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

Daniel Wiegand
Northwestern University/Argonne National Lab
@Pheno 2020

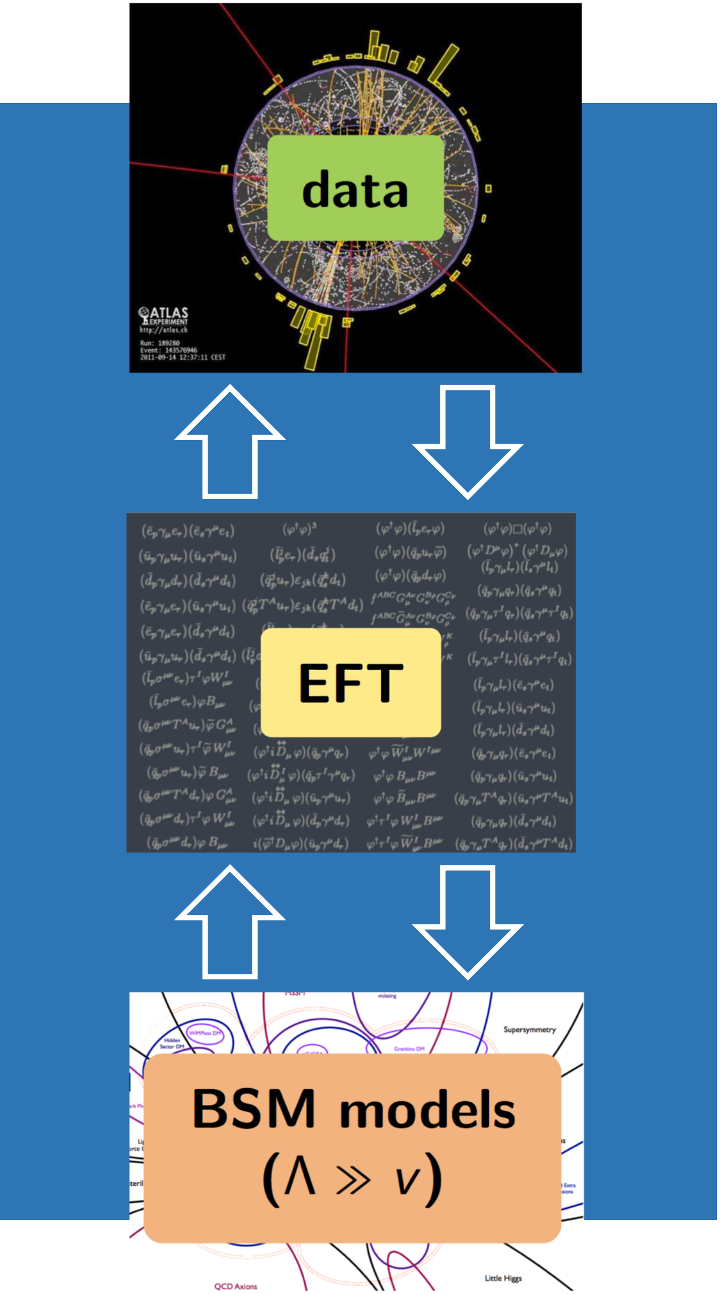
Argonne NATIONAL LABORATORY

Northwestern University

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**)

SMEFT - Motivation

Standard operating HEP procedure:

1) Pick BSM Model $\Rightarrow$ 2) Make Prediction $\Rightarrow$ 3) Compare to Data (ft Exclusion Plot) $\Rightarrow$ GoTo 1)

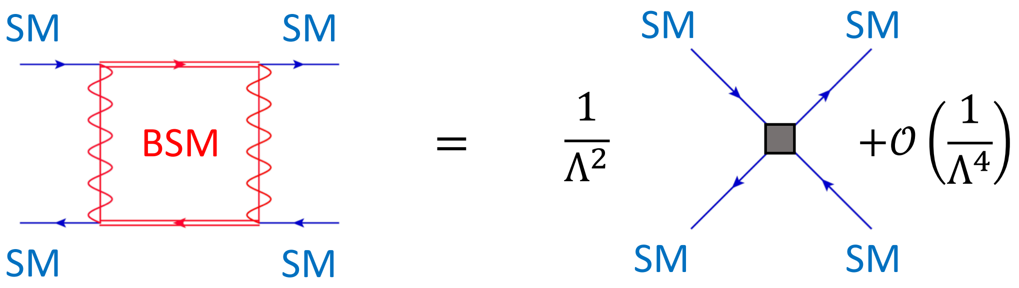
SMEFT - Motivation

Standard operating HEP procedure:

1) Pick BSM Model ⇒ 2) Make Prediction ⇒ 3) Compare to Data (ft Exclusion Plot) ⇒ GoTo 1)

More Economic Way:

Average over heavy modes at SM energies
(Effective Action: *Wilson et al*) ⇒



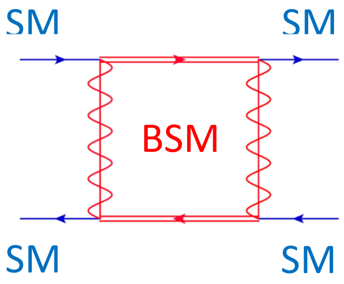
SMEFT - Motivation

Standard operating HEP procedure:

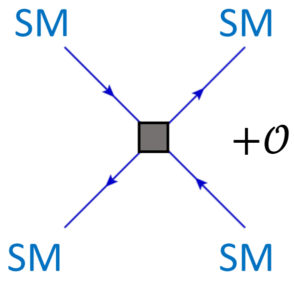
1) Pick BSM Model → 2) Make Prediction → 3) Compare to Data (ft Exclusion Plot) → GoTo 1)

More Economic Way:

Average over heavy modes at SM energies
(Effective Action: *Wilson et al*)



$$= \frac{1}{\Lambda^2}$$



$$+\mathcal{O}\left(\frac{1}{\Lambda^4}\right)$$

Non-SM operators suppressed by powers of $\frac{1}{\Lambda}$:

- Higher dimensional operators built from SM fields
- Modification of SM couplings/EWSB/…

Quantify deviation from SM through comparison with data

- Model independent constraints on new physics
- Maximal gain from data
- Part of the LHC legacy

The Warsaw Basis

$1: X^3$		$2: H^6$		$3: H^4D^2$		$5: \psi^2H^3 + \text{h.c.}$	
Q_G	$f^{ABC}G_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$	Q_H	$(H^\dagger H)^3$	$Q_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$	Q_{eH}	$(H^\dagger H)(\bar l_p e_r H)$
$Q_{\widetilde G}$	$f^{ABC}\widetilde G_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$			Q_{HD}	$(H^\dagger D_\mu H)^*(H^\dagger D_\mu H)$	Q_{uH}	$(H^\dagger H)(\bar q_p u_r \widetilde H)$
Q_W	$\epsilon^{IJK}W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$					Q_{dH}	$(H^\dagger H)(\bar q_p d_r H)$
$Q_{\widetilde W}$	$\epsilon^{IJK}\widetilde W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$						

$4: X^2H^2$		$6: \psi^2XH + \text{h.c.}$		$7: \psi^2H^2D$	
Q_{HG}	$H^\dagger H\, G^A_{\mu\nu}G^{A\mu\nu}$	Q_{eW}	$(\bar l_p\sigma^{\mu\nu}e_r)\tau^I H W^I_{\mu\nu}$	$Q_{Hl}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar l_p\gamma^\mu l_r)$
$Q_{H\widetilde G}$	$H^\dagger H\, \widetilde G^A_{\mu\nu}G^{A\mu\nu}$	Q_{eB}	$(\bar l_p\sigma^{\mu\nu}e_r)H B_{\mu\nu}$	$Q_{Hl}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar l_p\tau^I\gamma^\mu l_r)$
Q_{HW}	$H^\dagger H\, W^I_{\mu\nu}W^{I\mu\nu}$	Q_{uG}	$(\bar q_p\sigma^{\mu\nu}T^A u_r)\widetilde H\, G^A_{\mu\nu}$	Q_{He}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar e_p\gamma^\mu e_r)$
$Q_{H\widetilde W}$	$H^\dagger H\, \widetilde W^I_{\mu\nu}W^{I\mu\nu}$	Q_{uW}	$(\bar q_p\sigma^{\mu\nu}u_r)\tau^I\widetilde H\, W^I_{\mu\nu}$	$Q_{Hq}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar q_p\gamma^\mu q_r)$
Q_{HB}	$H^\dagger H\, B_{\mu\nu}B^{\mu\nu}$	Q_{uB}	$(\bar q_p\sigma^{\mu\nu}u_r)\widetilde H\, B_{\mu\nu}$	$Q_{Hq}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar q_p\tau^I\gamma^\mu q_r)$
$Q_{H\widetilde B}$	$H^\dagger H\, \widetilde B_{\mu\nu}B^{\mu\nu}$	Q_{dG}	$(\bar q_p\sigma^{\mu\nu}T^A d_r)H\, G^A_{\mu\nu}$	Q_{Hu}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar u_p\gamma^\mu u_r)$
Q_{HWB}	$H^\dagger\tau^I H\, W^I_{\mu\nu}B^{\mu\nu}$	Q_{dW}	$(\bar q_p\sigma^{\mu\nu}d_r)\tau^I H\, W^I_{\mu\nu}$	Q_{Hd}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar d_p\gamma^\mu d_r)$
$Q_{H\widetilde WB}$	$H^\dagger\tau^I H\, \widetilde W^I_{\mu\nu}B^{\mu\nu}$	Q_{dB}	$(\bar q_p\sigma^{\mu\nu}d_r)H\, B_{\mu\nu}$	Q_{Hud} + h.c.	$i(\widetilde H^\dagger D_\mu H)(\bar u_p\gamma^\mu d_r)$

$8: (\bar LL)(\bar LL)$		$8: (\bar RR)(\bar RR)$		$8: (\bar LL)(\bar RR)$	
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}	$(\bar e_p\gamma_\mu e_r)(\bar d_s\gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar q_p\gamma_\mu q_r)(\bar u_s\gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar u_p\gamma_\mu u_r)(\bar d_s\gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar q_p\gamma_\mu T^A q_r)(\bar u_s\gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar u_p\gamma_\mu T^A u_r)(\bar d_s\gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar q_p\gamma_\mu q_r)(\bar d_s\gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar q_p\gamma_\mu T^A q_r)(\bar d_s\gamma^\mu T^A d_t)$

$8: (\bar LR)(\bar RL) + \text{h.c.}$		$8: (\bar LR)(\bar LR) + \text{h.c.}$	
Q_{ledq}	$(\bar l_p^j e_r)(\bar d_s q_{tj})$	$Q_{quqd}^{(1)}$	$(\bar q_p^j u_r)\epsilon_{jk}(\bar q_s^k d_t)$
		$Q_{quqd}^{(8)}$	$(\bar q_p^j T^A u_r)\epsilon_{jk}(\bar q_s^k T^A d_t)$
		$Q_{lequ}^{(1)}$	$(\bar l_p^j e_r)\epsilon_{jk}(\bar q_s^k u_t)$
		$Q_{lequ}^{(3)}$	$(\bar l_p^j\sigma_{\mu\nu} e_r)\epsilon_{jk}(\bar q_s^k\sigma^{\mu\nu} u_t)$

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!

Lot's of tricks to eliminate redundant operators, e.g.

Integration-by-Parts (IBP) $$(\partial_\mu\phi)\partial^\mu(\partial^2\phi) \leftrightarrow -\phi\partial^4\phi$$

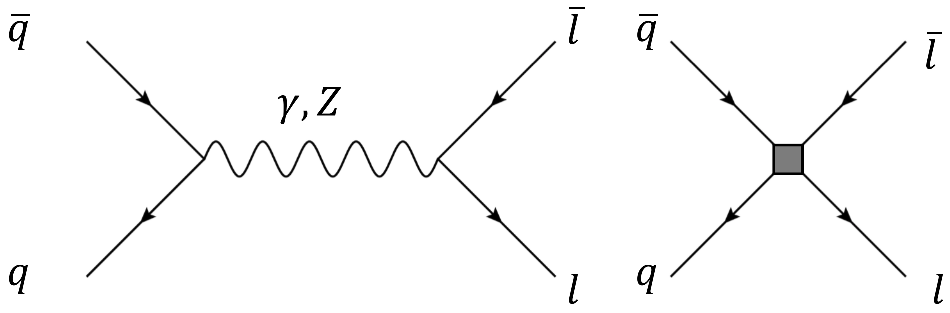
Many equivalent bases – not all created equal

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

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

We focus at 1-loop/Dim-6 **4-Fermi**
(Z-coupling better probed @ Z-Pole)

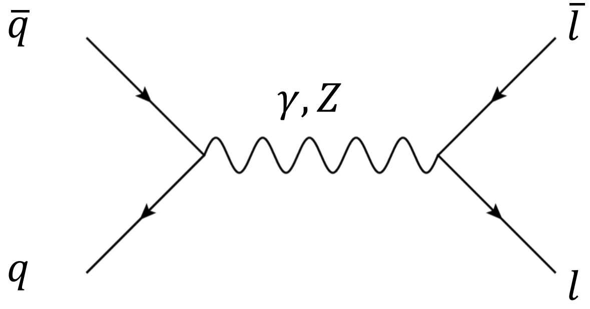
Flat Directions: Drell-Yan

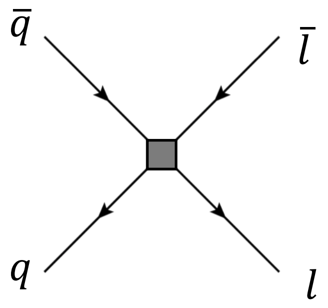


<u>What's a flat direction?</u>

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

Flat Directions: Drell-Yan

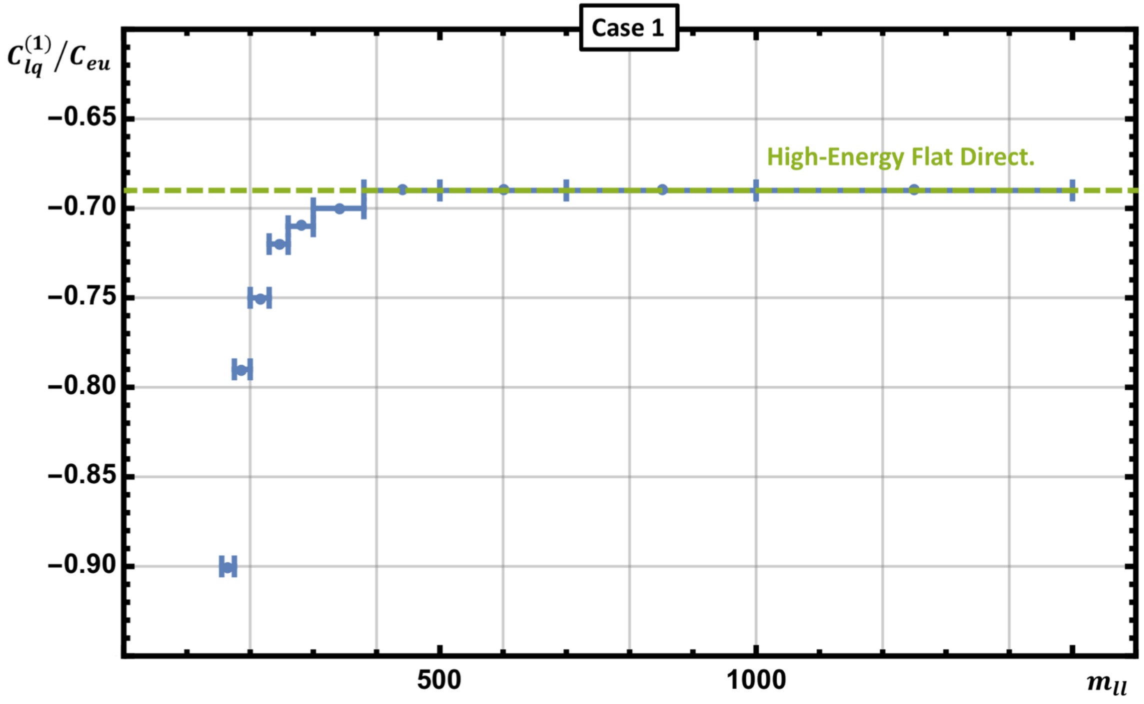




<u>What's a flat direction?</u>

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

Boughezal/Petriello/DW (2004.00748)



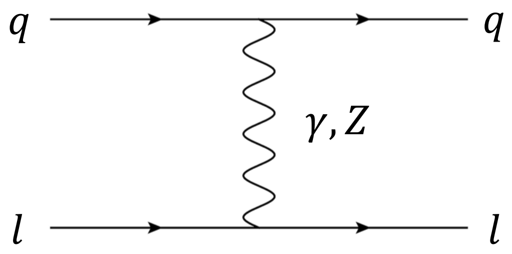
Approximate flat-direction in Drell-Yan fit (high m_{ll} bins)

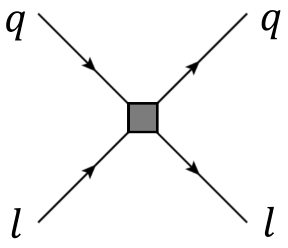
More Wilson Coefficients than kinematic variables

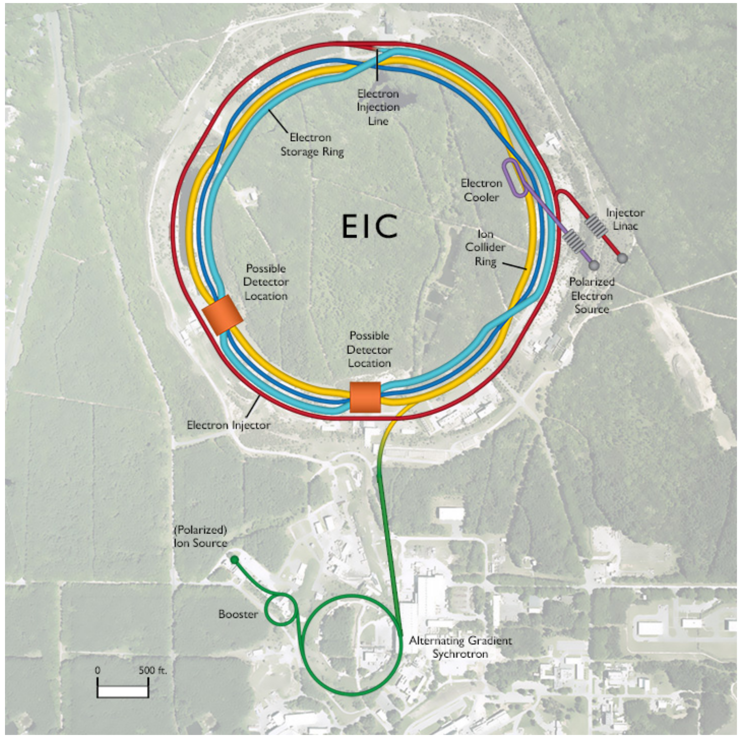
⇨ Example: Drell-Yan observables only sensitive to a few combinations (Rapiditi/Letpon m_{ll} distributions)

Alte/König/Shepherd (1812.07575)

EIC - Overview







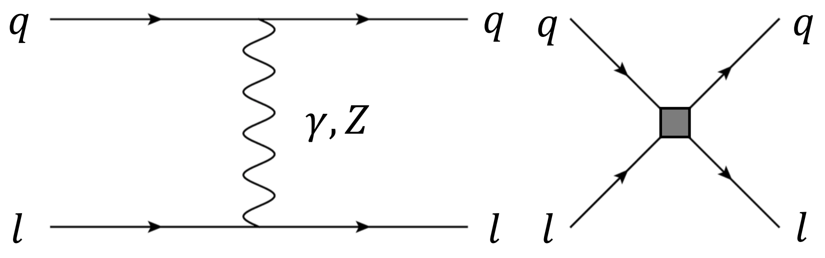
https://www.bnl.gov/eic/

Aschenauer et al (1309.5327, 1705.08831)

Technical Specifications:

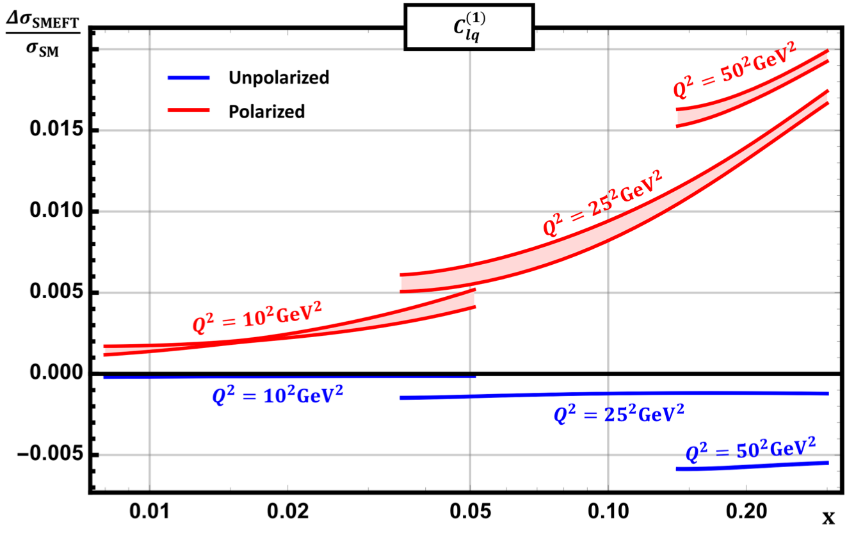
- CoM Energy up to $\sqrt{S} = 140\text{GeV}$
- Polarized Electron and pol/unpol Proton Beam (70%)
- Projected Luminosity $\mathcal{L} \sim 10\ \text{fb}^{-1}\ (100\ \text{fb}^{-1}?)$
- Assume angular variable $0.1 < y < 0.9$ and **momentum fraction x** < 0.2

EIC - Overview

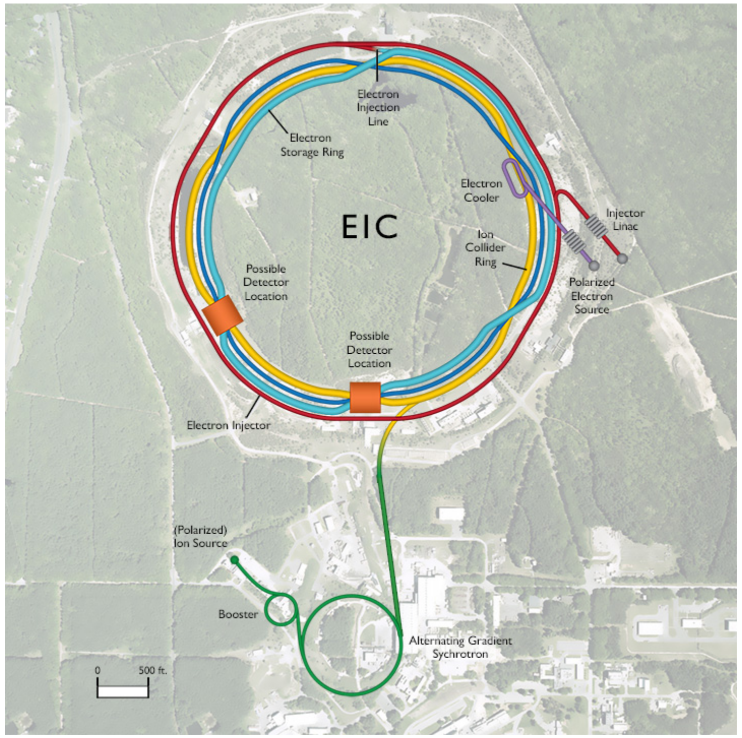


Technical Specifications:

- 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



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

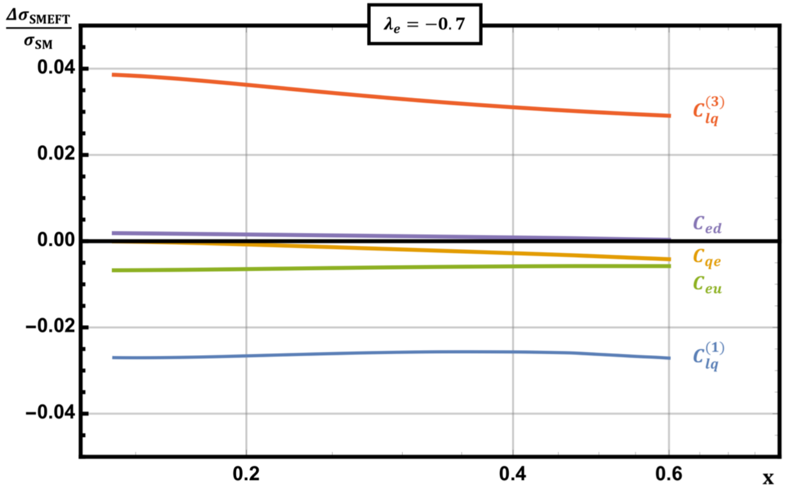


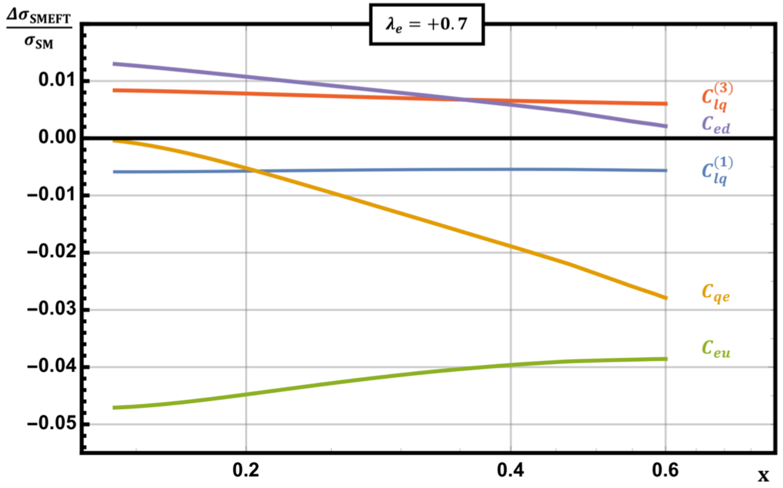
https://www.bnl.gov/eic/

Aschenauer et al (1309.5327, 1705.08831)

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

Probing SMEFT at EIC



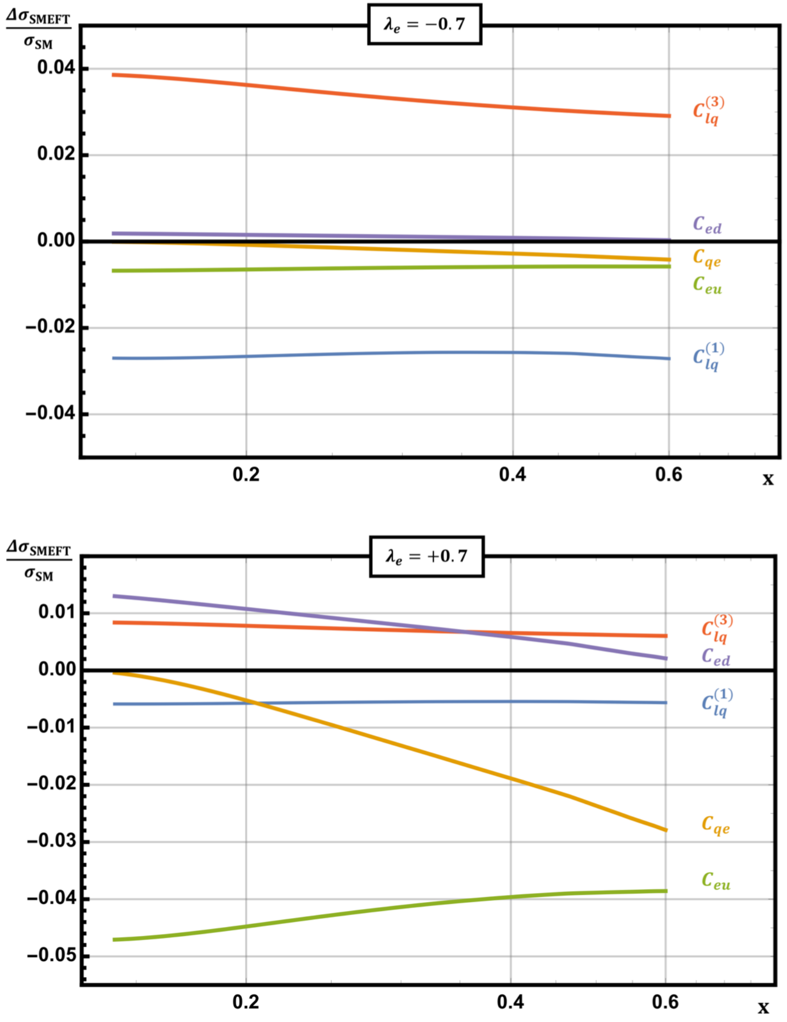


<u>General Idea:</u>

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

Different Wilson coefficients contribute for different Electron polarizations

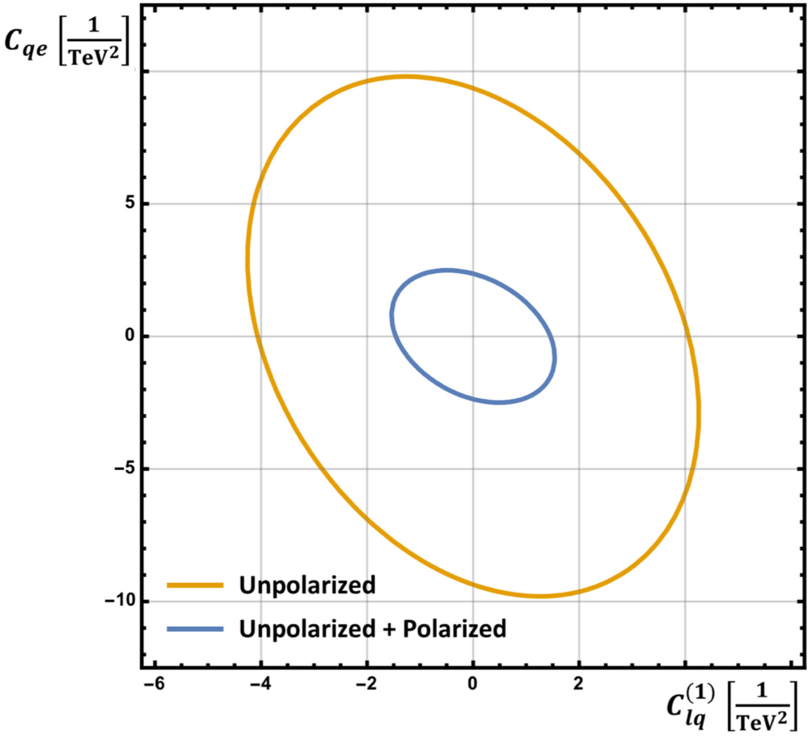
Probing SMEFT at EIC



Different Wilson coefficients contribute for different Electron polarizations

<u>General Idea:</u>

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



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):

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

DY+EIC: Best Bounds Yet

Fitting Methodology (68% CL):

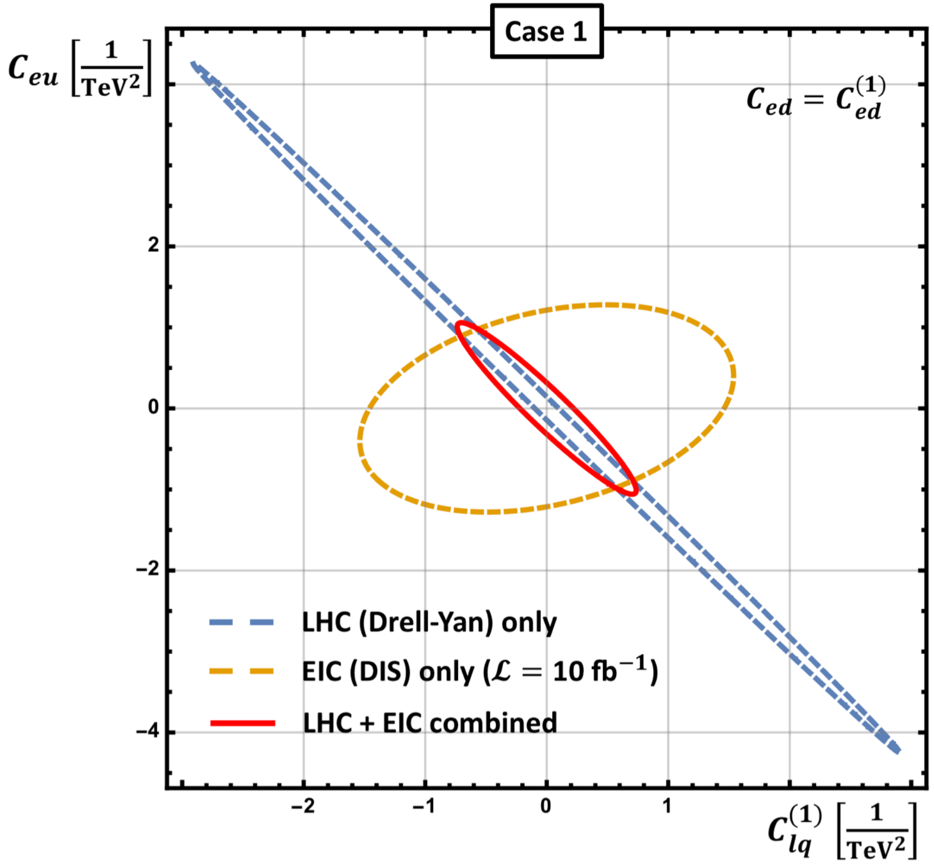
For EIC/DIS:
- Integrate over (x, Q^2) bins
- Assume uncorrelated errors
- $\Delta\sigma_{SMFT}$ measures deviation from SM

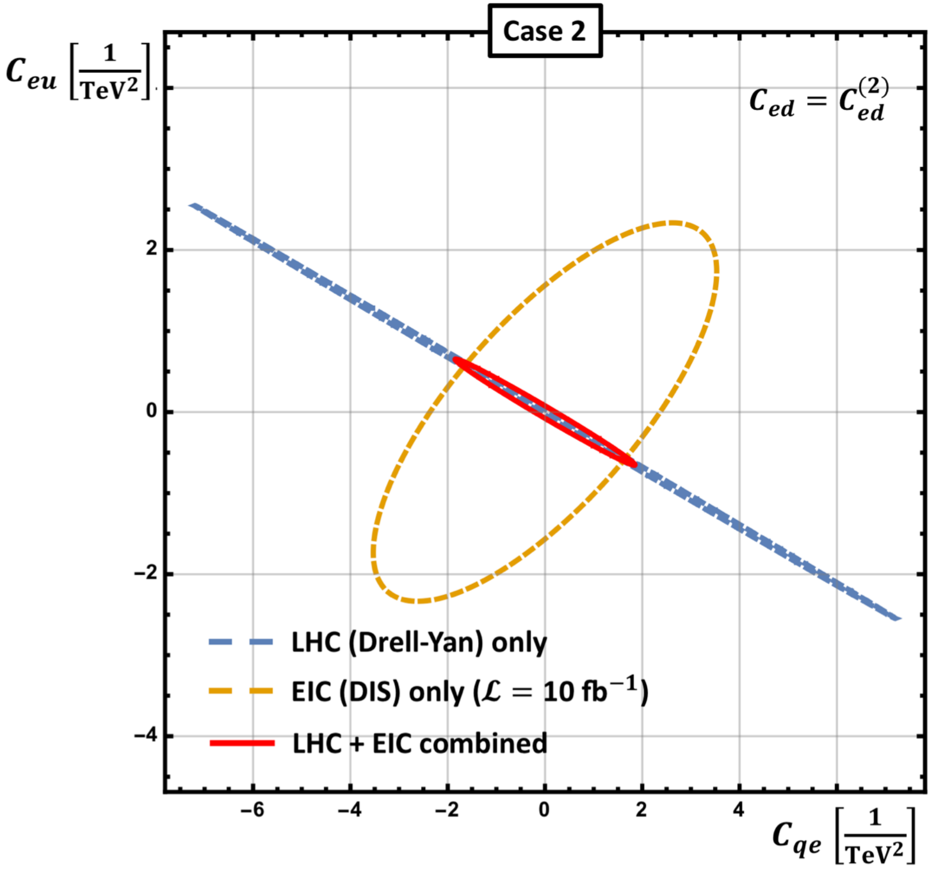
For LHC/DY:
- Integrate over m_{ll} bins
- Error Correlation from *ATLAS*
- Data deviation from SM

ATLAS Collab. (1606.01736)

Define χ^2 test statistic (DIS case):

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





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!