

The interplay between the LHC and DIS experiments in probing SMEFT

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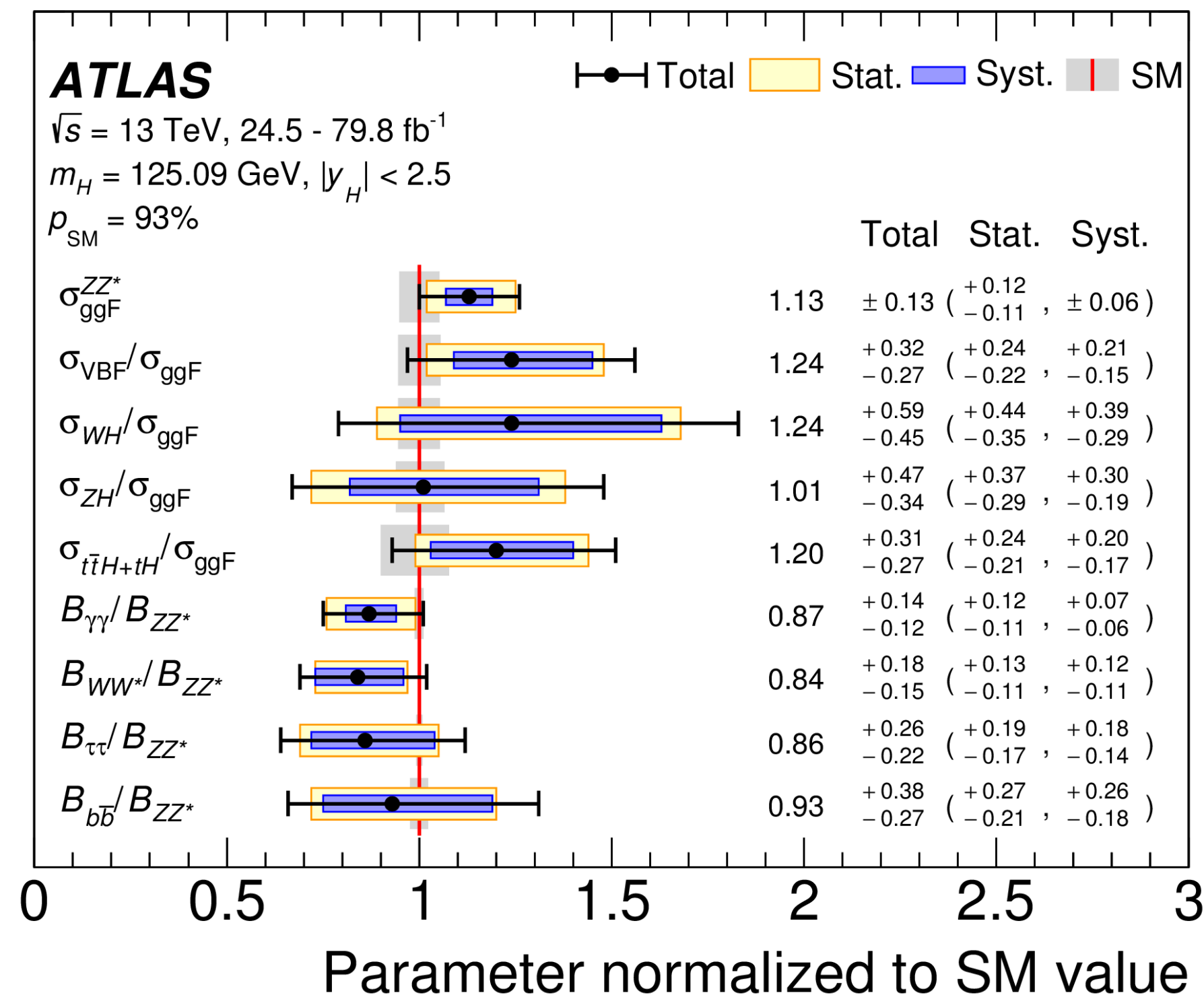
Uncovering New Laws of Nature at the EIC

BNL, November 20, 2024

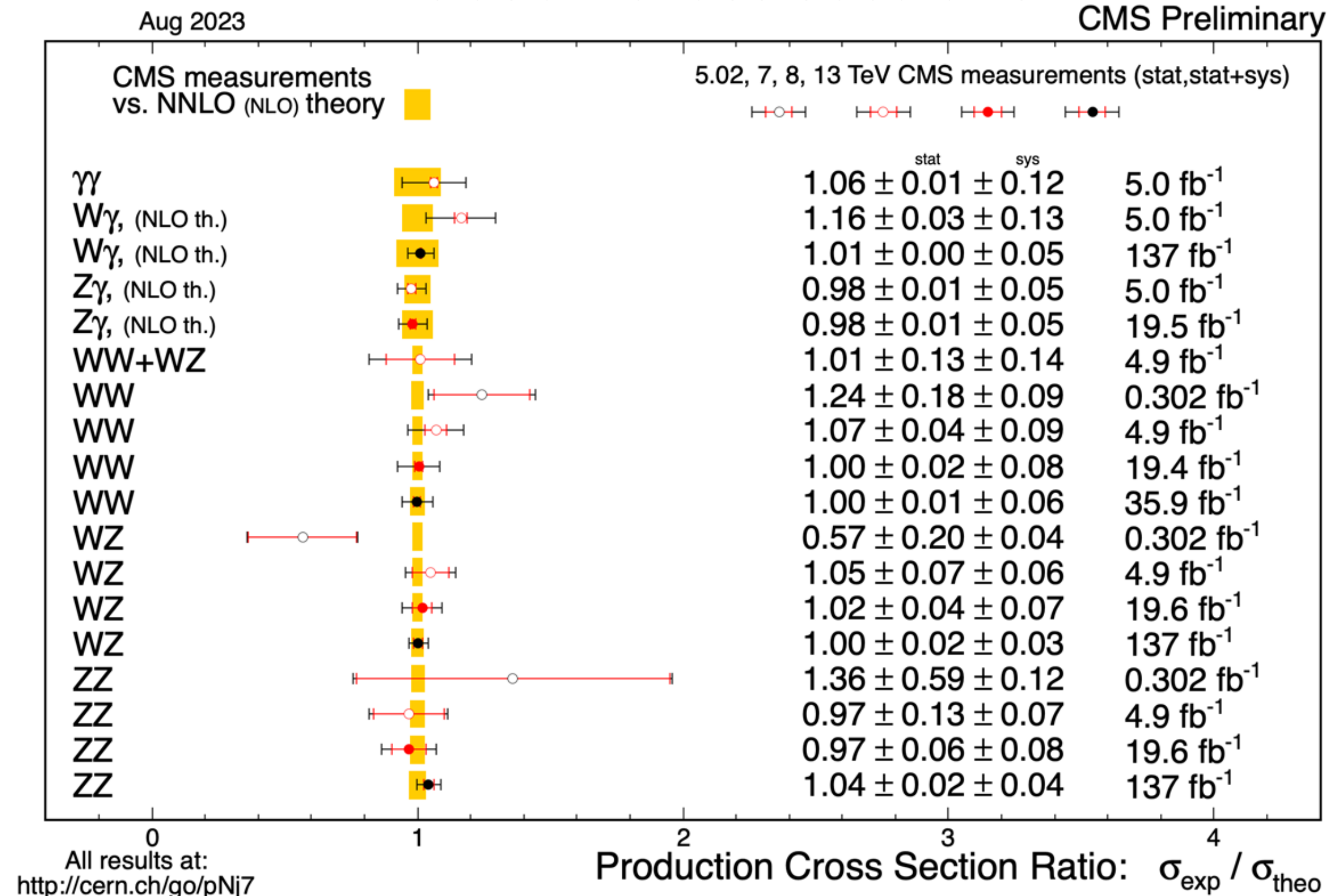
Status of the Standard Model

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

Higgs production and decay

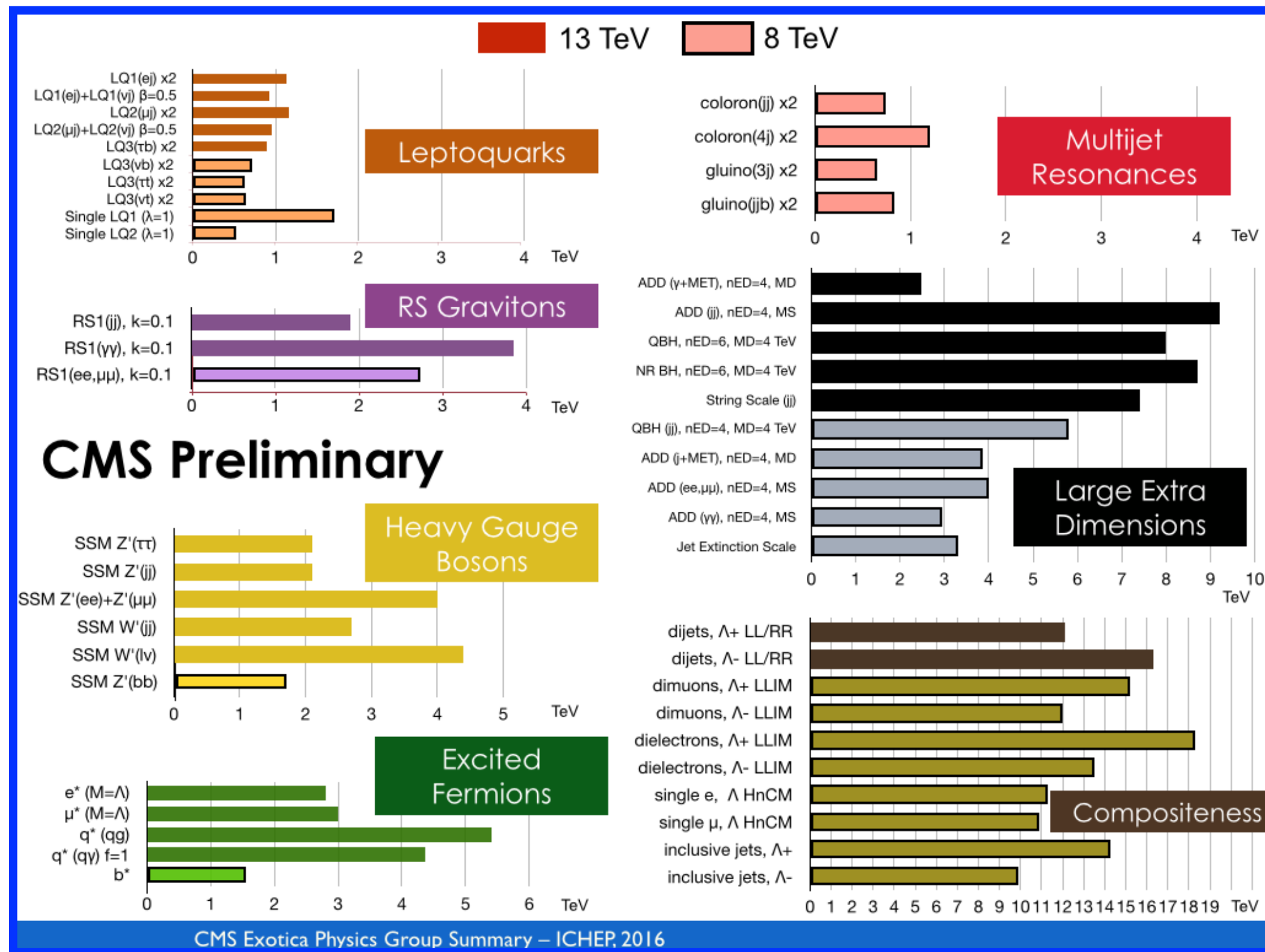


Di-boson cross sections



+ many more examples

Looking for new physics @ LHC



ATLAS Exotics Searches* - 95% CL Upper Exclusion Limits

Status: May 2020

ATLAS Preliminary
 $\int \mathcal{L} dt = (3.2 - 139) \text{ fb}^{-1}$ $\sqrt{s} = 8, 13 \text{ TeV}$

Model	ℓ, γ	Jets †	E_T^{miss}	$\int \mathcal{L} dt [\text{fb}^{-1}]$	Limit	Reference	
Extra dimensions	ADD $G_{KK} + g/q$	$0 e, \mu$	$1-4 j$	Yes	36.1	M_{Pl} 7.7 TeV	$n=2$ 1711.03301
	ADD non-resonant $\gamma\gamma$	2γ	-	-	36.7	M_{Pl} 8.6 TeV	$n=3$ HLZ NLO 1707.04147
	ADD QBH	-	$2 j$	-	37.0	M_{Pl} 8.9 TeV	$n=6$ 1606.02265
	ADD BH High Σp_T	$\geq 1 e, \mu$	$\geq 2 j$	-	32.0	M_{Pl} 8.2 TeV	$n=6, M_{\text{Pl}} = 3 \text{ TeV}$, rot BH 1512.02586
	ADD BH multijet	-	$\geq 3 j$	-	3.6	M_{Pl} 9.55 TeV	$n=6, M_{\text{Pl}} = 3 \text{ TeV}$, rot BH 1707.04147
	RS1 $G_{KK} \rightarrow \gamma\gamma$	2γ	-	-	36.7	G_{KK} mass 4.1 TeV	$k/\overline{M}_{\text{Pl}} = 0.1$ 1707.04147
	Bulk RS $G_{KK} \rightarrow WW/ZZ$	multi-channel	-	-	36.1	G_{KK} mass 2.3 TeV	$k/\overline{M}_{\text{Pl}} = 1.0$ 1808.02580
	Bulk RS $G_{KK} \rightarrow WV \rightarrow \ell\nu qq$	$1 e, \mu$	$2 j / 1 J$	Yes	139	G_{KK} mass 2.0 TeV	$k/\overline{M}_{\text{Pl}} = 1.0$ 2004.14636
	Bulk RS $G_{KK} \rightarrow tt$	$1 e, \mu$	$\geq 1 b, \geq 1 J/2 j$	Yes	36.1	G_{KK} mass 3.8 TeV	$\Gamma/m = 15\%$ 1804.10823
	2UED / RPP	$1 e, \mu$	$\geq 2 b, \geq 3 j$	Yes	36.1	KK mass 1.8 TeV	Tier (1,1), $\mathcal{B}(A^{(1,1)} \rightarrow tt) = 1$ 1803.09678
Gauge bosons	SSM $Z' \rightarrow \ell\ell$	$2 e, \mu$	-	-	139	Z' mass 5.1 TeV	$\Gamma/m = 1.2\%$ 1903.06248
	SSM $Z' \rightarrow \tau\tau$	2τ	-	-	36.1	Z' mass 2.42 TeV	1709.07242
	Leptophobic $Z' \rightarrow bb$	-	$2 b$	-	36.1	Z' mass 2.1 TeV	1805.09299
	Leptophobic $Z' \rightarrow tt$	$0 e, \mu$	$\geq 1 b, \geq 2 J$	Yes	139	Z' mass 4.1 TeV	2005.05138
	SSM $W' \rightarrow \ell\nu$	$1 e, \mu$	-	Yes	139	W' mass 6.0 TeV	1906.05609
	SSM $W' \rightarrow \tau\nu$	1τ	-	Yes	36.1	W' mass 3.7 TeV	1801.06992
	HVT $W' \rightarrow WZ \rightarrow \ell\nu qq$ model B	$1 e, \mu$	$2 j / 1 J$	Yes	139	W' mass 4.3 TeV	2004.14636
	HVT $V' \rightarrow WV \rightarrow qq qq$ model B	$0 e, \mu$	$2 J$	-	139	V' mass 3.8 TeV	1906.08589
	HVT $V' \rightarrow WH/ZH$ model B	multi-channel	-	-	36.1	V' mass 2.93 TeV	1712.06518
	HVT $W' \rightarrow WH$ model B	$0 e, \mu$	$\geq 1 b, \geq 2 J$	-	139	W' mass 3.2 TeV	CERN-EP-2020-073
CI	LRSM $W_R \rightarrow tb$	multi-channel	-	-	36.1	W_R mass 3.25 TeV	1807.10473
	LRSM $W_R \rightarrow \mu N_R$	2μ	$1 J$	-	80	W_R mass 5.0 TeV	1904.12679
	CI $qqqq$	-	$2 j$	-	37.0	A 21.8 TeV η_{LL}	1703.09127
DM	CI $\ell\ell qq$	$2 e, \mu$	-	-	139	A 35.8 TeV η_{LL}	CERN-EP-2020-066
	CI $tttt$	$\geq 1 e, \mu$	$\geq 1 b, \geq 1 j$	Yes	36.1	A 2.57 TeV	1811.02305
	Axial-vector mediator (Dirac DM)	$0 e, \mu$	$1-4 j$	Yes	36.1	m_{med} 1.55 TeV	$g_{\tau} = 0.25, g_{\tau} = 1.0, m(\chi) = 1 \text{ GeV}$ 1711.03301
LO	Colored scalar mediator (Dirac DM)	$0 e, \mu$	$1-4 j$	Yes	36.1	m_{med} 1.67 TeV	$g = 1.0, m(\chi) = 1 \text{ GeV}$ 1711.03301
	$VV\chi\chi$ EFT (Dirac DM)	$0 e, \mu$	$1 J, \leq 1 j$	Yes	3.2	M_{Pl} 700 GeV	$m(\chi) < 150 \text{ GeV}$ 1608.02372
	Scalar reson. $\phi \rightarrow t\bar{t}$ (Dirac DM)	$0-1 e, \mu$	$1 b, 0-1 J$	Yes	36.1	m_{ϕ} 3.4 TeV	$y = 0.4, t = 0.2, m(\chi) = 10 \text{ GeV}$ 1812.09743
Heavy quarks	Scalar LQ 1 st gen	$1, 2 e$	$\geq 2 j$	Yes	36.1	LQ mass 1.4 TeV	$\beta = 1$ 1902.00377
	Scalar LQ 2 nd gen	$1, 2 \mu$	$\geq 2 j$	Yes	36.1	LQ mass 1.56 TeV	$\beta = 1$ 1902.00377
	Scalar LQ 3 rd gen	2τ	$2 b$	-	36.1	LQ ² mass 1.03 TeV	$\mathcal{B}(LQ_2^+ \rightarrow b\tau) = 1$ 1902.08103
	Scalar LQ 3 rd gen	$0-1 e, \mu$	$2 b$	Yes	36.1	LQ ³ mass 970 GeV	$\mathcal{B}(LQ_3^+ \rightarrow \tau\tau) = 0$ 1902.08103
Excited fermions	VLQ $TT \rightarrow Ht/Zt/Wb + X$	multi-channel	-	-	36.1	T mass 1.37 TeV	SU(2) doublet 1808.02343
	VLQ $BB \rightarrow Wt/Zb + X$	multi-channel	-	-	36.1	B mass 1.34 TeV	SU(2) doublet 1808.02343
	VLQ $T_{5/3} T_{5/3} T_{5/3} \rightarrow Wt + X$	$2(SS)/\geq 3 e, \mu$	$\geq 1 b, \geq 1 j$	Yes	36.1	$T_{5/3}$ mass 1.64 TeV	$\mathcal{B}(T_{5/3} \rightarrow Wt) = 1, c(T_{5/3} W) = 1$ 1807.11883
	VLQ $Y \rightarrow Wb + X$	$1 e, \mu$	$\geq 1 b, \geq 1 j$	Yes	36.1	Y mass 1.85 TeV	$\mathcal{B}(Y \rightarrow Wb) = 1, c_{\tau}(Wb) = 1$ 1812.07343
Excited fermions	VLQ $B \rightarrow Hb + X$	$0 e, \mu, 2 \gamma$	$\geq 1 b, \geq 1 j$	Yes	79.8	B mass 1.21 TeV	$\kappa_B = 0.5$ ATLAS-CONF-2018-024
	VLQ $QQ \rightarrow WqWq$	$1 e, \mu$	$\geq 4 j$	Yes	20.3	Q mass 690 GeV	1509.04261
	Excited quark $q^* \rightarrow qg$	-	$2 j$	-	139	q^* mass 6.7 TeV	only u^* and d^* , $\Lambda = m(q^*)$ 1910.08447
	Excited quark $q^* \rightarrow q\gamma$	1γ	$1 j$	-	36.7	q^* mass 5.3 TeV	only u^* and d^* , $\Lambda = m(q^*)$ 1709.10440
Other	Excited quark $b^* \rightarrow bg$	-	$1 b, 1 j$	-	36.1	b^* mass 2.6 TeV	1805.09299
	Excited lepton ℓ^*	$3 e, \mu$	-	-	20.3	ℓ^* mass 3.0 TeV	$\Lambda = 3.0 \text{ TeV}$ 1411.2921
	Excited lepton ν^*	$3 e, \mu, \tau$	-	-	20.3	ν^* mass 1.6 TeV	$\Lambda = 1.6 \text{ TeV}$ 1411.2921
	Type III Seesaw	$1 e, \mu$	$\geq 2 j$	Yes	79.8	N^{μ} mass 560 GeV	$m(W_R) = 4.1 \text{ TeV}, g_L = g_R$ ATLAS-CONF-2018-020
LRSM Majorana ν	2μ	$2 j$	-	36.1	N_{μ} mass 870 GeV	1809.11105	
Higgs triplet $H^{\pm\pm} \rightarrow \ell\ell$	$2, 3, 4 e, \mu$ (SS)	-	-	36.1	$H^{\pm\pm}$ mass 3.2 TeV	DY production 1710.09748	
Higgs triplet $H^{\pm\pm} \rightarrow \ell\tau$	$3 e, \mu, \tau$	-	-	20.3	$H^{\pm\pm}$ mass 400 GeV	DY production, $\mathcal{B}(H^{\pm\pm} \rightarrow \ell\tau) = 1$ 1411.2921	
Multi-charged particles	-	-	-	36.1	multi-charged particle mass 1.22 TeV	DY production, $ q = 5e$ 1812.03673	
Magnetic monopoles	-	-	-	34.4	monopole mass 2.37 TeV	DY production, $ q = 1g_D$, spin 1/2 1905.10130	

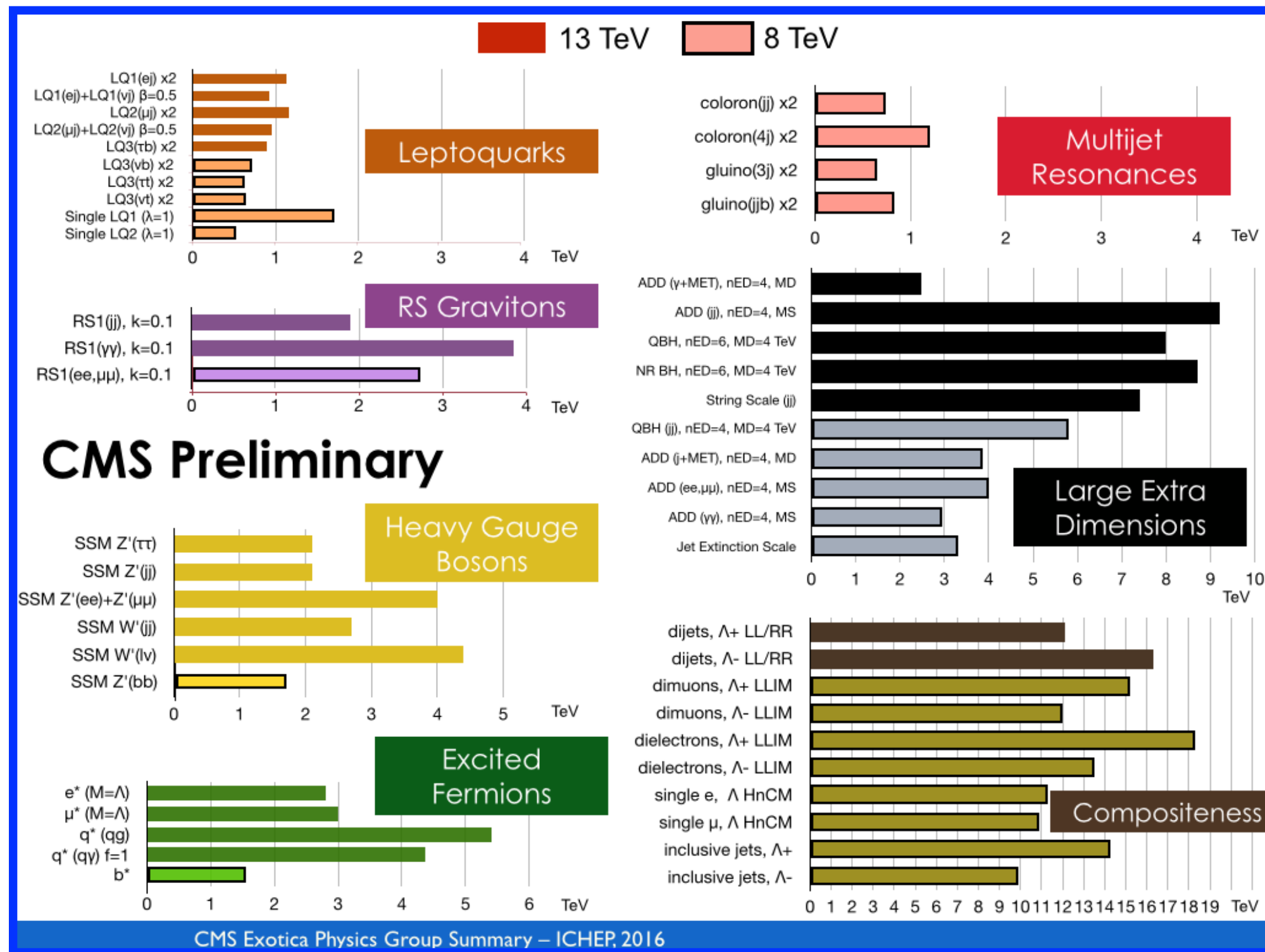
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	Bulk RS $G_{KK} \rightarrow tt$	1 e, μ	$\geq 1 b, \geq 1 J/2 j$	Yes	36.1	G_{KK} mass 3.8 TeV $\Gamma/m = 15\%$
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	Leptophobic Z' $\rightarrow tt$	0 e, μ	$\geq 1 b, \geq 2 J$	Yes	139	Z' mass 4.1 TeV
	SSM W' $\rightarrow \ell\nu$	1 e, μ	-	Yes	139	W' mass 6.0 TeV
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	VLQ $Y \rightarrow Wb + X$	1 e, μ	$\geq 1 b, \geq 1 j$	Yes	36.1	Y mass 1.85 TeV
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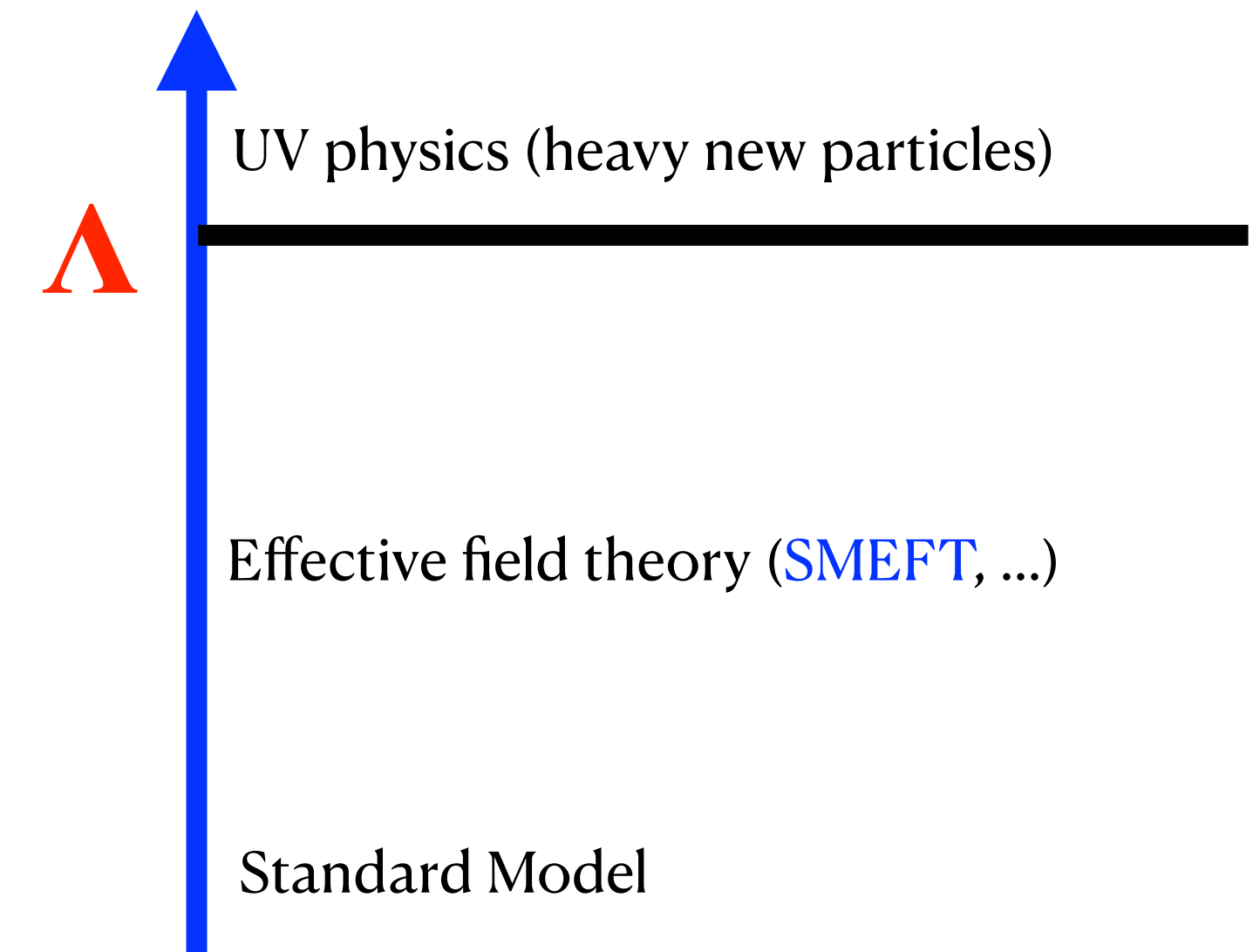
Broad model dependent searches haven't revealed new resonances so far

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

New physics might live at a scale beyond our direct colliders energy reach

Introduction to the SMEFT

- An EFT framework that incorporates this scale separation between the SM and new states 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



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

↑
↑

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

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

Accommodates a rich phenomenology in all sectors

X^3		φ^6 and $\varphi^4 D^2$		$\psi^2 \varphi^3$		$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
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_{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}	$(\bar{l}_p \gamma_\mu l_r)(\bar{e}_s \gamma^\mu e_t)$
$Q_{\tilde{G}}$	$f^{ABC} \tilde{G}_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger \varphi)\Box(\varphi^\dagger \varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger \varphi)(\bar{q}_p u_r \tilde{\varphi})$	$Q_{qq}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{q}_s \gamma^\mu q_t)$	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_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$(\varphi^\dagger D^\mu \varphi)^* (\varphi^\dagger D_\mu \varphi)$	$Q_{d\varphi}$	$(\varphi^\dagger \varphi)(\bar{q}_p d_r \varphi)$	$Q_{qq}^{(3)}$	$(\bar{q}_p \gamma_\mu \tau^I q_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$	Q_{dd}	$(\bar{d}_p \gamma_\mu d_r)(\bar{d}_s \gamma^\mu d_t)$	Q_{ld}	$(\bar{l}_p \gamma_\mu l_r)(\bar{d}_s \gamma^\mu d_t)$
$Q_{\tilde{W}}$	$\varepsilon^{IJK} \tilde{W}_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$					$Q_{lu}^{(1)}$	$(\bar{l}_p \gamma_\mu l_r)(\bar{q}_s \gamma^\mu q_t)$	Q_{eu}	$(\bar{e}_p \gamma_\mu e_r)(\bar{u}_s \gamma^\mu u_t)$	Q_{qe}	$(\bar{q}_p \gamma_\mu q_r)(\bar{e}_s \gamma^\mu e_t)$
$X^2 \varphi^2$		$\psi^2 X \varphi$		$\psi^2 \varphi^2 D$		$(\bar{L}L)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$		$(\bar{R}L)(\bar{R}R)$ and $(\bar{L}R)(\bar{R}R)$		B -violating	
$Q_{\varphi G}$	$\varphi^\dagger \varphi G_{\mu\nu}^A G^{A\mu\nu}$	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_{leqq}	$(\bar{l}_p e_r)(\bar{d}_s q_t^j)$	Q_{duqq}	$\varepsilon^{\alpha\beta\gamma} \varepsilon_{jk} [(d_p^\alpha)^T C u_r^\beta] [(q_s^\gamma)^T C l_t^k]$		
$Q_{\varphi \tilde{G}}$	$\varphi^\dagger \varphi \tilde{G}_{\mu\nu}^A G^{A\mu\nu}$	Q_{eB}	$(\bar{l}_p \sigma^{\mu\nu} e_r) \varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu^I \varphi)(\bar{l}_p \tau^I \gamma^\mu l_r)$	$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r) \varepsilon_{jk} (\bar{q}_s^k d_t)$	Q_{ququ}	$\varepsilon^{\alpha\beta\gamma} \varepsilon_{jk} [(q_p^{\alpha j})^T C q_r^{\beta k}] [(u_s^\gamma)^T C e_t]$		
$Q_{\varphi W}$	$\varphi^\dagger \varphi W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uG}	$(\bar{q}_p \sigma^{\mu\nu} T^A u_r) \tilde{\varphi} G_{\mu\nu}^A$	$Q_{\varphi e}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{e}_p \gamma^\mu e_r)$	$Q_{quqd}^{(8)}$	$(\bar{q}_p^j T^A u_r) \varepsilon_{jk} (\bar{q}_s^k T^A d_t)$	Q_{quqq}	$\varepsilon^{\alpha\beta\gamma} \varepsilon_{jkm} [(q_p^{\alpha j})^T C q_r^{\beta k}] [(q_s^m)^T C l_t^\gamma]$		
$Q_{\varphi \tilde{W}}$	$\varphi^\dagger \varphi \tilde{W}_{\mu\nu}^I W^{I\mu\nu}$	Q_{uW}	$(\bar{q}_p \sigma^{\mu\nu} u_r) \tau^I \tilde{\varphi} W_{\mu\nu}^I$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{q}_p \gamma^\mu q_r)$	$Q_{lequ}^{(1)}$	$(\bar{l}_p e_r) \varepsilon_{jk} (\bar{q}_s^k u_t)$	Q_{duuu}	$\varepsilon^{\alpha\beta\gamma} [(d_p^\alpha)^T C u_r^\beta] [(u_s^\gamma)^T C e_t]$		
$Q_{\varphi B}$	$\varphi^\dagger \varphi B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar{q}_p \sigma^{\mu\nu} u_r) \tilde{\varphi} B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu^I \varphi)(\bar{q}_p \tau^I \gamma^\mu q_r)$	$Q_{lequ}^{(3)}$	$(\bar{l}_p \sigma_{\mu\nu} e_r) \varepsilon_{jk} (\bar{q}_s^k \sigma^{\mu\nu} u_t)$				
$Q_{\varphi \tilde{B}}$	$\varphi^\dagger \varphi \tilde{B}_{\mu\nu} B^{\mu\nu}$	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}	$(\bar{q}_p \sigma^{\mu\nu} d_r) \tau^I \varphi W_{\mu\nu}^I$	$Q_{\varphi d}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{d}_p \gamma^\mu d_r)$						
$Q_{\varphi \tilde{W}B}$	$\varphi^\dagger \tau^I \varphi \tilde{W}_{\mu\nu}^I B^{\mu\nu}$	Q_{dB}	$(\bar{q}_p \sigma^{\mu\nu} d_r) \varphi B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\tilde{\varphi}^\dagger D_\mu \varphi)(\bar{u}_p \gamma^\mu d_r)$						

Gauge-Higgs interactions

Fermion-Higgs-gauge interactions

Four-fermion interactions

Baryon-number violating interactions

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	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_φ		$Q_{\varphi\Box}$	$(\varphi^\dagger D_\mu \varphi)^2$
$Q_{\tilde{G}}$	$f^{ABC} \tilde{G}_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi D}$	$(\varphi^\dagger D_\mu \varphi)(\varphi^\dagger D^\mu \varphi)$		
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				
$Q_{\tilde{W}}$	$\varepsilon^{IJK} \tilde{W}_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				
$X^2 \varphi^2$		ψ^2		$(\bar{L}L)(\bar{R}R)$	
$Q_{\varphi G}$	$\varphi^\dagger \varphi G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eW}	$(\bar{l}_p \sigma_{\mu\nu} e_r) W^{\mu\nu}$	Q_{le}	$(\bar{l}_p \gamma_\mu l_r)(\bar{e}_s \gamma^\mu e_t)$
$Q_{\varphi \tilde{G}}$	$\varphi^\dagger \varphi \tilde{G}_{\mu\nu}^A G^{A\mu\nu}$	Q_{eB}	$(\bar{l}_p \sigma_{\mu\nu} e_r) B^{\mu\nu}$	Q_{lu}	$(\bar{l}_p \gamma_\mu l_r)(\bar{u}_s \gamma^\mu u_t)$
$Q_{\varphi W}$	$\varphi^\dagger \varphi W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uG}	$(\bar{q}_p \sigma_{\mu\nu} u_r) G^{\mu\nu}$	Q_{ld}	$(\bar{l}_p \gamma_\mu l_r)(\bar{d}_s \gamma^\mu d_t)$
$Q_{\varphi \tilde{W}}$	$\varphi^\dagger \varphi \tilde{W}_{\mu\nu}^I W^{I\mu\nu}$	Q_{uW}	$(\bar{q}_p \sigma_{\mu\nu} u_r) W^{\mu\nu}$	Q_{qe}	$(\bar{q}_p \gamma_\mu q_r)(\bar{e}_s \gamma^\mu e_t)$
$Q_{\varphi B}$	$\varphi^\dagger \varphi B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar{q}_p \sigma_{\mu\nu} u_r) B^{\mu\nu}$	$Q_{qu}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{u}_s \gamma^\mu u_t)$
$Q_{\varphi \tilde{B}}$	$\varphi^\dagger \varphi \tilde{B}_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar{q}_p \sigma_{\mu\nu} d_r) G^{\mu\nu}$	$Q_{qu}^{(8)}$	$(\bar{q}_p \gamma_\mu T^A q_r)(\bar{u}_s \gamma^\mu T^A u_t)$
$Q_{\varphi WB}$	$\varphi^\dagger \tau^I \varphi W_{\mu\nu}^I B^{\mu\nu}$	Q_{dW}	$(\bar{q}_p \sigma_{\mu\nu} d_r) W^{\mu\nu}$	$Q_{qd}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{d}_s \gamma^\mu d_t)$
$Q_{\varphi \tilde{W}B}$	$\varphi^\dagger \tau^I \varphi \tilde{W}_{\mu\nu}^I B^{\mu\nu}$	Q_{dB}	$(\bar{q}_p \sigma^{\mu\nu} d_r) \varphi B_{\mu\nu}$	$Q_{qd}^{(8)}$	$(\bar{q}_p \gamma_\mu T^A q_r)(\bar{d}_s \gamma^\mu T^A d_t)$
		$Q_{\varphi ud}$	$i(\varphi^\dagger D_\mu \varphi)(\bar{u}_p \gamma^\mu d_r)$	violating	
				$Q_{lequ}^{(3)}$	$(\bar{l}_p^j \sigma_{\mu\nu} e_r) \varepsilon_{jkl} (\bar{q}_c^k \sigma^{\mu\nu} u_t)$

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

Brivio, Jiang, Trott (2017)

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- 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 $\varphi^4 D^2$		$\psi^2 \varphi^3$		$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger \varphi)^3$	$Q_{\varphi\Box}$	$(\varphi^\dagger \varphi) \Box (\varphi^\dagger \varphi)$	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}	$(\bar{l}_p \gamma_\mu l_r) (\bar{e}_s \gamma^\mu e_t)$
$Q_{\tilde{G}}$	$f^{ABC} \tilde{G}_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger \varphi) \Box (\varphi^\dagger \varphi)$	$Q_{\varphi\Box}$	$(\varphi^\dagger \varphi) \Box (\varphi^\dagger \varphi)$	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_{lu}	$(\bar{l}_p \gamma_\mu l_r) (\bar{u}_s \gamma^\mu u_t)$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$(\varphi^\dagger \varphi) D_\mu (\varphi^\dagger \varphi) D^\mu (\varphi^\dagger \varphi)$	$Q_{\varphi\Box}$	$(\varphi^\dagger \varphi) \Box (\varphi^\dagger \varphi)$	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_{ld}	$(\bar{l}_p \gamma_\mu l_r) (\bar{d}_s \gamma^\mu d_t)$
$Q_{\tilde{W}}$	$\varepsilon^{IJK} \tilde{W}_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$(\varphi^\dagger \varphi) D_\mu (\varphi^\dagger \varphi) D^\mu (\varphi^\dagger \varphi)$	$Q_{\varphi\Box}$	$(\varphi^\dagger \varphi) \Box (\varphi^\dagger \varphi)$	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}	$(\bar{l}_p \gamma_\mu l_r) (\bar{e}_s \gamma^\mu e_t)$
$X^2 \varphi^2$		$X^2 \varphi^2$		$X^2 \varphi^2$		$X^2 \varphi^2$		$X^2 \varphi^2$		$X^2 \varphi^2$	
$Q_{\varphi G}$	$\varphi^\dagger \varphi G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eW}	$(\bar{l}_p \gamma_\mu l_r) (\bar{e}_s \gamma^\mu e_t)$	Q_{eB}	$(\bar{l}_p \gamma_\mu l_r) (\bar{e}_s \gamma^\mu e_t)$	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_{lu}	$(\bar{l}_p \gamma_\mu l_r) (\bar{u}_s \gamma^\mu u_t)$
$Q_{\varphi \tilde{G}}$	$\varphi^\dagger \varphi \tilde{G}_{\mu\nu}^A G^{A\mu\nu}$	Q_{eB}	$(\bar{l}_p \gamma_\mu l_r) (\bar{e}_s \gamma^\mu e_t)$	Q_{uG}	$(\bar{q}_p \gamma_\mu q_r) (\bar{u}_s \gamma^\mu u_t)$	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_{ld}	$(\bar{l}_p \gamma_\mu l_r) (\bar{d}_s \gamma^\mu d_t)$
$Q_{\varphi W}$	$\varphi^\dagger \varphi W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uW}	$(\bar{q}_p \gamma_\mu q_r) (\bar{u}_s \gamma^\mu u_t)$	Q_{uB}	$(\bar{q}_p \gamma_\mu q_r) (\bar{u}_s \gamma^\mu u_t)$	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}	$(\bar{l}_p \gamma_\mu l_r) (\bar{e}_s \gamma^\mu e_t)$
$Q_{\varphi \tilde{W}}$	$\varphi^\dagger \varphi \tilde{W}_{\mu\nu}^I W^{I\mu\nu}$	Q_{uW}	$(\bar{q}_p \gamma_\mu q_r) (\bar{u}_s \gamma^\mu u_t)$	Q_{dB}	$(\bar{q}_p \gamma_\mu q_r) (\bar{d}_s \gamma^\mu d_t)$	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}	$(\bar{l}_p \gamma_\mu l_r) (\bar{e}_s \gamma^\mu e_t)$
$Q_{\varphi B}$	$\varphi^\dagger \varphi B_{\mu\nu} B^{\mu\nu}$	Q_{dB}	$(\bar{q}_p \gamma_\mu q_r) (\bar{d}_s \gamma^\mu d_t)$	Q_{dB}	$(\bar{q}_p \gamma_\mu q_r) (\bar{d}_s \gamma^\mu d_t)$	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}	$(\bar{l}_p \gamma_\mu l_r) (\bar{e}_s \gamma^\mu e_t)$
$Q_{\varphi \tilde{B}}$	$\varphi^\dagger \varphi \tilde{B}_{\mu\nu} B^{\mu\nu}$	Q_{dB}	$(\bar{q}_p \gamma_\mu q_r) (\bar{d}_s \gamma^\mu d_t)$	Q_{dB}	$(\bar{q}_p \gamma_\mu q_r) (\bar{d}_s \gamma^\mu d_t)$	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}	$(\bar{l}_p \gamma_\mu l_r) (\bar{e}_s \gamma^\mu e_t)$
$Q_{\varphi WB}$	$\varphi^\dagger \tau^I \varphi W_{\mu\nu}^I B^{\mu\nu}$	Q_{dB}	$(\bar{q}_p \gamma_\mu q_r) (\bar{d}_s \gamma^\mu d_t)$	Q_{dB}	$(\bar{q}_p \gamma_\mu q_r) (\bar{d}_s \gamma^\mu d_t)$	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}	$(\bar{l}_p \gamma_\mu l_r) (\bar{e}_s \gamma^\mu e_t)$
$Q_{\varphi \tilde{W}B}$	$\varphi^\dagger \tau^I \varphi \tilde{W}_{\mu\nu}^I B^{\mu\nu}$	Q_{dB}	$(\bar{q}_p \gamma_\mu q_r) (\bar{d}_s \gamma^\mu d_t)$	Q_{dB}	$(\bar{q}_p \gamma_\mu q_r) (\bar{d}_s \gamma^\mu d_t)$	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}	$(\bar{l}_p \gamma_\mu l_r) (\bar{e}_s \gamma^\mu e_t)$

The full operator basis up to dimension-12 is now known
Harlander, Kempkens, Schaaf (2023)

Gauge-Higgs interactions

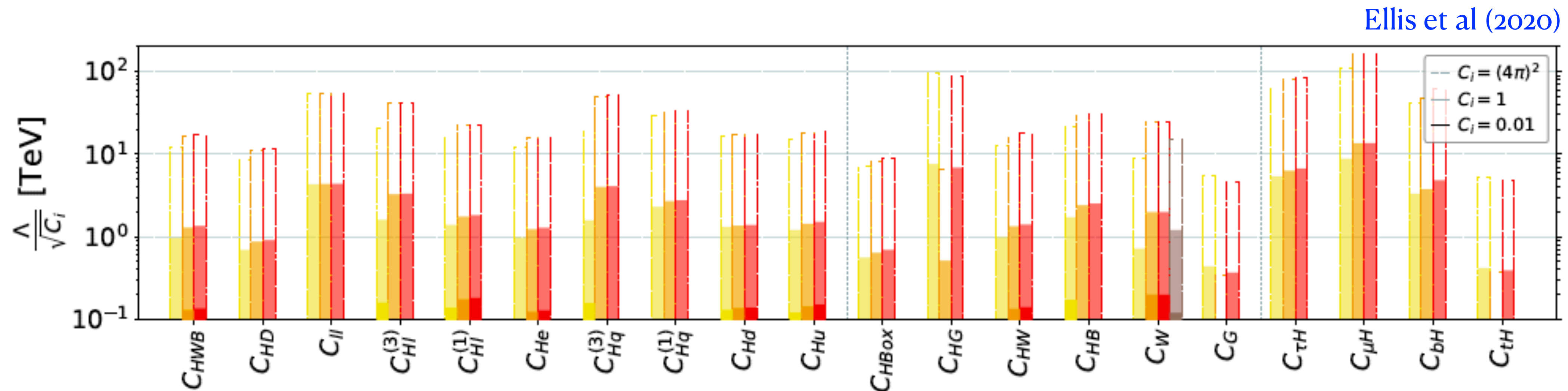
Fermion-Higgs-gauge interactions

Four-fermion interactions

Baryon-number violating interactions

Searching for the SMEFT

- The most natural experiments to look for SMEFT-induced deviations are high-energy ones such as the LHC, since the expansion parameter $C \cdot E^2 / \Lambda^2$ is maximized there. Global fits to the available data are pursued by both the experimental and theoretical collaborations.

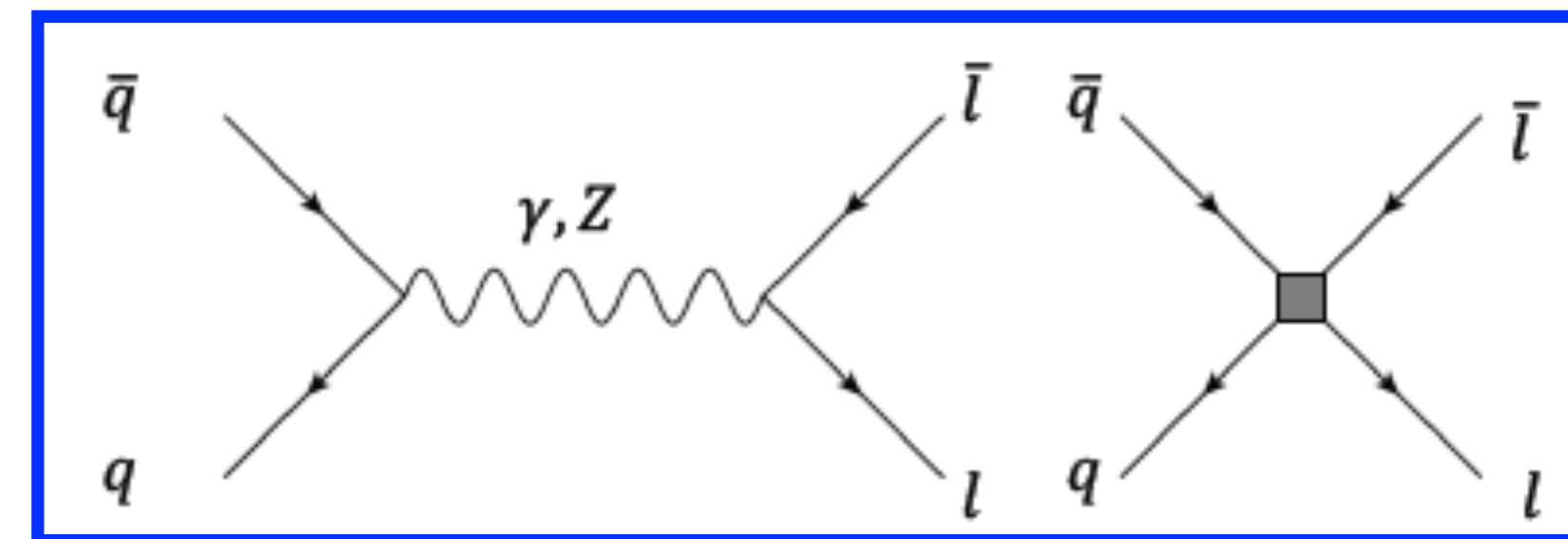
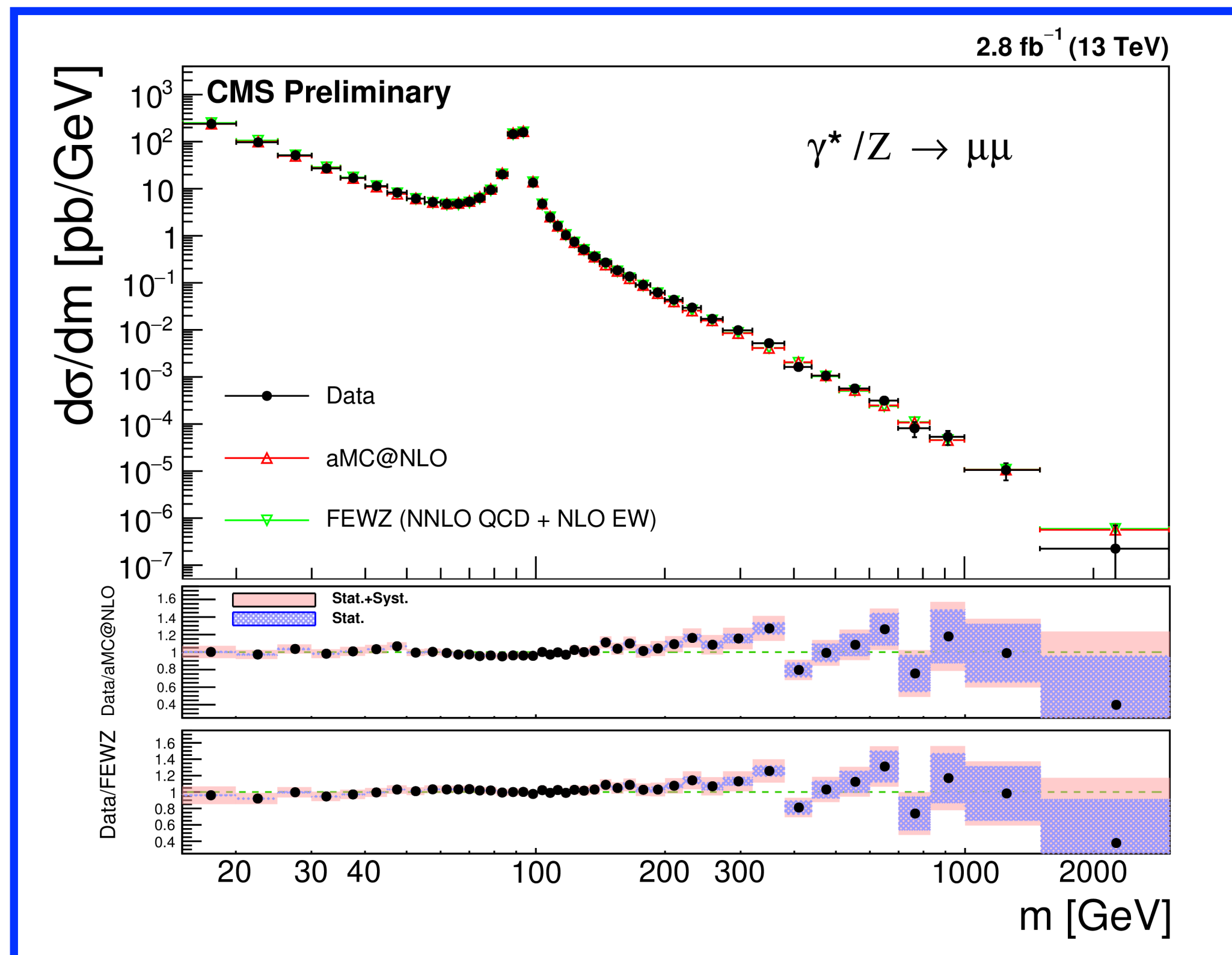


The LHC provides a rich program to search for a broad spectrum of coefficients to the TeV scale; we'll focus first on an example sector of SMEFT here

SMEFT probes at the LHC

Example: semi-leptonic four-fermion operators

- We will study in detail the LHC example of semi-leptonic four-fermion operators in the SMEFT. These are the relevant operators for models containing states such as Z' bosons and gravitons. The natural place to search for them at the LHC is through the Drell-Yan process at high energies.



Both data and theory are precise up to high invariant masses

Low-energy experiments

- Existing low-energy experiments also provide competitive constraints on four-fermion operators. Future experiments will be essential elements of global fits in order to remove degeneracies that exist with only collider data.

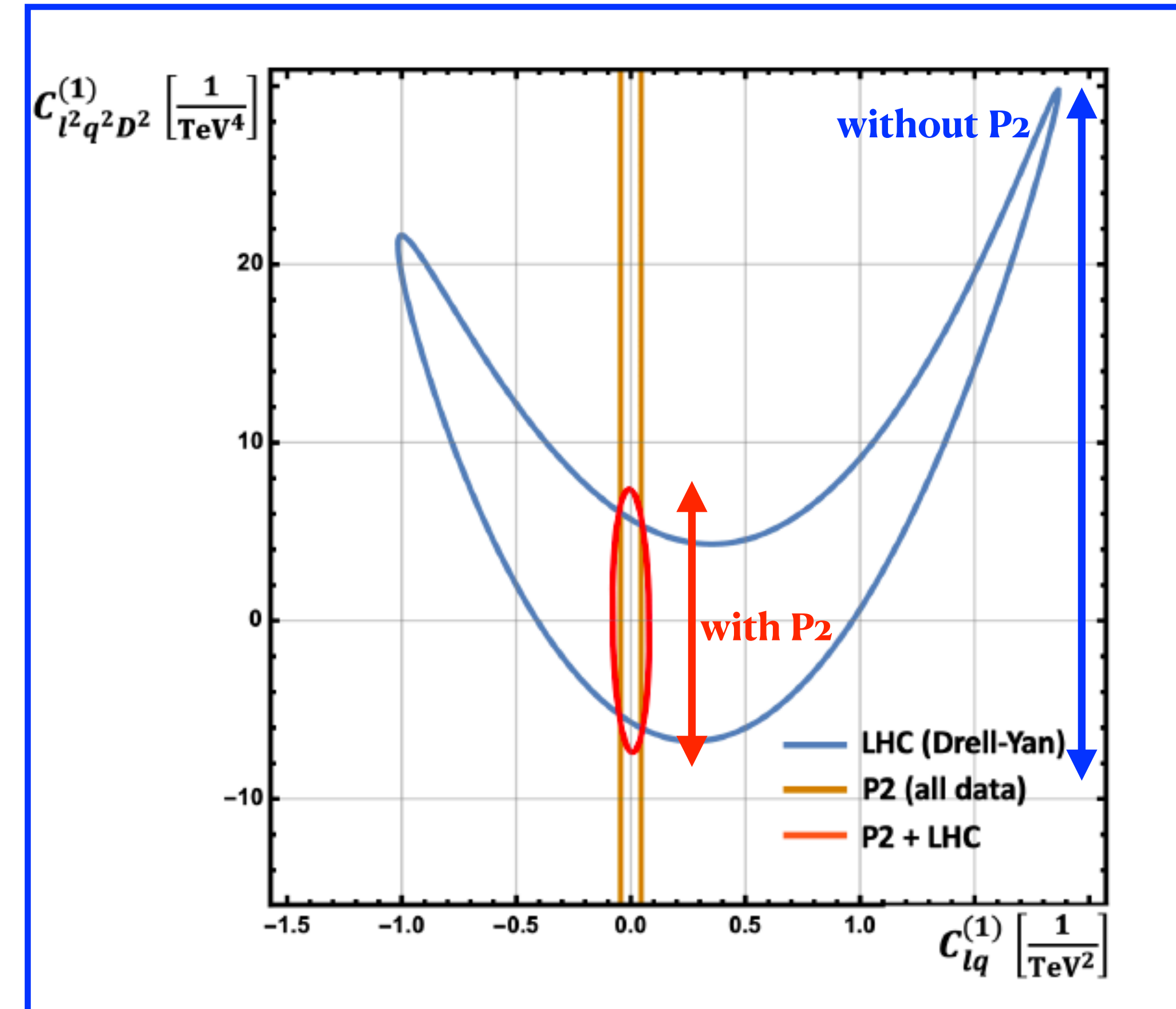
$(ee)(qq)$

	$[c_{\ell q}^{(3)}]_{1111}$	$[c_{\ell q}]_{1111}$	$[c_{\ell u}]_{1111}$	$[c_{\ell d}]_{1111}$	$[c_{eq}]_{1111}$	$[c_{eu}]_{1111}$	$[c_{ed}]_{1111}$
CHARM	-80 ± 180	700 ± 1800	370 ± 880	-700 ± 1800	x	x	x
APV	27 ± 19	1.6 ± 1.1	3.4 ± 2.3	3.0 ± 2.0	-1.6 ± 1.1	-3.4 ± 2.3	-3.0 ± 2.0
QWEAK	7.0 ± 12	-2.3 ± 4.0	-3.5 ± 6.0	-7 ± 12	2.3 ± 4.0	3.5 ± 6.0	7 ± 12
PVDIS	-8 ± 12	24 ± 35	38 ± 48	-77 ± 96	-77 ± 96	-12 ± 17	24 ± 35
SAMPLE	-8 ± 45	x	-17 ± 90	17 ± 90	x	-17 ± 90	17 ± 90
$d_j \rightarrow ul\nu$	0.38 ± 0.28	x	x	x	x	x	x
LEP-2	3.5 ± 2.2	-42 ± 28	-21 ± 14	42 ± 28	-18 ± 11	-9.0 ± 5.7	18 ± 11

$(\mu\mu)(qq)$

	$[c_{\ell q}^{(3)}]_{2211}$	$[c_{\ell q}]_{2211}$	$[c_{\ell u}]_{2211}$	$[c_{\ell d}]_{2211}$	$[c_{eq}]_{2211}$	$[c_{eu}]_{2211}$	$[c_{ed}]_{2211}$
PDG ν_μ	20 ± 15	4 ± 21	18 ± 19	-20 ± 37	x	x	x
SPS	0 ± 1000	0 ± 3000	0 ± 1500	0 ± 3000	40 ± 390	-20 ± 190	40 ± 390
$d_j \rightarrow ul\nu$	-0.4 ± 1.2	x	x	x	x	x	x

Falkowski, Gonzalez-Alonso, Mimouni (2017)



RB, Petriello, Wiegand (2021)

Operator basis

- The relevant four-fermion operators consist of 7 dim-6 and 14 dim-8 operators.

Dimension 6		Dimension 8		Dimension 8
$\mathcal{O}_{lq}^{(1)}$	$(\bar{l}\gamma^\mu l)(\bar{q}\gamma_\mu q)$	$\mathcal{O}_{l^2q^2D^2}^{(1)}$	$D^\nu(\bar{l}\gamma^\mu l)D_\nu(\bar{q}\gamma_\mu q)$	$\mathcal{O}_{8,ed\partial^2} = (\bar{e}\gamma_\mu \overleftrightarrow{D}_\nu e)(\bar{d}\gamma^\mu \overleftrightarrow{D}^\nu d),$
$\mathcal{O}_{lq}^{(3)}$	$(\bar{l}\gamma^\mu \tau^i l)(\bar{q}\gamma_\mu \tau^i q)$	$\mathcal{O}_{l^2q^2D^2}^{(3)}$	$D^\nu(\bar{l}\gamma^\mu \tau^i l)D_\nu(\bar{q}\gamma_\mu \tau^i q)$	$\mathcal{O}_{8,eu\partial^2} = (\bar{e}\gamma_\mu \overleftrightarrow{D}_\nu e)(\bar{u}\gamma^\mu \overleftrightarrow{D}^\nu u),$
\mathcal{O}_{eu}	$(\bar{e}\gamma^\mu e)(\bar{u}\gamma_\mu u)$	$\mathcal{O}_{e^2u^2D^2}^{(1)}$	$D^\nu(\bar{e}\gamma^\mu e)D_\nu(\bar{u}\gamma_\mu u)$	$\mathcal{O}_{8,ld\partial^2} = (\bar{l}\gamma_\mu \overleftrightarrow{D}_\nu l)(\bar{d}\gamma^\mu \overleftrightarrow{D}^\nu d),$
\mathcal{O}_{ed}	$(\bar{e}\gamma^\mu e)(\bar{d}\gamma_\mu d)$	$\mathcal{O}_{e^2d^2D^2}^{(1)}$	$D^\nu(\bar{e}\gamma^\mu e)D_\nu(\bar{d}\gamma_\mu d)$	$\mathcal{O}_{8,lu\partial^2} = (\bar{l}\gamma_\mu \overleftrightarrow{D}_\nu l)(\bar{u}\gamma^\mu \overleftrightarrow{D}^\nu u),$
\mathcal{O}_{lu}	$(\bar{l}\gamma^\mu l)(\bar{u}\gamma_\mu u)$	$\mathcal{O}_{l^2u^2D^2}^{(1)}$	$D^\nu(\bar{l}\gamma^\mu l)D_\nu(\bar{u}\gamma_\mu u)$	$\mathcal{O}_{8,qe\partial^2} = (\bar{e}\gamma_\mu \overleftrightarrow{D}_\nu e)(\bar{q}\gamma^\mu \overleftrightarrow{D}^\nu q).$
\mathcal{O}_{ld}	$(\bar{l}\gamma^\mu l)(\bar{d}\gamma_\mu d)$	$\mathcal{O}_{l^2d^2D^2}^{(1)}$	$D^\nu(\bar{l}\gamma^\mu l)D_\nu(\bar{d}\gamma_\mu d)$	$\mathcal{O}_{8,lq\partial^3} = (\bar{l}\gamma_\mu \overleftrightarrow{D}_\nu l)(\bar{q}\gamma^\mu \overleftrightarrow{D}^\nu q),$
\mathcal{O}_{qe}	$(\bar{q}\gamma^\mu q)(\bar{e}\gamma_\mu e)$	$\mathcal{O}_{q^2e^2D^2}^{(1)}$	$D^\nu(\bar{q}\gamma^\mu q)D_\nu(\bar{e}\gamma_\mu e)$	$\mathcal{O}_{8,lq\partial^4} = (\bar{l}\tau^I \gamma_\mu \overleftrightarrow{D}_\nu l)(\bar{q}\tau^I \gamma^\mu \overleftrightarrow{D}^\nu q)$

Relevant operators for our analysis; note q,l are left-handed doublets; e,u,d are right-handed singlets

Operator basis

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

Dawson, Giardino (2019)

$$O_{\varphi\ell}^{(1)} = (\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi) (\bar{\ell} \gamma^\mu \ell)$$

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

$$O_{\varphi e} = (\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi) (\bar{e} \gamma^\mu e)$$

$$O_{\varphi q}^{(1)} = (\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi) (\bar{q} \gamma^\mu q)$$

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

$$O_{\varphi u} = (\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi) (\bar{u} \gamma^\mu u)$$

$$O_{\varphi d} = (\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi) (\bar{d} \gamma^\mu d)$$

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

Other operators contribute as well, and shift the ffV vertices

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

Invariant mass and A_{FB} constraints

- We study constraints from existing data sets: invariant mass distributions and forward-backward asymmetries. Measurements at 13 TeV correspond to high integrated luminosity. The relevant data sets from ATLAS and CMS are summarized below.

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)	200-2210 GeV (ee)	[25]
				140 fb ⁻¹ ($\mu\mu$)	210-2290 GeV ($\mu\mu$)	
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]

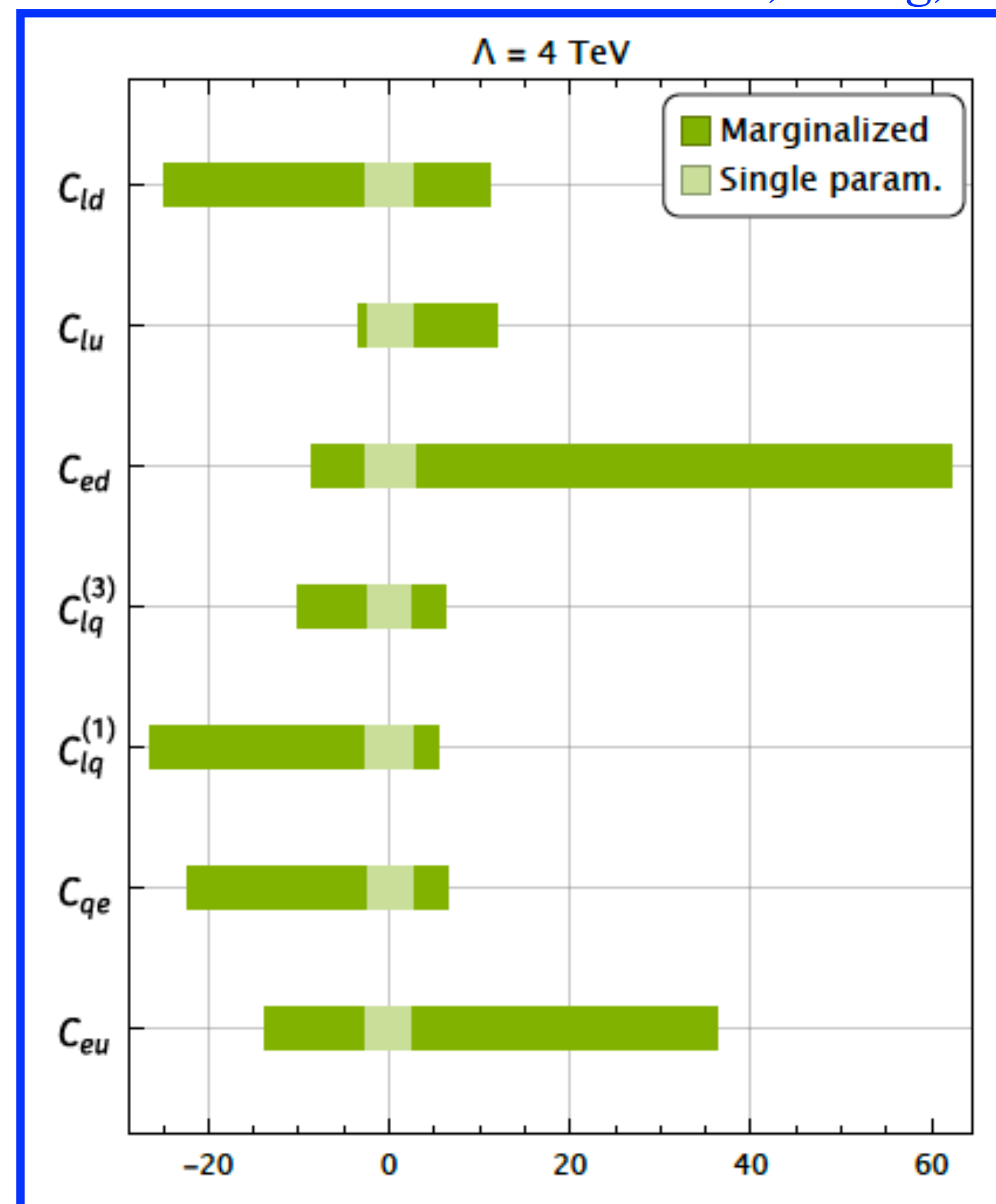
Excellent test case for how well LHC covers the SMEFT;
 significant high-luminosity, high-quality data

Single parameter vs. marginalized fits

- We begin with a fit to the linear dimension-6 SMEFT basis. There are seven relevant semi-leptonic four-fermion Wilson coefficients with this assumption. We first consider single-parameter versus 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}	$(\bar{q}\gamma^\mu q)(\bar{e}\gamma_\mu e)$

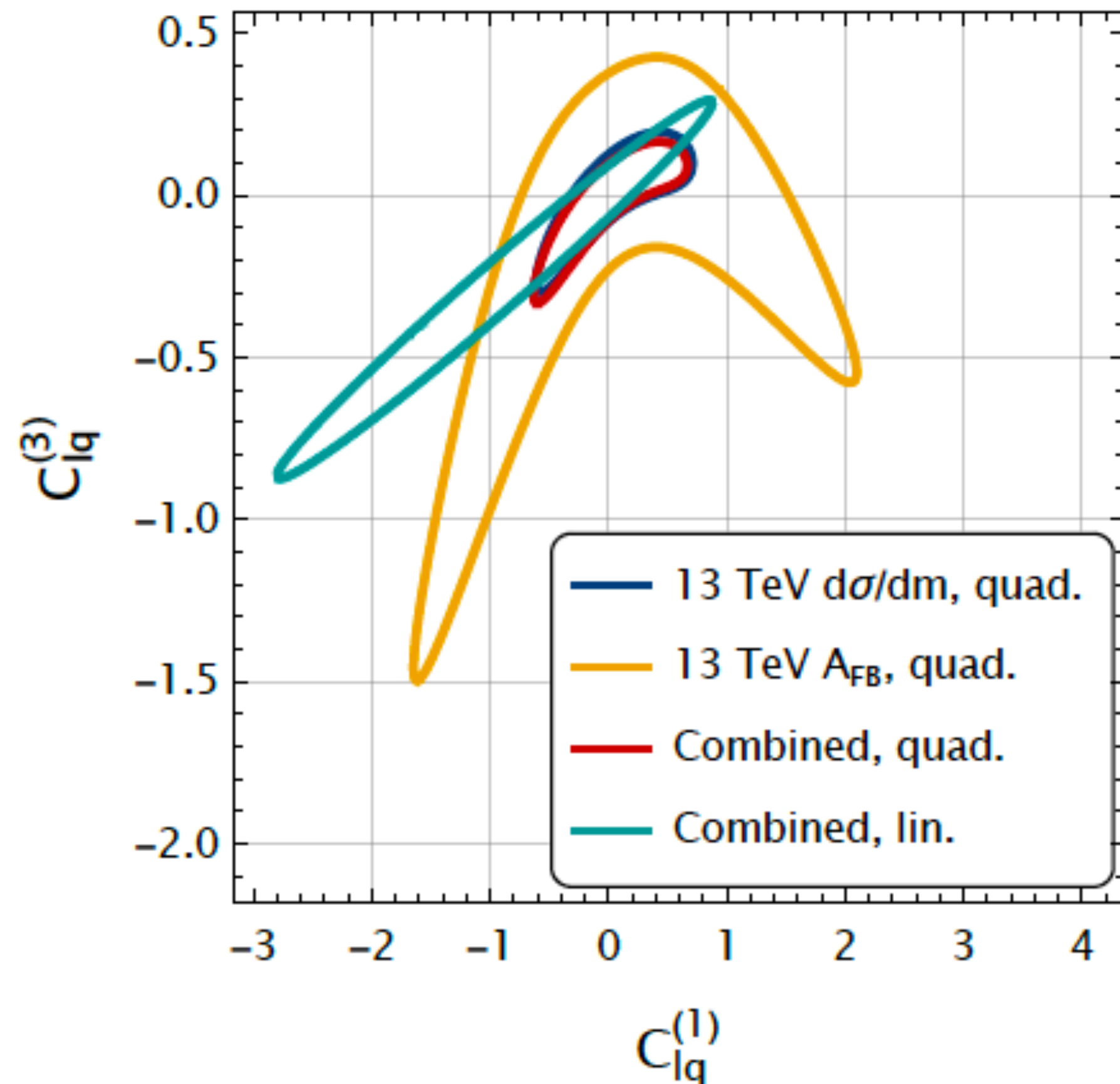


There is a significant difference between the single-parameter and marginalized fits, indicating the need to turn all Wilson coefficients on simultaneously

Linear vs. quadratic fits

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

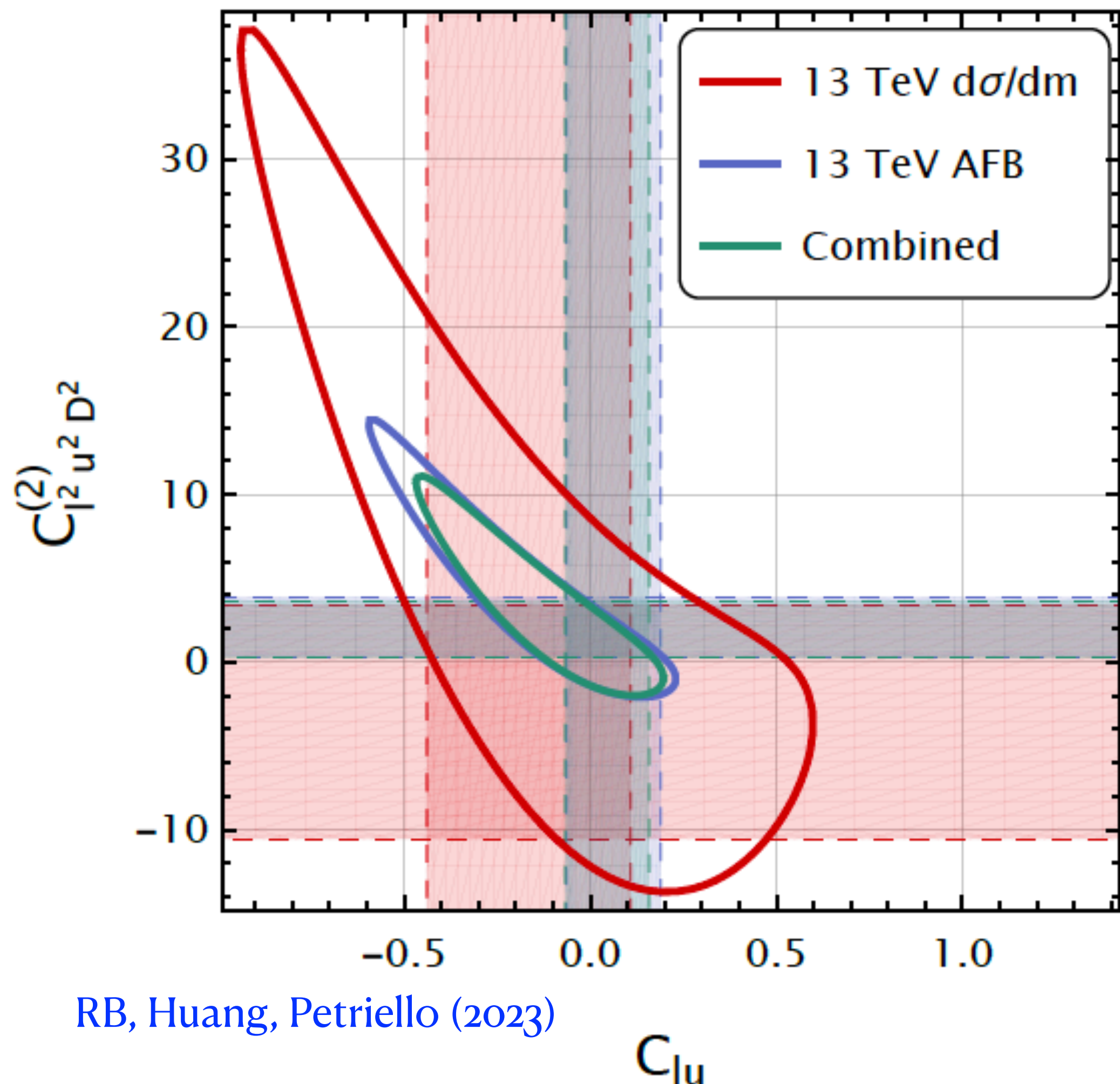
RB, Huang, Petriello (2023) $\Lambda = 4 \text{ TeV}$



- 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.



- 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} !
- RG running has minimal impact on these fits [RB, Huang, Petriello \(2024\)](#)

[RB, Huang, Petriello \(2023\)](#)

This is with all the relevant LHC DY data!

What have we learned so far?

- Single-parameter fits give bounds significantly different than those obtained from a full fit.
- The use of all available data is needed to help reduce degeneracies in the parameter space.
- Quadratic dimension-6 terms can have an important impact on SMEFT fits.
- Dimension-8 terms can have an important effect in fits (this is model-dependent: studies with certain Z' models matched to SMEFT indicate little impact from dimension-8 effects [RB, Huang, Petriello \(2024\)](#); [Dawson, Forsslund, Schnubel \(2024\)](#))

The LHC alone isn't enough to fully cover the parameter space, degeneracies exist between dim6 coefficients themselves and between dim6 and dim8.

Future electron-hadron experiments

- Another possibility of probing the SMEFT parameter space is with future DIS experiments. A host of facilities spanning low and high energies are planned for both the near and far future.

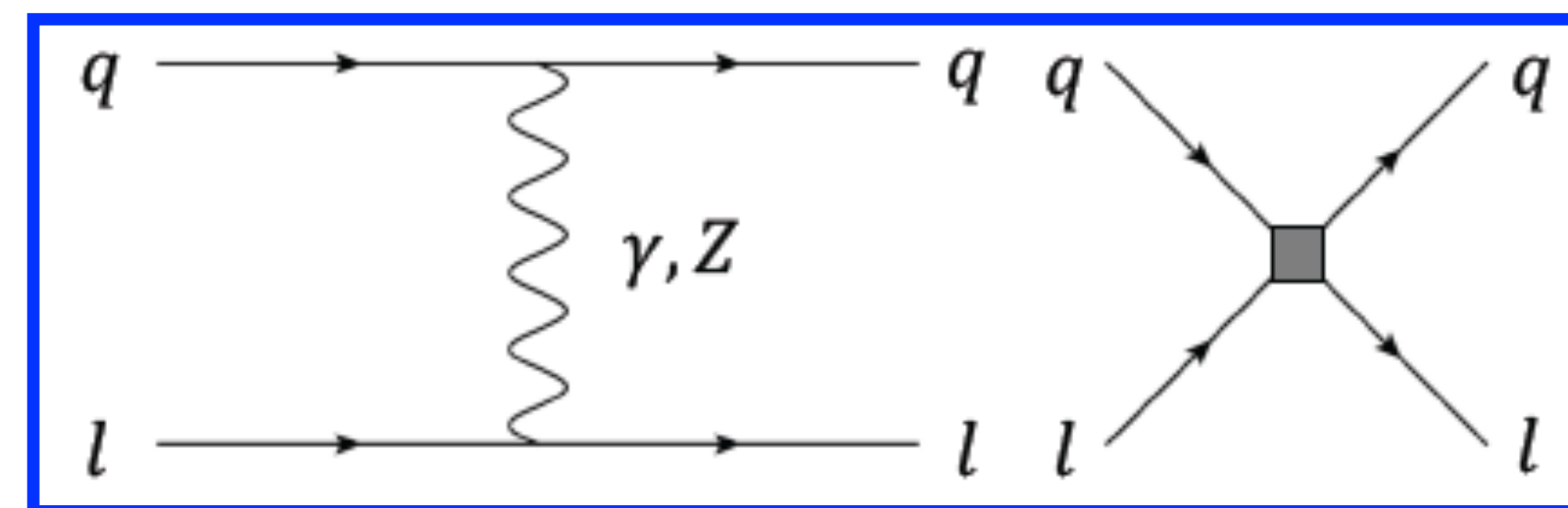
High energy DIS:

- Electron-Ion Collider (EIC): $\sqrt{s} \sim 140 \text{ GeV}$
- Future Circular Collider (FCC-eh): $\sqrt{s} \sim 3.4 \text{ TeV}$
- Large Hadron Electron Collider (LHeC): $\sqrt{s} \sim 1.3 \text{ TeV}$

Sensitive to the same operators as the Drell-Yan process at the LHC

Low energy PVES:

- Solenoidal Large Intensity Device (SoLID) at Jlab ($2 < Q^2 < 10 \text{ GeV}^2$, electron-deuteron scattering)
- P2 at Mainz (155 MeV electrons off hydrogen/carbon targets)



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A key feature shared by all of these experiments is the ability to polarize beams; a key distinction from the LHC!

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

Disentangle Wilson coefficients with polarization

SMEFT probes at the EIC

Key features of the EIC

- In our analysis of SMEFT at the EIC we assume the following run parameters:

Deuteron beam:

Proton beam:

D1	5 GeV × 41 GeV <i>eD</i> , 4.4 fb ⁻¹	P1	5 GeV × 41 GeV <i>ep</i> , 4.4 fb ⁻¹
D2	5 GeV × 100 GeV <i>eD</i> , 36.8 fb ⁻¹	P2	5 GeV × 100 GeV <i>ep</i> , 36.8 fb ⁻¹
D3	10 GeV × 100 GeV <i>eD</i> , 44.8 fb ⁻¹	P3	10 GeV × 100 GeV <i>ep</i> , 44.8 fb ⁻¹
D4	10 GeV × 137 GeV <i>eD</i> , 100 fb ⁻¹	P4	10 GeV × 275 GeV <i>ep</i> , 100 fb ⁻¹
D5	18 GeV × 137 GeV <i>eD</i> , 15.4 fb ⁻¹	P5	18 GeV × 275 GeV <i>ep</i> , 15.4 fb ⁻¹
		P6	18 GeV × 275 GeV <i>ep</i> , 100 fb ⁻¹

Additionally assume 70%
hadron beam
polarization, 80% electron
beam polarization

- Allows us to study the interplay between high energy/low luminosity (for example, P₅) versus low energy/high luminosity (for example, P₄).
- 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.

Observables at the EIC

- The ability to polarize both beams at the EIC, and potentially swap an electron beam for a positron beam, leads to a host of observables.

- Polarized electrons, unpolarized hadrons:

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

- Unpolarized electrons, polarized hadrons:

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

- Lepton charge asymmetries:

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

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

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

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

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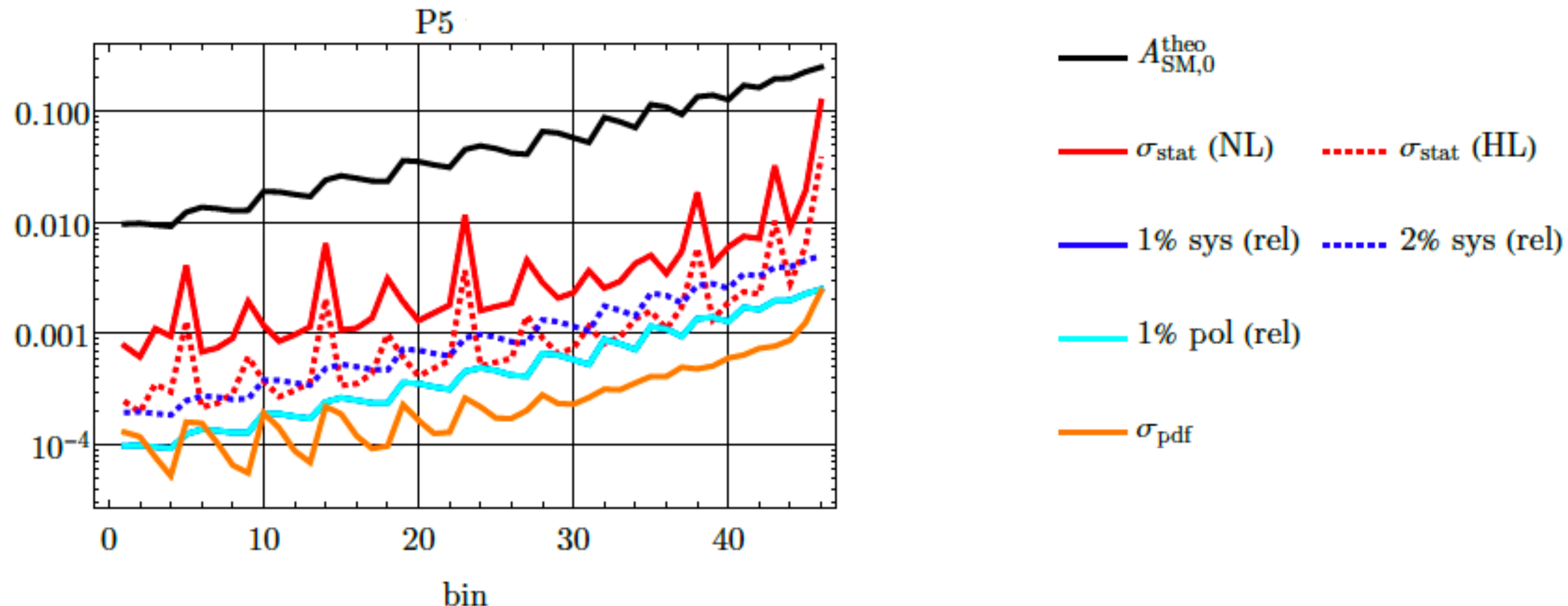
Simulation details:

- Smearing, bin migration accounted for
- Inelasticity cuts: $y > 0.1$, $y < 0.9$
- $x < 0.5$, $Q > 10$ GeV to avoid uncertainties from non-perturbative QCD and nuclear dynamics

Error budget example: unpolarized protons

- As an example of the expected EIC errors we will study the error budget for P5, the unpolarized high-energy proton scenario.
- 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

RB, Emmert, Kutz, Mantry, Nycz, Petriello, Simsek, Wiegand, Zheng, 2022



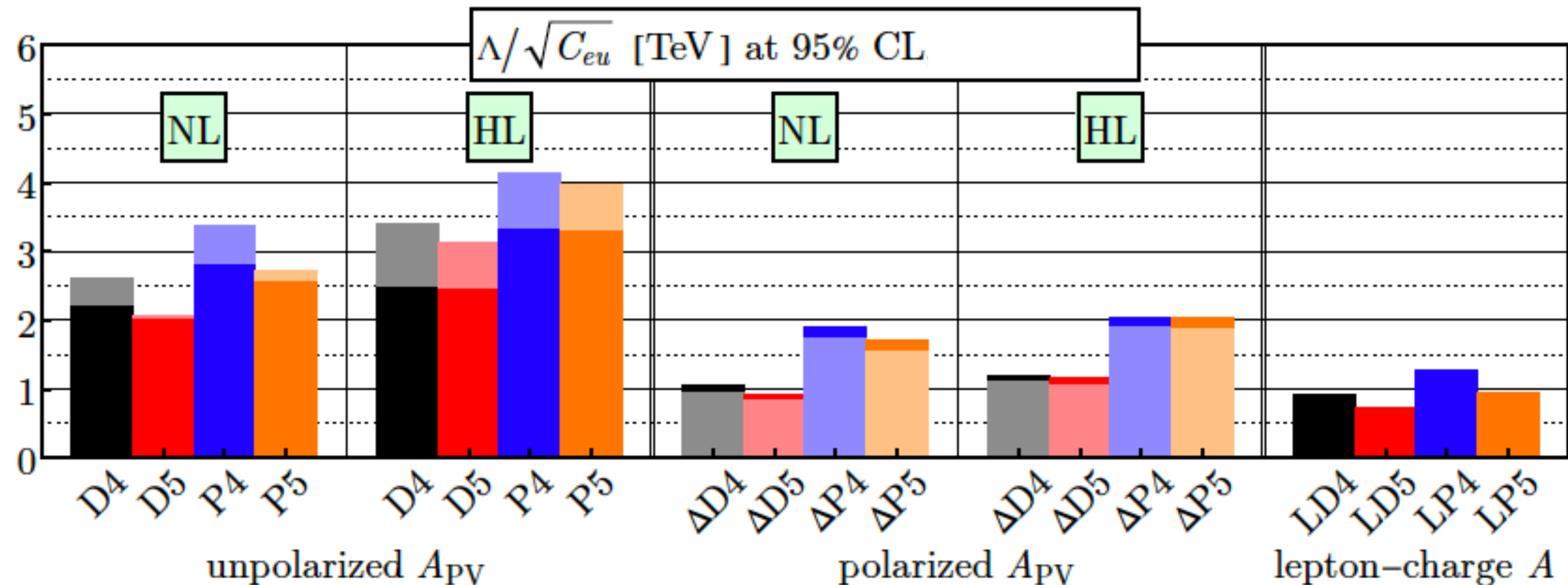
Statistical uncertainties dominant with nominal luminosity; systematic errors more relevant at high luminosity; PDF errors negligible. Asymmetry much larger than all uncertainties.

Single-parameter fits

- We will first consider the single-parameter fits, to understand the scales that can be probed at an EIC.

RB, Emmert, Kutz, Mantry, Nycz, Petriello, Simsek, Wiegand, Zheng, 2022

Note: lighter histograms obtained by fitting polarization uncertainty as a nuisance parameter in the fit; results in stronger constraints for polarized lepton cases



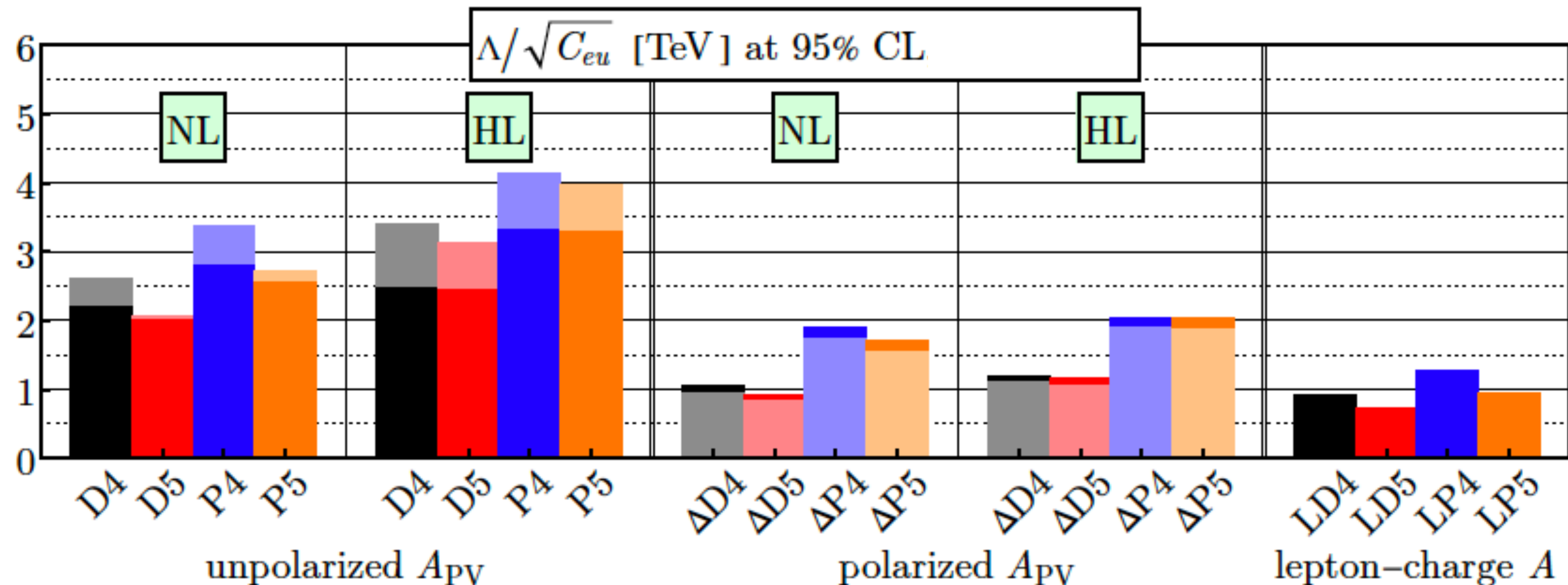
Trends:

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

Single-parameter fits

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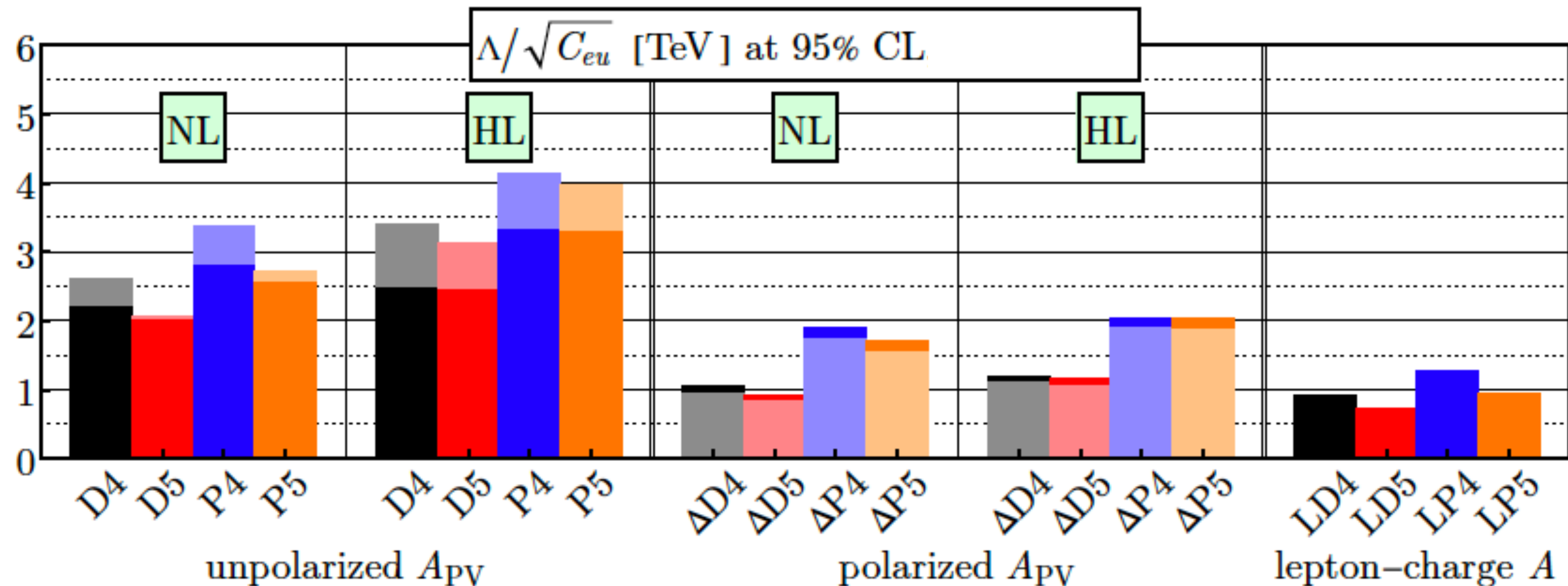
RB, Emmert, Kutz, Mantry, Nycz, Petriello, Simsek, Wiegand, Zheng, 2022



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

Single-parameter fits

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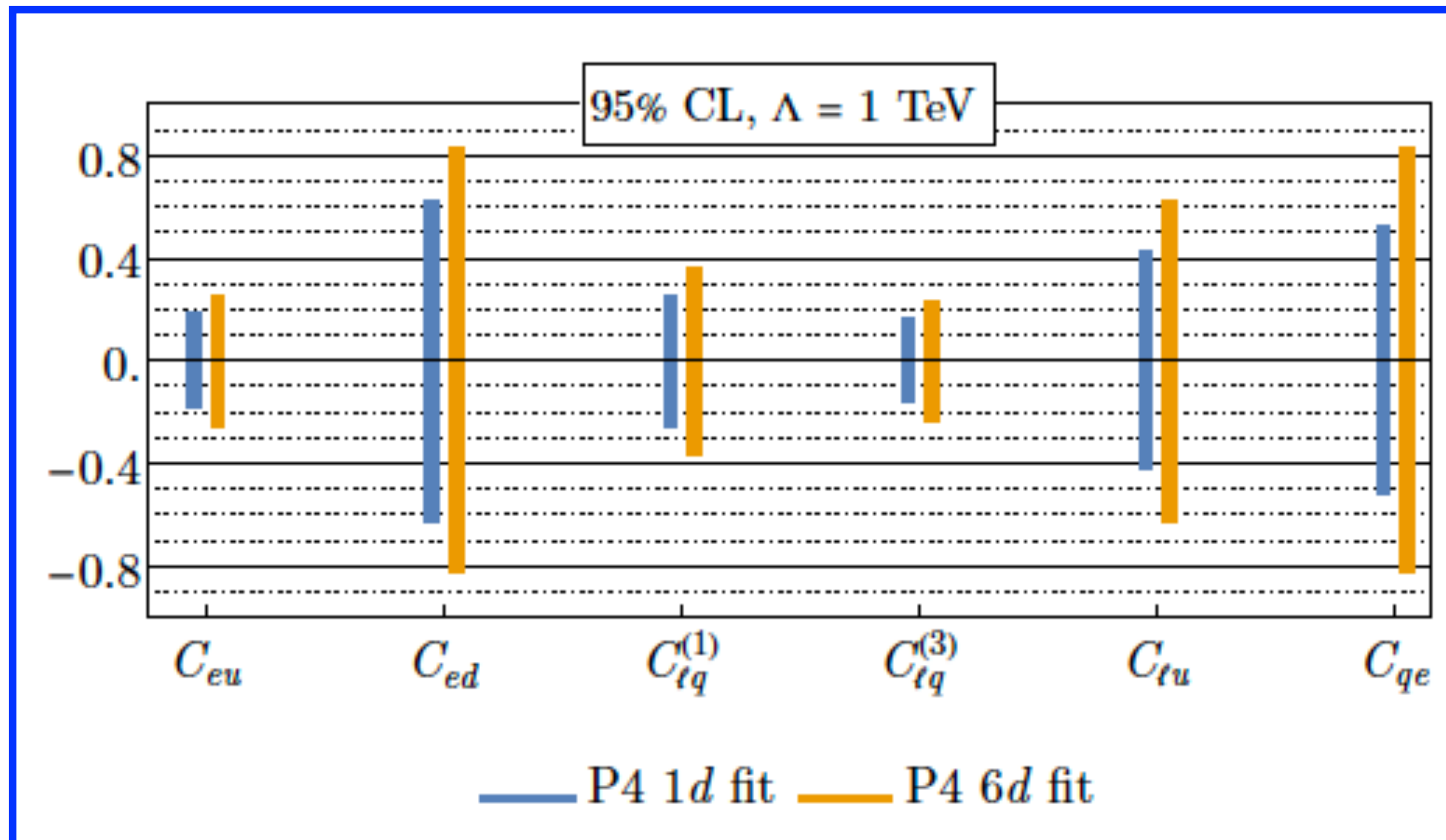
We have performed this study at dimension-6. Note that the Λ/\sqrt{C} bounds are much greater than the momentum transfer $Q < 50$ GeV. The expansion parameter $CQ^2/\Lambda^2 \ll 1$ unlike at the LHC, indicating that dim-8 is suppressed.

Allows us to focus on dim-6 without contamination with dim-8!

Multi-parameter fits

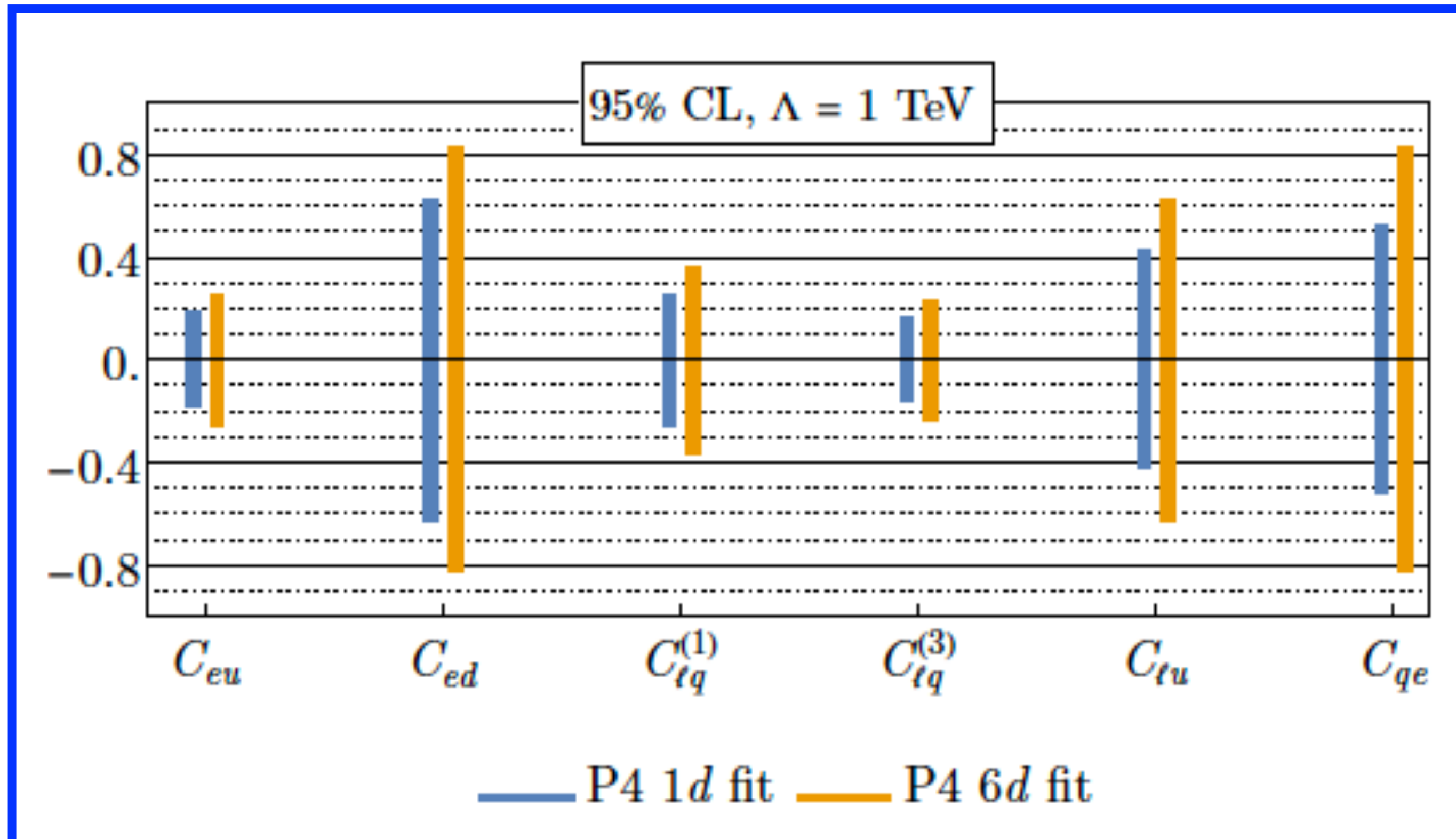
- We can turn on more Wilson coefficients to test for degeneracies and check for degradation of the bounds. Only slightly weaker bounds in a 6-dimensional fit. **The EIC can probe the full parameter space of semi-leptonic four-fermion Wilson coefficients.**

RB et al (2022)

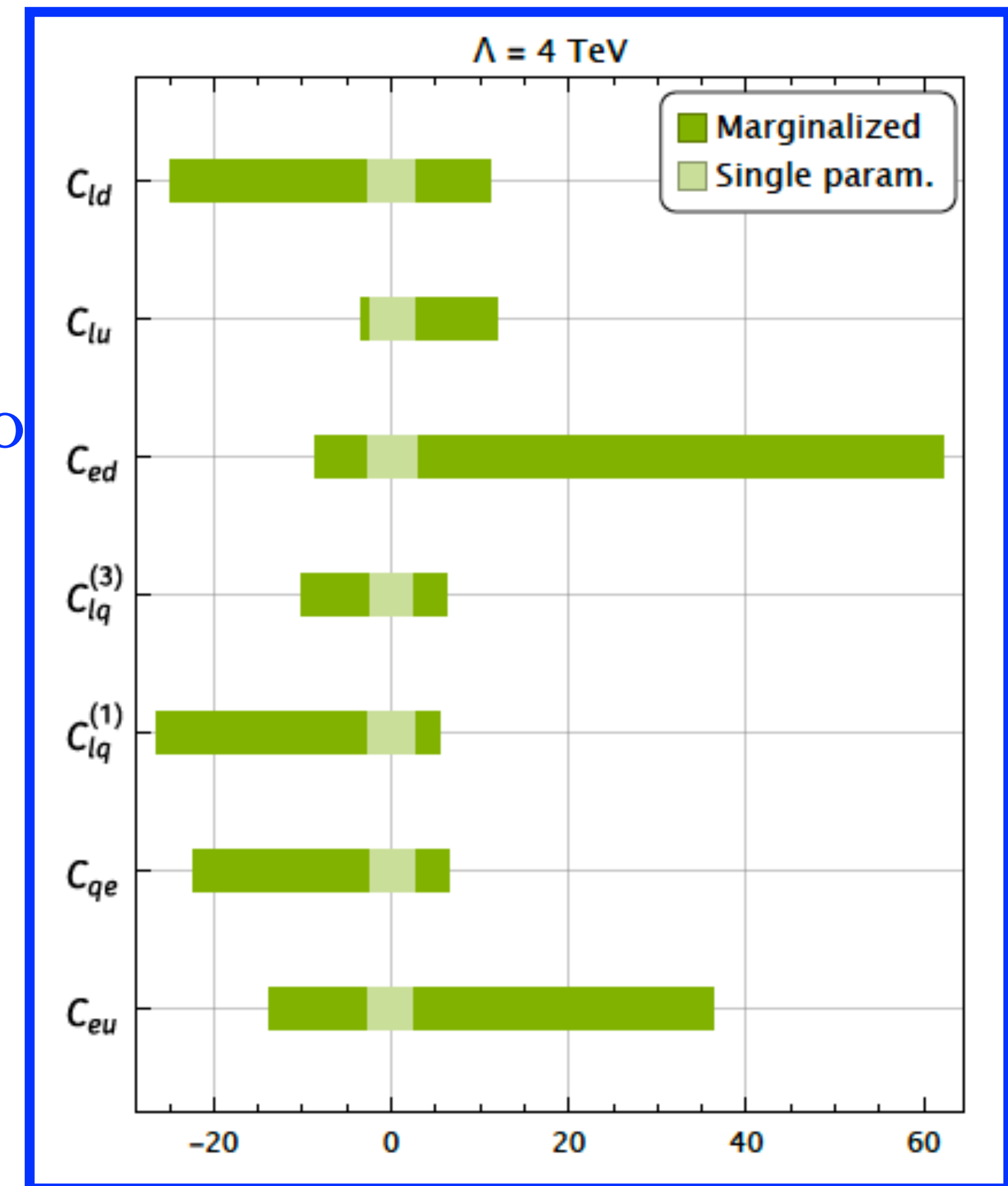


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Compare to the LHC:



Future high-energy DIS experiments (LHeC/FCC-eh)

Comparison of future high-energy DIS machines

- Next we turn our attention to proposed future DIS machines such as the LHeC and the FCC-eh. We will compare the potential of the EIC with these future machines.

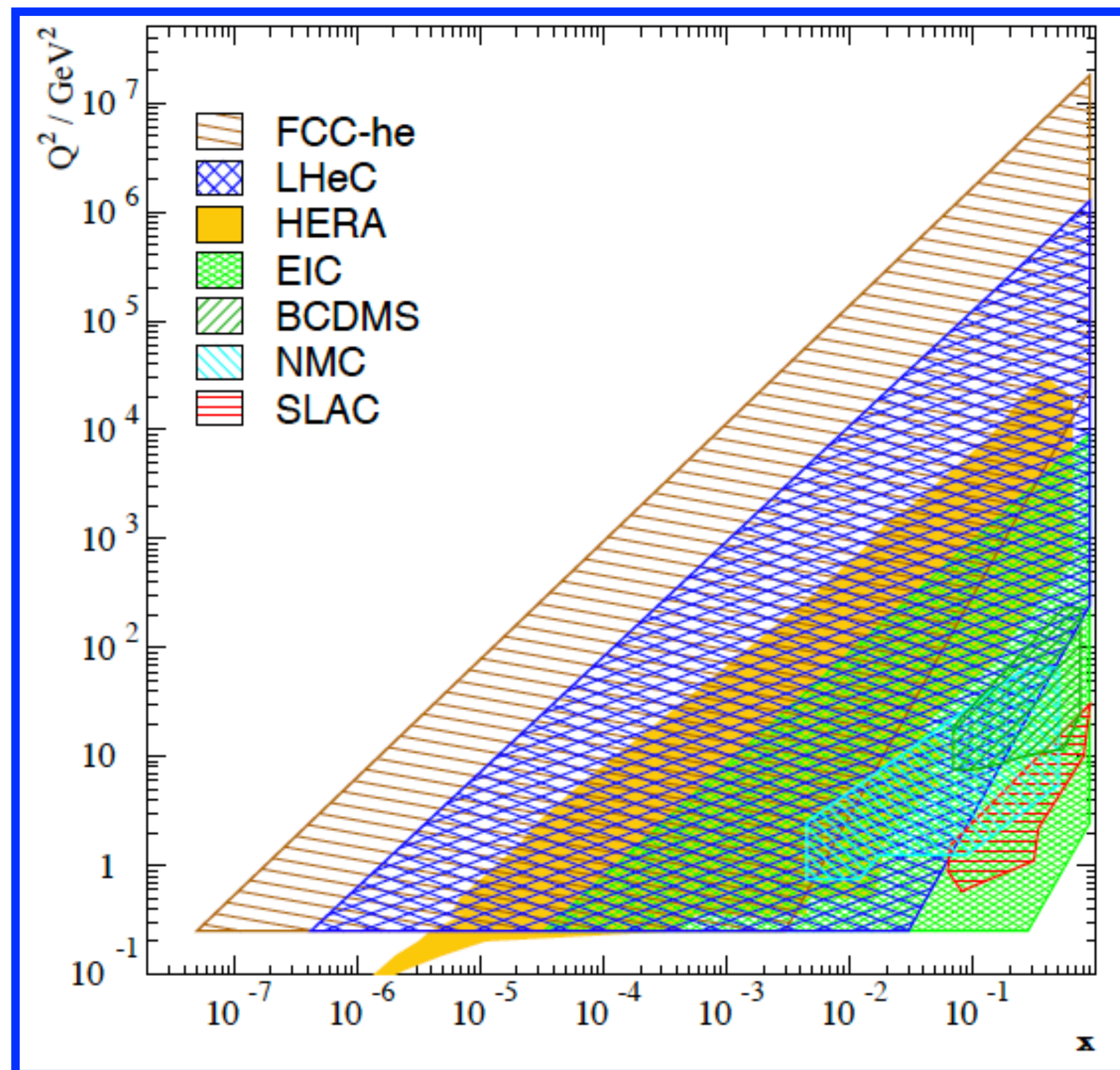
Experiment	Data set label	Data set configuration	Observable
LHeC	LHeC1	60 GeV \times 1000 GeV e^-p , $P_\ell = 0$, $\mathcal{L} = 100 \text{ fb}^{-1}$	σ_{NC}
	LHeC2	60 GeV \times 7000 GeV e^-p , $P_\ell = -80\%$, $\mathcal{L} = 100 \text{ fb}^{-1}$	
	LHeC3	60 GeV \times 7000 GeV e^-p , $P_\ell = +80\%$, $\mathcal{L} = 30 \text{ fb}^{-1}$	
	LHeC4	60 GeV \times 7000 GeV e^+p , $P_\ell = +80\%$, $\mathcal{L} = 10 \text{ fb}^{-1}$	
	LHeC5	60 GeV \times 7000 GeV e^-p , $P_\ell = -80\%$, $\mathcal{L} = 1000 \text{ fb}^{-1}$	
	LHeC6	60 GeV \times 7000 GeV e^-p , $P_\ell = +80\%$, $\mathcal{L} = 300 \text{ fb}^{-1}$	
	LHeC7	60 GeV \times 7000 GeV e^+p , $P_\ell = 0\%$, $\mathcal{L} = 100 \text{ fb}^{-1}$	
FCC-eh	FCCeh1	60 GeV \times 50000 GeV e^-p , $P_\ell = -80\%$, $\mathcal{L} = 2 \text{ ab}^{-1}$	σ_{NC}
	FCCeh2	60 GeV \times 50000 GeV e^-p , $P_\ell = +80\%$, $\mathcal{L} = 0.5 \text{ ab}^{-1}$	
	FCCeh3	60 GeV \times 50000 GeV e^+p , $P_\ell = 0$, $\mathcal{L} = 0.2 \text{ ab}^{-1}$	
EIC	D4	10 GeV \times 137 GeV e^-D , $P_\ell = 80\%$, $\mathcal{L} = 100 \text{ fb}^{-1}$	A_{PV}
	D5	18 GeV \times 137 GeV e^-D , $P_\ell = 80\%$, $\mathcal{L} = 15.4 \text{ fb}^{-1}$	
	P4	10 GeV \times 275 GeV e^-p , $P_\ell = 80\%$, $\mathcal{L} = 100 \text{ fb}^{-1}$	
	P5	18 GeV \times 275 GeV e^-p , $P_\ell = 80\%$, $\mathcal{L} = 15.4 \text{ fb}^{-1}$	
	Δ D4	The same as D4 but with $P_\ell = 0$ and $P_H = 70\%$	ΔA_{PV}
	Δ D5	The same as D5 but with $P_\ell = 0$ and $P_H = 70\%$	
	Δ P4	The same as P4 but with $P_\ell = 0$ and $P_H = 70\%$	
	Δ P5	The same as P5 but with $P_\ell = 0$ and $P_H = 70\%$	

Note different polarizations, lepton species (e^+ vs e^-).

LHeC, FCC-eh run scenarios taken from the literature. All three machines feature high luminosity, polarization

LHeC: a future high-energy DIS experiment

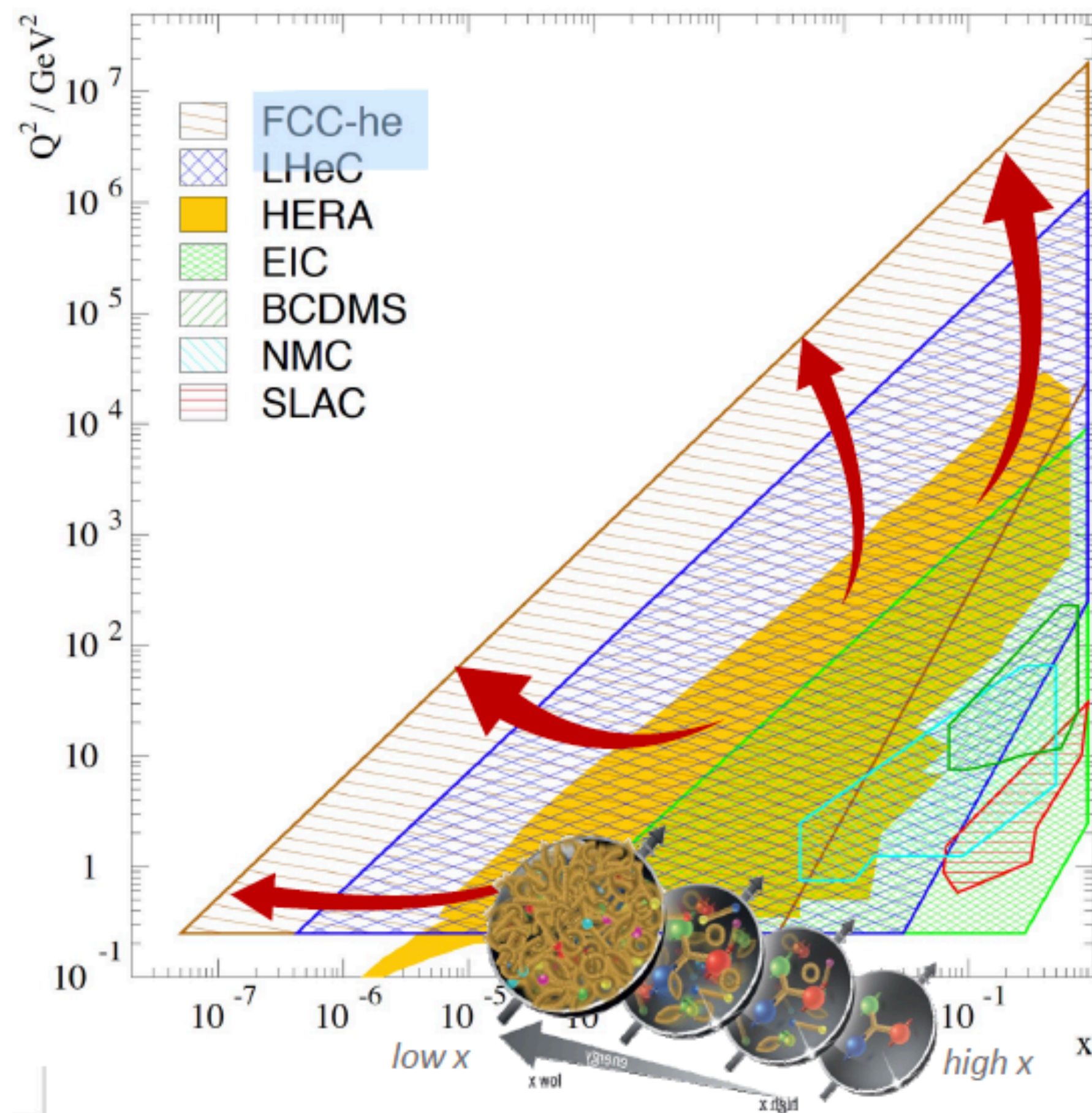
- **LHeC** (updated CDR: 2007.14491): a potential future high-energy DIS experiment based on the existing LHC experiment



- Would feature a 50 GeV electron beam scattering off existing LHC proton/ion beams with a center-of mass energy reaching 1.5 TeV; concurrent operation with HL-LHC possible
- The integrated luminosity of such a machine could reach 1000 fb⁻¹
- Momentum transfers exceeding 1 TeV
- Increased coverage in the (x, Q²) plane
- The possibility of polarizing the proton beam isn't considered, since the LHeC will reuse the LHC beam

FCC-eh: a second future high-energy DIS experiment

- **FCC-eh**: a proposed DIS experiment based upon a future circular collider complex at CERN

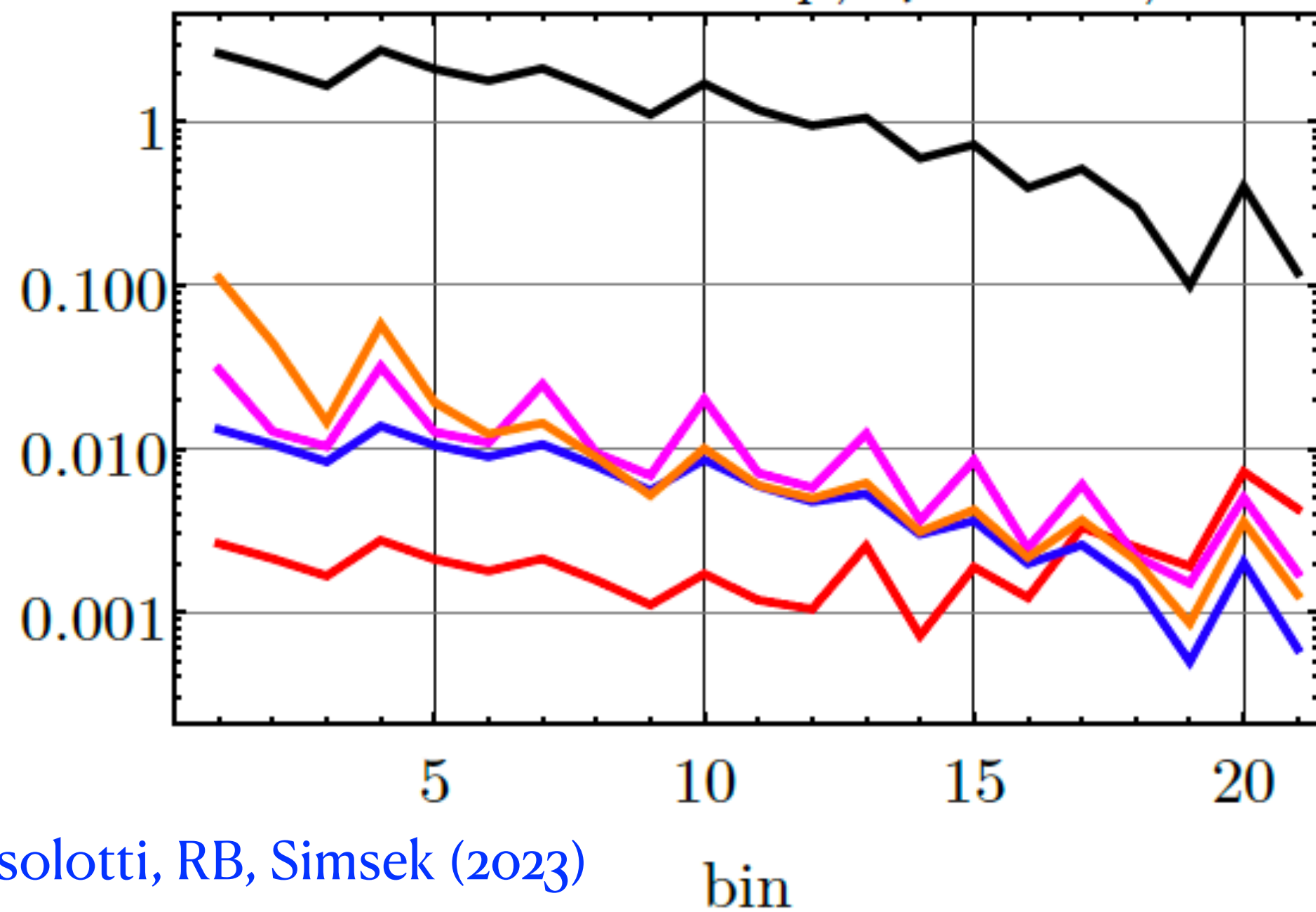


- Features a 60 GeV electron beam leading to a center-of mass energy of 3.5 TeV
- Up to several inverse attobarns of integrated luminosity
- Momentum transfers reaching 1.5 TeV
- Increased coverage in the (x, Q^2) plane

Error budgets for LHeC, FCC-eh

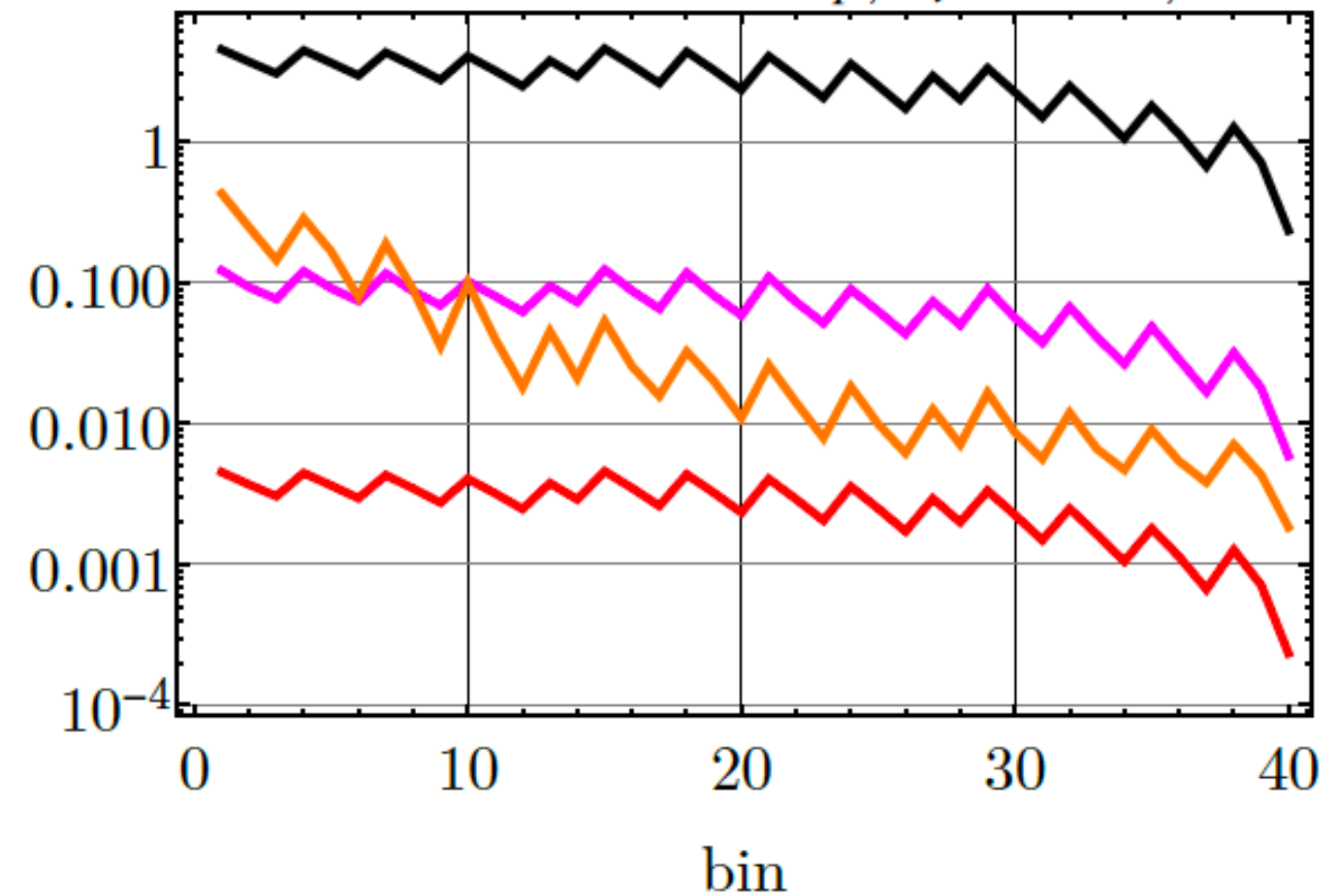
- Both future machines will be limited by systematic errors (purple lines in the plots below). Note that the estimated PDF errors (orange lines) are equal to or less than the systematic errors in most phase space. NLO QCD is included, error from NNLO negligible.

LHeC3: 60 GeV \times 7000 GeV $e^- p$, $P_t = +80\%$, $\mathcal{L} = 30 \text{ fb}^{-1}$



Bissolotti, RB, Simsek (2023)

FCCeh1: 60 GeV \times 50000 GeV $e^- p$, $P_t = -80\%$, $\mathcal{L} = 2 \text{ ab}^{-1}$



■ σ_{NC} ■ $\sigma_{\text{NC,stat}}$ ■ $\sigma_{\text{NC,ueff}}$ ■ $\sigma_{\text{NC,sys}}$ ■ $\sigma_{\text{NC,pdf}}$

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Marginalized constraints

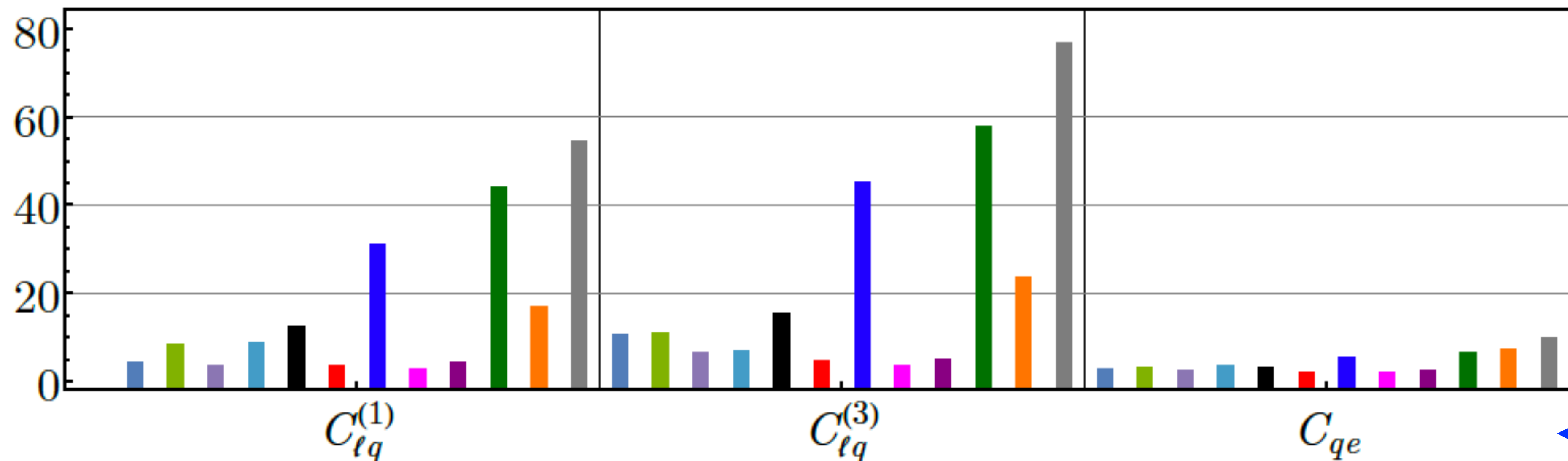
- Note that future machines do not suffer from parameter space degeneracies like the LHC. To show this we focus on an example where the SMEFT corrections to three run scenarios (LHeC2, LHeC4, LHeC5) approximately vanish, still focusing on four-fermion interactions.

$$\Lambda/\sqrt{C_k} \text{ [TeV] at 95\% CL, 3d fit}$$

Bissolotti, RB, Simsek (2023)

$$P_\ell = -80\%, C_{eu} \approx -13(C_{\ell q}^{(1)} - C_{\ell q}^{(3)}), C_{tu} \approx -0.052 C_{qe}, C_{ed} \approx -22(C_{\ell q}^{(1)} + C_{\ell q}^{(3)}), C_{td} \approx 0.12 C_{qe}$$

Fix these four; numbers come from combinations of SM EW couplings and correspond to the LHeC degeneracy



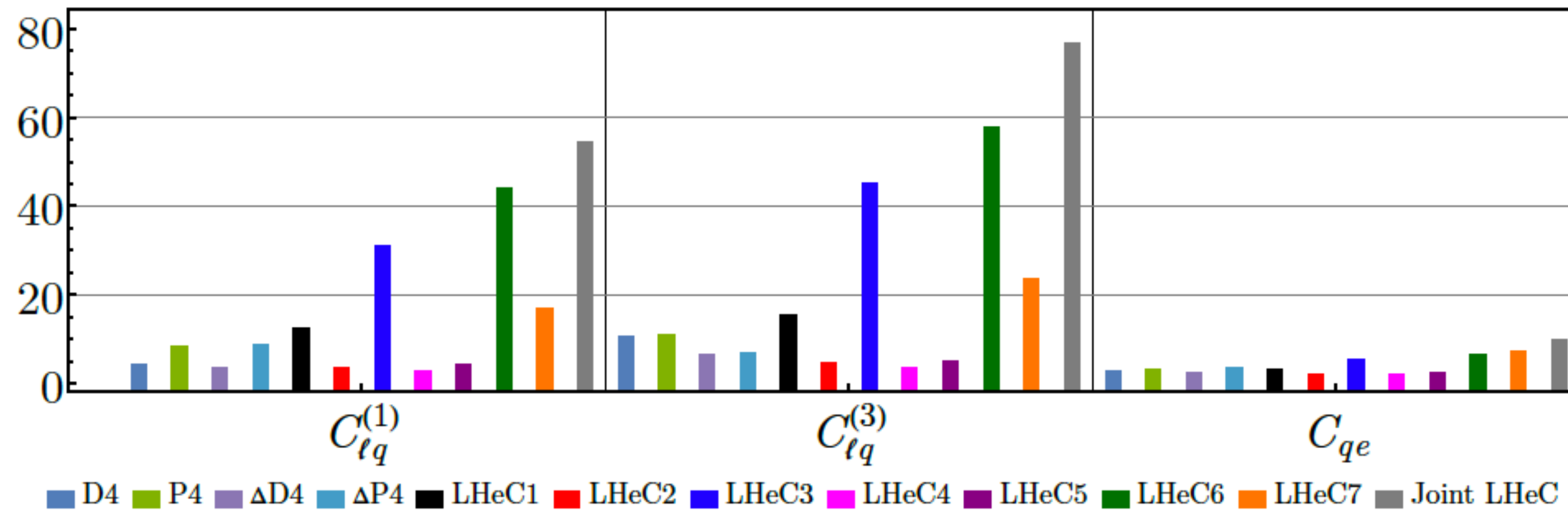
Fit these three

Marginalized constraints

$$\Lambda/\sqrt{C_k} \text{ [TeV] at 95\% CL, 3d fit}$$

Bissolotti, RB, Simsek (2023)

$$P_\ell = -80\%, C_{eu} \approx -13(C_{\ell q}^{(1)} - C_{\ell q}^{(3)}), C_{tu} \approx -0.052 C_{qe}, C_{ed} \approx -22(C_{\ell q}^{(1)} + C_{\ell q}^{(3)}), C_{td} \approx 0.12 C_{qe}$$



- Combined bounds on the effective UV scale from all LHeC runs reach at least 10 TeV for all three coefficients, 70 TeV for the strongest.
- **Note:** the effective UV scale probed is greater than the 1-1.5 TeV momentum transfer reached by these experiments; EFT expansion is valid and appropriate.
- Need all polarization, lepton species to cover the parameter space! No single LHeC run is the strongest for all three parameters.
- Not surprisingly, combined LHeC (and FCC-eh) bounds are far stronger than EIC bounds; higher energy and integrated luminosity.

Electroweak precision constraints

- The power of these future machines is so strong that we can improve upon the existing precision constraints on the ffV vertices driven primarily by LEP and SLC.

ffV		semi-leptonic four-fermion	
$C_{\varphi WB}$	$O_{\varphi WB} = (\varphi^\dagger \tau^I \varphi) W_{\mu\nu}^I B^{\mu\nu}$	$C_{lq}^{(1)}$	$O_{lq}^{(1)} = (\bar{l}\gamma_\mu l)(\bar{q}\gamma^\mu q)$
$C_{\varphi D}$	$O_{\varphi D} = (\varphi^\dagger D_\mu \varphi)^* (\varphi^\dagger D^\mu \varphi)$	$C_{lq}^{(3)}$	$(\bar{l}\gamma_\mu \tau^I l)(\bar{q}\gamma^\mu \tau^I q)$
$C_{\varphi l}^{(1)}$	$O_{\varphi l}^{(1)} = (\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{l}\gamma^\mu l)$	C_{eu}	$O_{eu} = (\bar{e}\gamma_\mu e)(\bar{u}\gamma^\mu u)$
$C_{\varphi l}^{(3)}$	$O_{\varphi l}^{(3)} = (\varphi^\dagger i \overleftrightarrow{D}_\mu \tau^I \varphi)(\bar{l}\gamma^\mu \tau^I l)$	C_{ed}	$O_{ed} = (\bar{e}\gamma_\mu e)(\bar{d}\gamma^\mu d)$
$C_{\varphi e}$	$O_{\varphi e} = (\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{e}\gamma^\mu e)$	C_{lu}	$O_{lu} = (\bar{l}\gamma_\mu l)(\bar{u}\gamma^\mu u)$
$C_{\varphi q}^{(1)}$	$O_{\varphi q}^{(1)} = (\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{q}\gamma^\mu q)$	C_{ld}	$O_{ld} = (\bar{l}\gamma_\mu l)(\bar{d}\gamma^\mu d)$
$C_{\varphi q}^{(3)}$	$O_{\varphi q}^{(3)} = (\varphi^\dagger i \overleftrightarrow{D}_\mu \tau^I \varphi)(\bar{q}\gamma^\mu \tau^I q)$	C_{qe}	$O_{qe} = (\bar{q}\gamma_\mu q)(\bar{e}\gamma^\mu e)$
$C_{\varphi u}$	$O_{\varphi u} = (\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{u}\gamma^\mu u)$		
$C_{\varphi d}$	$O_{\varphi d} = (\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{d}\gamma^\mu d)$		
C_{ll}	$O_{ll} = (\bar{l}\gamma_\mu l)(\bar{l}\gamma^\mu l)$		

We turn on the full 17 operators that contribute to DIS at tree-level in the EW couplings

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

Existing single-parameter constraints on the ffV Wilson coefficients are quite strong; can future DIS experiments improve upon these?

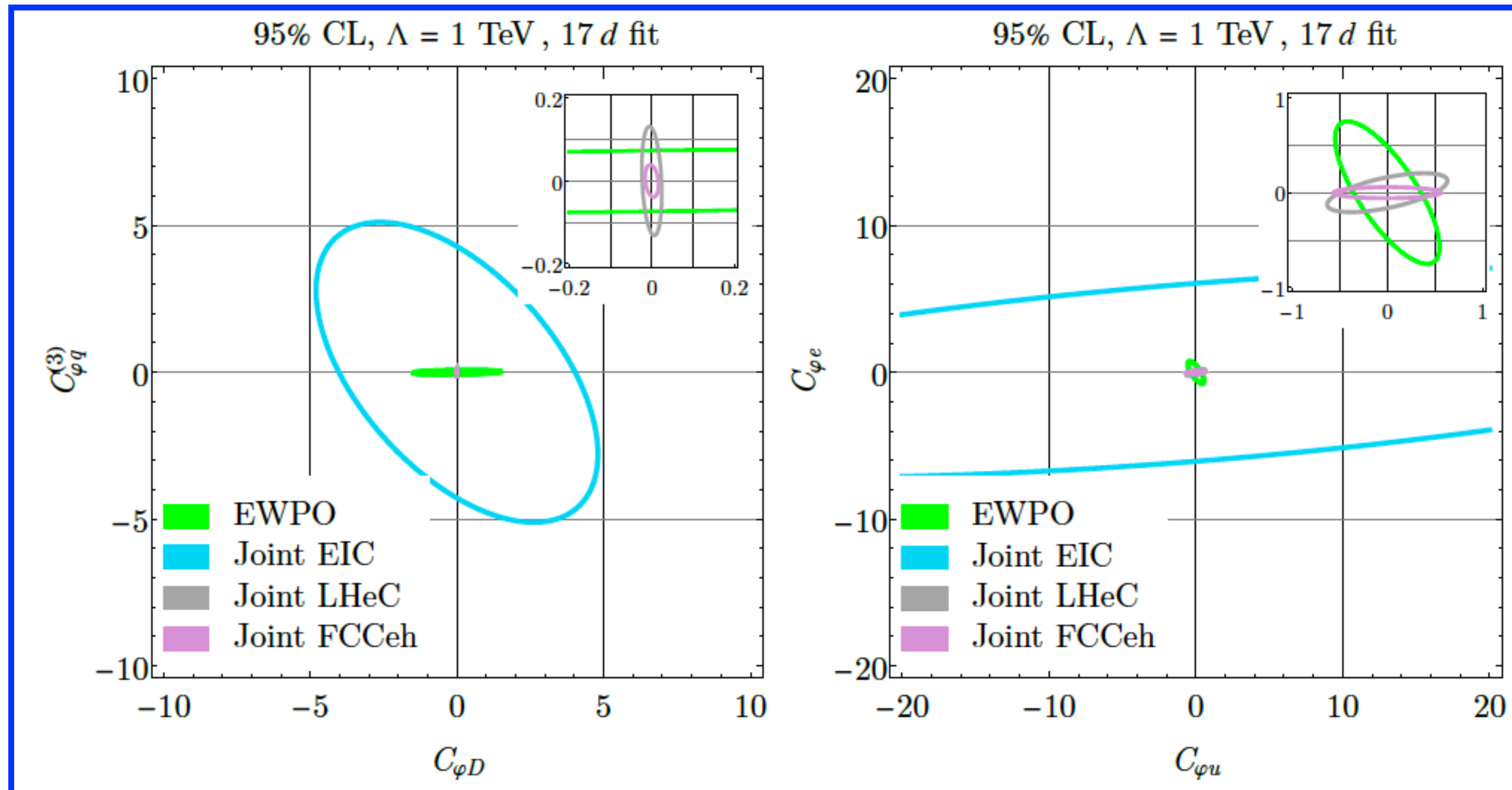
Dawson, Giardino (2019)

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

Electroweak precision constraints

- We consider the full 17-dim marginalized fit and show 2-dim projections below for all three machines: EIC, LHeC, FCC-eh. We take the EWPO fit from J.Ellis et al (2012.02779).

Bissolotti, RB Simsek (2023)



Two example projections of the full 17-dim fit. The FCC-eh can significantly improve on EWPO constraints!

Conclusions

- The current experimental landscape suggests that the coming decade will require increasingly precise indirect searches in order to find hints of deviation from the SM.
- The SMEFT framework is ideal for organizing and interpreting these searches.
- The EIC is capable of powerful indirect 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.
- LHeC and FCCeH will further advance searches for heavy new physics.
- Looking forward to a rich and exciting future DIS program!