Extraction of the Weak Mixing Angle at the EIC

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Electro-Weak & BSM Physics at the EIC

- Primary focus of the EIC is to address “fundamental questions in science”
  - Origin of nucleon spin & nucleon mass
  - 3-dimensional structure of protons and nuclei

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  - High luminosity
  - Polarized lepton & hadron beams
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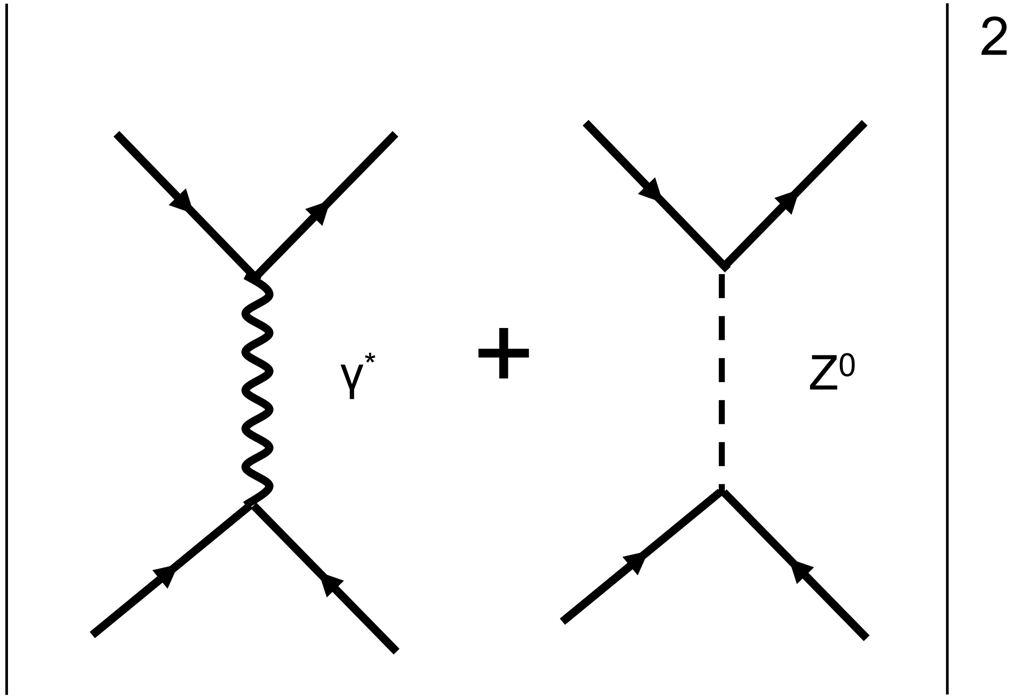
  } **Opportunity to study Electroweak and BSM physics**
- Electroweak and BSM physics at the EIC
  - Dark photon search
  - Charged lepton flavor violation (CLFV): See talks by **Bardh Quni** and **Emanuele Mereghetti**
  - **Provide constraints on $\sin^2\theta_W$ over a wide Q^2 range**

Neutral Current Electroweak Physics Studies at the EIC

$\sigma \sim$



Parity-Violating Deep Inelastic Scattering Asymmetry

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

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

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

Parity Violating Asymmetry

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

Where

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

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

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

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

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

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

Electroweak Neutral Current Study: Extraction of the Weak Mixing Angle

- Carried out a detailed study using both deuteron and proton beams
  - High precision data at the EIC makes the extraction of $\sin^2\theta_W$ from the proton possible
- Analysis uses realistic uncertainties for both theoretical and experimental systematics
  - CT18NLO, MMHT2014, and NNPDF31 PDF sets
- Results recently published
  - **Phys. Rev. D 106:** Neutral-Current Electroweak Physics and SMEFT Studies at the EIC

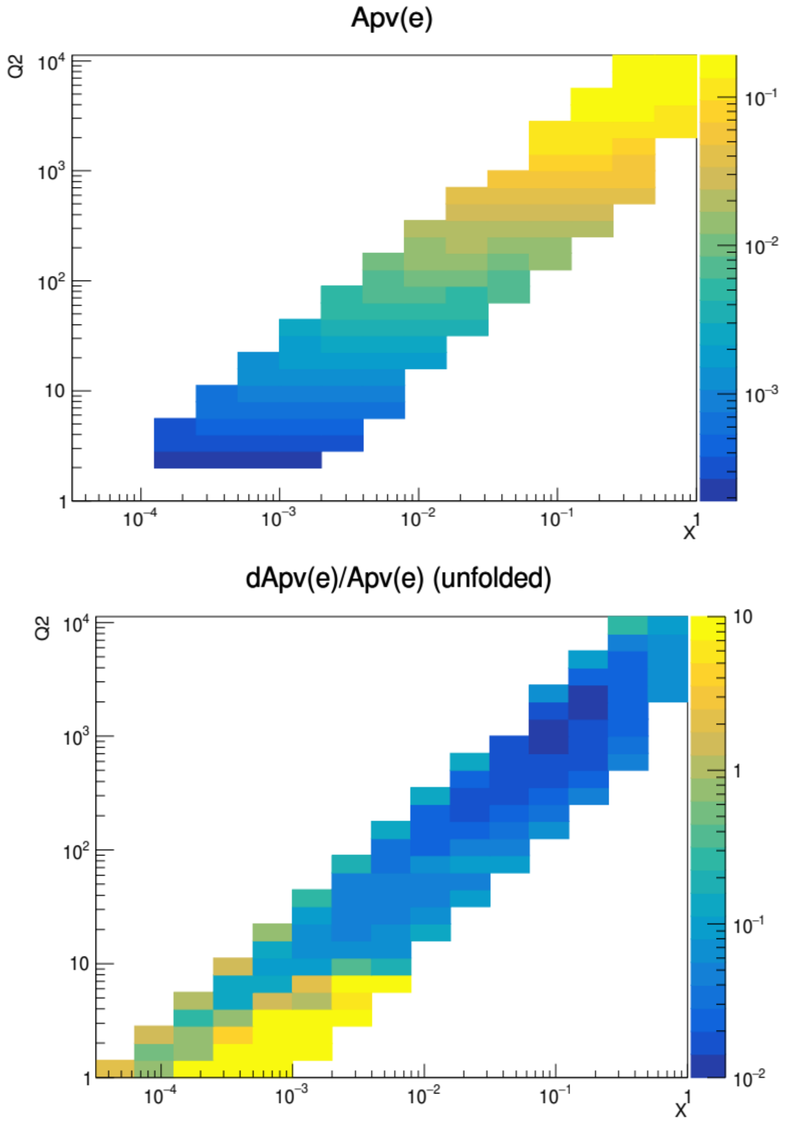
Simulation and Event Selection

Simulation

- Djangoh 4.6.16 combined with fast-smearing from single-electron gun simulation
- Modified user routine of Djangoh to calculate counts and size of A_{pv}
- Events unfolded to leptonic truth using R-matrix inversion method
- 20M events per energy/beam setting

Event selection

- $Q^2_{det} > 1.0$ GeV^2
- $y_{det} > 0.1$ & $y_{det} < 0.9$
- $\eta_{det} > -3.5$ and $\eta_{det} < 3.5$



e+p
- 18x275

Integrated Luminosity
- 100 fb^{-1}

Simulated Settings

ep				*ed*		
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				

EIC Yellow Report Setting

$\sin^2\theta_W$ extracted from each of the pseudo-data sets

Pseudo-Data

1. In each bin $(\sqrt{s}, Q^2, x)$
   - Nominal PDF set used to calculate A_{PV}^{theo}
2. Pseudo-experimental asymmetry generated utilizing the statistical and systematic uncertainties

$\sin^2\theta_W = 0.231$ used in generation of pseudo-data

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

Uncorrelated uncertainties

Correlated uncertainties

- r_b and r': random number drawn from Normal distribution
- r' common across all bins

Experimental Uncertainties

- Statistical: $dA_{stat} = \frac{1}{\sqrt{N}}$
- Systematics
  - Background: $\frac{\sigma_{bg}}{A} = 1\%$
  - Polarimetry: $\frac{\sigma_{pol}}{A} = 1\%$

    (e^- beam polarization = 80%)

Diagonal Terms

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

Off-Diagonal Terms

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

Experimental Uncertainty Matrix

$$\Sigma_0^2 = \begin{bmatrix} \sigma_1^2 & \sigma_1\sigma_2 & \cdots & \sigma_1\sigma_{N_{bin}} \\ & \sigma_2^2 & \cdots & \sigma_2\sigma_{N_{bin}} \\ & & \ddots & \vdots \\ & & & \sigma_{N_{bin}}^2 \end{bmatrix}$$

PDF Uncertainties

- PDF uncertainties were determined following the prescription of each PDF set (CT18NLO, MMHT2014, NNPDF31)
- Hessian

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

- Replica

$$\left(\Sigma^2_{pdf}\right)_{bb'} = \frac{1}{N_{pdf}}\sum_{m=1}^{N_{pdf}}\left(A^{theo}_{SM,m,b} - A^{theo}_{SM,0,b}\right)\left(A^{theo}_{SM,m,b'} - A^{theo}_{SM,0,b'}\right)$$

Accounted for both diagonal and off-diagonal elements of PDF uncertainty

PDF Uncertainty Matrix

$$\Sigma^2_{pdf} = \begin{bmatrix} \sigma^2_{1,pdf} & \sigma_{1,pdf}\sigma_{2,pdf} & \cdots & \sigma_{1,pdf}\,\sigma_{N_{bin},pdf} \\ & \sigma^2_{2,pdf} & \cdots & \sigma_2\sigma_{N_{bin},pdf} \\ & & \ddots & \vdots \\ & & & \sigma^2_{N_{bin},pdf} \end{bmatrix}$$

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

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

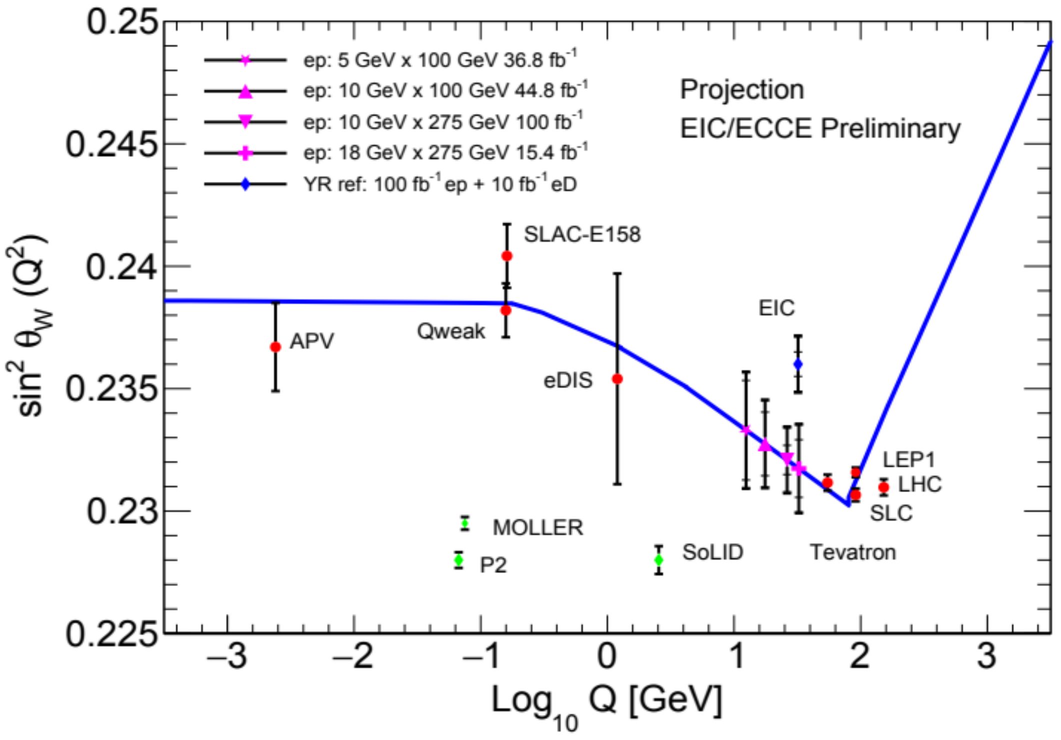
- $\boldsymbol{A^{theory}}$ is a function of $\sin^2\theta_W$ via the weak neutral couplings
- Single parameter fit to extract → $\boldsymbol{\sin^2\theta_W}$

Uncertainty Matrix

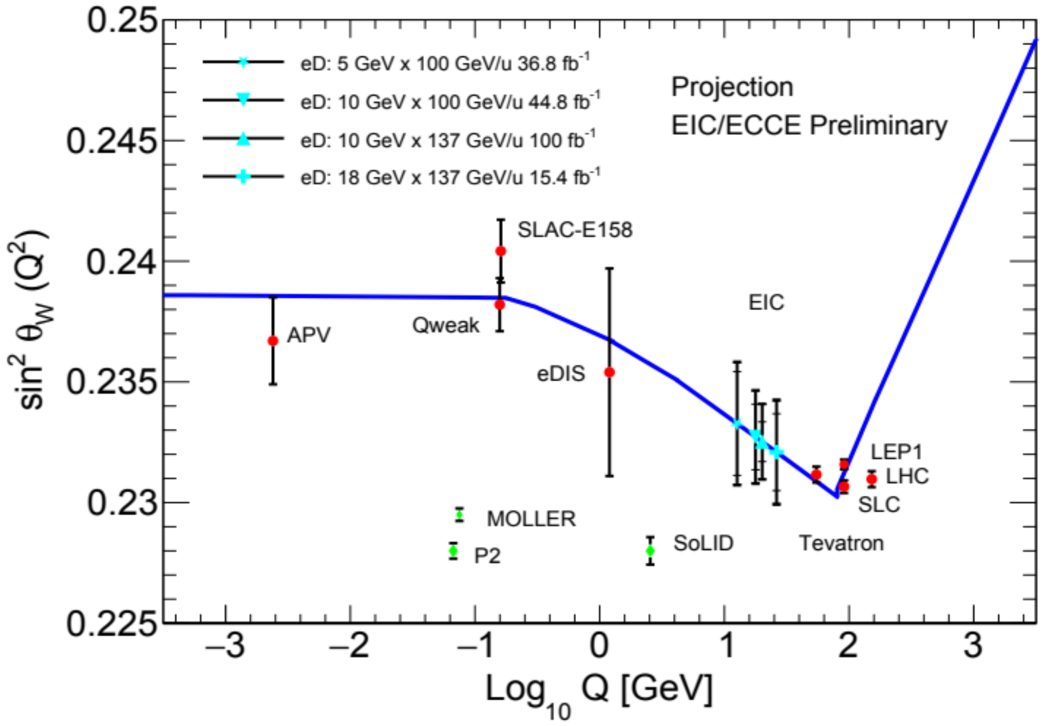
$$(\Sigma^2)_{bb'} = (\Sigma_0^2)_{bb'} + \left(\Sigma_{pdf}^2\right)_{bb'}$$

Fit Results

ep Results



eD Results



ep better than eD; statistical and beam polarimetry uncertainties dominate; moderate precision in an unmeasured energy region, multi-year run would help

Summary and Outlook

- We preformed a detailed study of the extraction of $\sin^2\theta_W$ at the EIC using the ECCE detector design for both the proton and deuteron beams
  - Accounted for statistical, systematic, and PDF uncertainties and their correlations
  - Will update once ePIC simulations are ready for physics analysis
- Focused on statistical, beam polarimetry, and PDF uncertainties for ECCE study
  - Uncertainty due to unfolding to be studied
- **The EIC has the potential to play an important role in Electroweak and BSM physics covering an energy scale between fixed target and collider experiments**

Thank You

Summary of Results

ep Results

EIC Yellow Report Setting ↓ (P6)

Beam type and energy	ep 5 × 100	ep 10 × 100	ep 10 × 275	ep 18 × 275	ep 18 × 275
Label	P2	P3	P4	P5	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
$(dA/A)_{\text{stat}}$	1.54%	0.98%	0.40%	0.80%	(0.31%)
$(dA/A)_{\text{stat+syst(bg)}}$	1.55%	1.00%	0.43%	0.81%	(0.35%)
$(dA/A)_{1\%\text{pol}}$	1.0%	1.0%	1.0%	1.0%	(1.0%)
$(dA/A)_{\text{tot}}$	1.84%	1.42%	1.09%	1.29%	(1.06%)
Experimental					
$d(\sin^2\theta_W)_{\text{stat+syst(bg)}}$	0.002032	0.001299	0.000597	0.001176	0.000516
$d(\sin^2\theta_W)_{\text{stat+syst+pol}}$	0.002342	0.001759	0.001297	0.001769	0.001244
with PDF					
$d(\sin^2\theta_W)_{\text{tot,CT18NLO}}$	0.002388	0.001807	0.001363	0.001823	0.001320
$d(\sin^2\theta_W)_{\text{tot,MMHT2014}}$	0.002353	0.001771	0.001319	0.001781	0.001270
$d(\sin^2\theta_W)_{\text{tot,NNPDF31}}$	0.002351	0.001789	0.001313	0.001801	0.001308

eD Results

Beam type and energy	eD 5 × 100	eD 10 × 100	eD 10 × 137	eD 18 × 137	eD 18 × 137
Label	D2	D3	D4	D5	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
$(dA/A)_{\text{stat}}$	1.46%	0.93%	0.54%	1.05%	(1.31%)
$(dA/A)_{\text{stat+bg}}$	1.47%	0.95%	0.56%	1.07%	(1.32%)
$(dA/A)_{\text{syst},1\%\text{pol}}$	1.0%	1.0%	1.0%	1.0%	(1.0%)
$(dA/A)_{\text{tot}}$	1.78%	1.38%	1.15%	1.46%	(1.66%)
Experimental					
$d(\sin^2\theta_W)_{\text{stat+bg}}$	0.002148	0.001359	0.000823	0.001591	0.001963
$d(\sin^2\theta_W)_{\text{stat+bg+pol}}$	0.002515	0.001904	0.001544	0.002116	0.002414
with PDF					
$d(\sin^2\theta_W)_{\text{tot,CT18}}$	0.002558	0.001936	0.001566	0.002173	0.00247
$d(\sin^2\theta_W)_{\text{tot,MMHT2014}}$	0.002527	0.001917	0.001562	0.002128	0.002424
$d(\sin^2\theta_W)_{\text{tot,NNPDF31}}$	0.002526	0.001915	0.001560	0.002127	0.002423

Tables from: [Phys. Rev. D 106, 016006]

ep better than eD; statistical and beam polarimetry uncertainties dominate;
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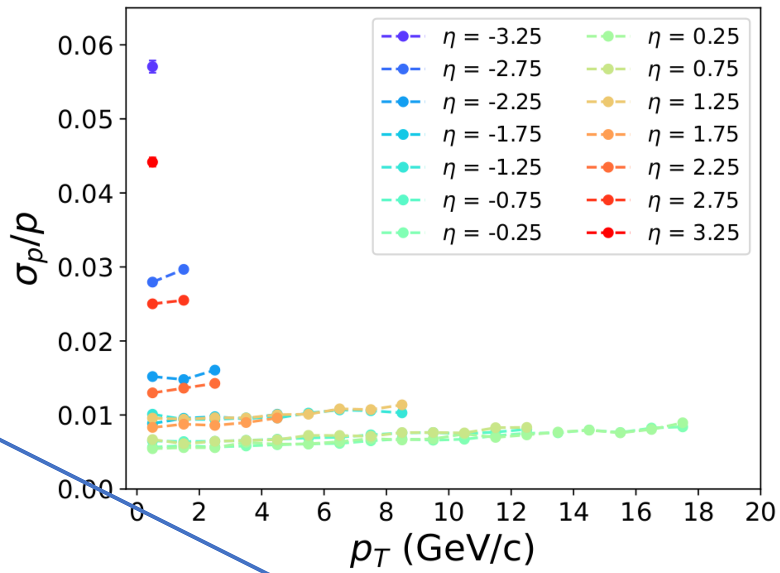
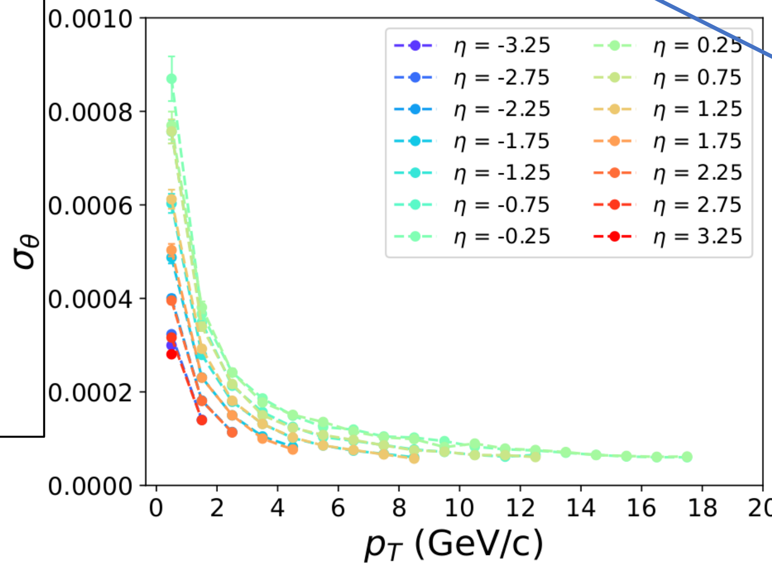
Neutral Current Electroweak Physics Studies at the EIC

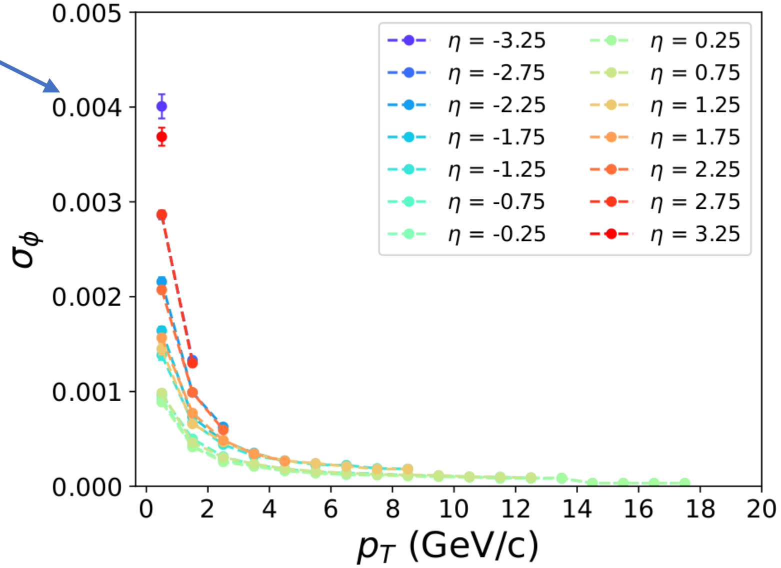
Simulation:

Fast-smearing performed on:

- Electron momentum, polar and azimuthal angles (θ,ϕ)
  - RMS of fast smearing spectra
- Provides for reliable projections
  - Limitation: selection of hadronic state not implemented
  - Could provide better identification DIS events



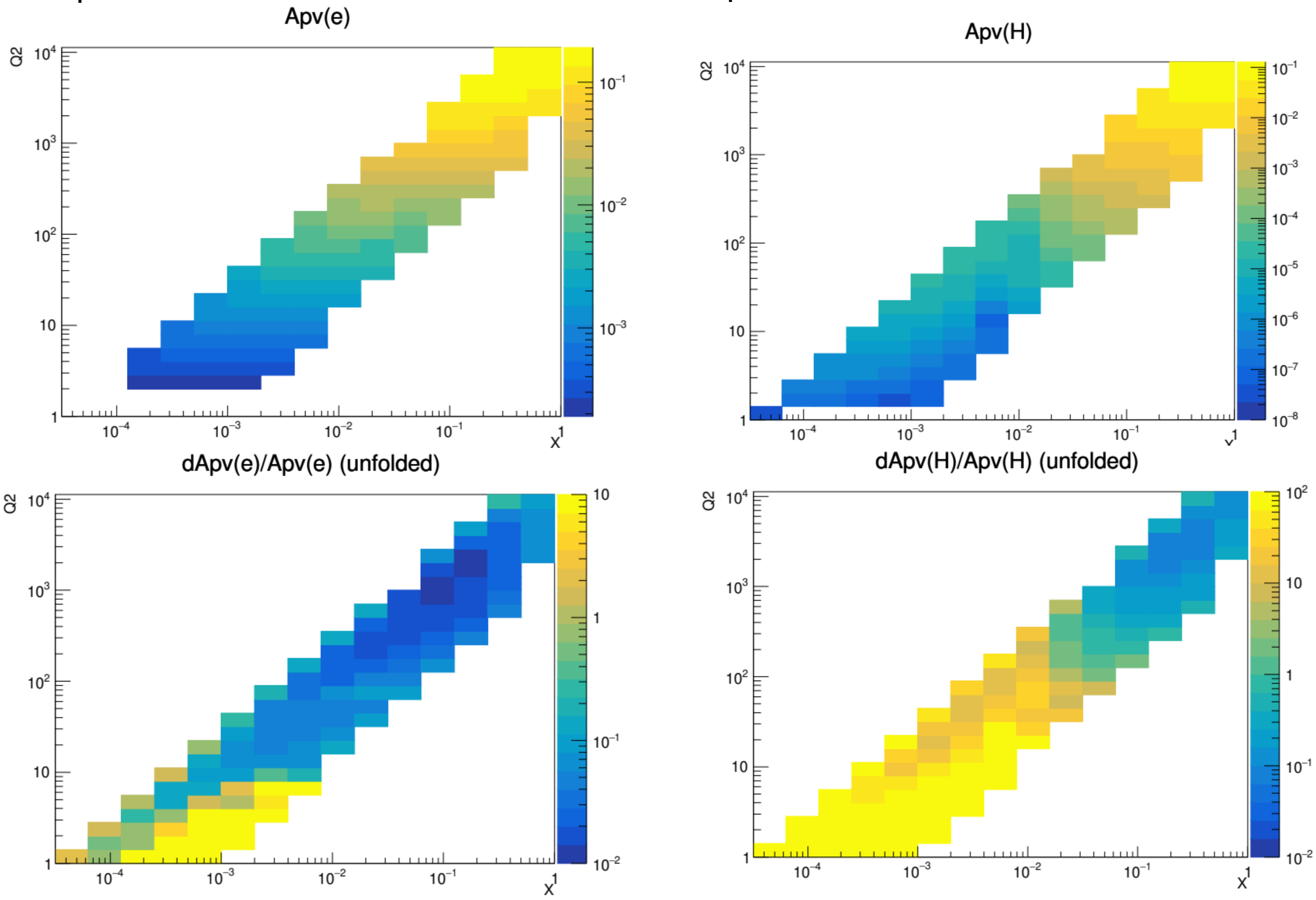




“unpolarized” PV

“polarized” PV

18x275 ep 100 fb^{-1}



These also represent precision on the “additional EW structure functions” (namely $g_{1,5}^{\gamma Z}$)