Extraction of the Weak Mixing Angle at the EIC

Michael Nycz

EW and BSM Physics at the EIC

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Collaborators

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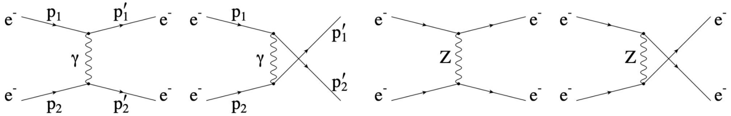
Outline

1. Planned future $\sin^2(\theta_W)$ measurements
2. Electroweak and BSM Physics at the EIC
3. $\sin^2(\theta_W)$ at the EIC
4. Simulation
5. Projected Results
6. Future Plans
7. Summary

Future Weak Mixing Angle Measurements

The MOLLER Experiment

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



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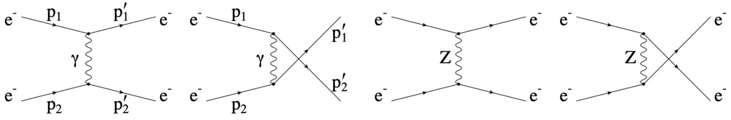
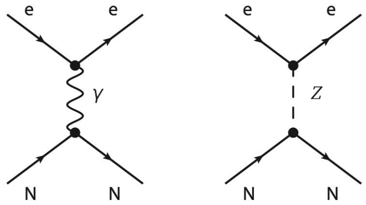


The P2 Experiment

- A_{PV} in elastic e-p scattering
- "Future high-precision measurement of the electroweak mixing angle"



Ultra-Precise Weak Mixing Angle

Make a "cut" on measurements with uncertainty ~ 0.0003X or better

*Krishna Kumar: BSM Searches at the Intensity Fronteir

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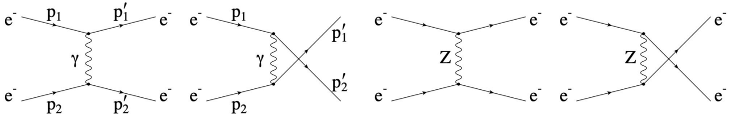

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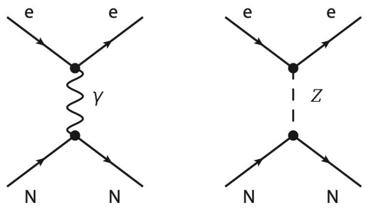
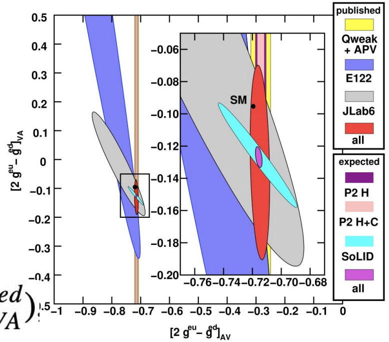
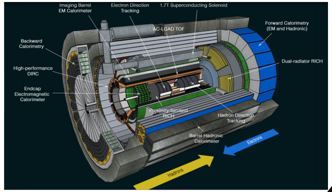




PVDIS with SoLID

- A_{PV} in DIS e-d scattering
- Isoscalar Dueteron
  - Cancellation of structure function effects
- Simultaneous fit of $(2g_{AV}^{eu} - g_{AV}^{ed})$ and $(2g_{VA}^{eu} - g_{VA}^{ed})$

Future Weak Mixing Angle Measurements



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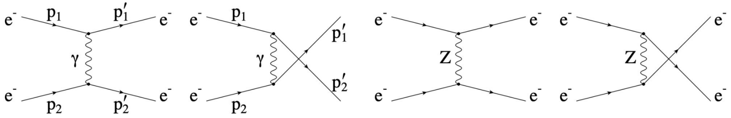

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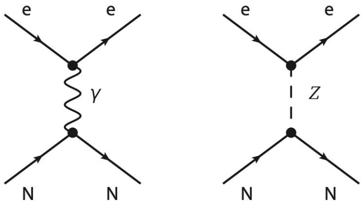

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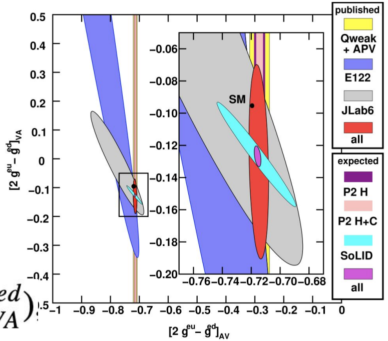
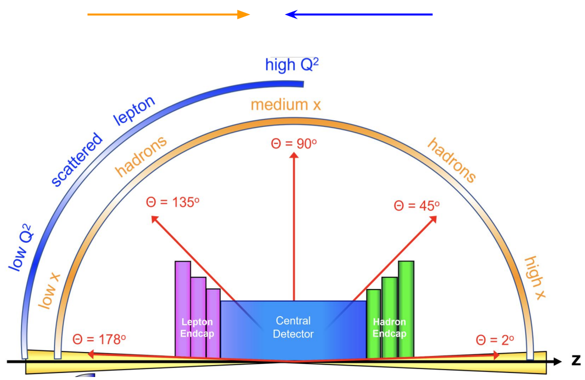


Electroweak & BSM Physics at the EIC

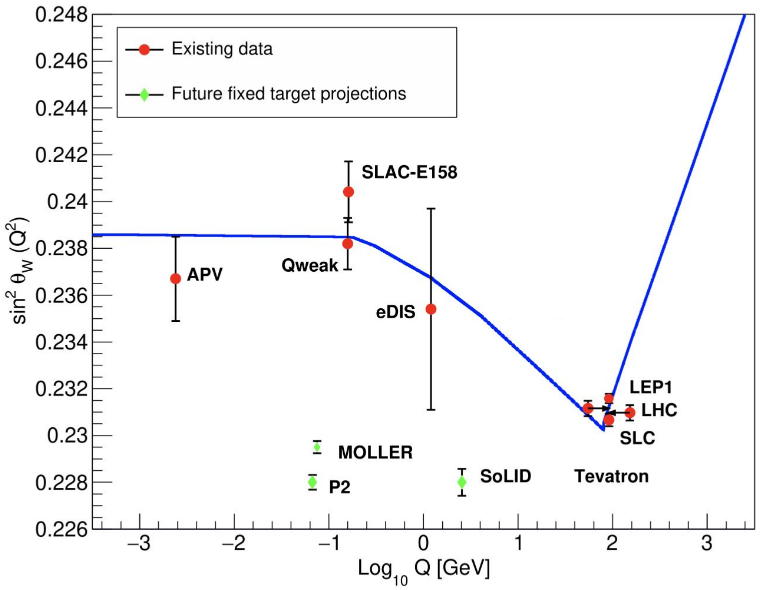
- Primary focus of the EIC
  - Origin of nucleon spin & nucleon mass
  - 3-dimensional structure of protons and nucleons
- Beam and detector design
  - Synergistic Electroweak & BSM physics
- EW & BSM physics opportunities
  - CFLV (talks by Emanuele Mereghetti & Andrew Hurley)
  - Dark photon search
  - Provide constraints on $\sin^2(\theta_W)$ over a wide Q^2 range



- Wide kinematic coverage
- High luminosity~ $1x10^{34}$
- Polarized e^- and hadron beams

Weak Mixing Angle at the EIC

- PVDIS experiments
  - 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*EIC Yellow Report



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Weak Mixing Angle at the EIC

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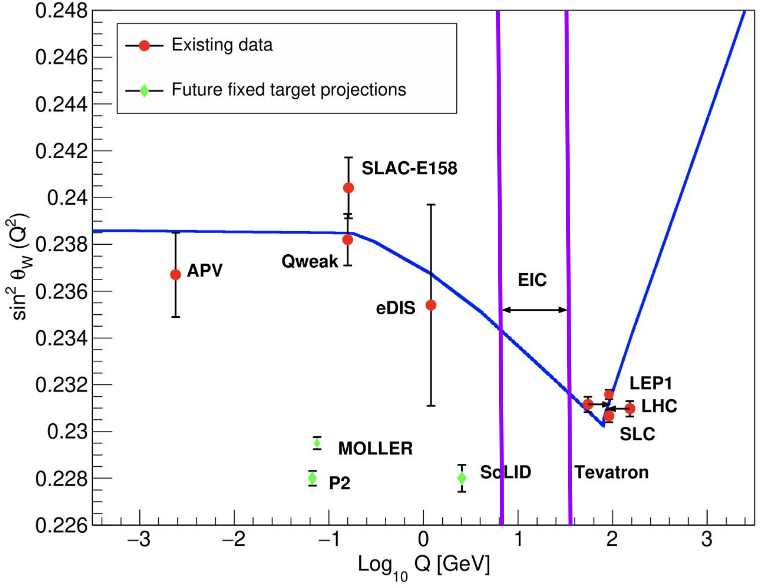
- High precision data at EIC may make extraction of $\sin^2(\theta_W)$ from the proton*EIC Yellow Report
- Energy range between those achievable in fixed-target and collider experiments
  - Over a range of Q^2 values not yet explored



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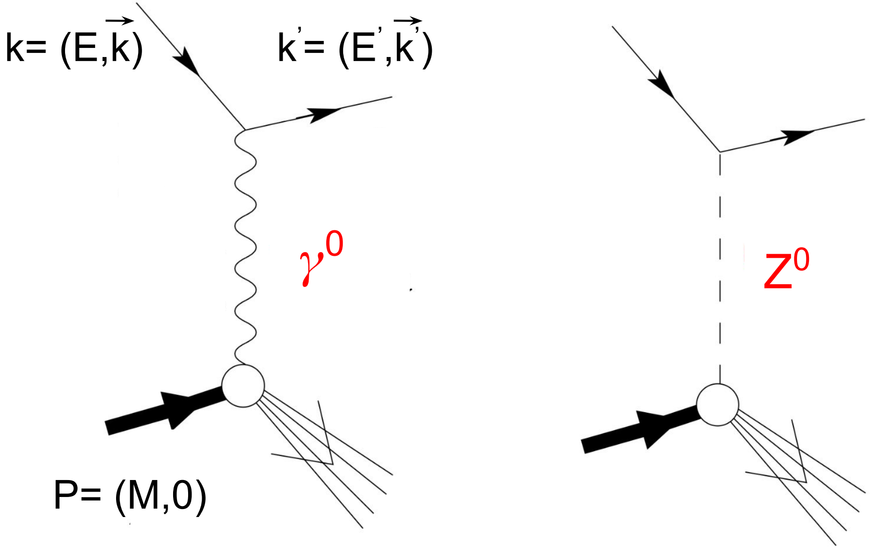
Neutral Current Electroweak Physics Studies at the EIC



Parity-Violating Deep Inelastic Scattering Asymmetry

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

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

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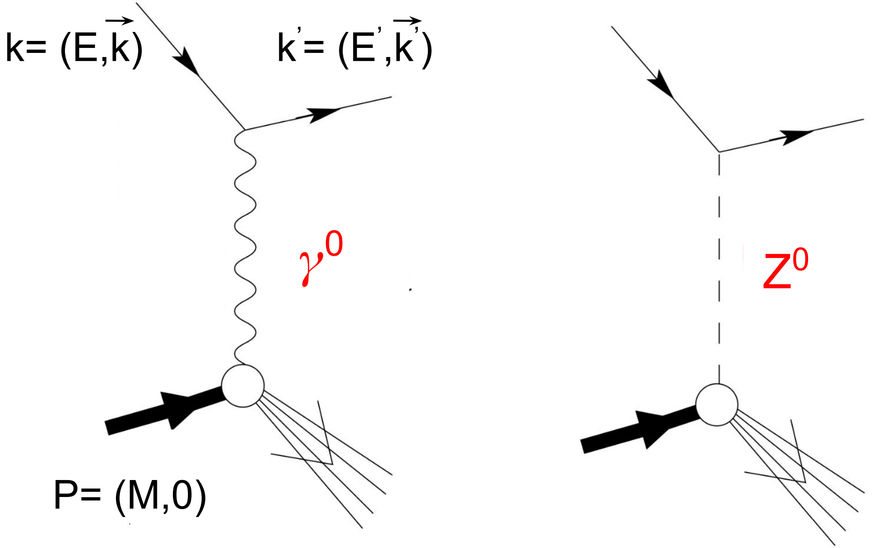

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$\sigma_{R,L}$: cross sections of right- and left-handed electrons

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

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

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

Where

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

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

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

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

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

Background and Status of Ongoing Projections

- Initial estimates performed for the EIC Yellow Report
- Updated for ECCE detector
  - Utilized “fast smearing” from single e^- simulation
  - Statistical, beam polarimetry,& PDF uncertainties
- Updated (in progress for ePIC)
  - Unfolding uncertainties
- Proceeding to include results from full simulation
  - Projection for the upcoming ePIC

Weak Mixing Angle Projections at the EIC

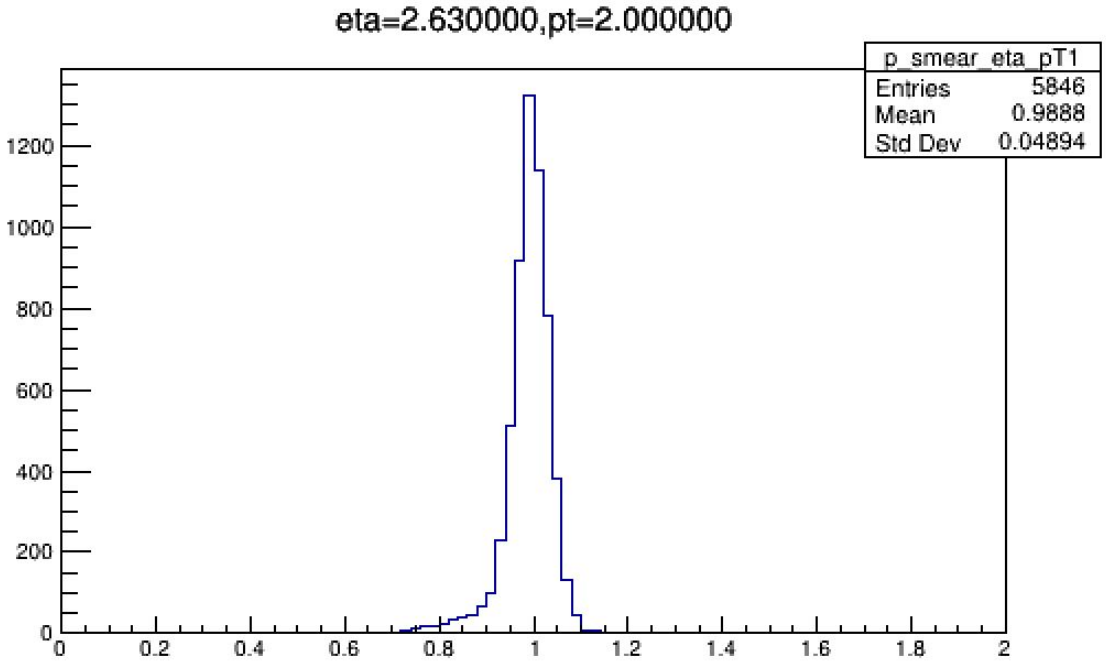
1. **Single electron gun simulation**
2. **DJANGOH event generator**
3. Pseudo-data generation
   a. Statistical, Experimental, and PDF uncertainties
4. $\sin^2(\theta_W)$ extraction from fit

What will be shown

1. Previous detailed study for ECCE
2. Ongoing work for ePIC

Simulation

- Djangoh event generator
  - Fast-smearing from single e^- gun simulation
- Modified Djangoh to calculate counts and size of A_{PV}
- Events unfolded to leptonics truth using R-matrix inversion method
- **Best way to treat uncertainty of unfolding & bin migration?**
- 20 M events per energy setting
- Inclusive electrons detected using tracking Ecal systems



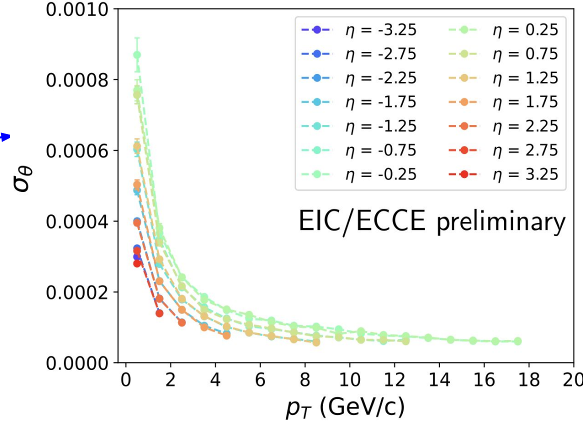
Electron momentum resolution

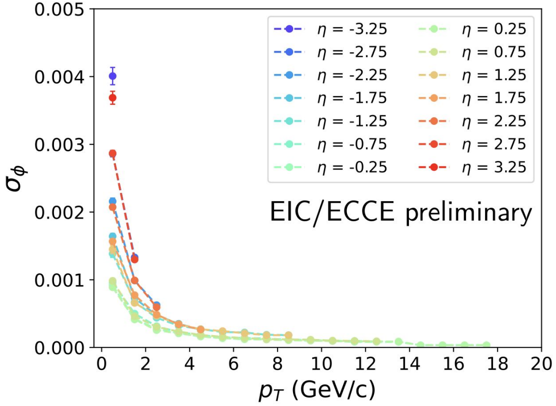
Simulation

ECCE

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





Event selection applied

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

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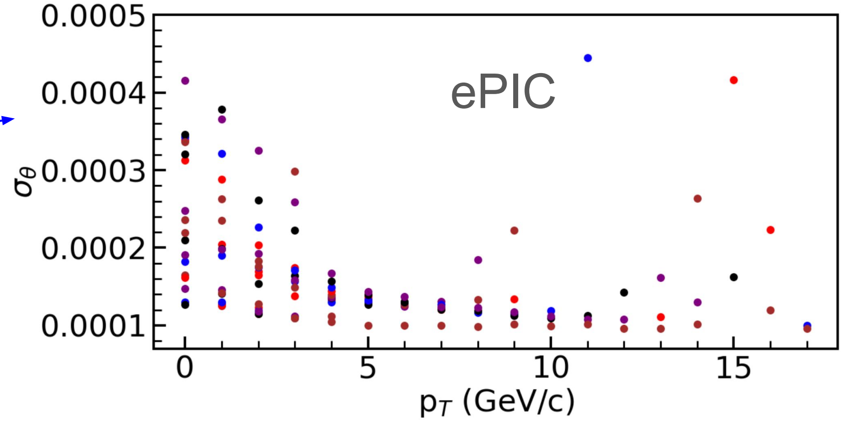

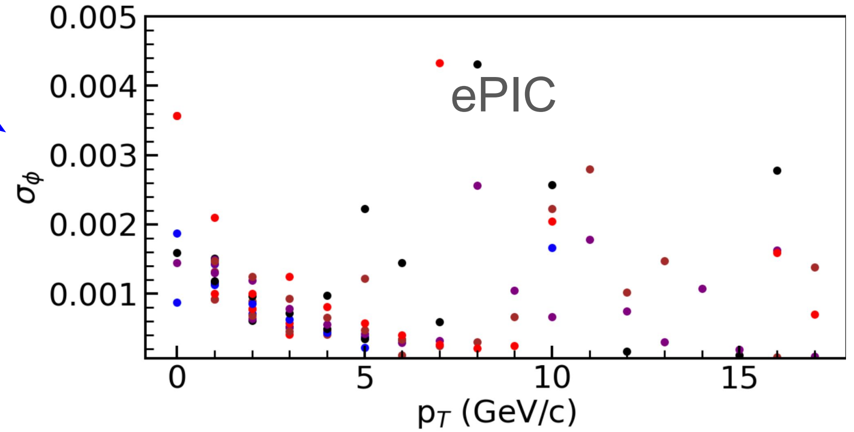

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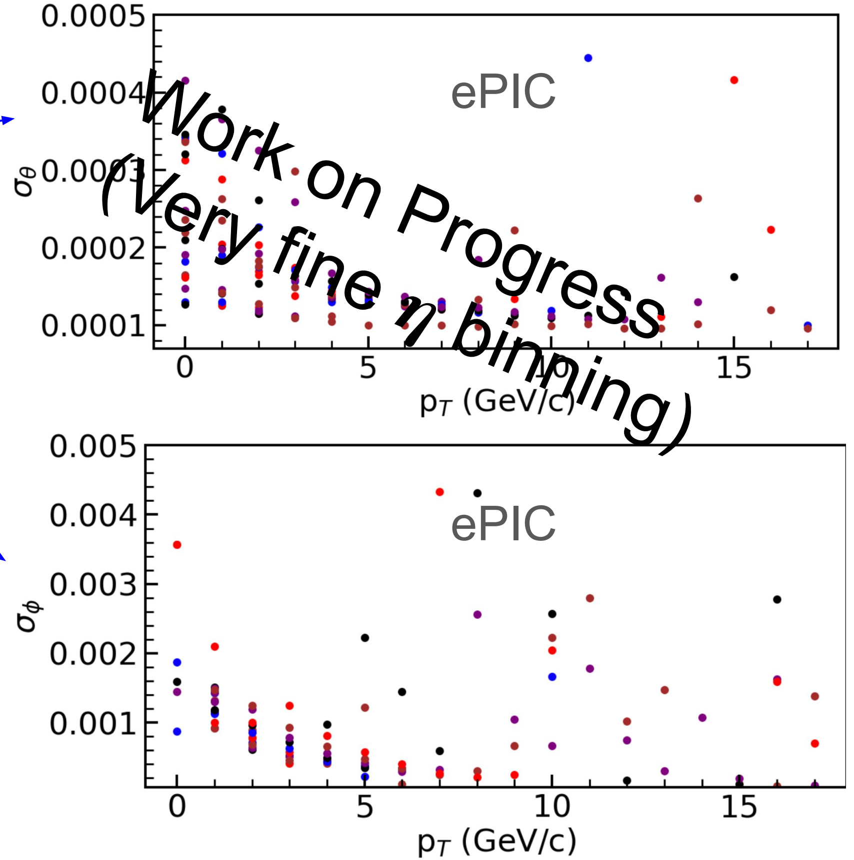

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2. DJANGOH event generator
3. **Pseudo-data generation**
    a. **Statistical, Experimental, and PDF uncertainties**
4. $\sin^2(\theta_W)$ extraction from fit

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}
2. Pseudo-experimental asymmetry generated utilizing the statistical and systematic uncertainties

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

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

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

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

- Replica

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

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

PDF Uncertainty Matrix

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

Weak Mixing Angle Projections at the EIC

1. Single electron gun simulation
2. DJANGOH event generator
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4. **$\sin^2(\theta_W)$ extraction from fit**

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

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

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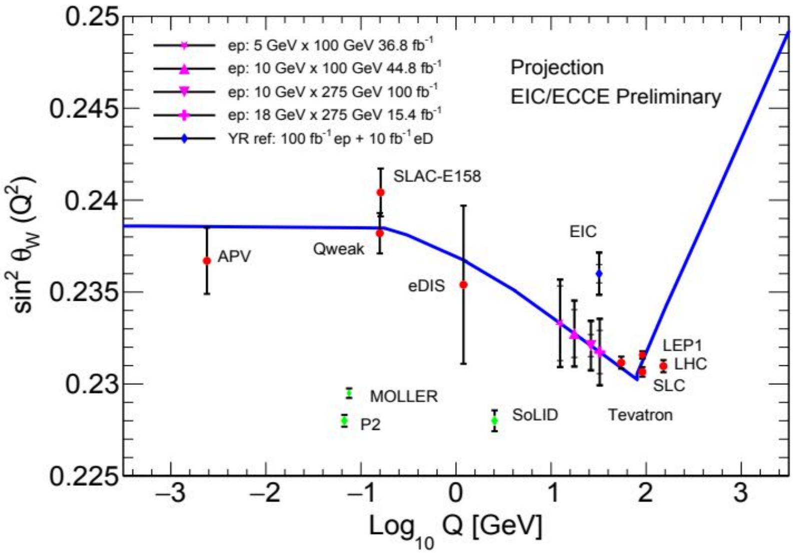
- $\boldsymbol{A^{theory}}$ is a function of $\sin^2\theta_W$ via the weak neutral couplings
- Single parameter fit to extract → $\boldsymbol{\sin^2\theta_W}$

Uncertainty Matrix

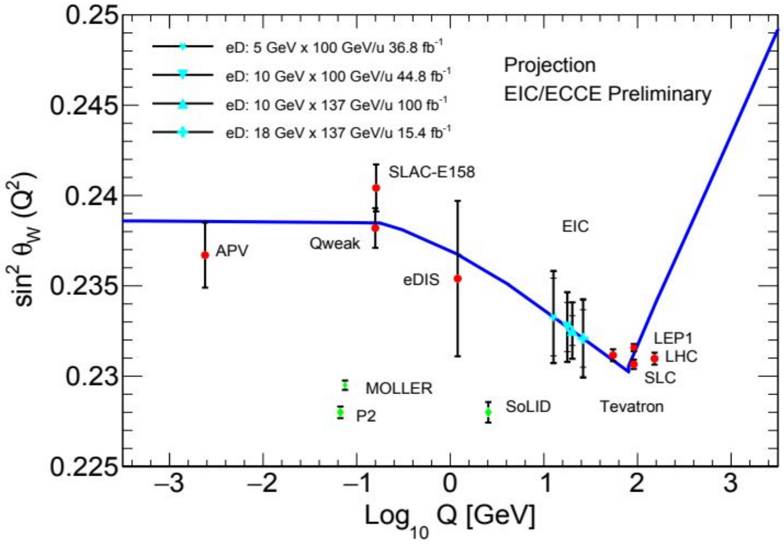
$$(\Sigma^2)_{bb'} = (\Sigma_0^2)_{bb'} + (\Sigma_{pdf}^2)_{bb'}$$

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

ep Results



eD Results



Statistical and beam polarimetry uncertainties dominate;
moderate precision in an unmeasured energy region, multi-year run would help
Combining ep + eD results, approach the sensitivity of Yellow Report: ~±0.00097

ep Results

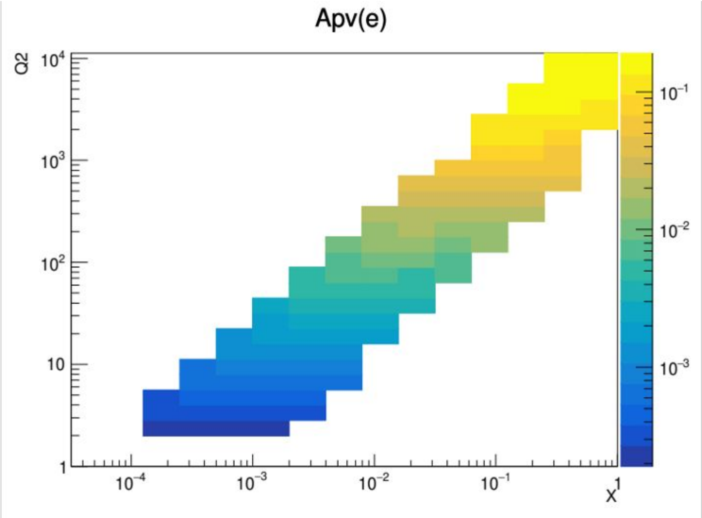
Beam type and energy Label	ep 5 × 100 P2	ep 10 × 100 P3	ep 10 × 275 P4	ep 18 × 275 P5	ep 18 × 275 P6
Luminosity (fb^{-1})	36.8	44.8	100	15.4	(100 YR ref)
$\langle Q^2 \rangle$ (GeV^2)	154.4	308.1	687.3	1055.1	1055.1
$\langle A_{PV} \rangle$ ($P_e = 0.8$)	−0.00854	−0.01617	−0.03254	−0.04594	−0.04594
$(dA/A)_{stat}$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

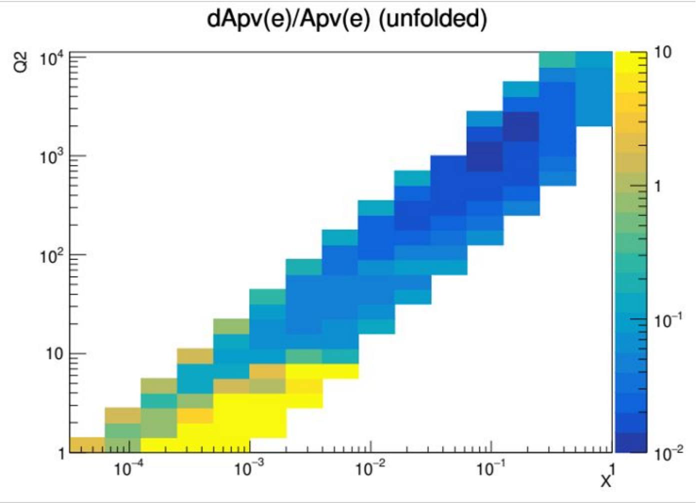
eD Results

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

Ongoing and Future Plans

- Completion of $\sin^2(\theta_W)$ projection using ePIC detector
  - Studying unfolding uncertainties



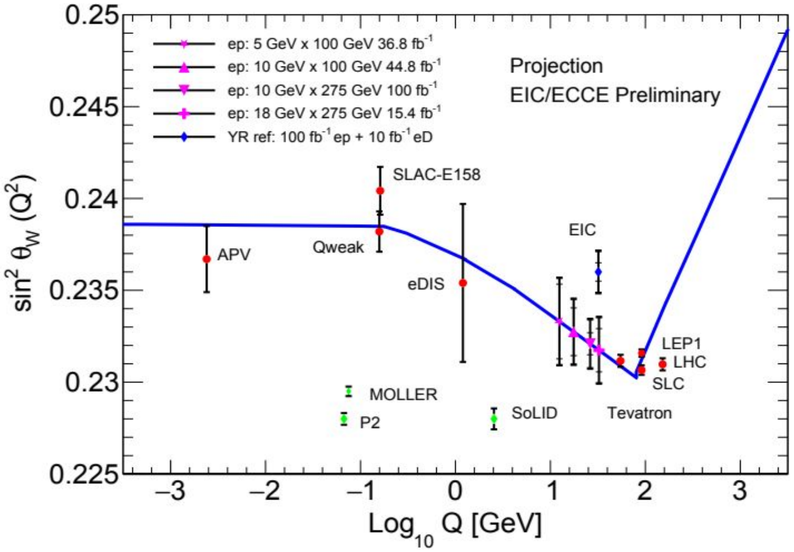


Ongoing and Future Plans

- Completion of $\sin^2(\theta_W)$ projection using ePIC detector
  - Studying unfolding uncertainties
- Utilizing full simulation instead of “fast smearing”
  - Pythia 8 vs DJANGOH
- Discussion
  - Represention of results
  - Consider multi-year run?
  - Suggestions?

Summary and Outlook

- Detailed study of the extraction of $\sin^2(\theta_W)$ at the EIC for both the proton and deuteron
- Overall uncertainties larger than those in Yellow Report
- The EIC can play a role in Electroweak and BSM physics
  - Covering energy scale between fixed target and collider experiments
  - Unexplored region
- Ongoing studies and future projections for ePIC detector
  - Expected results in 2 weeks and 2-3 month time scale



Thank You