The EIC and the Global Search for New Physics at High Luminosity

SM Tests and BSM Searches
Lecture II

Krishna Kumar
University of Massachusetts, Amherst

The 2026 IITB-CFNS-CTEQ School
February 8-15, 2026

Rationale for Lecture Flow

❖ In order to identify opportunities in new machines (such as EIC), it is important to know enough about BSM initiatives worldwide so you dont waste time looking at parameter space already ruled out by others.

❖ Therefore, yesterday I provided a broad overview of the BSM landscape relevant to potential EIC opportunities.

❖ Lecture 2 will now focus on reviewing these opportunities. Most of the ideas are in the early stages of development; you all can pick up problems for further study once you get beyond your PhD and start independent research

# What we covered Yesterday

- **Overview of the 4 Classes of Measurements (my classification)**

- **Broad Context for the Experiments Pursued and the Tools**

- **A Tour of the Most Important BSM Search Strategies**

Outline of Lecture II

- **Lepton-Nucleon Deep Inelastic Electroweak Scattering**

- **Weak Neutral Current Interactions and the Weak Mixing Angle**

- **Neutral Current Structure Function Reach**

- **Tau Lepton Appearance Analysis**

- **Other Example BSM Signatures With Potential EIC Impact**

- **Summary**

Deep Inelastic Scattering

Keping Xie

Deep Inelastic Scattering: Kinematics
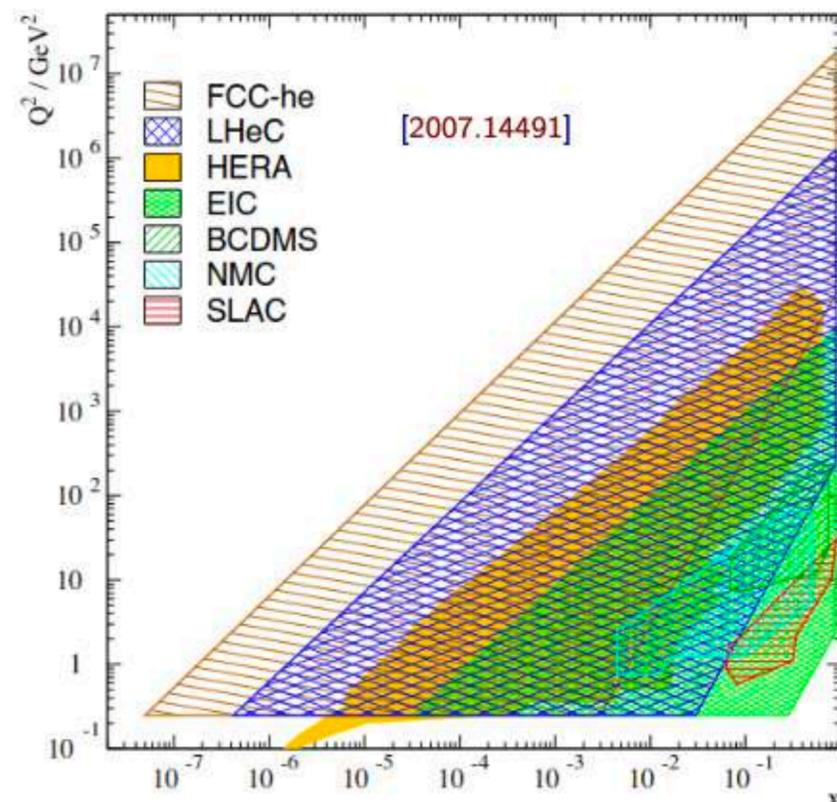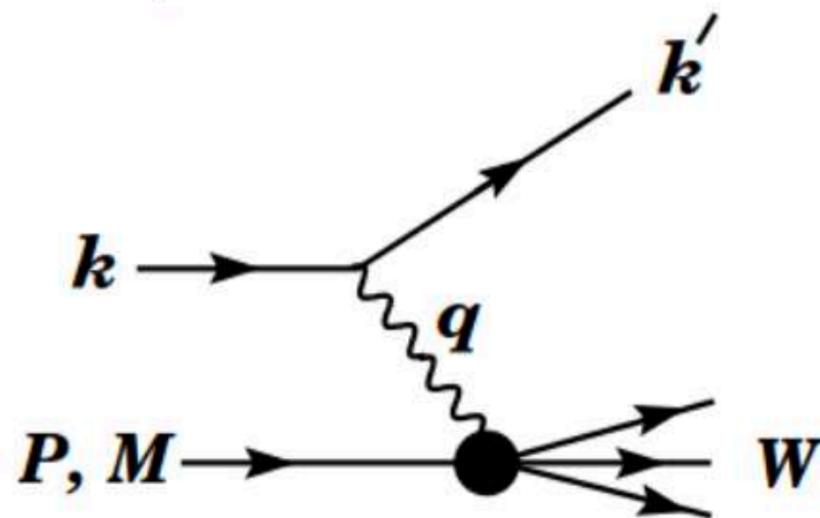
In the nucleon's rest frame

- $\nu = \frac{q \cdot P}{M} = E - E'$: lepton's energy loss
- $Q^2 = -q^2 = 2(EE' - \vec{k} \cdot \vec{k}') - m_\ell^2 - m_{\ell'}^2 \approx 2EE'(1 - \cos\theta)$: photon virtuality (momentum transfer)
- $x = \frac{Q^2}{2M\nu}$: Bjorken x, parton momentum fraction at the LO
- $y = \frac{q \cdot P}{k \cdot P} = \frac{\nu}{E} = 1 - \frac{E'}{E}$: inelasticity, lepton's energy loss fraction
- $W^2 = (P + q)^2 = M^2 + 2M\nu - Q^2$: squared mass of the X system
- $s = (k + P)^2 = \frac{Q^2}{xy} + M^2 + m_\ell^2$: center-of-mass energy square

DIS conditions:

- Deep: $Q^2 \gg M^2$
- Inelastic: $W^2 \gg M^2$ with a lower bound $(M + m_\pi)^2$

Structure Functions

Keping Xie

Schematically

$$d\sigma \sim \sum_X \left| \begin{array}{c} k' \\ k \quad q \\ P, M \quad W \end{array} \right|^2 \sim L^{\mu\nu} W_{\mu\nu}$$

- $L^{\mu\nu}$ Leptonic tensor, calculable with the electroweak interaction
- $W_{\mu\nu}$ Hadronic tensor, constrained by Lorentz invariance

Cross section

$$\frac{d^2\sigma^i}{dx\,dy} = \underbrace{\frac{4\pi\alpha^2}{xyQ^2}\,\eta^i}_{\text{Leptonic}} \underbrace{\left\{ \left(1 - y - \frac{x^2 y^2 M^2}{Q^2}\right) F_2^i + y^2 x F_1^i \mp \left(y - \frac{y^2}{2}\right) x F_3^i \right\}}_{\text{Hadronic}}$$

- Neutral Current: $\eta^{\text{NC}} = 1$ for unpolarized $e^{\pm}$,

$$F_2^{\text{NC}} = F_2^{\gamma} - (g_V^e \pm \lambda g_A^e)\,\eta_{\gamma Z}\,F_2^{\gamma Z} + \left(g_V^{e\,2} + g_A^{e\,2} \pm 2\lambda g_V^e g_A^e\right)\eta_Z\,F_2^Z$$

$$x F_3^{\text{NC}} = -(g_A^e \pm \lambda g_V^e)\,\eta_{\gamma Z}\,x F_3^{\gamma Z} + \left[2 g_V^e g_A^e \pm \lambda \left(g_V^{e\,2} + g_A^{e\,2}\right)\right]\eta_Z\,x F_3^Z$$

- Charged Current: $\eta^{\text{CC}} = (1 \pm \lambda)^2 \eta_W$

$$F_1^{\text{CC}} = F_1^W, \quad F_2^{\text{CC}} = F_2^W, \quad x F_3^{\text{CC}} = x F_3^W$$

New Structure Functions

Keping Xie

Neutral Current Couplings in S(2)XU(1): $g_V = T^3 - 2q \sin^2 \theta_W$ $g_A = T^3$

Neutral Current Cross-section: Pure photon exchange, weak-electromagnetic interference and pure Z exchange

Bjorken Scaling: In the Bjorken limit $Q^2, \nu \to \infty$, $F_i(x, Q^2) \to F_i(x)$

- Neutral Current

$$\left[F_2^\gamma, F_2^{\gamma Z}, F_2^Z\right] = x \sum_q \left[e_q^2, 2e_q g_V^q, (g_V^q)^2 + (g_A^q)^2\right](q + \bar{q}),$$

$$\left[F_3^\gamma, F_3^{\gamma Z}, F_3^Z\right] = \sum_q \left[0, 2e_q g_A^q, 2g_V^q g_A^q\right](q - \bar{q}),$$

- Charged Current
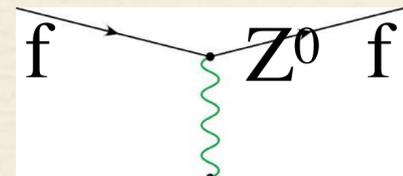
$$F_2^{W^-} = 2x\left(u + \bar{d} + \bar{s} + c\ldots\right),$$

$$F_3^{W^-} = 2\left(u - \bar{d} - \bar{s} + c\ldots\right),$$

- Callan-Gross relation: $F_2^i = 2xF_1^i$.

PV Asymmetries

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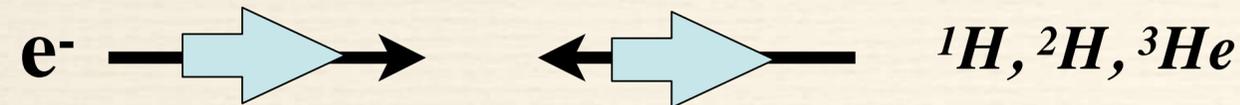
$$\frac{g}{\cos\theta_W} Z_\mu \bar{f}\gamma^\mu (T_{3f} - 2Q_f \sin^2\theta_W - T_{3f}\gamma_5)f, \quad T_{3f} = \pm 1/2$$

f $\longrightarrow$ Z^0 f

e⁻ $\longrightarrow$ $\longleftarrow$ ¹H, ²H, ³He

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

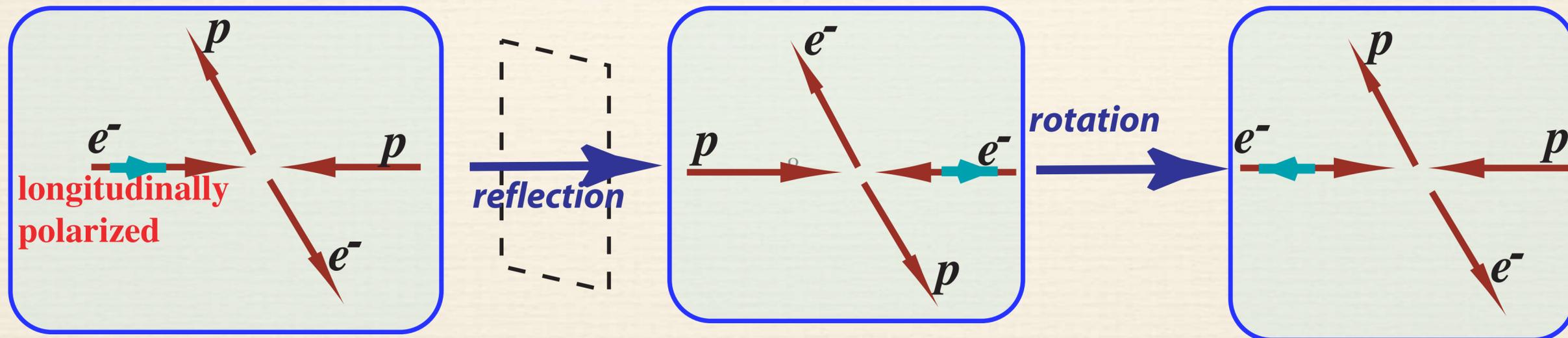$$\sim \left| A_{EM} \right|^2 + \boxed{2A_{EM}A^*_{weak}} + \ldots$$

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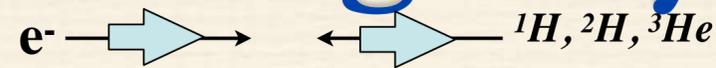
$$A_{PV} = \frac{\sigma_\uparrow - \sigma_\downarrow}{\sigma_\uparrow + \sigma_\downarrow} = -A_{LR}$$

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

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

p

e⁻

longitudinally
polarized

e⁻

reflection

e⁻

p

rotation

p

e⁻

e⁻

p

Parity-Violating Asymmetries

e⁻ → → ← **¹H, ²H, ³He**

polarized electron, *unpolarized* hadron

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

EIC neutral current event kinematics very clean: can very cleanly separate y-independent and y-dependent pieces and study Q² evolution

unpolarized electron, *polarized* hadron

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

proton

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

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

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

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

deuteron

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

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

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

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

• Electron Asymmetries are sensitive to the weak mixing angle

- *Deuteron is very clean but need a large data set going to be even part of the program*
- *Must control pdf uncertainties well enough to use proton events (the main data sample at EIC)*
- *Studies are required to use both low Q² (well-understood) and high Q²*
- *Over the next few years, QED and QCD radiative corrections will require a careful look*

• Hadron Asymmetries

- *Access to entirely new set of structure functions*
- *Can contribute to flavor separation of polarized pdfs*

Electron Asymmetry A$_{PV}$

Y. Zhao (SBU)

A. Deshpande (SBU)
J. Huang (BNL)
K. Kumar (UMass)
S. Riordan (SBU)

polarized electron; unpolarized proton

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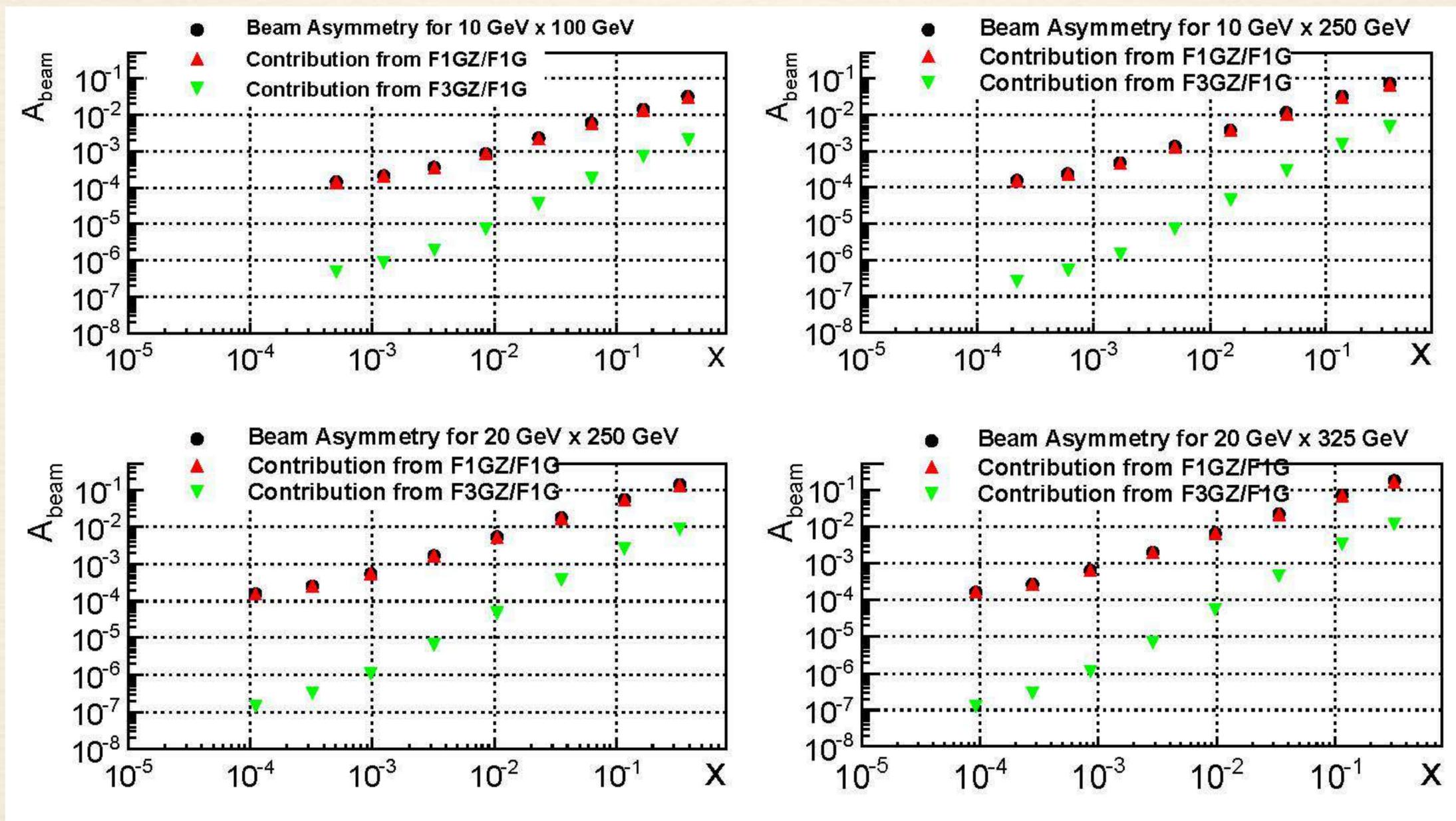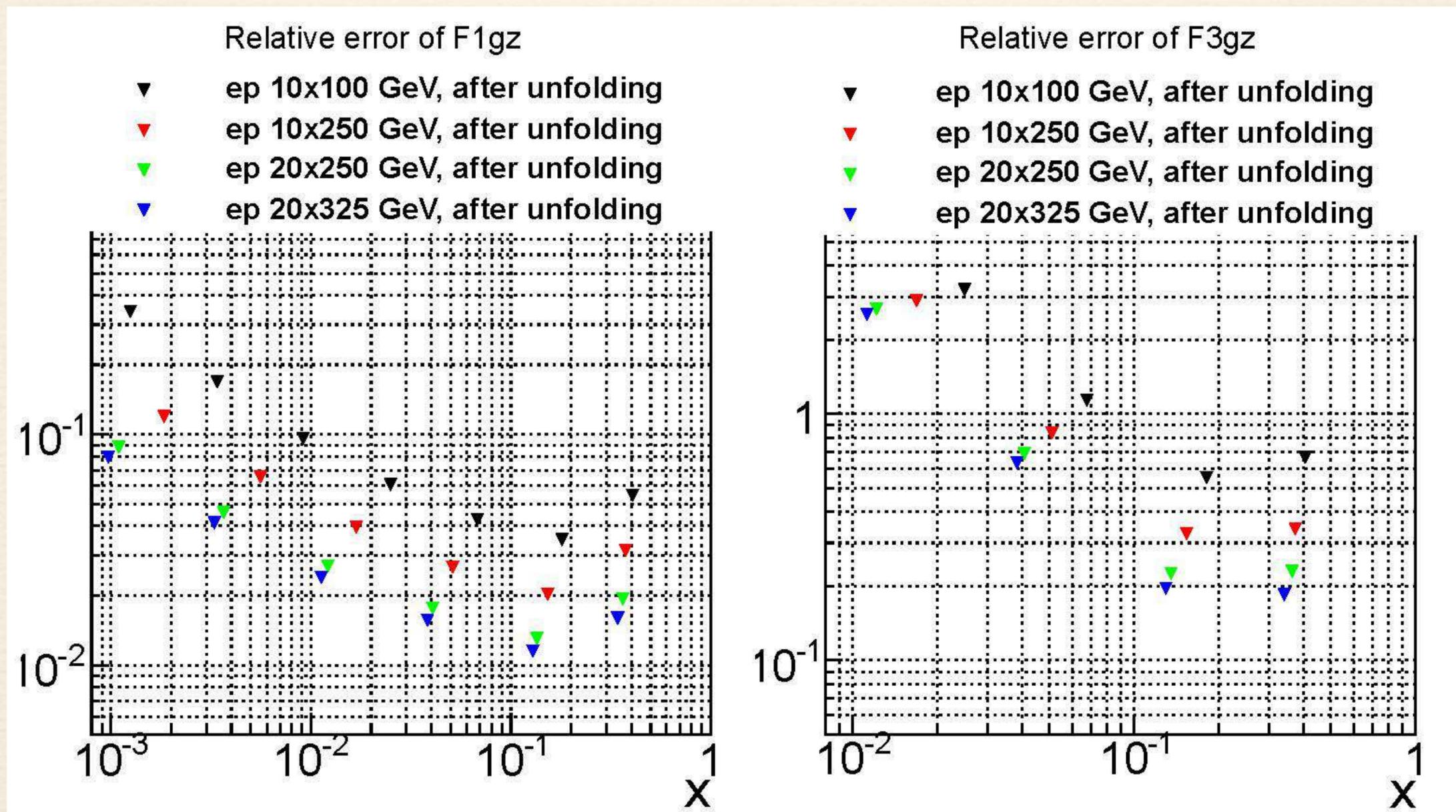
A_{PV} Fractional Error

100 fb^{-1}

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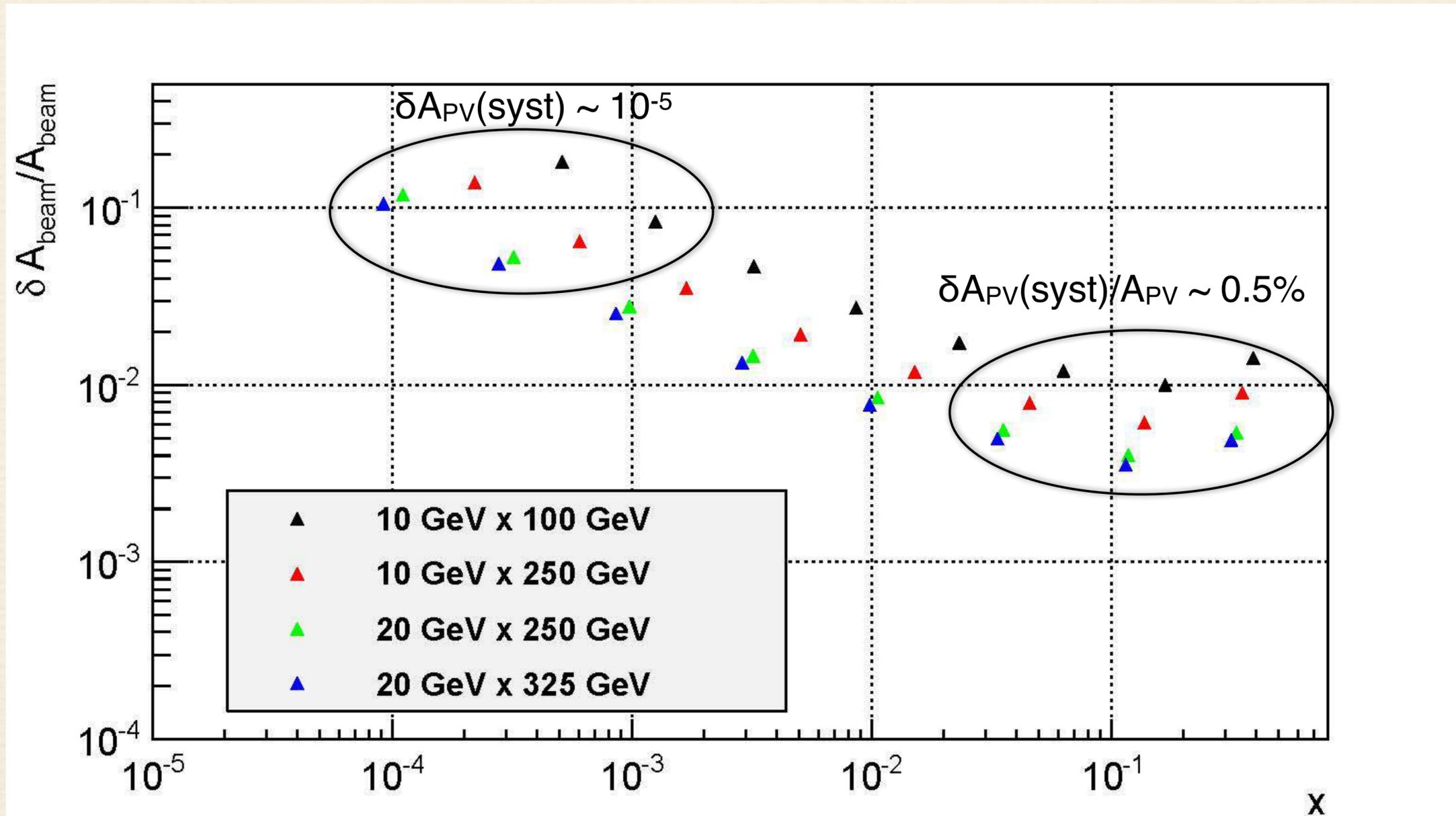
Fraction Statistical Errors on Structure Functions

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

Detour: QED Radiative Corrections

- *Feynman rules with electric charge*
- *Calculate $\sigma_1(e)$ for a test process*
- *Measure $\sigma_1(e)$ and extract e*
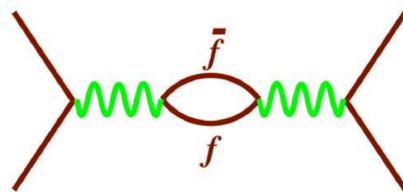- *Calculate $\sigma_2(e)$ for another process*

Not all Quantum Field Theories behave this way:

The ones that do are renormalizable theories

Electroweak theory: t'Hooft and Veltman
QCD: Gross, Politzer and Wilzcek

Fine structure constant: 1/137 at low energy, 1/128 at Z pole

total charge enclosed is less than q

dielectric

test charge q
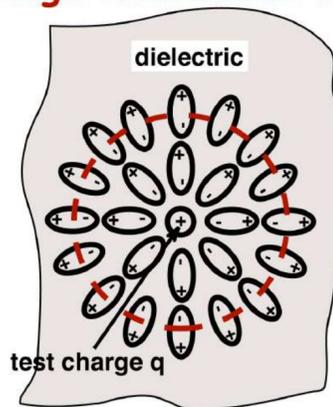
total charge depends on relative distance

effective charge increases with decreasing distance:

higher order terms in perturbative expansion

The shift $\Delta\alpha$ can be determined analytically for lepton loops and by a dispersion integral over the e+e- annihilation cross section for light quarks (u,d,s,c,b)
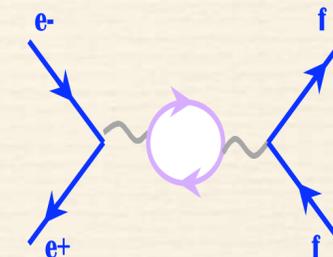
$\alpha(m^2_Z) = \alpha/(1-\Delta\alpha)$

Optical theorem

$$\Delta\alpha_{lepton} = \sum_{l=e,\mu,\tau} \frac{\alpha}{3\pi}\left(\log\frac{m_Z^2}{m_l^2} - \frac{5}{3}\right) + \dots$$
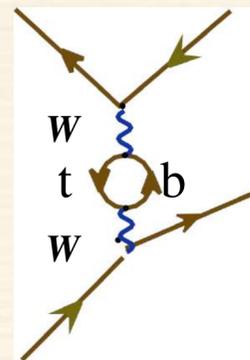
$$\Delta\alpha_{hadron} = -\frac{\alpha}{3\pi}\int_{4m_\pi^2}^{\infty} \frac{m_Z^2 ds}{s\left[s-m_Z^2\right]} \frac{\sigma(e^+e^- \to q\bar{q})}{\sigma(e^+e^- \to \mu^+\mu^-)}$$
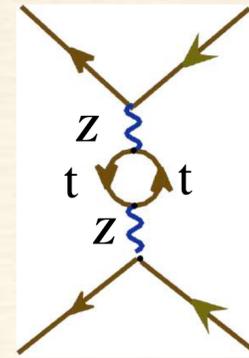
Segway to Precision Electroweak Physics

For electroweak interactions, 3 input parameters needed:

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

Muon decay   *Z production*

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

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

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

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

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

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

Important note for experimentalists: do not worry too much about the exact definition of $\sin^2\theta_W$. When designing experiments, all that matters is the projected uncertainty; the actual value does not matter. When the experiment is fully designed, then work with theorists to extract $\sin^2\theta_W(\mu)_{\overline{MS}}$ and properly account for radiative corrections.

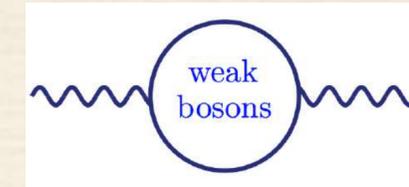# Best Weak Mixing Angle Measurements
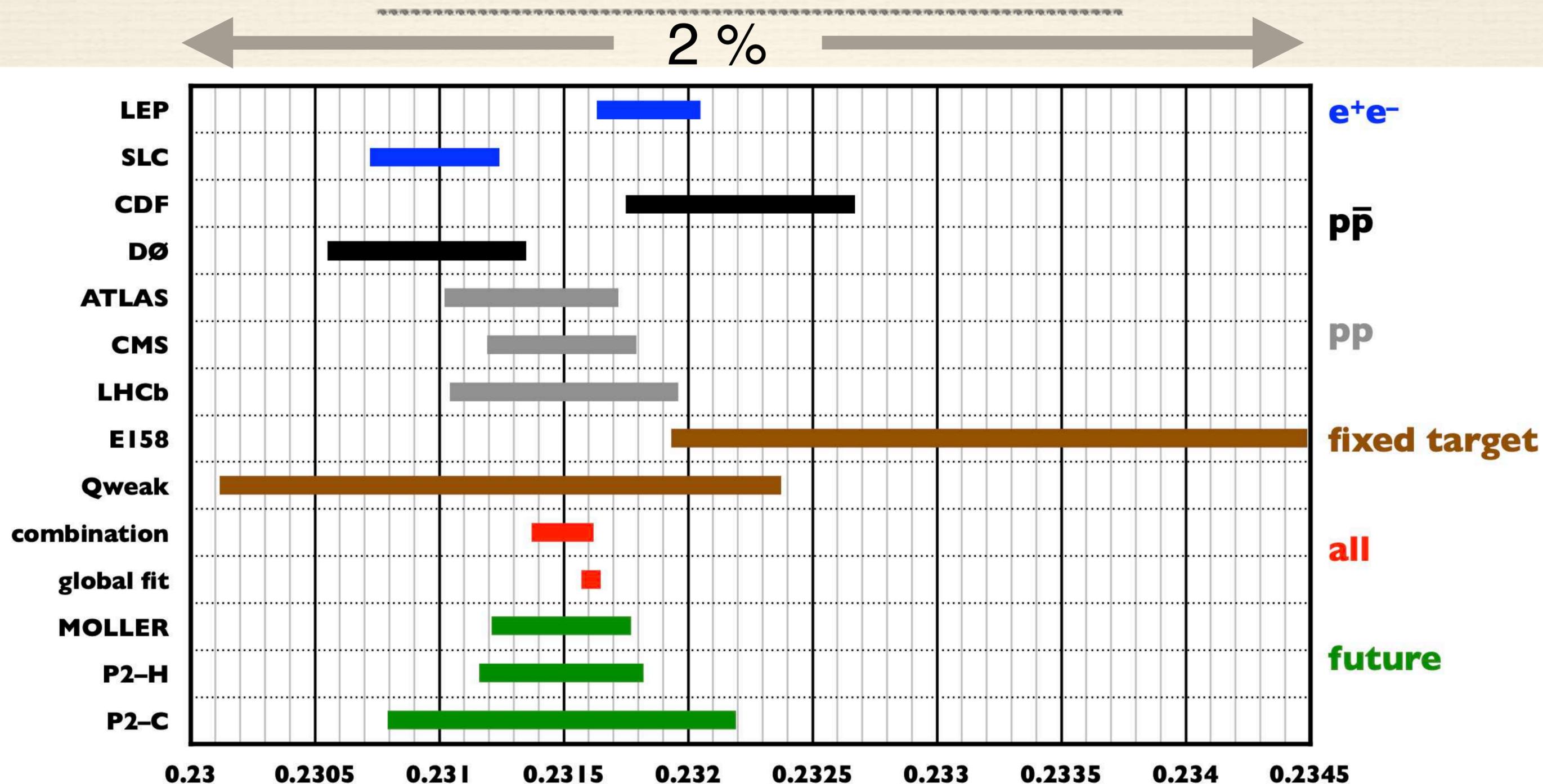
Heroic efforts of phenomenologists and experimentalists!
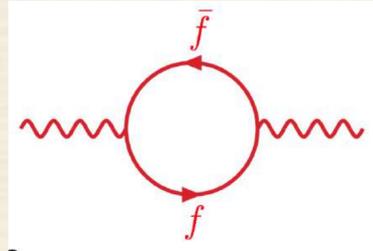
Precision Relations

The Electroweak Theory and Measurements at 1-Loop

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

$$(\Delta r)^{\text{expt}} = 1 - \left[\pi\alpha/\{\sqrt{2}G_F m_W^2(1 - m_W^2/m_Z^2)\}\right] = 0.0355(7)$$

$$(\Delta r)^{\text{SM}} = 0.0366(3) + 3.4 \times 10^{-3}\ln\left[m_H/126\text{ GeV}\right]$$

m$_t$, α$_s$ uncertainty

theory $\quad m_W = 80.360(6)$ GeV

expt. $\quad m_W = 80.377(12)$ GeV

PDG 2022

$$(\Delta\hat{r})^{\text{expt}} = 1 - \left[2\sqrt{2}\pi\alpha/\{G_F m_Z^2 \sin^2 2\theta_W(m_Z)_{\overline{\text{MS}}}\}\right] = 0.0595(4)$$

$$(\Delta\hat{r})^{\text{SM}} = 0.0597(1) + 1.4 \times 10^{-3}\ln\left[m_H/126\text{ GeV}\right]$$

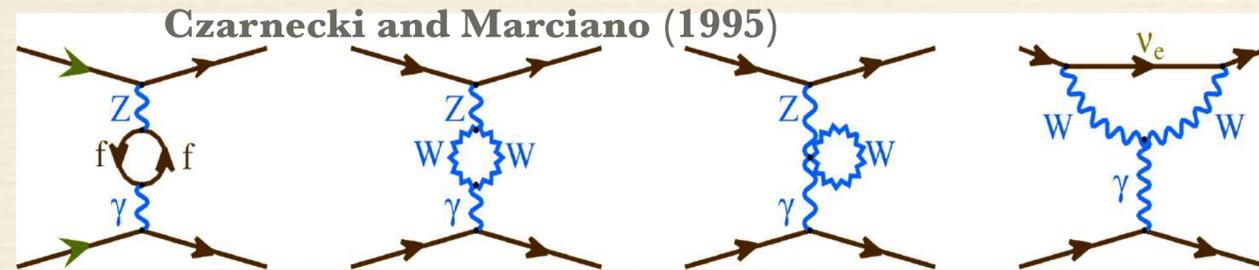theory $\quad \sin^2\theta_W(m_Z)_{\overline{\text{MS}}} = 0.23122(4)$

expt. $\quad \sin^2\theta_W(m_Z)_{\overline{\text{MS}}} = 0.23116(13)$

$$(\Delta r_{\overline{\text{MS}}})^{\text{expt}} = 1 - \left[\pi\alpha/\{\sqrt{2}G_F m_W^2 \sin^2\theta_W(m_Z)_{\overline{\text{MS}}}\}\right] = 0.0694(3)(5)$$

$$(\Delta r_{\overline{\text{MS}}})^{\text{SM}} = 0.0692(1) + 6.5 \times 10^{-4}\ln\left[m_H/126\text{ GeV}\right]$$

$$m_H = 91^{+18}_{-16}\text{ GeV}$$

The Running of the Weak Mixing Angle

Czarnecki and Marciano (1995)

Annu. Rev. Nucl. Part. Sci. 2013. 63:237–67

The *Annual Review of Nuclear and Particle Science* is online at nucl.annualreviews.org

This article's doi:
10.1146/annurev-nucl-102212-170556

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Low-Energy Measurements of the Weak Mixing Angle

K.S. Kumar,[1] Sonny Mantry,[2] W.J. Marciano,[3] and P.A. Souder[4]

[1]Department of Physics, University of Massachusetts, Amherst, Massachusetts 01003; email: kkumar@physics.umass.edu

[2]Argonne National Laboratory and Department of Physics and Astronomy, Northwestern University, Evanston, Illinois 60208

[3]Physics Department, Brookhaven National Laboratory, Upton, New York 11973

[4]Physics Department, Syracuse University, Syracuse, New York 13244

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

1-loop calculation
Czarnecki and Marciano
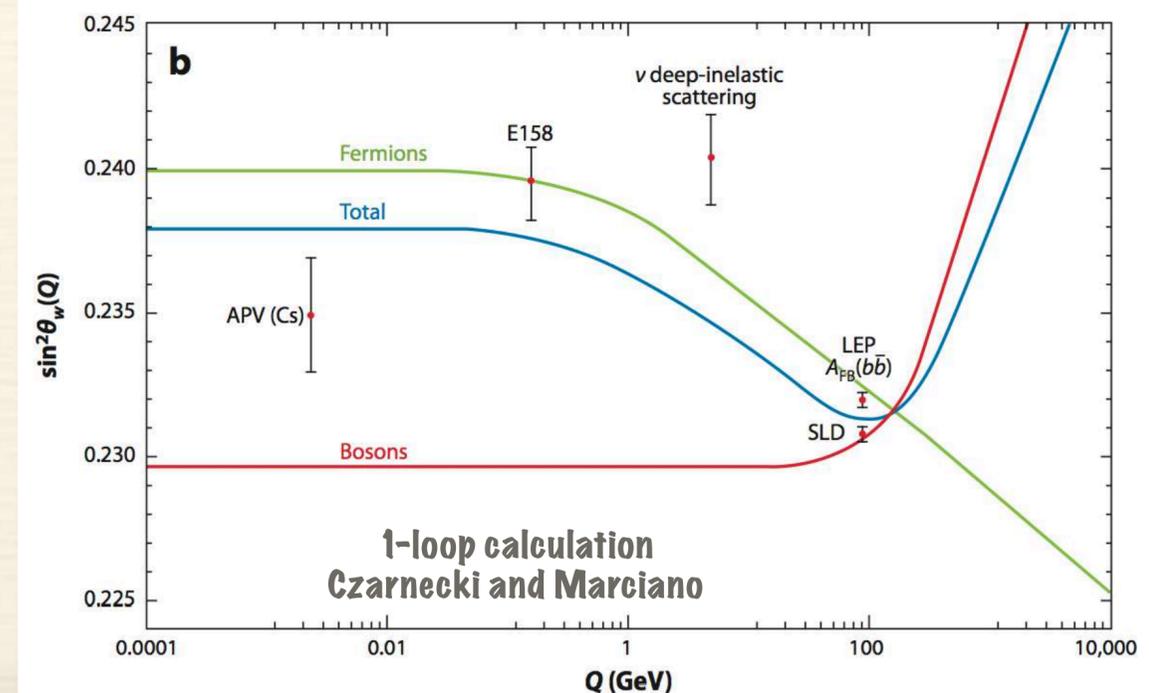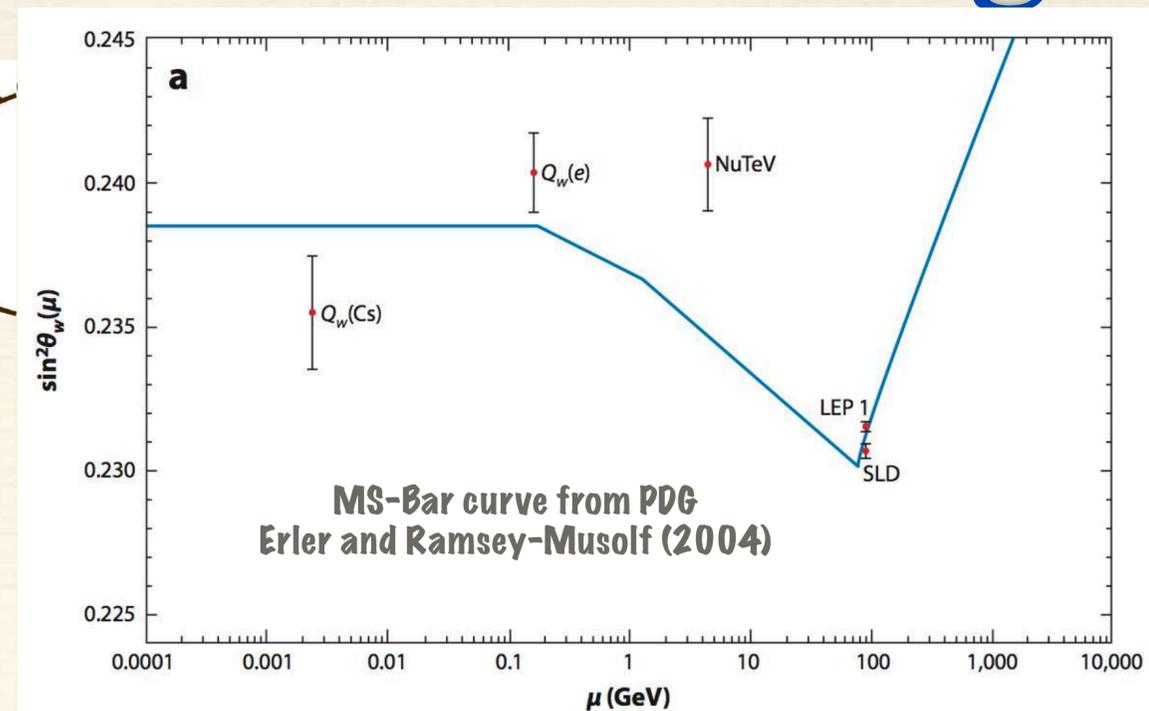
Status of Low Energy Measurements

The focus in on searches for new flavor conserving neutral current interactions


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

◆ **Atomic Parity Violation: Cs-133**
  ✦ future measurements challenging, theory improving

◆ **Neutrino Scattering: NuTeV**
  ✦ future measurements and theory challenging

◆ **PV Møller Scattering: E158 at SLAC**
  ✦ statistics limited, theory robust
  ✦ next generation: MOLLER (factor of 5 better)

◆ **PV elastic e-p scattering: Qweak**
  ✦ theory robust at low beam energy
  ✦ next generation: P2 (factor of 3 better)

◆ **PV Deep Inelastic Scattering: PVDIS**
  ✦ theory robust for ^{2}H in valence quark region
  ✦ factor of 5 improvement: SOLID

Erler and Ramsey-Musolf (2004)
Erler and Ferro-Hernandez (2018)
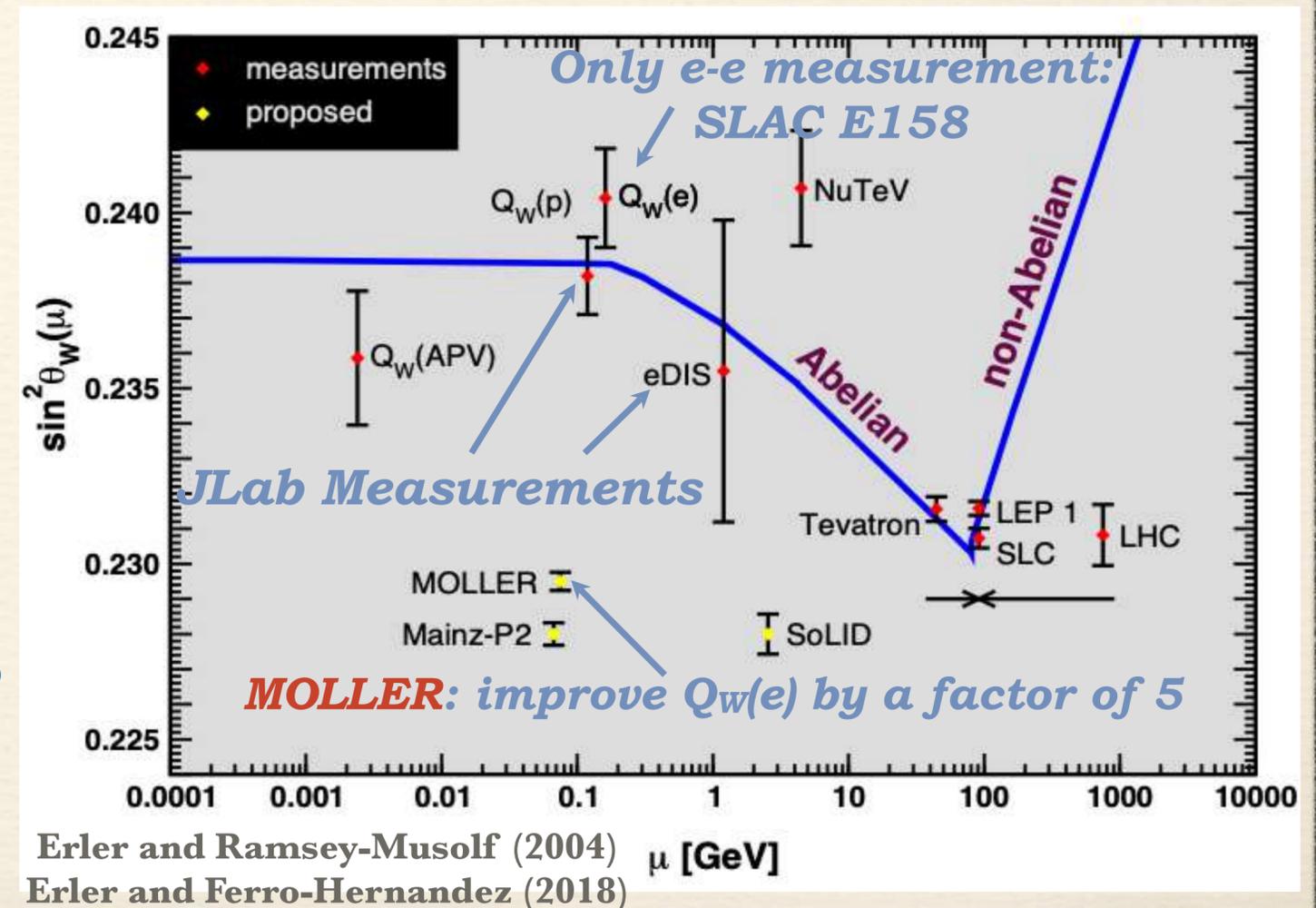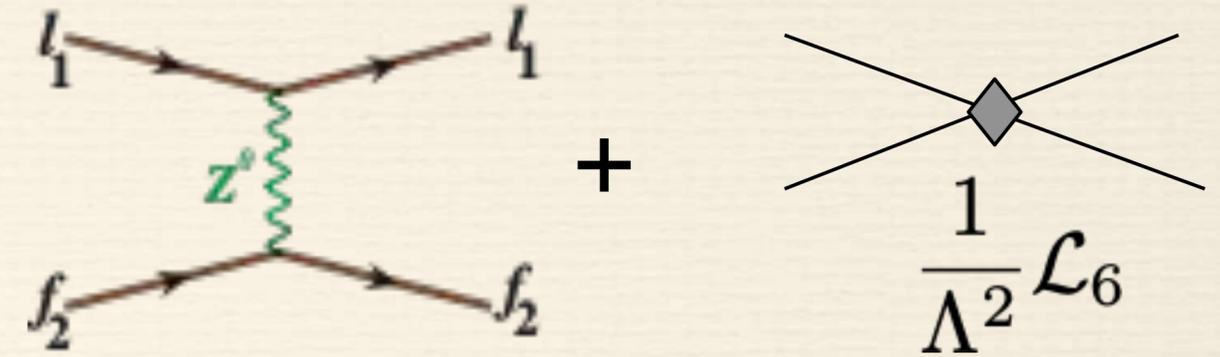
e-D: Weak Mixing Angle

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

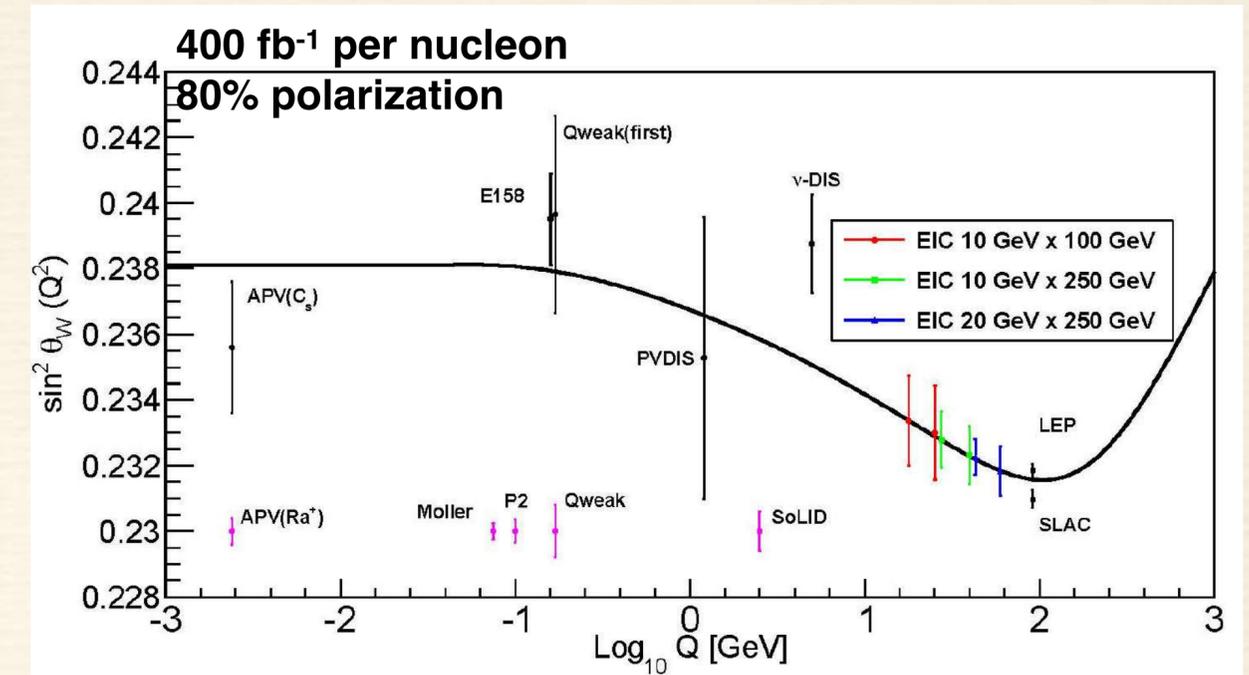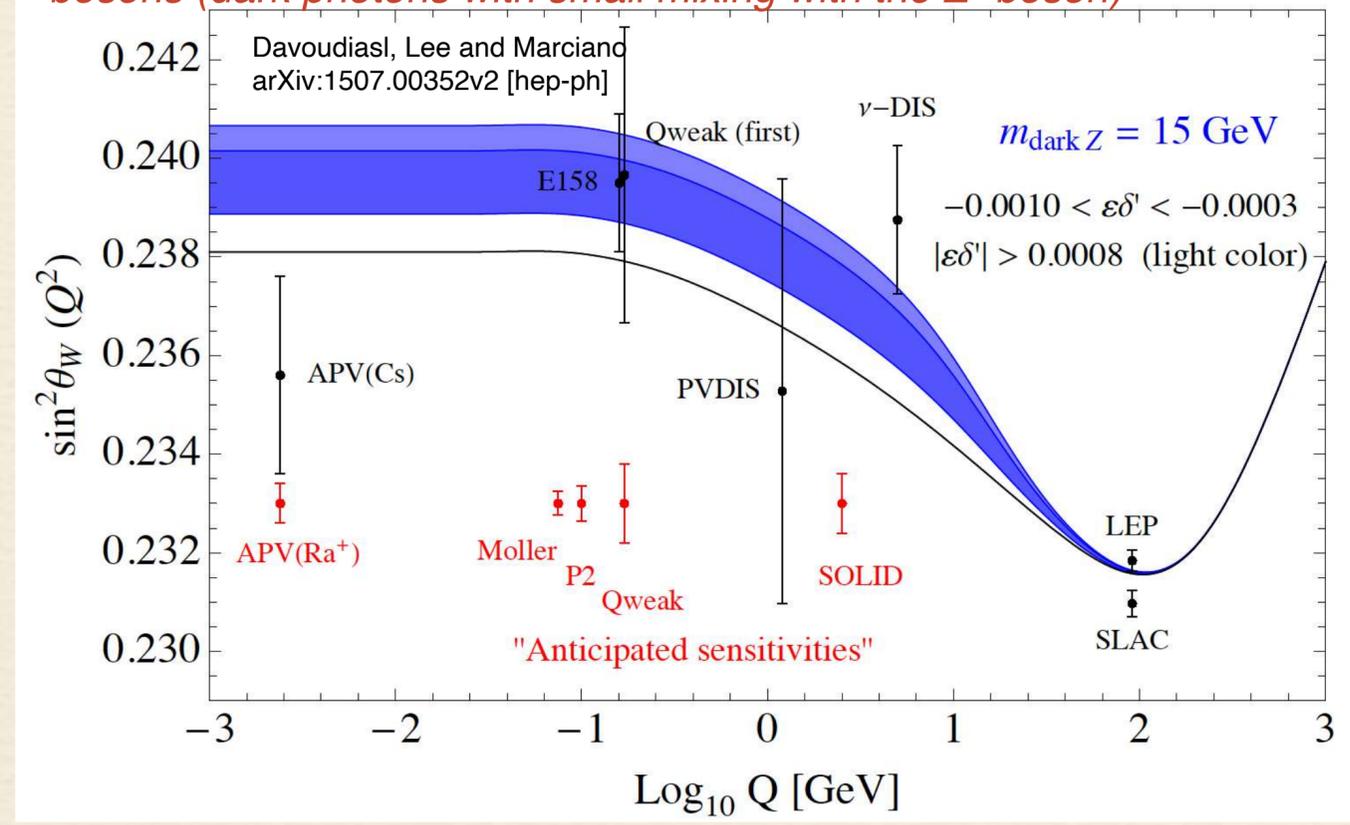**for a deuteron, structure functions cancel: assuming charge symmetry and neglecting strange quarks**

100 fb⁻¹ per nucleon
80% electron polarization
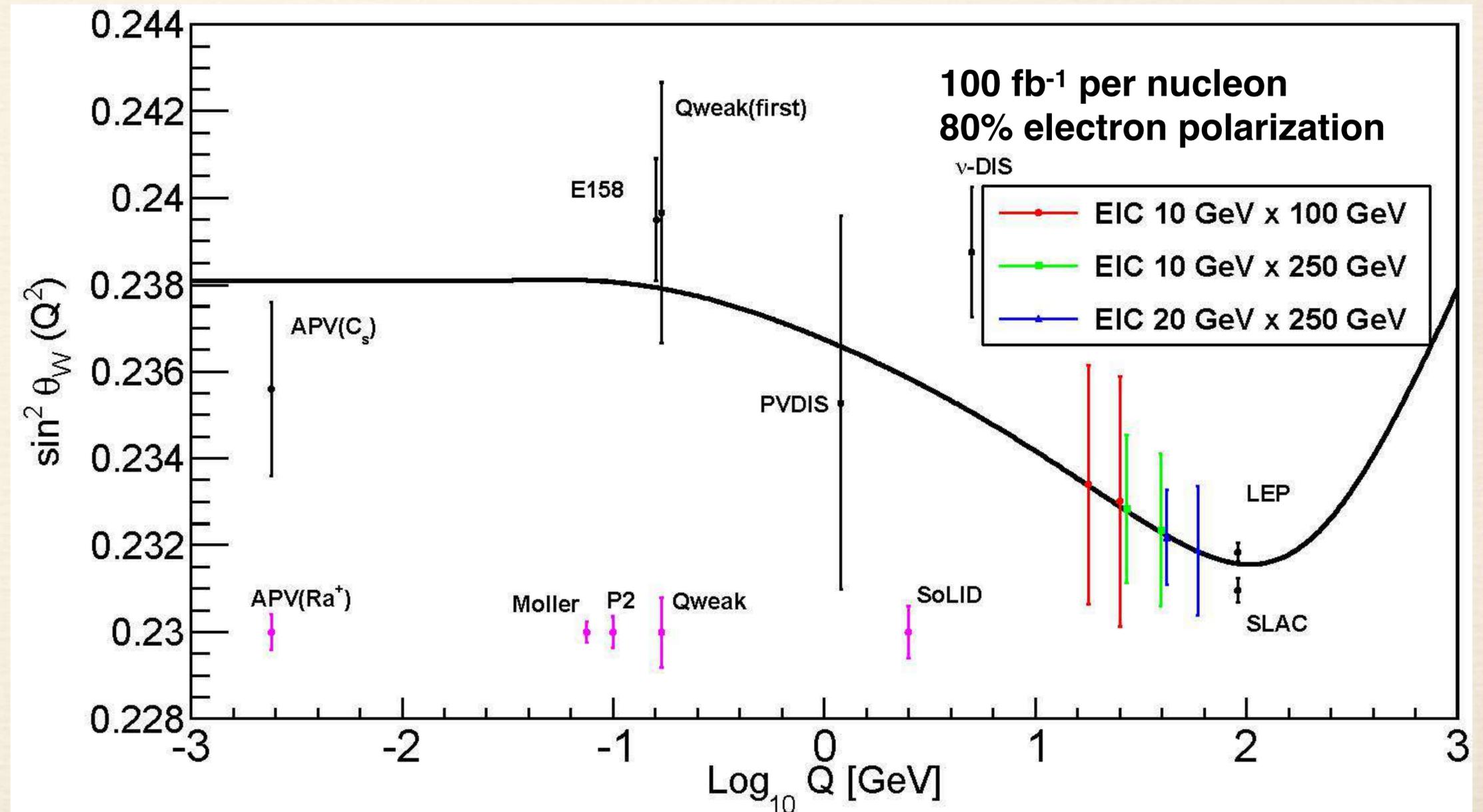
Implications of EIC Measurements

What will be the electroweak landscape in 2035?

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)


Davoudiasl, Lee and Marciano
arXiv:1507.00352v2 [hep-ph]

$m_{dark\,Z} = 15$ GeV

$-0.0010 < \varepsilon\delta' < -0.0003$
$|\varepsilon\delta'| > 0.0008$ (light color)

ν–DIS
Qweak (first)
E158
APV(Cs)
PVDIS
APV(Ra$^+$)
Moller
P2
Qweak
SOLID
LEP
SLAC
"Anticipated sensitivities"

400 fb^{-1} per nucleon
80% polarization

Qweak(first)
ν-DIS
E158
EIC 10 GeV x 100 GeV
EIC 10 GeV x 250 GeV
EIC 20 GeV x 250 GeV
APV(C$_s$)
PVDIS
LEP
APV(Ra$^+$)
Moller
P2
Qweak
SoLID
SLAC

- **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 $\sin^2\theta_W$?**
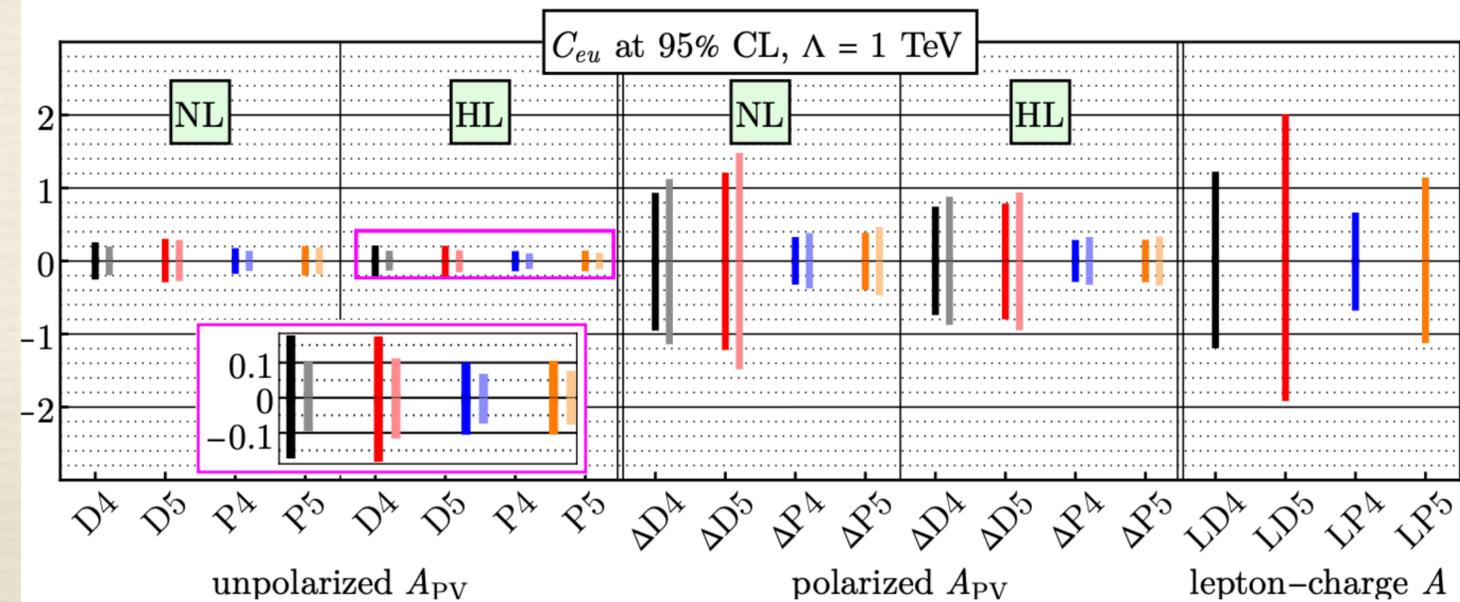
SMEFT Analysis of EIC NC DIS

$$\frac{C}{\Lambda^2}$$
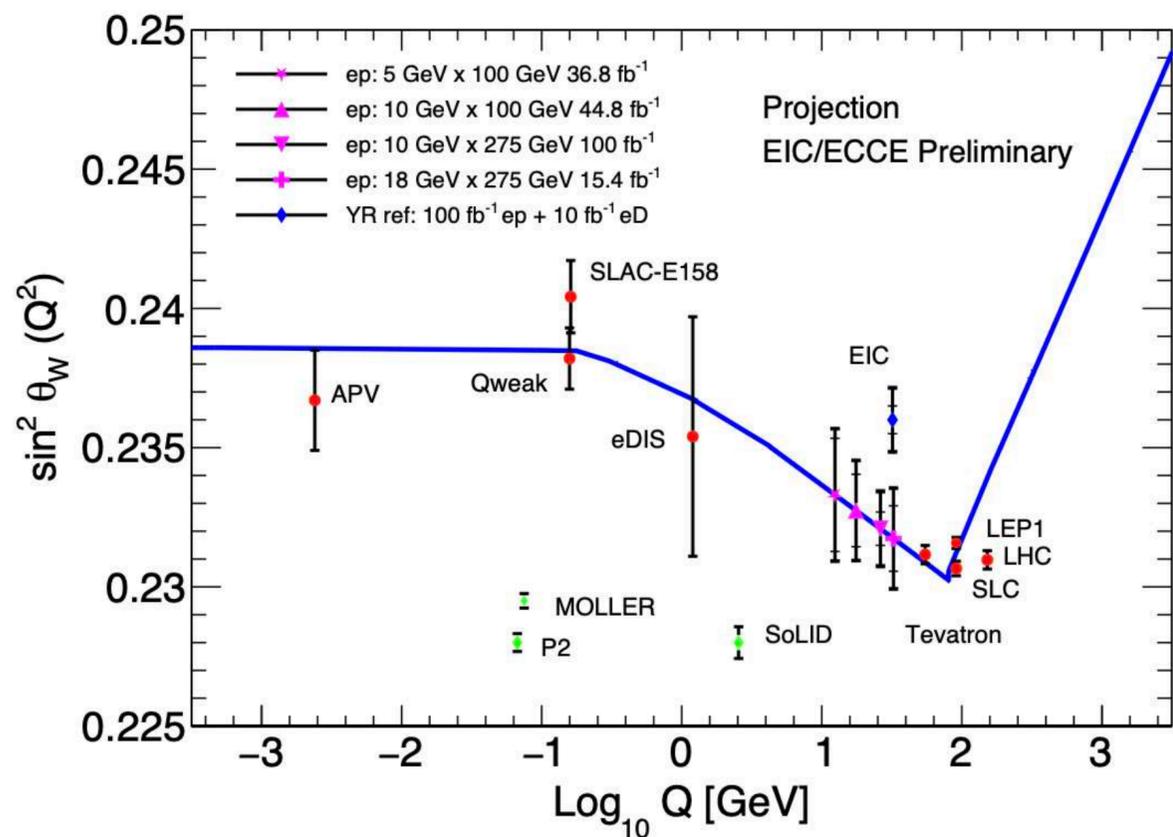
10 GeV $\times$137 GeV eD 100 fb^{-1}: D4, ΔD4, LD4 ,
18 GeV $\times$137 GeV eD 15.4 fb^{-1}: D5, ΔD5, LD5 ,
10 GeV $\times$275 GeV ep 100 fb^{-1}: P4, ΔP4, LP4 ,
18 GeV $\times$275 GeV ep 15.4 fb^{-1}: P5, ΔP5, LP5 .
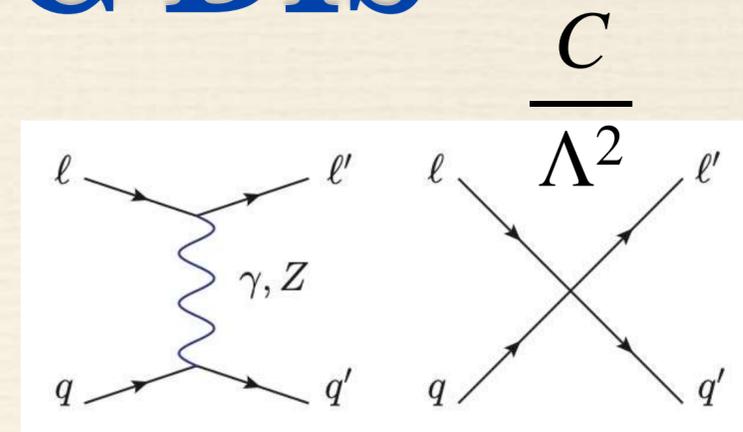
- They find that proton asymmetries are more sensitive
- The can overcome pdf uncertainties via global fits
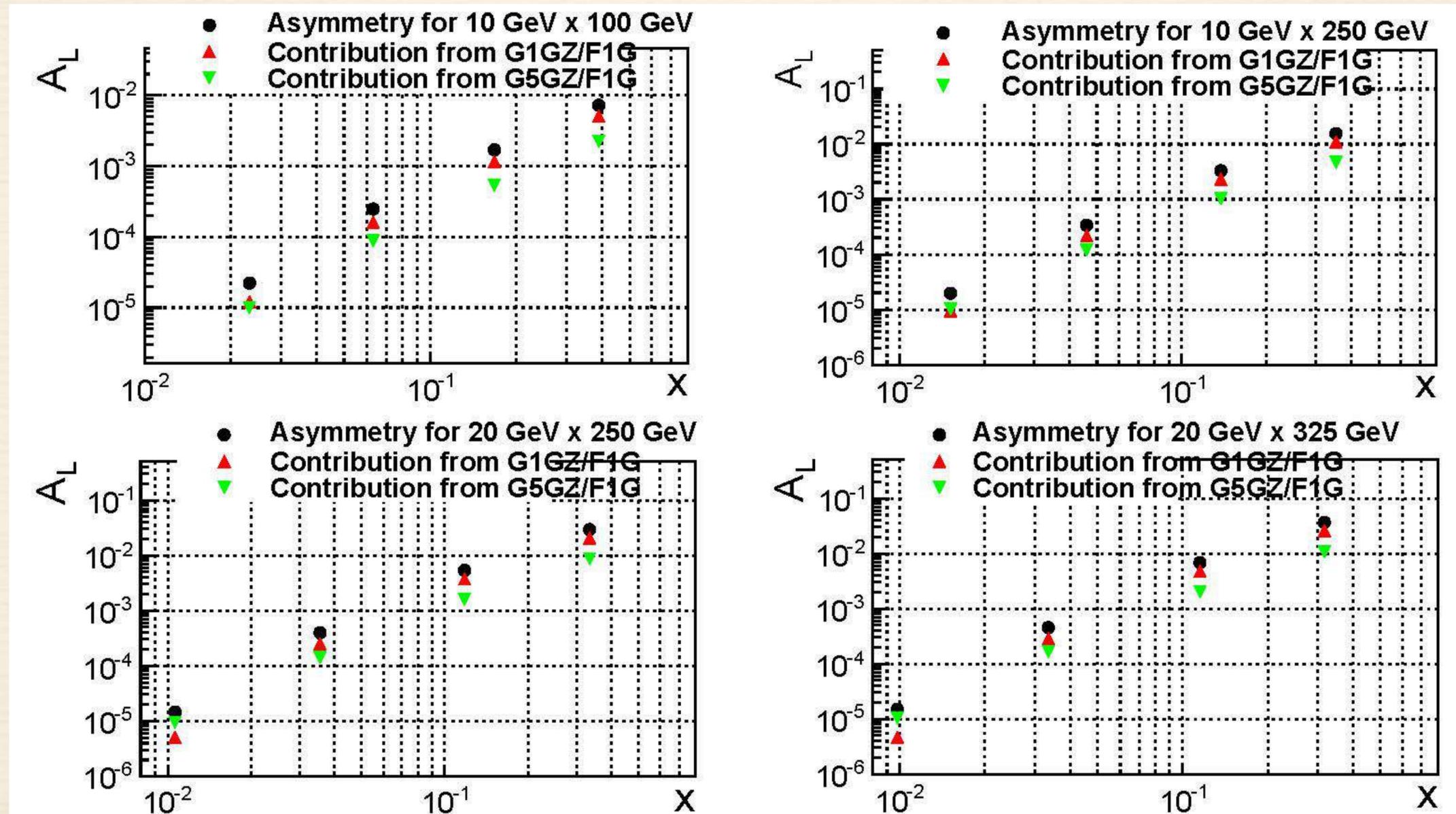- They find no "flat" dimensions in the parameter space

The future strategy is to do combined fits LHC Drell-Yan data with EIC asymmetry data; the LHC data alone does have "flat" dimensions
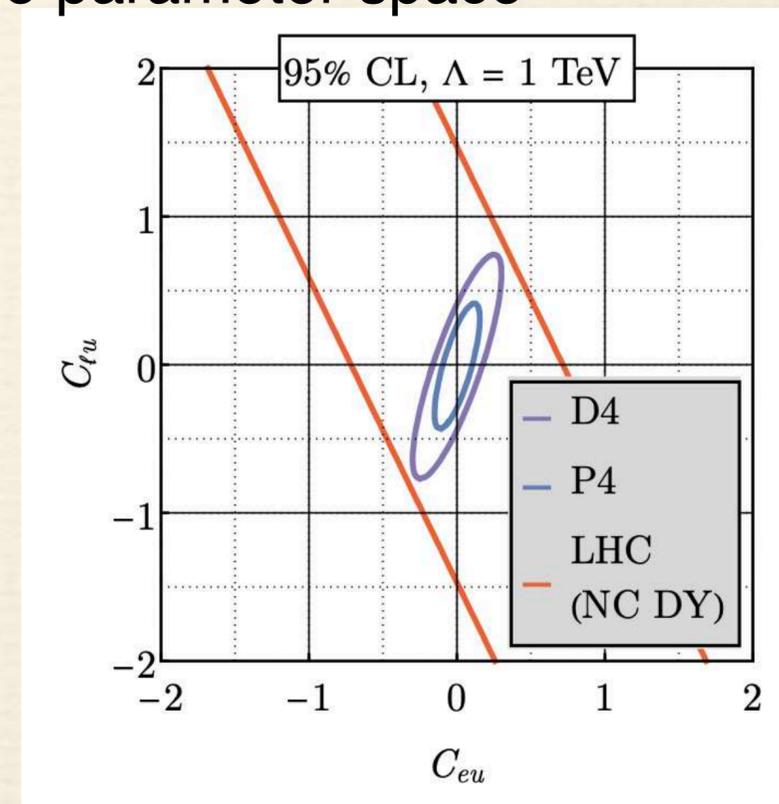
Hadron Asymmetry A_{TPV}

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

$$A_{TPV} = \frac{G_F Q^2}{2\sqrt{2}\pi\alpha}\left[g_V \frac{g_5^{\gamma Z}}{F_1^{\gamma}} + g_A f(y) \frac{g_1^{\gamma Z}}{F_1^{\gamma}}\right]$$
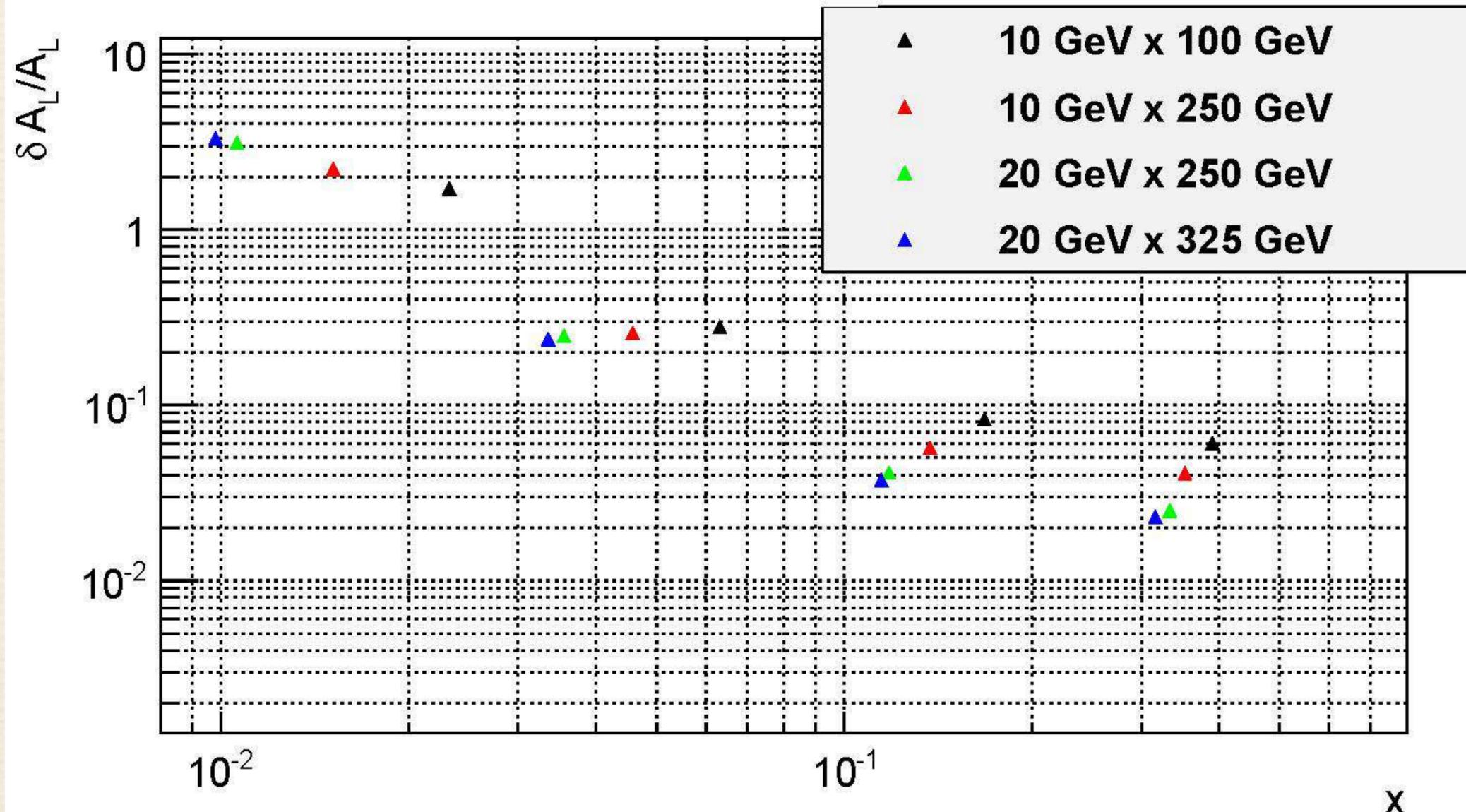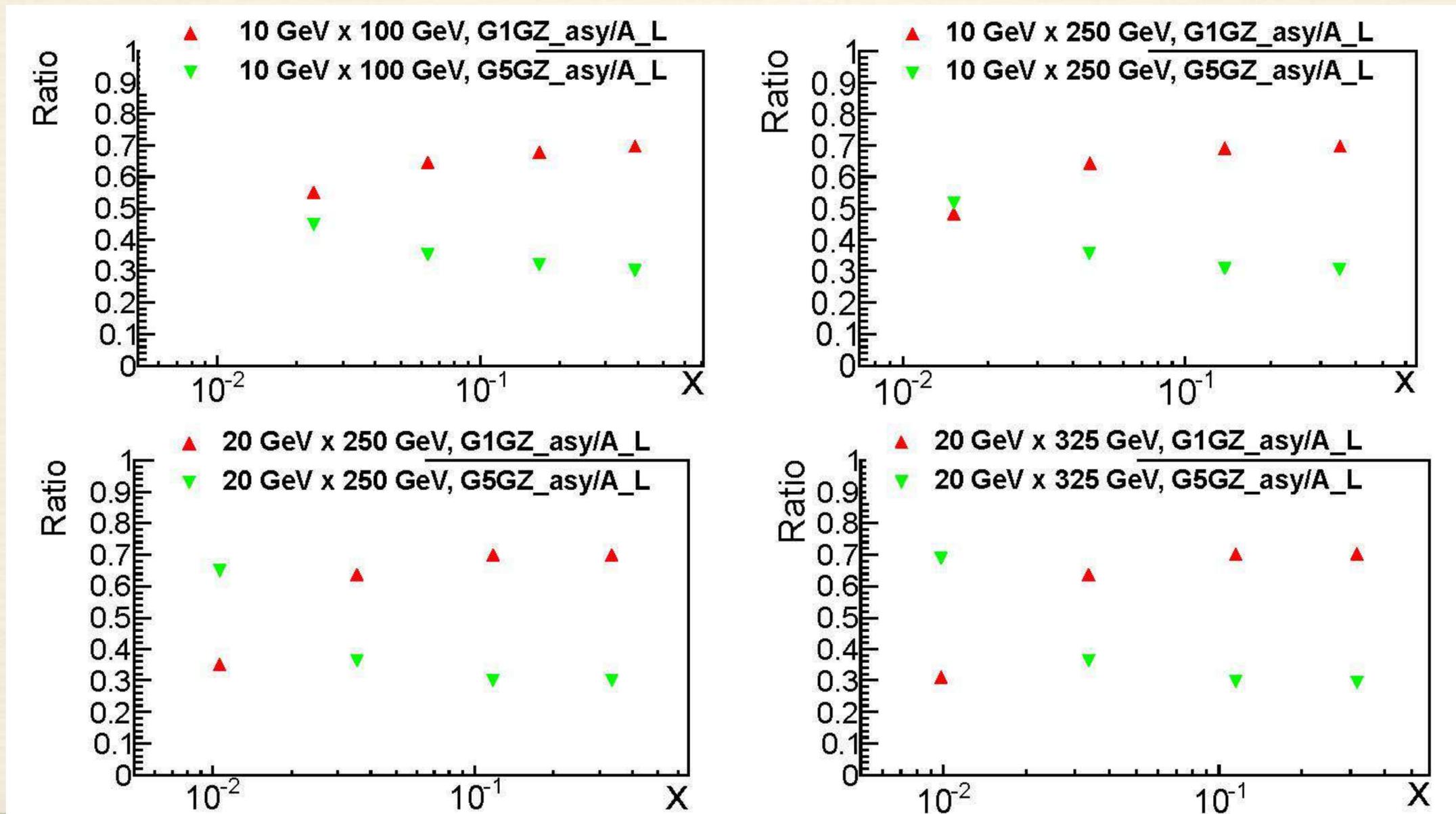
y-dependence separates g₁ and g₅

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

Fraction Statistical Errors on Structure Functions

$$g_1^{\gamma Z} \propto \Delta u + \Delta d + \Delta s$$
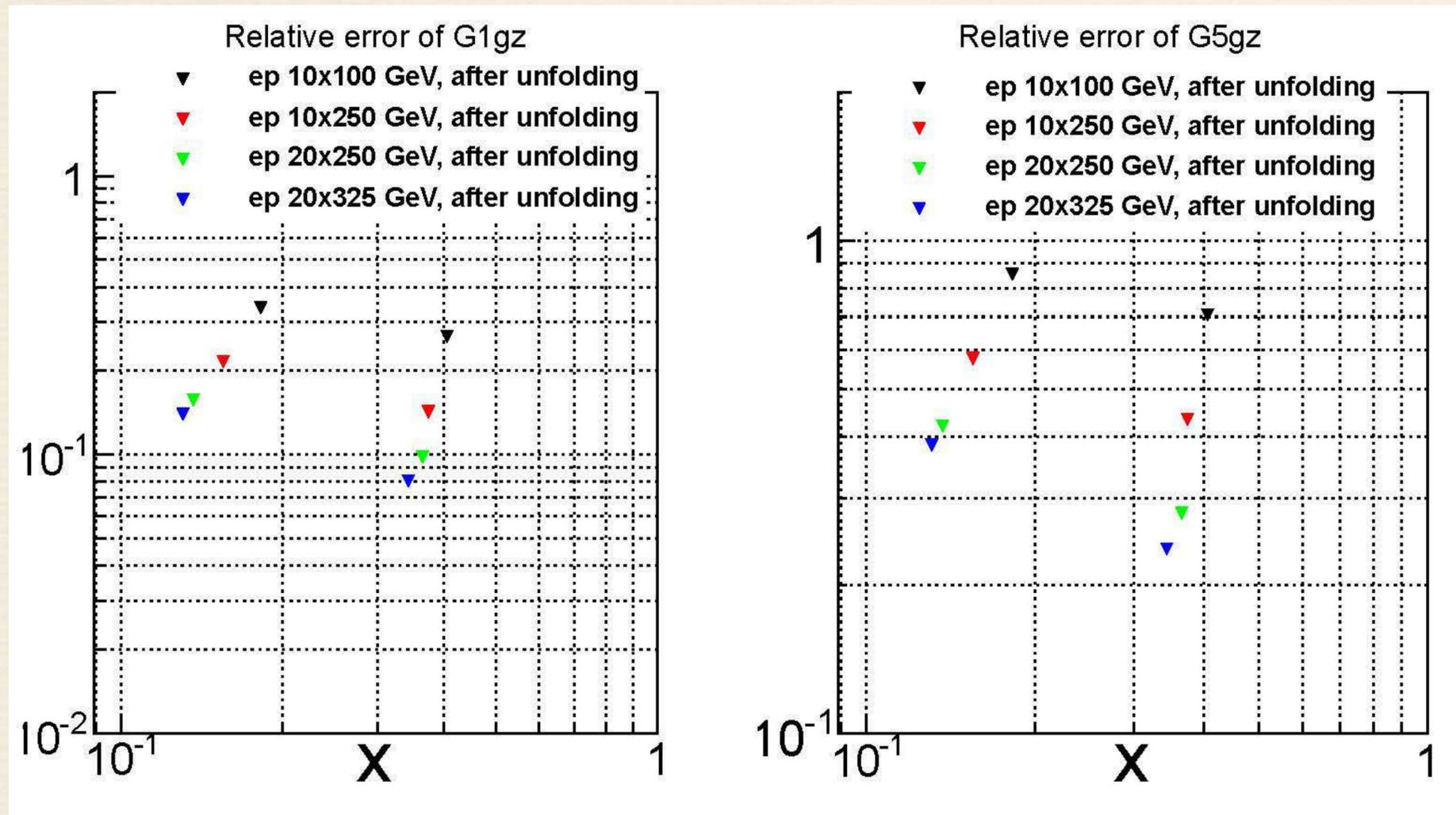
Important input to the measurement of the strange quark polarization contribution to the proton spin from an inclusive measurement!

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

First to Third Generation CLFV

$$\tau \rightarrow e \text{ or } e \rightarrow \tau$$
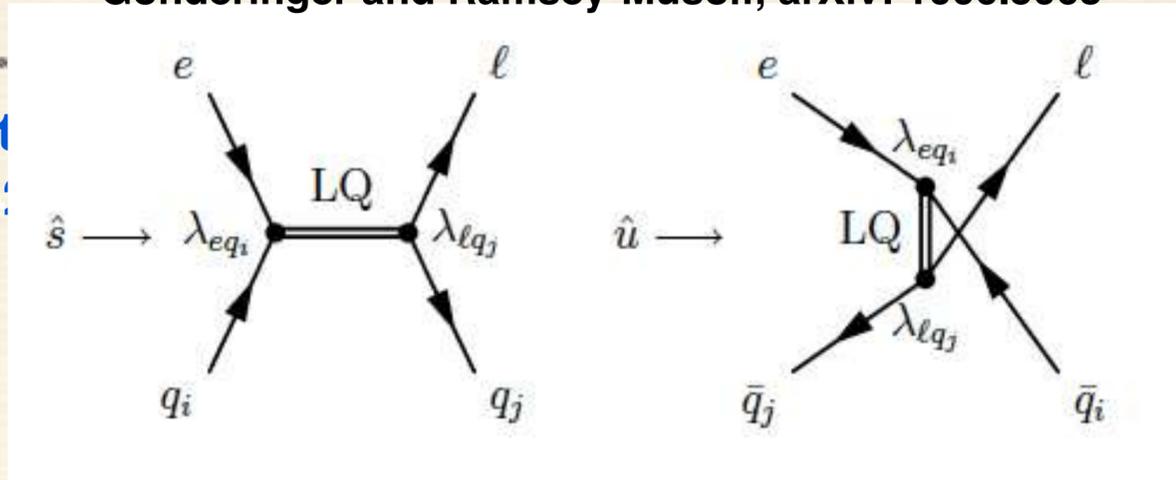
Gonderinger and Ramsey-Musolf, arXiv: 1006.5063

✦ **Various models predict enhanced sensit[ivity] for 1-3 transitions while suppressing 1-[2] transitions**

★ specific parameter space of MSSM see-saw model

★ SU(5) GUT with leptoquarks

✦ **Leptoquark models provide a good benchmark to study sensitivity**

Main Message: New discovery space if one can achieve 0.1 fb cross-section sensitivity

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

Lepto-Quark: $e\, q_i \rightarrow \tau\, q_j$

Lepto-Quark: $e\, q_i \rightarrow \tau\, q_j$

Gonderinger and Ramsey-Musolf, arXiv: 1006.5063

assume 0.1 fb cross-section sensitivity

e-τ Conversion Search

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

jet(s)

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

Tau Decay Modes and Branching Ratios

- **1-prong**   85.24 (0.06)%
  - $\mu^- \bar{\nu}_\mu \nu_\tau$ 17.39 (0.04)%
  - $e^- \bar{\nu}_e \nu_\tau$ 17.82 (0.04)%
  - $\pi^- \nu_\tau$ 10.82 (0.05)%
  - $\pi^- \pi^0 \nu_\tau$ 25.49 (0.09)%
  - $\pi^- 2\pi^0 \nu_\tau$ 9.26 (0.10)%
  - $\pi^- 3\pi^0 \nu_\tau$ 1.04 (0.07)%
  - others (kaon, etc)   3.24%

- **3-prong**   14.55 (0.06)%
  - $\pi^- \pi^+ \pi^- \nu_\tau$ 9.31 (0.05)%
  - $\pi^- \pi^+ \pi^- \pi^0 \nu_\tau$ 4.62 (0.05)%
  - others (kaon, etc)   1.28%

- others   0.21%

- If mixed in with hadron remnants, tau is boosted
- If forward along incident electron, the tau is 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 good triggers
  - tau vertex displaced 200 to 3000 microns: would greatly help background rejection and maintain high efficiency with the use of a vertex detector, which is included in EIC detector design

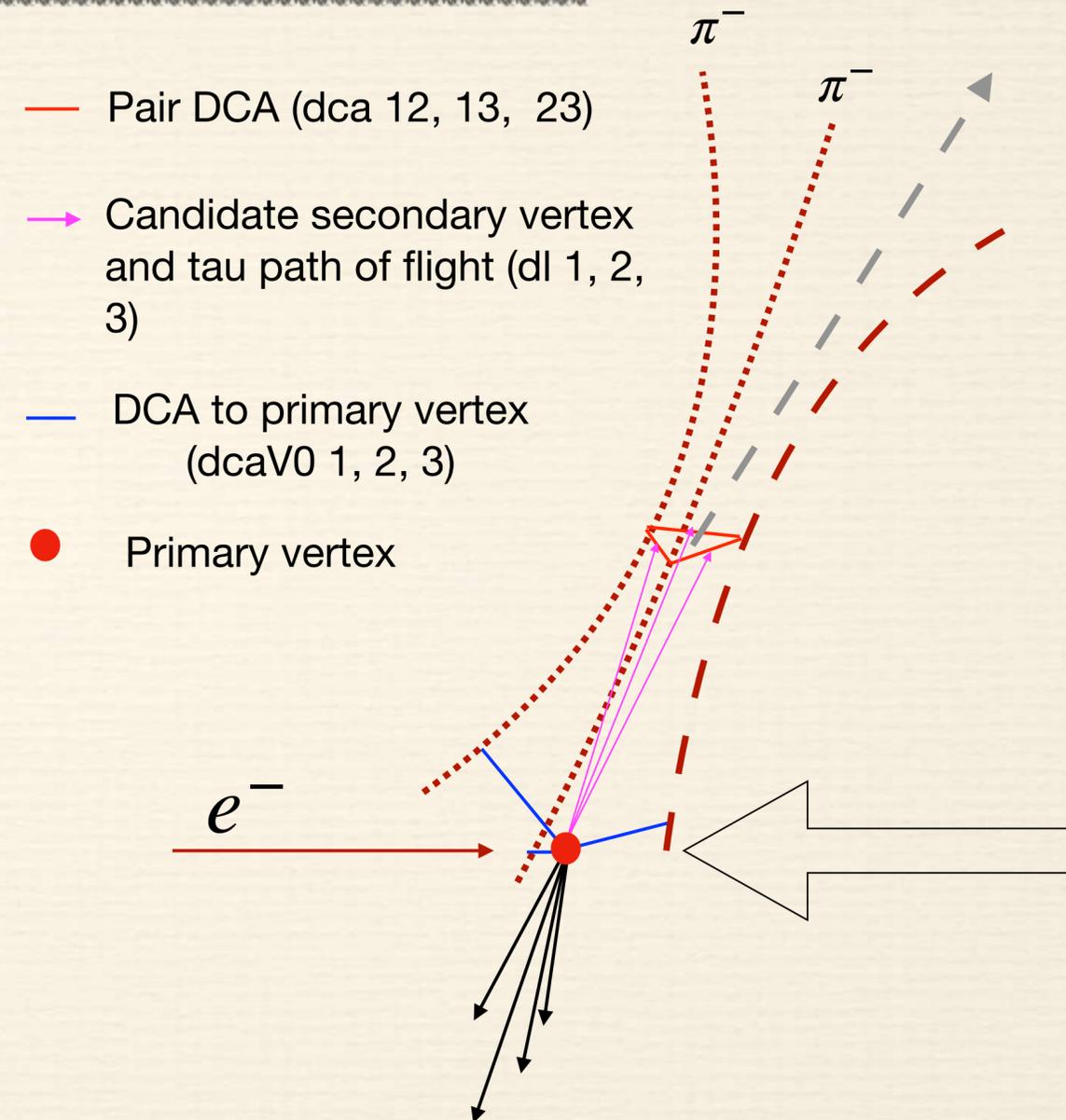**Is it possible to have greater than 10% efficiency with negligible background in a 100 fb⁻¹ data sample?**

HERA searches had ~ 2.5% efficiency but EIC detector capabilities and improved understanding of jet shapes should allow for significant improvement

Tau Appearance: First Attempt

## Generator Level Study, tau 3-prong decays

- Event generators:

  - LQGENEP 1.0 for Leptoquark events (L. Bellagamba, 2001)

  - DJANGOH 4.6.8 for DIS (NC + CC) events (H. Spiesberger 2005)

- Jets reconstructed from MC events

  - Anti-k_T, R = 1.0

  - Scattered electron for SM DIS and neutrinos **excluded**

- Secondary vertex finding from $\pi^- \pi^+ \pi^-$

—— Pair DCA (dca 12, 13, 23)

→ Candidate secondary vertex and tau path of flight (dl 1, 2, 3)

—— DCA to primary vertex (dcaV0 1, 2, 3)

● Primary vertex

π^-

π^-

e^-

fast simulation investigations will then be validated with full detector simulation and reconstruction

Tau Appearence: Event Selection

work of Jinlong Zhang
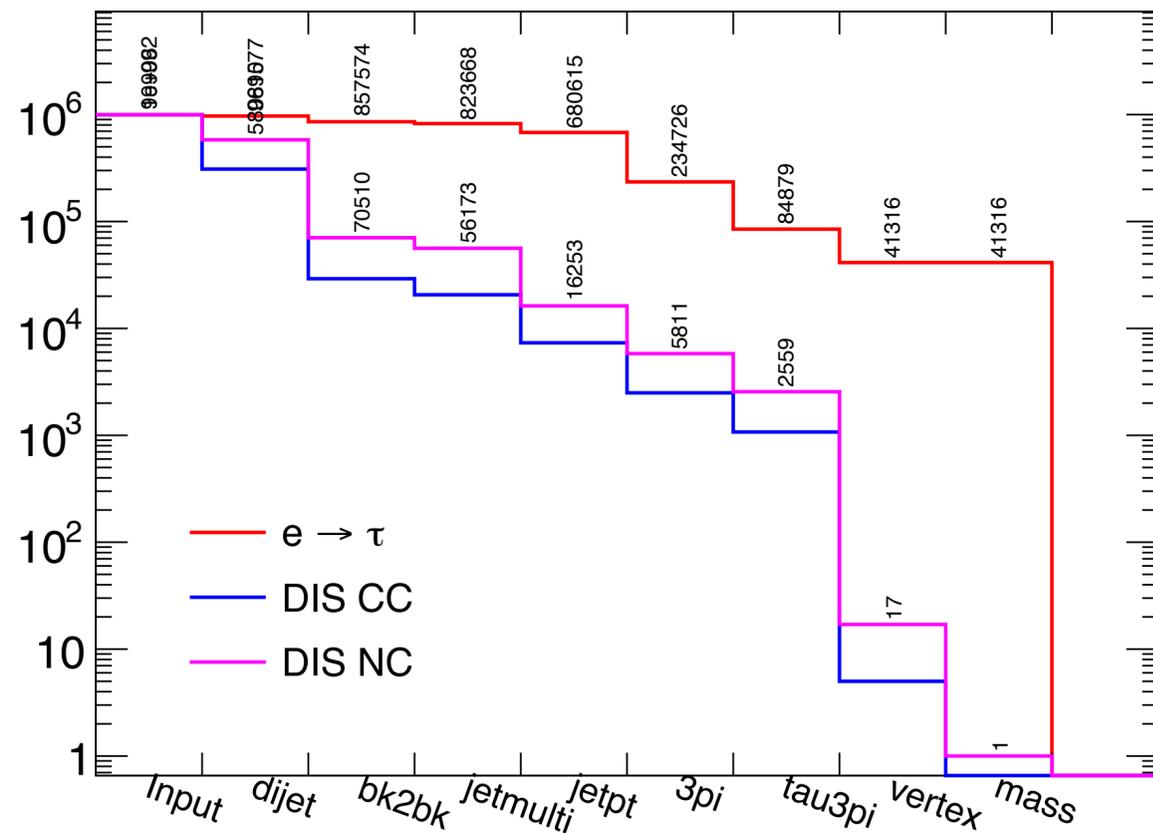
- – di-jet: number of jets >= 2

- – bk2bk: $cos\Delta\phi_{jet1-jet2}$ < -0.7

- – jetmulti: number of particles < 5 for at least one of the jets

- – jetpt: p_T (jet1) > 4.0 and p_T (jet2) > 2.5

- – 3pi: jet contain 3pi

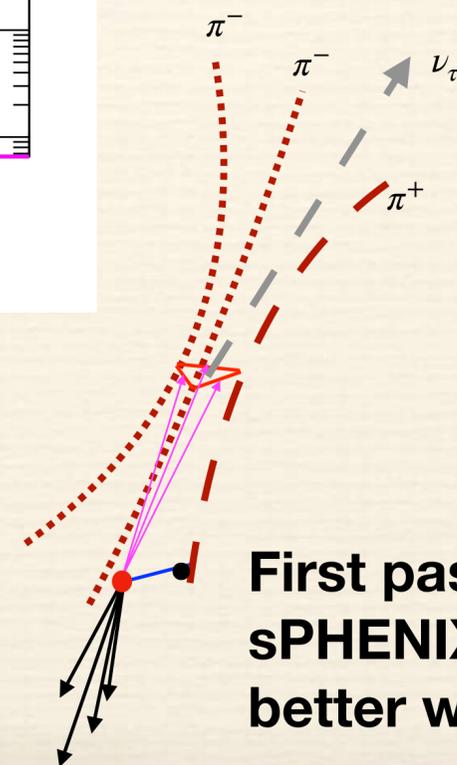- – tau3pi: 3pi jet aligns with missing p_T

- – mass: corrected mass < 1.8 GeV

- – vertex: dRsum < 0.2 && dl_asy < 0.2 mm && dl_ave < 0.2 mm

Collimation in (η, ϕ) space:

$$dRsum = \Delta R(\vec{1}, \vec{2}) + \Delta R(\vec{2}, \vec{3}) + \Delta R(\vec{1}, \vec{3})$$

Length matching:

$$dl\_asy = |dl_1 - dl_2| + |dl_1 - dl_3| + |dl_2 - dl_3|$$
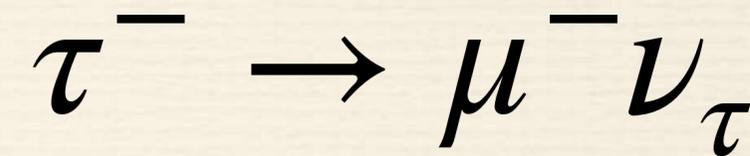
First pass: 15% of 3-prong signal efficiency from sPHENIX detector simulation: should be able to do better with further optimization of selection criteria

Ongoing Work on Tau Appearence

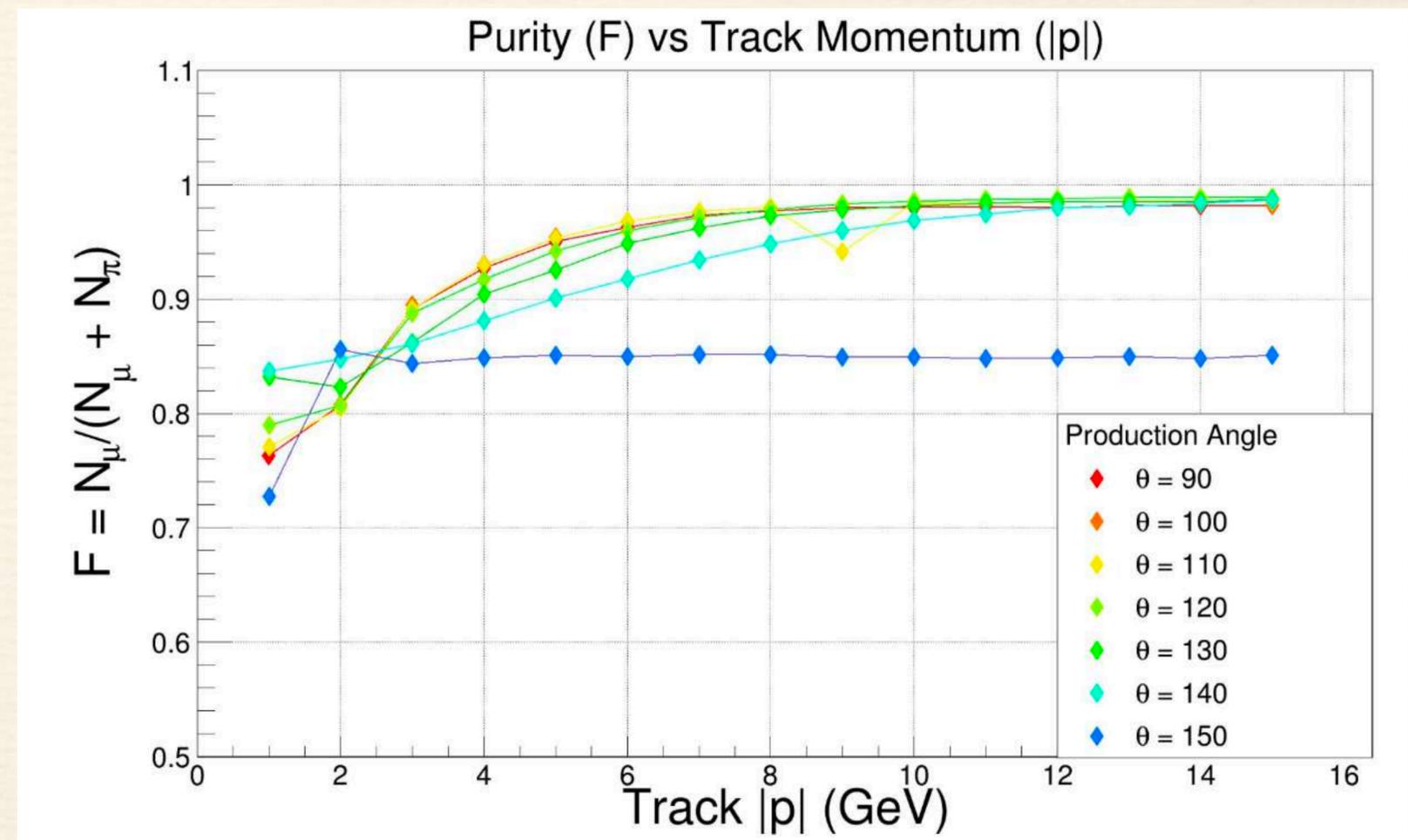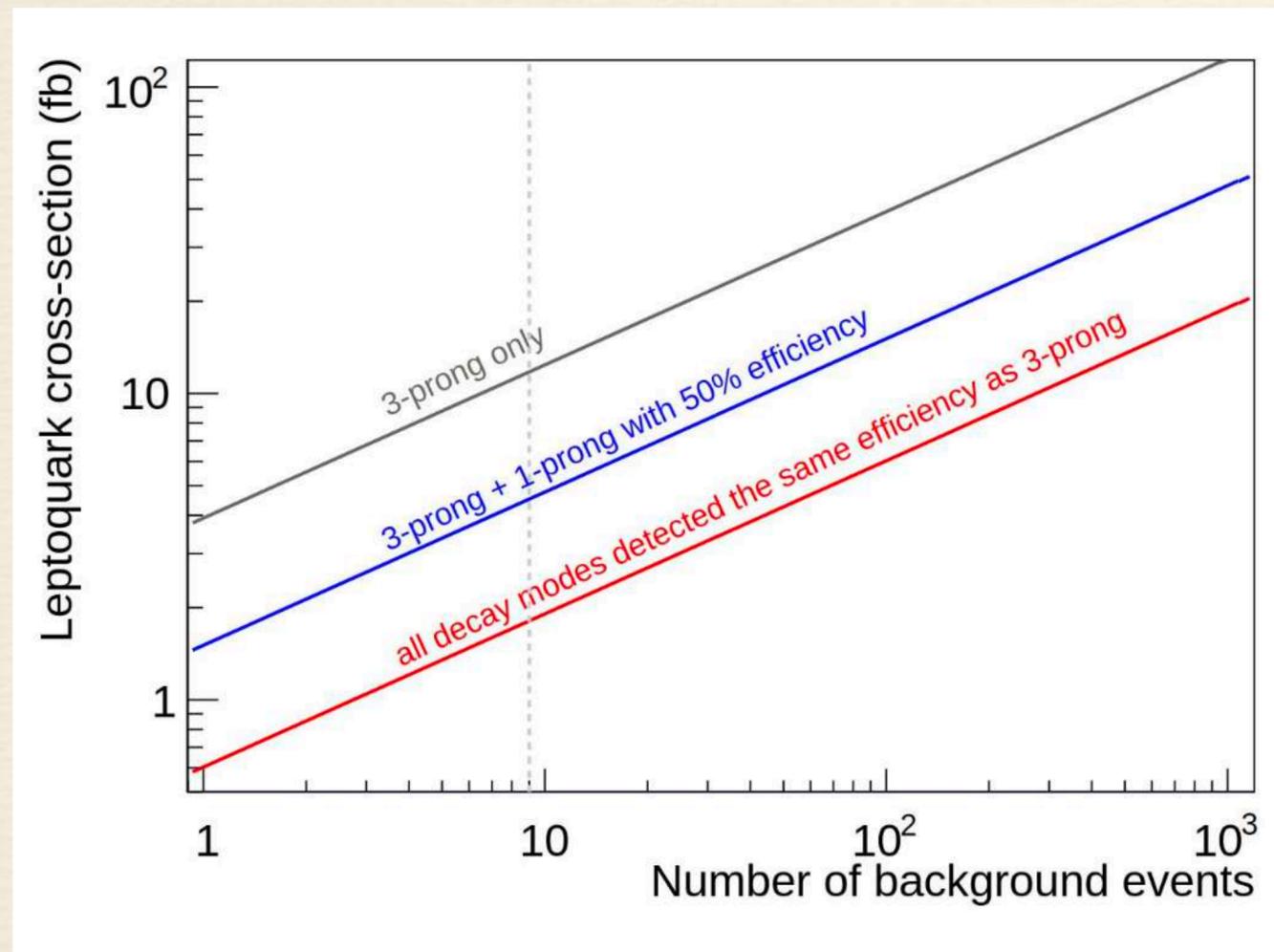Realistic Simulation with ECCE Detector configuration

Zhang et al, Nuclear Inst. and Methods in
Physics Research, A 1053 (2023) 168276

$$\tau^- \rightarrow \mu^- \nu_\tau$$

Andrew Hurley (UMass)

**Must work now to increase efficiency and
start to include other tau decay channels**

**Above 10 GeV, pion rejection to identify muons is good:
must work to improve rejection between 5 and 10 GeV**
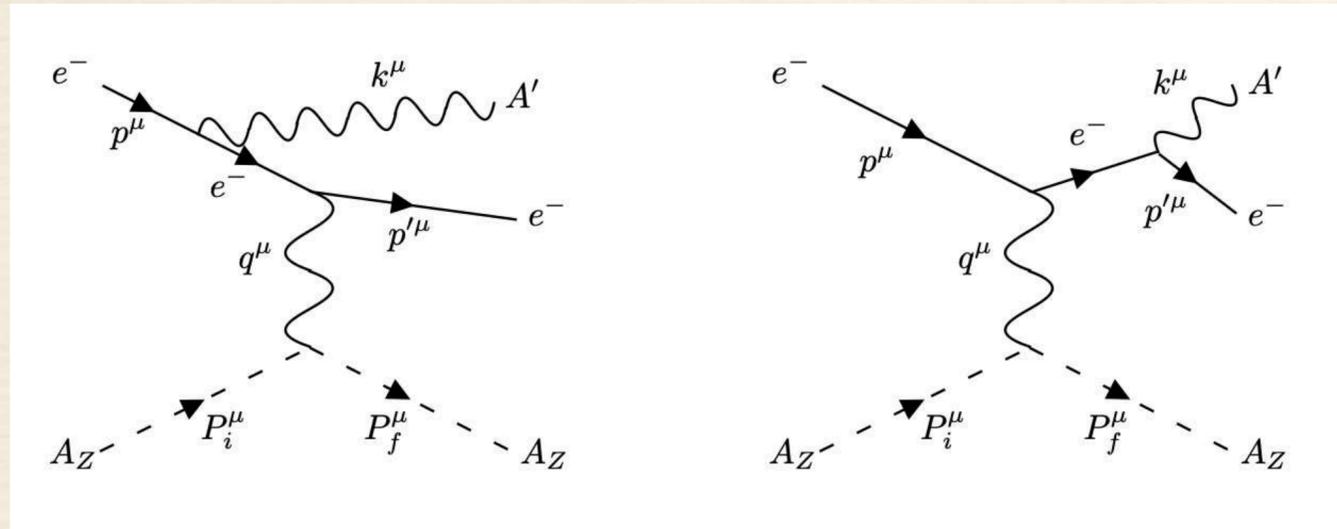
Dark Bosons

H. Davoudiasl talk at CFNS workshop

Simplest analog: Dark U(1), analog of electromagnetism

Dark photon (Kinetic mixing) or Dark Z (mass mixing)
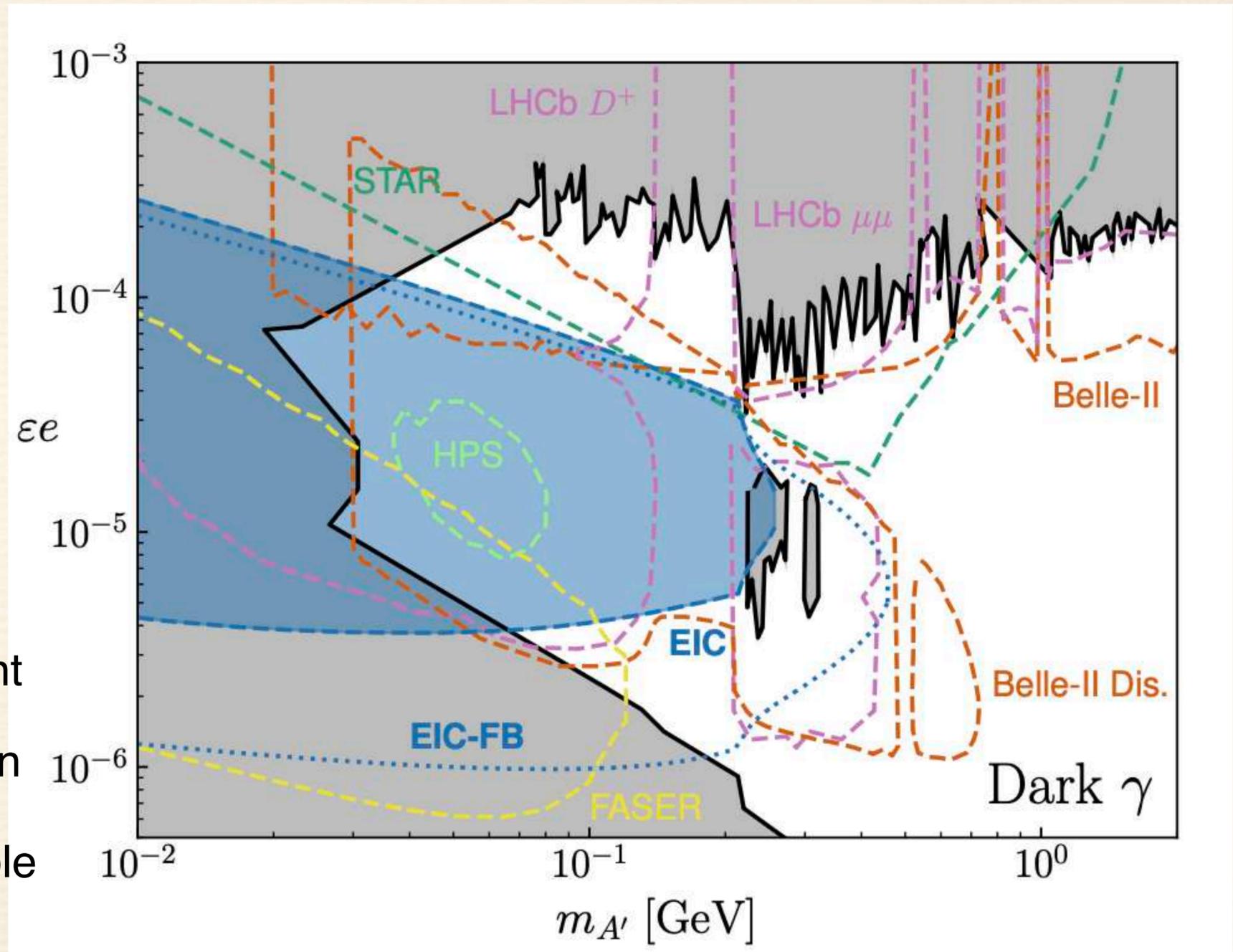
$$eA_Z \rightarrow eA_Z A' \quad (Z_d \leftrightarrow A')$$

Coherent production in e-A collisions: Z^2 enhancement

Detect the lepton pair as well as the scattered electron

The result on the left assumes background is negligible

arXiv:**2112.04513**:

Flavor Violating Axion-like Particle

Dark scalar: Axion-like particle; analog of QCD axion (pseudo-scalars)

$$e^- A_Z \to \tau^- (a \to \tau^- e^+) A_Z$$

BG: $\quad e^- A_Z \to e^- A_Z \tau^+ \tau^-$
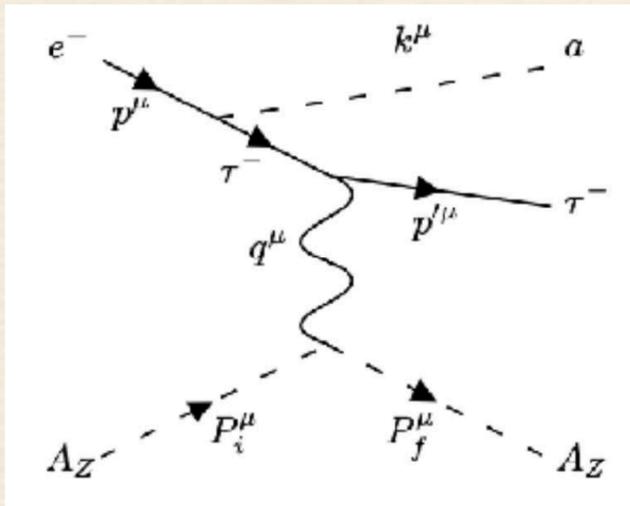
Improving signal efficiency (now 1%) and further background rejection can greatly improve sensitivity

Dashed lines are Belle-II projections

Selection criteria:

1. One tau identified in the final state;
2. One e+ identified in the final state;
3. Veto on final-state e-;
4. Veto on nuclear breakup.

Two Ideas under Development

Lepton Number Violation Search and a T-Odd Observable

CFNS workshop talk by S. Quiroga

LNV process: $e^- p \rightarrow \ell^+ jjj$

μ^+ appearance

$e^- p \rightarrow \mu^+ jjj$

Zero-background 95% C.L. exclusion limits

Preliminary

- $\varepsilon_\mu = \varepsilon_e$
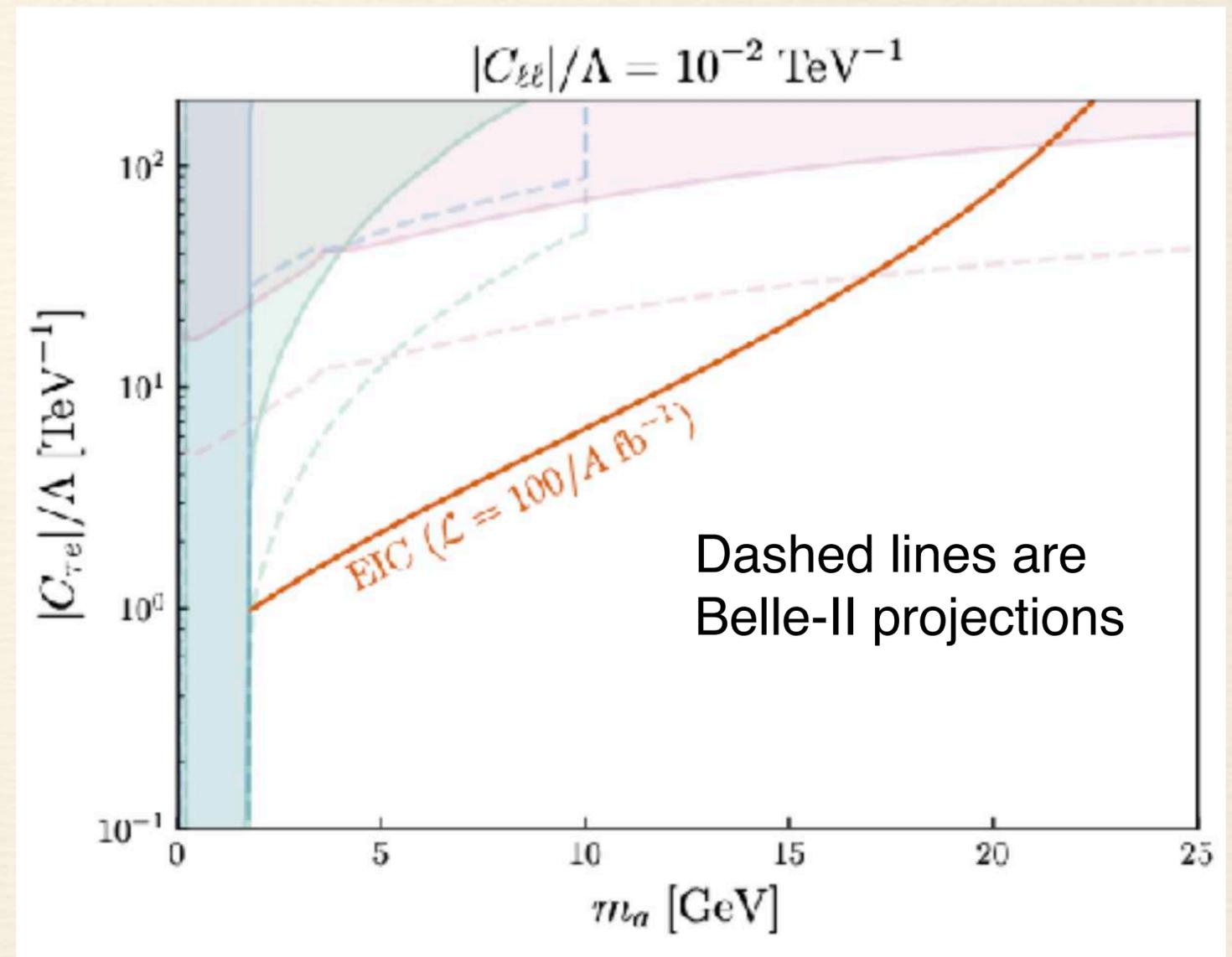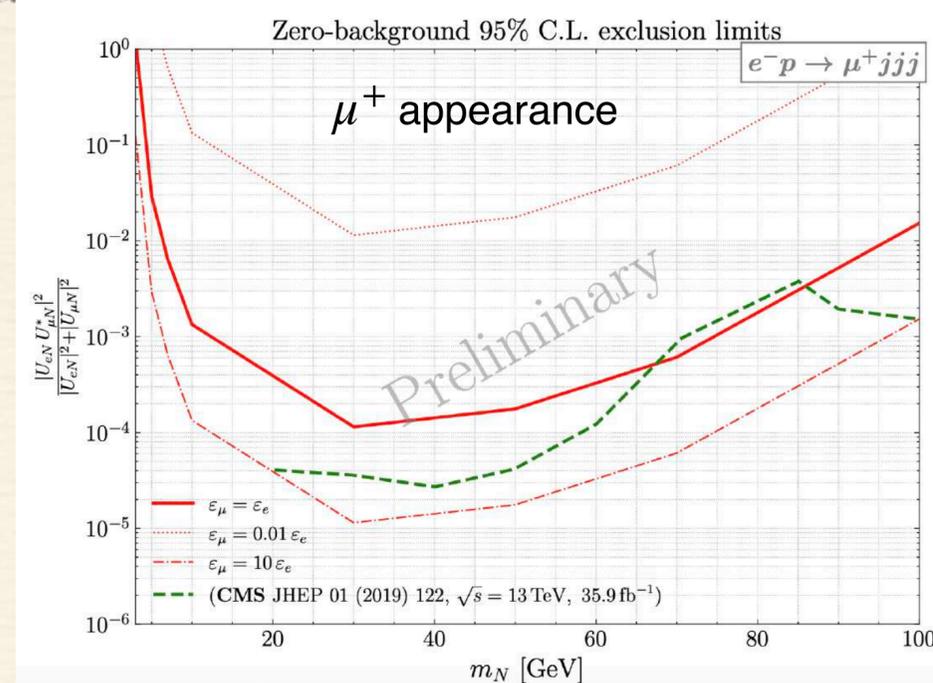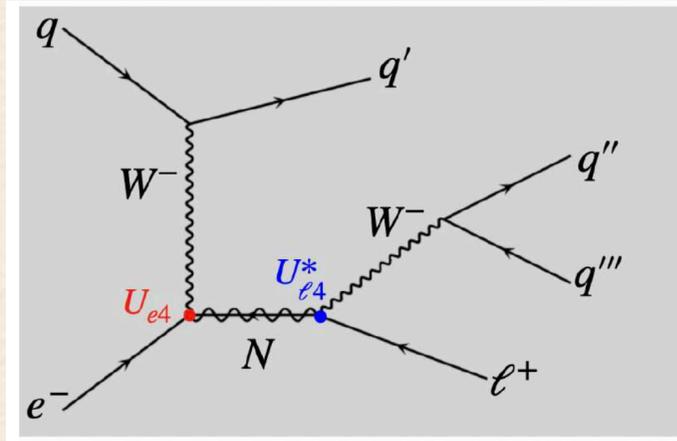- $\varepsilon_\mu = 0.01\,\varepsilon_e$
- $\varepsilon_\mu = 10\,\varepsilon_e$
- (**CMS** JHEP 01 (2019) 122, $\sqrt{s} = 13\,\text{TeV}$, $35.9\,\text{fb}^{-1}$)

High energy isolated positive lepton with 3 jets should be a background-free topology

Both positive muon appearance and positive tau appearance topologies look very promising for unique EIC reach

Inclusive Transverse Single Spin Asymmetries:

Probe of electric dipole operators: novel contribution to T-odd amplitudes

Sensitive to different linear combinations compared to EDM searches

The size of the Standard Model contribution is expected to to be small at high Q²; preliminary estimates are that they are of order 10^{-6}

Inclusive transverse single-spin transverse asymmetry

$\text{Re}[C_{e\gamma}] = v/\text{TeV}^2$

- Q=10 GeV
- Q=15 GeV
- Q=20 GeV
- Q=25 GeV
- Q=30 GeV
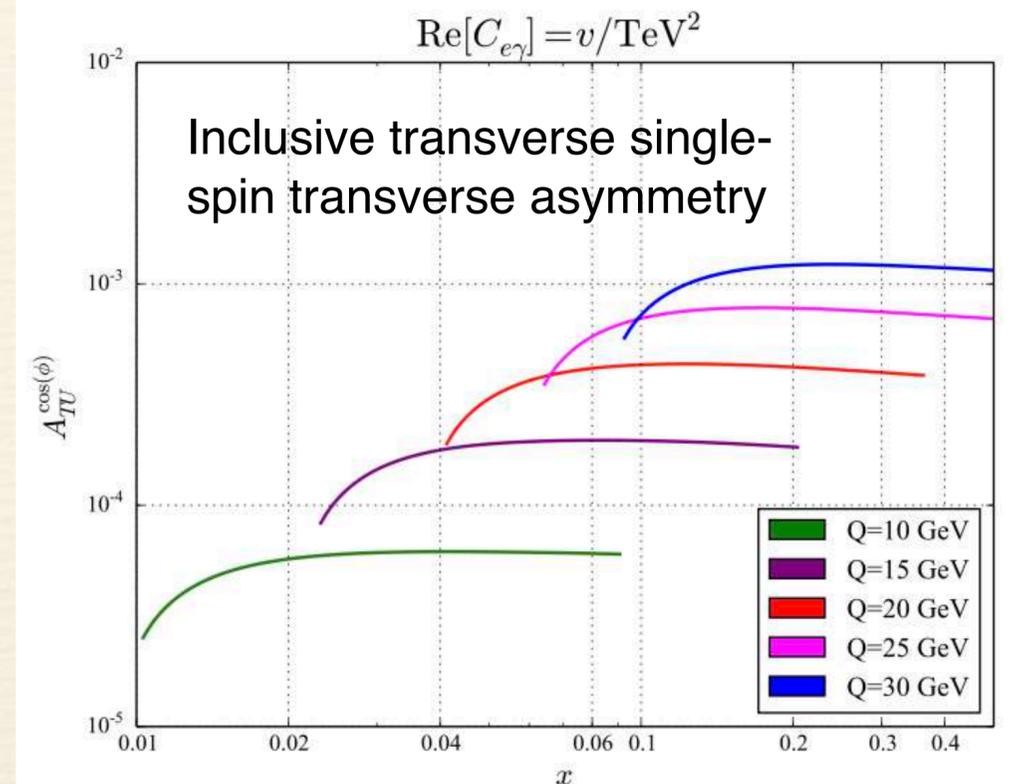
Boughezal et al   *Phys.Rev.D* 107 (2023) 7, 075028 • e-Print: 2301.02304 [hep-ph]

Lecture 2 Summary

- ## Neutral and Charged Current Structure Functions

  - *Complementary probe of BSM 6-D operators: address flat directions in global SMEFT analysis*
  - *Unpolarized and Polarized pdfs*
  - *Weak Mixing Angle: both proton and deuteron*
  - *Charged current measurements complementary to precision weak decays*

- ## Lepton Flavor Violation Search

  - *Tau appearance: strive for zero background and increased efficiency*
  - *Complementary lepton flavor and number violation search with multiple jets*

- ## Other BSM Topics

  - *Inclusive single spin asymmetries*
  - *Dark Boson and Axion-like particle searches*
  - *…*

New opportunities for beyond-the-Standard Model searches at the EIC

Center for Frontiers in Nuclear Science

https://indico.cfnssbu.physics.sunysb.edu/event/341/timetable/#20250722.detailed

BSM @ EIC Summary

- ## Intensity Frontier

  - *Absent direct particle discovery at the LHC, indirect BSM searches become central. In fact one could argue that certainly LHCb and even ATLAS and CMS are now Intensity Frontier experiments!*

- ## Electron Ion Collider

  - *Any new machine accessing new territory in intensity, luminosity, spin and center of mass energy space must be thoroughly explored for potential new BSM sensitivity*

  - *First ideas (Neutral currents, CLFV) have percolated for more than a decade*

  - *New ideas are continuing to come in…*

- ## Sharpen the Science Case

  - *It is now time to push the ideas that survive "on mass-shell"*

  - *Continue to explore new ideas while keeping a close eye on the rest of the BSM landscape over the next decade*
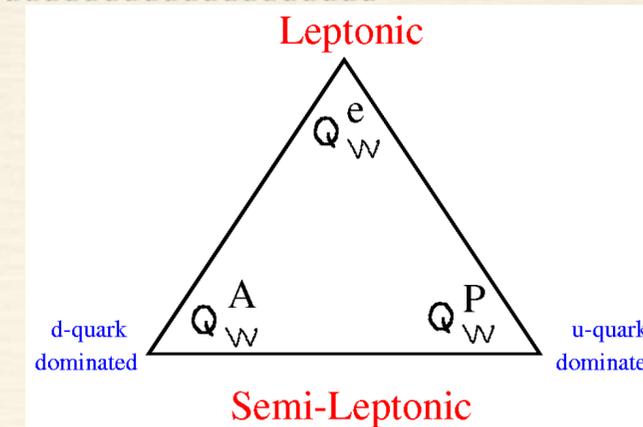
Backup

Other WNC Measurements

Physics sensitivity from contact interaction (LEP2 convention, $g^2 = 4pi$)

	precision	$\Delta \sin^2\overline{\theta}_W(0)$	Λ_{new} (expected)
SoLID	0.6 %	0.00057	22 TeV
PVES ^{12}C	0.3 %	0.0007	49 TeV

Courtesy: M. Ramsey-Musolf

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

axial-quark couplings

Where does the EIC fit in?
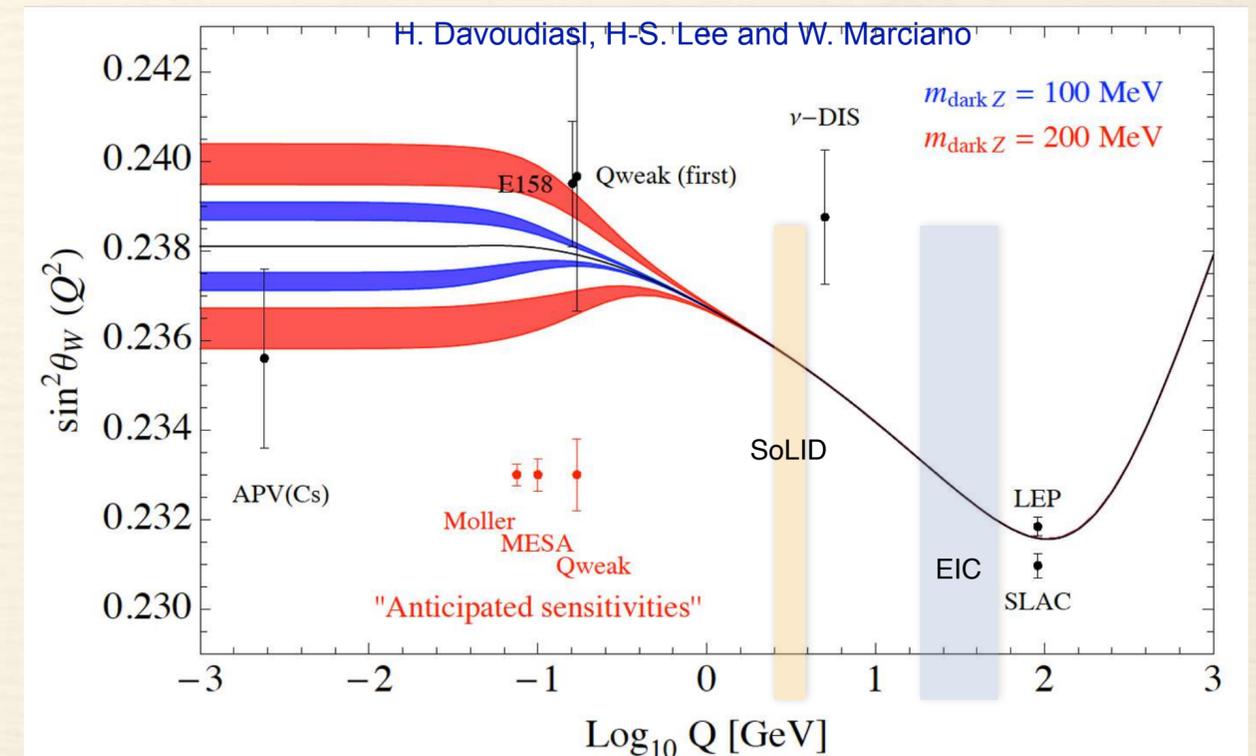
- *An entirely unexplored Q^2 regime, close to the Z pole i.e it is not just weak-electromagnetic interference*

- *It is best to just fold it into a SMEFT analysis and explore where the EIC helps with "flat" directions in coupling space*

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

✦Complementary to collider Drell-Yan Searches
✦Unique sensitivity to intermediate-scale dark Z's

The W Mass

PDG 2022

Special thanks: Ashutosh Kotwal

theory $m_W = 80.360(6)$ GeV

expt. $m_W = 80.377(12)$ GeV

Then the earthquake!

CDF II (2022)	80,433 ± 9.4	
ATLAS (2018)	80,370 ± 19	
LHCb (2022)	80,354 ± 32	
Tev. avg. (2022)	80,427 ± 9	
Tev. + LEP avg. (2022)	80,424 ± 9	

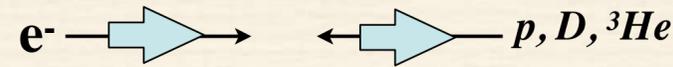W boson mass (MeV by per c²)

W boson mass (MeV by per c^2)
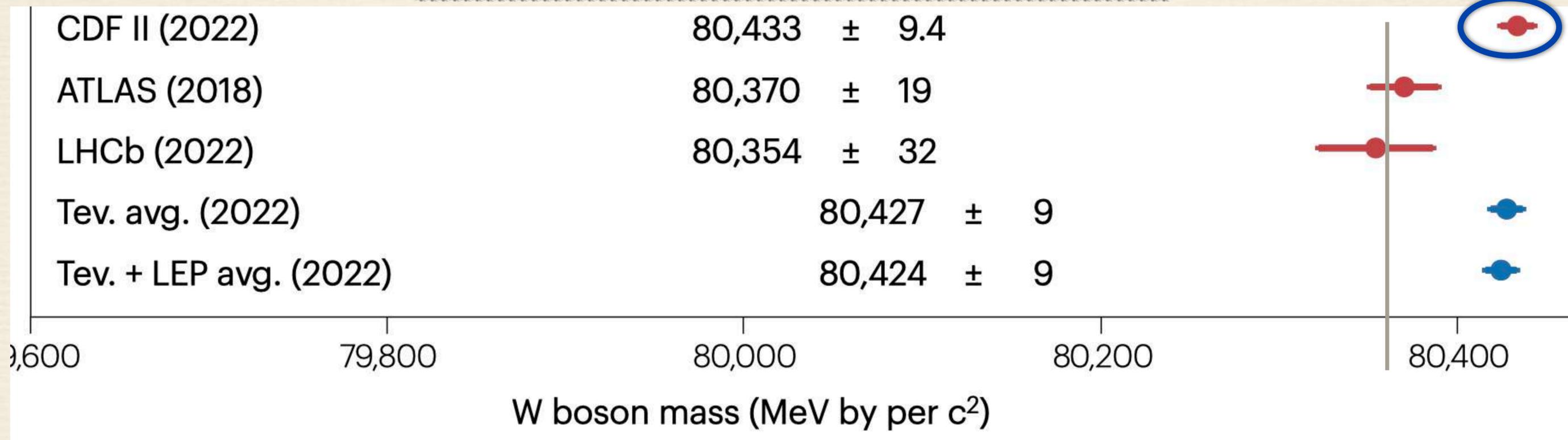
Comments

- *CDF - ATLAS: 63 +/- 21 MeV*

- *CDF has done more work since release; stick by their number*

- *Pdf issues much more challenging for LHC: low x pdfs vs high x at CDF*

My take

- *No point worrying about this until CDF and LHC resolve their differences*

- *If CDF result holds, EVERYTHING in the EW sector becomes even more important!*

- *If things resolve to SM, semi-leptonic WNC measurements can still look for BSM physics*

High Energy e-p scattering

$$e^- \longrightarrow \qquad \longleftarrow p, D, {}^3He$$

$$\frac{1}{2m_N} W^i_{\mu\nu} = -\frac{g_{\mu\nu}}{m_N} F^i_1 + \frac{p_\mu p_\nu}{m_N (p \cdot q)} F^i_2$$

$$+ i \frac{\epsilon_{\mu\nu\alpha\beta}}{2(p \cdot q)} \left[\frac{p^\alpha q^\beta}{m_N} F^i_3 + 2q^\alpha S^\beta g^i_1 - 4xp^\alpha S^\beta g^i_2 \right]$$

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

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

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

new sum rules

Similar expressions for neutral current structure functions

proton

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

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

Could begin to access this after 1 full year of running

proton

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

deuteron

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

High luminosity: precision measurements of PV observables