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

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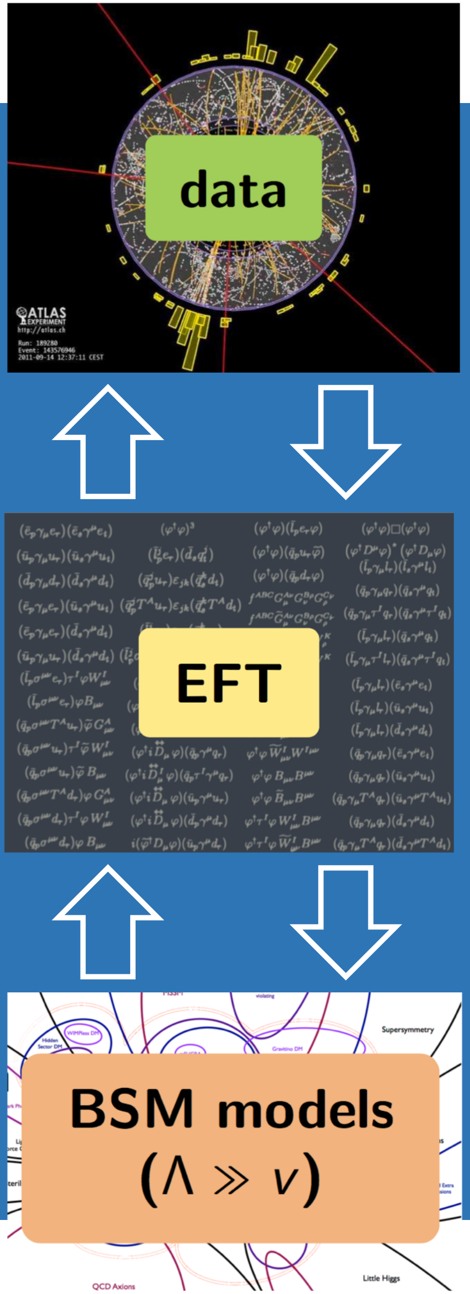
@Electroweak and BSM Physics at the EIC

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 before **global fit**

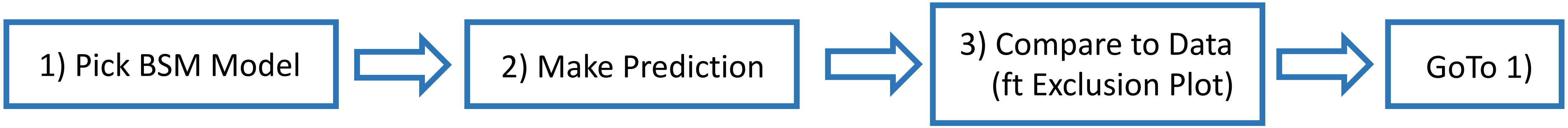
○ the How

- 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:



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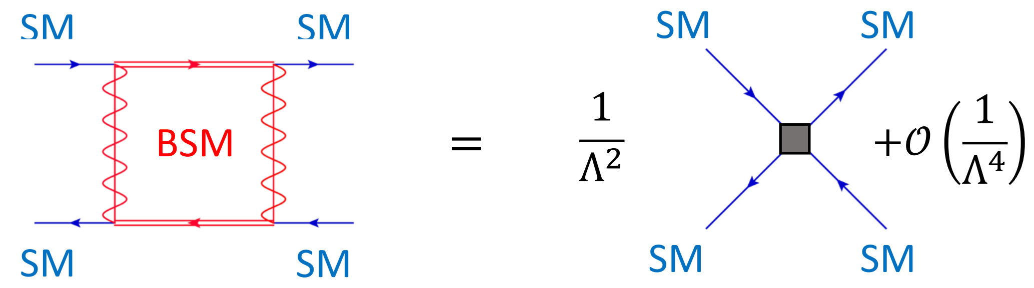
1) Pick BSM Model → 2) Make Prediction → 3) Compare to Data (ft Exclusion Plot) → GoTo 1)

More Economic Way:

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



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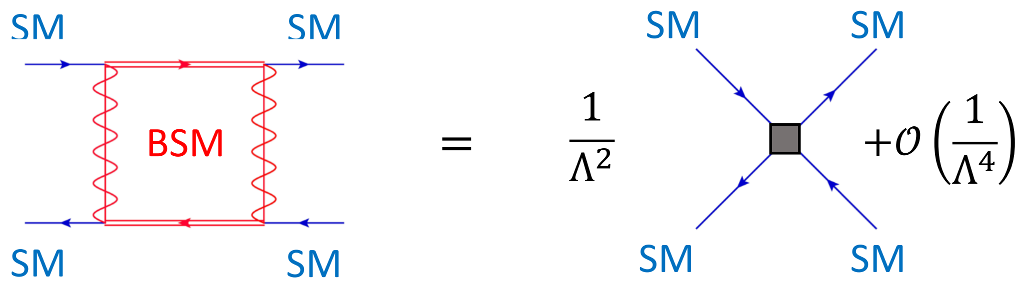

Non-SM operators **suppressed by powers of $\frac{1}{\Lambda}$:**

- 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

$1: X^3$	
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}	$H^\dagger H\, G_{\mu\nu}^A G^{A\mu\nu}$
$Q_{H\widetilde{G}}$	$H^\dagger H\, \widetilde{G}_{\mu\nu}^A G^{A\mu\nu}$
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Q_{HWB}	$H^\dagger \tau^I H\, W_{\mu\nu}^I B^{\mu\nu}$
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$6: \psi^2 X H + \text{h.c.}$	
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}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{e}_p \gamma^\mu e_r)$
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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}	$(\bar{l}_p \gamma_\mu l_r)(\bar{l}_s \gamma^\mu l_t)$
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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) $\quad (\partial_\mu \phi)\partial^\mu(\partial^2\phi) \leftrightarrow -\phi\partial^4\phi$

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Many equivalent bases – not all created equal

⇨ go **for least number of derivatives**

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

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$8: (\bar{L}L)(\bar{L}L)$		$8: (\bar{R}R)(\bar{R}R)$		$8: (\bar{L}L)(\bar{R}R)$	
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}	$(\bar{l}_p\gamma_\mu l_r)(\bar{e}_s\gamma^\mu e_t)$
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		$Q_{ud}^{(1)}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{u}_s\gamma^\mu T^A u_t)$
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Q_{ledq}	$(\bar{l}_p^j e_r)(\bar{d}_s q_{tj})$	$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r)\epsilon_{jk}(\bar{q}_s^k d_t)$
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		$Q_{lequ}^{(3)}$	$(\bar{l}_p^j\sigma_{\mu\nu}e_r)\epsilon_{jk}(\bar{q}_s^k\sigma^{\mu\nu}u_t)$

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.

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

Many equivalent bases – not all created equal

⇒ 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 **4-Fermi**

(Z-couplings better probed @ Z-Pole)

Flat Directions: Drell-Yan

What's a flat direction?

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

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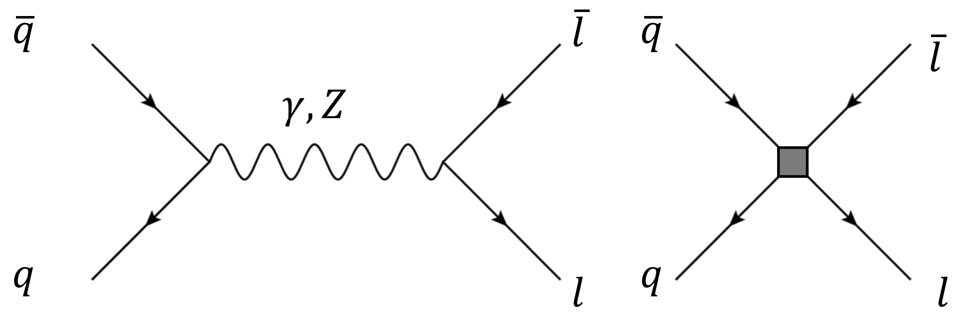

Example: **Drell-Yan** observables are only sensitive to a few combinations

Too many Wilson Coefficients:
kinematic variable distributions show flat directions
(e.g.: Rapidity , Lepton m_{ll}, …)

Alte/König/Shepherd (1812.07575)

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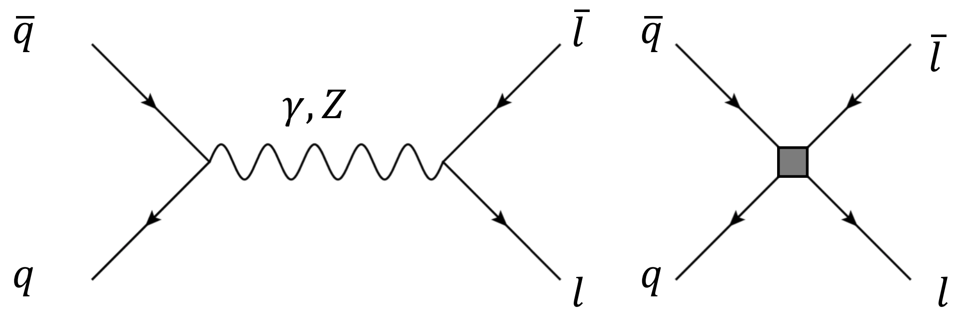
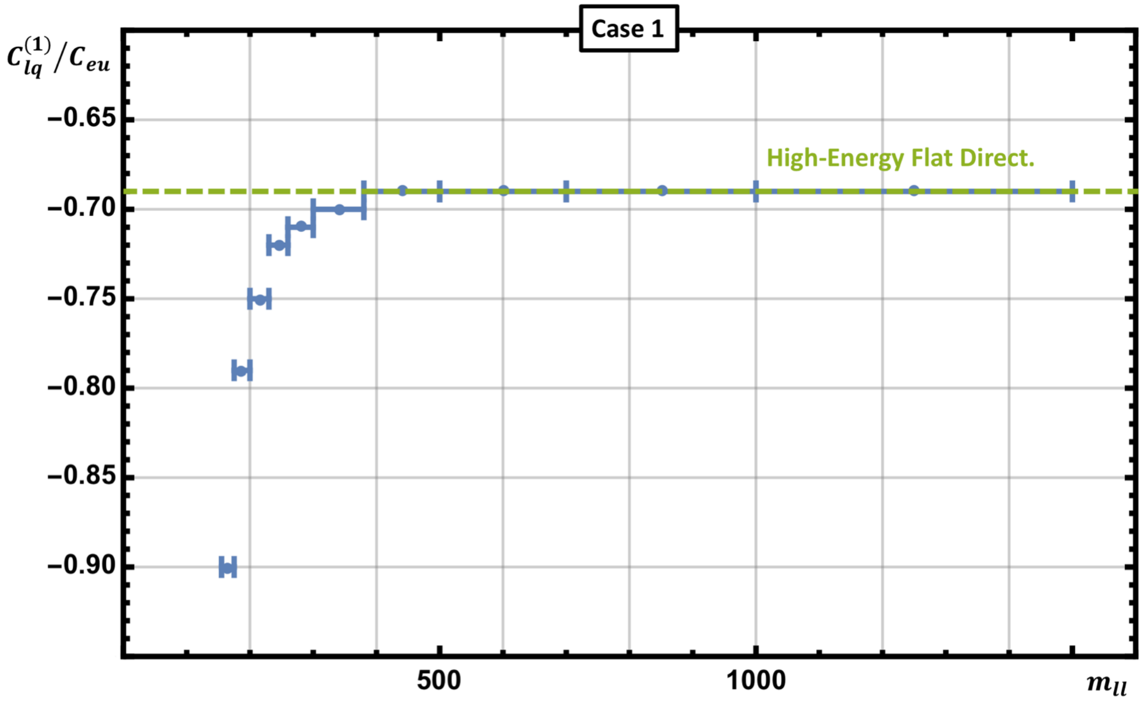
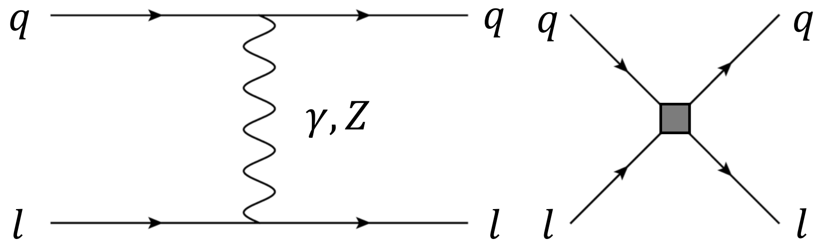




Approximate flat-direction in Drell-Yan fit (high m_{ll} bins)

Boughezal/Petriello/DW (2004.00748)

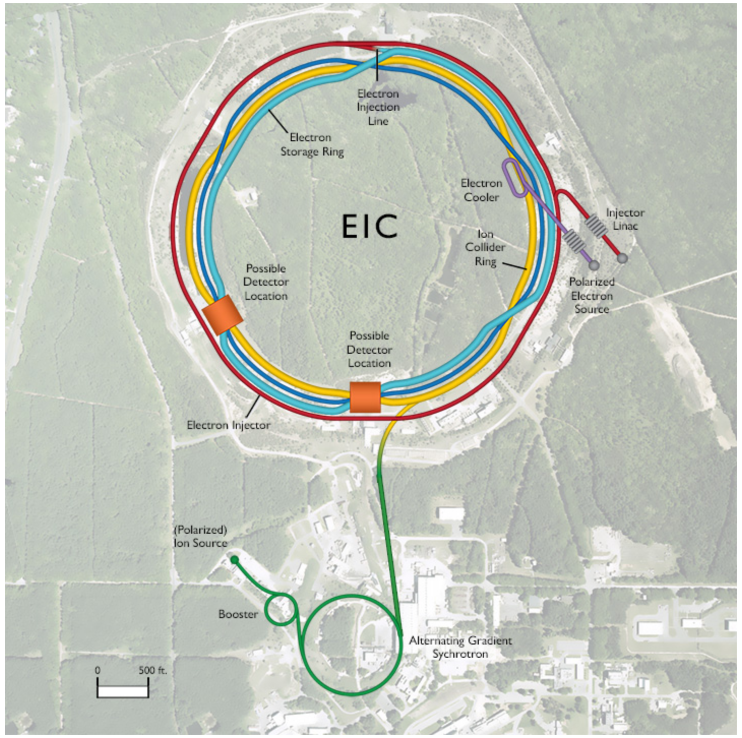
EIC - Overview



Standard Model and SMEFT contributions
(here: **leading order**, NLO under control)

Technical assumptions of the analysis:

- CoM Energy up to $\sqrt{\boldsymbol{S}} = \mathbf{140GeV}$
- 70% Polarized electron and proton Beams
- Projected luminosity $\boldsymbol{\mathcal{L}} \sim \mathbf{10\ fb^{-1}}$ $(100\ \mathrm{fb}^{-1}?)$
- 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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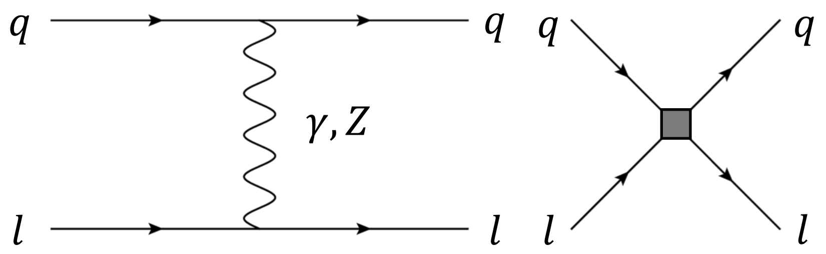

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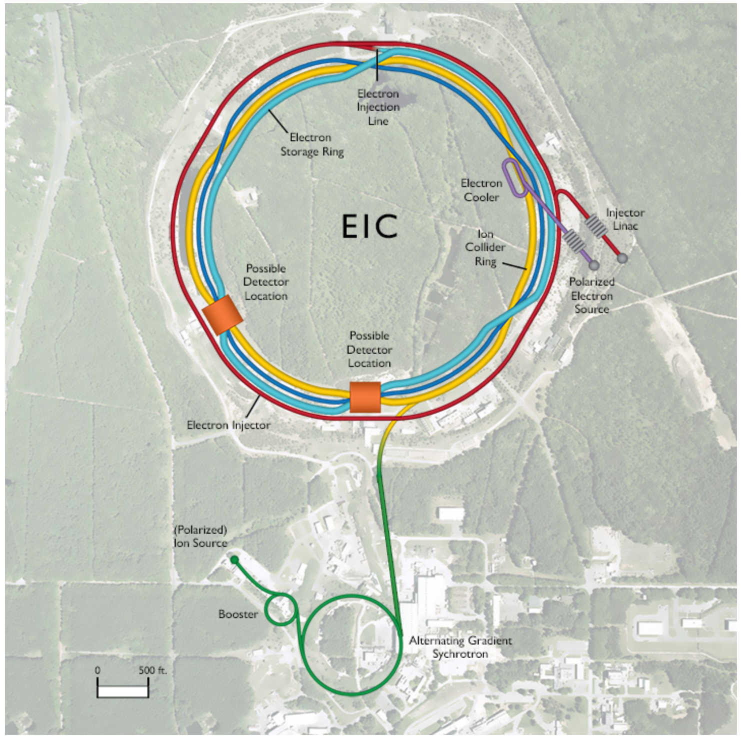

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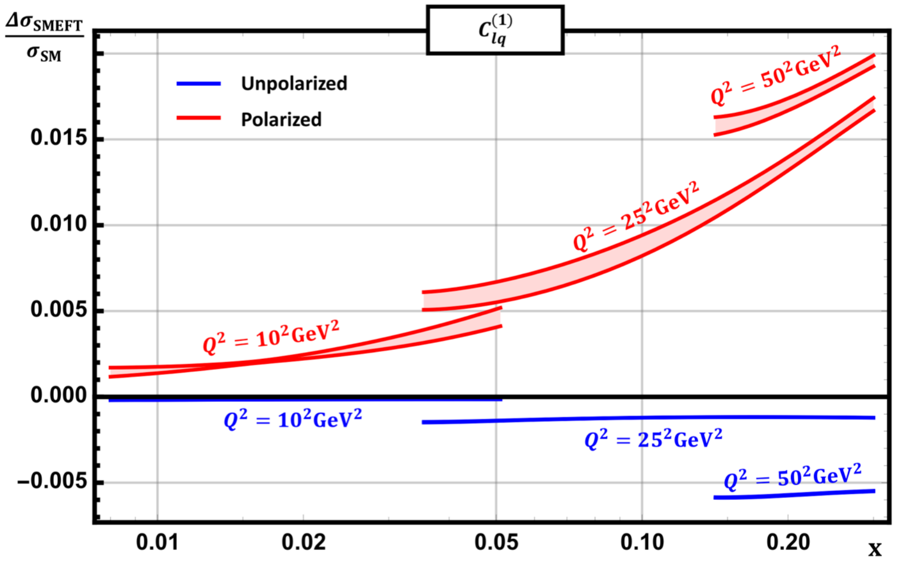

Expected size of SMEFT effect in DIS (including PDF error, $\Lambda = 1\mathrm{TeV}$)

Probing SMEFT at EIC (I)

General Idea:

- Use different **combinations of polarized observables** to lift flat directions
- Observables: Polarized/Unpolarized Protons vs 2 Electron Polarizations
- Ultimate Goal: **Simultaneous fit of PDFs AND Wilson Coefficients**

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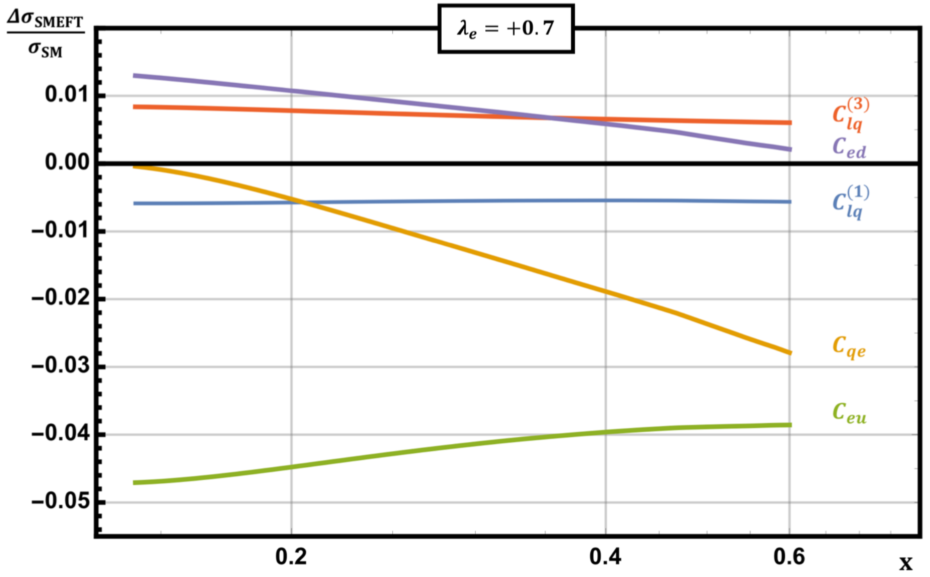

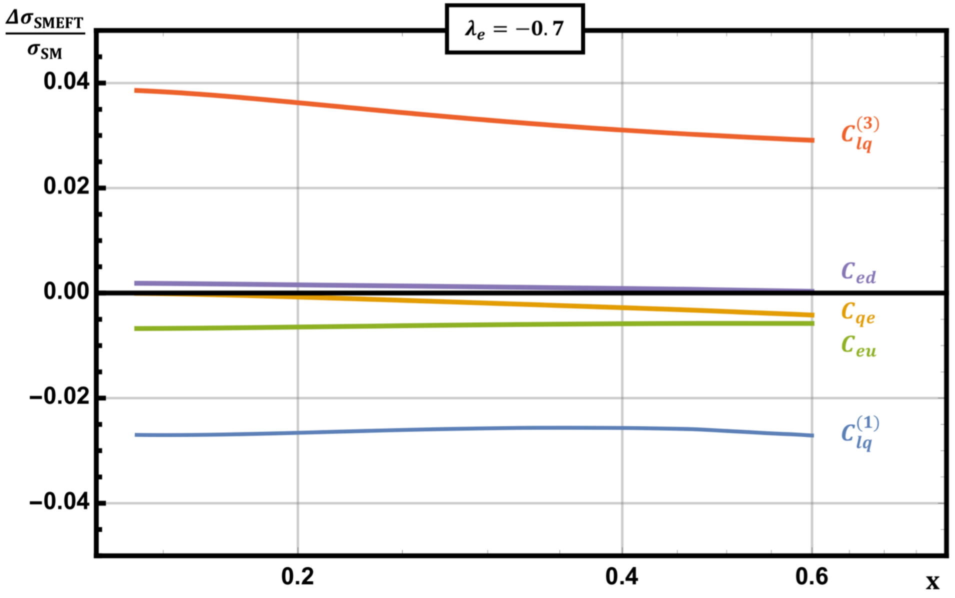

Different Wilson coefficients contribute for different electron polarizations

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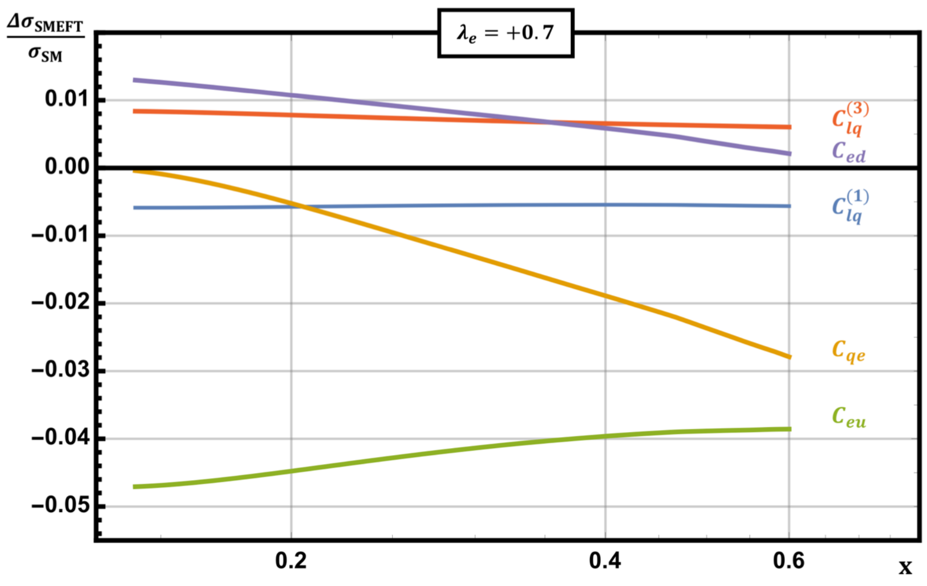
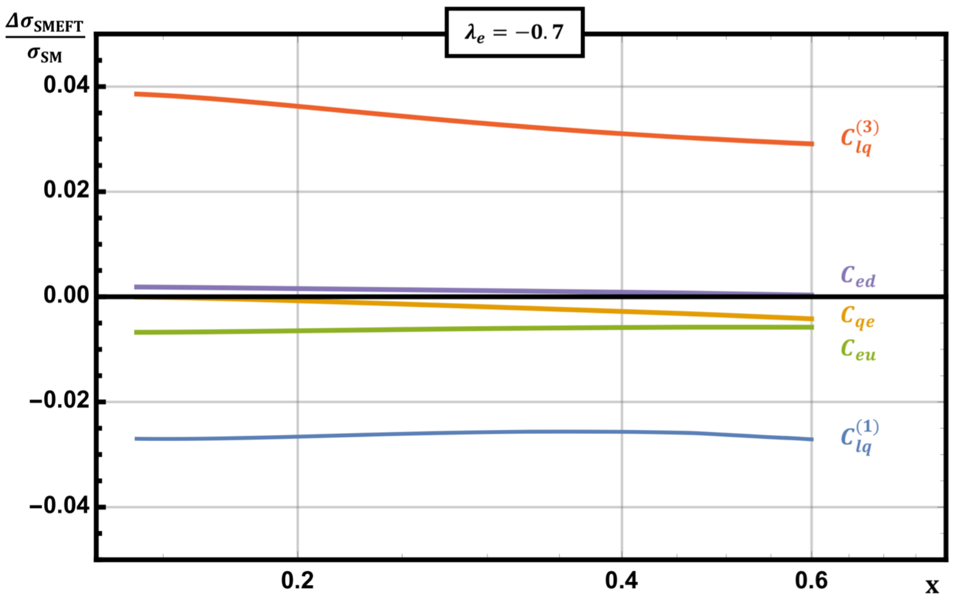




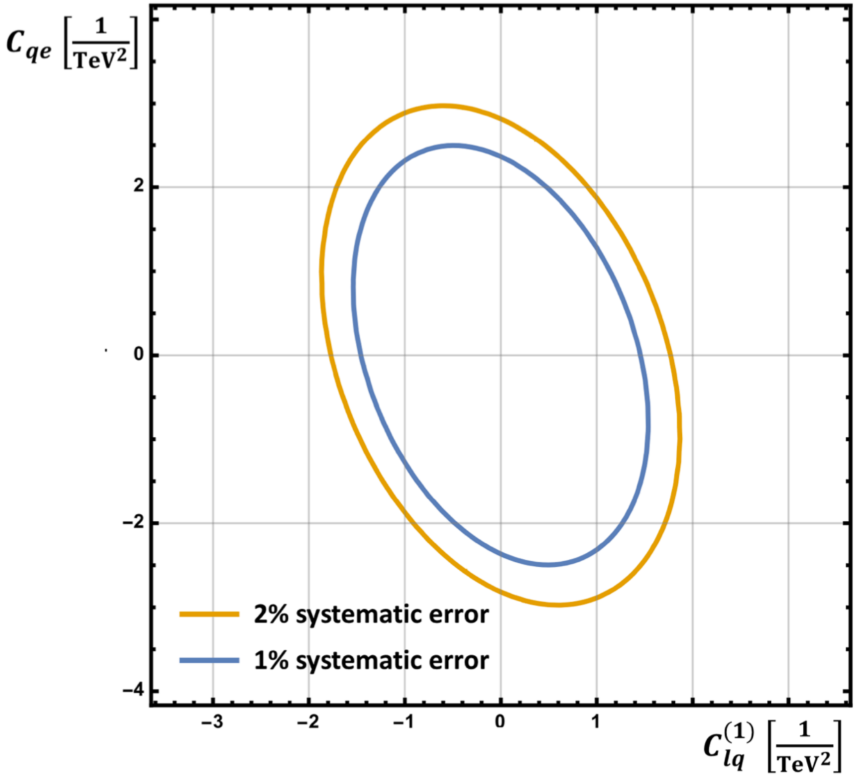
Different Wilson coefficients contribute for different electron polarizations

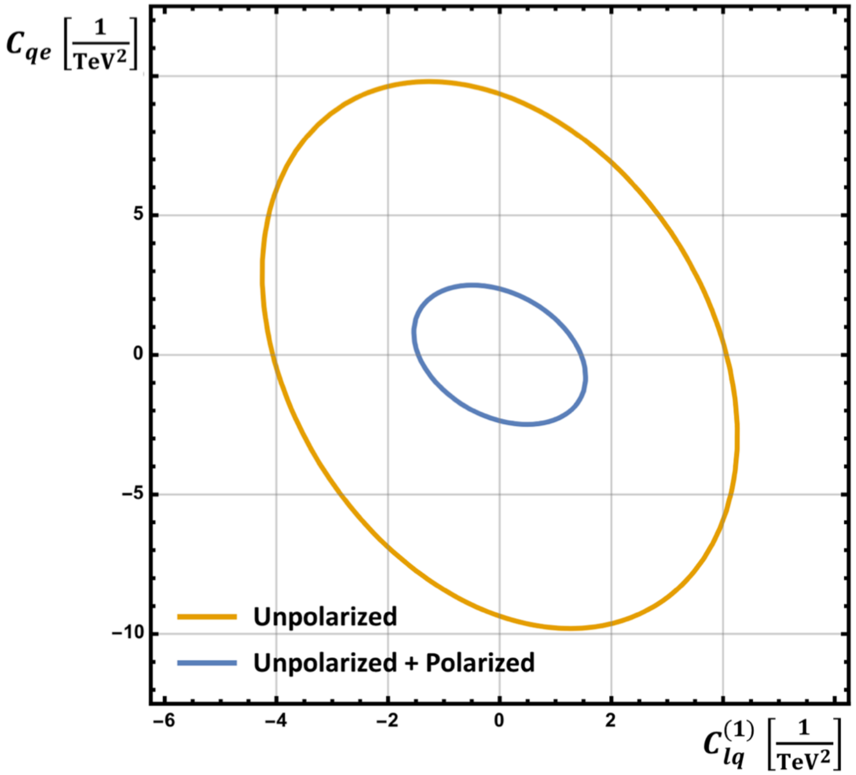
Additional Contribution: Charged Current $u\ e^- \to d\ \nu_e$ ⇨ Signature not as clean but only sensitive to $C_{lq}^{(3)}$

(Off-shell W-analysis for Drell-Yan at LHC not available yet though)

Probing SMEFT at EIC (II)

Impact of Systematic Errors (left) and polarized proton beam data (right)





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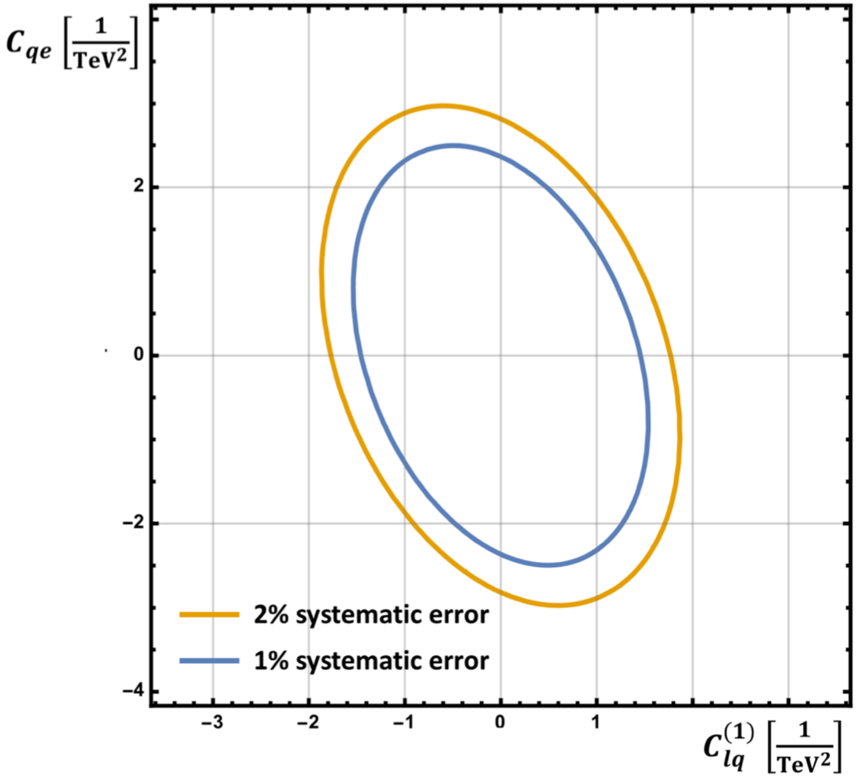

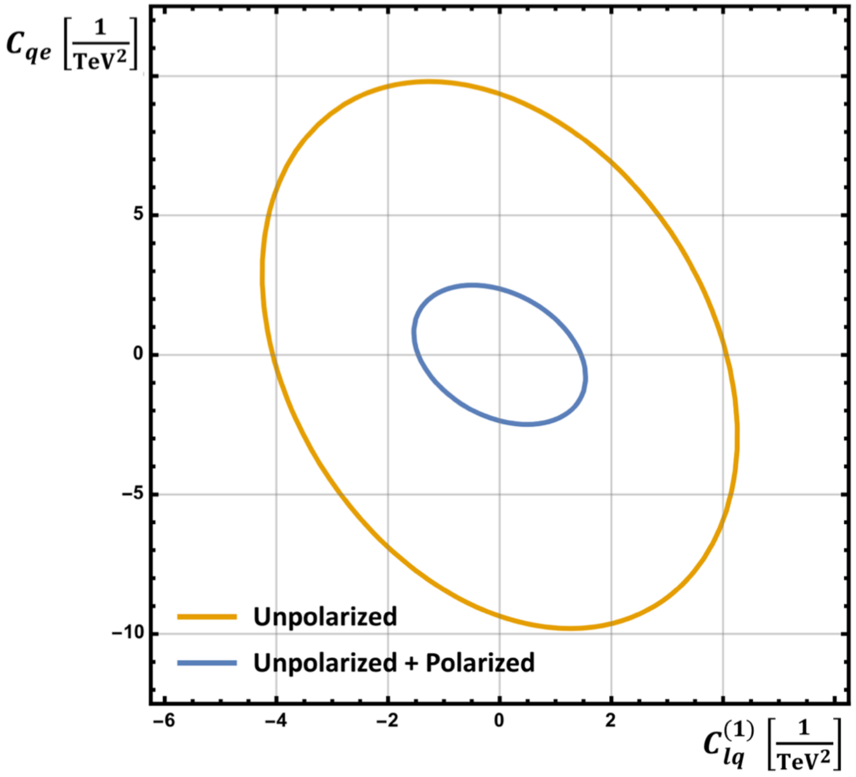

<u>**Takeaways to keep in mind:**</u>

- **Polarized observables** are crucial (even though larger experimental uncertainty)
- Impact of systematic error on bounds is fairly small
- **High Q^2/High x bins** are most important (best SMEFT/SM ratio)

DY+EIC: Best Bounds Yet

Fitting Methodology (68% CL):

For EIC/DIS:

- Integrate over (x, Q^2) bins

⇨ Determine binning through syst./stat. uncertainties

- Assume uncorrelated errors
- $\Delta\sigma_{SMFT}$ measures deviation from SM

Define $\boldsymbol{\chi^2}$ **test statistic** (DIS case):

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

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ATLAS Collab. (1606.01736)

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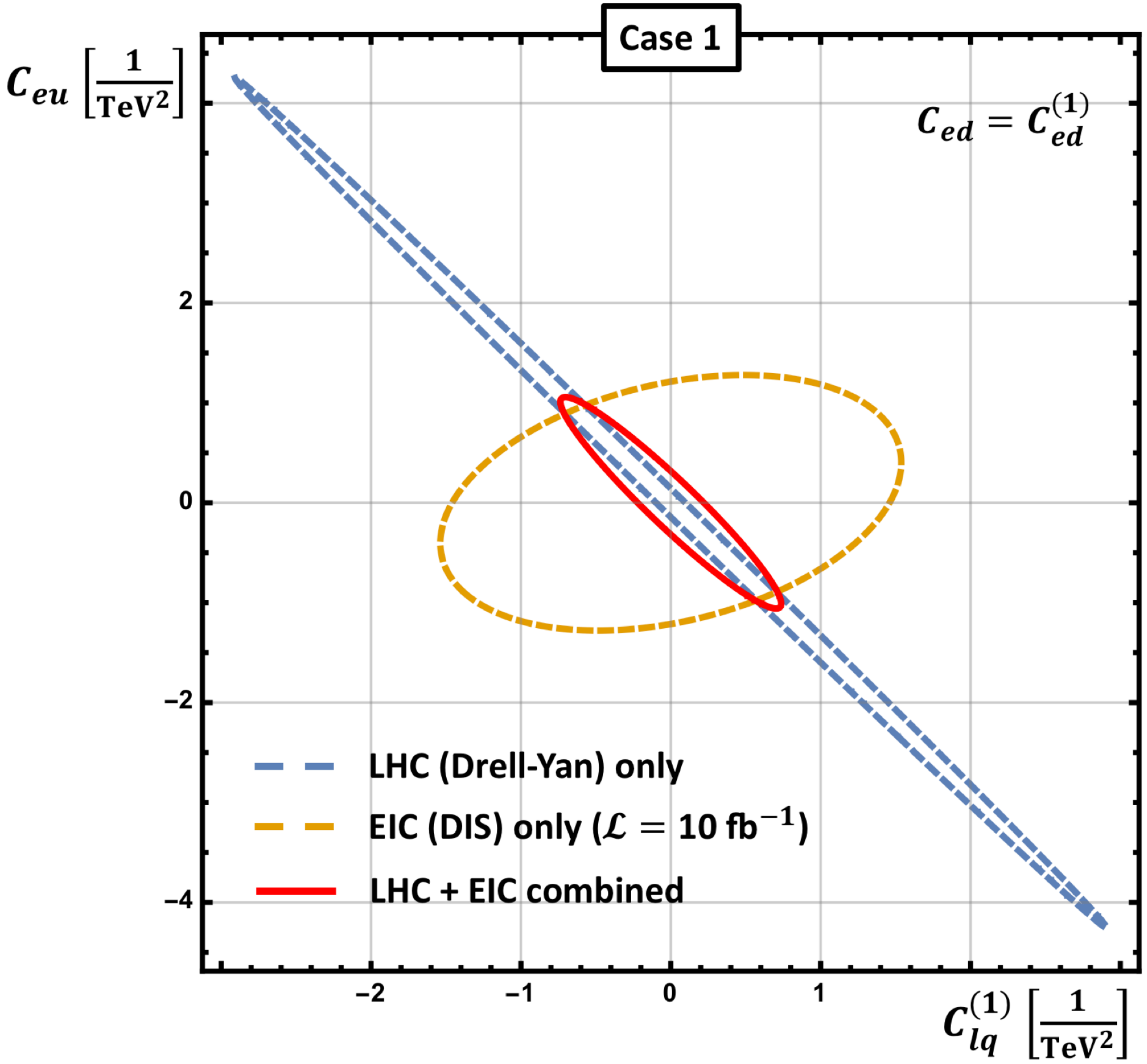

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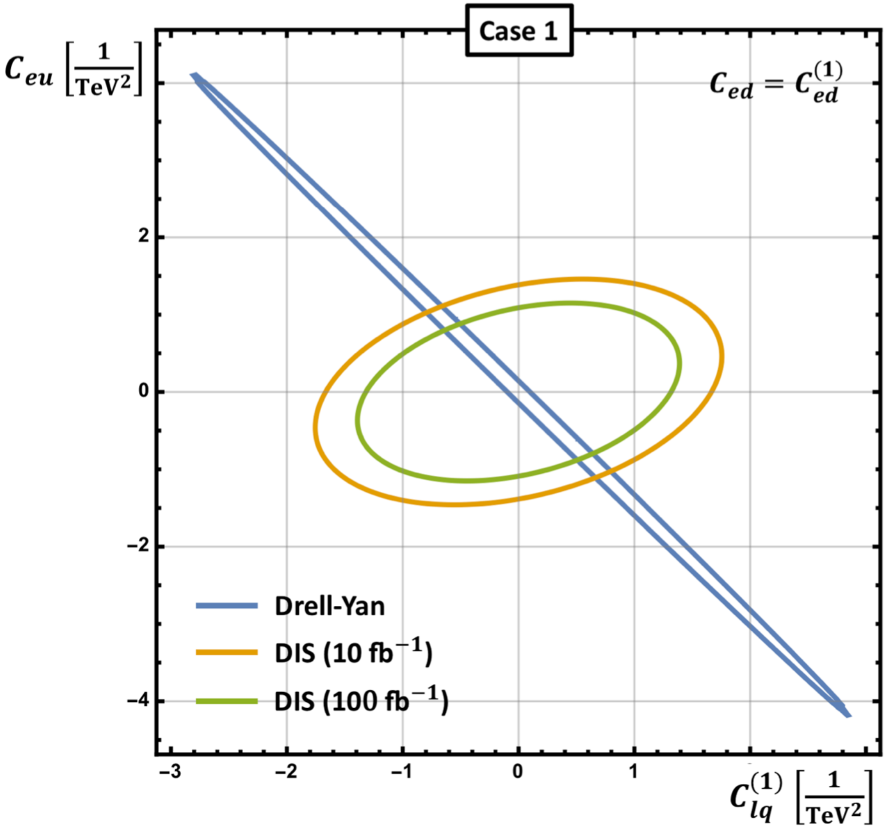

<u>Combined DY-DIS bounds:</u>

- Luminosity increase only has moderate impact
- Correlation (= flat direction) is determined by degree of polarization of beam(s)
- **EIC data tightens LHC bounds considerably!**

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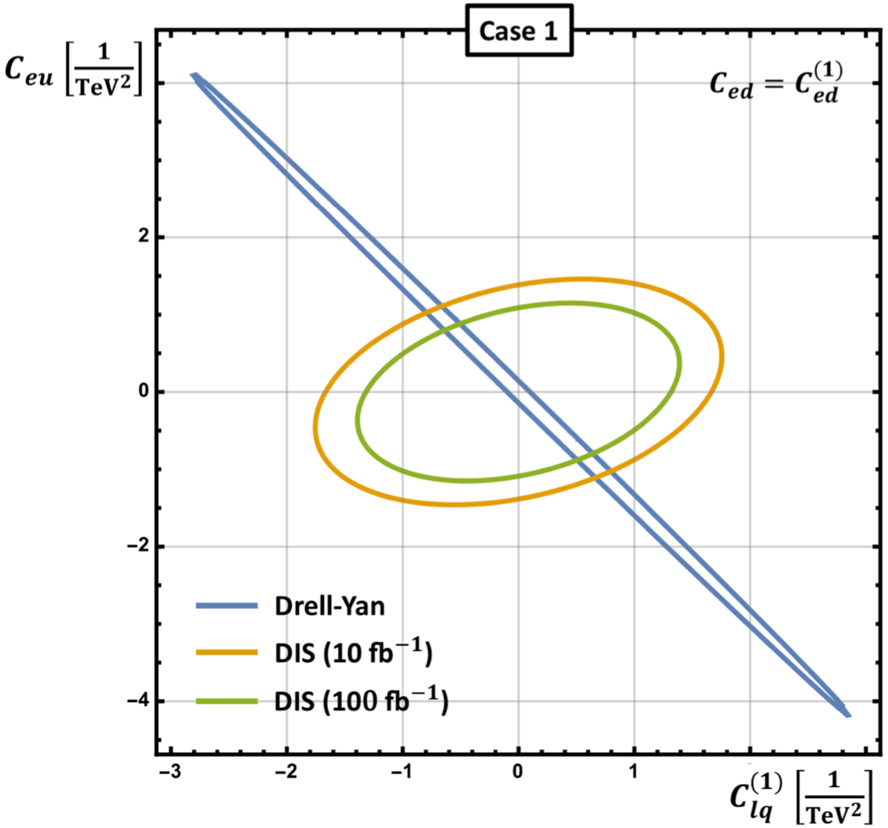
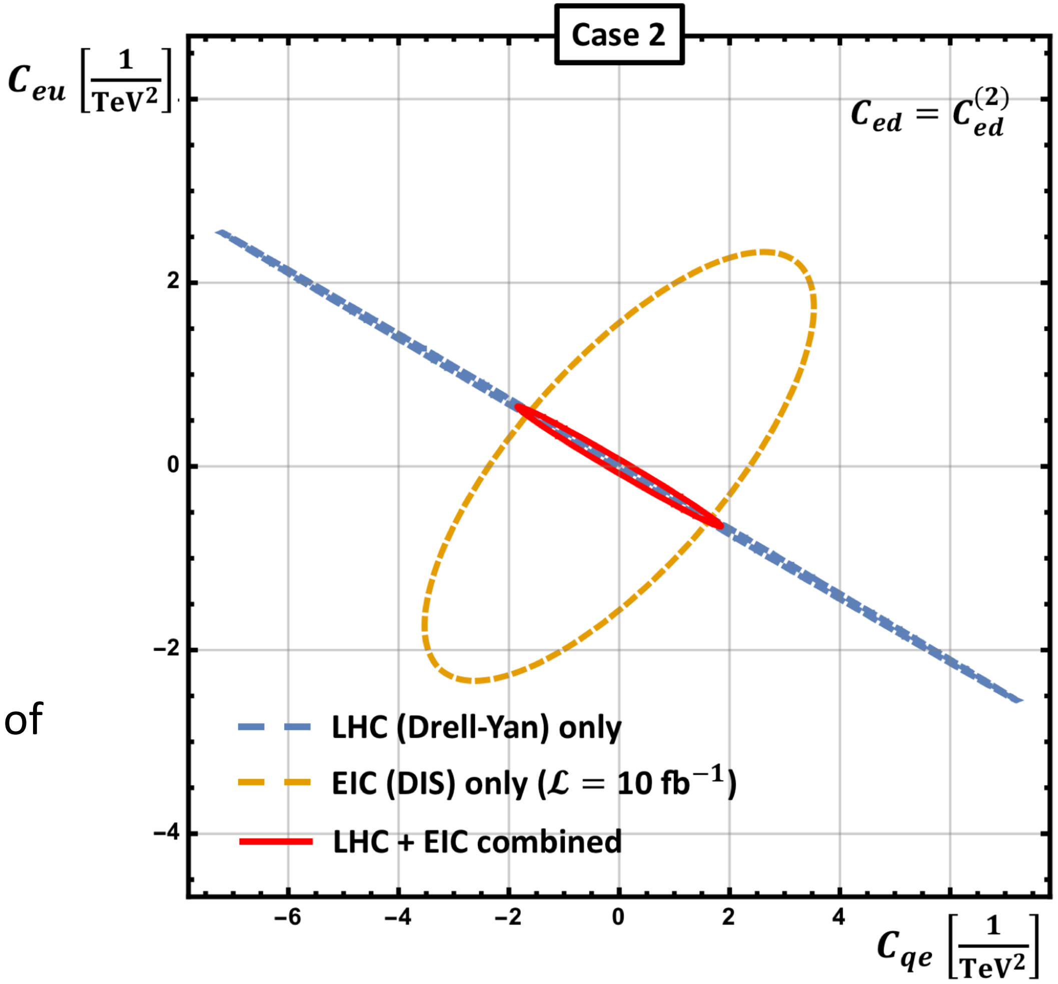


Additional Drell-Yan flat direction can lifted analogously through EIC observables, e.g.:



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Summary and Outlook

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SMEFT suffers from a large number of flat directions

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

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

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Possible Future Directions:

- How to probe higher generation coefficients, e.g. C_{eu}^{2211}? (COMPASS ($p + \mu^{\pm}$) might be starting point, but needs higher COM energy)
- $pp \to \mu^{+}\mu^{-}$ Drell-Yan bounds from LHC (Compare with SEAQUEST?)

Thank you!