The LHC/EIC Synergy in Searches for New Physics

Radja Boughezal

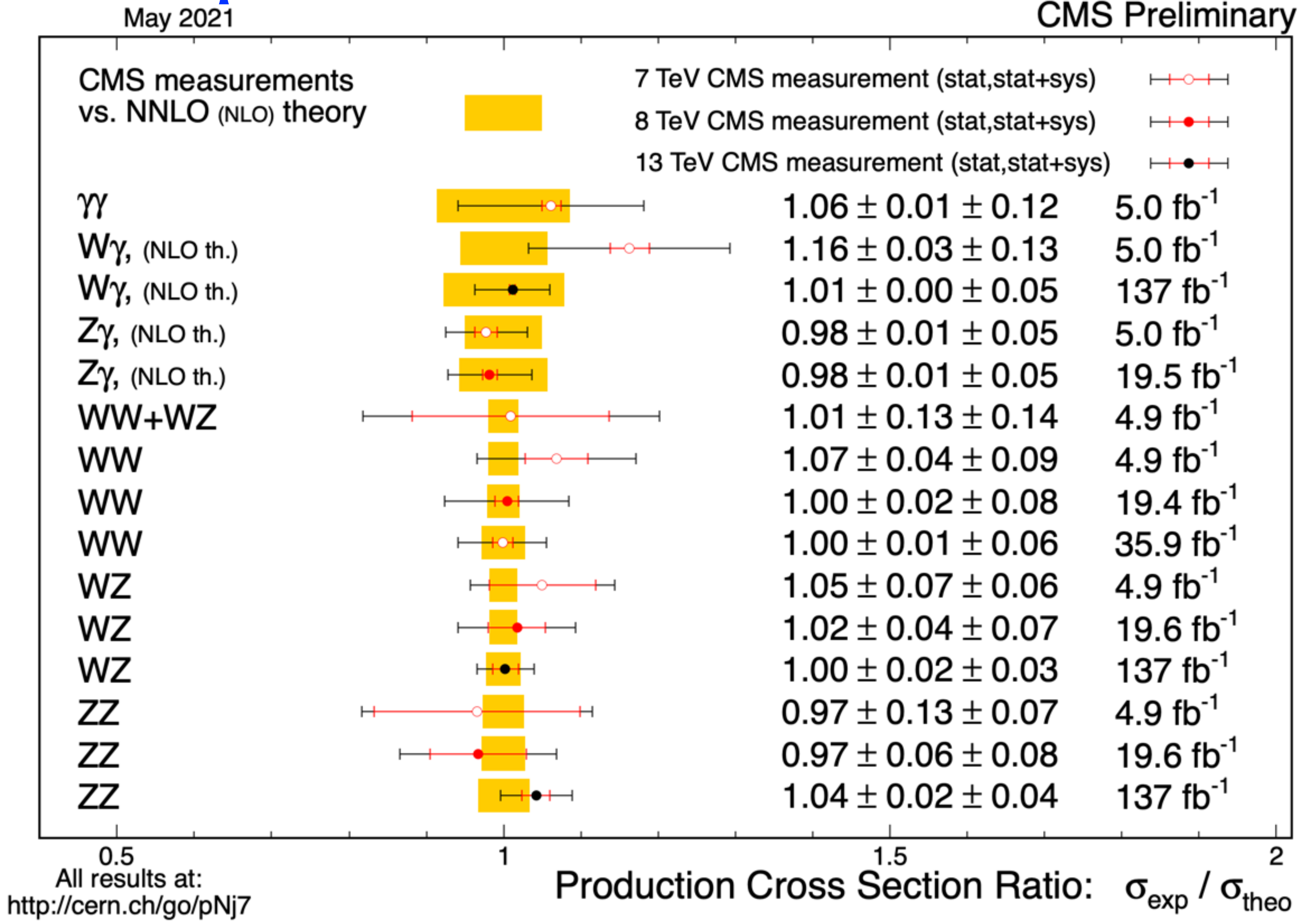
Argonne National Laboratory

14th Conference on the Intersections of Particle and Nuclear Physics, CIPANP 2022

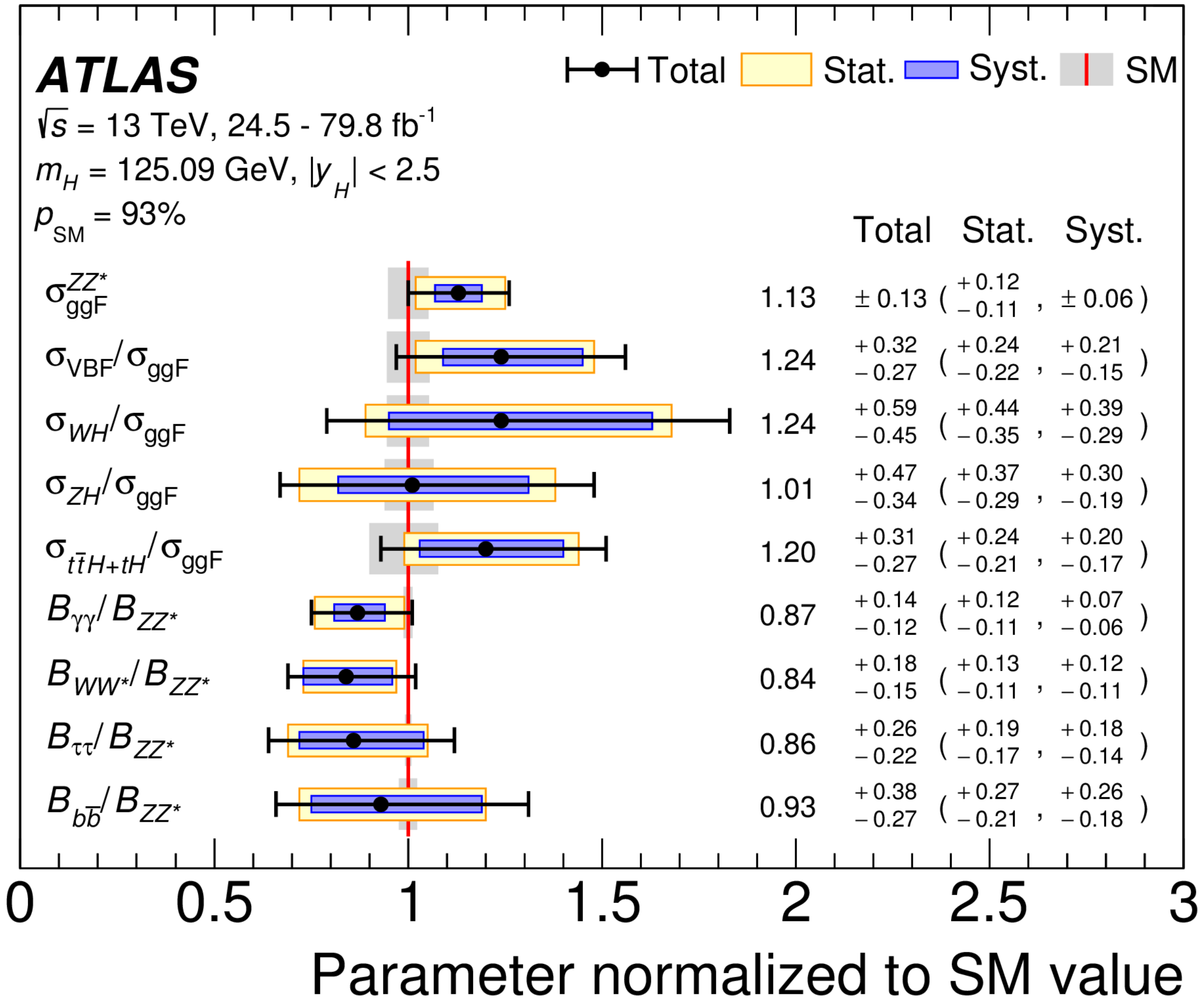
August 30, 2022

Status of the Standard Model

Example: di-boson cross sections

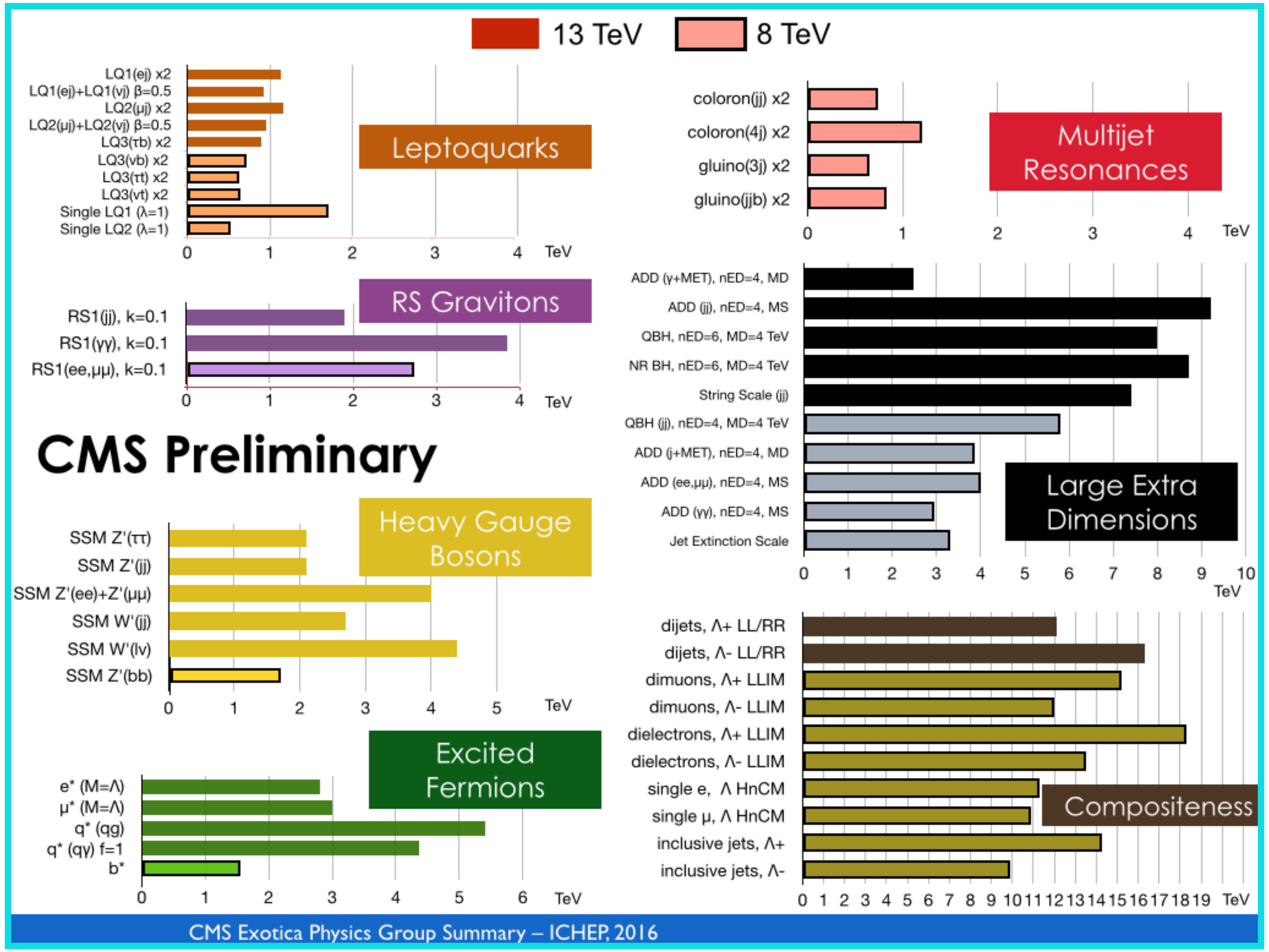


Example: Higgs production and decay



Remarkable agreement between SM theory and experiment over all sectors of the theory, and spanning orders of magnitude in cross section

BSM Searches



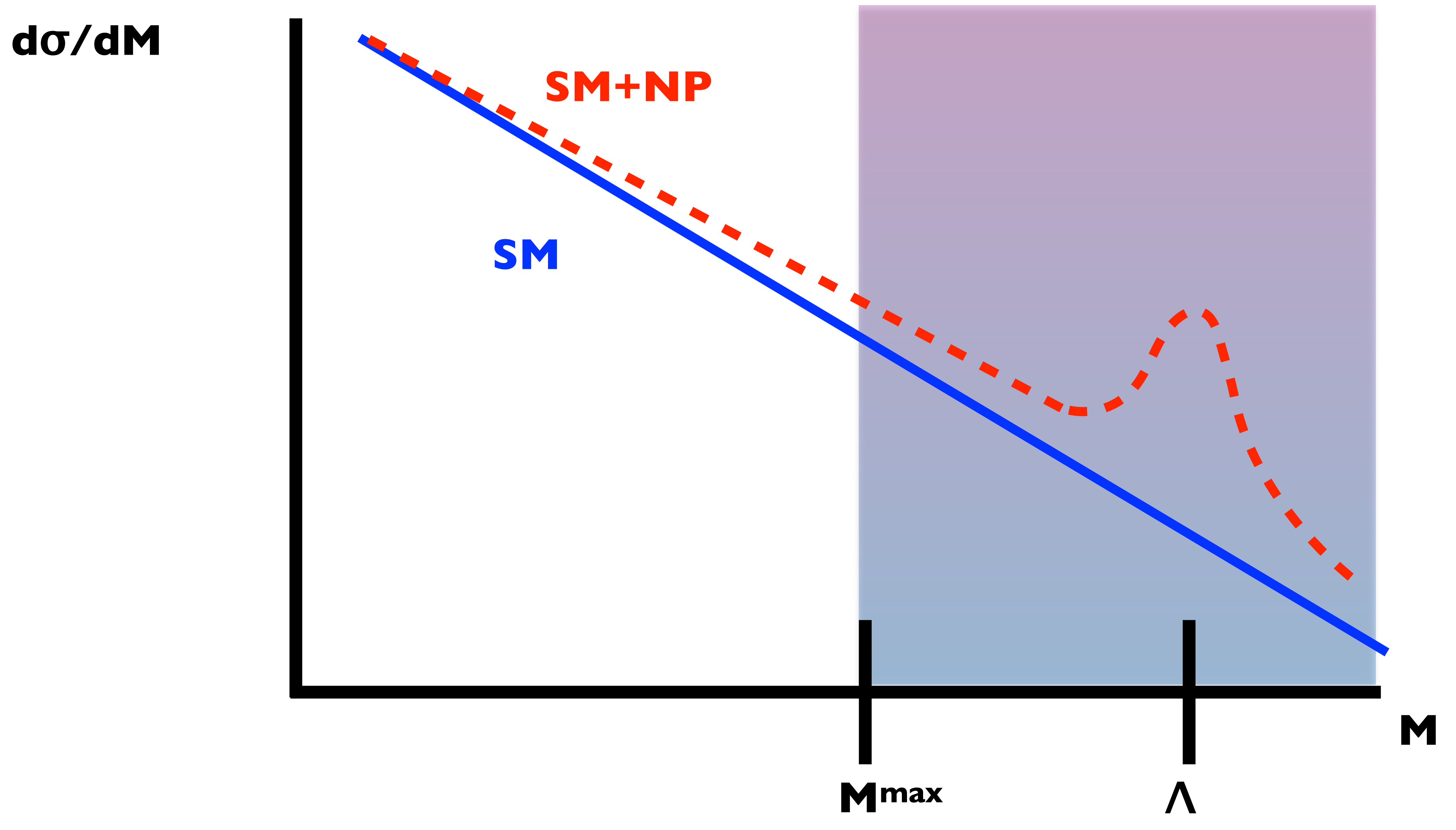
No conclusive evidence of BSM physics so far, despite a broad spectrum of searches.

Limits on new physics mass scale exceed 1 or more TeV in many cases

Motivation

What do we learn from the remarkable success of the SM, combined with the null searches so far at the LHC and elsewhere?

- The data suggests (although it doesn't require) a mass gap between the SM and any new physics



- M^{max} is the maximum energy probed at the LHC and elsewhere
- Λ is the scale where new particles appear

We hope that Λ isn't too far above M^{max}!

Introduction to SMEFT

- An EFT framework that incorporates the mass gap is the Standard Model Effective Field Theory (SMEFT): assume the SM field content and gauge symmetry, and include all possible higher-dimensional operators suppressed by a scale Λ

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{\Lambda^2}\sum_i C_6^i(\mu)\mathcal{O}_6^i(\mu) + \frac{1}{\Lambda^4}\sum_i C_8^i(\mu)\mathcal{O}_8^i(\mu) + \ldots$$

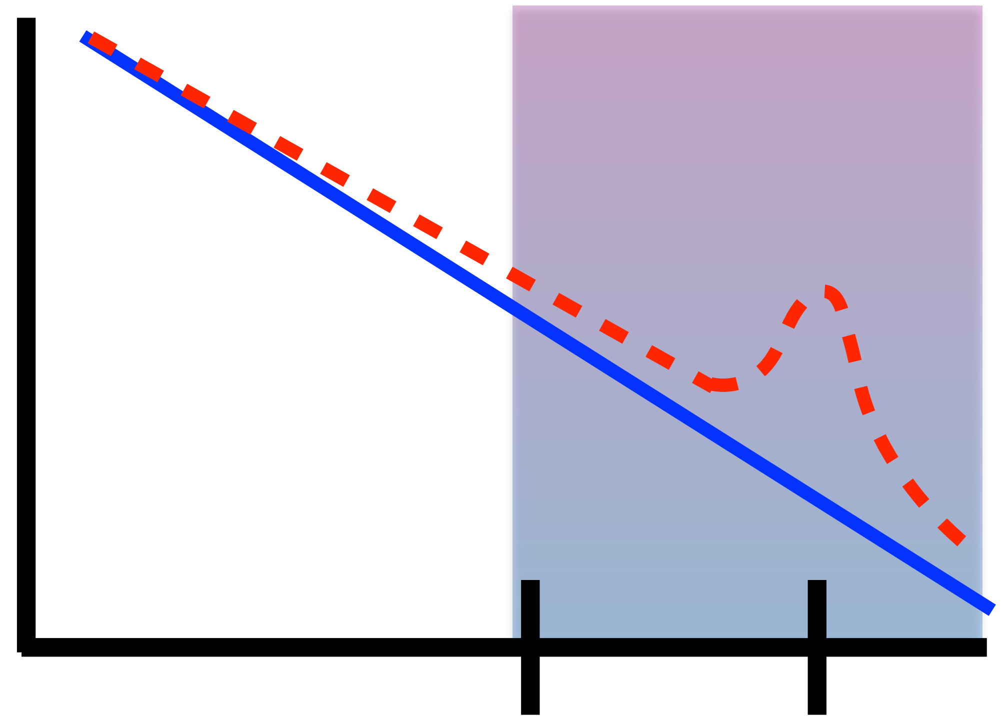
Dimension-6 Dimension-8

- $\Lambda \gg E, v$ (Higgs vev) must both be satisfied
- Odd dimensions violate lepton or baryon number; neglected here
- RG running important when comparing experiments at disparate energies

Introduction to SMEFT

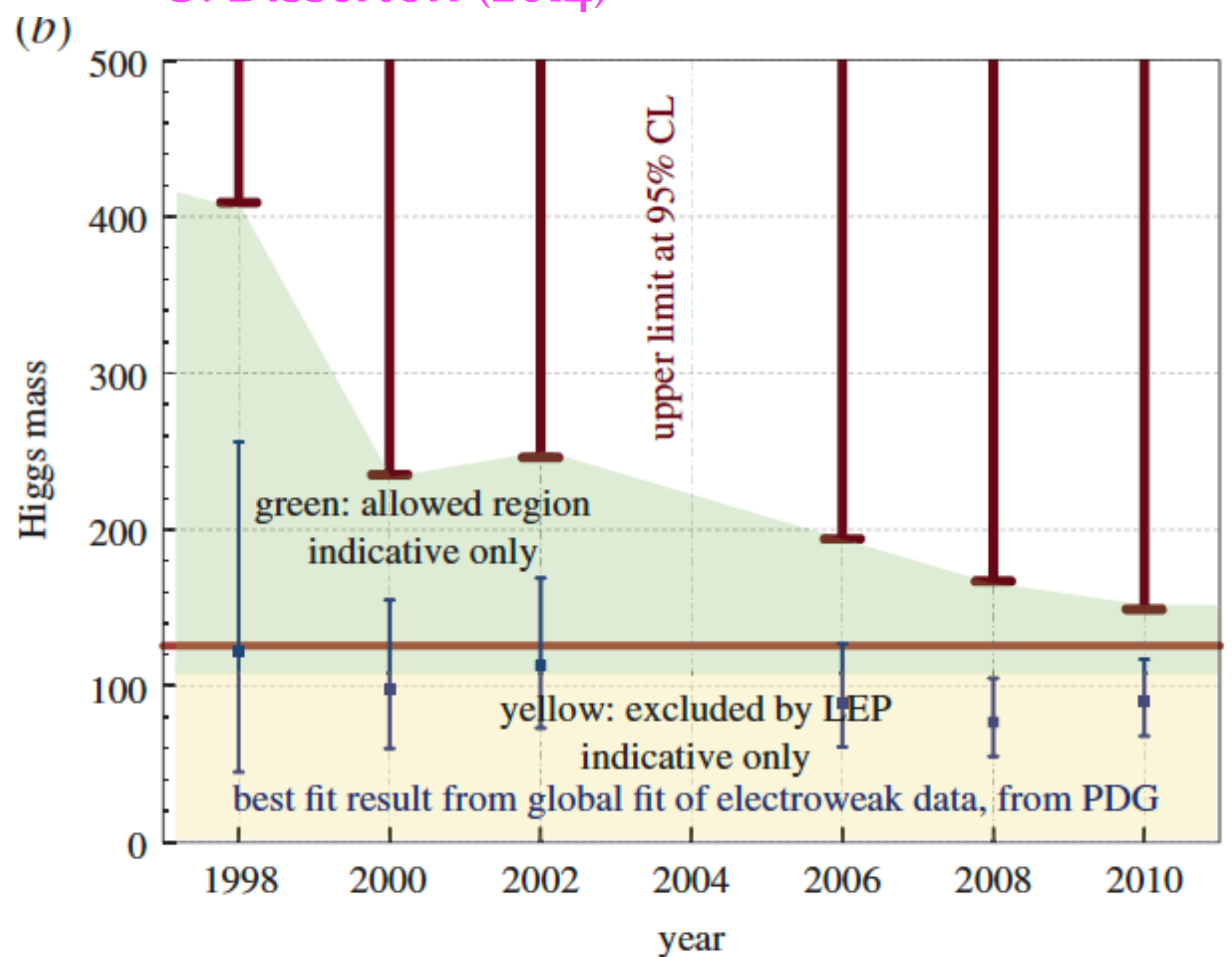
- What might we find when we analyze data using this framework?

Best case: a non-zero value for a Wilson coefficient C^i indicating a mass scale slightly above probed values. Gives a definite energy target for future experiments.



Otherwise: stringent constraints on the C^i from the wealth of available data that also suggest where to focus future searches and model-building efforts. Recall the success of indirect EW constraints in suggesting the Higgs mass scale.

G. Dissertori (2014)



Constructing the SMEFT

- First step is to construct a complete and non-redundant basis of operators at each dimension. One commonly-used possibility at dimension-6 is the Warsaw basis.

Buchmuller, Wyler (1986); Grzadkowski et al (2010); Brivio, Jiang, Trott (2017)

Pure Gauge interactions

	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	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^* \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				
	$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G^A_{\mu\nu} G^{A\mu\nu}$	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}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$		
$Q_{quqd}^{(1)}$	$(\bar q_p^j u_r)\varepsilon_{jk}(\bar q_s^k d_t)$	Q_{qqu}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$		
$Q_{quqd}^{(8)}$	$(\bar q_p^j T^A u_r)\varepsilon_{jk}(\bar q_s^k T^A d_t)$	Q_{qqq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jn}\varepsilon_{km}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$		
$Q_{lequ}^{(1)}$	$(\bar l_p^j e_r)\varepsilon_{jk}(\bar q_s^k u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$		
$Q_{lequ}^{(3)}$	$(\bar l_p^j \sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar q_s^k \sigma^{\mu\nu} u_t)$				

Gauge-Higgs interactions

Fermion-Higgs-gauge interactions

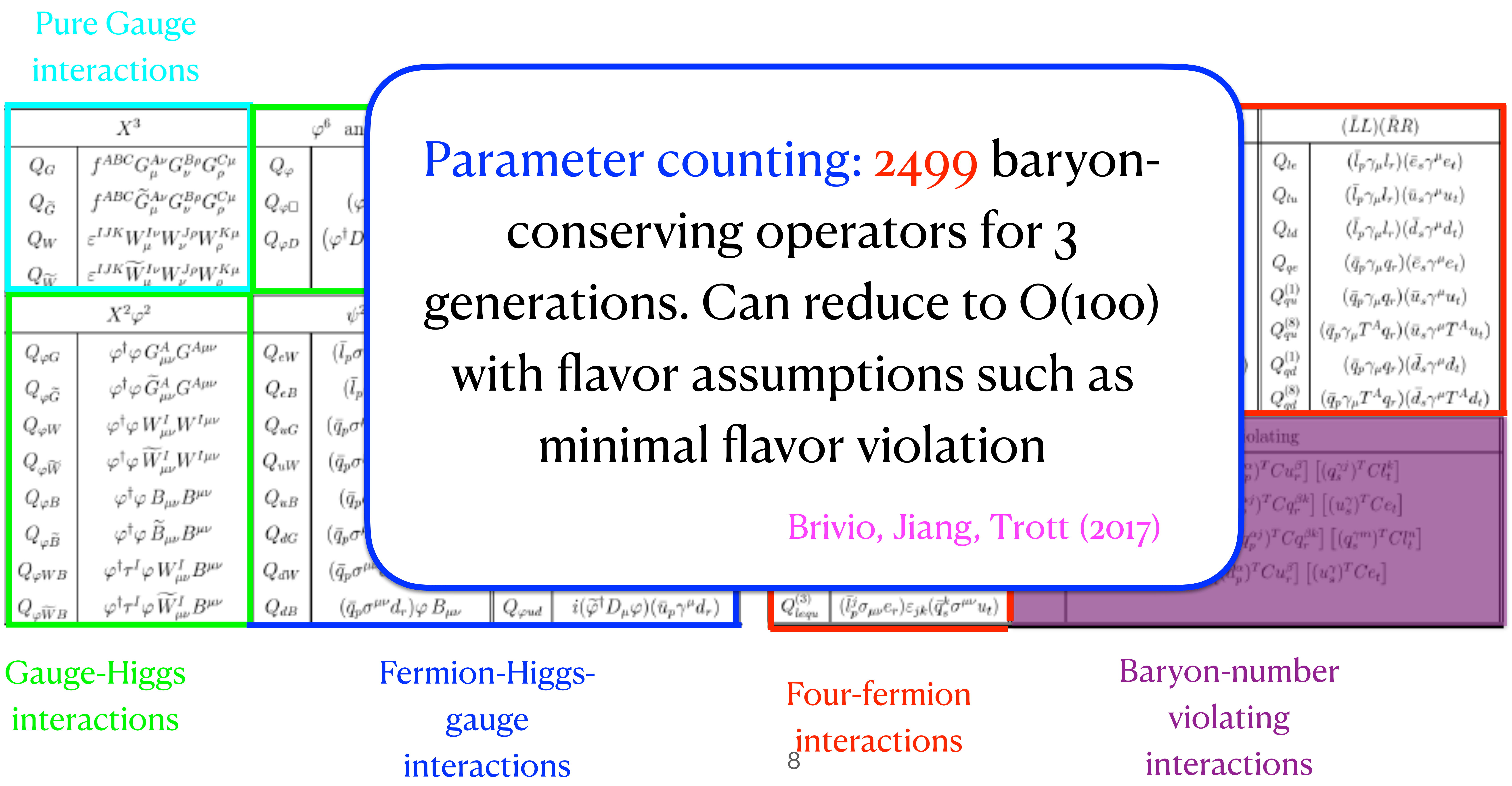
Four-fermion interactions

Baryon-number violating interactions (not considered here)

Constructing the SMEFT

- First step is to construct a complete and non-redundant basis of operators at each dimension. One commonly-used possibility at dimension-6 is the Warsaw basis.

Buchmuller, Wyler (1986); Grzadkowski et al (2010); Brivio, Jiang, Trott (2017)



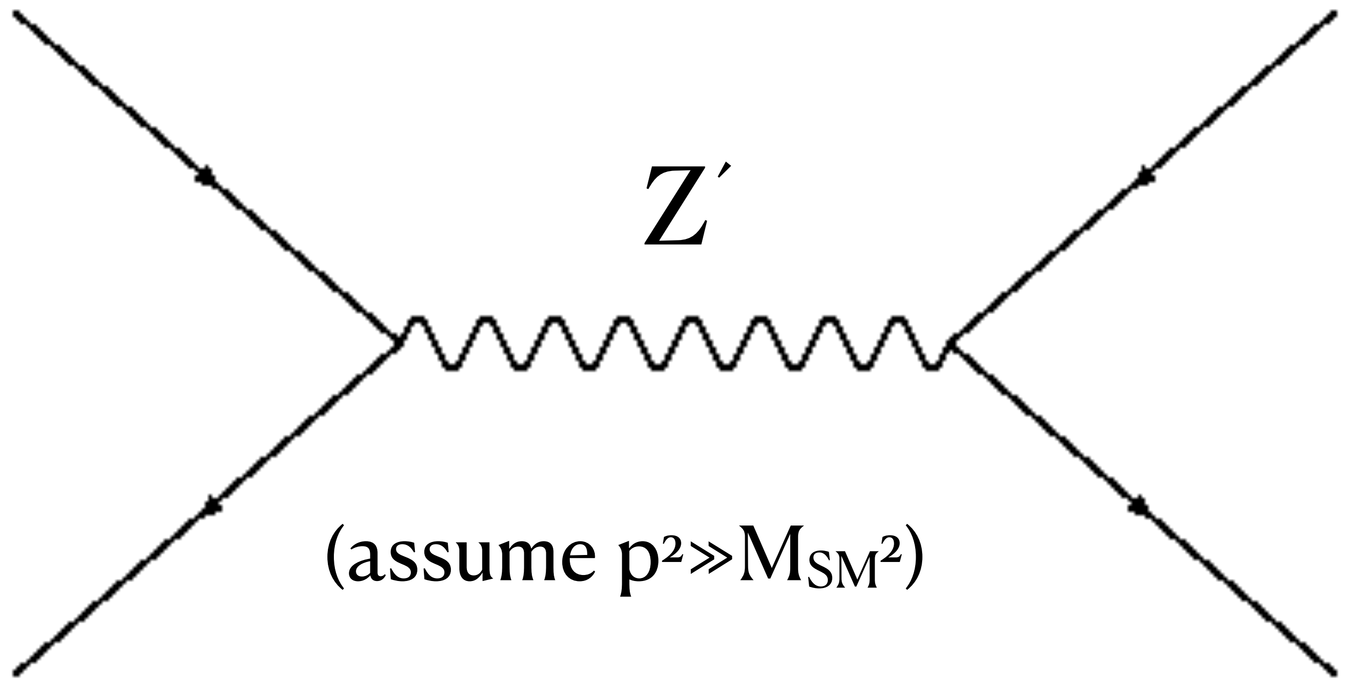
Parameter counting: 2499 baryon-conserving operators for 3 generations. Can reduce to O(100) with flavor assumptions such as minimal flavor violation

Brivio, Jiang, Trott (2017)

Matching new physics models to SMEFT

- How do we translate theories with new particles into the SMEFT framework? Let's consider a few examples, beginning with a Z' boson. Study its tree-level amplitude.

Example 1:



(assume $p^2 \gg M_{SM}^2$)

dim-6 ↓ dim-8 ↓

$$\sim -\frac{g_{Z'}^2}{p^2 - M_{Z'}^2} \approx \frac{g_{Z'}^2}{M_{Z'}^2} + \frac{g_{Z'}^2 p^2}{M_{Z'}^4} + \ldots$$

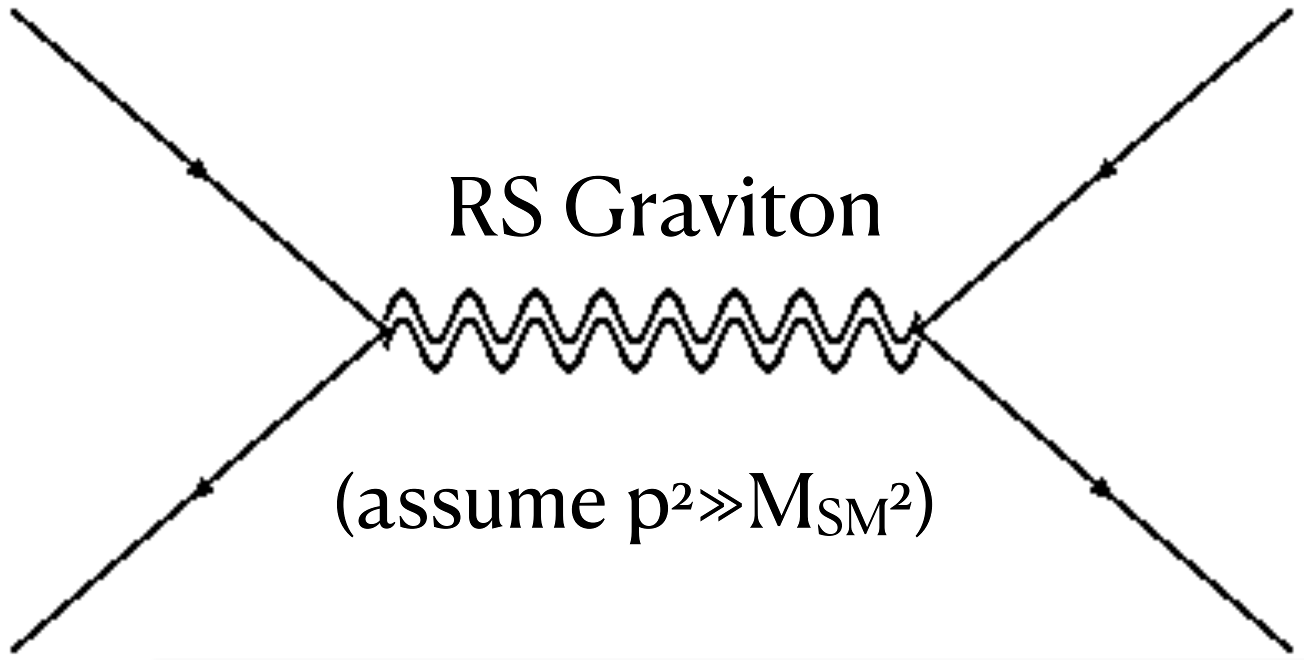
$$\sigma \sim |\mathcal{M}_{SM}|^2 + \frac{1}{\Lambda^2} 2\mathrm{Re}\left[\mathcal{M}_6 \mathcal{M}_{SM}^*\right] + \frac{1}{\Lambda^4}\left\{|\mathcal{M}_6|^2 + 2\mathrm{Re}\left[\mathcal{M}_8 \mathcal{M}_{SM}^*\right]\right\}$$

$|\mathcal{M}_{SM}|^2 \to \frac{g_{SM}^4}{p^4}$, $\quad 2\mathrm{Re}[\mathcal{M}_6\mathcal{M}_{SM}^*] \to \frac{g_{SM}^2 g_{Z'}^2}{p^2 M_{Z'}^2}$, $\quad |\mathcal{M}_6|^2 \to \frac{g_{Z'}^4}{M_{Z'}^4}$, $\quad 2\mathrm{Re}[\mathcal{M}_8\mathcal{M}_{SM}^*] \to \frac{g_{SM}^2 g_{Z'}^2}{M_{Z'}^4}$

Example 2: matching gravitons to the SMEFT

- Now let's consider the exchange of a Randall-Sundrum graviton, and derive its cross section.

Example 2:



dim-6 dim-8

$$\sim 0 + \frac{p^2}{M_S^4} + \ldots$$

Han, Lykken, Zhang (1998)

$$\sigma \sim |\mathcal{M}_{SM}|^2 + \frac{1}{\Lambda^2} 2\mathrm{Re}\left[\mathcal{M}_6 \mathcal{M}_{SM}^*\right] + \frac{1}{\Lambda^4}\left\{|\mathcal{M}_6|^2 + 2\mathrm{Re}\left[\mathcal{M}_8 \mathcal{M}_{SM}^*\right]\right\}$$

$\frac{g_{SM}^4}{p^4}$ 0 0 $\frac{g_{SM}^2}{M_S^4}$

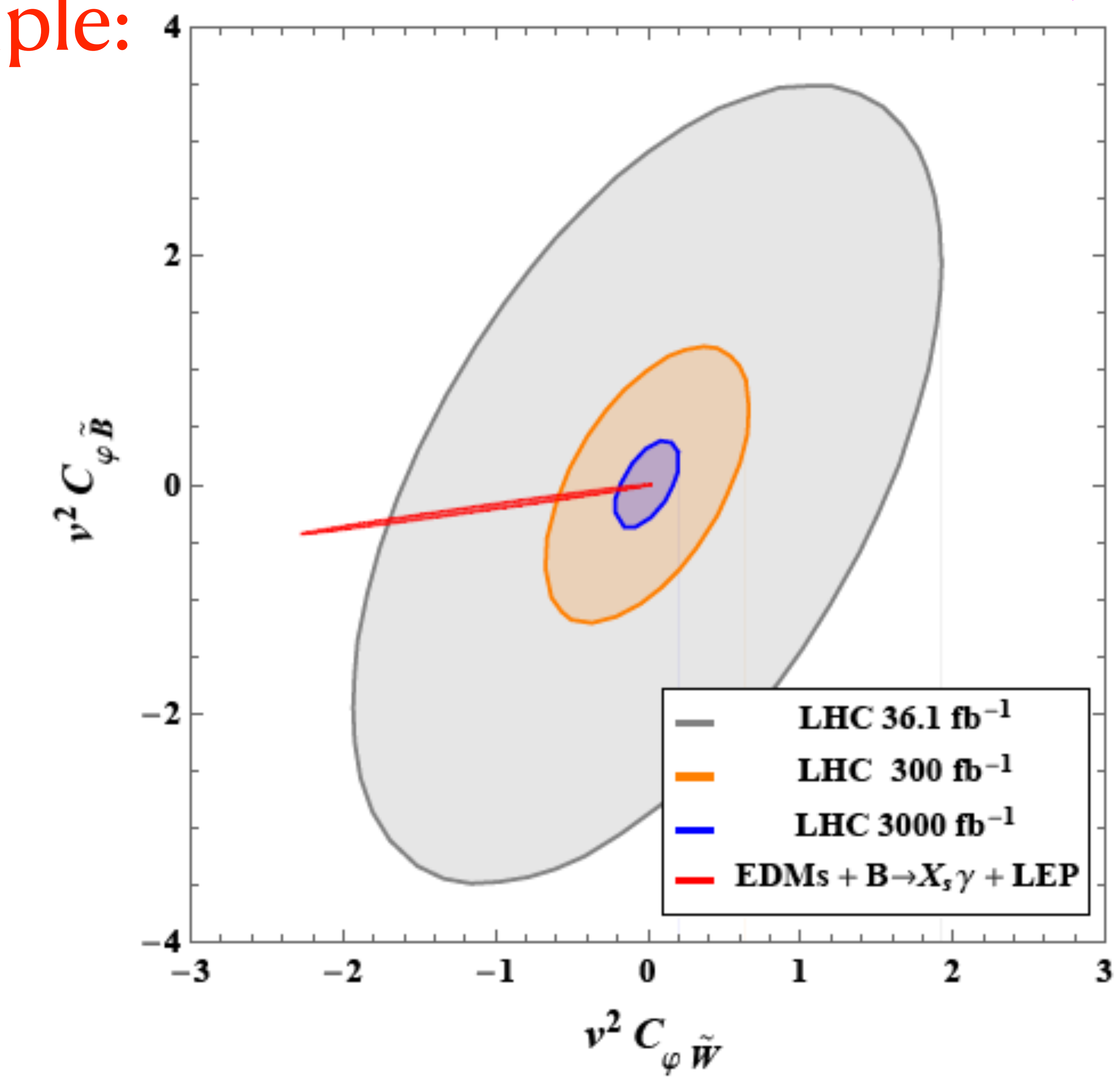
Dimension-6 vanishes and dimension-8 is the leading effect. Terms beyond $O(1/\Lambda^2)$ required for reliable predictions

Nice Features of the SMEFT

- As demonstrated, the EFT framework encapsulates a broad swath of BSM theories; determine the constraints on the C^i, then work out the C^i for a given model of new physics.
- Allows straightforward comparisons of different experiments.

Example:

Cirigliano et al (2019)



$C_{\varphi\tilde{B}}$: $\phi^\dagger \phi B_{\mu\nu} \tilde{B}^{\mu\nu}$

$C_{\varphi\tilde{W}}$: $\phi^\dagger \phi W_{\mu\nu} \tilde{W}^{\mu\nu}$

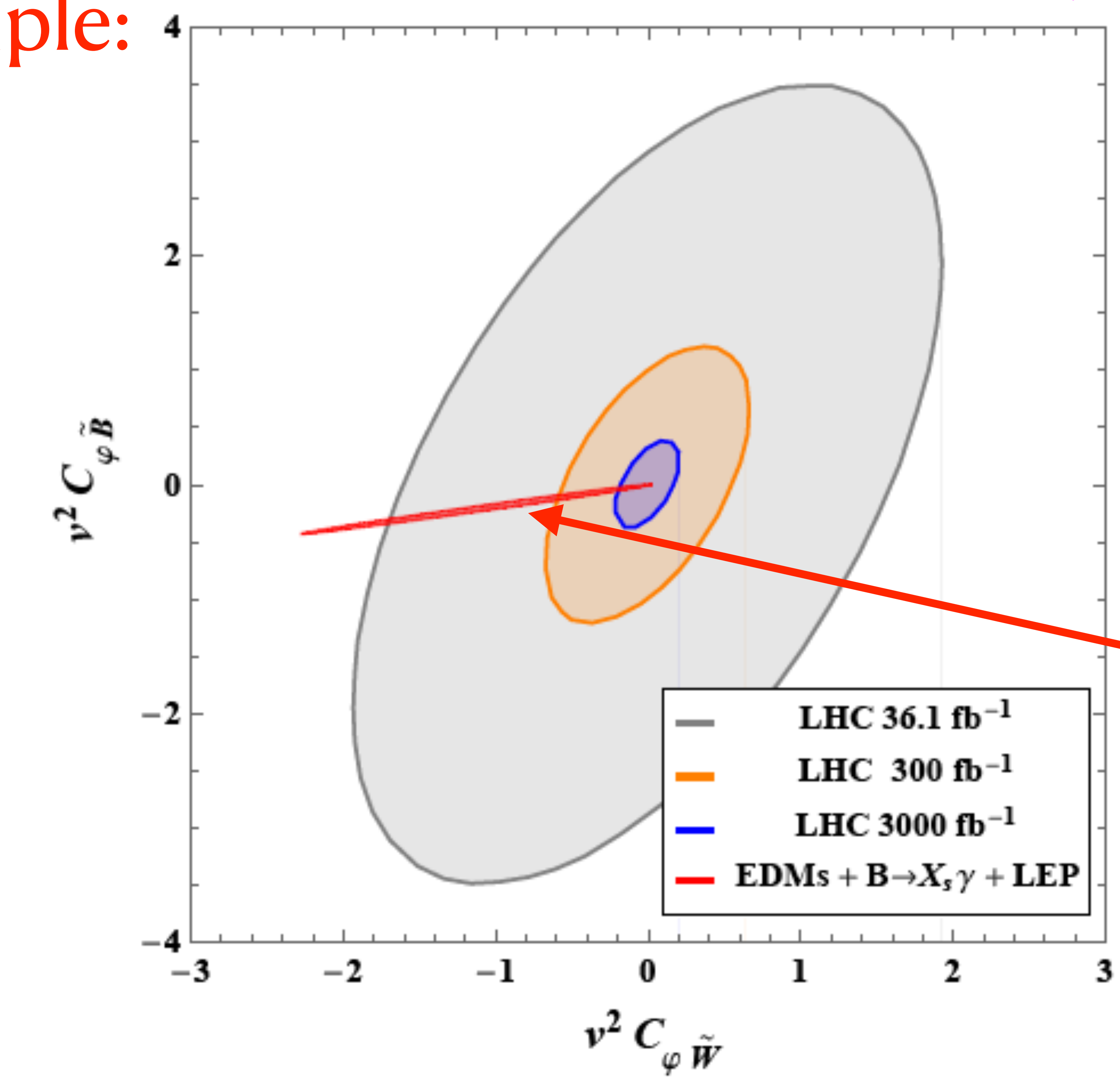
Can compare constraints on CP-violating gauge-Higgs interactions from low-energy observables such as EDMs with high-energy LHC probes

Challenges in the SMEFT

- As demonstrated, the EFT framework encapsulates a broad swath of BSM theories; determine constraints on the C^i, then work out the C^i for a given model of new physics.
- Allows straightforward comparisons of different experiments.

Cirigliano et al (2019)

Example:



$C_{\varphi\tilde{B}}$: $\phi^\dagger \phi B_{\mu\nu} \tilde{B}^{\mu\nu}$

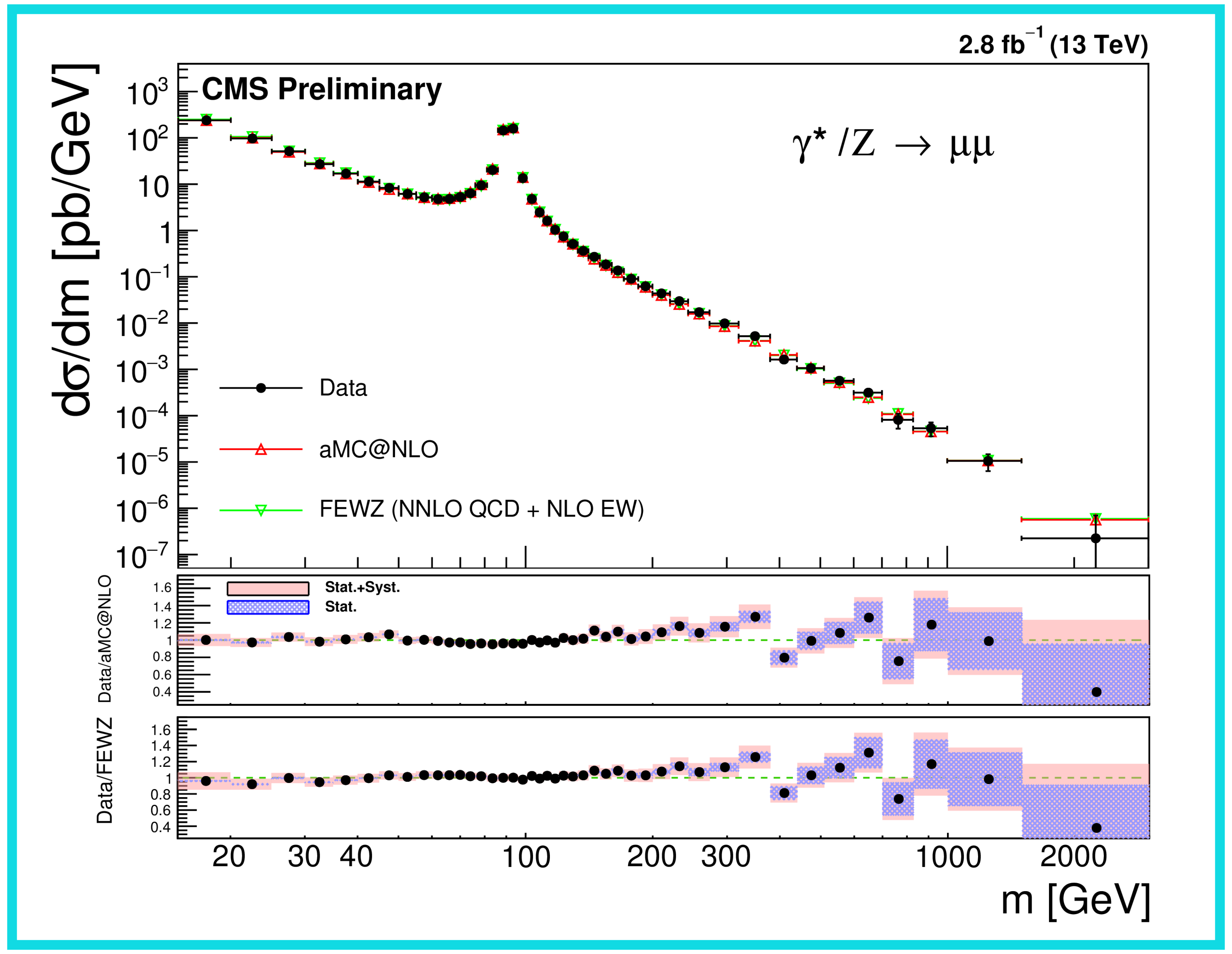
$C_{\varphi\tilde{W}}$: $\phi^\dagger \phi W_{\mu\nu} \tilde{W}^{\mu\nu}$

An example of a flat direction: low-energy experiments can only probe one linear combination of the C^i; need another experiment (the LHC in this case) to break the degeneracy

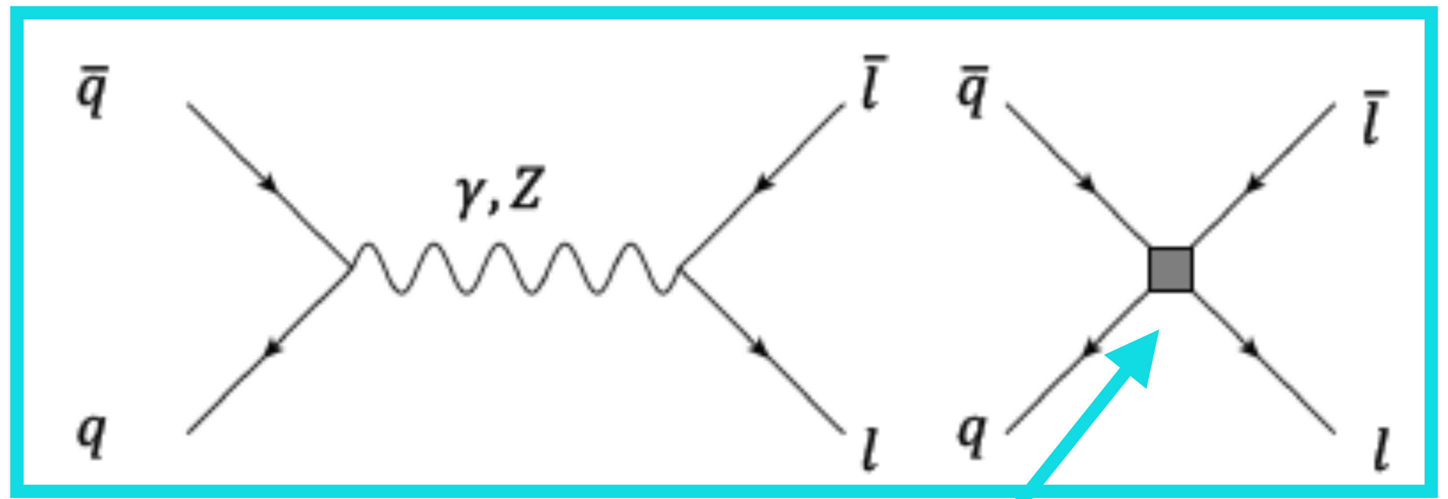
Removing LHC flat directions with a future Electron-Ion collider (EIC)

qqll operators at the LHC

- Study the issue of flat directions in the semi-leptonic four-fermion sector of the SMEFT. Strongest constraints expected from Drell-Yan data at the LHC.



Neutral current DY



$\mathcal{O}_{lq}^{(1)}$	$(\bar{l}\gamma^\mu l)(\bar{q}\gamma_\mu q)$	$\mathcal{O}_{lu}$	$(\bar{l}\gamma^\mu l)(\bar{u}\gamma_\mu u)$
$\mathcal{O}_{lq}^{(3)}$	$(\bar{l}\gamma^\mu \tau^I l)(\bar{q}\gamma_\mu \tau^I lq)$	$\mathcal{O}_{ld}$	$(\bar{l}\gamma^\mu l)(\bar{d}\gamma_\mu d)$
$\mathcal{O}_{eu}$	$(\bar{e}\gamma^\mu e)(\bar{u}\gamma_\mu u)$	$\mathcal{O}_{qe}$	$(\bar{q}\gamma^\mu q)(\bar{e}\gamma_\mu e)$
$\mathcal{O}_{ed}$	$(\bar{e}\gamma^\mu e)(\bar{d}\gamma_\mu d)$		

l, q: left handed doublets
e, u, d: right handed singlets

Precise data and theory up to high invariant masses at the LHC

Relevant dimension-6 operators at the LHC

qqll operators at the LHC

- Why are we looking only at four-fermion operators contributions?
- Other operators contribute as well, and shift the ffV vertices

Dawson, Giardino 1909.02000

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

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)

High-invariant mass cross section

- Let's examine the structure of the DY-cross section at the LHC for $\hat{s} \gg M_Z^2$. It depends on the invariant mass M of the lepton pair, the rapidity Y of the lepton pair, and an angle θ:

$$\frac{d\sigma}{dM^2 dY dc_\theta} \sim A_1 \hat{t}^2 + A_2 \hat{u}^2$$

c_θ: CM-frame scattering angle of the negatively charged lepton

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

$$A_1 = -\frac{8\pi\alpha Q_u}{3}\left[(C_{lu} + C_{qe})\right] + \frac{2g_Z^2}{3}\left[g_R^u g_L^e C_{lu} + g_R^e g_L^u C_{qe}\right]$$

$$A_2 = -\frac{8\pi\alpha Q_u}{3}\left[(C_{eu} + C_{lq}^{(1)} - C_{lq}^{(3)})\right] + \frac{2g_Z^2}{3}\left[g_R^u g_R^e C_{eu} + g_L^u g_L^e C_{lq}^{(1)} - g_L^u g_L^e C_{lq}^{(3)}\right]$$

$d\sigma_{\gamma\mathrm{SMEFT}}{}^{\mathrm{uubar}} + d\sigma_{Z\mathrm{SMEFT}}{}^{\mathrm{uubar}}$

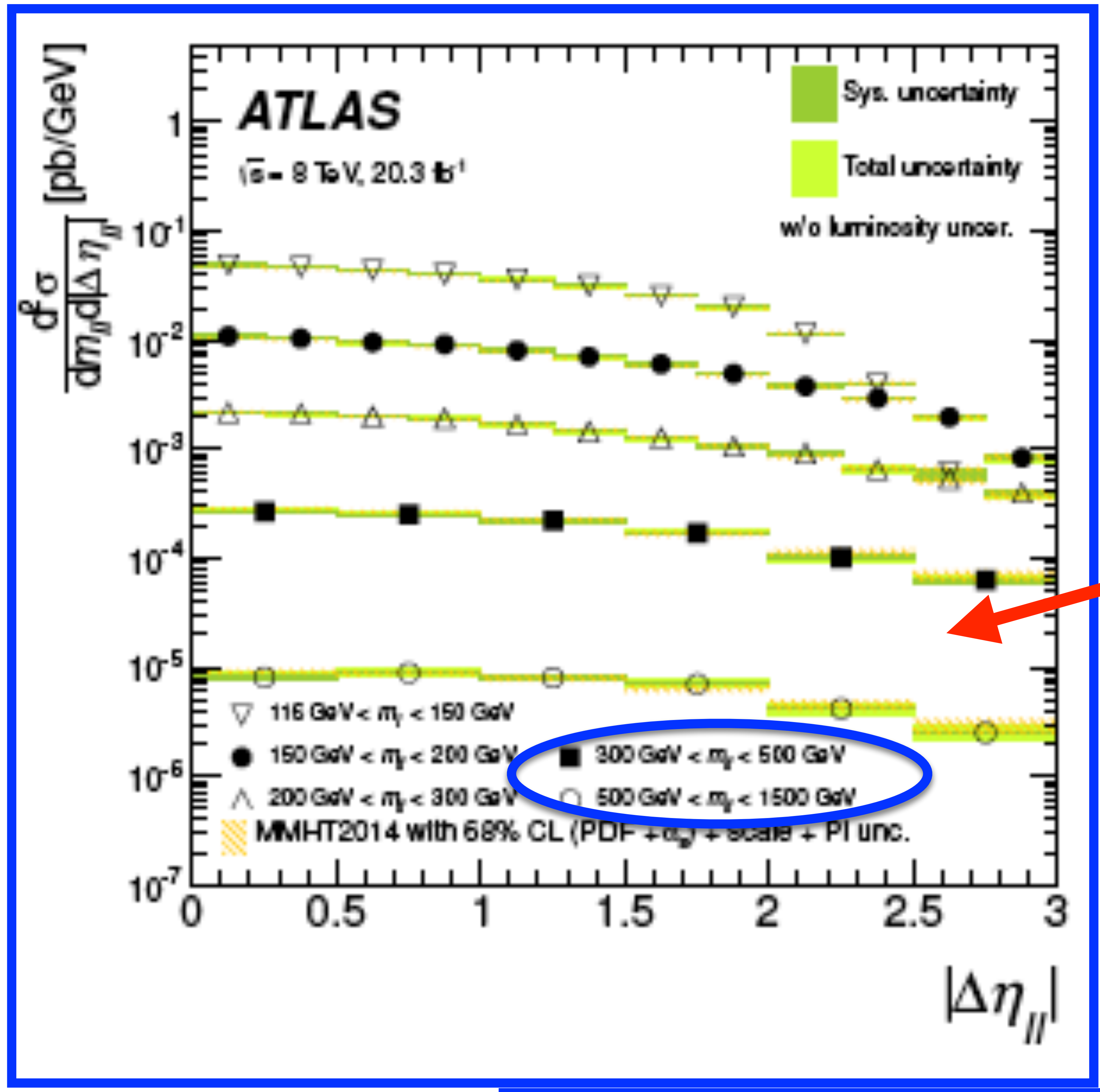
Best case: can only probe these two combinations of the seven total Wilson coefficients

- Upon integration over any symmetric range of c_θ:

$$\frac{d\sigma}{dM^2 dY} \sim A_1 + A_2$$

M^2, Y distributions only probe one combination of Wilson coefficient

Current high-mass measurements



1606.01736

$$|\Delta\eta_{ll}| = 2\,|\text{arctanh}(c_\theta)|$$

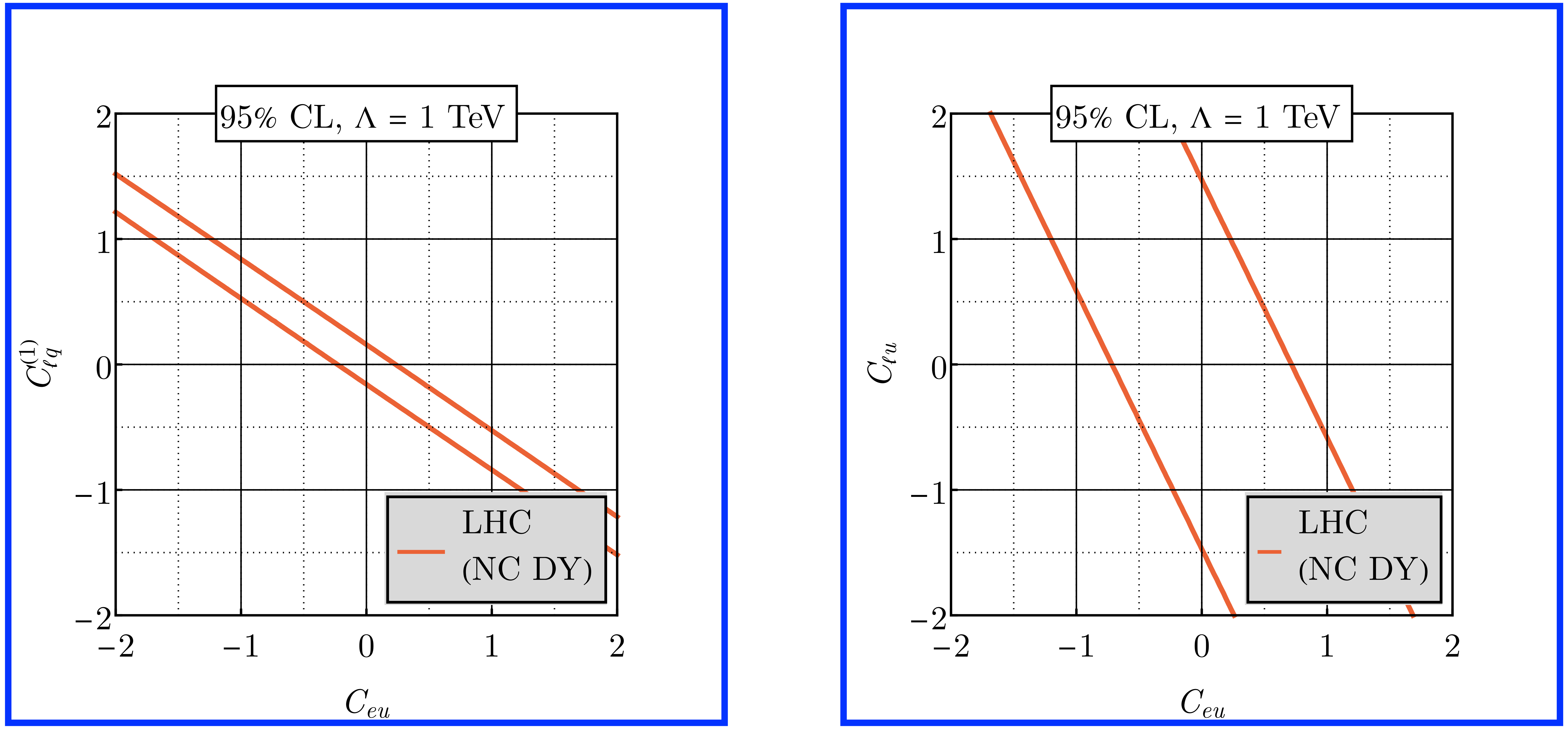
We will use this representative 8 TeV, 20 fb^{-1} Drell-Yan data set in our example fits. While it goes to 1.5 TeV in m_{ll} and not higher, ATLAS gave a detailed accounting of the experimental error matrix (it was originally intended as a SM measurement)

Note that the pseudo-rapidity difference measured in this data is symmetric under $c_\theta \to -c_\theta$ and therefore only probes the same single combination A1+A2.

Existing high-mass measurements probe only a single combination of Wilson coefficients

Blind spots in the LHC coverage

- The explicit fit to the previously shown LHC data demonstrates that there are blind spots in the LHC coverage; it is insensitive to certain linear combinations of the Wilson coefficients

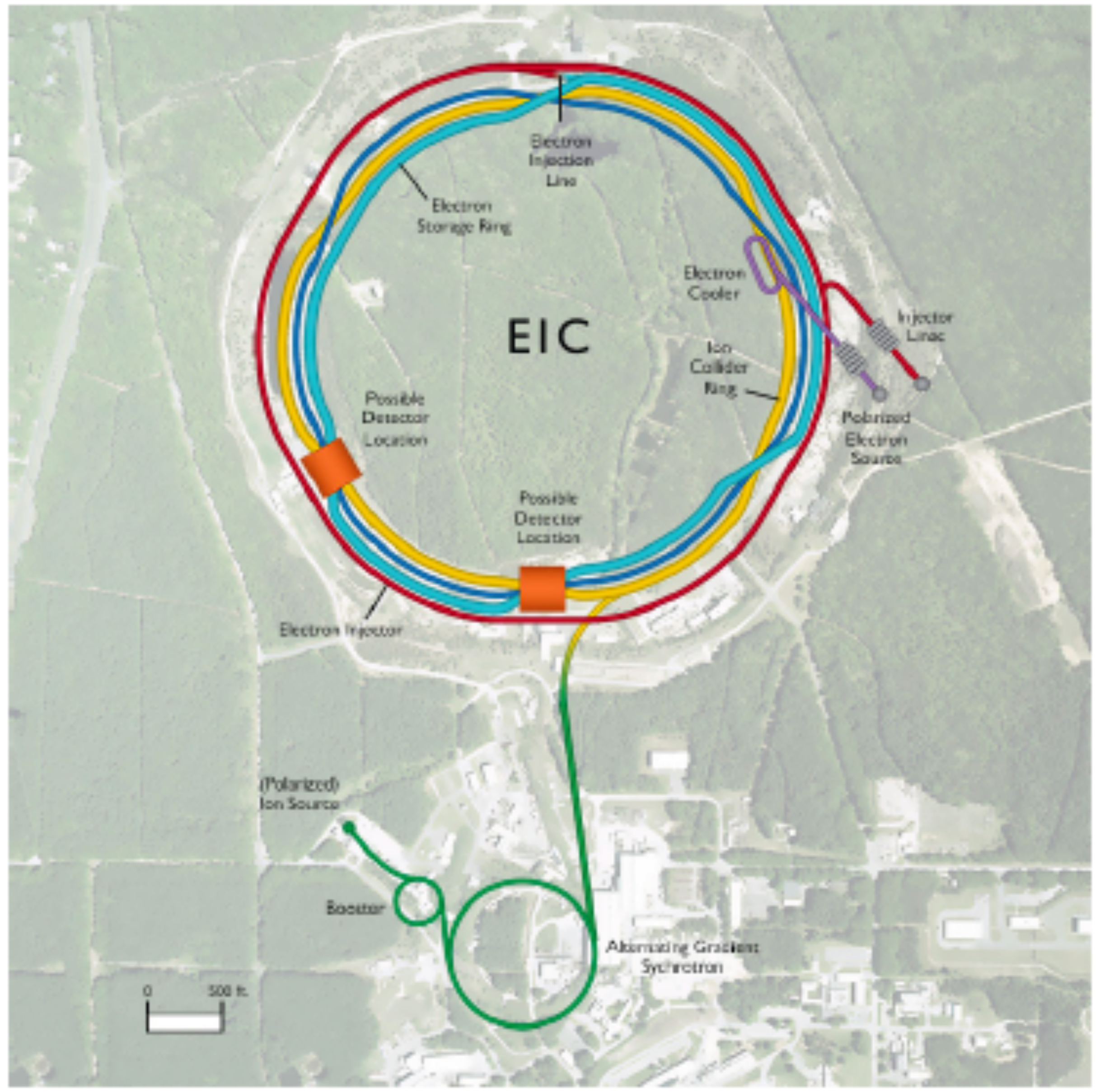


RB, Petriello, Wiegand 2004.00748

- The analysis was repeated using 13 TeV data sets and the conclusions remain unchanged

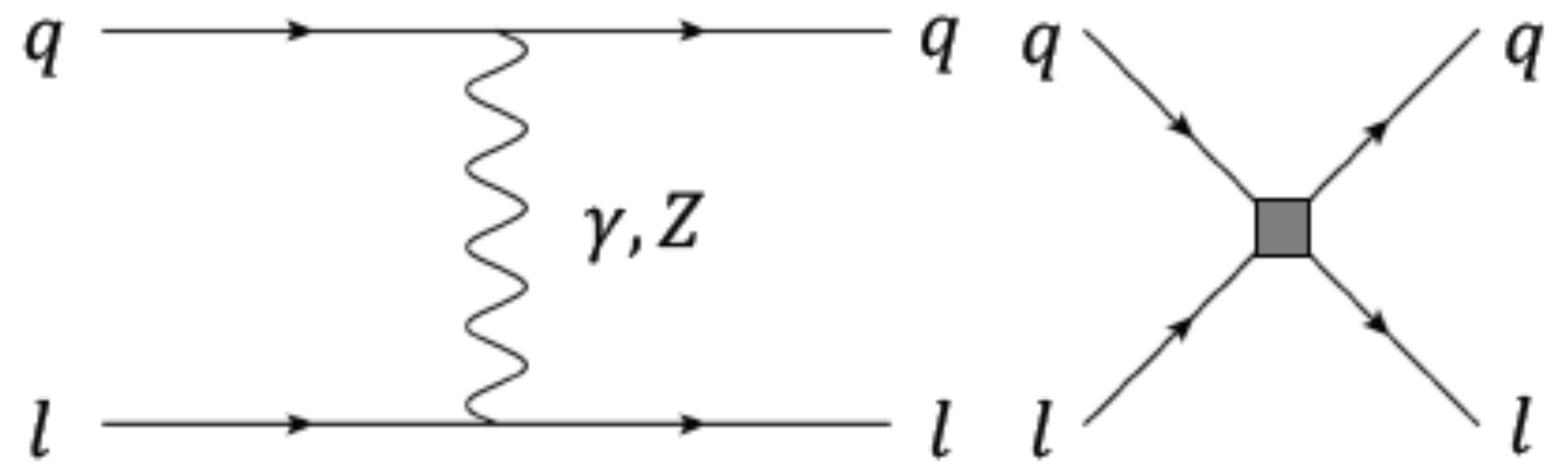
DIS at a future EIC

- Another experimental option to probe these Wilson coefficients in the future is through polarized DIS at the EIC.



https://www.bnl.gov/eic/

contributing diagrams



Example contribution to the cross section

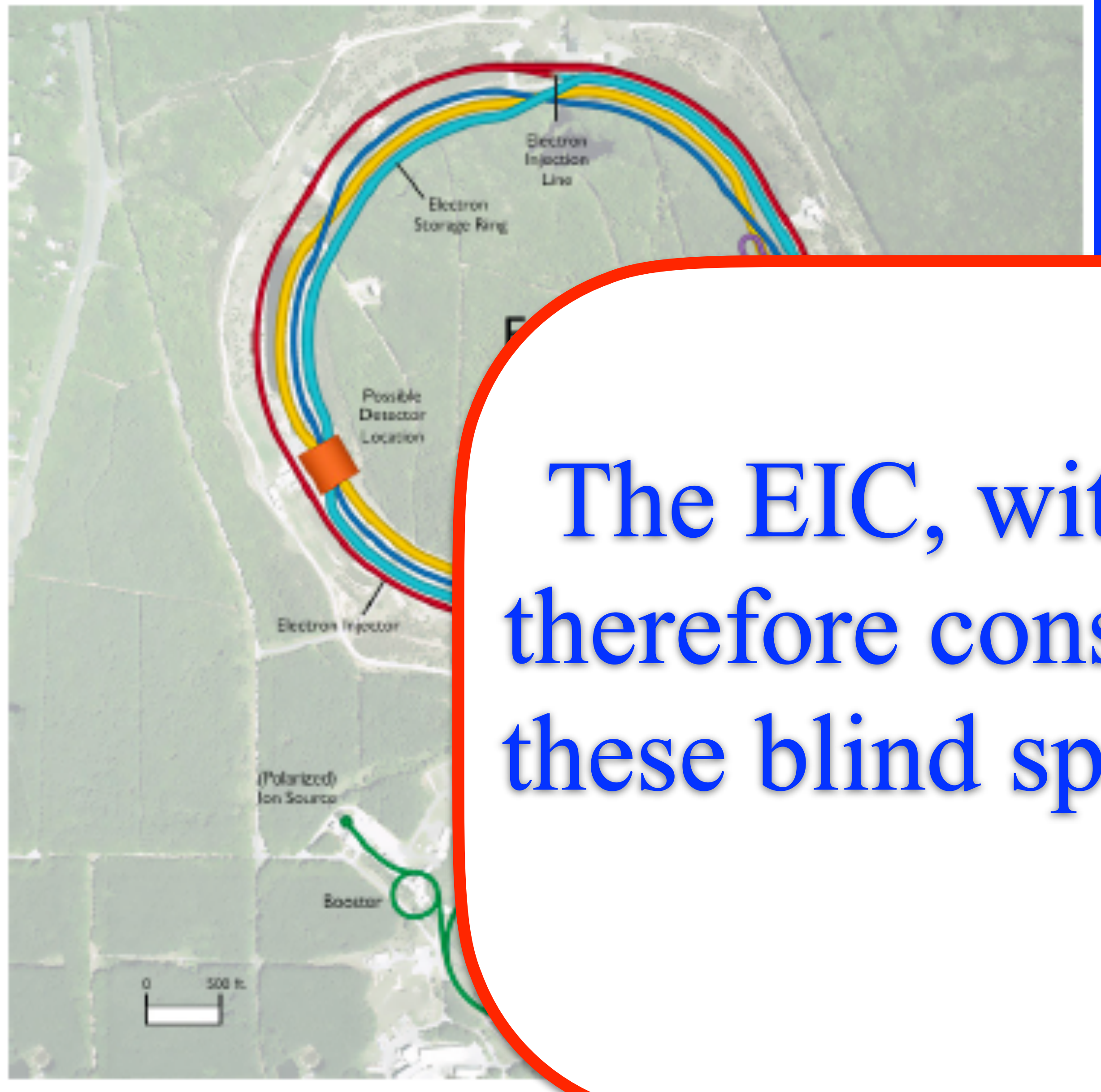
y = Q^2/x s

$$\frac{d^2\sigma_u^{\gamma SMEFT}}{dx dQ^2} = -x\frac{Q_u Q^2}{8\pi\alpha}\Big[C_{eu}(1+\lambda_u)(1+\lambda_e) + (C_{lq}^{(1)} - C_{lq}^{(3)})(1-\lambda_u)(1-\lambda_e) + (1-y)^2 C_{lu}(1+\lambda_u)(1-\lambda_e) + (1-y)^2 C_{qe}(1-\lambda_u)(1+\lambda_e)\Big]$$

Disentangle Wilson coefficients with polarization

DIS at a future EIC

- Another experimental option to probe these Wilson coefficients in the future is through polarized DIS at the EIC.

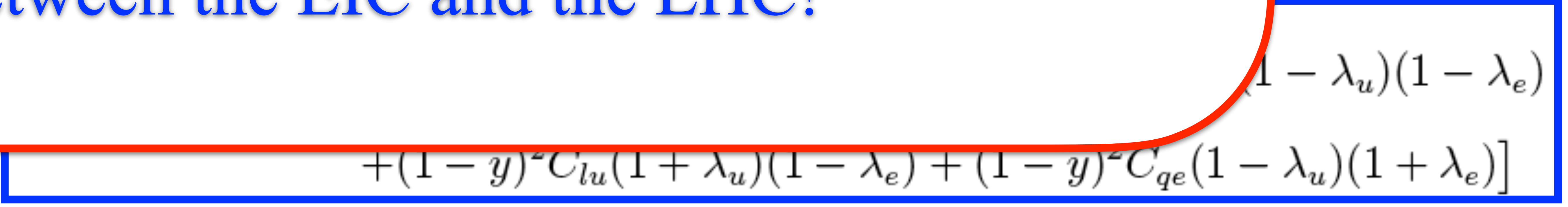


https://www.bnl.gov/eic/

contributing diagrams

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!

y = Q^2/x s



Disentangle Wilson coefficients with polarization

Observables

- We can form the following cross sections using polarized beams at the EIC

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

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

$$d\sigma_H = \frac{1}{4}\sum_q \Delta f_{q/H}[d\sigma^{++} - d\sigma^{+-} + d\sigma^{-+} - d\sigma^{--}] : \text{unpol. } \ell + \text{pol. } H$$

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

Polarized electrons, unpolarized hadrons

$$A_{\rm PV} = \frac{d\sigma_\ell}{d\sigma_0}$$

unpolarized electrons, polarized hadrons

$$\Delta A_{\rm PV} = \frac{d\sigma_H}{d\sigma_0}$$

PV: parity-violating
LC: lepton charge

Lepton charge asymmetries

$$A_{\rm LC} = \frac{d\sigma_0(e^+H) - d\sigma_0(e^-H)}{d\sigma_0(e^+H) + d\sigma_0(e^-H)}$$

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

Details of the simulation

- We generate EIC pseudodata with the following effects included
  - We perform a detailed experimental simulation using the current best information regarding expected EIC detector performance (see 2204.07557 for details)
  - 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

Data sets

- We consider the following data sets that span the spectrum of possible EIC beam configurations. We refer to the indicated luminosities as "nominal luminosity (NL)".

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 configurations in this talk.
- Polarized deuteron and proton copies of these data sets are also studied, and labeled as ΔD, ΔP.
- Data sets where the lepton charge asymmetry is considered are labeled as LD, LP.
- We also consider a high-luminosity version of P5, D5, ΔP5, ΔD5 with a factor of 10 more integrated luminosity.

Error sources in the simulation

Error type	polarized lepton $A_{\rm PV}$ (D, P)	polarized hadron $\Delta A_{\rm PV}$ (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	✓	✓	✓

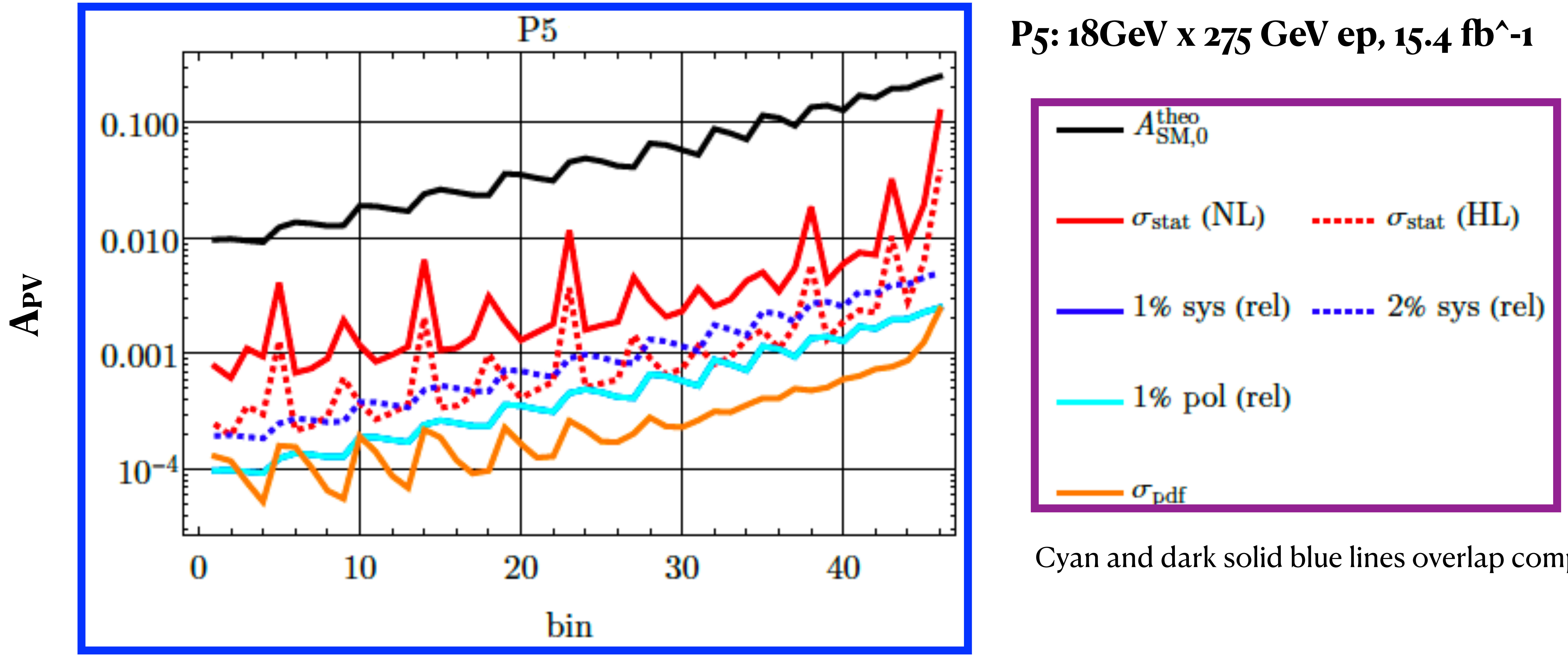
P_l: lepton polarization
P_H: hadron polarization

PDF sets used:
NNPDF3.1 NLO
NNPDFpol1.1 NLO

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

Error budget: unpolarized protons

- Bins first ordered in Q^2. Within each Q^2 bin we then order in x. HL is a proposed high-luminosity option with an increase by a factor of 10 w.r.t the nominal integrated luminosity



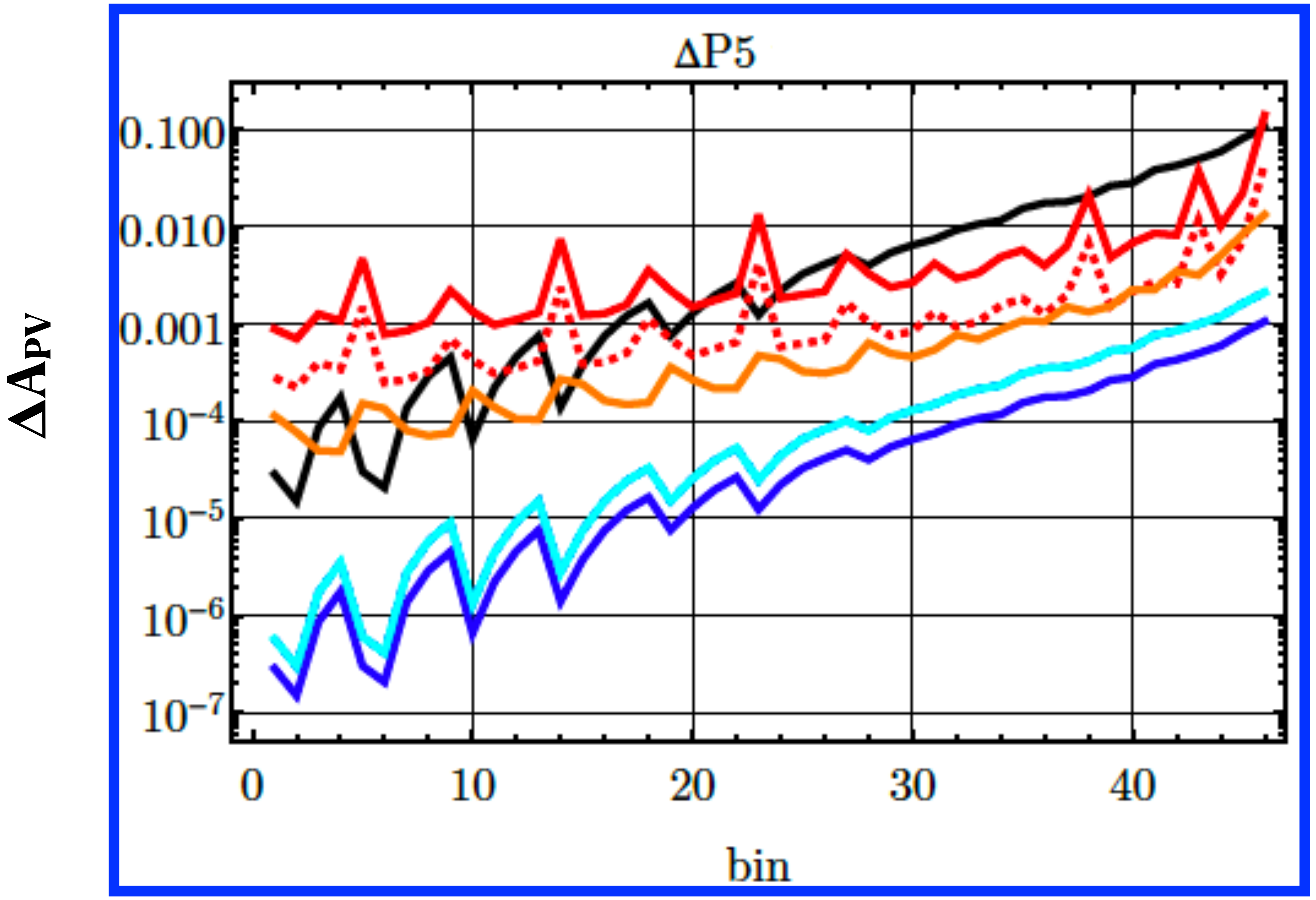
P5: 18GeV x 275 GeV ep, 15.4 fb^-1

Cyan and dark solid blue lines overlap completely

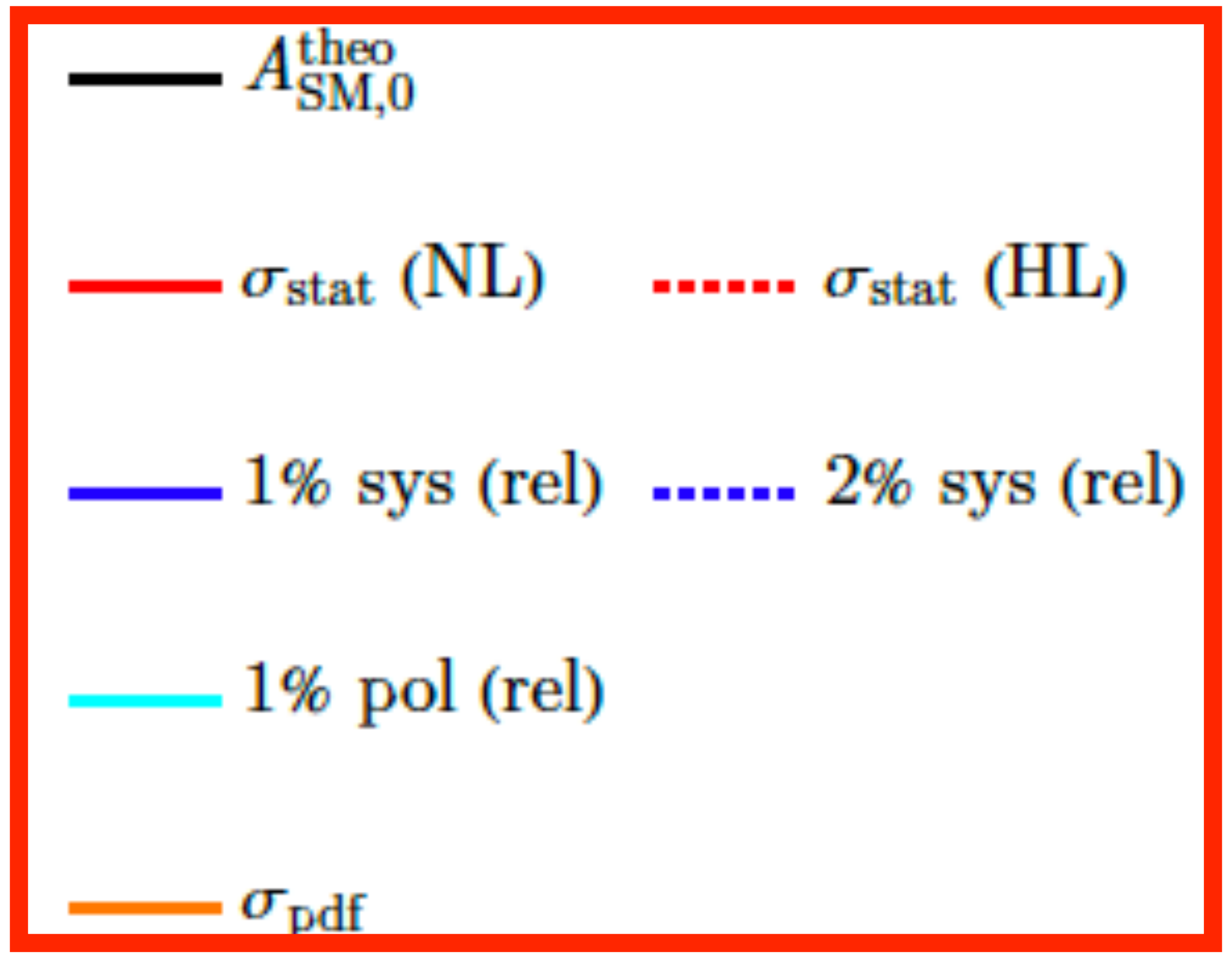
- Polarized lepton asymmetry much larger than all uncertainties. Statistical uncertainties dominant with the nominal luminosity; systematic errors more important with high luminosity than with nominal luminosity. PDF errors negligible.

Error budget: polarized protons

- Bins first ordered in Q^2. Within each Q^2 bin we then order in x. HL is a proposed high-luminosity option with an increase by a factor of 10 w.r.t the nominal integrated luminosity



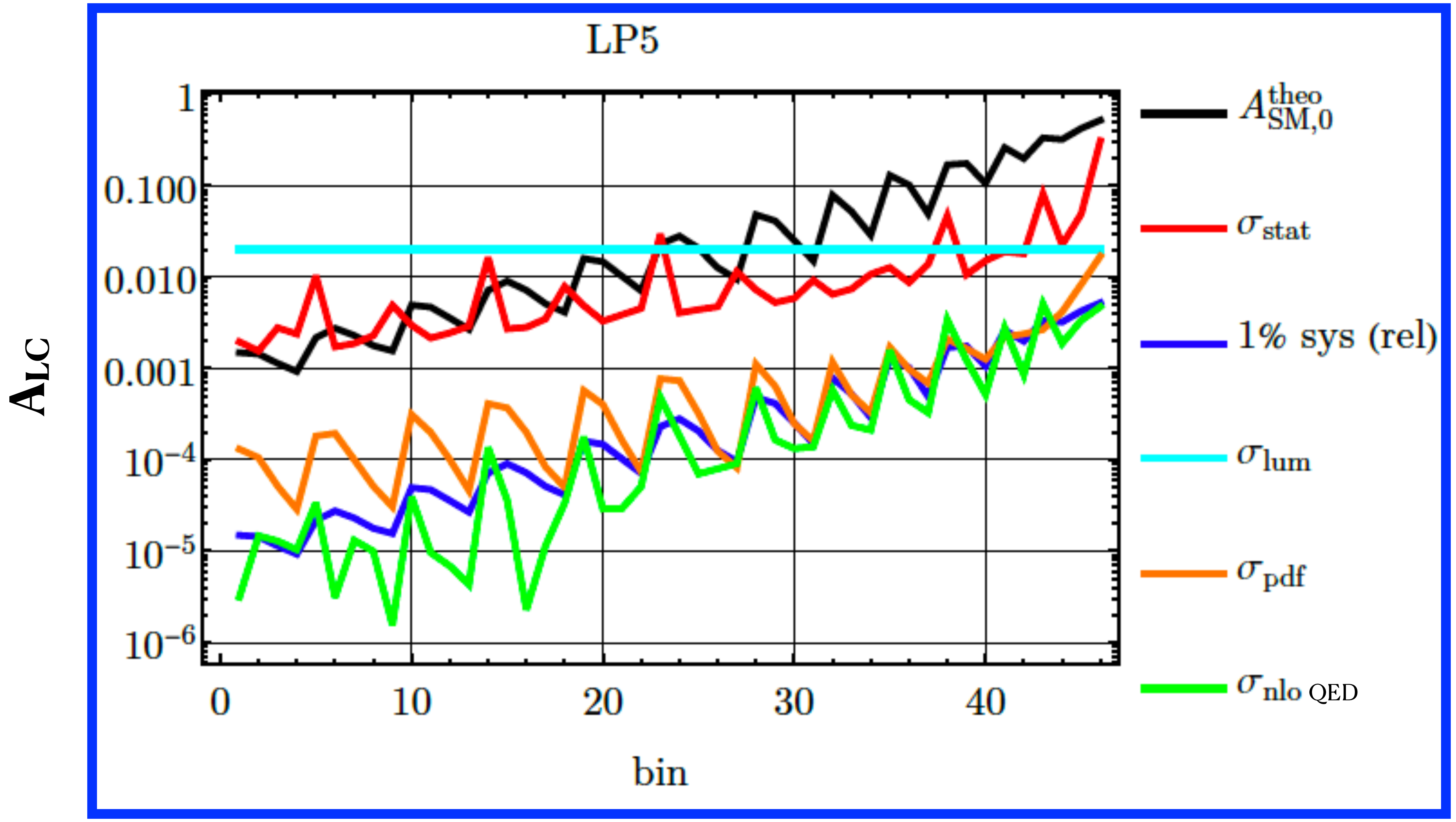
ΔP5: 18GeV x 275 GeV ep, 15.4 fb^-1



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

Error budget: lepton-charge asymmetry

- Bins first ordered in Q^2. Within each Q^2 bin we then order in x. HL is a proposed high-luminosity option with an increase by a factor of 10 w.r.t the nominal integrated luminosity



LP5: 18GeV x 275 GeV ep, 15.4 fb^-1

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

Pseudo data generation

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

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

uncorrelated errors; separate r_b for each bins

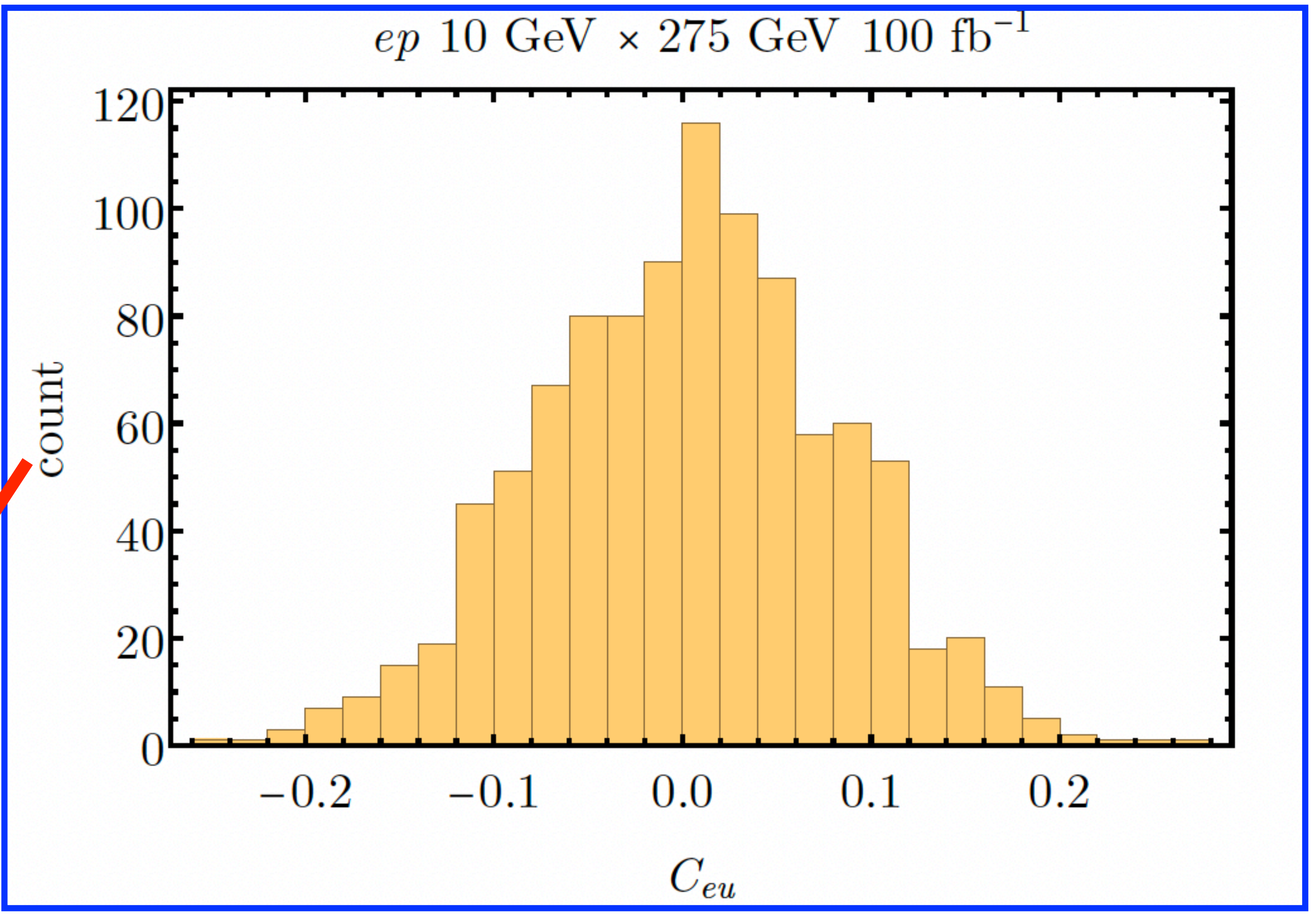
correlated errors; same r' for all bins

b = bin index

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

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

Best-fit values:

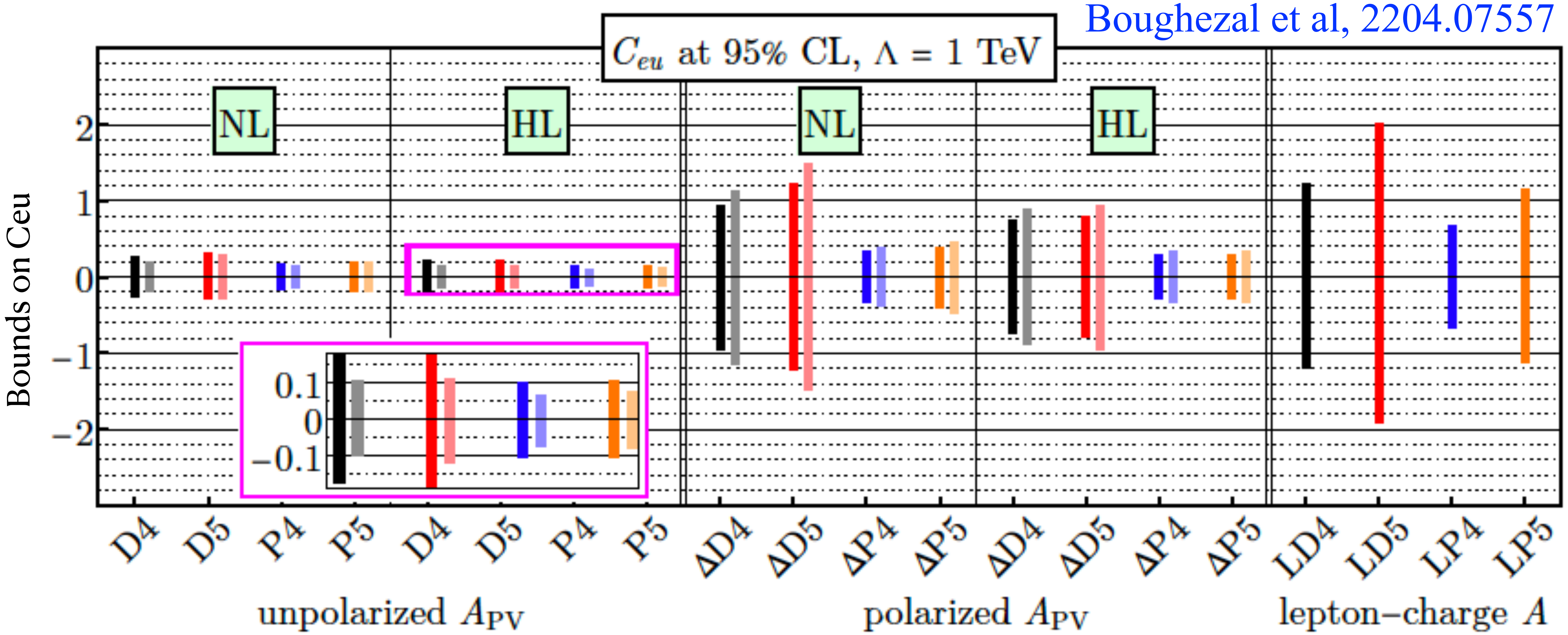


Nfit: number of Wilson coefficients turned on at a time.
count: the number of pseudo experiments with a given best fit value of Ceu

SMEFT results: 1-d fits

- Begin by turning on one representative Wilson coefficient (results for other Wilson coefficients look similar)

Boughezal et al, 2204.07557



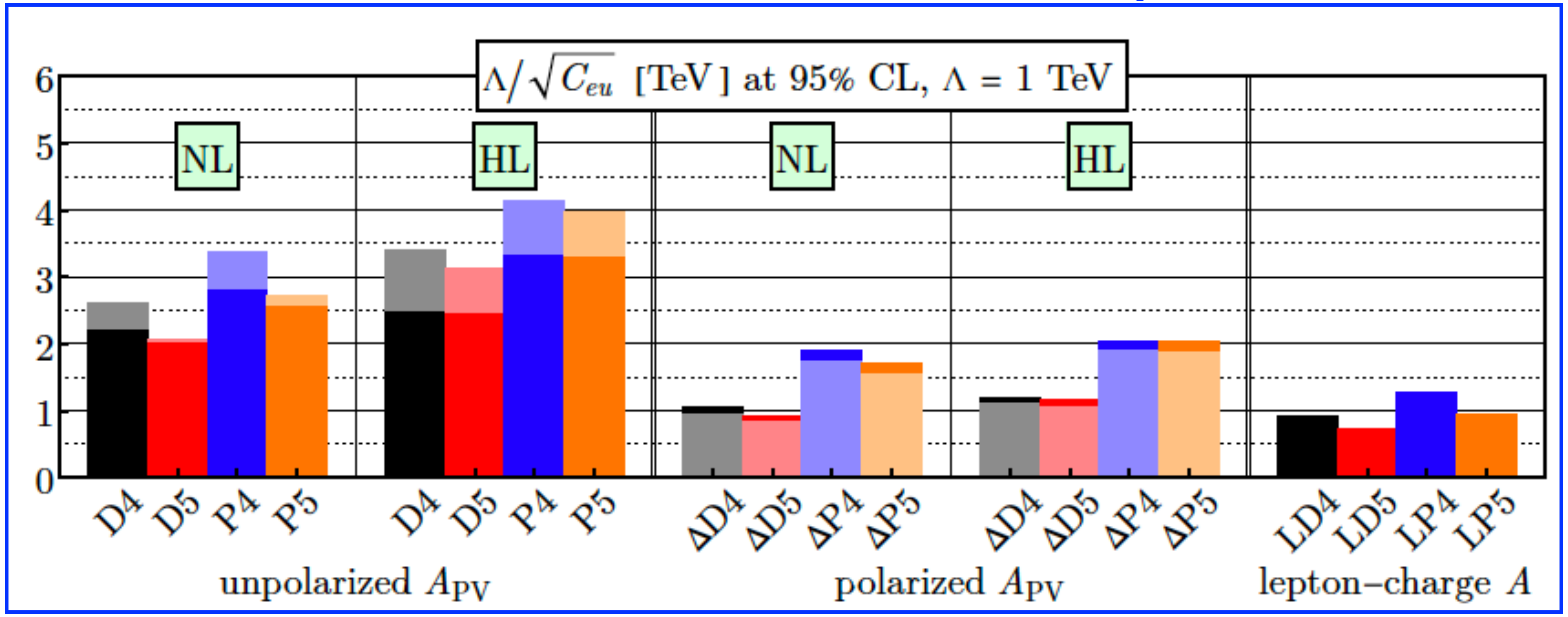
Trends:

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

SMEFT results: 1-d fits

- Convert these bounds to effective UV scales probes. Note that the SMEFT deviation goes as C/Λ² which motivates the choice of the effective scale.

Boughezal et al, 2204.07557



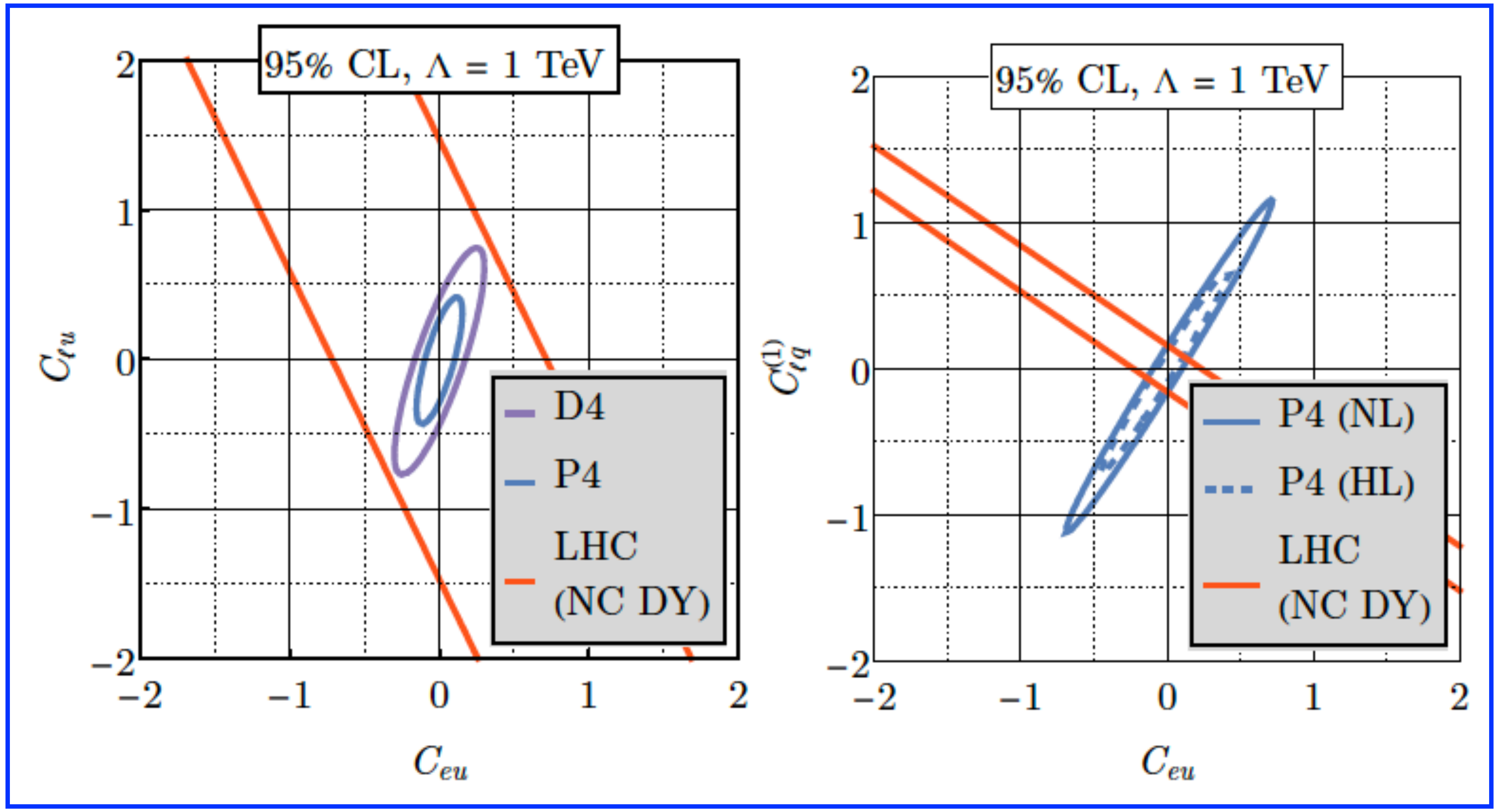
3 TeV scales probed with the nominal luminosity, 4 TeV with high luminosity. Competitive with current LHC bounds.

SMEFT results: 2-d fits

- Let's consider now two Wilson coefficients turned on simultaneously. An original motivation was to see if the EIC could help resolve degeneracies that appear with LHC NC DY data

Boughezal et al, 2204.07557

- Can resolve the degeneracies that remain after LHC measurements! No degeneracies remain in the SMEFT parameter space with the nominal EIC program
- Note that the EIC and LHC constraints are orthogonal. Can combine them to strengthen further the bounds on the parameter space.



P4: 10 GeV x 275 GeV ep, 100 fb^-1
D4: 10 GeV x 137 GeV eD, 100 fb^-1

Higher-dimensional fits

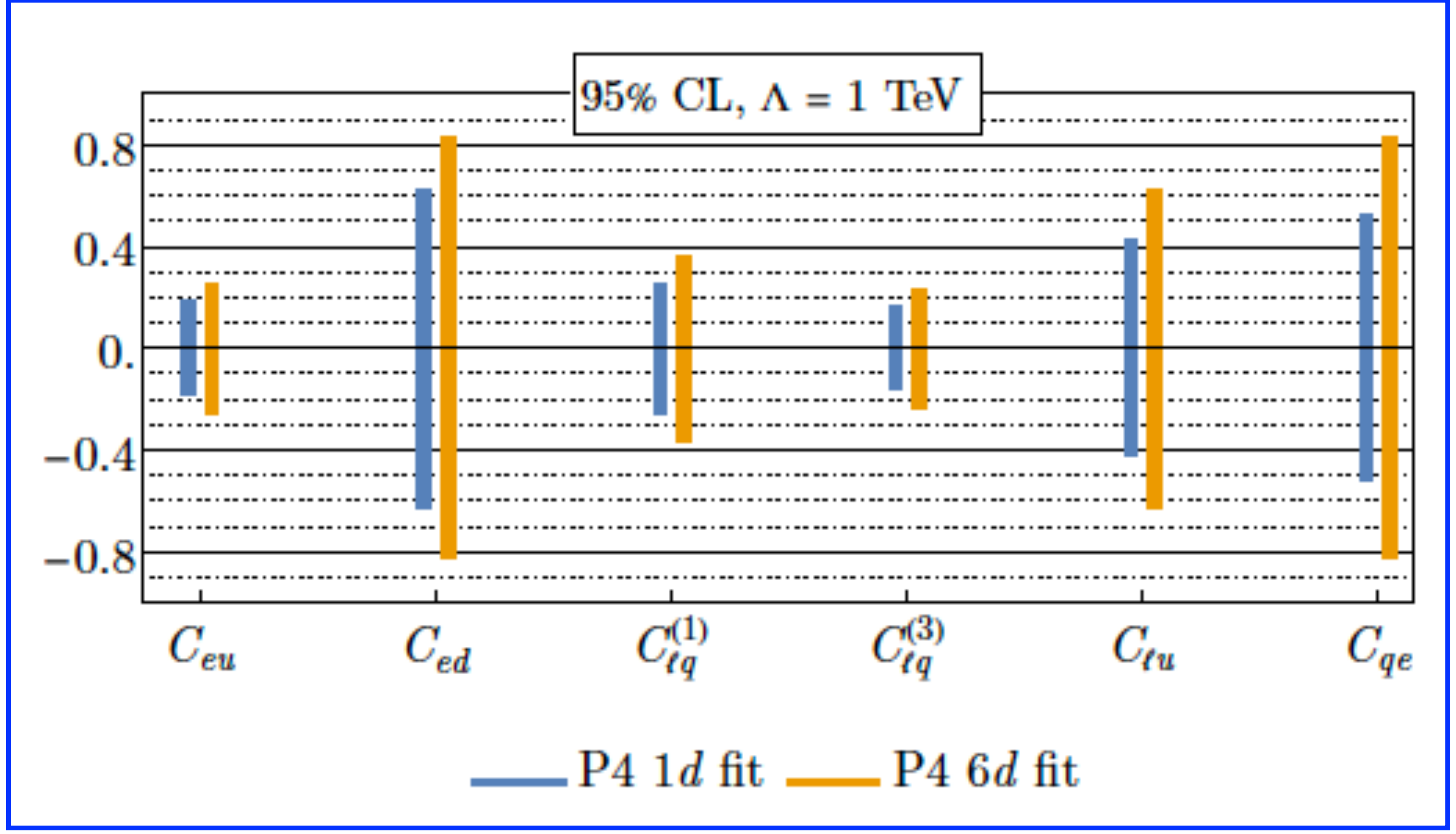
- Can turn on more Wilson coefficients to further search for degeneracies and check degradation of sensitivities. Requires more pseudo-experiments.

Boughezal et al, 2204.07557

Nfit: number of Wilson coefficients turned on at a time.

Nexp: number of pseudo experiments required for the analysis

$N_{\rm fit}$	$N_{\rm exp}$
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.

Conclusions

- SMEFT is a convenient framework for parametrizing UV physics in a model independent way
- The EIC is capable of powerful probes of BSM effects difficult to access at the LHC due to its ability to polarize both beams
- We have shown that the EIC can remove degeneracies in the four-fermion sector of the SMEFT that the LHC cannot distinguish
- Looking forward to a rich and exciting research program at the EIC!