Removing Flat Directions in SMEFT Fits: Complementing the LHC with polarized EIC data

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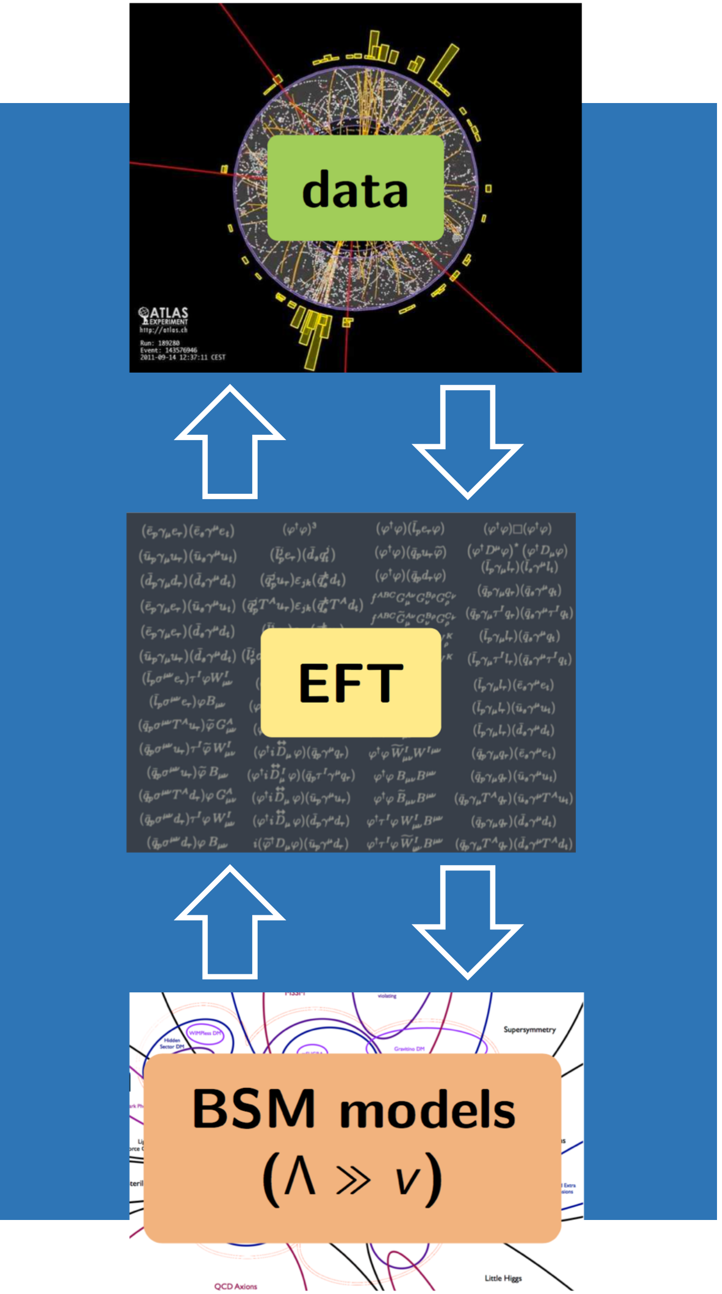
@Snowmass Community Planning Meeting 2020

Based on:

Boughezal/Petriello/DW - (arXiv: 2004.00748)

The Why, the What and the How



○ the Why

- **No smoking gun(s) at LHC**
- Standard Model Effective Theory (**SMEFT**) is a systematic way to combine and analyze data and look for New Physics in a model-independent way

○ the What

- Four-Fermi Operators are a large class of SMEFT operators
- **Flat directions** are a prevalent problem ⇨ resolve for **global fit**

○ the How

- Future **Electron-Ion** Collider (EIC) :

  ⇨ Lift flat directions by combining polarized observables

- Combine with LHC data for strongest bounds (here: **Drell-Yan**)

The Warsaw Basis

$1: X^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$
$Q_{\widetilde{G}}$	$f^{ABC} \widetilde{G}_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$
Q_W	$\epsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$
$Q_{\widetilde{W}}$	$\epsilon^{IJK} \widetilde{W}_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$

$2: H^6$	
Q_H	$(H^\dagger H)^3$

$3: H^4 D^2$	
$Q_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$
Q_{HD}	$\left(H^\dagger D_\mu H\right)^* \left(H^\dagger D_\mu H\right)$

$5: \psi^2 H^3 + \text{h.c.}$	
Q_{eH}	$(H^\dagger H)(\bar{l}_p e_r H)$
Q_{uH}	$(H^\dagger H)(\bar{q}_p u_r \widetilde{H})$
Q_{dH}	$(H^\dagger H)(\bar{q}_p d_r H)$

$4: X^2 H^2$	
Q_{HG}	$H^\dagger H\, G_{\mu\nu}^A G^{A\mu\nu}$
$Q_{H\widetilde{G}}$	$H^\dagger H\, \widetilde{G}_{\mu\nu}^A G^{A\mu\nu}$
Q_{HW}	$H^\dagger H\, W_{\mu\nu}^I W^{I\mu\nu}$
$Q_{H\widetilde{W}}$	$H^\dagger H\, \widetilde{W}_{\mu\nu}^I W^{I\mu\nu}$
Q_{HB}	$H^\dagger H\, B_{\mu\nu} B^{\mu\nu}$
$Q_{H\widetilde{B}}$	$H^\dagger H\, \widetilde{B}_{\mu\nu} B^{\mu\nu}$
Q_{HWB}	$H^\dagger \tau^I H\, W_{\mu\nu}^I B^{\mu\nu}$
$Q_{H\widetilde{W}B}$	$H^\dagger \tau^I H\, \widetilde{W}_{\mu\nu}^I B^{\mu\nu}$

$6: \psi^2 X H + \text{h.c.}$	
Q_{eW}	$(\bar{l}_p \sigma^{\mu\nu} e_r) \tau^I H W_{\mu\nu}^I$
Q_{eB}	$(\bar{l}_p \sigma^{\mu\nu} e_r) H B_{\mu\nu}$
Q_{uG}	$(\bar{q}_p \sigma^{\mu\nu} T^A u_r) \widetilde{H}\, G_{\mu\nu}^A$
Q_{uW}	$(\bar{q}_p \sigma^{\mu\nu} u_r) \tau^I \widetilde{H}\, W_{\mu\nu}^I$
Q_{uB}	$(\bar{q}_p \sigma^{\mu\nu} u_r) \widetilde{H}\, B_{\mu\nu}$
Q_{dG}	$(\bar{q}_p \sigma^{\mu\nu} T^A d_r) H\, G_{\mu\nu}^A$
Q_{dW}	$(\bar{q}_p \sigma^{\mu\nu} d_r) \tau^I H\, W_{\mu\nu}^I$
Q_{dB}	$(\bar{q}_p \sigma^{\mu\nu} d_r) H\, B_{\mu\nu}$

$7: \psi^2 H^2 D$	
$Q_{Hl}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{l}_p \gamma^\mu l_r)$
$Q_{Hl}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}_\mu^I H)(\bar{l}_p \tau^I \gamma^\mu l_r)$
Q_{He}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{e}_p \gamma^\mu e_r)$
$Q_{Hq}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{q}_p \gamma^\mu q_r)$
$Q_{Hq}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}_\mu^I H)(\bar{q}_p \tau^I \gamma^\mu q_r)$
Q_{Hu}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{u}_p \gamma^\mu u_r)$
Q_{Hd}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{d}_p \gamma^\mu d_r)$
Q_{Hud} + h.c.	$i(\widetilde{H}^\dagger D_\mu H)(\bar{u}_p \gamma^\mu d_r)$

$8: (\bar{L}L)(\bar{L}L)$	
Q_{ll}	$(\bar{l}_p \gamma_\mu l_r)(\bar{l}_s \gamma^\mu l_t)$
$Q_{qq}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{q}_s \gamma^\mu q_t)$
$Q_{qq}^{(3)}$	$(\bar{q}_p \gamma_\mu \tau^I q_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$
$Q_{lq}^{(1)}$	$(\bar{l}_p \gamma_\mu l_r)(\bar{q}_s \gamma^\mu q_t)$
$Q_{lq}^{(3)}$	$(\bar{l}_p \gamma_\mu \tau^I l_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$

$8: (\bar{R}R)(\bar{R}R)$	
Q_{ee}	$(\bar{e}_p \gamma_\mu e_r)(\bar{e}_s \gamma^\mu e_t)$
Q_{uu}	$(\bar{u}_p \gamma_\mu u_r)(\bar{u}_s \gamma^\mu u_t)$
Q_{dd}	$(\bar{d}_p \gamma_\mu d_r)(\bar{d}_s \gamma^\mu d_t)$
Q_{eu}	$(\bar{e}_p \gamma_\mu e_r)(\bar{u}_s \gamma^\mu u_t)$
Q_{ed}	$(\bar{e}_p \gamma_\mu e_r)(\bar{d}_s \gamma^\mu d_t)$
$Q_{ud}^{(1)}$	$(\bar{u}_p \gamma_\mu u_r)(\bar{d}_s \gamma^\mu d_t)$
$Q_{ud}^{(8)}$	$(\bar{u}_p \gamma_\mu T^A u_r)(\bar{d}_s \gamma^\mu T^A d_t)$

$8: (\bar{L}L)(\bar{R}R)$	
Q_{le}	$(\bar{l}_p \gamma_\mu l_r)(\bar{e}_s \gamma^\mu e_t)$
Q_{lu}	$(\bar{l}_p \gamma_\mu l_r)(\bar{u}_s \gamma^\mu u_t)$
Q_{ld}	$(\bar{l}_p \gamma_\mu l_r)(\bar{d}_s \gamma^\mu d_t)$
Q_{qe}	$(\bar{q}_p \gamma_\mu q_r)(\bar{e}_s \gamma^\mu e_t)$
$Q_{qu}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{u}_s \gamma^\mu u_t)$
$Q_{qu}^{(8)}$	$(\bar{q}_p \gamma_\mu T^A q_r)(\bar{u}_s \gamma^\mu T^A u_t)$
$Q_{qd}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{d}_s \gamma^\mu d_t)$
$Q_{qd}^{(8)}$	$(\bar{q}_p \gamma_\mu T^A q_r)(\bar{d}_s \gamma^\mu T^A d_t)$

$8: (\bar{L}R)(\bar{R}L) + \text{h.c.}$	
Q_{ledq}	$(\bar{l}_p^j e_r)(\bar{d}_s q_{tj})$

$8: (\bar{L}R)(\bar{L}R) + \text{h.c.}$	
$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r)\epsilon_{jk}(\bar{q}_s^k d_t)$
$Q_{quqd}^{(8)}$	$(\bar{q}_p^j T^A u_r)\epsilon_{jk}(\bar{q}_s^k T^A d_t)$
$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r)\epsilon_{jk}(\bar{q}_s^k u_t)$
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j \sigma_{\mu\nu} e_r)\epsilon_{jk}(\bar{q}_s^k \sigma^{\mu\nu} u_t)$

Warsaw Basis: 59 Operators $(\delta B = 0, \delta L = 0)$

Grzadkowski/Iskrzynski/Misiak/Rosiek (1008.4884)

Write down all possible operators that new physics could induce

- Stay consistent with SM **symmetries**!
- Build from SM field content!

Many equivalent bases to parametrize new physics

$\Rightarrow$ go **for least number of derivatives**

$$\mathcal{L}_{SMEFT} \supset \underbrace{\mathcal{L}_{SM} + \frac{C_5}{\Lambda}\mathcal{O}^5 + \frac{C_6^i}{\Lambda^2}\mathcal{O}_i^6}_{} + \frac{C_7^i}{\Lambda^3}\mathcal{O}_i^7 + \cdots$$

We focus at 1-loop/Dim-6 **Semi-hadronic 4-Fermi Operators**

(Potential Z-coupling shifts are better probed with Z-Pole observables)

Overview: Previous Constraints

Previous constraints mostly from low-energy and EW precision data *Falkowski et al (1706.03783)*

Below the Z pole:

DIS e^-/μ^- scattering

β, π, n^0 decay

Atomic Parity Violation

Weak charge $Q_W(Z,N)$ (PVDIS @6GeV, SPS data,…)

Above the Z pole:

Low-energy di-Jet Production (LEP2 data, also KEKB)

Combined observables are only sensitive to certain **combinations of Wilson coefficients**:

$$\hat{C}_{qe} = C_{qe} + C_{lq}^{(1)}$$

$$\hat{C}_{eu} = C_{eu} - C_{lq}^{(1)}$$

$$\hat{C}_{lu} = C_{lu} + C_{lq}^{(1)} - C_{qe}$$

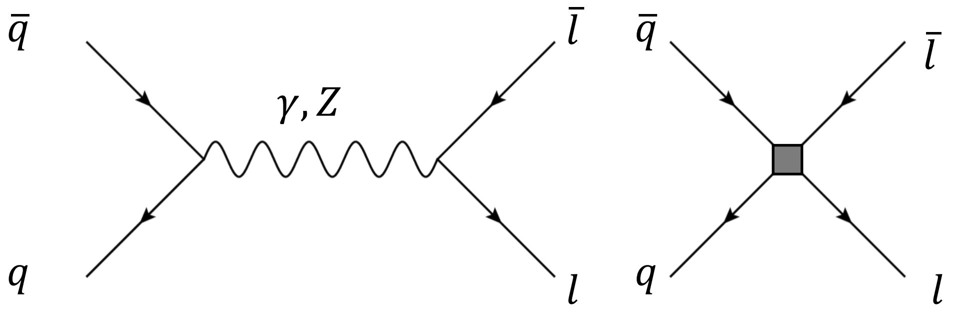
$$\hat{C}_{ed} = C_{ed} - C_{lq}^{(1)}$$

$$\hat{C}_{ld} = C_{ld} + C_{lq}^{(1)} - C_{qe}$$

$\hat{C}_{qe}$	$C_{lq}^{(3)}$	$\hat{C}_{lu}$	$\hat{C}_{ld}$	$\hat{C}_{eu}$	$\hat{C}_{ed}$
< 2.8	< 0.05	< 0.16	< 0.28	< 0.11	< 0.25

Bounds on the absolute values of the linear combinations of Wilson Coefficients (from *1706.03783*) ($\Lambda = 1$TeV)

Flat Directions: Drell-Yan



<u>What's a flat direction (more generally)?</u>

- More Wilson coefficients than observables
- Either **exact** or **approximate** (in a certain regime)
- Worsens possible bounds on individual coefficients

Alte/König/Shepherd (1812.07575)

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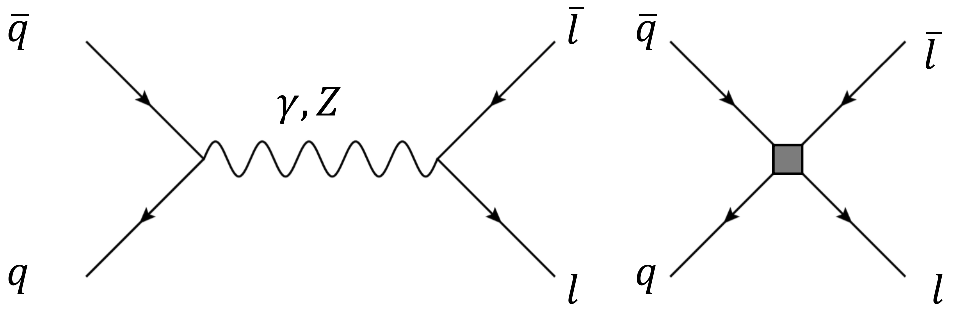

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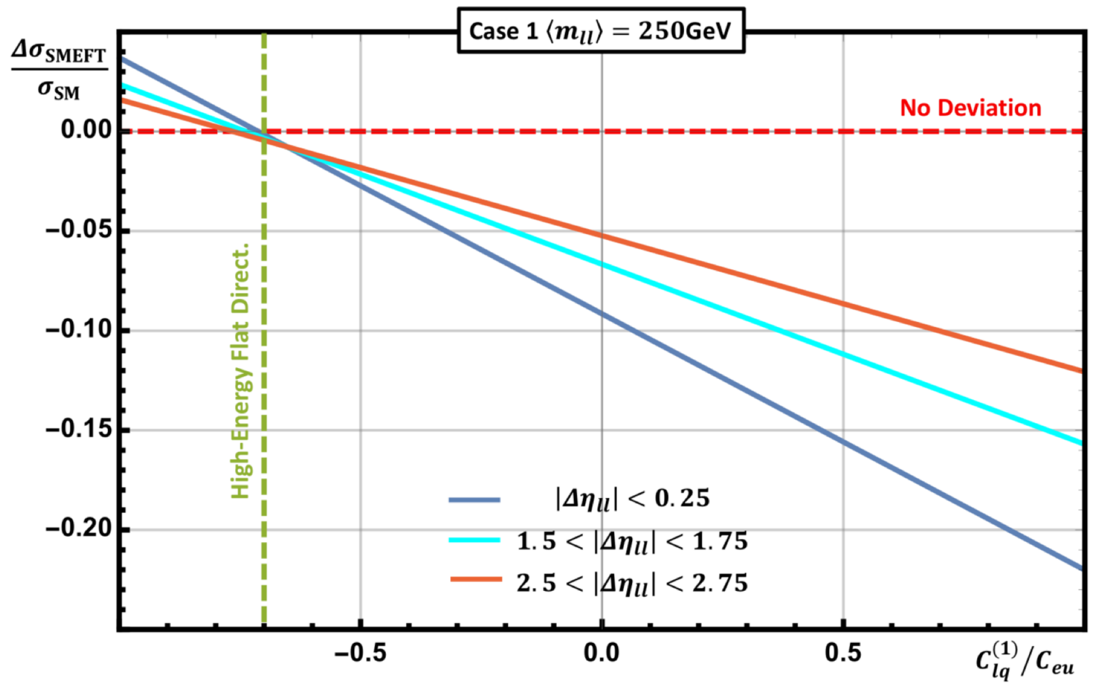
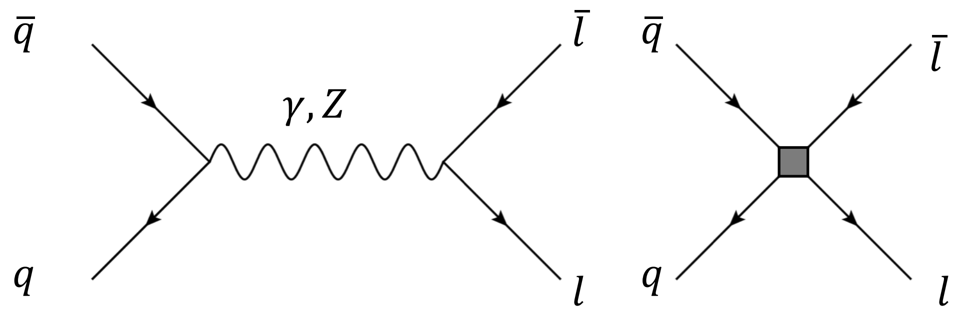


Resolving different rapidity bins leads to no new information near the high-energy flat direction

Boughezal/Petriello/DW (2004.00748)

The **flat directions limit how far the bounds can be pushed**, even with significantly more data (e.g. HL-LHC) or when measuring different differential distributions

Flat Directions: Drell-Yan



$\Rightarrow$ Drell-Yan SMEFT deviation greatest for high m_{ll}

BUT More Wilson Coefficients than kinematic variables

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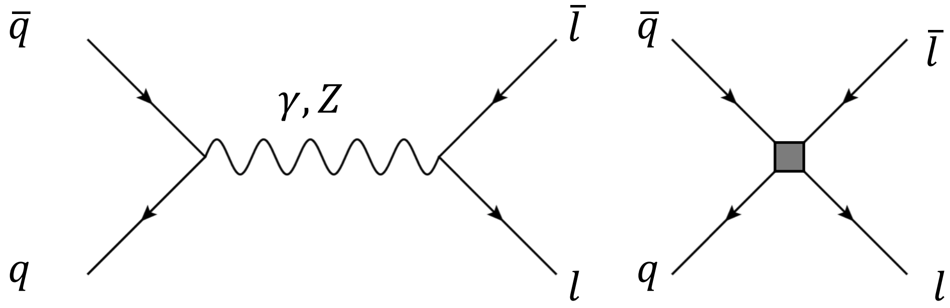

⇨ Drell-Yan SMEFT deviation greatest for high m_{ll}

BUT More Wilson Coefficients than kinematic variables

⇨ The SMEFT contribution to σ_{DY} depends at $s \ggg m_{ll}$ **only** on

$$\Delta\sigma_{SMEFT} \sim \begin{cases} -\dfrac{4\alpha\pi}{9c_W^2}\left(C_{qe} + 2C_{lu}\right) \\ -\dfrac{2\alpha\pi}{9c_W^2 s_W^2}\left[\left(C_{lq}^{(1)} - C_{lq}^{(3)}\right)(3 - 2s_W^2) + 8s_W^2 C_{eu}\right] \end{cases}$$

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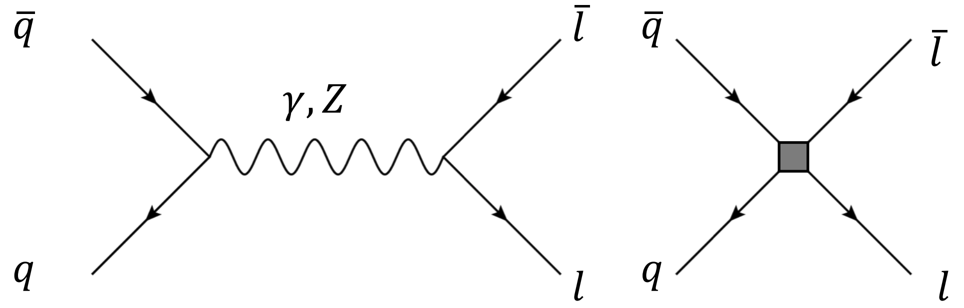

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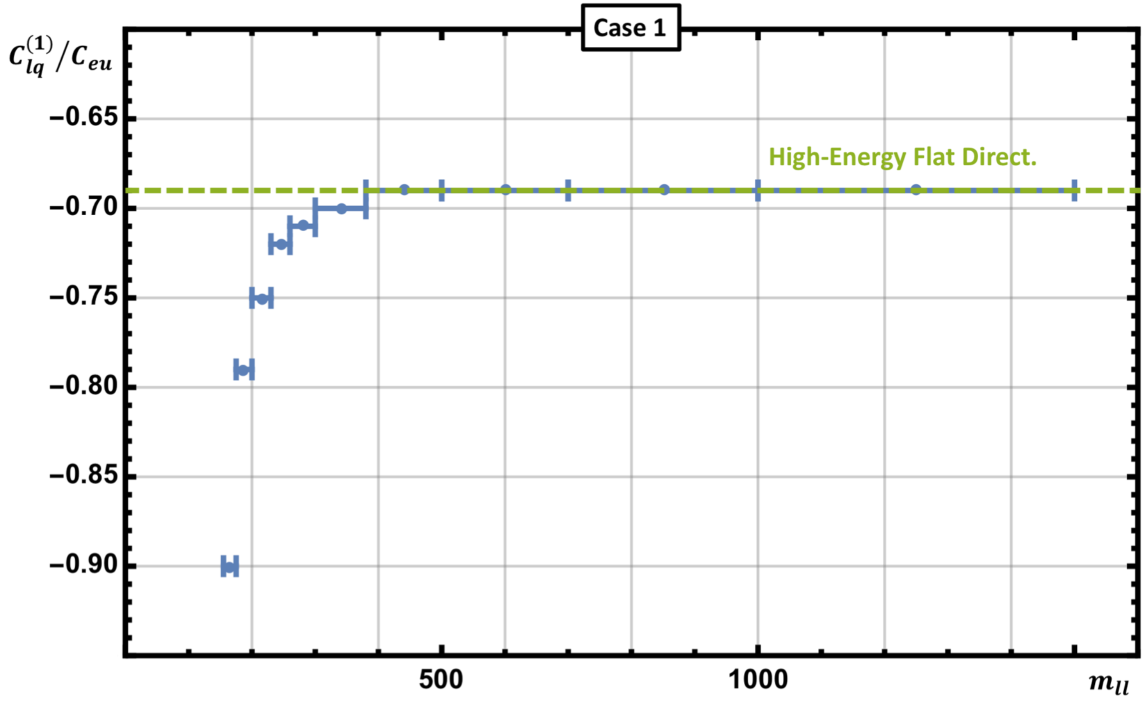
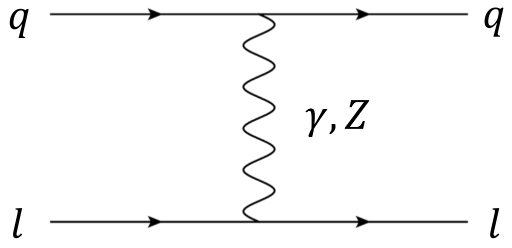


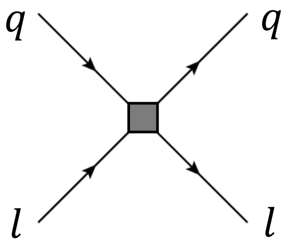
Approximate flat-direction in Drell-Yan fit (high m_{ll} bins)

Boughezal/Petriello/DW (2004.00748)

When fitting e.g. $C_{lq}^{(1)}$ and C_{eu}, **for** $\boldsymbol{C_{lq}^{(1)} = -\frac{8s_W^2}{3-2s_W^2} C_{eu} \approx -0.69 C_{eu}}$, $\Delta\sigma_{SMEFT} = 0$, marking a flat direction

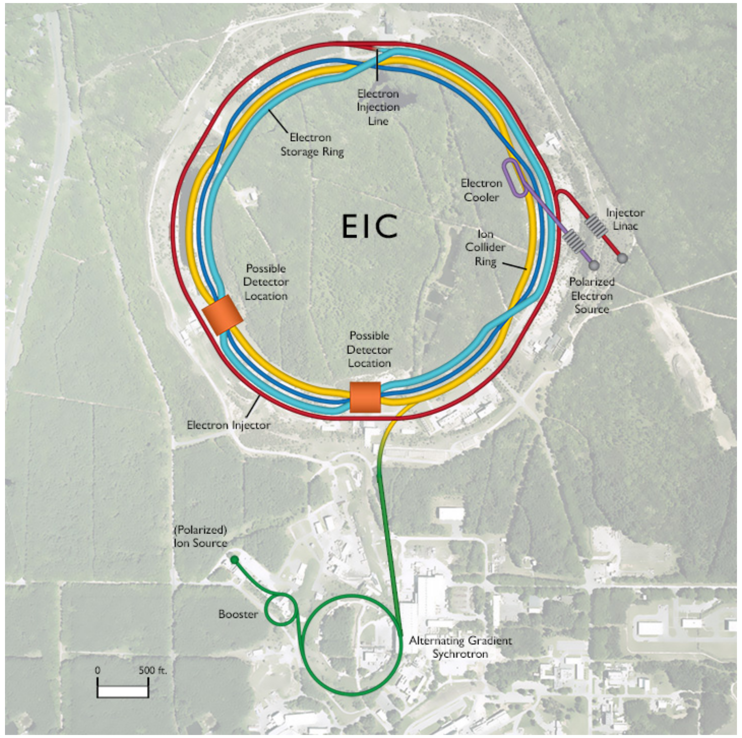
EIC - Overview





Technical Specifications:

- CoM Energy up to $\sqrt{S} = 140\text{GeV}$
- Polarized Electron and pol/unpol Proton Beam (70%)
- Projected Luminosity $\mathcal{L} \sim 10\ \text{fb}^{-1}$ $(100\ \text{fb}^{-1}?)$
- Assume angular variable $0.1 < y < 0.9$ and **momentum fraction** $\boldsymbol{x} < 0.2$



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

Aschenauer et al (1309.5327, 1705.08831)

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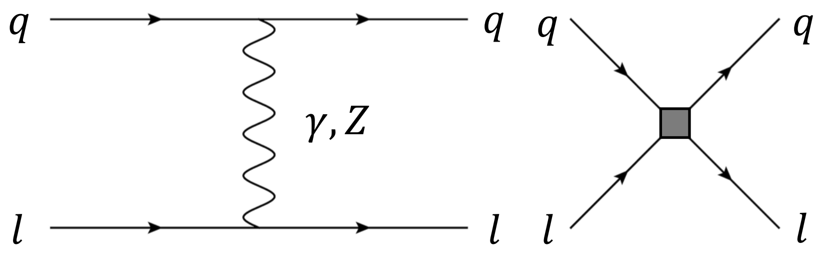

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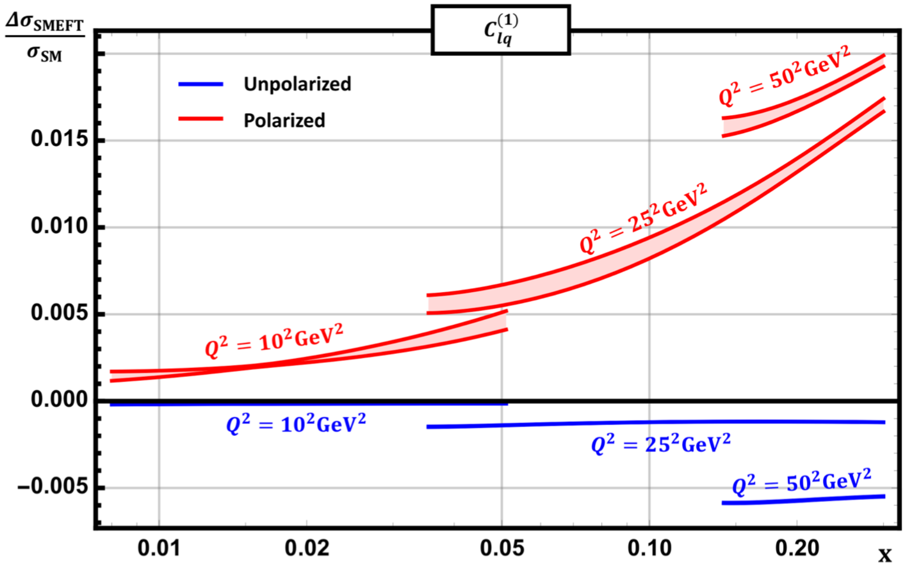
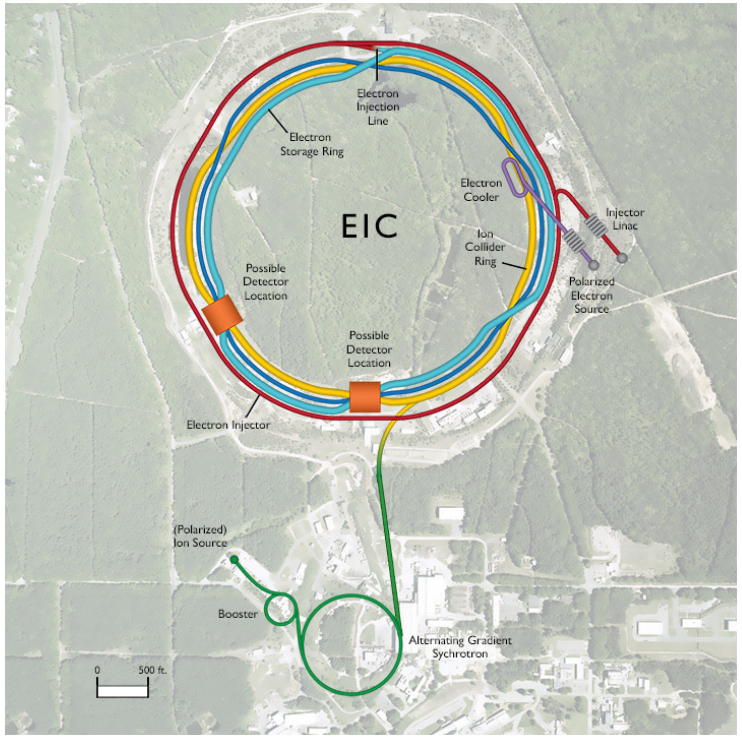


Expected size of SMEFT effect in DIS (including PDF error, $\Lambda = 1\text{TeV}$)



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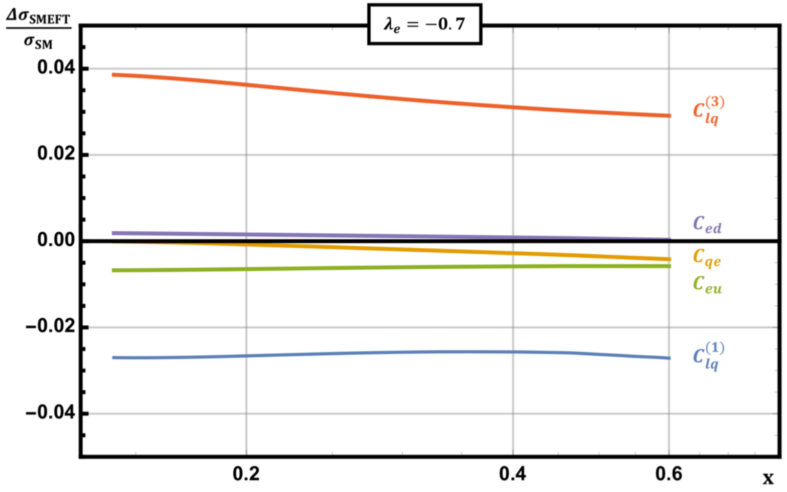
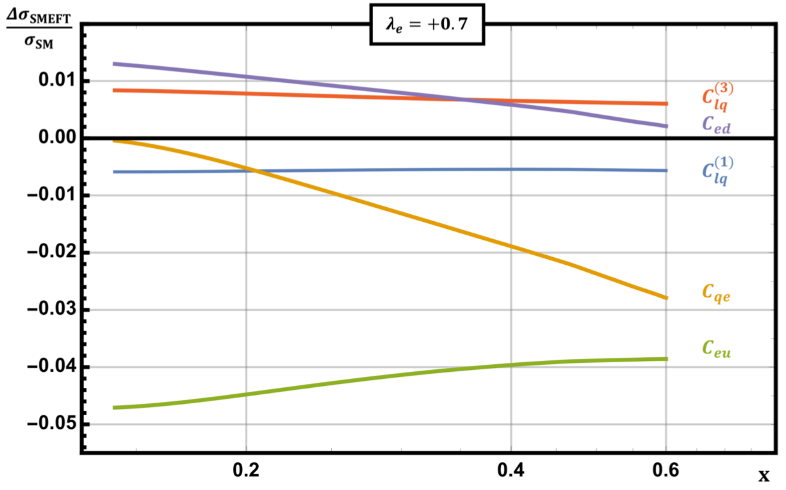
Also Interesting: Charged Current (not as clean but only sensitive to $C_{lq}^{(3)}$)

Probing SMEFT at EIC





Different Wilson coefficients contribute for different Electron polarizations

General Idea:

- Use different polarization combinations to lift flat directions
- Polarized/Unpolarized Protons vs 2 Electron Polarizations
- Ultimately: Global fit of PDFs and Wilson Coefficients

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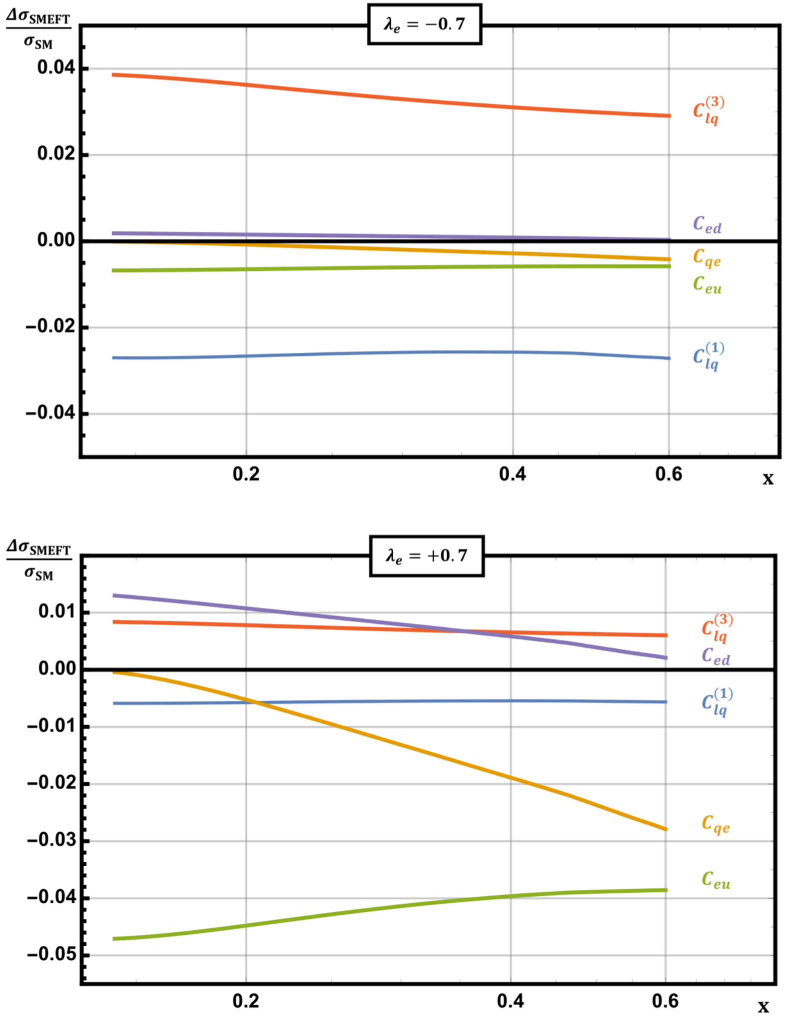

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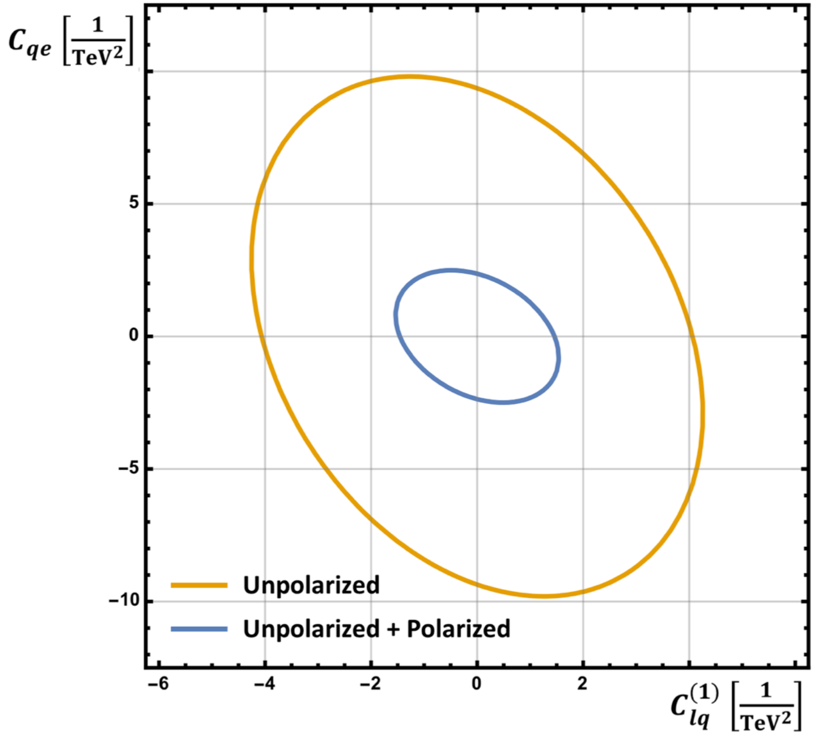

Different Wilson coefficients contribute for different Electron polarizations

Bounds with and without polarized proton beam data

DY+EIC: Best Bounds Yet

Fitting Methodology (68% CL):

For EIC/DIS:

- Integrate over (x, Q^2) bins
- Assume uncorrelated errors
- $\Delta\sigma_{SMFT}$ measures deviation from SM

For LHC/DY:

- Integrate over m_{ll} bins
- Error Correlation from *ATLAS*
- Data deviation from SM

ATLAS Collab. (1606.01736)

Define χ^2 test statistic (DIS case):

$$\chi^2 = \sum_{\mathrm{Bins}} \sum_{\mathrm{Pol}/\pm} \left(\frac{\Delta\sigma_{SMFT}}{\Delta\sigma_{Err}}\right)^2$$

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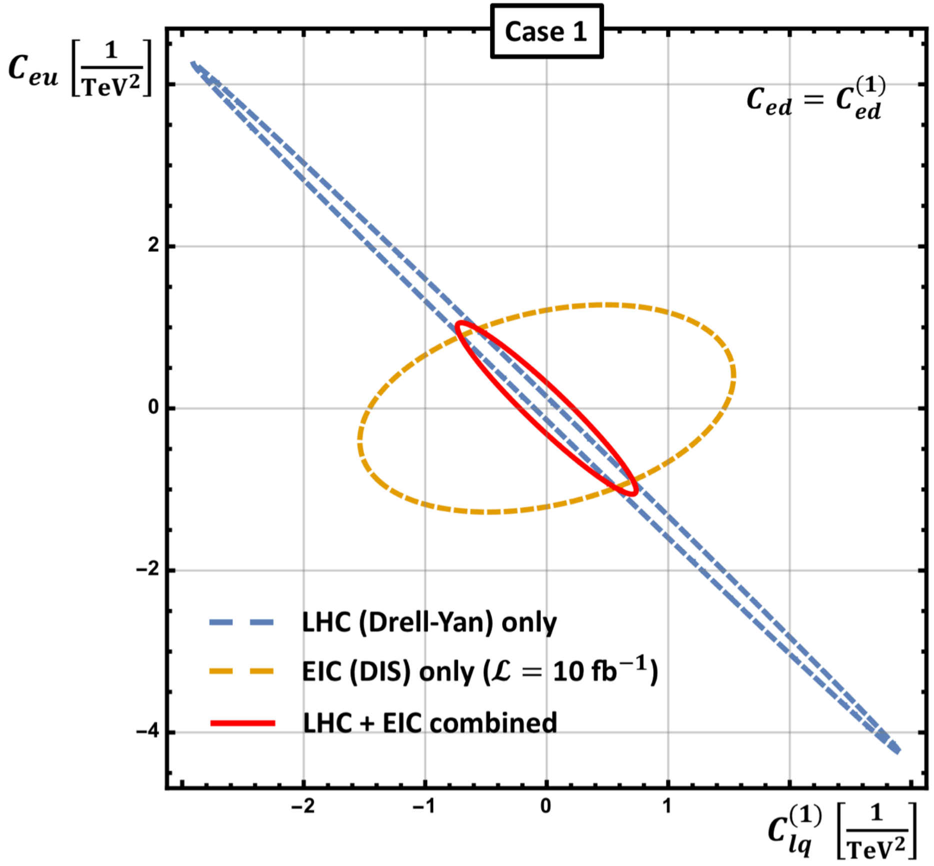

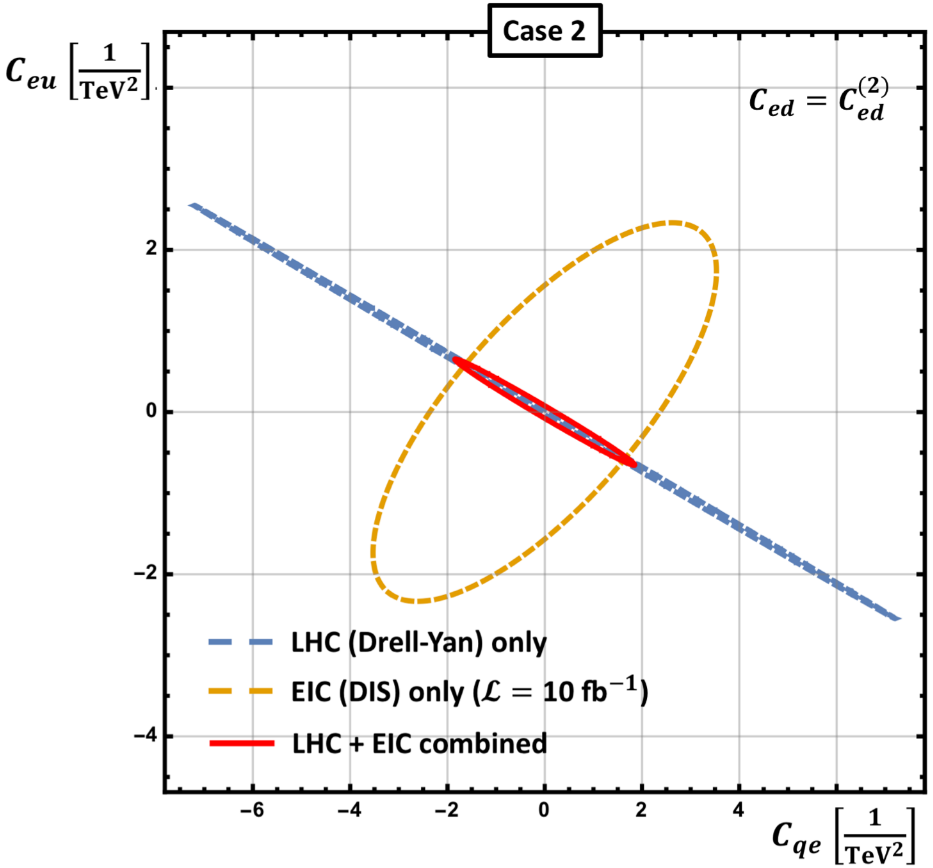

Summary and Conclusions

SMEFT is a practical framework to constrain new physics!

SMEFT suffers from a large number of flat directions

⮡ Requires additional observables before global fit

⮡ We presented a strategy to lift 4-Fermi **flat directions**

The future **EIC** will complement LHC data

⮡ Combine EIC observables with **different polarizations** additionally to LHC measurements

⮡ Interplay of different measurements improve bounds significantly

Thanks!