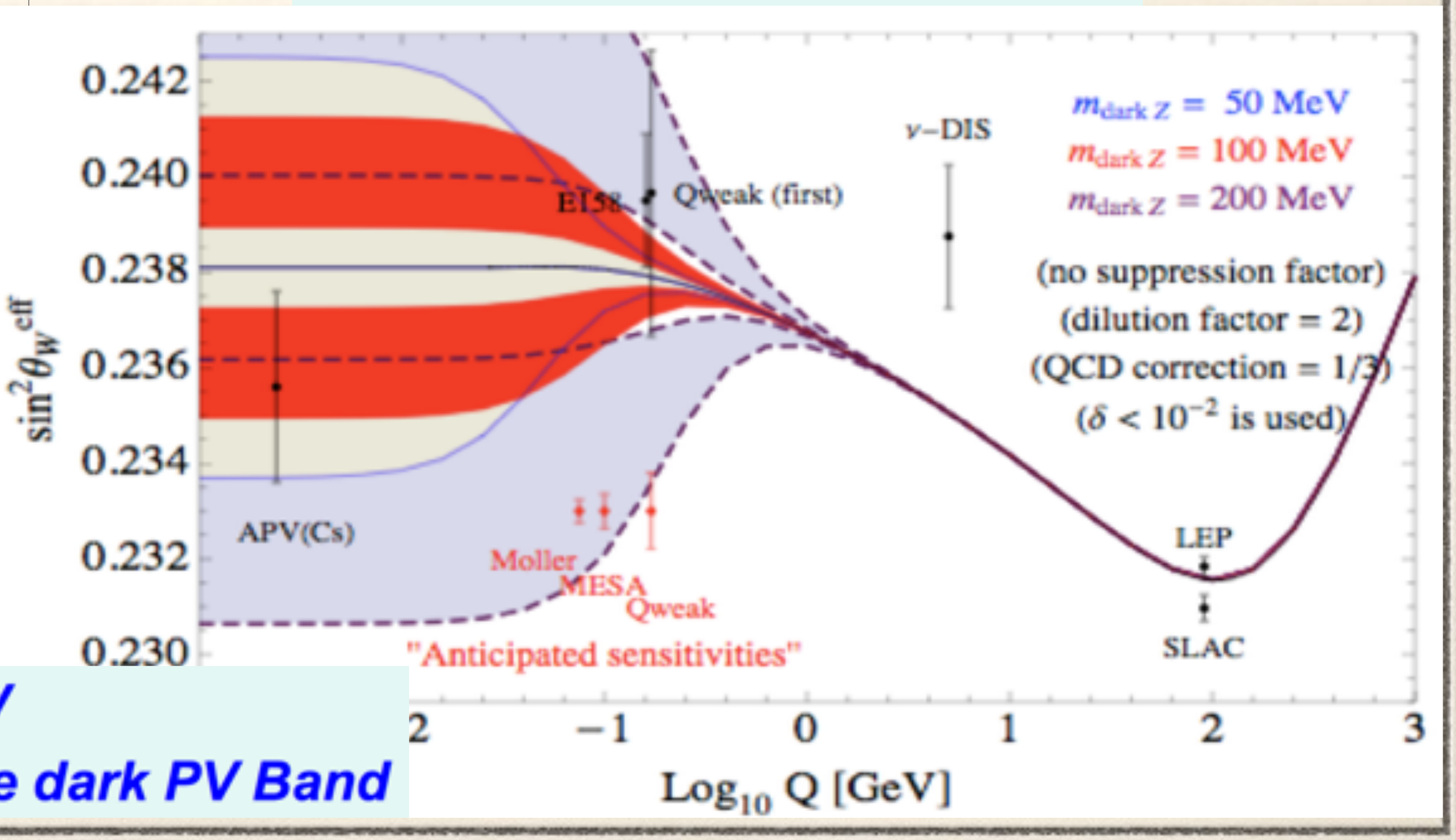
$$\epsilon_Z = \frac{m_{Z_d}}{M_Z}\delta$$

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

  APV & Polarized Electron Scattering at low <Q>

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

δ^2 roughly probed to 10^{-6}



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

ε and δ effects could partially cancel!

Suppression by ~1/6 allows Z_d~100MeV

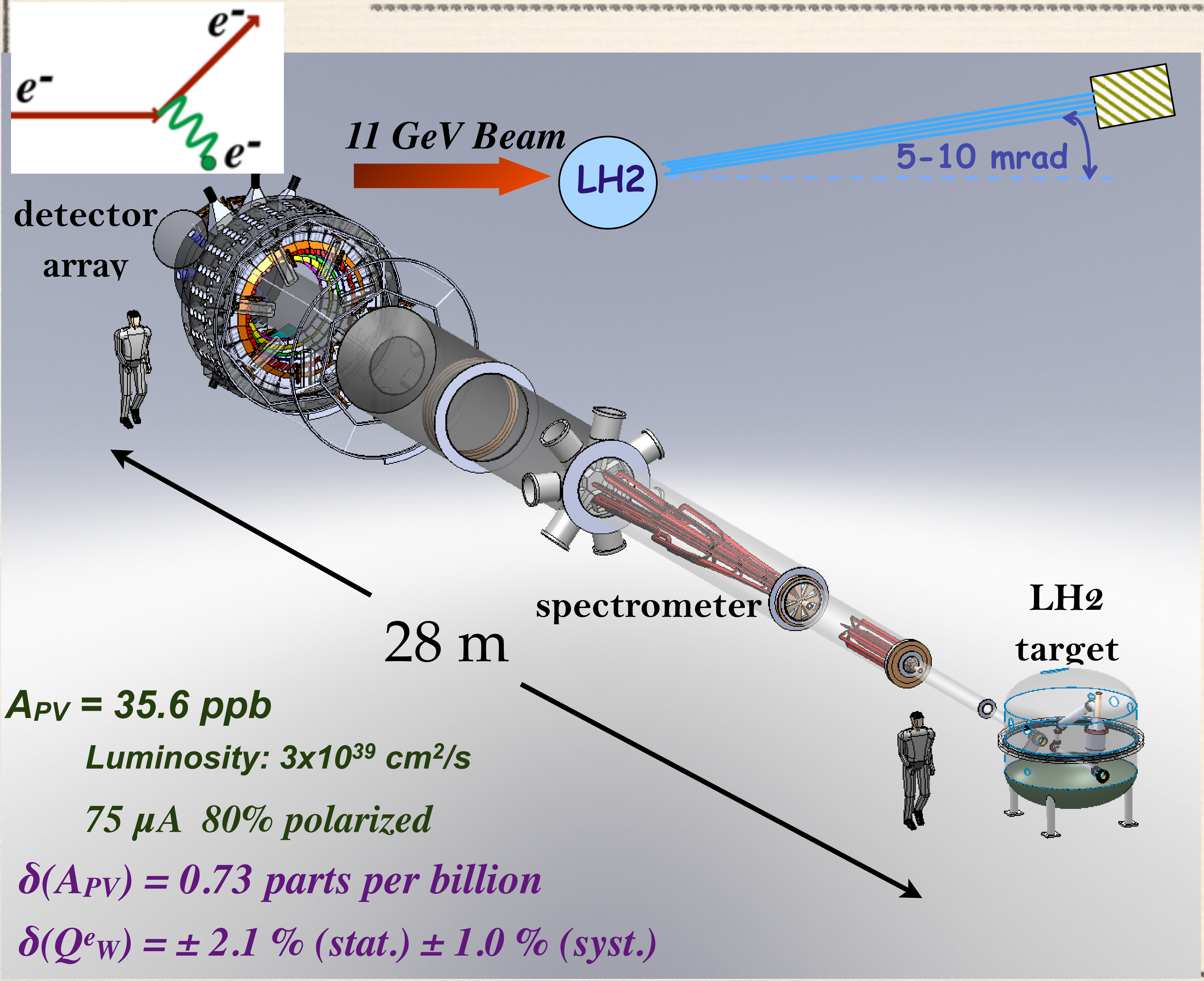
Combined with muon g-2 → observable dark PV Band

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

11 GeV Møller scattering

MOLLER at JLab

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



A_{PV} = 35.6 ppb

Luminosity: 3×10^{39} cm^2/s

75 μA 80% polarized

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

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

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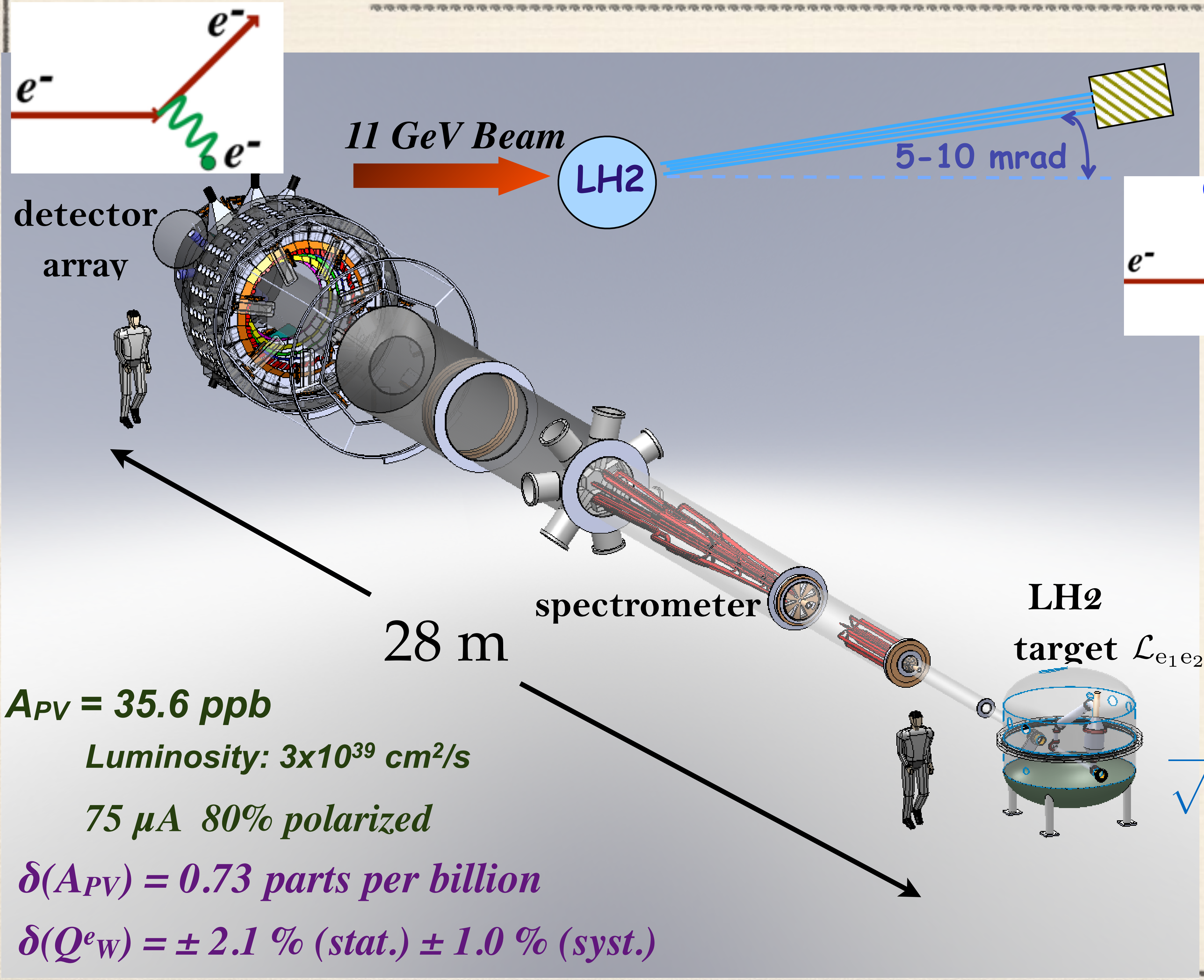

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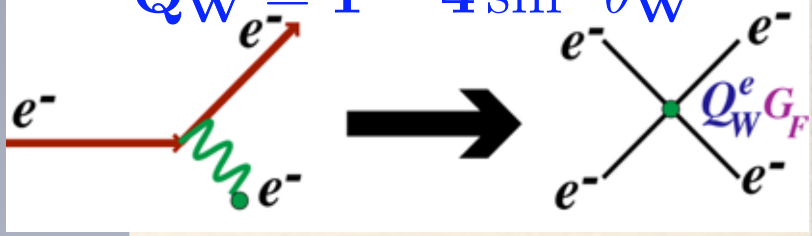
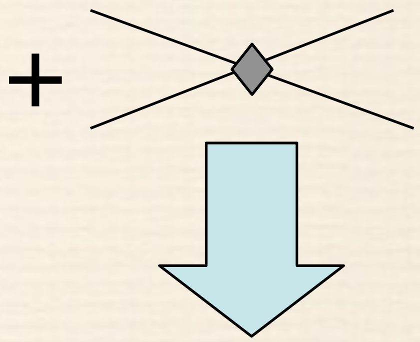
δ(Q^e_W) = ± 2.1 % (stat.) ± 1.0 % (syst.)

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





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

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

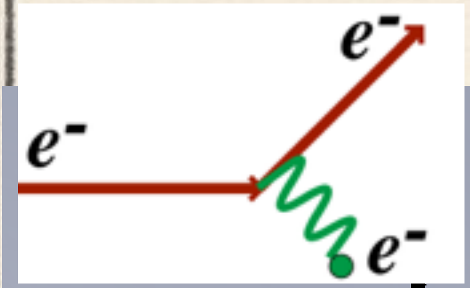
$$\frac{\Lambda}{\sqrt{|g_{RR}^2 - g_{LL}^2|}} = 7.5\ \text{TeV}$$

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

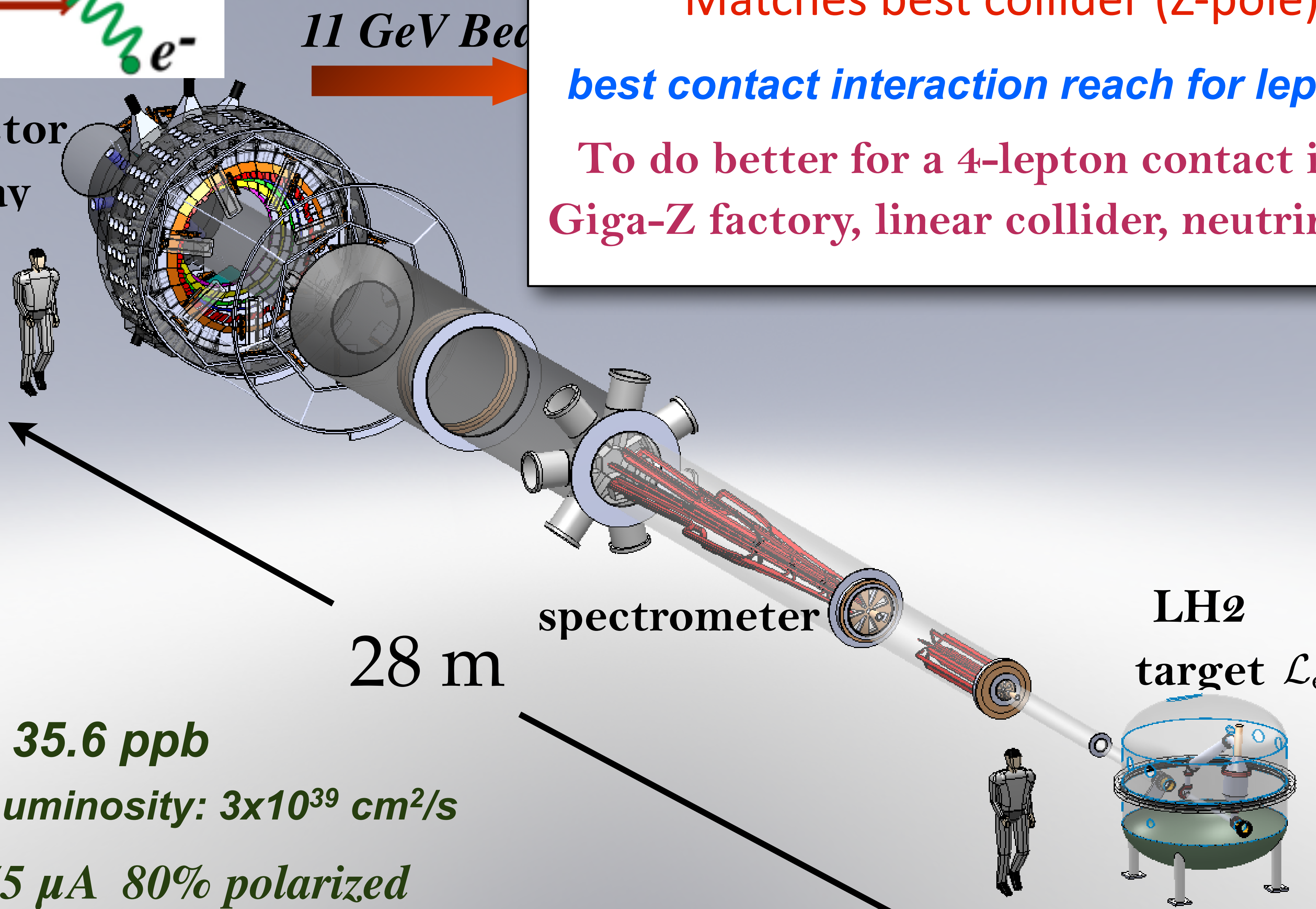


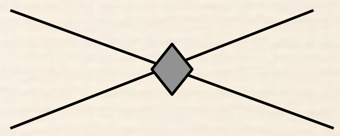
$\delta(\sin^2\theta_W) = \pm 0.00026$ (stat.) ± 0.00012 (syst.) → ~ 0.1%

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



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

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Luminosity: 3×10^{39} cm²/s

75 μA 80% polarized

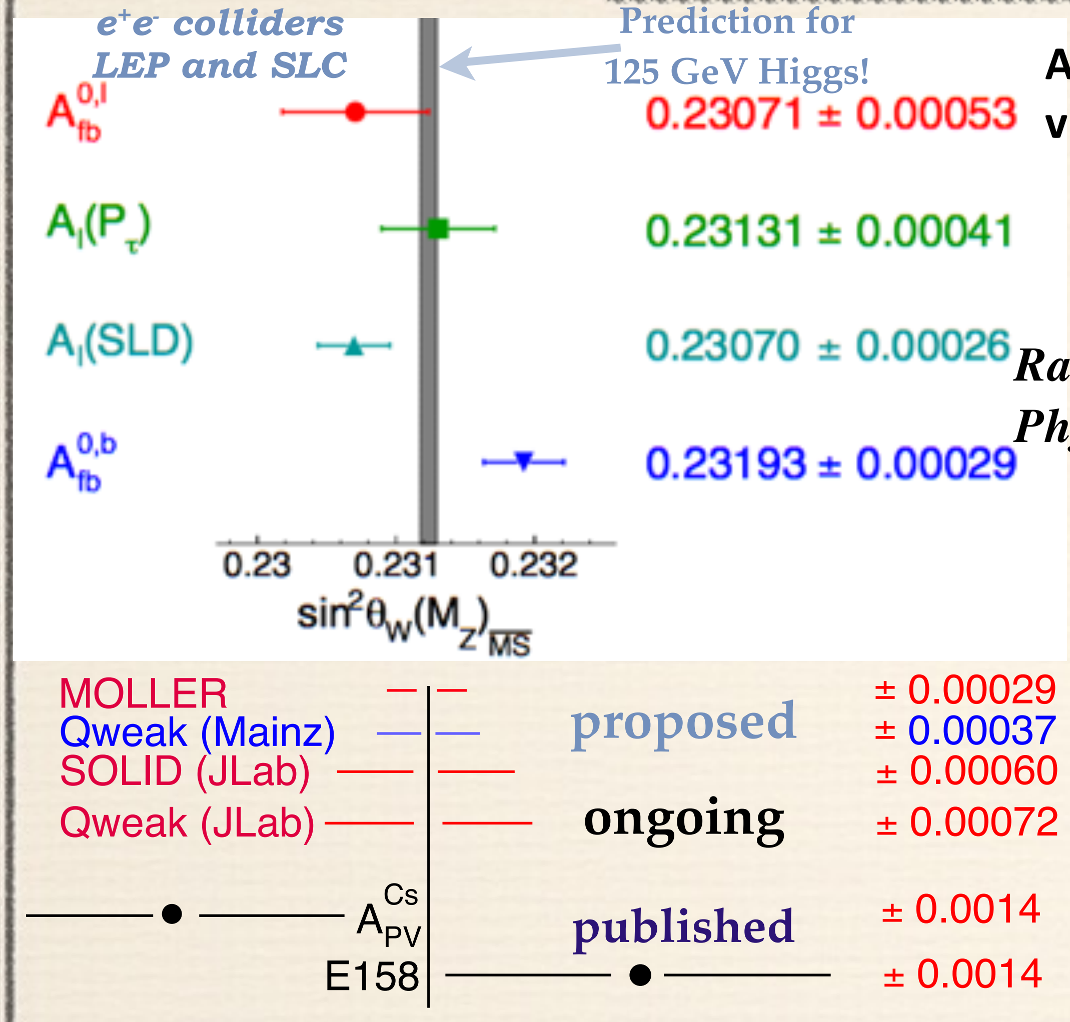
$\delta(A_{PV})$ = 0.73 parts per billion

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

- **~ 20M$ MIE funding required**
- **3-4 years construction**
- **2-3 years running**

Physics Examples: Beyond LHC

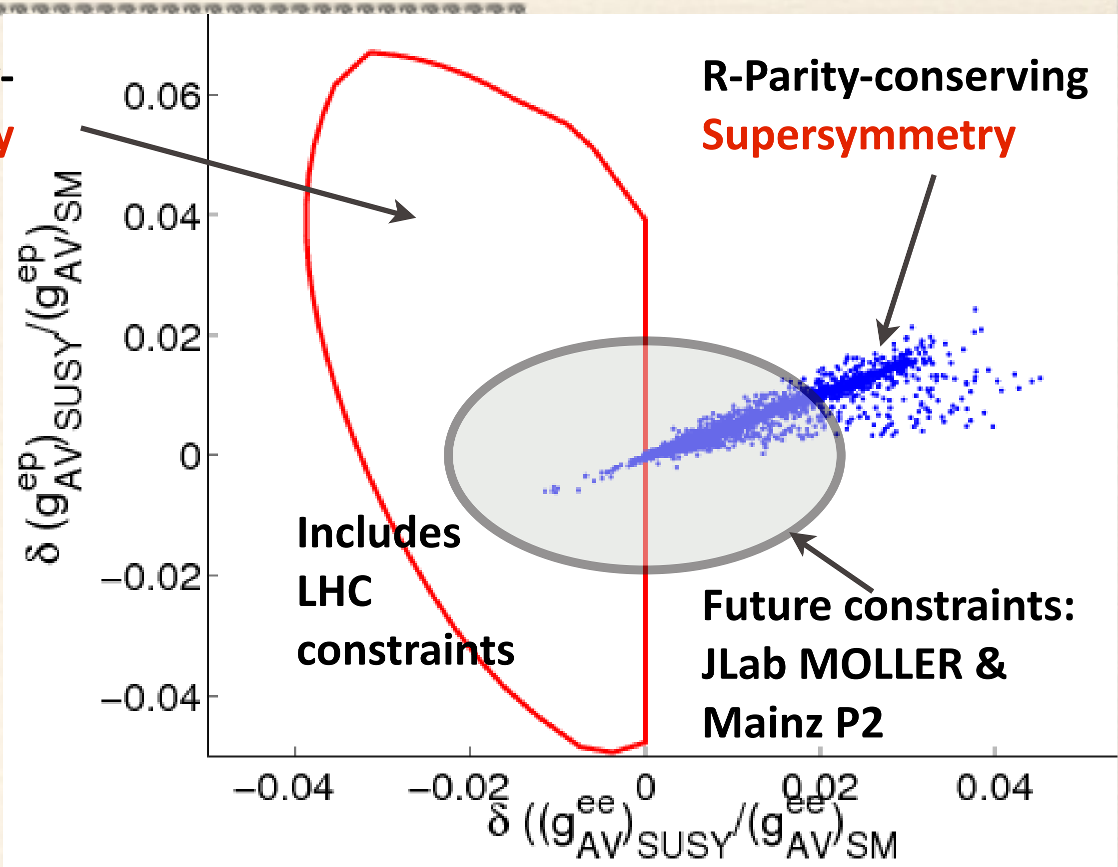
Z resonance measurements: little sensitivity to new contact interactions



Allowed region: R-Parity-violating **Supersymmetry**

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

Erler and Su, arXiv:1303.5522



R-Parity-conserving **Supersymmetry**

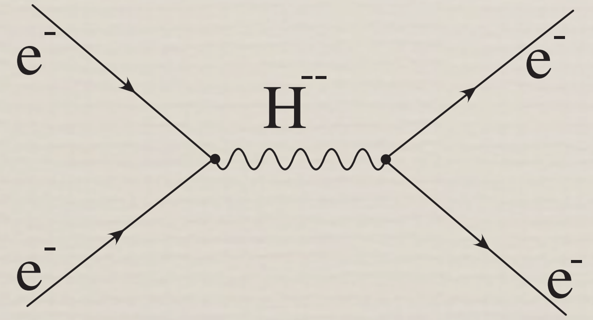
Includes LHC constraints

Future constraints: JLab MOLLER & Mainz P2

Lepton Number Violation

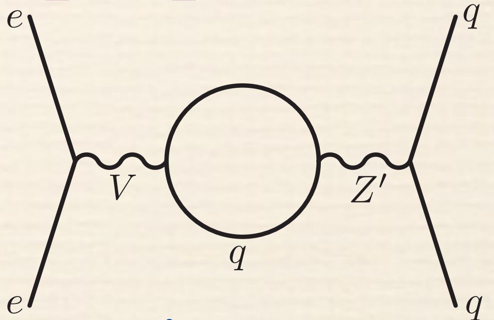
Λ > 5 TeV

Doubly-Charged Scalars



Significant reach beyond LEP-200

Leptophobic Z'



SOLID can improve sensitivity:
100-200 GeV range

MOLLER Status

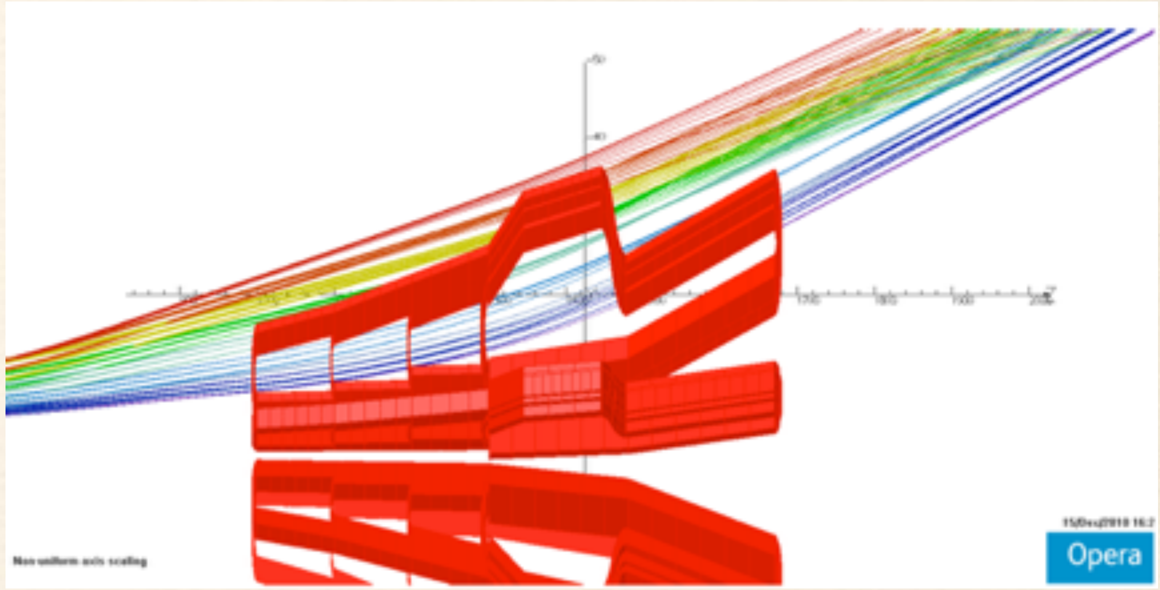
Director's Review chaired by C. Prescott: strong, positive endorsement

Technical Challenges

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

- **MOLLER Collaboration**

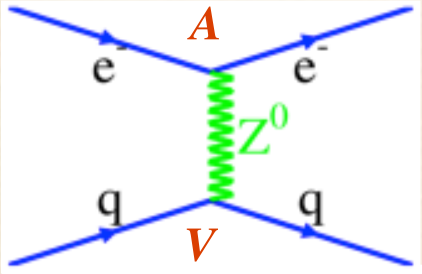
- ~ 100 authors, ~ 30 institutions
- Expertise from SAMPLE, A4, HAPPEX, G0, PREX, Qweak, E158
- 4th generation JLab parity experiment



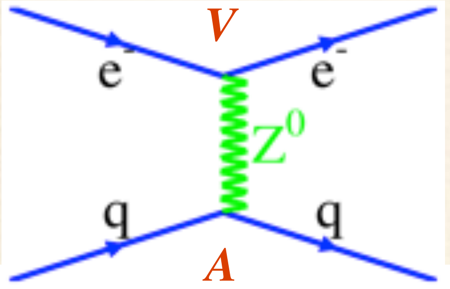
- **20M$ proposal to DoE NP**
- **2-3 years construction**
- **2-3 years running**

Elastic and deep-inelastic electron-nucleon scattering

Semi-Leptonic Interactions



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



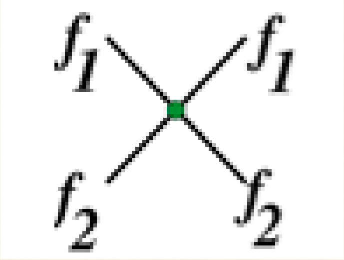
$C_{2i} \equiv 2g_V^e g_A^i$

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

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

+

new physics



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

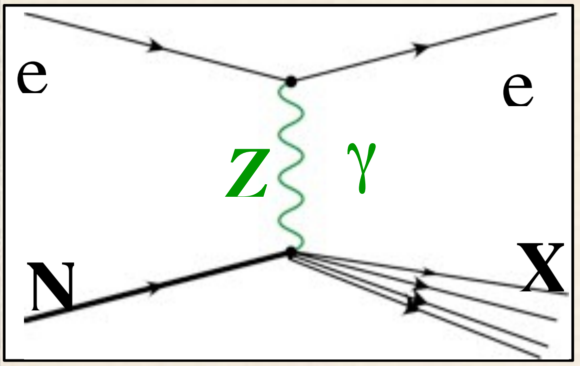
$C_{1q} \propto (g_{RR}^{eq})^2 + (g_{RL}^{eq})^2 - (g_{LR}^{eq})^2 - (g_{LL}^{eq})^2$ ⇨ ***PV elastic e-p scattering, Atomic parity violation***

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

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

Deep Inelastic Scattering on LD_2

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



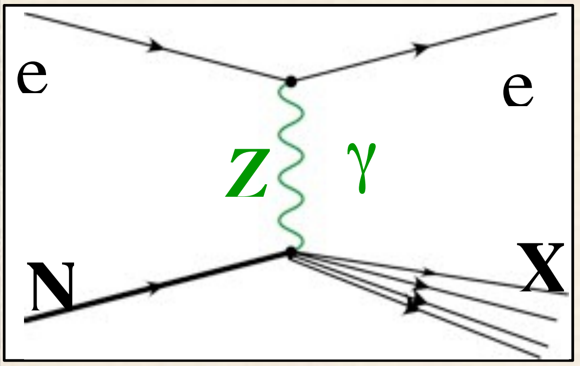
$$A_{PV} = \frac{G_F Q^2}{2\sqrt{2}\pi\alpha}\left[g_A \frac{F_1^{\gamma Z}}{F_1^{\gamma}} + g_V \frac{f(y)}{2}\frac{F_3^{\gamma Z}}{F_1^{\gamma}}\right]$$

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

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

Deep Inelastic Scattering on LD$_2$

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



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

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

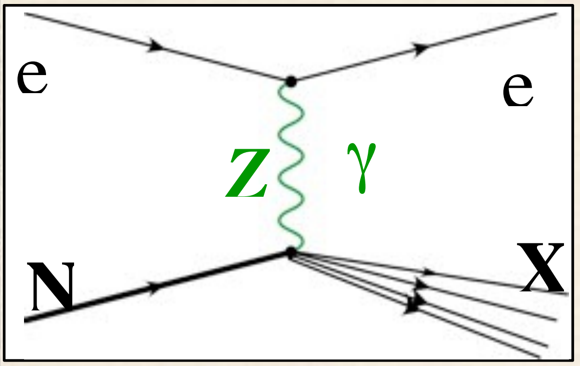
a(x): function of C_{1i}'s

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

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

Deep Inelastic Scattering on LD$_2$

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



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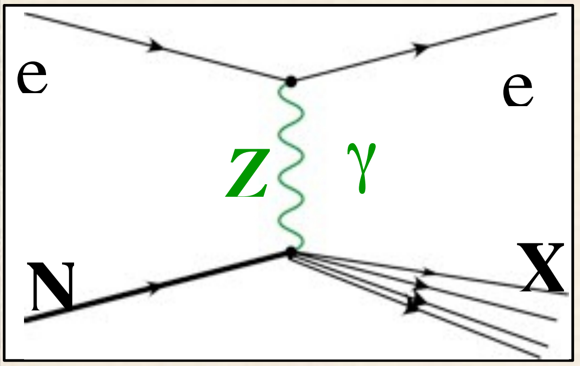
For ^{2}H, assuming charge symmetry, structure functions cancel in the ratio:

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

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

Deep Inelastic Scattering on LD_2

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



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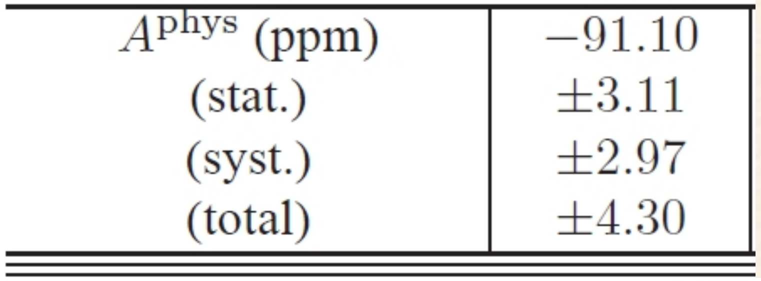
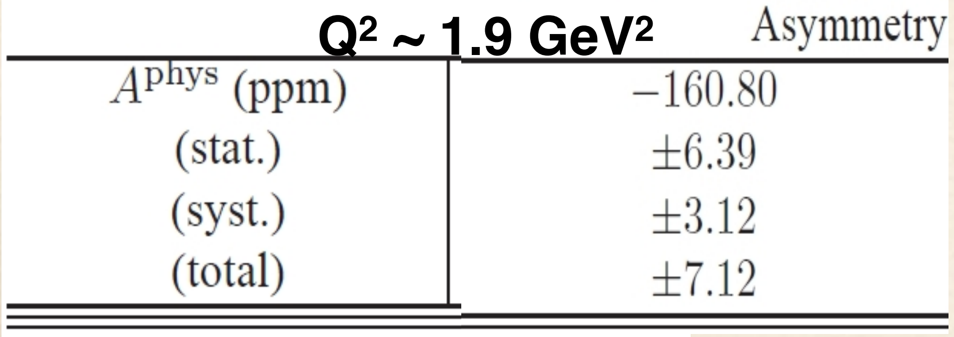
6 GeV run results

$Q^2 \sim 1.1$ GeV^2



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

$Q^2 \sim 1.9$ GeV^2

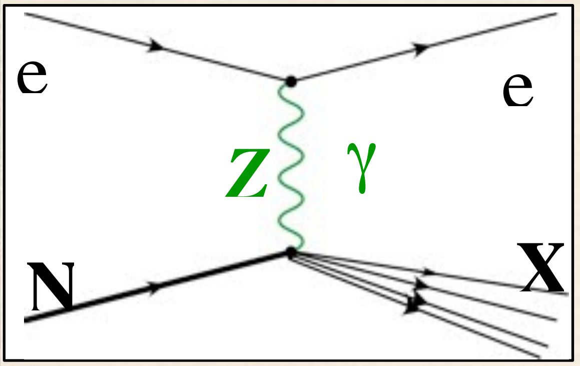


	Asymmetry
A^{phys} (ppm)	−160.80
(stat.)	±6.39
(syst.)	±3.12
(total)	±7.12

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

Deep Inelastic Scattering on LD_2

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



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

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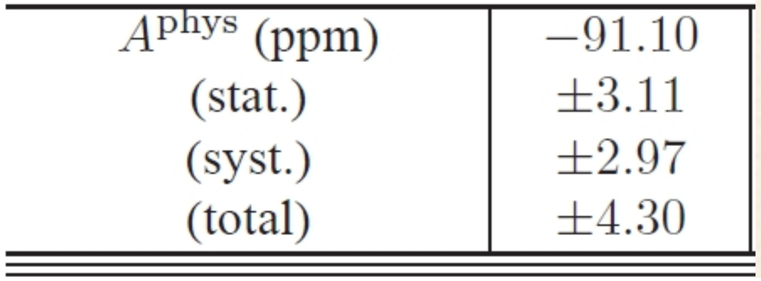
6 GeV run results

Q^2 ~ 1.1 GeV^2



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

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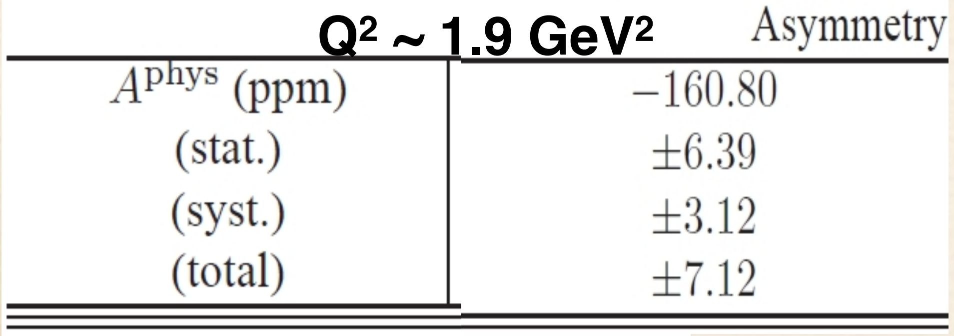

	Asymmetry
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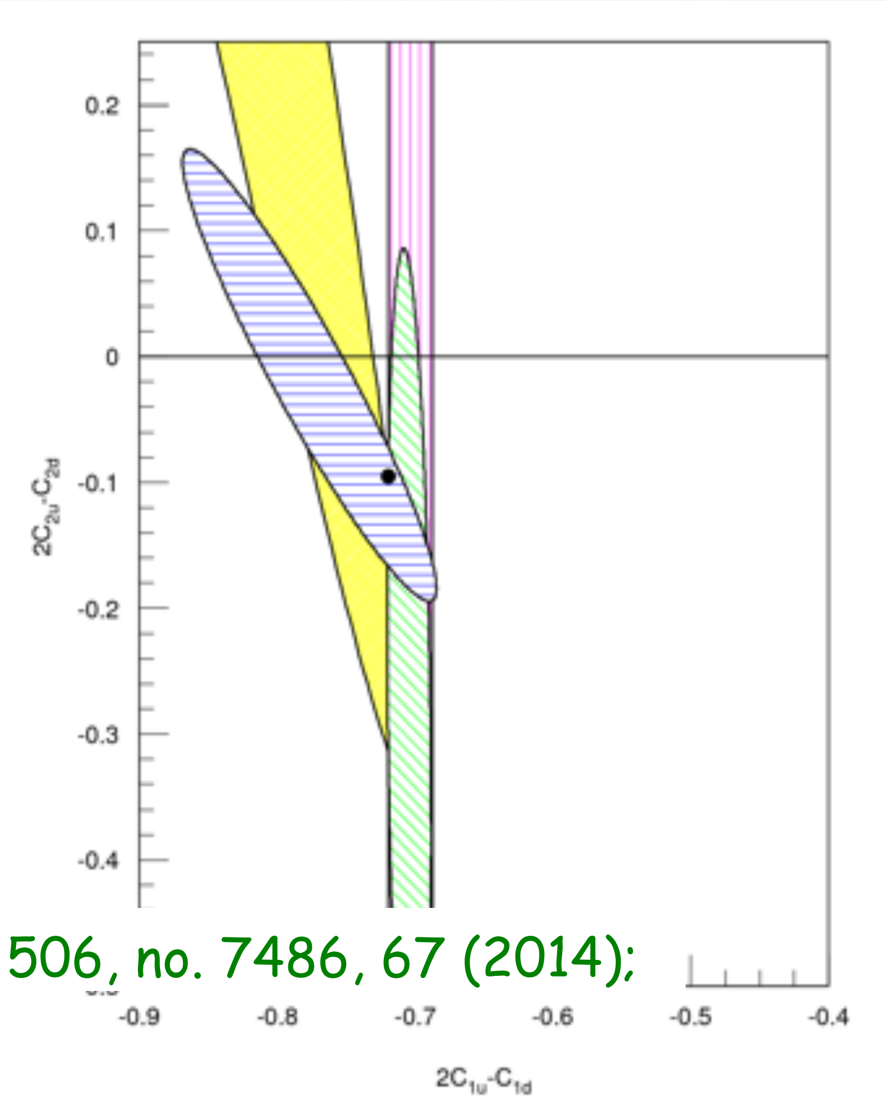
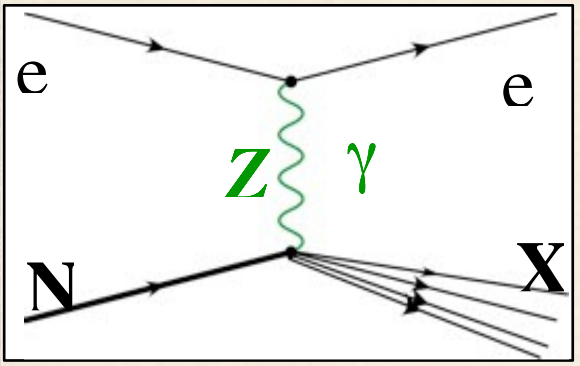


Wang et al., Nature 506, no. 7486, 67 (2014);

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

Deep Inelastic Scattering on LD$_2$

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



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

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

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

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

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

$$a(x) = \frac{\sum_i C_{1i} Q_i f_i(x)}{\sum_i Q_i^2 f_i(x)} \qquad b(x) = \frac{\sum_i C_{2i} Q_i f_i(x)}{\sum_i Q_i^2 f_i(x)}$$

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

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

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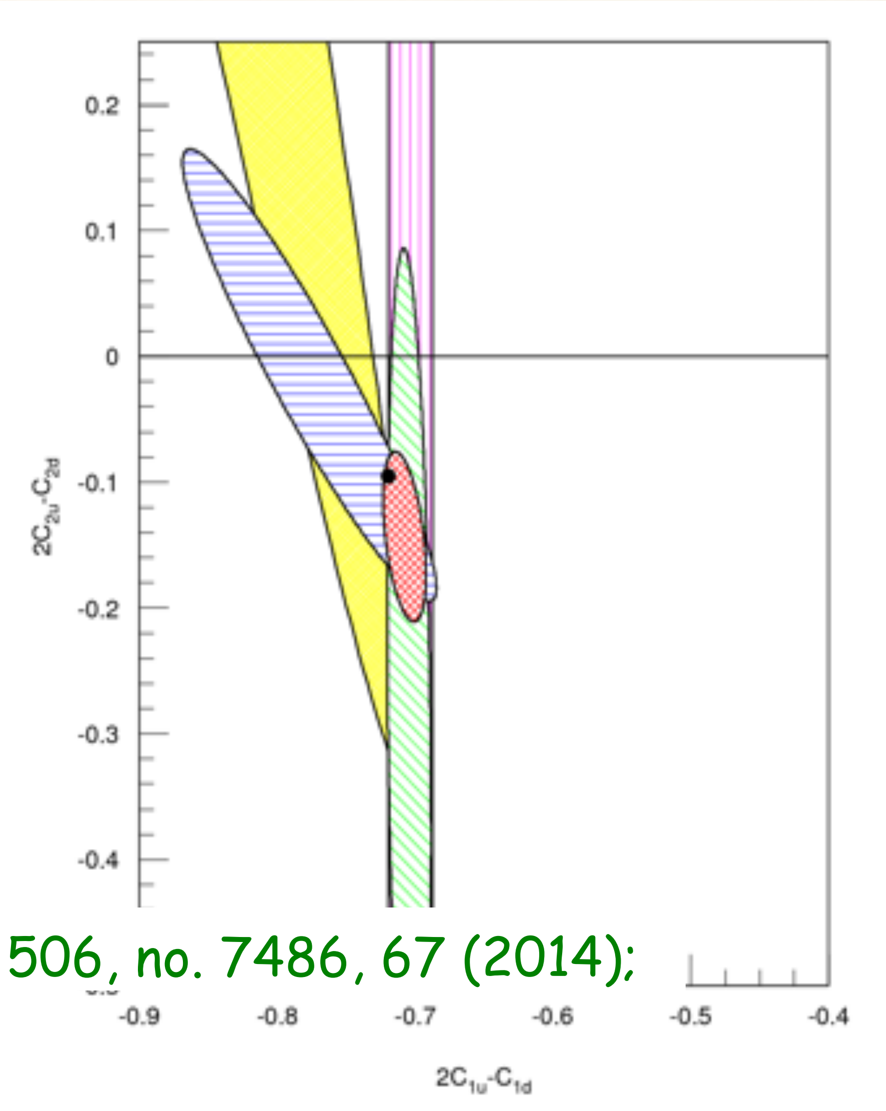

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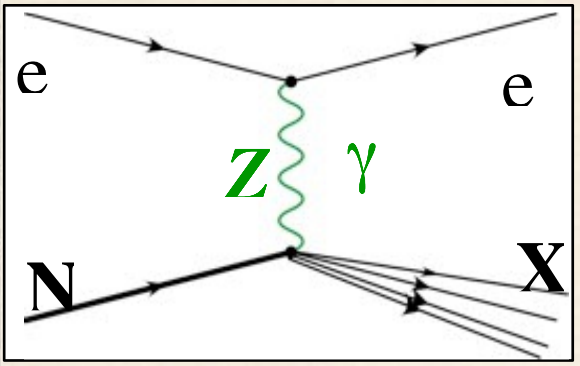

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$$A_{PV} = \frac{G_F Q^2}{\sqrt{2}\pi\alpha}\left[a(x) + f\right.$$

PARTICLE PHYSICS

Quarks are not ambidextrous

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

W. Marciano
article in Nature

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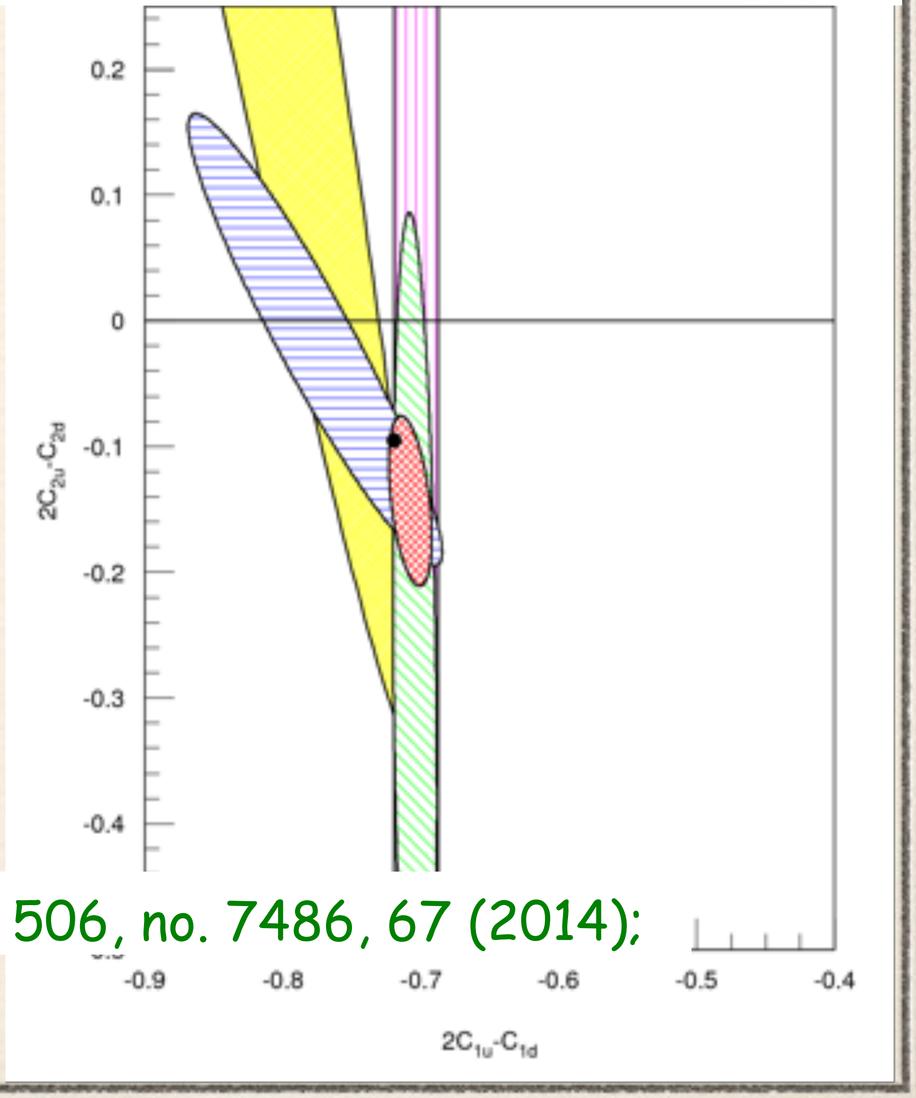

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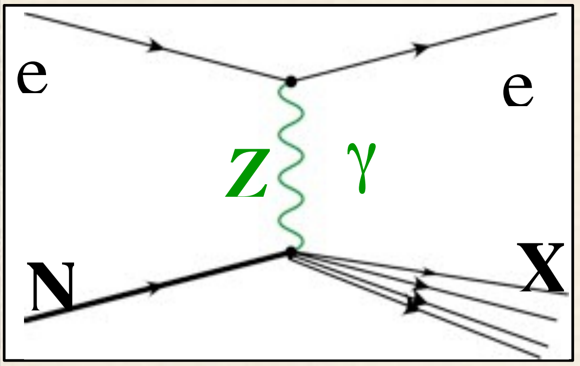

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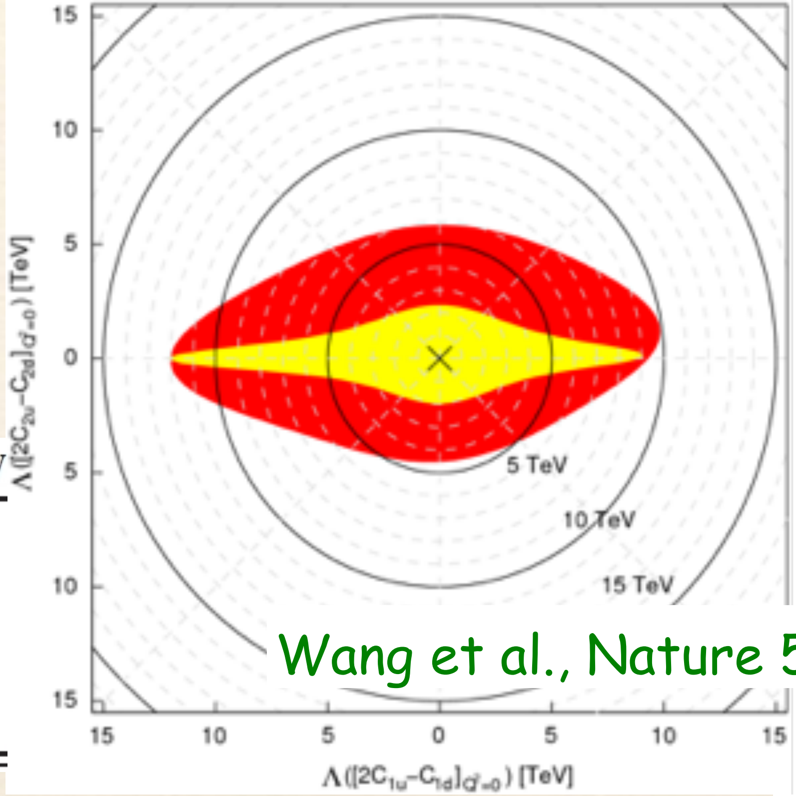
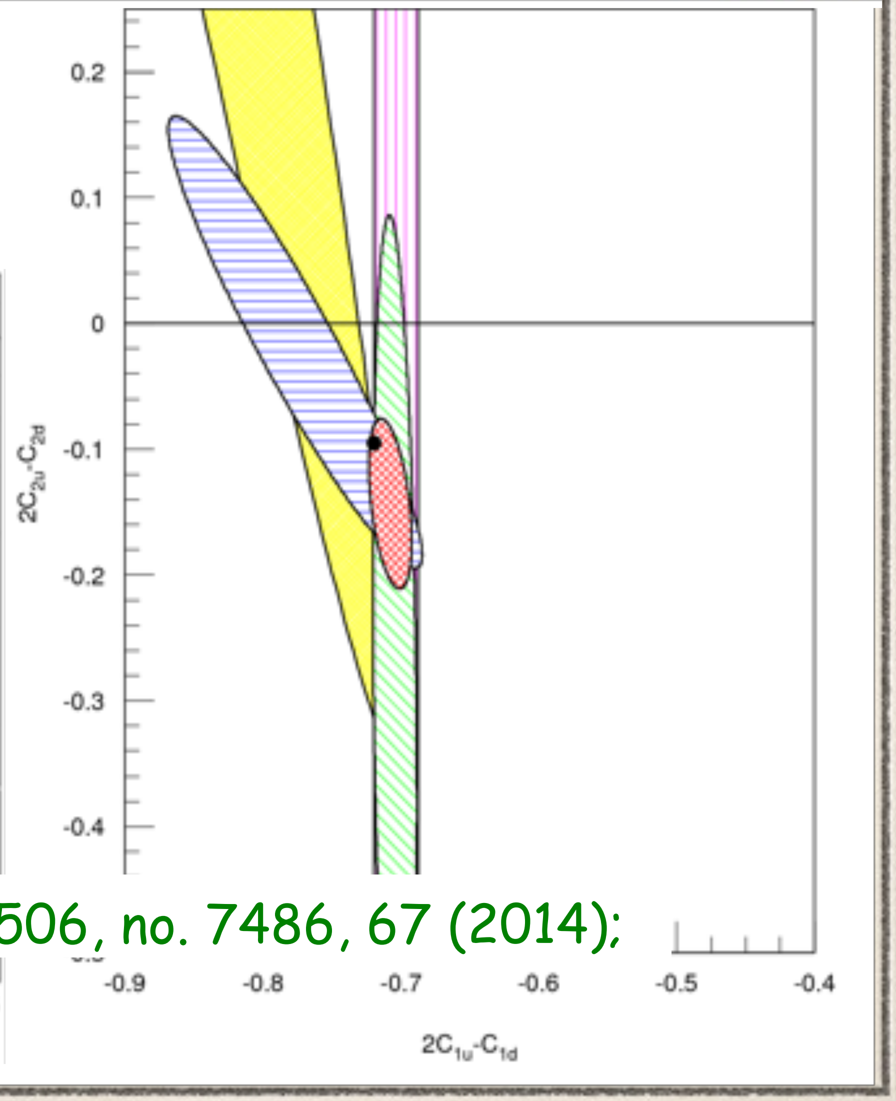




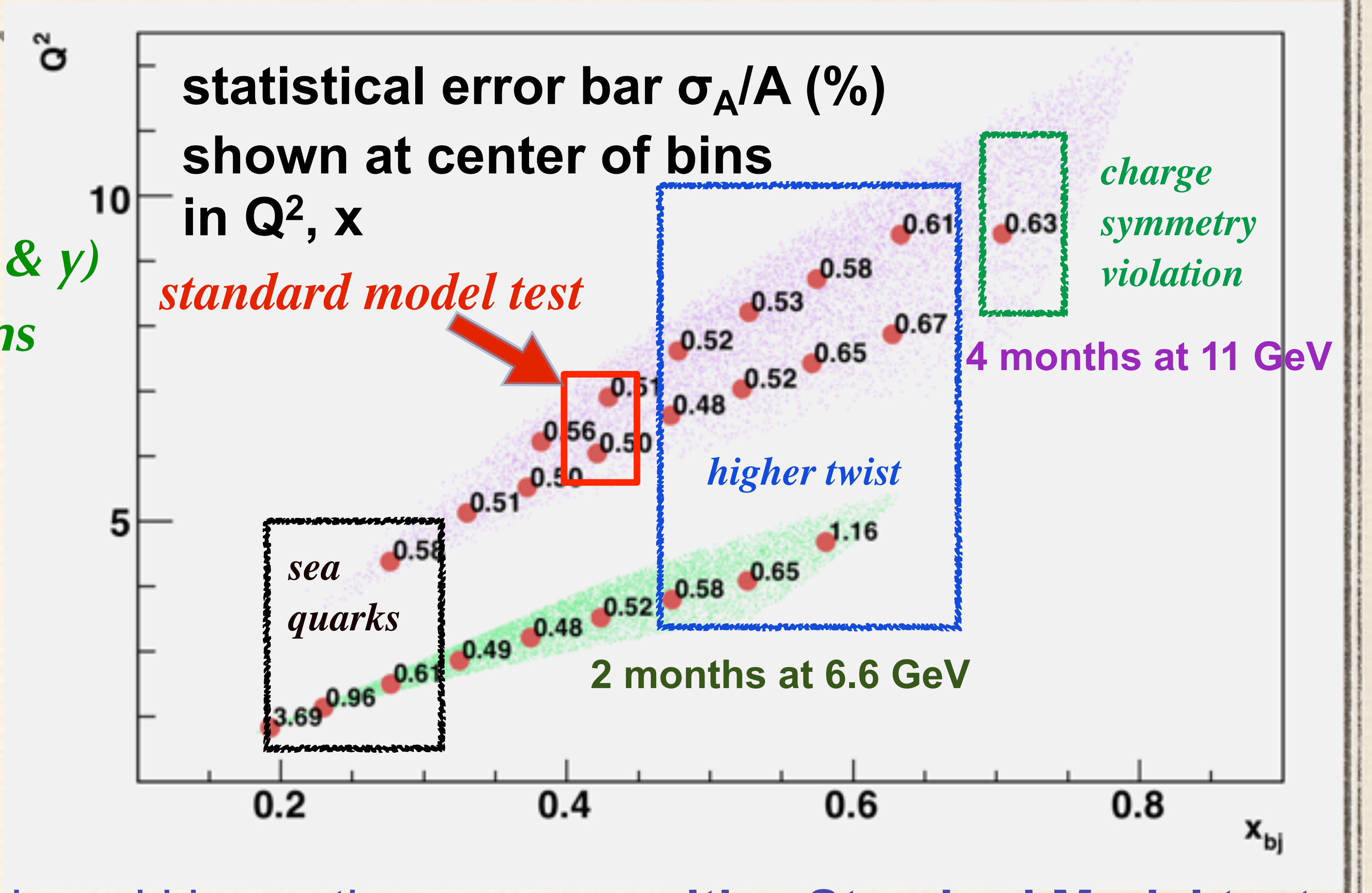
Wang et al., Nature 506, no. 7486, 67 (2014);

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***

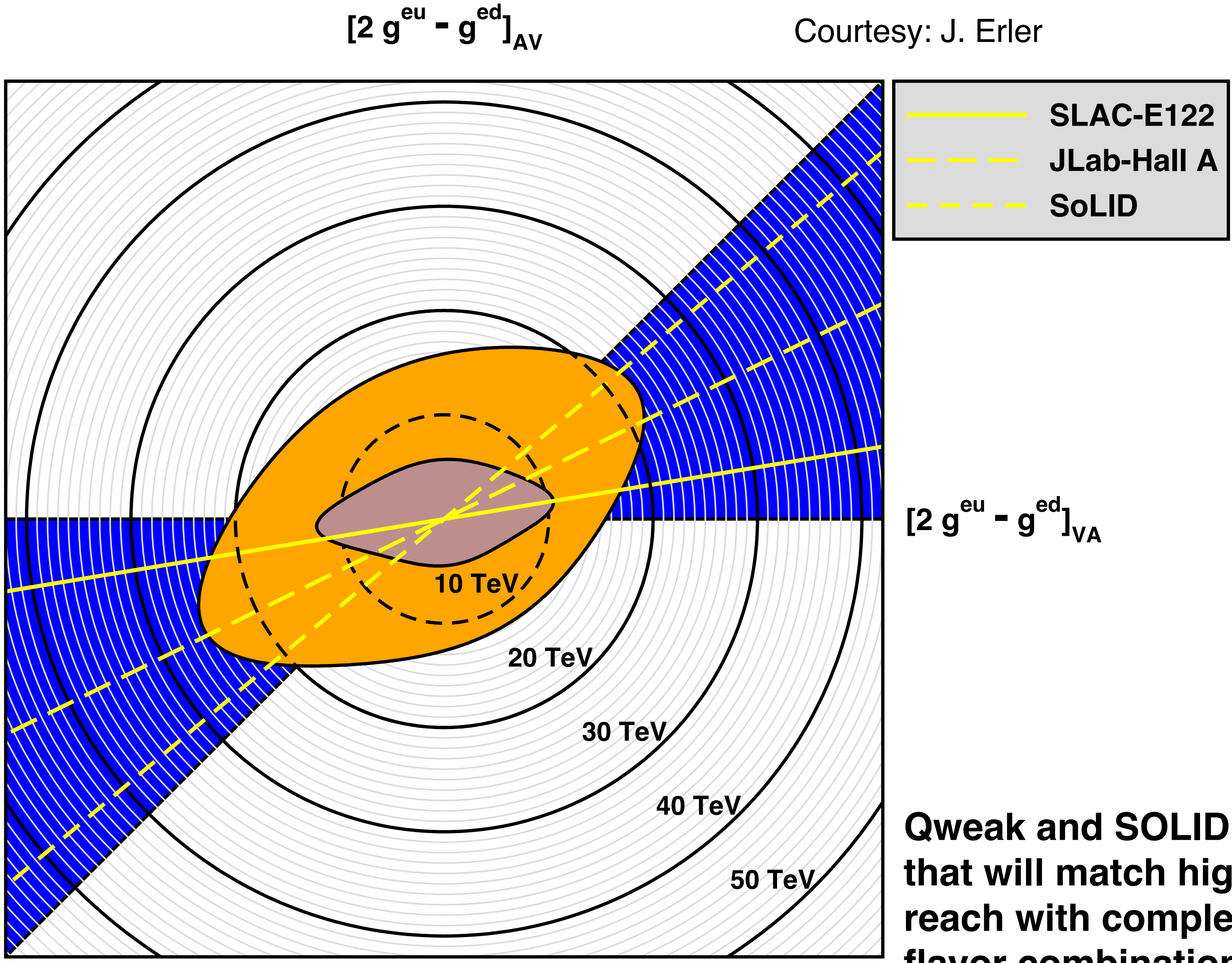


Strategy: **sub-1% precision** over broad kinematic range: **sensitive Standard Model test** *and* **detailed study of hadronic structure contributions**

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

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

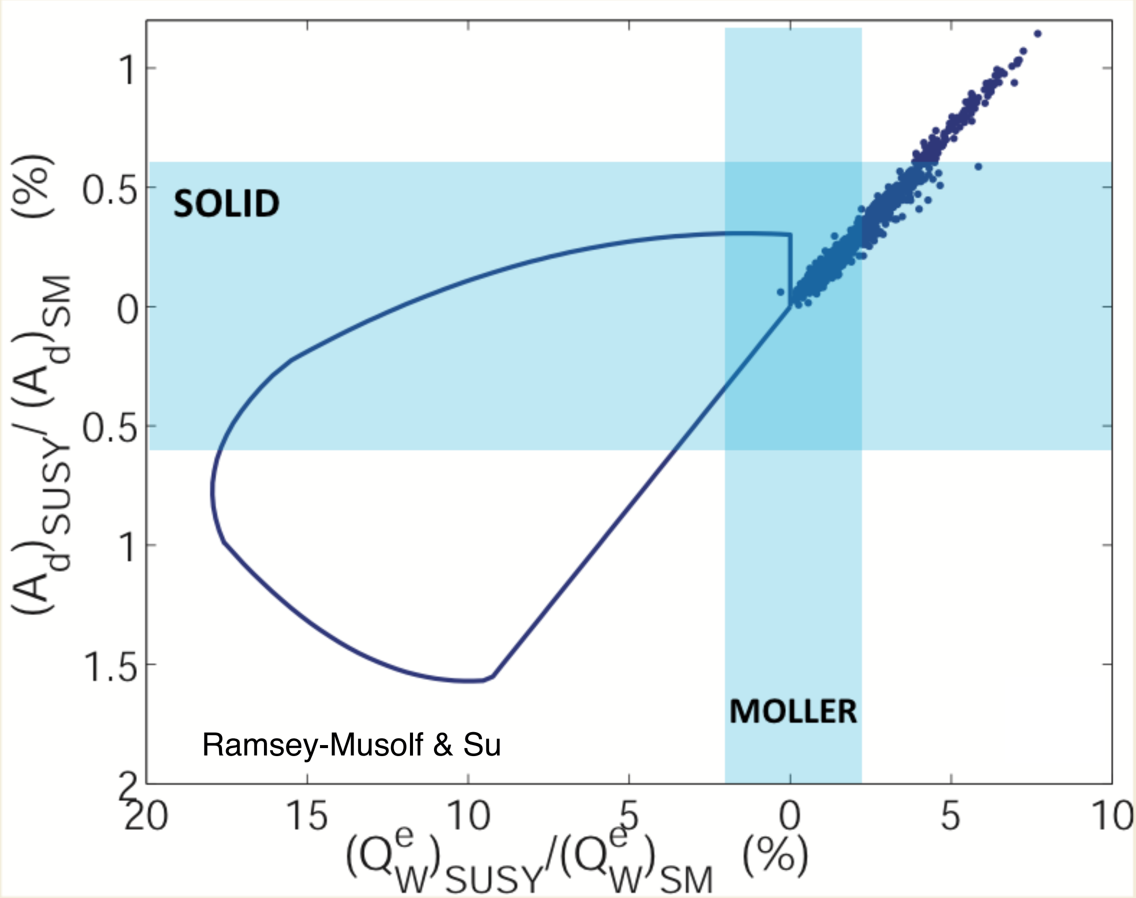
SOLID Sensitivity

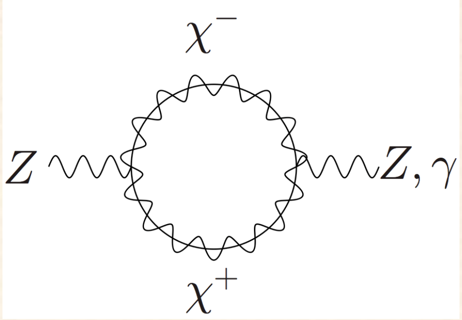


Qweak and SOLID will expand sensitivity that will match high luminosity LHC reach with complementary chiral and flavor combinations

Final Qweak result + projected SOLID

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

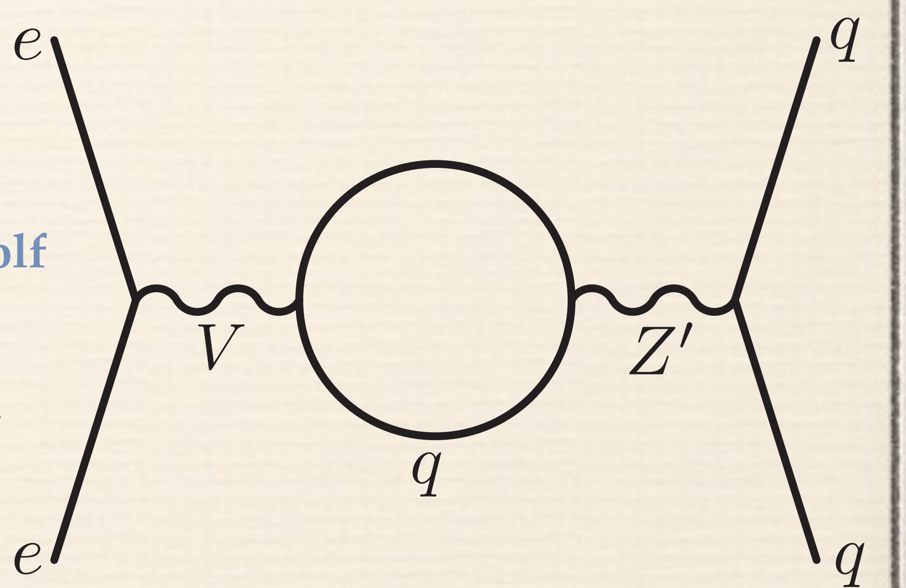
Leptophobic Z'

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***

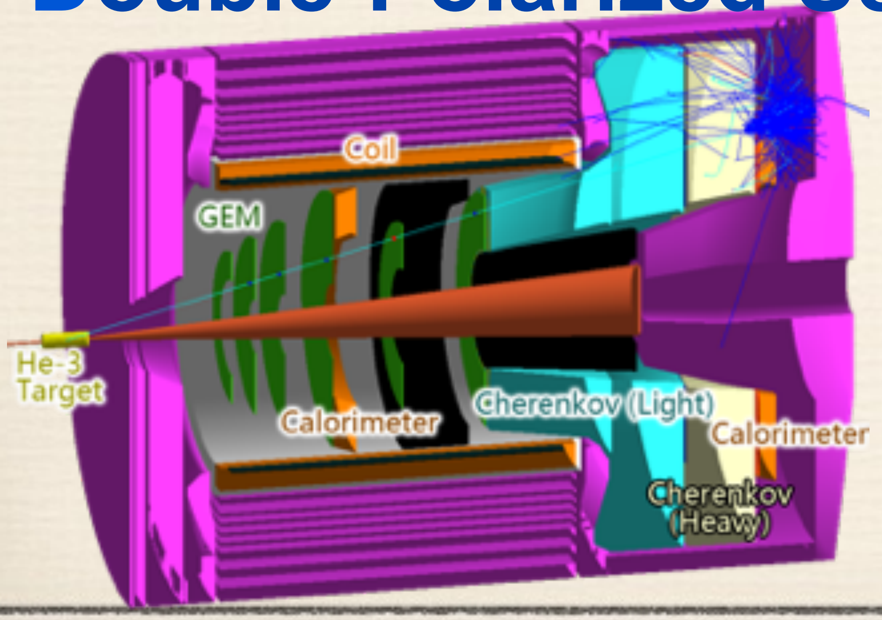


SOLID can improve sensitivity: 100-200 GeV range

Inclusive and Semi-inclusive deep inelastic scattering

Broad Program with SOLID

- ^{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 (New proposal submitted)*
    - Search for novel manifestation of isovector-dependent medium modification (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)*

Longstanding issue in proton structure

d/u at high x

PV-DIS off the proton (hydrogen target)

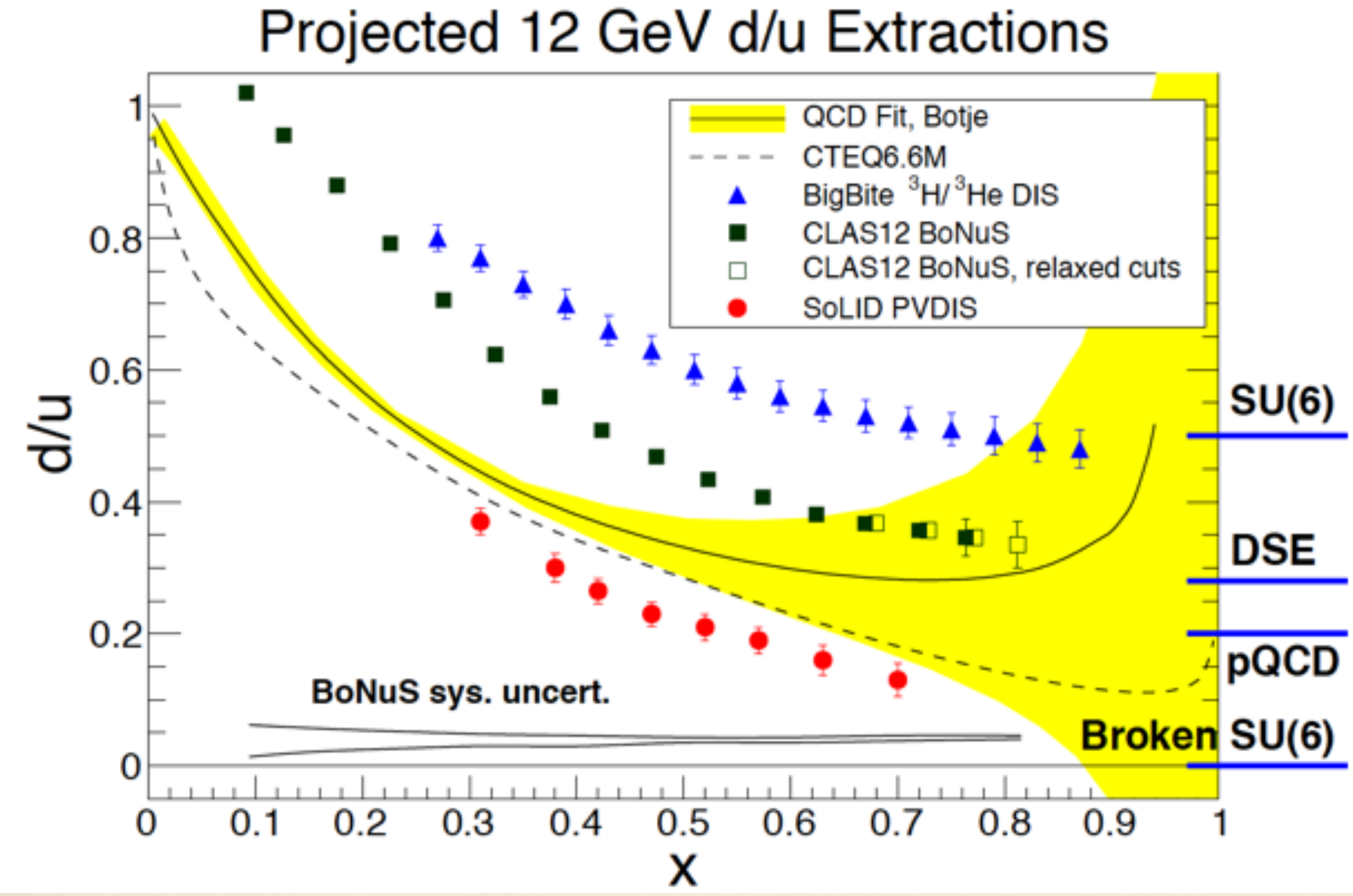
SU(6): d/u~1/2

Valence Quark: d/u~0

Perturbative QCD: d/u~1/5

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

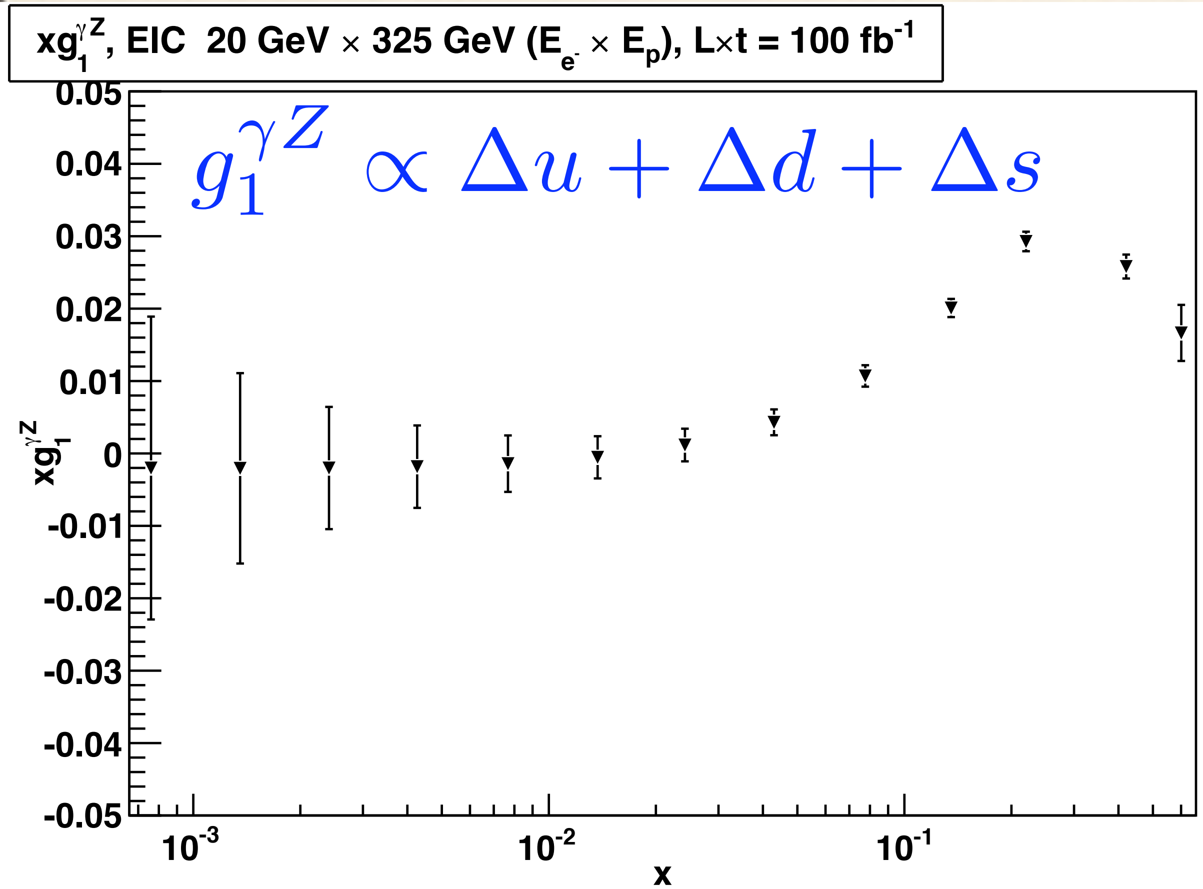
$$a^P(x) \approx \frac{u(x) + 0.91d(x)}{u(x) + 0.25d(x)}$$



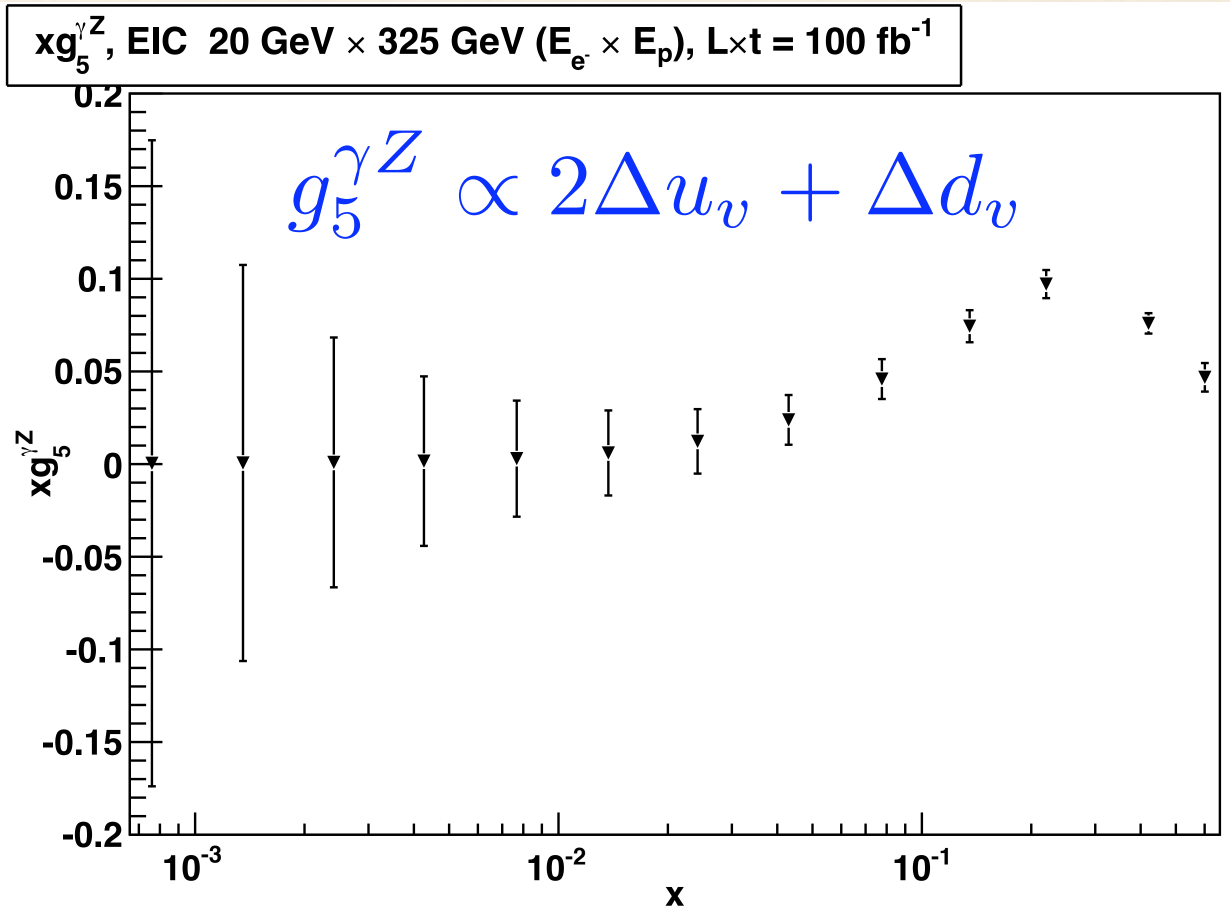
- Three JLab 12 GeV experiments:
  - CLAS12 BoNuS - spectator tagging
  - BigBite - DIS $^3\mathrm{H}/^3\mathrm{He}$ Ratio
  - SoLID - PVDIS *ep*
- The SoLID extraction of d/u is made directly from *ep* DIS: *no nuclear corrections*

Including quark and anti-quark polarizations

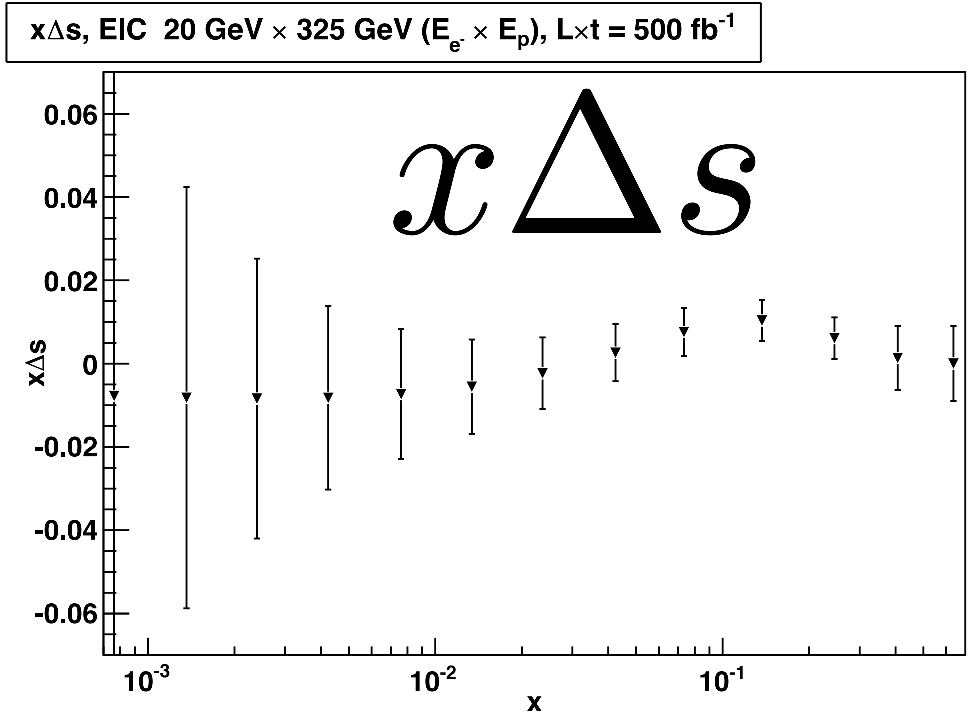
Help 6-Flavor Separation



$xg_1^{\gamma Z}$, EIC 20 GeV × 325 GeV (E_{e^-} × E_p), L×t = 100 fb^{-1}



$xg_5^{\gamma Z}$, EIC 20 GeV × 325 GeV (E_{e^-} × E_p), L×t = 100 fb^{-1}



$x\Delta s$, EIC 20 GeV × 325 GeV (E_{e^-} × E_p), L×t = 500 fb^{-1}

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