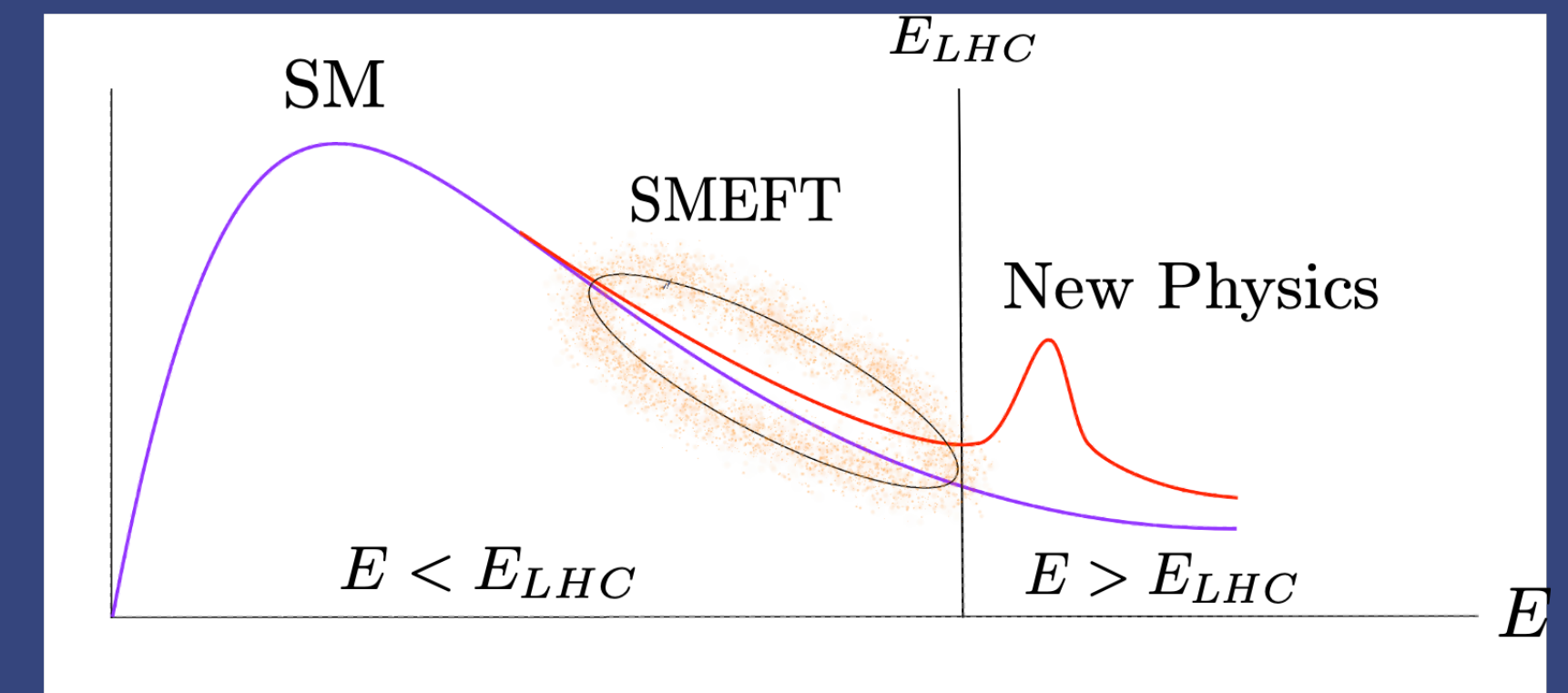


NLO and RGE effects on SMEFT global analyses

In collaboration with Anke Biekötter and Tobias Hurth ([2311.04963](#) and [2412.09674](#))

SMEFT-Tools, MITP, 31 January 2025



Outline

1. Global analyses in the flavour symmetric SMEFT

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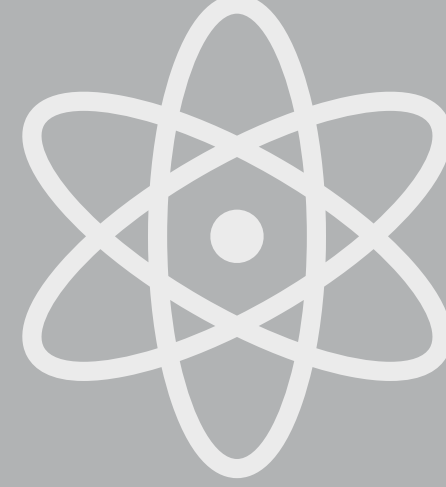
2. Global analysis with LO predictions (and Dijets+ γ)

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3. Global analysis with NLO predictions

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4. RGE effects on the global analysis

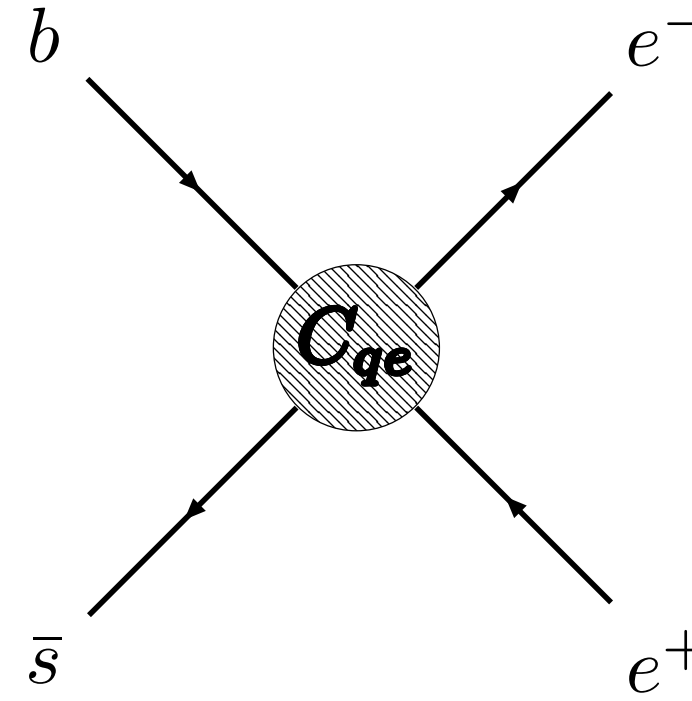


Global analyses in the flavour symmetric SMEFT

SMEFT and flavour symmetry

Symmetry assumption on NP:

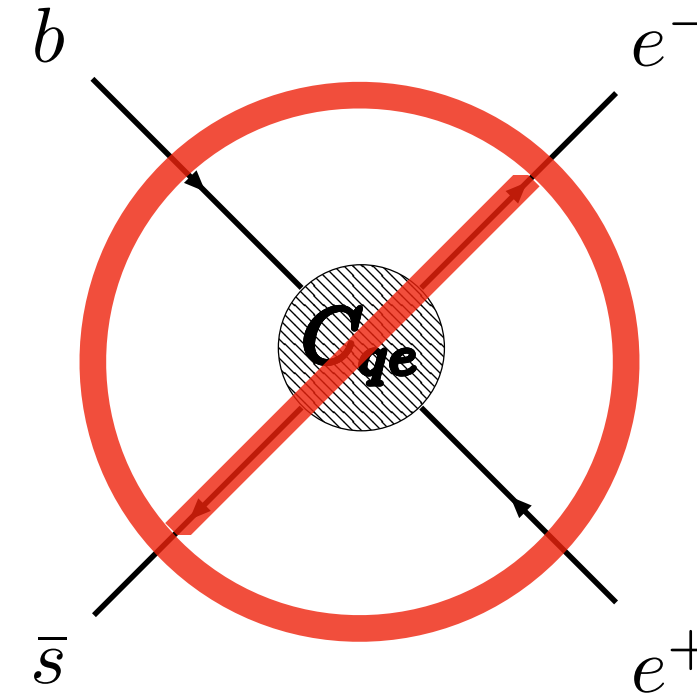
$$U(3)^5 = U(3)_\ell \times U(3)_q \times U(3)_e \times U(3)_u \times U(3)_d$$



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From 2499 dimension six operators to 41 (CP even)

[2005.05366: Faroughy, Isidori, Wilsch, Yamamoto]

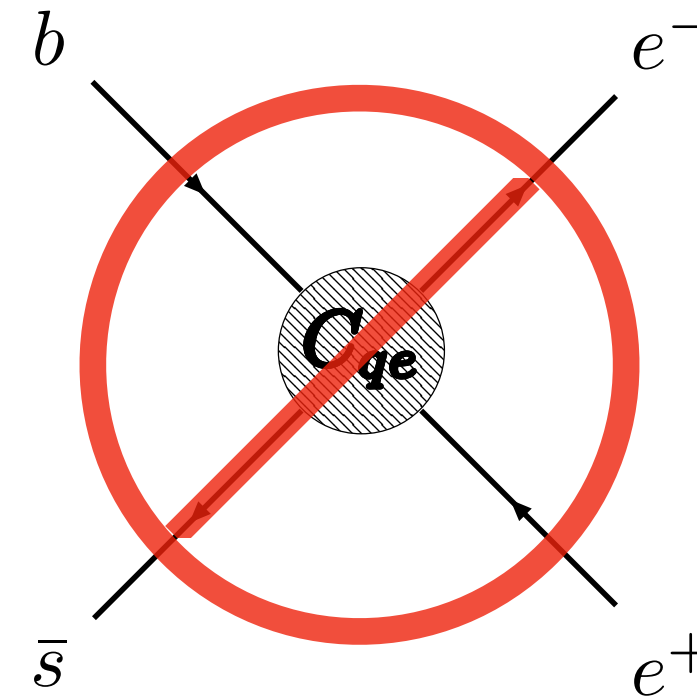
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- According to this assumption also Yukawa-like operators are excluded because they add additional source of flavour violation BSM.

	$\psi^2 \varphi^3$
$Q_{e\varphi}$	$(\varphi^\dagger \varphi)(\bar{l}_p e_r \varphi)$
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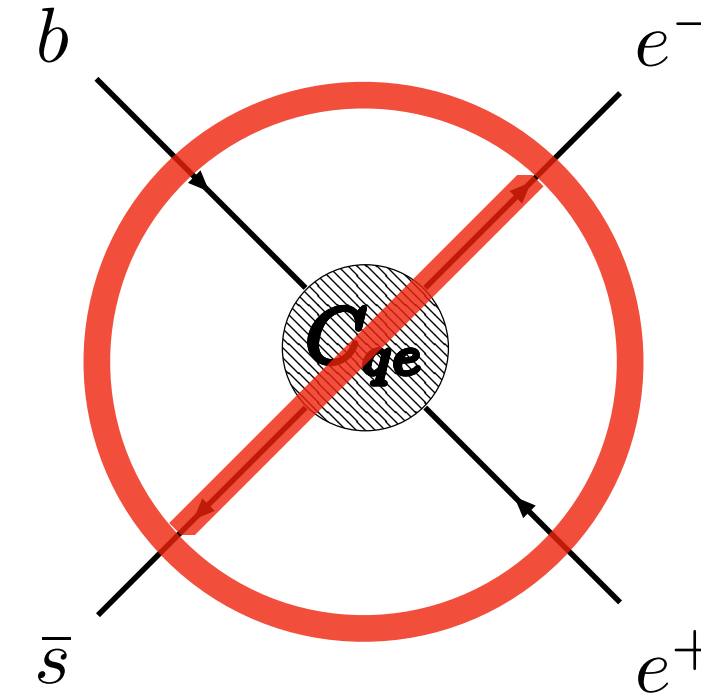
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- For some 4-fermion operators there are two independent ways to contract the flavour indices to get a flavour conserving operator.

$$Q_{ll} = (\bar{l}_i \gamma_\mu l_j)(\bar{l}_k \gamma^\mu l_l)$$

$$C_{ll} \delta_{ij} \delta_{lk} \quad \text{and} \quad C'_{ll} \delta_{ik} \delta_{jl}.$$

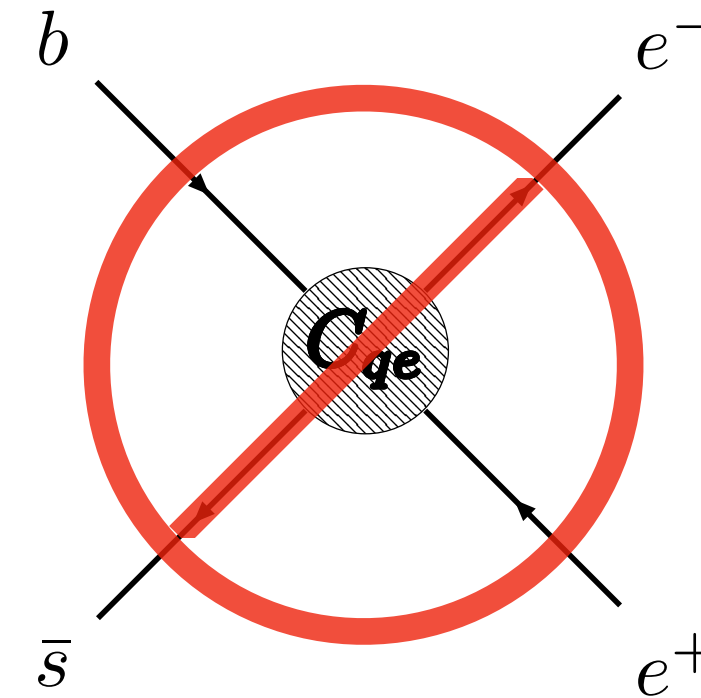
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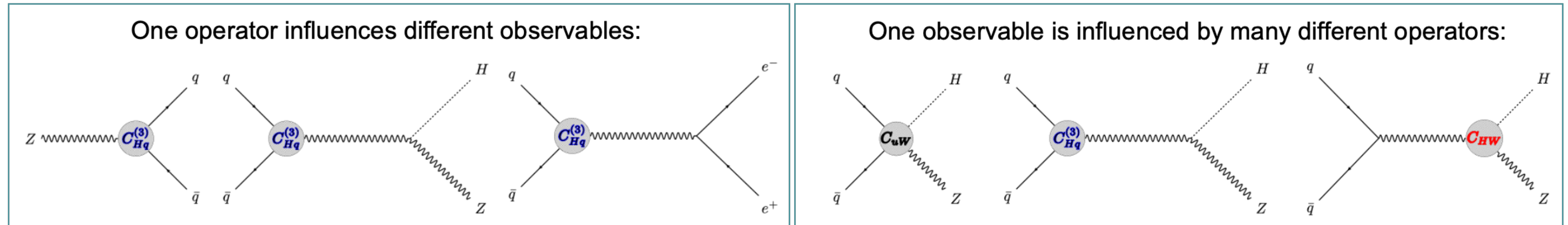
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This assumption corresponds to minimal version of MFV: it contains the minimum and non-removable amount of flavour violation.

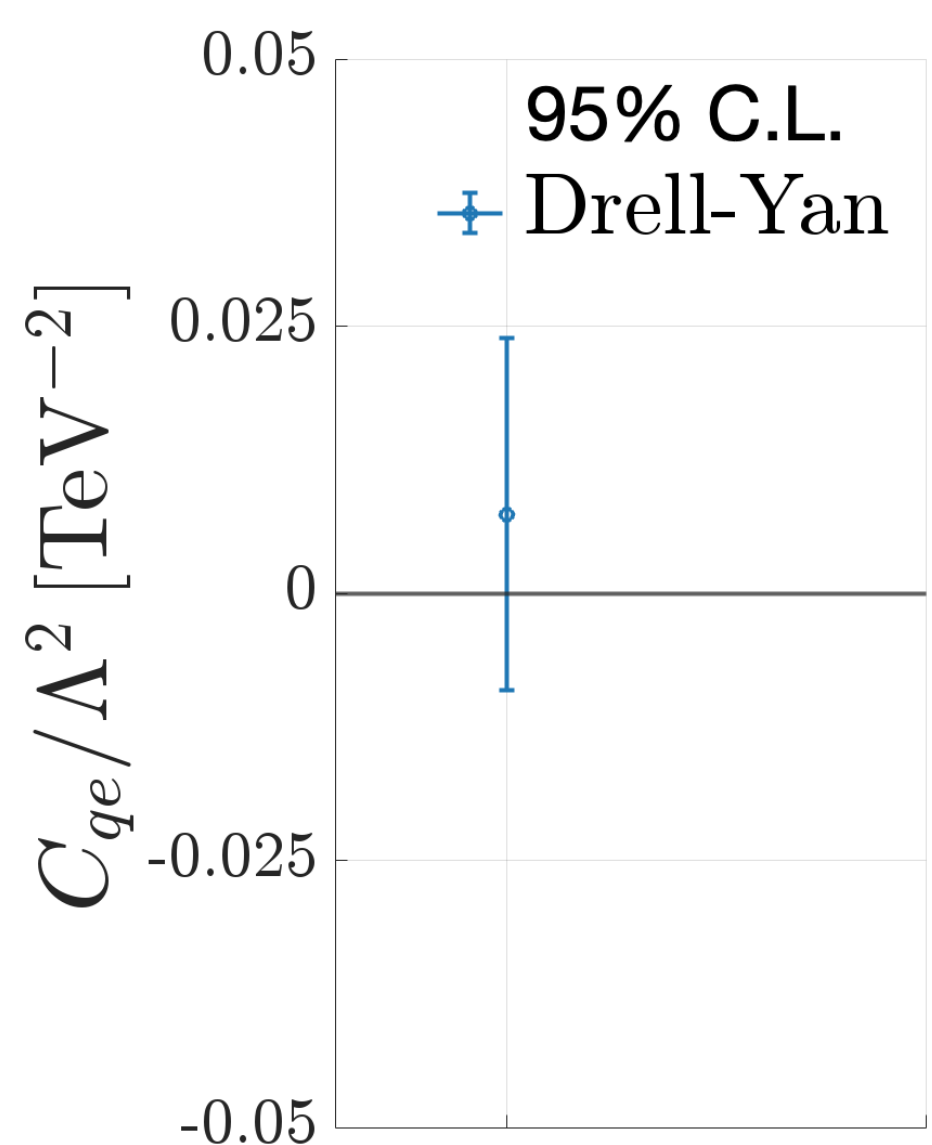
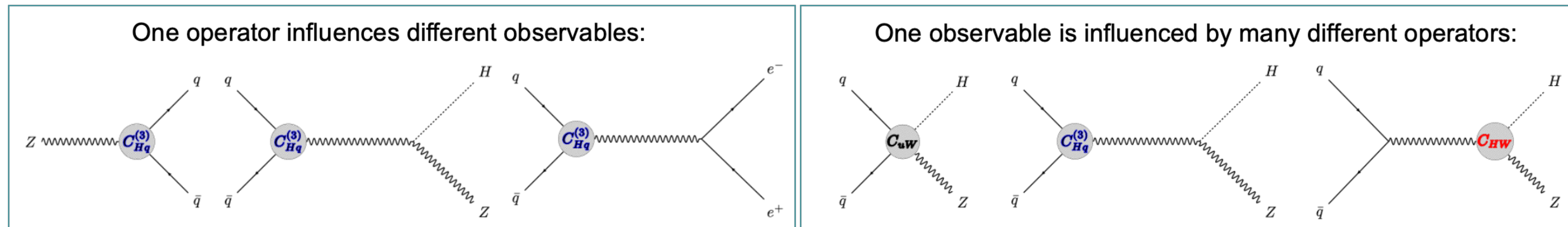
Global analyses in the SMEFT

Wilson coefficients in SMEFT are **highly correlated** and only **global analysis** can give meaningful results.



Global analyses in the SMEFT

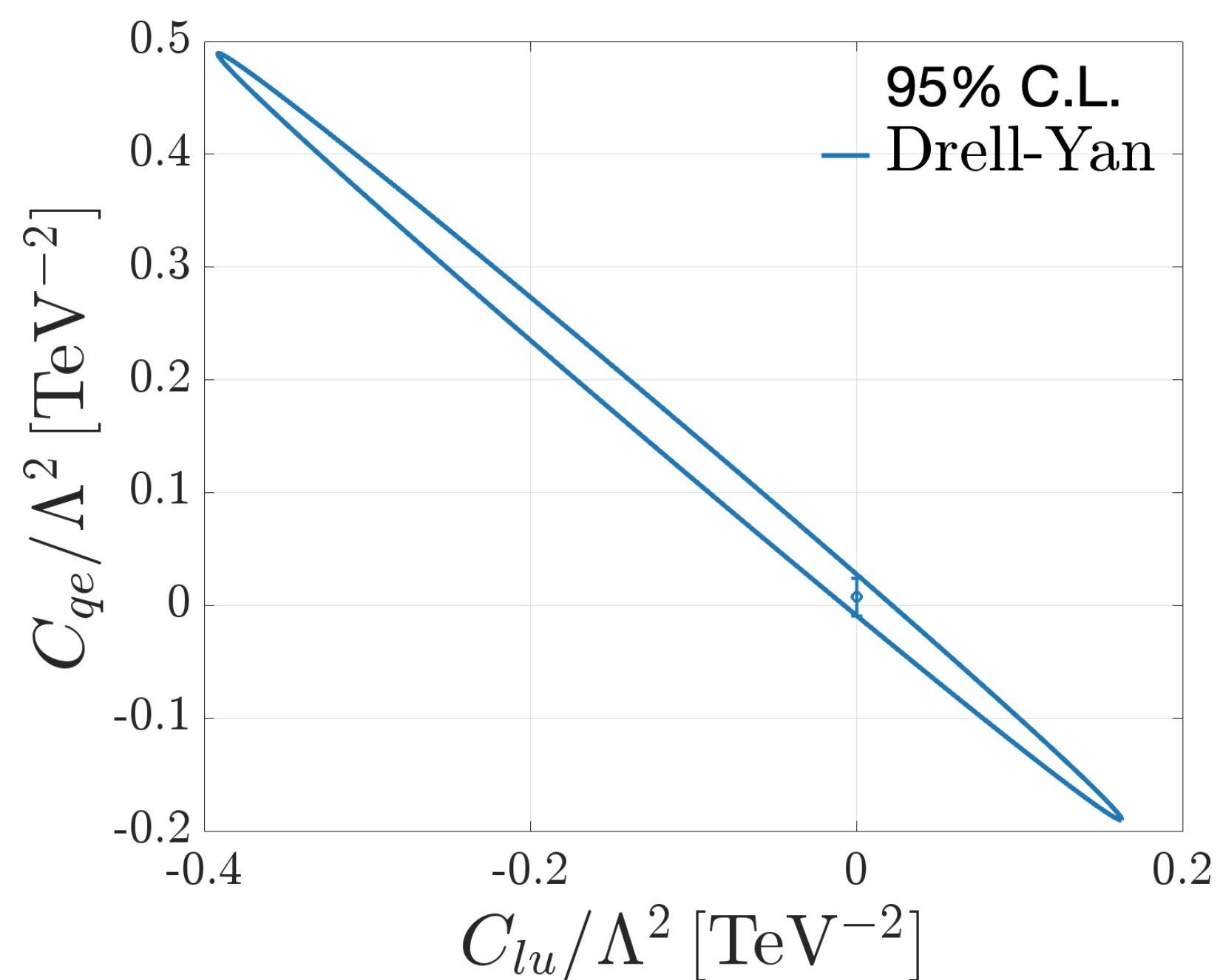
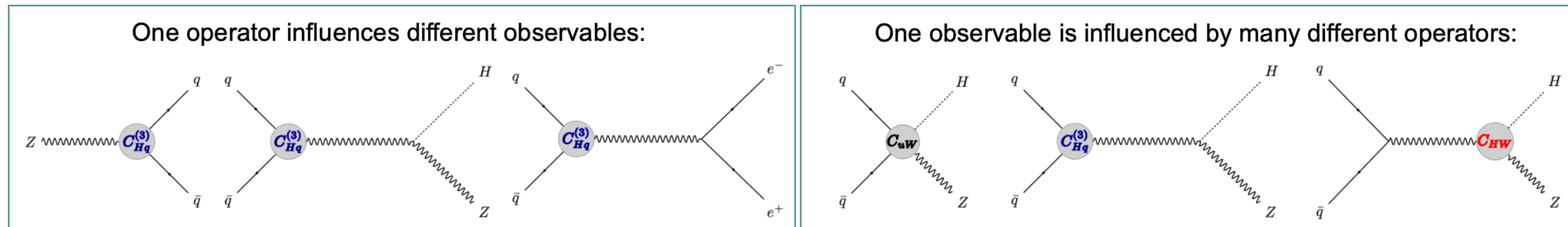
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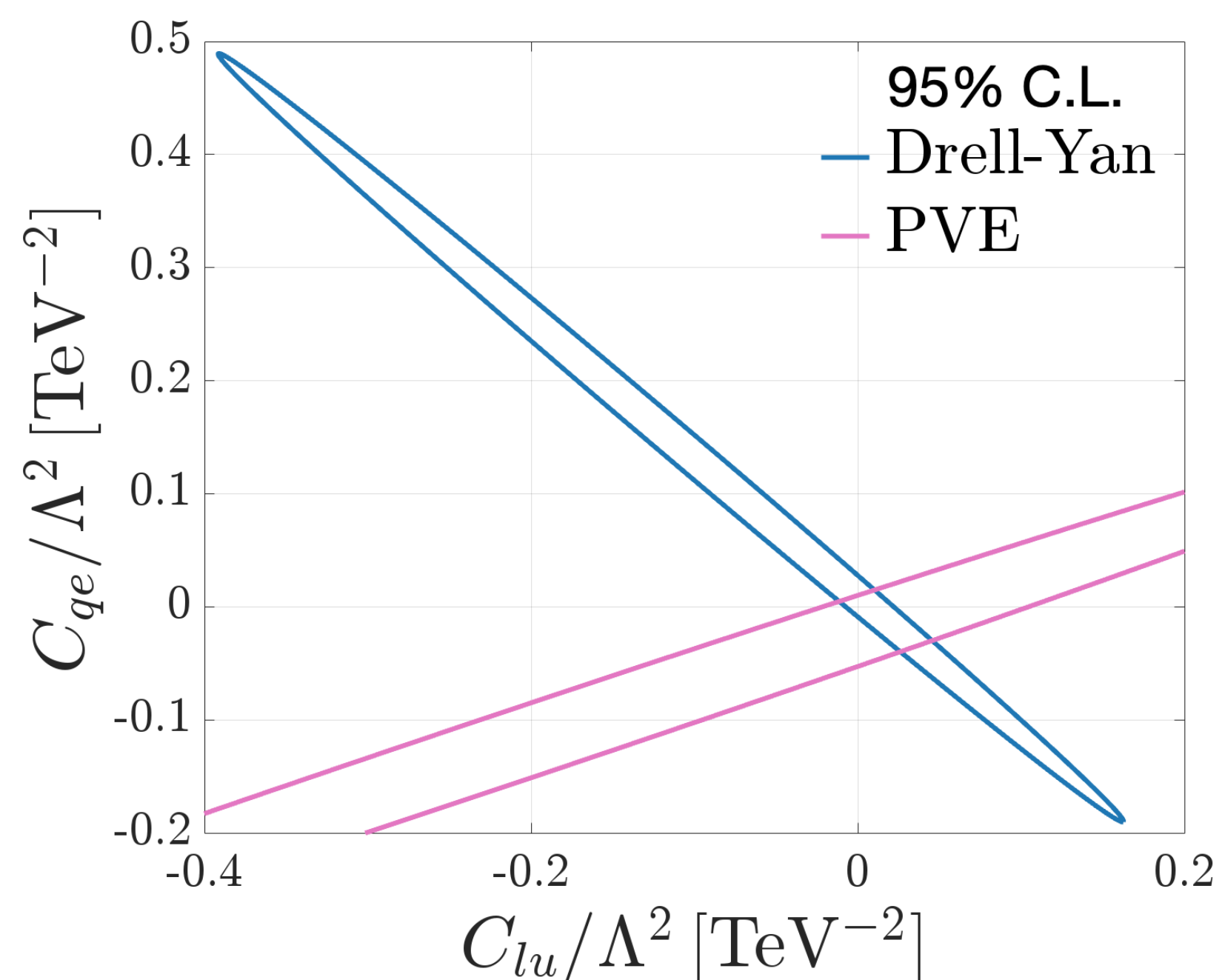
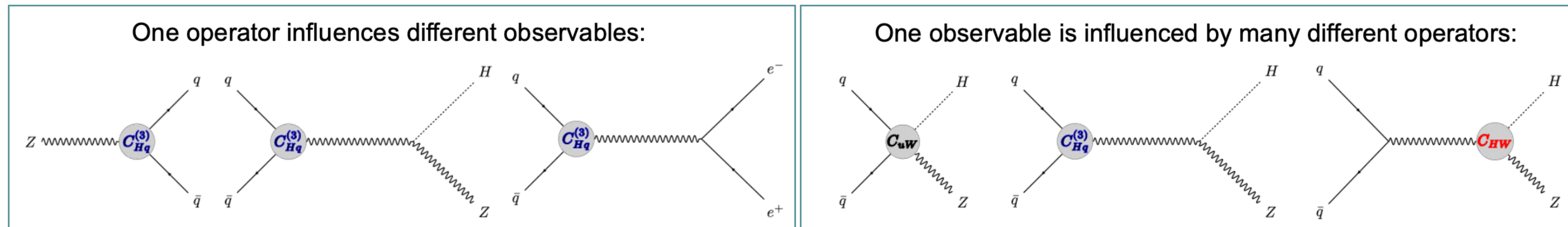
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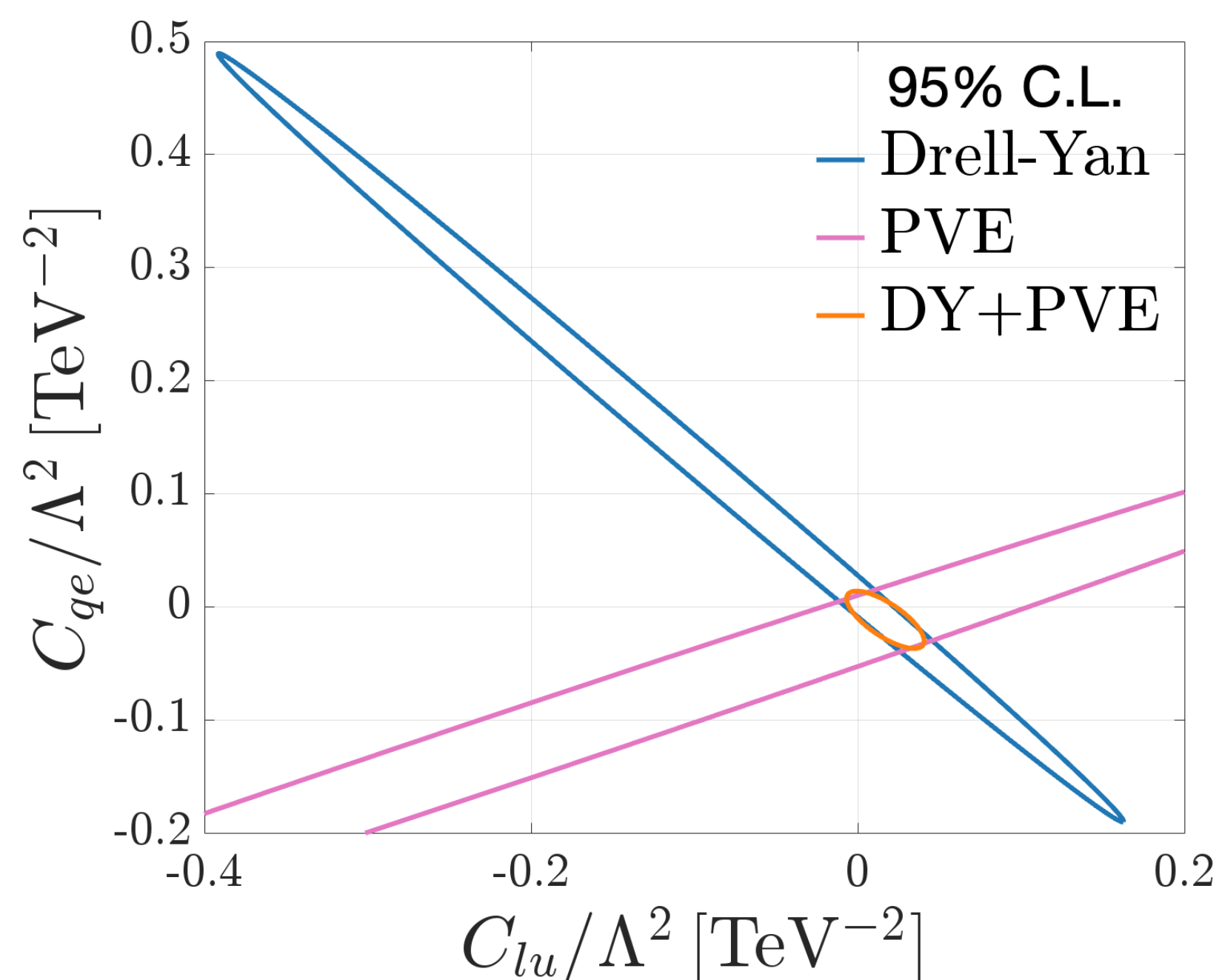
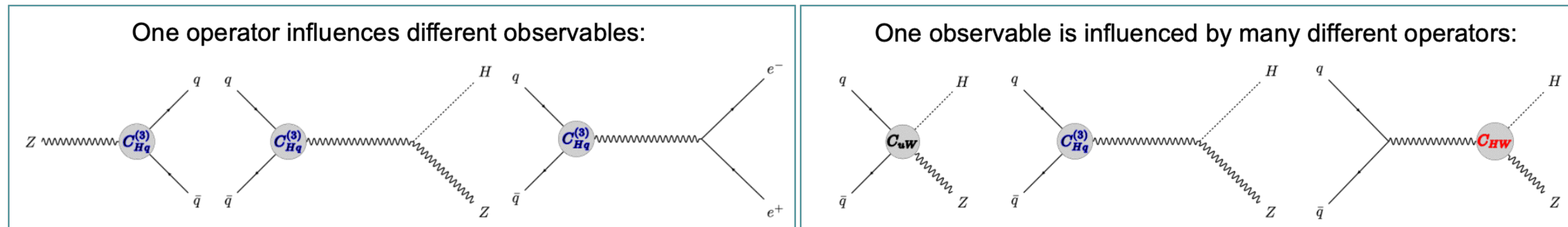
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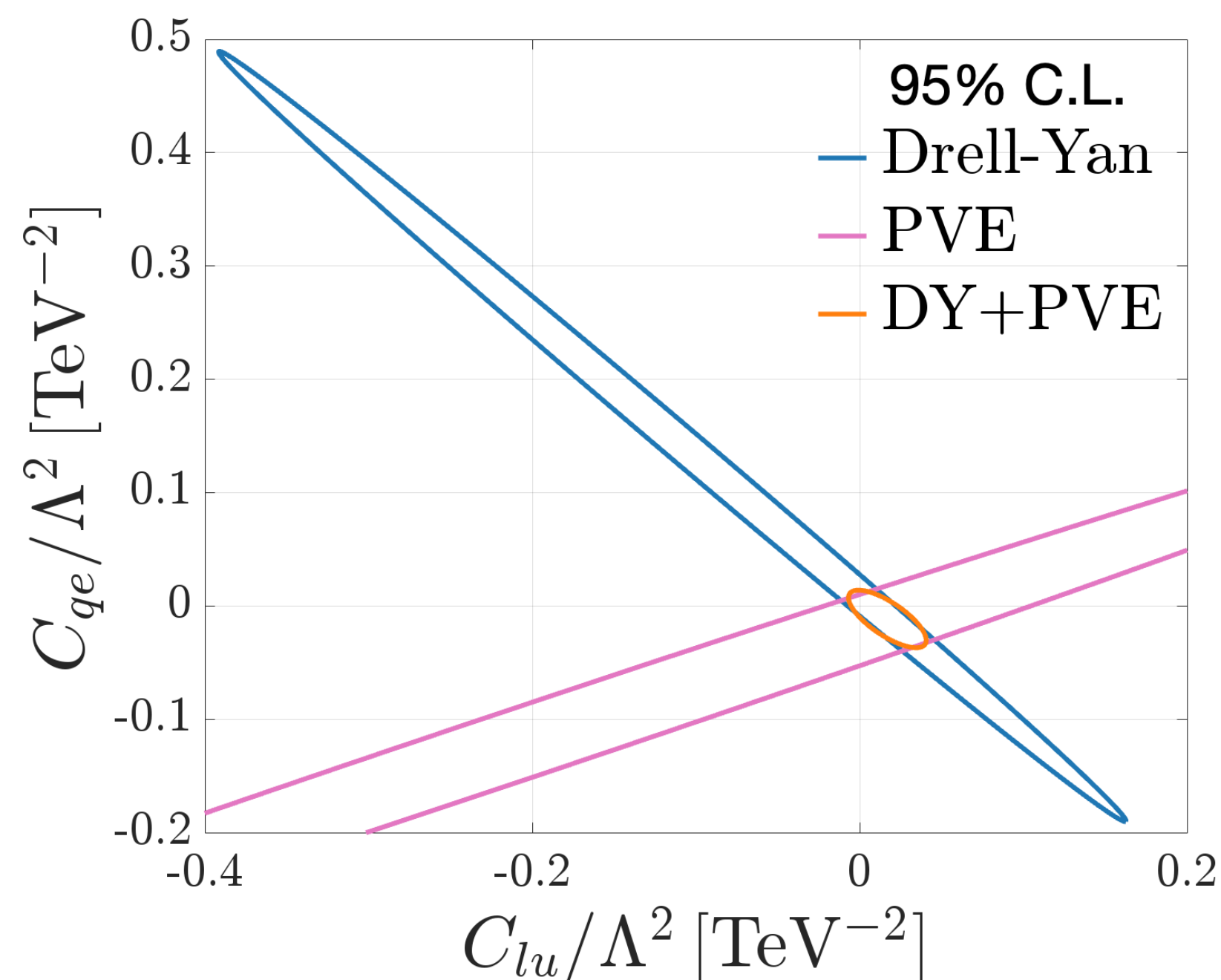
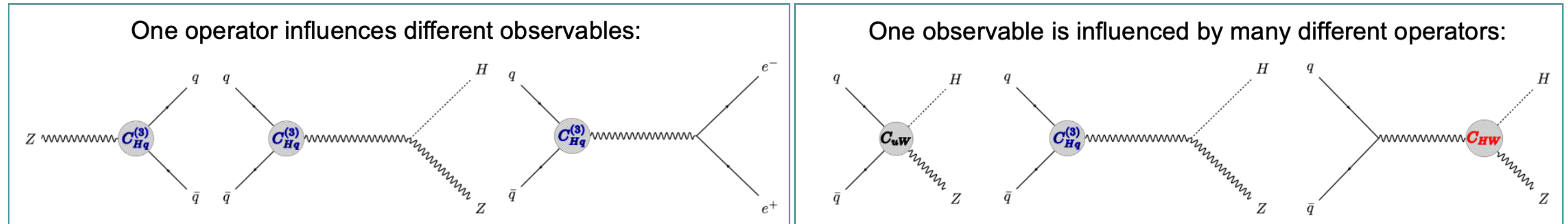
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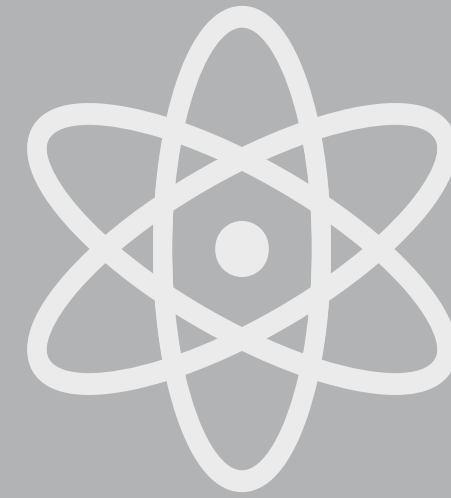


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Goal: Constrain all the possible directions
 (linear combinations of Wilson coefficients)

High and low
energy data

Identify
correlations



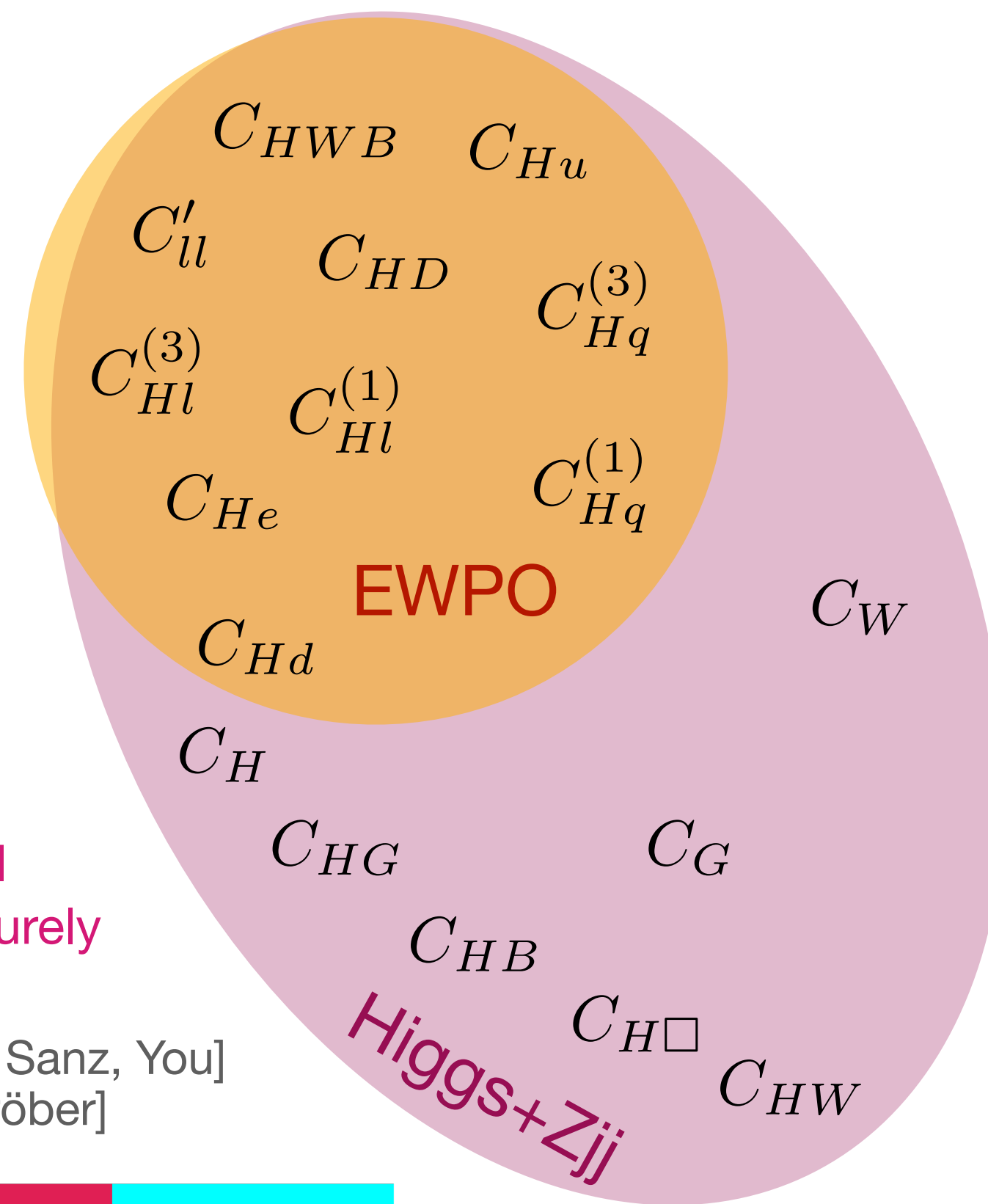
Global analysis with LO predictions

Datasets

EWPO:

Dominantly constrain these 10 operators, but leave two flat directions.

[1909.02000: Dawson, Giardino]



FITMAKER

Higgs:

Breaks EW flat directions and constrains some additional purely boson operators.

[2012.02779: Ellis, Madigan, Mimasu, Sanz, You]

[2202.02333: Alasfar, de Blas, Gröber]

Constrained operators: 17

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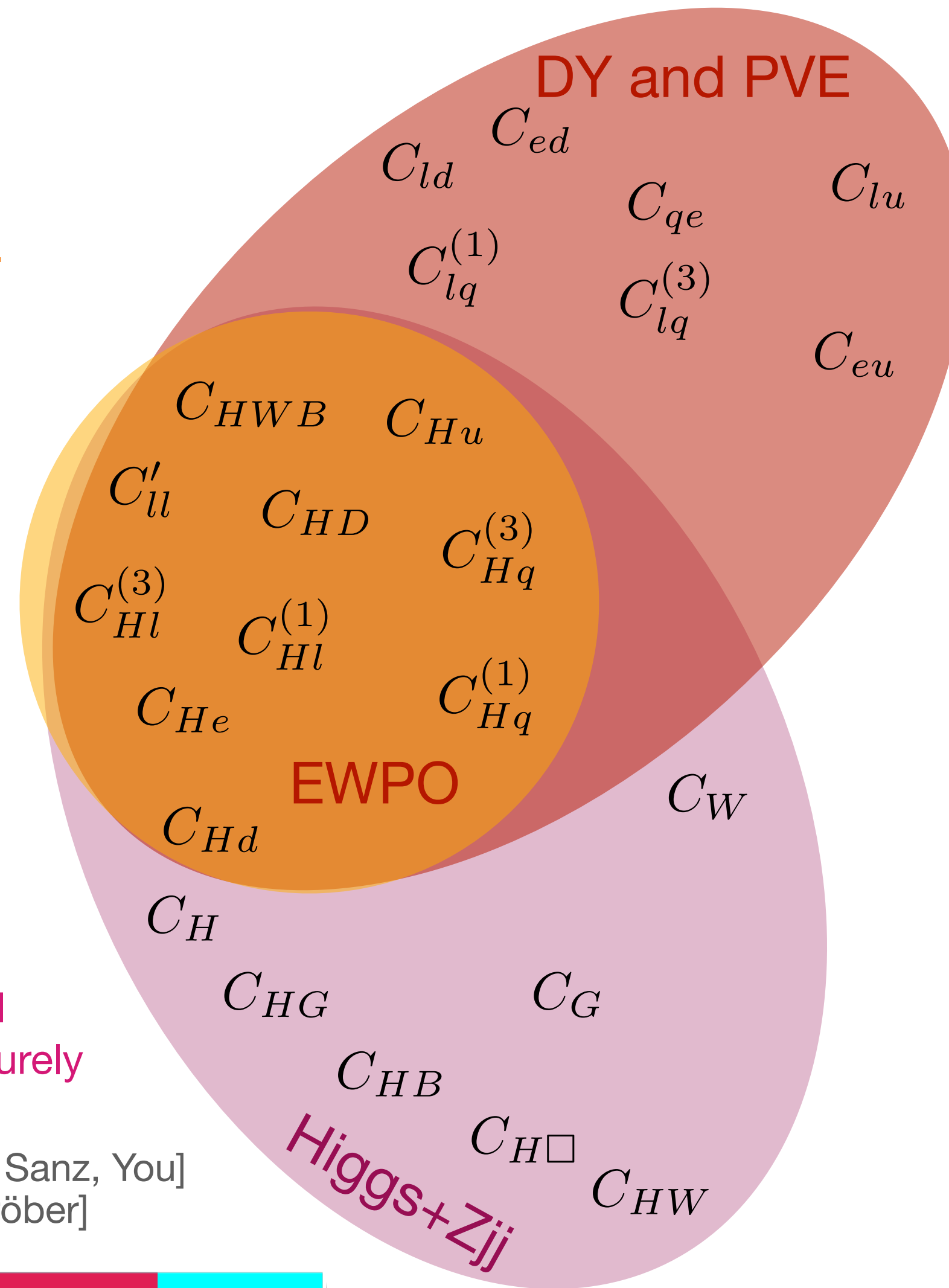
HighPT

Drell-Yan and PVE:

Their interplay is needed in order to constrain semi-leptonic operators.

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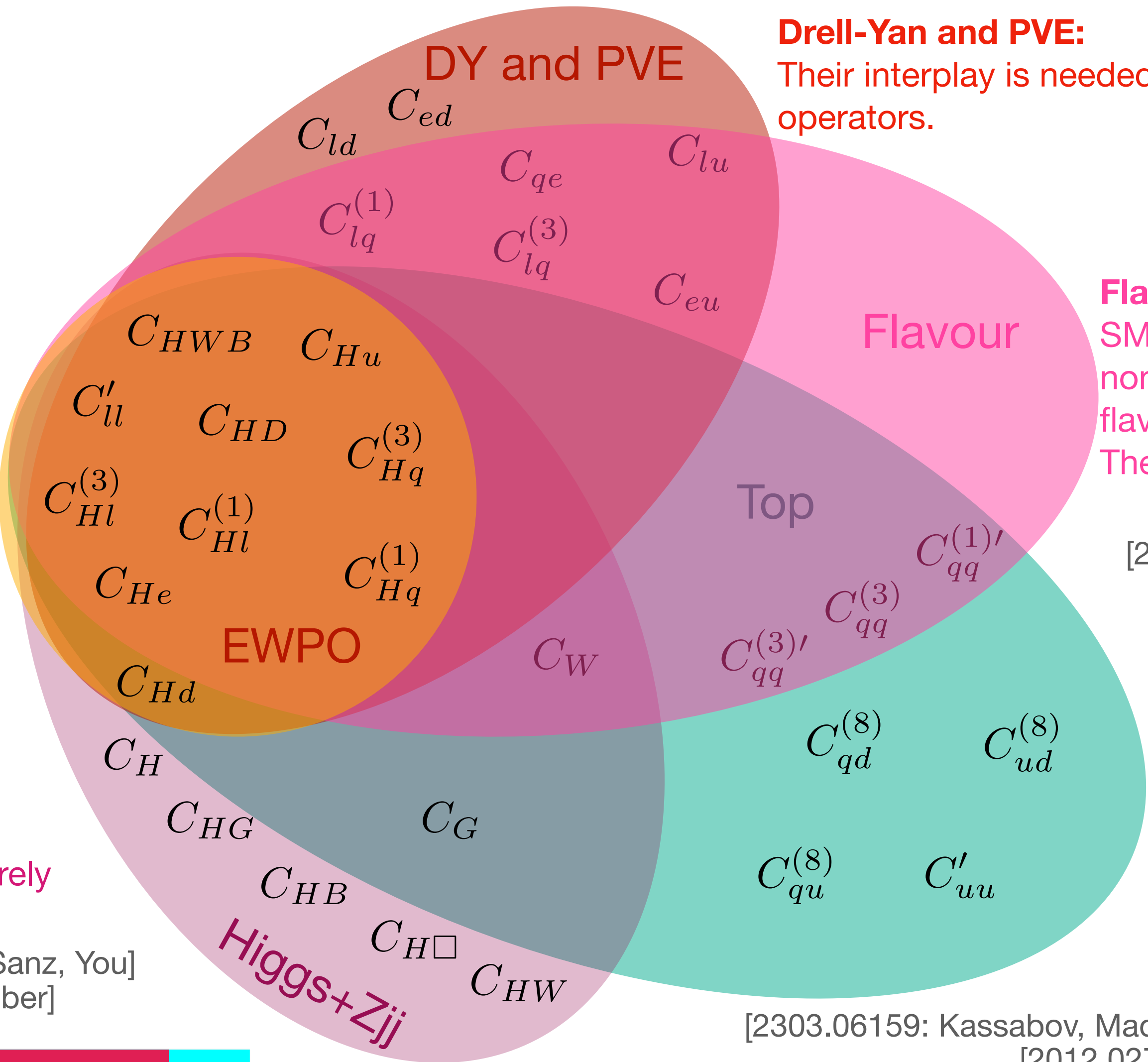
flavio

Flavour:
SMEFT operators are flavour symmetric, nonetheless Yukawa couplings give rise to flavour violating observables via loop. These bounds lift correlations present in Top.
[1810.08132: Straub]
[2003.05432: Aoude, Hurth, Renner, Shepherd]

SMEFiT/FITMAKER

Top:
Put constraints on 4-quark operators involving up-type quark. Some operators suffer from correlations.

[2303.06159: Kassabov, Madigan, Mantani, Moore, Alvarado, Rojo, Ubiali]
[2012.02779: Ellis, Madigan, Mimasu, Sanz, You]



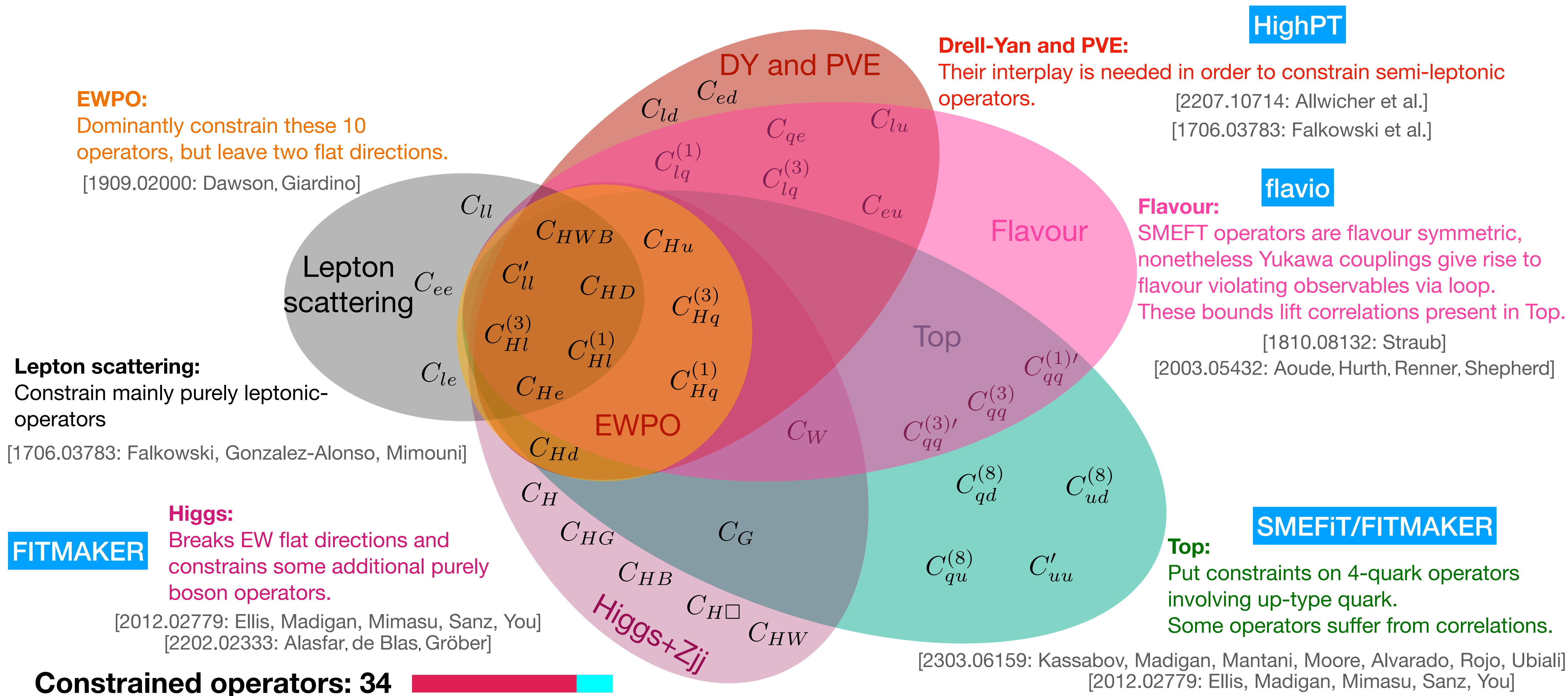
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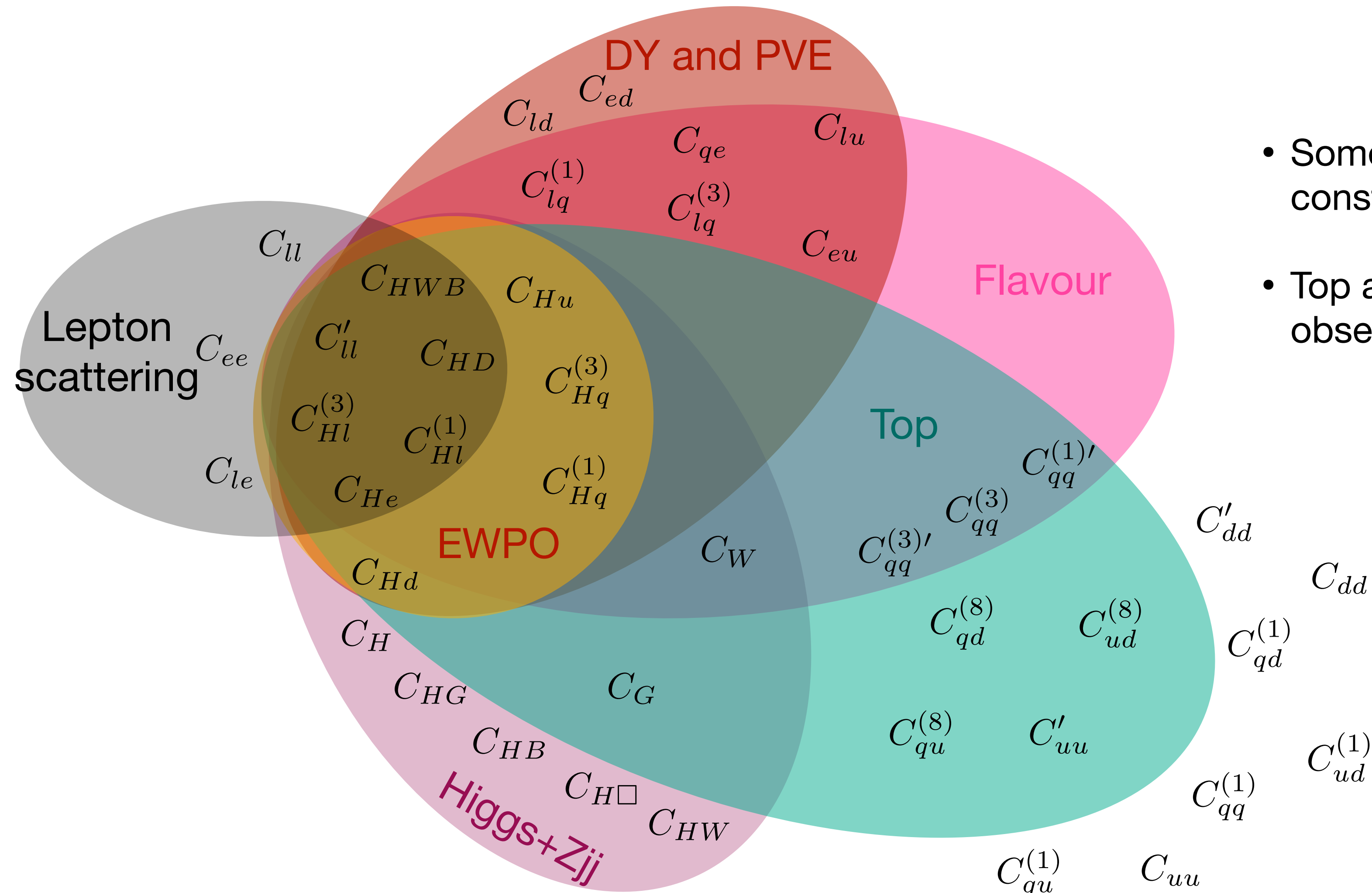
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Constrained operators: 31

Datasets





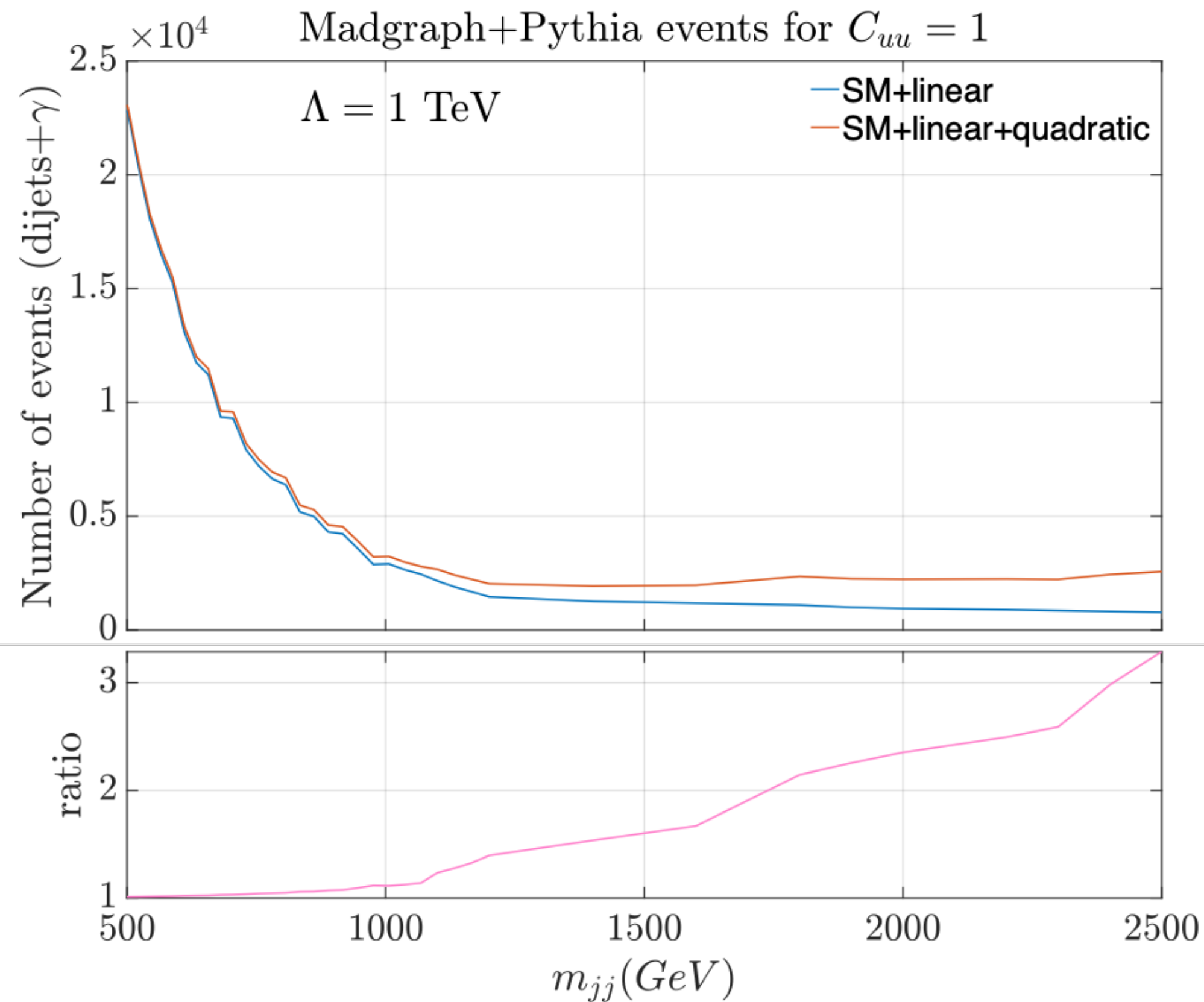
- Some four-quark operators are particularly hard to constrain.
- Top and flavour cannot constrain them and also NLO observables are not enough to get constraints.

- Dijets are the perfect observable to address them, but due to LHC trigger thresholds, only very high energy data are available, possibly leading to inconsistency.

[1907.13160: Keilmann, Sheperd]

Constrained operators: 34

While dijets are powerful for probing the unbounded 4-quark operators, due to trigger thresholds at LHC **only very high energy** data are available.



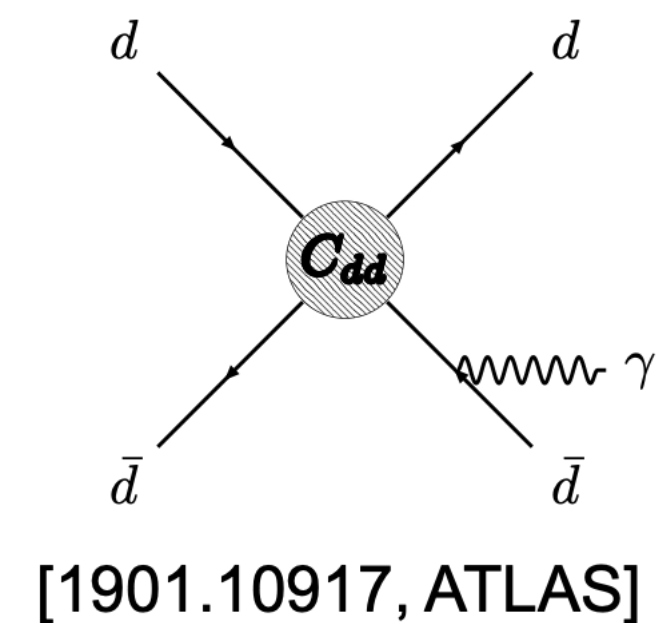
$$\sigma \propto \frac{|C_{dd}|^2}{\Lambda^4} s$$

Energy squared enhancement for quadratic contributions

At high energies, it is no longer possible to neglect $1/\Lambda^4$ terms, and dimension 8 operators also become relevant

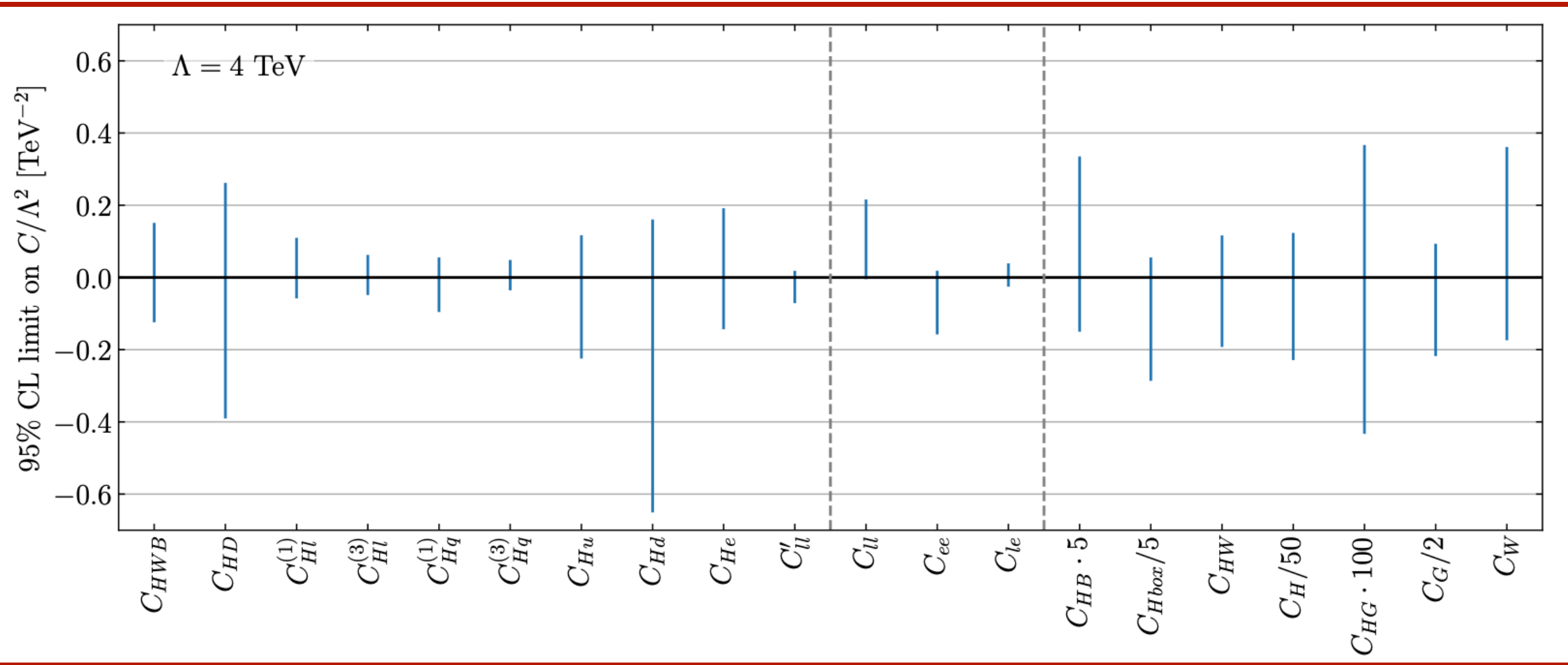
Therefore, we utilise a different process: **dijets+ γ** production. This allows us probe the dijet invariant mass range **below 1.1 TeV**.

MADGRAPH/SMEFTsim



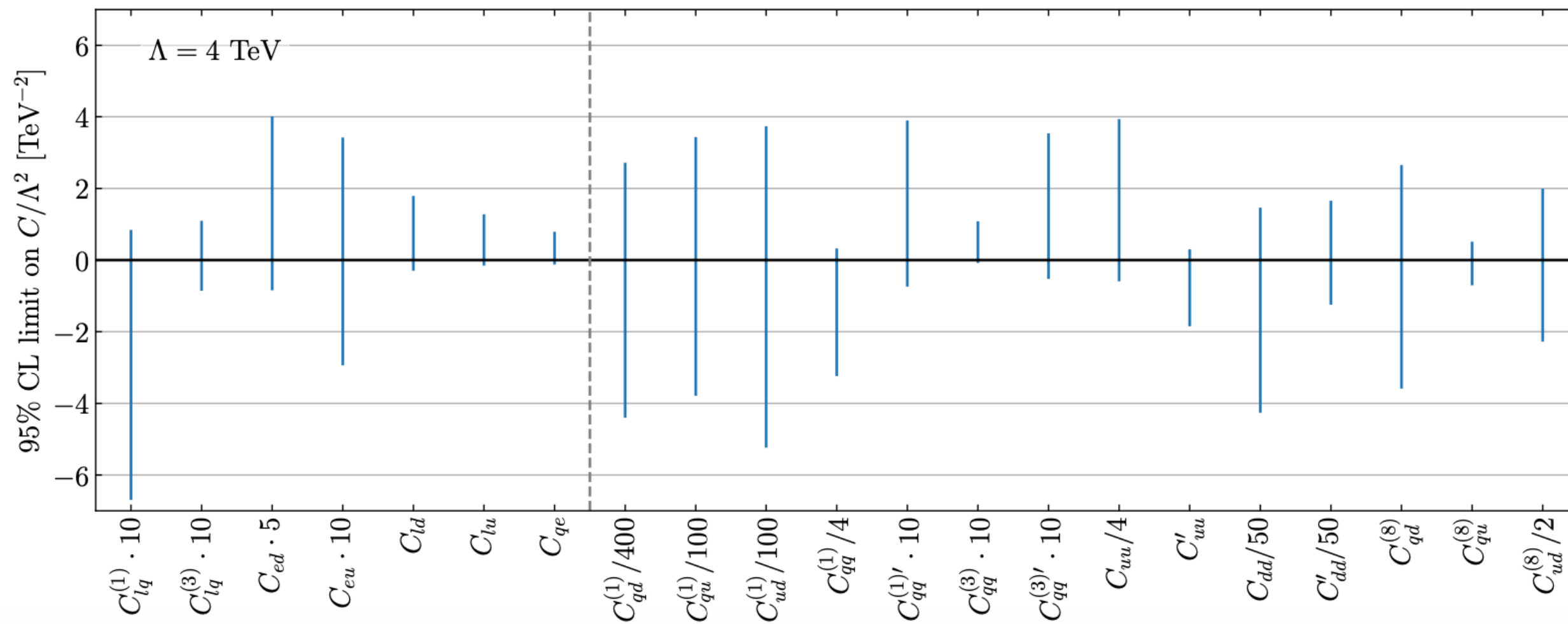
LO fit results

EW-Higgs operators

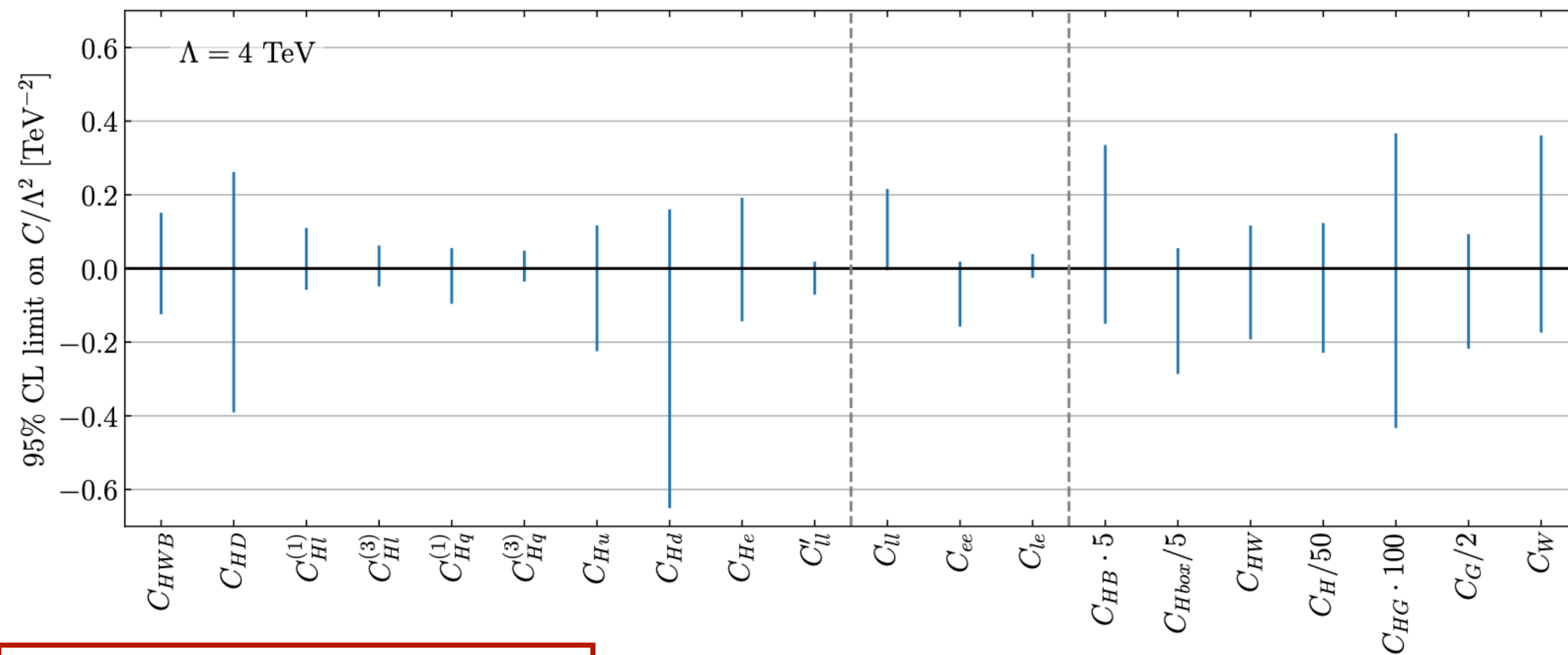


Comments:

- All the operators of the Higgs-EW sector (first panel) are constrained within $|C|/\Lambda^2 < 1/TeV^2$ except C_H

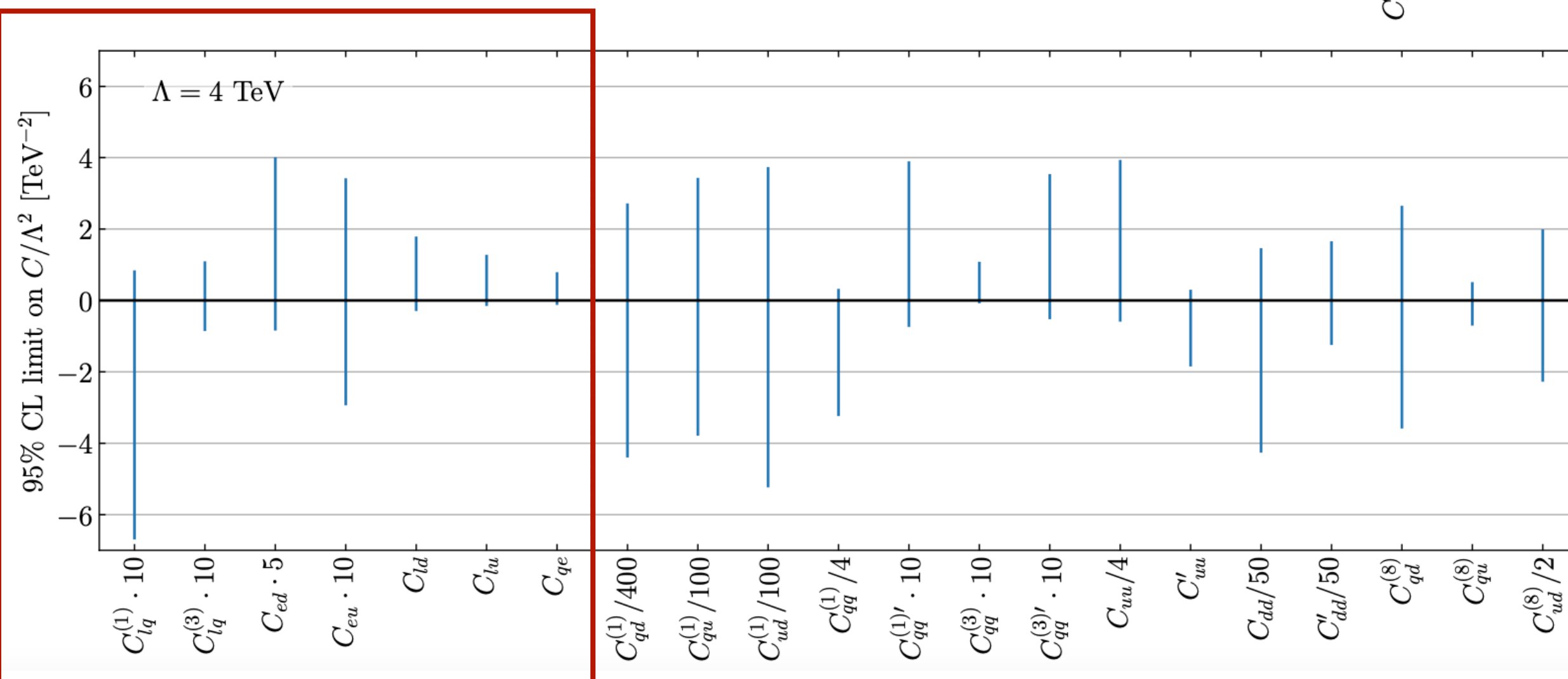


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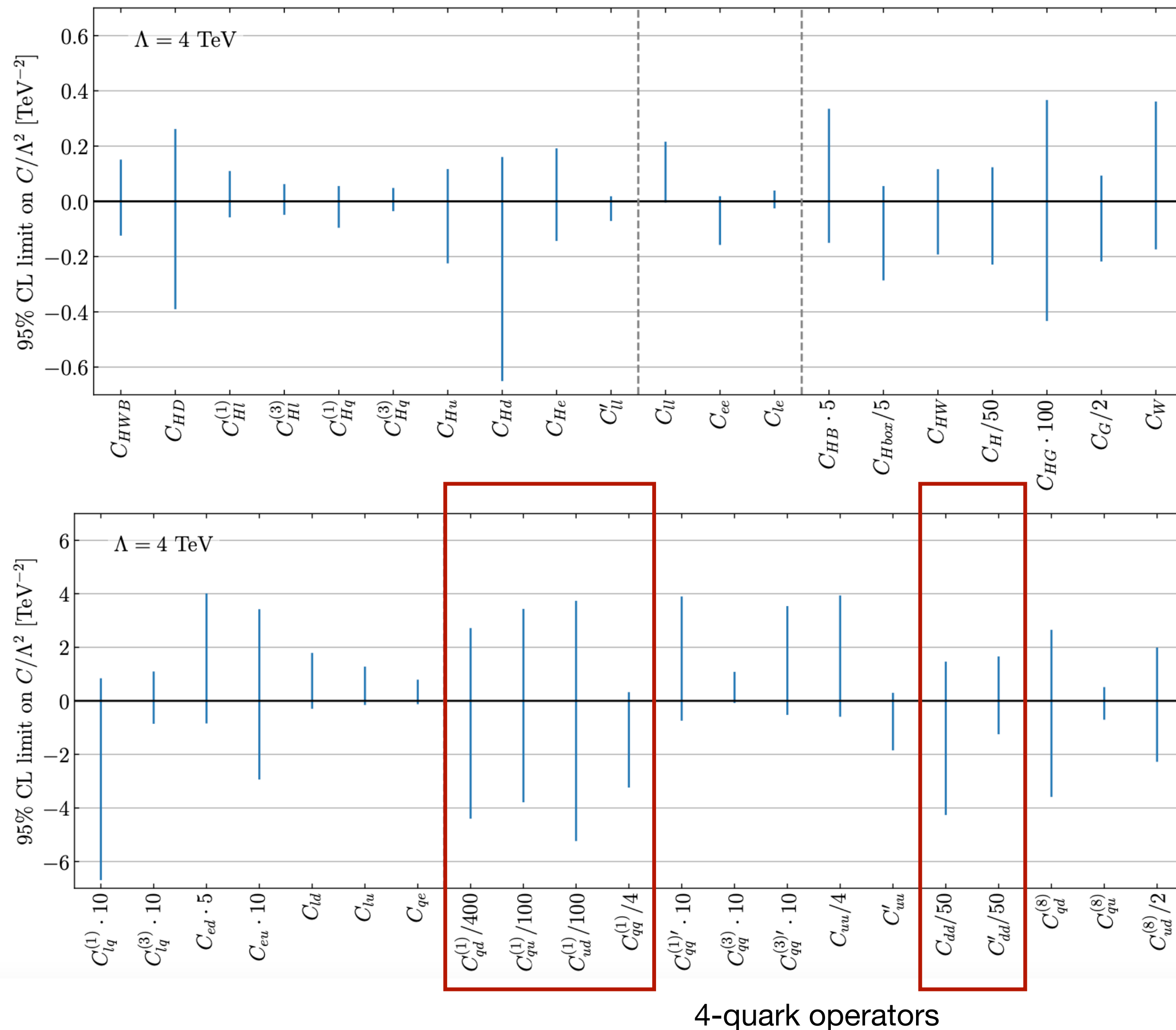
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semileptonic operators

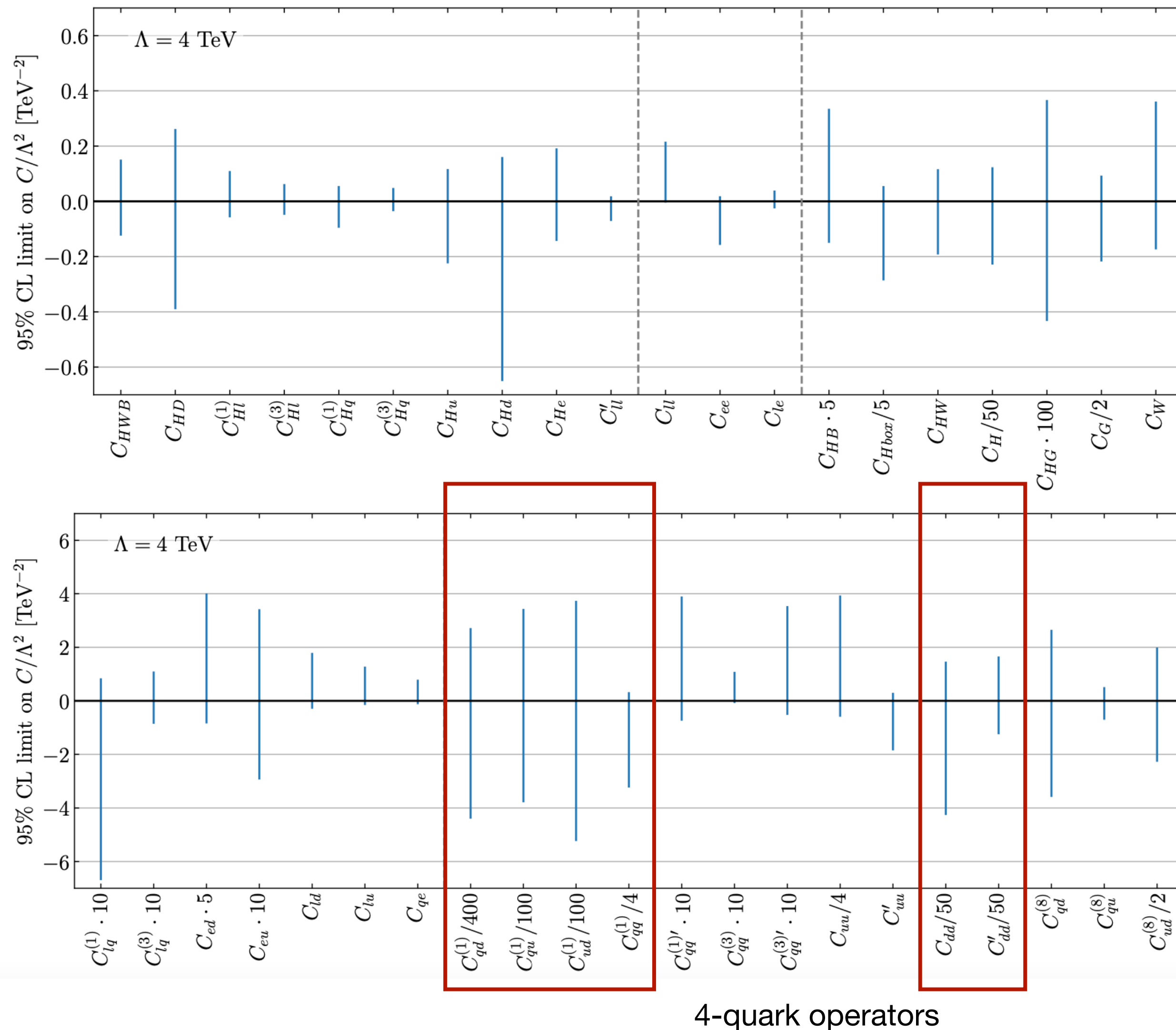
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- $C_{qu}^{(1)}$, $C_{qd}^{(1)}$, $C_{ud}^{(1)}$, C_{dd} , C'_{dd} are essentially unconstrained

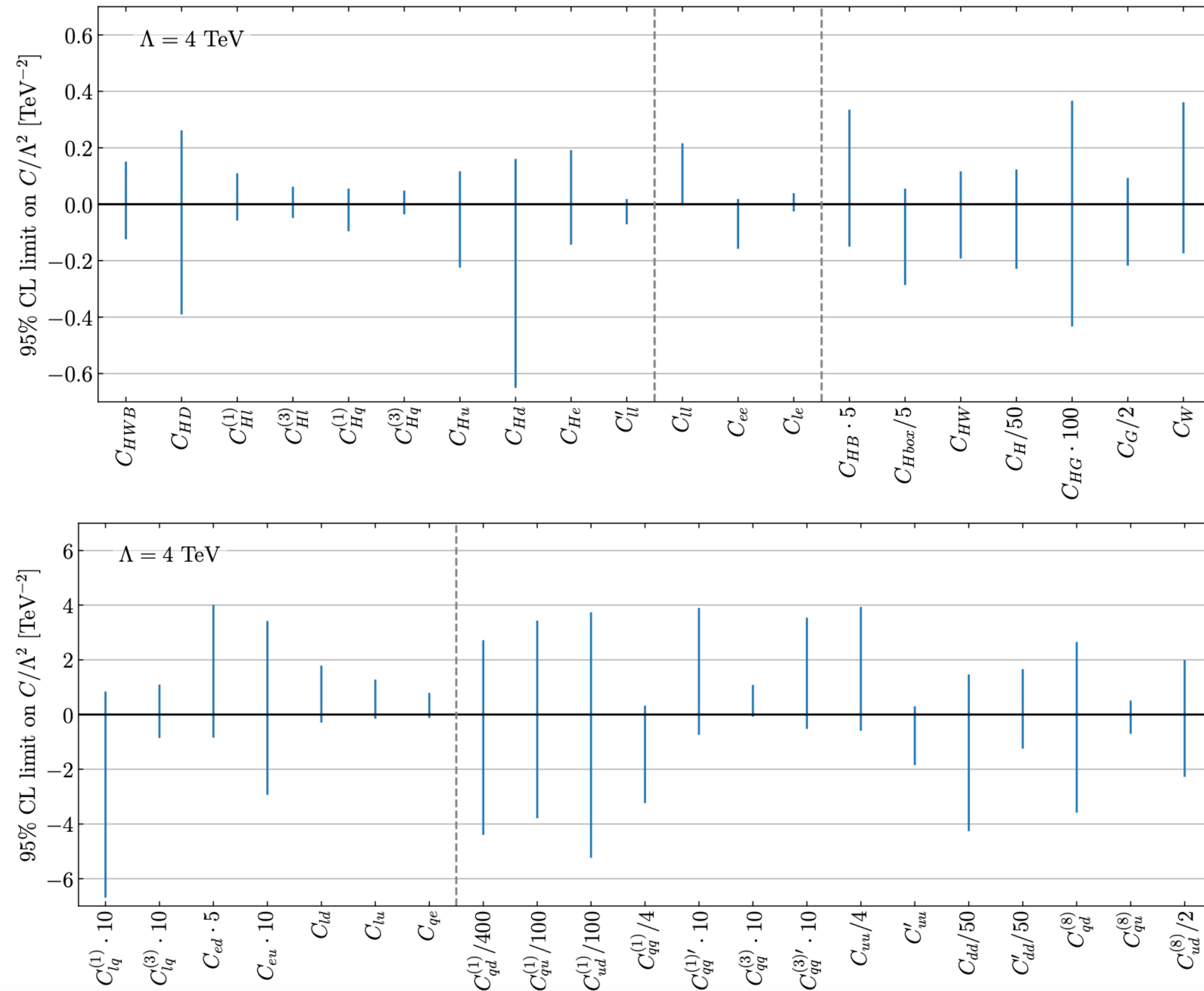
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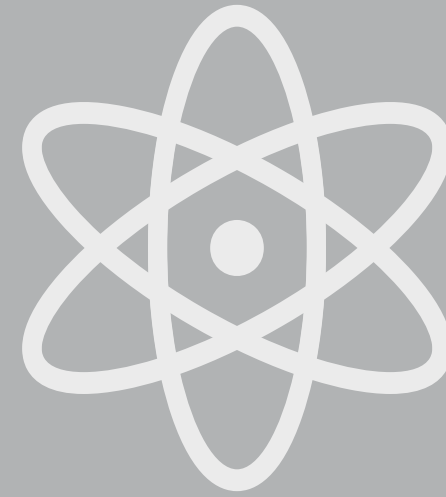
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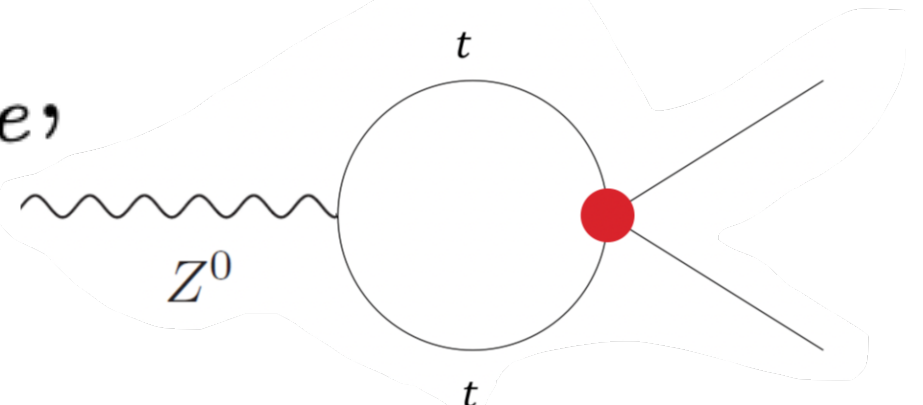
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- $C_{qu}^{(1)}$, $C_{qd}^{(1)}$, $C_{ud}^{(1)}$, C_{dd} , C'_{dd} are essentially unconstrained
- Nevertheless, their inclusion does not invalidate the limits on the other coefficients
- There are no coefficients deviating more than 2 sigma from the SM

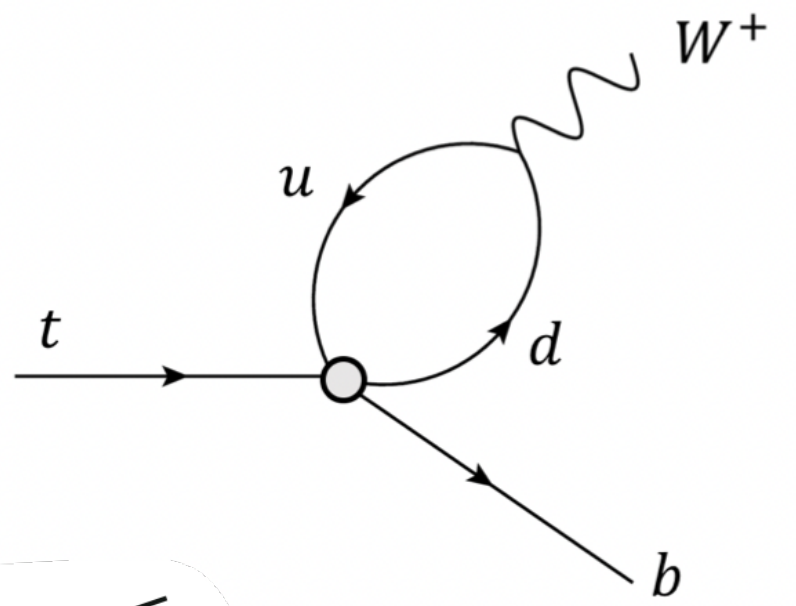


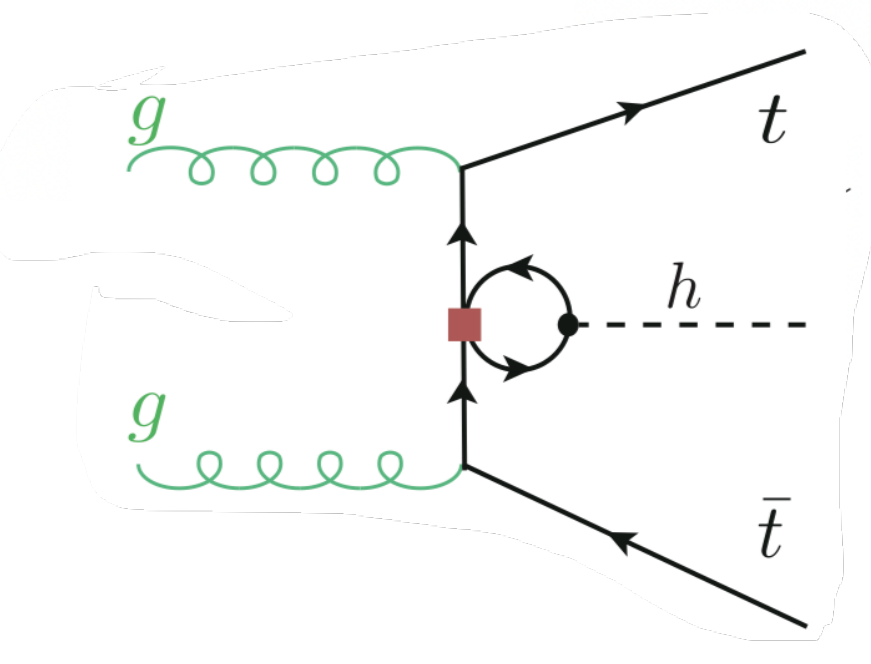
Global analysis with NLO predictions

NLO datasets

NLO corrections include one loop EW and/or QCD corrections to:

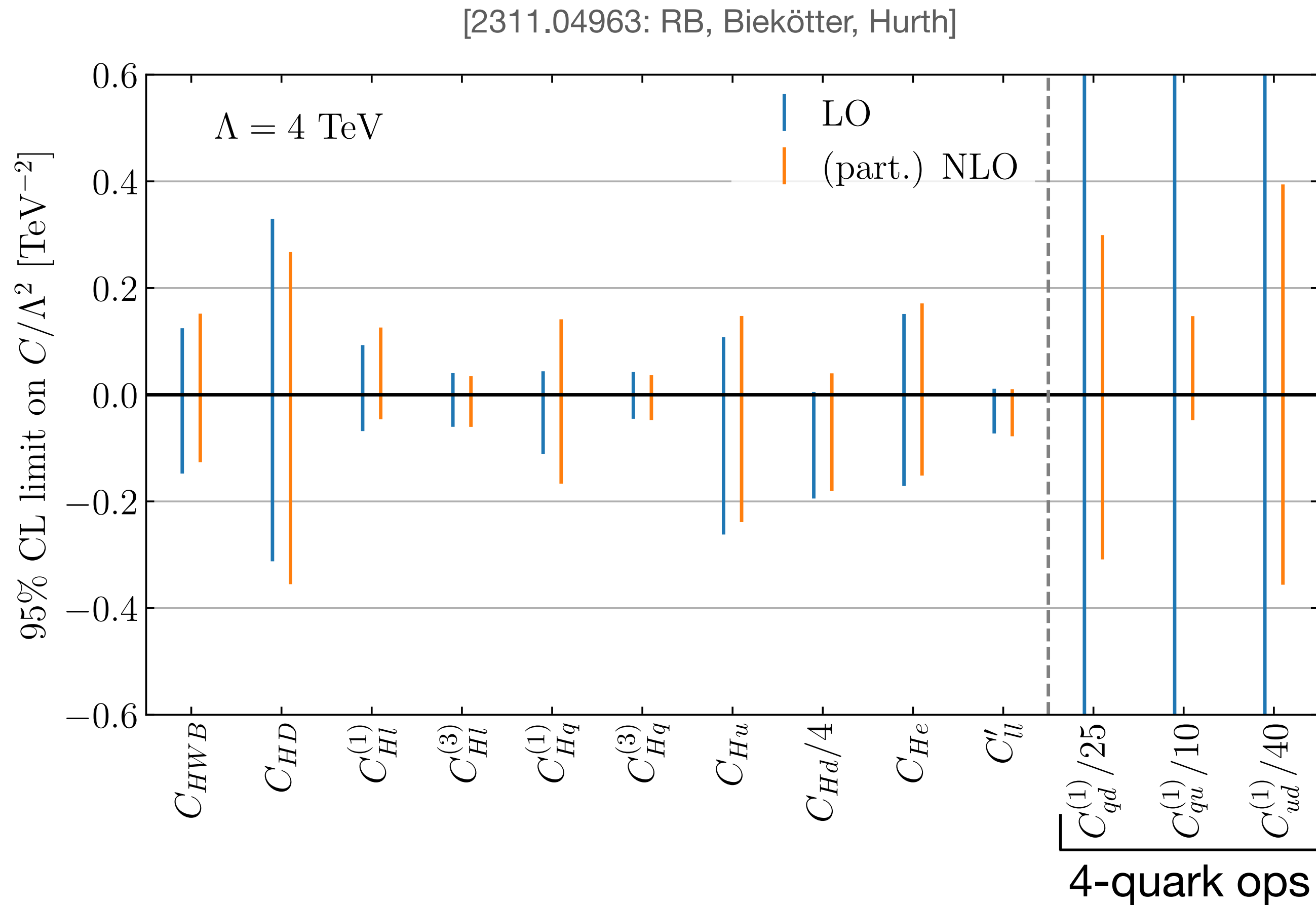
- EWPO: $\{C_{ll}, C_{ee}, C_{le}, C_{HB}, C_{H\Box}, C_{HW}, C_W, C_{lq}^{(1)}, C_{lq}^{(3)}, C_{ed}, C_{eu}, C_{ld}, C_{lu}, C_{qe}, C_{qd}^{(1)}, C_{qu}^{(1)}, C_{ud}^{(1)}, C_{qq}^{(1)}, C_{qq}^{(1)'}, C_{qq}^{(3)}, C_{qq}^{(3)'}, C_{uu}, C'_{uu}, C_{dd}, C'_{dd}\}$ 
[1909.02000: Dawson, Giardino]

- Top (m_{tt} differential distributions and asymmetry) $\{C_{qd}^{(1)}, C_{qu}^{(1)}, C_{ud}^{(1)}, C_{qq}^{(1)}, C_{uu}\}$ 
[2303.06159: Kassabov, Madigan, Mantani, Moore, Alvarado, Rojo, Ubiali]

- Higgs (single production and decay) $\{C_{qu}^{(1)}, C_{qq}^{(1)}, C_{qq}^{(3)}, C_{uu}, C_{qu}^{(8)}\}$ 
[2202.02333: Alasfar, de Blas, Gröber]

[1907.00997: Radja Boughezal et al.]

LO vs NLO fit



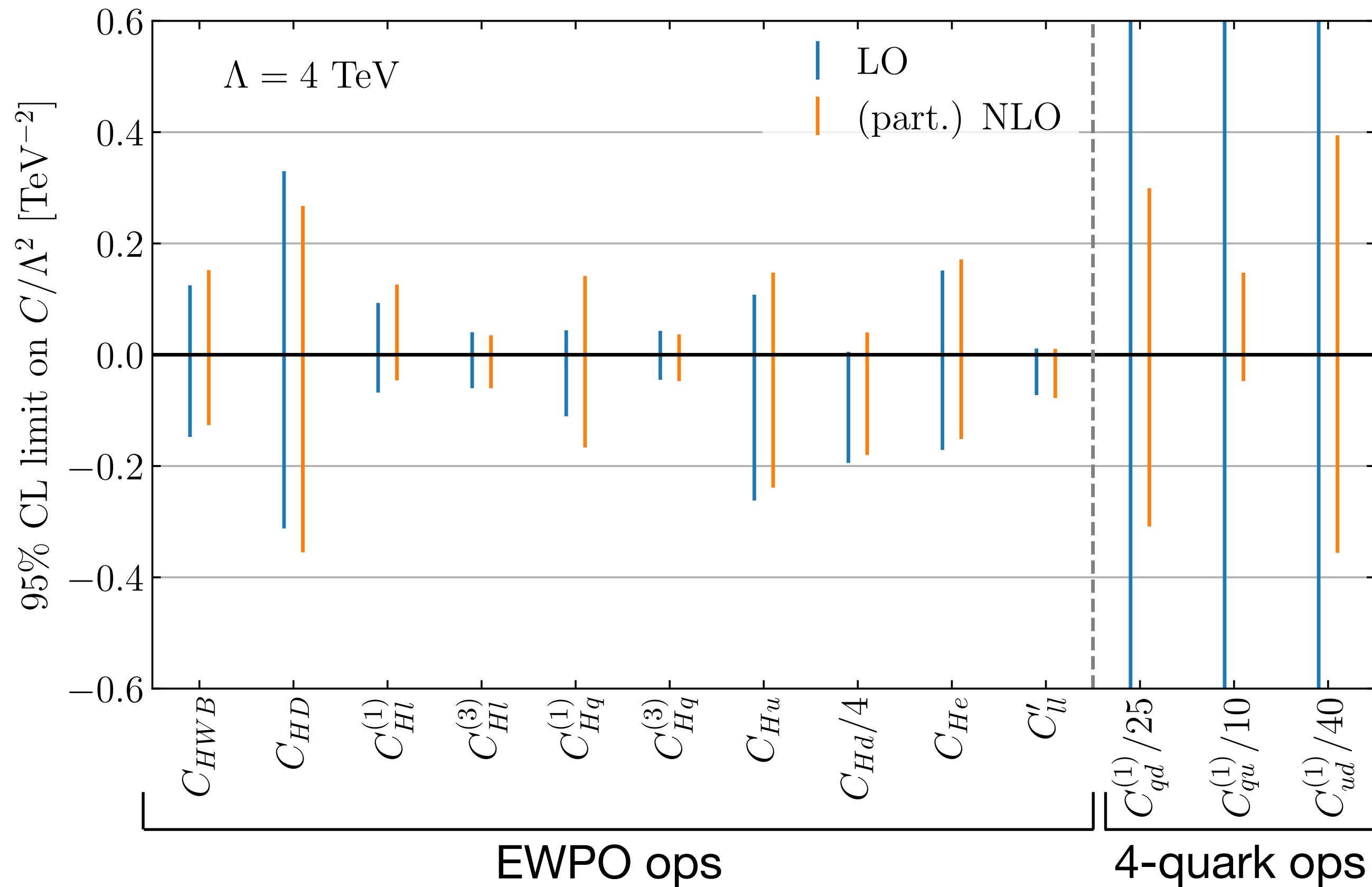
- Some operators, poorly constrained using only LO observables, result much better bounded when NLO observables are included.

Constraints on $C_{qu}^{(1)}$ at LO: Dijets

Constraints on $C_{qu}^{(1)}$ at LO+NLO: Dijets, Higgs, EWPO, Top

LO vs NLO fit

[2311.04963: RB, Biekötter, Hurth]



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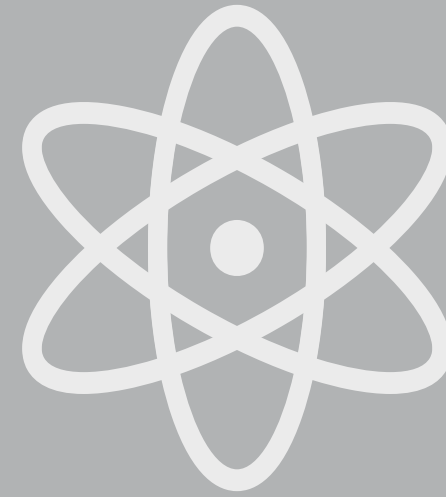
Constraints on $C_{qu}^{(1)}$ at LO: Dijets

Constraints on $C_{qu}^{(1)}$ at LO+NLO: Dijets, Higgs, EWPO, Top

- Even after the inclusion of NLO predictions for EWPO observables, the bounds on EW operators did not significantly change.

Number of operators occurring in EWPO at LO: 10

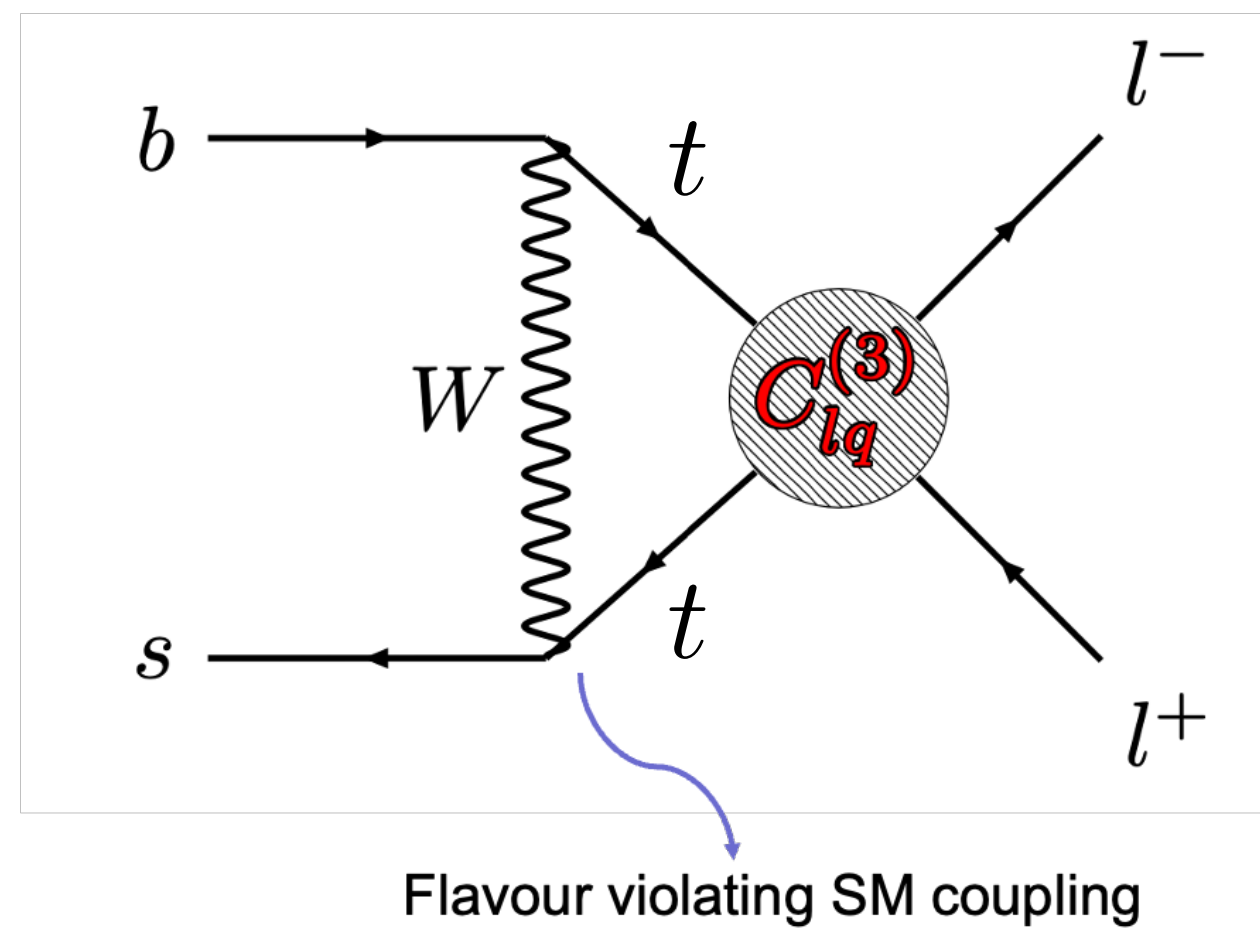
Number of operators occurring in EWPO at NLO: 35



RGE effects on the global analysis

Flavour violation in MFV SMEFT

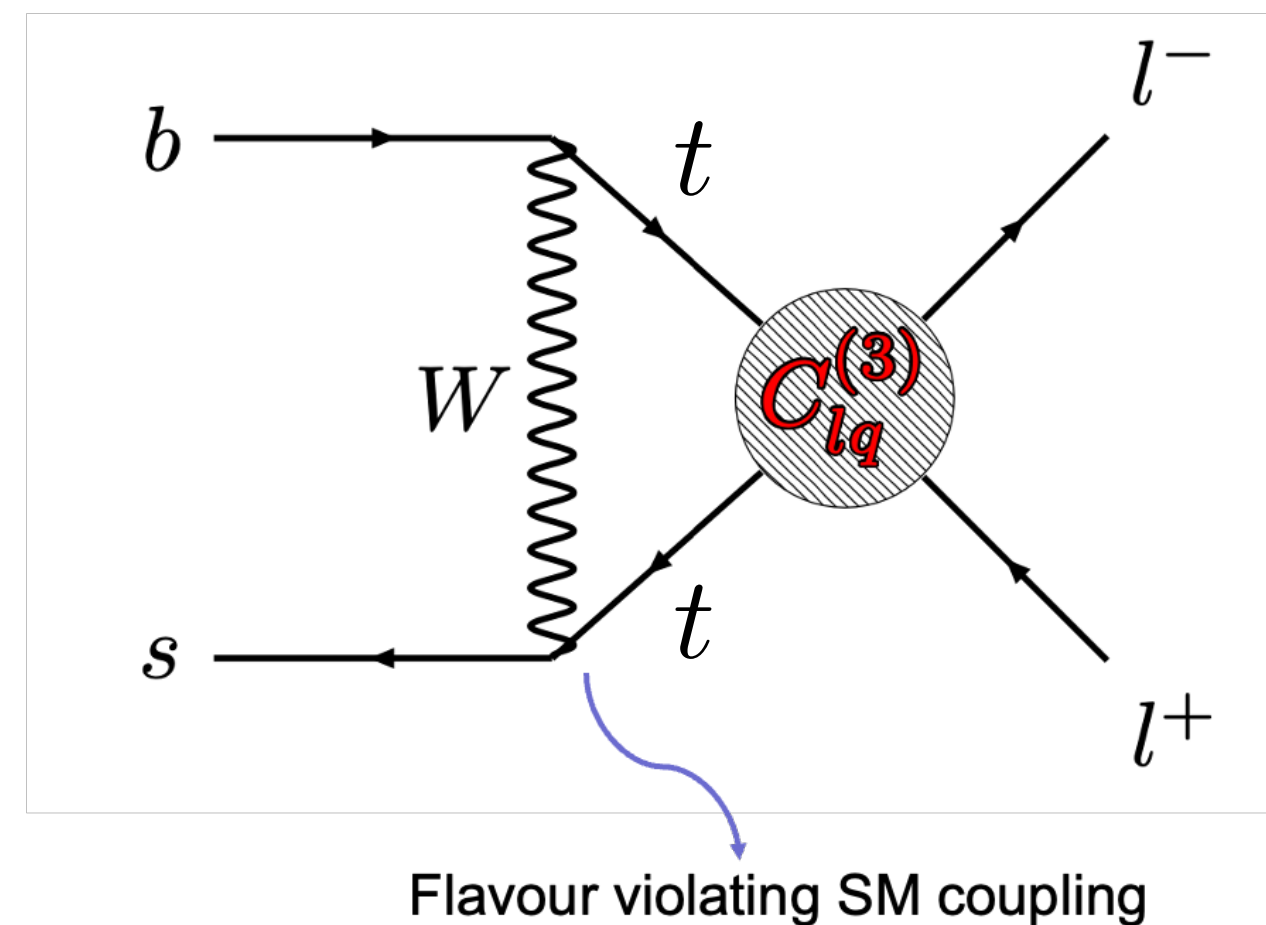
NP operators are flavour symmetric, but SM Yukawa couplings break this symmetry. **RGE** generates also **flavour violating contributions** depending on flavour-symmetric coefficients.



[2003.05432: Aoude, Hurth, Renner, Shepherd]

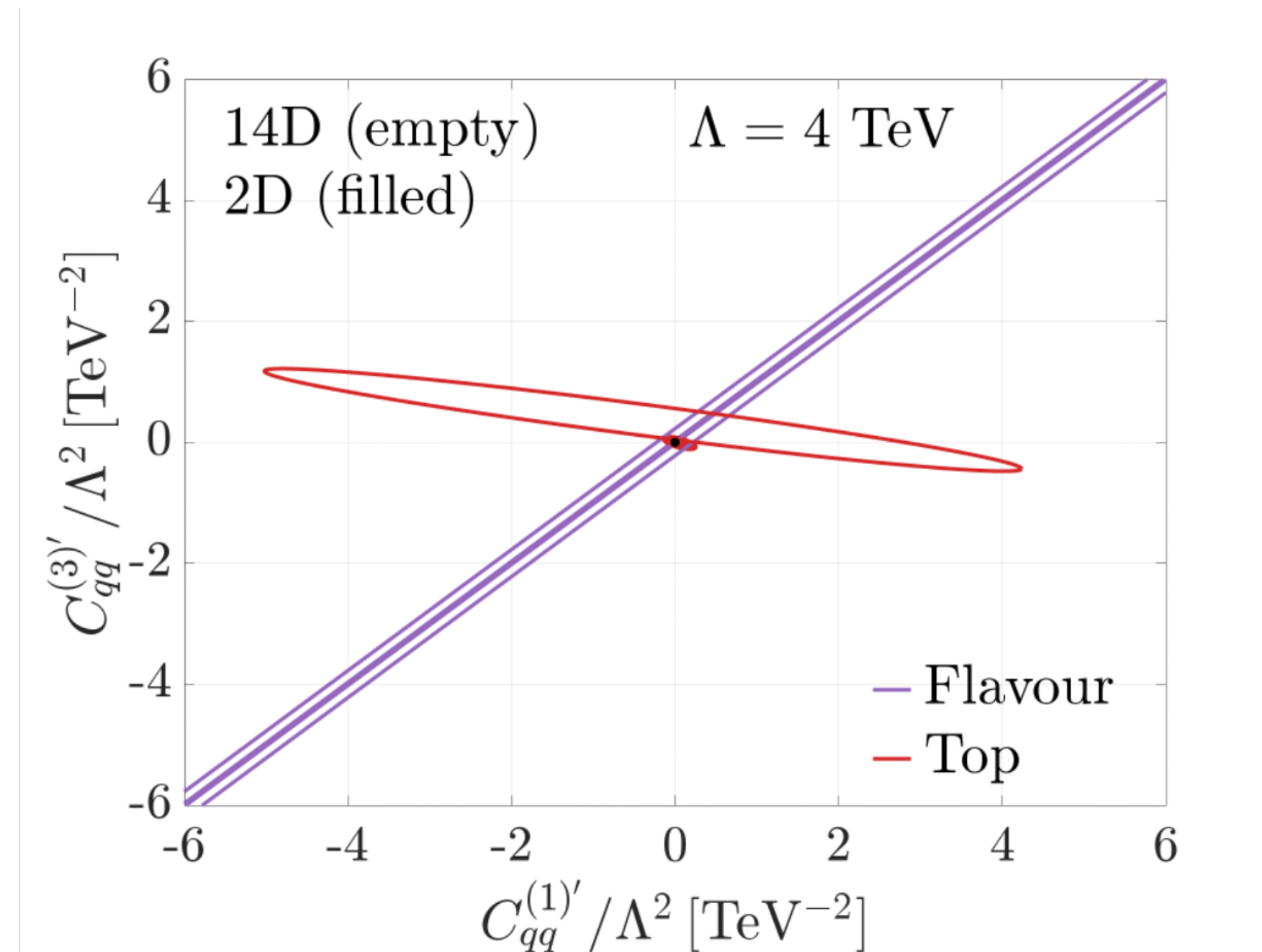
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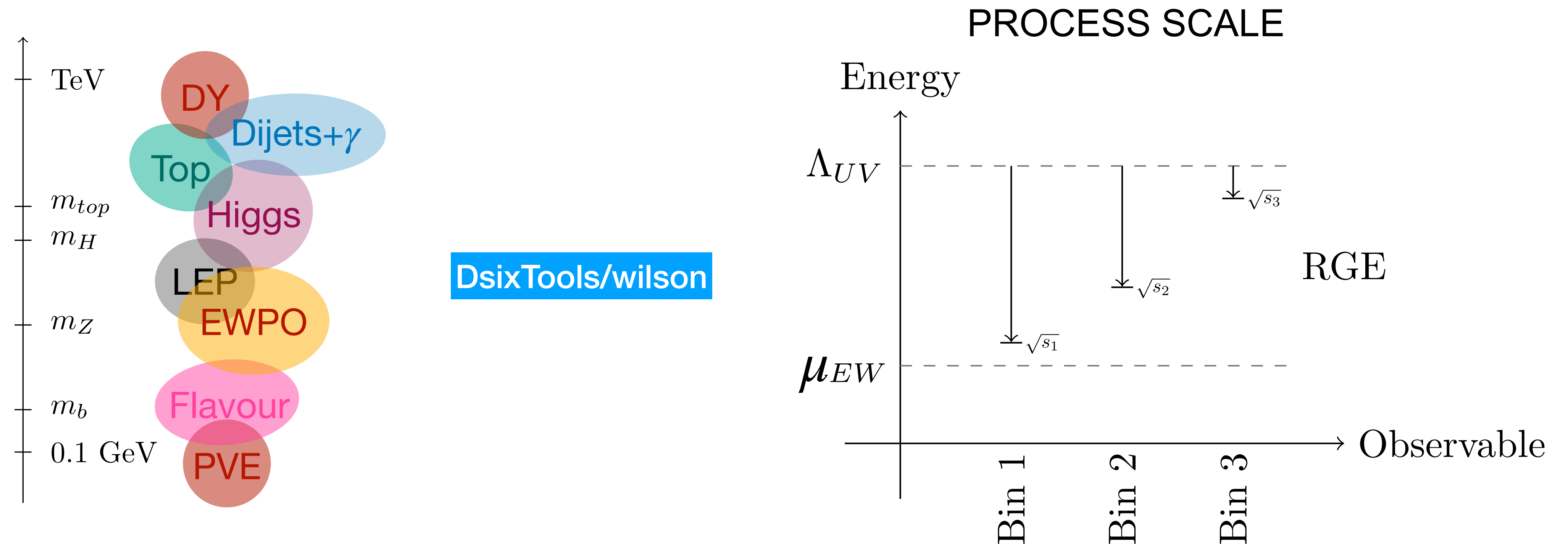
Even if suppressed flavour observables constrain **different directions** of the parameter space compared to top, thus improving significantly the bounds.



[2311.04963: RB, Biekötter, Hurth]

Fixed scale VS Process scale

Collider observables span a wide range of energies, therefore running and mixing effects depend on the renormalisation scale choice.



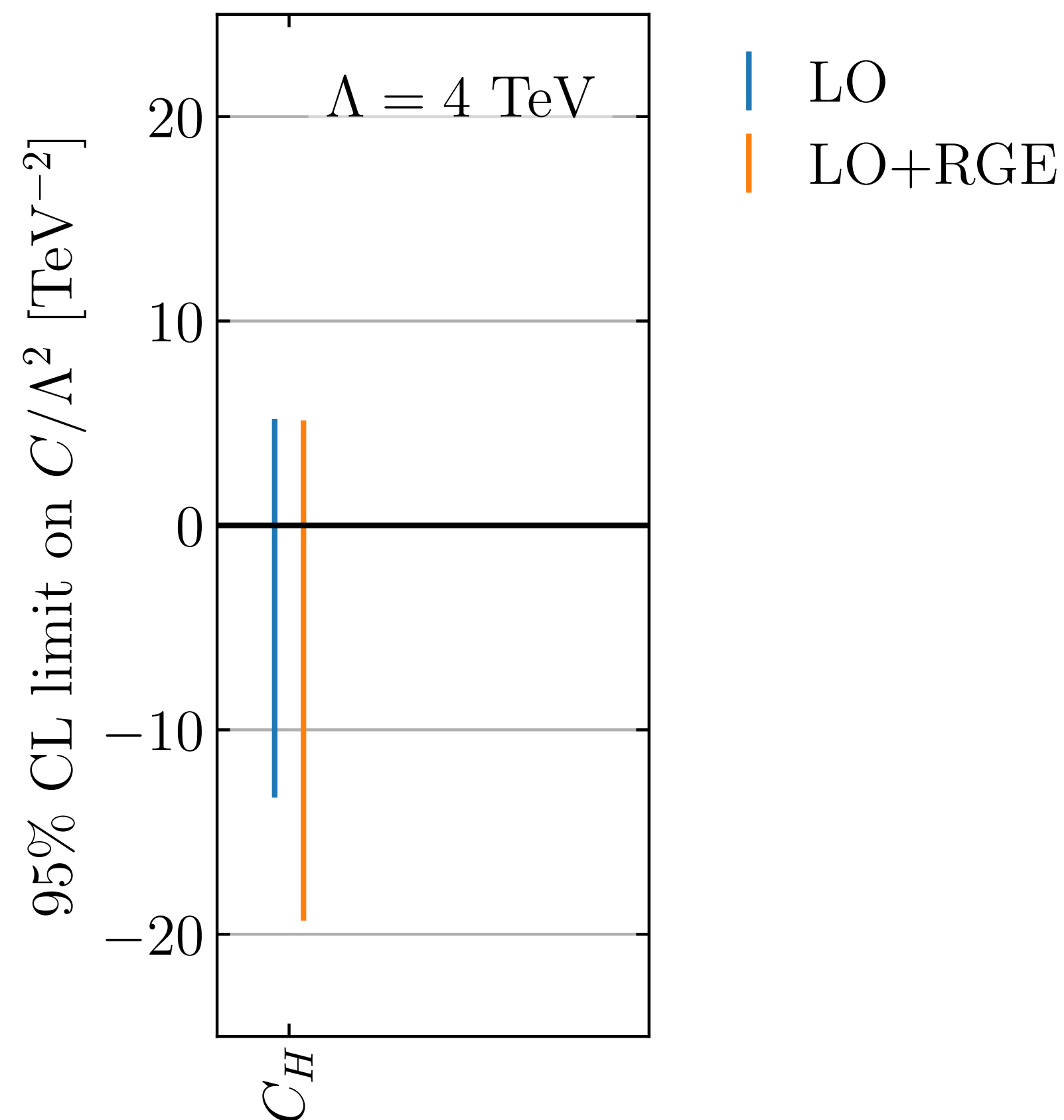
Choosing a dynamical scale instead of a fixed scale can sizeably influence the constraints on the Wilson coefficients.

[2212.05067: Aoude et al.]
 [2409.19578: Heinrich and Lang]
 [2312.11327: Di Noi, Gröber]

RGE effects on the global analysis

Diagonal running effect:

There are operators like C_H that run diagonally bringing to different bounds between the fit with no running and the fit with running.



$$C_H(\mu_{EW}) = 0.65 C_H(\mu_\Lambda)$$

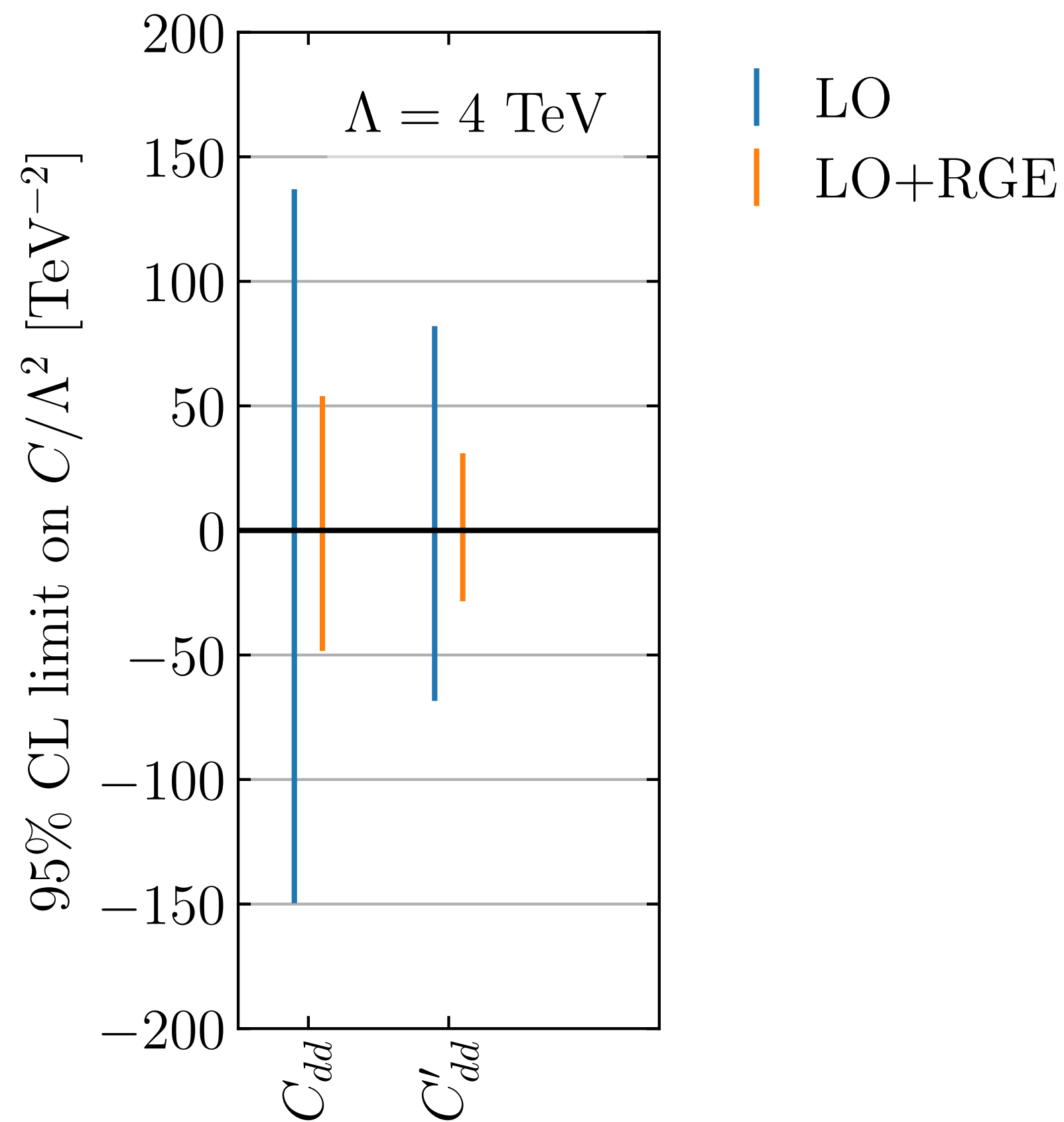
The operator C_H at the EW scale is 35% smaller than the same operator at the NP scale. Since this operator is constrained almost independently in di-Higgs production, its bound is weakened of this factor.

[2412.09674: RB, Biekötter, Hurth]

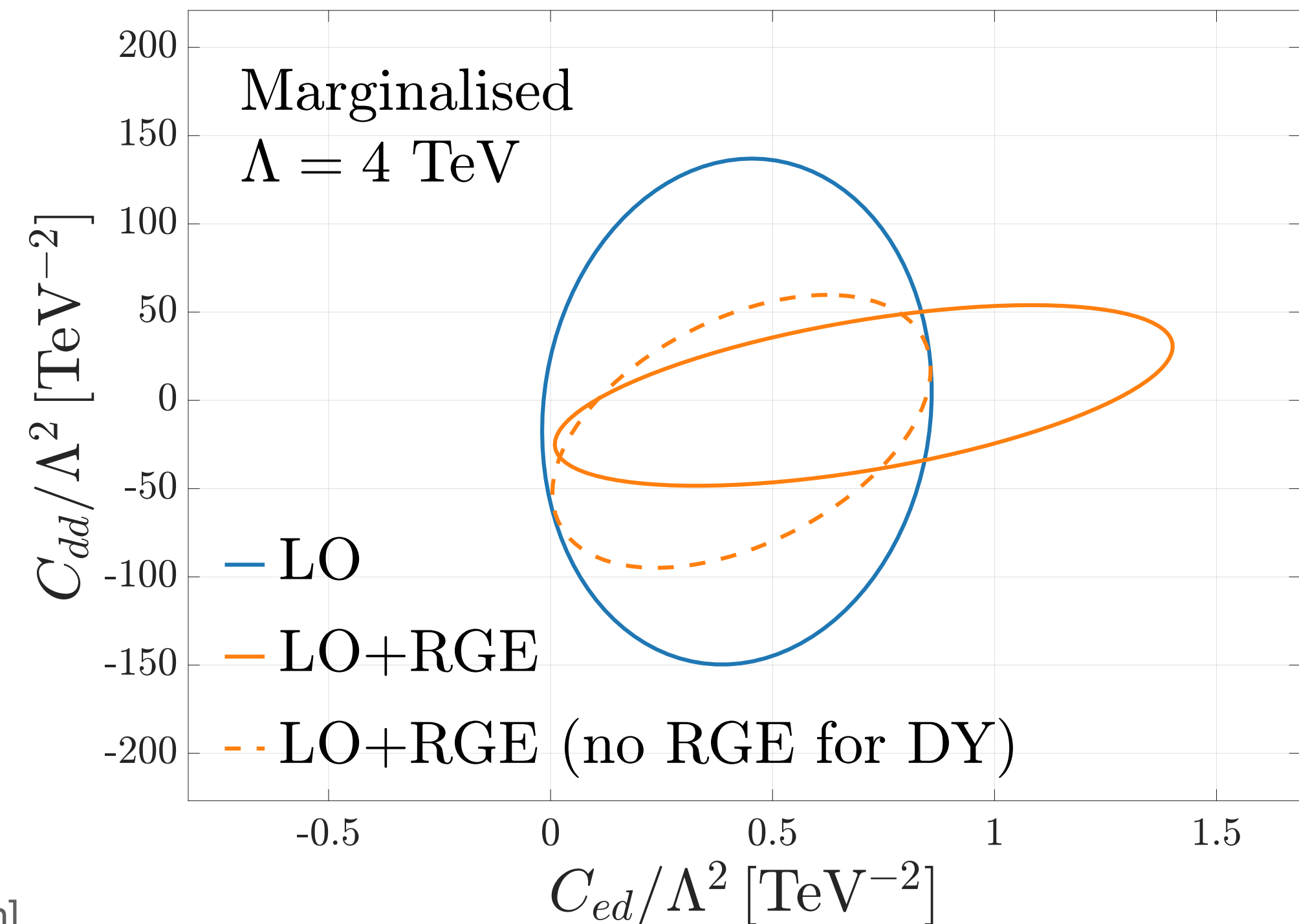
RGE effects on the global analysis

Non-diagonal running effect:

The weakly constrained operators C_{dd} and C'_{dd} run in the operators C_{ed} and C_{ld} which are well constrained by Drell-Yan.



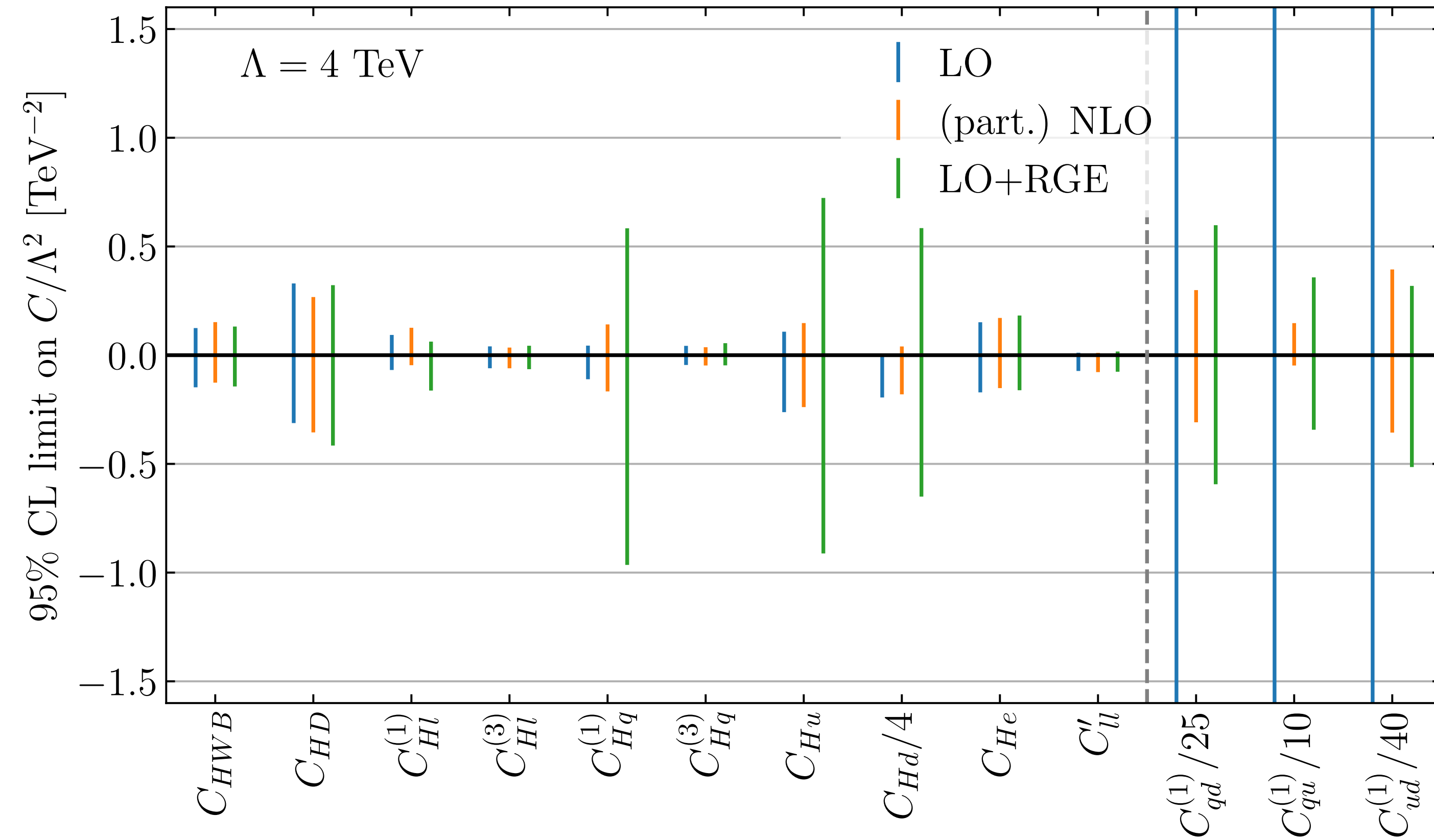
$$C_{ed}(\mu_{EW}) = -0.03C_{dd}(\mu_{\Lambda}) - 0.01C'_{dd}(\mu_{\Lambda})$$



[2412.09674: RB, Biekötter, Hurth]

RGE vs NLO

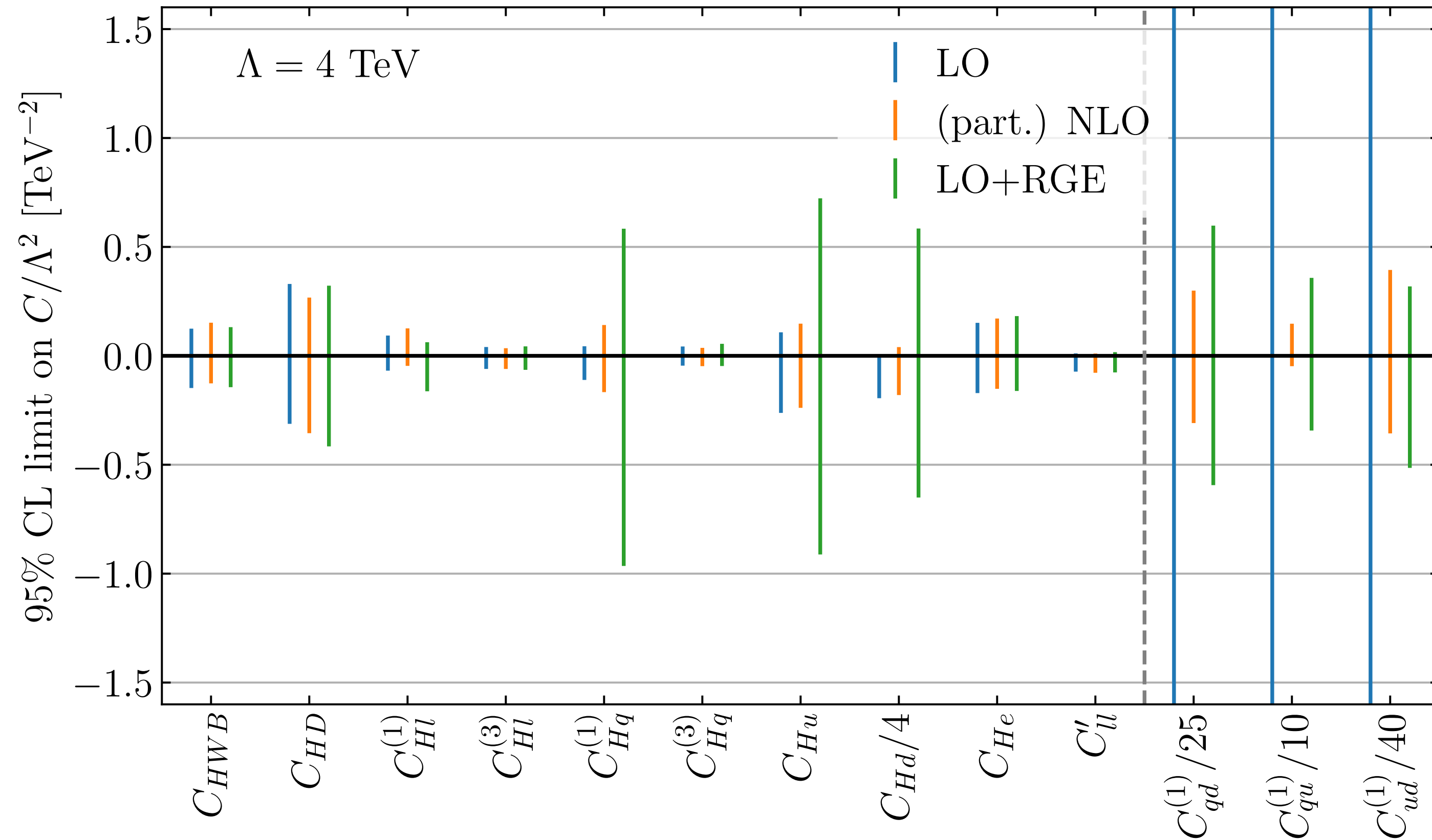
Including the RGE effects influences significantly EWPO operators



[2412.09674: RB, Biekötter, Hurth]

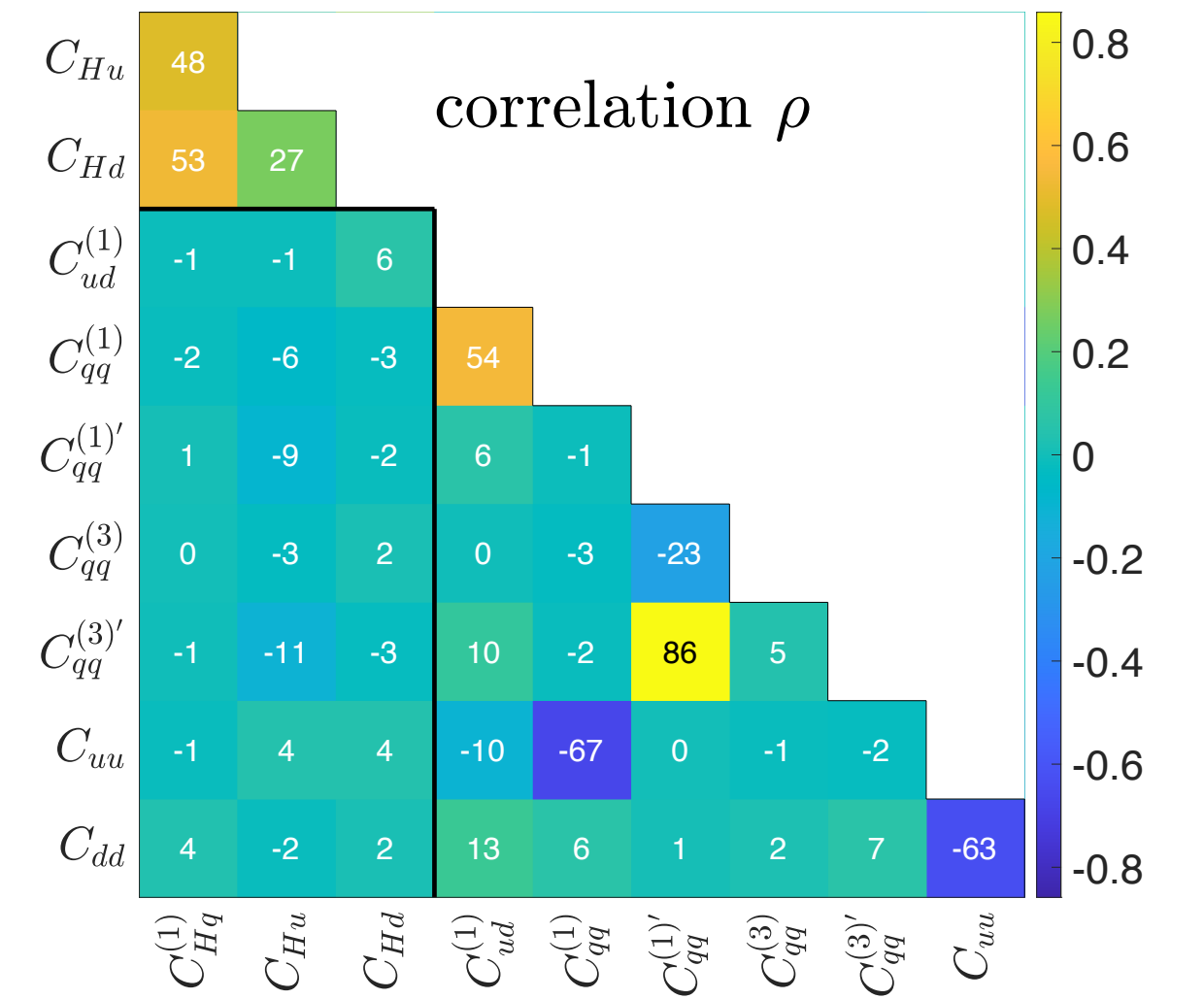
RGE vs NLO

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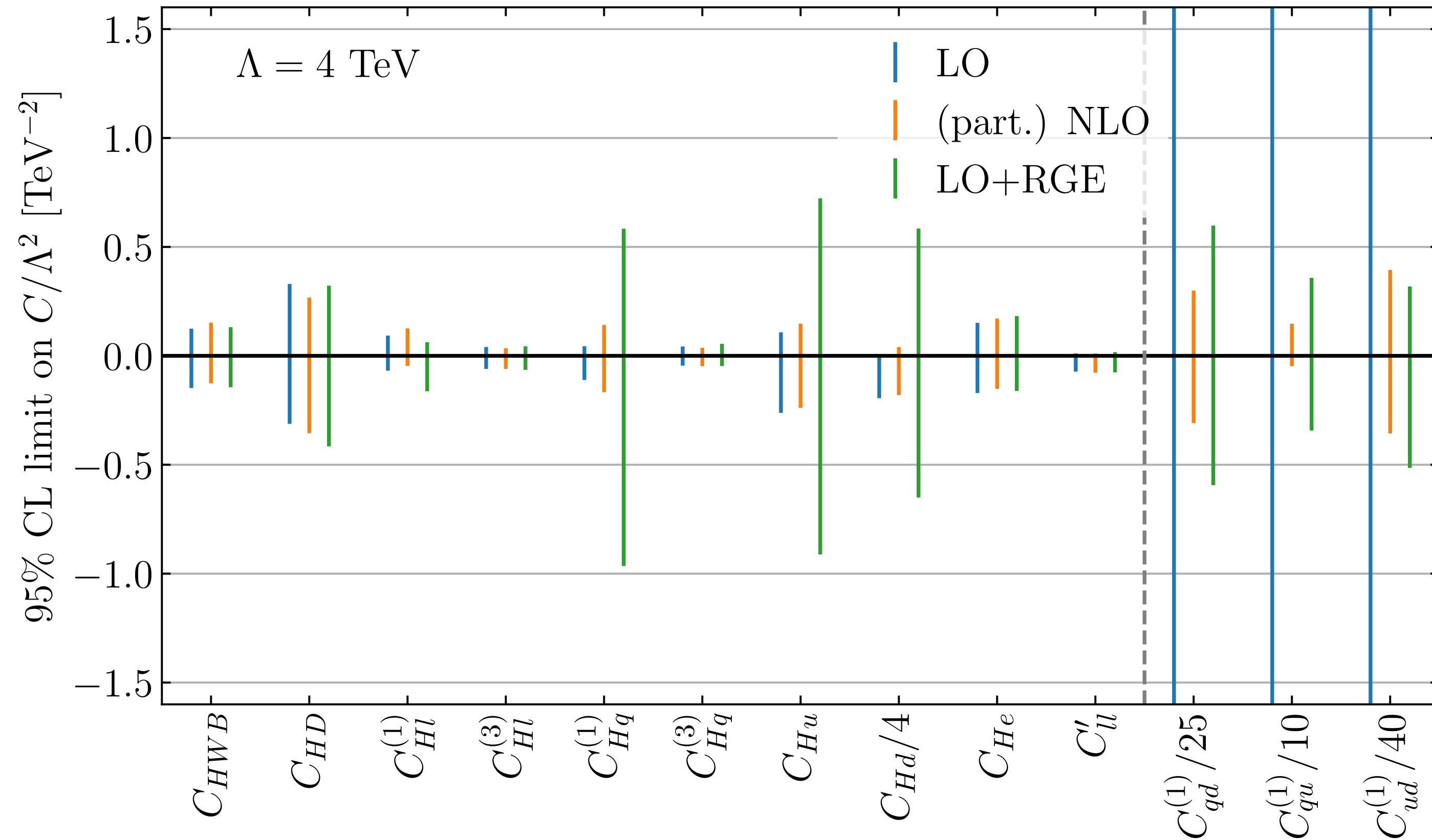
[2412.09674: RB, Biekötter, Hurth]

LO



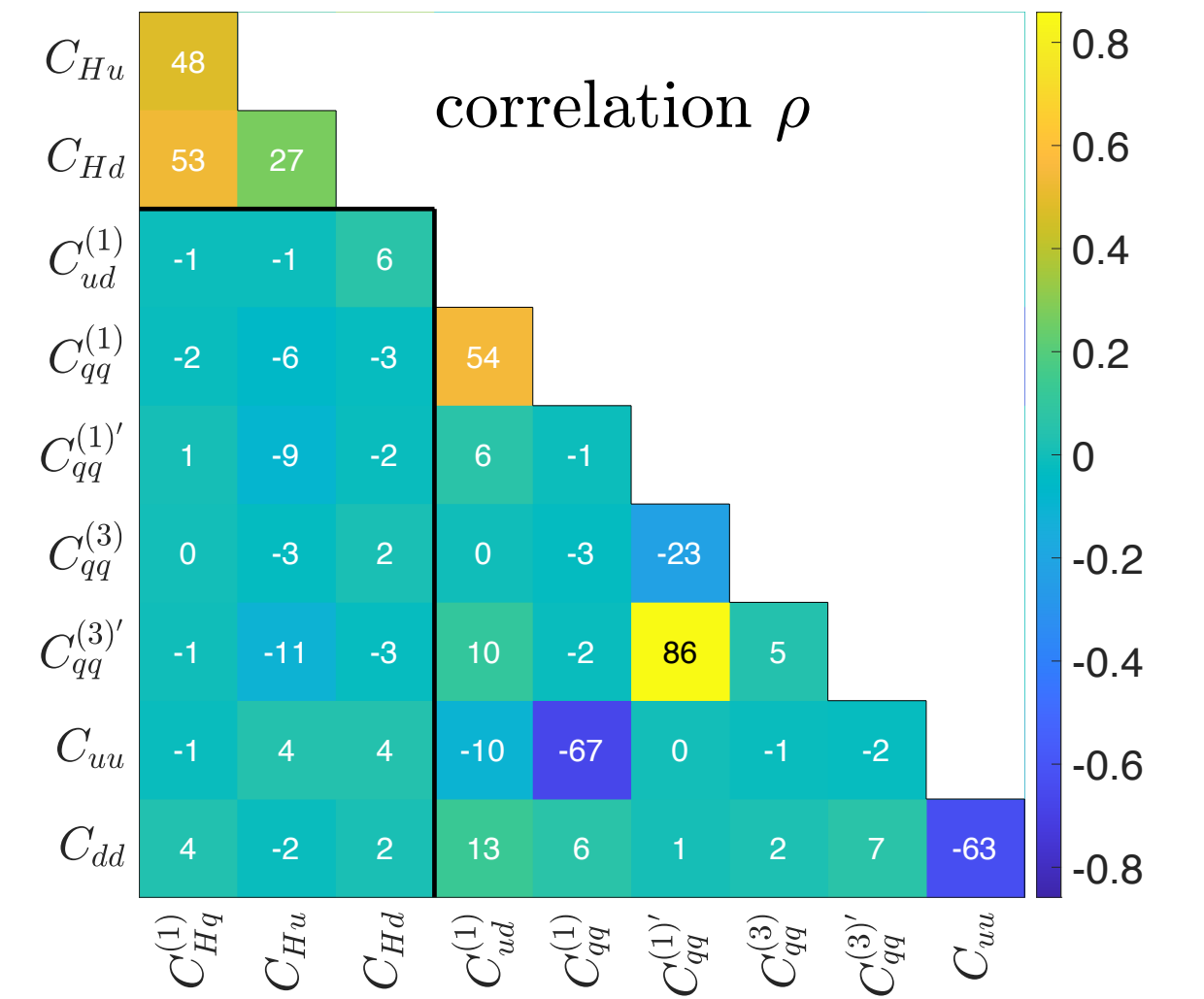
RGE vs NLO

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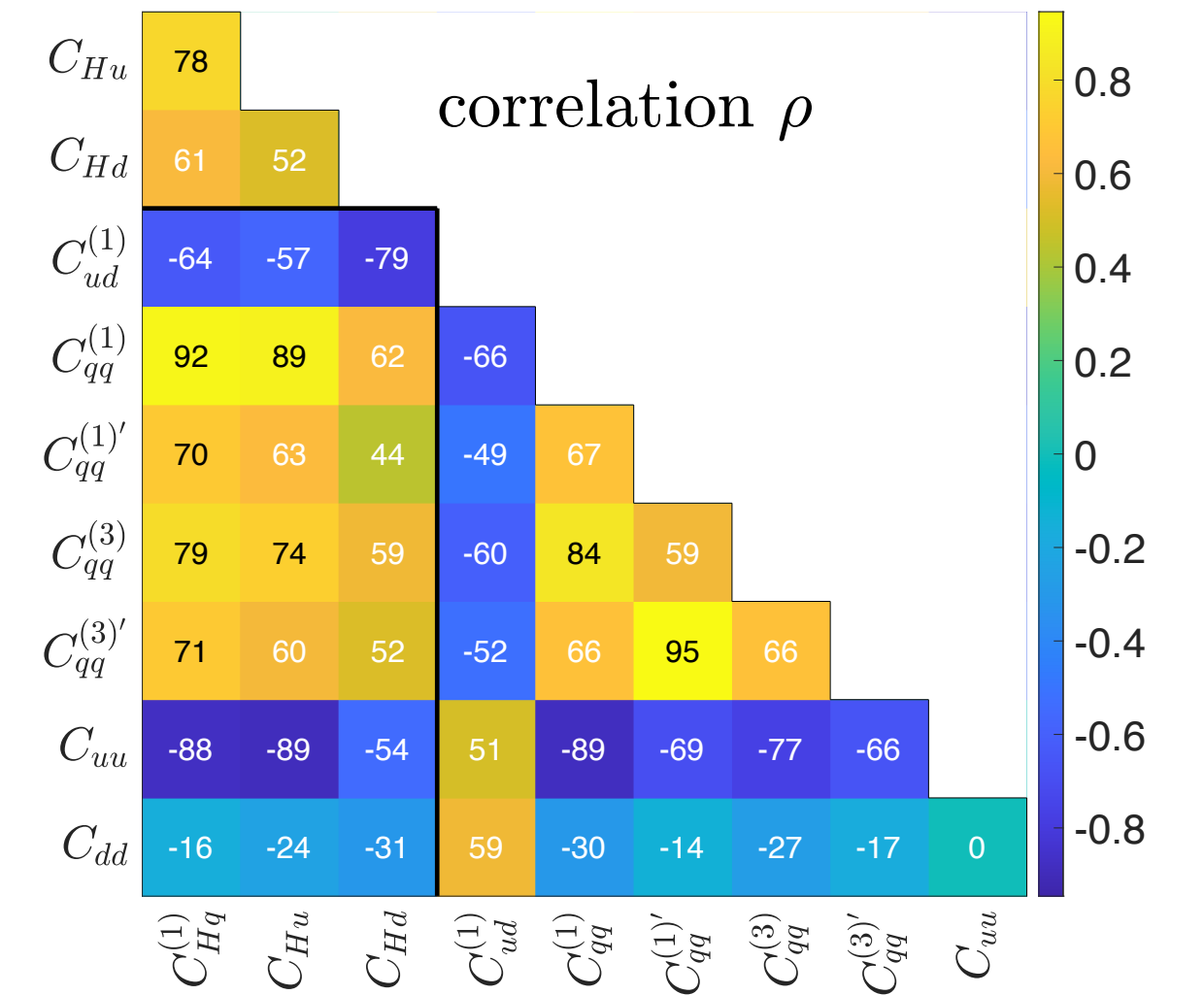


[2412.09674: RB, Biekötter, Hurth]

LO



LO+RGE



Summary and outlook

$U(3)^5$ SMEFT global fit

Under this assumption, all the operators can be bounded without surviving flat directions

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NLO and RGE effects are sizeable for several operators. Their inclusion is needed to have consistent results in global analyses.

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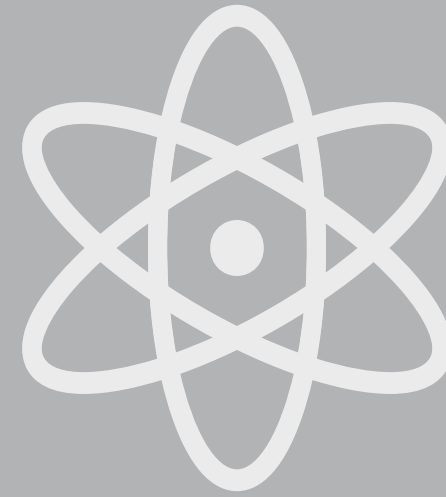
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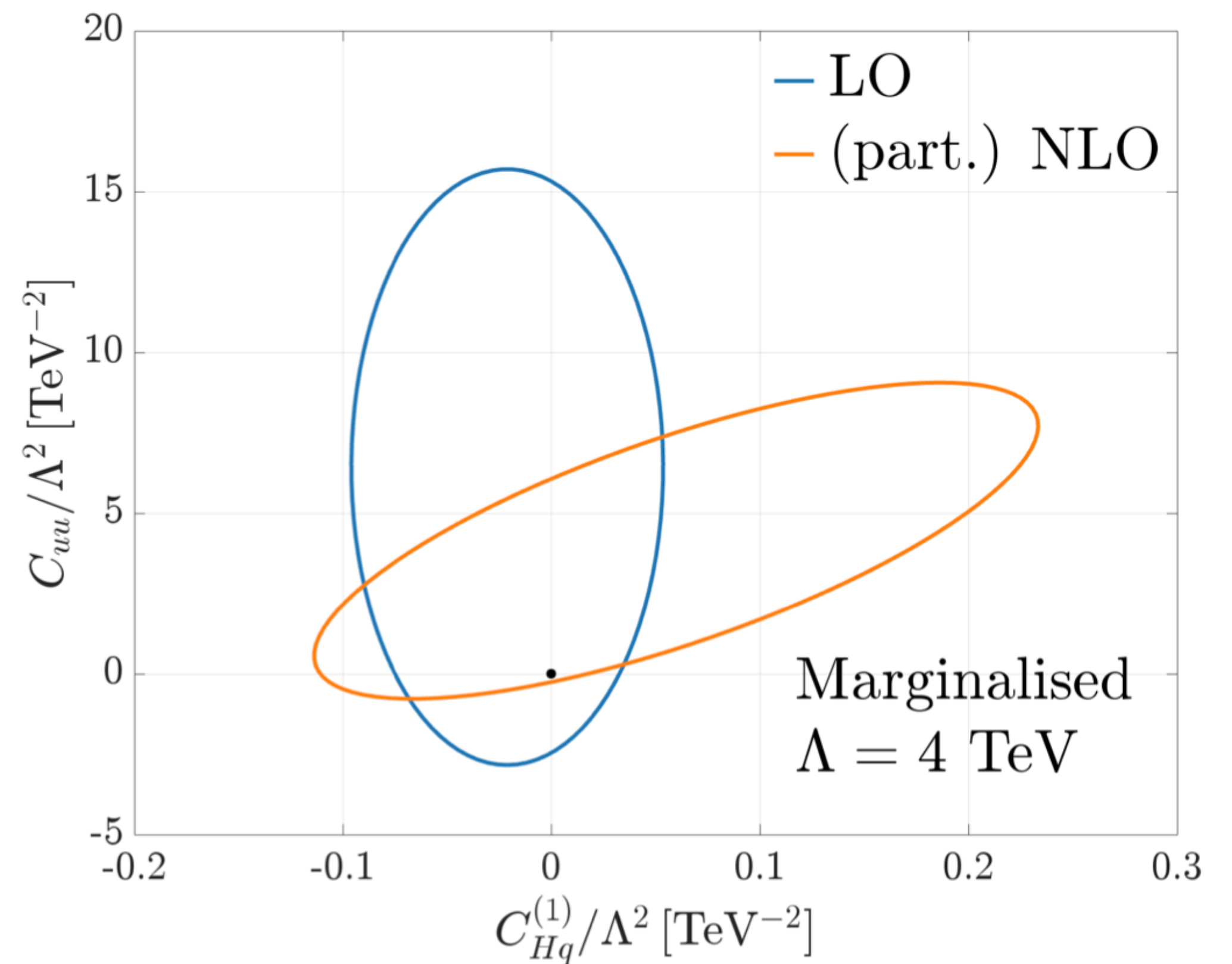
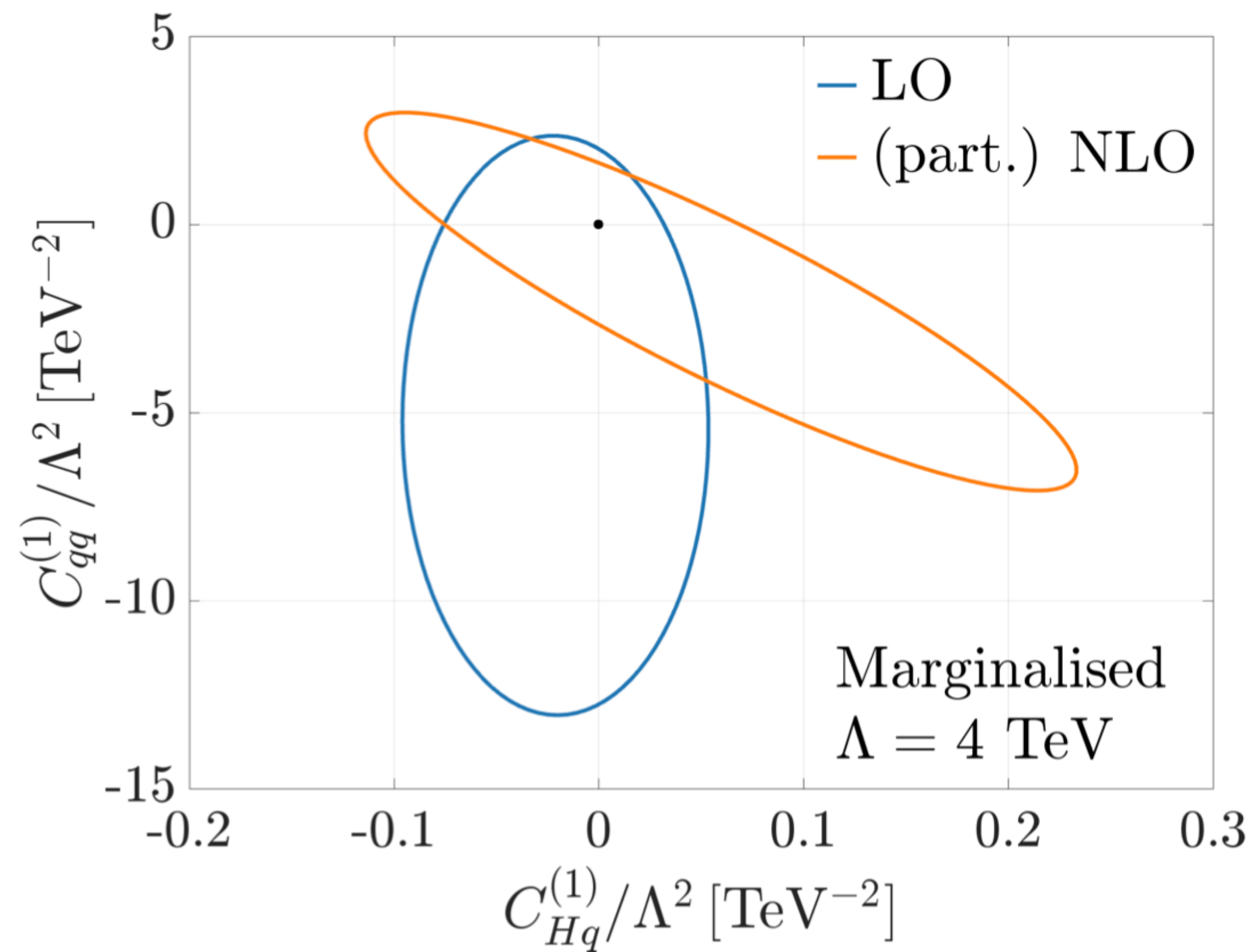
Thank you for your attention!



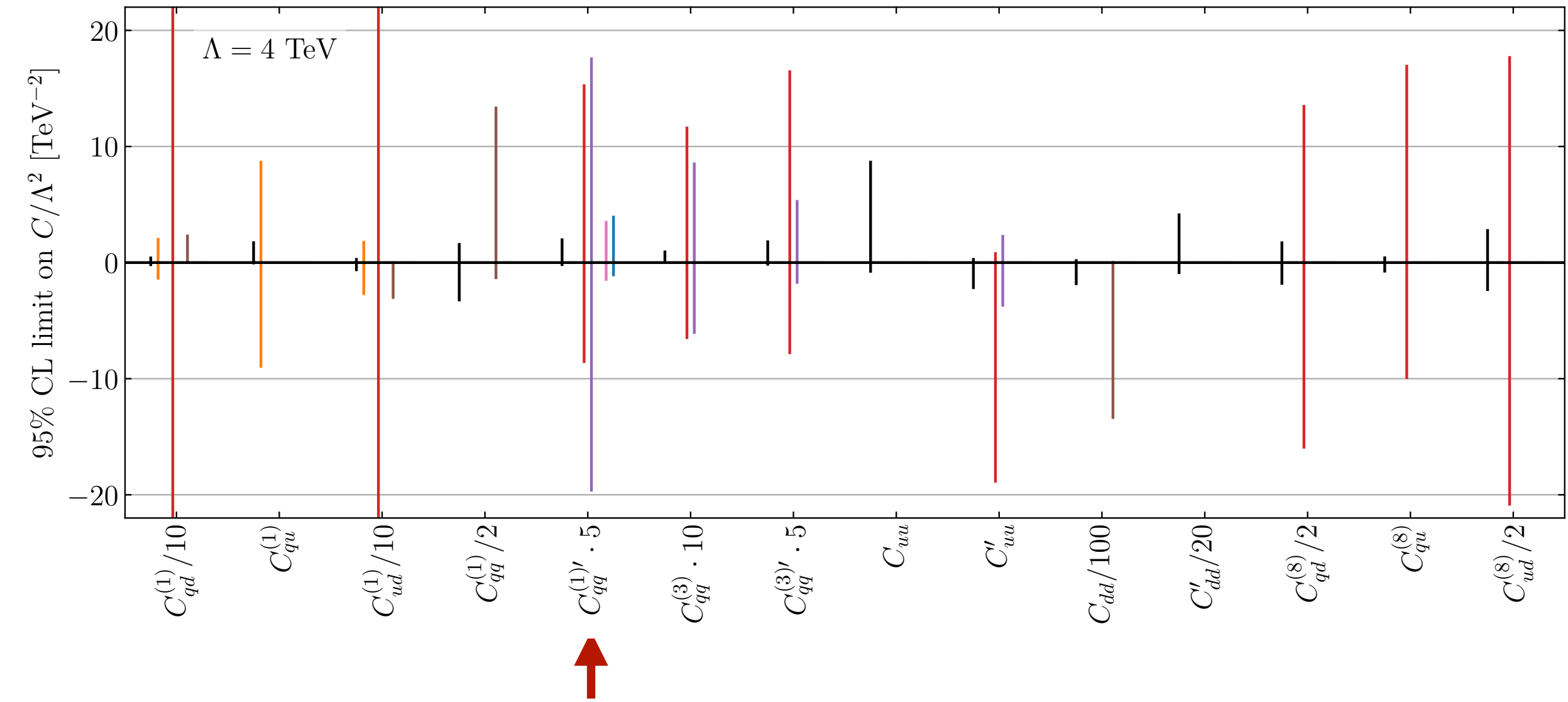
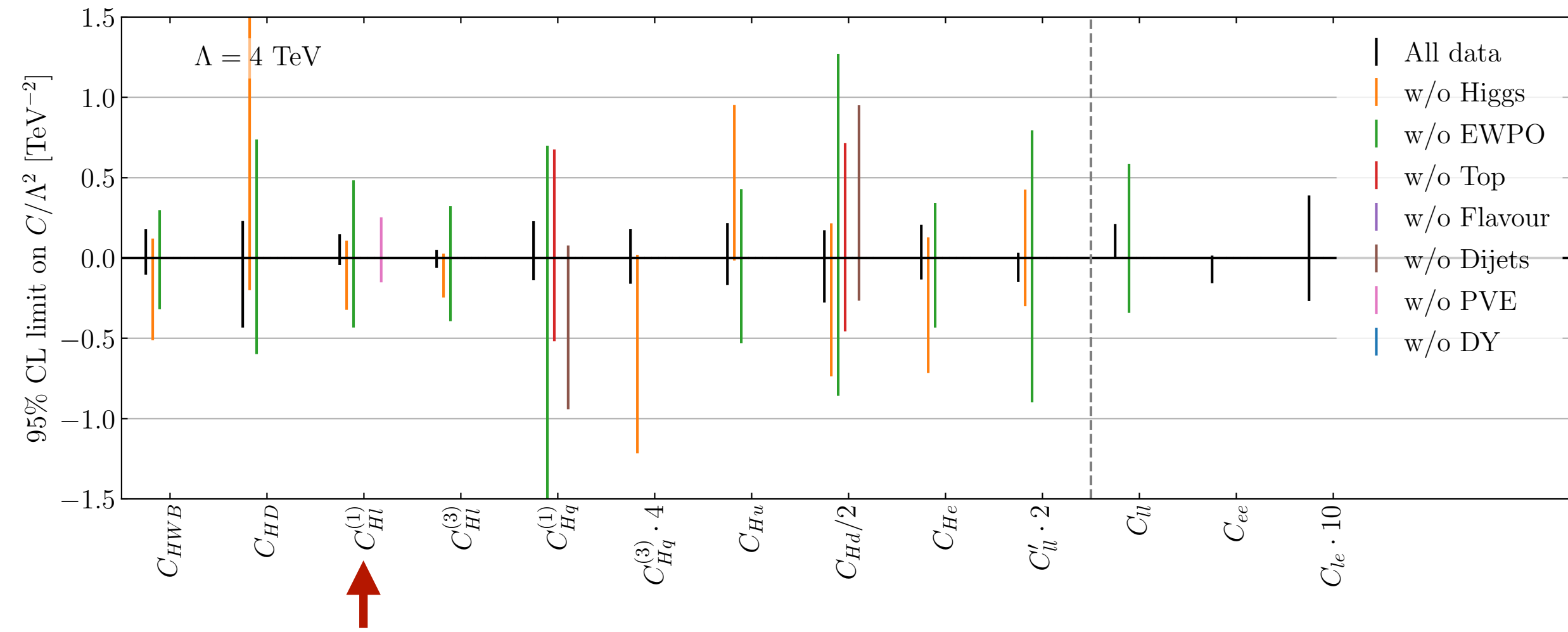
Back up slides

The $C_{Hq}^{(1)}$ case

The only weakened bound with NLO contributions is $C_{Hq}^{(1)}$. At LO there are no visible correlations with four-quark operators, but at NLO there is a strong correlation with C_{uu} and $C_{qq}^{(1)}$ due to EWPO.



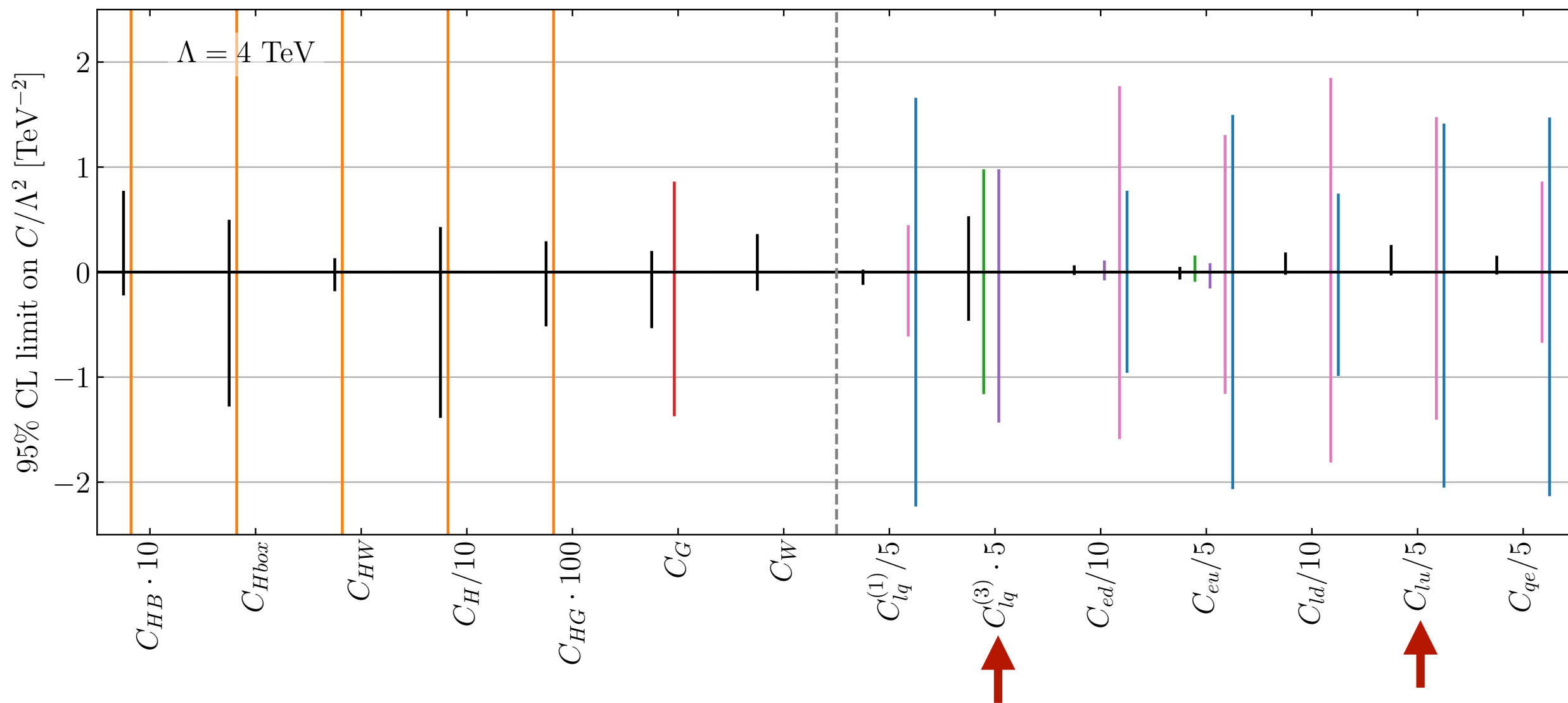
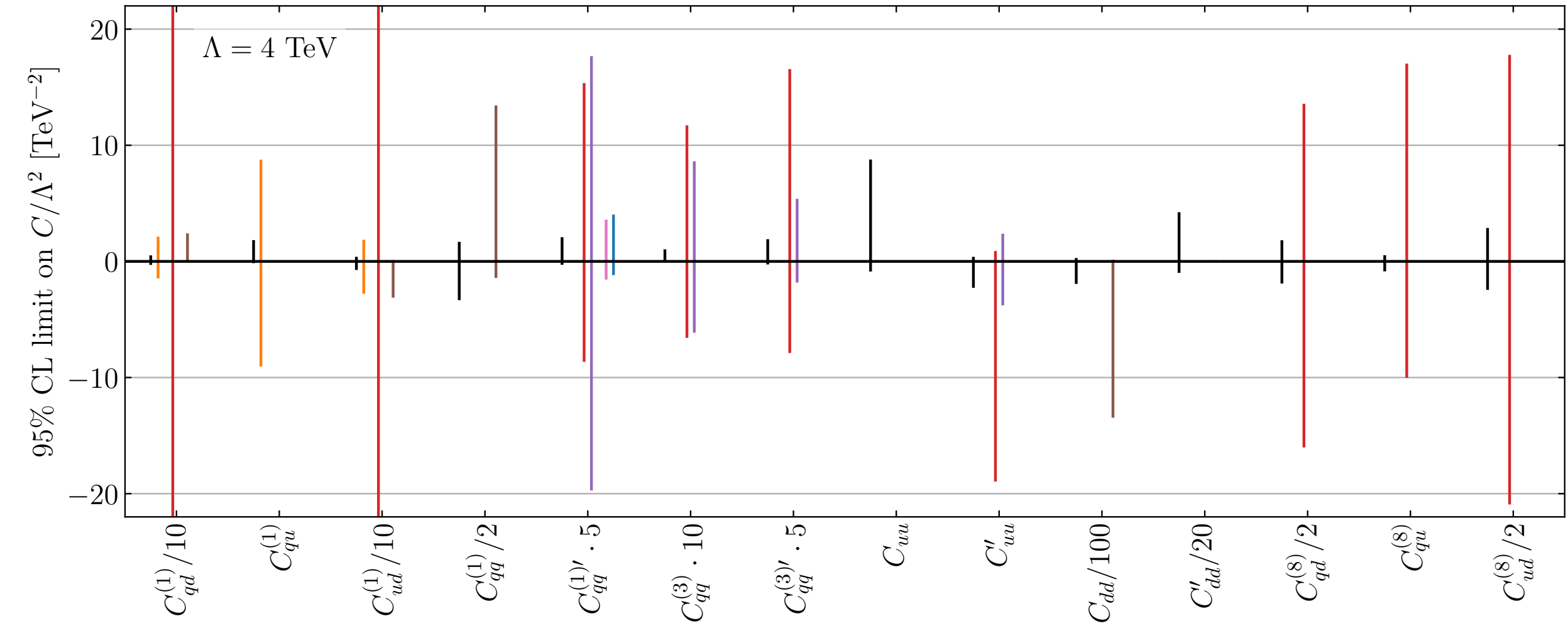
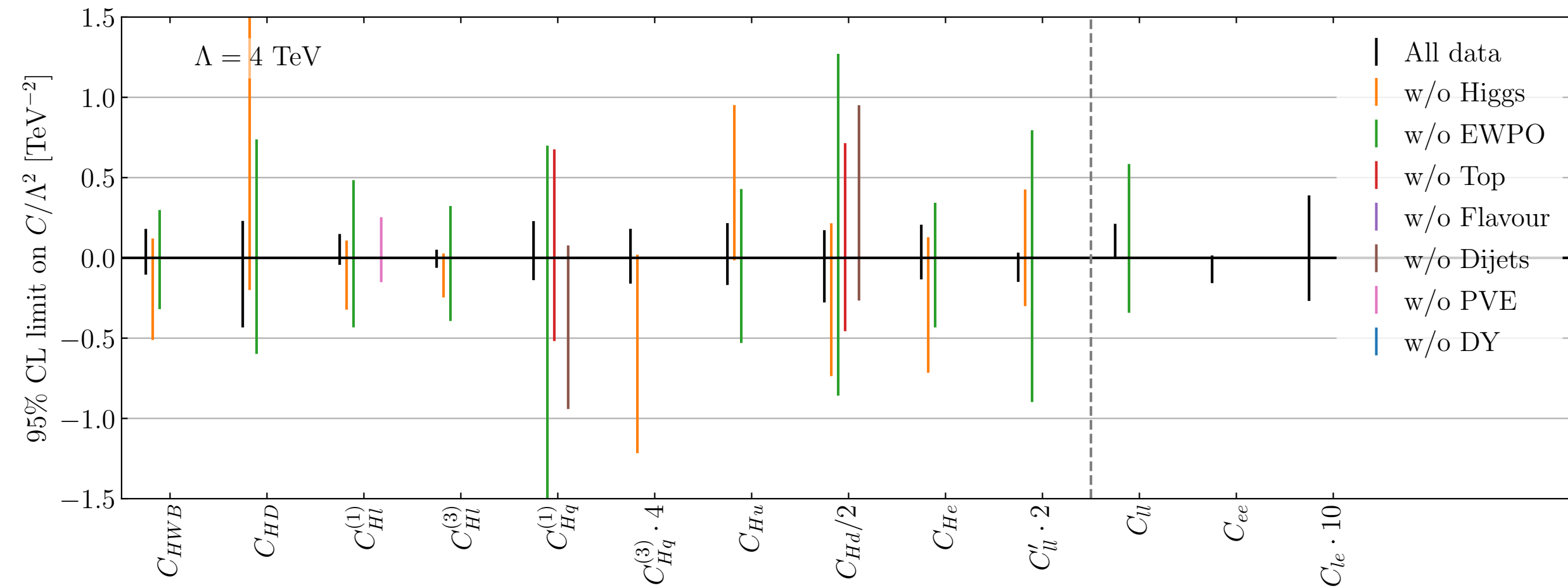
Full results removing datasets



- PVE impact on $C_{Hl}^{(1)}$ and $C_{qq}^{(1)'}$

[2311.04963: RB, Biekötter, Hurth]

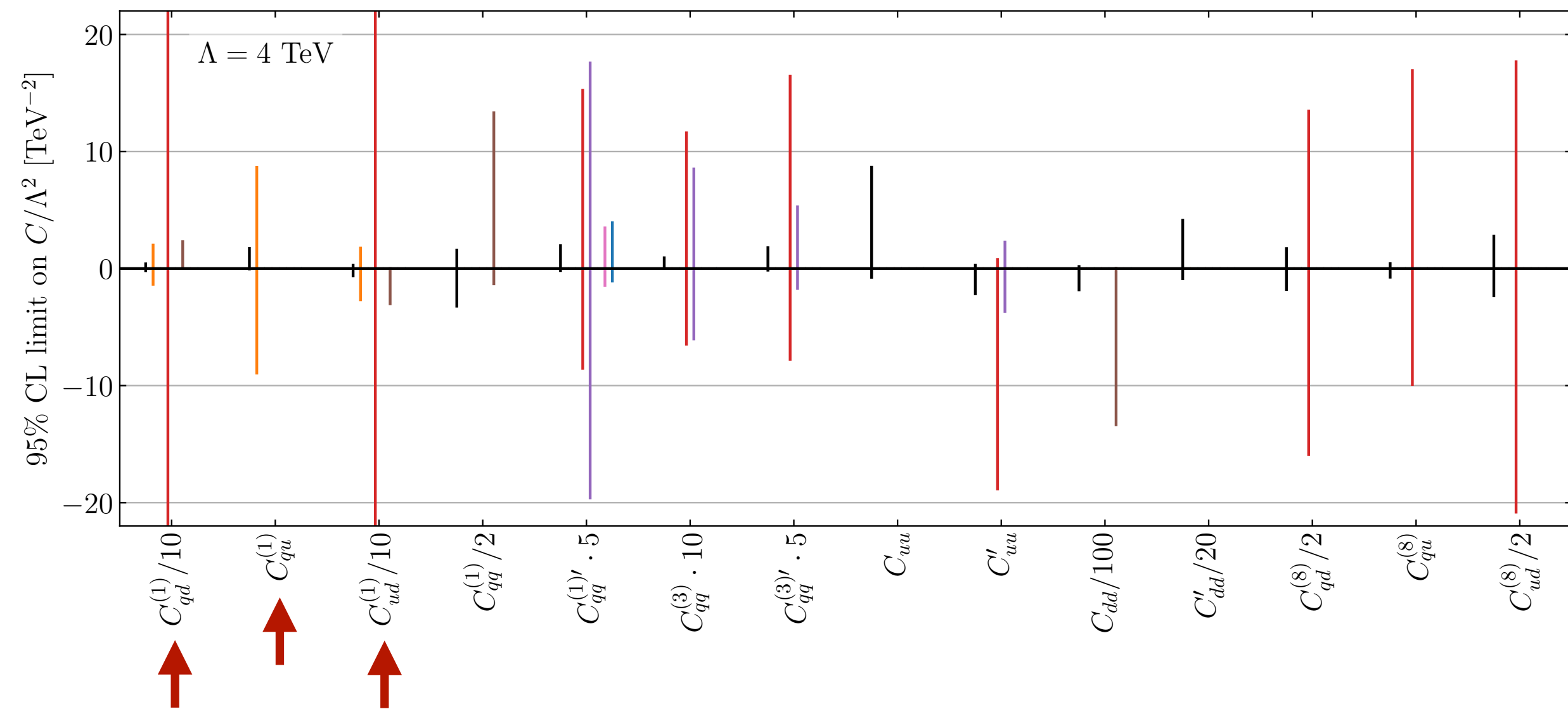
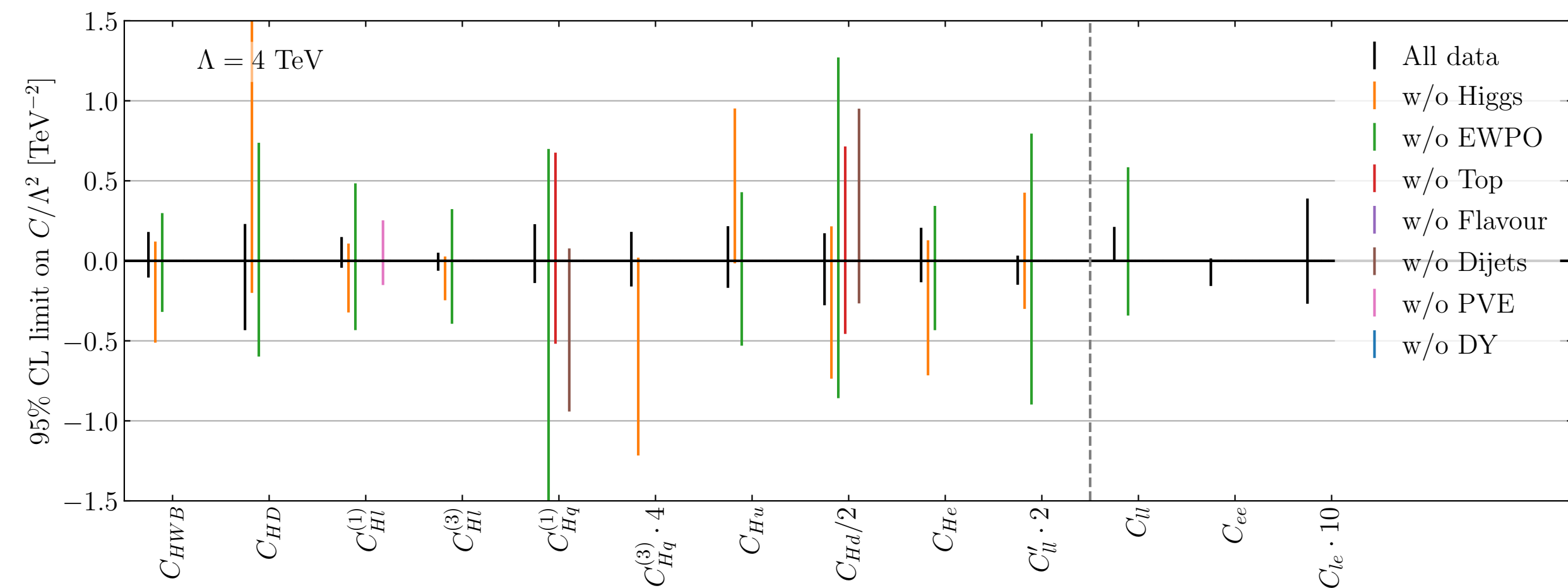
Full results removing datasets



- PVE impact on $C_{Hl}^{(1)}$ and $C_{qq}^{(1)'}$
- NLO EWPO impact on $C_{lq}^{(3)}$ and C_{lu}

[2311.04963: RB, Biekötter, Hurth]

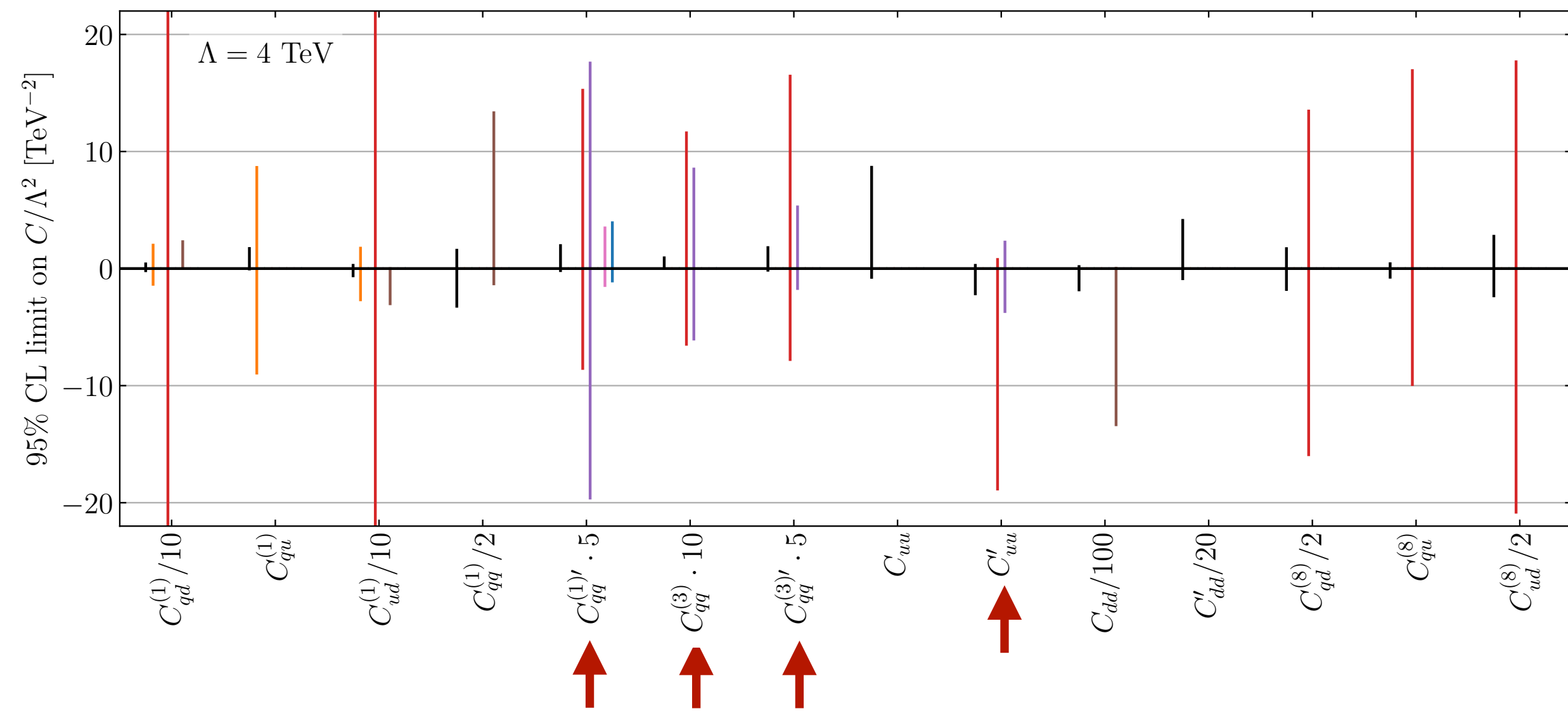
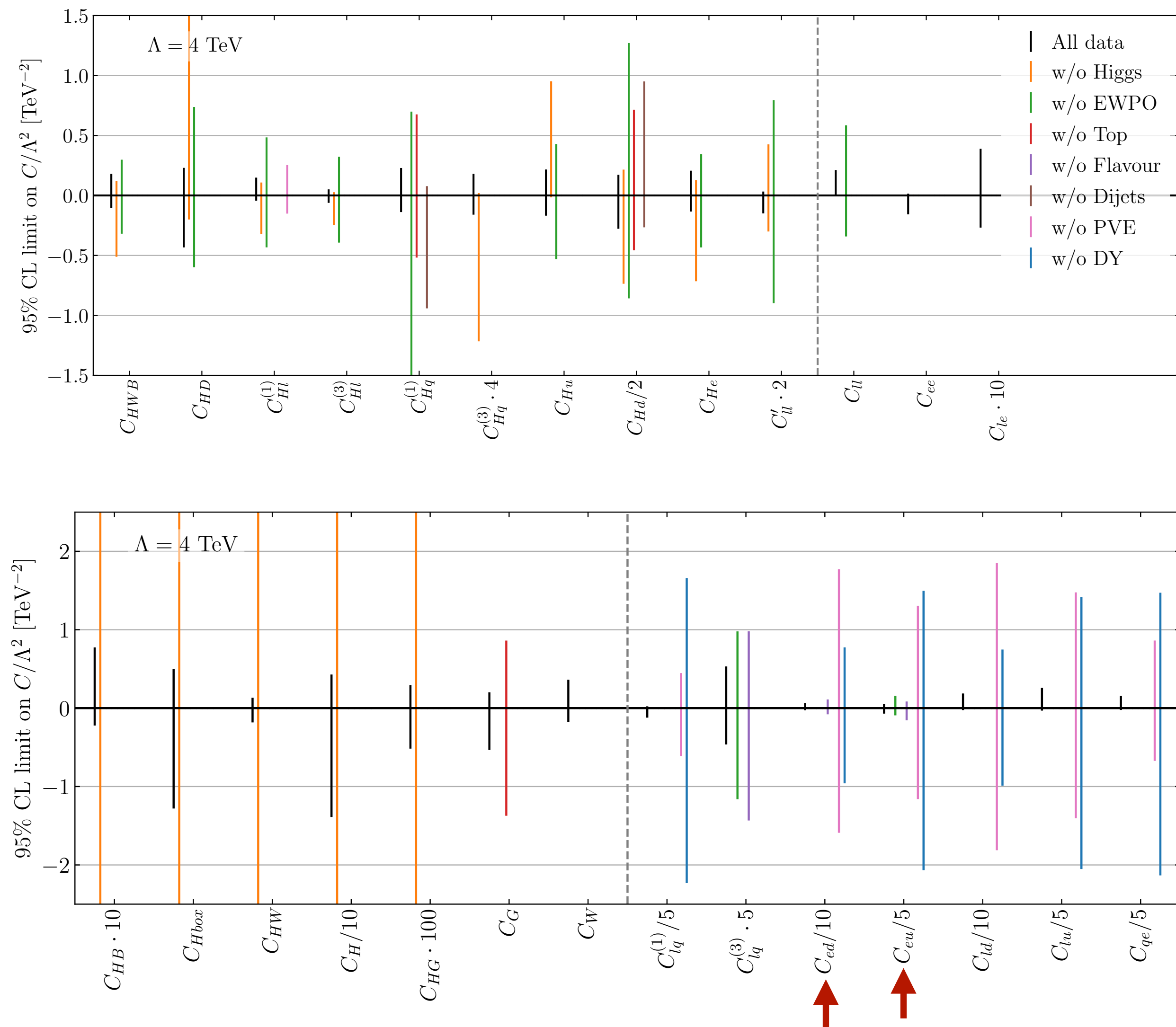
Full results removing datasets



- PVE impact on $C_{Hl}^{(1)}$ and $C_{qq}^{(1)'}$
- NLO EWPO impact on $C_{lq}^{(3)}$ and C_{lu}
- NLO Top and Higgs impact on $C_{qd}^{(1)}$, $C_{qu}^{(1)}$ and $C_{ud}^{(1)}$

[2311.04963: RB, Biekötter, Hurth]

Full results removing datasets

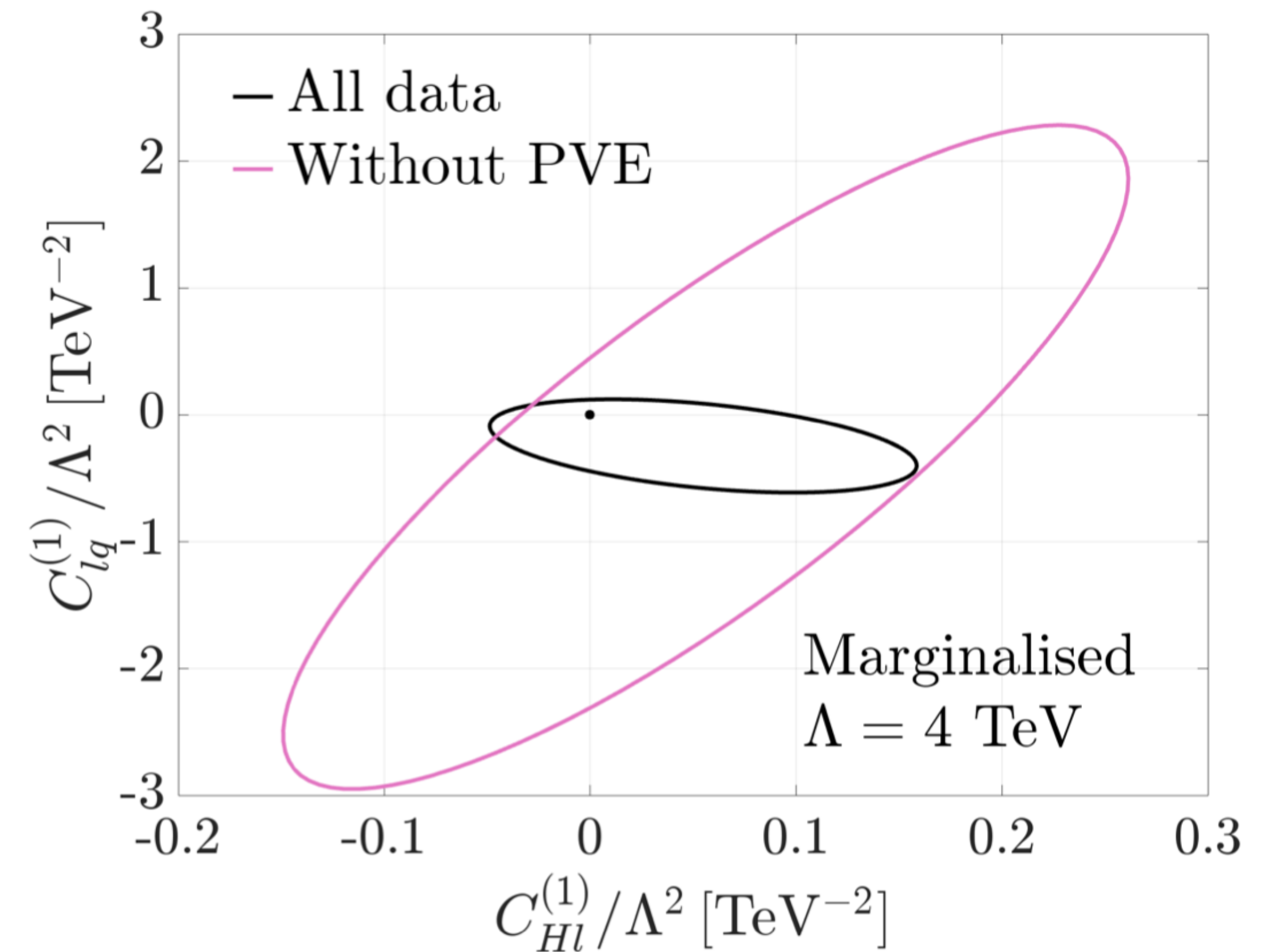
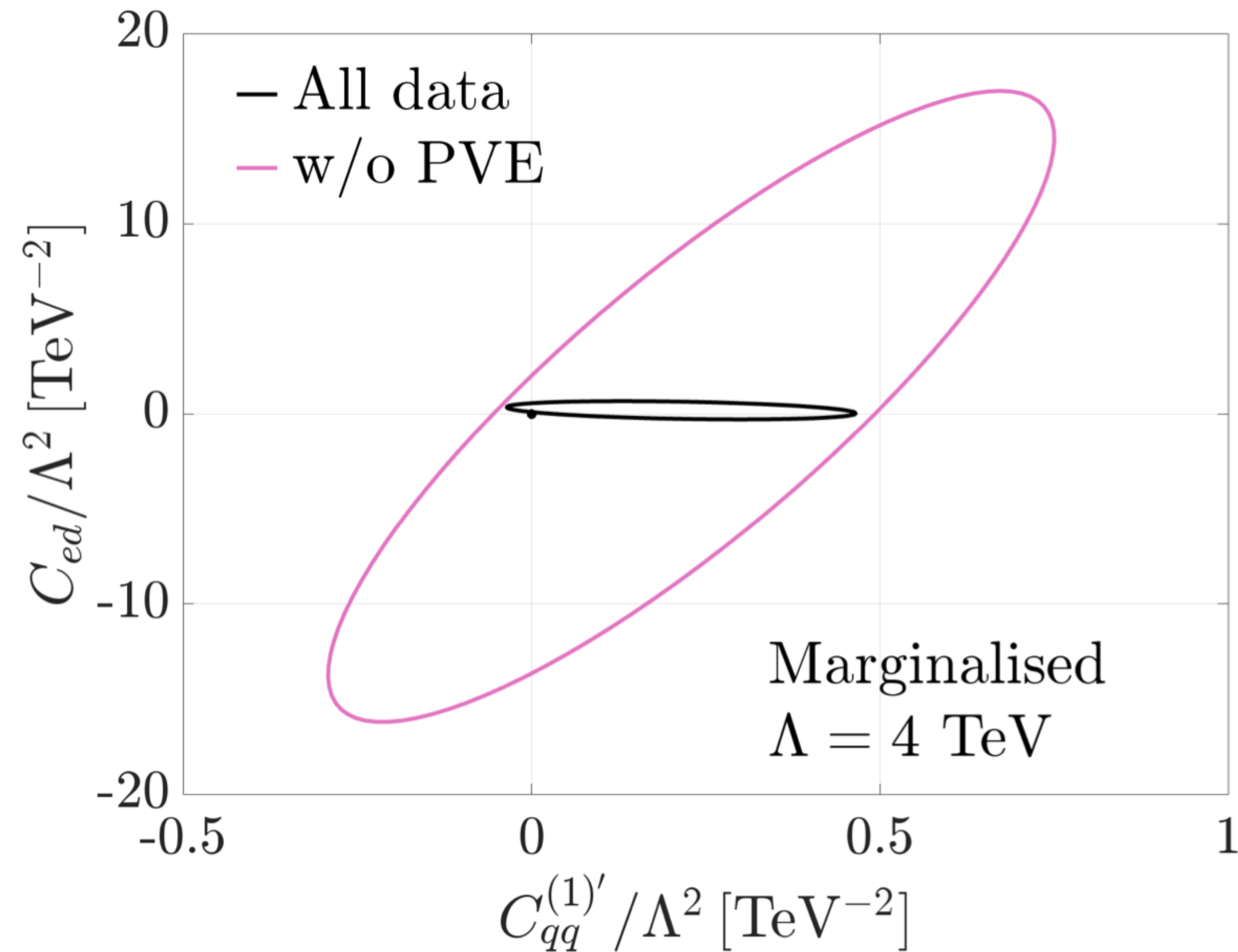


- PVE impact on $C_{Hl}^{(1)}$ and $C_{qq}^{(1)'}$
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- NLO Top and Higgs impact on $C_{qd}^{(1)}$, $C_{qu}^{(1)}$ and $C_{ud}^{(1)}$
- Flavour impact on semi-leptonic and 4-quark operators (more details later)

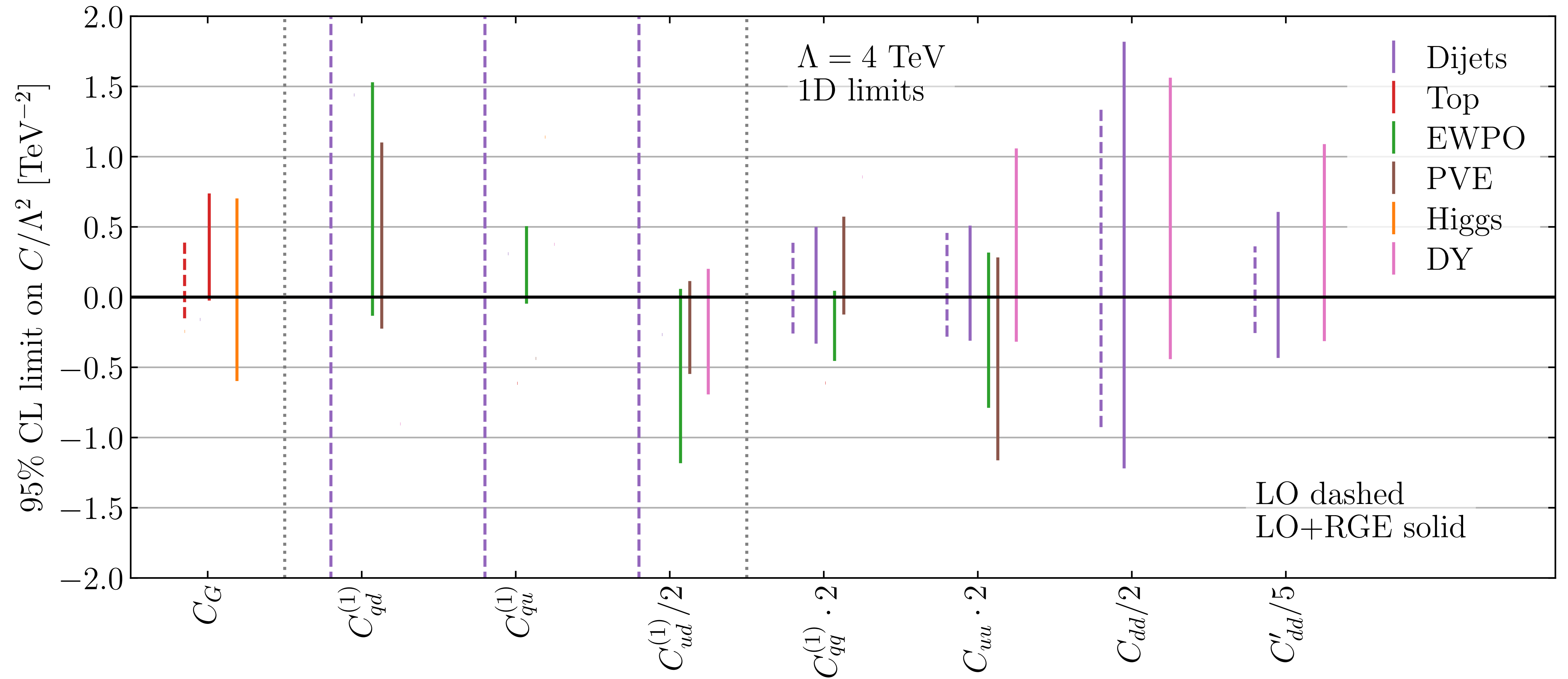
[2311.04963: RB, Biekötter, Hurth]

PVE effects on the global fit

PVE bounds on C_{ed} and $C_{lq}^{(1)}$ lifts the correlation of these operators with $C_{qq}^{(1)'}$ and $C_{Hl}^{(1)}$.



RGE impact on 1D bounds



Warsaw basis

X^3		φ^6 and $\varphi^4 D^2$		$\psi^2 \varphi^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger \varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger \varphi)(\bar{l}_p e_r \varphi)$
$Q_{\tilde{G}}$	$f^{ABC} \tilde{G}_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger \varphi)\Box(\varphi^\dagger \varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger \varphi)(\bar{q}_p u_r \tilde{\varphi})$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$(\varphi^\dagger D^\mu \varphi)^* (\varphi^\dagger D_\mu \varphi)$	$Q_{d\varphi}$	$(\varphi^\dagger \varphi)(\bar{q}_p d_r \varphi)$
$Q_{\tilde{W}}$	$\varepsilon^{IJK} \tilde{W}_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				
$X^2 \varphi^2$		$\psi^2 X \varphi$		$\psi^2 \varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger \varphi G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eW}	$(\bar{l}_p \sigma^{\mu\nu} e_r) \tau^I \varphi W_{\mu\nu}^I$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{l}_p \gamma^\mu l_r)$
$Q_{\varphi \tilde{G}}$	$\varphi^\dagger \varphi \tilde{G}_{\mu\nu}^A G^{A\mu\nu}$	Q_{eB}	$(\bar{l}_p \sigma^{\mu\nu} e_r) \varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu^I \varphi)(\bar{l}_p \tau^I \gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger \varphi W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uG}	$(\bar{q}_p \sigma^{\mu\nu} T^A u_r) \tilde{\varphi} G_{\mu\nu}^A$	$Q_{\varphi e}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{e}_p \gamma^\mu e_r)$
$Q_{\varphi \tilde{W}}$	$\varphi^\dagger \varphi \tilde{W}_{\mu\nu}^I W^{I\mu\nu}$	Q_{uW}	$(\bar{q}_p \sigma^{\mu\nu} u_r) \tau^I \tilde{\varphi} W_{\mu\nu}^I$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{q}_p \gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger \varphi B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar{q}_p \sigma^{\mu\nu} u_r) \tilde{\varphi} B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu^I \varphi)(\bar{q}_p \tau^I \gamma^\mu q_r)$
$Q_{\varphi \tilde{B}}$	$\varphi^\dagger \varphi \tilde{B}_{\mu\nu} B^{\mu\nu}$	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}	$(\bar{q}_p \sigma^{\mu\nu} d_r) \varphi B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\tilde{\varphi}^\dagger D_\mu \varphi)(\bar{u}_p \gamma^\mu d_r)$

$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
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}	$(\bar{l}_p \gamma_\mu l_r)(\bar{e}_s \gamma^\mu e_t)$
$Q_{qq}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{q}_s \gamma^\mu q_t)$	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}	$(\bar{e}_p \gamma_\mu e_r)(\bar{d}_s \gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{u}_s \gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar{u}_p \gamma_\mu u_r)(\bar{d}_s \gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar{q}_p \gamma_\mu T^A q_r)(\bar{u}_s \gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar{u}_p \gamma_\mu T^A u_r)(\bar{d}_s \gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{d}_s \gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar{q}_p \gamma_\mu T^A q_r)(\bar{d}_s \gamma^\mu T^A d_t)$
$(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$		B -violating			
Q_{ledq}	$(\bar{l}_p^j e_r)(\bar{d}_s^j q_t^j)$	Q_{duq}	$\varepsilon^{\alpha\beta\gamma} \varepsilon_{jk} [(d_p^\alpha)^T C u_r^\beta] [(q_s^{\gamma j})^T C l_t^k]$		
$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r) \varepsilon_{jk} (\bar{q}_s^k d_t)$	Q_{qqu}	$\varepsilon^{\alpha\beta\gamma} \varepsilon_{jk} [(q_p^{\alpha j})^T C q_r^{\beta k}] [(u_s^\gamma)^T C e_t]$		
$Q_{quqd}^{(8)}$	$(\bar{q}_p^j T^A u_r) \varepsilon_{jk} (\bar{q}_s^k T^A d_t)$	Q_{qqq}	$\varepsilon^{\alpha\beta\gamma} \varepsilon_{jn} \varepsilon_{km} [(q_p^{\alpha j})^T C q_r^{\beta k}] [(q_s^{\gamma m})^T C l_t^n]$		
$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r) \varepsilon_{jk} (\bar{q}_s^k u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma} [(d_p^\alpha)^T C u_r^\beta] [(u_s^\gamma)^T C e_t]$		
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j \sigma_{\mu\nu} e_r) \varepsilon_{jk} (\bar{q}_s^k \sigma^{\mu\nu} u_t)$				

Global analyses in the SMEFT

Many different global analyses have been performed:

Combinations:

[arXiv:2304.12837: Grunwald, Hiller, Kröninger, Nollen]

[arXiv:1909.13632: Bißmann, Erdmann, Grunwald, Hiller, Kröninger]

[arXiv:2012.02779: Ellis, Madigan, Mimasu, Sanz, You]

[arXiv:2105.00006: Ethier et al.]

Low energy:

[1706.03783: Falkowski, González-Alonso, Mimouni]

Higgs-EW:

[1812.07587: Biekötter, Corbett, Plehn]

[1908.03952: Kraml, Quang Loc, Thi Nhung, Duc Ninh]

[2007.01296: Dawson, Homiller, D. Lane]

[2007.01296: Eduardo da Silva Almeida, et al.]

Top:

[arXiv:1512.03360: Andy Buckley, et al.]

[arXiv:1802.07237: J. A. Aguilar Saavedra, et al.]

[arXiv:1910.03606: I. Brivio, et al.]

[arXiv:2212.05067: Brivio et al.]

Flavour:

[arXiv:2101.07273: Bruggisser, Schäfer, van Dyk, Westhoff]

[arXiv:2003.05432: Aoude, Hurth, Renner, Shepherd]

Experiments:

ATL-PHYS-PUB-2022-037

CMS-PAS-SMP-24-003

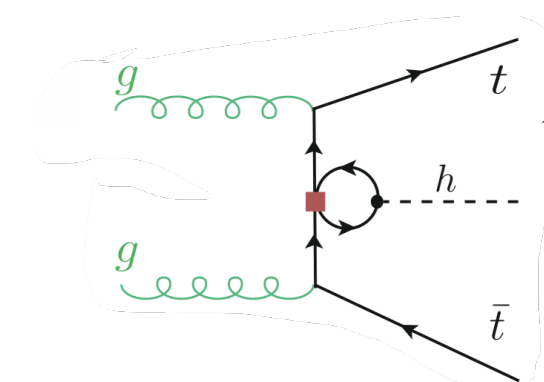
and many others...

In particular in this talk:

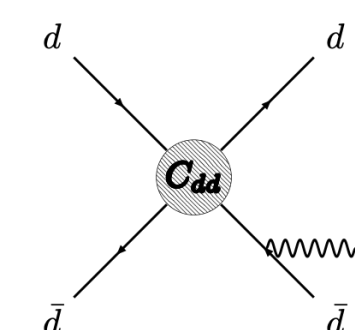
- The operator selection comes purely from symmetry assumptions

$$U(3)^5 = U(3)_\ell \times U(3)_q \times U(3)_e \times U(3)_u \times U(3)_d$$

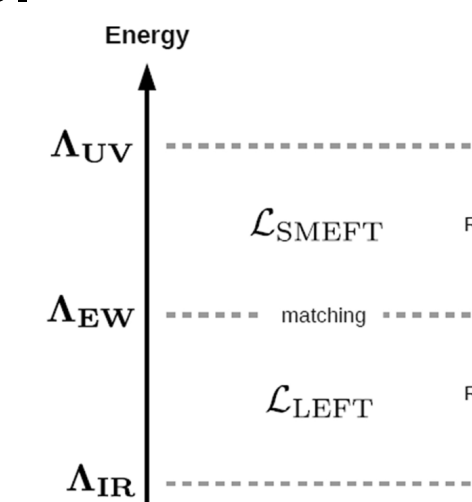
- Inclusion of NLO observables in a global fit without flat directions



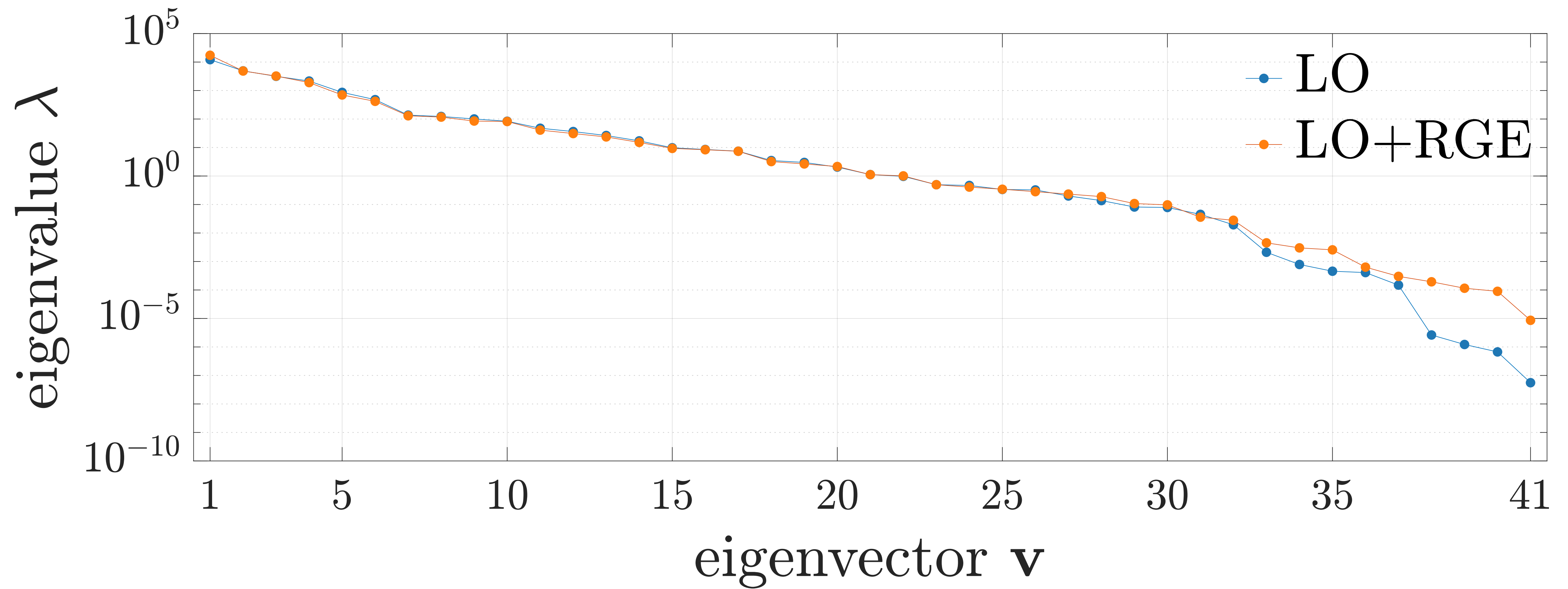
- Inclusion of dijet observables below 1.1 TeV



- Inclusion of RGE effects in global analysis.



Principal component analysis



Flavour symmetris in the SMEFT

Class	Operators	No symmetry				$U(3)^5$					
		3 Gen.		1 Gen.		Exact		$\mathcal{O}(Y_{e,d,u}^1)$		$\mathcal{O}(Y_e^1, Y_d^1 Y_u^2)$	
1–4	$X^3, H^6, H^4 D^2, X^2 H^2$	9	6	9	6	9	6	9	6	9	6
5	$\psi^2 H^3$	27	27	3	3	–	–	3	3	4	4
6	$\psi^2 X H$	72	72	8	8	–	–	8	8	11	11
7	$\psi^2 H^2 D$	51	30	8	1	7	–	7	–	11	1
8	$(\bar{L}L)(\bar{L}L)$	171	126	5	–	8	–	8	–	14	–
	$(\bar{R}R)(\bar{R}R)$	255	195	7	–	9	–	9	–	14	–
	$(\bar{L}L)(\bar{R}R)$	360	288	8	–	8	–	8	–	18	–
	$(\bar{L}R)(\bar{R}L)$	81	81	1	1	–	–	–	–	–	–
	$(\bar{L}R)(\bar{L}R)$	324	324	4	4	–	–	–	–	4	4
total:		1350	1149	53	23	41	6	52	17	85	26

Table 1: Number of independent operators in $U(3)^5$, MFV and without symmetry. In each column the left (right) number corresponds to the number of CP-even (CP-odd) coefficients. $\mathcal{O}(X^n)$ stands for including terms up to $\mathcal{O}(X^n)$.

[2005.05366: Faroughy, Isidori, Wilsch, Yamamoto]

Models compatible with our assumption

These scalar extensions of the SM match at 1-loop only on flavour symmetric operators:

Complex colour sextet, isospin singlet: $\chi_3 \equiv (6_C, 1_L, -\frac{2}{3}|_Y)$

$$\mathcal{L}_{\chi_3} = \mathcal{L}_{\text{SM}}^{d \leq 4} + (D_\mu \chi_3)^\dagger (D^\mu \chi_3) - m_{\chi_3}^2 \chi_3^\dagger \chi_3 - \eta_{\chi_3} H^\dagger H \chi_3^\dagger \chi_3 - \lambda_{\chi_3} (\chi_3^\dagger \chi_3)^2 \\ - \left\{ y_{\chi_3} \left(d_R^{\{A\}} \right)^T C (\chi_3^{AB})^\dagger d_R^{\{B\}} + \text{h.c.} \right\} \quad \square$$

Complex Singlet: $\mathcal{S}_2 \equiv (1_C, 1_L, 2|_Y)$

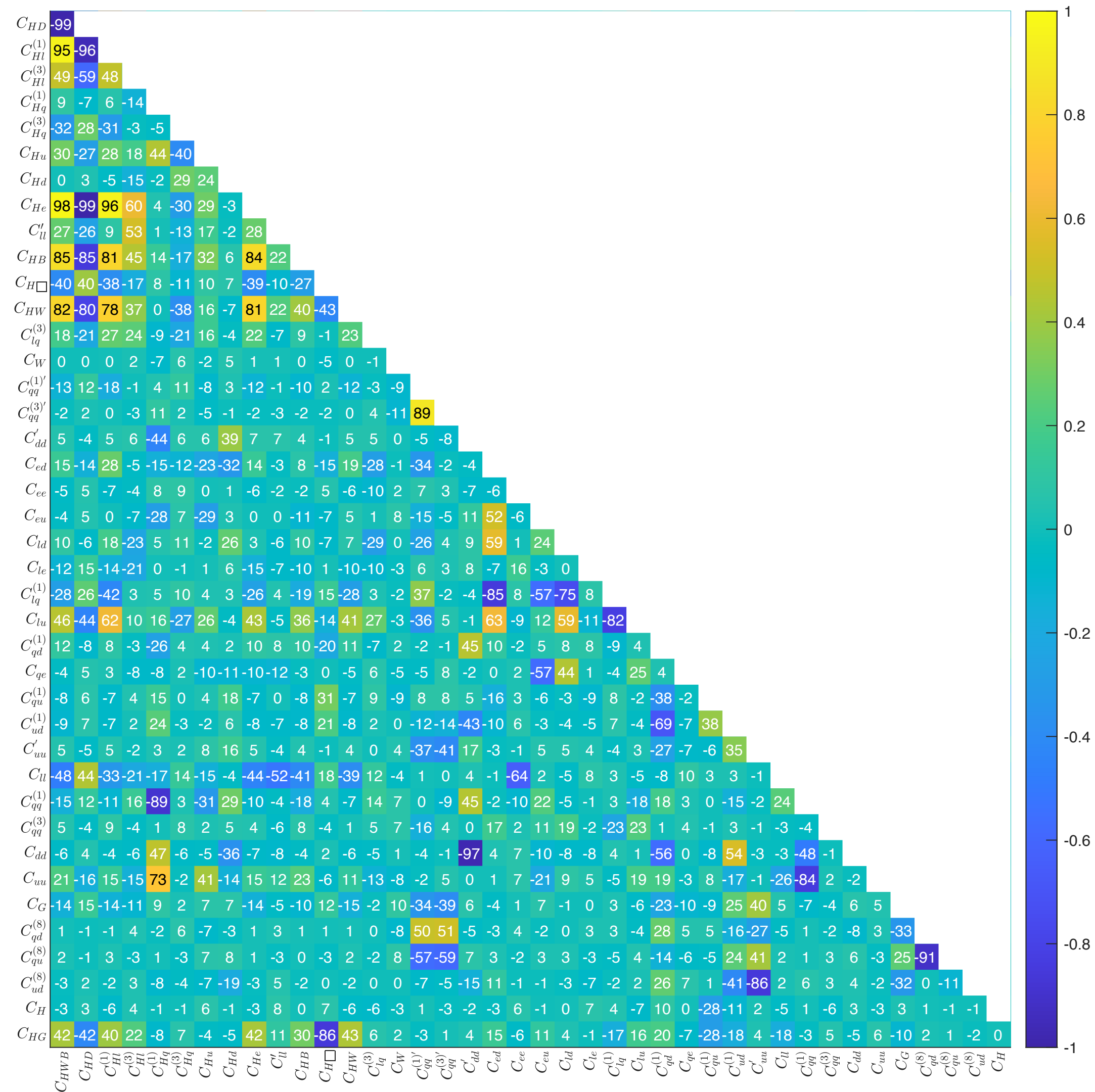
$$\mathcal{L}_{\mathcal{S}_2} = \mathcal{L}_{\text{SM}}^{d \leq 4} + (D_\mu \mathcal{S}_2)^\dagger (D^\mu \mathcal{S}_2) - m_{\mathcal{S}_2}^2 \mathcal{S}_2^\dagger \mathcal{S}_2 - \eta_{\mathcal{S}_2} |H|^2 |\mathcal{S}_2|^2 - \lambda_{\mathcal{S}_2} |\mathcal{S}_2|^4 \\ - \left\{ y_{\mathcal{S}_2} e_R^T C e_R \mathcal{S}_2 + \text{h.c.} \right\} \quad \square$$

Complex colour triplet, isospin singlet: $\varphi_2 \equiv (3_C, 1_L, -\frac{4}{3}|_Y)$

$$\mathcal{L}_{\varphi_2} = \mathcal{L}_{\text{SM}}^{d \leq 4} + (D_\mu \varphi_2)^\dagger (D^\mu \varphi_2) - m_{\varphi_2}^2 \varphi_2^\dagger \varphi_2 - \eta_{\varphi_2} H^\dagger H \varphi_2^\dagger \varphi_2 - \lambda_{\varphi_2} (\varphi_2^\dagger \varphi_2)^2 \\ + \left\{ y_{\varphi_2} \varphi_2^{\alpha\dagger} d_R^{\alpha T} C e_R + \text{h.c.} \right\} \quad \square$$

[arXiv:2111.05876: Anisha, Das Bakshi, Banerjee, Biekötter, Chakraborty, Patra, Spannowsky]

Correlation matrix



Full LO vs NLO results

