EW/BSM Manuscript Update 1

We have extended the SMEFT analysis in the EW/BSM note to include:

- polarized hadron Apv(p), Apv(D)
- a possible future ten-fold luminosity upgrade of EIC (HL-EIC, see CFNS workshop 2022)
- lepton-charge asymmetry using a possible future positron beam at EIC

We have updated the determination of the weak mixing angle

- to include properly PDF uncertainties

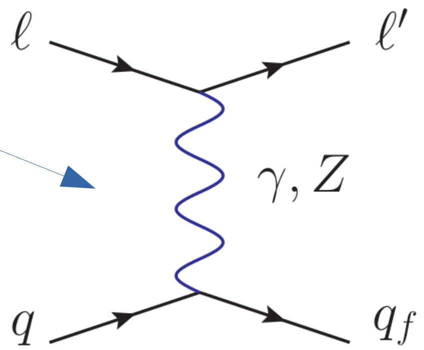
We also included

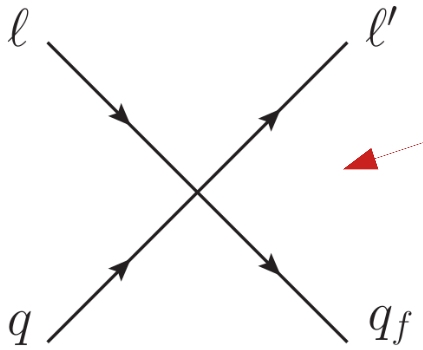
- DIS cross section formalism that accounts for both electron and hadron polarizations, tripled checked
- (note: g2,3 terms omitted, TMC terms derived but not included)

(this is a short author list paper targeted for Phys. Rev. D; 50 pages of main texts plus 40 pages of Appendices. We hope to post this to arXiv the first week of April and will appreciate your feedback.)

Neutral Current Electroweak Physics and SMEFT Studies at the EIC

SM (one-boson exchange)





SMEFT

("effective" dimension-6 operators)

$$\mathcal{L}_{\text{SMEFT}} = \frac{1}{\Lambda^2} \sum_r C_r \mathcal{O}_r + \cdots$$

Note: all Lagragians should be dimension-4

To facilitate communication, we also "translated" all SMEFT operators to the language of hadronic tensor and structure functions

$$\mathcal{L}_{\text{SMEFT}} = \frac{1}{\Lambda^2} \sum_r \tilde{C}_r \Big\{ \sum_f \bar{e}\gamma^\mu (c^e_{V_r} - c^e_{A_r}\gamma_5) e \, \bar{q}_f \gamma^\mu (c^f_{V_r} - c^f_{A_r}\gamma_5) q_f \Big\} + \cdots ,$$

$$\frac{d^2\sigma}{dx dy} = \frac{2\pi y \alpha^2}{Q^4} L^\gamma_{\mu\nu} \Big\{ \eta^\gamma W^{\mu\nu}_\gamma - \eta^{\gamma Z}(g^e_V - \lambda_e g^e_A) W^{\mu\nu}_{\gamma Z} + \eta^Z (g^e_V - \lambda_e g^e_A)^2 W^{\mu\nu}_Z$$
$$- \sum_r \xi^{\gamma r}(c^e_{V_r} - \lambda_e c^e_{A_r}) W^{\mu\nu}_{\gamma r} + \sum_r \xi^{Zr}(c^e_{V_r} - \lambda_e c^e_{A_r})(g^e_V - \lambda_e g^e_A) W^{\mu\nu}_{Zr} \Big\}.$$

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DIS cross sections: $d\sigma = d\sigma_0 + P_e\, d\sigma_e + P_H\, d\sigma_H + P_e P_H\, d\sigma_{eH}$

$$
\begin{aligned}
d\sigma_0 &= \frac{1}{4}\Big[\, d\sigma|_{\lambda_e=+1,\lambda_H=+1} + d\sigma|_{\lambda_e=+1,\lambda_H=-1} + d\sigma|_{\lambda_e=-1,\lambda_H=+1} + d\sigma|_{\lambda_e=-1,\lambda_H=-1} \,\Big],\\
d\sigma_e &= \frac{1}{4}\Big[\, d\sigma|_{\lambda_e=+1,\lambda_H=+1} + d\sigma|_{\lambda_e=+1,\lambda_H=-1} - d\sigma|_{\lambda_e=-1,\lambda_H=+1} - d\sigma|_{\lambda_e=-1,\lambda_H=-1} \,\Big],\\
d\sigma_H &= \frac{1}{4}\Big[\, d\sigma|_{\lambda_e=+1,\lambda_H=+1} - d\sigma|_{\lambda_e=+1,\lambda_H=-1} + d\sigma|_{\lambda_e=-1,\lambda_H=+1} - d\sigma|_{\lambda_e=-1,\lambda_H=-1} \,\Big],\\
d\sigma_{eH} &= \frac{1}{4}\Big[\, d\sigma|_{\lambda_e=+1,\lambda_H=+1} - d\sigma|_{\lambda_e=+1,\lambda_H=-1} - d\sigma|_{\lambda_e=-1,\lambda_H=+1} + d\sigma|_{\lambda_e=-1,\lambda_H=-1} \,\Big],
\end{aligned}
$$

Parity-Violating asymmetries:

$$A_{PV}^{(e)} \equiv \frac{d\sigma_e}{d\sigma_0} \qquad A_{PV}^{(H)} \equiv \frac{d\sigma_H}{d\sigma_0}$$

Double-spin asymmetries:

$$A_{PV}^{(eH)} \equiv \frac{d\sigma_{eH}}{d\sigma_0}$$

Lepton-charge asymmetries:

$$A_{LC,H} \equiv \frac{d\sigma_0^{e+} - d\sigma_0^{e-}}{d\sigma_0^{e+} + d\sigma_0^{e-}}$$

$$
\begin{aligned}
\frac{d^2\sigma_0}{dxdy} = \frac{4\pi\alpha^2}{xyQ^2}\Big\{&(1-y)\left[F_2^\gamma - g_V^e \eta_{\gamma Z} F_2^{\gamma Z} + ({g_V^e}^2 + {g_A^e}^2)\eta_Z F_2^Z\right]\\
&+xy^2\left[F_1^\gamma - g_V^e \eta_{\gamma Z} F_1^{\gamma Z} + ({g_V^e}^2 + {g_A^e}^2)\eta_Z F_1^Z\right]\\
&-\frac{xy}{2}(2-y)\left[g_A^e \eta_{\gamma Z} F_3^{\gamma Z} - 2 g_V^e g_A^e \eta_Z F_3^Z\right]\Big\}\ ,\\
\frac{d^2\sigma_e}{dxdy} = \frac{4\pi\alpha^2}{xyQ^2}\Big\{&(1-y)\left[g_A^e \eta_{\gamma Z} F_2^{\gamma Z} - 2 g_V^e g_A^e \eta_Z F_2^Z\right] + xy^2\left[g_A^e \eta_{\gamma Z} F_1^{\gamma Z} - 2 g_V^e g_A^e \eta_Z F_1^Z\right]\\
&+\frac{xy}{2}(2-y)\left[g_V^e \eta_{\gamma Z} F_3^{\gamma Z} - ({g_V^e}^2 + {g_A^e}^2)\eta_Z F_3^Z\right]\Big\}\ ,\\
\frac{d^2\sigma_H}{dxdy} = \frac{4\pi\alpha^2}{xyQ^2}\Big\{&(2-y)\,xy\left[g_A^e \eta_{\gamma Z} g_1^{\gamma Z} - 2 g_V^e g_A^e \eta_Z g_1^Z\right]\\
&-(1-y)\left[-g_V^e \eta_{\gamma Z} g_4^{\gamma Z} + ({g_V^e}^2 + {g_A^e}^2)\eta_Z g_4^Z\right]\\
&-xy^2\left[-g_V^e \eta_{\gamma Z} g_5^{\gamma Z} + ({g_V^e}^2 + {g_A^e}^2)\eta_Z g_5^Z\right]\Big\}\ ,\\
\frac{d^2\sigma_{eH}}{dxdy} = \frac{4\pi\alpha^2}{xyQ^2}\Big\{&(2-y)\,xy\left[g_1^\gamma - g_V^e \eta_{\gamma Z} g_1^{\gamma Z} + ({g_V^e}^2 + {g_A^e}^2)\eta_Z g_1^Z\right]\\
&-(1-y)\left[g_A^e \eta_{\gamma Z} g_4^{\gamma Z} - 2 g_V^e g_A^e \eta_Z g_4^Z\right] + xy^2\left[g_A^e \eta_{\gamma Z} g_5^{\gamma Z} - 2 g_V^e g_A^e \eta_Z g_5^Z\right]\Big\}\ .
\end{aligned}
$$

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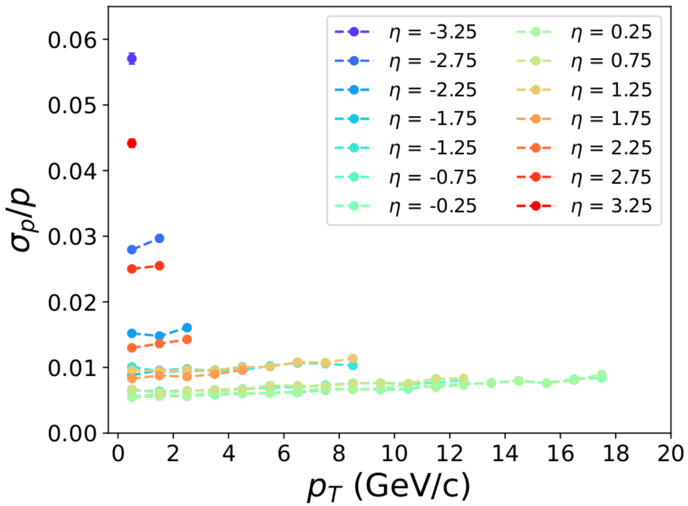
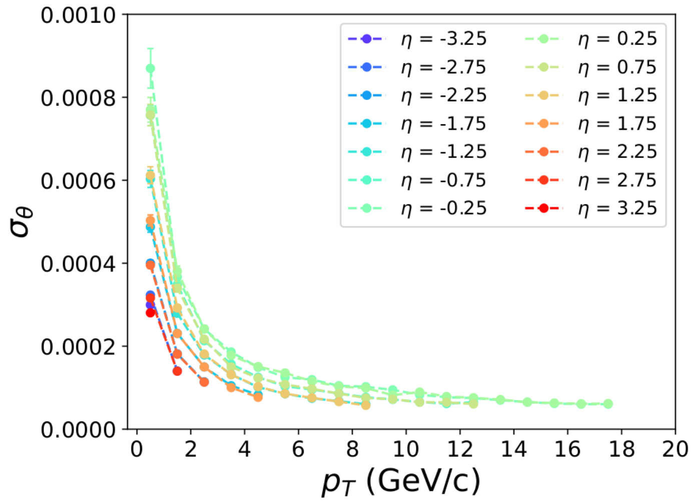
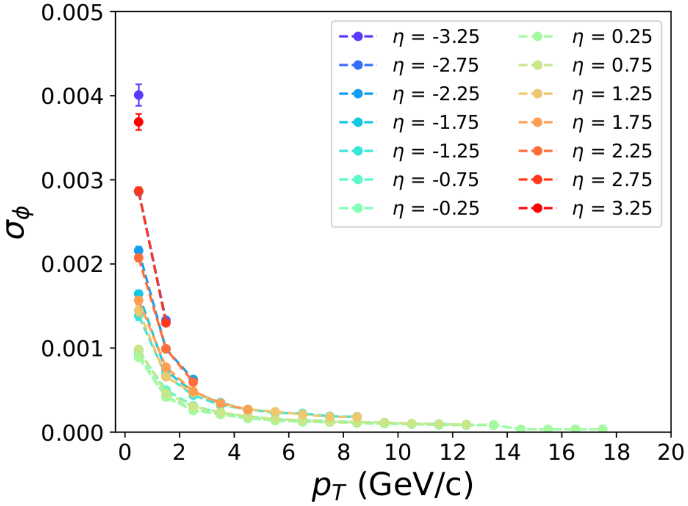
Simulation:

- July 2021 concept, Djangoh 4.6.16 combined with fast smearing from single-electron gun simulation
- Modified user routine of Djangoh to calculate counts and size of Apv
- Events unfolded to leptonic truth using R-matrix inversion method
- 20M events per energy/beam setting



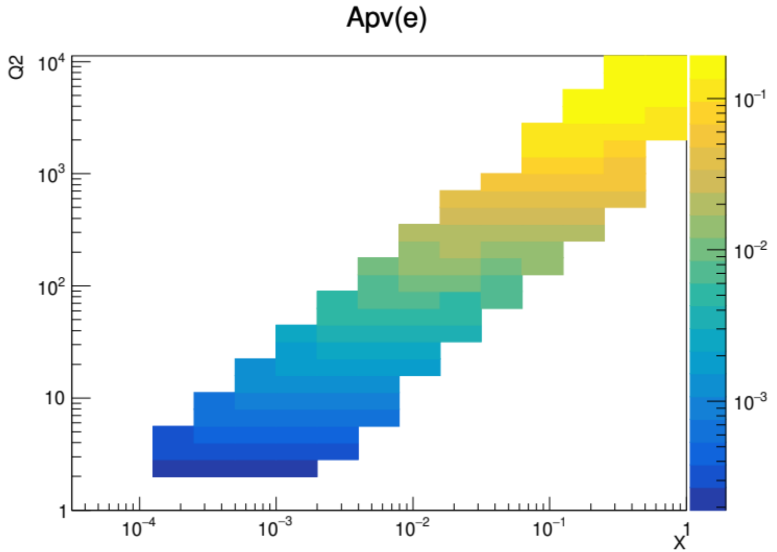


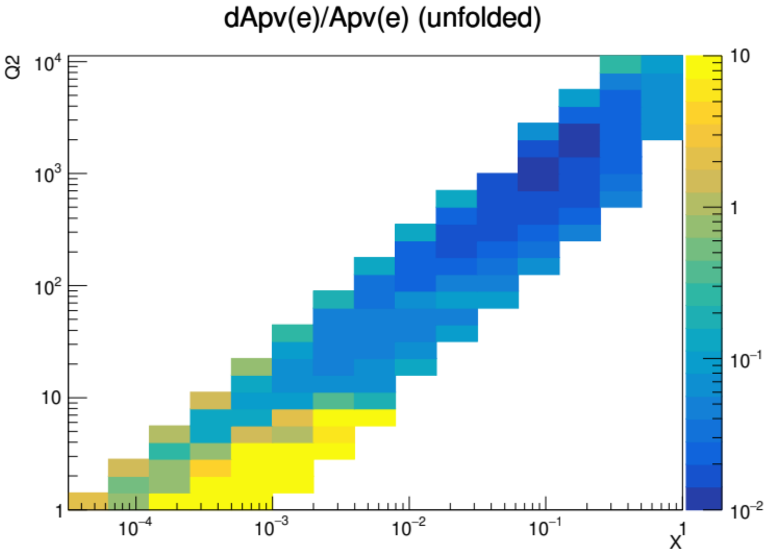


Data sets simulated and processed:

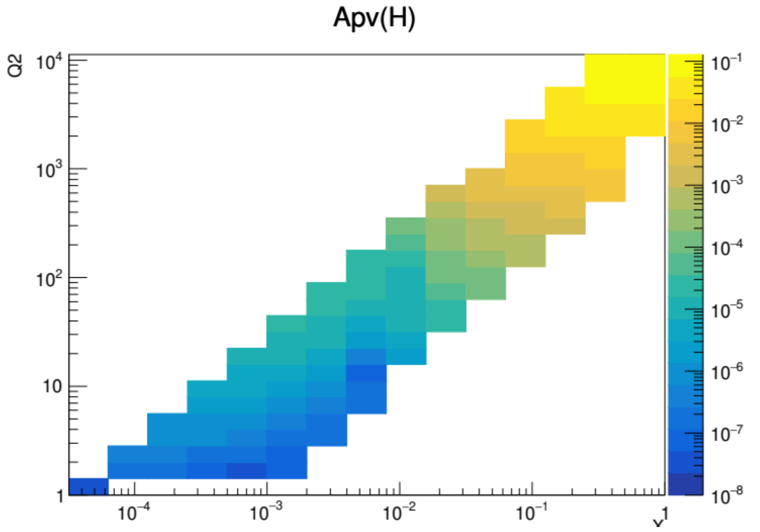
D1	5 GeV $\times$ 41 GeV eD, 4.4 fb^{-1}	P1	5 GeV $\times$ 41 GeV ep, 4.4 fb^{-1}
D2	5 GeV $\times$ 100 GeV eD, 36.8 fb^{-1}	P2	5 GeV $\times$ 100 GeV ep, 36.8 fb^{-1}
D3	10 GeV $\times$ 100 GeV eD, 44.8 fb^{-1}	P3	10 GeV $\times$ 100 GeV ep, 44.8 fb^{-1}
D4	10 GeV $\times$ 137 GeV eD, 100 fb^{-1}	P4	10 GeV $\times$ 275 GeV ep, 100 fb^{-1}
D5	18 GeV $\times$ 137 GeV eD, 15.4 fb^{-1}	P5	18 GeV $\times$ 275 GeV ep, 15.4 fb^{-1}
		P6	18 GeV $\times$ 275 GeV ep, 100 fb^{-1}

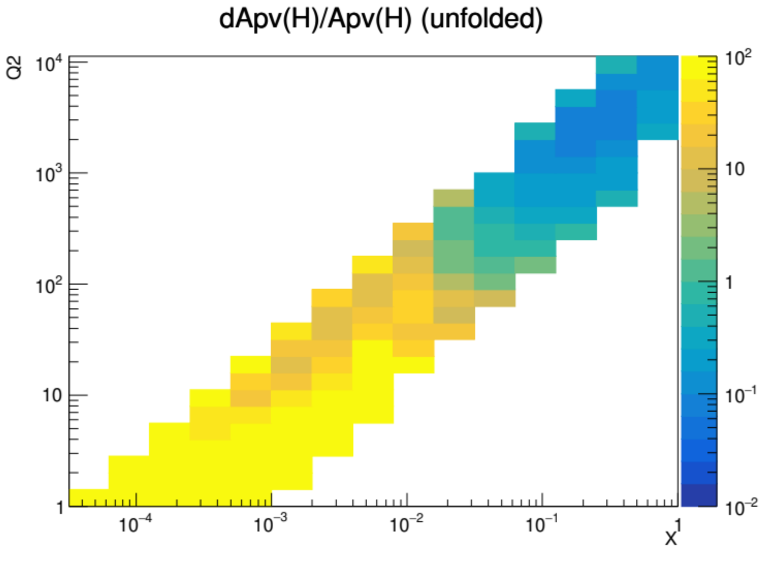
“unpolarized” PV





“polarized” PV





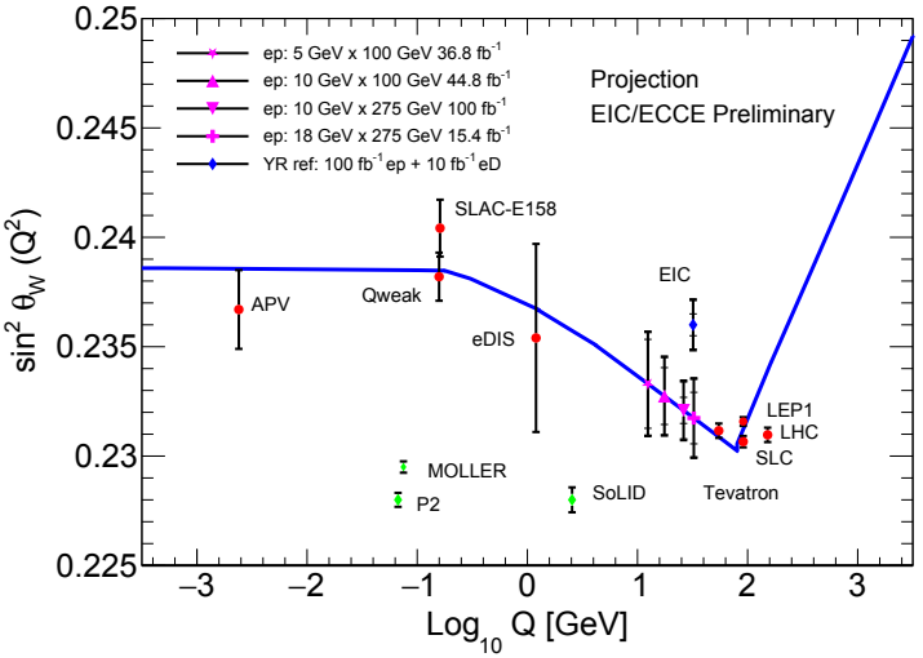
18x275 ep 100 fb^{-1}

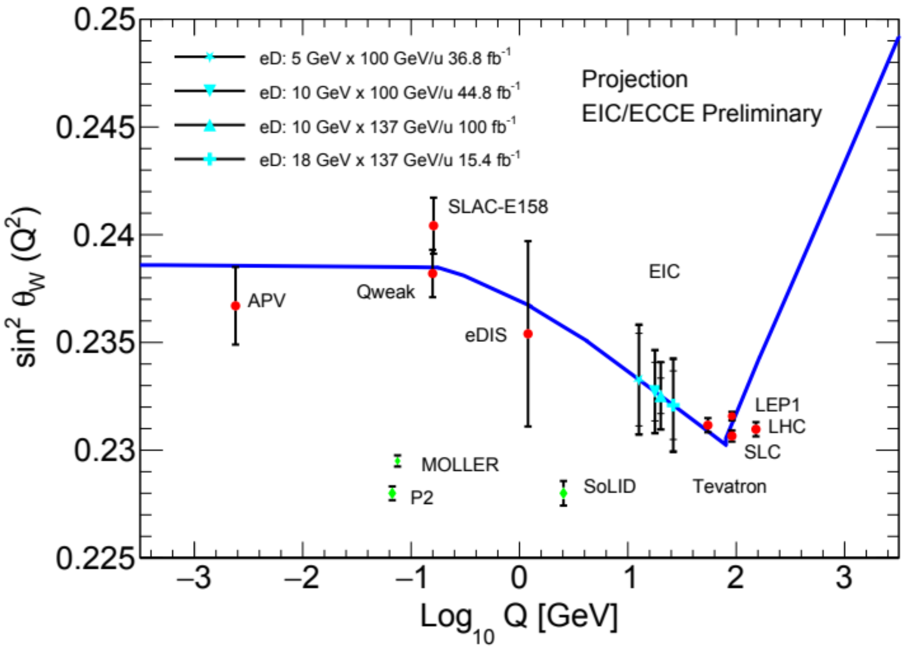
These also represent precision on the “additional EW structure functions” (namely $g_{1,5}^{\gamma Z}$)

fitting of weak mixing angle

$$A_{RL}^{e^-}=\frac{|\lambda|\eta_{\gamma Z}\left[g_A^e\,2y\,F_1^{\gamma Z}+g_A^e\left(\frac{2}{xy}-\frac{2}{x}-\frac{2M^2xy}{Q^2}\right)F_2^{\gamma Z}+g_V^e(2-y)F_3^{\gamma Z}\right]}{2y\,F_1^{\gamma}+\left(\frac{2}{xy}-\frac{2}{x}-\frac{2M^2xy}{Q^2}\right)F_2^{\gamma}-\eta_{\gamma Z}\left[g_V^e\,2y\,F_1^{\gamma Z}+g_V^e\left(\frac{2}{xy}-\frac{2}{x}-\frac{2M^2xy}{Q^2}\right)F_2^{\gamma Z}+g_A^e(2-y)F_3^{\gamma Z}\right]}$$

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

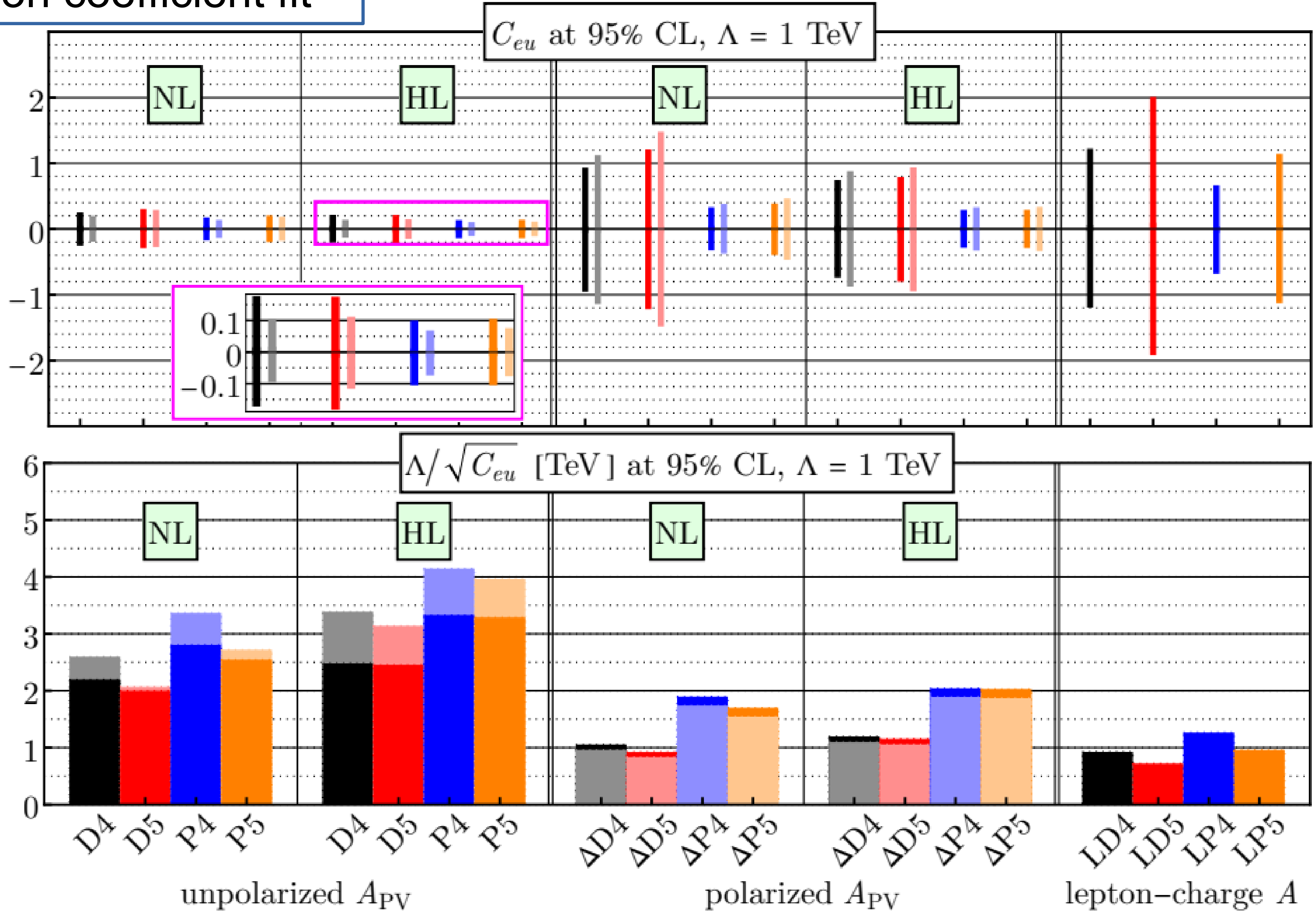




Take-way: ep better than eD; statistical and beam polarimetry uncertainties dominate; PDF uncertainty not a big issue; moderate precision in an unmeasured energy region, multi-year run would help

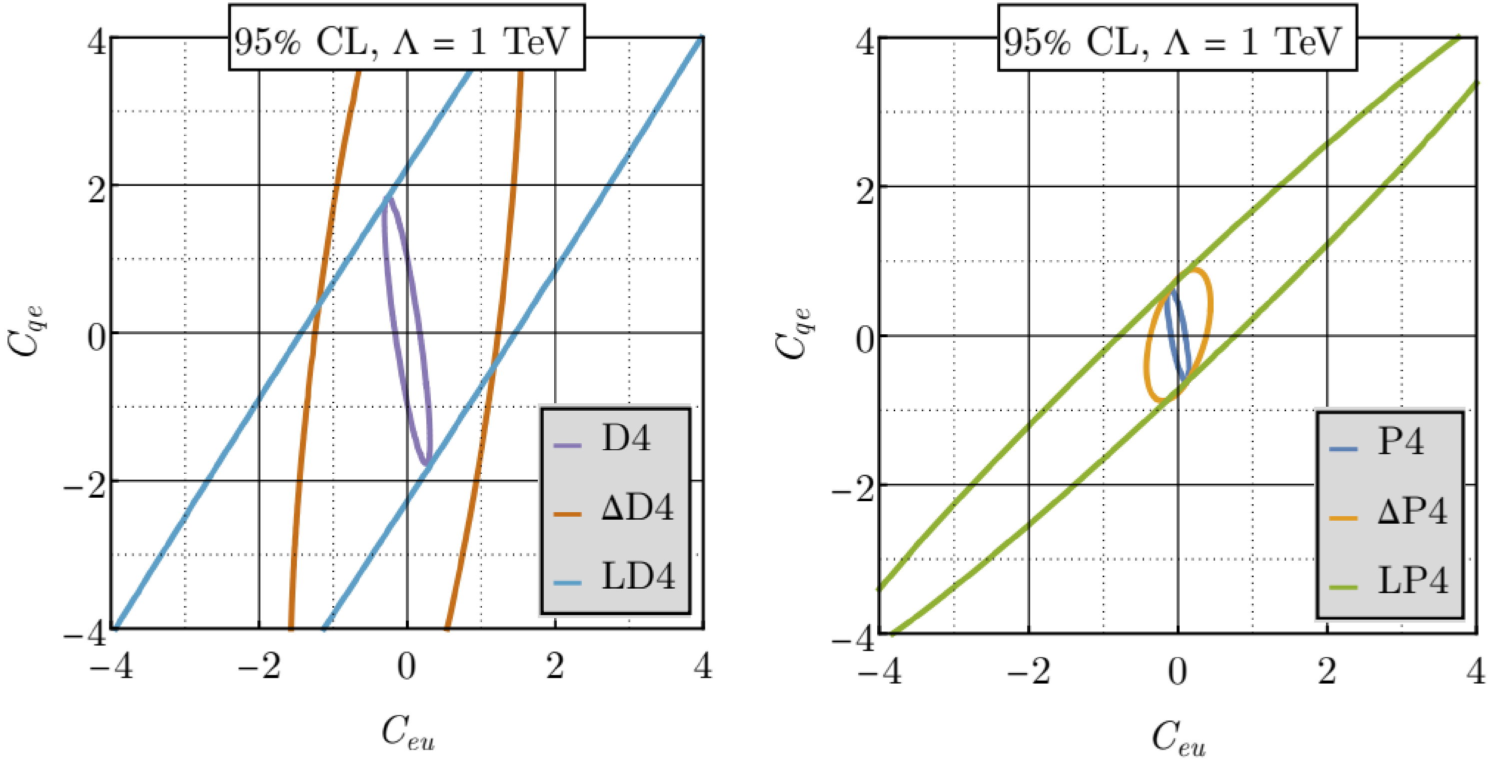
SMEFT single Wilson coefficient fit

lighter shades: exploratory fitting method that includes beam polarization



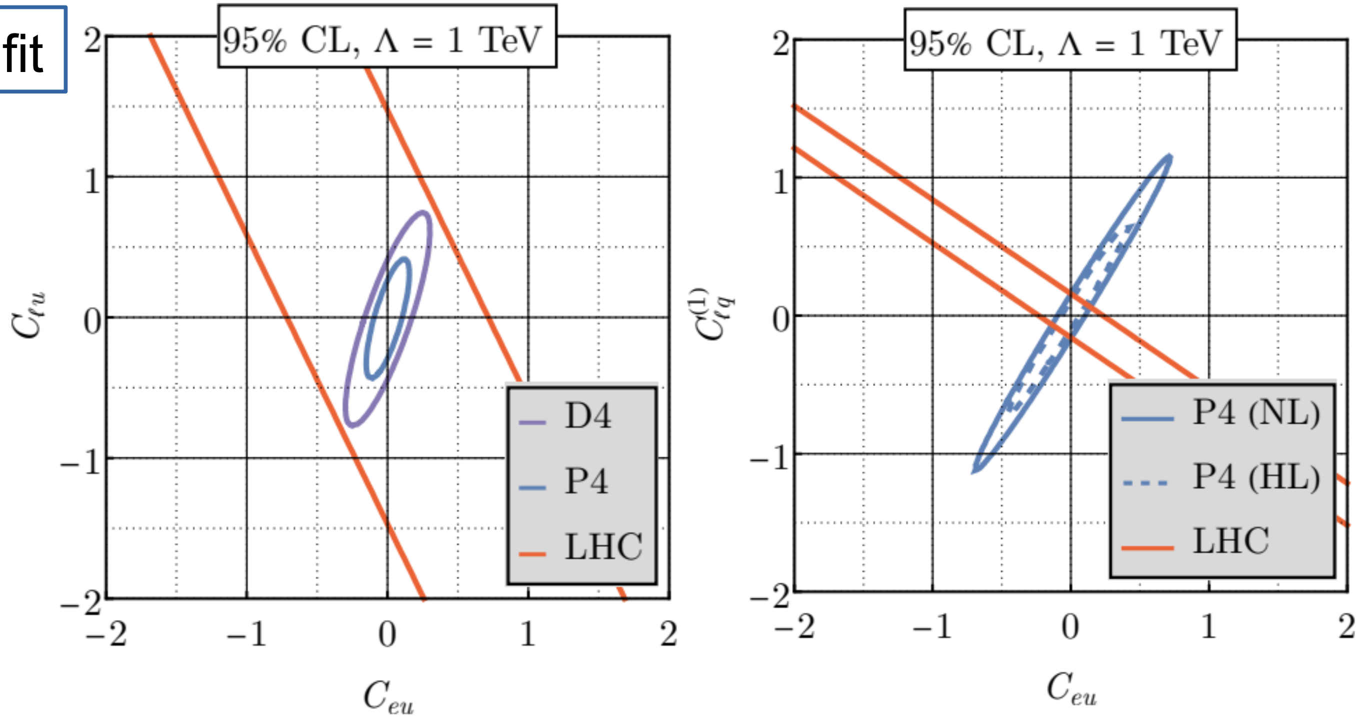
Apv(e) from proton provides best limits, ~3TeV with NL, ~4TeV with HL

SMEFT two Wilson coefficient fit



Apv(e) from proton provides best limits, Apv(p) provide complementarity but not as competitive. Positrons add okay constraints with limited precision.

SMEFT two Wilson coefficient fit



Our complete study of correlations between Wilson coefficients finds that no degeneracies remain upon combining all EIC data sets. This is not the case with LHC Drell-Yan measurements, in which numerous degeneracies exist, and will continue to occur even after LHC's high luminosity running.

This demonstrates that although the EIC is primarily thought of as a QCD machine, it is in fact a powerful probe of potential BSM effects with a broad coverage of heavy new physics parameter space, and is in many ways competitive with the higher energy LHC.