SMEFT probes with LHC Drell-Yan data

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Alioli, Boughezal, Mereghetti, FP PLB 809 (2020) 135703
Boughezal, Mereghetti, FP PRD 104 (2021) 9 095022
Boughezal, Huang, FP PRD 106 (2022) 3 036020
Boughezal, Huang, FP PRD 108 (2023) 7 076008

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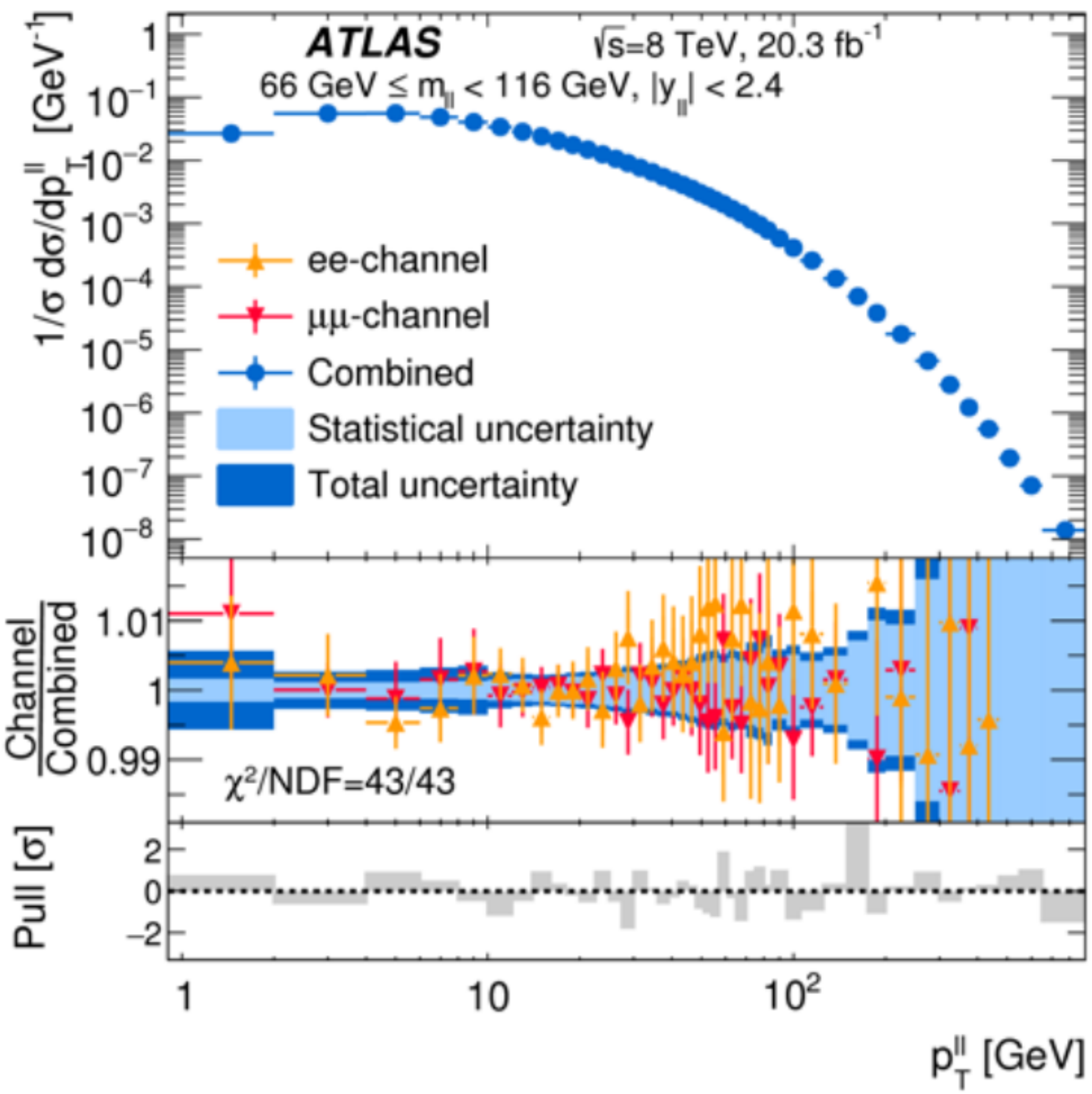
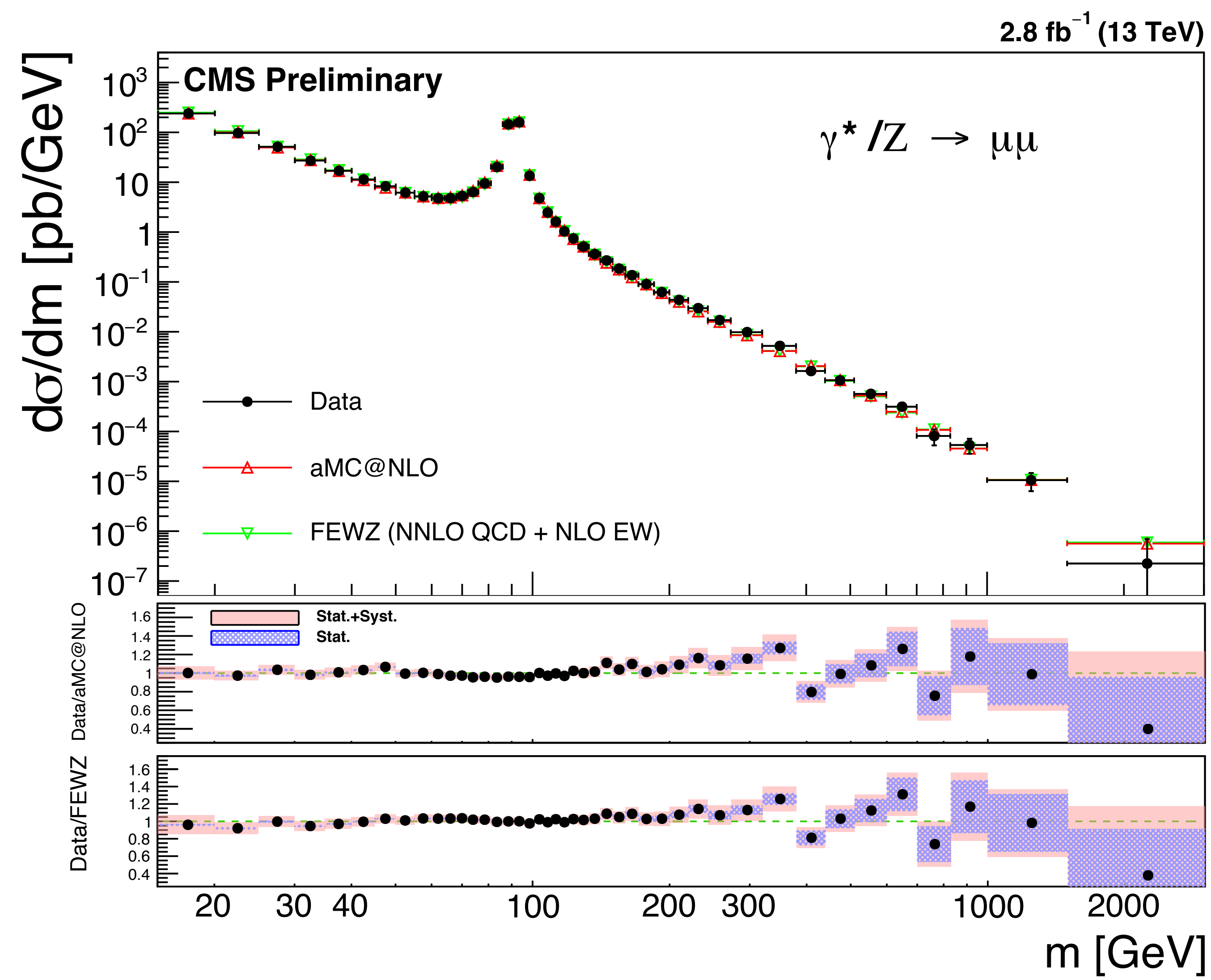
Outline

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

Status of the Drell-Yan process





- Experimental precision approaching percent-level for well-measured observables such as the transverse momentum and invariant mass distributions

Take advantage of this wealth of high-precision data to search for subtle deviations from SM predictions

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 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**

(odd dimensions violate lepton number, not considered here)

$\Lambda \gg M_{SM}$, 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 (2010); Brivio, Jiang, Trott (2017)
- Dim-8 basis has been derived Li, Ren, Shu, Xiao, Yu, Zheng (2005) Murphy (2005)

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 impact of higher-dim operators see A. Martin, W. Shepherd talks

Questions for SMEFT analyses

- 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

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 consisted of seven dim-6 and 14 dim-8 operators.

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

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

There are more dim-8 operators which will be discussed later; they are either too small or only relevant for particular analyses

Dim-6 vertex operators

- The relevant four-fermion operators consisted 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, but these are better constrained by precision Z-pole data at LEP, SLC

Invariant mass and A_{FB} constraints

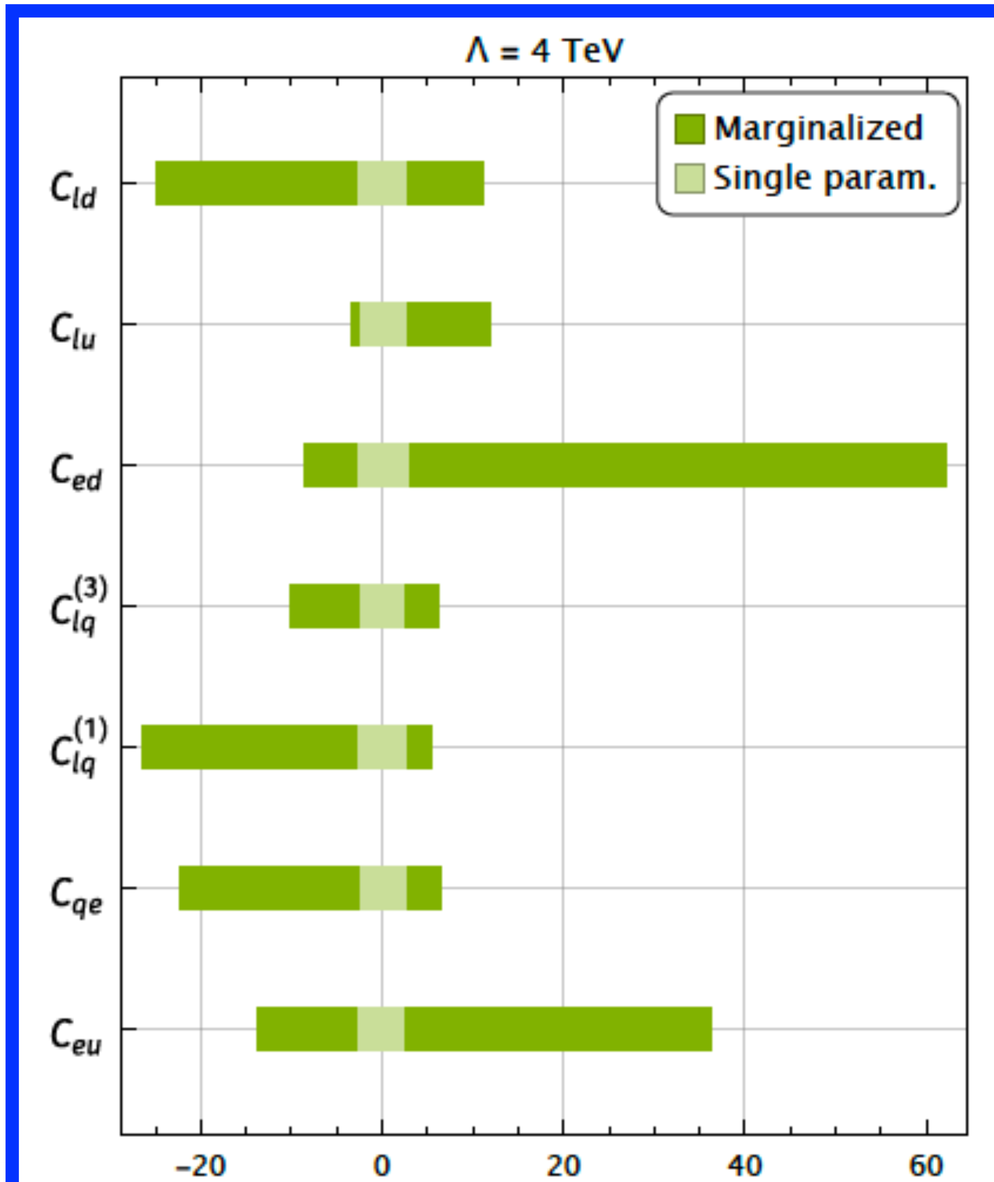
- We first consider existing invariant mass and forward-backward asymmetry data sets. There are several high-statistic data sets reaching large invariant masses with sensitivity to SMEFT effects.

No.	Experiment	$\sqrt{s}$	Measurement	Luminosity	m_{ll}^{low}	Ref.
I	ATLAS	8 TeV	$\mathrm{d}\sigma/\mathrm{d}m$	20.3 fb^{-1}	116-1000 GeV	[24]
II	CMS	13 TeV	$\mathrm{d}\sigma/\mathrm{d}m$	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.

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

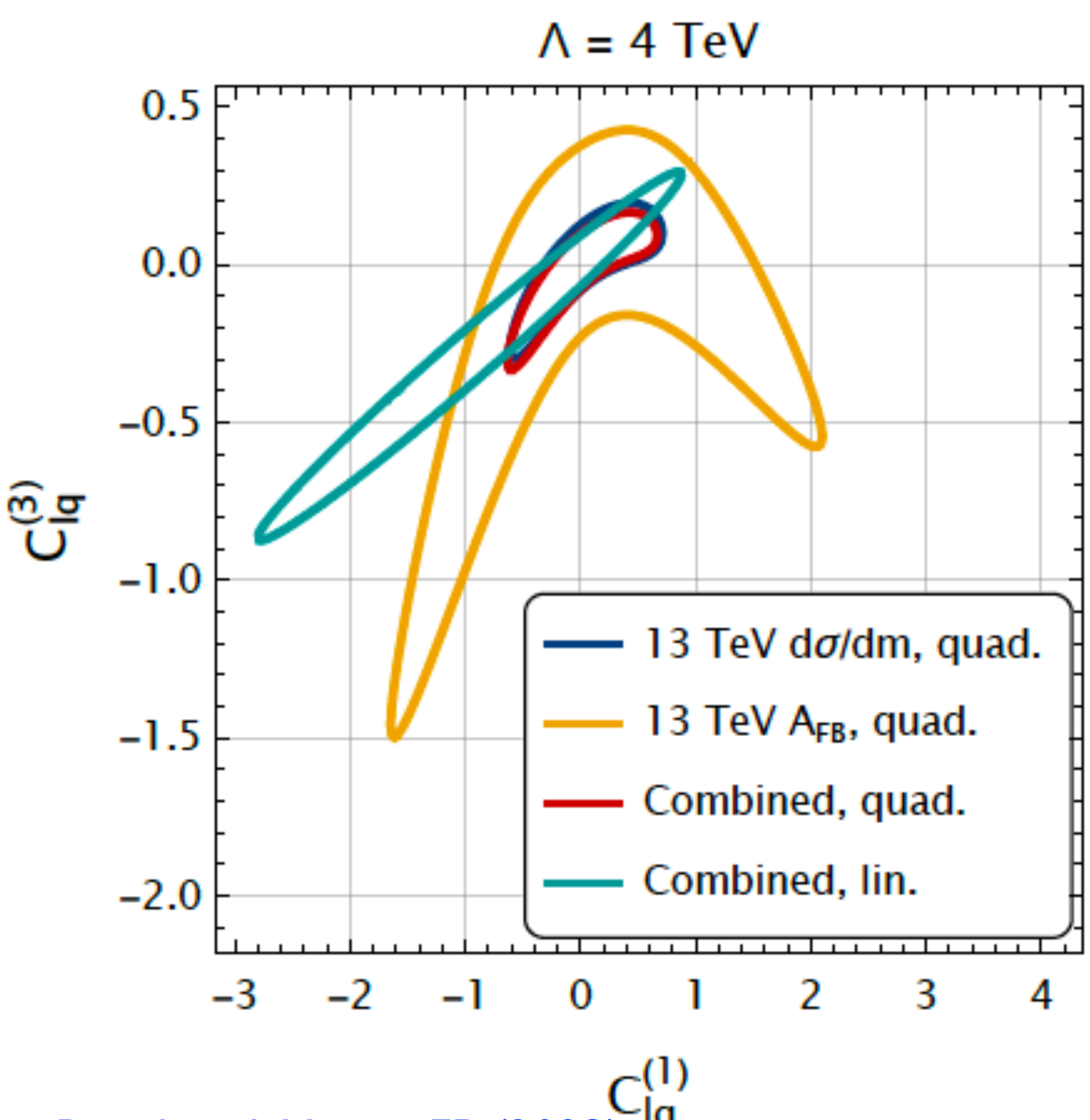


There is a significant difference between the single-parameter and marginalized fits, indicating the need to turn all Wilson coefficients on simultaneously

Boughezal, Huang, FP (2023)

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.

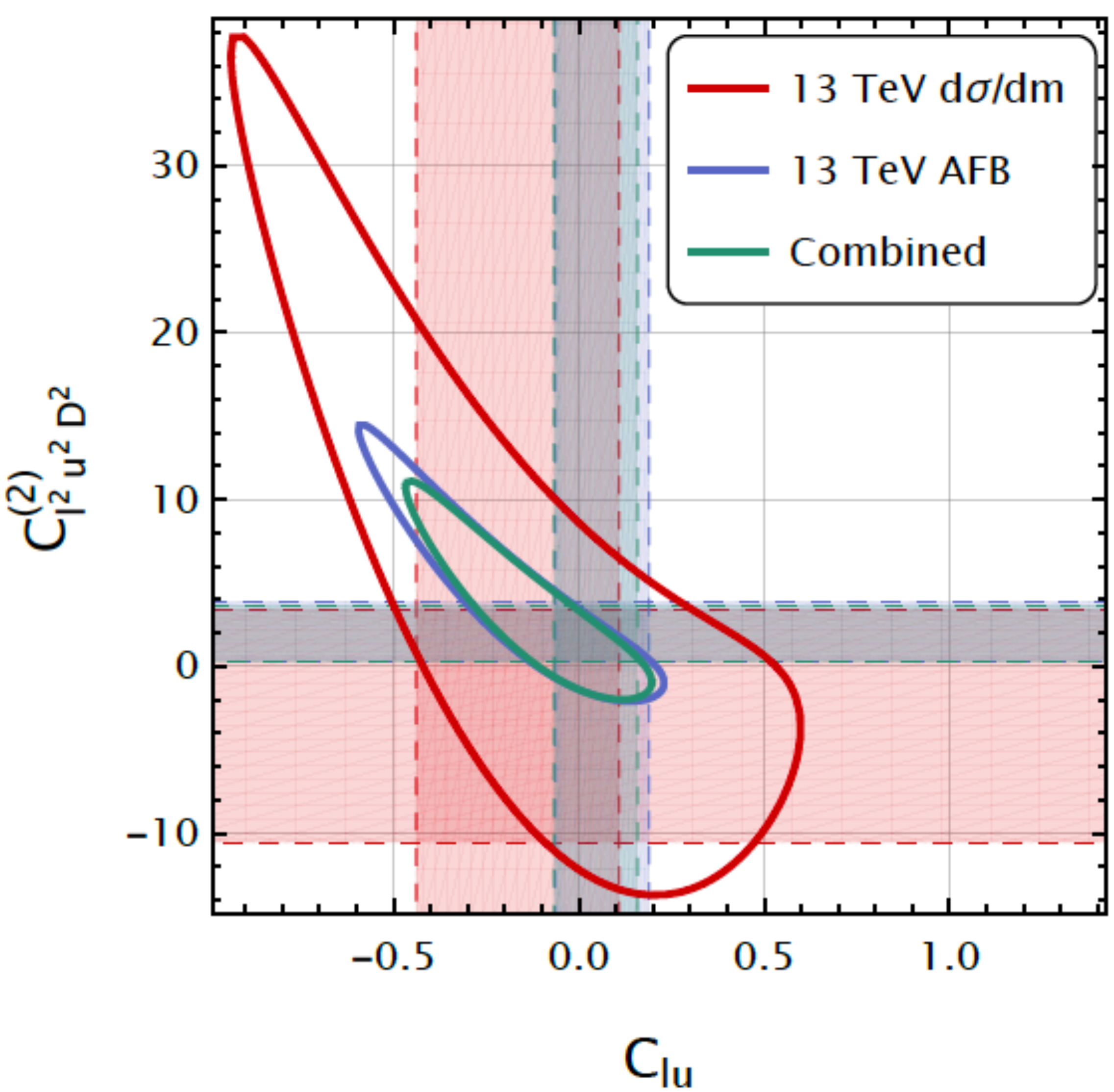


Boughezal, Huang, FP (2023)

- The A_{FB} data set (boomerang shape) alone exhibits significant degeneracies; need to fit to multiple data sets to remove these!
- 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 dim-6 terms have an effect, dimension-8 terms should as well. Test this with an example.

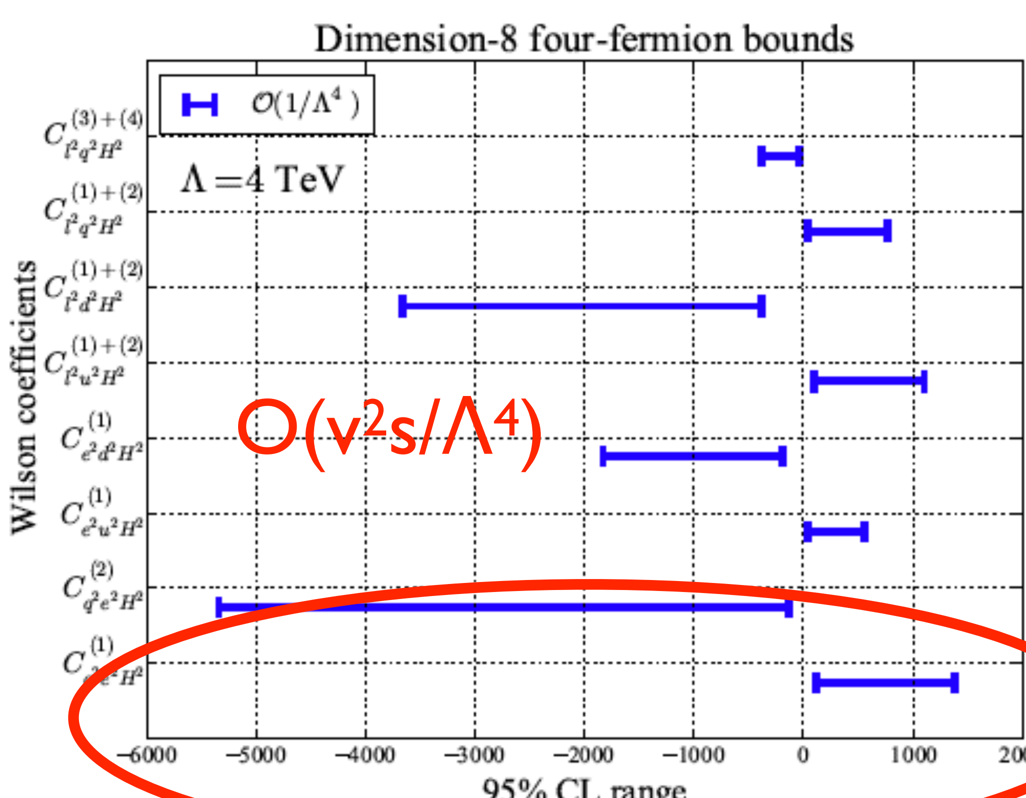


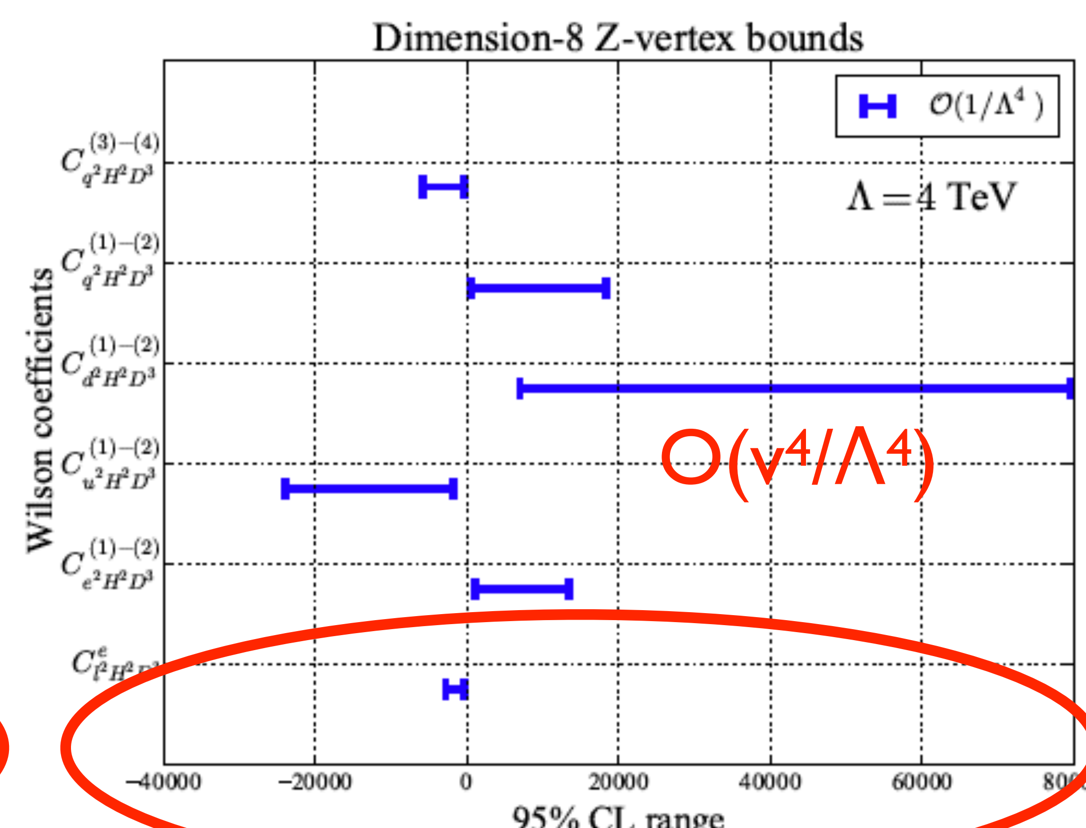
Boughezal, Huang, FP (2023)

- 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 -0.6 with dim-8 turned on; in the single parameter fit it extends only to -0.1.
- Note this time constraints primarily from A_{FB} this time.

Impact on analyses

- 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.





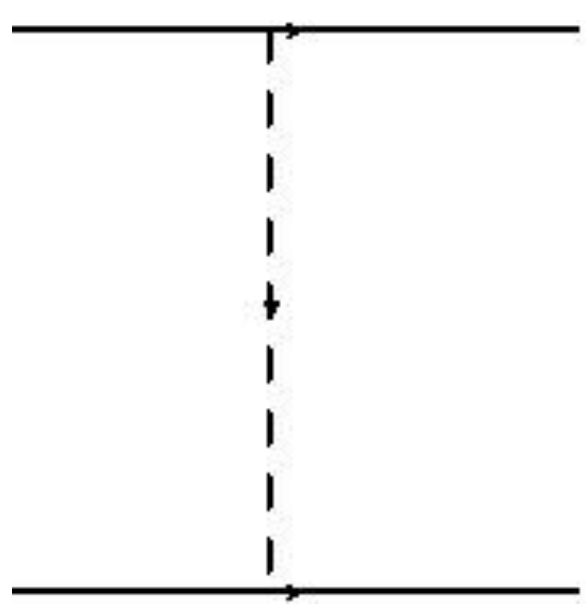
These are tiny and negligible

Boughezal, Mereghetti, FP(2021)

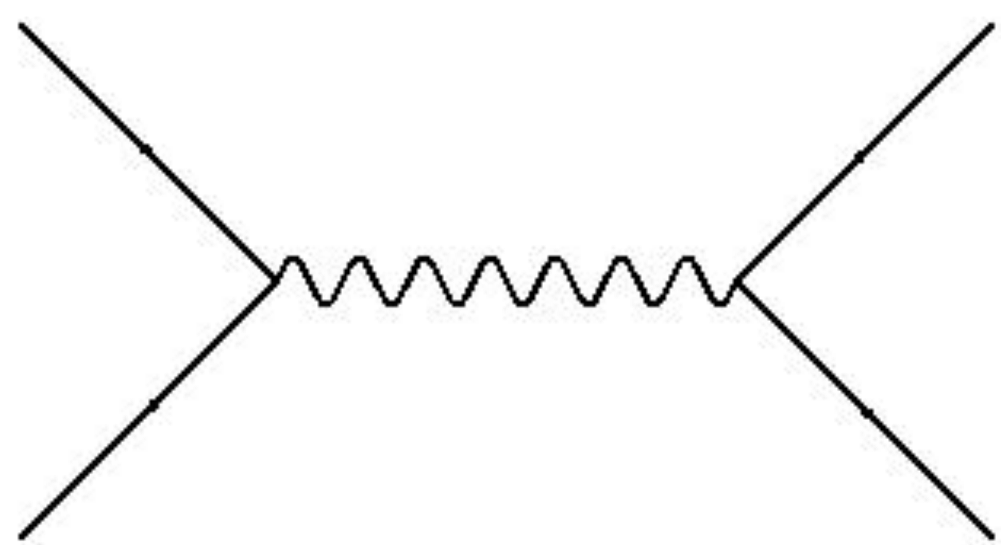
Model discrimination

- The analysis shown so far indicates that both dim-6 and dim-8 are potentially observable with LHC 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



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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 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 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

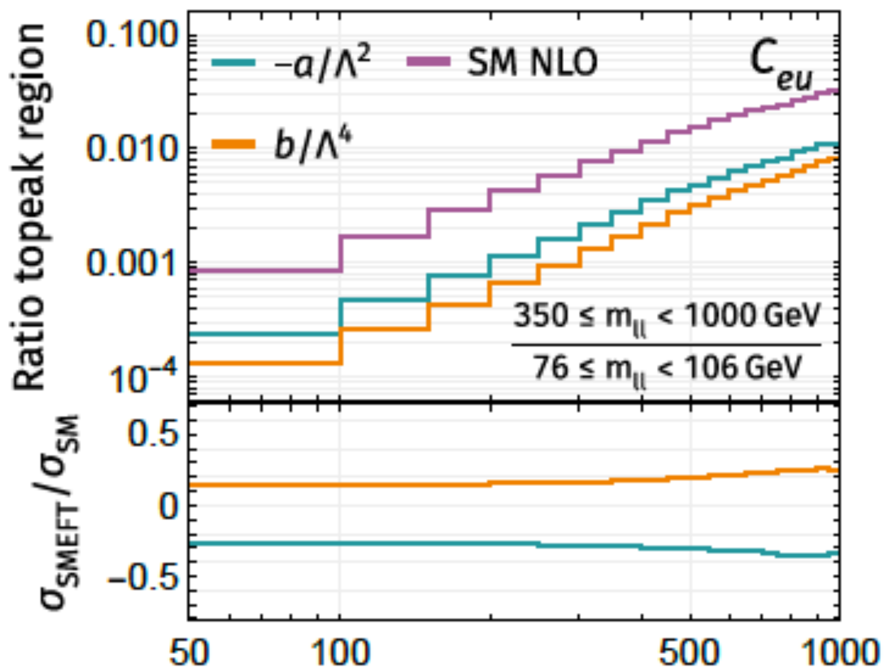
Determination of this operator through measurements of the transverse momentum distribution can distinguish between these two different particles

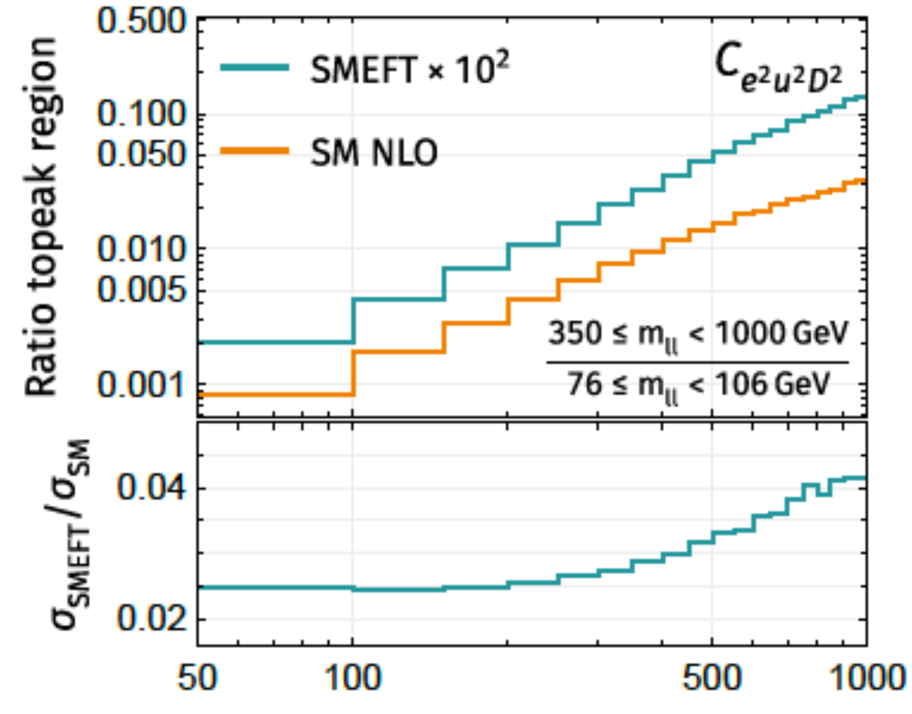
$$\frac{C_{e^2u^2\tilde{G}}}{\Lambda^4} = 0,$$

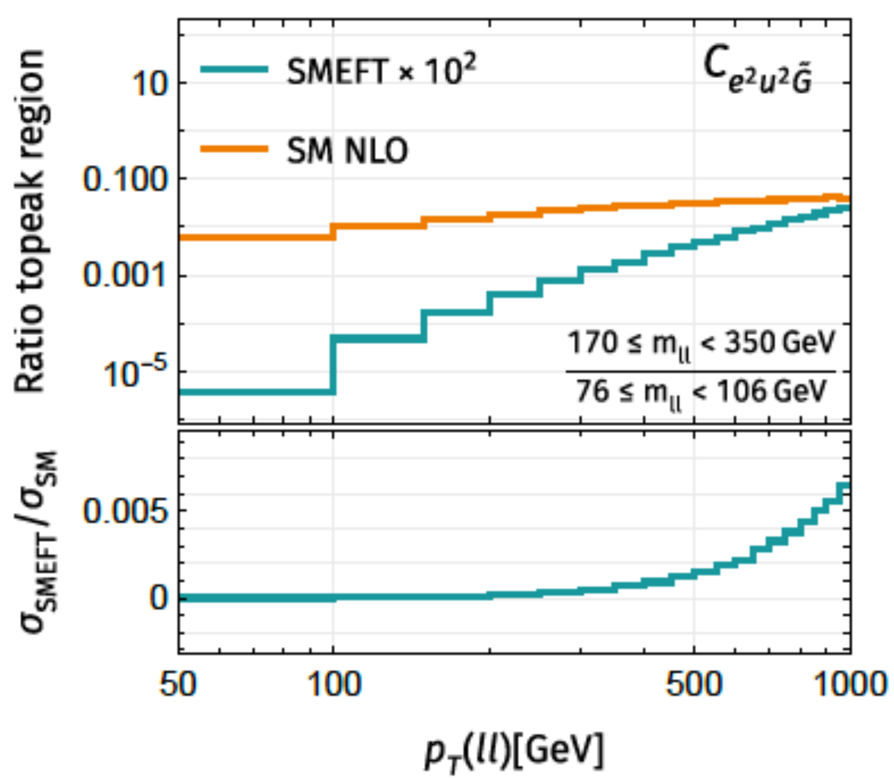
$$\frac{C_{e^2u^2\tilde{G}}}{\Lambda^4} = -\frac{h_U^2 g_s(1-\kappa_U)}{2M_U^4}$$

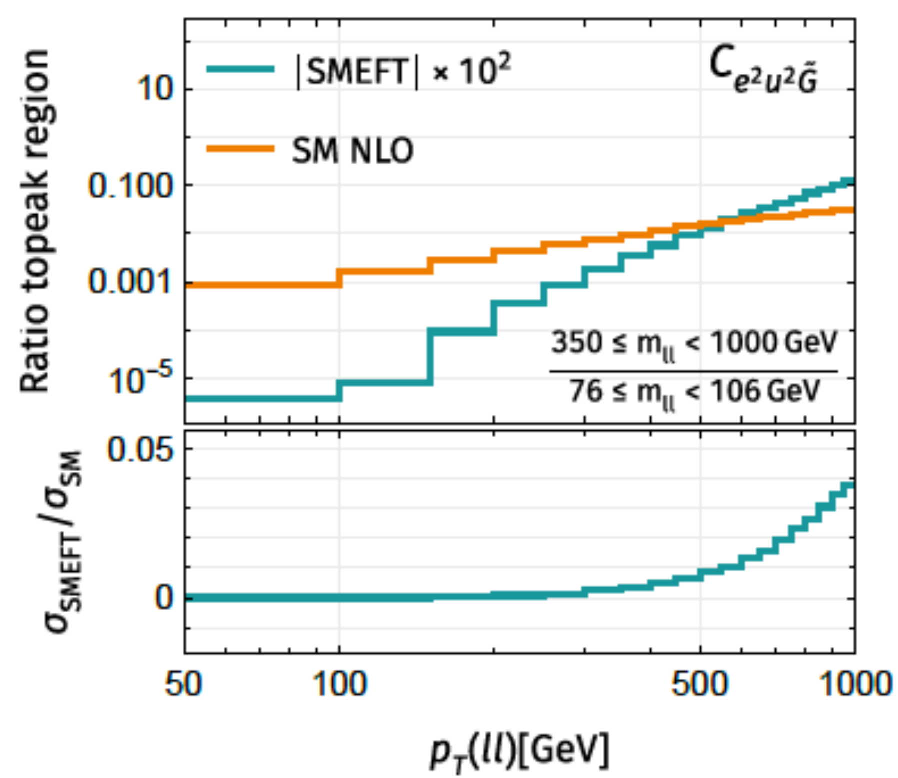
p_T distribution

- These operators generate very different p_T distributions.







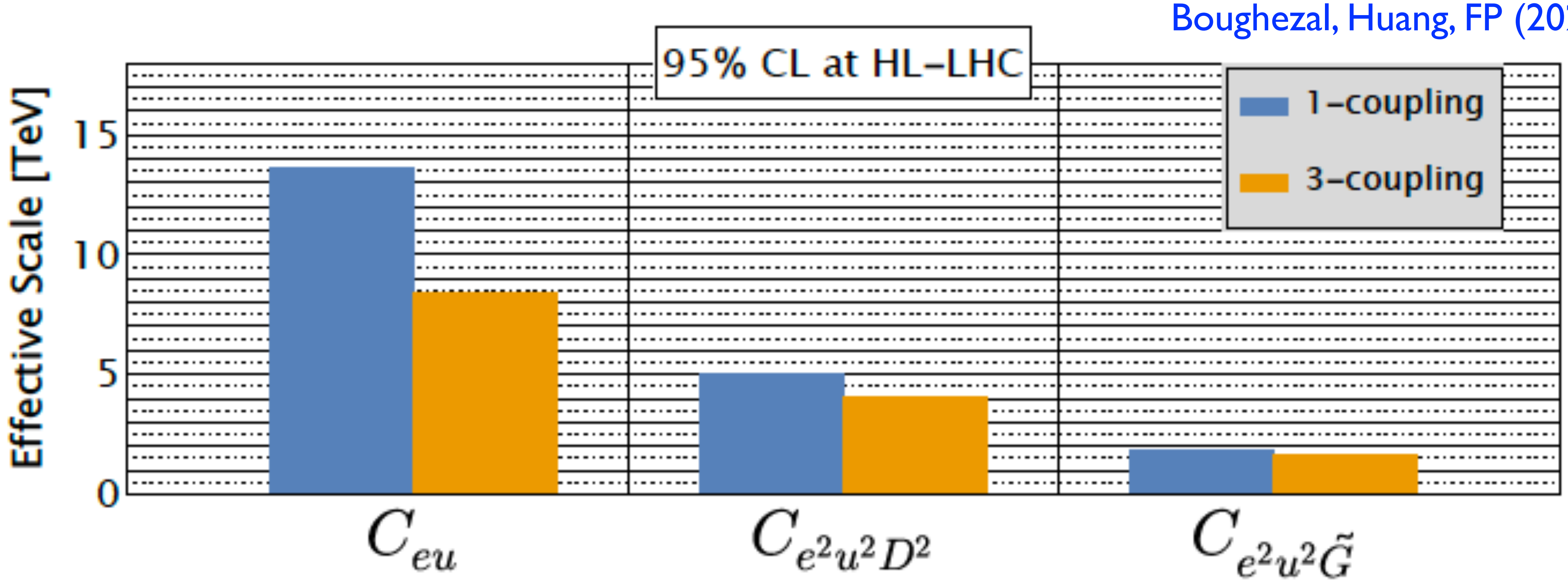


Boughezal, Huang, FP (2022)

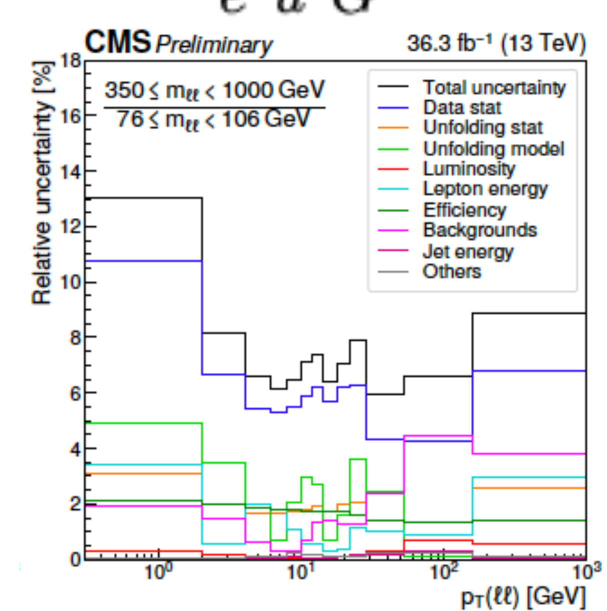
HL-LHC probes

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

Boughezal, Huang, FP (2022)



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

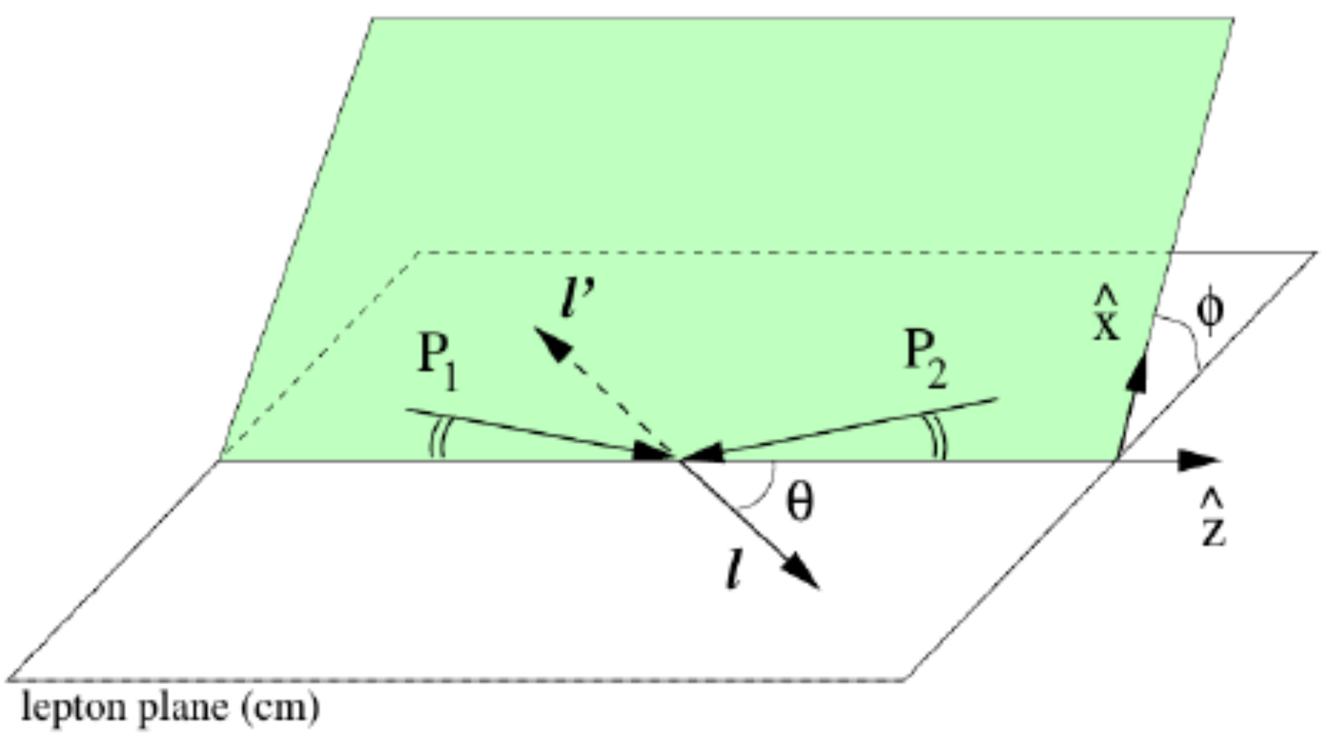


Angular structure of DY

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

Usually described by:

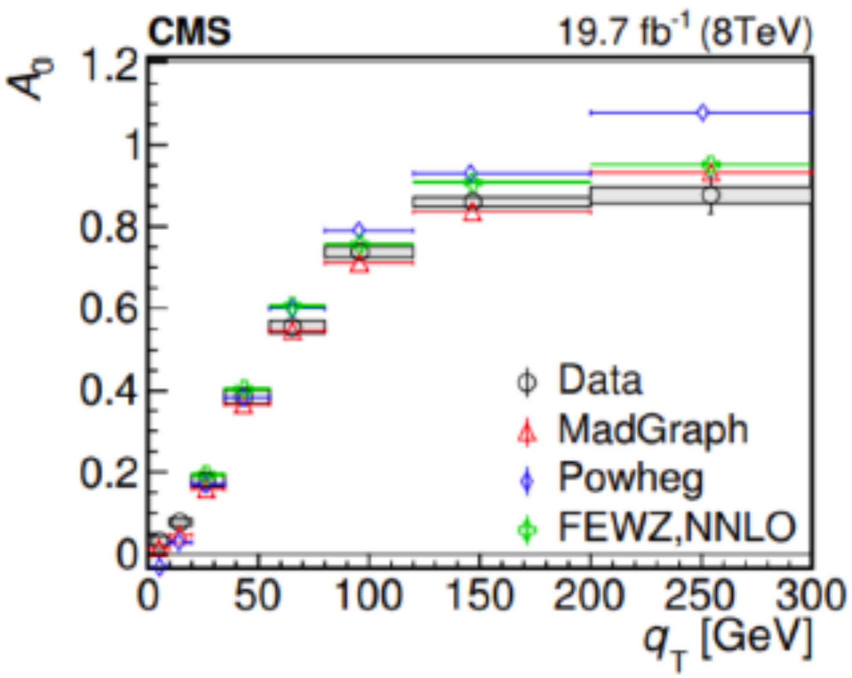
$$\frac{d\sigma}{dm_{ll}^2 dy d\Omega_l} = \frac{3}{16\pi}\frac{d\sigma}{dm_{ll}^2 dy}\Big\{(1+c_\theta^2)+\frac{A_0}{2}(1-3c_\theta^2) + A_1 s_{2\theta}c_\phi + \frac{A_2}{2}s_\theta^2 c_{2\phi} + A_3 s_\theta c_\phi + A_4 c_\theta + A_5 s_\theta^2 s_{2\phi} + A_6 s_{2\theta}s_\phi + A_7 s_\theta s_\phi\Big\}$$

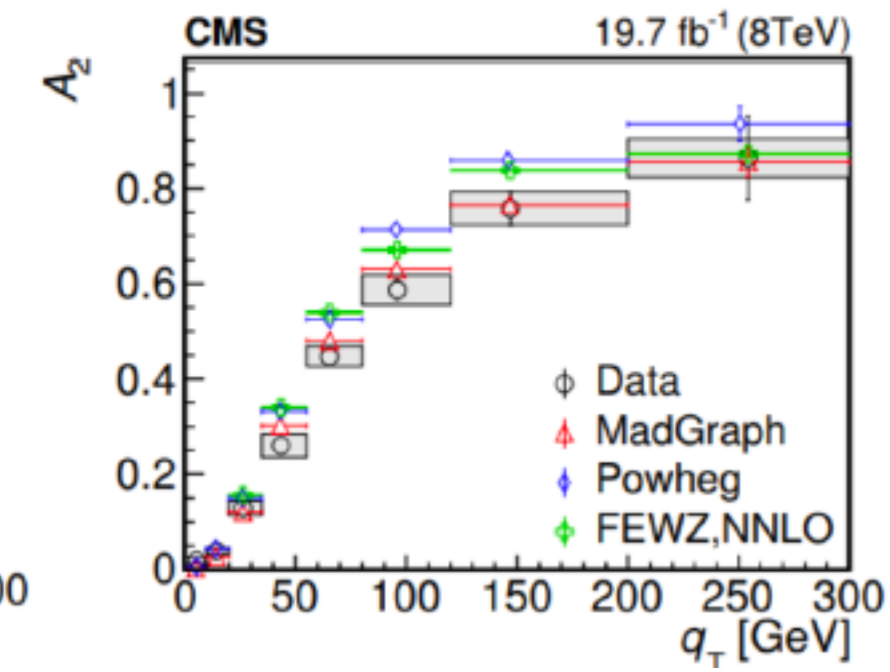


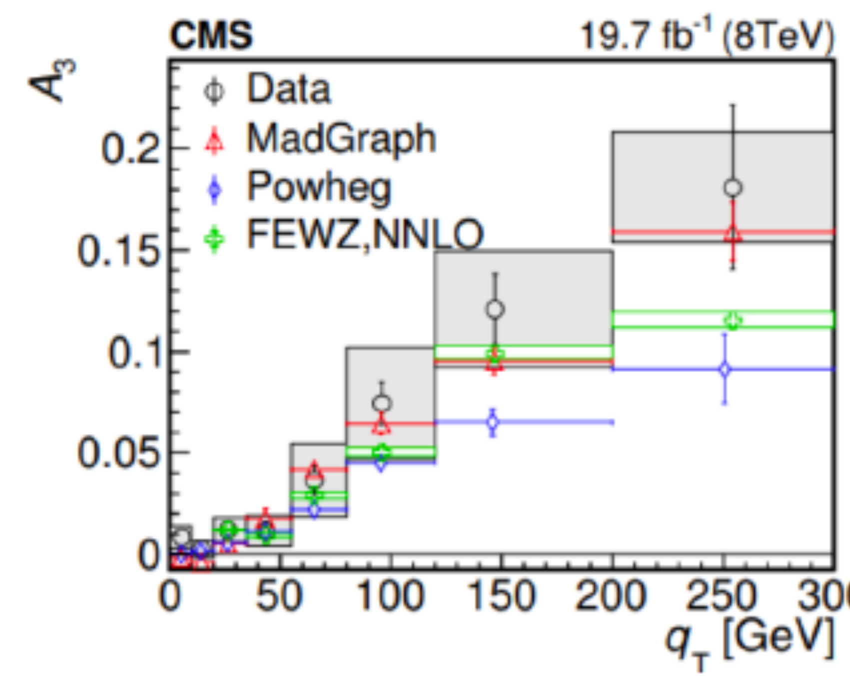
Y_m^l expansion through l=2 due to spin-1 nature of Z-boson

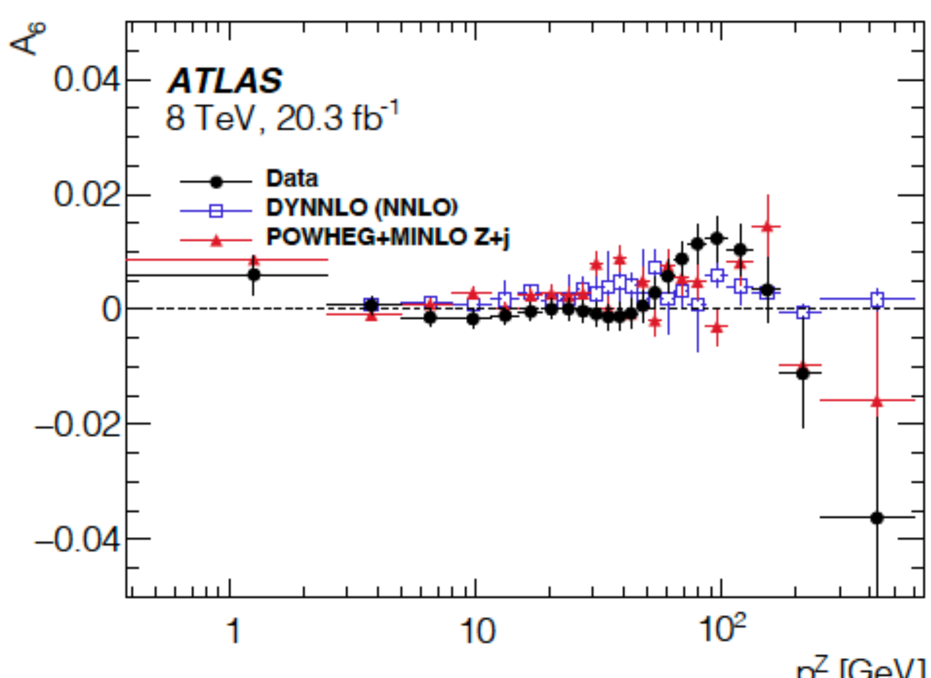
- A_4: parity violation and $\sin^2\theta$
- $A_0=A_2$: Lam-Tung relation
- A_5-A_7: naive T-reversal violation

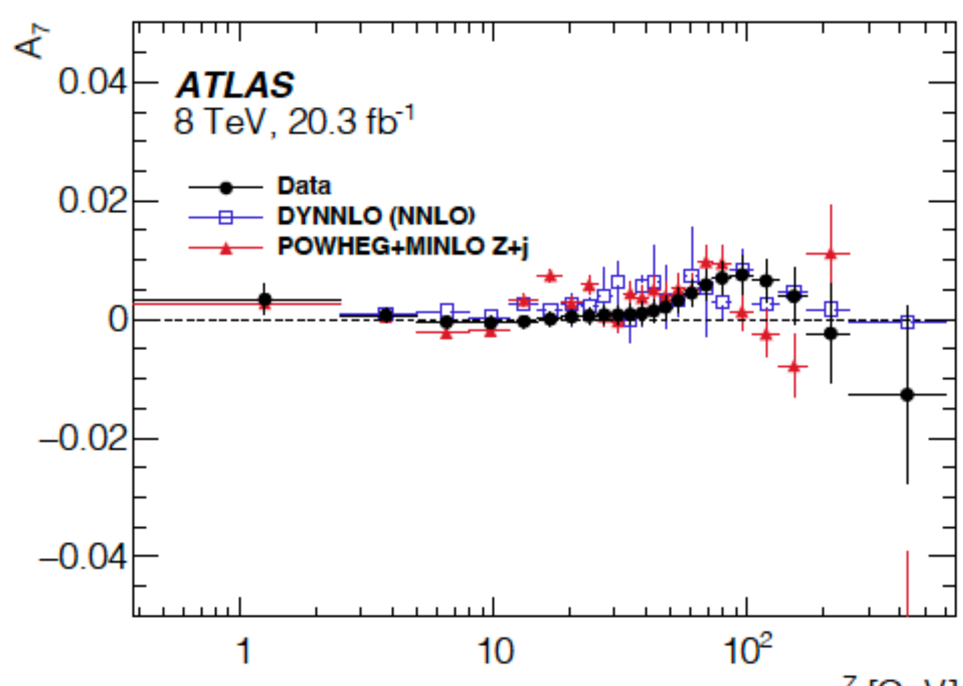
Angular structure of DY











Can measure the full spectrum of coefficients at the LHC

DY structure at dimension-6

- 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 study in Alioli, Dekens, Girard, Mereghetti (2018)

DY structure at dimension-8

- 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

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

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

DY structure at dimension-8

- Study the dimension-8 operators affecting DY:

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

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

c_θ^3 dependence not accounted for in current analyses

Angular momentum

- Two-derivative structure in the operators below leads to l=2 partial waves; 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 in the UV from integrating out spin-2 states.

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

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

A new angular basis

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

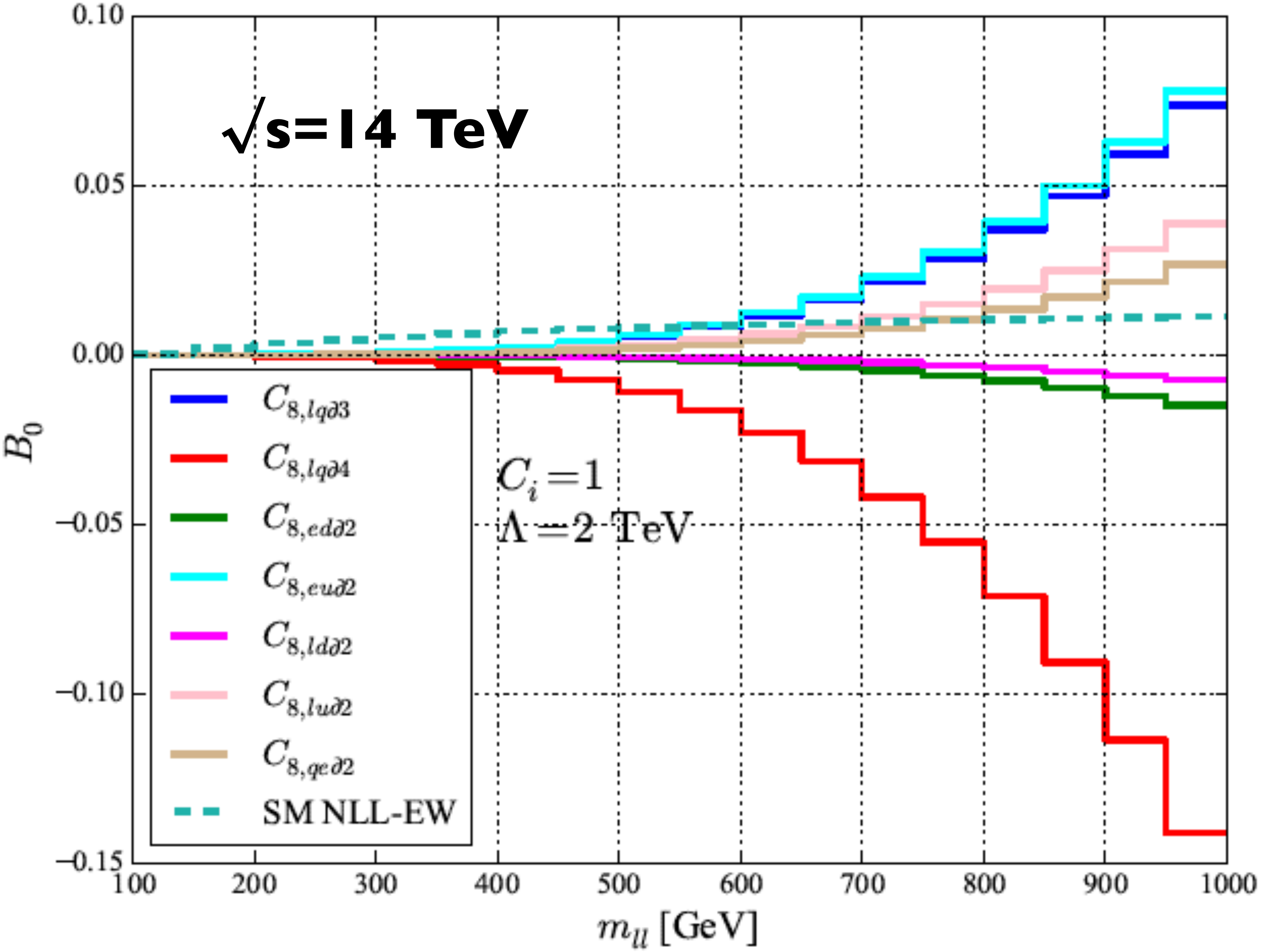
$$\frac{\alpha}{\pi}\ln\frac{\hat{s}}{M_Z^2}\ln\left[f(c_\theta)\right]$$

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

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

- 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 $O(1/\Lambda^4)$

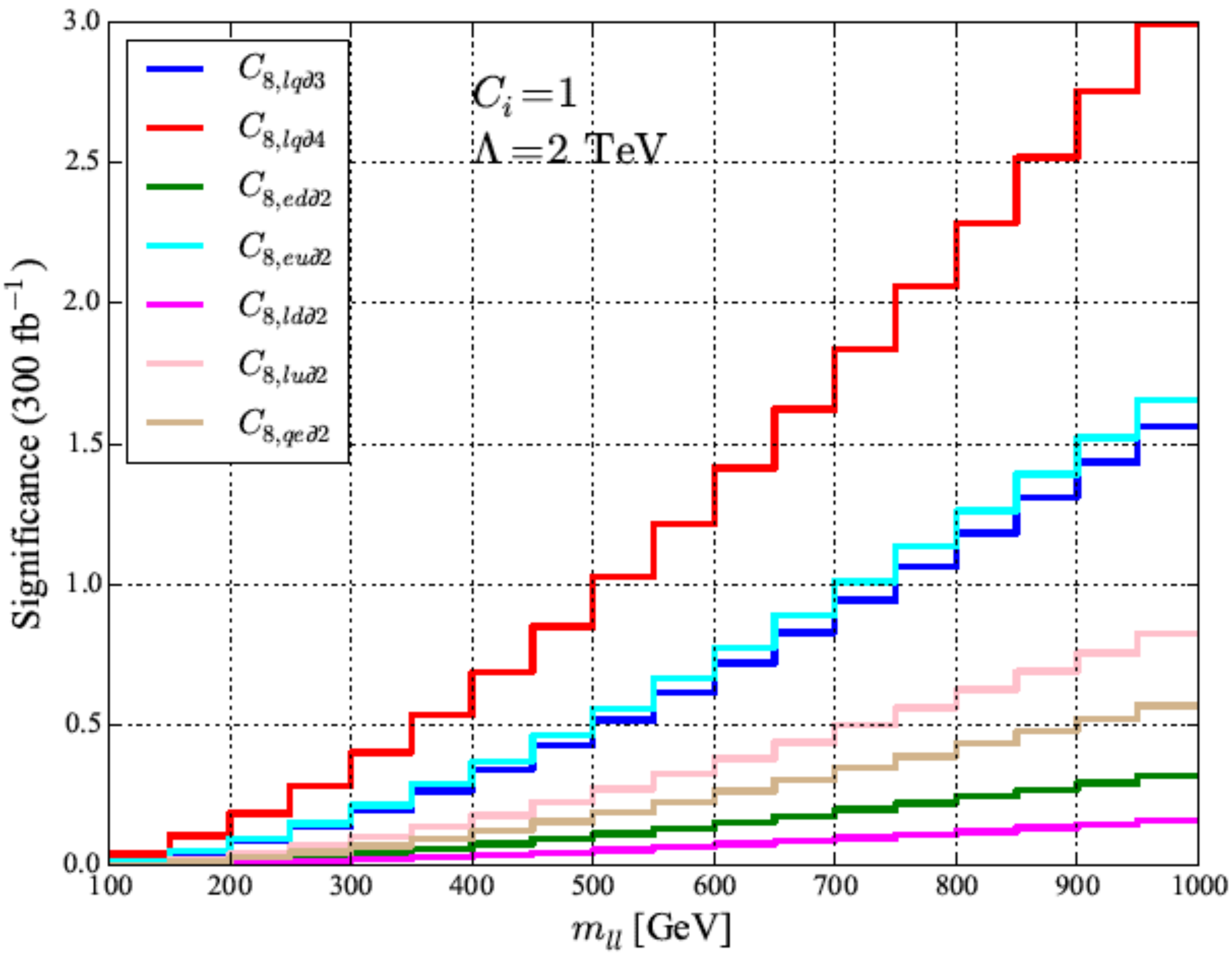
Numerical results



Alioli, Boughezal, Mereghetti, FP (2020)

- Turn on each operator separately, set UV scale Λ=2 TeV
- Several operators lead to significant deviations from SM predictions
- dim-8^2 corrections to cross section 30% or less; truncation to dim-8 justified

Numerical results



Alioli, Boughezal, Mereghetti, FP (2020)

- 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 $\sqrt{10}$

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

Conclusions

- 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.