NEUTRAL CURRENT SMEFT STUDIES WITH EIC AND LHEC DIS PSEUDO DATA

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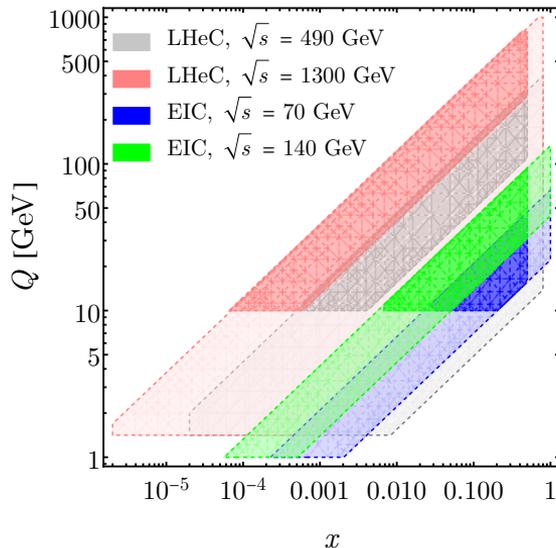
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OUR WORK IN A NUTSHELL

📌 We study the **BSM** potential of the LHeC and the EIC

→ detailed accounting of anticipated uncertainties on **pseudo data**

📌 **Multidimensional fits**
of NC DIS cross section and asymmetries performed in the **SMEFT** framework

📌 We show that both the **EIC** and **LHeC** can improve upon the existing bound on the Z-boson couplings

SMEFT

Standard Model Effective Field Theory

in this work $\quad n = 6$

$$\mathscr{L}_{\mathrm{SMEFT}} = \mathscr{L}_{\mathrm{SM}} + \sum_{n>4} \frac{1}{\Lambda^{n-4}} \sum_k \mathcal{C}_k^{(n)} O_k^{(n)}$$
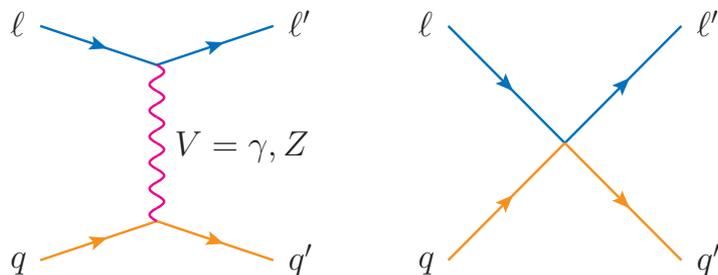
📌 Model independent

📌 Warsaw basis

17 Wilson coefficients affect NC DIS matrix elements at LO

	ffV		semi-leptonic four-fermion
$C_{\varphi WB}$	$O_{\varphi WB} = (\varphi^\dagger \tau^I \varphi) W_{\mu\nu}^I B^{\mu\nu}$	$C_{\ell q}^{(1)}$	$O_{\ell q}^{(1)} = (\bar{\ell}\gamma_\mu \ell)(\bar{q}\gamma^\mu q)$
$C_{\varphi D}$	$O_{\varphi D} = (\varphi^\dagger D_\mu \varphi)^*(\varphi^\dagger D^\mu \varphi)$	$C_{\ell q}^{(3)}$	$(\bar{\ell}\gamma_\mu \tau^I \ell)(\bar{q}\gamma^\mu \tau^I q)$
$C_{\varphi \ell}^{(1)}$	$O_{\varphi \ell}^{(1)} = (\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{\ell}\gamma^\mu \ell)$	C_{eu}	$O_{eu} = (\bar{e}\gamma_\mu e)(\bar{u}\gamma^\mu u)$
$C_{\varphi \ell}^{(3)}$	$O_{\varphi \ell}^{(3)} = (\varphi^\dagger i \overleftrightarrow{D}_\mu \tau^I \varphi)(\bar{\ell}\gamma^\mu \tau^I \ell)$	C_{ed}	$O_{ed} = (\bar{e}\gamma_\mu e)(\bar{d}\gamma^\mu d)$
$C_{\varphi e}$	$O_{\varphi e} = (\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{e}\gamma^\mu e)$	$C_{\ell u}$	$O_{\ell u} = (\bar{\ell}\gamma_\mu \ell)(\bar{u}\gamma^\mu u)$
$C_{\varphi q}^{(1)}$	$O_{\varphi q}^{(1)} = (\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{q}\gamma^\mu q)$	$C_{\ell d}$	$O_{\ell d} = (\bar{\ell}\gamma_\mu \ell)(\bar{d}\gamma^\mu d)$
$C_{\varphi q}^{(3)}$	$O_{\varphi q}^{(3)} = (\varphi^\dagger i \overleftrightarrow{D}_\mu \tau^I \varphi)(\bar{q}\gamma^\mu \tau^I q)$	C_{qe}	$O_{qe} = (\bar{q}\gamma_\mu q)(\bar{e}\gamma^\mu e)$
$C_{\varphi u}$	$O_{\varphi u} = (\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{u}\gamma^\mu u)$		
$C_{\varphi d}$	$O_{\varphi d} = (\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{d}\gamma^\mu d)$		
$C_{\ell \ell}$	$O_{\ell \ell} = (\bar{\ell}\gamma_\mu \ell)(\bar{\ell}\gamma^\mu \ell)$		

ℓ, q: left handed doublets
e, u, d: right handed singlets
φ : SU(2) Higgs doublet

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DEEP INELASTIC SCATTERING
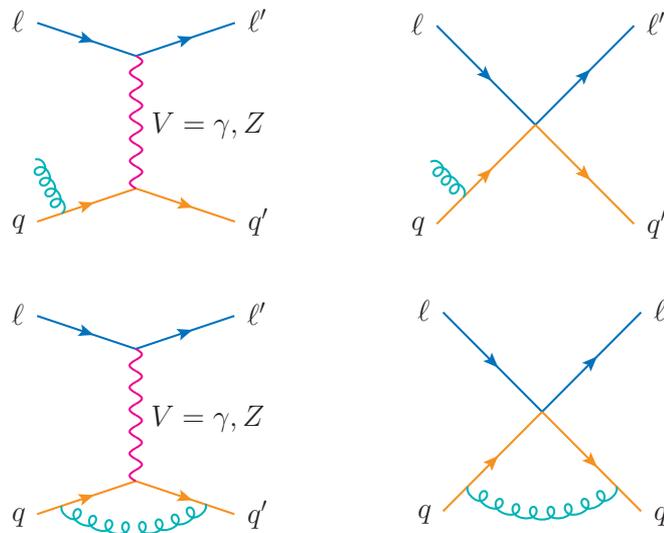

LO

Feynman diagrams for the partonic process mediating

$$\ell + H \to \ell' + X$$

NLO QCD

corrections modify only the quark lines

they are identical for both SM and SMEFT cross sections

SMEFT THEORY PREDICTIONS

Structure of observables

We linearize our SMEFT expressions $\mathcal{T}$

$$\mathcal{T} = \mathcal{T}^{\mathrm{SM}} + \sum_k \mathcal{C}_k \; \delta\mathcal{T}_k + \mathcal{O}(\mathcal{C}_k^2)$$

SMEFT shift associated with the Wilson coefficient $\mathcal{C}_k$

k runs over the active Wilson coefficients

SMEFT cross section

$$\sigma = \sigma^{\mathrm{SM}} + \sum_i^{N_{\mathrm{d6}}} \frac{\mathcal{C}_i}{\Lambda^2} k_i + \sum_{ij}^{N_{\mathrm{d6}}} \frac{\mathcal{C}_i \mathcal{C}_j}{\Lambda^4} \tilde{k}_{ij} + \dots$$

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KINEMATIC COVERAGE

of pseudo data

📌 complementarity of LHeC and EIC

Legend:
- LHeC, $\sqrt{s}$ = 490 GeV
- LHeC, $\sqrt{s}$ = 1300 GeV
- EIC, $\sqrt{s}$ = 70 GeV
- EIC, $\sqrt{s}$ = 140 GeV

$x \leq 0.5$

$Q \geq 10$ GeV

$0.1 \leq y \leq 0.9$

Data set label	Data set configuration	Observable
LHeC1	60 GeV × 1000 GeV $e^- p$, $P_\ell = 0$, $\mathcal{L} = 100$ fb^{-1}	σ_{NC}
LHeC2	60 GeV × 7000 GeV $e^- p$, $P_\ell = -80\%$, $\mathcal{L} = 100$ fb^{-1}	
LHeC3	60 GeV × 7000 GeV $e^- p$, $P_\ell = +80\%$, $\mathcal{L} = 30$ fb^{-1}	
LHeC4	60 GeV × 7000 GeV $e^+ p$, $P_\ell = +80\%$, $\mathcal{L} = 10$ fb^{-1}	
LHeC5	60 GeV × 7000 GeV $e^- p$, $P_\ell = -80\%$, $\mathcal{L} = 1000$ fb^{-1}	
LHeC6	60 GeV × 7000 GeV $e^- p$, $P_\ell = +80\%$, $\mathcal{L} = 300$ fb^{-1}	
LHeC7	60 GeV × 7000 GeV $e^+ p$, $P_\ell = 0\%$, $\mathcal{L} = 100$ fb^{-1}	
D4	10 GeV × 137 GeV $e^- D$, $P_\ell = 80\%$, $\mathcal{L} = 100$ fb^{-1}	A_{PV}
D5	18 GeV × 137 GeV $e^- D$, $P_\ell = 80\%$, $\mathcal{L} = 15.4$ fb^{-1}	
P4	10 GeV × 275 GeV $e^- p$, $P_\ell = 80\%$, $\mathcal{L} = 100$ fb^{-1}	
P5	18 GeV × 275 GeV $e^- p$, $P_\ell = 80\%$, $\mathcal{L} = 15.4$ fb^{-1}	
ΔD4	The same as D4 but with $P_\ell = 0$ and $P_H = 70\%$	ΔA_{PV}
ΔD5	The same as D5 but with $P_\ell = 0$ and $P_H = 70\%$	
ΔP4	The same as P4 but with $P_\ell = 0$ and $P_H = 70\%$	
ΔP5	The same as P5 but with $P_\ell = 0$ and $P_H = 70\%$	

UNCERTAINTIES
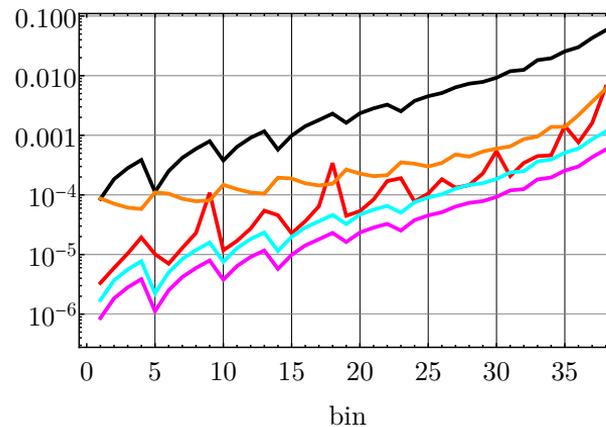
📌 bins are ordered first in Q, then in x

LHeC

LHeC3: 60 GeV ×7000 GeV e^-p, $P_\ell = +80\%$, $\mathcal{L} = 30$ fb^{-1}

bin

■ σ_{NC} ■ $\sigma_{\mathrm{NC,stat}}$ ■ $\sigma_{\mathrm{NC,ueff}}$ ■ $\sigma_{\mathrm{NC,sys}}$ ■ $\sigma_{\mathrm{NC,pdf}}$

EIC

ΔP4: 10 GeV ×275 GeV e^-p, $P_\ell = 0$, $\mathcal{L} = 100$ fb^{-1}

bin

■ ΔA_{PV} ■ $\delta\Delta A_{\mathrm{PV,stat}}$ ■ $\delta\Delta A_{\mathrm{PV,sys}}$ ■ $\delta\Delta A_{\mathrm{PV,pol}}$ ■ $\delta\Delta A_{\mathrm{PV,pdf}}$

PDF set

NNPDF 3.1 NLO

NNPDF POL 1.1

PSEUDODATA AND χ^2

e experiment
b bin

SM prediction

uncertainties

$$\mathcal{O}_{e,b} = \mathcal{O}_b^{\text{SM}} + r_{e,b}\, \delta\mathcal{O}_{\text{unc},b} + \sum_j r'_{j,e}\, \delta\mathcal{O}_{\text{cor}_j,b}$$

pseudodata

$r_{e,b}\,, r'_{j,e} \in \mathcal{N}(0,1)$

each correlated error has its own random coefficient $r'_{j,e}$

covariance matrix

$$\chi_e^2 = \sum_{i,j=1}^{\text{N}_{\text{bin}}} (\mathcal{T}_i - \mathcal{O}_{e,i}) V_{ij}^{-1} (\mathcal{T}_j - \mathcal{O}_{e,j})$$

SMEFT expression

RESULTS

EFFECTIVE UV SCALES

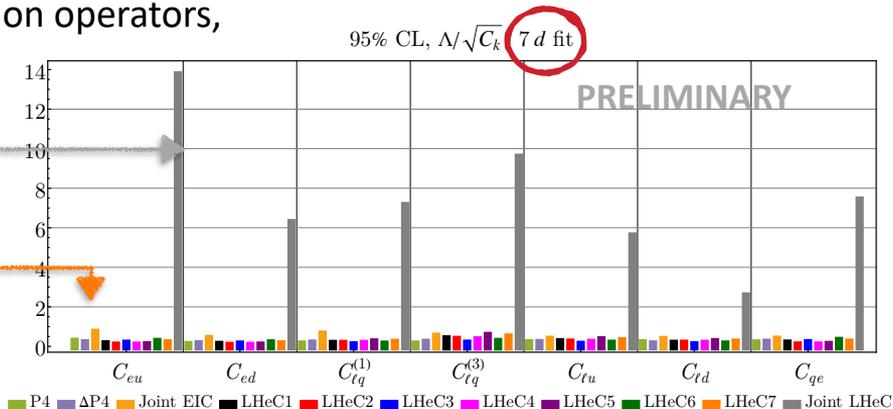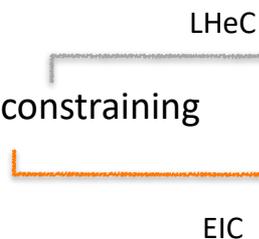95% CL, $\Lambda/\sqrt{C_k}$, 1 d fit

PRELIMINARY

$$\frac{\Lambda}{\sqrt{C_k}}$$

upper bound of marginalized interval

📌 when we activate the entire sector of four-fermion operators, we observe strong correlations

95% CL, $\Lambda/\sqrt{C_k}$ 7 d fit

PRELIMINARY

LHeC

📌 joint fits keep their constraining power

EIC

CONFIDENCE ELLIPSES

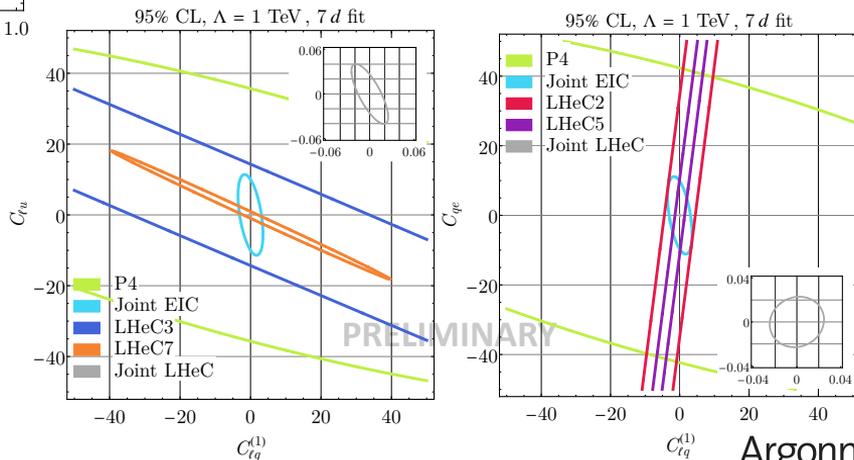## Four-fermion $\mathcal{C}_k$

2D

📌 no flat directions here

📌 LHeC more constraining than EIC
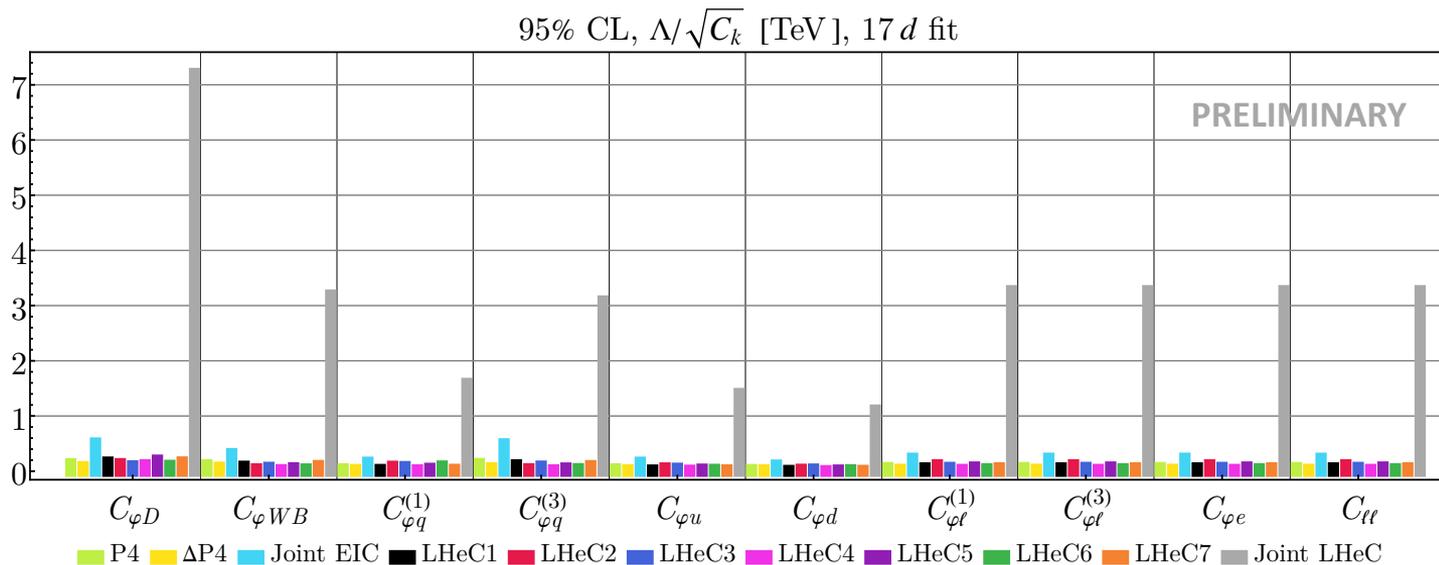
7D

📌 flat directions emerge in LHeC fits

→ resolved by individual and joint EIC fits and joint LHeC

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17D FIT

UV effective scales

📌 17-parameter fit on the Wilson coefficients that induce the semi-leptonic four-fermion contact interaction

95% CL, $\Lambda/\sqrt{C_k}$ [TeV], 17d fit

PRELIMINARY

Legend: P4, ΔP4, Joint EIC, LHeC1, LHeC2, LHeC3, LHeC4, LHeC5, LHeC6, LHeC7, Joint LHeC

X-axis labels: $C_{\varphi D}$, $C_{\varphi WB}$, $C_{\varphi q}^{(1)}$, $C_{\varphi q}^{(3)}$, $C_{\varphi u}$, $C_{\varphi d}$, $C_{\varphi \ell}^{(1)}$, $C_{\varphi \ell}^{(3)}$, $C_{\varphi e}$, $C_{\ell\ell}$
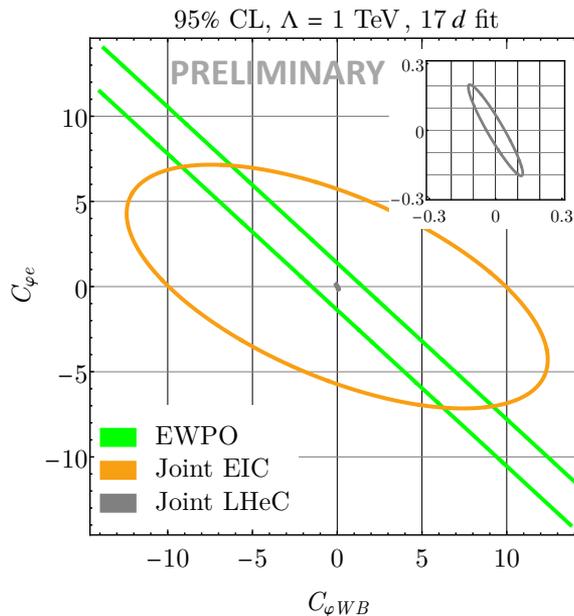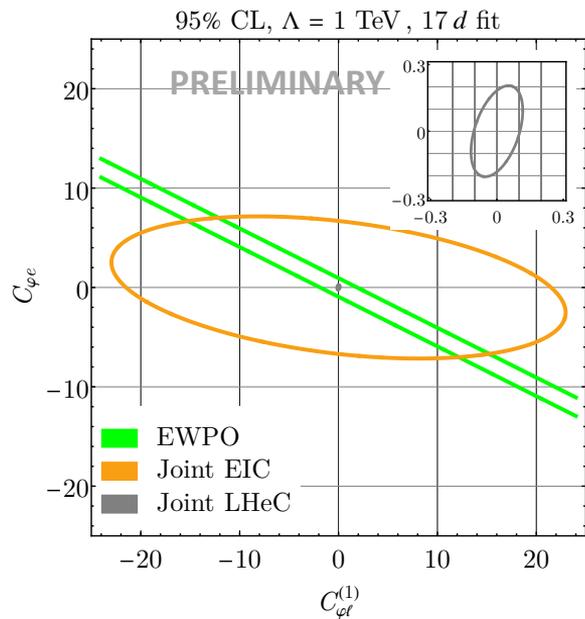
📌 very similar situation to 7D fit, joint fits have the most constraining power

LHeC can probe up to 7 TeV scale

17D FIT

Confidence ellipses

95% CL, $\Lambda = 1$ TeV, 17 d fit

PRELIMINARY

$C_{\varphi e}$ / $C_{\varphi \ell}^{(1)}$

95% CL, $\Lambda = 1$ TeV, 17 d fit

PRELIMINARY

$C_{\varphi e}$ / $C_{\varphi WB}$

EWPO
Joint EIC
Joint LHeC

34D EWPO fits

J. Ellis, M. Madigan, K. Mimasu
V. Sanz, T. You
JHEP04 (2021) 279

📌 resolving blind spots observed in the fits of Wilson coefficients in the f f V sector using Z and W pole observables (EWPO) data

CORRELATION MATRIX

joint LHeC fit

📌 expected strong correlations

$$(\mathcal{C}_{\ell q}^{(1)}, \mathcal{C}_{\ell q}^{(3)})$$

📌 unexpected strong correlations

$$(\mathcal{C}_{\ell \ell}, \mathcal{C}_{\varphi D}) \quad (\mathcal{C}_{\ell u}, \mathcal{C}_{\ell d})$$

📌 non trivial relation with experimental uncertainties

📌 more correlation ⟷ weaker bounds

CONCLUSIONS

📌 We performed 1D, 2D, 7D and **17D fits** of EIC and LHeC pseudo data

📌 **LHeC** can probe scales up to **7 TeV**

📌 (Some of) the **blind spots** observed by Ellis et al. are **resolved** by EIC and LHeC

EIC and LHeC have both great potential for BSM studies

95% CL, $\Lambda = 1$ TeV , $17\,d$ fit

PRELIMINARY

Legend:
- EWPO (green)
- Joint EIC (orange)
- Joint LHeC (gray)

Axes: $C_{\varphi e}$ (vertical), $C_{\varphi \ell}^{(1)}$ (horizontal)

BACKUP

OBSERVABLES

Reduced Neutral Current (NC) DIS cross section

$$\frac{\mathrm{d}^2 \sigma_{r,\mathrm{NC}}^{\ell}}{\mathrm{d}x\,\mathrm{d}Q^2} = \left\{ \frac{2\pi\alpha^2}{xQ^4}[1 + (1-y)^2] \right\}^{-1} \frac{\mathrm{d}^2 \sigma_{\mathrm{NC}}^{\ell}}{\mathrm{d}x\,\mathrm{d}Q^2}$$

LHeC

Unpolarized hadron

$$\frac{\mathrm{d}^2 \Delta\sigma_{r,\mathrm{NC}}^{\ell}}{\mathrm{d}x\,\mathrm{d}Q^2} = \left\{ \frac{4\pi\alpha^2}{xQ^4}[1 + (1-y)^2] \right\}^{-1} \frac{\mathrm{d}^2 \Delta\sigma_{\mathrm{NC}}^{\ell}}{\mathrm{d}x\,\mathrm{d}Q^2}$$

Polarized hadron

- -

Parity-violating (PV) DIS asymmetries

unpolarized

$$A_{\mathrm{PV}} = \frac{\sigma_{\mathrm{NC}}^+ - \sigma_{\mathrm{NC}}^-}{\sigma_{\mathrm{NC}}^+ + \sigma_{\mathrm{NC}}^-}$$

EIC

polarized

$$\Delta A_{\mathrm{PV}} = \frac{\Delta\sigma_{\mathrm{NC}}^0}{\sigma_{\mathrm{NC}}^0}$$

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WILSON COEFFICIENTS BOUNDS

Marginalized bound of $\mathcal{C}_k$

$$\Delta C_k = \sqrt{\Delta\chi^2(1,c)(F^{-1})_{kk}}$$

F is the Fisher matrix of the fitted parameters

quantile of the χ^2 distribution for $d = 1,2$ marginalized fitted parameters at confidence level c

Confidence ellipses

$$\begin{pmatrix} C_k & C_{k'} \end{pmatrix} \begin{pmatrix} (F^{-1})_{kk} & (F^{-1})_{kk'} \\ (F^{-1})_{k'k} & (F^{-1})_{k'k'} \end{pmatrix}^{-1} \begin{pmatrix} C_k \\ C_{k'} \end{pmatrix} = \Delta\chi^2(2,c)$$

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COVARIANCE MATRIX

Experimental error matrix

uncorrelated errors

correlated errors

i, j bins

$$E_{ij}^{\mathrm{exp}} = \begin{cases} (\sqrt{(\delta\mathcal{O}_{\mathrm{unc},i})^2 + (\delta\mathcal{O}_{\mathrm{cor},j})^2})^2 , & i = j \\ \delta\mathcal{O}_{\mathrm{cor},i} \ \delta\mathcal{O}_{\mathrm{cor},j} , & i \neq j \end{cases}$$

full correlation among bins

PDF error matrix

SM prediction with m^{th} PDF member

SM prediction with central PDF

$$E_{ij}^{\mathrm{PDF}} = \frac{1}{N_{\mathrm{PDF}}} \sum_{m=1}^{N_{\mathrm{PDF}}} (\mathcal{O}_{m,i} - \mathcal{O}_{0,i})(\mathcal{O}_{m,j} - \mathcal{O}_{0,j})$$

number of PDF members

COVARIANCE MATRIX

Total covariance matrix

$$V_{ij} = E_{ij}^{\mathrm{exp}} + E_{ij}^{\mathrm{PDF}}$$

for joint fits, with more than one experiment

joint covariance matrix

LHeC case

$$V = \begin{pmatrix} V_1 & J_{12} & \cdots & J_{17} \\ & V_2 & \cdots & J_{27} \\ & & \ddots & \vdots \\ & & & V_7 \end{pmatrix}$$
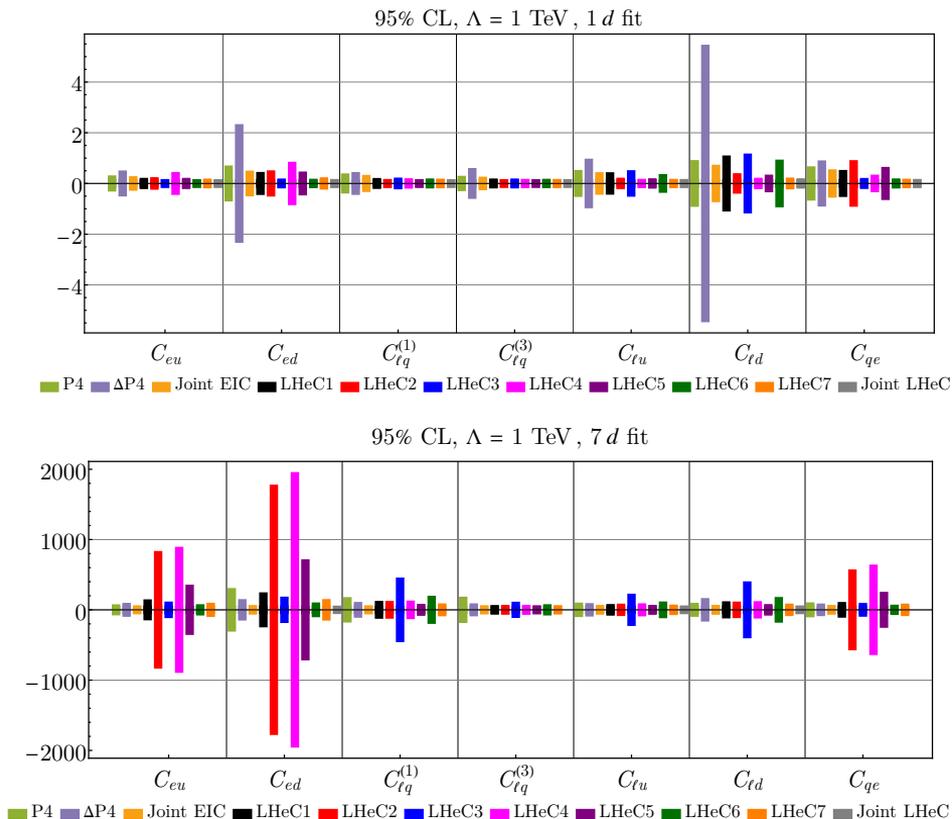
$$J_{nn'} = J_{nn'}^{\mathrm{exp}} + J_{nn'}^{\mathrm{PDF}}$$

$n, n' = 1, \dots, 7$
are the LHeC run indices

V_n is the covariance matrix of the nth LHeC set

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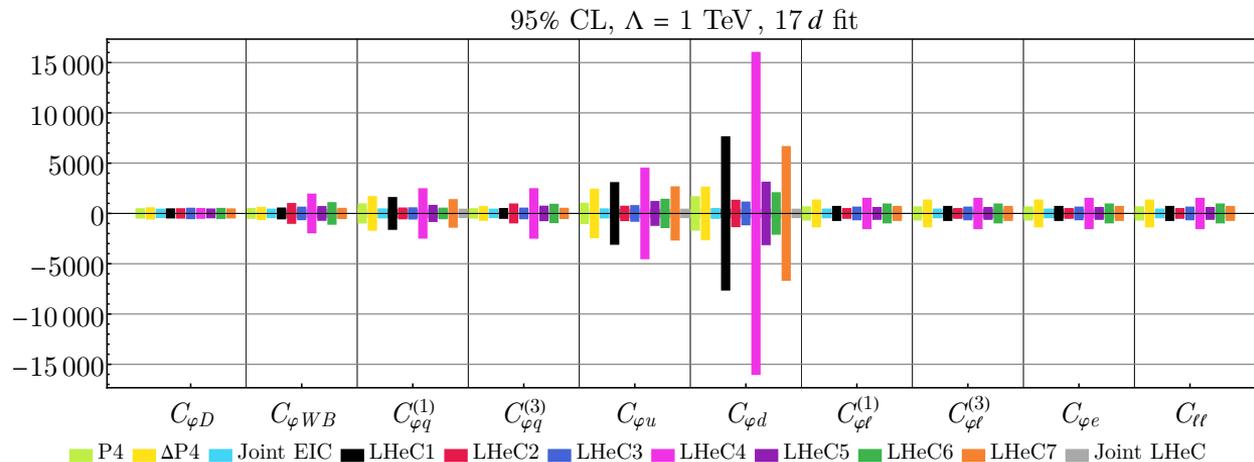Argonne
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MARGINALIZED BOUNDS

Four-fermion Wilson coefficients

17D FIT

Marginalized bounds

17D FIT

Marginalized bounds

	Joint EIC	Joint LHeC	EW diboson, Higgs, and top data
$C_{\varphi D}$	$[-3.8, 3.8]$	$[-0.019, 0.019]$	$[-1.6, 0.81]$
$\frac{\Lambda}{\sqrt{C_{\varphi D}}}$	0.51	7.2	0.91
$C_{\varphi WB}$	$[-9.9, 9.9]$	$[-0.098, 0.098]$	$[-0.36, 0.73]$
$\frac{\Lambda}{\sqrt{C_{\varphi WB}}}$	0.32	3.2	1.4
$C_{\varphi q}^{(1)}$	$[-38., 38.]$	$[-0.40, 0.40]$	$[-0.27, 0.18]$
$\frac{\Lambda}{\sqrt{C_{\varphi q}^{(1)}}}$	0.16	1.6	2.1
$C_{\varphi q}^{(3)}$	$[-4.1, 4.1]$	$[-0.11, 0.11]$	$[-0.11, 0.012]$
$\frac{\Lambda}{\sqrt{C_{\varphi q}^{(3)}}}$	0.49	3.1	4.1
$C_{\varphi u}$	$[-38., 38.]$	$[-0.51, 0.51]$	$[-0.63, 0.25]$
$\frac{\Lambda}{\sqrt{C_{\varphi u}}}$	0.16	1.4	1.5
$C_{\varphi d}$	$[-84., 84.]$	$[-0.82, 0.82]$	$[-0.91, 0.13]$
$\frac{\Lambda}{\sqrt{C_{\varphi d}}}$	0.11	1.1	1.4
$C_{\varphi \ell}^{(1)}$	$[-18., 18.]$	$[-0.094, 0.094]$	$[-0.19, 0.41]$
$\frac{\Lambda}{\sqrt{C_{\varphi \ell}^{(1)}}}$	0.23	3.3	1.8
$C_{\varphi \ell}^{(3)}$	$[-4.1, 4.1]$	$[-0.060, 0.060]$	$[-0.13, 0.055]$
$\frac{\Lambda}{\sqrt{C_{\varphi \ell}^{(3)}}}$	0.49	4.1	3.3
$C_{\varphi e}$	$[-5.7, 5.7]$	$[-0.16, 0.16]$	$[-0.41, 0.79]$
$\frac{\Lambda}{\sqrt{C_{\varphi e}}}$	0.42	2.5	1.3
$C_{\ell\ell}$	$[-7.7, 7.7]$	$[-0.039, 0.039]$	$[-0.084, 0.02]$
$\frac{\Lambda}{\sqrt{C_{\ell\ell}}}$	0.36	5.1	4.4