SMEFT Probes Using LHC Drell-Yan data

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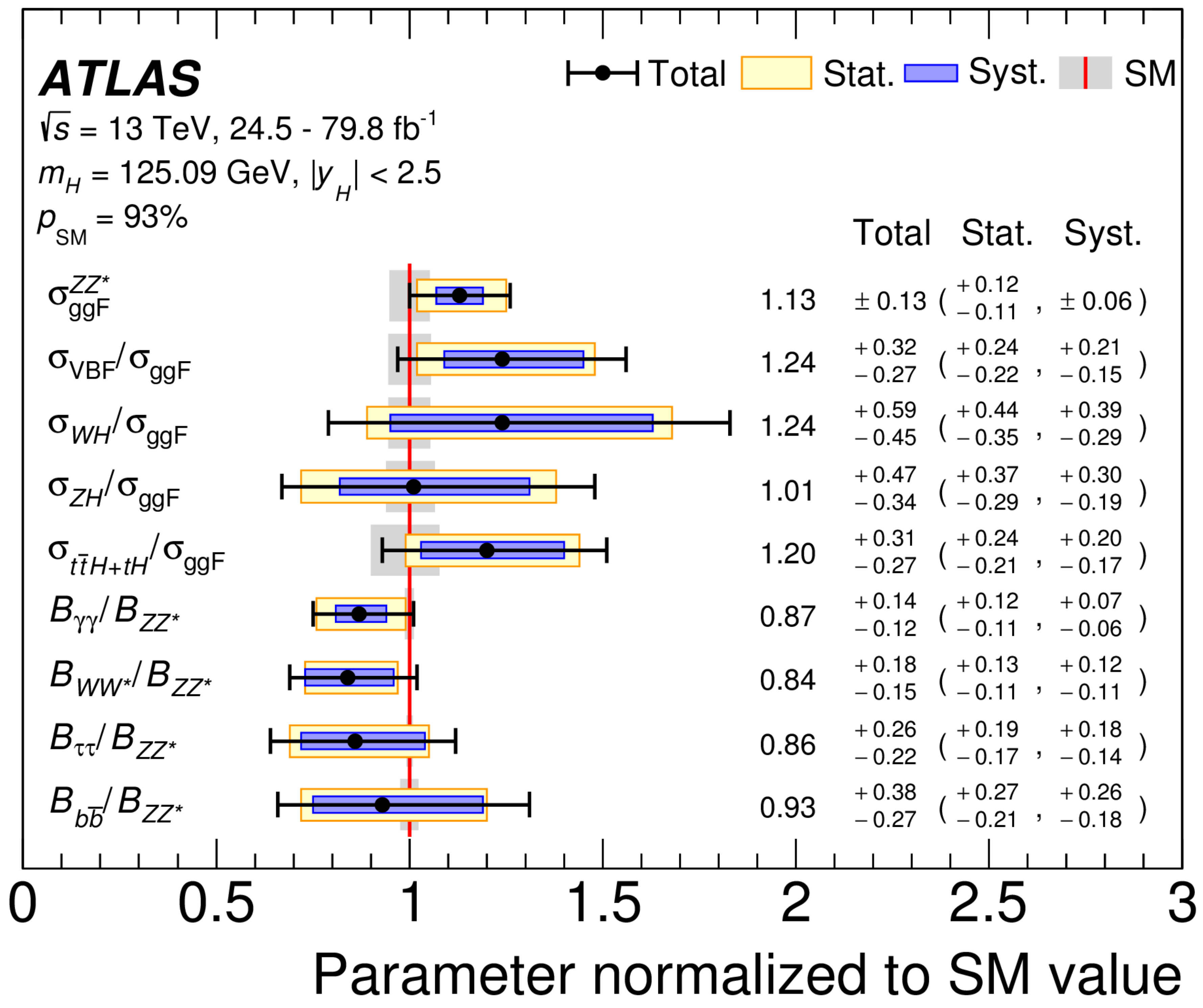
Outline

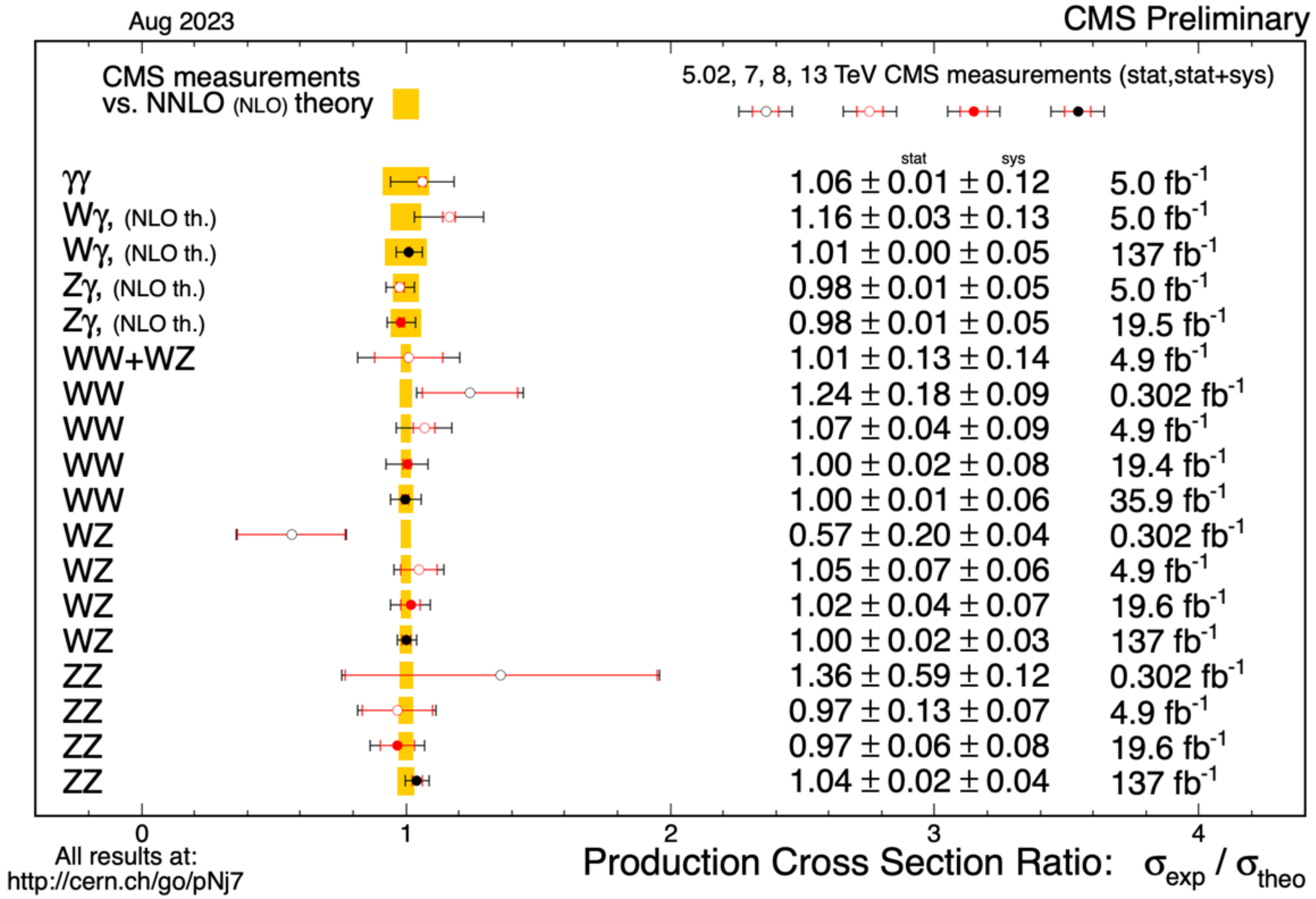
- Motivation and introduction to the SMEFT
- Sensitivity to higher-dimension operators in the Drell-Yan process
- Model discrimination with transverse momentum data
- Extending the Collins-Soper framework to SMEFT

Status of the Standard Model

Example: Higgs production and decay

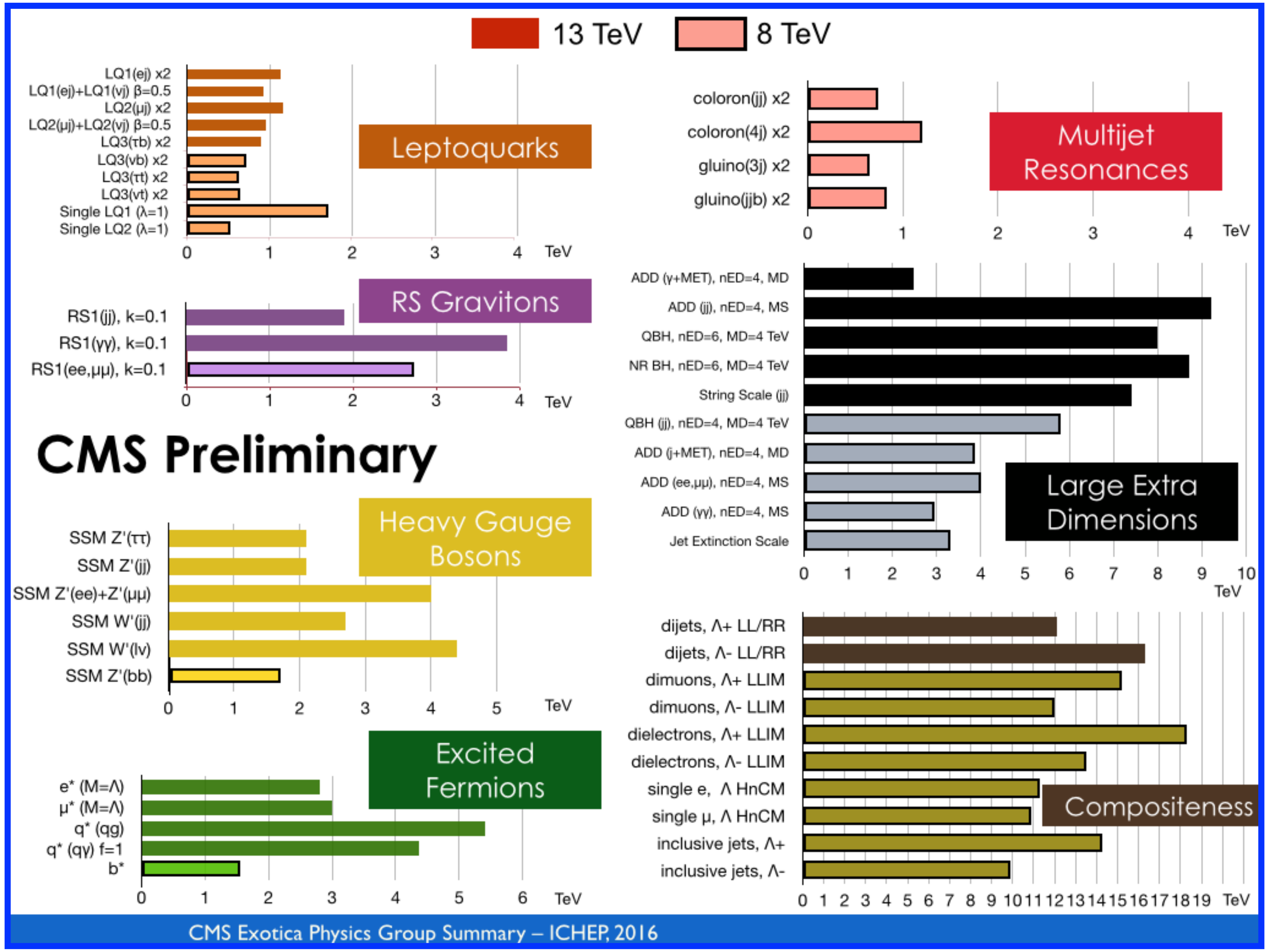


Example: di-boson cross sections



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

LHC searches for new physics



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

Limits on new physics mass scale exceed several TeV in many cases

Model-dependent vs independent searches

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

- 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

$$\boxed{\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{\Lambda^2}\sum_i \underbrace{C_6^i(\mu)\mathcal{O}_6^i(\mu)}_{\text{Dimension-6}} + \frac{1}{\Lambda^4}\sum_i \underbrace{C_8^i(\mu)\mathcal{O}_8^i(\mu)}_{\text{Dimension-8}} + \ldots}$$

- Λ»E,v (Higgs vev) must both be satisfied
- Odd dimensions violate lepton number; not our focus here
- RG running important when comparing experiments at disparate energies

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

Pure Gauge interactions

Accommodates a rich phenomenology in all sectors

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	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$(\varphi^\dagger D^\mu\varphi)^* (\varphi^\dagger D_\mu\varphi)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				

$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eW}	$(\bar l_p \sigma^{\mu\nu} e_r)\tau^I \varphi W_{\mu\nu}^I$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar l_p \gamma^\mu l_r)$
$Q_{\varphi\widetilde G}$	$\varphi^\dagger\varphi\, \widetilde G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eB}	$(\bar l_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I \varphi)(\bar l_p \tau^I\gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uG}	$(\bar q_p \sigma^{\mu\nu} T^A u_r)\widetilde\varphi\, G_{\mu\nu}^A$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar e_p \gamma^\mu e_r)$
$Q_{\varphi\widetilde W}$	$\varphi^\dagger\varphi\, \widetilde W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uW}	$(\bar q_p \sigma^{\mu\nu} u_r)\tau^I \widetilde\varphi\, W_{\mu\nu}^I$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar q_p \gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar q_p \sigma^{\mu\nu} u_r)\widetilde\varphi\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I \varphi)(\bar q_p \tau^I\gamma^\mu q_r)$
$Q_{\varphi\widetilde B}$	$\varphi^\dagger\varphi\, \widetilde B_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar q_p \sigma^{\mu\nu} T^A d_r)\varphi\, G_{\mu\nu}^A$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar u_p \gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W_{\mu\nu}^I B^{\mu\nu}$	Q_{dW}	$(\bar q_p \sigma^{\mu\nu} d_r)\tau^I \varphi\, W_{\mu\nu}^I$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar d_p \gamma^\mu d_r)$
$Q_{\varphi\widetilde WB}$	$\varphi^\dagger\tau^I\varphi\, \widetilde W_{\mu\nu}^I B^{\mu\nu}$	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

Dim-6 operators

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
- Dim-8 basis has been derived Li, Ren, Shu, Xiao, Yu, Zheng 2005.00008; Murphy 2005.00059
- Now known through dim-12 Harlander, Kempkens, Schaaf (2023)

Structure of a SMEFT cross section

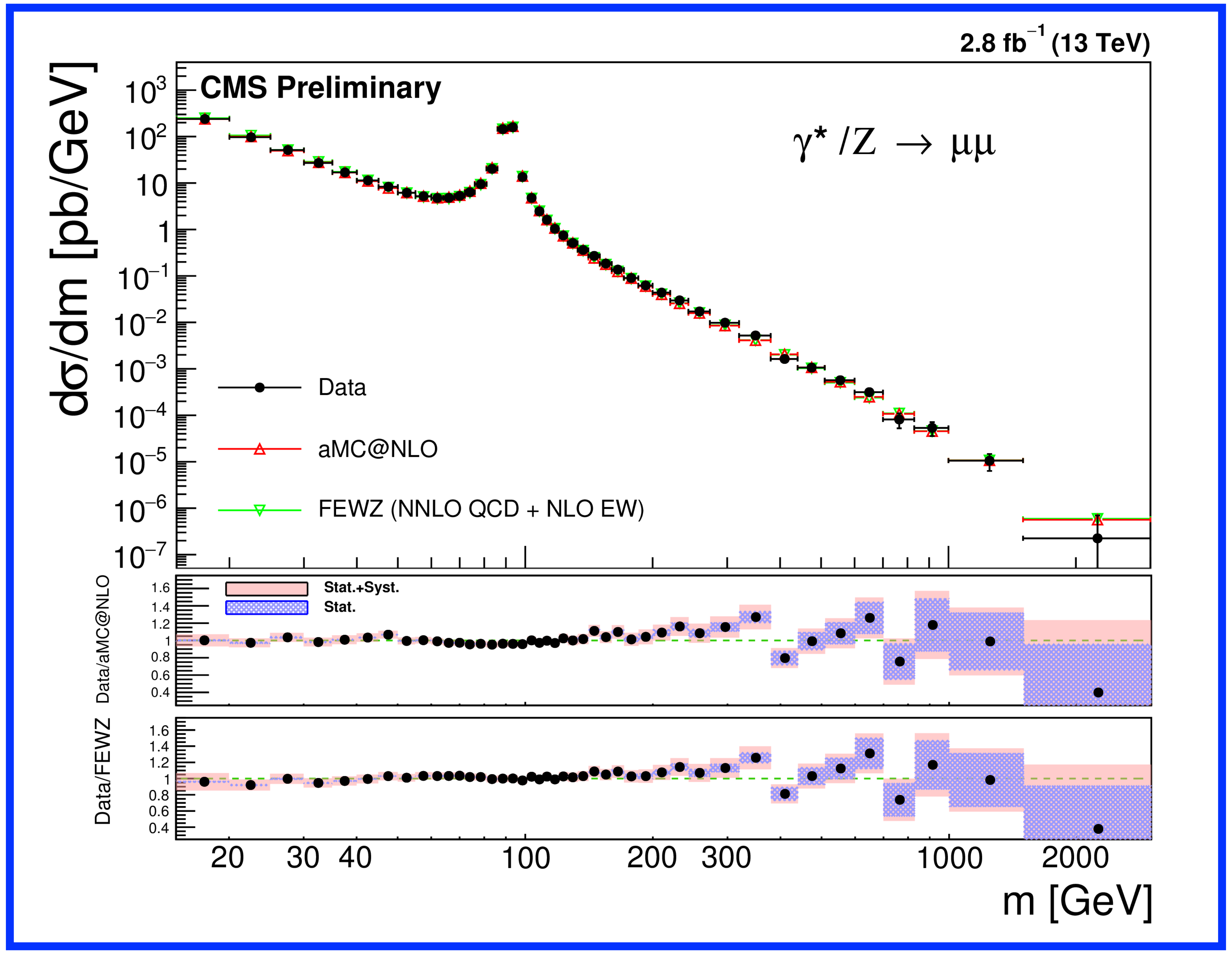
$$\boxed{\sigma \sim |\mathcal{M}_{SM}|^2 + \frac{1}{\Lambda^2} 2\mathrm{Re}\left[\mathcal{M}_6 \mathcal{M}_{SM}^*\right] + \frac{1}{\Lambda^4}\left\{|\mathcal{M}_6|^2 + 2\mathrm{Re}\left[\mathcal{M}_8 \mathcal{M}_{SM}^*\right]\right\}}$$

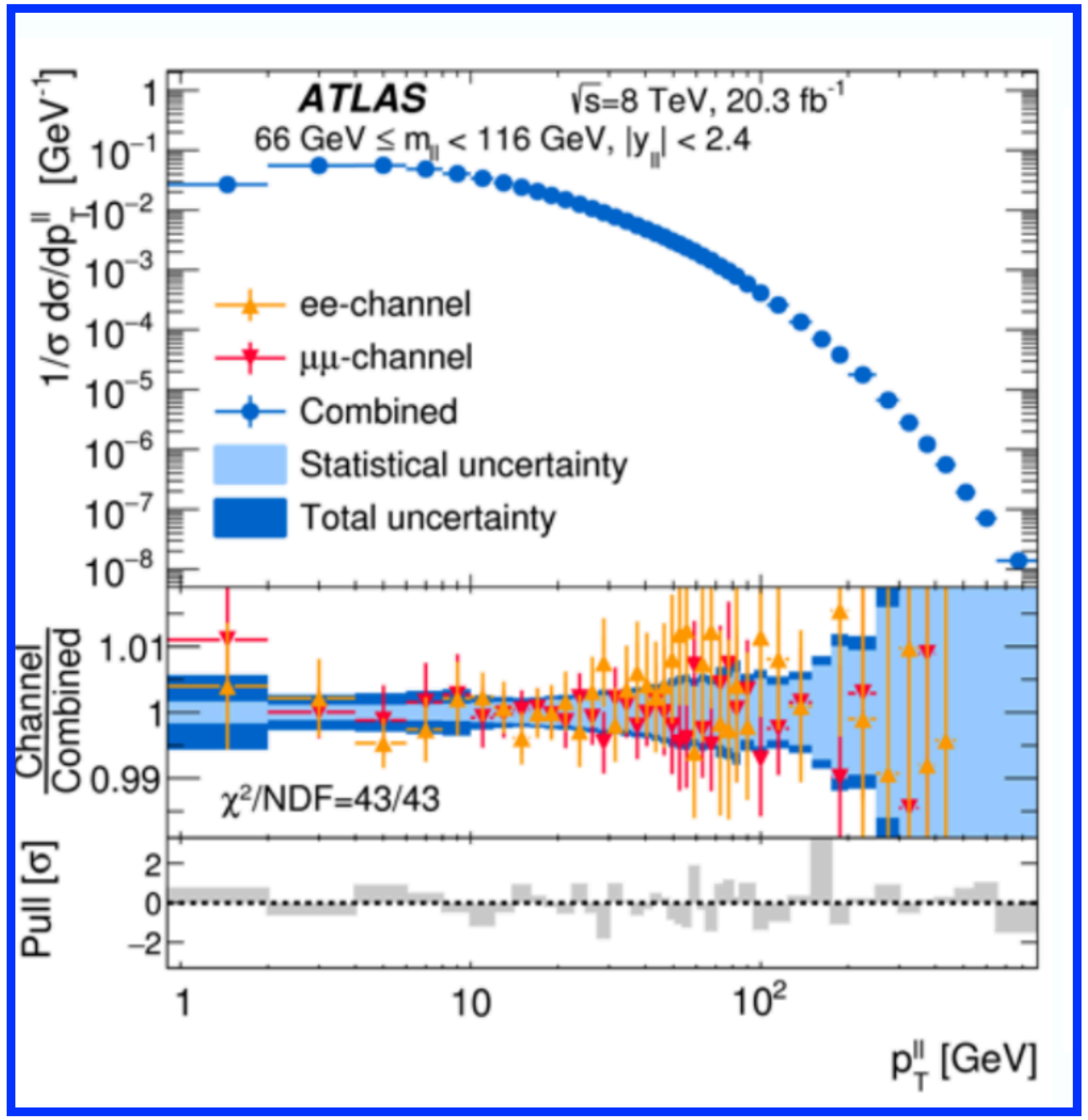
Leading SMEFT correction

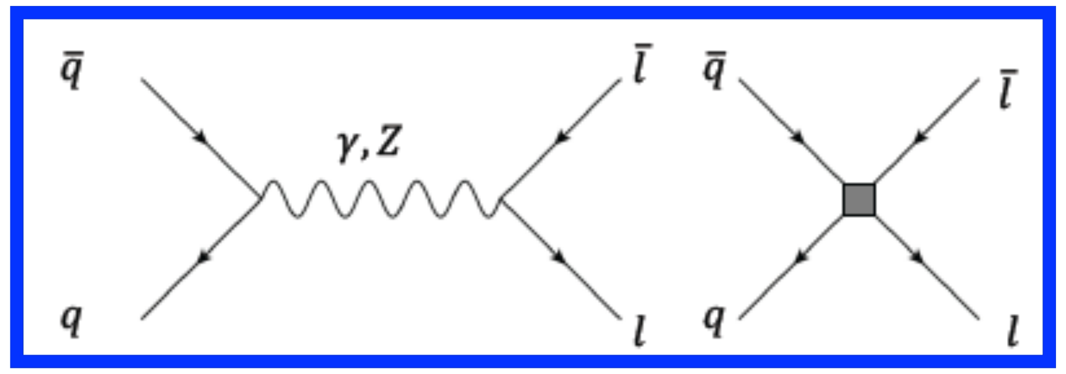
Sub-leading; neglected in many analyses; size of $|M_6|^2$ often used to estimate the impact of higher-dim operators

Probing SMEFT using Drell-Yan data

- We will focus on the semi-leptonic four fermion sector of the SMEFT. The natural place to search for them at the LHC is through the Drell-Yan process at high energies.







Take advantage of the high precision data to search for subtle deviations from the SM

Questions for SMEFT analysis

- Are dimension-8 and higher effects important at LHC? Do they give qualitatively different effects than dim-6?

We'll discuss an angular momentum argument that allows a clean probe of dim-8 using LHC Drell-Yan data

We'll show the importance of dim-8 corrections in a global fit of the 13 TeV Drell-Yan data

- Can we discriminate between UV completions of the SMEFT?

We'll show how Drell-Yan transverse momentum measurements can help with this

Basis for Drell-Yan studies at the LHC

- The relevant four-fermion operators for our analysis consist of seven dim-6 and 14 dim-8 operators.

Dimension 6		Dimension 8	
$\mathcal{O}_{lq}^{(1)}$	$(\bar{l}\gamma^{\mu}l)\,(\bar{q}\gamma_{\mu}q)$	$\mathcal{O}_{l^2q^2D^2}^{(1)}$	$D^{\nu}\,(\bar{l}\gamma^{\mu}l)\,D_{\nu}\,(\bar{q}\gamma_{\mu}q)$
$\mathcal{O}_{lq}^{(3)}$	$(\bar{l}\gamma^{\mu}\tau^{i}l)\,(\bar{q}\gamma_{\mu}\tau^{i}q)$	$\mathcal{O}_{l^2q^2D^2}^{(3)}$	$D^{\nu}\,(\bar{l}\gamma^{\mu}\tau^{i}l)\,D_{\nu}\,(\bar{q}\gamma_{\mu}\tau^{i}q)$
$\mathcal{O}_{eu}$	$(\bar{e}\gamma^{\mu}e)\,(\bar{u}\gamma_{\mu}u)$	$\mathcal{O}_{e^2u^2D^2}^{(1)}$	$D^{\nu}\,(\bar{e}\gamma^{\mu}e)\,D_{\nu}\,(\bar{u}\gamma_{\mu}u)$
$\mathcal{O}_{ed}$	$(\bar{e}\gamma^{\mu}e)\,(\bar{d}\gamma_{\mu}d)$	$\mathcal{O}_{e^2d^2D^2}^{(1)}$	$D^{\nu}\,(\bar{e}\gamma^{\mu}e)\,D_{\nu}\,(\bar{d}\gamma_{\mu}d)$
$\mathcal{O}_{lu}$	$(\bar{l}\gamma^{\mu}l)\,(\bar{u}\gamma_{\mu}u)$	$\mathcal{O}_{l^2u^2D^2}^{(1)}$	$D^{\nu}\,(\bar{l}\gamma^{\mu}l)\,D_{\nu}\,(\bar{u}\gamma_{\mu}u)$
$\mathcal{O}_{ld}$	$(\bar{l}\gamma^{\mu}l)\,(\bar{d}\gamma_{\mu}d)$	$\mathcal{O}_{l^2d^2D^2}^{(1)}$	$D^{\nu}\,(\bar{l}\gamma^{\mu}l)\,D_{\nu}\,(\bar{d}\gamma_{\mu}d)$
$\mathcal{O}_{qe}$	$(\bar{q}\gamma^{\mu}q)\,(\bar{e}\gamma_{\mu}e)$	$\mathcal{O}_{q^2e^2D^2}^{(1)}$	$D^{\nu}\,(\bar{q}\gamma^{\mu}q)\,D_{\nu}\,(\bar{e}\gamma_{\mu}e)$

Dimension 8

$$
\begin{aligned}
\mathcal{O}_{8,ed\partial 2} &= (\bar{e}\gamma_{\mu}\overleftrightarrow{D}_{\nu}e)(\bar{d}\gamma^{\mu}\overleftrightarrow{D}^{\nu}d),\\
\mathcal{O}_{8,eu\partial 2} &= (\bar{e}\gamma_{\mu}\overleftrightarrow{D}_{\nu}e)(\bar{u}\gamma^{\mu}\overleftrightarrow{D}^{\nu}u),\\
\mathcal{O}_{8,ld\partial 2} &= (\bar{l}\gamma_{\mu}\overleftrightarrow{D}_{\nu}l)(\bar{d}\gamma^{\mu}\overleftrightarrow{D}^{\nu}d),\\
\mathcal{O}_{8,lu\partial 2} &= (\bar{l}\gamma_{\mu}\overleftrightarrow{D}_{\nu}l)(\bar{u}\gamma^{\mu}\overleftrightarrow{D}^{\nu}u),\\
\mathcal{O}_{8,qe\partial 2} &= (\bar{e}\gamma_{\mu}\overleftrightarrow{D}_{\nu}e)(\bar{q}\gamma^{\mu}\overleftrightarrow{D}^{\nu}q).\\
\mathcal{O}_{8,lq\partial 3} &= (\bar{l}\gamma_{\mu}\overleftrightarrow{D}_{\nu}l)(\bar{q}\gamma^{\mu}\overleftrightarrow{D}^{\nu}q),\\
\mathcal{O}_{8,lq\partial 4} &= (\bar{l}\tau^{I}\gamma_{\mu}\overleftrightarrow{D}_{\nu}l)(\bar{q}\tau^{I}\gamma^{\mu}\overleftrightarrow{D}^{\nu}q)
\end{aligned}
$$

Note q,l are left-handed doublets; e,u,d are right-handed singlets

Basis for Drell-Yan studies at the LHC

- The relevant four-fermion operators for our analysis consist of seven dim-6 and 14 dim-8 operators.

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

Dawson, Giardino (2019)

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

Other dim-6 ffV vertex operators contribute as well, these are better constrained by precision Z-pole data at LEP, SLC

Invariant mass and A_{FB} constraints

- We first consider existing invariant mass and forward-backward asymmetry data sets. There are several high-statistic data sets reaching large invariant masses with sensitivity to SMEFT effects.

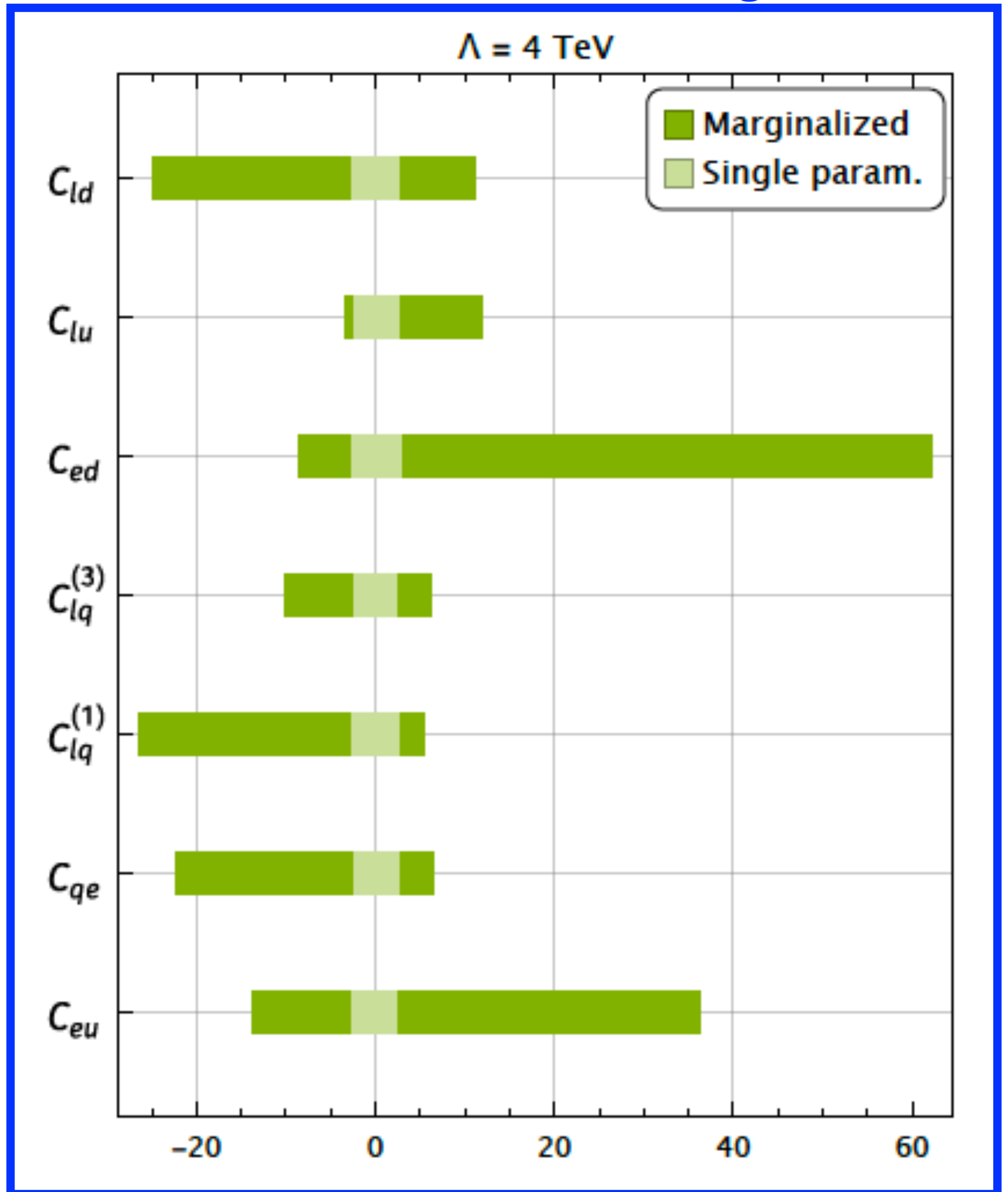
No.	Experiment	$\sqrt{s}$	Measurement	Luminosity	m_{ll}^{low}	Ref.
I	ATLAS	8 TeV	$d\sigma/dm$	20.3 fb^{-1}	116-1000 GeV	[24]
II	CMS	13 TeV	$d\sigma/dm$	137 fb^{-1} (ee) 140 fb^{-1} $(\mu\mu)$	200-2210 GeV (ee) 210-2290 GeV $(\mu\mu)$	[25]
III	CMS	8 TeV	A^*_{FB}	19.7 fb^{-1}	120-500 GeV	[26]
IV	CMS	13 TeV	A_{FB}	138 fb^{-1}	170-1000 GeV	[27]

Single-parameter vs. marginalized fits

- We begin with a fit to the linear dimension-6 basis which includes seven operators, and study the difference between single-parameter and marginalized fits.

RB, Huang, Petriello (2023)

Dimension 6	
$\mathcal{O}_{lq}^{(1)}$	$(\bar{l}\gamma^{\mu}l)(\bar{q}\gamma_{\mu}q)$
$\mathcal{O}_{lq}^{(3)}$	$(\bar{l}\gamma^{\mu}\tau^{i}l)(\bar{q}\gamma_{\mu}\tau^{i}q)$
$\mathcal{O}_{eu}$	$(\bar{e}\gamma^{\mu}e)(\bar{u}\gamma_{\mu}u)$
$\mathcal{O}_{ed}$	$(\bar{e}\gamma^{\mu}e)(\bar{d}\gamma_{\mu}d)$
$\mathcal{O}_{lu}$	$(\bar{l}\gamma^{\mu}l)(\bar{u}\gamma_{\mu}u)$
$\mathcal{O}_{ld}$	$(\bar{l}\gamma^{\mu}l)(\bar{d}\gamma_{\mu}d)$
$\mathcal{O}_{qe}$	$(\bar{q}\gamma^{\mu}q)(\bar{e}\gamma_{\mu}e)$

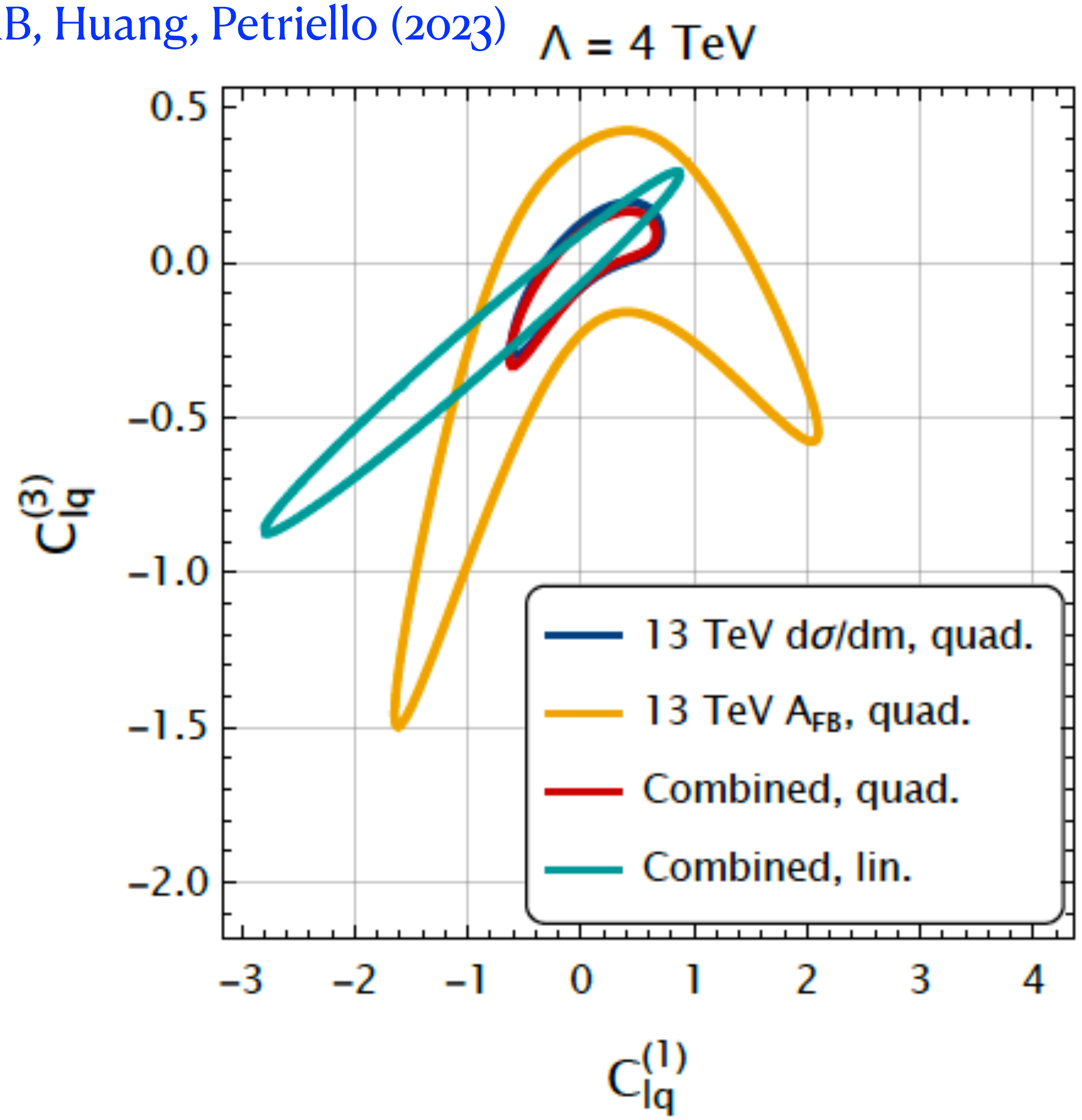


There is a significant difference between the single-parameter and marginalized fits, indicating the need to turn all Wilson coefficients on simultaneously

Linear vs. quadratic fits

- We now consider the difference between expanding the dim-6 SMEFT to the linear and quadratic orders. As an illustrative example we turn on two coefficients only.

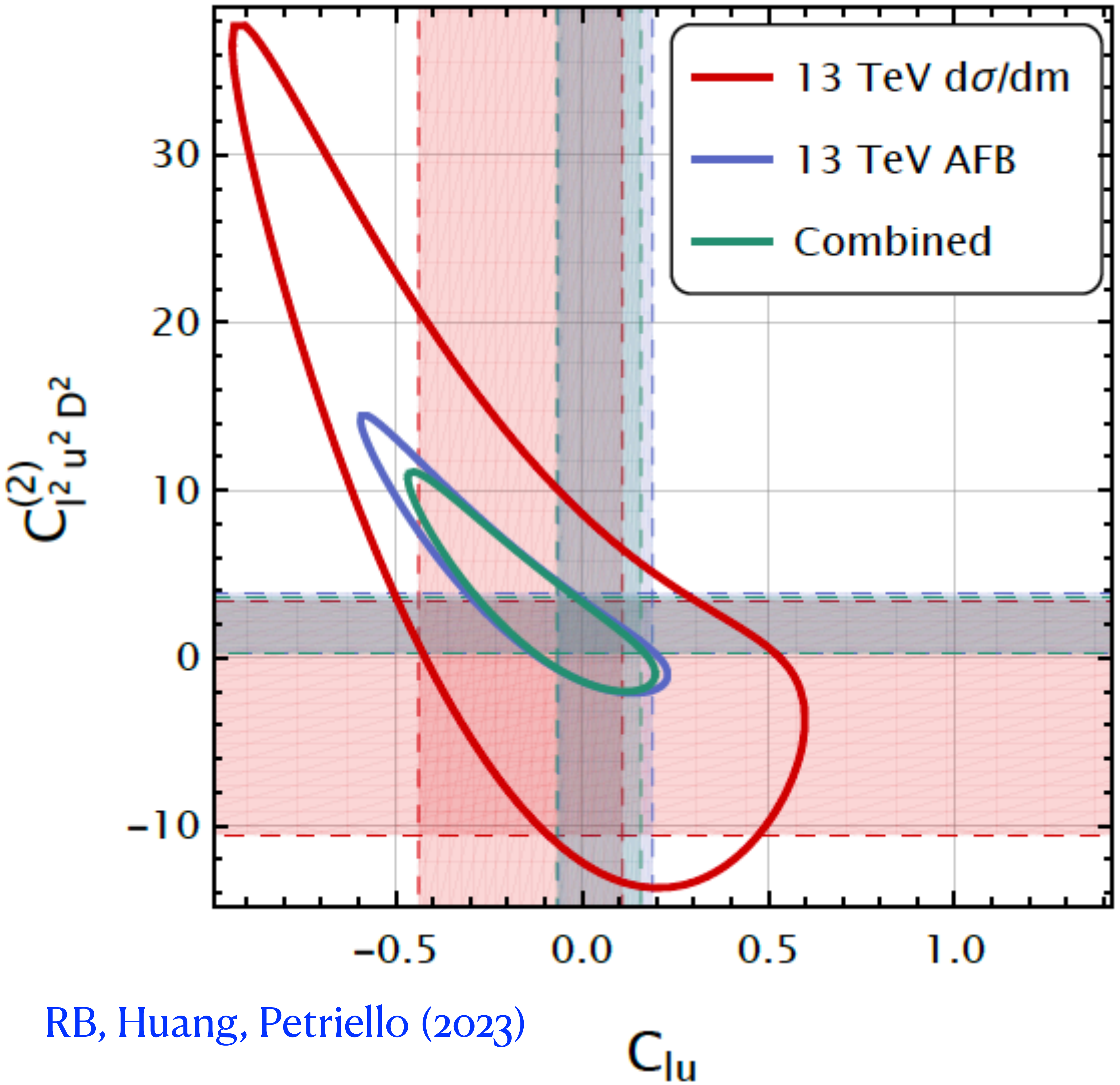
RB, Huang, Petriello (2023)



- The A_{FB} data set (boomerang shape) alone exhibits significant degeneracies; need to fit to multiple data sets!
- Linear (cyan) and quadratic (red) combined fits differ significantly; important to include higher-order terms in the SMEFT expansion!
- Note that A_{FB} data doesn't improve the combined fit; the power comes from the invariant mass data

Dimension-8 effects

- If quadratic dimension-6 terms have an effect, dimension-8 terms should as well. Test this with an example.



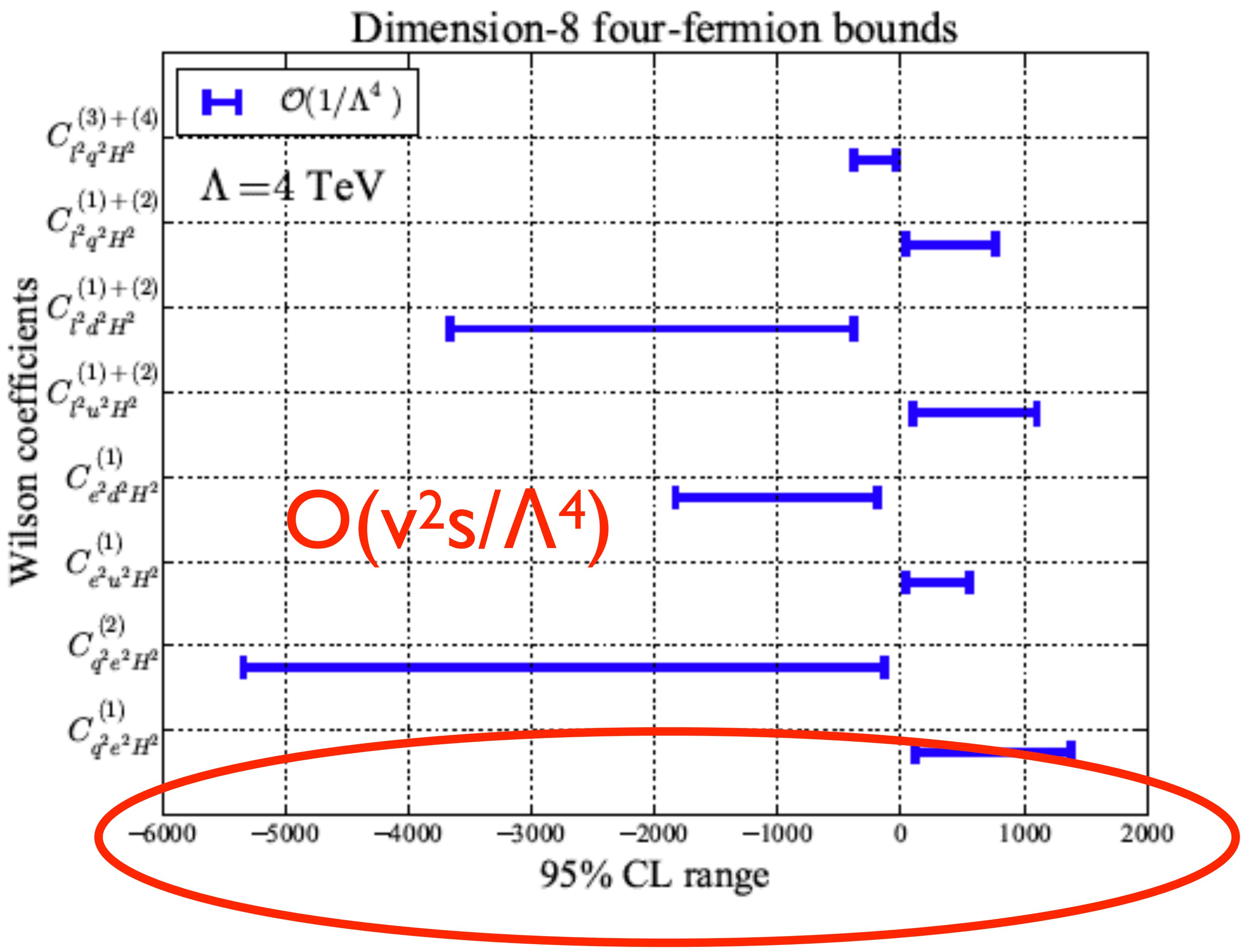
- Turn on left-handed lepton coupling to right handed up quark at dim-6 and dim-8 as an example.
- Shaded regions are the one-parameter constraints at 95% CL. Ellipses are when both parameters are turned on.
- Significant shifts! For example, the allowed region of C_{lu} extends to -0.5 with dim-8 turned on; in the single parameter fit it extends only to -0.1.
- Note this time constraints primarily from A_{FB}!

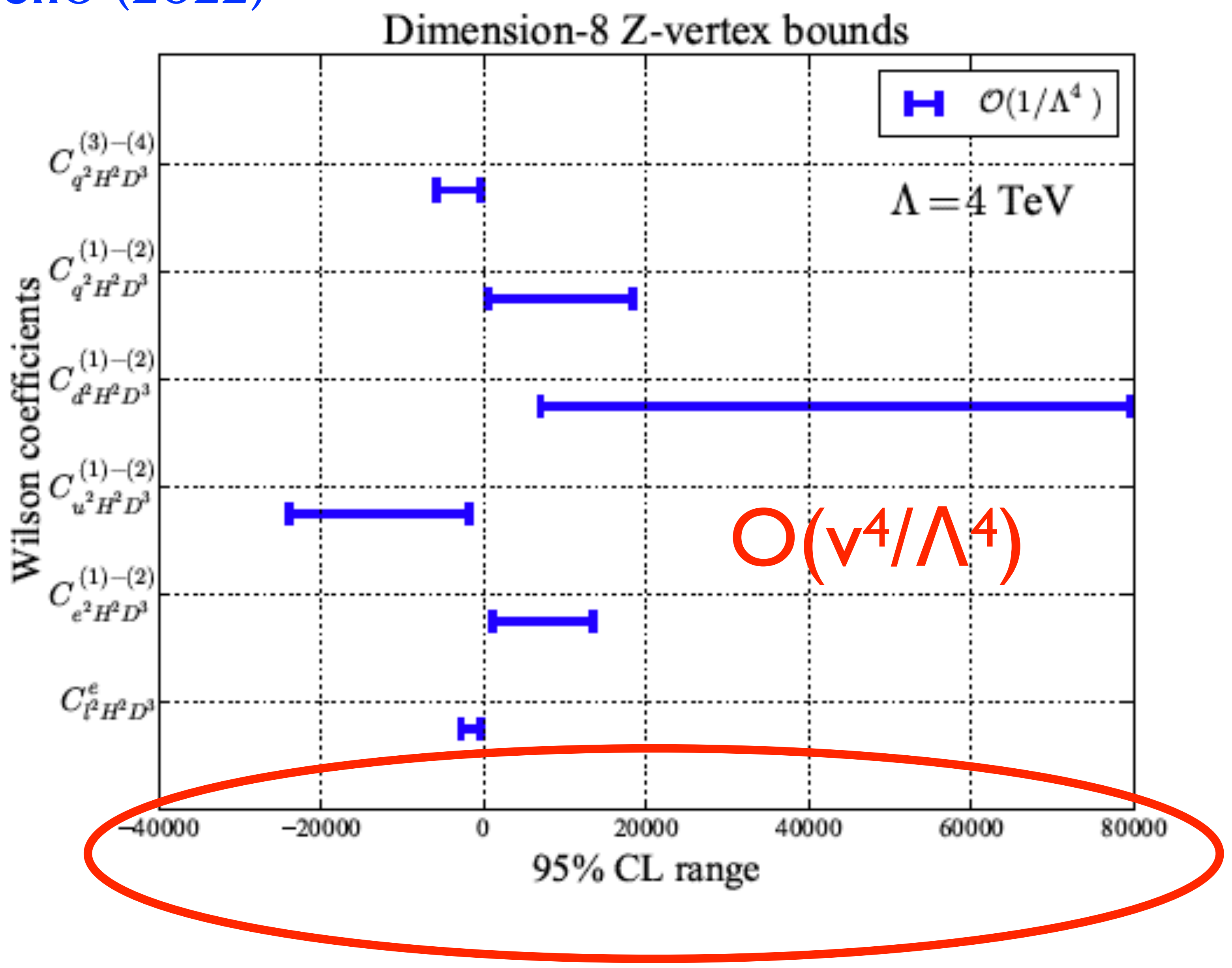
RB, Huang, Petriello (2023)

Impact on analysis

- Important to consider all data sets in analyses. In some of the examples invariant mass gave the strongest constraints; in others A_{FB} did.
- All terms that go as $1/\Lambda^4$ in the SMEFT expansion, including dim-6^2 and dim-8, have an important impact on the analysis.
- The good news: only a limited subset of dim-8 operators that grow as s^2/Λ^4 are relevant for LHC studies.

RB, Mereghetti, Petriello (2022)

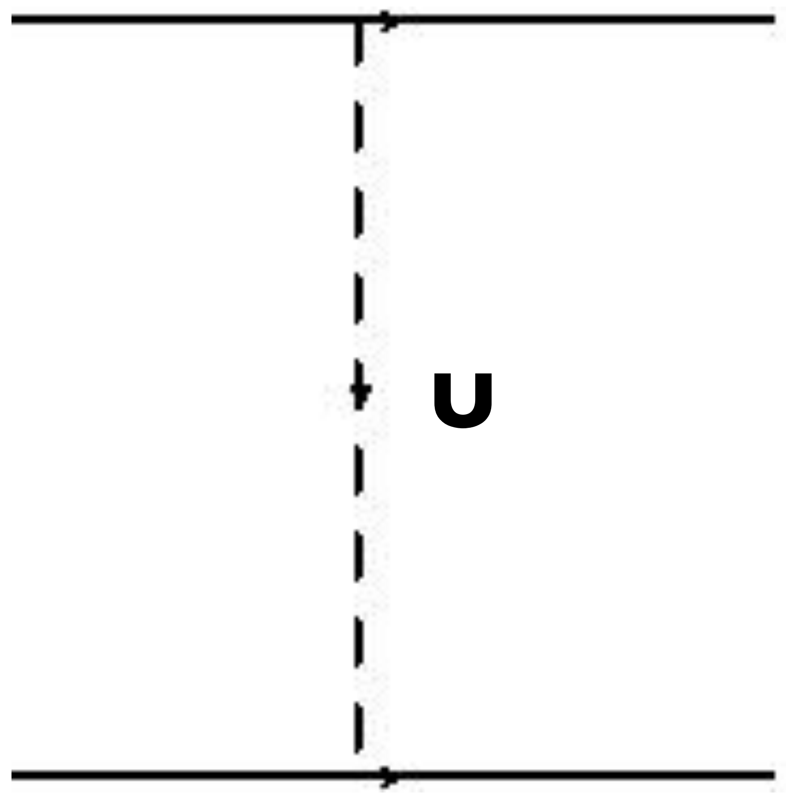




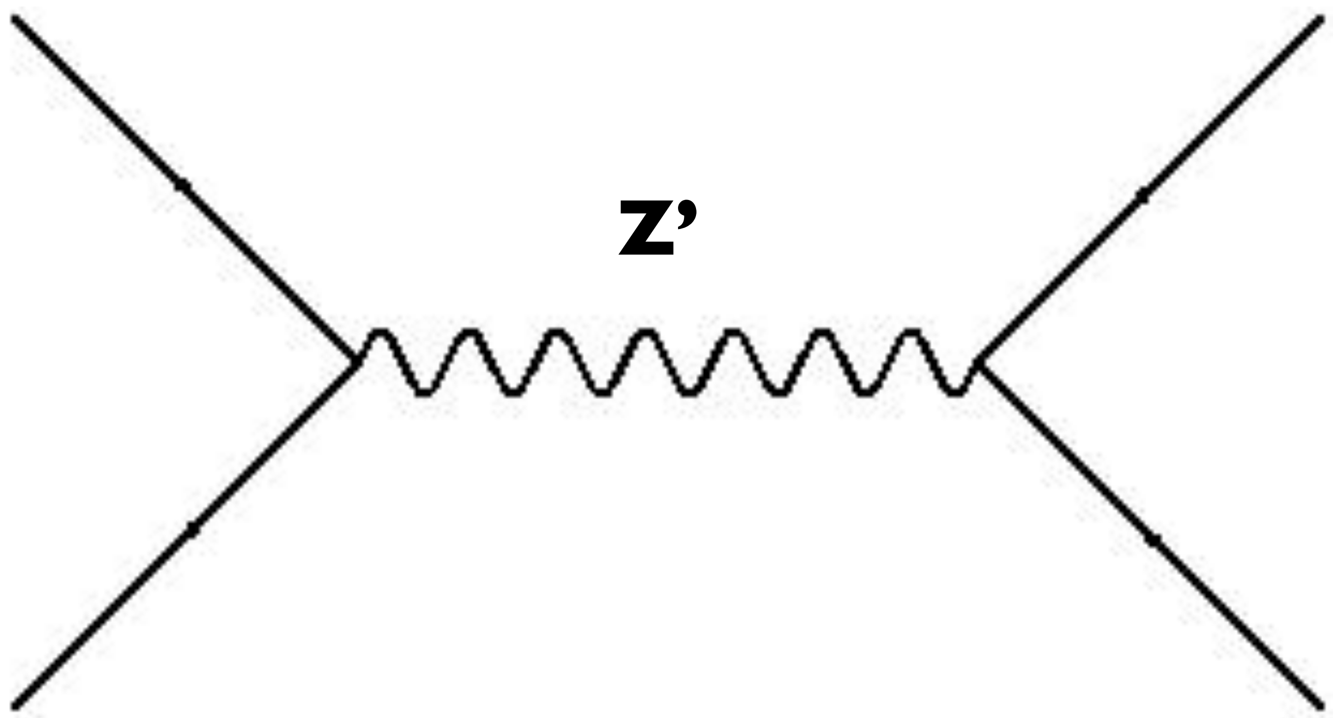
Model discrimination

- The analysis shown so far indicates that both dim-6 and dim-8 are potentially observable with LHC DY data. Does the ability to measure multiple coefficients allow us to distinguish between UV completions if we can't produce new physics directly?

Vector leptoquark



Z' boson



Two examples of UV particles that modify the DY process

Model discrimination

- The analysis shown so far indicates that both dim-6 and dim-8 are potentially observable with LHC DY data. Does the ability to measure multiple coefficients allow us to distinguish between UV completions if we can't produce new physics directly?

CP-even	
$\mathcal{O}^{(1)}_{l^2q^2\tilde{G}}$	$(\bar{l}\gamma^{\mu}l)(\bar{q}\gamma^{\nu}T^{A}q)\tilde{G}^{A}_{\mu\nu}$
$\mathcal{O}^{(2)}_{l^2q^2\tilde{G}}$	$(\bar{l}\tau^{I}\gamma^{\mu}l)(\bar{q}\tau^{I}\gamma^{\nu}T^{A}q)\tilde{G}^{A}_{\mu\nu}$
$\mathcal{O}_{e^2u^2\tilde{G}}$	$(\bar{e}\gamma^{\mu}e)(\bar{u}\gamma^{\nu}T^{A}u)\tilde{G}^{A}_{\mu\nu}$
$\mathcal{O}_{e^2d^2\tilde{G}}$	$(\bar{e}\gamma^{\mu}e)(\bar{d}\gamma^{\nu}T^{A}d)\tilde{G}^{A}_{\mu\nu}$
$\mathcal{O}_{l^2u^2\tilde{G}}$	$(\bar{l}\gamma^{\mu}l)(\bar{u}\gamma^{\nu}T^{A}u)\tilde{G}^{A}_{\mu\nu}$
$\mathcal{O}_{l^2d^2\tilde{G}}$	$(\bar{l}\gamma^{\mu}l)(\bar{d}\gamma^{\nu}T^{A}d)\tilde{G}^{A}_{\mu\nu}$
$\mathcal{O}_{q^2e^2\tilde{G}}$	$(\bar{e}\gamma^{\mu}e)(\bar{q}\gamma^{\nu}T^{A}q)\tilde{G}^{A}_{\mu\nu}$

To discuss these we need to extend the operator basis to include operators with gluon emission. These generate a correction to the DY transverse momentum distribution.

Model discrimination

- The analysis shown so far indicates that both dim-6 and dim-8 are potentially observable with LHC DY data. Does the ability to measure multiple coefficients allow us to distinguish between UV completions if we can't produce new physics directly?

Match these to the SMEFT:

Z' boson

$$\frac{C_{eu}}{\Lambda^2} = -\frac{g_{Z'}^2 g_R^u g_R^e}{M_{Z'}^2},$$

$$\frac{C^{(1)}_{e^2u^2D^2}}{\Lambda^4} = -\frac{g_{Z'}^2 g_R^u g_R^e}{M_{Z'}^4}.$$

$$\frac{C_{e^2u^2\tilde{G}}}{\Lambda^4} = 0.$$

Vector leptoquark

$$\frac{C_{eu}}{\Lambda^2} = \frac{h_U^2}{M_U^2},$$

$$\frac{C^{(1)}_{e^2u^2D^2}}{\Lambda^4} = -\frac{h_U^2}{4M_U^4}.$$

$$\frac{C_{e^2u^2\tilde{G}}}{\Lambda^4} = -\frac{h_U^2 g_s(1-\kappa_U)}{2M_U^4}$$

Model discrimination

- The analysis shown so far indicates that both dim-6 and dim-8 are potentially observable with LHC DY data. Does the ability to measure multiple coefficients allow us to distinguish between UV completions if we can't produce new physics directly?

Z' boson

Vector leptoquark

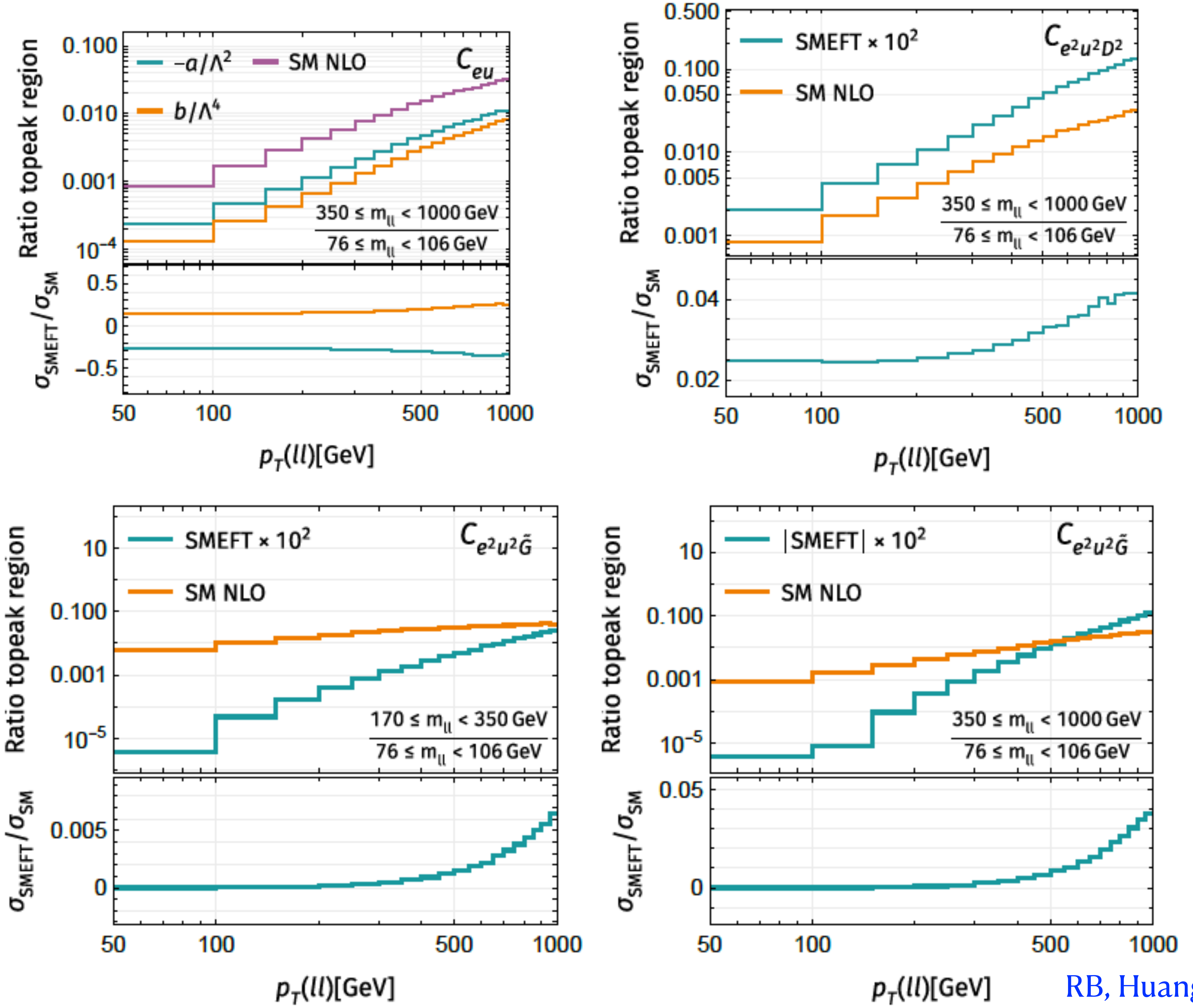
Determination of this operator through measurements of the transverse momentum distribution can distinguish between these two different particles

$$\frac{C_{e^2u^2\tilde{G}}}{\Lambda^4} = 0.$$

$$\frac{C_{e^2u^2\tilde{G}}}{\Lambda^4} = -\frac{h_U^2 g_s(1-\kappa_U)}{2M_U^4}$$

pT distribution

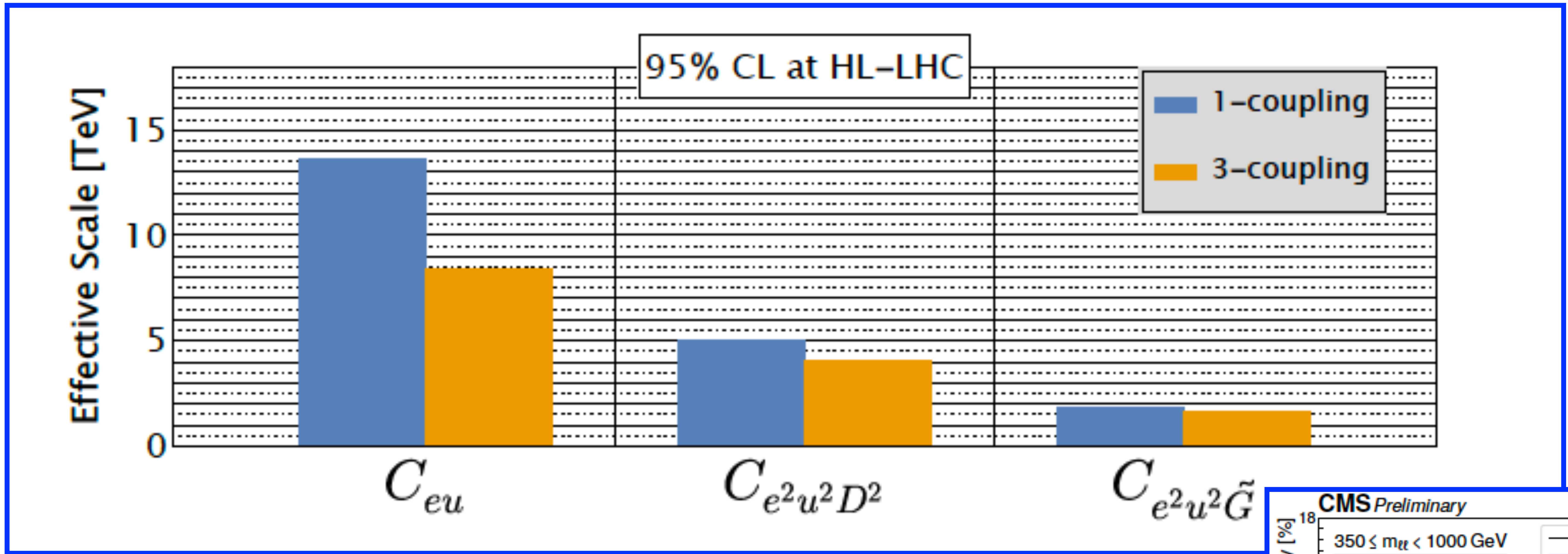
- These operators generate very different p_T distributions.



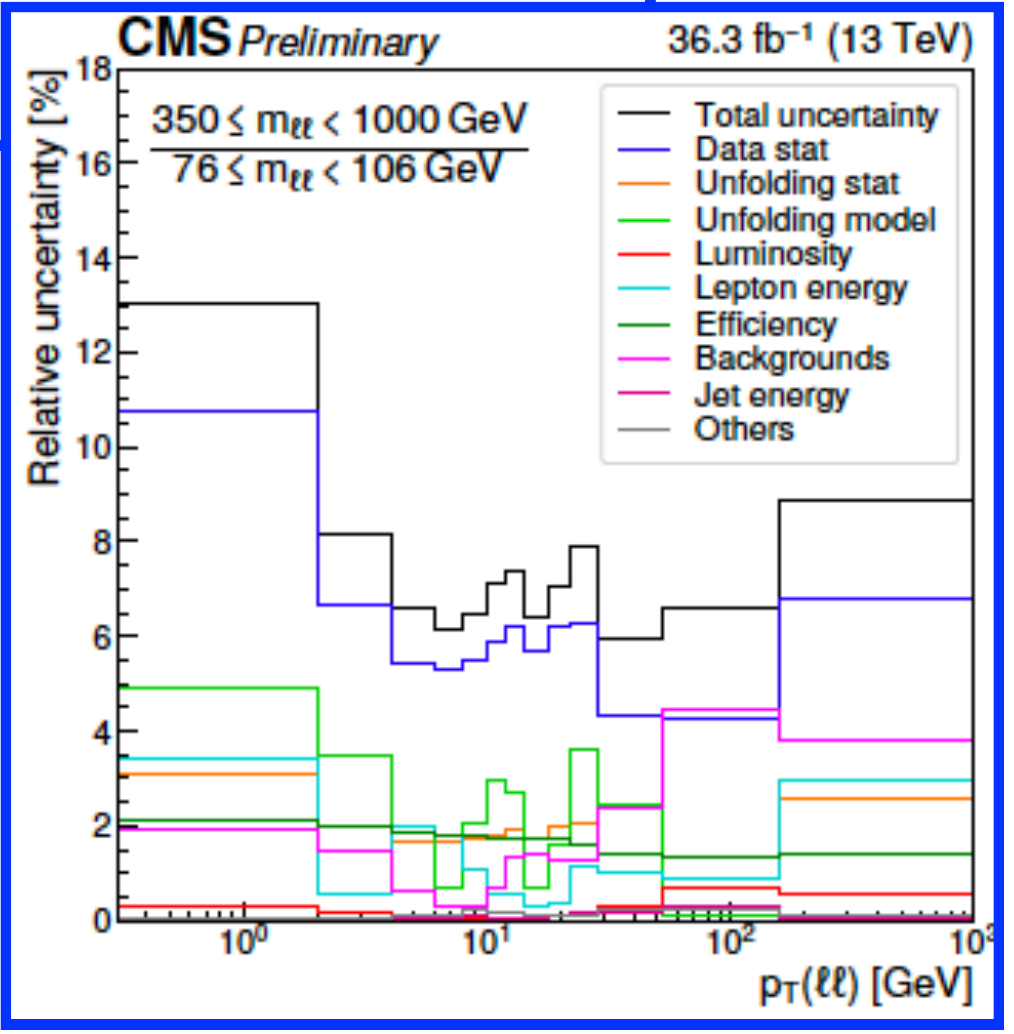
RB, Huang, Petriello, 2022

HL-LHC probes

- This is not a measurement that can be done with the current data, but it becomes possible at a high-luminosity LHC.

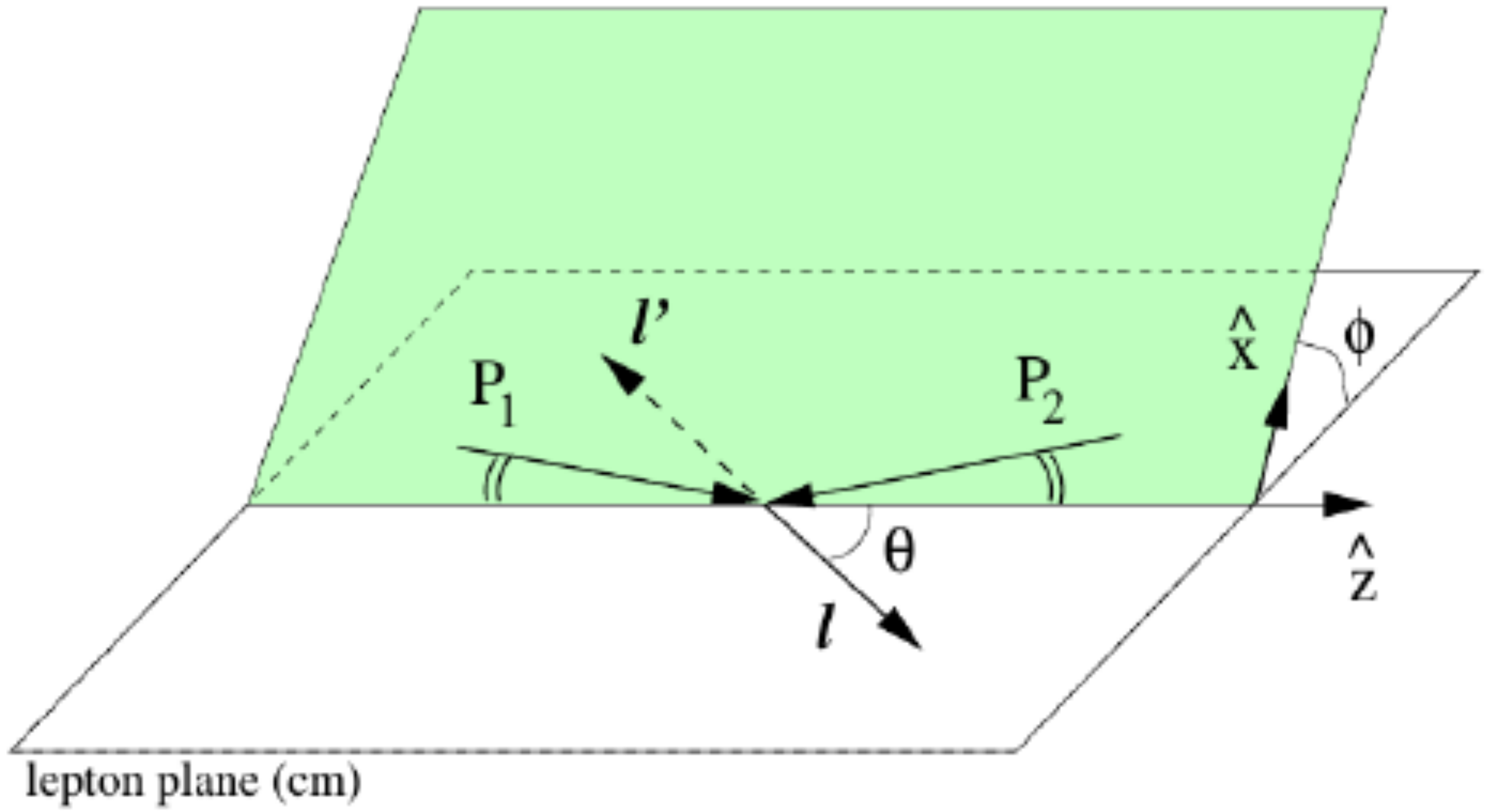


Needed: measurement of high transverse momentum above the Z-peak. Will become interesting with more data!



Angular structure of DY

- Let's consider other observables. Drell-Yan has a rich angular structure sensitive to many subtleties of theory predictions. Copious high-mass data, precise theory make it a target for probing the importance of SMEFT effects.

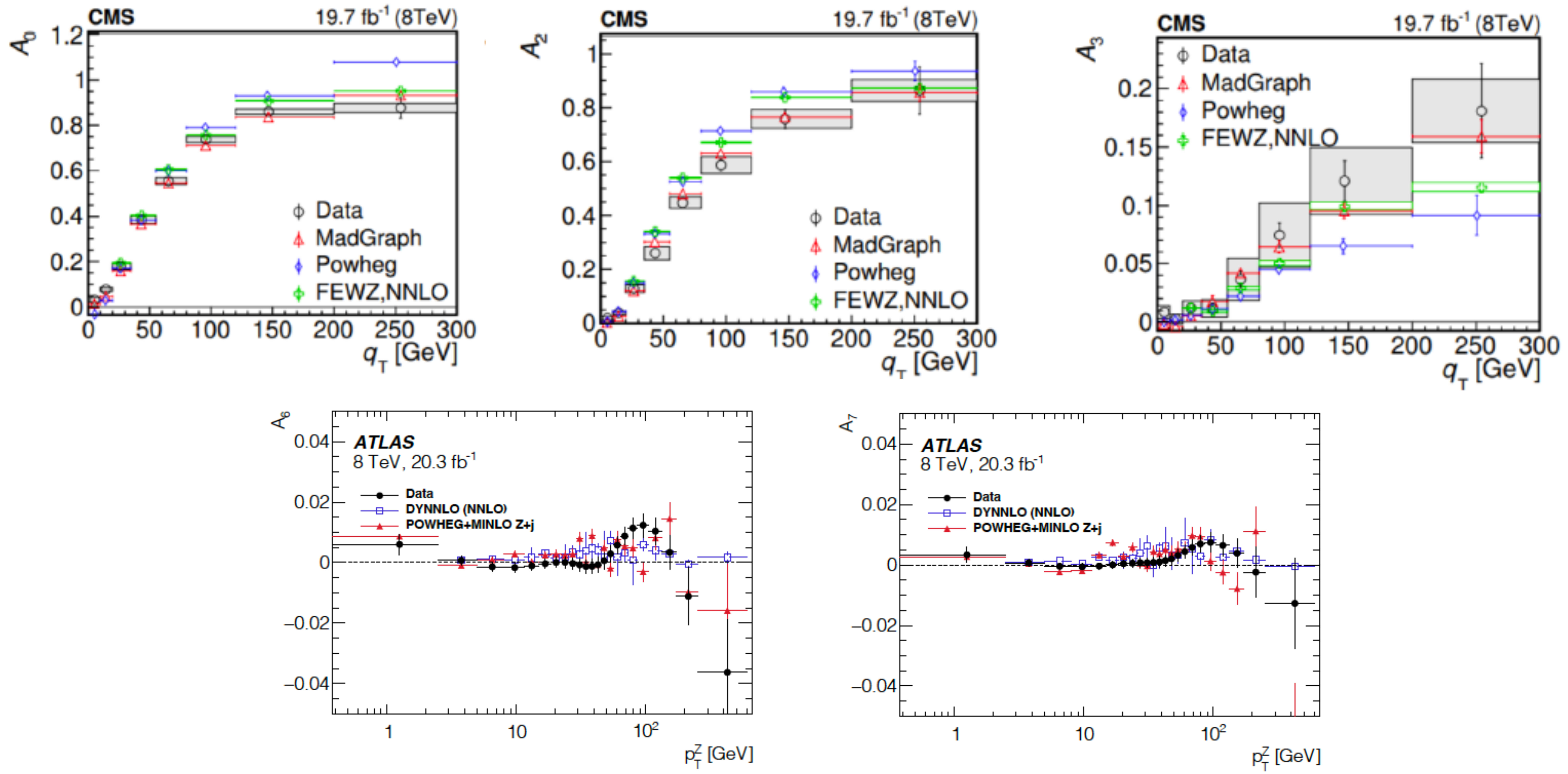


Usually described by:

$$\boxed{\begin{aligned}\frac{d\sigma}{dm_{ll}^2\,dy\,d\Omega_l} = \frac{3}{16\pi}\frac{d\sigma}{dm_{ll}^2\,dy}\Big\{&(1+c_\theta^2)+\frac{A_0}{2}(1-3c_\theta^2)\\ &+A_1 s_{2\theta}c_\phi+\frac{A_2}{2}s_\theta^2 c_{2\phi}+A_3 s_\theta c_\phi+A_4 c_\theta\\ &+A_5 s_\theta^2 s_{2\phi}+A_6 s_{2\theta}s_\phi+A_7 s_\theta s_\phi\Big\}\end{aligned}}$$

Spherical harmonics expansion through l=2
due to spin-1 nature of Z-boson

Angular structure of DY



Can measure the full spectrum of coefficients at the LHC

DY structure at dim-6

- Let's study the dimension-6 operators affecting DY:

Category: **Example**

$$\psi^2\phi^2 D : (\phi^\dagger i\overleftrightarrow{D}_\mu\phi)(\bar{e}\gamma^\mu e)$$
$$\psi^4 : (\bar{e}\gamma^\mu e)(\bar{u}\gamma^\mu u)$$

Shift relative importance of left, right-handed couplings, but same angular dependence as in SM

$$\psi^2 X\phi : (\bar{l}\sigma^{\mu\nu} e)\tau^I \phi W^I_{\mu\nu}$$
$$\psi^4 : (\bar{l}^i e)(\bar{d}q^i)$$

Different chiral structure than in SM; can lead to large deviations from SM predictions but qualitatively no new structure

Detailed studies in Alioli, Dekens, Girard, Mereghetti (2018); Alioli, RB, Mereghetti, Petriello (2020)

DY structure at dim-8

- Let's study the dimension-8 operators affecting DY:

$$\psi^2\phi^4 D : (\bar{q}\gamma^\mu q)(\phi^\dagger i\overleftrightarrow{D}_\mu\phi)(\phi^\dagger\phi)$$

$$\psi^2\phi^2 D^3 : (\bar{q}i\gamma^\mu D^\nu q)(D^2_{\mu\nu}\phi^\dagger\phi)$$

$$\psi^4\phi^2 : (\bar{e}\gamma^\mu e)(\bar{u}\gamma_\mu u)(\phi^\dagger\phi)$$

These only shift the couplings already present at dim-4 and dim-6

$\psi^4 D^2$:

$$\mathcal{O}_{8,lq\partial 1} = (\bar{l}\gamma_\mu l)\partial^2(\bar{q}\gamma^\mu q),$$
$$\mathcal{O}_{8,lq\partial 2} = (\bar{l}\tau^I\gamma_\mu l)\partial^2(\bar{q}\tau^I\gamma^\mu q),$$
$$\mathcal{O}_{8,lq\partial 3} = (\bar{l}\gamma_\mu \overleftrightarrow{D}_\nu l)(\bar{q}\gamma^\mu \overleftrightarrow{D}^\nu q),$$
$$\mathcal{O}_{8,lq\partial 4} = (\bar{l}\tau^I\gamma_\mu \overleftrightarrow{D}_\nu l)(\bar{q}\tau^I\gamma^\mu \overleftrightarrow{D}^\nu q)$$

Energy-dependent shift of the existing dim-6 four-fermion corrections

DY structure at dim-8

- Let's study the dimension-8 operators affecting DY:

$$\psi^2\phi^4 D : (\bar{q}\gamma^\mu q)(\phi^\dagger i\overleftrightarrow{D}_\mu \phi)(\phi^\dagger\phi)$$
$$\psi^2\phi^2 D^3 : (\bar{q} i\gamma^\mu D^\nu q)(D^2_{\mu\nu}\phi^\dagger\phi)$$
$$\psi^4\phi^2 : (\bar{e}\gamma^\mu e)(\bar{u}\gamma_\mu u)(\phi^\dagger\phi)$$

These only shift the couplings already present at dim-4 and dim-6

$\psi^4 D^2$:

$$\begin{aligned}
\mathcal{O}_{8,lq\partial 1} &= (\bar{l}\gamma_\mu l)\partial^2(\bar{q}\gamma^\mu q),\\
\mathcal{O}_{8,lq\partial 2} &= (\bar{l}\tau^I\gamma_\mu l)\partial^2(\bar{q}\tau^I\gamma^\mu q),\\
\mathcal{O}_{8,lq\partial 3} &= (\bar{l}\gamma_\mu \overleftrightarrow{D}_\nu l)(\bar{q}\gamma^\mu \overleftrightarrow{D}^\nu q),\\
\mathcal{O}_{8,lq\partial 4} &= (\bar{l}\tau^I\gamma_\mu \overleftrightarrow{D}_\nu l)(\bar{q}\tau^I\gamma^\mu \overleftrightarrow{D}^\nu q)
\end{aligned}$$

$$\Delta|\mathcal{M}_{u\bar{u}}|^2 = -\frac{C_{8,lq\partial 3}}{\Lambda^4}\hat{c}_\theta(1+\hat{c}_\theta)^2\frac{\hat{s}^2}{6}\times \left[e^2 Q_u Q_e + \frac{g^2 g_L^u g_L^e \hat{s}}{c_W^2(\hat{s}-M_Z^2)}\right]$$

c_θ^3 dependence not accounted for in current analyses

operators definition from C. Murphy 2005

Angular momentum

- Two-derivative structure in the operators below leads to l=2 spherical harmonics; interference with the l=1 SM then populates l=3 spherical harmonics in the cross section
- Cannot get this structure from dim-6×dim-6; a unique signature of dim-8. Could arise from a UV model through integrating out spin-2 states or from t-channel exchanges.

Dimension 8

$$\mathcal{O}_{8,ed\partial 2} = (\bar{e}\gamma_\mu \overleftrightarrow{D}_\nu e)(\bar{d}\gamma^\mu \overleftrightarrow{D}^\nu d),$$
$$\mathcal{O}_{8,eu\partial 2} = (\bar{e}\gamma_\mu \overleftrightarrow{D}_\nu e)(\bar{u}\gamma^\mu \overleftrightarrow{D}^\nu u),$$
$$\mathcal{O}_{8,ld\partial 2} = (\bar{l}\gamma_\mu \overleftrightarrow{D}_\nu l)(\bar{d}\gamma^\mu \overleftrightarrow{D}^\nu d),$$
$$\mathcal{O}_{8,lu\partial 2} = (\bar{l}\gamma_\mu \overleftrightarrow{D}_\nu l)(\bar{u}\gamma^\mu \overleftrightarrow{D}^\nu u),$$
$$\mathcal{O}_{8,qe\partial 2} = (\bar{e}\gamma_\mu \overleftrightarrow{D}_\nu e)(\bar{q}\gamma^\mu \overleftrightarrow{D}^\nu q).$$
$$\mathcal{O}_{8,lq\partial 3} = (\bar{l}\gamma_\mu \overleftrightarrow{D}_\nu l)(\bar{q}\gamma^\mu \overleftrightarrow{D}^\nu q),$$
$$\mathcal{O}_{8,lq\partial 4} = (\bar{l}\tau^I\gamma_\mu \overleftrightarrow{D}_\nu l)(\bar{q}\tau^I\gamma^\mu \overleftrightarrow{D}^\nu q)$$

A new angular basis

- Not generated by QCD corrections at any order; arise first from next-to-leading logarithmic angular-dependent electroweak Sudakov corrections

$$\frac{\alpha}{\pi}\ln\frac{\hat{s}}{M_Z^2}\ln\left[f(c_\theta)\right] \longrightarrow$$

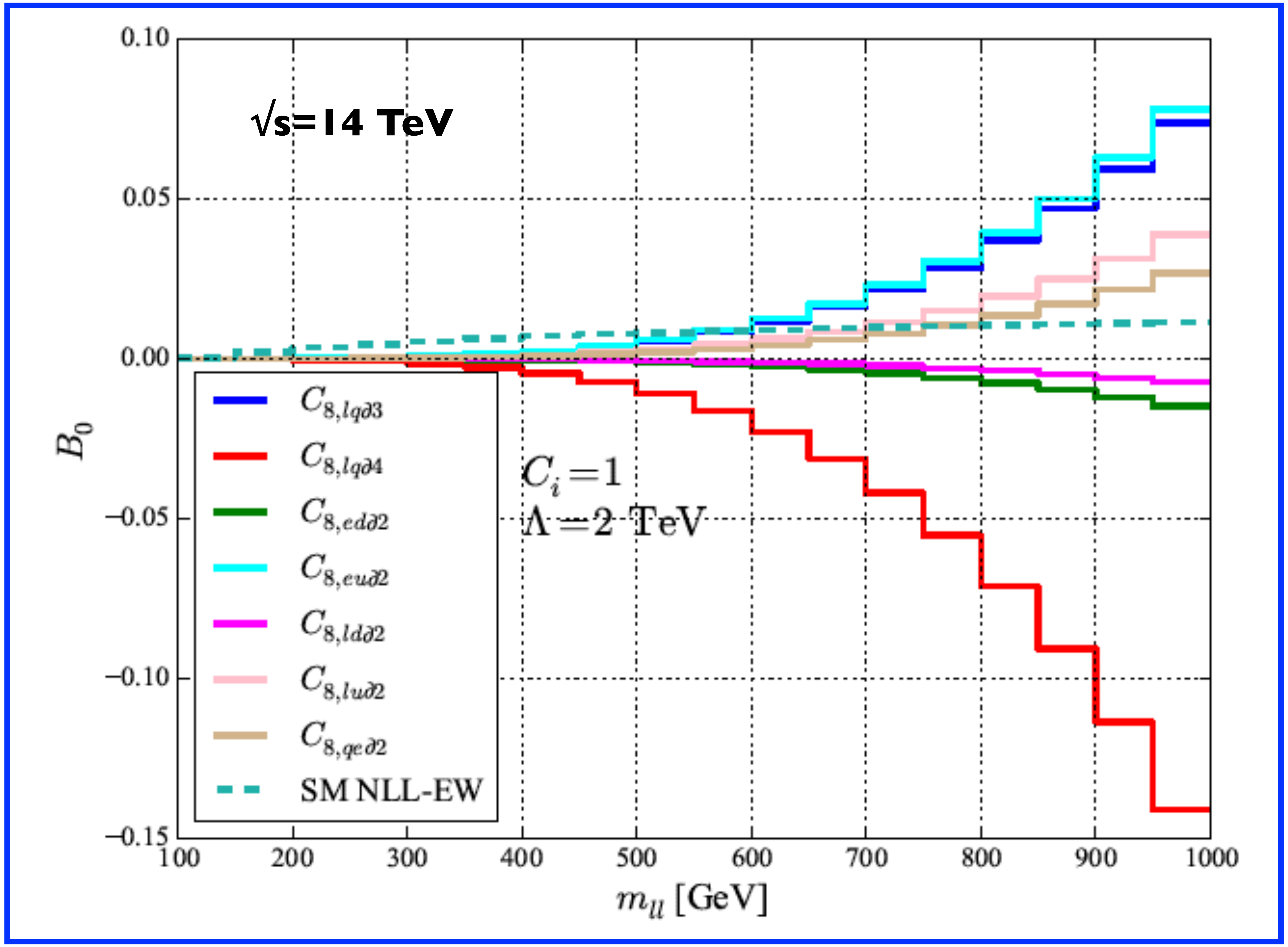
grow logarithmically with ŝ while the dim-8 corrections grow quadratically

$$\begin{aligned}\frac{d\sigma}{dm_{ll}^2 dy d\Omega_l} = \frac{3}{16\pi}\frac{d\sigma}{dm_{ll}^2 dy}\Bigg\{&(1+c_\theta^2)+\frac{A_0}{2}(1-3c_\theta^2)\\ &+A_1 s_{2\theta}c_\phi+\frac{A_2}{2}s_\theta^2 c_{2\phi}+A_3 s_\theta c_\phi+A_4 c_\theta\\ &+A_5 s_\theta^2 s_{2\phi}+A_6 s_{2\theta}s_\phi+A_7 s_\theta s_\phi\\ &+B_3^e s_\theta^3 c_\phi+B_3^o s_\theta^3 s_\phi+B_2^e s_\theta^2 c_\theta c_{2\phi}\\ &+B_2^o s_\theta^2 c_\theta s_{2\phi}+\frac{B_1^e}{2}s_\theta(5c_\theta^2-1)c_\phi\\ &+\frac{B_1^o}{2}s_\theta(5c_\theta^2-1)s_\phi+\frac{B_0}{2}(5c_\theta^3-3c_\theta)\Bigg\}\end{aligned}$$

Alioli, RB, Mereghetti, Petriello (2020)

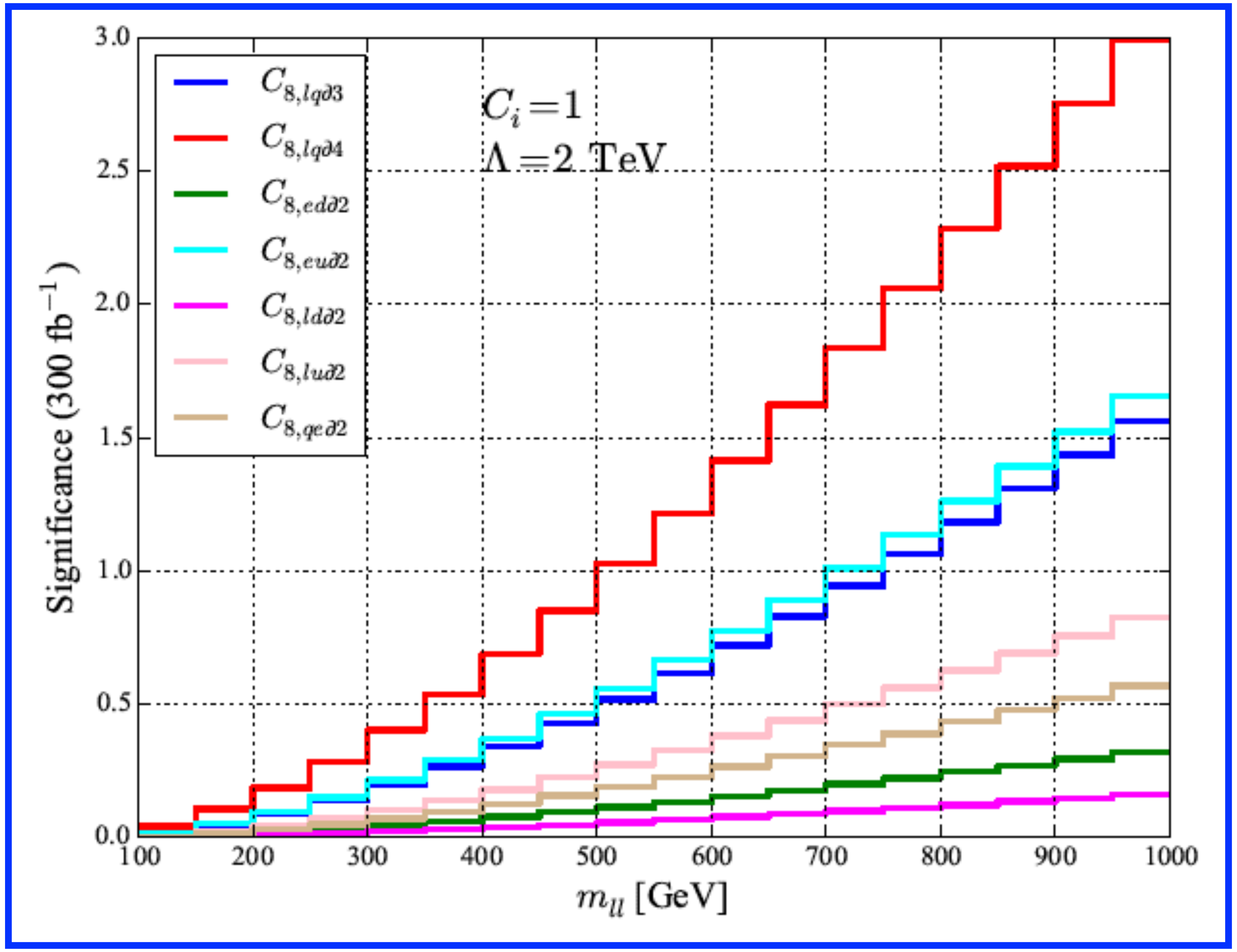
- The B_i account for the potential l=3 angular behavior at dim-8
- $B_{1\text{-}3}$ first generated at $O(\alpha_s/\Lambda^4)$
- Focus on B_0, which is generated at $O(1/\Lambda^4)$

LHC reach with angular analysis



- Turn on each operator separately, set UV scale Λ=2 TeV
- Several operators lead to significant deviations from SM predictions

LHC reach with angular analysis



- Single-bin significance reaches 3 for largest operator with 300 fb^{-1}
- Combining 600-1000 GeV bins leads to Sig>6 for largest operator, Sig>3.5 for next two
- HL-LHC increases these results by √10
- We have discovery potential at the LHC for some of these coefficients!

Promising "smoking gun" signature of dim-8 at the LHC!

Summary

- The wealth of high-precision DY data from the LHC unlocks a rich program of BSM probes within the SMEFT framework.
- Important to include both $1/\Lambda^2$ and a subset of $1/\Lambda^4$ terms in any analysis framework, and to include the full spectrum of data. Invariant mass and A_{FB} data probe different regions of parameter space.
- HL-LHC measurements of high invariant mass transverse momentum distributions will be very interesting probes of unexplored regions of SMEFT parameter space.
- Extensions of the DY angular analysis may reveal dim-8 effects in the SMEFT.