# Electroweak and BSM prospects with ePIC

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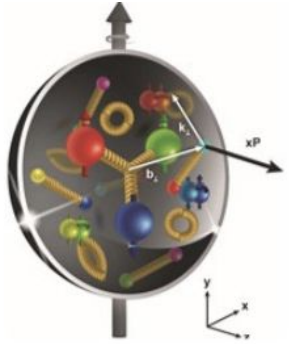
Diffraction and Low-*x* 2024
Palermo Italy,
September 8 -14 2024

# Electron-Ion Collider Physics

*"The Electron-Ion Collider (EIC) will address some of the most fundamental questions in science regarding the visible world, including"*

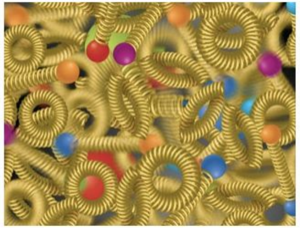
Origin of nucleon spin

Origin of nucleon mass




How are quark & gluons distributed in momentum and space

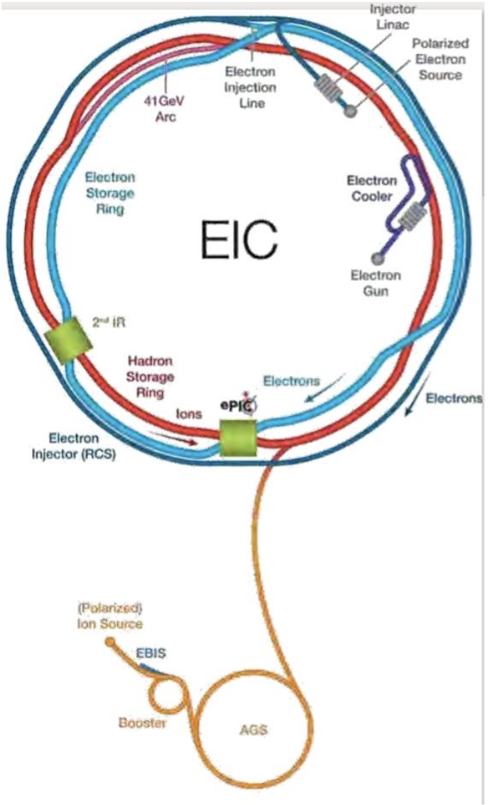
How do quarks and gluons interact with nuclear medium



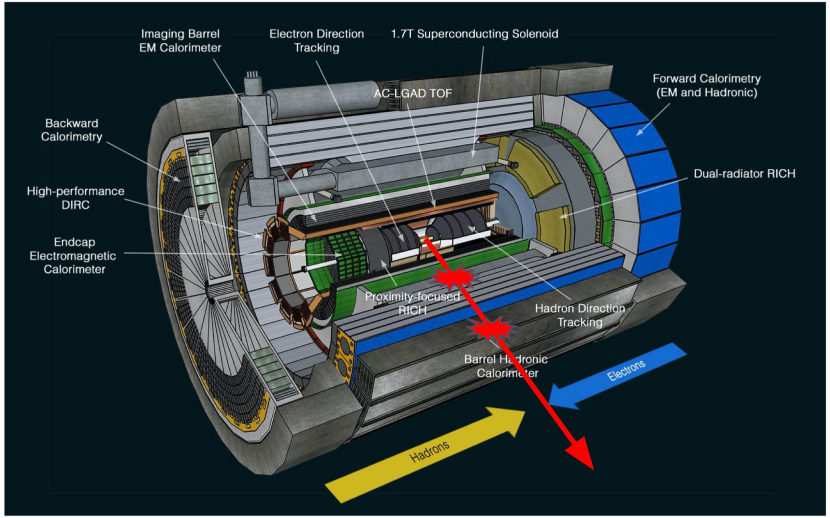
What are the emergent properties of dense system of gluons

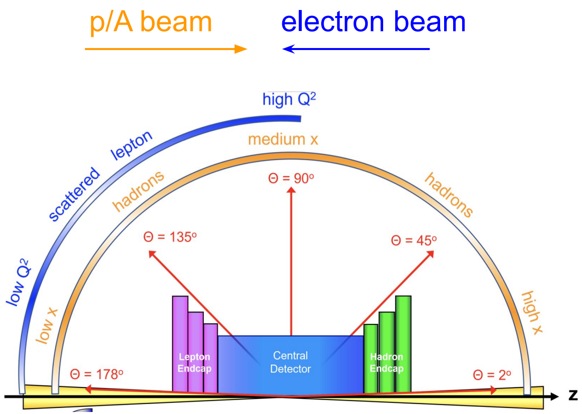
# Electron-Ion Collider

- High luminosity machine
  - ($10^{33}$ - $10^{34}$ cm$^{-2}$ s$^{-1}$)
- Large center-of-mass energy range
  - √21-140 GeV
- Polarized $e^-$, protons and light ions beams
  - ≥70%
- Ions beam from deuteron to heavier nuclei
  - Gold, lead, or uranium



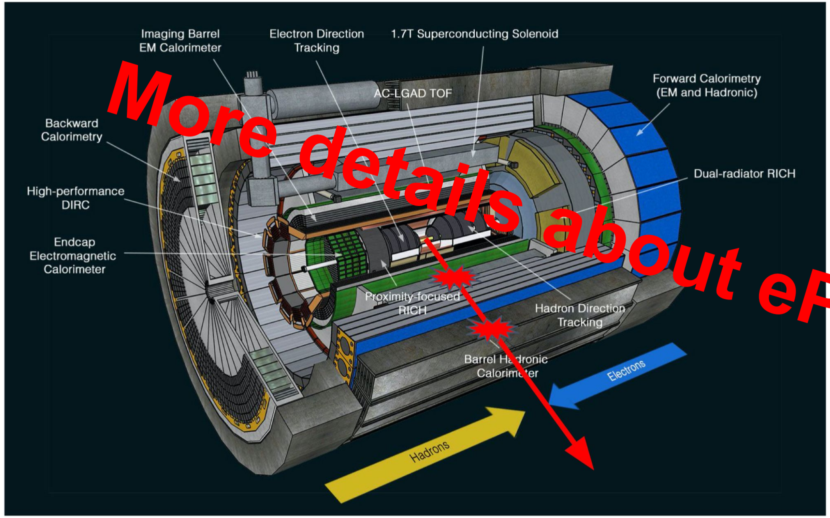
# The ePIC Detector

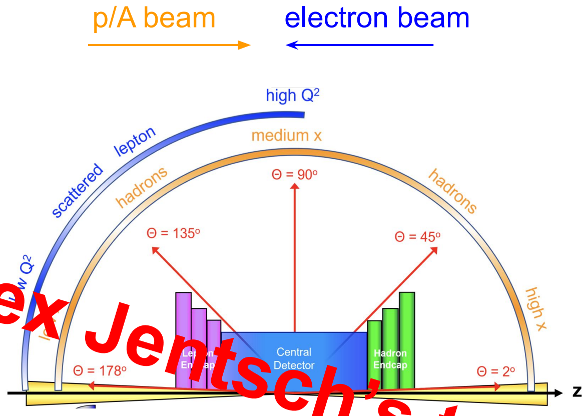



- ➔ Large $\eta$ coverage (-3.5 < $\eta$ < 3.5)
- ➔ High precision silicon detectors for tracking
- ➔ Excellent calorimeters for measuring energy of EM particle showers
- ➔ Extended PID for hadron ID

# The ePIC Detector




**More details about ePIC in Alex Jentsch's talk**

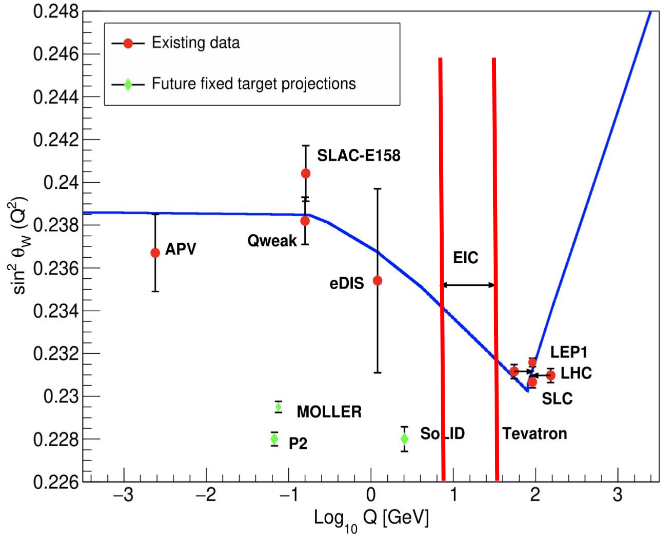
- ➔ Large $\eta$ coverage ($-3.5 < \eta < 3.5$)
- ➔ High precision silicon detectors for tracking
- ➔ Excellent calorimeters for measuring energy of EM particle showers
- ➔ Extended PID for hadron ID

# Electroweak & BSM Physics at the EIC

- Primary focus of the EIC
  - Answering fundamental questions in QCD
- Beam and detector design synergistic for Electroweak & BSM physics
  - Wide kinematic coverage
  - High luminosity ~ $1x10^{34}$
  - Polarized $e^-$ and protons and light ions beams
- EW & BSM physics prospects at the EIC with ePIC
  - Charged Flavor Lepton Violation (CFLV)
  - Dark photon search
  - Provide constraints on $\sin^2(\theta_W)$ over a $Q^2$ range
  - BSM using **T**ransverse **S**ingle **S**pin **A**symmetries (TNSSA)

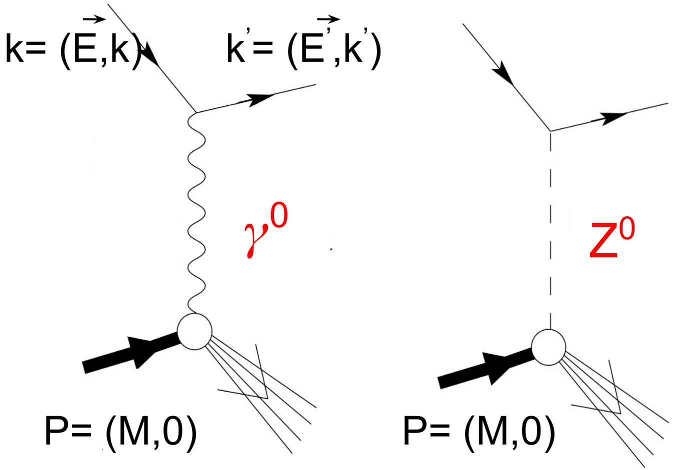
# Weak Mixing Angle at the EIC

- Weak mixing angle
  - Parameter of Standard Model
  - Sensitive to BSM physics
- Parity Violating DIS
  - Extraction of $\sin^2(\theta_W)$ from the isoscalar deuteron
  - **Cancelation of structure function effects**
- High precision data at EIC may make extraction of $\sin^2(\theta_W)$ from the proton
  - Will require precise knowledge of PDFs
- Kinematics
  - Energy range between those in fixed-target and collider experiments
  - Over a range of $Q^2$ values not yet explored




J Arrington et al 2023 J. Phys. G: Nucl. Part. Phys. 50

# Neutral Current Electroweak Physics Studies at the EIC




**Parity-Violating Deep Inelastic Scattering Asymmetry**

$$A_{PV}^{(e)} \equiv \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} = \frac{d\sigma_e}{d\sigma_0}$$

$$A_{RL}^{e^-} = \frac{|\lambda|\eta_{\gamma Z}\left[g_A^e 2yF_1^{\gamma Z} + g_A^e\left(\frac{2}{xy} - \frac{2}{x} - \frac{2M^2xy}{Q^2}\right)F_2^{\gamma Z} + g_V^e(2-y)F_3^{\gamma Z}\right]}{2yF_1^{\gamma} + \left(\frac{2}{xy} - \frac{2}{x} - \frac{2M^2xy}{Q^2}\right)F_2^{\gamma} - \eta_{\gamma Z}\left[g_V^e 2yF_1^{\gamma Z} + g_V^e\left(\frac{2}{xy} - \frac{2}{x} - \frac{2M^2xy}{Q^2}\right)F_2^{\gamma Z} + g_A^e(2-y)F_3^{\gamma Z}\right]}$$

**Where**

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

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

$$g_A^e = -\tfrac{1}{2} \qquad g_A^q = \pm\tfrac{1}{2}$$

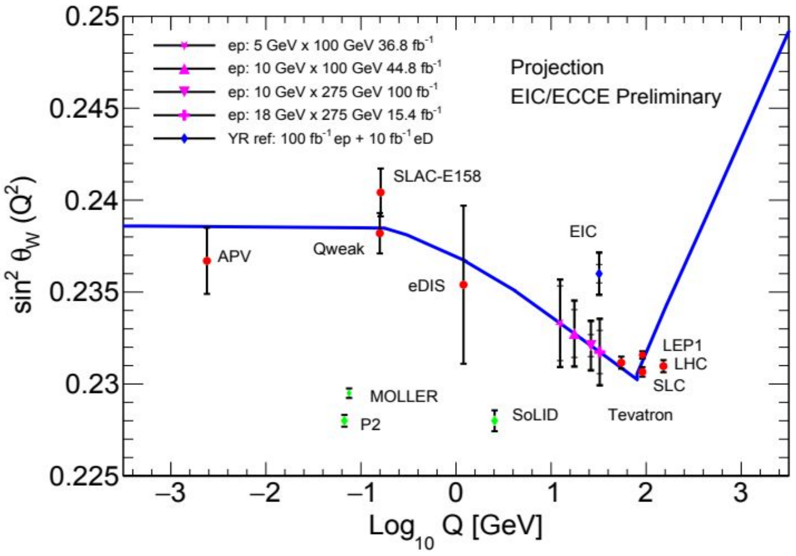
$$g_V^e = -\tfrac{1}{2} + 2\sin^2\theta_W \qquad g_V^q = \pm\tfrac{1}{2} - 2e_q\sin^2\theta_W$$

$g_A^{e(q)}$ and $g_V^{e(q)}$: axial and vector neutral weak couplings of the electron (quark)

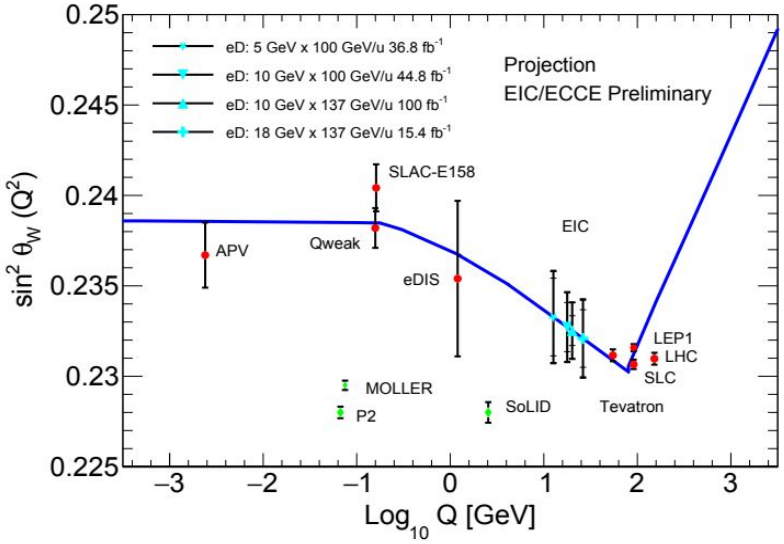
# Parity Violating DIS Outlook

R. Boughezal et al., Neutral-current electroweak physics and SMEFT studies at the EIC, Phys. Rev. D

## ep Results




## eD Results




- ❖ Detailed study of the extraction of $\sin^2(\theta_W)$ at the EIC for both the proton and deuteron performed
- ❖ Will cover an energy scale between fixed target and collider experiments
  - ➢ Unexplored region

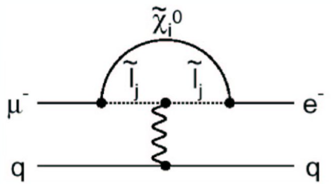
# Charged Lepton Flavor Violation

- ❖ Neutrino oscillations
  - ➢ Provided evidence for lepton flavor violation
- ❖ No experimental evidence for flavor violation in charged lepton sector
- ❖ Predicted CLFV branching ratio
  - ➢ $Br(\mu \to e\gamma) < 10^{-54}$
- ❖ Example: Supersymmetry prediction
  - ➢ $Br(\mu \to e\gamma) \sim 10^{-15}$
- ❖ $Br(\mu \to e\gamma) < 10^{-13}$ : Current limit (MEG experiment)
  - ➢ [Baldini, A.M., Bao, Y., Baracchini, E. et al. Eur. Phys. J. C 76, 434]
- ❖ $e \to \tau$ transition constraints - much weaker
  - ➢ $Br(e \to \tau Y) \sim 10^{-8}$

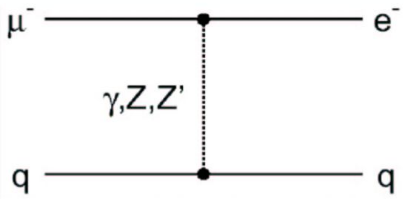
Leptoquarks

- Color triplet particles
- Couple to leptons & quarks
- Mediate CLFV processes at tree-level

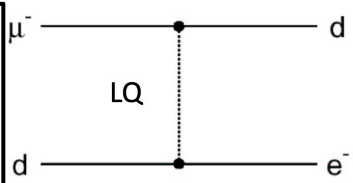
Supersymmetry




Heavy Z




Leptoquarks




BSM models that predict CLFV

# Decay Channel(s)

<u>1 Prong</u>

$$\tau \rightarrow \mu \bar{\nu}_\mu \nu_\tau$$

1. Larger branching ratio ~ 17%
2. Suppression of SM background
3. Needs (good) $\mu$ identification

Preliminary

- No dedicated muon detector
  - Limit tracks to those MIPs in calorimerter
- Utilize E/p in both barrel calorimeters

$\mu$ channel

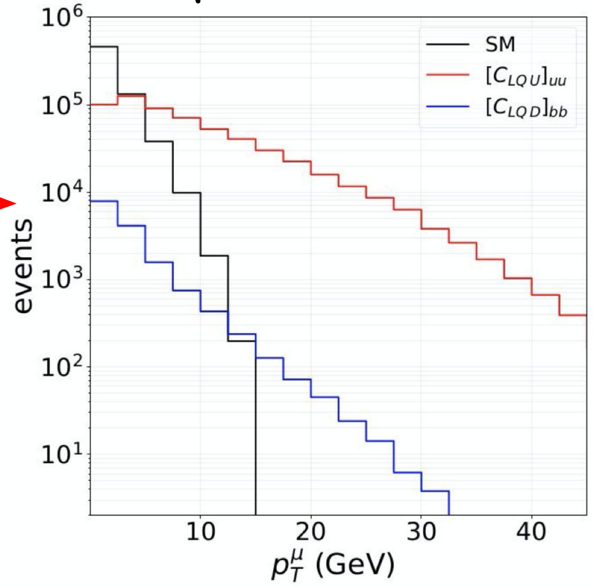



*Image courtesy of Emanuele Mereghetti

[Charged Lepton Flavor Violation at the EIC]

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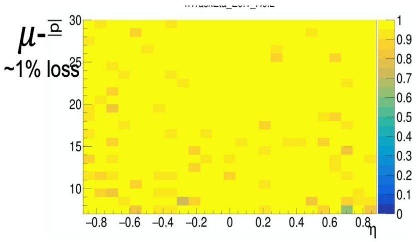
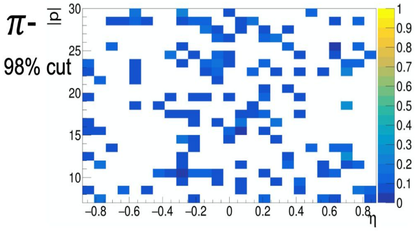
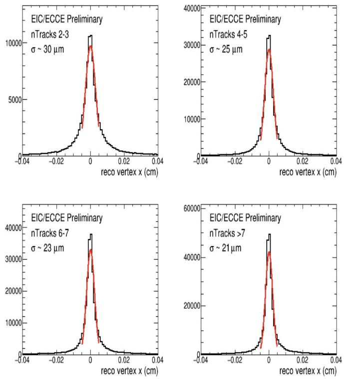


# Decay Channel(s)

- Utilized a leptoquark generator (LQGENEP)
  - Signal MC events
- Djangoh and Pythia generators to produce background DIS & photoproduction events
- Large mass of leptoquark
  - Used the 18x275 GeV ep collision
- Critical requirement
  - secondary vertex reconstruction




<u>3 Prong (from $e \to \tau$)</u>

$$\tau \to \pi^- \pi^+ \pi^- \nu_\tau$$

1. Identification is easier than 1 prong channel

1. Primary vertex reconstructed
2. $\Sigma_h(E\text{-}p_z)$>18 GeV
3. Missing $p_T$: ($1<p_T<9$) GeV
4. $3\pi$ candidate
5. $p_T$ of $3\pi$ < 3 GeV
6. No scattered $e^-$ detected

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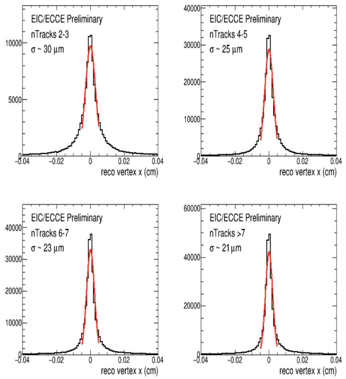


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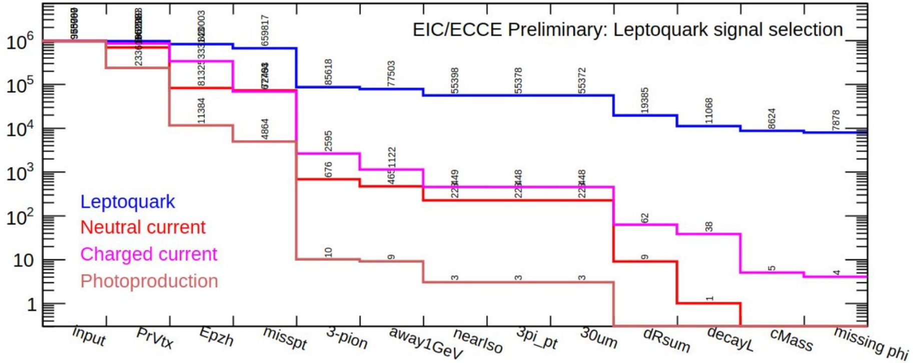
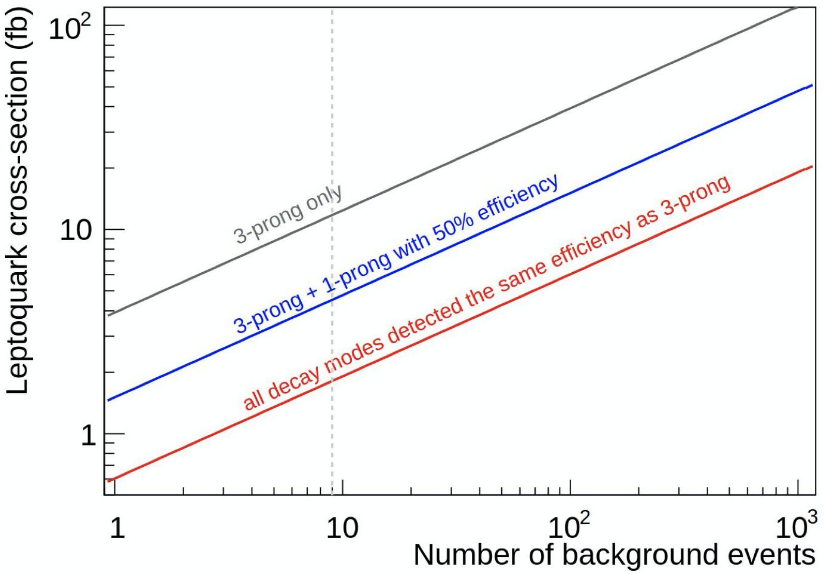


# CLFV Outlook

- 3 Prong study completed
  - J. Zhang et. al, Charged Lepton Flavor Violation Study at the EIC, in Electroweak and BSM physics at the EIC
- 1 Prong study: ongoing
- Refine & add additional constraints / cuts
  - Shower shape
  - $p_T$ imbalance from missing neutrinos ($\nu$)
  - Large hadronic Jet $p_T$




Sensitivity for leptoquark cross section vs backgroun events

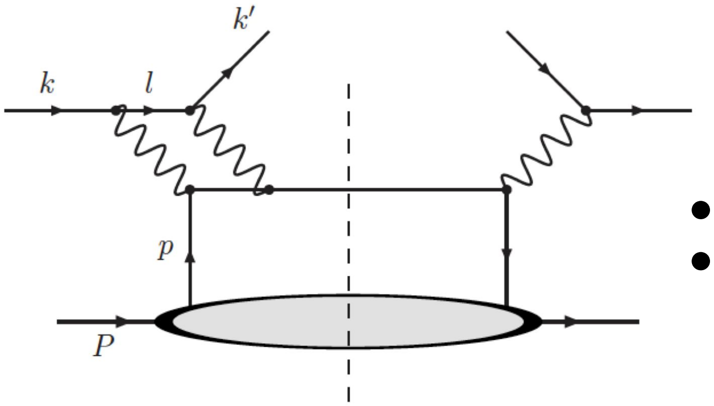
# Transverse Single Spin Asymmetries (DIS)

1. **$e^-$ polarized ⊥ to scattering plane (unpolarized target)**
2. Unpolarized $e^-$ and transversely polarized target

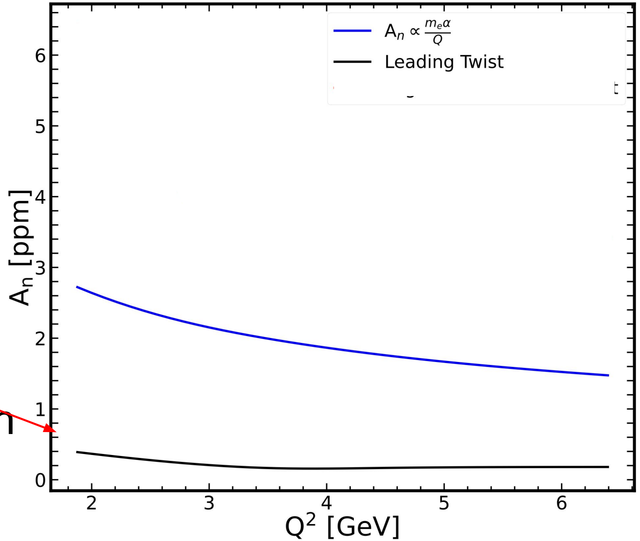
$$\frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}}$$

$$A_n = \frac{\alpha_{EM} m_l \left|\vec{S}_T\right| \sin(\varphi_s)}{2Q} \frac{y^2\sqrt{1-y}}{1-y+\frac{1}{2}y^2} \frac{\sum_q e_q^3 q(x)}{\sum_q e_q^2 q(x)}$$

- Zero at Born level
- Two-photon exchange can lead to non-zero asymmetry




- $A_{TU}$ is small (~$10^{-6}$)
- Possible place to search for new physics

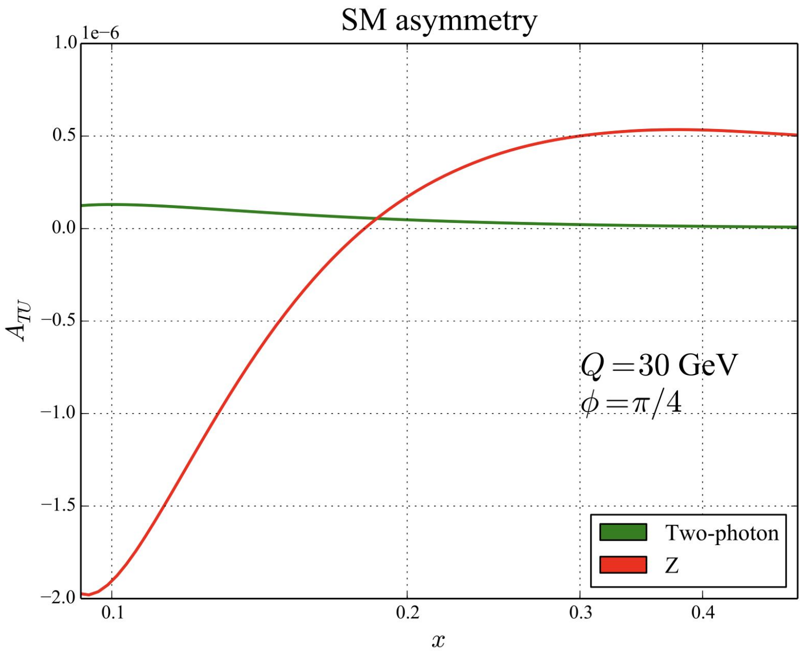


# Transverse Single Spin Asymmetries

[R. Boughezal, D. de Florian, F. Petriello, and W. Vogelsang, Transverse spin asymmetries at the EIC as a probe of anomalous electric and magnetic dipole moments, Phys. Rev. D 107, 075028 (2023)]

At the EIC, also need to account for SM contributions mediated by Z-boson

$$A_{TU}^{Z}(\phi) = \frac{2}{s_W^2 c_W^2} \frac{m_l Q}{M_Z^2} \frac{y\sqrt{1-y}}{1-y+y^2/2} \cos(\phi) \frac{\sum_q Q_q f_q(x) \left[g_{al} g_{vq}(1-y) + g_{vl} g_{aq} y\right]}{\sum_q Q_q^2 f_q(x)}$$



# Transverse SSAs: standard model effective field theory (SMEFT)

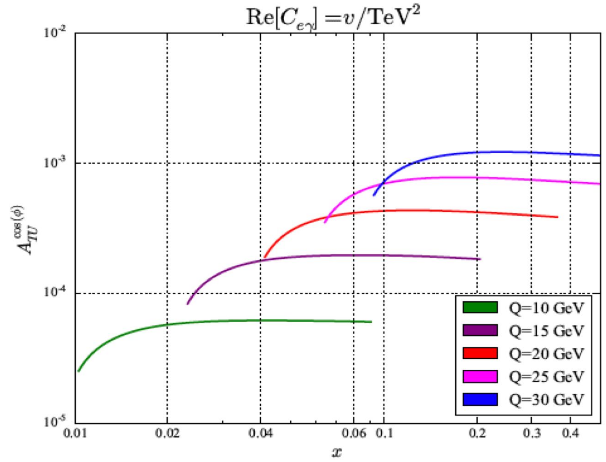
SMEFT: an effective field theory extension of the SM that includes terms suppressed by a high energy scale $\Lambda$

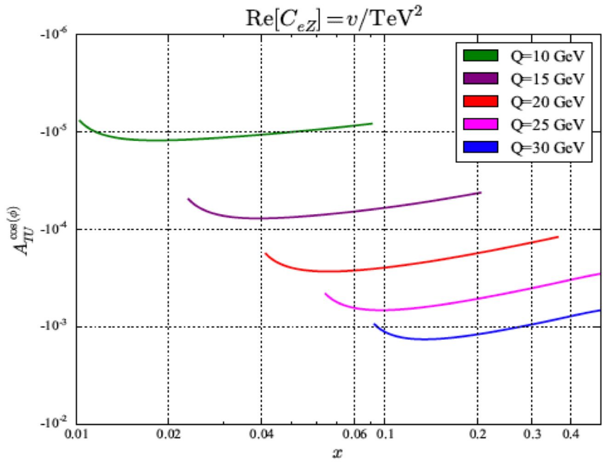
SMEFT-induced correction to beam normal asymmetry $\Rightarrow$

$$\Delta A_{TU}(\phi) = \frac{g_Z}{2\pi\alpha}\frac{Q^3}{M_Z^2}\frac{y\sqrt{1-y}}{1-y+\frac{y^2}{2}}\frac{\sum_q Q_q f_q(x)\left\{g_{aq}\mathrm{Re}[C_{eZ}e^{-i\phi}] - \frac{\mathrm{Re}[C_{e\gamma}e^{-i\phi}]}{s_W c_W}\left[g_{vq}g_{al}(1-2/y) - g_{aq}g_{vl}\right]\right\}}{\sum_q Q_q^2 f_q(x)}$$

$c_{e\gamma}$

Wilson coefficient of the operator that describes the anomalous magnetic and electric dipole moments of the electron




*Precision compared to size of asymmetry needs further evaluation

# Summary and Outlook

- ➔ There are many interesting Electroweak and BSM physics topics to explore for the future EIC!
- ➔ Completed and ongoing impact studies with ePIC
  - R. Boughezal et al., Neutral-current electroweak physics and SMEFT studies at the EIC, Phys. Rev. D
  - J. Zhang et. al, Charged Lepton Flavor Violation Study at the EIC, in Electroweak and BSM physics at the EIC
  - R. Boughezal, D. de Florian, F. Petriello, and W. Vogelsang, Transverse spin asymmetries at the EIC as a probe of anomalous electric and magnetic dipole moments, Phys. Rev. D 107, 075028 (2023)
  - 1 prong study of CLFV - Andrew Hurley (UMass Amherst)
- ➔ Future work
  - Dark photons, 1 prong study of CLFV, precision of SMEFT indued asymmetry, etc.…
- ➔ Interested in Electroweak & BSM physics at the EIC
  - Electroweak & BSM working group (Ciprian Gal and Juliette Mammei)
  - eic-projdet-inclusive-l@lists.bnl.gov & eic-projdet-bsmew-l@lists.bnl.gov

## ep Results

| Beam type and energy<br>Label | $ep$ 5 × 100<br>P2 | $ep$ 10 × 100<br>P3 | $ep$ 10 × 275<br>P4 | $ep$ 18 × 275<br>P5 | $ep$ 18 × 275<br>P6 |
|---|---|---|---|---|---|
| Luminosity ($fb^{-1}$) | 36.8 | 44.8 | 100 | 15.4 | (100 YR ref) |
| $\langle Q^2 \rangle$ ($GeV^2$) | 154.4 | 308.1 | 687.3 | 1055.1 | 1055.1 |
| $\langle A_{PV} \rangle$ ($P_e = 0.8$) | −0.00854 | −0.01617 | −0.03254 | −0.04594 | −0.04594 |
| $(dA/A)_{stat}$ | 1.54% | 0.98% | 0.40% | 0.80% | (0.31%) |
| $(dA/A)_{stat+syst(bg)}$ | 1.55% | 1.00% | 0.43% | 0.81% | (0.35%) |
| $(dA/A)_{1\%pol}$ | 1.0% | 1.0% | 1.0% | 1.0% | (1.0%) |
| $(dA/A)_{tot}$ | 1.84% | 1.42% | 1.09% | 1.29% | (1.06%) |
| Experimental | | | | | |
| $d(\sin^2\theta_W)_{stat+syst(bg)}$ | 0.002032 | 0.001299 | 0.000597 | 0.001176 | 0.000516 |
| $d(\sin^2\theta_W)_{stat+syst+pol}$ | 0.002342 | 0.001759 | 0.001297 | 0.001769 | 0.001244 |
| with PDF | | | | | |
| $d(\sin^2\theta_W)_{tot,CT18NLO}$ | 0.002388 | 0.001807 | 0.001363 | 0.001823 | 0.001320 |
| $d(\sin^2\theta_W)_{tot,MMHT2014}$ | 0.002353 | 0.001771 | 0.001319 | 0.001781 | 0.001270 |
| $d(\sin^2\theta_W)_{tot,NNPDF31}$ | 0.002351 | 0.001789 | 0.001313 | 0.001801 | 0.001308 |

## eD Results

| Beam type and energy<br>Label | $eD$ 5 × 100<br>D2 | $eD$ 10 × 100<br>D3 | $eD$ 10 × 137<br>D4 | $eD$ 18 × 137<br>D5 | $eD$ 18 × 137<br>N/A |
|---|---|---|---|---|---|
| Luminosity ($fb^{-1}$) | 36.8 | 44.8 | 100 | 15.4 | (10 YR ref) |
| $\langle Q^2 \rangle$ ($GeV^2$) | 160.0 | 316.9 | 403.5 | 687.2 | 687.2 |
| $\langle A_{PV} \rangle$ ($P_e = 0.8$) | −0.01028 | −0.01923 | −0.02366 | −0.03719 | −0.03719 |
| $(dA/A)_{stat}$ | 1.46% | 0.93% | 0.54% | 1.05% | (1.31%) |
| $(dA/A)_{stat+bg}$ | 1.47% | 0.95% | 0.56% | 1.07% | (1.32%) |
| $(dA/A)_{syst,1\%pol}$ | 1.0% | 1.0% | 1.0% | 1.0% | (1.0%) |
| $(dA/A)_{tot}$ | 1.78% | 1.38% | 1.15% | 1.46% | (1.66%) |
| Experimental | | | | | |
| $d(\sin^2\theta_W)_{stat+bg}$ | 0.002148 | 0.001359 | 0.000823 | 0.001591 | 0.001963 |
| $d(\sin^2\theta_W)_{stat+bg+pol}$ | 0.002515 | 0.001904 | 0.001544 | 0.002116 | 0.002414 |
| with PDF | | | | | |
| $d(\sin^2\theta_W)_{tot,CT18}$ | 0.002558 | 0.001936 | 0.001566 | 0.002173 | 0.00247 |
| $d(\sin^2\theta_W)_{tot,MMHT2014}$ | 0.002527 | 0.001917 | 0.001562 | 0.002128 | 0.002424 |
| $d(\sin^2\theta_W)_{tot,NNPDF31}$ | 0.002526 | 0.001915 | 0.001560 | 0.002127 | 0.002423 |