xFitter workshop

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SMEFT STUDIES WITH EIC AND LHEC DIS PSEUDO DATA

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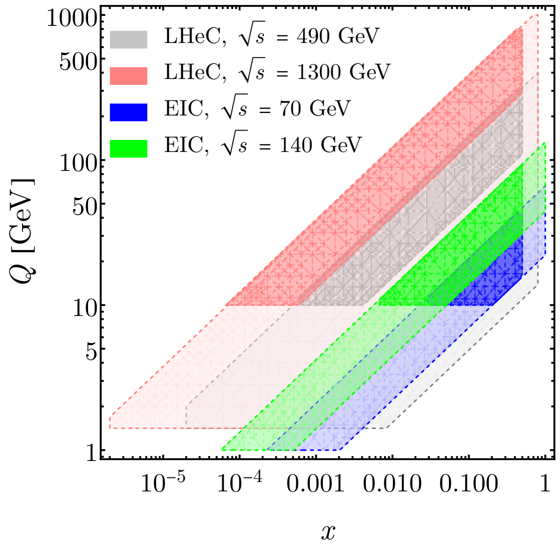
OUR WORK IN A NUTSHELL



- 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

BEFORE STARTING …

📌 In this talk **preliminary results**

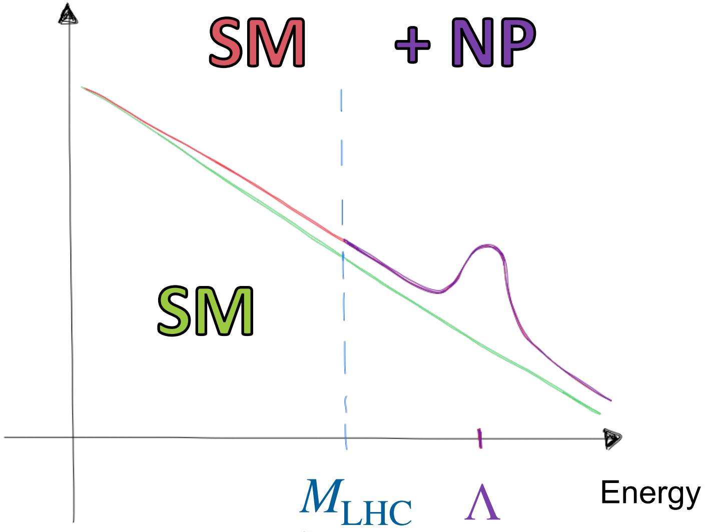
one possibile idea could be to use xFitter to **benchmark** our findings

xFitter + **SMEFT** framework

📌 xFitter + **LHeC** pseudo data

BEYOND STANDARD MODEL

Searches



maximum scale probed at LHC
and elsewhere

scale where new particles
appear

📌 All **new physics** is assumed to be heavier than all SM states and accessible collider energy

→ **SMEFT**

Standard Model Effective Field Theory

SMEFT

Standard Model Effective Field Theory

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

in this work $n = 6$

- Model independent
- Patterns and correlations among operators and observables are key
- What might we find?

Best case: a non-zero value for $\mathcal{C}_k$

indicating a mass scale slightly above probed values

Otherwise: stringent constraints on the $\mathcal{C}_k$

suggest where to focus future searches

WILSON COEFFICIENTS

Dimension 6 operators

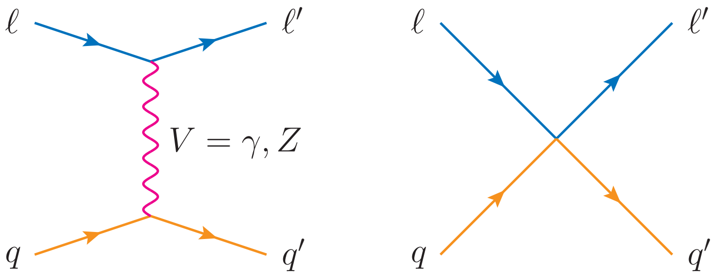
- Warsaw basis

17 Wilson coefficients affect **NC DIS** matrix elements at **LO**

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

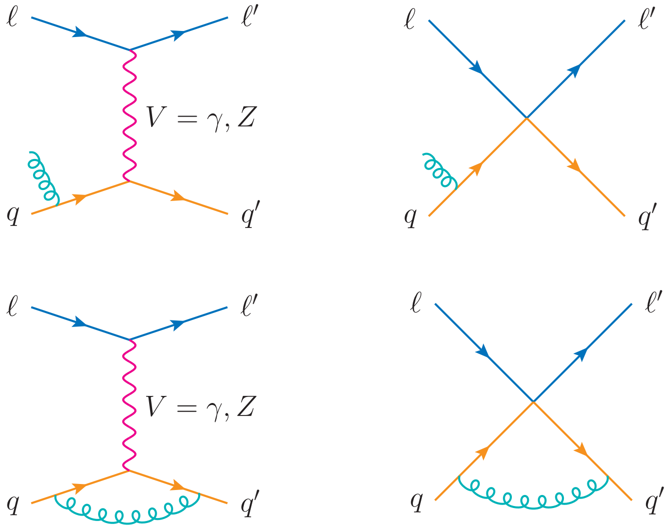
DEEP INELASTIC SCATTERING



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 $\mathcal{T}$

$$\mathcal{T} = \mathcal{T}^{\rm SM} + \sum_{\boxed{k}} \boxed{\mathcal{C}_k \; \delta\mathcal{T}_k} + \mathcal{O}(\mathcal{C}_k^2)$$

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

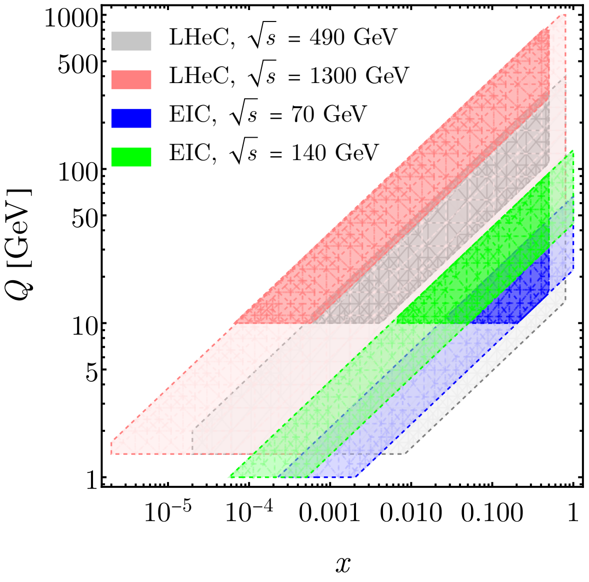
k runs over the active Wilson coefficients

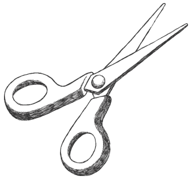
SMEFT cross section

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

KINEMATIC COVERAGE

of pseudo data





$x \leq 0.5$

$Q \geq 10$ GeV

$0.1 \leq y \leq 0.9$

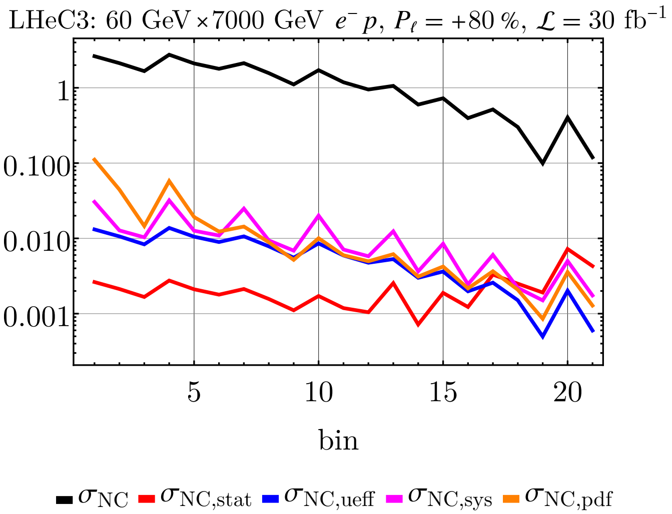
complementarity of LHeC and EIC

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

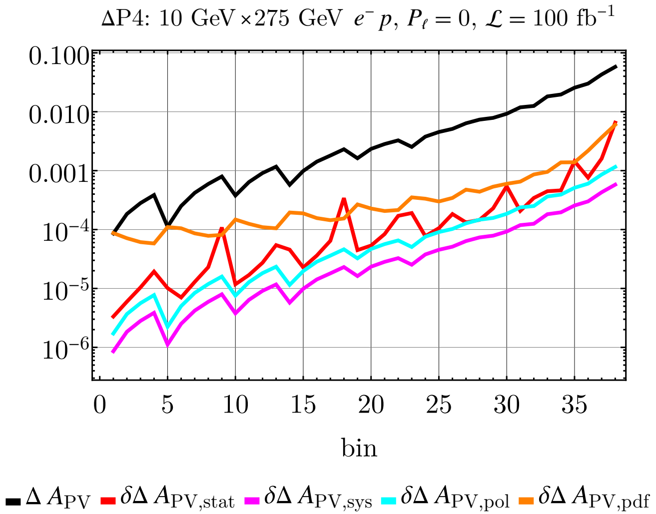
UNCERTAINTIES

- bins are ordered first in Q, then in x

LHeC



EIC



PDF set

NNPDF 3.1 NLO

NNPDF POL 1.1

PSEUDODATA AND χ^2

e experiment
b bin

SM prediction

uncertainties

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

pseudodata

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

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

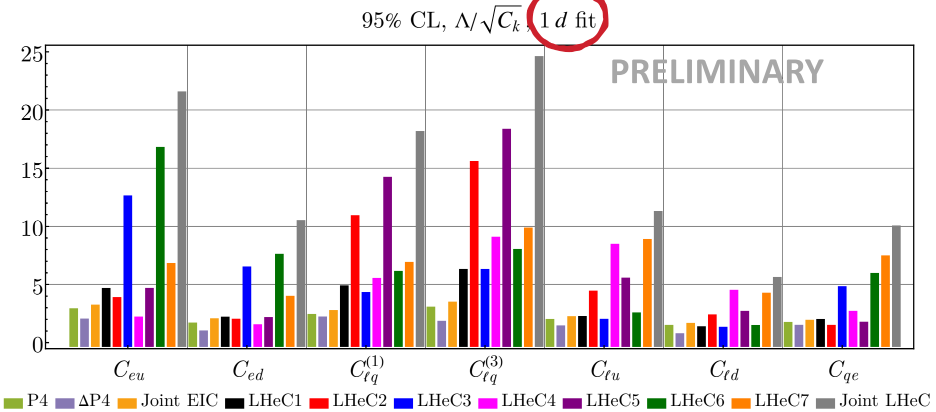
covariance matrix

$$\chi^2_e = \sum_{i,j=1}^{\mathrm{N_{bin}}} (\mathcal{T}_i - \mathcal{O}_{e,i}) V^{-1}_{ij} (\mathcal{T}_j - \mathcal{O}_{e,j})$$

SMEFT expression

RESULTS

EFFECTIVE UV SCALES



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

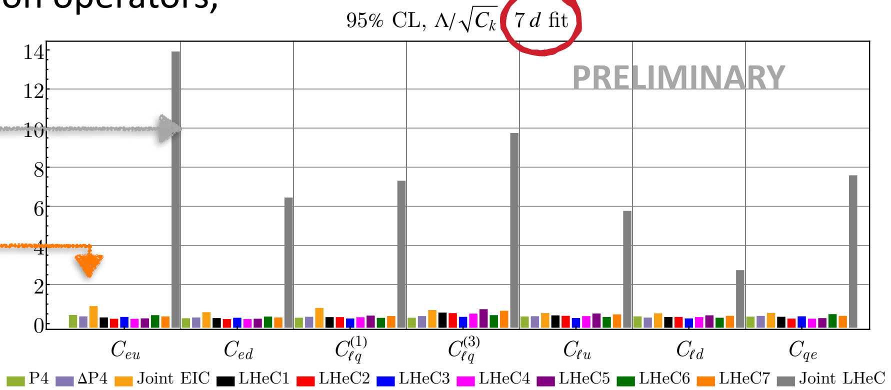
upper bound of marginalized interval

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

LHeC

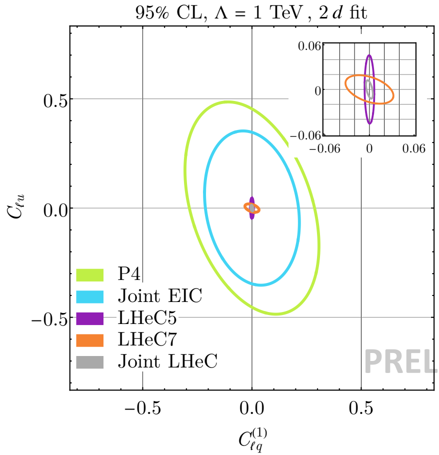
- joint fits keep their constraining power

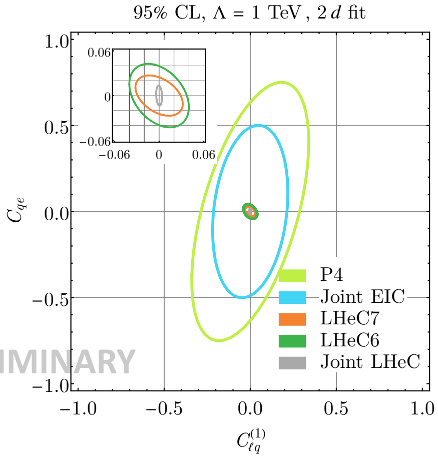
EIC



CONFIDENCE ELLIPSES

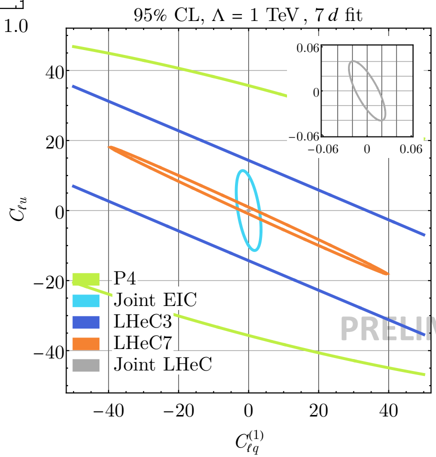
Four-fermion $\mathcal{C}_k$

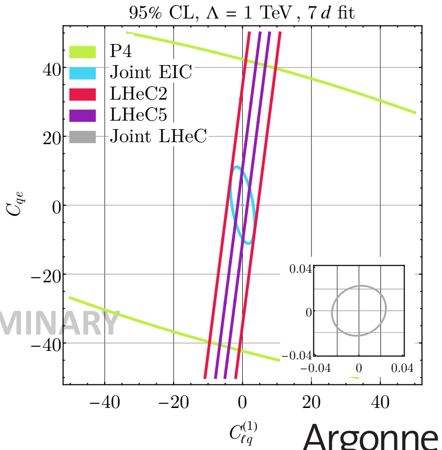




2D

- no flat directions here
- LHeC more constraining than EIC





7D

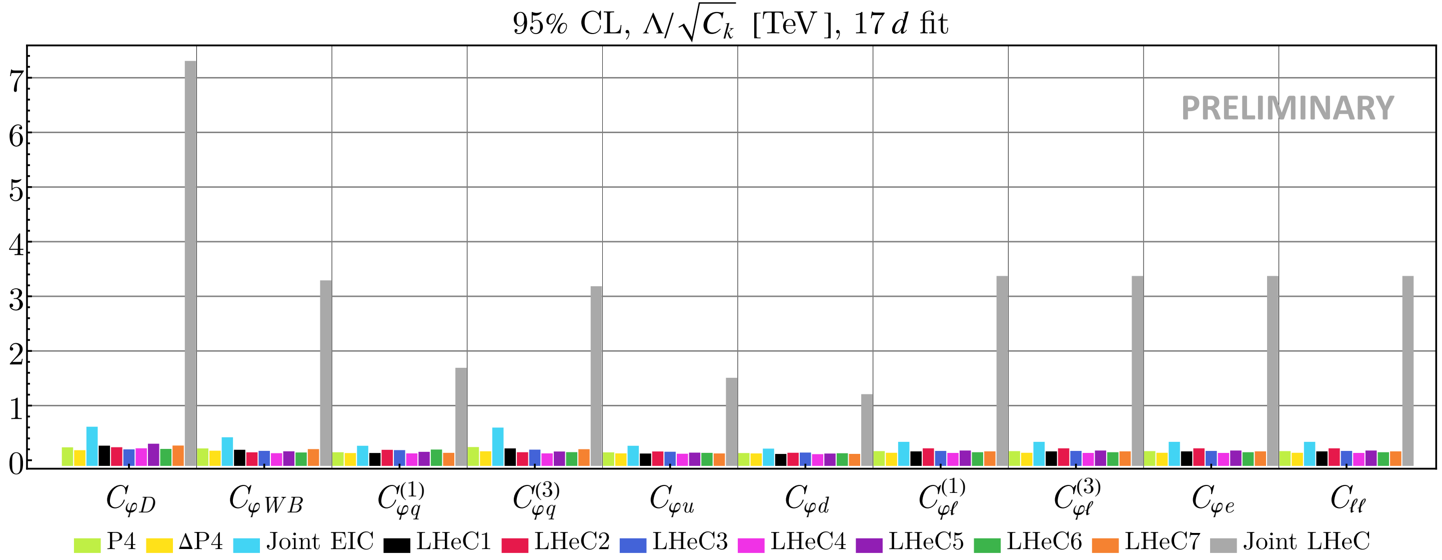
- flat directions emerge in LHeC fits

resolved by individual and joint EIC fits and joint LHeC

17D FIT

UV effective scales

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

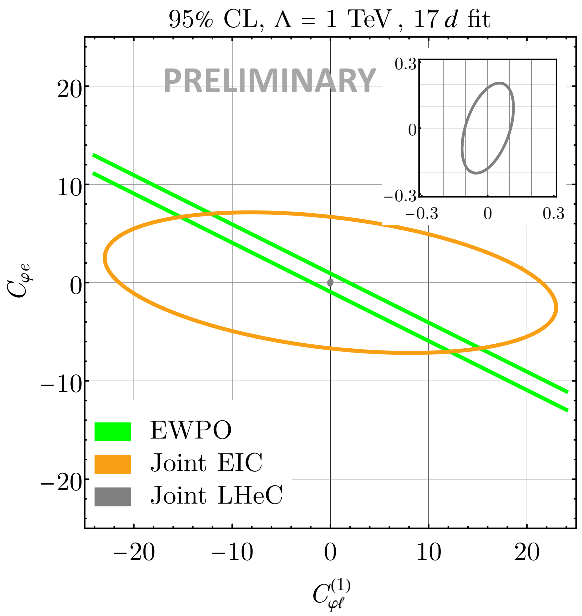


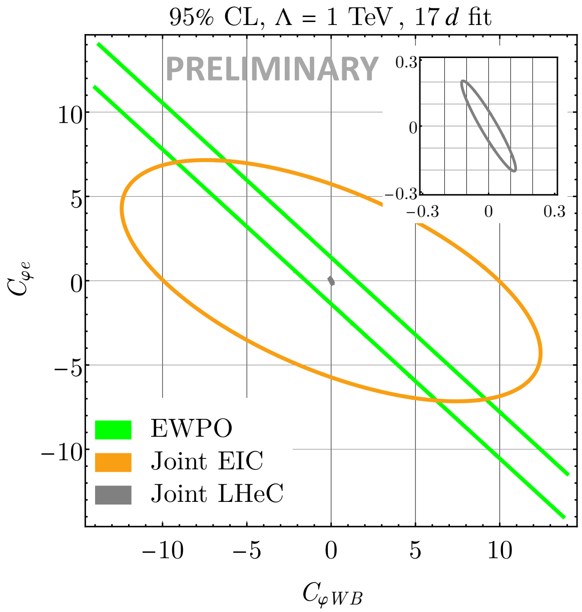
- very similar situation to 7D fit, joint fits have the most constraining power

→ LHeC can probe up to 7 TeV scale

17D FIT

Confidence ellipses





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

PRELIMINARY

joint LHeC fit

- expected strong correlations

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

- unexpected strong correlations

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

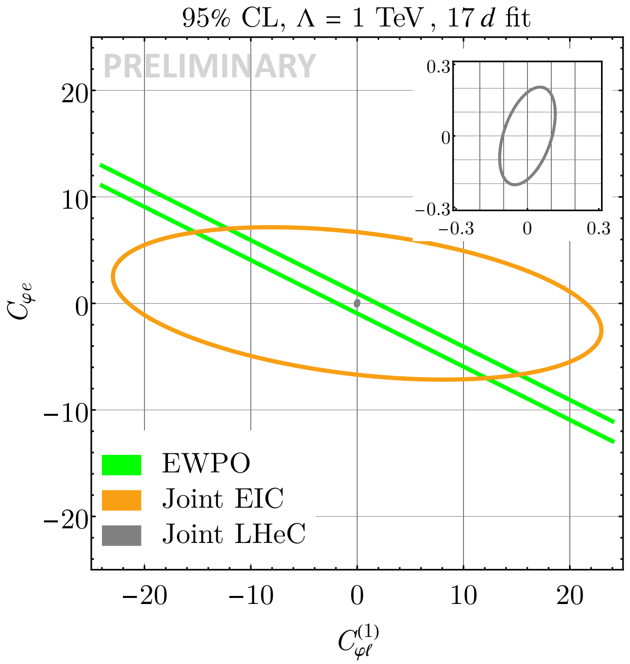
- non trivial relation with experimental uncertainties

- more correlation ⟺ weaker bounds

	$C_{\varphi D}$	$C_{\varphi WB}$	$C_{\varphi q}^{(1)}$	$C_{\varphi q}^{(3)}$	$C_{\varphi u}$	$C_{\varphi d}$	$C_{\varphi \ell}^{(1)}$	$C_{\varphi \ell}^{(3)}$	$C_{\varphi e}$	$C_{\ell\ell}$	C_{eu}	C_{ed}	$C_{\ell q}^{(1)}$	$C_{\ell q}^{(3)}$	$C_{\ell u}$	$C_{\ell d}$	C_{qe}
$C_{\varphi D}$	100.	−40.5	0.5	−24.4	−12.2	14.9	−77.	8.4	19.2	−100.	−32.3	−35.3	−8.6	−8.6	−9.1	−5.5	17.4
$C_{\varphi WB}$	−40.5	100.	−7.1	94.	−49.4	−43.7	−18.	−80.1	−94.1	40.5	53.8	68.4	−1.8	−3.5	−7.6	−5.2	1.1
$C_{\varphi q}^{(1)}$	0.5	−7.1	100.	4.4	−22.6	2.	−9.2	−13.8	−2.8	−0.5	−2.7	−14.9	−42.3	−47.3	59.7	57.9	−38.6
$C_{\varphi q}^{(3)}$	−24.4	94.	4.4	100.	−59.8	−42.	−41.2	−95.7	−99.8	24.4	43.9	54.1	−9.4	−11.4	1.2	7.6	5.2
$C_{\varphi u}$	−12.2	−49.4	−22.6	−59.8	100.	88.5	50.4	63.	60.9	12.2	−51.3	−39.2	1.4	1.4	16.5	2.9	−36.
$C_{\varphi d}$	14.9	−43.7	2.	−42.	88.5	100.	11.2	36.6	42.2	−14.9	−62.2	−48.9	−17.5	−19.5	35.3	23.1	−44.8
$C_{\varphi \ell}^{(1)}$	−77.	−18.	−9.2	−41.2	50.4	11.2	100.	57.2	45.2	77.	6.5	5.4	16.7	18.	2.1	−6.9	−19.5
$C_{\varphi \ell}^{(3)}$	8.4	−80.1	−13.8	−95.7	63.	36.6	57.2	100.	95.2	−8.4	−31.3	−36.9	15.1	17.1	−8.5	−17.8	−8.2
$C_{\varphi e}$	19.2	−94.1	−2.8	−99.8	60.9	42.2	45.2	95.2	100.	−19.2	−43.9	−54.9	9.2	11.2	0.9	−5.3	−6.1
$C_{\ell\ell}$	−100.	40.5	−0.5	24.4	12.2	−14.9	77.	−8.4	−19.2	100.	32.3	35.3	8.6	8.6	9.1	5.5	−17.4
C_{eu}	−32.3	53.8	−2.7	43.9	−51.3	−62.2	6.5	−31.3	−43.9	32.3	100.	87.2	11.7	11.4	−23.8	−19.7	14.9
C_{ed}	−35.3	68.4	−14.9	54.1	−39.2	−48.9	5.4	−36.9	−54.9	35.3	87.2	100.	15.1	14.7	−31.3	−28.4	27.8
$C_{\ell q}^{(1)}$	−8.6	−1.8	−42.3	−9.4	1.4	−17.5	16.7	15.1	9.2	8.6	11.7	15.1	100.	98.3	−78.3	−85.2	29.8
$C_{\ell q}^{(3)}$	−8.6	−3.5	−47.3	−11.4	1.4	−19.5	18.	17.1	11.2	8.6	11.4	14.7	98.3	100.	−77.2	−85.5	32.4
$C_{\ell u}$	−9.1	−7.6	59.7	1.2	16.5	35.3	2.1	−8.5	0.9	9.1	−23.8	−31.3	−78.3	−77.2	100.	94.3	−58.3
$C_{\ell d}$	−5.5	−5.2	57.9	7.6	2.9	23.1	−6.9	−17.8	−5.3	5.5	−19.7	−28.4	−85.2	−85.5	94.3	100.	−39.5
C_{qe}	17.4	1.1	−38.6	5.2	−36.	−44.8	−19.5	−8.2	−6.1	−17.4	14.9	27.8	29.8	32.4	−58.3	−39.5	100.

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

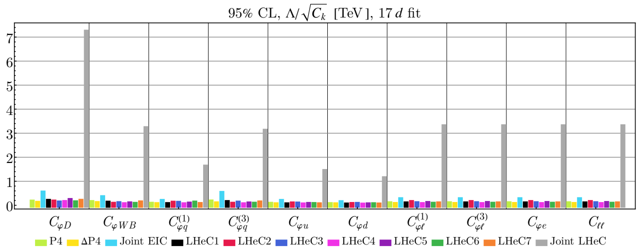
OUTLOOK

xFitter + SMEFT

perform **impact studies**

benchmark

- fit **LHeC** pseudo data with SM PDFs



PDFs + SMEFT

simultaneous fit

- growing interest in the community

see Tim's talk

BACKUP

OBSERVABLES

LHeC

Reduced Neutral Current (NC) DIS cross section

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

Unpolarized hadron

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

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

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

WILSON COEFFICIENTS BOUNDS

Marginalized bound of 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

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

COVARIANCE MATRIX

Experimental error matrix

uncorrelated errors

correlated errors

i, j bins

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

full correlation among bins

PDF error matrix

SM prediction with m^{th} PDF member

SM prediction with central PDF

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

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

$$V = \begin{pmatrix} V_1 & J_{12} & \cdots & J_{17} \\ & V_2 & \cdots & J_{27} \\ & & \ddots & \vdots \\ & & & V_7 \end{pmatrix}$$

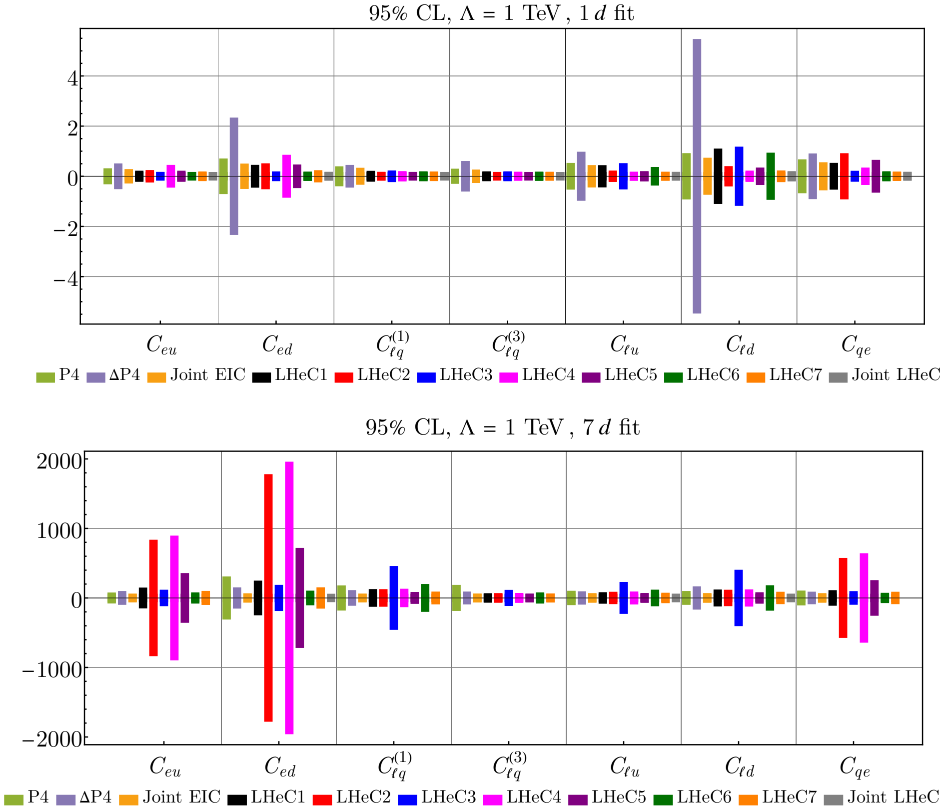
$$\boxed{J_{nn'}} = J_{nn'}^{\mathrm{exp}} + J_{nn'}^{\mathrm{PDF}}$$

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

V_n is the covariance matrix of the
n^{th} LHeC set

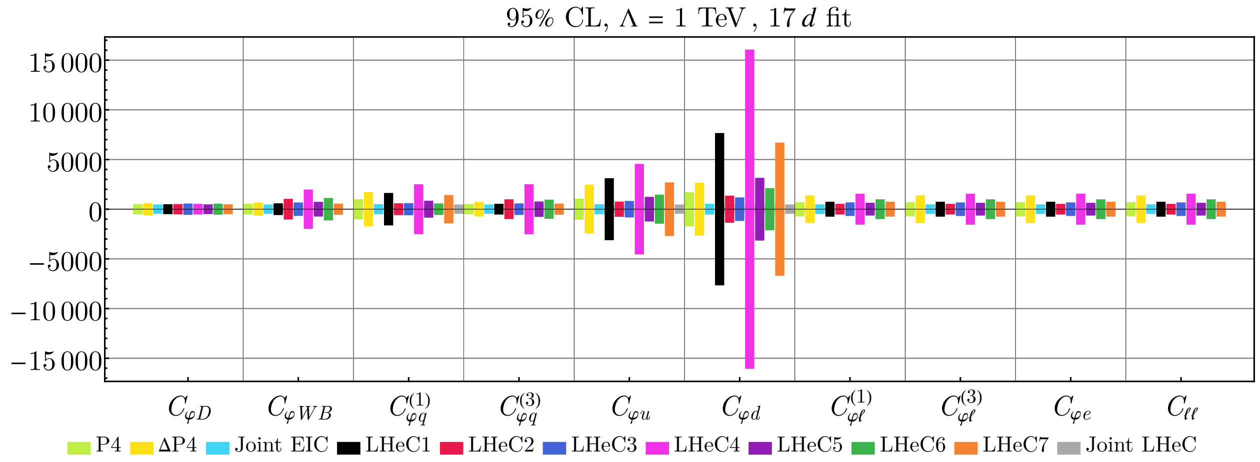
MARGINALIZED BOUNDS

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