Impact of Forward-Backward Asymmetry on SMEFT fits with high m_{ll} Drell-Yan data

Yingsheng Huang

Northwestern U. & Argonne

In collaboration with:

Radja Boughezal and **Frank Petriello**

Northwestern University

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SMEFT

- No conclusive evidence of new physics, suggest new physics is probably above TeV scale
- Limitations of current experiments motivate indirect searches that probe deviations from SM predictions

SMEFT

- ◇ No conclusive evidence of new physics, suggest new physics is probably above TeV scale
- ◇ Limitations of current experiments motivate indirect searches that probe deviations from SM predictions

- Standard Model Effective Field Theory (SMEFT)
  - extension to SM
  - degrees of freedom & symmetries of SM
  - power counting: new physics scale Λ

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \boxed{\frac{1}{\Lambda^2}\sum C_6\mathcal{O}_6} + \boxed{\frac{1}{\Lambda^4}\sum C_8\mathcal{O}_8} + \cdots$$

  - ▶ omitting odd dimensions due to lepton & baryon number violation
  - ▶ $\boxed{\mathcal{L}_6}$ (Warsaw basis): 76 B-preserving Lagrangian terms, 2499 parameters

Grzadkowski et al. 2010

  - ▶ $\boxed{\mathcal{L}_8}$: 1031 Lagrangian terms, 44807 parameters **Murphy 2020; Li et al. 2021**
  - ▶ Non-redundant basis known up to dimension-12: **2305.06832**

DIM-6 OPERATORS Warsaw basis Grzadkowski et al. 2010

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	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$
$Q_{\widetilde{W}}$	$\varepsilon^{IJK} \widetilde{W}_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$

φ^6 and $\varphi^4 D^2$	
Q_φ	$(\varphi^\dagger\varphi)^3$
$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$
$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu \varphi\right)^\star \left(\varphi^\dagger D_\mu \varphi\right)$

$\psi^2\varphi^3$	
$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar{l}_p e_r \varphi)$
$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar{q}_p u_r \widetilde{\varphi})$
$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar{q}_p d_r \varphi)$

$X^2\varphi^2$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G^A_{\mu\nu} G^{A\mu\nu}$
$Q_{\varphi\widetilde{G}}$	$\varphi^\dagger\varphi\, \widetilde{G}^A_{\mu\nu} G^{A\mu\nu}$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W^I_{\mu\nu} W^{I\mu\nu}$
$Q_{\varphi\widetilde{W}}$	$\varphi^\dagger\varphi\, \widetilde{W}^I_{\mu\nu} W^{I\mu\nu}$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$
$Q_{\varphi\widetilde{B}}$	$\varphi^\dagger\varphi\, \widetilde{B}_{\mu\nu} B^{\mu\nu}$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W^I_{\mu\nu} B^{\mu\nu}$
$Q_{\varphi\widetilde{W}B}$	$\varphi^\dagger\tau^I\varphi\, \widetilde{W}^I_{\mu\nu} B^{\mu\nu}$

$\psi^2 X\varphi$	
Q_{eW}	$(\bar{l}_p\sigma^{\mu\nu} e_r)\tau^I\varphi\, W^I_{\mu\nu}$
Q_{eB}	$(\bar{l}_p\sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$
Q_{uG}	$(\bar{q}_p\sigma^{\mu\nu} T^A u_r)\widetilde{\varphi}\, G^A_{\mu\nu}$
Q_{uW}	$(\bar{q}_p\sigma^{\mu\nu} u_r)\tau^I\widetilde{\varphi}\, W^I_{\mu\nu}$
Q_{uB}	$(\bar{q}_p\sigma^{\mu\nu} u_r)\widetilde{\varphi}\, B_{\mu\nu}$
Q_{dG}	$(\bar{q}_p\sigma^{\mu\nu} T^A d_r)\varphi\, G^A_{\mu\nu}$
Q_{dW}	$(\bar{q}_p\sigma^{\mu\nu} d_r)\tau^I\varphi\, W^I_{\mu\nu}$
Q_{dB}	$(\bar{q}_p\sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$

$\psi^2\varphi^2 D$	
$Q^{(1)}_{\varphi l}$	$(\varphi^\dagger \overleftrightarrow{iD_\mu}\, \varphi)(\bar{l}_p\gamma^\mu l_r)$
$Q^{(3)}_{\varphi l}$	$(\varphi^\dagger \overleftrightarrow{iD^I_\mu}\, \varphi)(\bar{l}_p\tau^I\gamma^\mu l_r)$
$Q_{\varphi e}$	$(\varphi^\dagger \overleftrightarrow{iD_\mu}\, \varphi)(\bar{e}_p\gamma^\mu e_r)$
$Q^{(1)}_{\varphi q}$	$(\varphi^\dagger \overleftrightarrow{iD_\mu}\, \varphi)(\bar{q}_p\gamma^\mu q_r)$
$Q^{(3)}_{\varphi q}$	$(\varphi^\dagger \overleftrightarrow{iD^I_\mu}\, \varphi)(\bar{q}_p\tau^I\gamma^\mu q_r)$
$Q_{\varphi u}$	$(\varphi^\dagger \overleftrightarrow{iD_\mu}\, \varphi)(\bar{u}_p\gamma^\mu u_r)$
$Q_{\varphi d}$	$(\varphi^\dagger \overleftrightarrow{iD_\mu}\, \varphi)(\bar{d}_p\gamma^\mu d_r)$
$Q_{\varphi ud}$	$i(\widetilde{\varphi}^\dagger D_\mu\varphi)(\bar{u}_p\gamma^\mu d_r)$

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

$(\bar{R}R)(\bar{R}R)$	
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}	$(\bar{e}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu d_t)$
$Q^{(1)}_{ud}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{d}_s\gamma^\mu d_t)$
$Q^{(8)}_{ud}$	$(\bar{u}_p\gamma_\mu T^A u_r)(\bar{d}_s\gamma^\mu T^A d_t)$

$(\bar{L}L)(\bar{R}R)$	
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}	$(\bar{q}_p\gamma_\mu q_r)(\bar{e}_s\gamma^\mu e_t)$
$Q^{(1)}_{qu}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{u}_s\gamma^\mu u_t)$
$Q^{(8)}_{qu}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{u}_s\gamma^\mu T^A u_t)$
$Q^{(1)}_{qd}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{d}_s\gamma^\mu d_t)$
$Q^{(8)}_{qd}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{d}_s\gamma^\mu T^A d_t)$

$(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$	
Q_{ledq}	$(\bar{l}^j_p e_r)(\bar{d}_s q^j_t)$
$Q^{(1)}_{quqd}$	$(\bar{q}^j_p u_r)\varepsilon_{jk}(\bar{q}^k_s d_t)$
$Q^{(8)}_{quqd}$	$(\bar{q}^j_p T^A u_r)\varepsilon_{jk}(\bar{q}^k_s T^A d_t)$
$Q^{(1)}_{lequ}$	$(\bar{l}^j_p e_r)\varepsilon_{jk}(\bar{q}^k_s u_t)$
$Q^{(3)}_{lequ}$	$(\bar{l}^j_p\sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar{q}^k_s\sigma^{\mu\nu} u_t)$

B-violating	
Q_{duq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$
Q_{qqu}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$
Q_{qqq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jn}\varepsilon_{km}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$

- Relevant to Drell-Yan at tree-level
- Minimal flavor violation (MFV):

  Yukawa terms are the only sources of flavor symmetry violation
- 3 relevant categories:
  - $\psi^2 X\varphi$
  - $\psi^2\varphi^2 D$
  - ψ^4

Relevant operators dimension-6

Boughezal, Mereghetti and Petriello
2106.05337

- Study scaling of cross sections in high energy limit (Mandelstam s, Higgs vev. v)
- Only show some examples for each category
- q, l: left-handed fermion doublets

  e, u, d: right-handed fermion singlets

  ϕ: Higgs doublet

$\mathcal{L}_{\psi^2 X \phi}$	$\mathcal{L}_{\psi^2 \phi^2 D}$	$\mathcal{L}_{\psi^4}$
$\frac{C_{eB}}{\Lambda^2} \bar{l} \sigma^{\mu\nu} B_{\mu\nu} \phi e$	$\frac{C_{Hl}^{(1)}}{\Lambda^2} \phi^\dagger \overleftrightarrow{D^\mu} \phi \bar{l} \gamma_\mu l$	$\frac{C_{lq}^{(1)}}{\Lambda^2} \bar{l} \gamma^\mu l q \gamma_\mu q$
$\frac{C_{uW}}{\Lambda^2} \bar{q} \sigma^{\mu\nu} \tau^I W_{\mu\nu}^I \phi u$	$\frac{C_{Hu}}{\Lambda^2} \phi^\dagger \overleftrightarrow{D^\mu} \phi \bar{u} \gamma_\mu u$	$\frac{C_{ld}}{\Lambda^2} \bar{l} \gamma^\mu l d \gamma_\mu d$
Dipole coupling	Z-vertex corrections	Four-fermion interactions
assume massless fermion		
$\sim \mathcal{O}(v^2 s/\Lambda^4)$	$\sim \mathcal{O}(v^2/\Lambda^2)$	$\sim \mathcal{O}(s/\Lambda^2)$

Dipole coupling & vertex corrections are numerically verified to be much smaller than four fermion operators

Relevant operators dimension-6

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- Study scaling of cross sections in high energy limit (Mandelstam s, Higgs vev. v)
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- q, l: left-handed fermion doublets

  $e,$ [illegible] right-handed fermion singlets

  ϕ:

7 dim-6 four-fermion operators (for high m_{ll} data):

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

$\frac{C}{\Lambda}$

$\frac{C_{uW}}{\Lambda^2}$

Dipole coupling

assume massless fermion

$\sim \mathcal{O}(v^2 s/\Lambda^4)$

Z-vertex corrections

$\sim \mathcal{O}(v^2/\Lambda^2)$

Four-fermion interactions

$\sim \mathcal{O}(s/\Lambda^2)$

Dipole coupling & vertex corrections are numerically verified to be much smaller than four fermion operators

Flat directions

degeneracies among Wilson coefficients

Example:

Total cross section $\sigma \propto C_1 + C_2$

σ can not distinguish Wilson coefficients C_1 and C_2

Flat directions

degeneracies among Wilson coefficients

Four fermion operators in Drell-Yan:

- Flat directions in low-energy observables

  Falkowski, González-Alonso, and Mimouni 2017

- and high m_{ll} bins at hadron colliders

  Alte, König, and Shepherd 2019

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One solution: future experiments that probe independent combinations of coefficients

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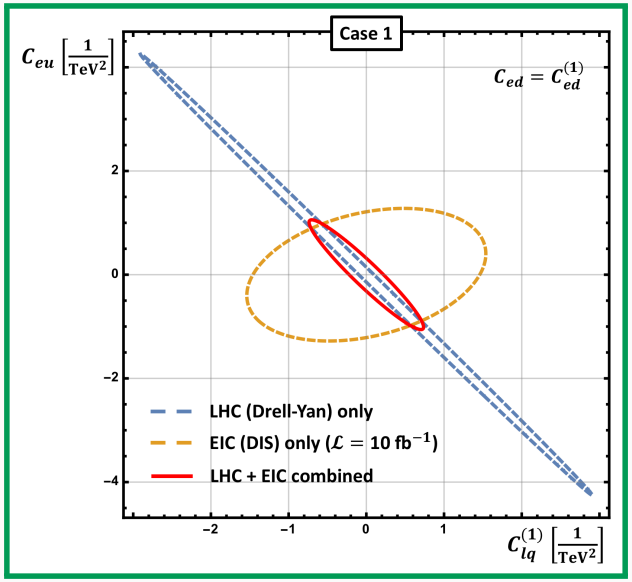
One solution: future experiments that probe independent combinations of coefficients

- EIC **Boughezal, Petriello, and Wiegand 2020**



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One solution: future experiments that probe independent combinations of coefficients

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- low energy Parity-Violating Electron Scattering (PVES)

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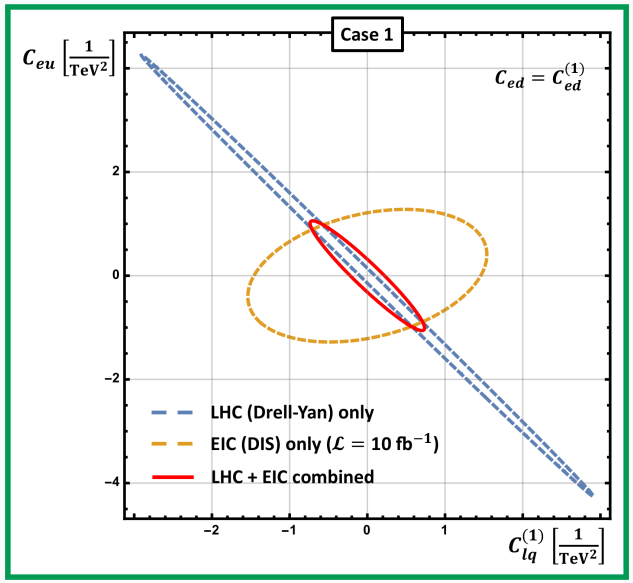

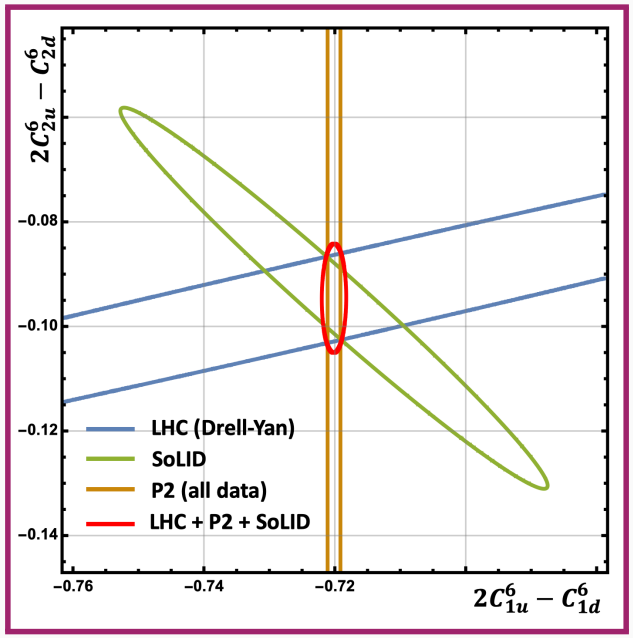

FLAT DIRECTIONS Drell-Yan/four fermion

Flat directions

degeneracies among Wilson coefficients

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dependent combinations of coefficients

- EIC **Boughezal, Petriello, and Wiegand 2020**
- low energy Parity-Violating Electron Scattering (PVES)

  Boughezal, Petriello, and Wiegand 2021

This talk:

remove flat directions by combining

- **invariant mass dist.**
- **forward-backward asymmetry (AFB)**

at the LHC.

LO SMEFT contributions to partonic cross section in **high energy limit**

$$\frac{\mathrm{d}\sigma^x}{dm_{ll}^2 dY dc_\theta} \sim \frac{1}{\Lambda^2}\frac{A_1^x \hat{u}^2 + A_2^x \hat{t}^2}{\hat{s}^2}$$

where $\hat{t} = -\frac{\hat{s}}{2}(1 - c_\theta)$, $\hat{u} = -\frac{\hat{s}}{2}(1 + c_\theta)$, $c_\theta \equiv \cos(\theta)$ (θ: polar angle in parton C.M. frame).

- A_i^x: linear in $C_i^{(6)}$;
- A does not depend on kinematic variables
- x: partonic channel u or d

LO SMEFT contributions to partonic cross section in **high energy limit**

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condition of a flat direction

u & d channels: same condition of $C_i^{(6)}$ for the SMEFT corrections to vanish

Examples of Wilson coefficients combination (C_1 & C_2)

$$\begin{cases} \sigma^u \sim C_1 + C_2 \\ \sigma^d \sim C_1 + C_2 \end{cases} \Rightarrow \text{same combination in both channels} \Rightarrow \text{flat direction}$$

$$\begin{cases} \sigma^u \sim C_1 + C_2 \\ \sigma^d \sim C_1 - C_2 \end{cases} \Rightarrow \text{different combination in both channels} \Rightarrow \text{no flat direction}$$

LO SMEFT contributions to partonic cross section in **high energy limit**

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Replace $\hat{u}, \hat{t}$ with c_θ

$$\frac{\mathrm{d}\sigma^x}{dm_{ll}^2 dY dc_\theta} \sim \frac{1}{4\Lambda^2}\left[(A_1^x + A_2^x)(1 + {c_\theta}^2) + 2(A_1^x - A_2^x)c_\theta\right]$$

- $\mathrm{d}\sigma/\mathrm{d}m$ is only sensitive to $A_1 + A_2$
- $A_1 - A_2$: vanish under integration over c_θ, can be probed by angular dist.

LO SMEFT contributions to partonic cross section in **high energy limit**

$$\frac{\mathrm{d}\sigma^x}{dm_{ll}^2 dY dc_\theta} \sim \frac{1}{\Lambda^2}\frac{A_1^x \hat{u}^2 + A_2^x \hat{t}^2}{\hat{s}^2}$$

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If C_1 and C_2 exist in A_1 and A_2 separately, angular observables that probe $A_1 - A_2$ may cancel out the flat directions from $A_1 + A_2$

➡ **AFB**

$$dm_{ll}^2 dY dc_\theta \qquad 4\Lambda^2 [($$

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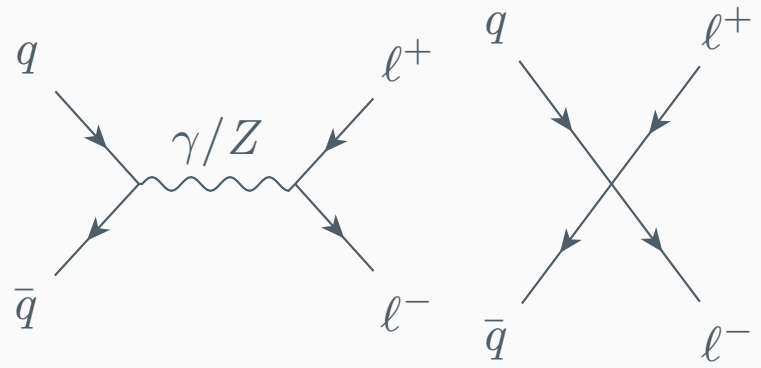
- $A_1 - A_2$: vanish under integration over c_θ, can be probed by angular dist.

Forward-backward Asymmetry in neutral current Drell-Yan

Forward-backward Asymmetry (AFB)

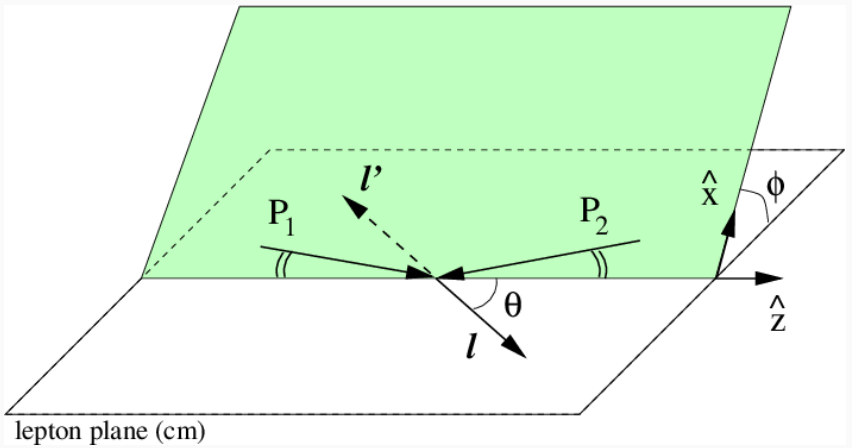
$$A_{\mathrm{FB}} = \frac{\sigma_{\mathrm{F}} - \sigma_{\mathrm{B}}}{\sigma_{\mathrm{F}} + \sigma_{\mathrm{B}}}$$

- depends on Collins-Soper angle θ^*
  - σ_F: forward ($\cos\theta^* > 0$)
  - σ_B: backward ($\cos\theta^* < 0$)



Collins-Soper angle Collins and Soper 1977

$$\cos\theta^* = \frac{2\left(P_1^+ P_2^- - P_1^- P_2^+\right)}{\sqrt{Q^2\left(Q^2 + Q_{\mathrm{T}}^2\right)}} \quad (\text{hadron C.M.})$$



- angle between the incoming quark and the outgoing lepton (negatively charged) in the dilepton rest frame

Forward-backward Asymmetry in neutral current Drell-Yan

Forward-backward Asymmetry (AFB)

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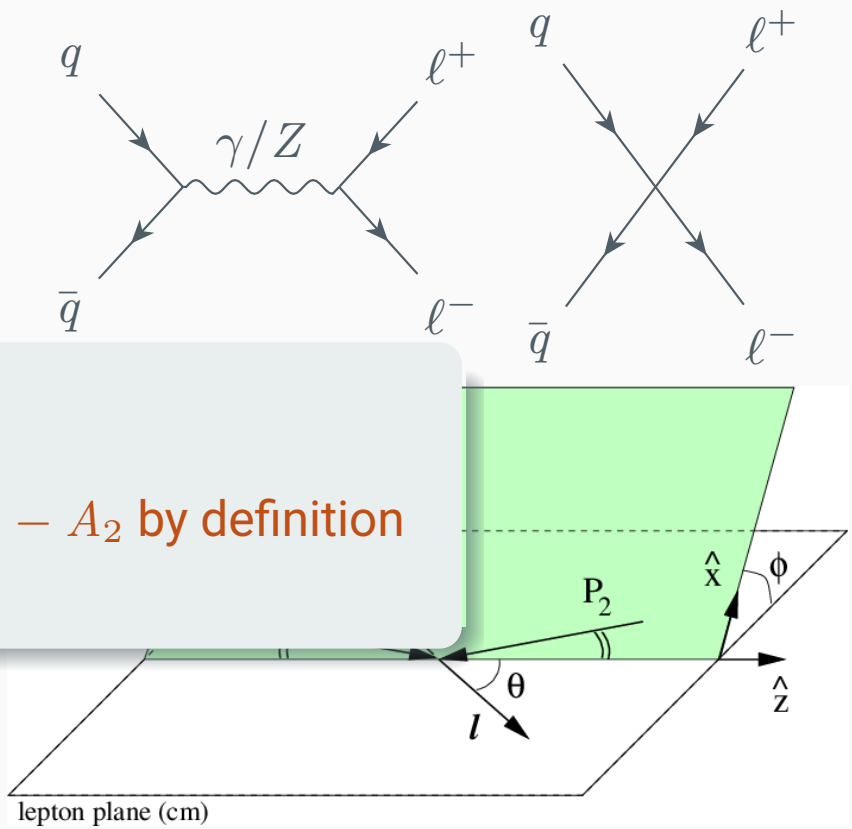
- depends on Collins-Soper angle θ^*
  - σ_F: forwa
  - σ_B: backv

AFB is only sensitive to $A_1 - A_2$ by definition



Collins-Soper ang

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SMEFT CORRECTIONS TO CROSS SECTION & AFB

Structure of the SMEFT cross section

$$\mathrm{d}\sigma = \mathrm{d}\sigma_{\mathrm{SM}} + \sum_i \frac{a_i^{(6)}}{\Lambda^2} C_i^{(6)} + \sum_{i,j} \frac{b_{ij}^{(6)}}{\Lambda^4} C_i^{(6)} C_j^{(6)}$$

Structure of the SMEFT AFB

$$A_{\mathrm{FB}} = A_{\mathrm{FB}}^{\mathrm{SM}} + \sum_i \frac{C_i^{(6)}}{\Lambda^2} \frac{\sigma_{\mathrm{SM}} \Delta a_i^{(6)} - a_i^{(6)} \Delta\sigma_{\mathrm{SM}}}{\sigma_{\mathrm{SM}}^2}$$

$$+ \sum_{ij} \frac{C_i^{(6)} C_j^{(6)}}{\Lambda^4} \frac{\left(a_i^{(6)}\right)^2 \Delta\sigma_{\mathrm{SM}} - a_i^{(6)} \Delta a_i^{(6)} \Delta\sigma_{\mathrm{SM}} - b_{ij}^{(6)} \sigma_{\mathrm{SM}} \Delta\sigma_{\mathrm{SM}} + \Delta b_{ij}^{(6)} \sigma_{\mathrm{SM}}^2}{\sigma_{\mathrm{SM}}^3}$$

- $\sigma \equiv \sigma_F + \sigma_B$, $\Delta\sigma \equiv \sigma_F - \sigma_B$
- a_i, b_{ij} terms: SMEFT corrections
  - a_i: coefficients of terms linear in $C_i^{(6)}$
  - b_{ij}: coefficients of terms quadratic in $C_i^{(6)}$
- AFB expanded up to $\mathcal{O}(1/\Lambda^4)$, including dim-6 linear and quadratic contributions

No.	Exp.	$\sqrt{s}$	Obs.	Lumi. $[\mathrm{fb}^{-1}]$	m_{ll}^{low} [GeV]
I	ATLAS[1]	8 TeV	$\mathrm{d}\sigma/\mathrm{d}m$	20.3	$116-1000$
II	CMS[2]	13 TeV	$\mathrm{d}\sigma/\mathrm{d}m$	137 (ee) 140 $(\mu\mu)$	$200-2210$ (ee) $210-2290$ $(\mu\mu)$
III	CMS[3]	8 TeV	A_{FB}^{*}	19.7	$120-500$
IV	CMS[4]	13 TeV	A_{FB}	138	$170-1000$

- 2 $\mathrm{d}\sigma/\mathrm{d}m$ data sets: (I & II)
- 2 AFB data sets: (III & IV)
- 2 data sets @8 TeV, ~ 20 fb^{-1} (I & III)
- 2 data sets @13 TeV, ~ 140 fb^{-1} (II & IV)

- include only high m_{ll} bins
- Experimental statistics & systematic uncertainties included
- no correlation across data sets

[1] Aad et al. 2016.
[2] Sirunyan et al. 2021.
[3] Khachatryan et al. 2016.
[4] Tumasyan et al. 2022.

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III	CMS	8 TeV	A_{FB}^{*}	19.7	$120-500$
IV	CMS	13 TeV	A_{FB}	138	$170-1000$

- SM: NLO QCD + NLL Sudakov
  - NNLO QCD $\sim 2\%$ for most bins
  - EW: reach 10% for some high m_{ll} bins
- SMEFT: LO in QCD
  - NLO QCD corrections to SMEFT have no impact on the angular structure, thus won't change the flat directions
- PDF set: `NNPDF 3.1 NNLO`
- PDF uncertainties (SM): 100 replicas
- Scale uncertainties (SM): Envelope btw. 7 scales

$$\frac{1}{2} \leq \mu_{R,F}/\mu_0 \leq 2, \quad \frac{1}{2} \leq \mu_R/\mu_F \leq 2.$$

BOUNDS w/ linear contribution only

- First include only linear terms, where flat directions manifest
- Enabling 2 or 3 operators at a time
- Study 2-d bounds:
  - 2 cases that have flat directions
  - 2 cases that don't have flat direction, but still highly correlated
- Show 68% CL bounds with:
  - one $\mathrm{d}\sigma/\mathrm{d}m$ data set only
  - one AFB data set only
  - combining all 4 $\mathrm{d}\sigma/\mathrm{d}m$ and AFB data sets ("combined" fit)

	A_1	A_2
u	$C_{eu}, C_{lq}^{(1)}, C_{lq}^{(3)}$	C_{lu}, C_{qe}
d	$C_{ed}, C_{lq}^{(1)}, C_{lq}^{(3)}$	C_{ld}, C_{qe}

Dependence of $A_{1,2}$ on $C^{(6)}$

CASE I enabling C_{eu}, C_{ed} and C_{qe}

- In high energy limit, solve $\begin{cases} \sigma^u = 0 \\ \sigma^d = 0 \end{cases}$

	A_1	A_2
u	C_{eu}, $C_{lq}^{(1)}$, $C_{lq}^{(3)}$	C_{lu}, C_{qe}
d	C_{ed}, $C_{lq}^{(1)}$, $C_{lq}^{(3)}$	C_{ld}, C_{qe}

- Condition for both partonic channels to vanish after integration over c_θ^*

$$C_{ed}^{(1)} \equiv C_{ed} = C_{eu} \frac{Q_u e^2 - g_Z^2 g_L^u g_R^e}{Q_u e^2 - g_Z^2 g_R^e g_R^u} \frac{Q_d e^2 - g_Z^2 g_R^e g_R^d}{Q_d e^2 - g_Z^2 g_L^d g_R^e}$$

where the SM fermion couplings are: **Denner 1993**

$$g_L^f = I_3^f - Q_f s_W^2, \quad g_R^f = -Q_f s_W^2.$$

- Flat direction in C_{qe}-C_{eu} plane when C_{ed} is fixed as $C_{ed}^{(1)}$
- C_{qe} & C_{eu} are in different A terms

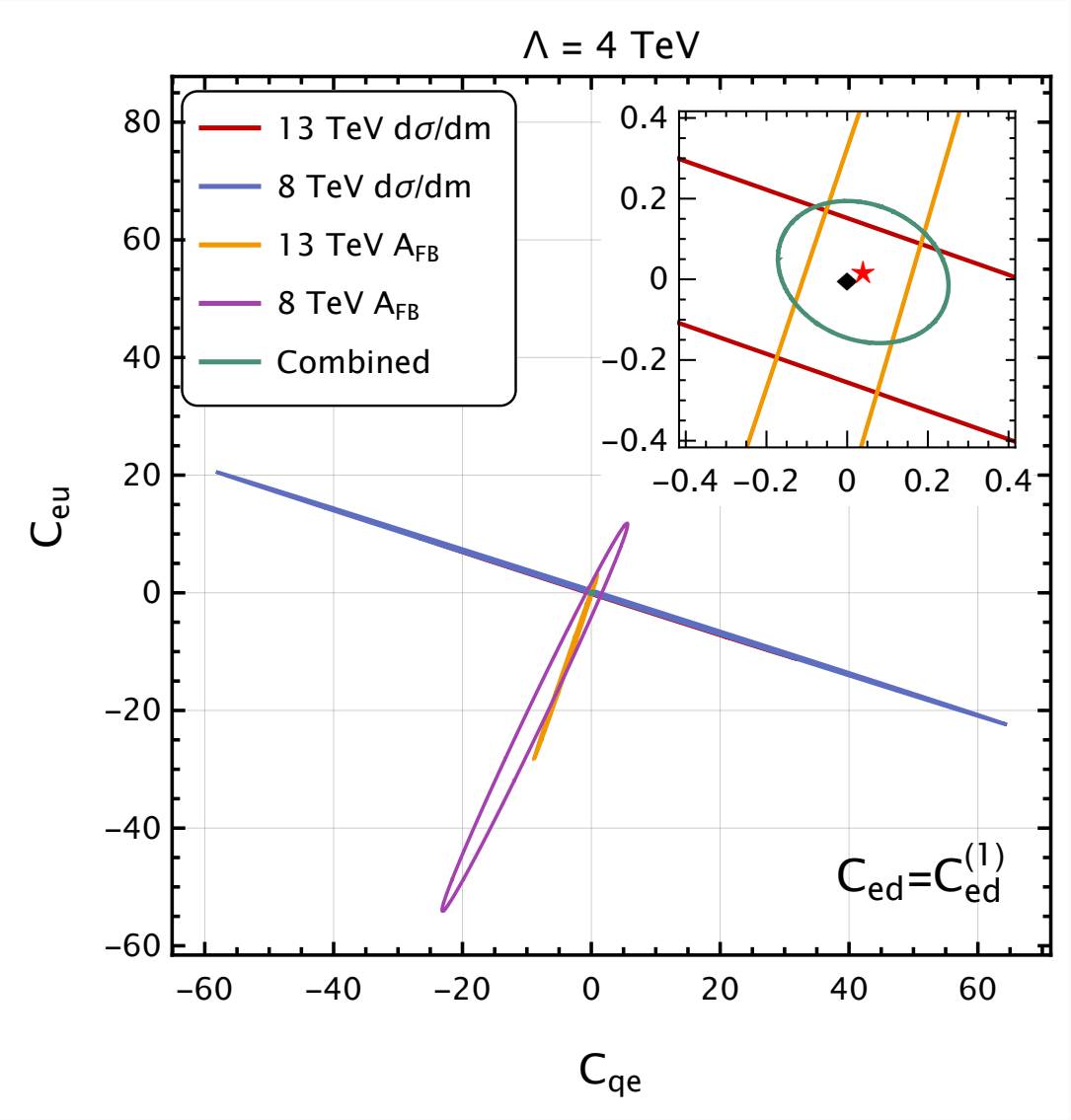
➡ AFB can cancel out flat directions in $\mathrm{d}\sigma/\mathrm{d}m$

CASE I enabling C_{eu}, C_{ed} and C_{qe}

- $C_{ed} = C_{ed}^{(1)}$
- both $\mathrm{d}\sigma/\mathrm{d}m$ and AFB exhibit flat directions
- ellipses nearly orthogonal to each other
  $\Rightarrow$no flat direction in the combined fit
- the bound is improved in the combined fit

◆ SM value $(0, 0)$

★ best fit



CASE II enabling C_{eu}, C_{ed} and $C_{lq}^{(1)}$

- In high energy limit, solve $\begin{cases} \sigma^u = 0 \\ \sigma^d = 0 \end{cases}$

	A_1	A_2
u	C_{eu}, $C_{lq}^{(1)}$, $C_{lq}^{(3)}$	C_{lu}, C_{qe}
d	C_{ed}, $C_{lq}^{(1)}$, $C_{lq}^{(3)}$	C_{ld}, C_{qe}

- Condition for both partonic channels to vanish after integration over c_θ^*

$$C_{ed}^{(2)} \equiv C_{ed} = C_{eu} \frac{Q_u e^2 - g_Z^2 g_R^u g_R^e}{Q_u e^2 - g_Z^2 g_L^e g_L^u} \frac{Q_d e^2 - g_Z^2 g_L^e g_L^d}{Q_d e^2 - g_Z^2 g_R^d g_R^e}.$$

- Flat direction in $C_{lq}^{(1)}$-C_{eu} plane when C_{ed} is fixed as $C_{ed}^{(2)}$
- $C_{lq}^{(1)}$ & C_{eu} are both in A_1

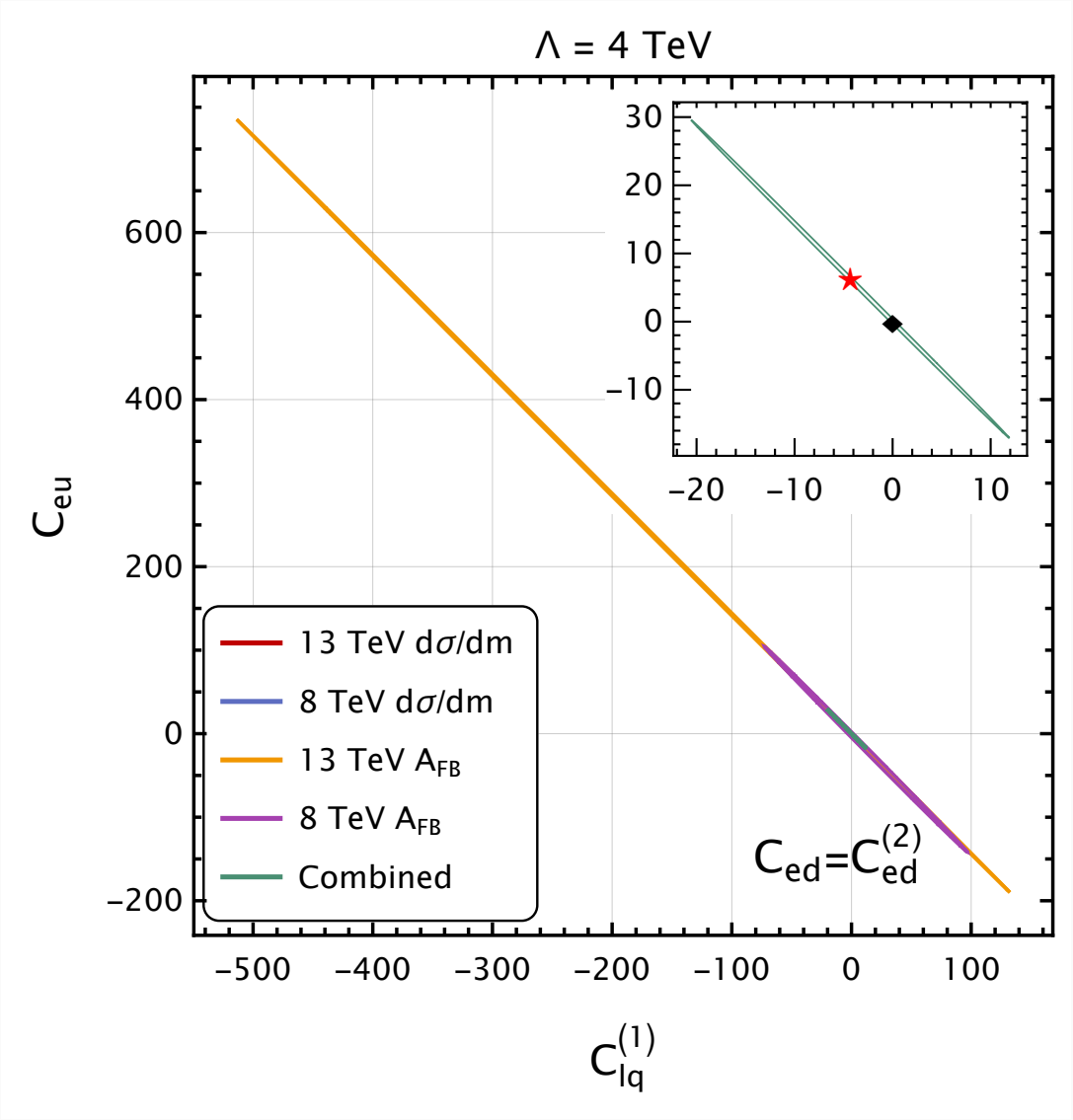
➡ AFB can not cancel out flat directions in $\mathrm{d}\sigma/\mathrm{d}m$

CASE II enabling C_{eu}, C_{ed} and $C_{lq}^{(1)}$

- $C_{ed} = C_{ed}^{(2)}$
- both $\mathrm{d}\sigma/\mathrm{d}m$ and AFB exhibit flat directions
- ellipses pointing at the same direction
  $\Rightarrow$flat direction still in the combined fit
- AFB does not remove the degeneracy, nor improve the bound

◆ SM value $(0, 0)$

★ best fit



CASE III enabling C_{qe} and $C_{lq}^{(1)}$

- In high energy limit, solve $\begin{cases} \sigma^u = 0 \\ \sigma^d = 0 \end{cases}$
- up-quark channel:

$$C_{lq}^{(1)} = -C_{qe}\frac{Q_u e^2 - g_Z^2 g_L^u g_R^e}{Q_u e^2 - g_Z^2 g_L^e g_L^u}$$

- down-quark channel:

$$C_{lq}^{(1)} = -C_{qe}\frac{Q_d e^2 - g_Z^2 g_L^d g_R^e}{Q_u e^2 - g_Z^2 g_L^e g_L^d}$$

- no common solution $\Rightarrow$no flat direction

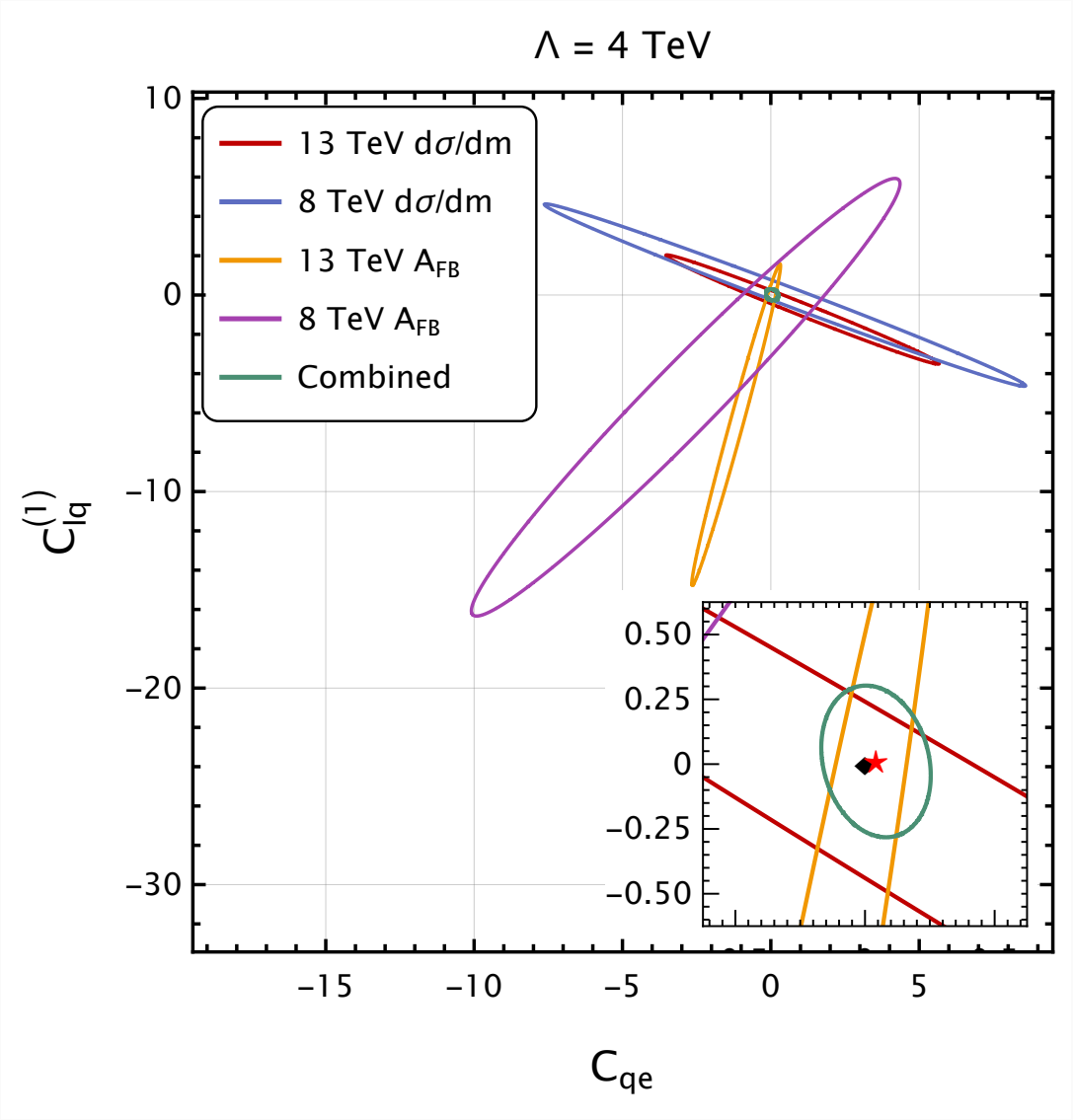
CASE III enabling C_{qe} and $C_{lq}^{(1)}$

	A_1	A_2
u	$C_{lq}^{(1)}$	C_{qe}
d	$C_{lq}^{(1)}$	C_{qe}

- C_{qe} & $C_{lq}^{(1)}$ are highly correlated
- C_{qe} & $C_{lq}^{(1)}$ are in different A terms
  $\Rightarrow$ellipses with $\mathrm{d}\sigma/\mathrm{d}m$ & AFB pointing in opposite directions
- bound improved in the combined fit

◆ SM value $(0, 0)$

★ best fit



CASE IV enabling $C_{lq}^{(1)}$ and $C_{lq}^{(3)}$

- In high energy limit, solve $\begin{cases} \sigma^u = 0 \\ \sigma^d = 0 \end{cases}$
- up-quark channel depends on the combination $C_{lq}^{(1)} + C_{lq}^{(3)}$
- down-quark channel depends on the combination $C_{lq}^{(1)} - C_{lq}^{(3)}$
- no common solution $\Rightarrow$no flat direction

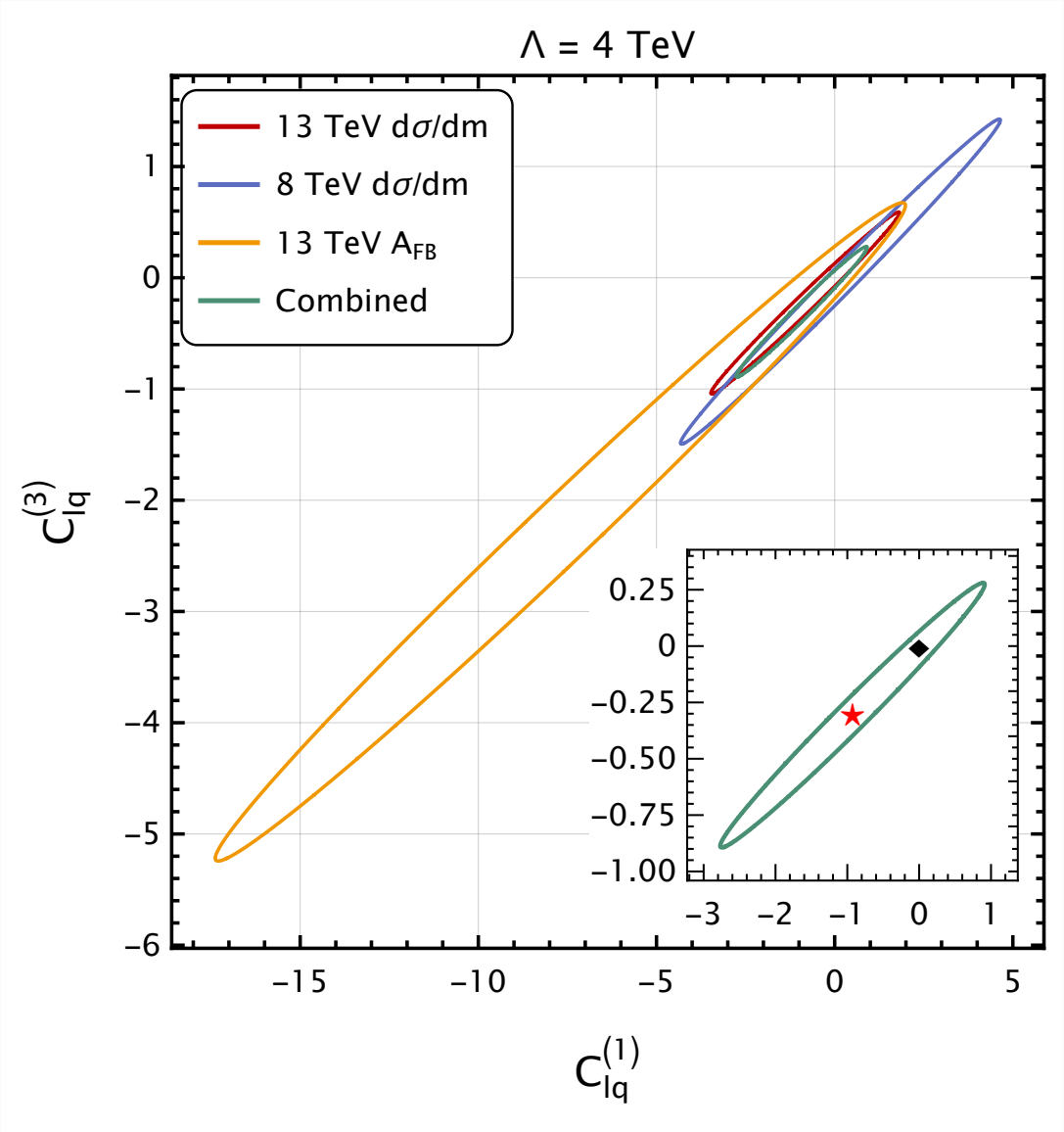
CASE IV enabling $C_{lq}^{(1)}$ and $C_{lq}^{(3)}$

	A_1	A_2
u	$C_{lq}^{(1)}$, $C_{lq}^{(3)}$	
d	$C_{lq}^{(1)}$, $C_{lq}^{(3)}$	

- $C_{lq}^{(1)}$ & $C_{lq}^{(3)}$ are highly correlated
- $C_{lq}^{(1)}$ & $C_{lq}^{(3)}$ are both in A_1 $\Rightarrow$ellipses with $\mathrm{d}\sigma/\mathrm{d}m$ & AFB pointing in the same direction
- bound not improved in the combined fit

◆ SM value $(0, 0)$

★ best fit



Quadratic contributions

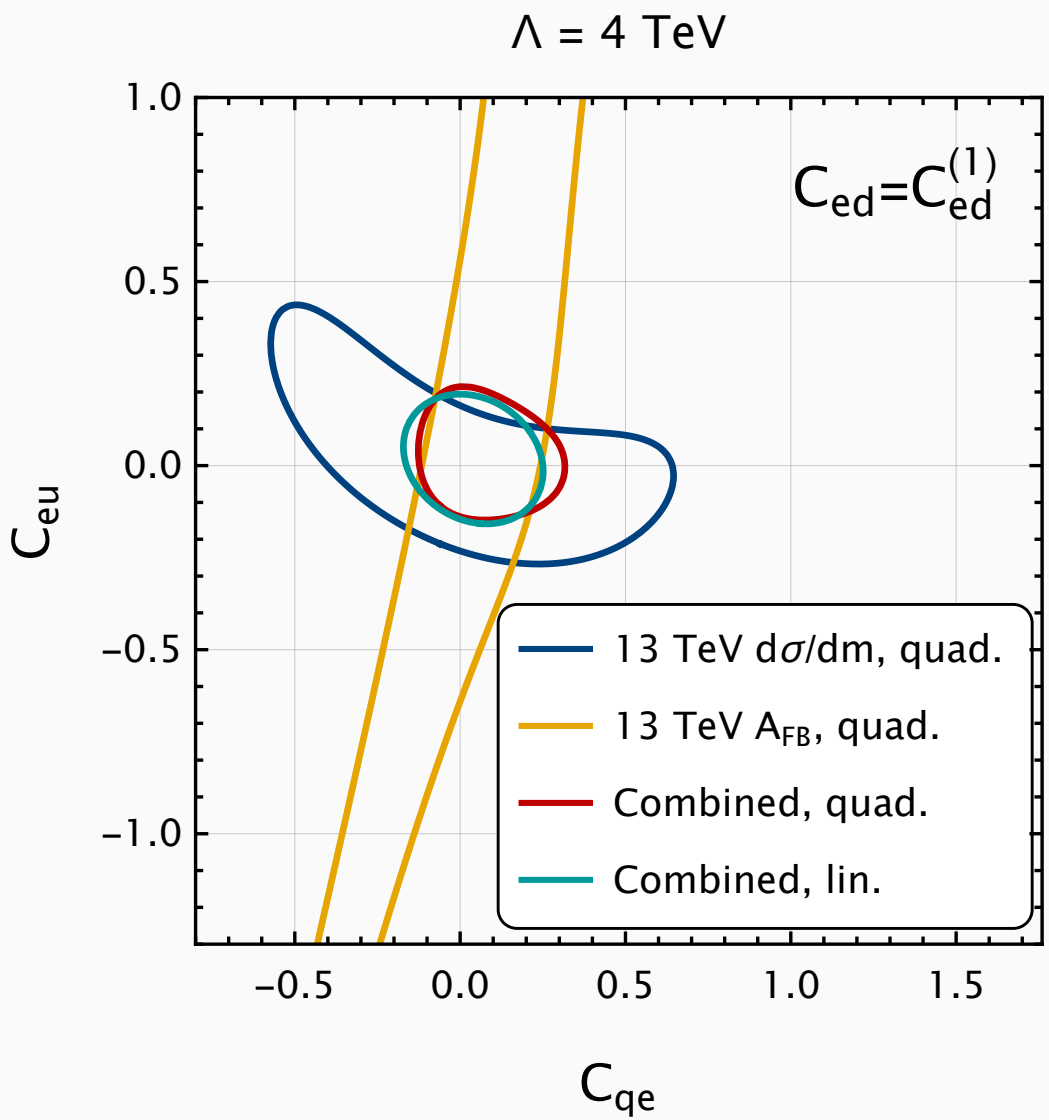
LO SMEFT contributions to partonic cross section in high energy limit

$$\frac{\mathrm{d}\sigma^x}{dm_{ll}^2 dY dc_\theta^*} \sim \frac{1}{\Lambda^2}\frac{A_1^x \hat{u}^2 + A_2^x \hat{t}^2}{\hat{s}^2} + \frac{1}{\Lambda^4}\left(B_1^x \hat{u}^2 + B_2^x \hat{t}^2\right)$$

- $B_1^u \propto C_{eu}^2 + \left(C_{lq}^{(1)} - C_{lq}^{(3)}\right)^2$
- $B_1^d \propto C_{ed}^2 + \left(C_{lq}^{(1)} + C_{lq}^{(3)}\right)^2$
- $B_2^u \propto C_{lu}^2 + C_{qe}^2$
- $B_2^d \propto C_{ld}^2 + C_{qe}^2$
- Adding quadratic terms breaks flat directions appearing in linear terms

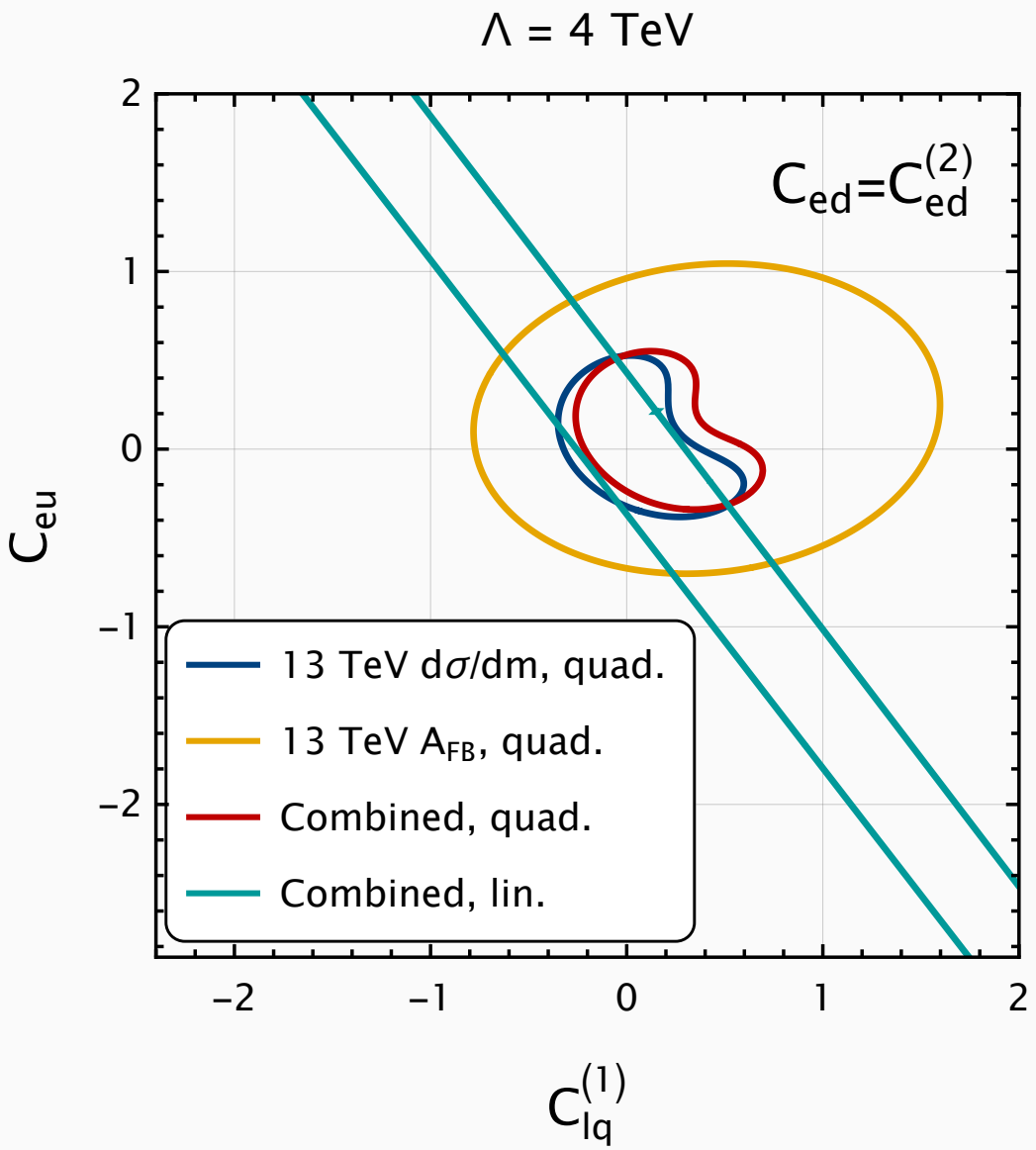
CASE I W/ QUADRATIC TERMS enabling C_{eu}, C_{ed} and C_{qe}

- $C_{ed} = C_{ed}^{(1)}$
- Single data set: Quadratic contributions break degeneracies
- Combined fit:
  - Linear: AFB **cancels** degeneracies in $\mathrm{d}\sigma/\mathrm{d}m$
  - Adding quadratic contributions to combined fit: **no improvement**



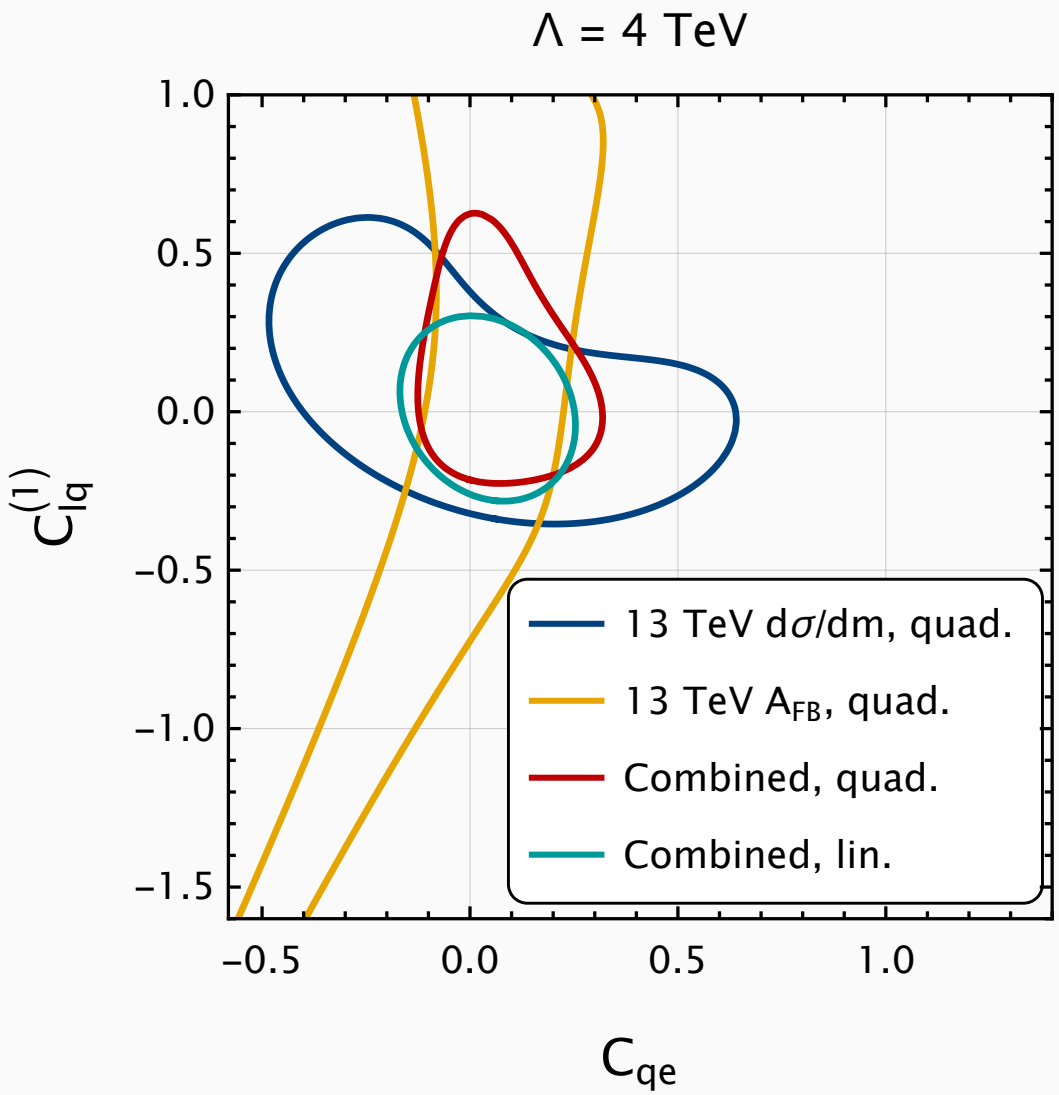
CASE II W/ QUADRATIC TERMS enabling C_{eu}, C_{ed} and $C_{lq}^{(1)}$

- $C_{ed} = C_{ed}^{(2)}$
- Single data set: Quadratic contributions break degeneracies
- Combined fit:
  - Linear: AFB **can not** cancel degeneracies in $\mathrm{d}\sigma/\mathrm{d}m$
  - Quadratic contributions **improve** the combined fit significantly



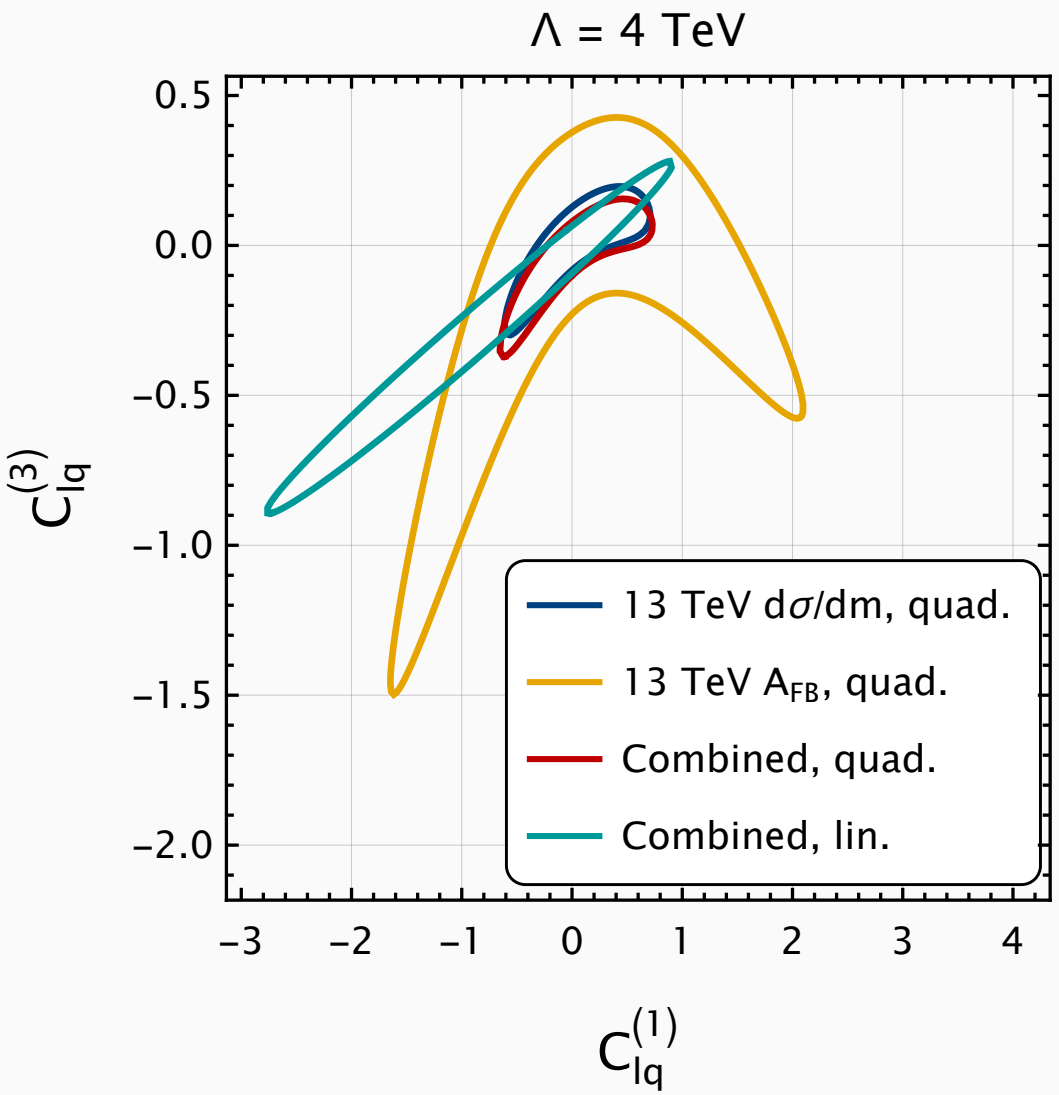
CASE III W/ QUADRATIC TERMS enabling C_{qe} and $C_{lq}^{(1)}$

- strong correlation but no flat directions
- Single data set: Quadratic contributions reduce correlations
- Combined fit:
  - Linear: Combining AFB & $\mathrm{d}\sigma/\mathrm{d}m$ reduces correlation
  - Little differences btw. linear and quadratic combined fits

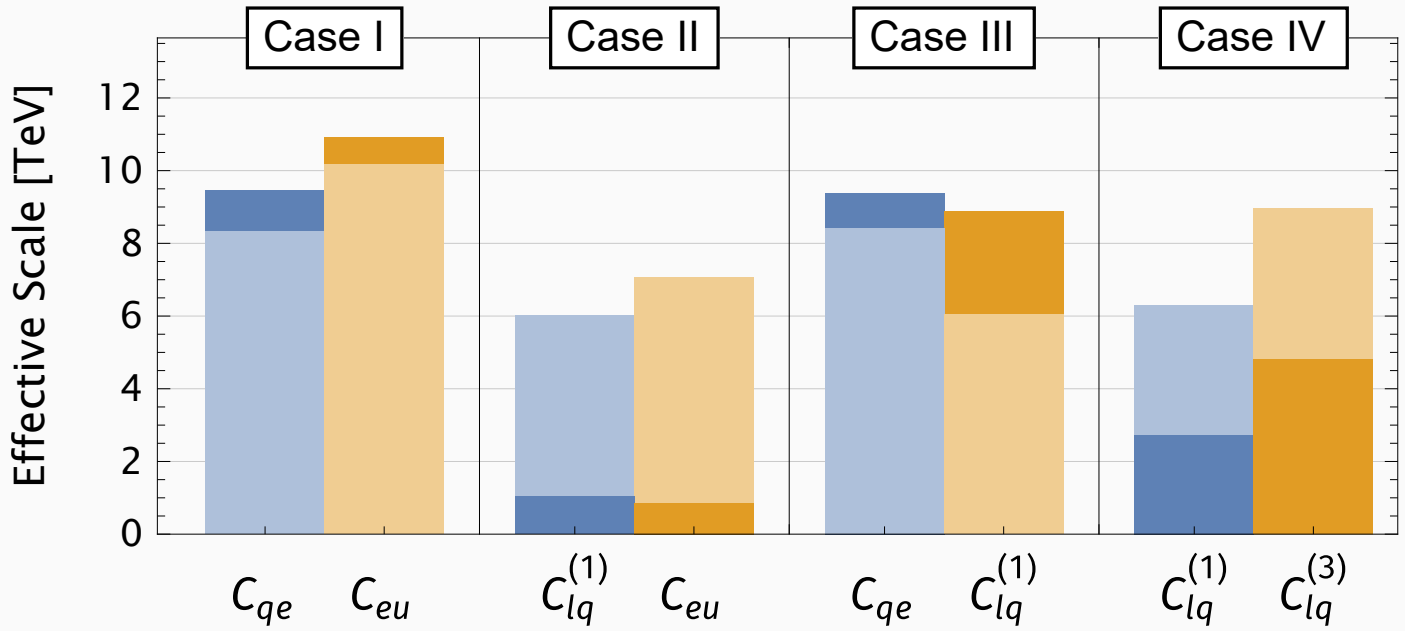


CASE IV W/ QUADRATIC TERMS enabling $C_{lq}^{(1)}$ and $C_{lq}^{(3)}$

- strong correlation but no flat directions
- Single data set: Quadratic contributions reduce correlations
- Combined fit:
  - Linear: Narrow ellipse ⇒Supplementing $\mathrm{d}\sigma/\mathrm{d}m$ w/ AFB is unable to reduce such correlation
  - Quadratic contributions improve the combined fit significantly



Effective scale



- Effective scales M from 68% CL bounds (choosing $g = 1, \Lambda = 4\ \mathrm{TeV}$)

$$\frac{C}{\Lambda^2} \sim \frac{g^2}{M^2}$$

- Include only the combined fit
  - darker bars: only linear terms
  - lighter bars: quadratic terms included
- improvement from quadratic terms in case II & IV (where AFB didn't help), but not I & III

Summary

- Combining measurements of $\mathrm{d}\sigma/\mathrm{d}m$ and AFB in neutral-current Drell-Yan
- Fits to the four-fermion sector of the SMEFT at dimension-6
- In some cases (case I & III):
  - AFB can break degeneracies in $\mathrm{d}\sigma/\mathrm{d}m$
  - Even when there's no flat direction, if two operators are highly correlated, AFB can drastically improve bounds
  - Quadratic corrections are negligible in the combined fit
- In other cases (case II & IV):
  - AFB can not fix flat directions in $\mathrm{d}\sigma/\mathrm{d}m$
  - When there's no flat direction but two operators are highly correlated, AFB provides no improvement on bounds
  - Quadratic corrections are important in the combined fit

Thanks for your attention!

Backup

Two prescriptions of AFB quark direction

- A_{FB}^{*}: quark direction approximated w/ dilepton momentum

$$\cos\theta_R = \frac{|Q^z|}{Q^z}\cos\theta^*.$$

  Asymmetry diluted when quark direction not aligned with dilepton direction (e.g. small $|y|$ region)

- A_{FB} (the "true" AFB): using Monte-Carlo as template, identify quark direction at parton level **Tumasyan et al. 2022; Accomando et al. 2016**
  - Gluon initiated processes: In our calculations, we assign quark direction that's consistent with the cancellation of collinear singularities
    i.e. $g\bar{q}$: quark direction set to gluon direction
  - Huge scale uncertainties, higher order effects

Uncertainties

- No correlation between the data sets
- Data set I: experimental uncertainties provided by ATLAS, including full statistical and systematic errors
- Rest of the data sets: no correlated systematic error provided
  - Data set II: assume no correlation between different bins & channels
  - Data set III: assume no correlation between different bins, it's tested that the correlations have little effect
  - Data set IV: assume no correlation between different bins, same as data set III
- Theoretical uncertainties:
  - correlated PDF errors across bins and data sets
  - uncorrelated scale uncertainties
  - NNLO QCD corrections less than 2% for most bins
  - electroweak corrections as much as 10% for high $m_{\ell\ell}$ bins
  - Scale choice: $\mu_0 = m_{\ell\ell}$ for data set I, II, III
  - Data set IV: Use $\mu_0 = H_T$ [5] as the central value. Calculate both $\mu_0 = m_{\ell\ell}$ & $\mu_0 = H_T$ along with their 6 scale variations, then take the envelope.

[5] H_T is the sum of transverse masses of all final state particles

Event numbers in data set II

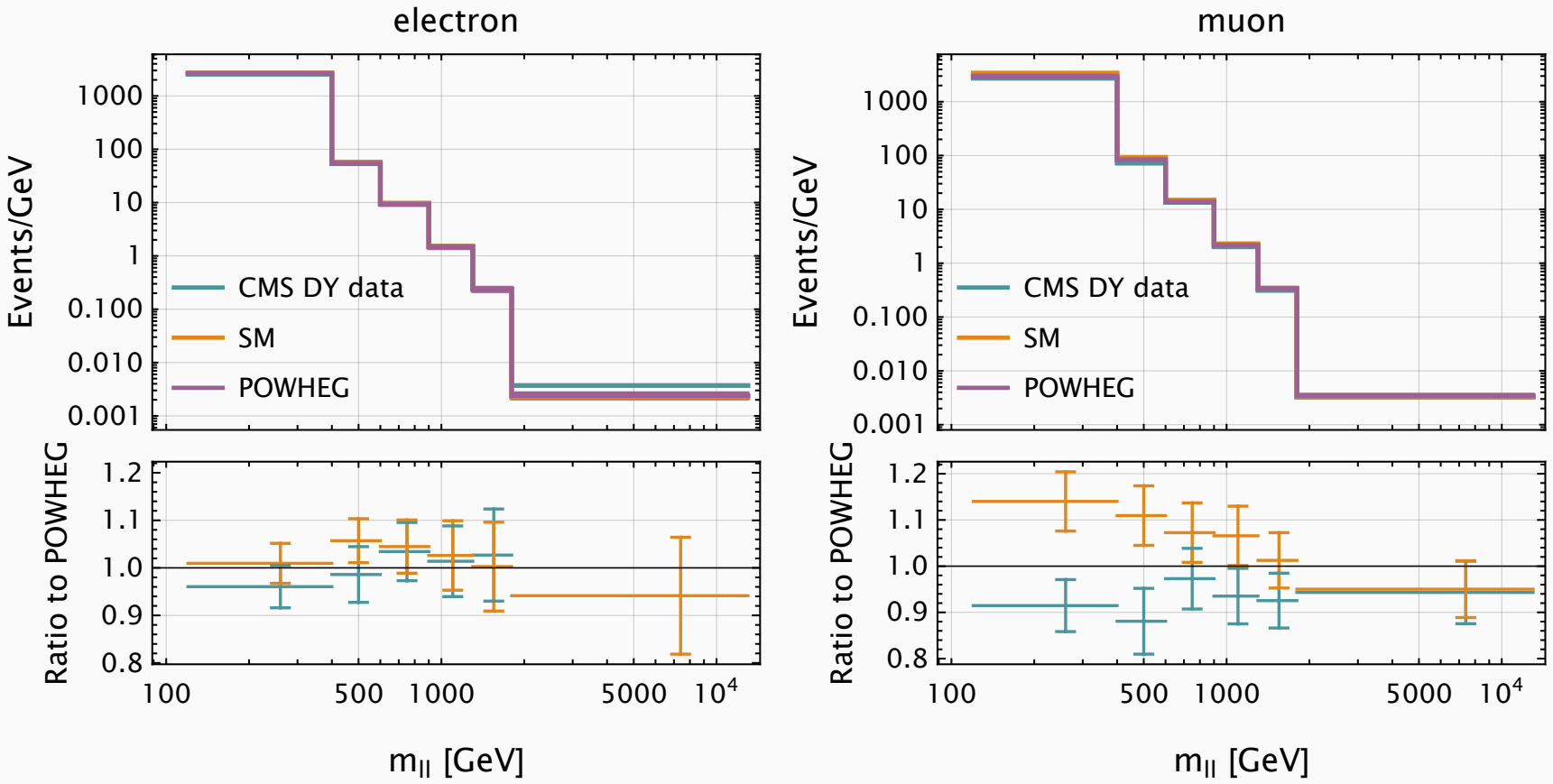


Figure: Event yields in the electron (left) and muon (right) channels for the $13\ \mathrm{TeV}$ data set II. The green lines show the observed total event yields minus all non-Drell-Yan backgrounds. The orange lines show our SM predictions with electroweak Sudakov corrections. The purple line shows the `POWHEG` estimate for the Drell-Yan background. The lower inset shows the ratio to the Drell-Yan background estimations in Ref. Sirunyan et al. 2021. The error bars represent uncertainties from the `POWHEG` estimates.

Scale choice w/ data set IV

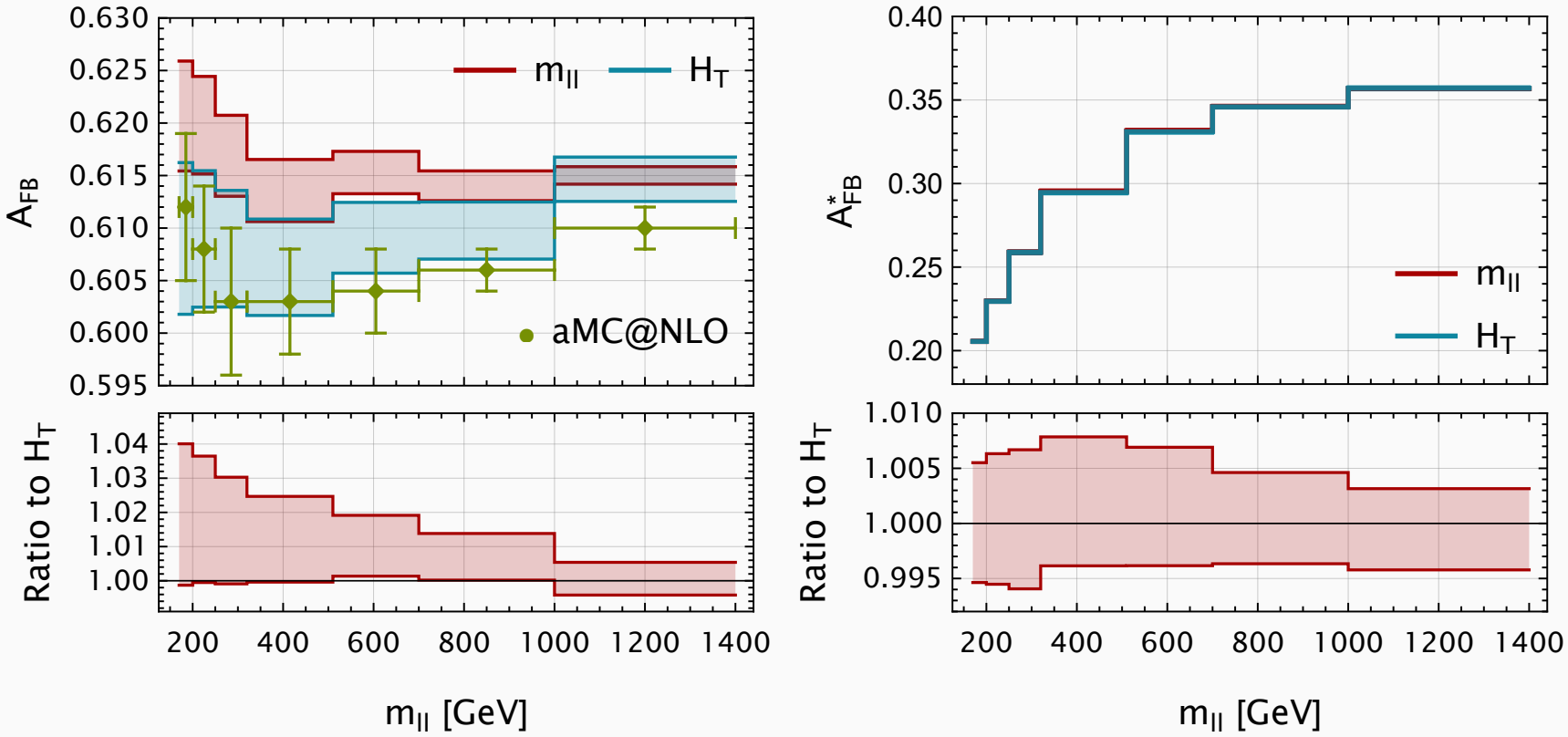


Figure: Left panel: The "true" forward-backward asymmetry A_{FB} for data set IV with dynamic scale $\mu_0 = m_{ll}$ (red) and $\mu_0 = H_T$ (blue). The bands represent the range of scale variation ($1/2 \leq \mu_{R,F}/\mu_0 \leq 2,\ \ 1/2 \leq \mu_R/\mu_F \leq 2$) for both scale choices. The `aMC@NLO` simulation in Ref. Tumasyan et al. 2022 is shown by the green points. Right panel: the same comparison for A^*_{FB}.

Case I: Condition for x-sec to vanish

- Receive contributions from $A_1^u(C_{eu}), A_1^d(C_{ed}), A_2^{u/d}(C_{qe})$
- Contributions from all 3 operators won't vanish simultaneously
  $\Rightarrow$ pick one slice in $C_{qe} - C_{eu}$ plane where flat direction is present
- Conditions for the cross section to vanish after integration over c_θ^* for each channel

$$u: C_{qe} = -C_{eu} \frac{Q_u e^2 - g_Z^2 g_L^u g_R^e}{Q_u e^2 - g_Z^2 g_R^e g_R^u},$$
$$d: C_{qe} = -C_{ed} \frac{Q_d e^2 - g_Z^2 g_L^d g_R^e}{Q_d e^2 - g_Z^2 g_R^e g_R^d},$$

  the SM left-handed and right-handed fermion couplings: **Denner 1993**

$$g_L^f = I_3^f - Q_f s_W^2, \quad g_R^f = -Q_f s_W^2.$$

- These conditions are simultaneously satisfied when

$$C_{ed}^{(1)} \equiv C_{ed} = C_{eu} \frac{Q_u e^2 - g_Z^2 g_L^u g_R^e}{Q_u e^2 - g_Z^2 g_R^e g_R^u} \frac{Q_d e^2 - g_Z^2 g_R^e g_R^d}{Q_d e^2 - g_Z^2 g_L^d g_R^e}$$

DIM-8 EFFECTS

- Relevant operators: $\psi^4 D^2$

  i.e.

$$\mathcal{O}^{(2)}_{q^2 e^2 D^2} = \left(\overline{e}\gamma^{(\mu} \overleftrightarrow{D^{\nu)}} e\right)\left(\overline{q}\gamma_{\mu(} \overleftrightarrow{D_{\nu)}} q\right)$$

- Shaded area:

  1-d bounds of single Wilson coefficient