Weak Mixing Angle at the EIC

Michael Nycz

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

July 21-24

Outline

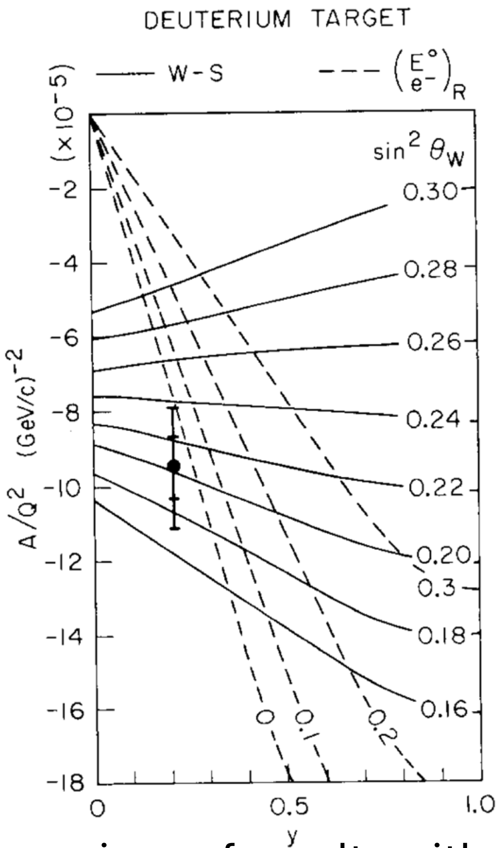
- Background & Motivation
- Summary of $\sin^2\theta_W$ measurements
  - Past, present, & future experiments
- Overview of $\sin^2\theta_W$ impact study at the EIC
- Summary and Outlook

Motivation: Weak Mixing Angle

- $\sin^2 \theta_W$: Fundamental parameter of the Standard Model

$$\sin^2 \theta_W^0 = e_0^2/g_0^2 = 1 - m_W^{02}/m_Z^{02}$$

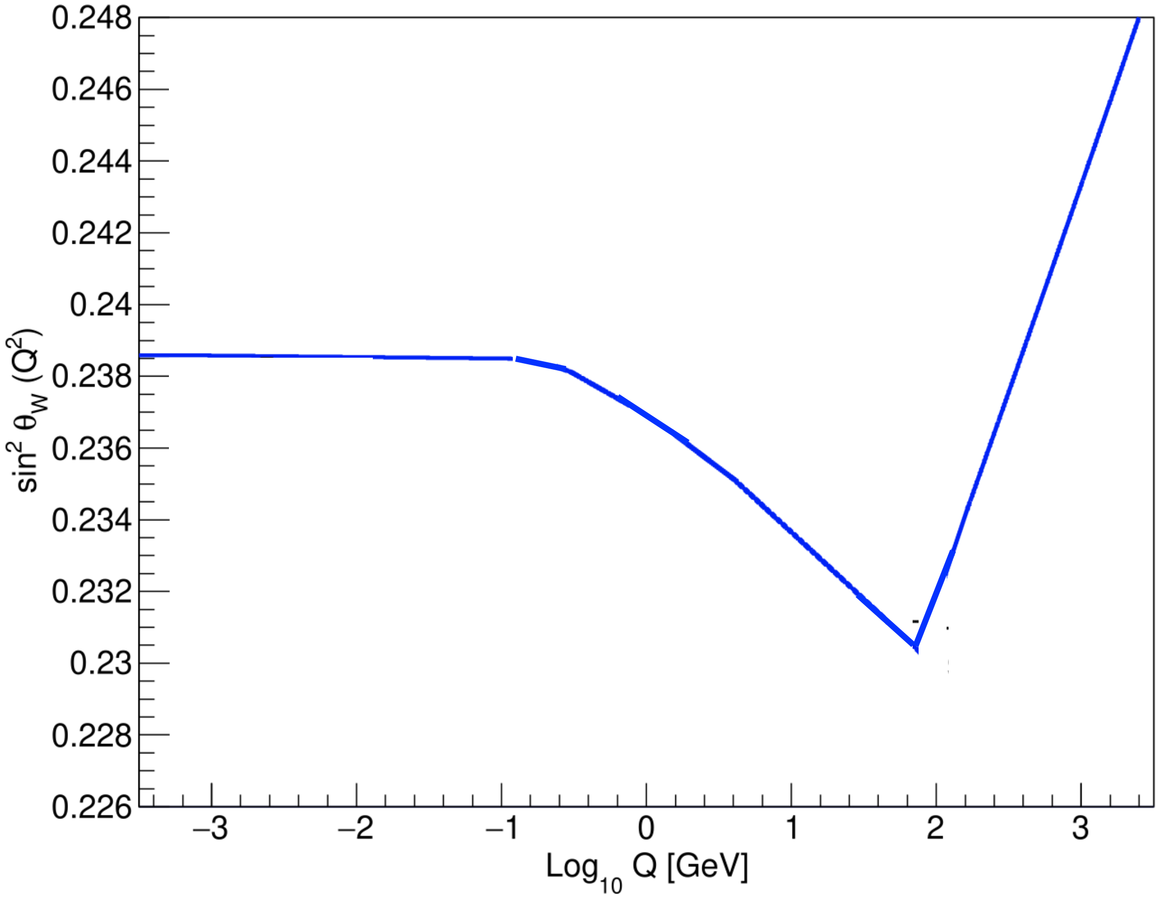
- Accessed through different measurements & energies
  - $e^- e^+$ collisions
  - Parity violation measurements
  - Atomic measurement
- (Potential) tension
  - SLC and LEP1
  - NuTeV
- High precision measurements
  - Beyond the Standard Model Physics searches



Comparison of results with SU(2)⨉U(1) theories
1. Weinberg-Salam (solid line)
2. Hybrid (dashed line

PARITY NON-CONSERVATION IN INELASTIC ELECTRON SCATTERIN

Running of the Weak Mixing Angle



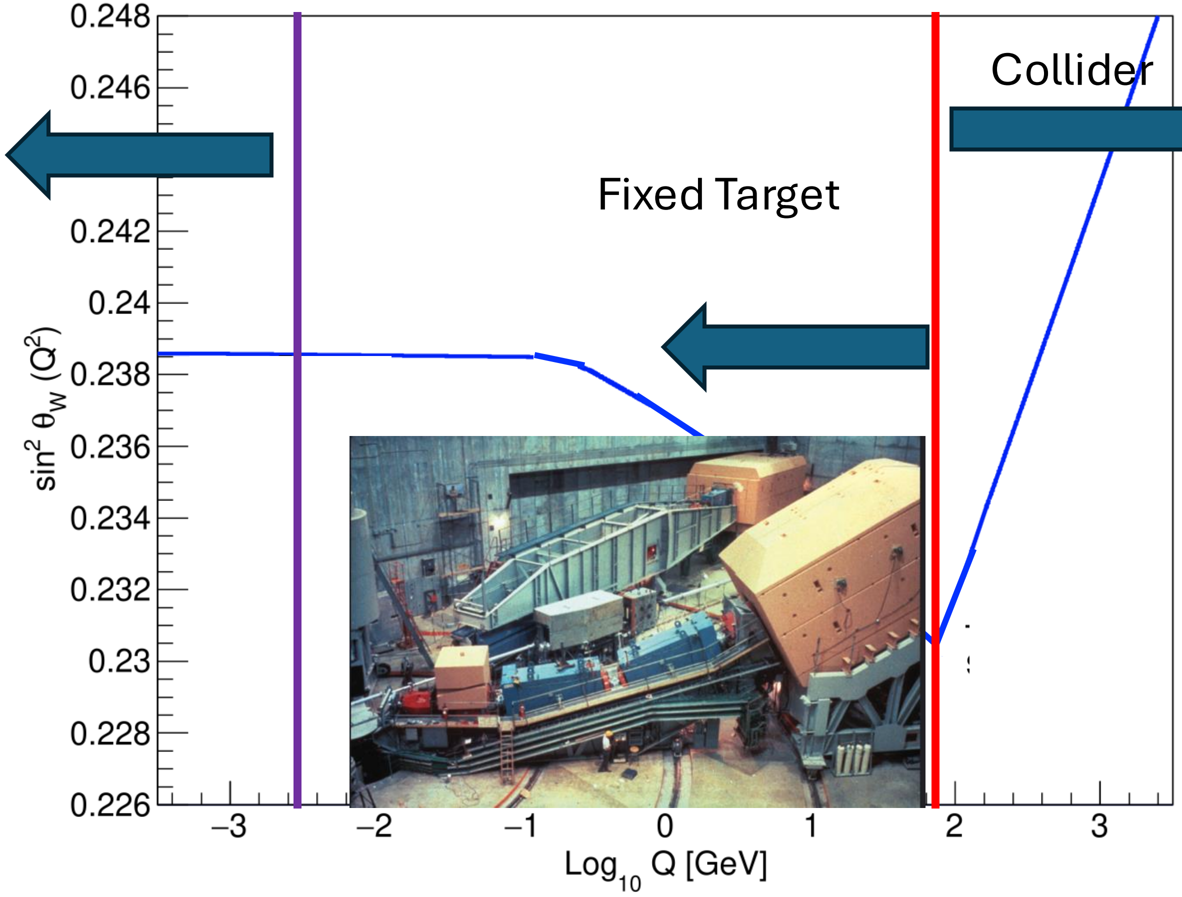
[Scale dependence of the weak mixing angle in ("MS") ̅renormalization scheme]

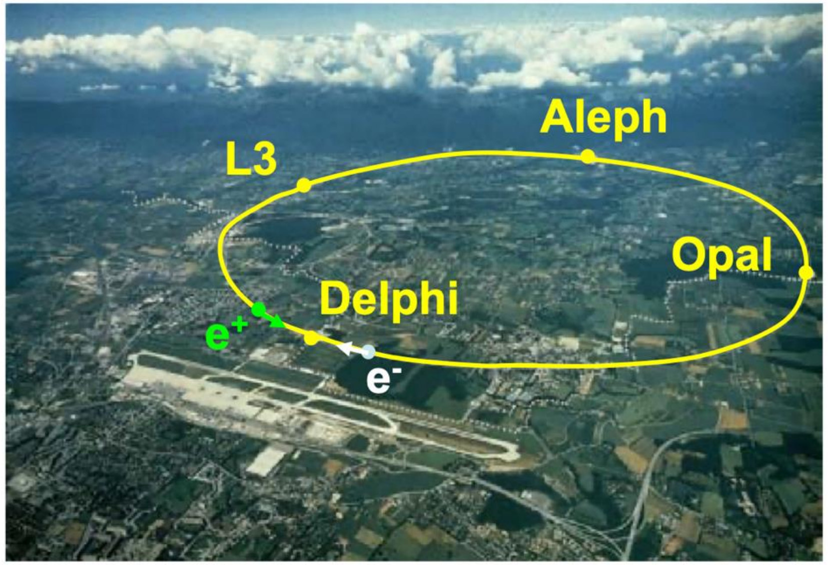
Weak Mixing Angle Measurements

Atomic Parity Violation

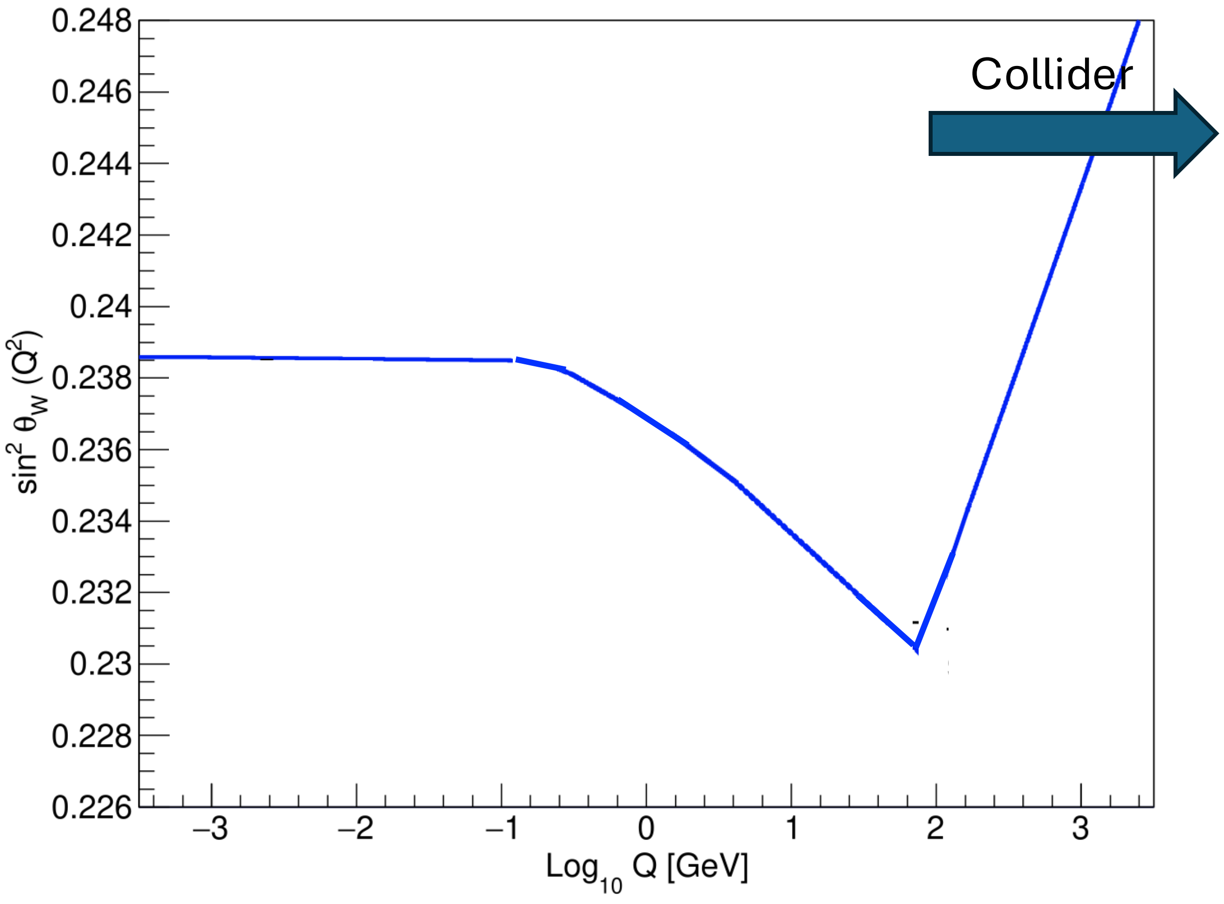
Fixed Target

Collider

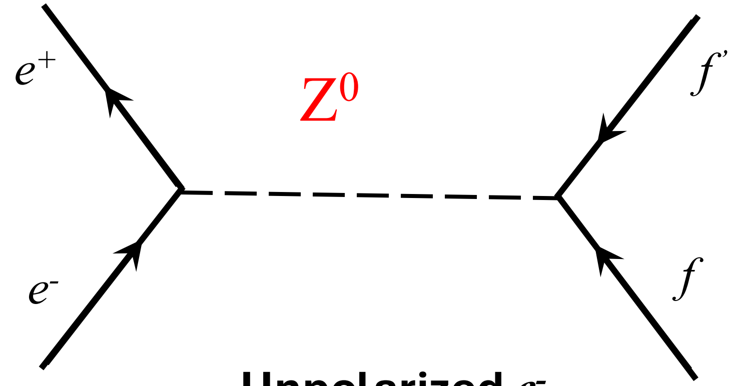




Weak Mixing Angle Measurements



LEP1



Unpolarized e^-

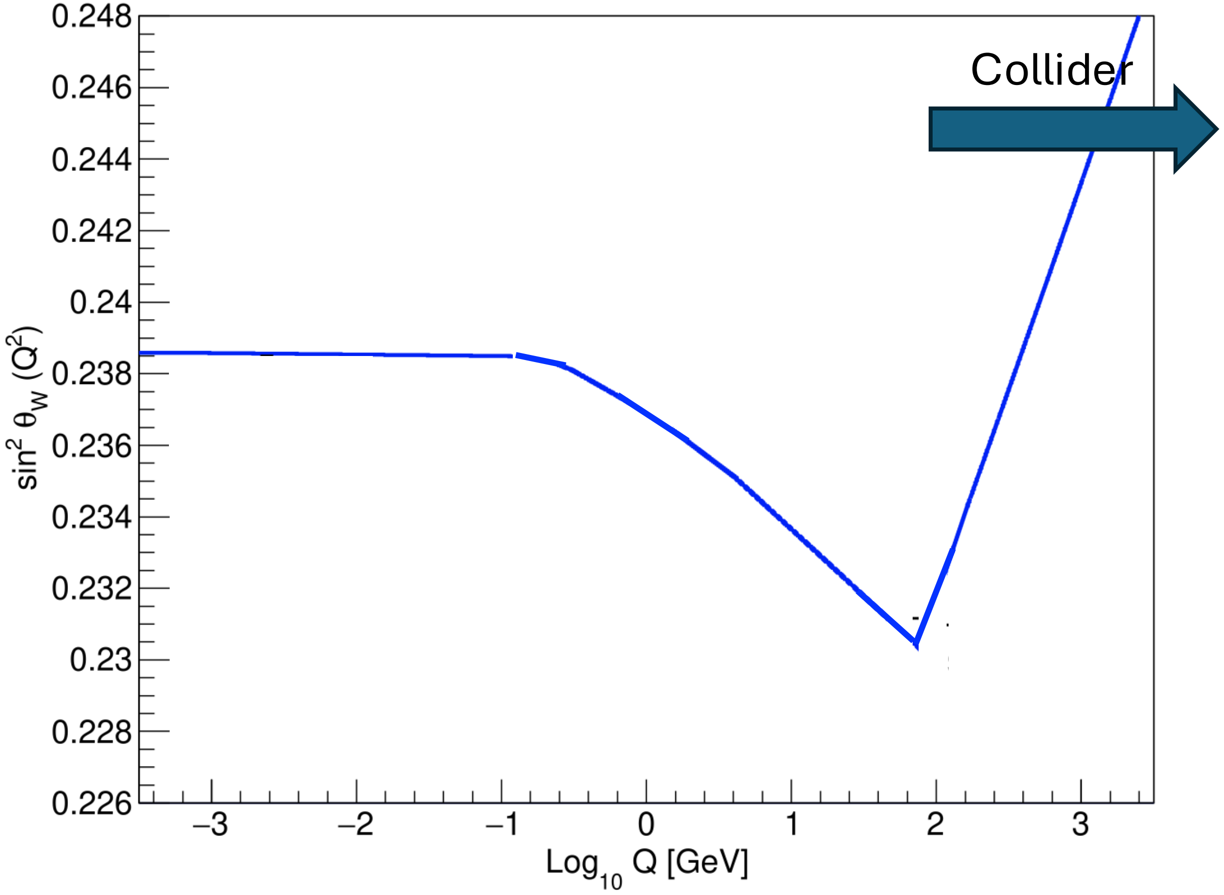
Backward-forward asymmetry

$$A_{FB}^0 = \frac{\sigma_F^f - \sigma_B^f}{\sigma_F^f + \sigma_B^f}$$

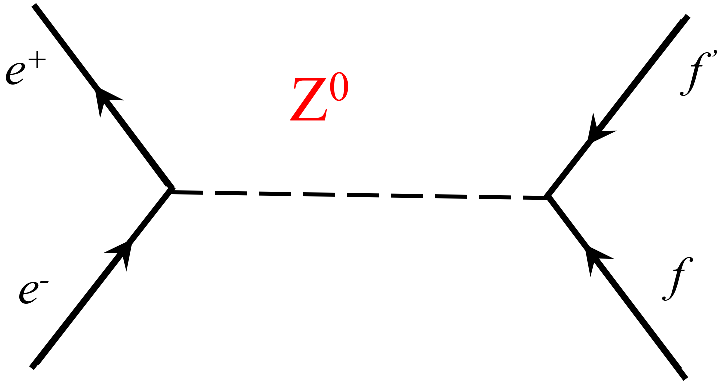
Asymmetry measured for final states:

1. $e^+ e^-$
2. $\mu^+ \mu^-$
3. $\tau^+ \tau^-$
4. $q\bar{q}$

Weak Mixing Angle Measurements



SLC



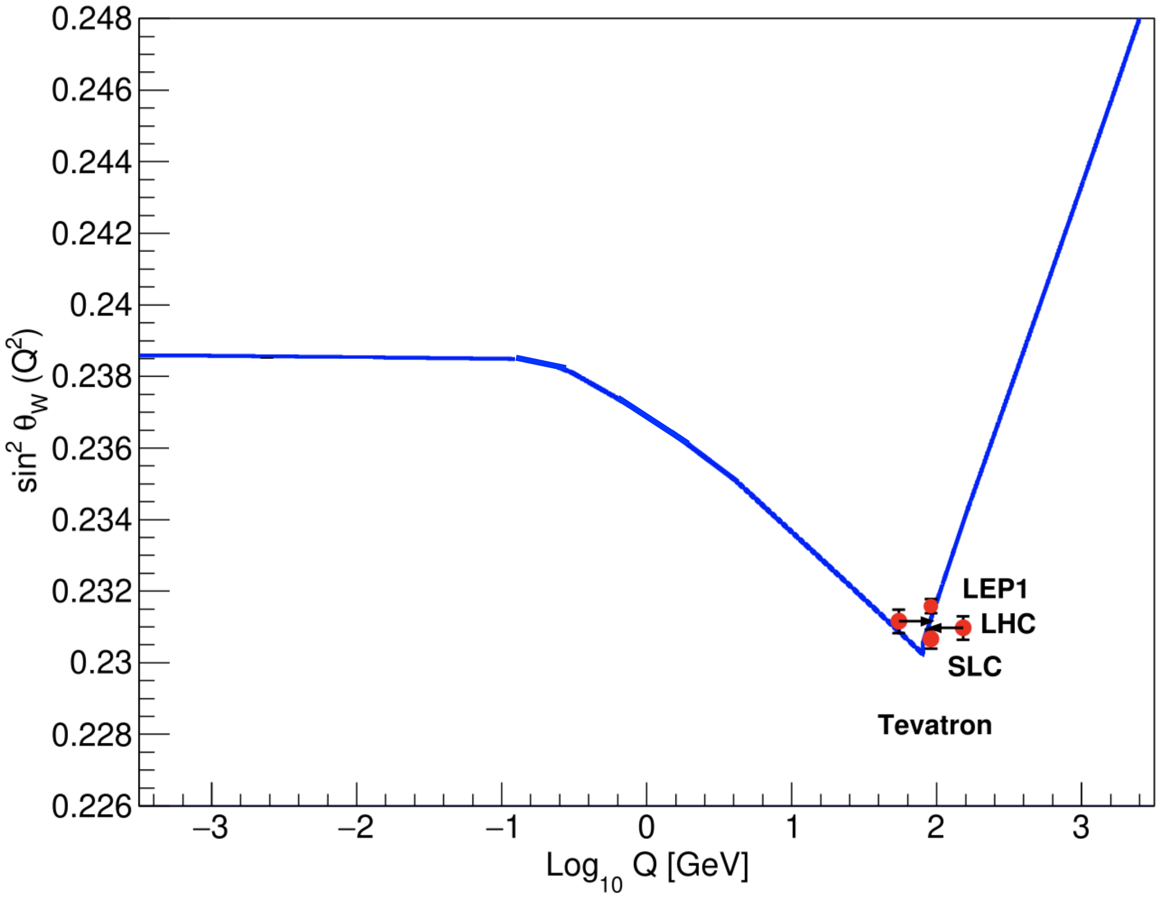
Polarized e^-

Left-right asymmetry

$$A^0_{LR} = \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R}$$

$$A^0_{LR} = \frac{2 v_e a_e}{v_e^2 + a_e^2} \equiv \frac{2\left[1 - 4\sin^2\theta_W^{\text{eff}}\right]}{1 + \left[1 - 4\sin^2\theta_W^{\text{eff}}\right]^2}$$

Weak Mixing Angle Measurements



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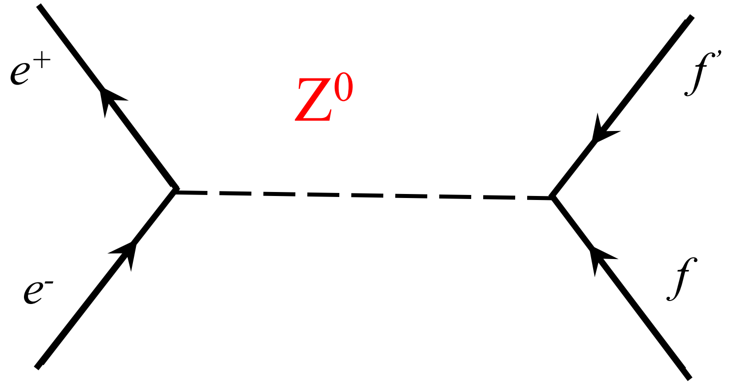

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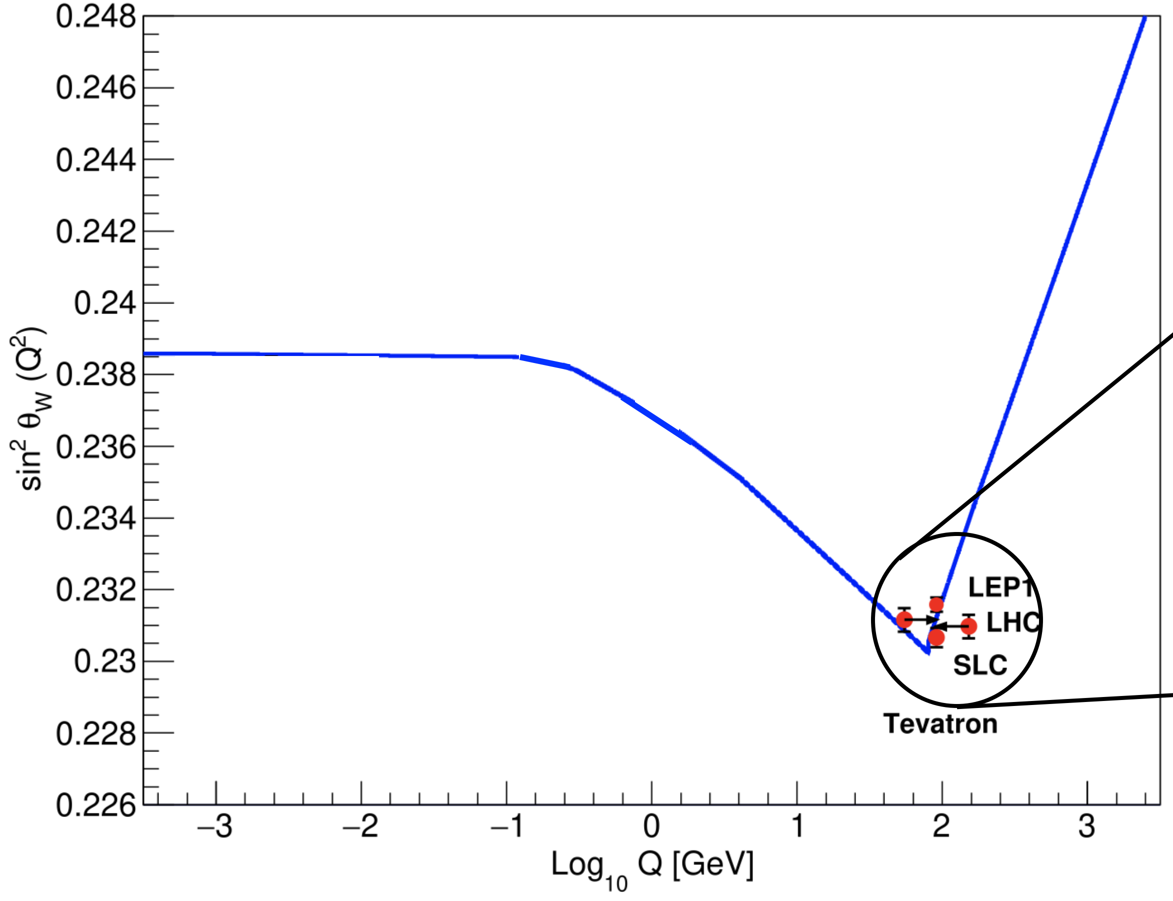
Weak Mixing Angle Measurements

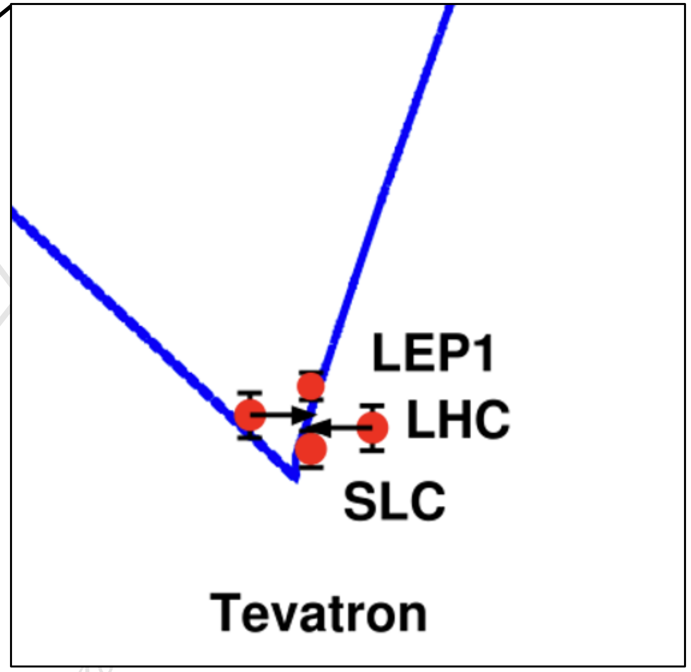
SLD at Stanford Linear Collider

e- e+ collisions (near Z pole)

Z measured through decay of Z to -> tau+ tau-

e- polarized

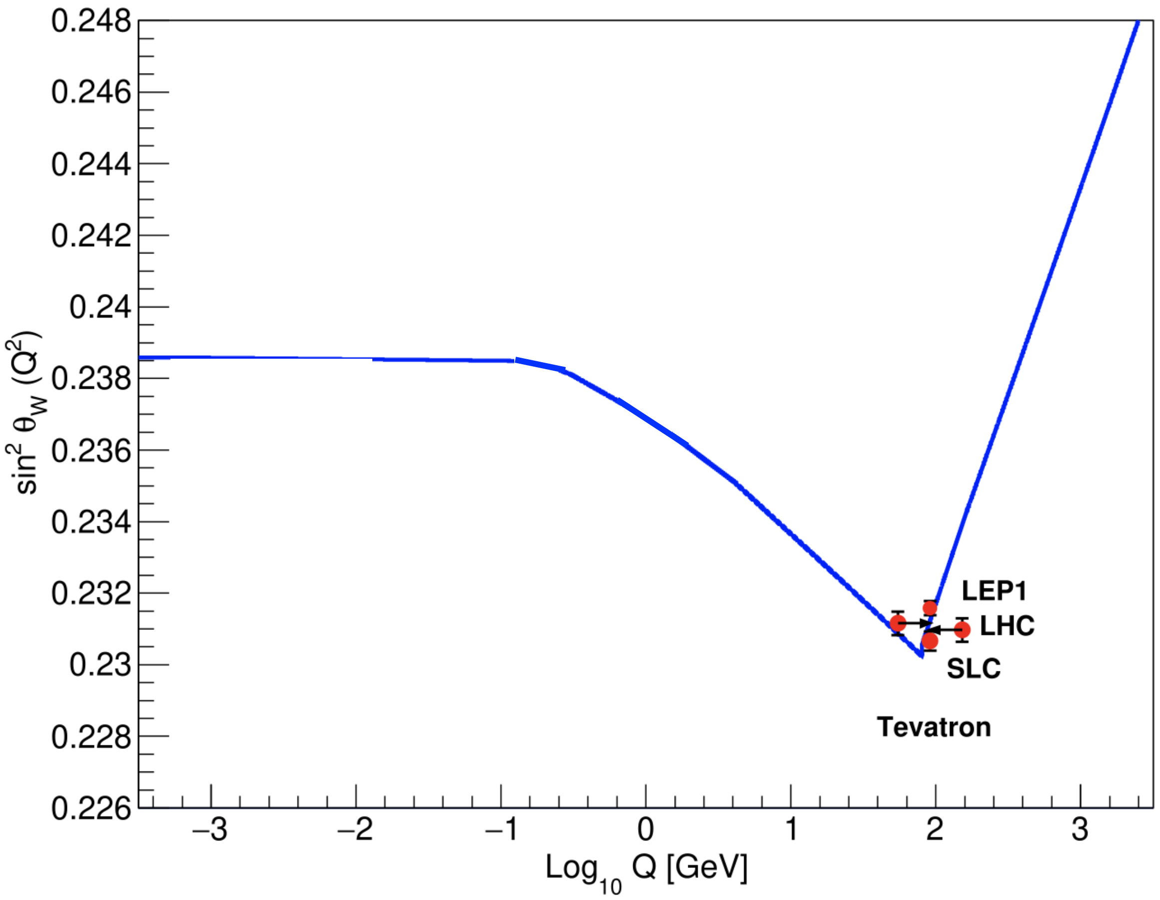


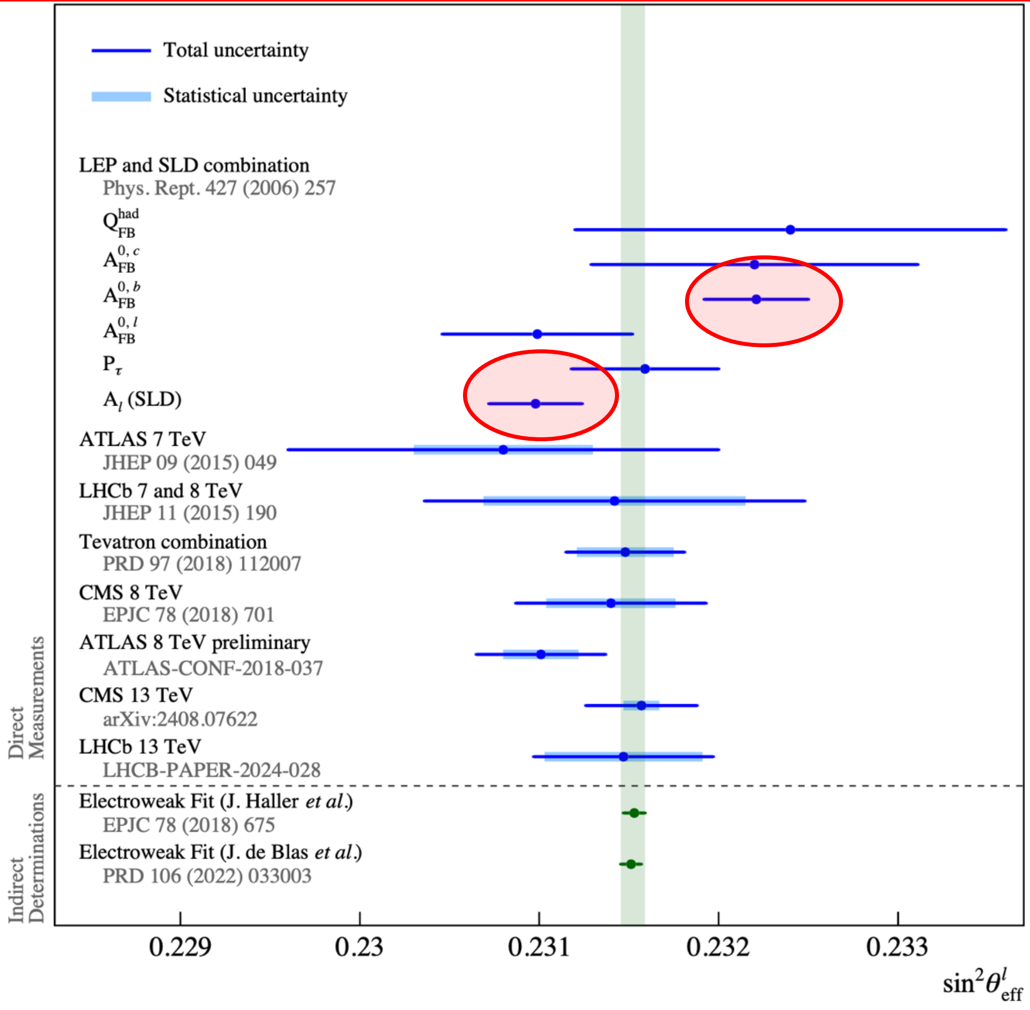


LEP1 and SLC: ~3.2 σ difference

$$A_{LR}^0 = \frac{2 v_e a_e}{v_e^2 + a_e^2} \equiv \frac{2\left[1 - 4\sin^2\theta_W^{\mathrm{eff}}\right]}{1 + \left[1 - 4\sin^2\theta_W^{\mathrm{eff}}\right]^2}$$

Weak Mixing Angle Measurements



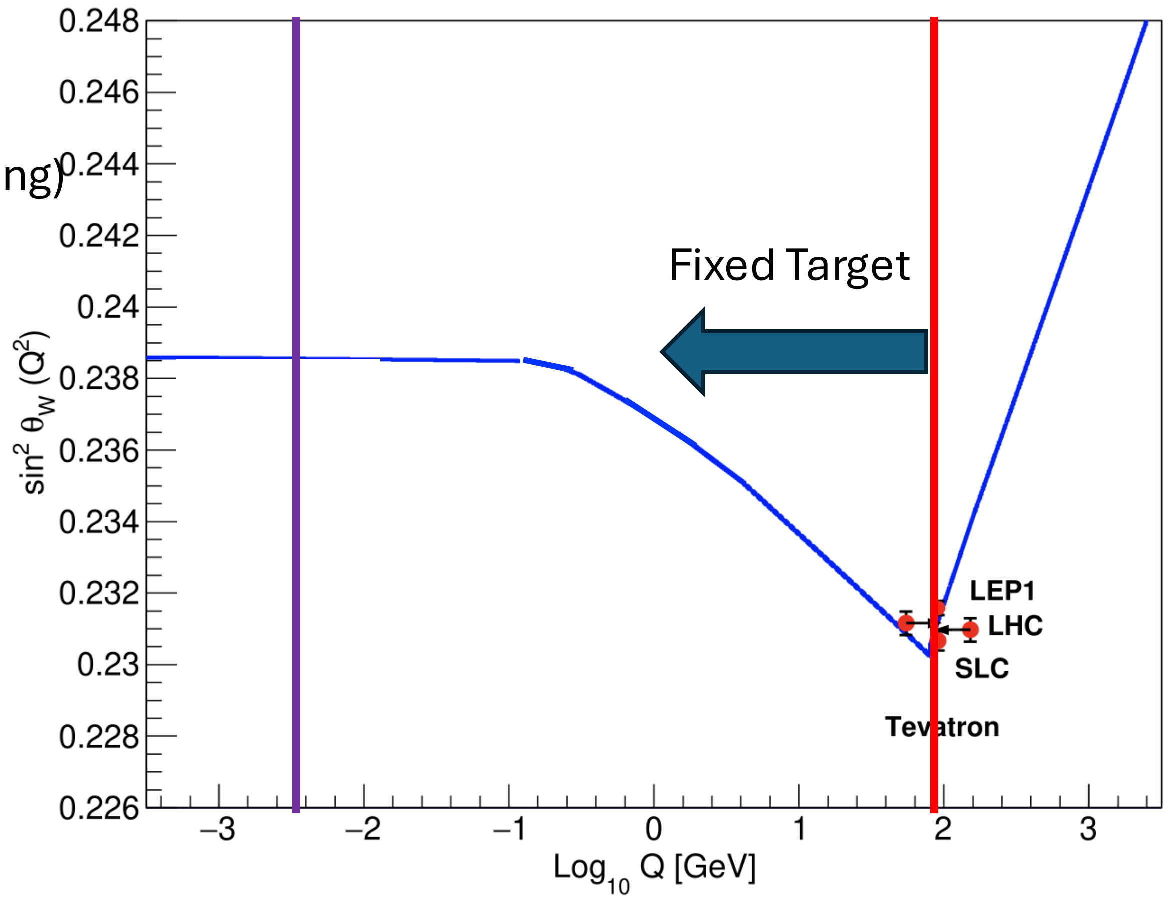


Weak Mixing Angle Measurements

<u>PVES</u>

1. Lepton-lepton scattering (Moller scattering)
2. Lepton-proton (elastic)
3. Lepton-deuteron (deep inelastic)

- Longitudinally polarized electron
- γ-Z interference



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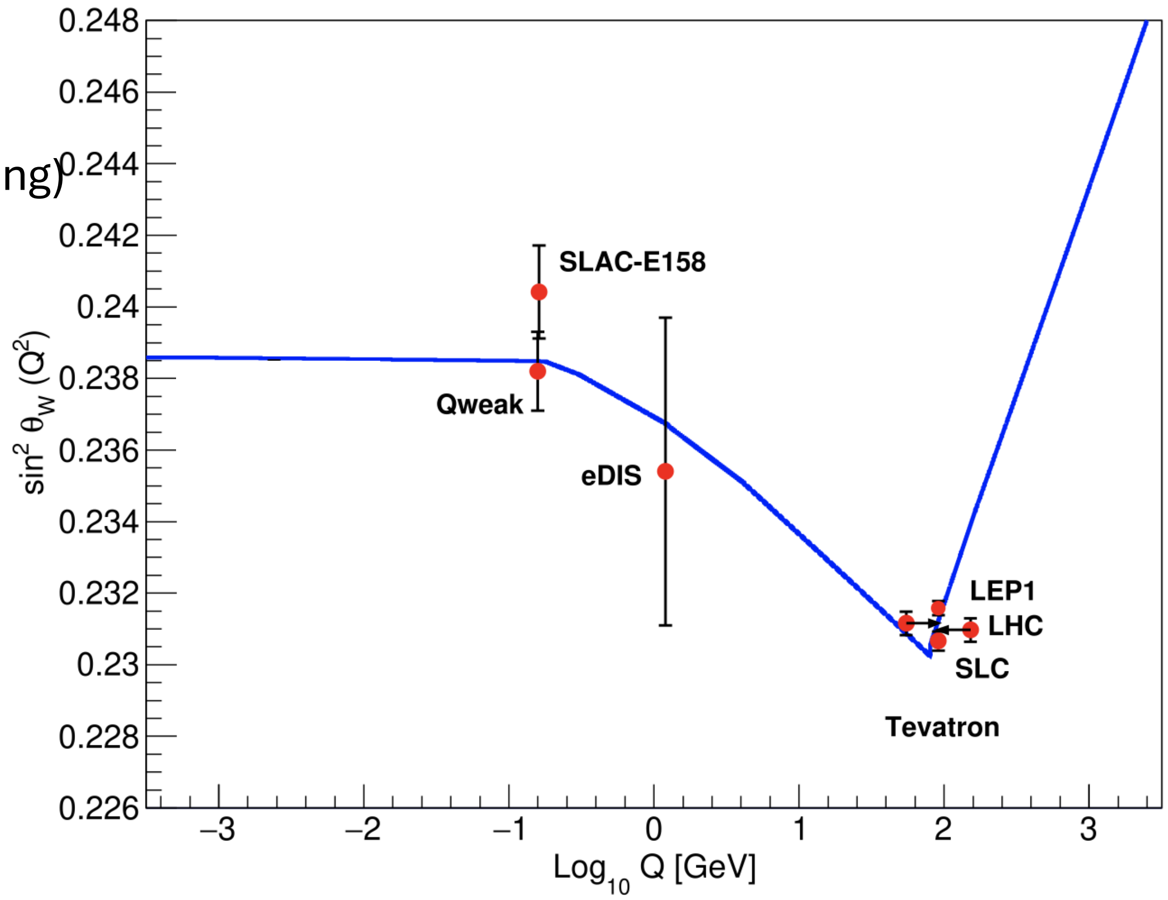

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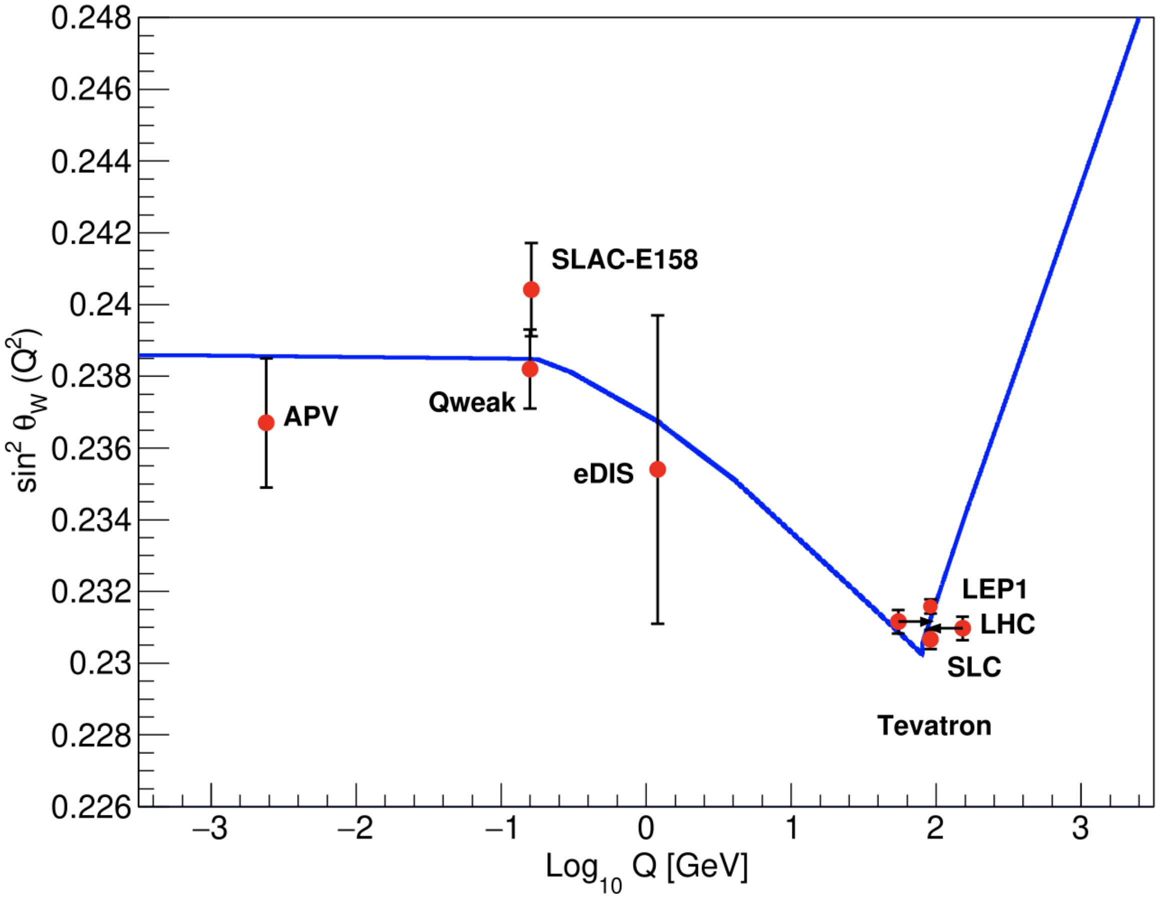

Future Measurements

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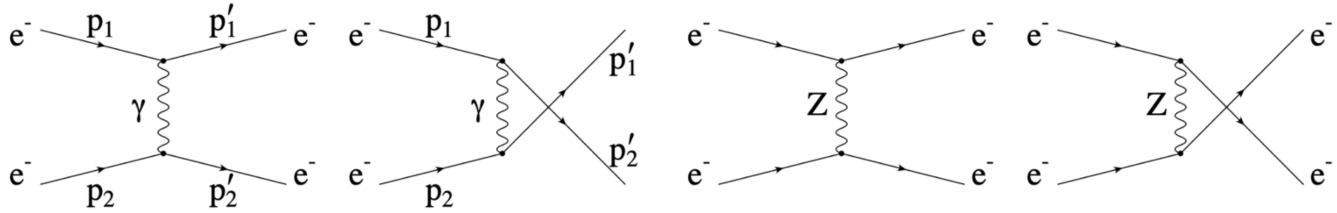
The MOLLER Experiment

- A_{PV} in Møller scattering
- Purely leptonic
- "Ultra-precise measurement of $\sin^2(\theta_W)$"



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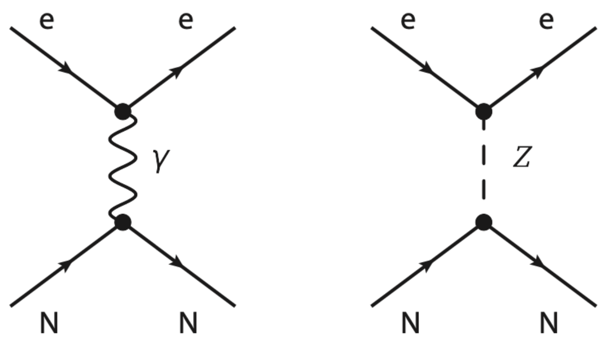

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- 2 % in weak proton charge
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Parity-Violation DIS with SoLID

- A_{PV} in in DIS e^--**deuteron** scattering

1. **Independent of pdfs**, x W
2. Well-defined SM prediction for Q^2 & y
3. PVDIS Asymmetry is sensitive to both g_{VA}^{eq} and g_{AV}^{eq}
4. PVES (elastic) Asymmetry only sensitive to g_{AV}^{eq}

Low energy electron-quark effective couplings

- $g_{AV}^{eu} = 2g_A^e g_V^u = -\frac{1}{2} + \frac{4}{3}\sin^2\theta_W$
- $g_{VA}^{eu} = 2g_V^e g_A^u = -\frac{1}{2} - 2\sin^2\theta_W$
- $g_{AV}^{ed} = 2g_A^e g_V^d \approx -\frac{1}{2} + \frac{2}{3}\sin^2\theta_W$
- $g_{VA}^{ed} = 2g_V^e g_A^d \approx \frac{1}{2} - 2\sin^2\theta_W$

Future Measurements

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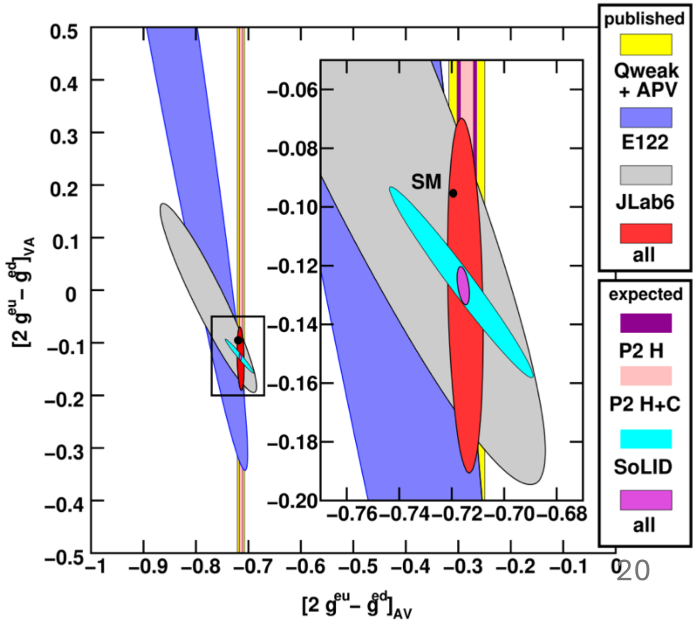
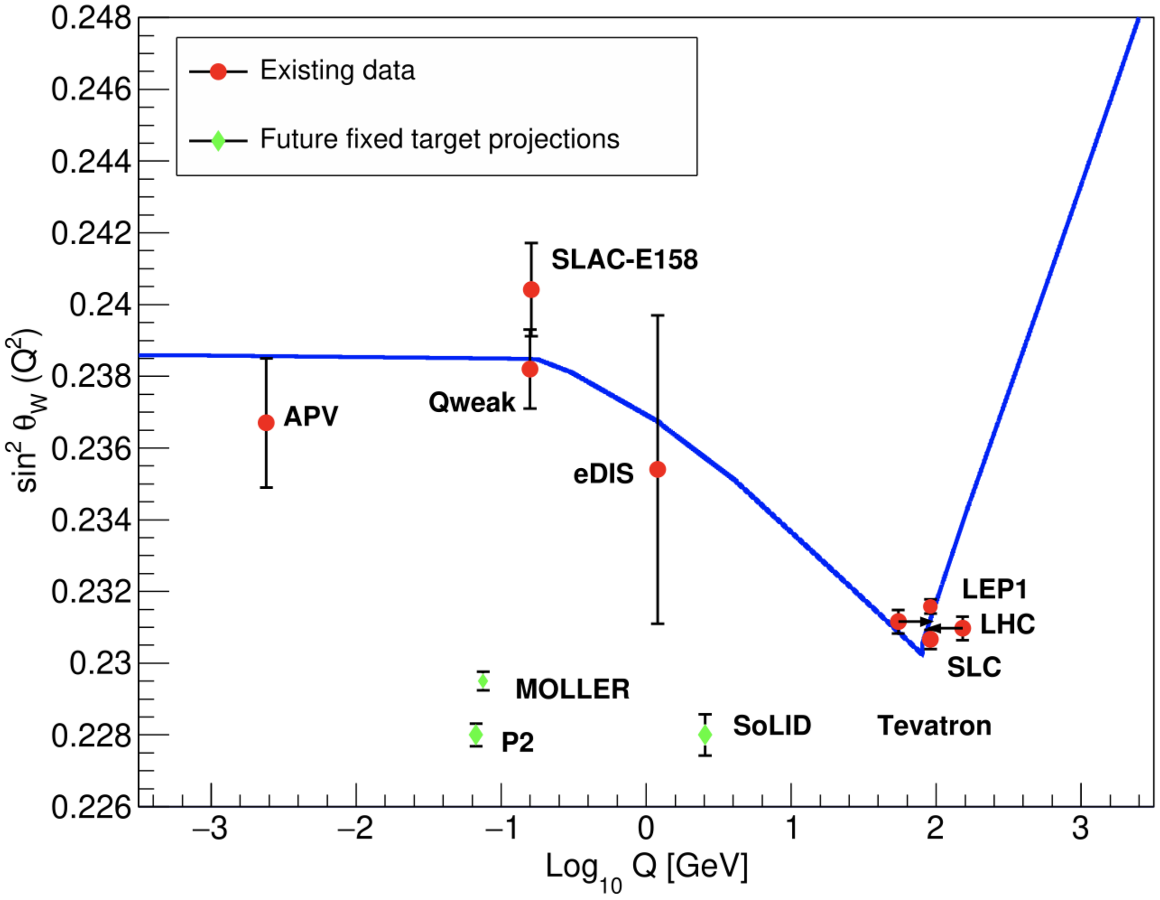


Weak Mixing Angle Measurements



Weak Mixing Angle at the EIC

- PVDIS
- Impact Study

Neutral-current electroweak physics and SMEFT studies at the EIC

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Parity Violation DIS

$$A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L}$$

$\sigma_{R,L}$: cross sections of right- and left-handed electrons

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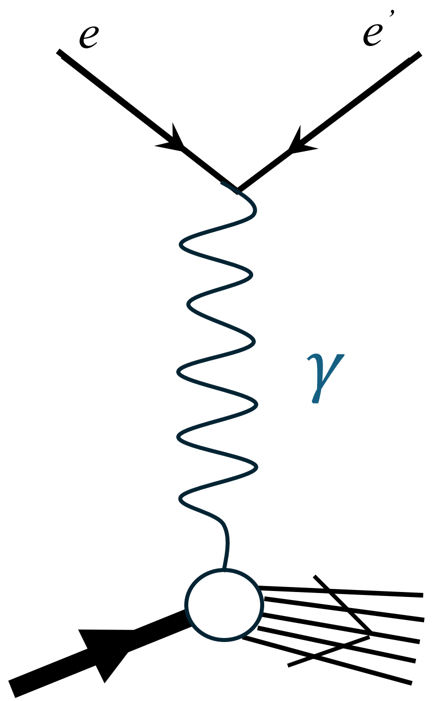
EM Interaction

Parity conserving



Parity Violation DIS

$$A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L}$$

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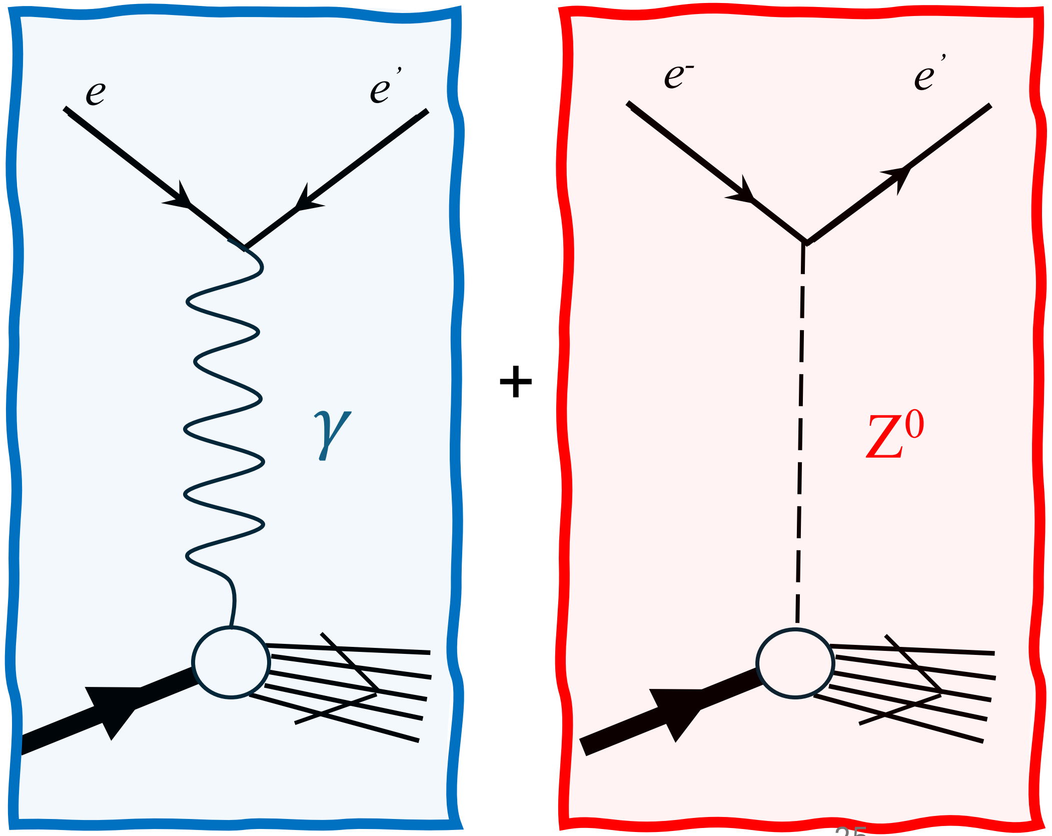
A_{PV} is due to the interference between electromagnetic and weak interaction

EM Interaction — Parity conserving

Weak Interaction — Parity violating



Parity Violation DIS

$$A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L}$$

$\sigma_{R,L}$: cross sections of right- and left-handed electrons

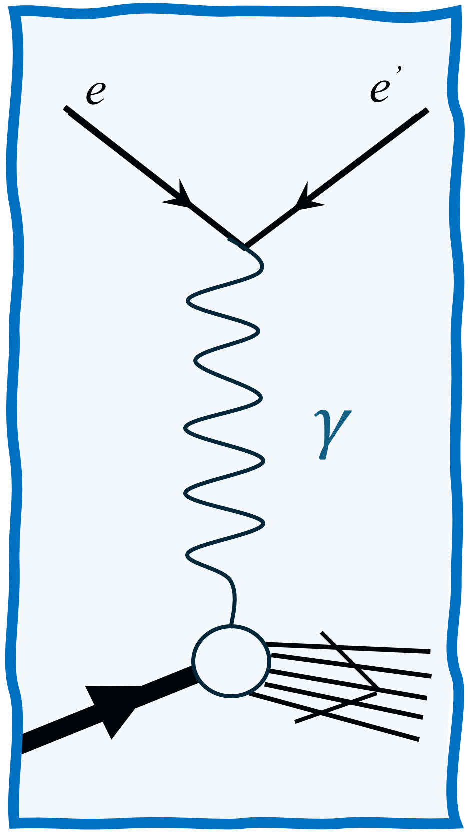
A_{PV} is due to the interference between electromagnetic and weak interaction

$$\sigma_R \propto \left|M_{EM} + M_Z^R\right|^2$$
$$\sigma_L \propto \left|M_{EM} + M_Z^L\right|^2$$

$$A_{PV} \sim \frac{M_Z^R - M_Z^L}{M_{EM}}$$

EM Interaction

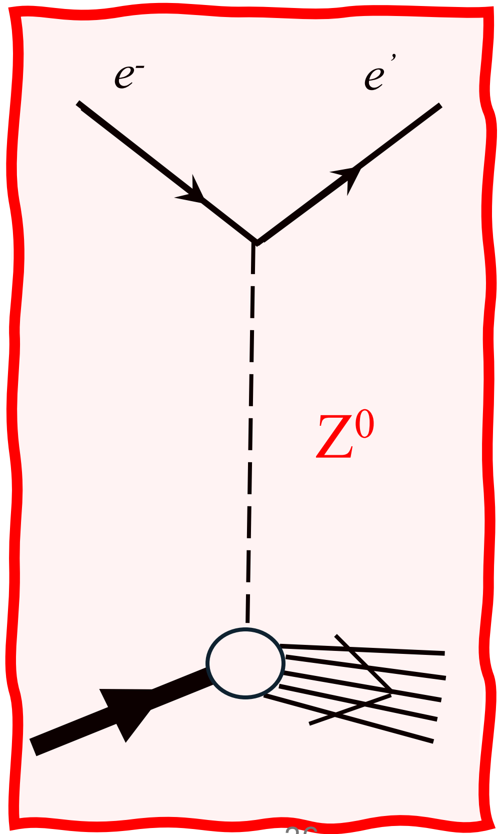
Parity conserving



+

Weak Interaction

Parity violating



PVDIS Asymmetry at the EIC

$$A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L}$$

Polarized cross section

$$\frac{d^2\sigma_0}{dxdy} = \frac{4\pi\alpha^2}{xyQ^2}\left\{xy^2\left[F_1^{\gamma} - g_V^e\eta_{\gamma Z}F_1^{\gamma Z} + \left(g_V^{e^2} + g_A^{e^2}\right)\eta_Z F_1^Z\right] + (1-y)\left[F_2^{\gamma} - g_V^e\eta_{\gamma Z}F_2^{\gamma Z} + \left(g_V^{e^2} + g_A^{e^2}\right)\eta_Z F_2^Z\right] - \frac{xy}{2}(2-y)\left[g_A^e\eta_{\gamma Z}F_3^{\gamma Z} - 2g_V^e g_A^e\eta_Z F_3^Z\right]\right\}$$

PVDIS Asymmetry at the EIC

$$A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L}$$

$$\frac{\text{Polarized cross section}}{\text{Unpolarized cross section}}$$

$$\frac{d^2\sigma_e}{dxdy} = \frac{4\pi\alpha^2}{xyQ^2}\left\{\left[g_A^e \eta_{\gamma Z} F_1^{\gamma Z} - 2 g_V^e g_A^e \eta_Z F_1^Z\right] + (1-y)\left[g_A^e \eta_{\gamma Z} F_2^{\gamma Z} - 2 g_V^e g_A^e \eta_Z F_2^Z\right] + \frac{xy}{2}(2-y)\left[g_V^e \eta_{\gamma Z} F_3^{\gamma Z} - \left(g_V^{e^2} + g_A^{e^2}\right)\eta_Z F_3^Z\right]\right\}$$

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PVDIS Asymmetry at the EIC

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

Where

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

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

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

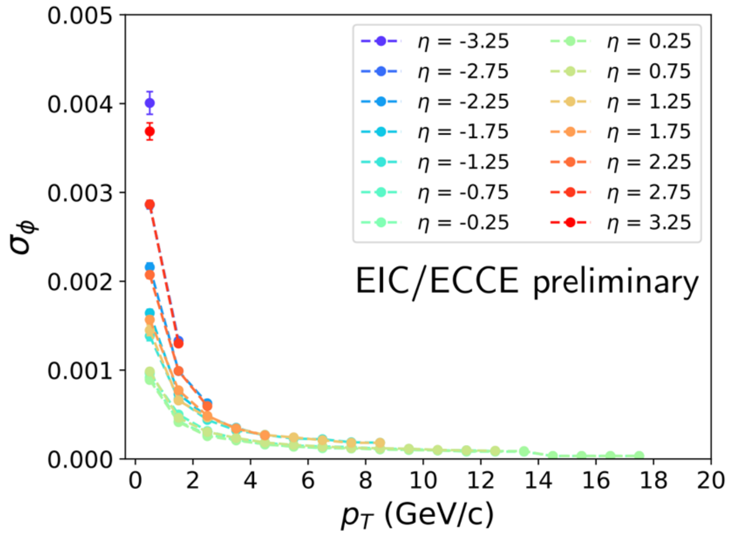
$$g_V^e = -\frac{1}{2} + 2\sin^2\theta_W \qquad g_V^q = \pm\frac{1}{2} - 2e_q \sin^2\theta_W$$

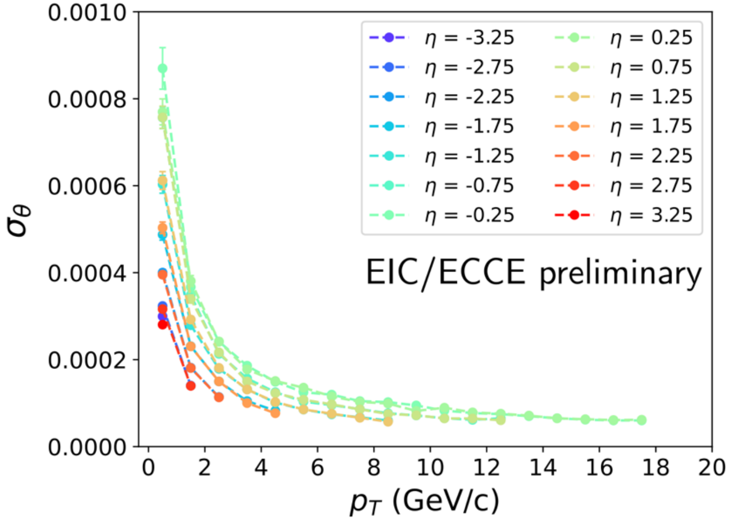
$$\eta_{\gamma Z} = \frac{G_F Q^2}{2\sqrt{2}\pi\alpha}\frac{M_Z^2}{M_Z^2 + Q^2}$$

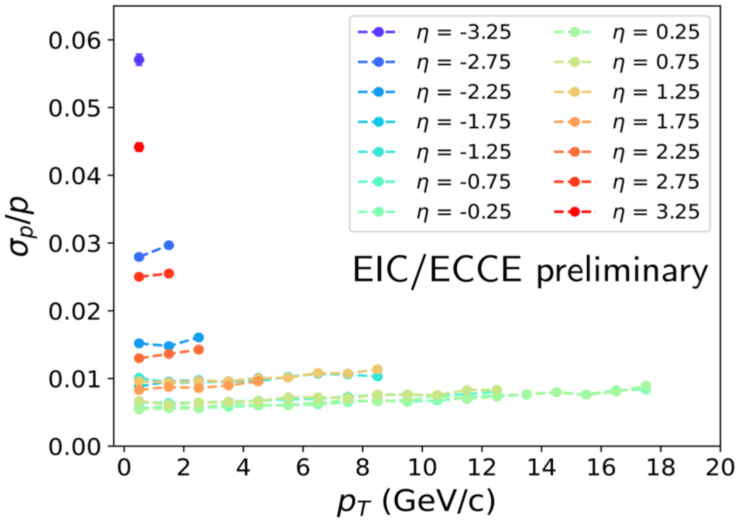
$g_A^{e(q)}$ and $g_V^{e(q)}$ are the : axial and vector neutral weak couplings of the electron (quark)

Weak Mixing Angle: Sensitivity of the EIC

- Single event gun simulation
  - Detector fast smearing
- Proton & Deuteron targets
- DJANGOH event generator
- Pseudo-data generation
  - Statistical, experimental, and PDF uncertainties
- **$\sin^2(\theta_W)$ extraction from fit**







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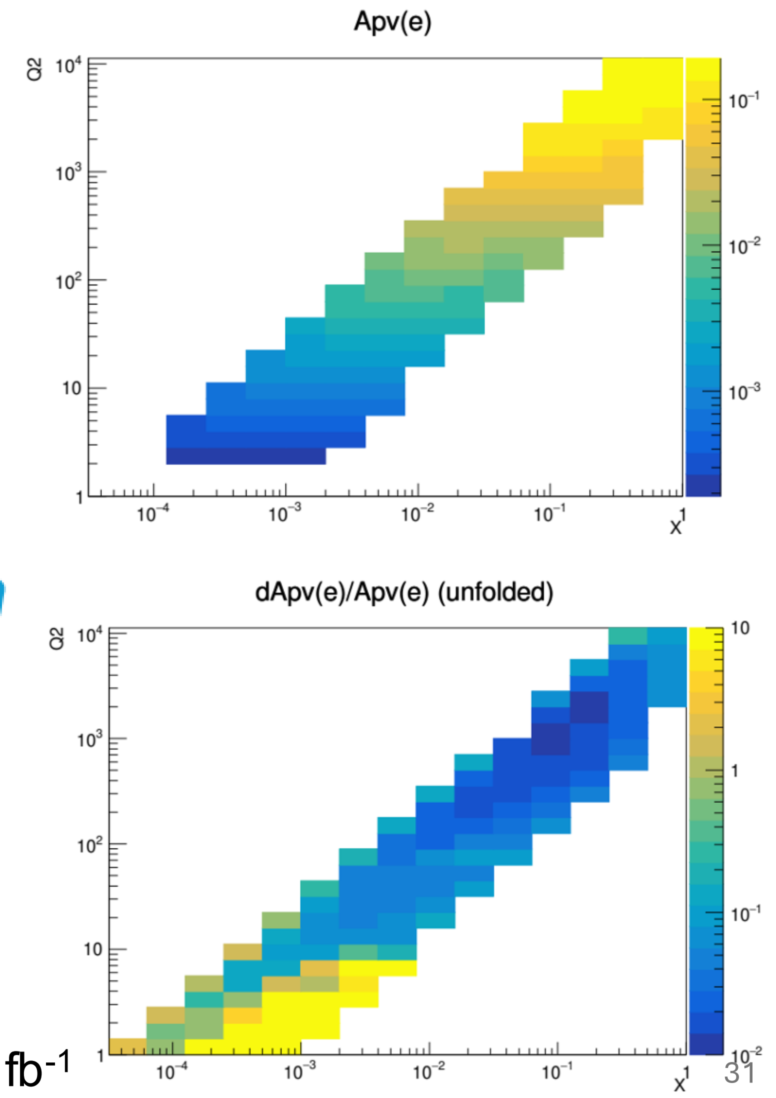
Event selection

- Q^2_{det}>1.0 GeV2
- y_{det}>0.1 & y_{det} <0.9
- η_{det} >-3.5 and η_{det} <3.5

e+p (18x275)
Integrated Luminosity • 100 fb^{-1}



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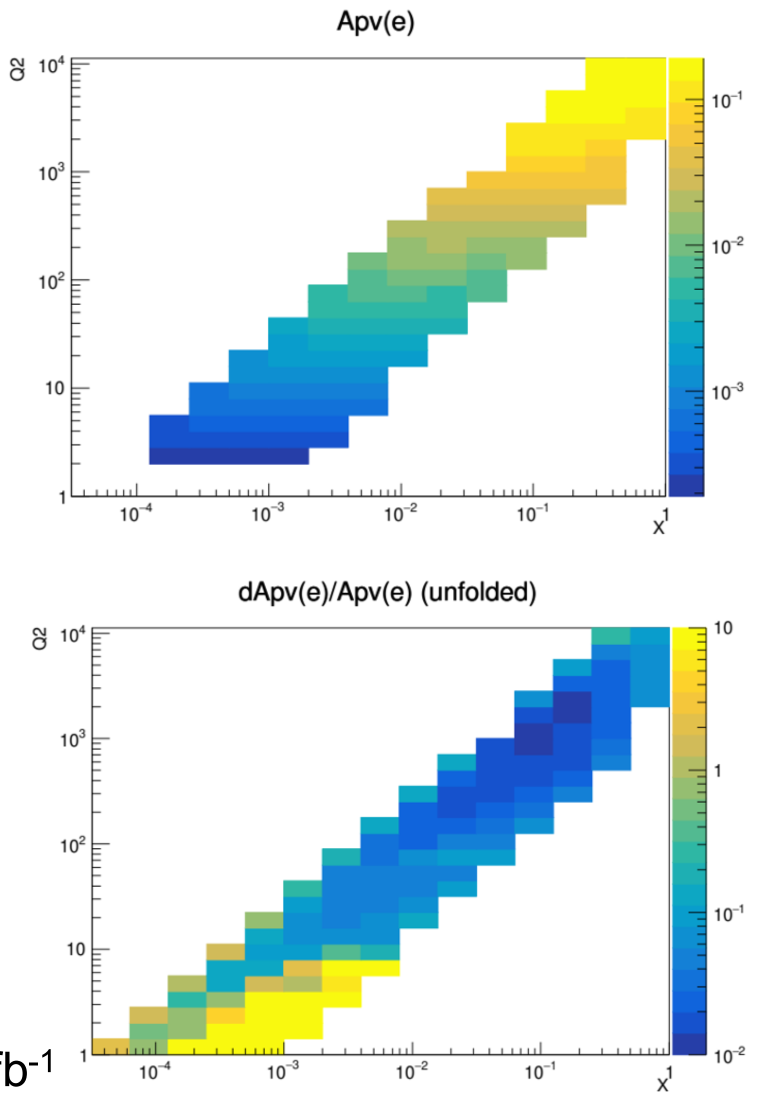

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Weak Mixing Angle EIC: Choice of targets

Jlab PVDIS (6 GeV) & **SoLID** PVDIS: Deuteron target ✓

$$A_{PV} = -\frac{G_F Q^2}{4\sqrt{2}\pi\alpha}\left[a_1(x) + a_3(x)Y\right]$$

For an Isoscalar Deuteron target, A_{PV} reduces to: **Independent of pdfs**, x W

$$\rightarrow A_{PV,(d)}^{SM} = \frac{3G_F Q^2}{10\sqrt{2}\pi\alpha}\left[\left(2g_{AV}^{eu} - g_{AV}^{ed}\right) + R_V Y\left(2g_{VA}^{eu} - g_{VA}^{ed}\right)\right]$$

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- Anticipation of precision data of EIC – improved PDFs
  - Potential to measure A_{PV} of the proton as well: Hydrogen target ✓

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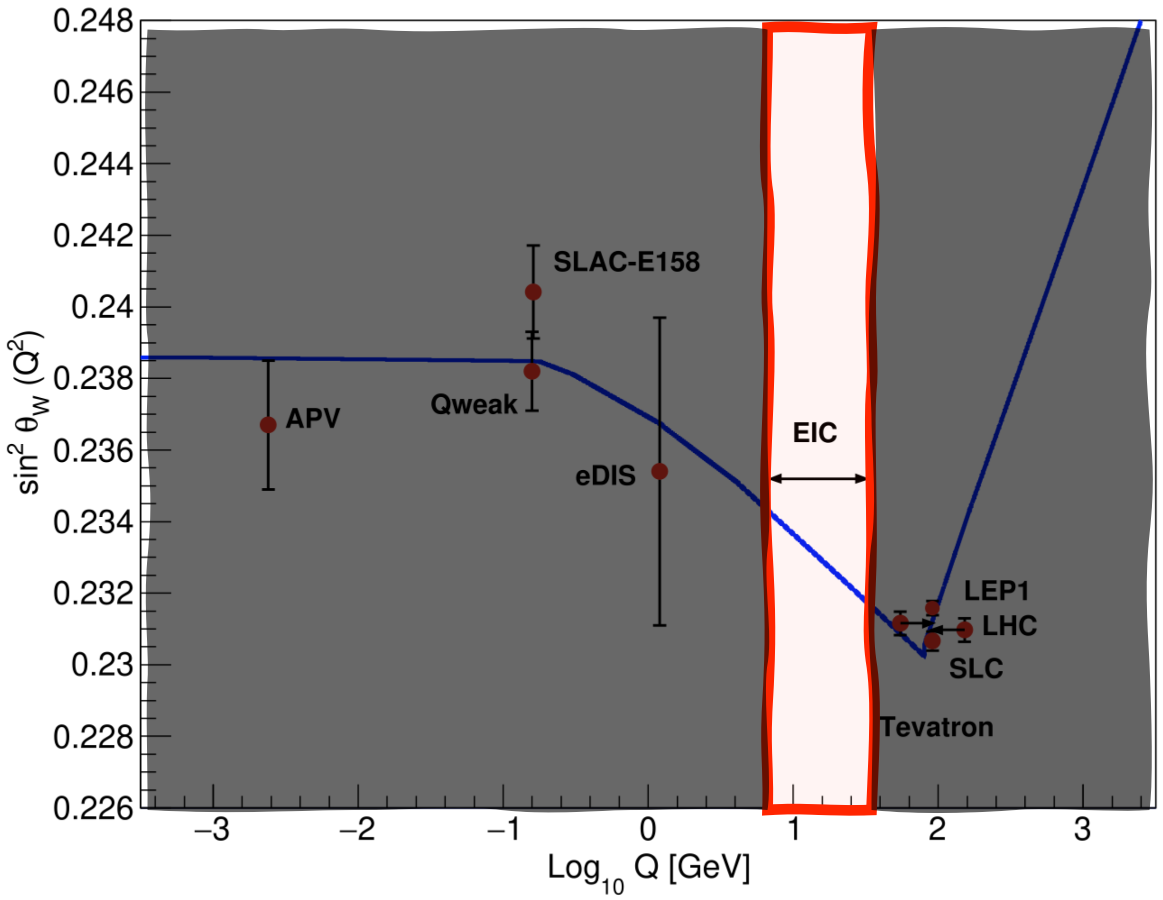
  - Detector fast smearing
- Deuteron and hydrogen targets
- DJANGOH event generator
- Pseudo-data generation
  - Statistical, experimental, and PDF uncertai
- **$\sin^2(\theta_W)$ extraction from fit**
- Deuteron and hydrogen targets
- Measure A_{PV} in an unexplored region
  - 10 GeV < μ< 70 GeV



Simulated Settings

Electron Energy [GeV]	Proton Energy [GeV]	Annual Luminosity [fb^{-1}]		Electron Energy [GeV]	Deuteron Energy [GeV]	Annual Luminosity [fb^{-1}]
5	41	4.4		5	41	4.4
5	100	36.8		5	100	36.8
10	100	44.8		10	100	44.8
10	275	100		10	137	100
18	275	15.4		18	137	15.4
18	275	100				

Pseudo-Data

1. In each bin $(\sqrt{s}, Q^2, x)$
   - Nominal PDF set used to calculate A_{PV}^{theo}

- Pseudo-experimental asymmetry generated utilizing the statistical & systematic uncertainties

$$(A_{PV})_b^{pseudo} = (A_{PV})_{SM,b}^{theo} + r_b \sqrt{\sigma_{stat}^2 + \left[(A_{PV})_{SM,b}^{theo}\left(\frac{\sigma_{sys}}{A}\right)_b\right]^2} + r' \sqrt{\left[(A_{PV})_{SM,b}^{theo}\left(\frac{\sigma_{pol}}{A}\right)_b\right]^2}$$

Uncorrelated uncertainties

1. Statistical: σ_{stat}
2. Particle background: σ_{syst}

Correlated uncertainties

1. Beam polarization: σ_{pol}

Experimental Uncertainties

Experimental Uncertainty Matrix

$$\Sigma_0^2 = \begin{bmatrix} \sigma_1^2 & \cdots & \sigma_1\sigma_N \\ \vdots & \ddots & \vdots \\ \sigma_N\sigma_1 & \cdots & \sigma_{N\,bin}^2 \end{bmatrix}$$

Diagonal Terms

$$\sigma_b^2 = \sigma_{stat,b}^2 + \left[(A_{PV})_{SM,0,b}^{theo} \left(\frac{\sigma_{sys}}{A}\right)_b\right]^2 + \left[(A_{PV})_{SM,b}^{theo} \left(\frac{\sigma_{pol}}{A}\right)_b\right]^2$$

Off-Diagonal Terms

$$\sigma_b = (A_{PV})_{SM,0,b}^{theo}(A_{PV})_{SM,b}^{theo} \left(\frac{\sigma_{pol}}{A}\right)_b$$

Experimental Uncertainties

1. Statistical Uncertainty
   - $dA_{\text{stat}} = \frac{1}{\sqrt{N}}$
2. Systematic Uncertainty
   - Background: $\frac{\sigma_{bg}}{A} = 1\%$
   - Polarimetry: $\frac{\sigma_{pol}}{A} = 1\%$
3. e^- beam polarization = 80%

Experimental Uncertainty Matrix

$$\Sigma_0^2 = \begin{bmatrix} \sigma_1^2 & \cdots & \sigma_1\sigma_N \\ \vdots & \ddots & \vdots \\ \sigma_N\sigma_1 & \cdots & \sigma_{N\,bin}^2 \end{bmatrix}$$

Diagonal Terms

$$\sigma_b^2 = \sigma_{stat,b}^2 + \left[(A_{PV})_{SM,0,b}^{theo}\left(\frac{\sigma_{sys}}{A}\right)_b\right]^2 + \left[(A_{PV})_{SM,b}^{theo}\left(\frac{\sigma_{pol}}{A}\right)_b\right]^2$$

Off-Diagonal Terms

$$\sigma_b = (A_{PV})_{SM,0,b}^{theo}(A_{PV})_{SM,b}^{theo}\left(\frac{\sigma_{pol}}{A}\right)_b$$

PDF Uncertainties

- Multiple standard PDF sets used in analysis
  - CT18NLO, MMHT2014, NNPDF31
- PDF uncertainties were determined following the prescription of each PDF set
- Hessian

$$\left(\Sigma^2_{pdf}\right)_{bb'} = \frac{1}{4}\sum_{m=1}^{N_{pdf}/2}\left(A^{theo}_{SM,2m,b} - A^{theo}_{SM,2m-1,b}\right)\left(A^{theo}_{SM,2m,b'} - A^{theo}_{SM,2m-1,b'}\right)$$

Analysis accounted for both diagonal and off-diagonal elements of the PDF uncertainty

$$\Sigma^2_{pdf} = \begin{bmatrix} \sigma^2_{1,pdf} & \cdots & \sigma_{1,pdf}\sigma_{N,pdf} \\ \vdots & \ddots & \vdots \\ \sigma_N\sigma_1 & \cdots & \sigma^2_{N\,bin,pdf} \end{bmatrix}$$

Extraction of the Weak Mixing Angle

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

- Extraction of $\sin^2\theta_W$ from minimization of the χ^2

$$\chi^2 = \left[A^{pseudo-data} - \boldsymbol{A^{theory}}\right]^T (\Sigma^2)^{-1} \left[A^{pseudo-data} - \boldsymbol{A^{theory}}\right]$$

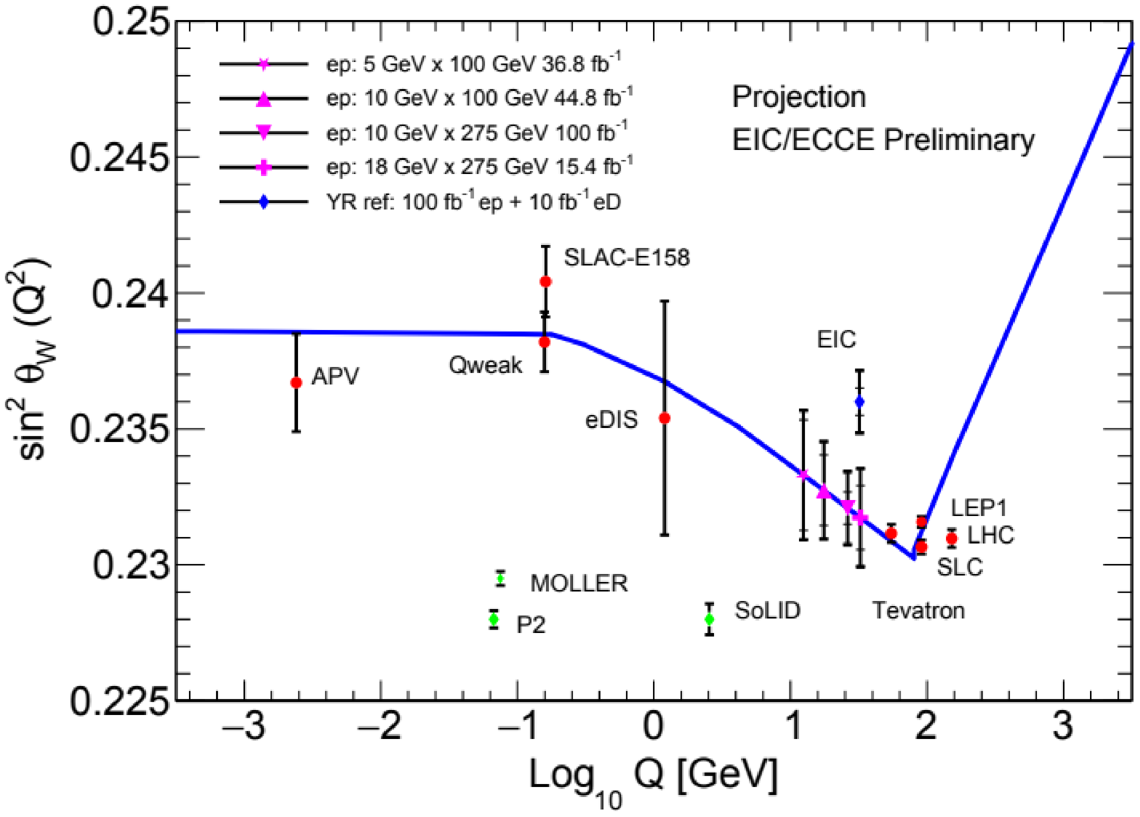
- $\boldsymbol{A^{theory}}$ is a function of $\sin^2\theta_W$ via the weak neutral couplings
- Single parameter fit to extract → $\boldsymbol{\sin^2\theta_W}$

Uncertainty Matrix

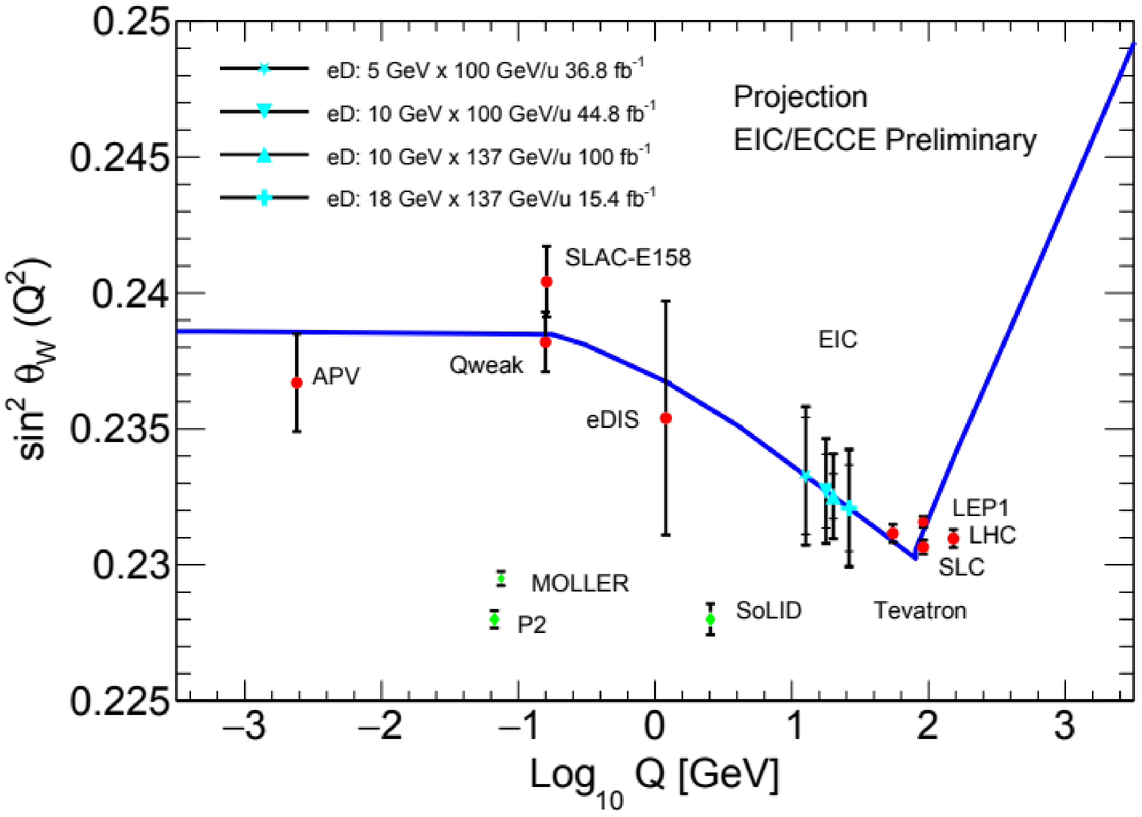
$$(\Sigma^2)_{bb'} = (\Sigma_0^2)_{bb'} + (\Sigma_{pdf}^2)_{bb'}$$

Projected Results: Weak Mixing Angle

ep Results



eD Results



1. Statistical and beam polarimetry uncertainties dominate;
2. Moderate precision in an unmeasured energy region
3. Combining ep + eD results, approach the sensitivity of Yellow Report: ~±**0.00097**

Projected Results: Weak Mixing Angle

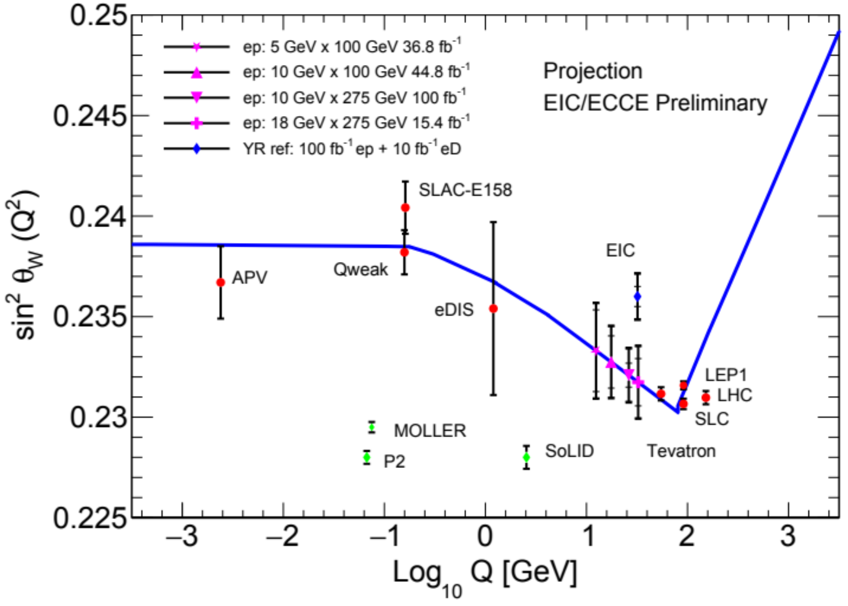
Beam type and energy Label	ep 5 × 100 P2	ep 10 × 100 P3	ep 10 × 275 P4	ep 18 × 275 P5	ep 18 × 275 P6
Luminosity (fb^{-1})	36.8	44.8	100	15.4	(100 YR ref)
$\langle Q^2 \rangle$ (GeV^2)	154.4	308.1	687.3	1055.1	1055.1
$\langle A_{PV} \rangle$ ($P_e = 0.8$)	−0.00854	−0.01617	−0.03254	−0.04594	−0.04594
$(dA/A)_{stat}$	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

Beam type and energy Label	eD 5 × 100 D2	eD 10 × 100 D3	eD 10 × 137 D4	eD 18 × 137 D5	eD 18 × 137 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

1. Statistical and beam polarimetry uncertainties dominate;
2. Moderate precision in an unmeasured energy region
3. Combining ep + eD results, approach the sensitivity of Yellow Report: ~±**0.00097**

Summary and Outlook

- Several upcoming precision measurements of the weak mixing angle
  - Moller, P2, SoLID
- A detailed study was preformed to study the potential impact at the EIC
  - Accounted for statistical, systematic, and PDF uncertainties and their correlations
- Potential to measure A_{PV} in an unexplored regior
  - Uncertainty larger than Yellow Report
  - Moderate precision
- Should update utilizing the full simulation
  - (Talk by Tyler K.)



Thank You