Neutral-current electroweak physics and SMEFT studies at the EIC

Frank Petriello

Jet physics: from RHIC/LHC to EIC

June 29, 2022

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NORTHWESTERN UNIVERSITY

Argonne NATIONAL LABORATORY

Removing flat directions in SMEFT fits: how polarized electron-ion collider data can complement the LHC

Radja Boughezal[1], Frank Petriello[1,2] and Daniel Wiegand[1,2]

2004.00748

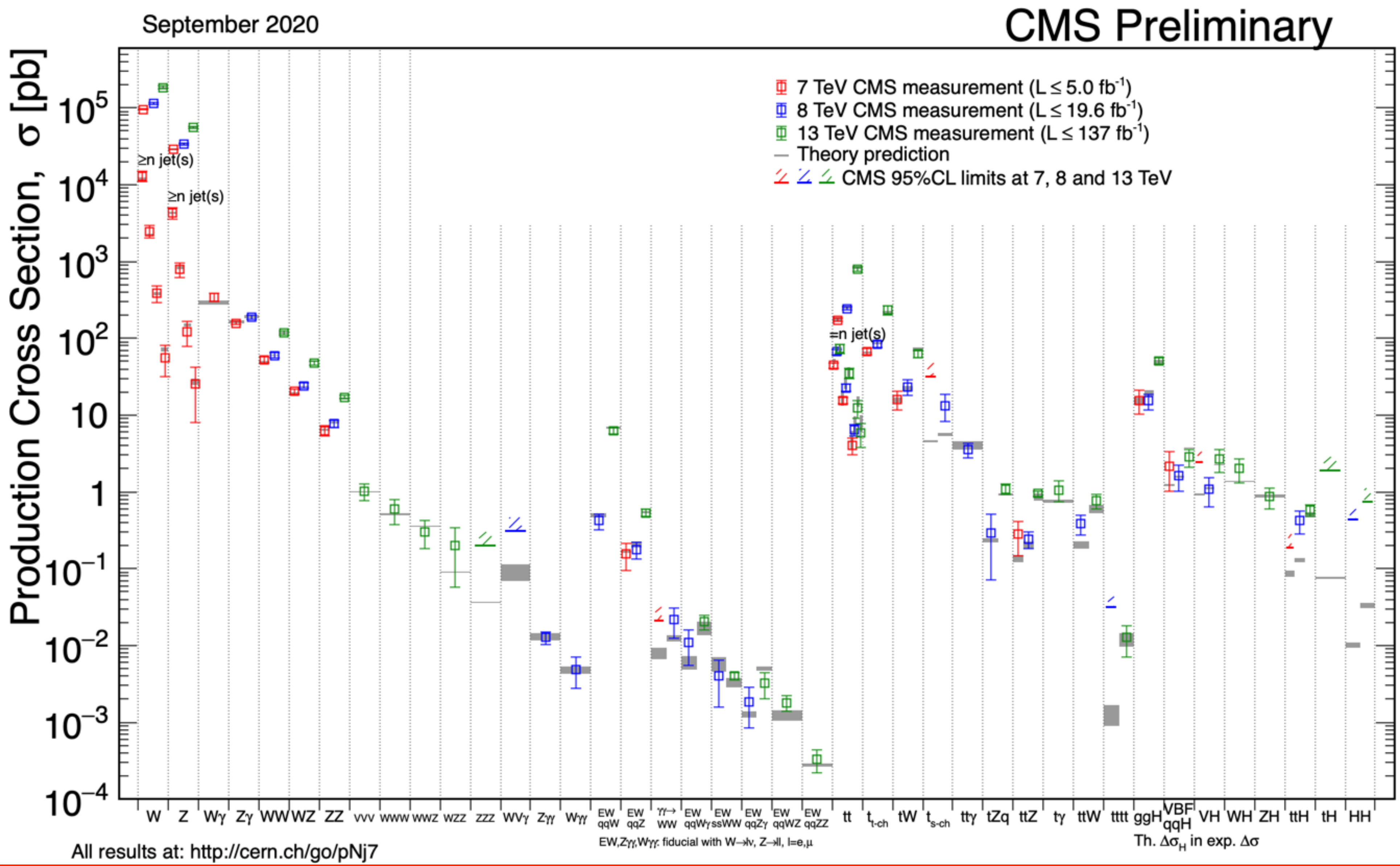
Neutral-Current Electroweak Physics and SMEFT Studies at the EIC

Radja Boughezal[1], Alexander Emmert[2], Tyler Kutz[3], Sonny Mantry[4], Michael Nycz[2], Frank Petriello[1,5], Kağan Şimşek[5], Daniel Wiegand[5], Xiaochao Zheng[2]

2204.07557

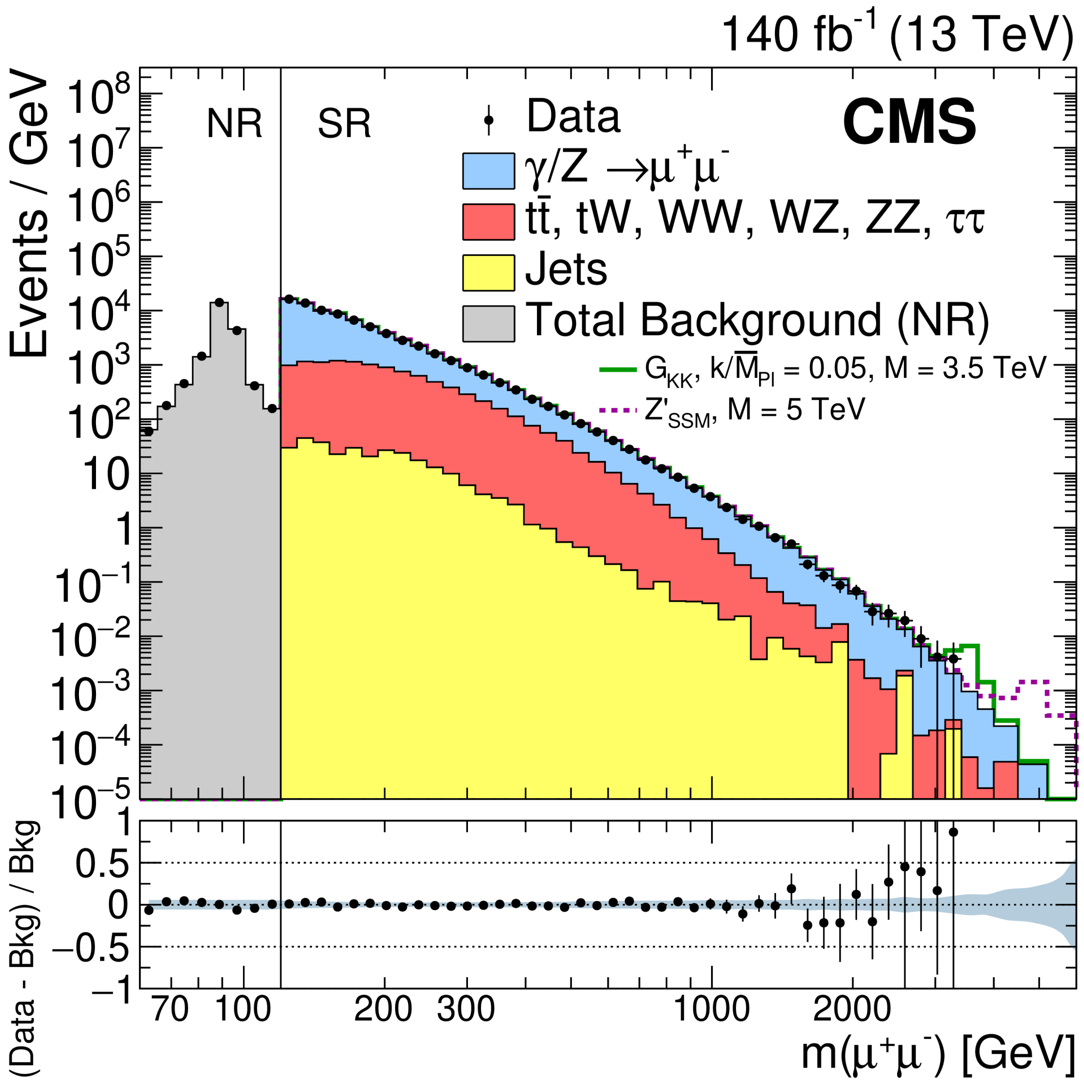
- Goals of this talk:
  - Introduce the Standard Model Effective Field Theory (SMEFT) as the appropriate framework for future new physics searches at the LHC, EIC and elsewhere
  - Show that the EIC has an important role to play in resolving LHC blind spots in the SMEFT parameter space, due to its high luminosity, low systematic errors, and ability to polarize beams
  - Explain why the EIC will be competitive in these measurements even with a high-luminosity LHC

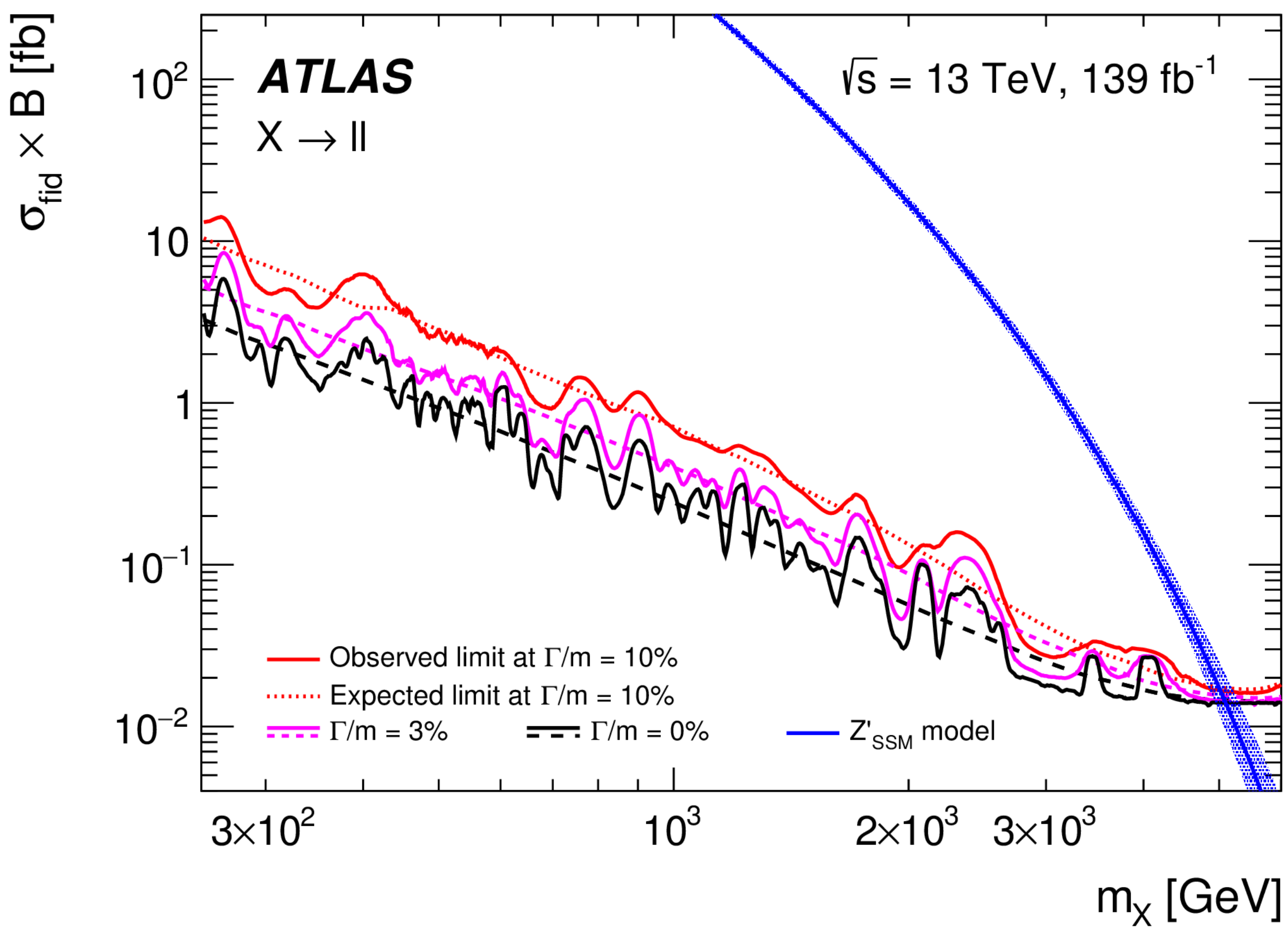
Status of the SM



Remarkable agreement between SM theory and experiment over dozens of processes and orders of magnitude in cross section. No BSM states found so far!

Searches in the Drell-Yan channel





Sensitivity to new resonances in the Drell-Yan channel has reached 5 TeV in some models. Suggests a mass gap between SM and new physics; indirect searches increasingly important

Framework for future searches

- Two approaches for future indirect searches:
  - Formulate specific BSM models, calculate predictions for the LHC and other experiments
  - Adopt an EFT framework that encapsulates a broad swath of possible BSM theories

- Standard Model Effective Field Theory (SMEFT): all operators consistent with SM symmetries, containing SM particles, and assuming a mass gap to any new physics

$$\boxed{\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{\Lambda^2}\sum_i C_{6,i}\mathcal{O}_{6,i} + \frac{1}{\Lambda^4}\sum_i C_{8,i}\mathcal{O}_{8,i}}$$

Dimension-6 **Dimension-8**

$\Lambda \gg M_{SM}$, E

Expand in large Λ

Warsaw basis

- Complete and independent dim-6 basis known: 2499 baryon conserving operators for 3 fermion generations; (can reduce assuming MFV, etc. to O(100)) Grzadkoswki, Iskrzynski, Misiak, Rosiek 1008.4884; Brivio, Jiang, Trott 1709.06492

X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar l_p e_r \varphi)$
$Q_{\widetilde G}$	$f^{ABC} \widetilde G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p u_r \widetilde\varphi)$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				
$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eW}	$(\bar l_p \sigma^{\mu\nu} e_r)\tau^I \varphi W^I_{\mu\nu}$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar l_p \gamma^\mu l_r)$
$Q_{\varphi\widetilde G}$	$\varphi^\dagger\varphi\, \widetilde G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eB}	$(\bar l_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar l_p \tau^I \gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uG}	$(\bar q_p \sigma^{\mu\nu} T^A u_r)\widetilde\varphi\, G^A_{\mu\nu}$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar e_p \gamma^\mu e_r)$
$Q_{\varphi\widetilde W}$	$\varphi^\dagger\varphi\, \widetilde W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uW}	$(\bar q_p \sigma^{\mu\nu} u_r)\tau^I \widetilde\varphi\, W^I_{\mu\nu}$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar q_p \gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar q_p \sigma^{\mu\nu} u_r)\widetilde\varphi\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar q_p \tau^I \gamma^\mu q_r)$
$Q_{\varphi\widetilde B}$	$\varphi^\dagger\varphi\, \widetilde B_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar q_p \sigma^{\mu\nu} T^A d_r)\varphi\, G^A_{\mu\nu}$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar u_p \gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W^I_{\mu\nu} B^{\mu\nu}$	Q_{dW}	$(\bar q_p \sigma^{\mu\nu} d_r)\tau^I \varphi\, W^I_{\mu\nu}$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar d_p \gamma^\mu d_r)$
$Q_{\varphi\widetilde WB}$	$\varphi^\dagger\tau^I\varphi\, \widetilde W^I_{\mu\nu} B^{\mu\nu}$	Q_{dB}	$(\bar q_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu \varphi)(\bar u_p \gamma^\mu d_r)$

$(\bar LL)(\bar LL)$		$(\bar RR)(\bar RR)$		$(\bar LL)(\bar RR)$	
Q_{ll}	$(\bar l_p \gamma_\mu l_r)(\bar l_s \gamma^\mu l_t)$	Q_{ee}	$(\bar e_p \gamma_\mu e_r)(\bar e_s \gamma^\mu e_t)$	Q_{le}	$(\bar l_p \gamma_\mu l_r)(\bar e_s \gamma^\mu e_t)$
$Q_{qq}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar q_s \gamma^\mu q_t)$	Q_{uu}	$(\bar u_p \gamma_\mu u_r)(\bar u_s \gamma^\mu u_t)$	Q_{lu}	$(\bar l_p \gamma_\mu l_r)(\bar u_s \gamma^\mu u_t)$
$Q_{qq}^{(3)}$	$(\bar q_p \gamma_\mu \tau^I q_r)(\bar q_s \gamma^\mu \tau^I q_t)$	Q_{dd}	$(\bar d_p \gamma_\mu d_r)(\bar d_s \gamma^\mu d_t)$	Q_{ld}	$(\bar l_p \gamma_\mu l_r)(\bar d_s \gamma^\mu d_t)$
$Q_{lq}^{(1)}$	$(\bar l_p \gamma_\mu l_r)(\bar q_s \gamma^\mu q_t)$	Q_{eu}	$(\bar e_p \gamma_\mu e_r)(\bar u_s \gamma^\mu u_t)$	Q_{qe}	$(\bar q_p \gamma_\mu q_r)(\bar e_s \gamma^\mu e_t)$
$Q_{lq}^{(3)}$	$(\bar l_p \gamma_\mu \tau^I l_r)(\bar q_s \gamma^\mu \tau^I q_t)$	Q_{ed}	$(\bar e_p \gamma_\mu e_r)(\bar d_s \gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar u_s \gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar u_p \gamma_\mu u_r)(\bar d_s \gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar q_p \gamma_\mu T^A q_r)(\bar u_s \gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar u_p \gamma_\mu T^A u_r)(\bar d_s \gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar d_s \gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar q_p \gamma_\mu T^A q_r)(\bar d_s \gamma^\mu T^A d_t)$
$(\bar LR)(\bar RL)$ and $(\bar LR)(\bar LR)$		B-violating			
Q_{ledq}	$(\bar l_p^j e_r)(\bar d_s q_t^j)$	Q_{duq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d^\alpha_p)^T C u^\beta_r\right]\left[(q^{\gamma j}_s)^T C l^k_t\right]$		
$Q_{quqd}^{(1)}$	$(\bar q_p^j u_r)\varepsilon_{jk}(\bar q_s^k d_t)$	Q_{qqu}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q^{\alpha j}_p)^T C q^{\beta k}_r\right]\left[(u^\gamma_s)^T C e_t\right]$		
$Q_{quqd}^{(8)}$	$(\bar q_p^j T^A u_r)\varepsilon_{jk}(\bar q_s^k T^A d_t)$	Q_{qqq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jn}\varepsilon_{km}\left[(q^{\alpha j}_p)^T C q^{\beta k}_r\right]\left[(q^{\gamma m}_s)^T C l^n_t\right]$		
$Q_{lequ}^{(1)}$	$(\bar l_p^j e_r)\varepsilon_{jk}(\bar q_s^k u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d^\alpha_p)^T C u^\beta_r\right]\left[(u^\gamma_s)^T C e_t\right]$		
$Q_{lequ}^{(3)}$	$(\bar l_p^j \sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar q_s^k \sigma^{\mu\nu} u_t)$				

Dim-6 operators

SMEFT cross sections

- Complete and independent dim-6 basis known: 2499 baryon conserving operators for 3 fermion generations; (can reduce assuming MFV, etc. to O(100)) Grzadkoswki, Iskrzynski, Misiak, Rosiek 1008.4884; Brivio, Jiang, Trott 1709.06492

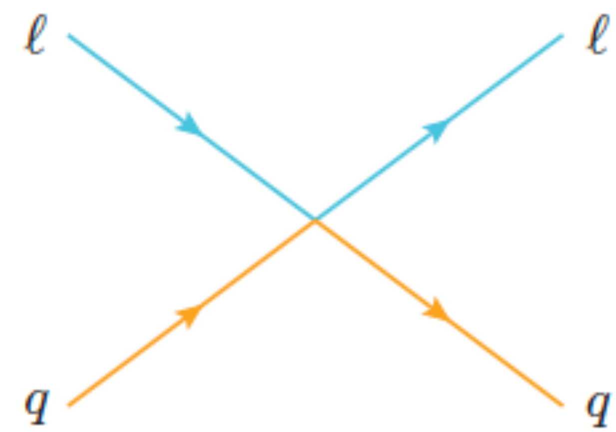
Structure of a SMEFT cross section:

$$\boxed{\sigma \sim |\mathcal{M}_{SM}|^2 + \frac{1}{\Lambda^2}\underbrace{2\mathrm{Re}\left[\mathcal{M}_6\mathcal{M}^*_{SM}\right]}_{\text{Leading SMEFT correction}} + \frac{1}{\Lambda^4}\underbrace{\left\{|\mathcal{M}_6|^2 + 2\mathrm{Re}\left[\mathcal{M}_8\mathcal{M}^*_{SM}\right]\right\}}_{\text{Sub-leading; neglected in many analyses, including this talk}}}$$

Semi-leptonic four-fermion operators

- Focus here on semi-leptonic four-fermion operators, relevant for both Drell-Yan at the LHC and DIS an the EIC

$\ell\ell qq$
$O_{\ell q}^{(1)} = (\bar{\ell}\gamma_\mu \ell)(\bar{q}\gamma^\mu q)$
$O_{\ell q}^{(3)} = (\bar{\ell}\gamma_\mu \tau^I \ell)(\bar{q}\gamma^\mu \tau^I q)$
$O_{eu} = (\bar{e}\gamma_\mu e)(\bar{u}\gamma^\mu u)$
$O_{ed} = (\bar{e}\gamma_\mu e)(\bar{d}\gamma^\mu d)$
$O_{\ell u} = (\bar{\ell}\gamma_\mu \ell)(\bar{u}\gamma^\mu u)$
$O_{\ell d} = (\bar{\ell}\gamma_\mu \ell)(\bar{d}\gamma^\mu d)$
$O_{qe} = (\bar{q}\gamma_\mu q)(\bar{e}\gamma^\mu e)$



$$i[\gamma_\mu][\gamma^\mu]g_{11}^{(\ell q)} + i[\gamma_\mu][\gamma^\mu\gamma_5]g_{15}^{(\ell q)}$$
$$+i[\gamma_\mu\gamma_5][\gamma^\mu]g_{51}^{(\ell q)} + i[\gamma_\mu\gamma_5][\gamma^\mu\gamma_5]g_{55}^{(\ell q)}$$

$$g_{11}^{(eu)} = \tfrac{1}{4}[C_{eu} + (C_{\ell q}^{(1)} - C_{\ell q}^{(3)}) + C_{\ell u} + C_{qe}]$$
$$g_{15}^{(eu)} = \tfrac{1}{4}[C_{eu} - (C_{\ell q}^{(1)} - C_{\ell q}^{(3)}) + C_{\ell u} - C_{qe}]$$
$$g_{51}^{(eu)} = \tfrac{1}{4}[C_{eu} - (C_{\ell q}^{(1)} - C_{\ell q}^{(3)}) - C_{\ell u} + C_{qe}]$$
$$g_{55}^{(eu)} = \tfrac{1}{4}[C_{eu} + (C_{\ell q}^{(1)} - C_{\ell q}^{(3)}) - C_{\ell u} - C_{qe}]$$

Can transform the SMEFT basis to vector and axial couplings

LEP constraints

- Other operators contribute as well, and shift the ffV vertices

$$O_{\varphi\ell}^{(1)} = (\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{\ell}\gamma^\mu \ell)$$
$$O_{\varphi\ell}^{(3)} = (\varphi^\dagger i \overleftrightarrow{D}_\mu \tau^I \varphi)(\bar{\ell}\gamma^\mu \tau^I \ell)$$
$$O_{\varphi e} = (\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{e}\gamma^\mu e)$$
$$O_{\varphi q}^{(1)} = (\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{q}\gamma^\mu q)$$
$$O_{\varphi q}^{(3)} = (\varphi^\dagger i \overleftrightarrow{D}_\mu \tau^I \varphi)(\bar{q}\gamma^\mu \tau^I q)$$
$$O_{\varphi u} = (\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{u}\gamma^\mu u)$$
$$O_{\varphi d} = (\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{d}\gamma^\mu d)$$

Dawson, Giardino 1909.02000

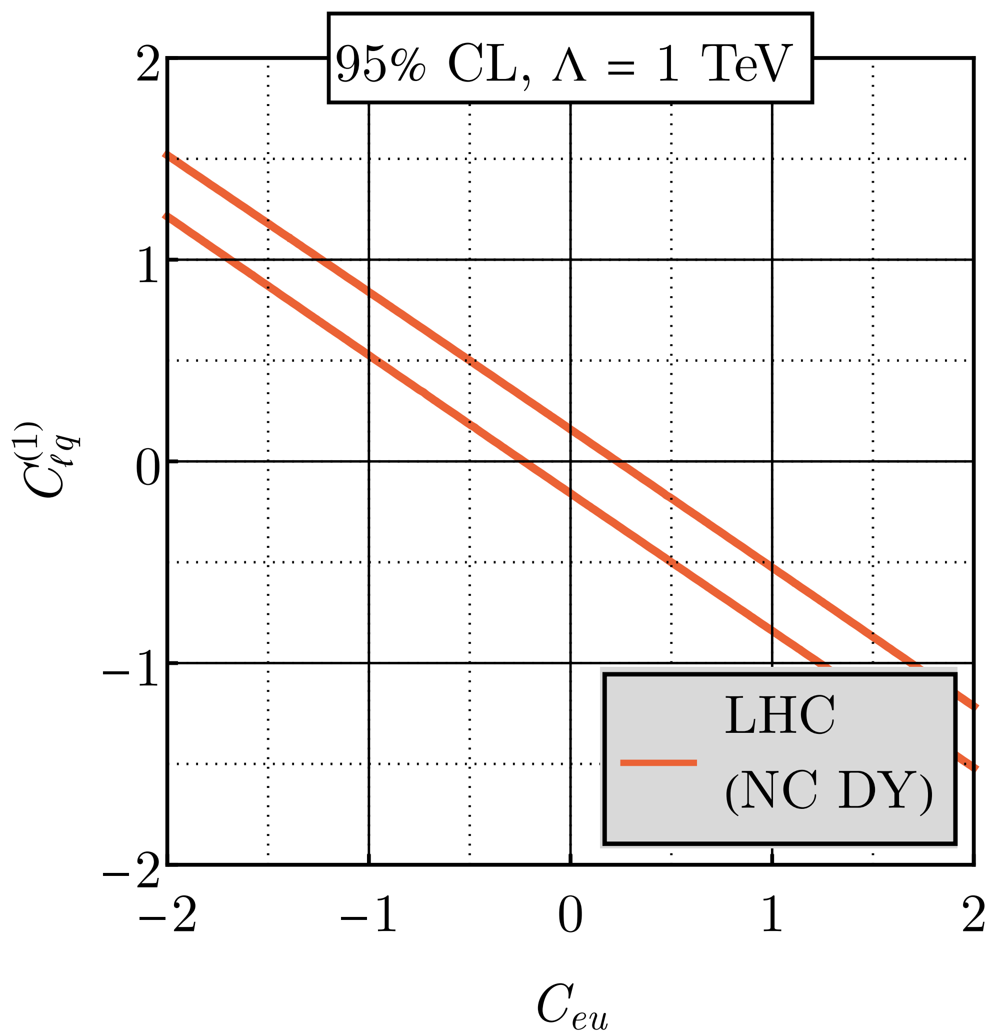
C_k	95% CL, $\Lambda = 1$ TeV
$C_{\varphi\ell}^{(1)}$	$[-0.043, 0.012]$
$C_{\varphi\ell}^{(3)}$	$[-0.012, 0.0029]$
$C_{\varphi e}$	$[-0.013, 0.0094]$
$C_{\varphi q}^{(1)}$	$[-0.027, 0.043]$
$C_{\varphi q}^{(3)}$	$[-0.011, 0.014]$
$C_{\varphi u}$	$[-0.072, 0.091]$
$C_{\varphi d}$	$[-0.16, 0.060]$
$C_{\varphi WB}$	$[-0.0088, 0.0013]$

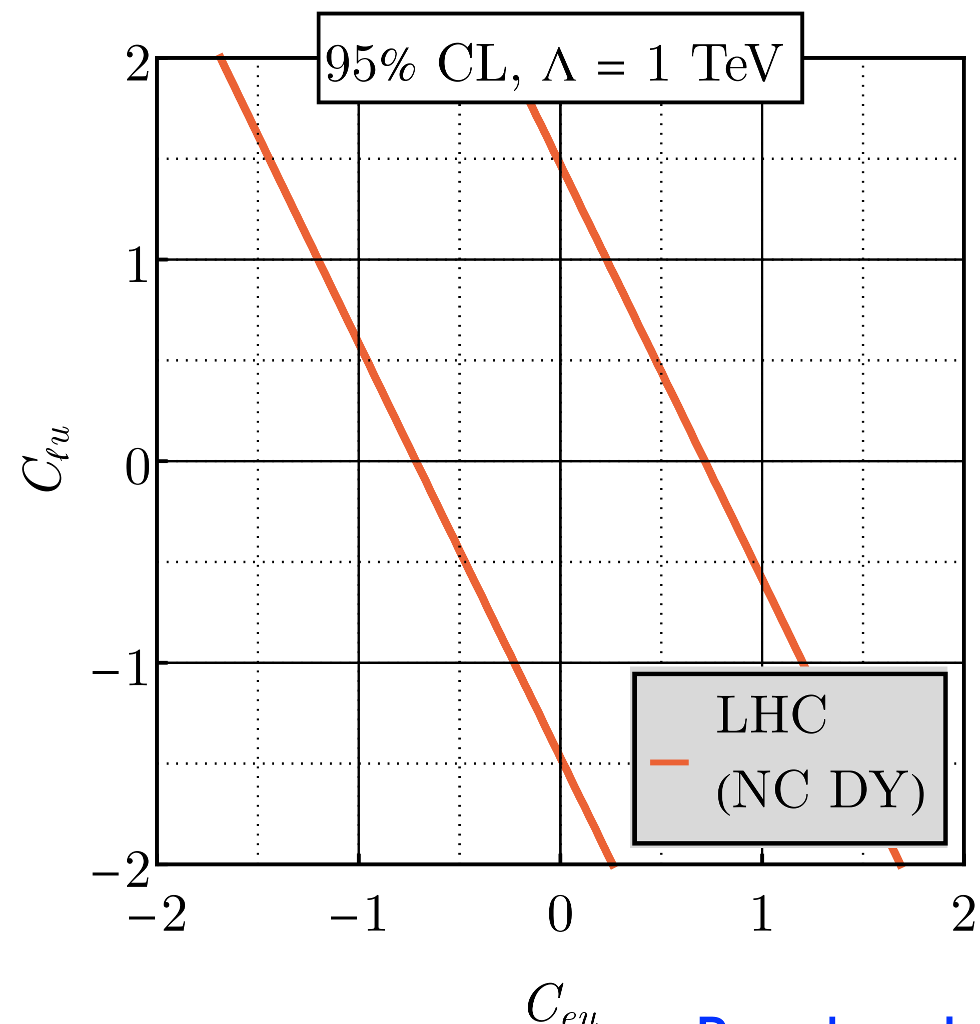
These are strongly constrained by the precision Z-pole data of LEP, SLC; however, these experiments only weakly constrain four-fermion operators

Falkowski et al, 1706.03783

Flat directions

- First thought to constrain qqll operators: LHC Drell-Yan
- But, LHC Drell-Yan is blind to certain combinations of coefficients. This is due to the observables measured, not the amount of integrated luminosity (more on this later).



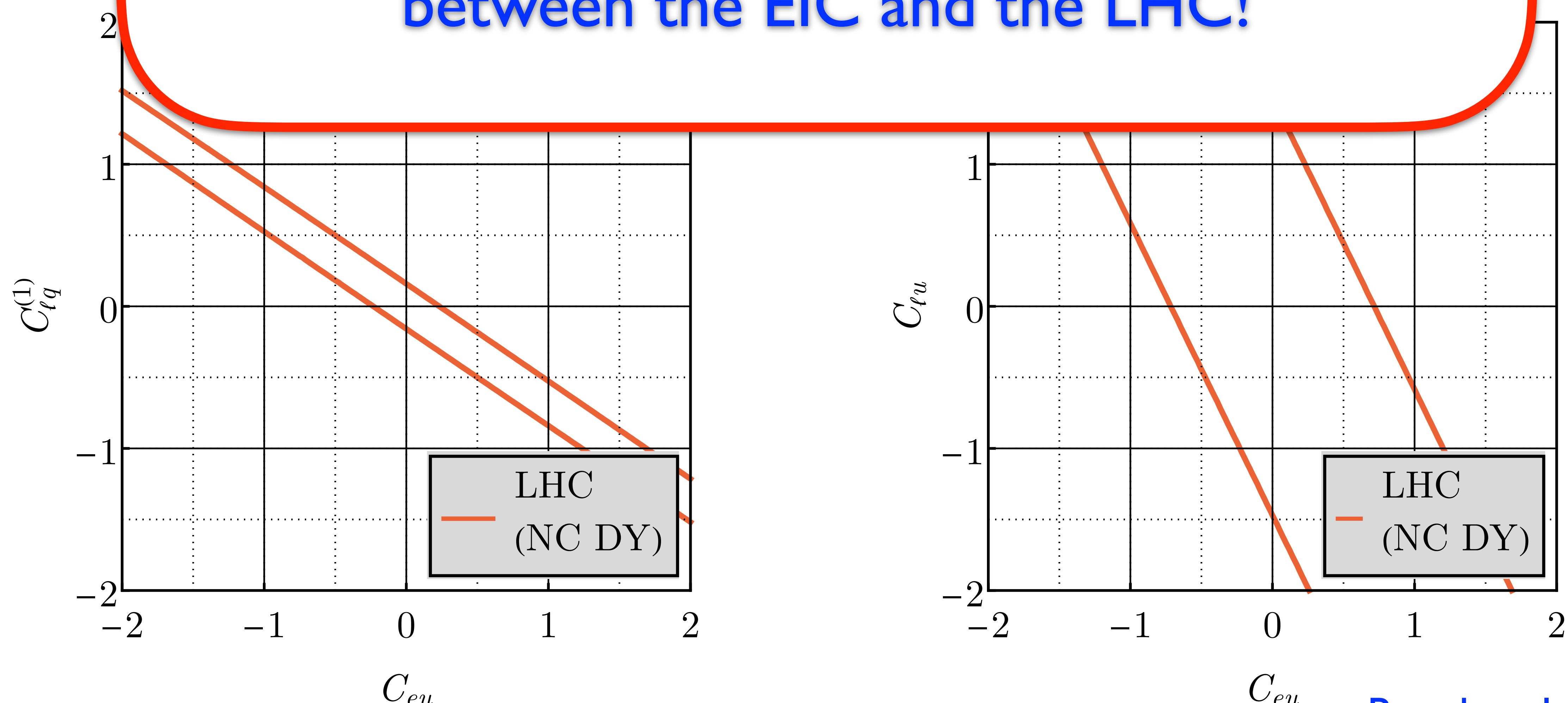


Boughezal, FP, Wiegand 2004.00748

Flat directions

- Firs… …an
- But… coe… …ot the amo…

The EIC, with the possibility of polarizing both beams and therefore constructing more observables, doesn't suffer from these blind spots. Excellent opportunity for complementarity between the EIC and the LHC!



Boughezal, FP, Wiegand 2004.00748

Observables

- We consider several asymmetries at the EIC, in order to partially cancel both experimental and theoretical errors

- Polarized electrons, unpolarized hadrons: $\boxed{A_{\mathrm{PV}} = \frac{d\sigma_\ell}{d\sigma_0}}$

- unpolarized electrons, polarized hadrons: $\boxed{\Delta A_{\mathrm{PV}} = \frac{d\sigma_H}{d\sigma_0}}$

- lepton charge asymmetries: $\boxed{A_{\mathrm{LC}} = \frac{d\sigma_0(e^+H) - d\sigma_0(e^-H)}{d\sigma_0(e^+H) + d\sigma_0(e^-H)}}$

(positron beam not part of the nominal EIC configuration, under discussion for future upgrades)

$$d\sigma_0 = \frac{1}{4}\sum_q f_{q/H}[d\sigma^{++} + d\sigma^{+-} + d\sigma^{-+} + d\sigma^{--}]$$

$$d\sigma_\ell = \frac{1}{4}\sum_q f_{q/H}[d\sigma^{++} + d\sigma^{+-} - d\sigma^{-+} - d\sigma^{--}]$$

$$d\sigma_H = \frac{1}{4}\sum_q \Delta f_{q/H}[d\sigma^{++} - d\sigma^{+-} + d\sigma^{-+} - d\sigma^{--}]$$

Details of simulation

- We generate EIC pseudodata with the following effects included
  - Full EW radiative events with the Djangoh event generator
  - Smearing in electron energy and angles applied to each event
  - Bin migration, unfolding accounted for
  - Assume 80% electron, 70% hadron polarization
  - Inelasticity cuts: $y>0.1$ to avoid large bin migration and unfolding errors, $y<0.9$ to avoid photo-production backgrounds
  - SMEFT analysis: $x<0.5$, $Q>10$ GeV to avoid uncertainties from non-perturbative QCD and nuclear dynamics
- "Theory-only" simulation without any smearing, bin migration or unfolding reproduces the SMEFT sensitivities at the 20-30% level

Data sets

- We consider the following data sets that span the spectrum of possible EIC beam configurations

Deuteron		Proton	
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}

- Red data sets provide the most sensitive probes of the SMEFT; we focus on these results in this talk.
- Polarized deuteron and proton copies of these data sets are also studied, and labeled as ΔD, ΔP
- We also consider a high-luminosity version of P5, D5, ΔP5, ΔD5 with x10 integrated luminosity

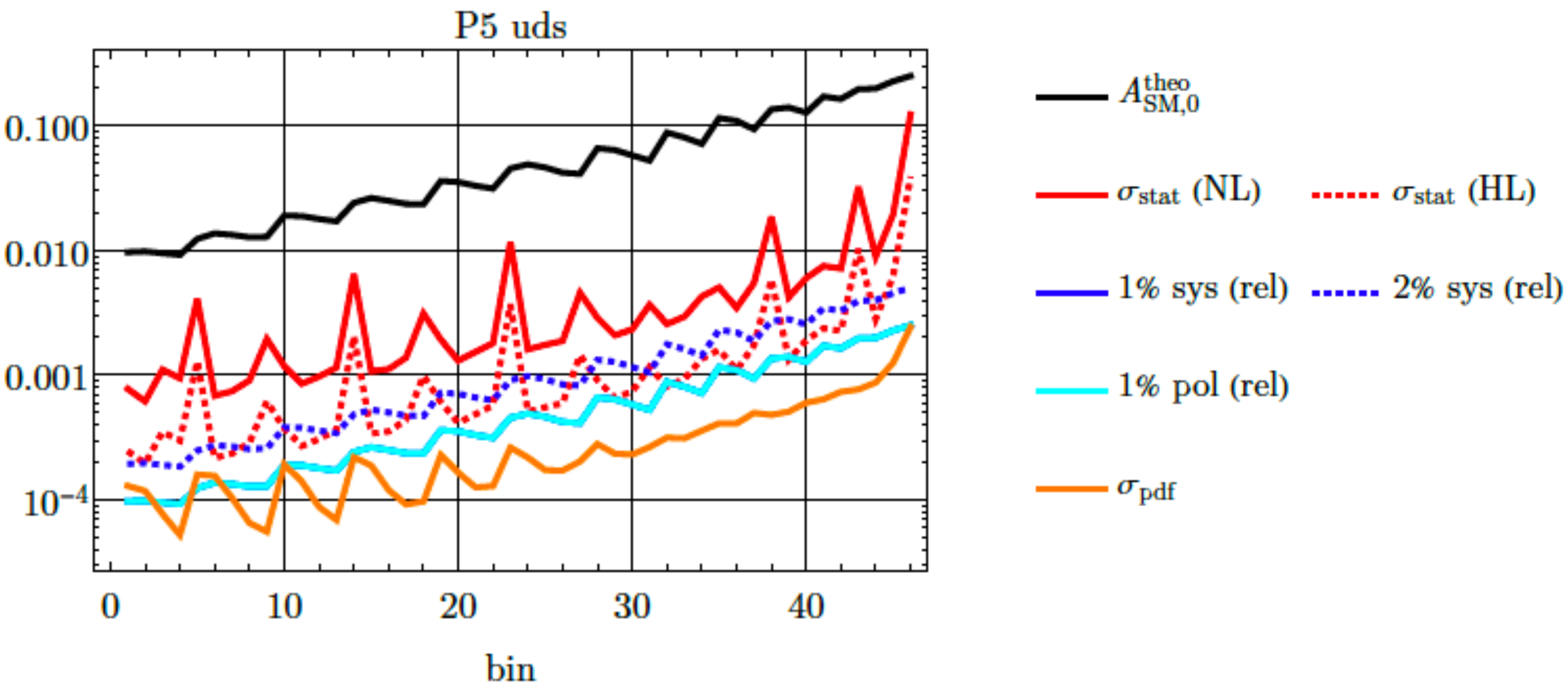
Error sources

Error type	lepton polarized $A_{\rm PV}$ (D, P)	hadron polarized $\Delta A_{\rm PV}$ (ΔD, ΔP)	charge asymmetry $A_{\rm LC}$ (LD, LP)
statistical	$\sigma_{\rm stat}$	$\frac{P_\ell}{P_H}\sigma_{\rm stat}$	$\sqrt{10}P_\ell\sigma_{\rm stat}$
uncorrelated systematic	1% rel.	1% rel.	1% rel.
fully correlated beam polarization	1% rel.	2% rel.	✗
fully correlated luminosity	✗	✗	2% abs.
uncorrelated QED NLO	✗	✗	$5\% \times (A_{\rm LC}^{\rm NLO} - A_{\rm LC}^{\rm Born})$
fully correlated PDF	✓	✓	✓

Electron, positron data would be taken in separate runs; luminosity difference possible

Error budget: unpolarized protons

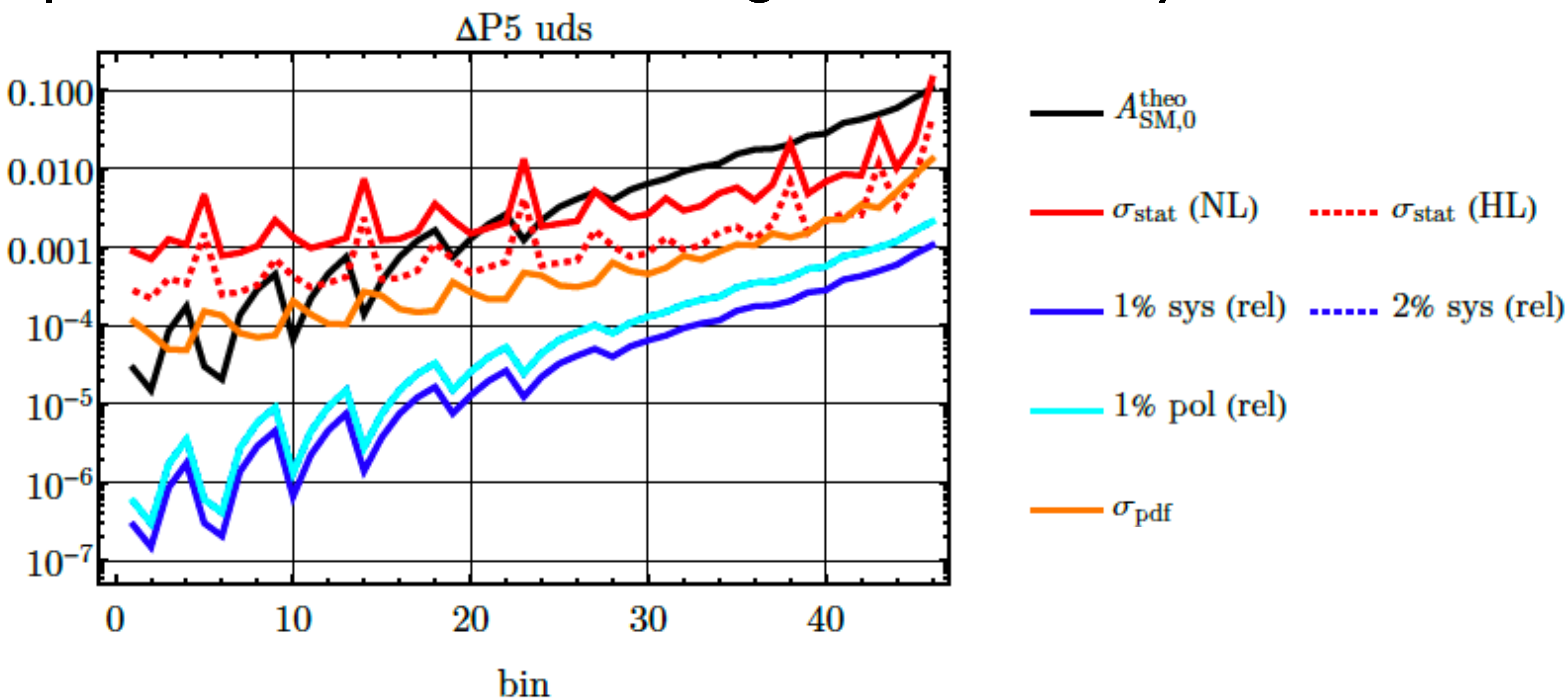
- Bins ordered in Q^2, x; HL is a proposed high-luminosity option with x10 nominal integrated luminosity



- Statistical uncertainties dominant with nominal luminosity; systematic errors more important with high luminosity; PDF errors negligible. Asymmetry much larger than all uncertainties.

Error budget: polarized protons

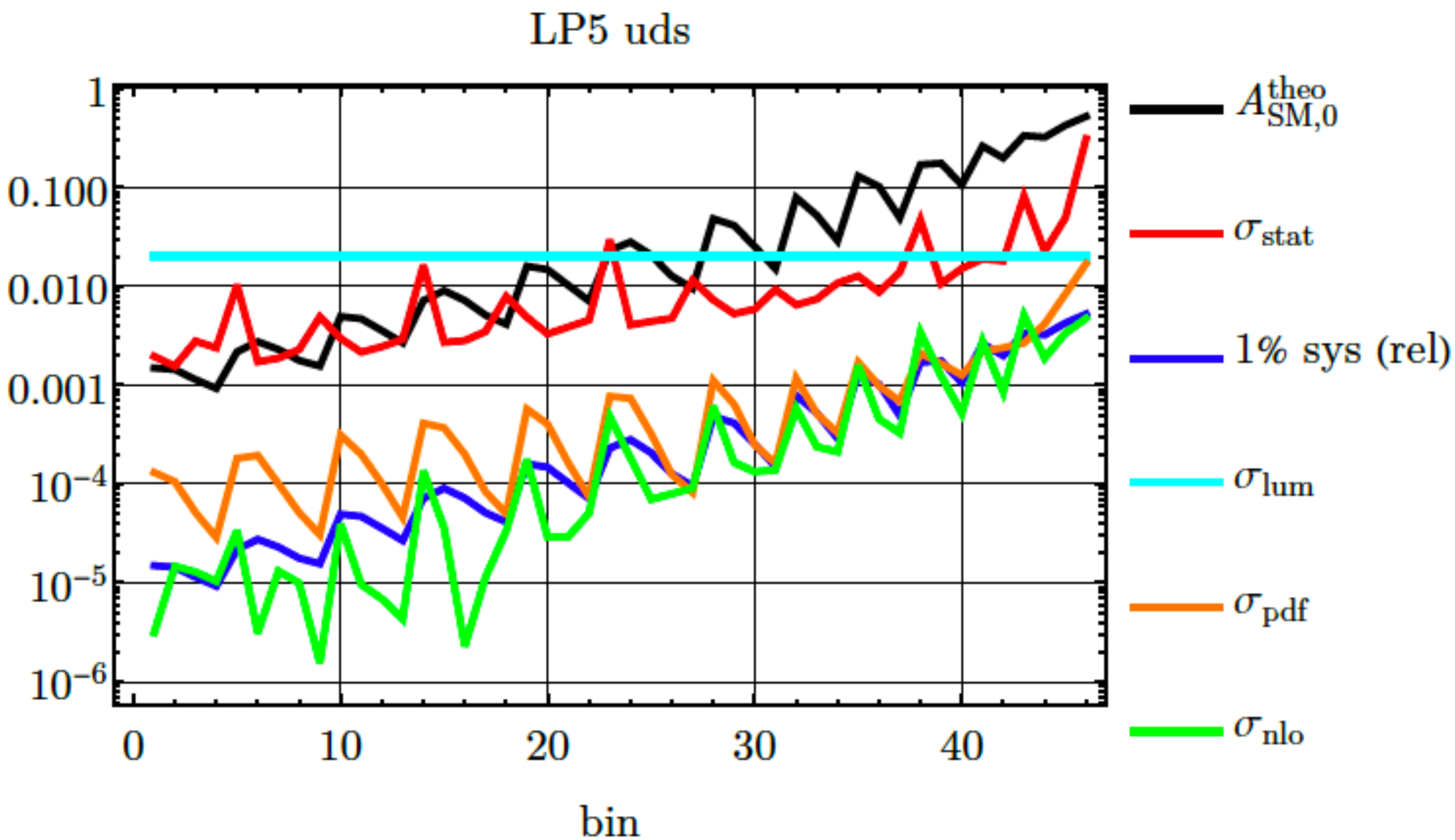
- Bins ordered in Q^2, x; HL is a proposed high-luminosity option with x10 nominal integrated luminosity



- Statistical uncertainties still dominant but PDF errors non-negligible, particularly with high luminosity option. Asymmetry only larger than statistical uncertainties in higher Q^2 bins.

Error budget: lepton-charge asymmetry

- Bins ordered in Q^2, x; HL is a proposed high-luminosity option with x10 nominal integrated luminosity



- Luminosity error dominant in this measurement; larger than asymmetry until high Q^2

Pseudodata generation

$$A^{(e)}_{\mathrm{pseudo},b} = A_{\mathrm{SM},b} + r^{(e)}_b \sigma^{\mathrm{unc}}_b + r'^{(e)} \sigma^{\mathrm{cor}}_b$$

r_b, r'=random numbers in range [0,1]

uncorrelated errors; separate r_b for each bins

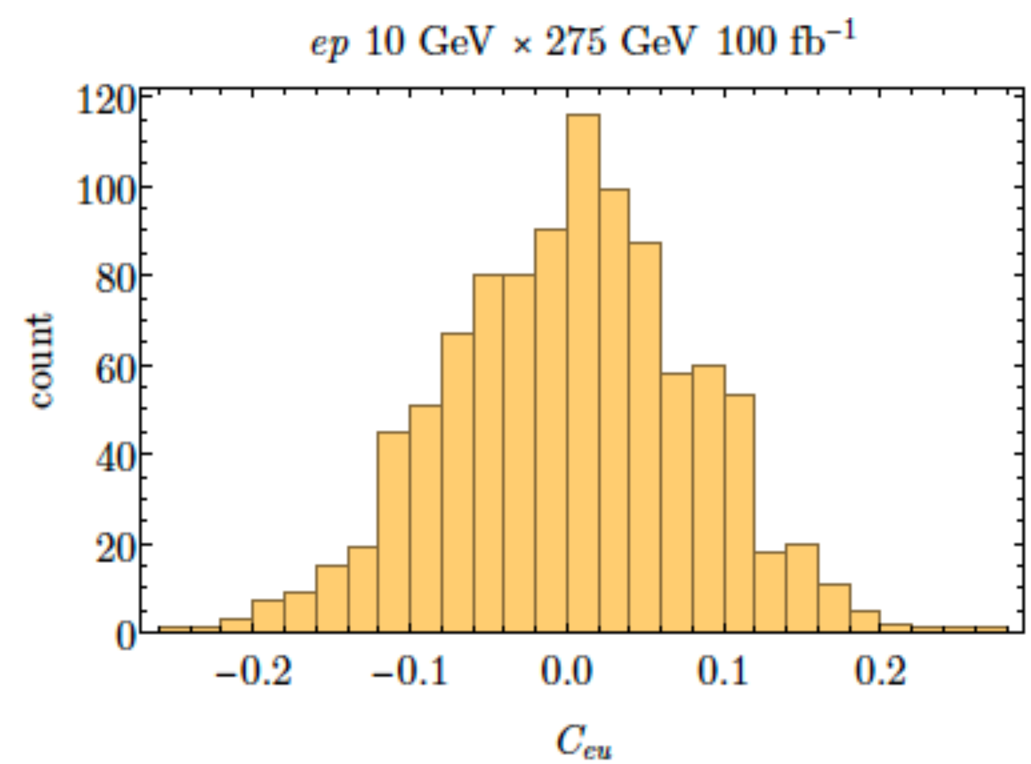
correlated errors; same r' for all bins

b=bin index

e=pseudo-experiment index (we average over numerous realizations of the EIC to remove fluctuations)

$$A_{\mathrm{SMEFT},b} = \frac{\sigma^{(0)}_{\mathrm{num},b} + \sum_{k=1}^{N_{\mathrm{fit}}} C_k \sigma^{(1)}_{\mathrm{num},b}}{\sigma^{(0)}_{\mathrm{den},b} + \sum_{k=1}^{N_{\mathrm{fit}}} C_k \sigma^{(1)}_{\mathrm{den},b}}$$

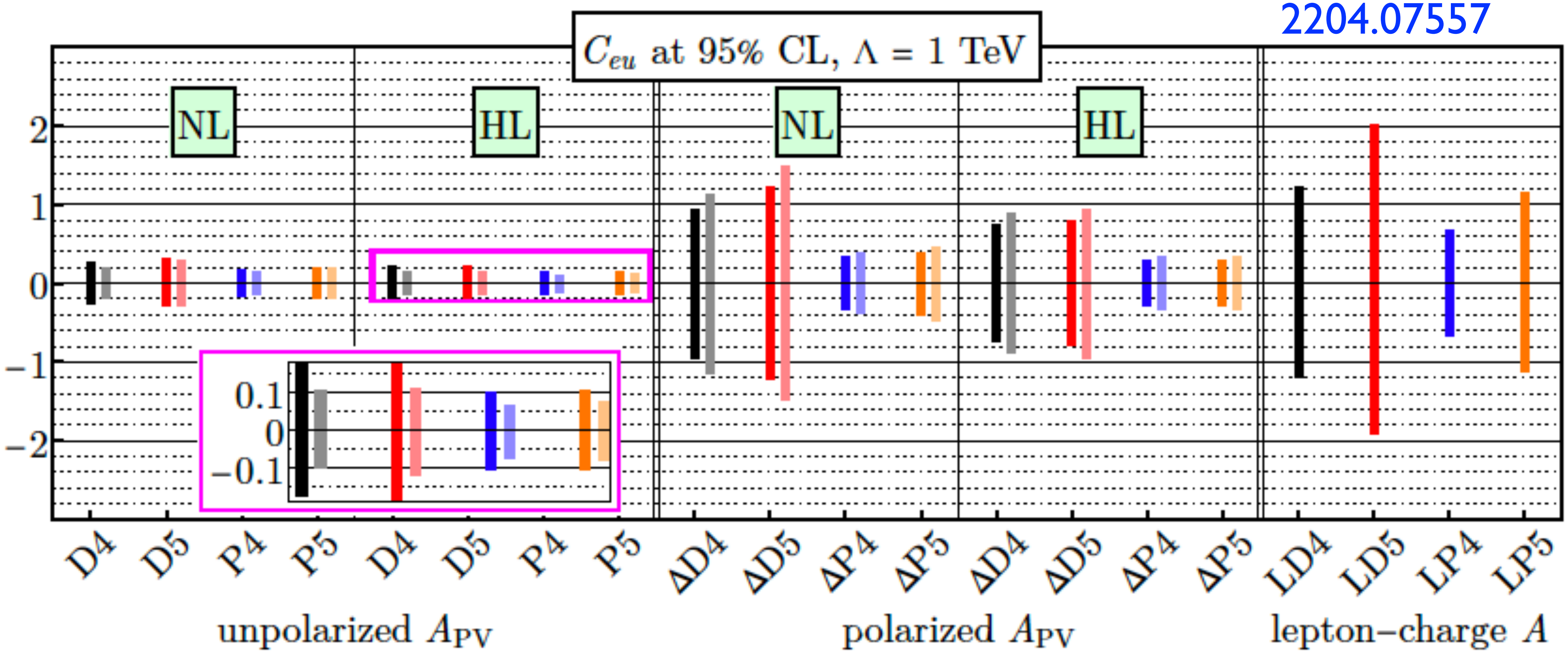
Best-fit values:



SMEFT results: 1-d fits

- Begin by turning on single Wilson coefficients

Boughezal et al, 2204.07557



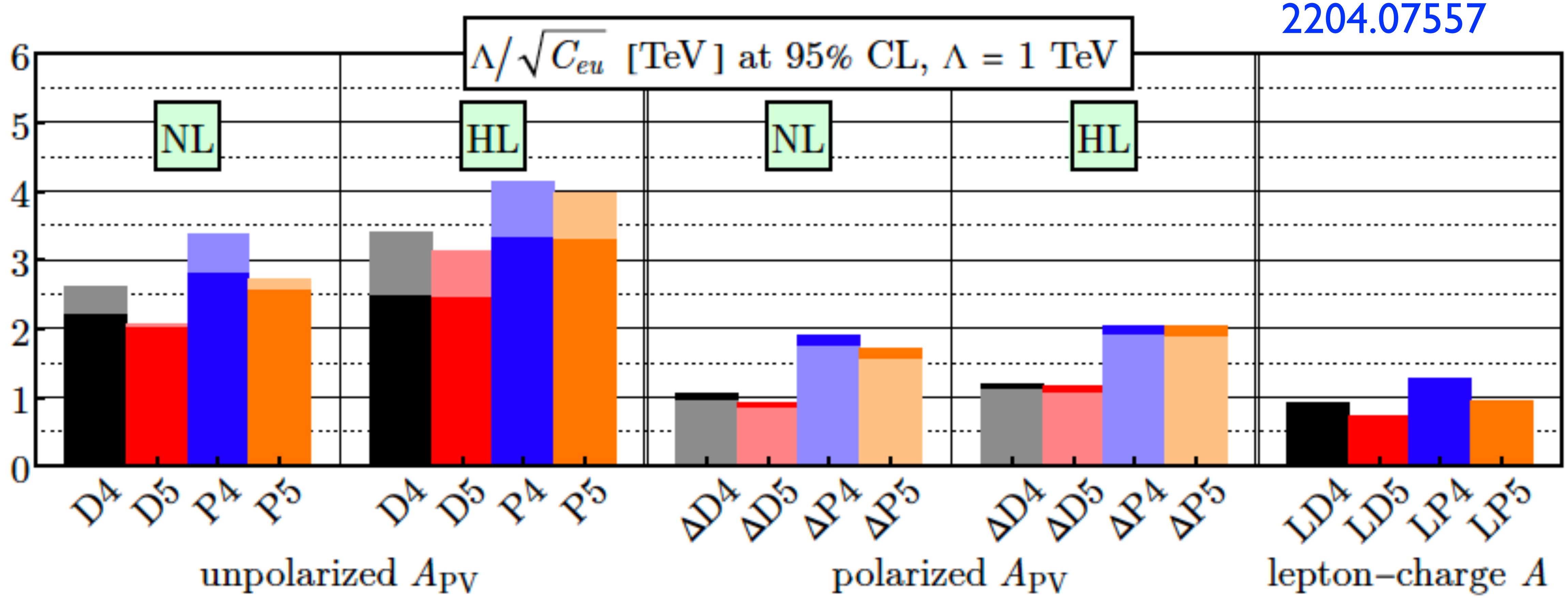
Trends:

- Proton sensitivities stronger than deuteron ones
- Unpolarized hadrons, polarized electrons offer strongest probes
- Lepton-charge asymmetries provide weakest probes

SMEFT results: 1-d fits

- Convert these bounds to effective UV scales probes

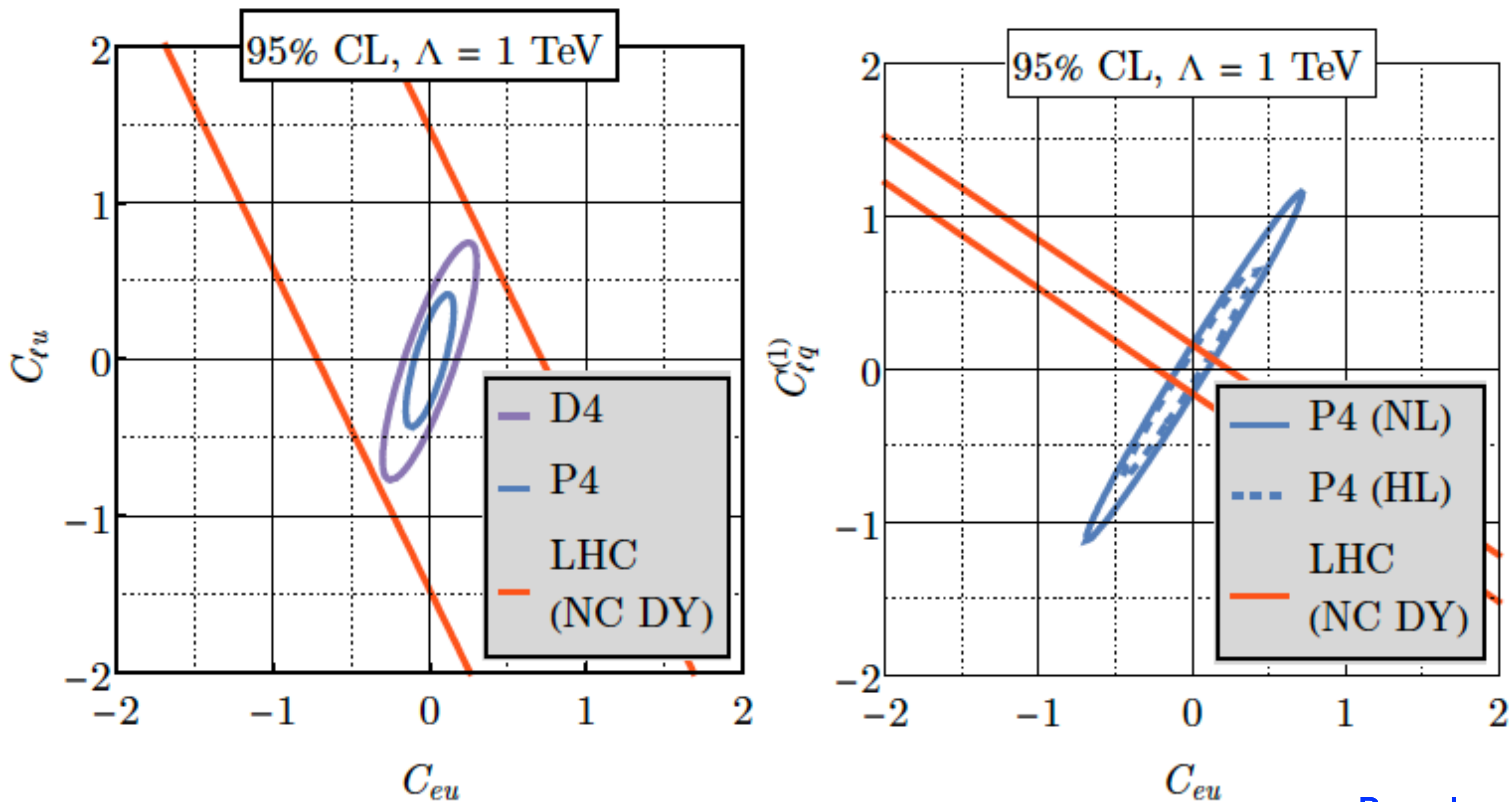
Boughezal et al, 2204.07557



3 TeV scales probes with nominal luminosity, 4 TeV with high luminosity. Competitive with current LHC bounds.

SMEFT results: 2-d fits

- Can resolve the degeneracies that remain after LHC measurements! No degeneracies remain in the SMEFT parameter space with the nominal EIC program



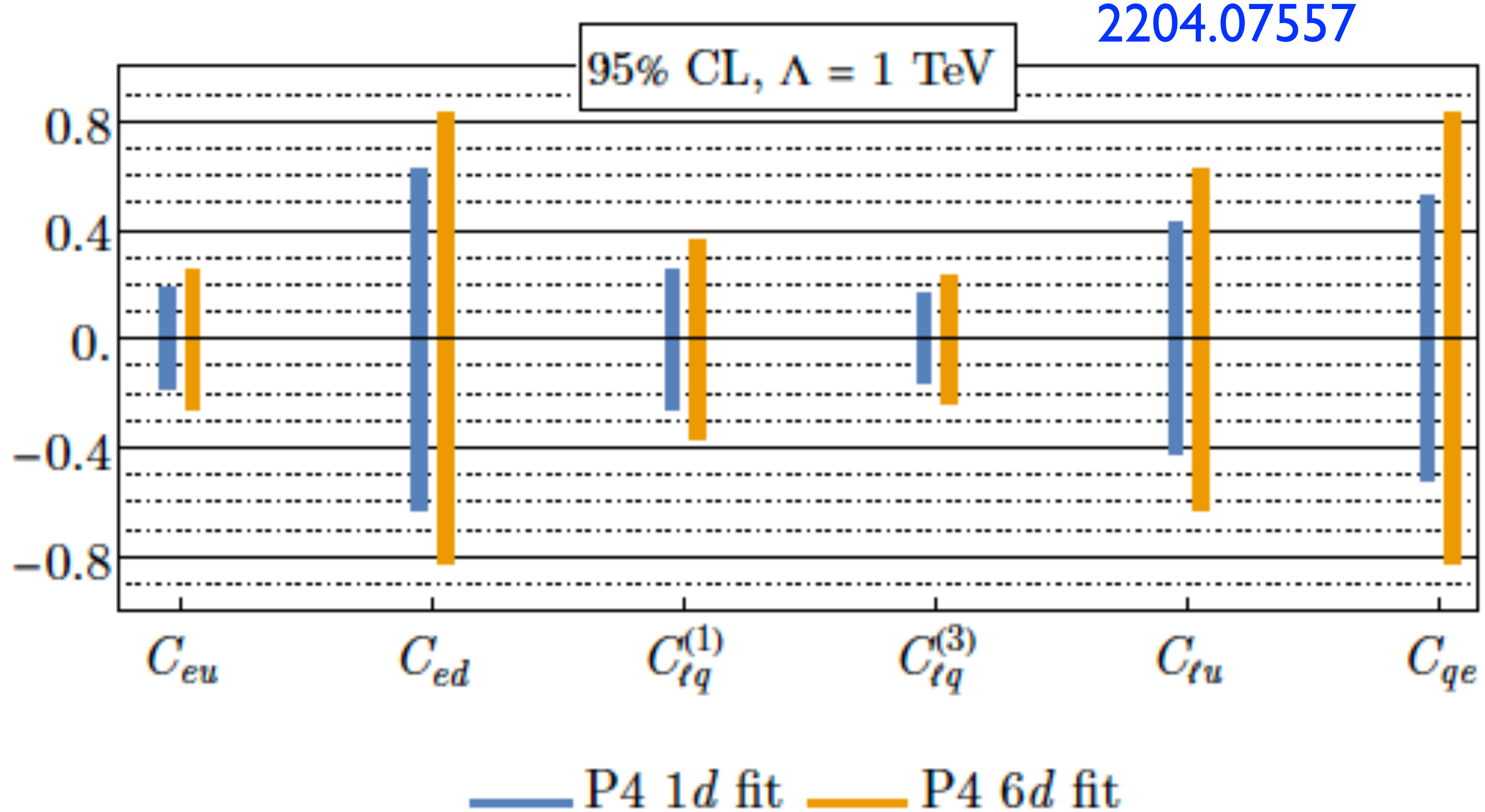
Boughezal et al, 2204.07557

Higher-dimensional fits

- Can turn on more Wilson coefficients to further search for degeneracies and check degradation of sensitivities. Requires more pseudo-experiments.

Boughezal et al, 2204.07557

N_{fit}	N_{exp}
2	10^3
3	10^4
4	10^5
5	10^6
6	10^7



- No degeneracies in higher-d fits; only slightly weaker bounds. The EIC can probe the full 7-dimensional parameter space in this sector of the SMEFT.

Future LHC prospects

- The degeneracies at the LHC are due to the structure of the matrix elements, not the integrated luminosity. Limited room for improvement at the HL-LHC.

interference of photon diagram with SMEFT

Drell-Yan cross section in SMEFT:

red counts couplings, blue counts structures

$$\frac{d\hat{\sigma}^{\gamma SMEFT}_{u\bar{u}}}{dM^2 dY dc_\theta} = -\frac{8\pi\alpha Q_u}{3}\frac{\underbrace{(\overset{1}{C_{lu}} + \overset{2}{C_{qe}})\hat{t}^2}_{1} + \underbrace{(\overset{3}{C_{eu}} + \overset{4}{C^{(1)}_{lq}} - \overset{5}{C^{(3)}_{lq}})\hat{u}^2}_{2}}{\hat{s}},$$

$$\frac{d\hat{\sigma}^{ZSMEFT}_{u\bar{u}}}{dM^2 dY dc_\theta} = \frac{2g_Z^2}{3}\frac{\underbrace{(g^u_R g^e_L C_{lu} + g^e_R g^u_L C_{qe})\hat{t}^2}_{3} + \underbrace{(g^u_R g^e_R C_{eu} + g^u_L g^e_L C^{(1)}_{lq} - g^u_L g^e_L C^{(3)}_{lq})\hat{u}^2}_{4}}{\hat{s} - M_Z^2}$$

interference of Z diagram with SMEFT

Best case: in up-quark channel get four independent structures if we measure invariant mass and angle, for five SMEFT coefficients

Future LHC prospects

- The degeneracies at the LHC are due to the structure of the matrix elements, not the integrated luminosity. Limited room for improvement at the HL-LHC.

- In the high energy limit, $\hat{s} \gg M_Z^2$, we can no longer separately measure the SMEFT interferences with the photon and Z; both propagators become equivalent:

$$\frac{1}{\hat{s}-M_Z^2} \approx \frac{1}{\hat{s}}$$

- Can only measure two coupling structures, not four:

$$\boxed{\begin{array}{rl} -\frac{8\pi\alpha Q_u}{3}\left[(C_{lu}+C_{qe})\right]+\frac{2g_Z^2}{3}\left[g_R^u g_L^e C_{lu}+g_R^e g_L^u C_{qe}\right] & \hat{t}^2 \\ -\frac{8\pi\alpha Q_u}{3}\left[(C_{eu}+C_{lq}^{(1)}-C_{lq}^{(3)})\right]+\frac{2g_Z^2}{3}\left[g_R^u g_R^e C_{eu}+g_L^u g_L^e C_{lq}^{(1)}-g_L^u g_L^e C_{lq}^{(3)}\right] & \hat{u}^2 \end{array}}$$

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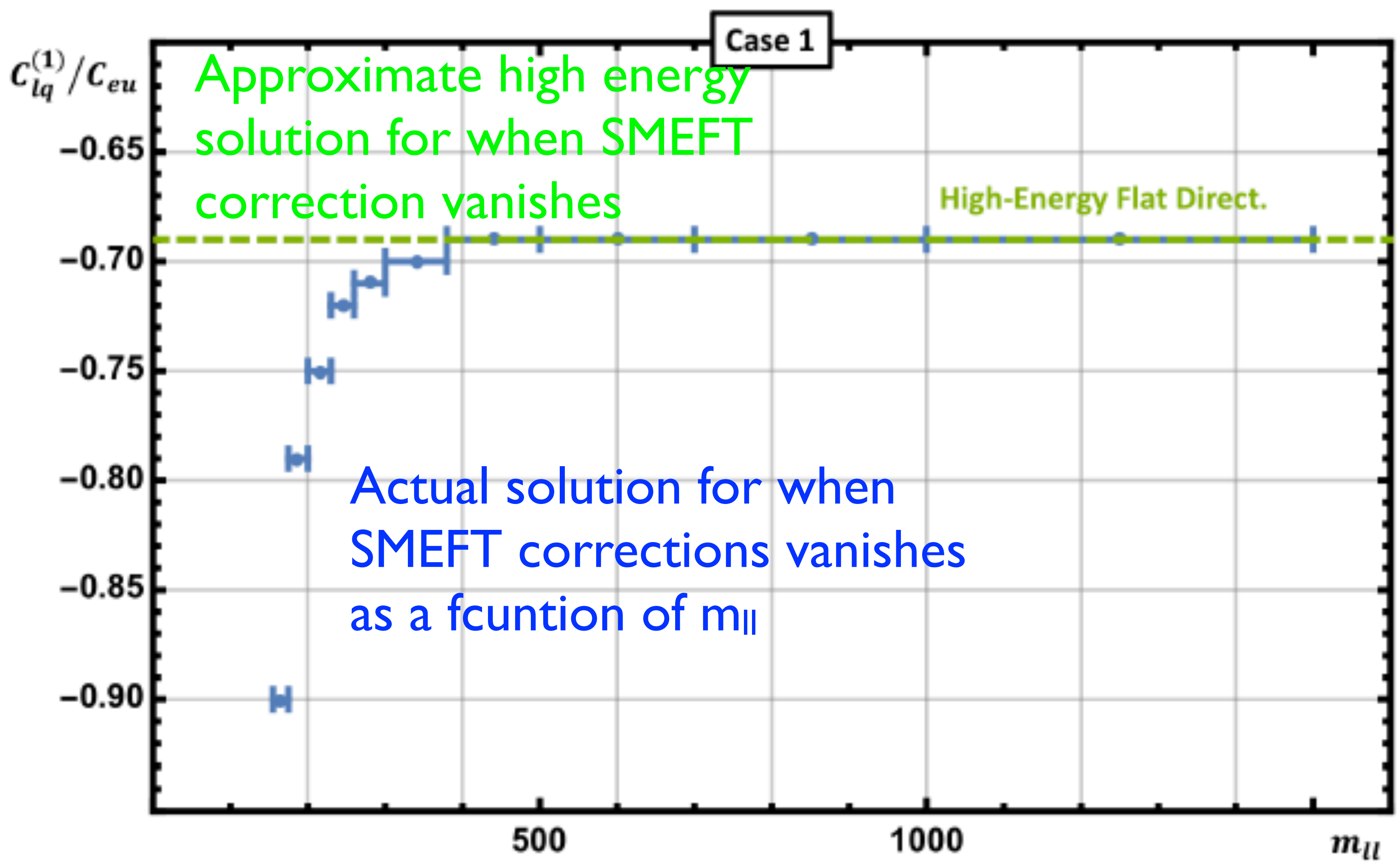

Boughezal, FP, Wiegand 2004.00748

High energy limit almost exact by $m_{ll} \approx 300$ GeV; no advantage from the high energy of the LHC

Future LHC prospects

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Recall $\hat{t} = -\frac{\hat{s}}{2}(1 - c_\theta), \quad \hat{u} = -\frac{\hat{s}}{2}(1 + c_\theta)$

If the observable integrates over a symmetric range of cos(θ), LHC DY is only proportional to a *single* linear combination of couplings; many degeneracies in the parameter space for such observables! Most LHC measurements (invariant mass, transverse momentum, rapidity) fall in this category

Future LHC prospects

- The degeneracies at the LHC are due to the structure of the matrix elements, not the integrated luminosity. Limited room for improvement at the HL-LHC.

- How can the LHC compete with the EIC in exploring this parameter space? Need triply-differential distributions (m_{ll}, Y_{ll}, $\cos(\theta)$) in the invariant mass region 100-300 GeV (no sensitivity on the Z-peak due to M_Z/Γ_Z suppression of SMEFT; below the Z-peak there is contamination from on-peak Z radiative events). There is limited ATLAS data for this in the region m_{ll}<200 GeV.

This is an ideal BSM science target for the EIC!