Cluster of Excellence PRISMA+ Precision Physics, Fundamental Interactions and Structure of Matter

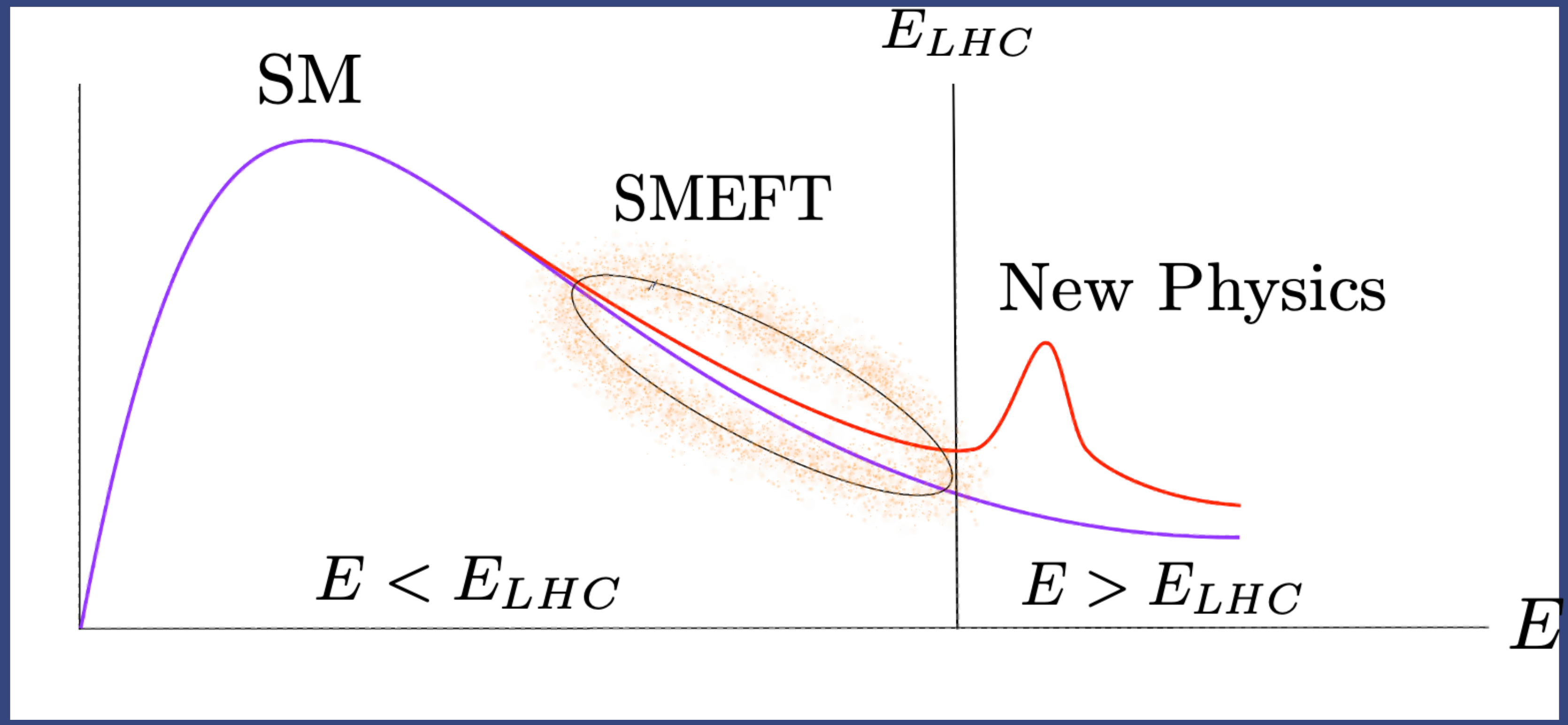
Mainz Institute for Theoretical Physics

DISCRETE 2024 in Ljubljana

Advancing SMEFT Global Analyses

RGE effects and flavour physics

In collaboration with Anke Biekötter and Tobias Hurth (arxiv:2311.04963)



DISCRETE 2024, Ljubljana, 4 December 2024

Riccardo Bartocci - JGU Mainz

Outline

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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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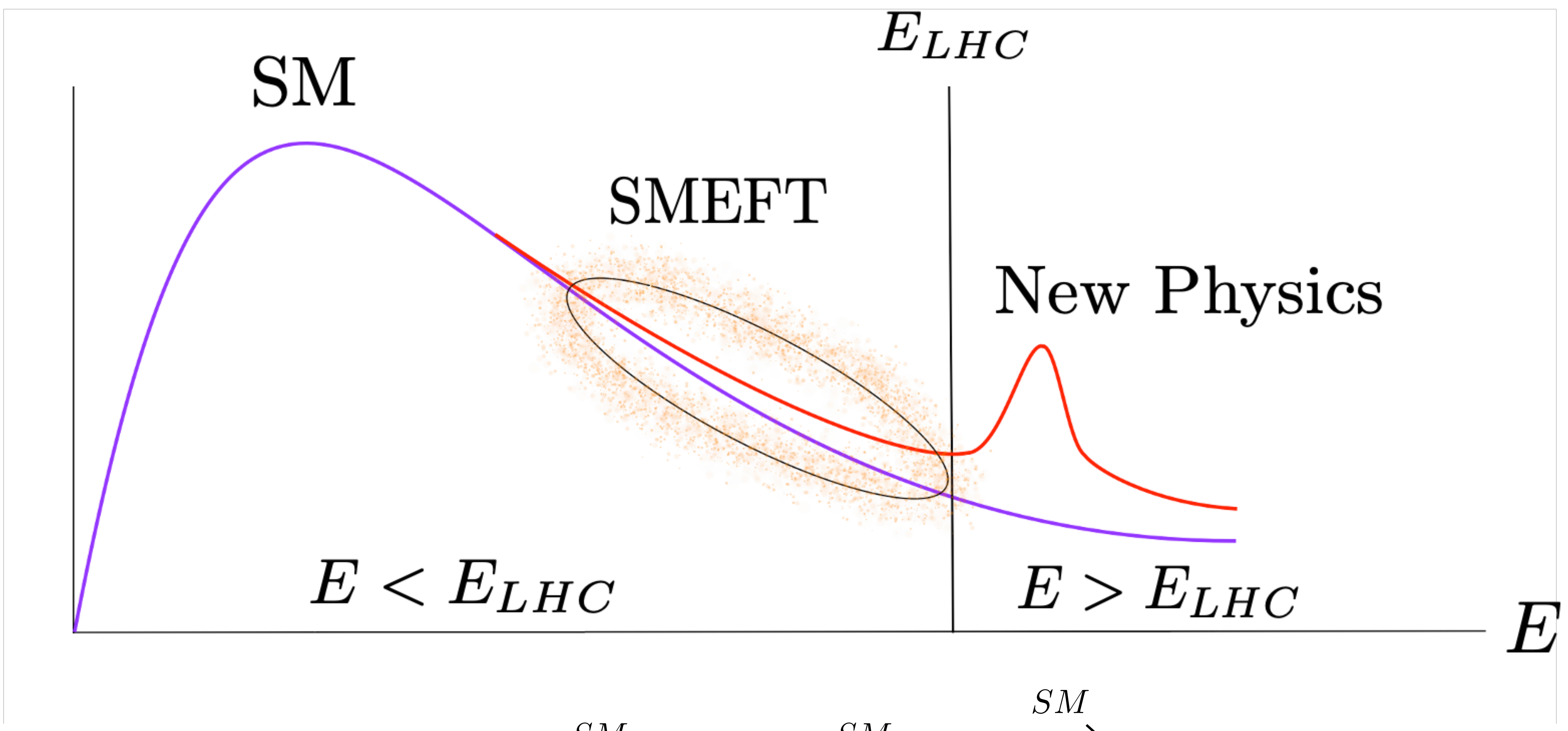
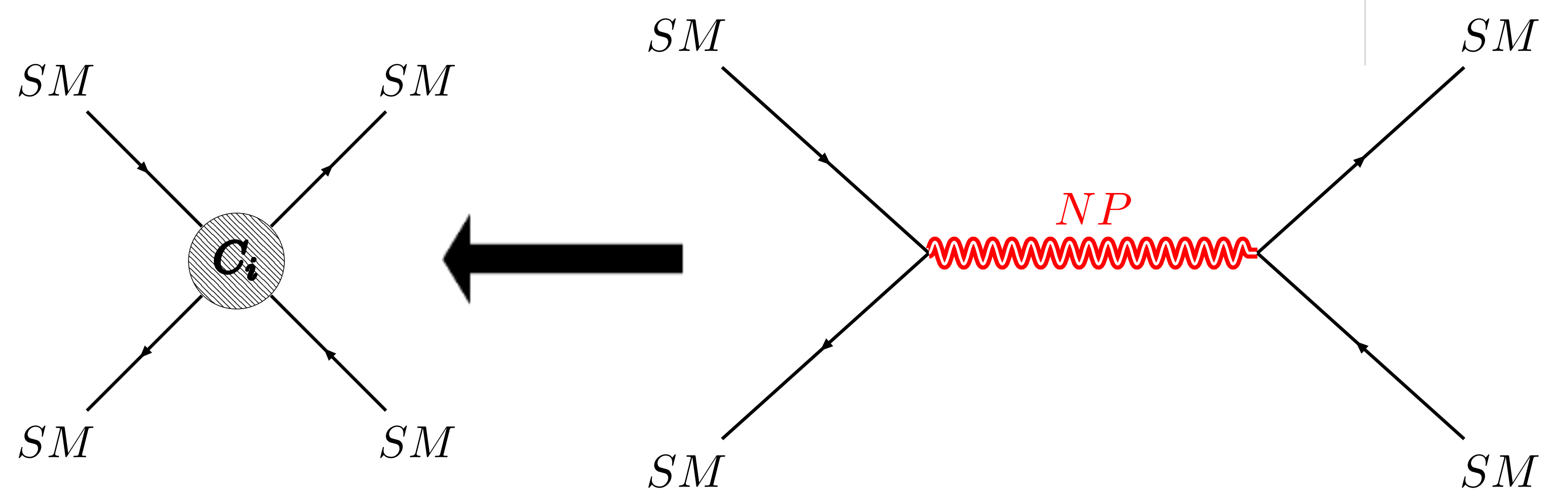
3. RGE effects on the global analysis

Global analyses in the flavour symmetric SMEFT

SMEFT and flavour symmetry





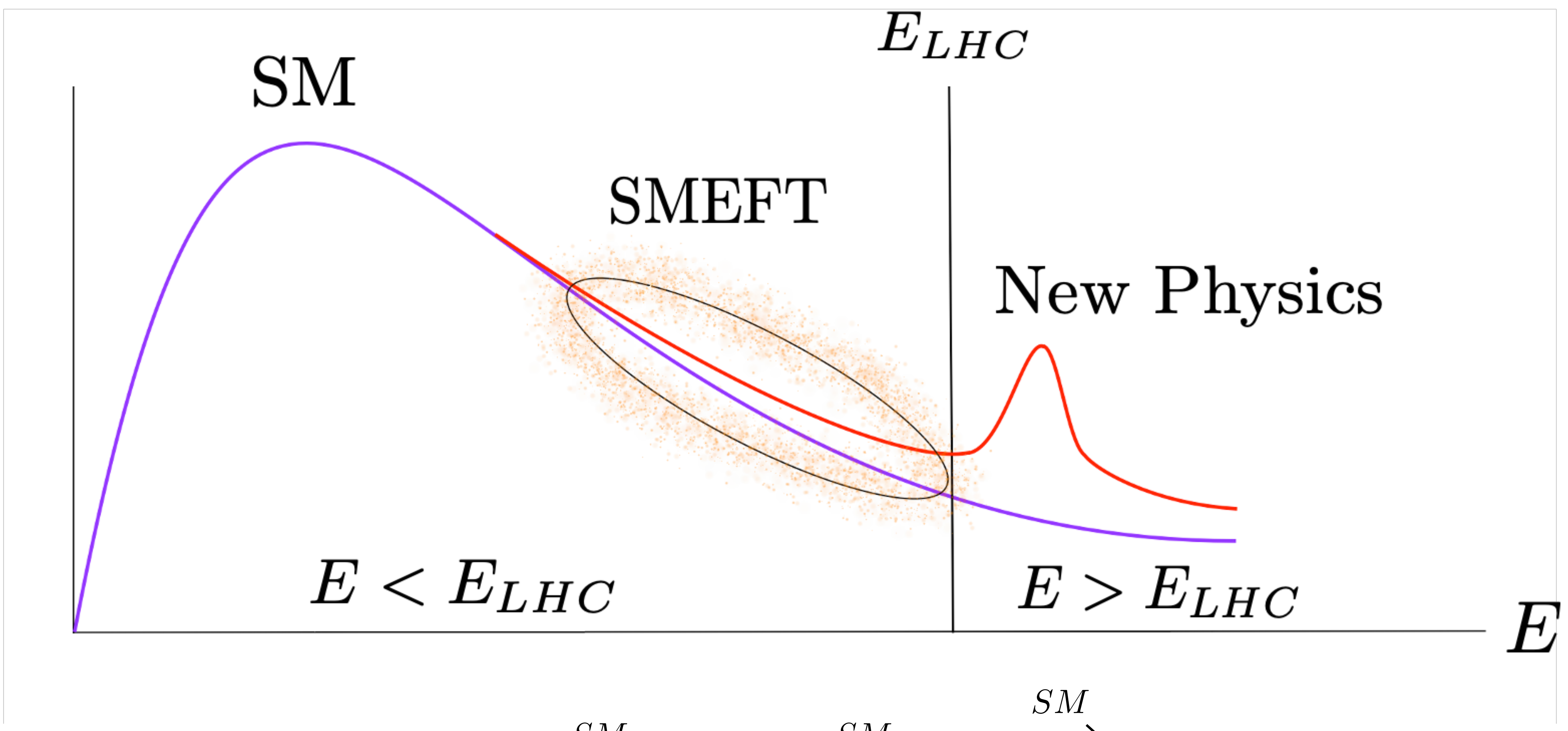
SMEFT: EFT for heavy NP model-agnostic study

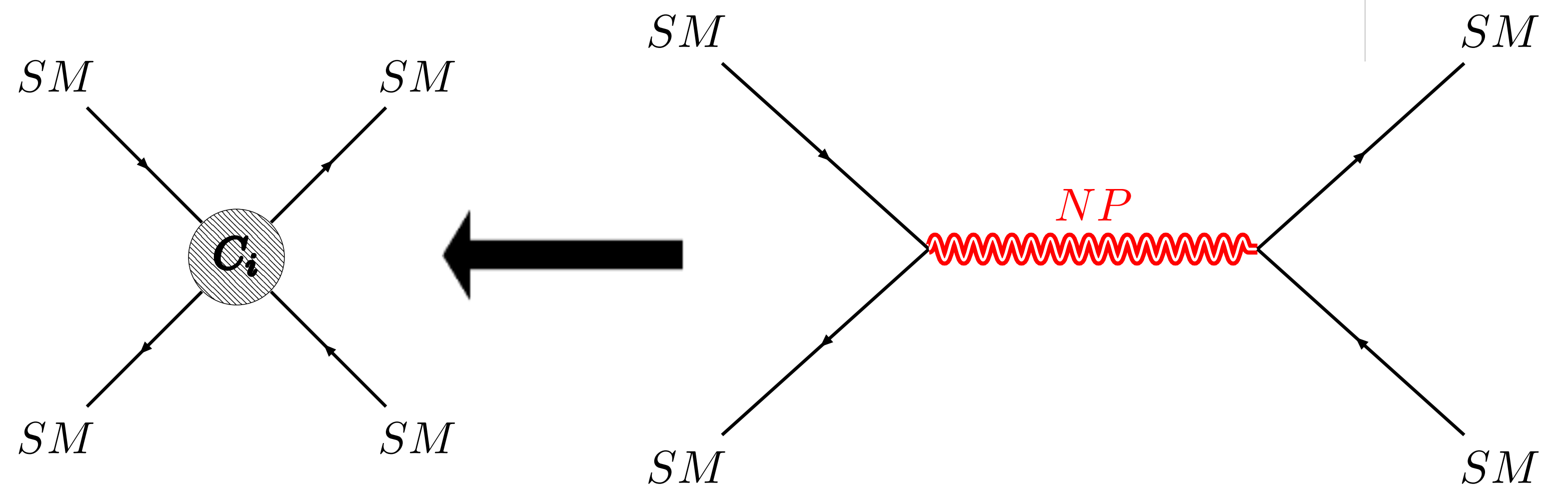
$$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM} + \sum_i \frac{C_i^{(6)}}{\Lambda^2} O_i^{(6)} + \ldots$$

2499 operators

[1008.4884, Grzadkowski et al.]

SMEFT and flavour symmetry





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$$\sigma \propto |\mathcal{A}|^2 = \underbrace{|\mathcal{A}_{\rm SM}|^2}_{\text{SM background}} + \underbrace{\frac{2C_6}{\Lambda^2}\mathrm{Re}(\mathcal{A}_{\rm d6}\mathcal{A}^*_{\rm SM})}_{\text{signal}} + \underbrace{\frac{C_6^2}{\Lambda^4}|\mathcal{A}_{\rm d6}|^2 + \frac{2C_8}{\Lambda^4}\mathrm{Re}(\mathcal{A}_{\rm d8}\mathcal{A}^*_{\rm SM})}_{\text{theoretical uncertainty}} + \ldots$$

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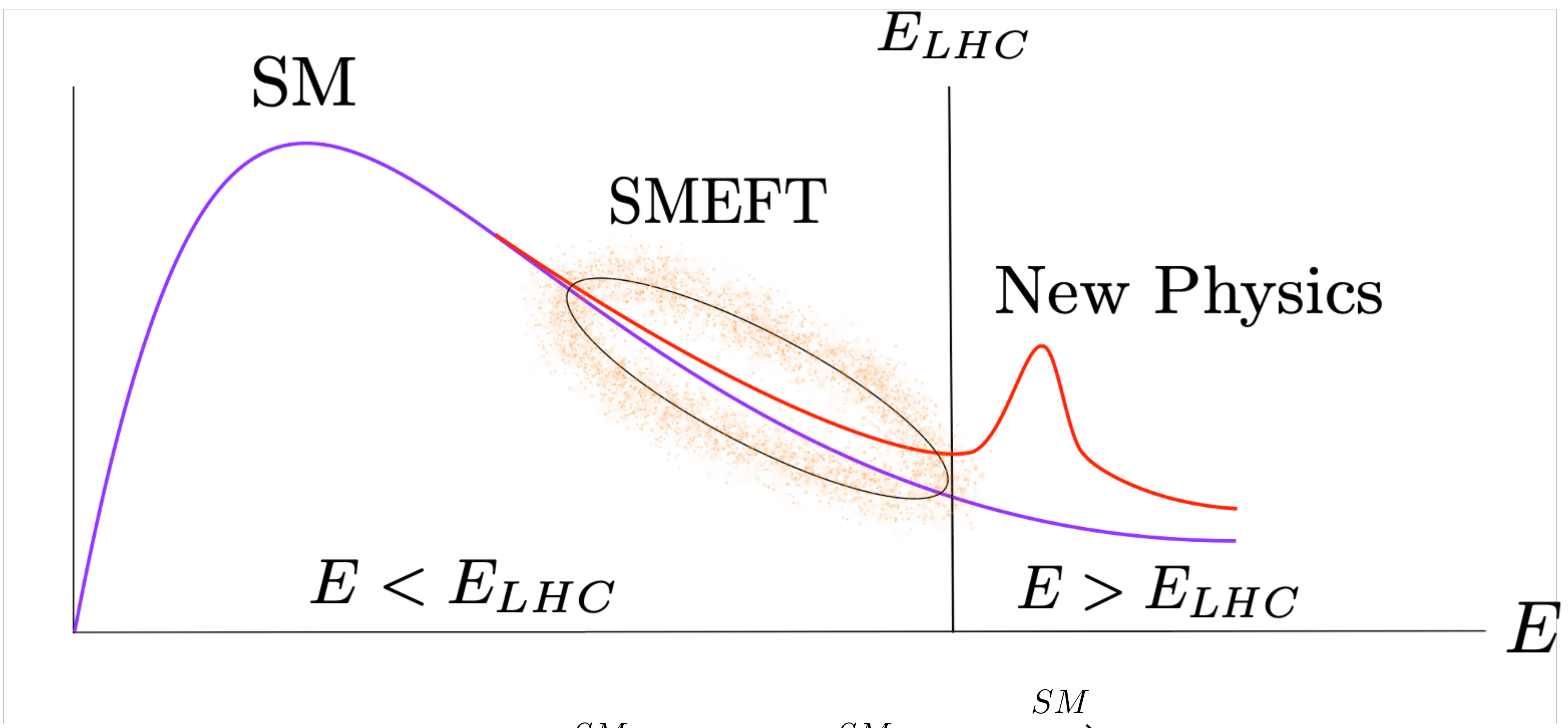

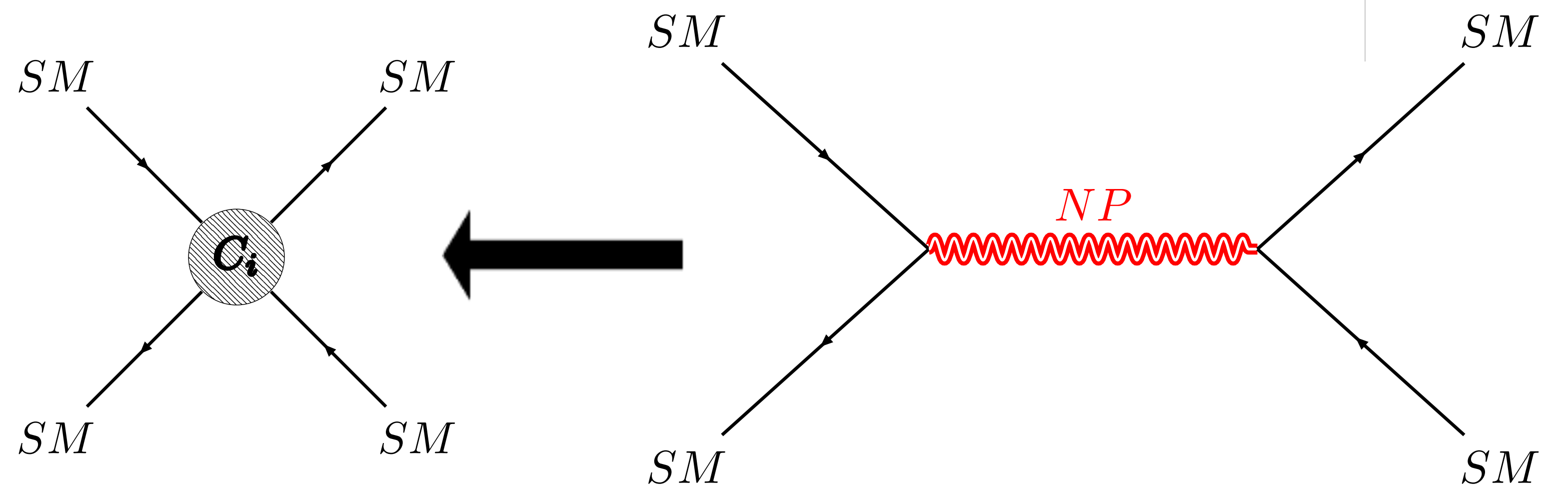

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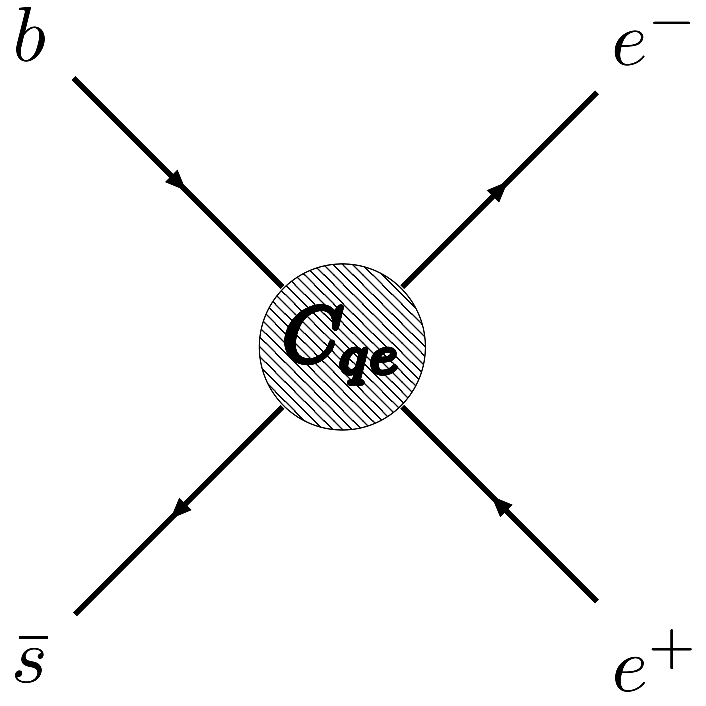

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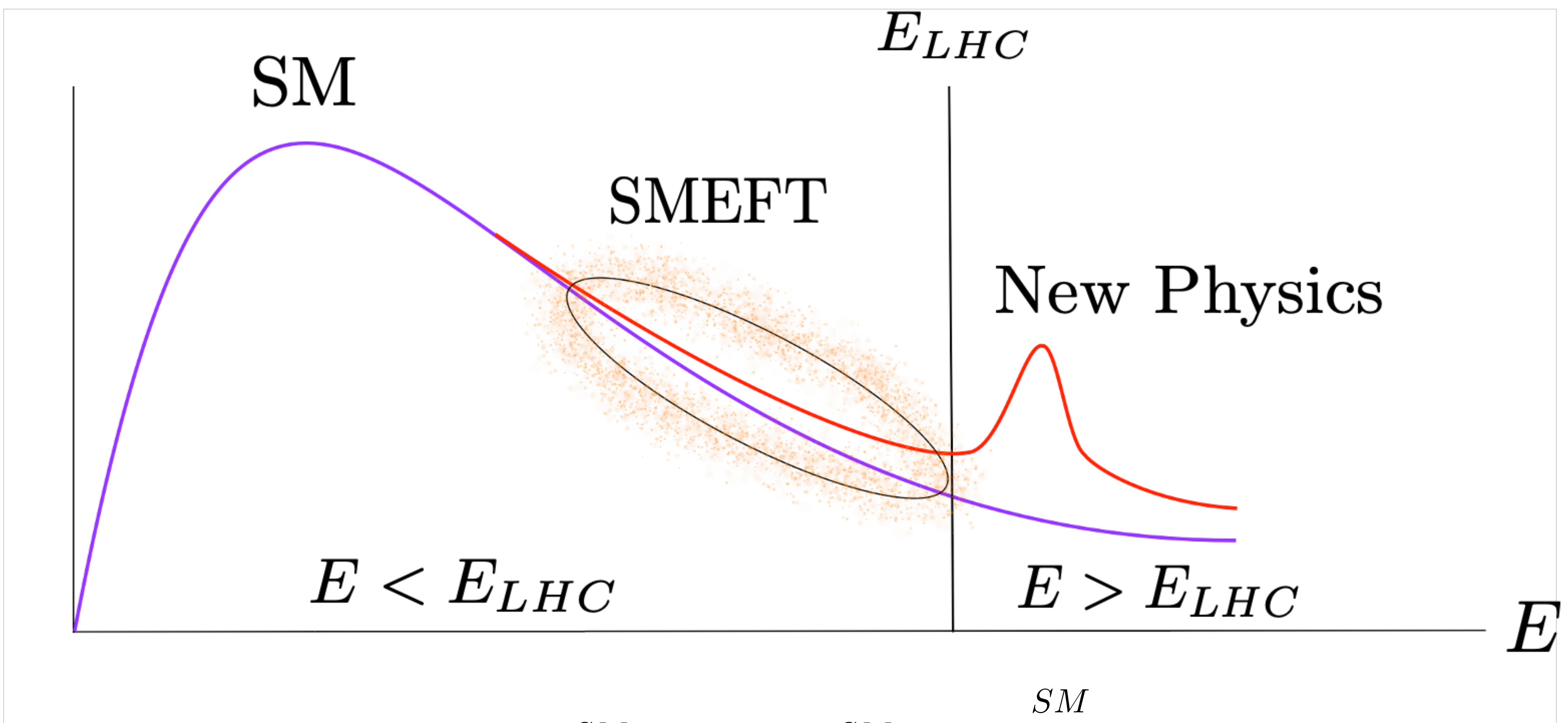

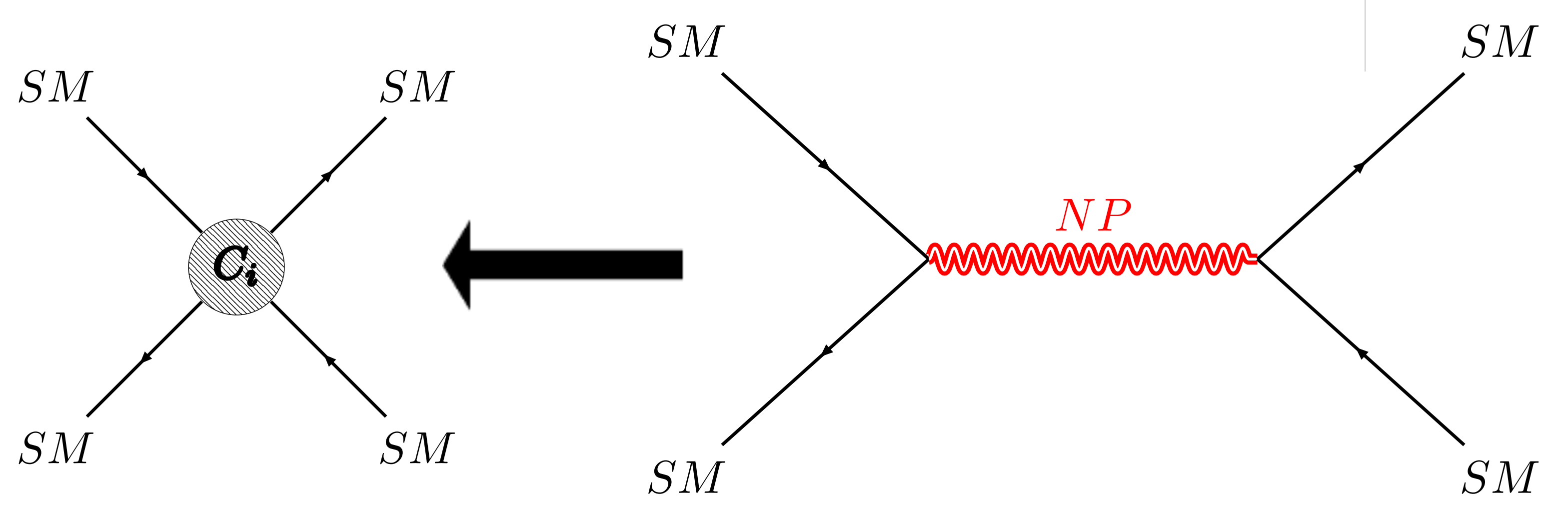

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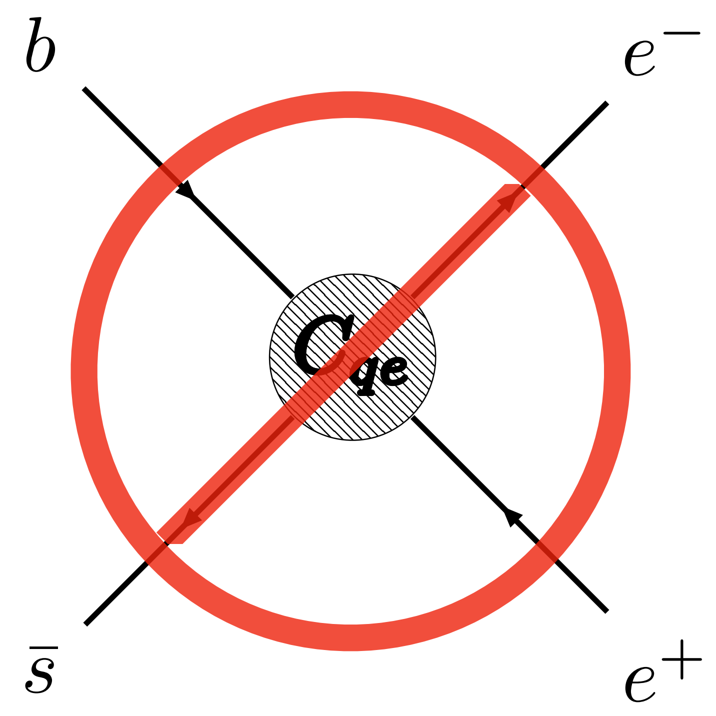
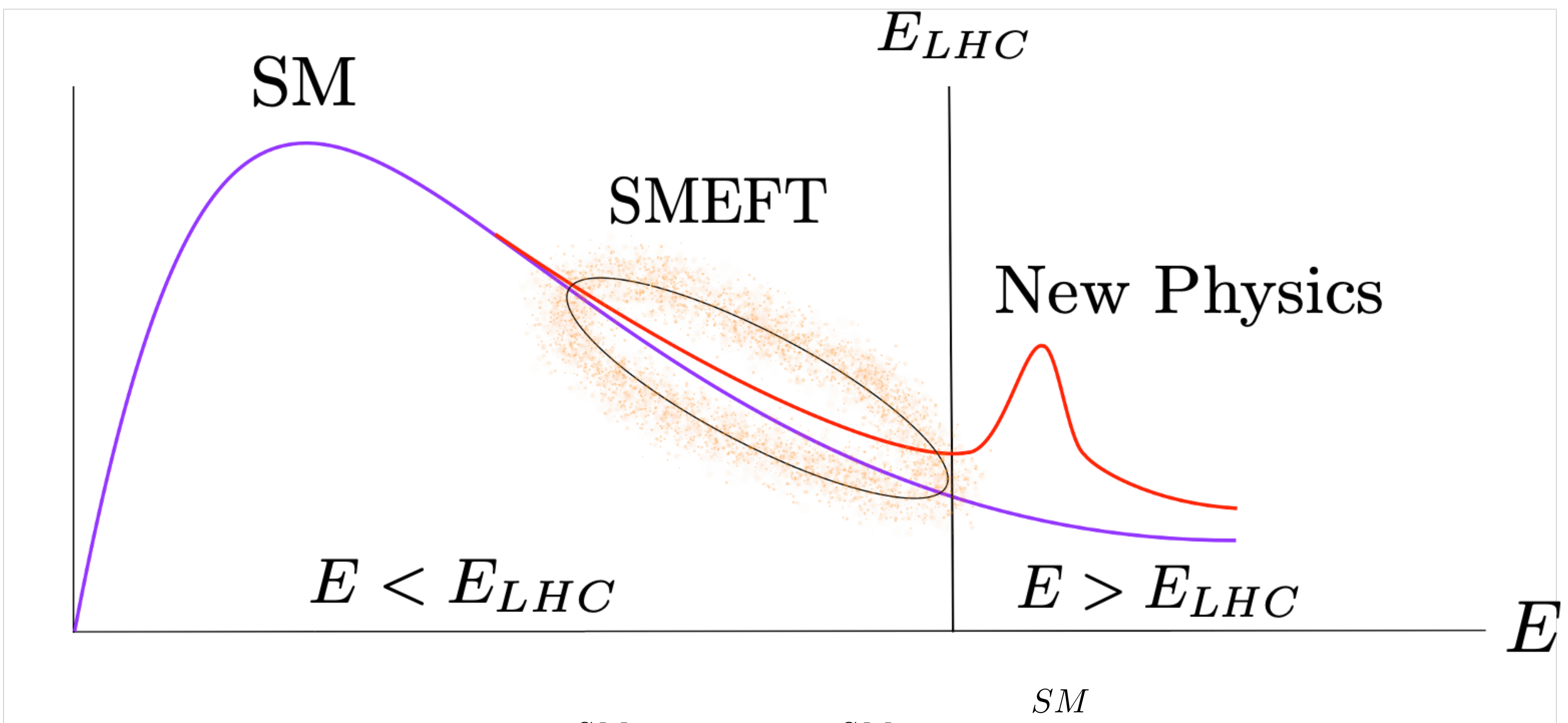
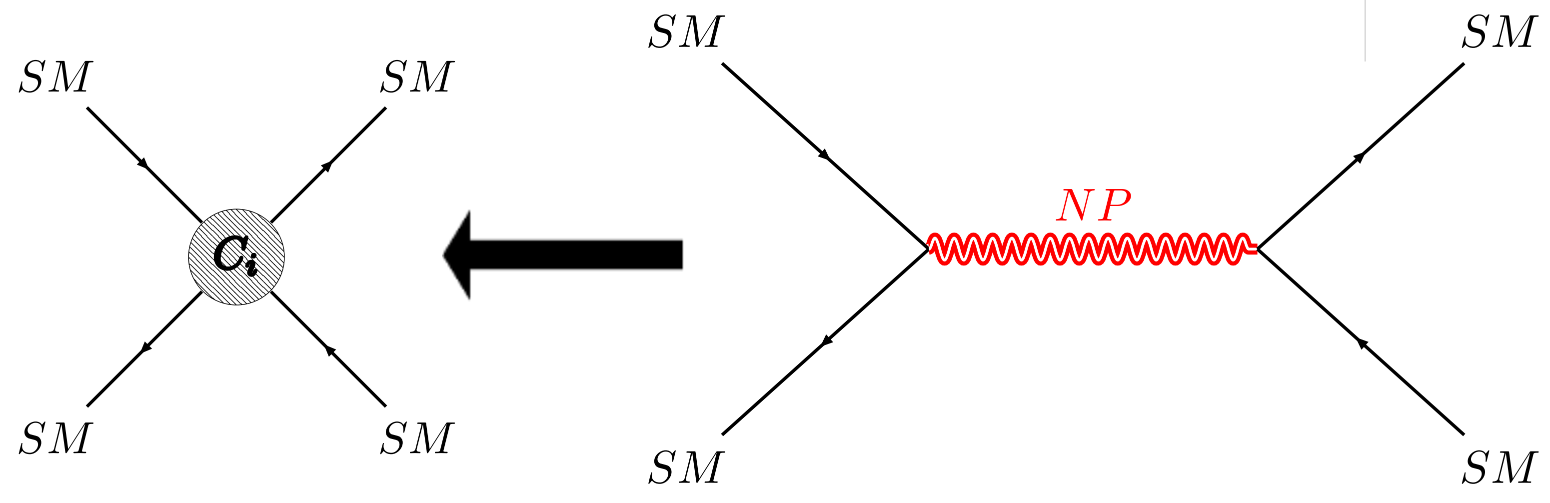


From 2499 dimension six operators to 41 (CP even)

[2005.05366: Faroughy, Isidori, Wilsch, Yamamoto]

SMEFT and flavour symmetry





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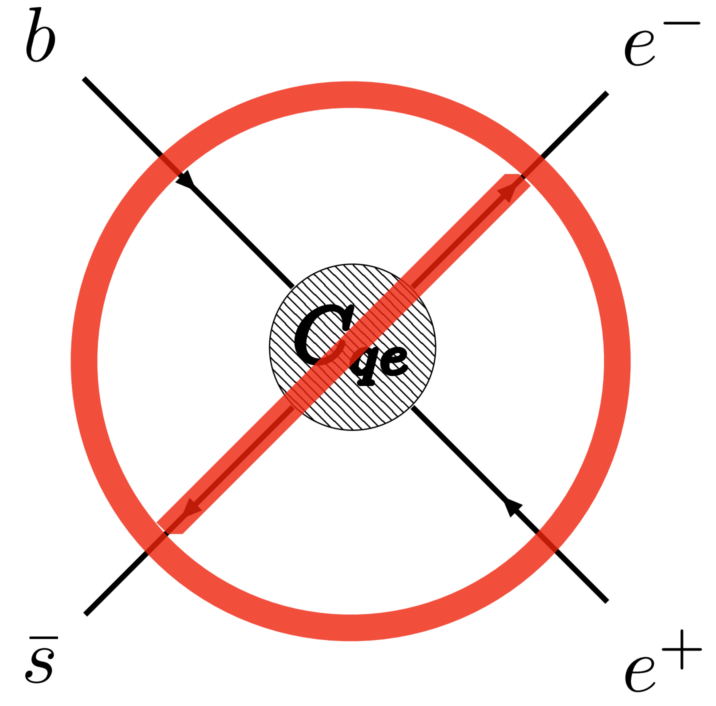

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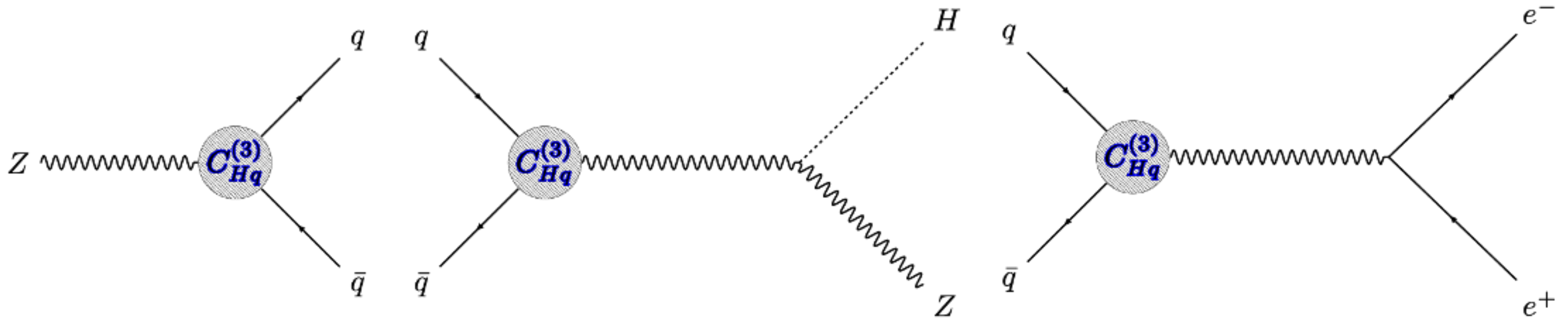
This assumption corresponds to minimal version of MFV: it contains the minimum and non-removable amount of flavour violation.

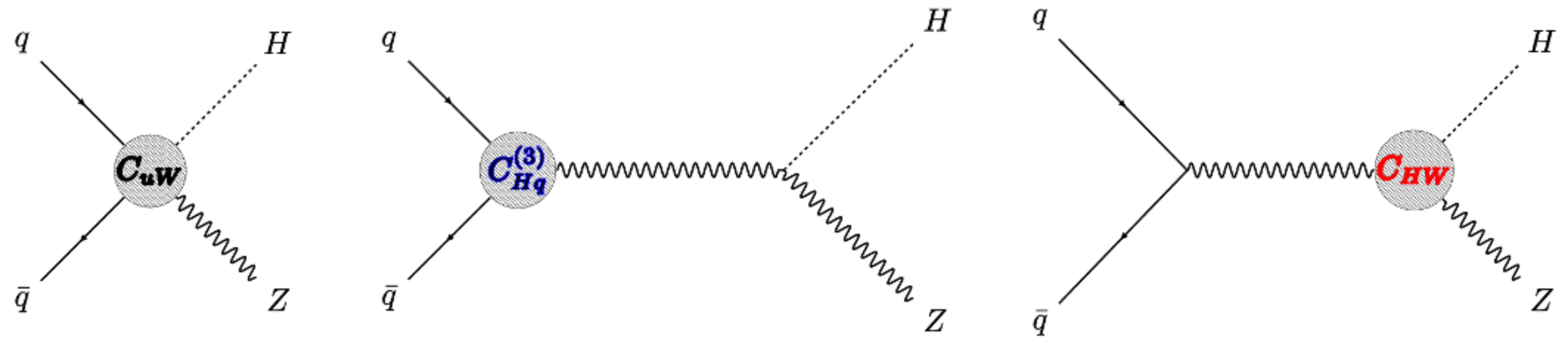
Global analyses in the SMEFT

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

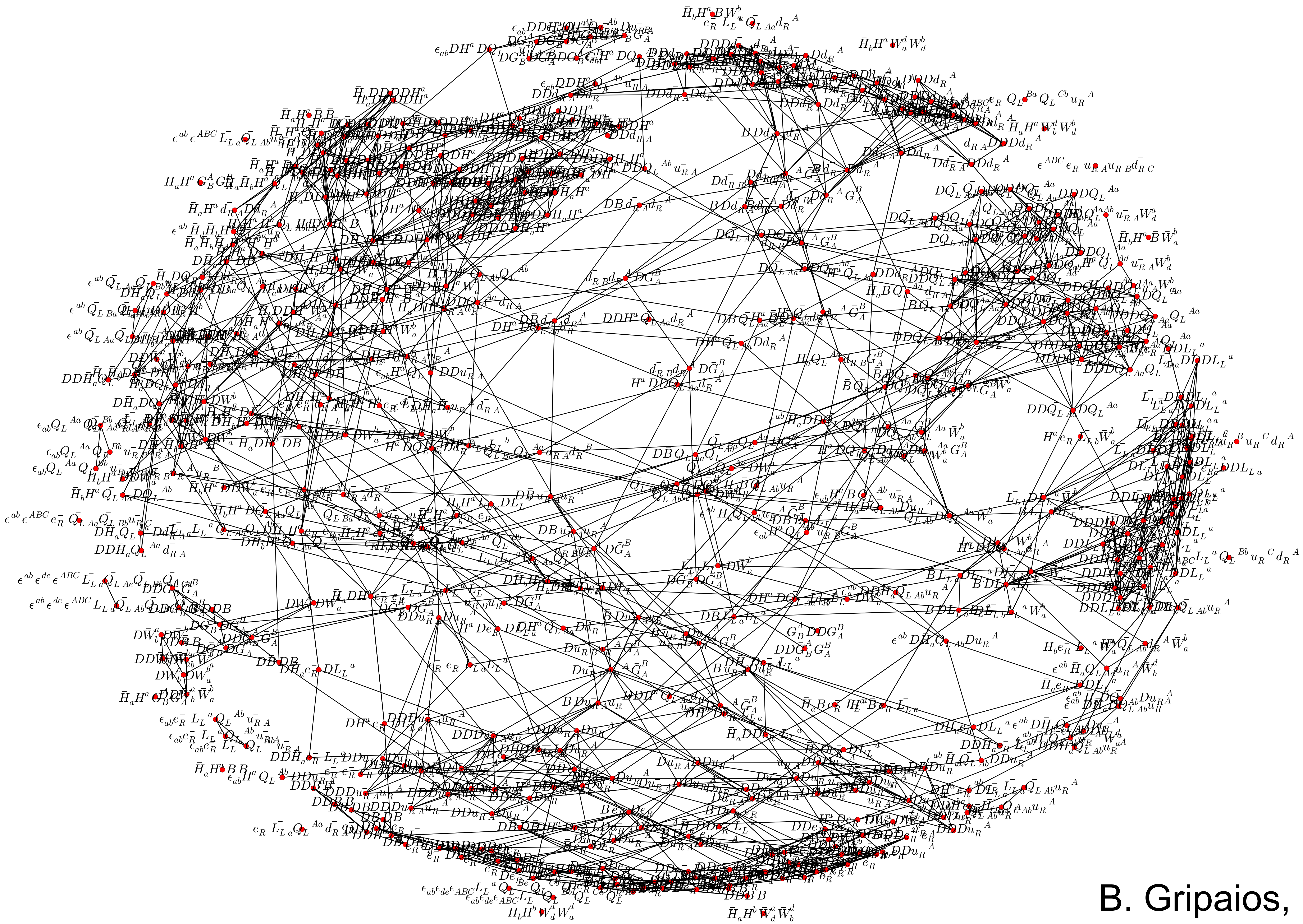
One operator influences different observables:



One observable is influenced by many different operators:



Global analyses in the SMEFT

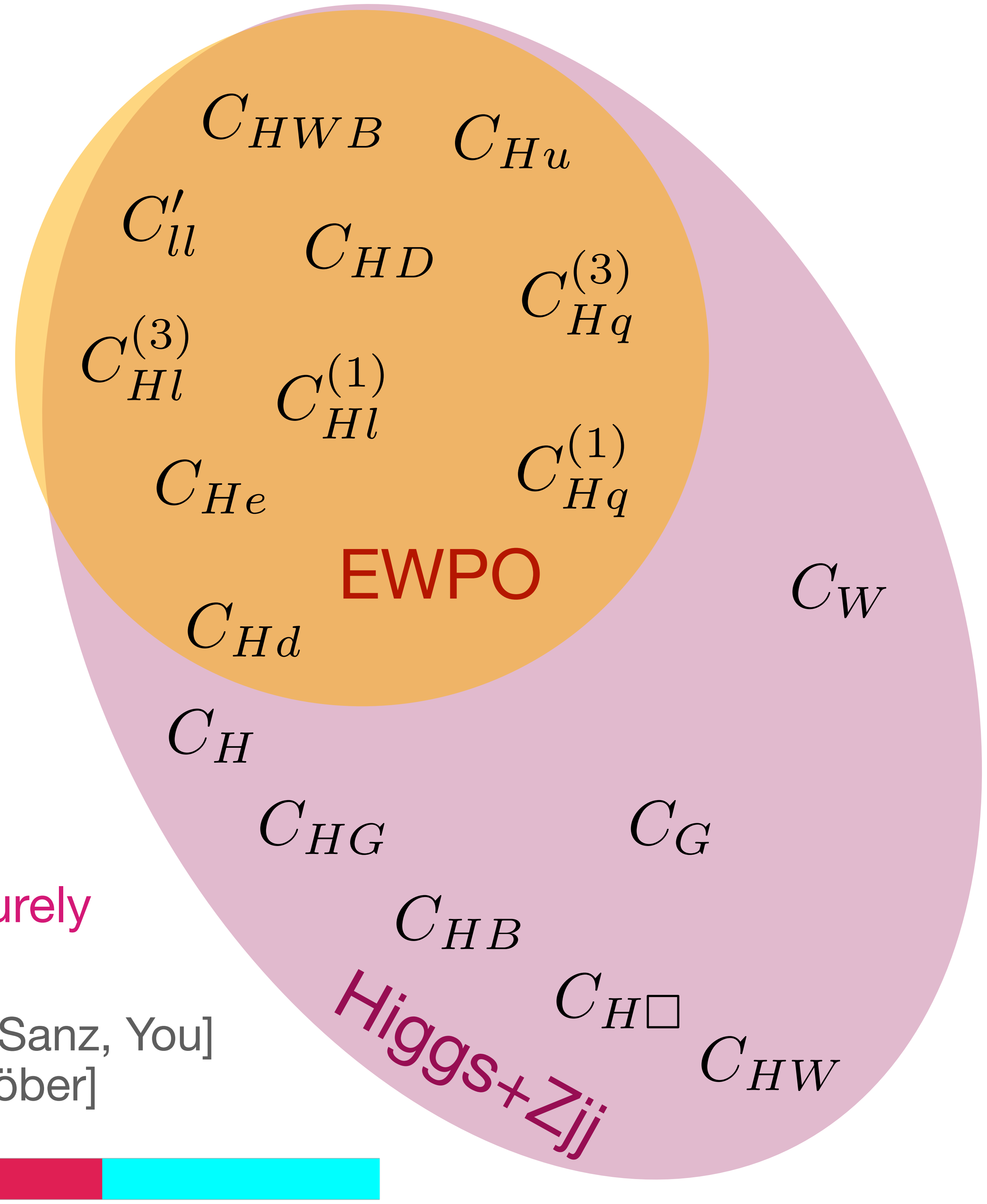


B. Gripaios, HEFT 2018

Global analysis with LO predictions

Datasets

EWPO:
Dominantly constrain these 10 operators, but leaves two flat directions.
[1909.02000: Dawson, Giardino]



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

Datasets

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Drell-Yan and PVE:
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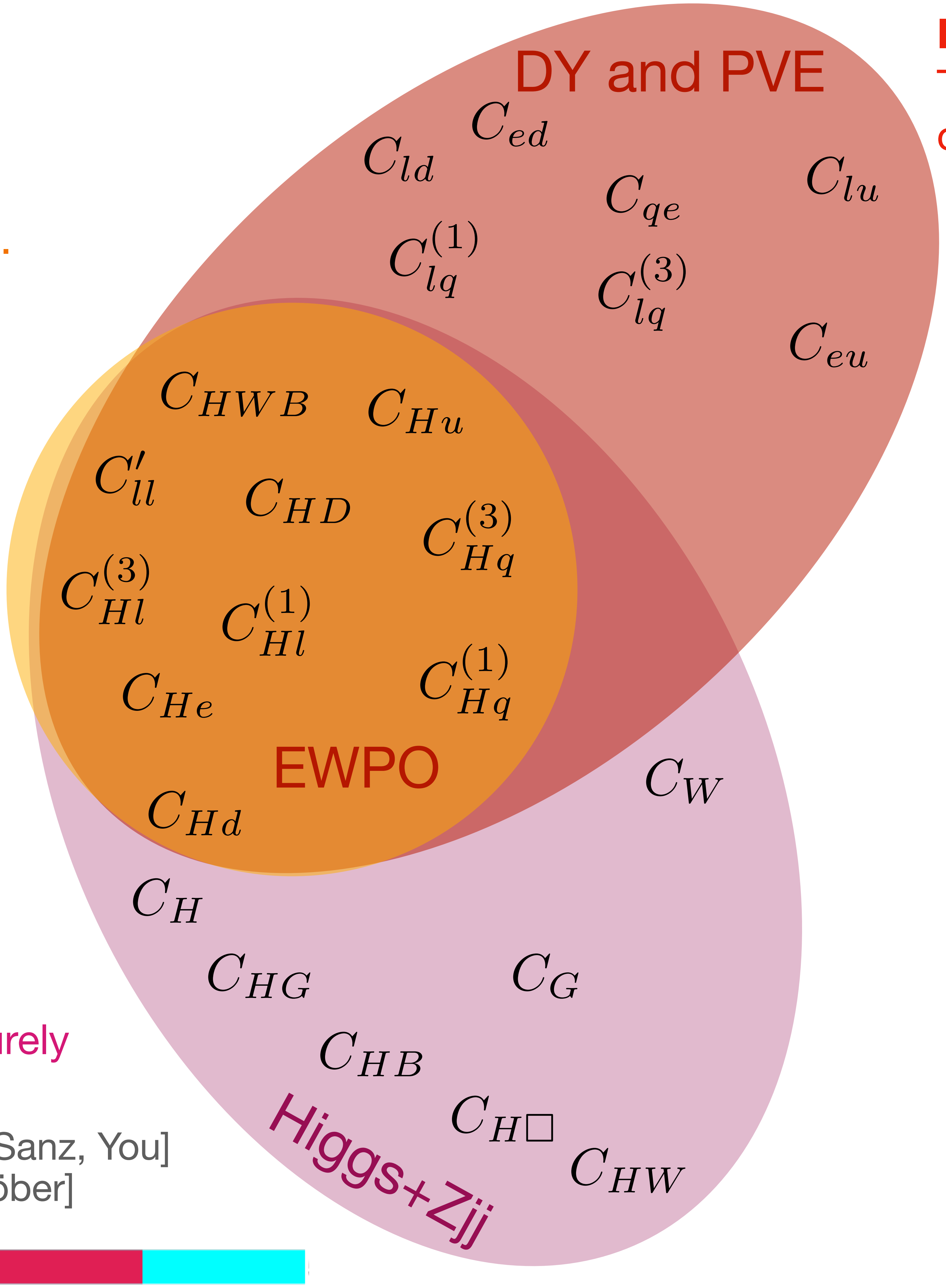

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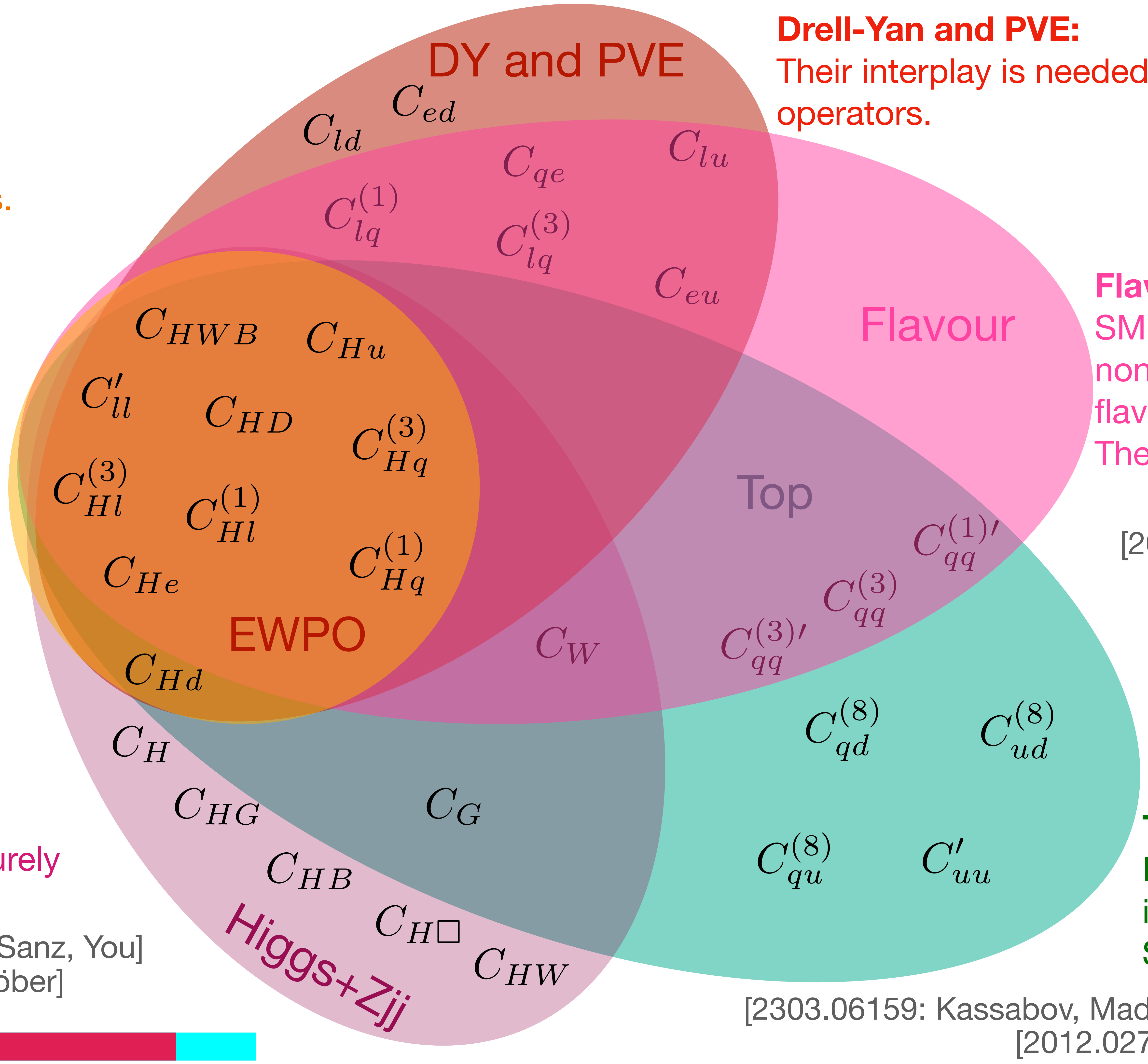

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SMEFT operators are flavour symmetric, nonetheless Yukawa couplings give rise to flavour violating observables via loop.
These bounds lift correlations present in Top.
[1810.08132: Straub]
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Top:
Put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

Constrained operators: 31

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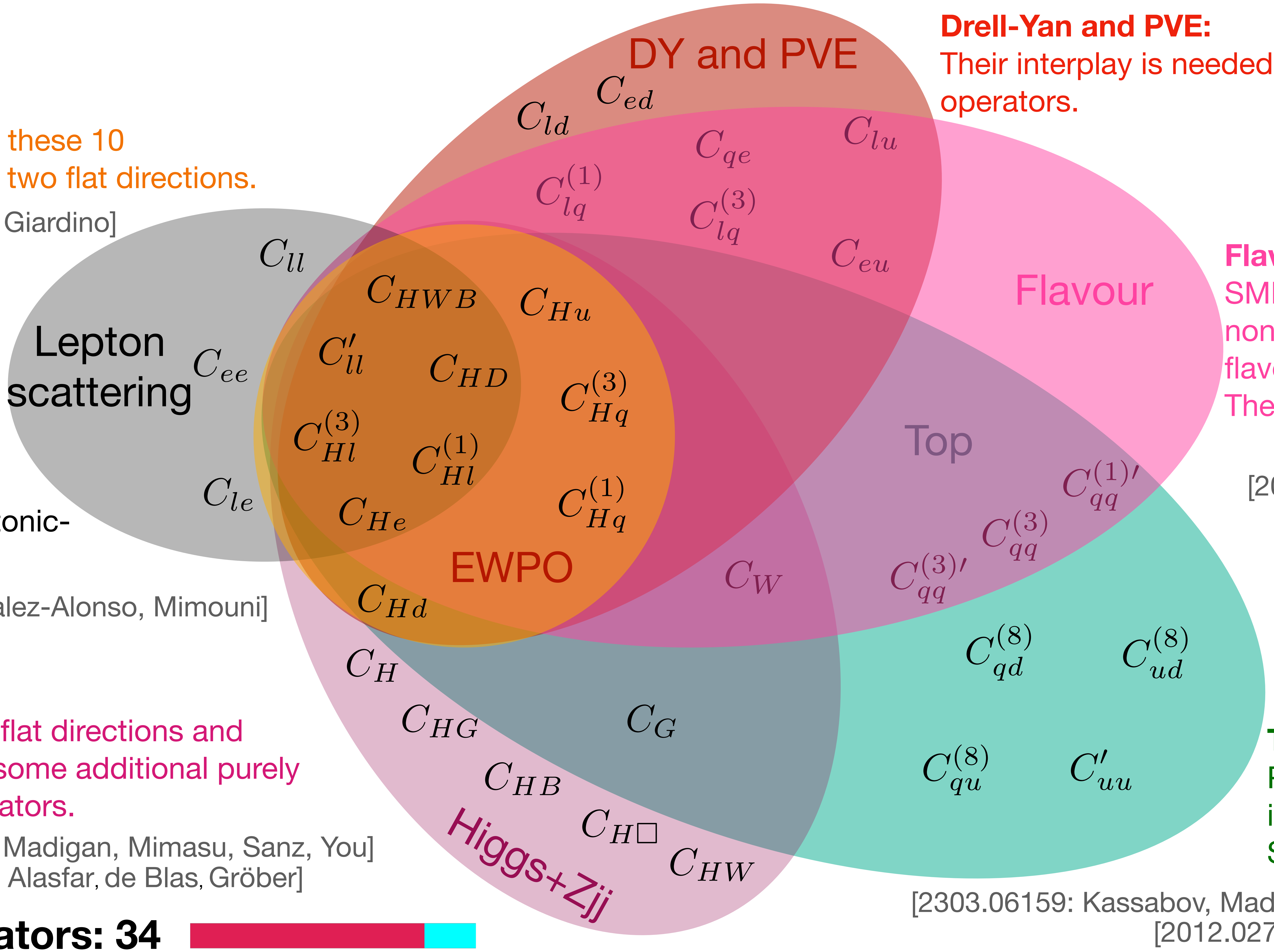

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Lepton scattering:
Constrain mainly purely leptonic-operators
[1706.03783: Falkowski, Gonzalez-Alonso, Mimouni]

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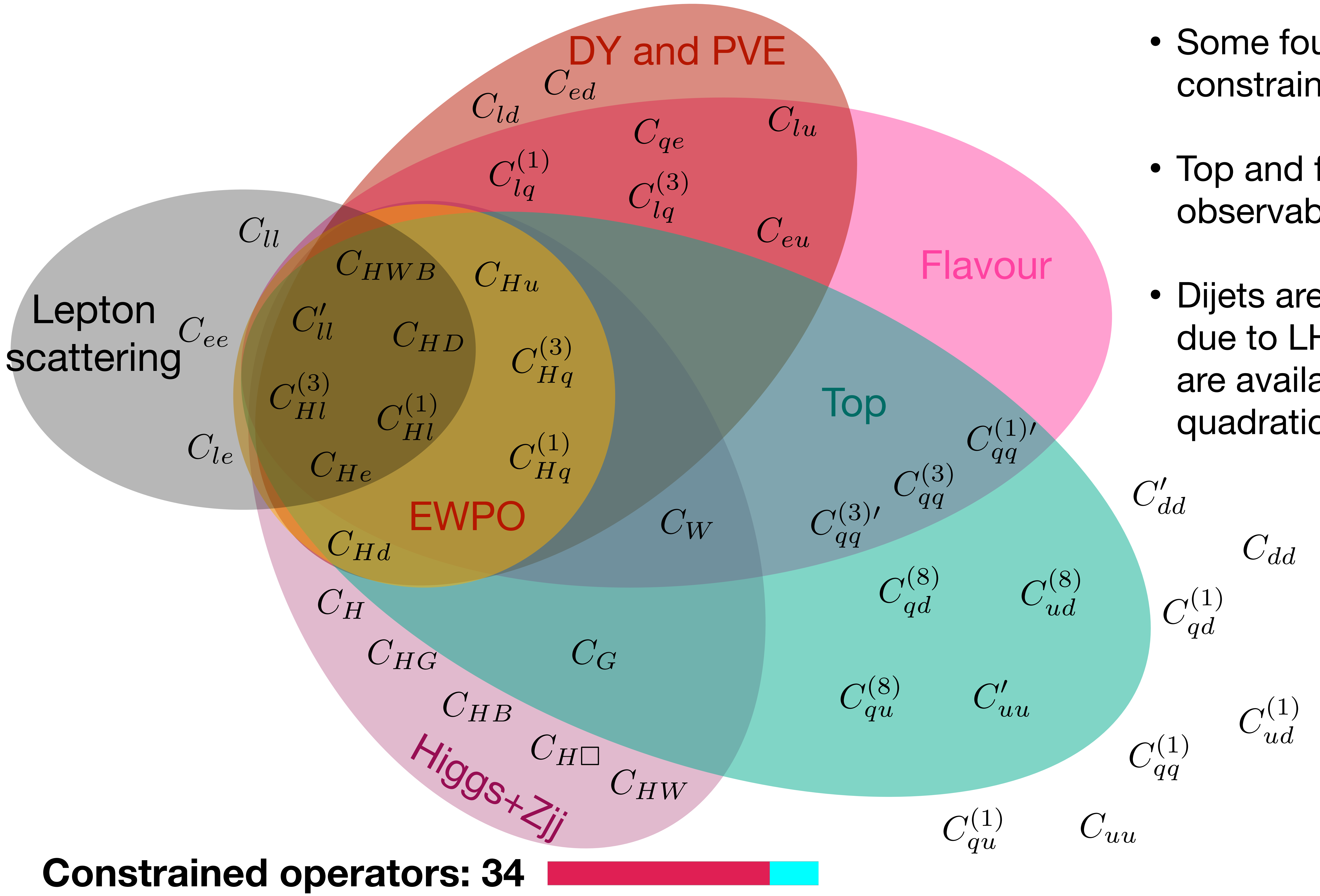
Constrained operators: 34

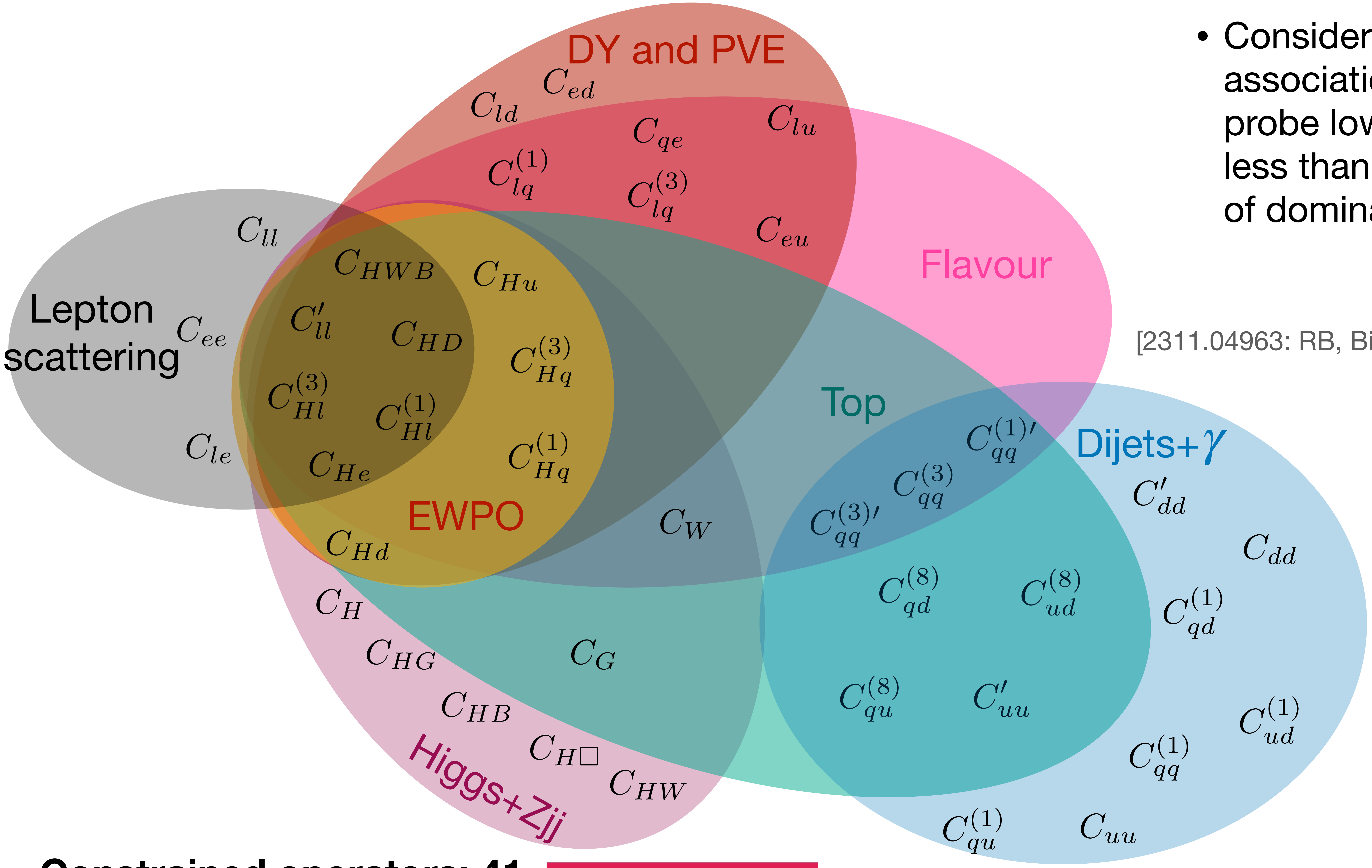
Dijets+γ



Constrained operators: 34

- 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, leading to inconsistencies: dominant quadratic terms, breaking of the EFT validity.

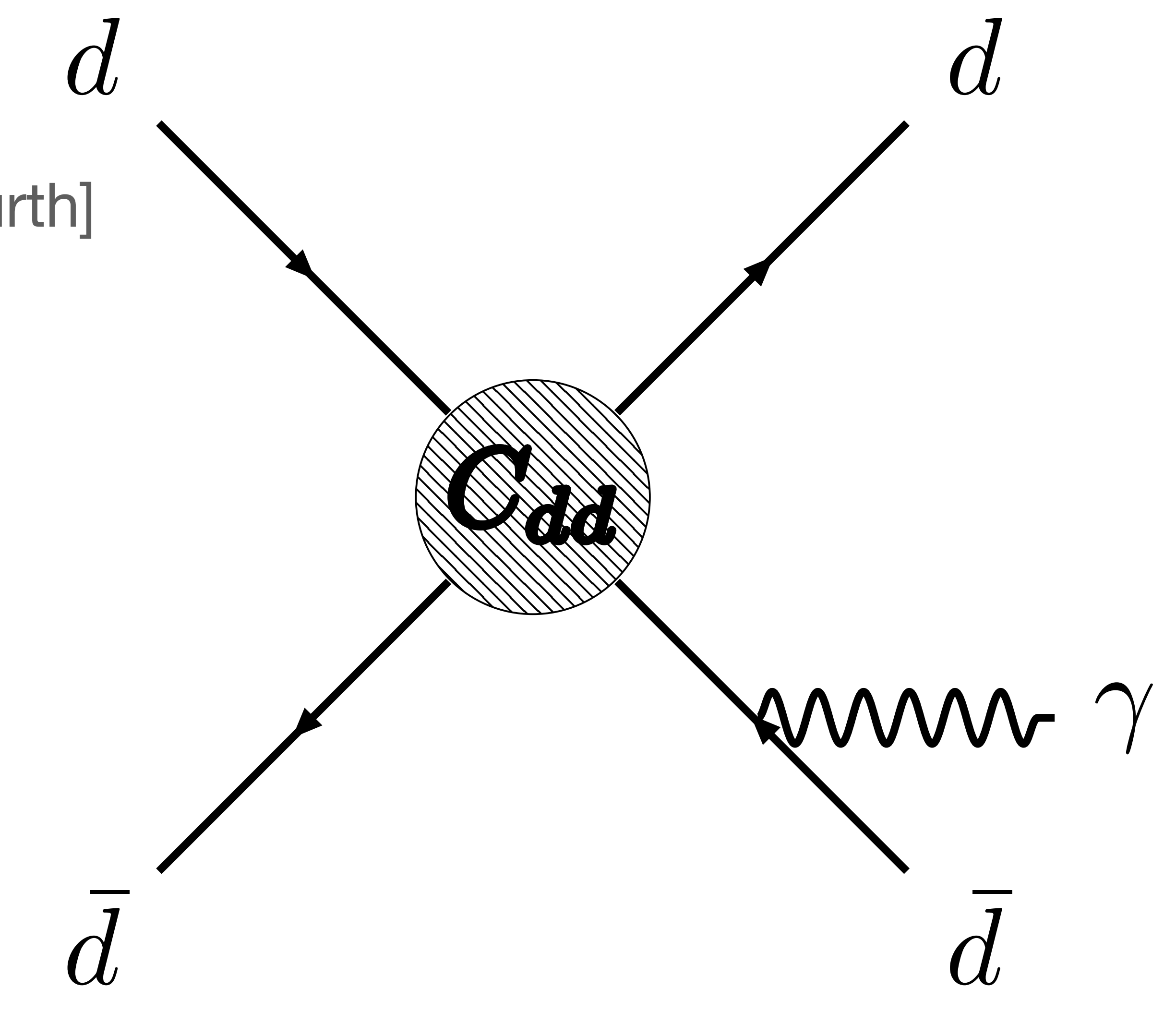
Dijets+γ



Constrained operators: 41

- Considering the production of two jets in association with a photon enables us to probe lower dijet invariant-mass ranges less than 1.1 TeV and circumvent the issue of dominant quadratic terms.

[2311.04963: RB, Biekötter, Hurth]

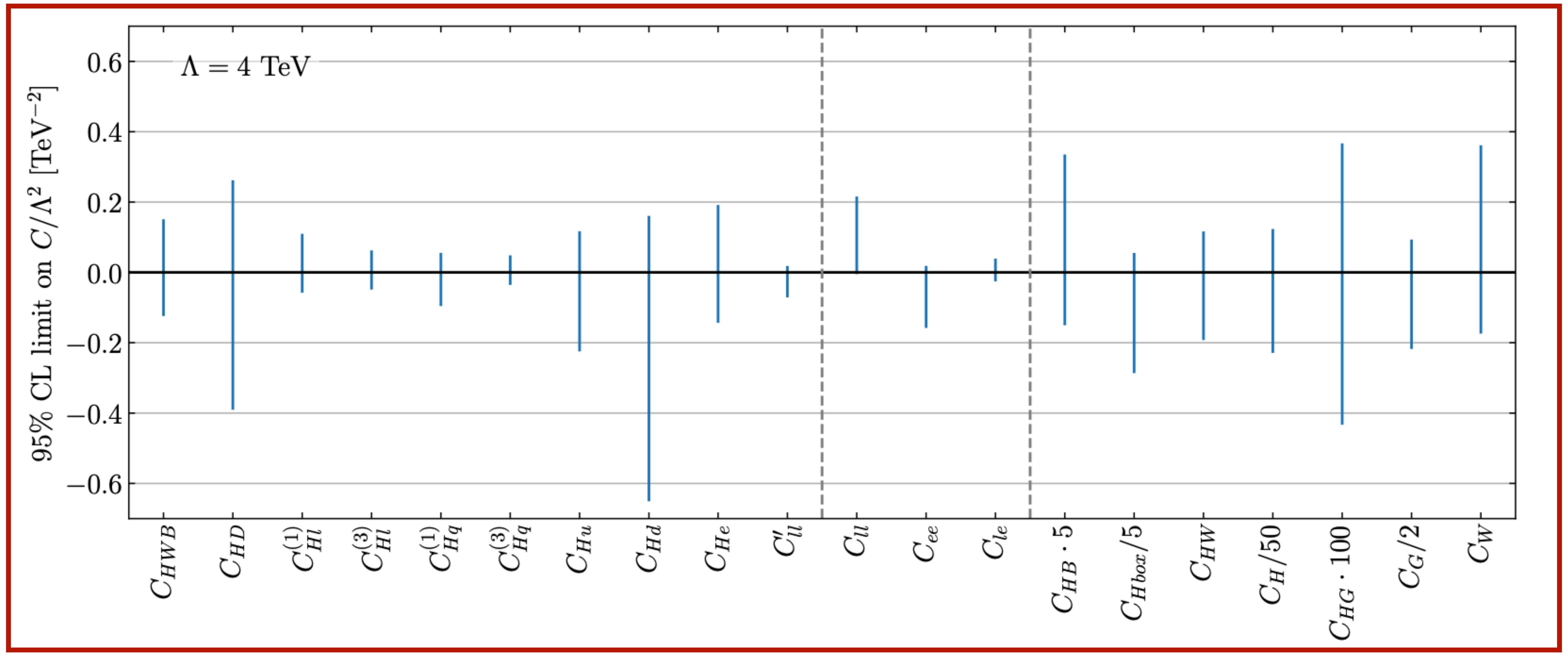


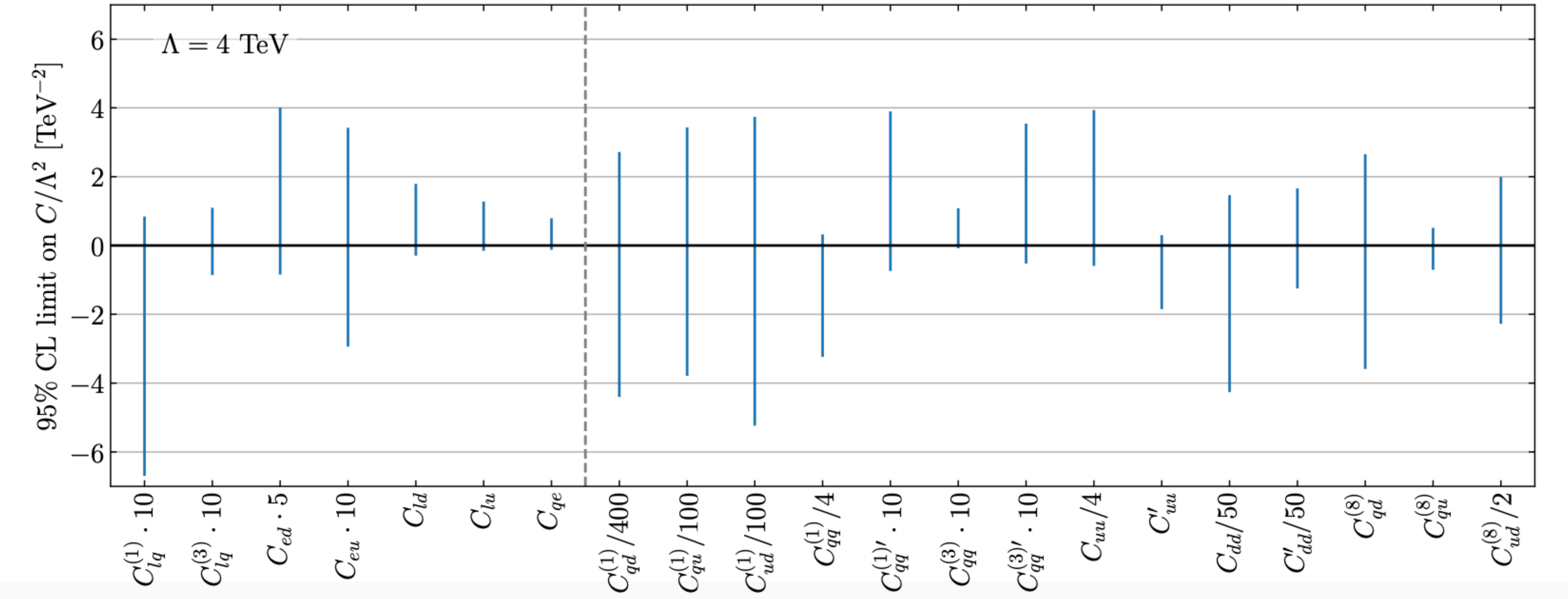
Dijet mass range: 225 GeV - 1.1 TeV

[ATLAS: 1901.10917]

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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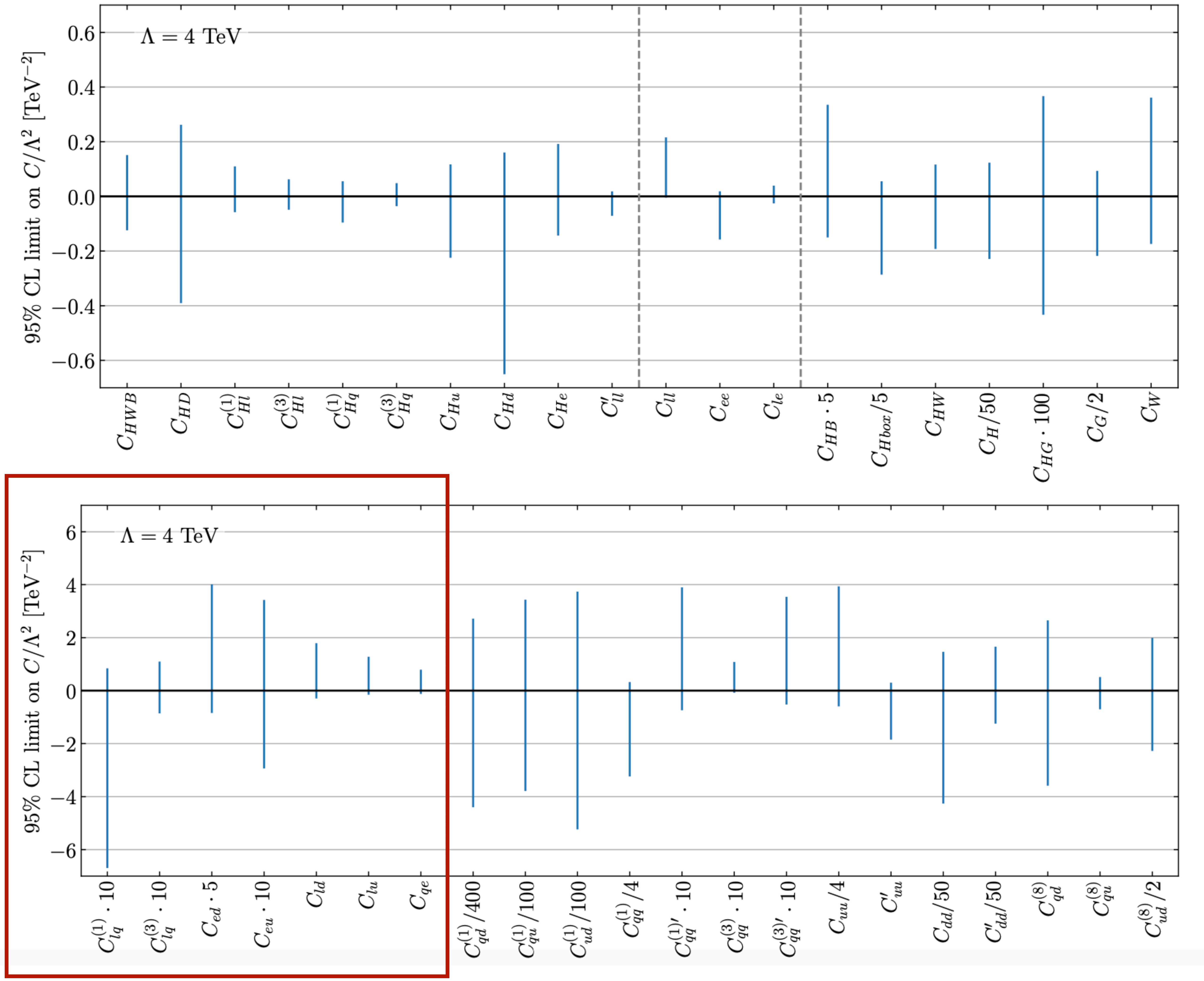

semileptonic operators

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- Semileptonic and most 4-quark operators exceed this bound on at least one side

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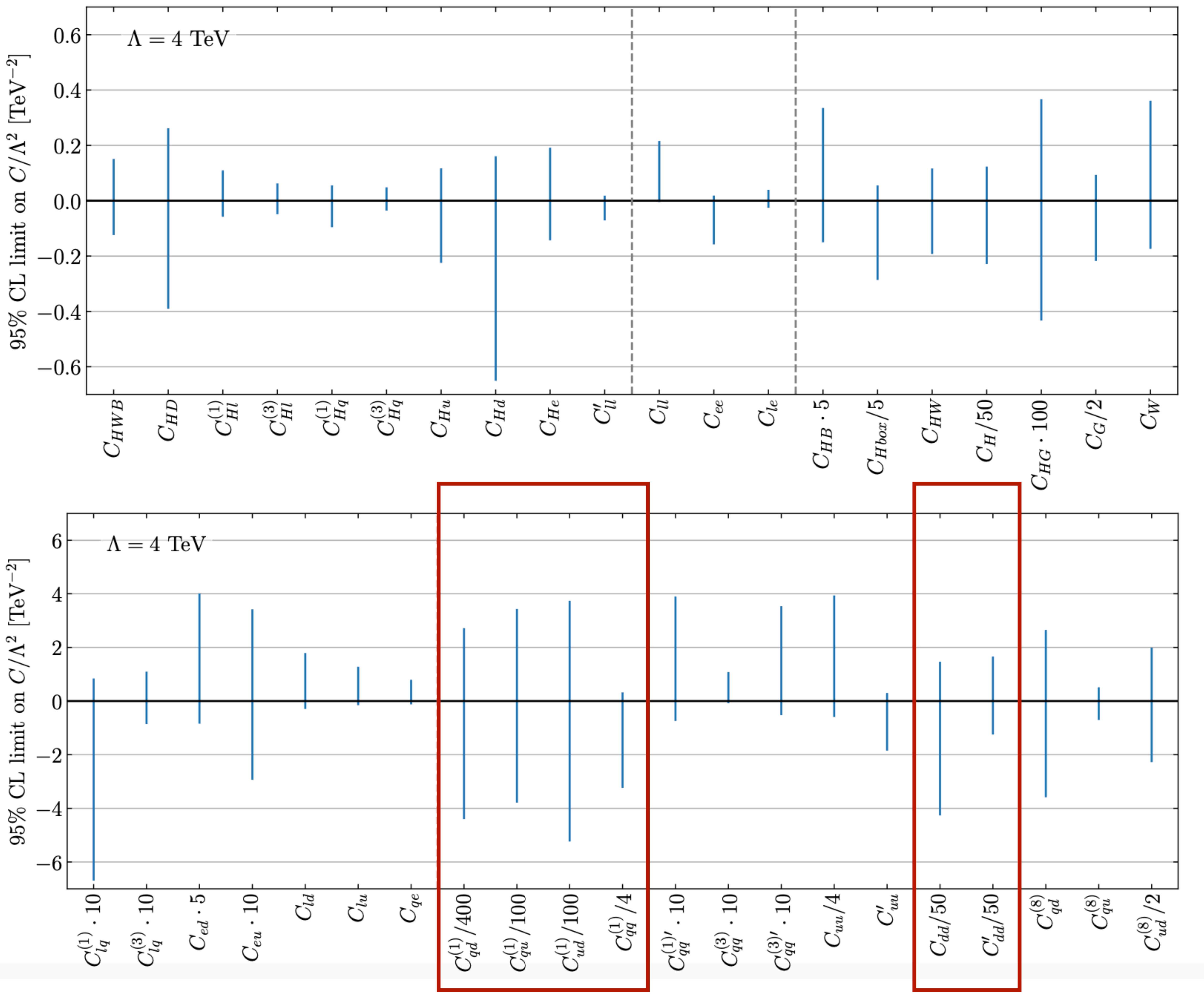

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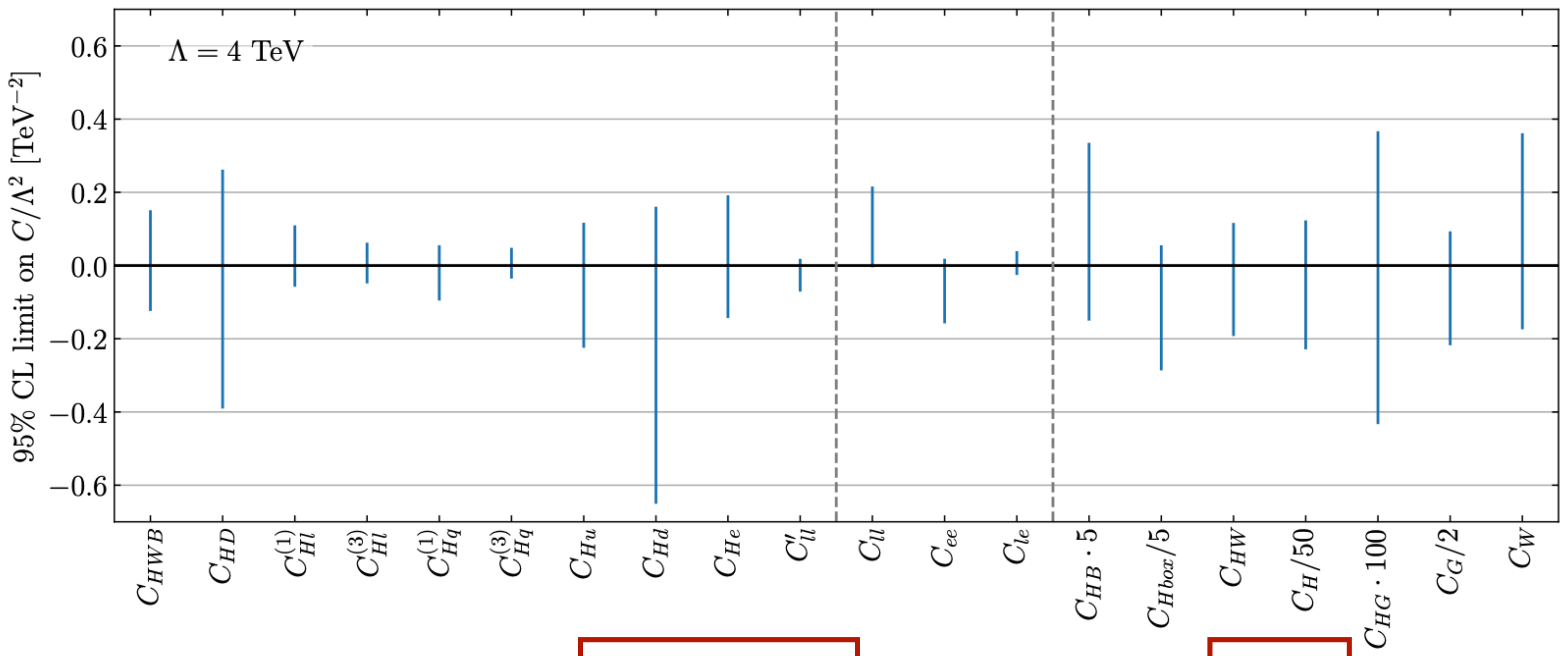

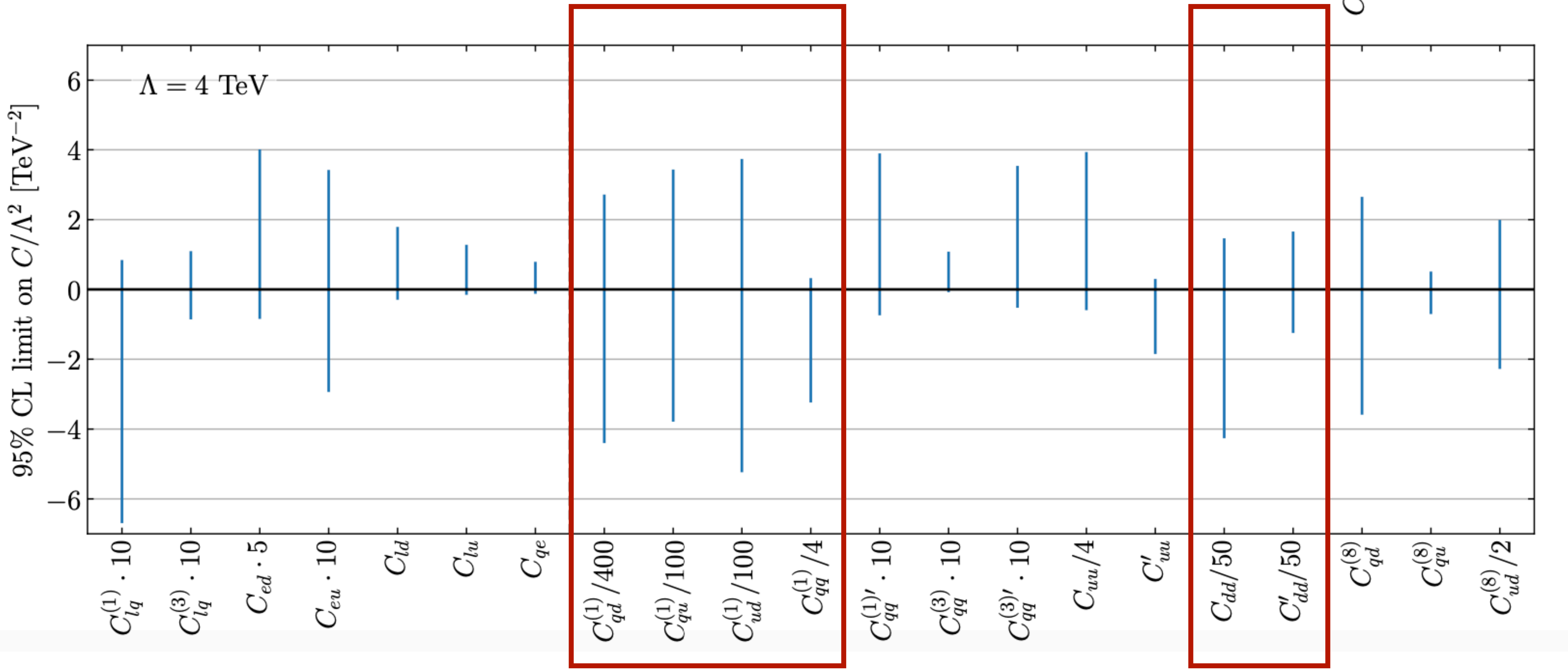

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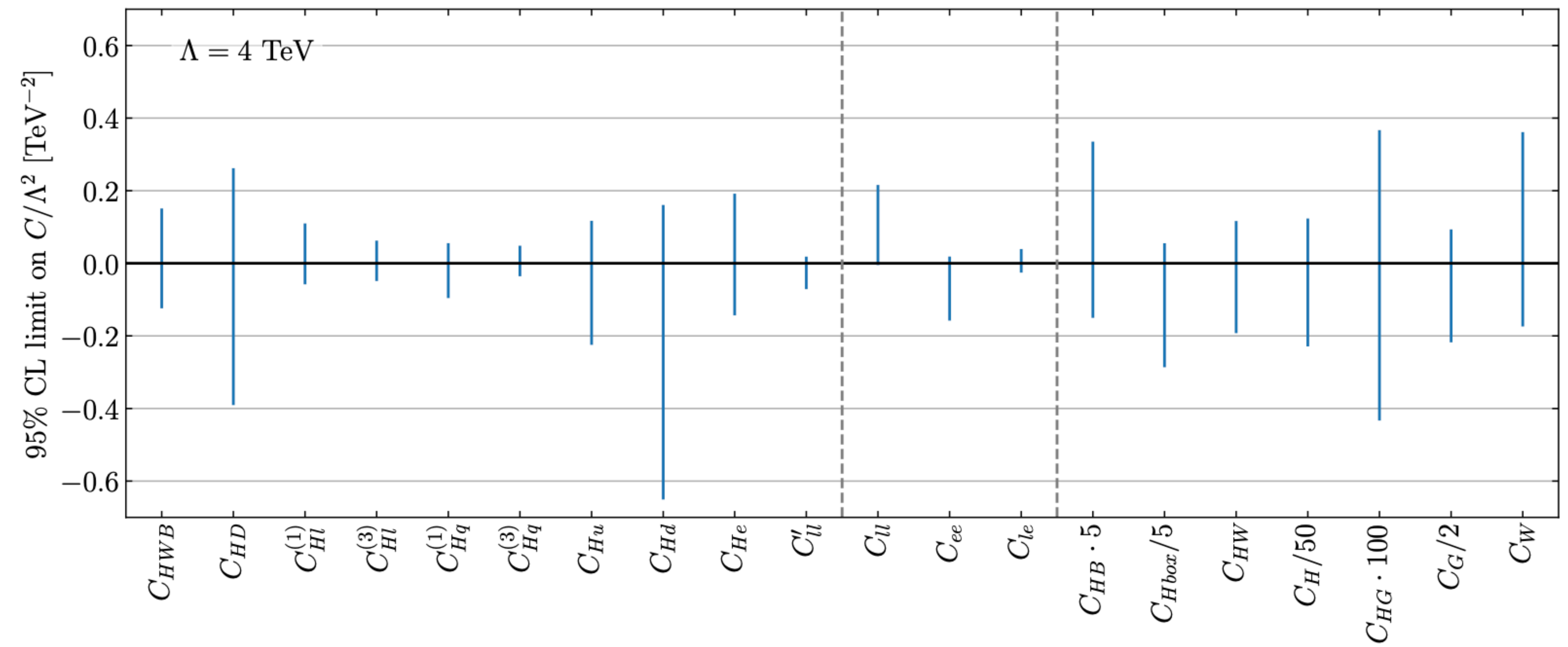

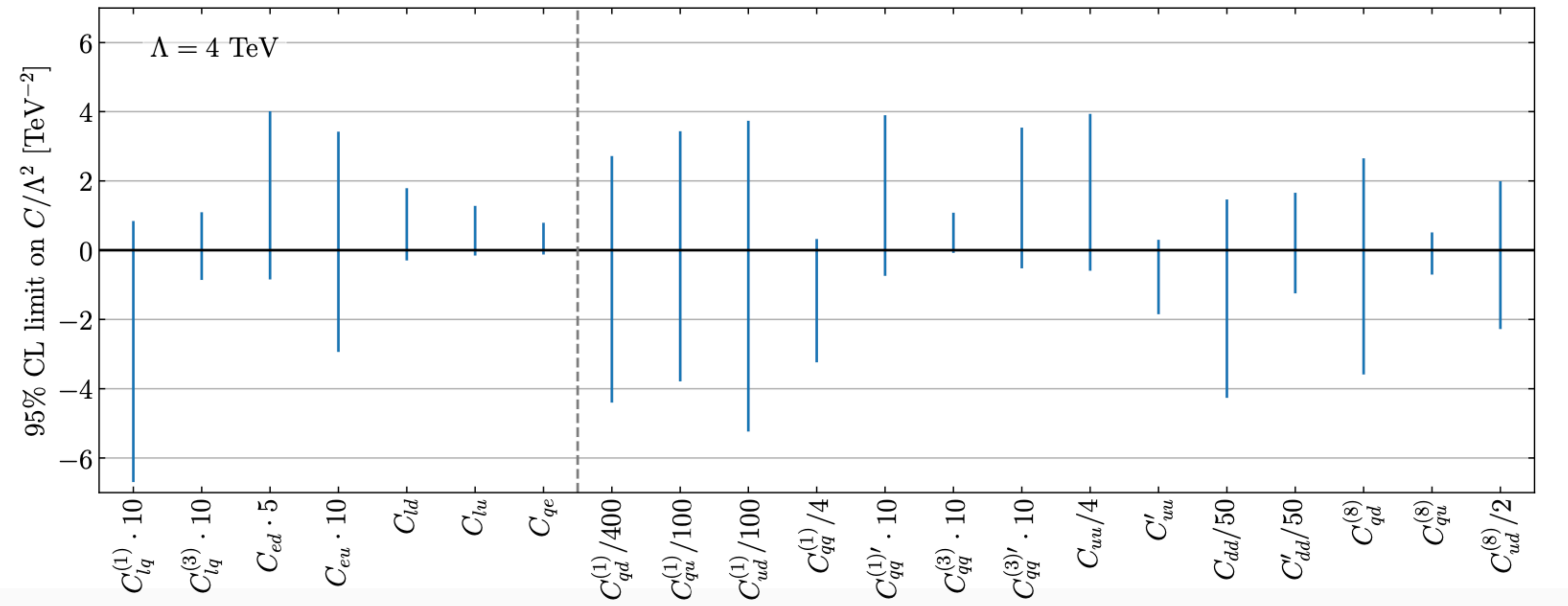

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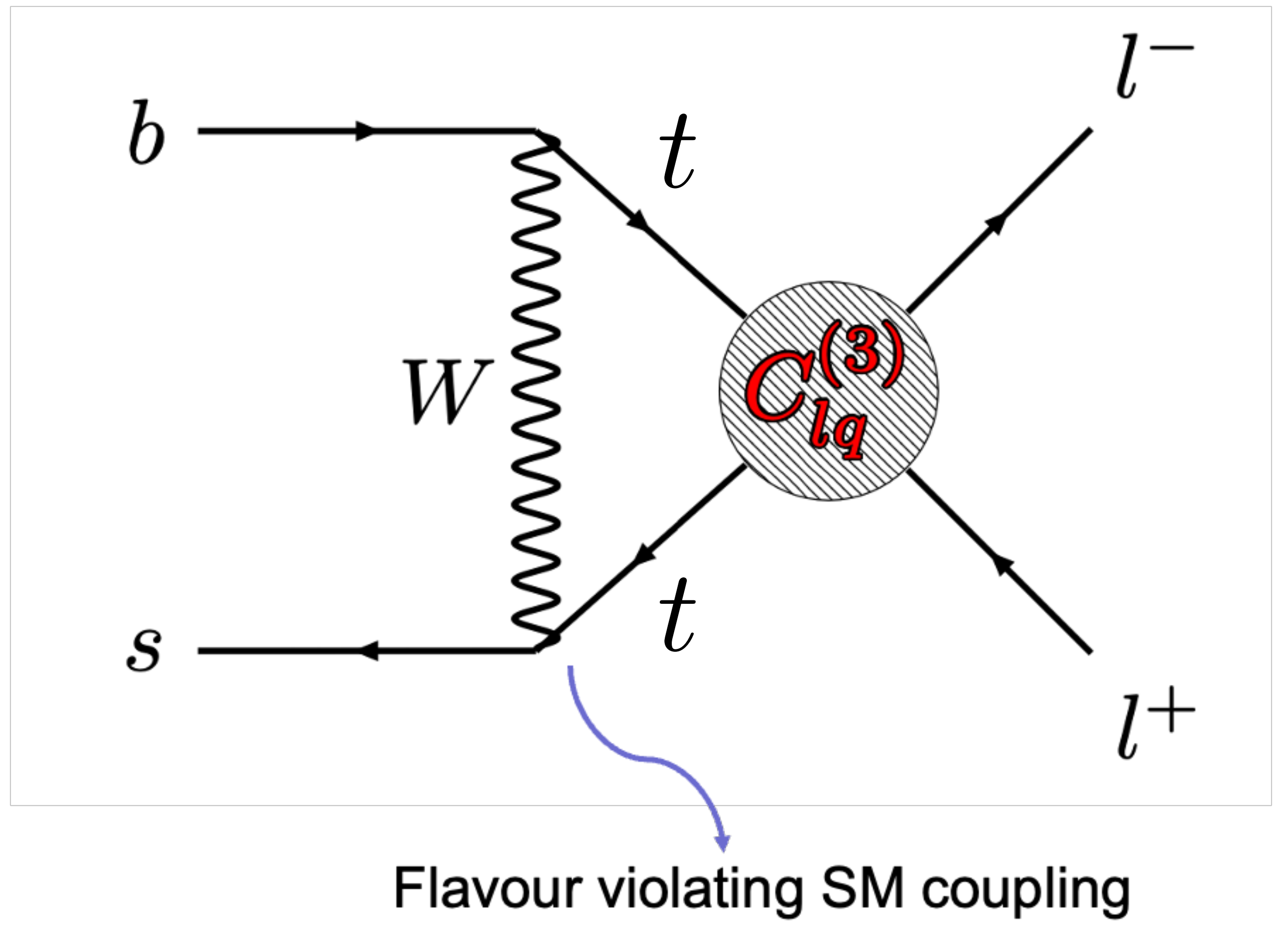
- $C_{qu}^{(1)}, C_{qd}^{(1)}, C_{ud}^{(1)}, C_{dd}, C'_{dd}$ are essentially unconstrained
- Nevertheless, their inclusion does not invalidate the limits on the other coefficients
- There are no coefficients deviating more then 2 sigma from the SM

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.



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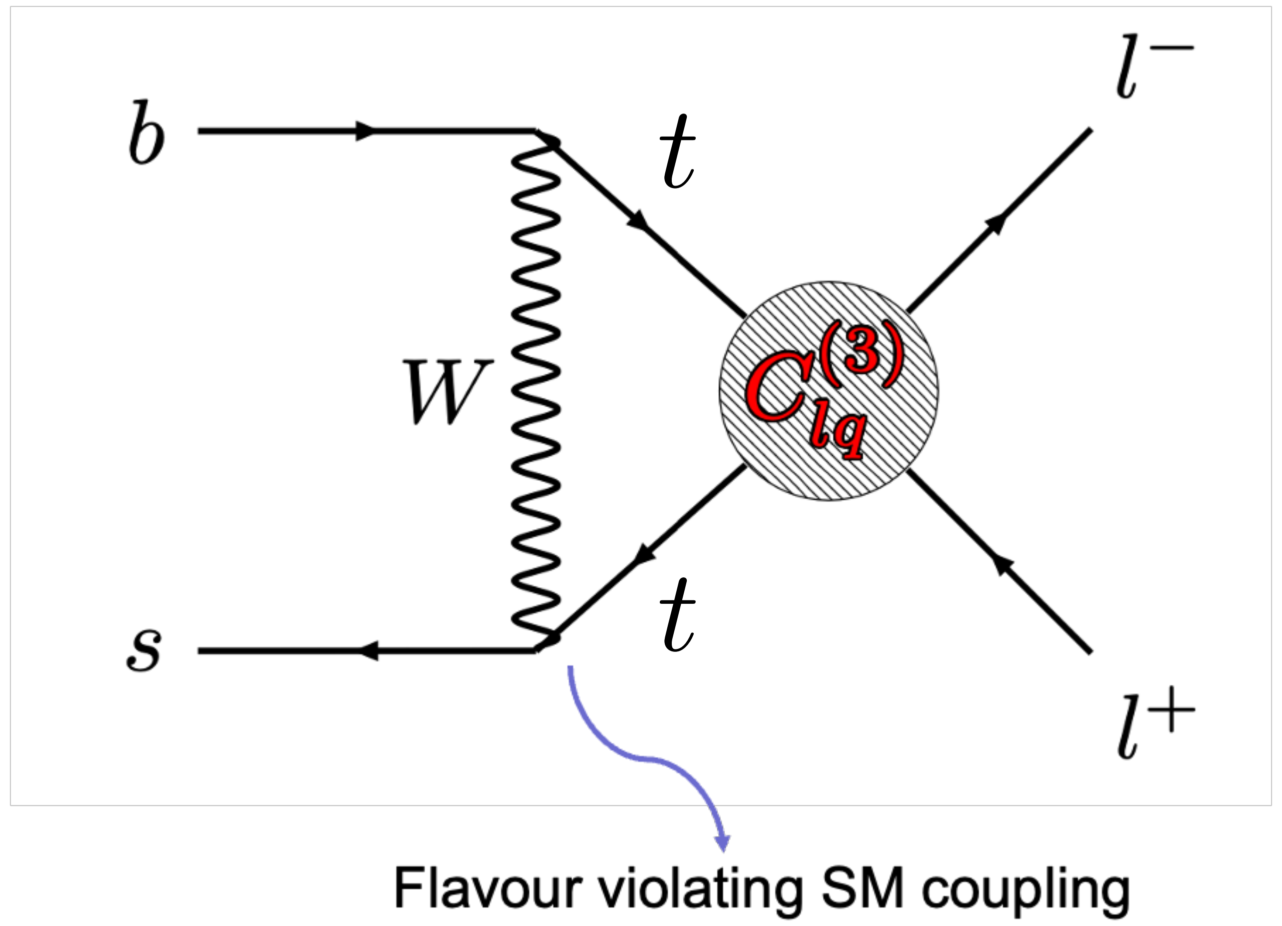
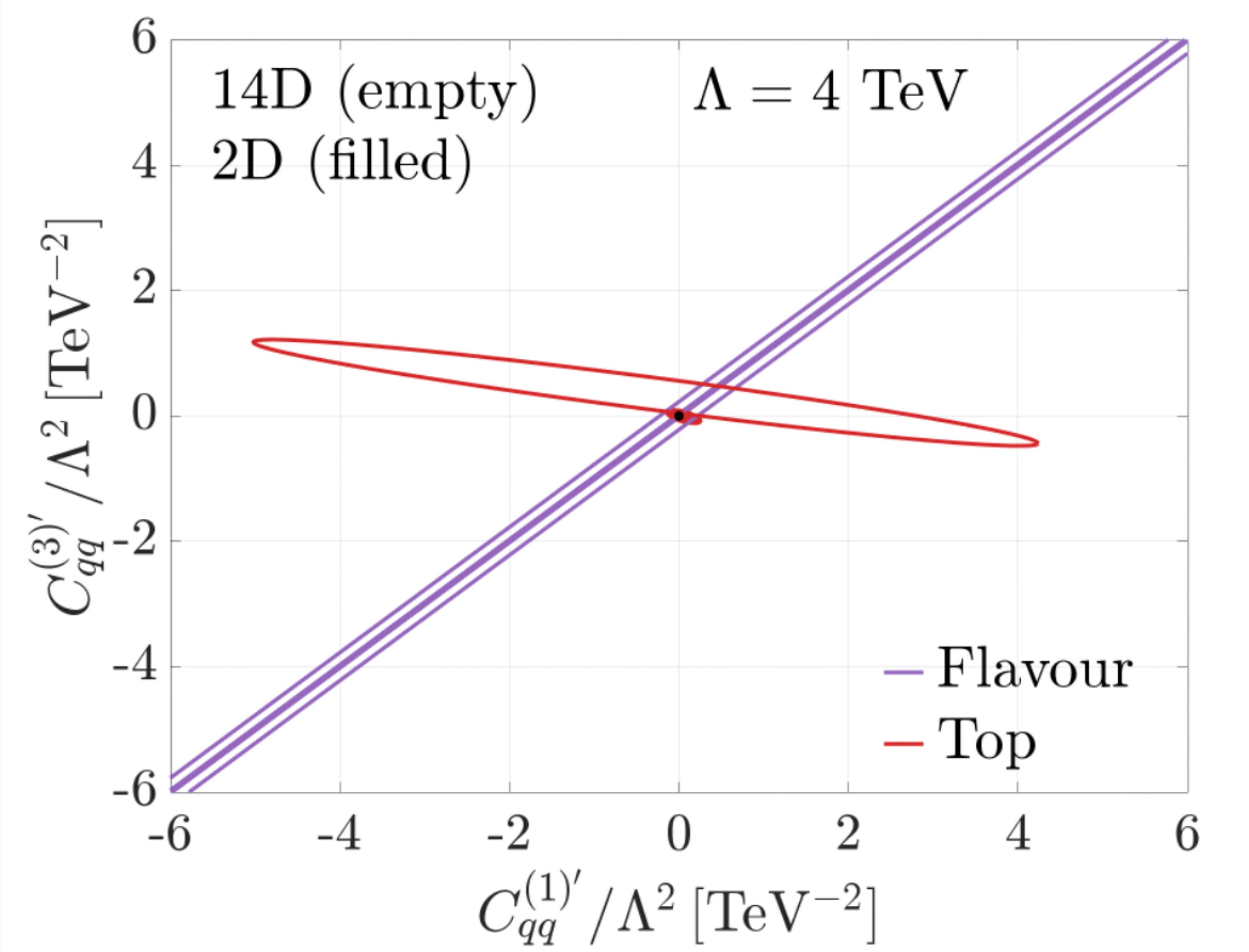


[2003.05432: Aoude, Hurth, Renner, Shepherd]

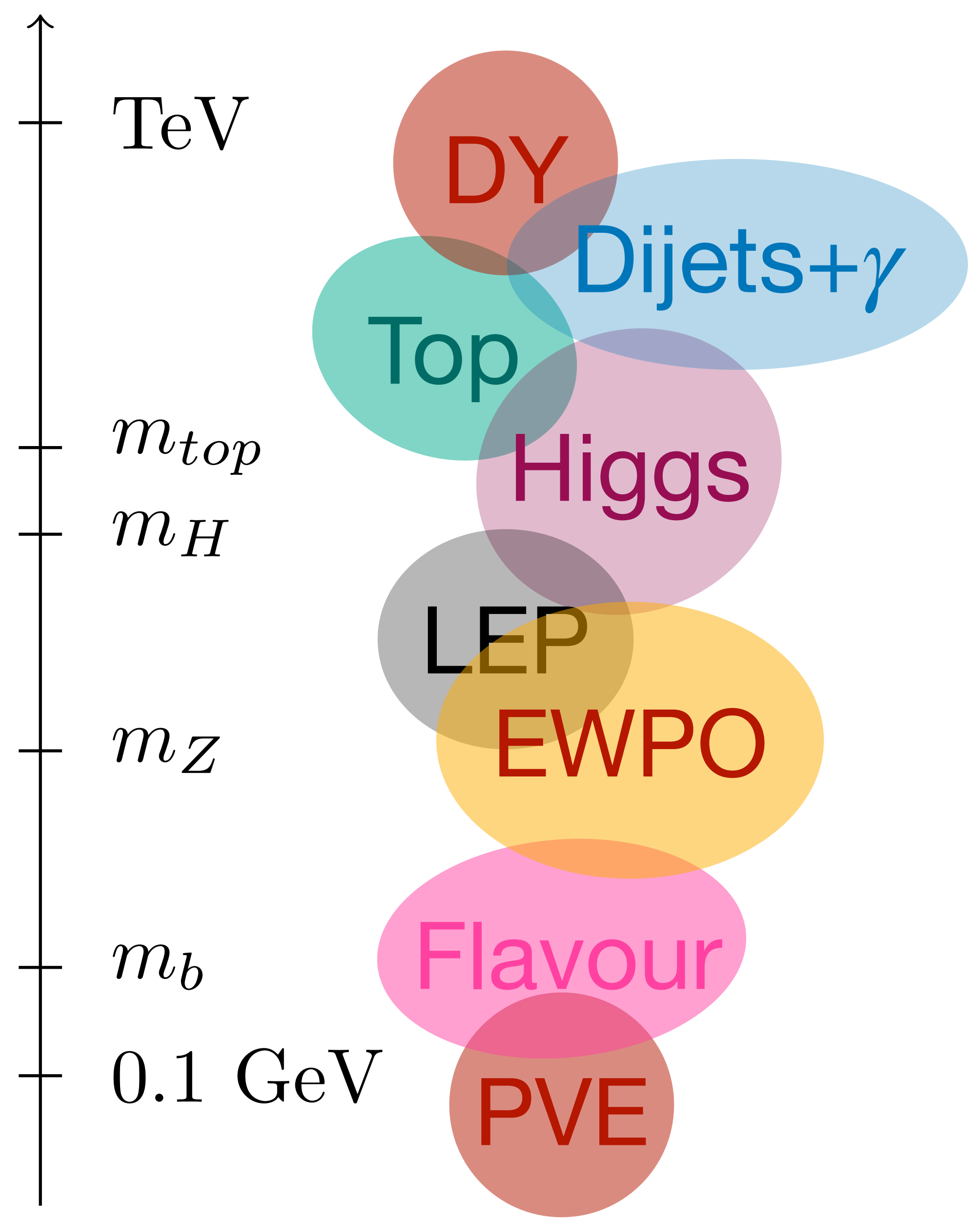
Even if suppressed flavour observables constrain **different directions** of the parameter space compared to top, thus improving significantly the bounds.



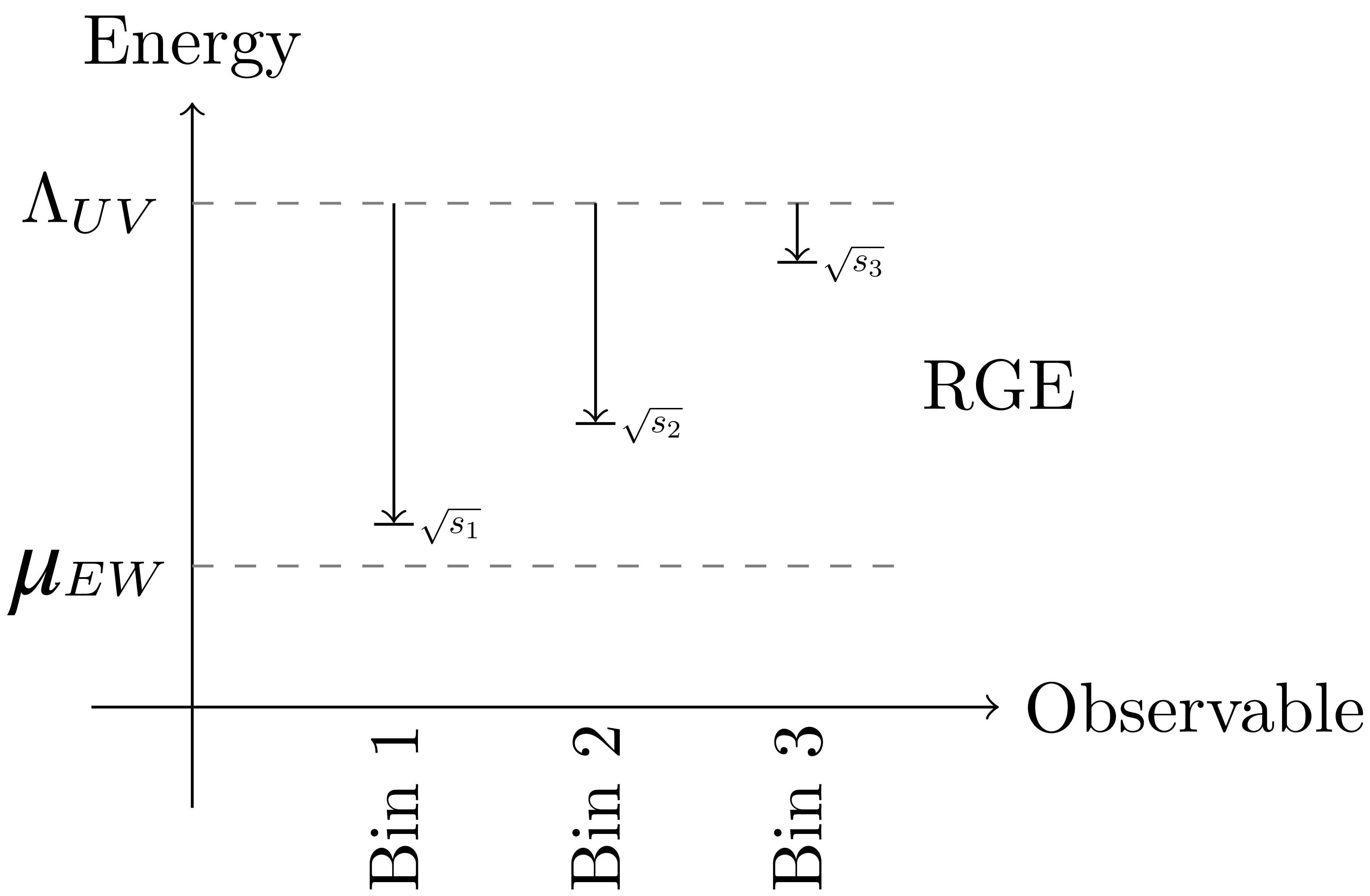
[2311.04963: RB, Biekötter, Hurth]

Fixed scale VS Process scale

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



PROCESS SCALE



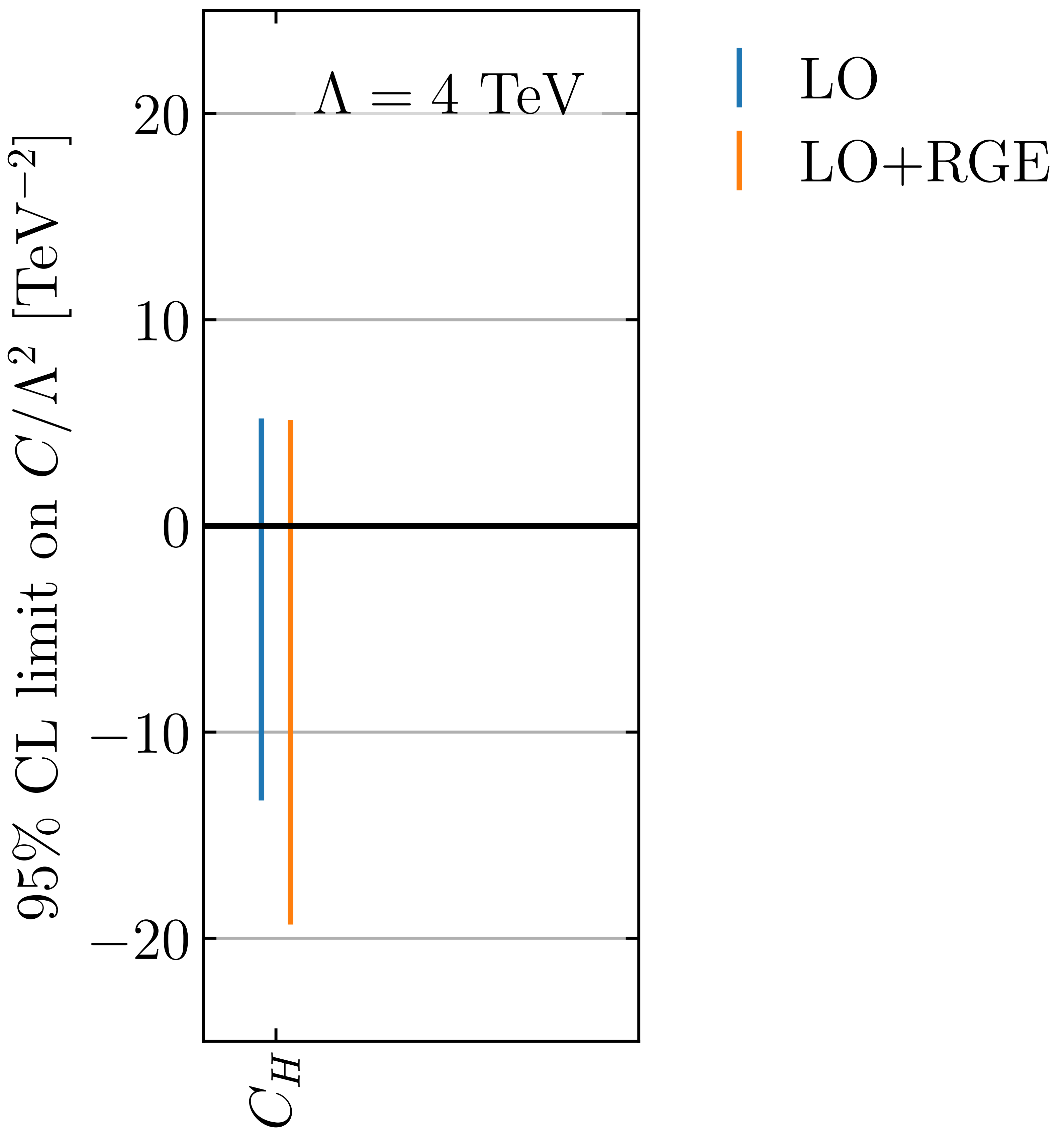
Choosing a dynamical scale instead of a fixed scale can sizeably influence the constraints on the Wilson coefficients.

[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.



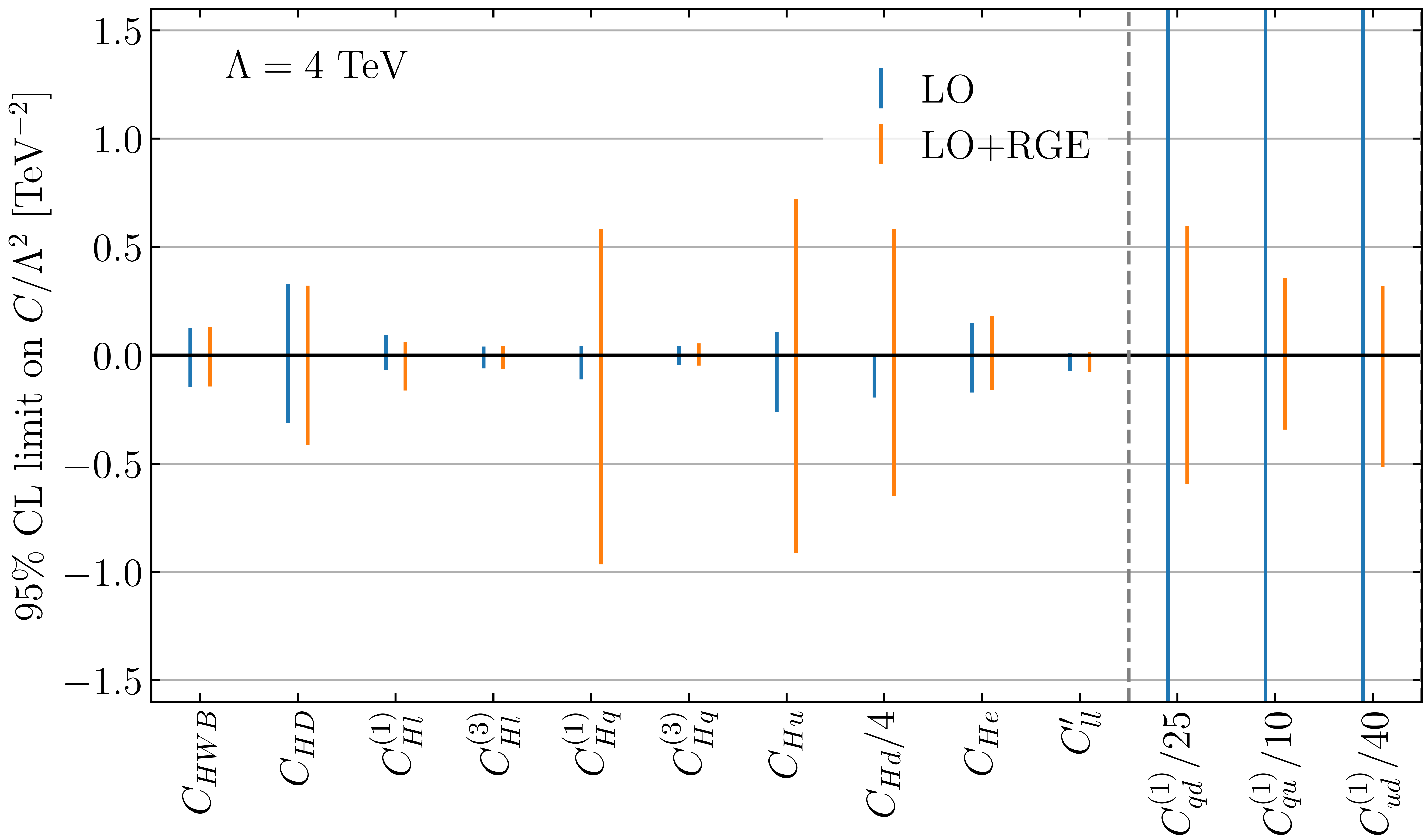
$$C_H(\mu_{EW}) = 0.65 C_H(\mu_\Lambda)$$

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.

RGE and correlations

Non-diagonal running effect:

$$C_{ed}(\mu_{EW}) = 0.02C_{ud}^{(1)}(\mu_\Lambda) + 0.01C_{qd}^{(1)}(\mu_\Lambda)$$



Including the RGE effects influences significantly EWPO operators

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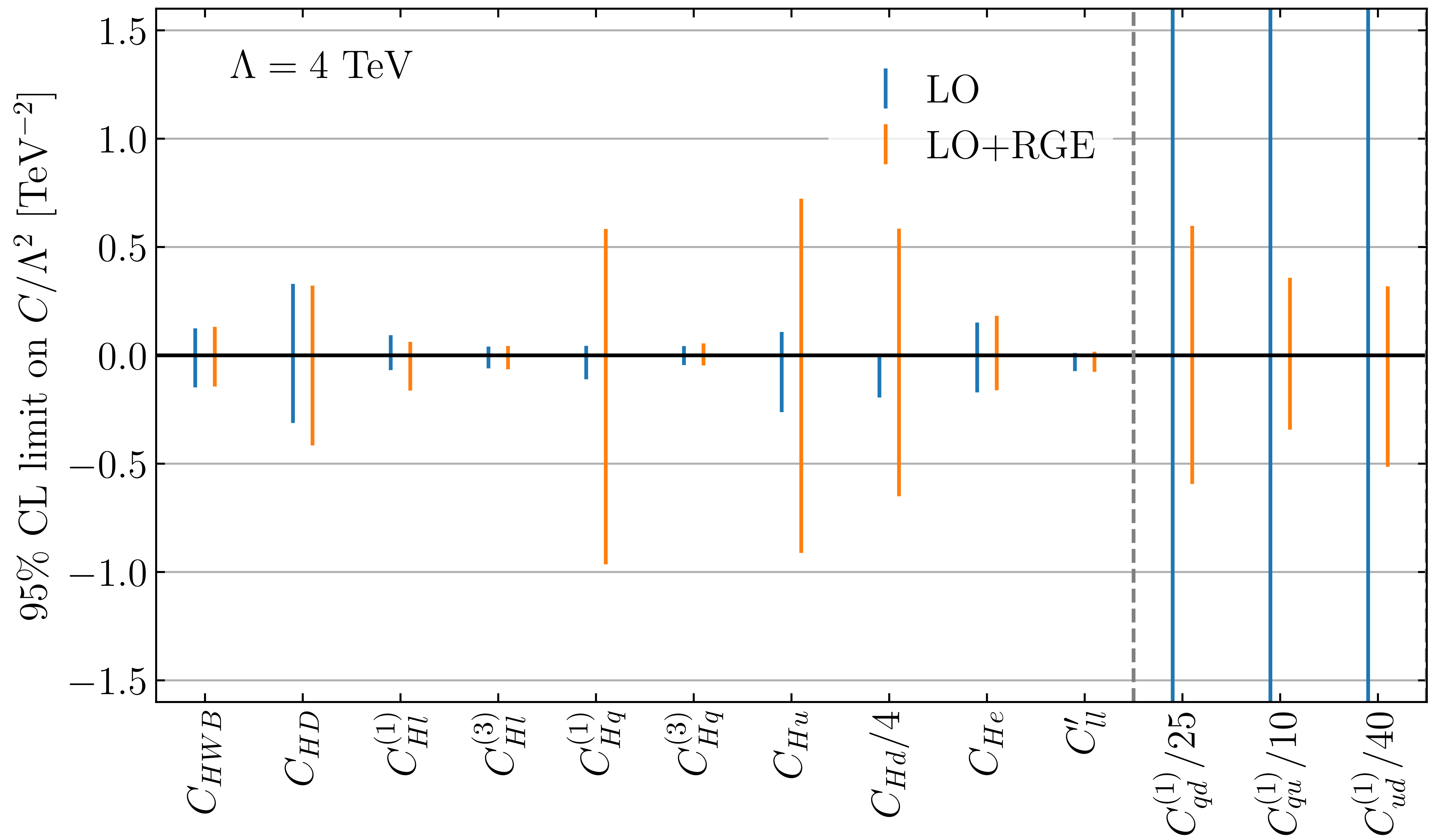
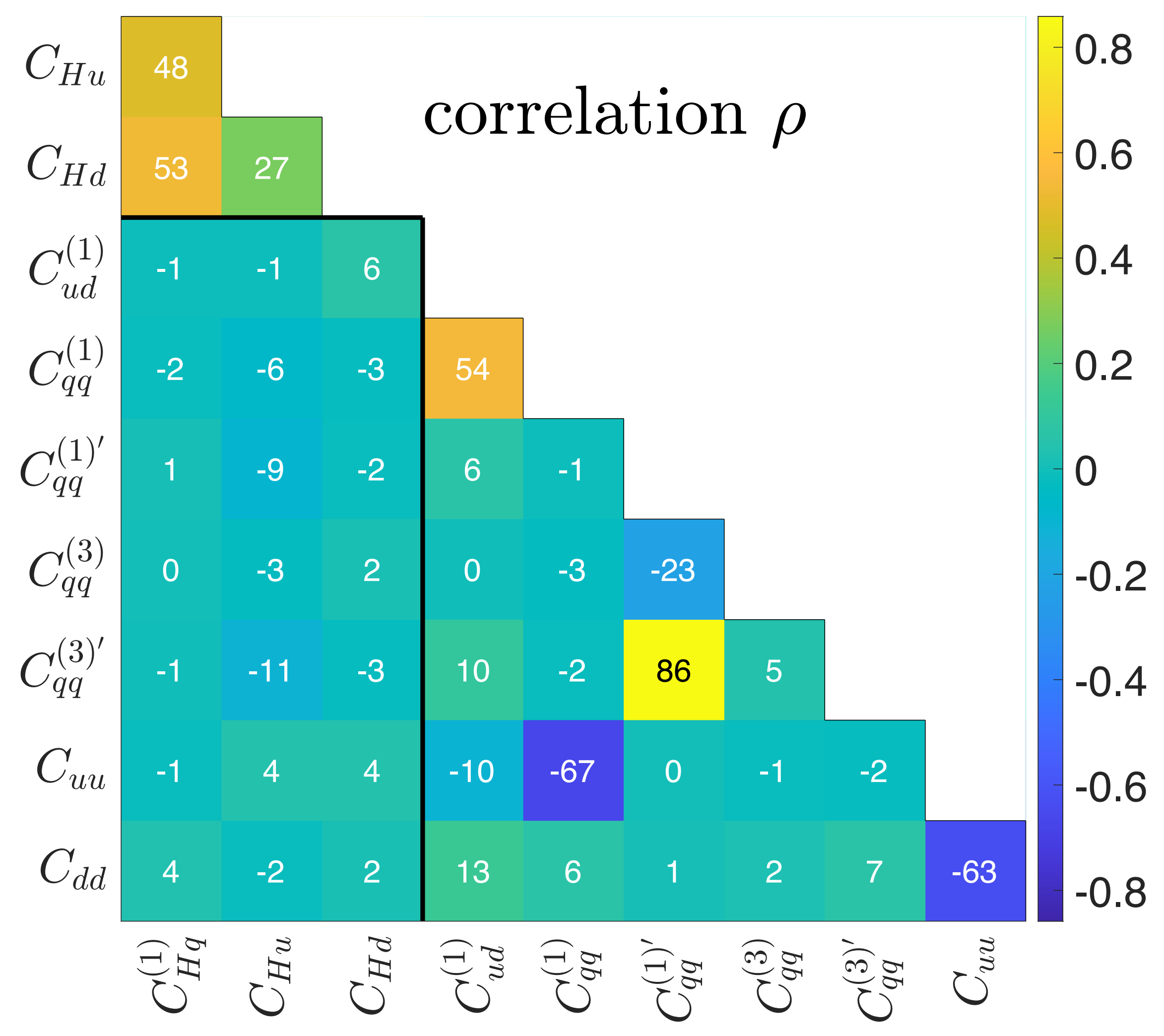


LO



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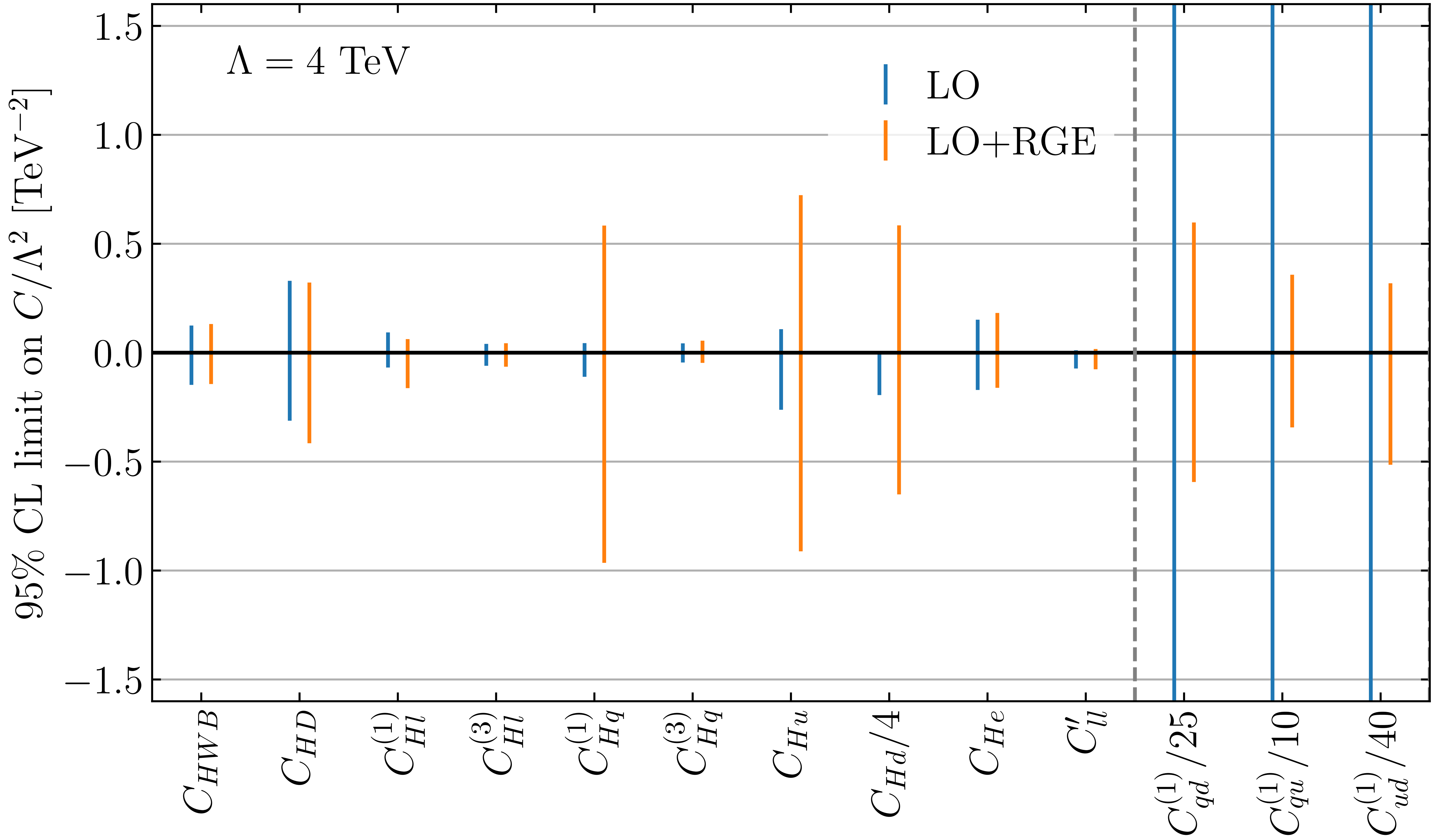
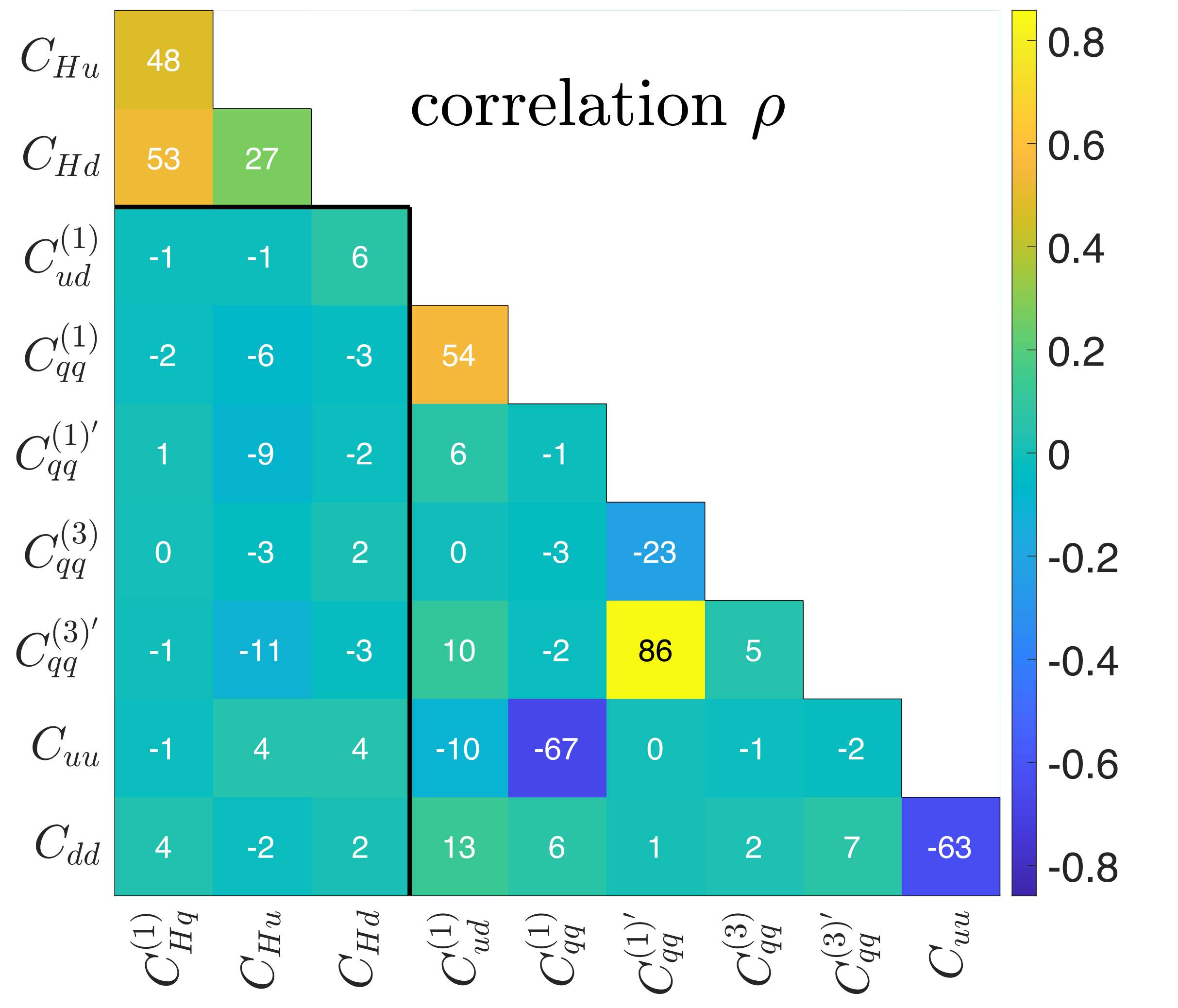
Non-diagonal running effect:

$$C_{ed}(\mu_{EW}) = 0.02 C^{(1)}_{ud}(\mu_\Lambda) + 0.01 C^{(1)}_{qd}(\mu_\Lambda)$$

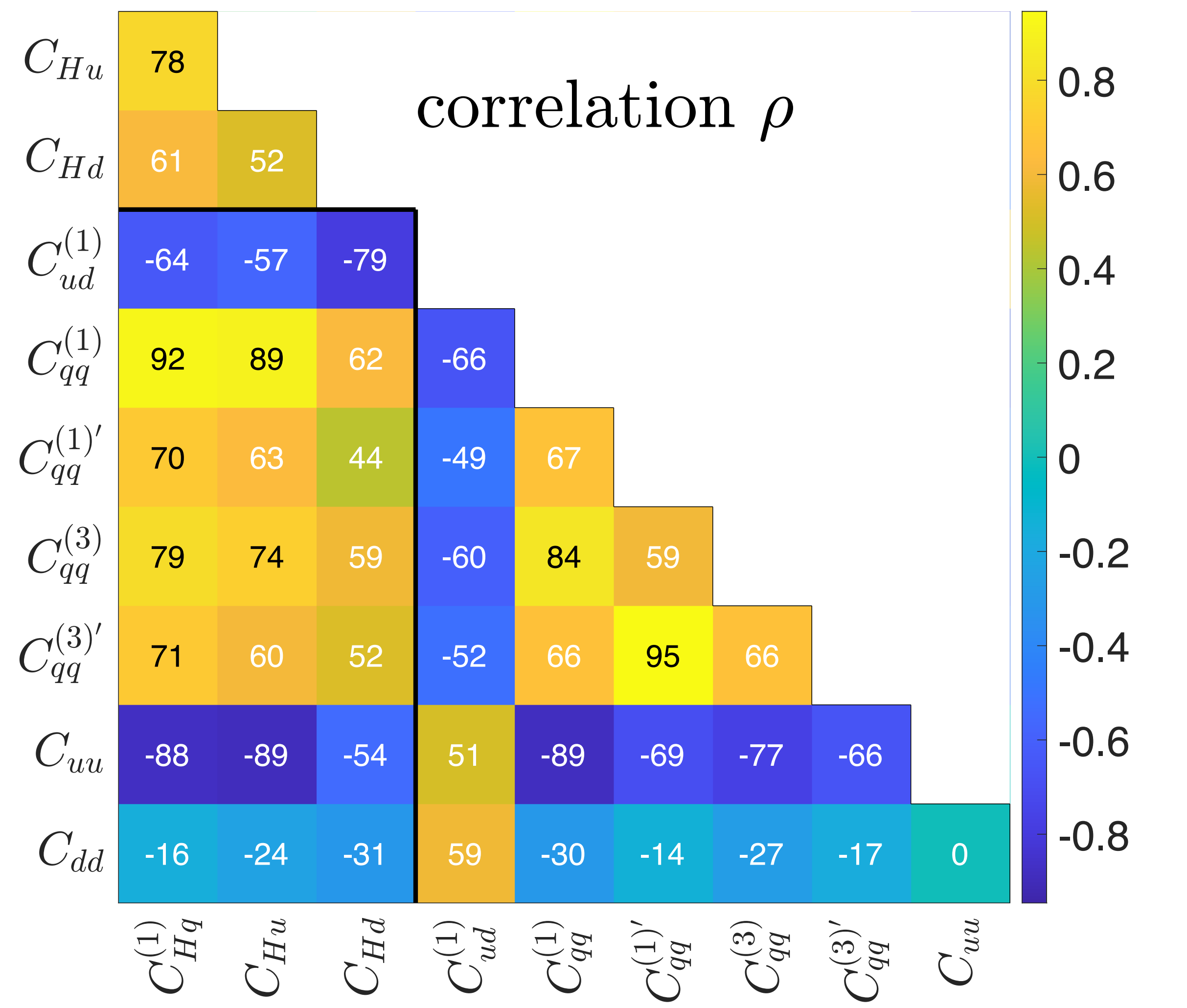


Including the RGE effects influences significantly EWPO operators

LO



LO+RGE



Summary and outlook

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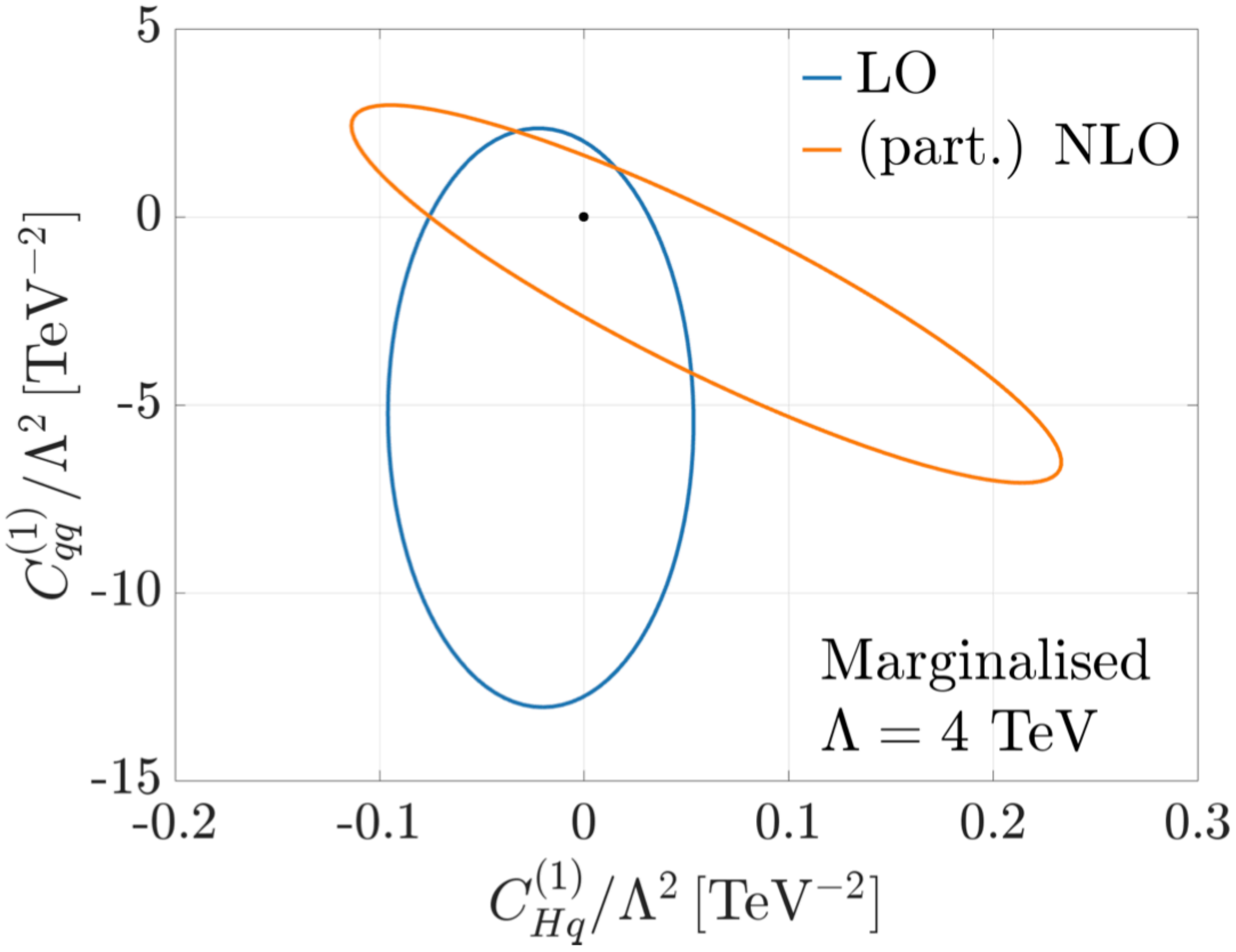
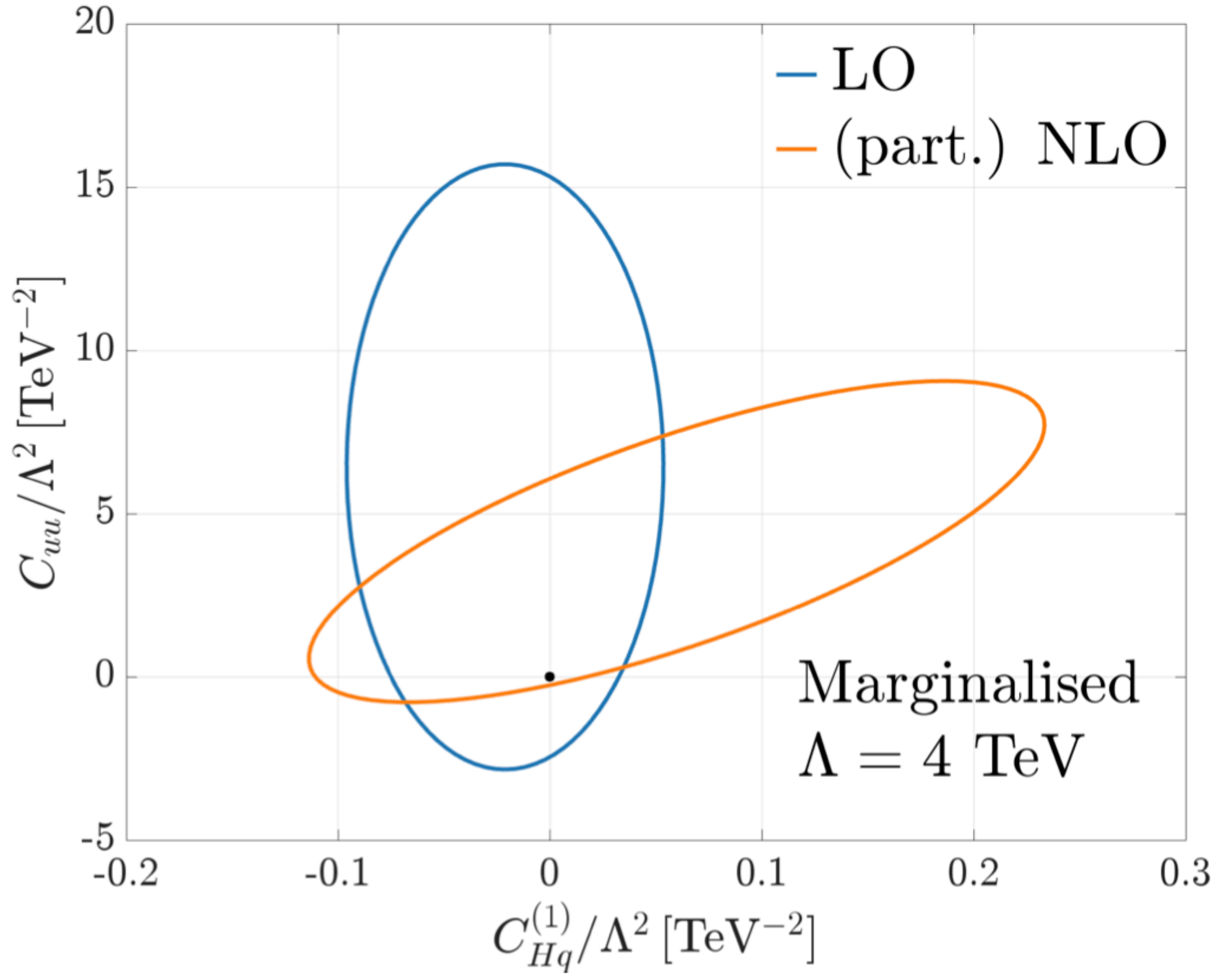
Thank you for your attention!

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.

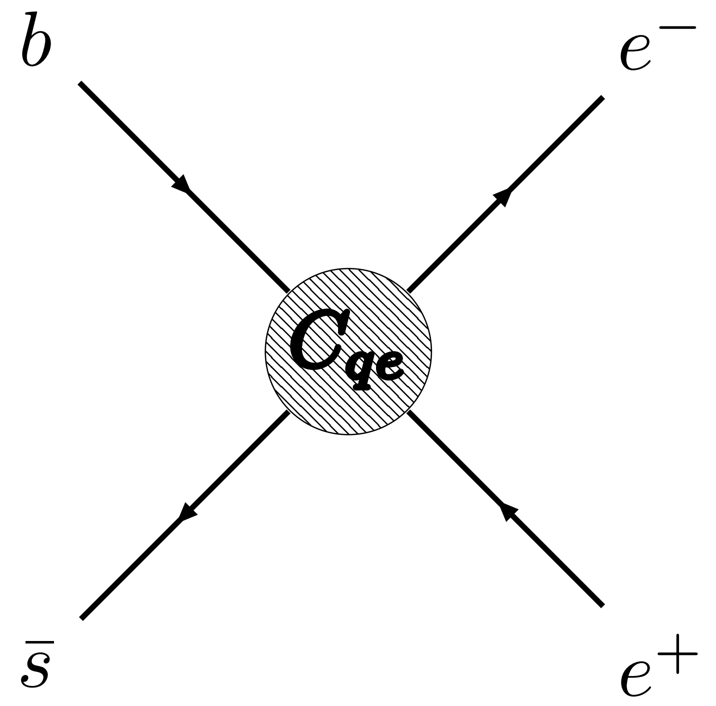




SMEFT and flavour symmetry

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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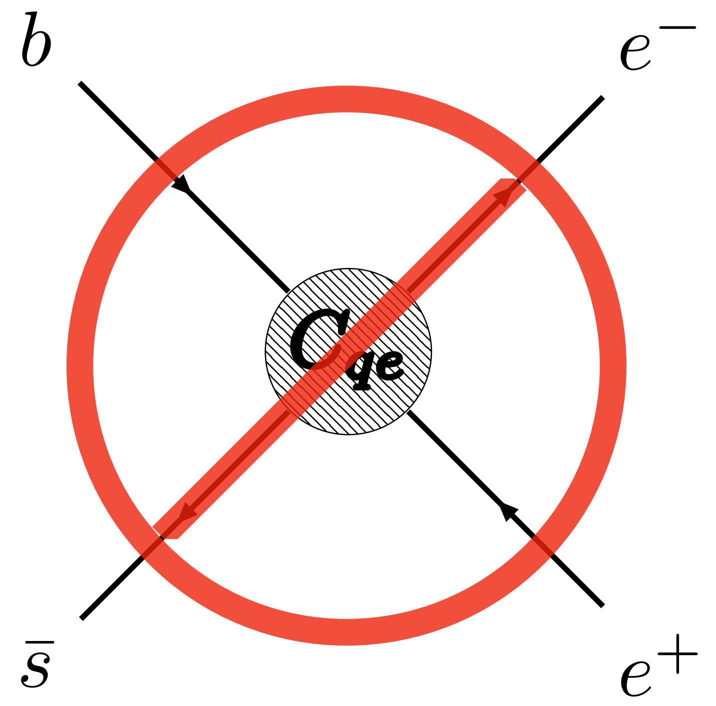

From 2499 dimension six operators to 41 (CP even)

[2005.05366: Faroughy, Isidori, Wilsch, Yamamoto]

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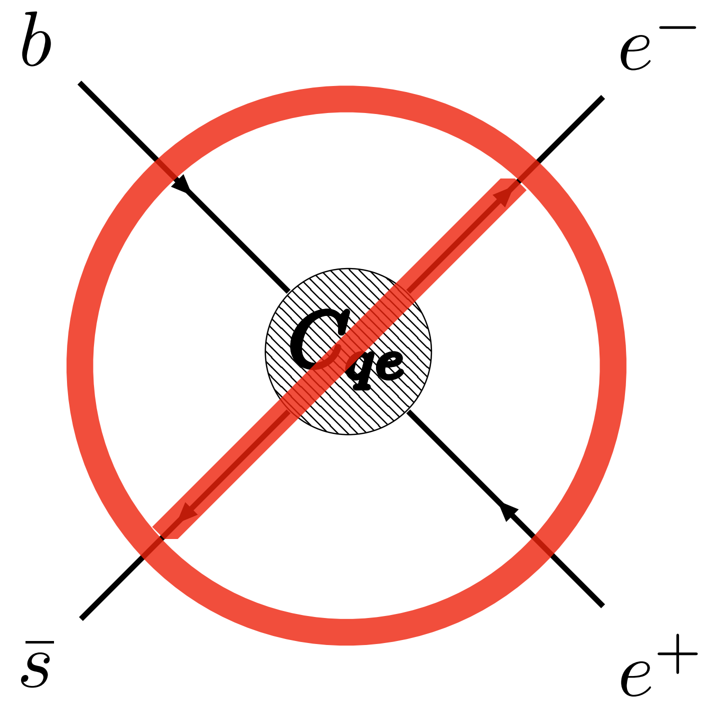

From 2499 dimension six operators to 41 (CP even)

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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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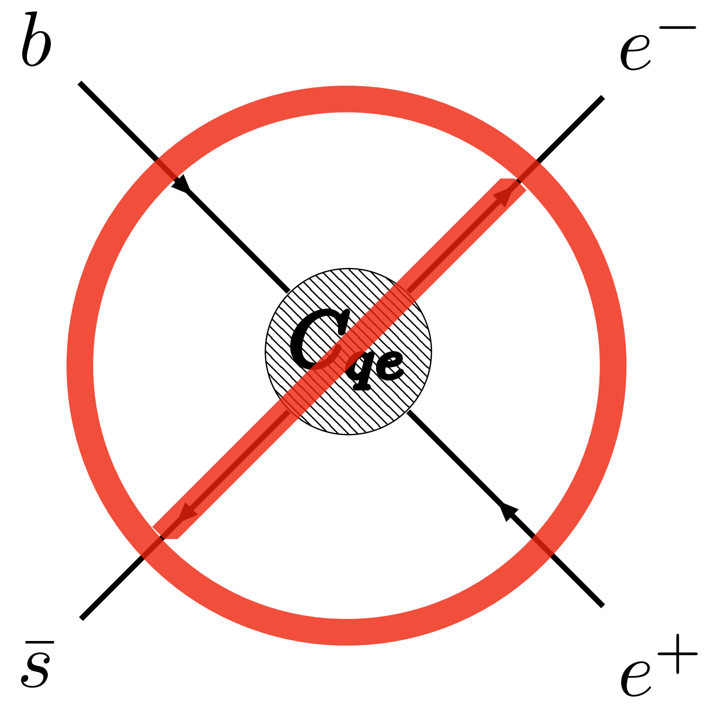

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- For some 4-fermion operators there are two independent ways to contract the flavour indices to get a flavour conserving operator.

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

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

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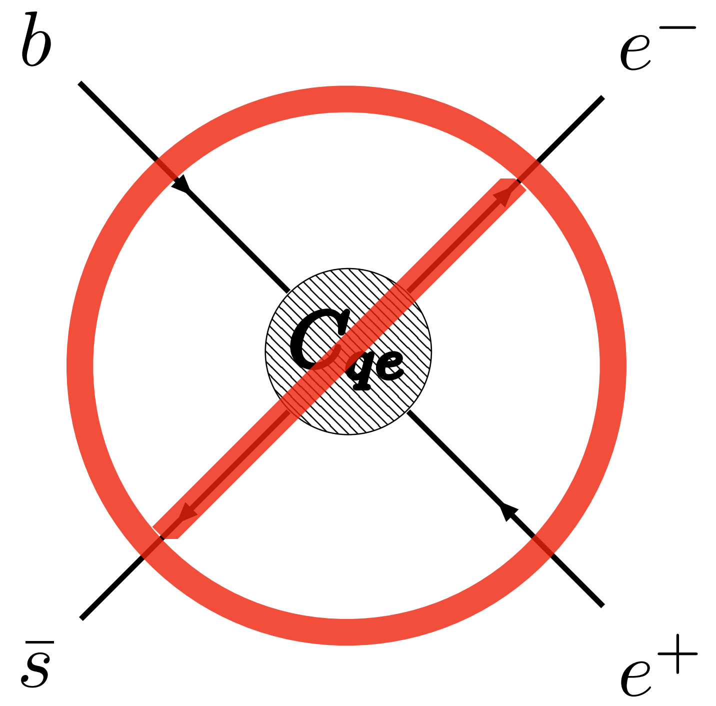

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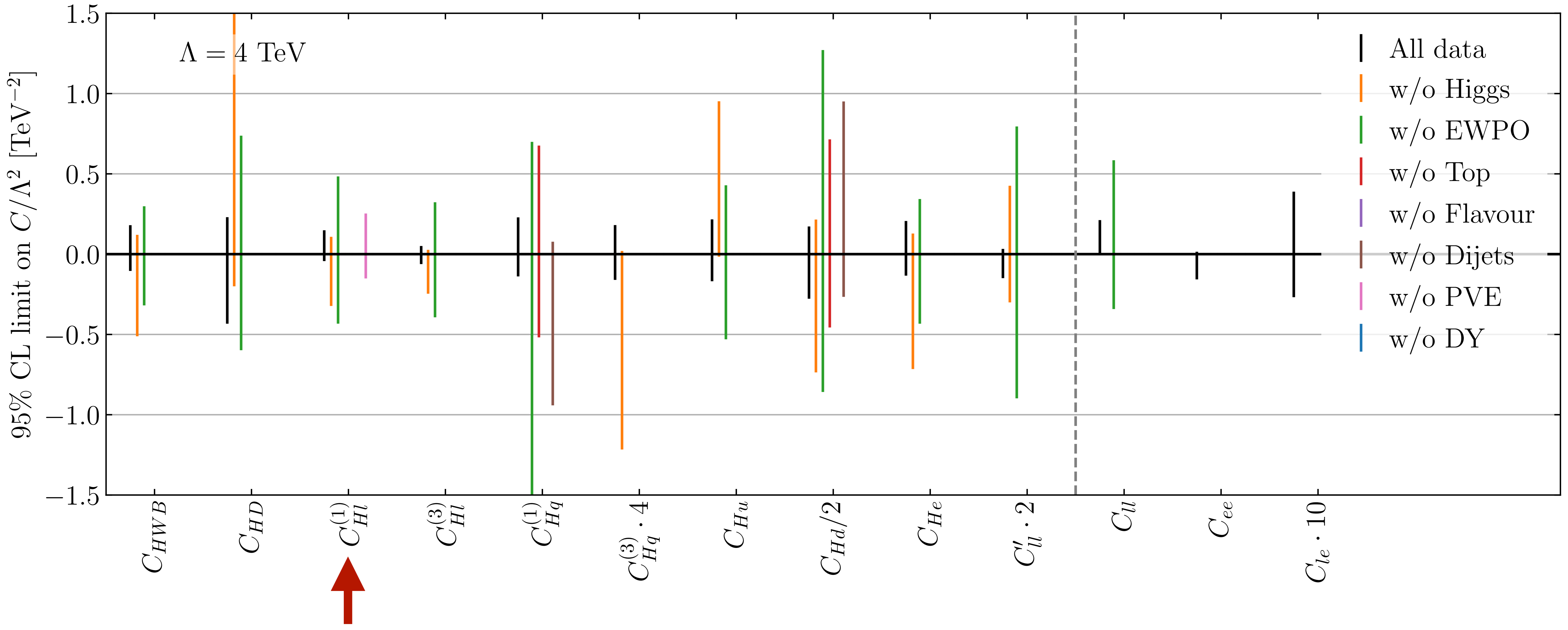
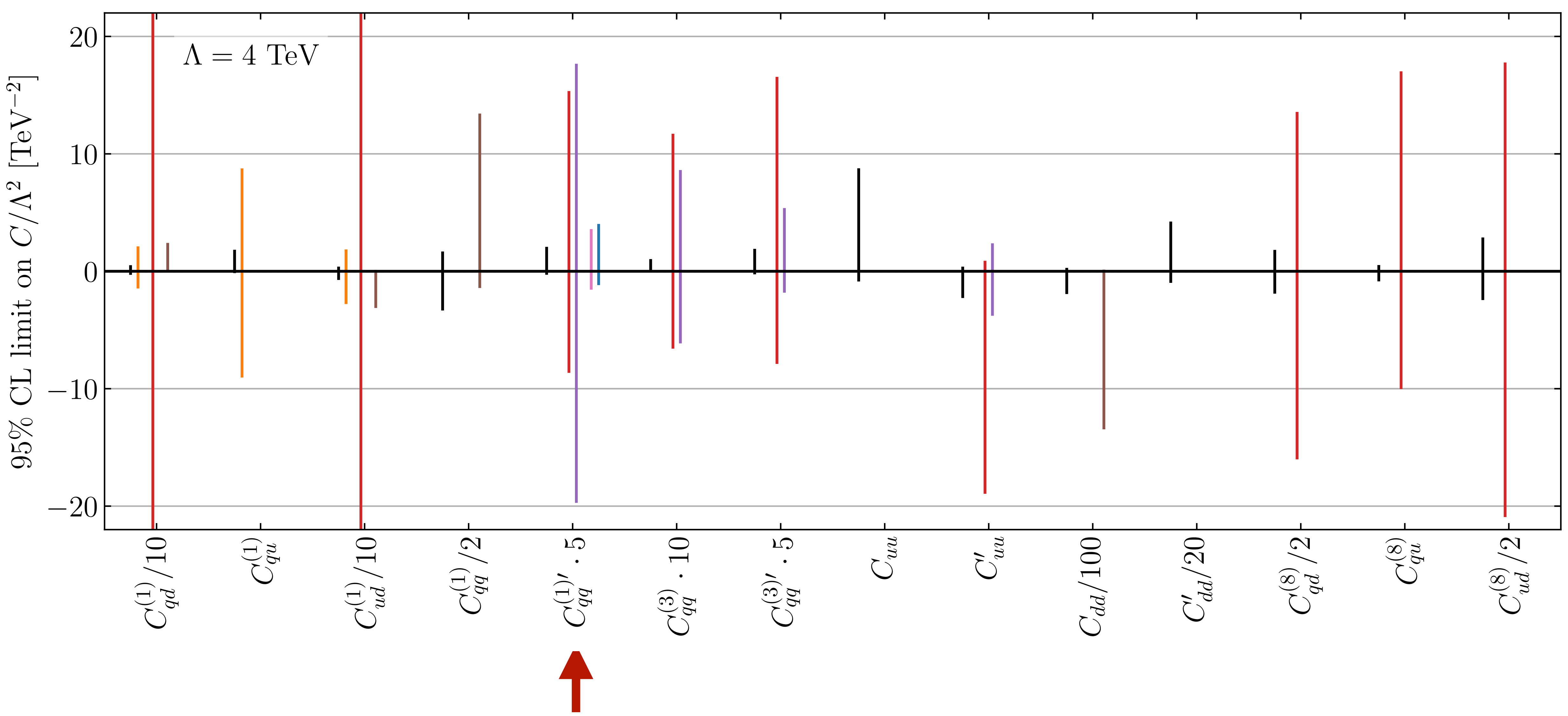
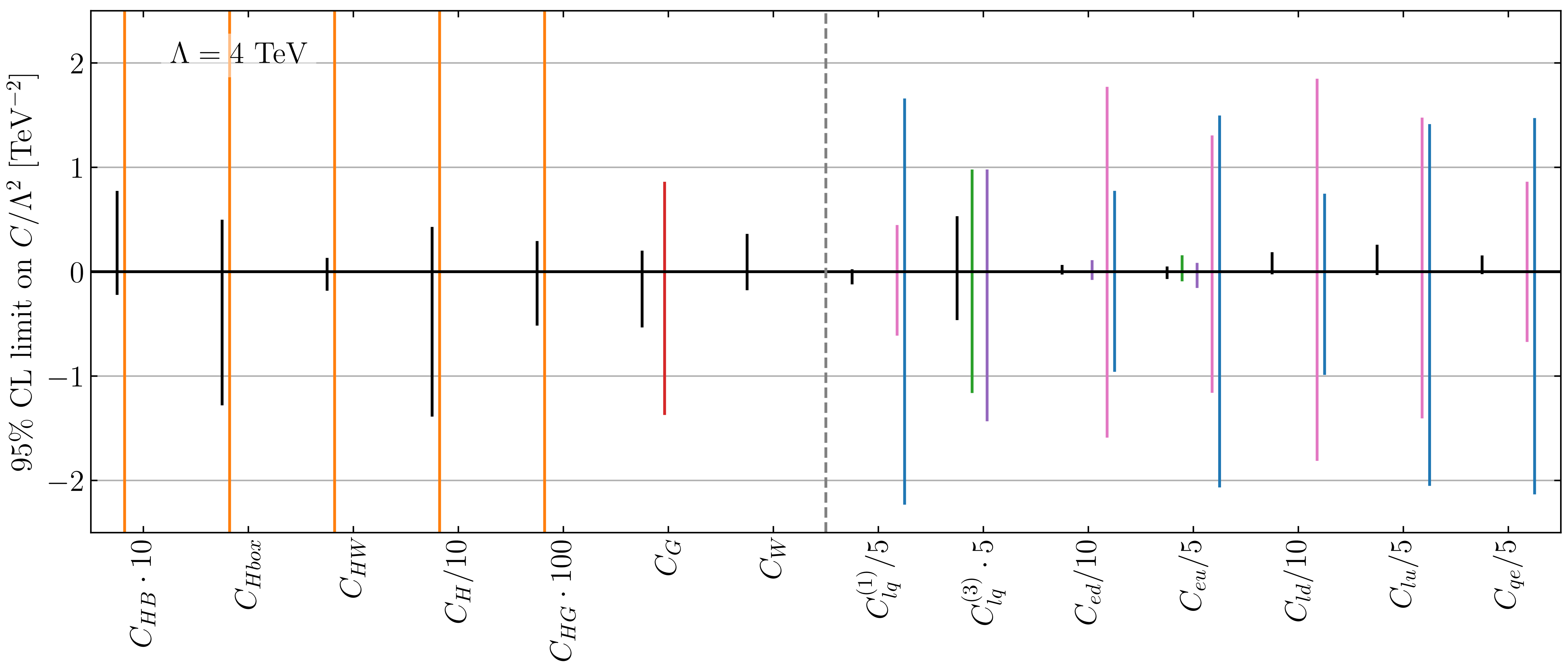
This assumption corresponds to minimal version of MFV: it contains the minimum and non-removable amount of flavour violation.

Full results removing datasets



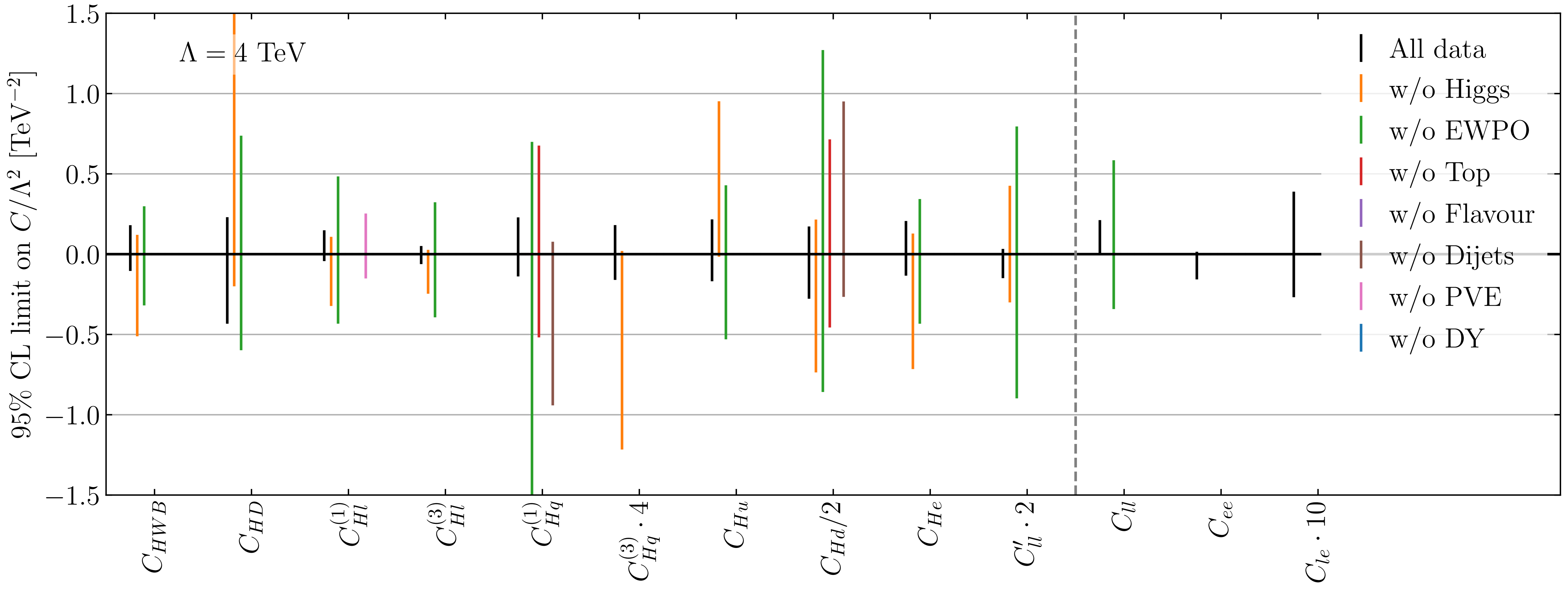


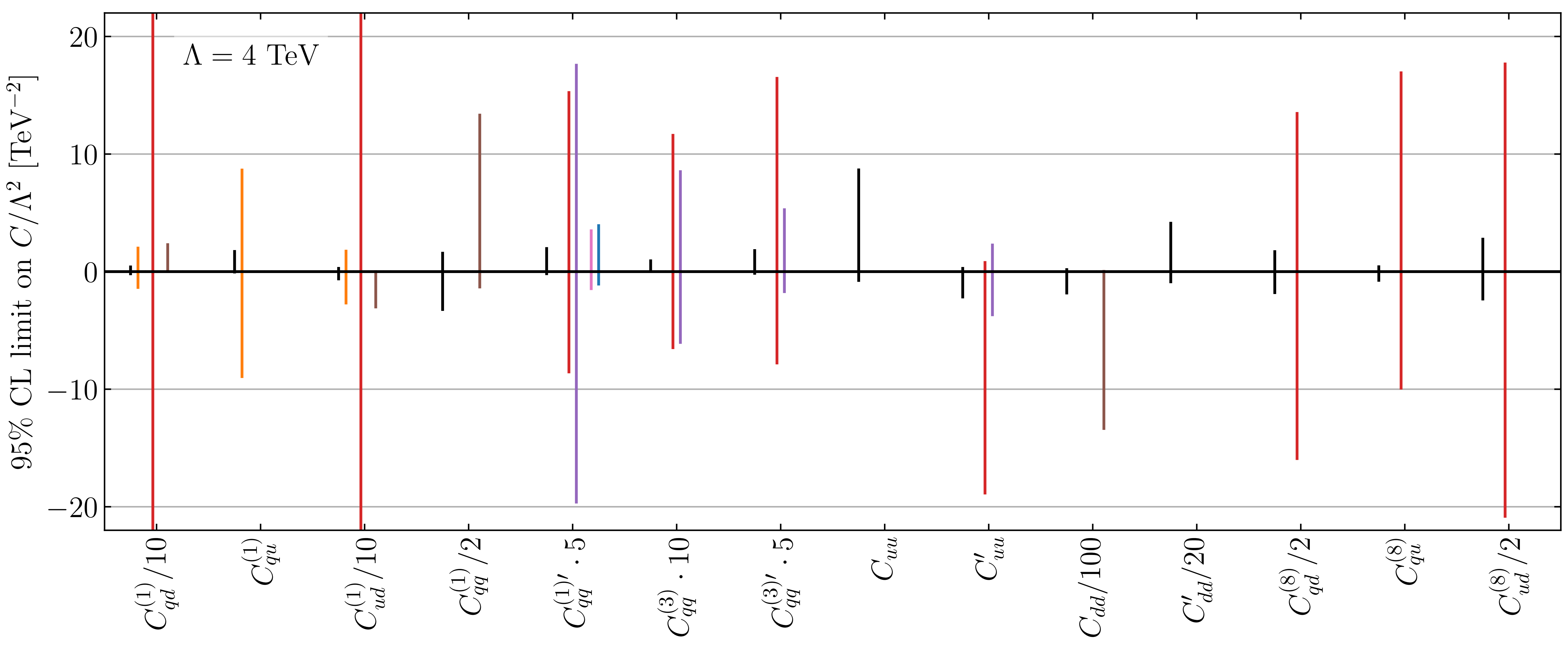


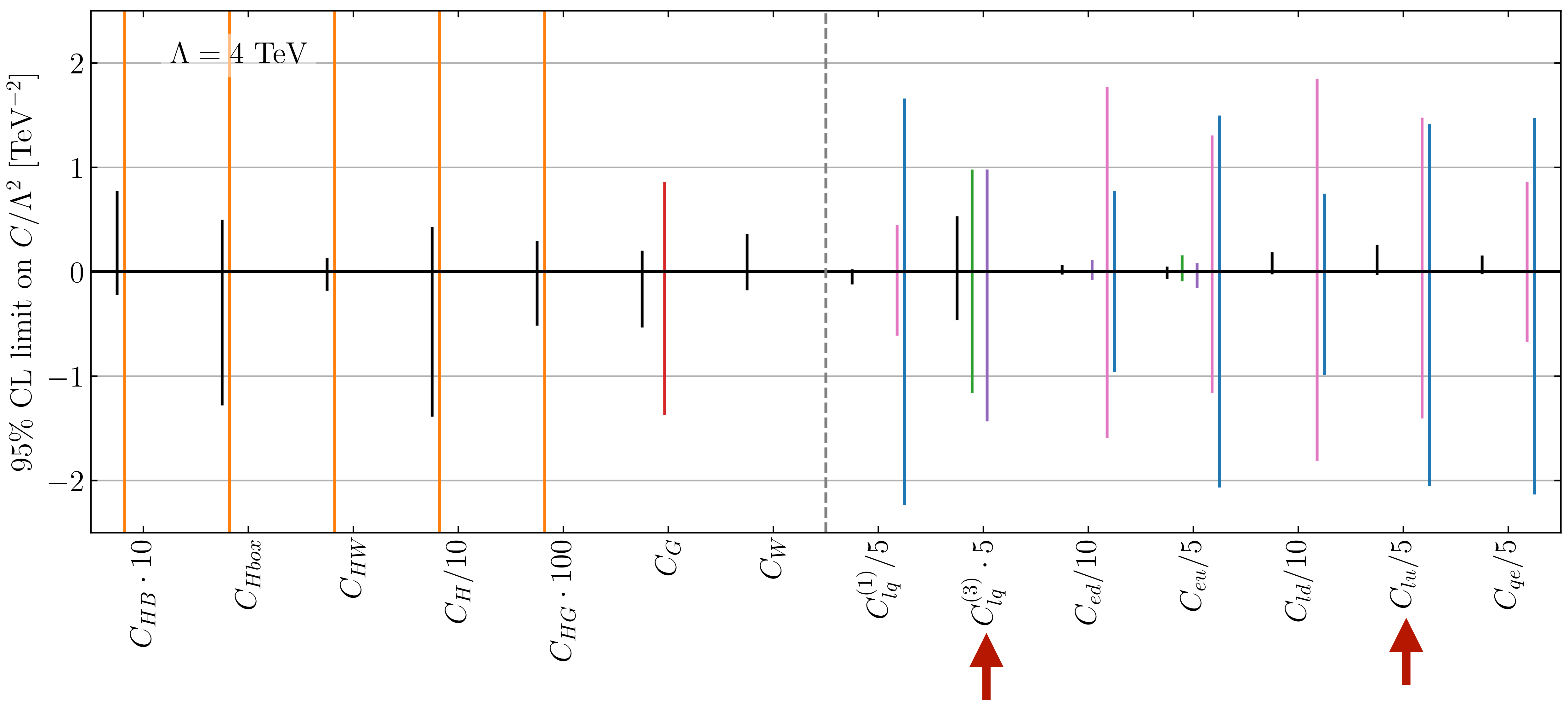
- PVE impact on $C_{Hl}^{(1)}$ and $C_{qq}^{(1)\prime}$

[2311.04963: RB, Biekötter, Hurth]

Full results removing datasets



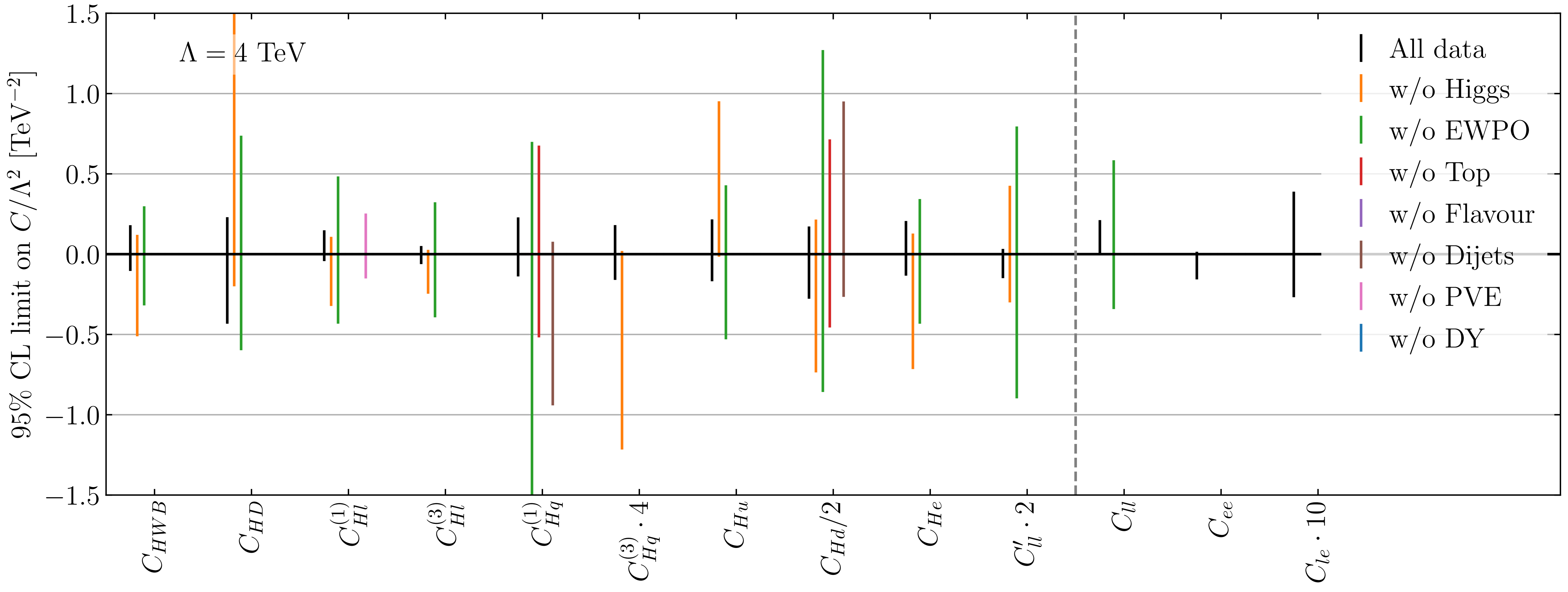


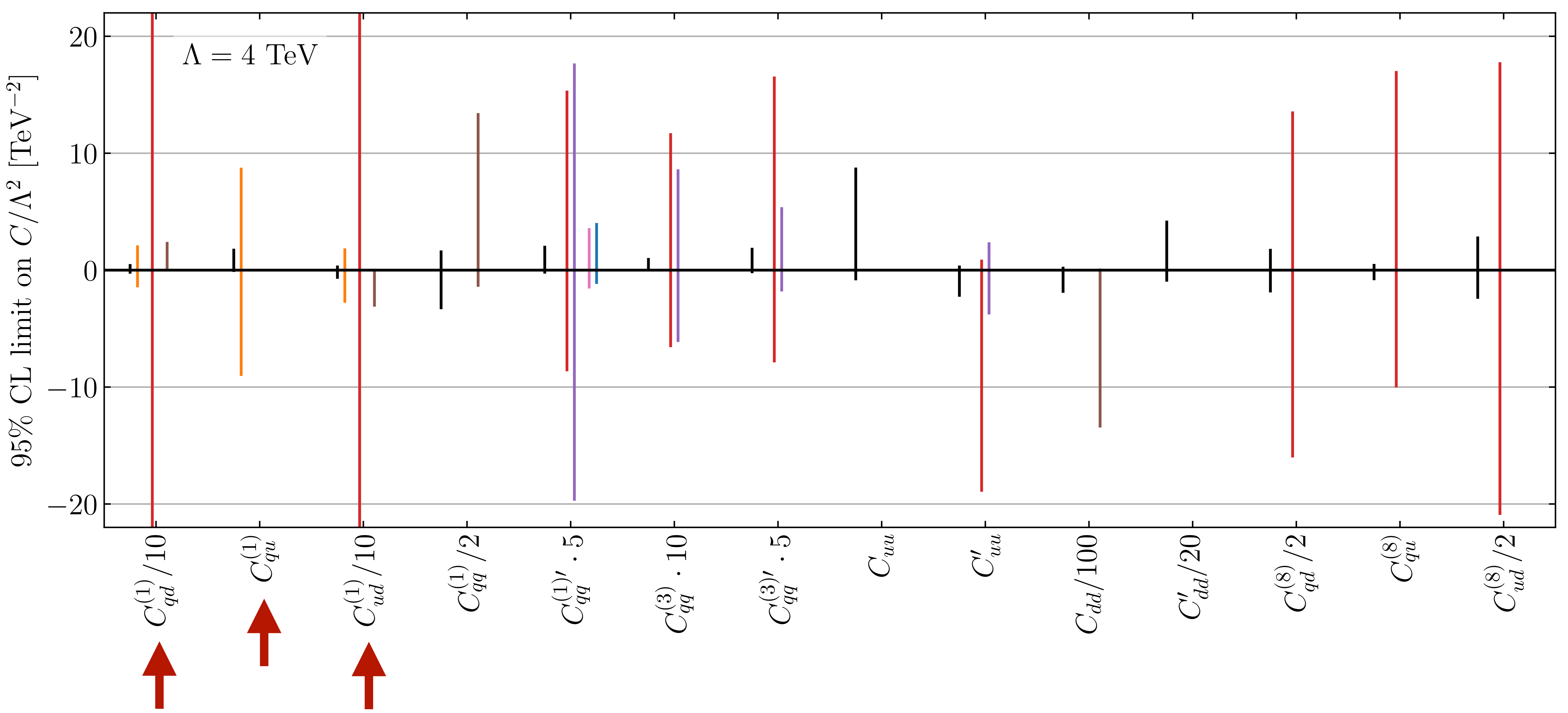


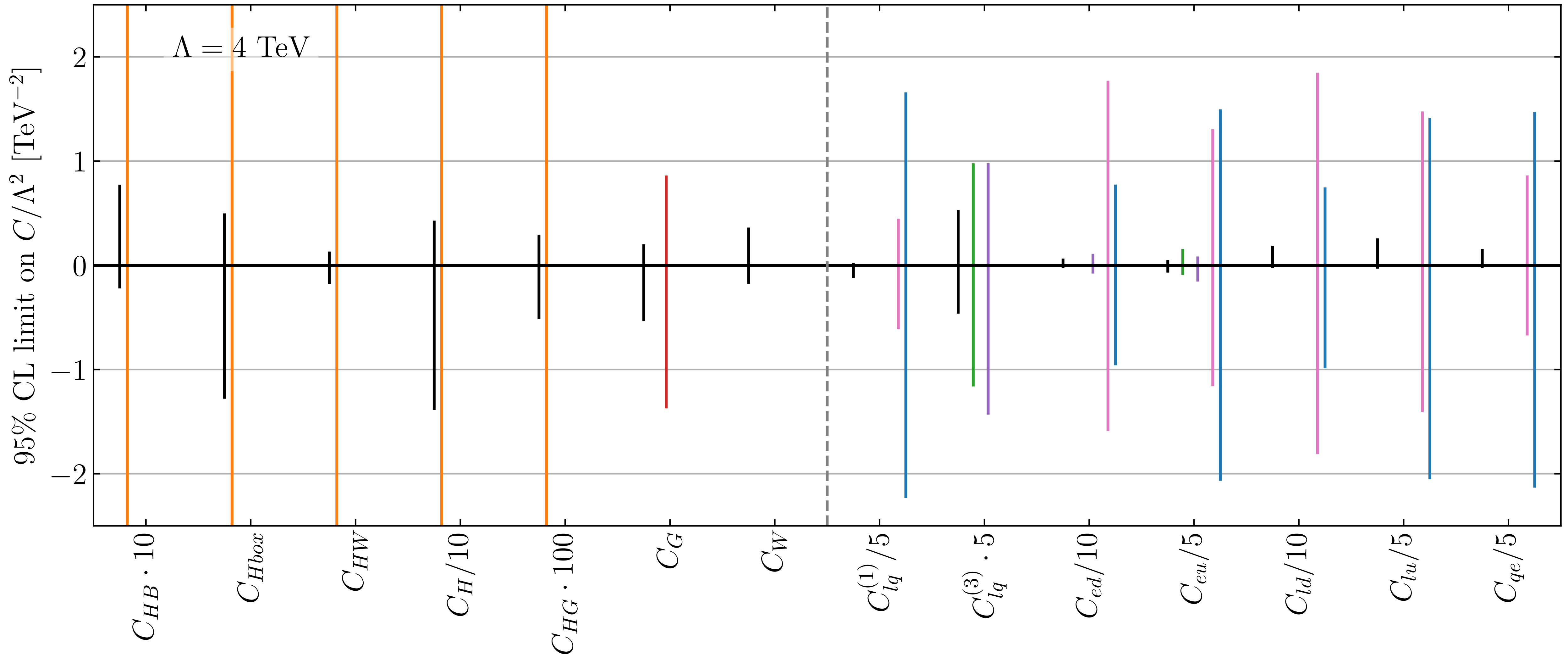
- PVE impact on $C_{Hl}^{(1)}$ and $C_{qq}^{(1)'}$
- NLO EWPO impact on $C_{lq}^{(3)}$ and C_{lu}

[2311.04963: RB, Biekötter, Hurth]

Full results removing datasets







- PVE impact on $C_{Hl}^{(1)}$ and $C_{qq}^{(1)\prime}$
- 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]

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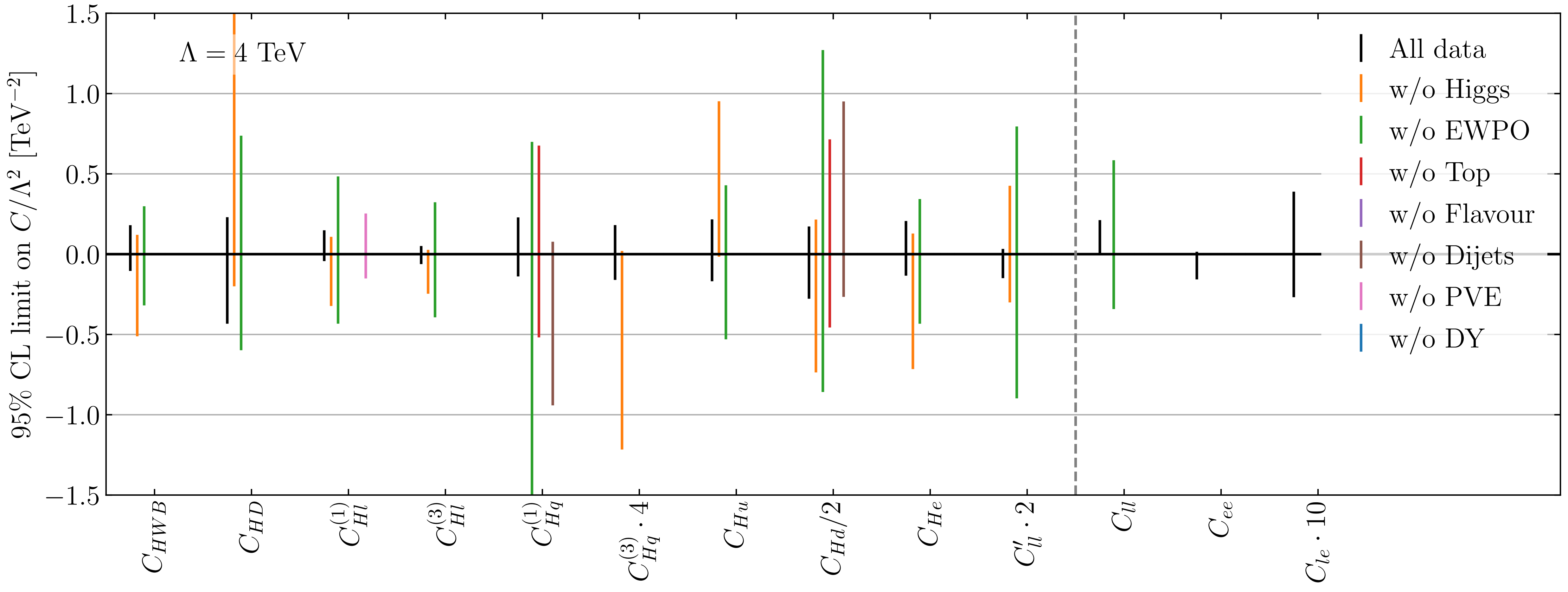

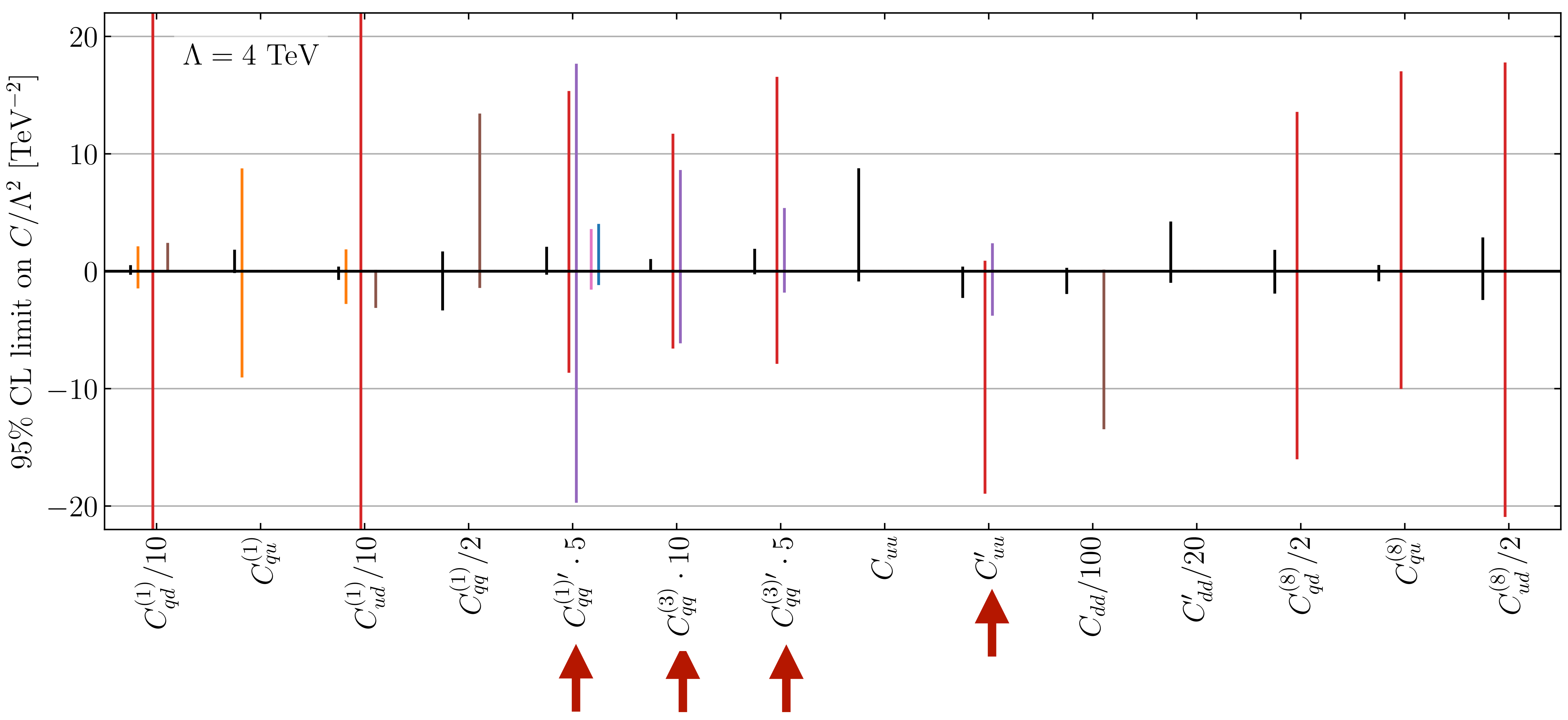

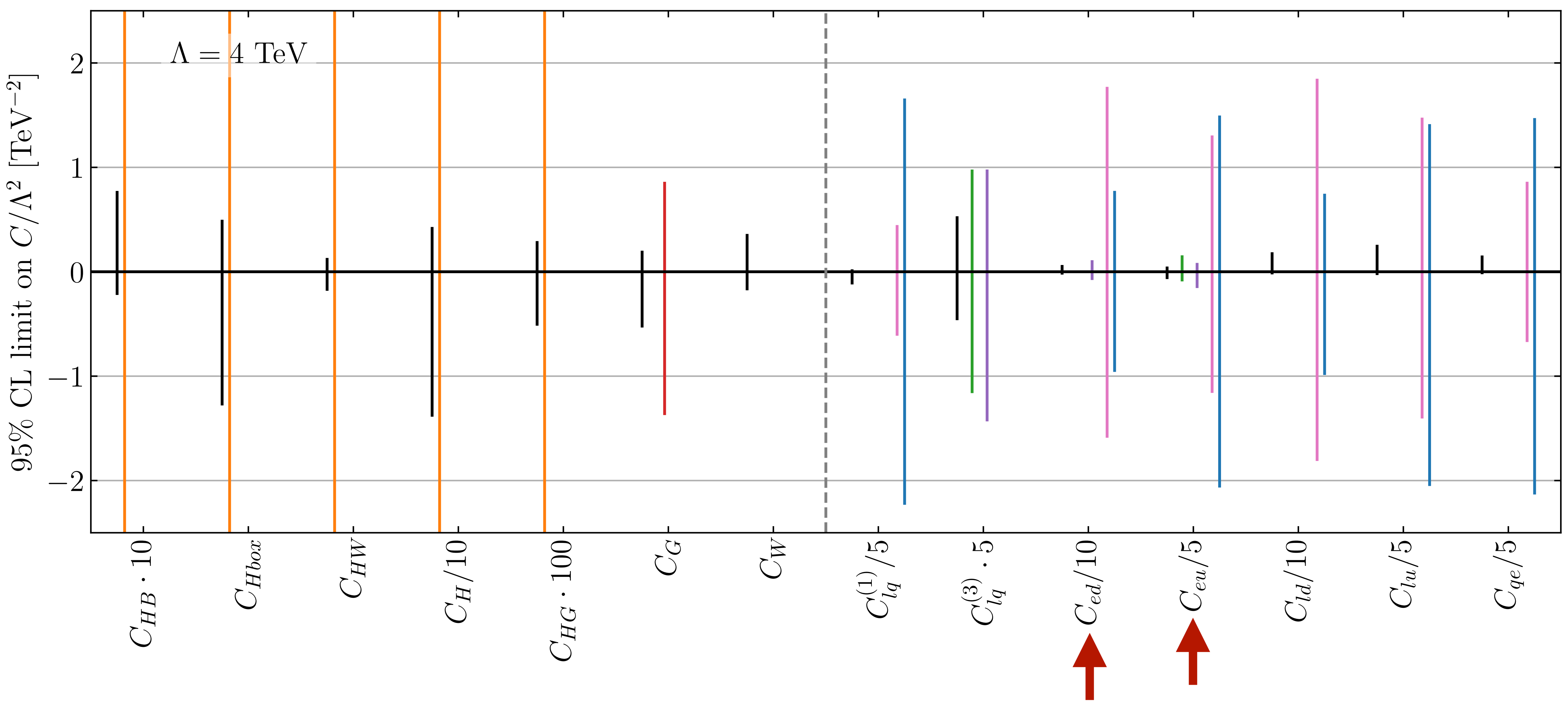

- PVE impact on $C_{Hl}^{(1)}$ and $C_{qq}^{(1)\prime}$
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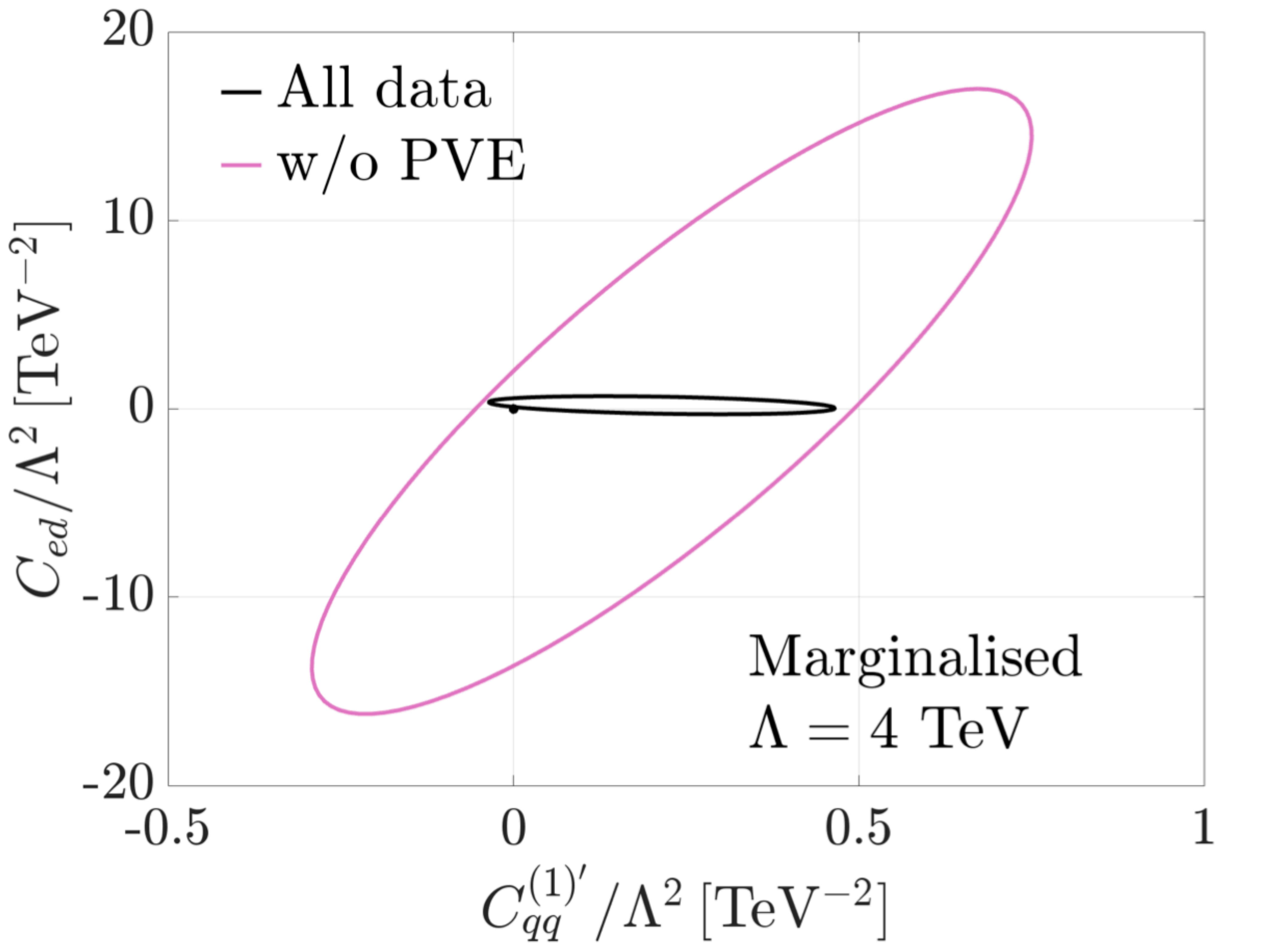
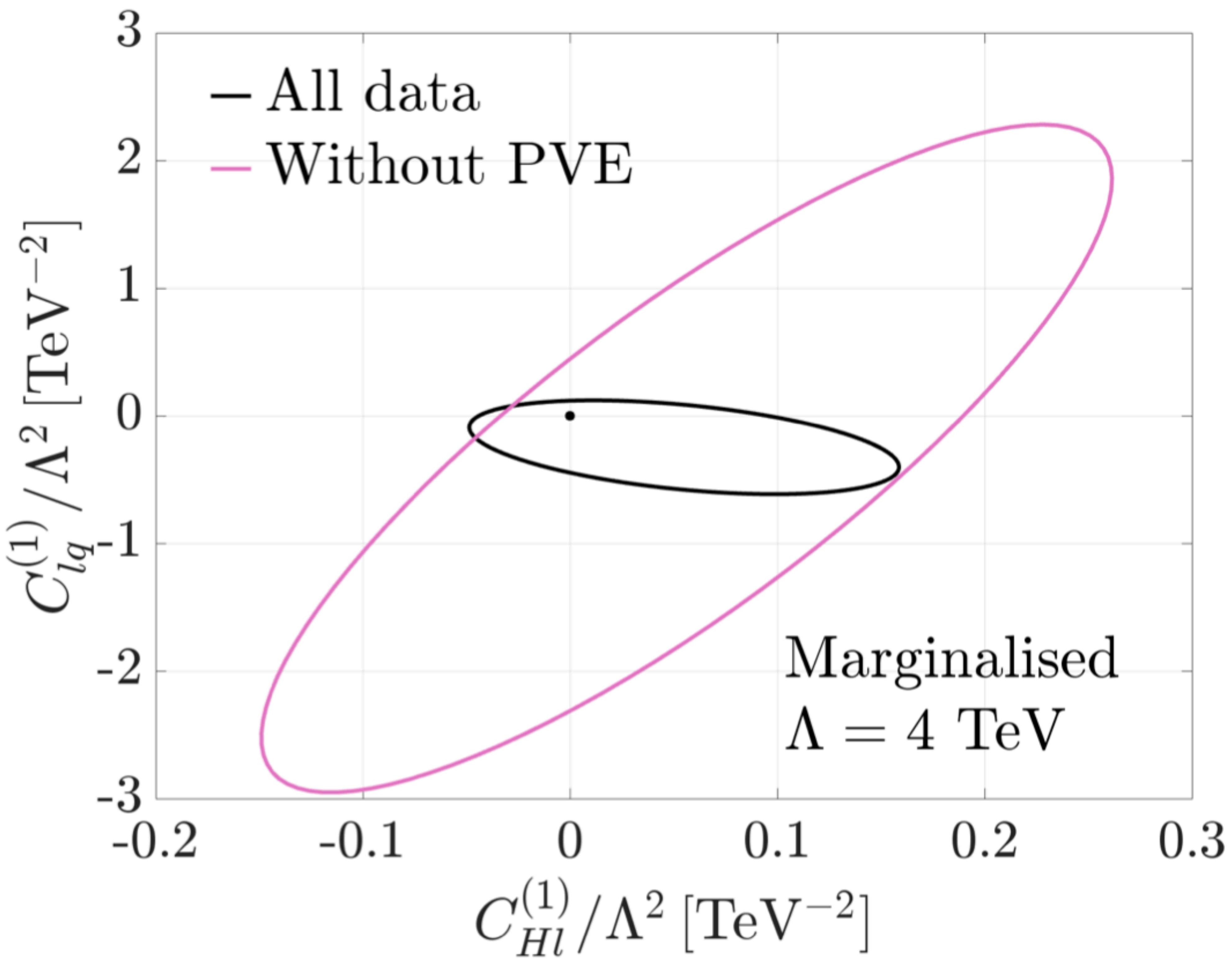
- NLO Top and Higgs impact on $C_{qd}^{(1)}$, $C_{qu}^{(1)}$ and $C_{ud}^{(1)}$
- Flavour impact on semi-leptonic and 4-quark operators (more details later)

[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 $C_{qq}^{(1)\prime}$ and $C_{Hl}^{(1)}$.





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	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar{l}_p e_r \varphi)$
$Q_{\widetilde{G}}$	$f^{ABC} \widetilde{G}_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar{q}_p u_r \widetilde{\varphi})$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar{q}_p d_r \varphi)$
$Q_{\widetilde{W}}$	$\varepsilon^{IJK} \widetilde{W}_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				

$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eW}	$(\bar{l}_p\sigma^{\mu\nu}e_r)\tau^I\varphi W_{\mu\nu}^I$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\,\varphi)(\bar{l}_p\gamma^\mu l_r)$
$Q_{\varphi\widetilde{G}}$	$\varphi^\dagger\varphi\, \widetilde{G}_{\mu\nu}^A G^{A\mu\nu}$	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}	$(\bar{q}_p\sigma^{\mu\nu}T^A u_r)\widetilde{\varphi}\, G_{\mu\nu}^A$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\,\varphi)(\bar{e}_p\gamma^\mu e_r)$
$Q_{\varphi\widetilde{W}}$	$\varphi^\dagger\varphi\, \widetilde{W}_{\mu\nu}^I W^{I\mu\nu}$	Q_{uW}	$(\bar{q}_p\sigma^{\mu\nu}u_r)\tau^I\widetilde{\varphi}\, W_{\mu\nu}^I$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\,\varphi)(\bar{q}_p\gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu}B^{\mu\nu}$	Q_{uB}	$(\bar{q}_p\sigma^{\mu\nu}u_r)\widetilde{\varphi}\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I\,\varphi)(\bar{q}_p\tau^I\gamma^\mu q_r)$
$Q_{\varphi\widetilde{B}}$	$\varphi^\dagger\varphi\, \widetilde{B}_{\mu\nu}B^{\mu\nu}$	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}	$(\bar{q}_p\sigma^{\mu\nu}d_r)\tau^I\varphi\, W_{\mu\nu}^I$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\,\varphi)(\bar{d}_p\gamma^\mu d_r)$
$Q_{\varphi\widetilde{W}B}$	$\varphi^\dagger\tau^I\varphi\, \widetilde{W}_{\mu\nu}^I B^{\mu\nu}$	Q_{dB}	$(\bar{q}_p\sigma^{\mu\nu}d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde{\varphi}^\dagger D_\mu\varphi)(\bar{u}_p\gamma^\mu d_r)$

$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
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}	$(\bar{l}_p^j e_r)(\bar{d}_s q_t^j)$	Q_{duq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$
$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r)\varepsilon_{jk}(\bar{q}_s^k d_t)$	Q_{qqu}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{quqd}^{(8)}$	$(\bar{q}_p^j T^A u_r)\varepsilon_{jk}(\bar{q}_s^k T^A d_t)$	Q_{qqq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jn}\varepsilon_{km}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r)\varepsilon_{jk}(\bar{q}_s^k u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j\sigma_{\mu\nu}e_r)\varepsilon_{jk}(\bar{q}_s^k\sigma^{\mu\nu}u_t)$		

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

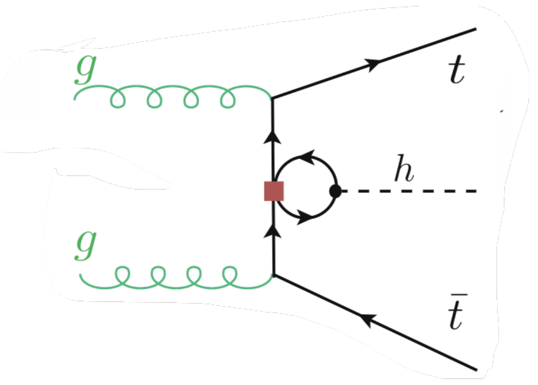
and many others…

In particular in this talk:

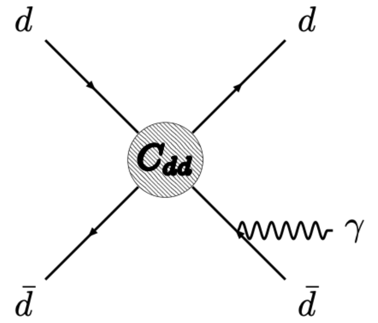
- The operator selection comes purely from symmetry assumptions

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

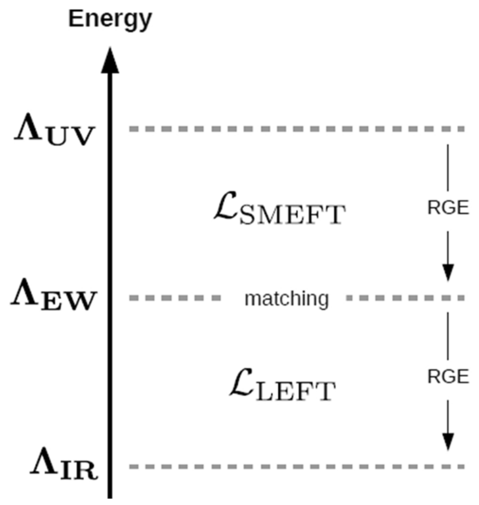
- Inclusion of NLO observables in a global fit without flat directions



- Inclusion of dijet observables below 1.1 TeV



- Inclusion of RGE effects in global analysis.



Flavour symmetris in the SMEFT

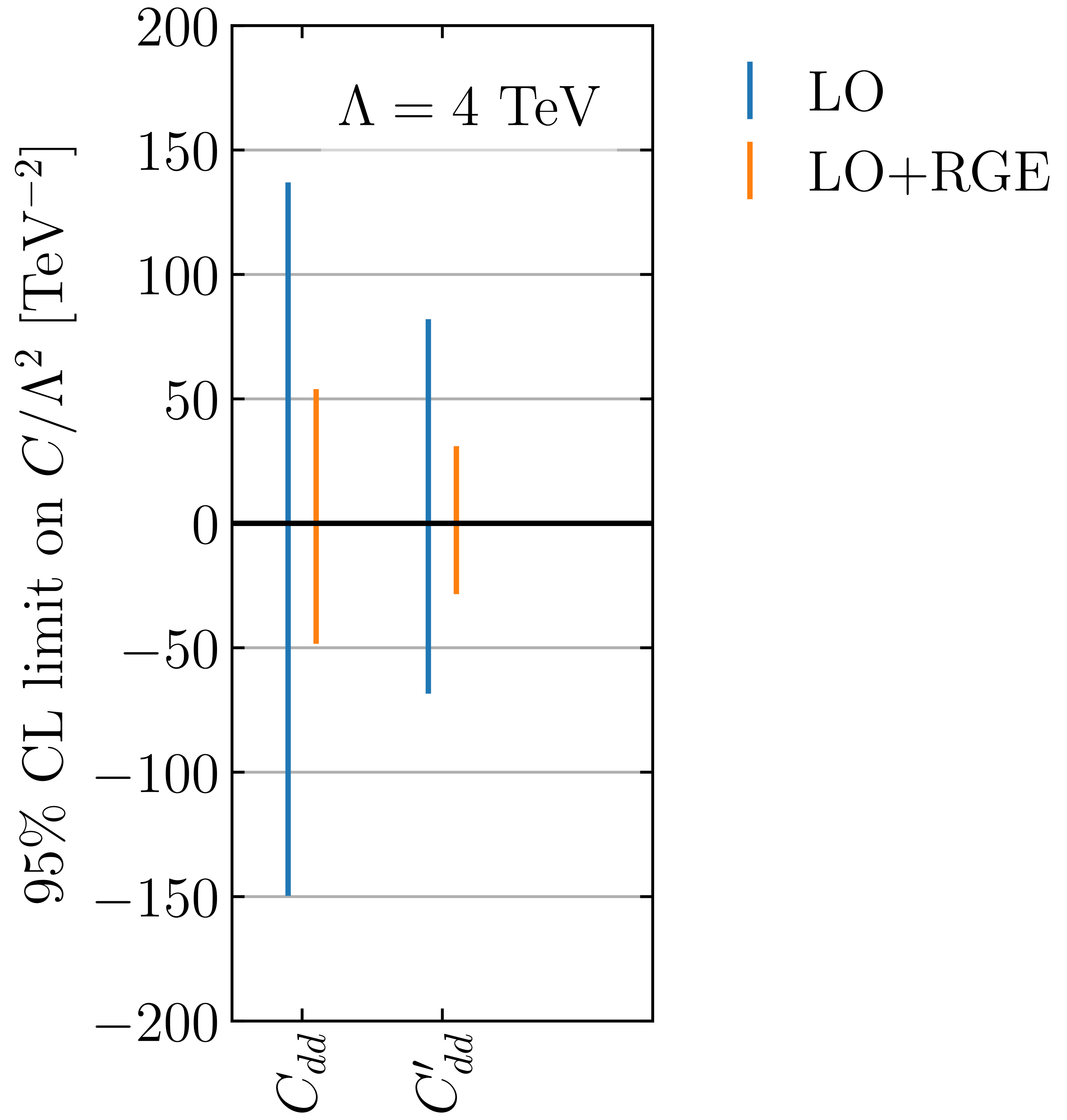
Class	Operators	No symmetry 3 Gen.		No symmetry 1 Gen.		$U(3)^5$ Exact		$U(3)^5$ $\mathcal{O}(Y^1_{e,d,u})$		$U(3)^5$ $\mathcal{O}(Y^1_e, Y^1_d Y^2_u)$	
1–4	X^3, H^6, H^4D^2, X^2H^2	9	6	9	6	9	6	9	6	9	6
5	$\psi^2 H^3$	27	27	3	3	–	–	3	3	4	4
6	$\psi^2 XH$	72	72	8	8	–	–	8	8	11	11
7	$\psi^2 H^2 D$	51	30	8	1	7	–	7	–	11	1
	$(\bar{L}L)(\bar{L}L)$	171	126	5	–	8	–	8	–	14	–
	$(\bar{R}R)(\bar{R}R)$	255	195	7	–	9	–	9	–	14	–
8	$(\bar{L}L)(\bar{R}R)$	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 $\mathcal{O}(X^n)$.

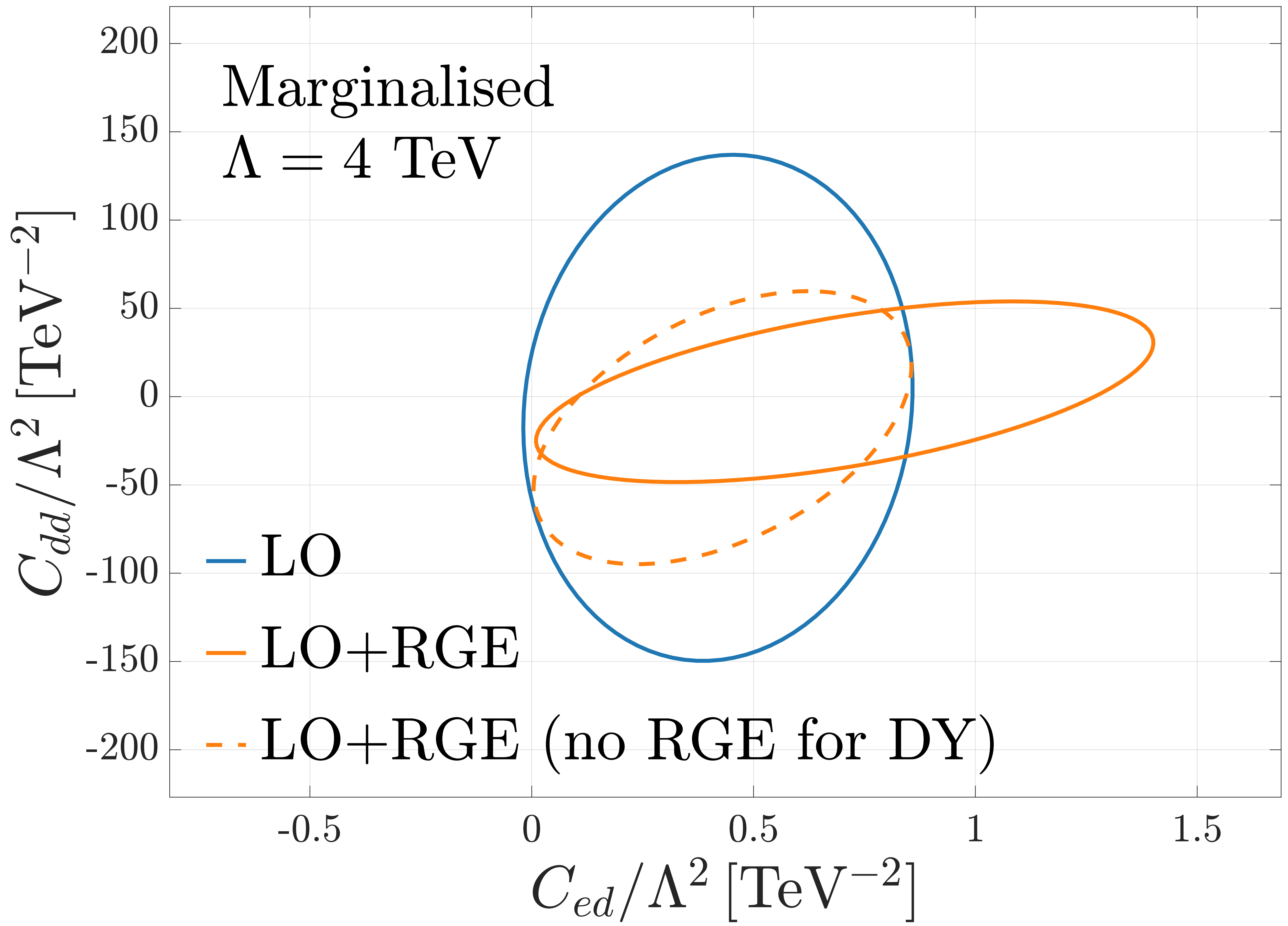
[2005.05366: Faroughy, Isidori, Wilsch, Yamamoto]

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.



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



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

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

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

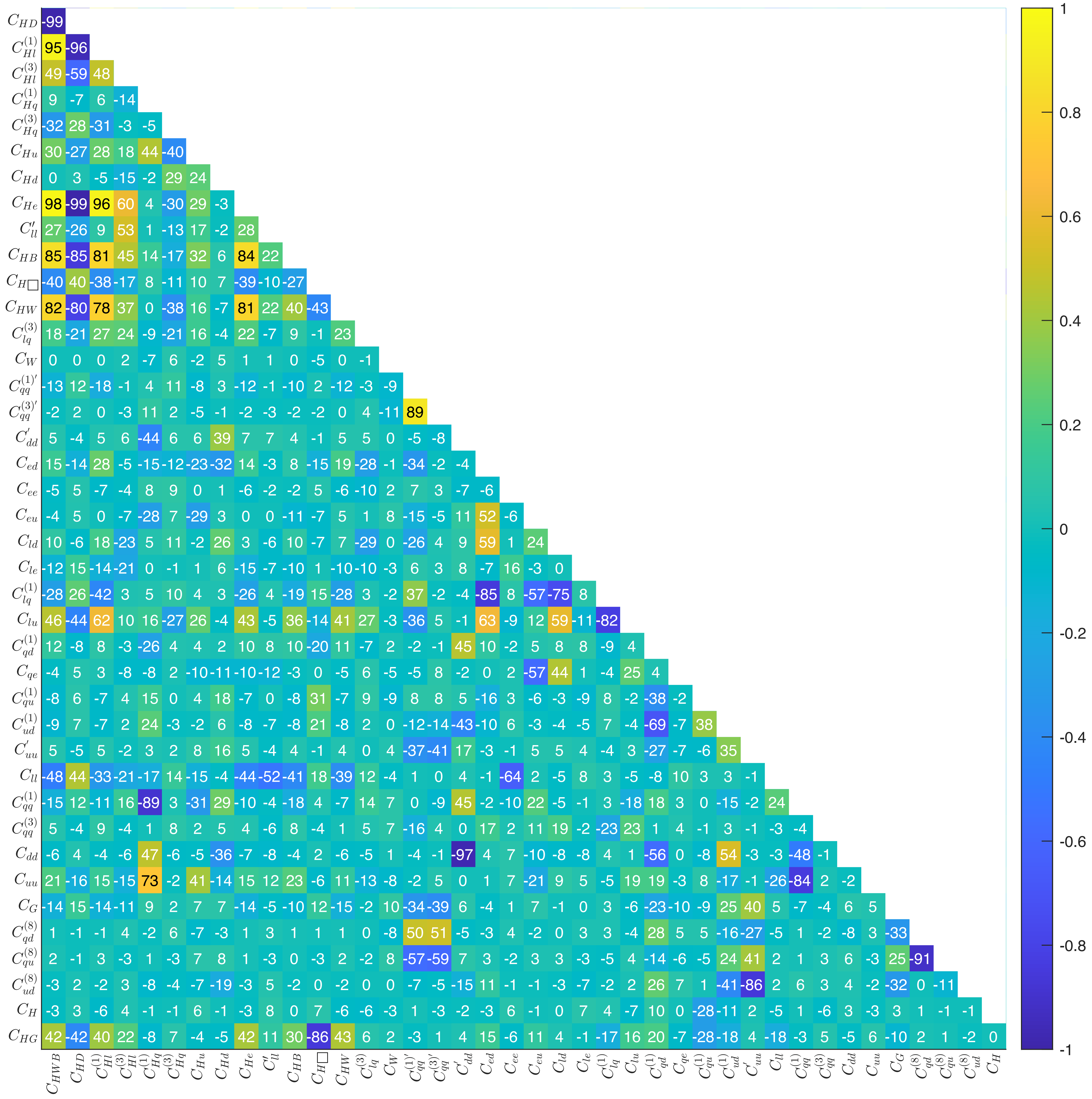
$$\mathcal{L}_{\mathcal{S}_2} = \mathcal{L}_{\rm SM}^{d\leq 4} + (D_\mu \mathcal{S}_2)^\dagger (D^\mu \mathcal{S}_2) - m_{\mathcal{S}_2}^2 \mathcal{S}_2^\dagger \mathcal{S}_2 - \eta_{\mathcal{S}_2} |H|^2 |\mathcal{S}_2|^2 - \lambda_{\mathcal{S}_2} |\mathcal{S}_2|^4 - \left\{ y_{\mathcal{S}_2} e_R^T C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

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

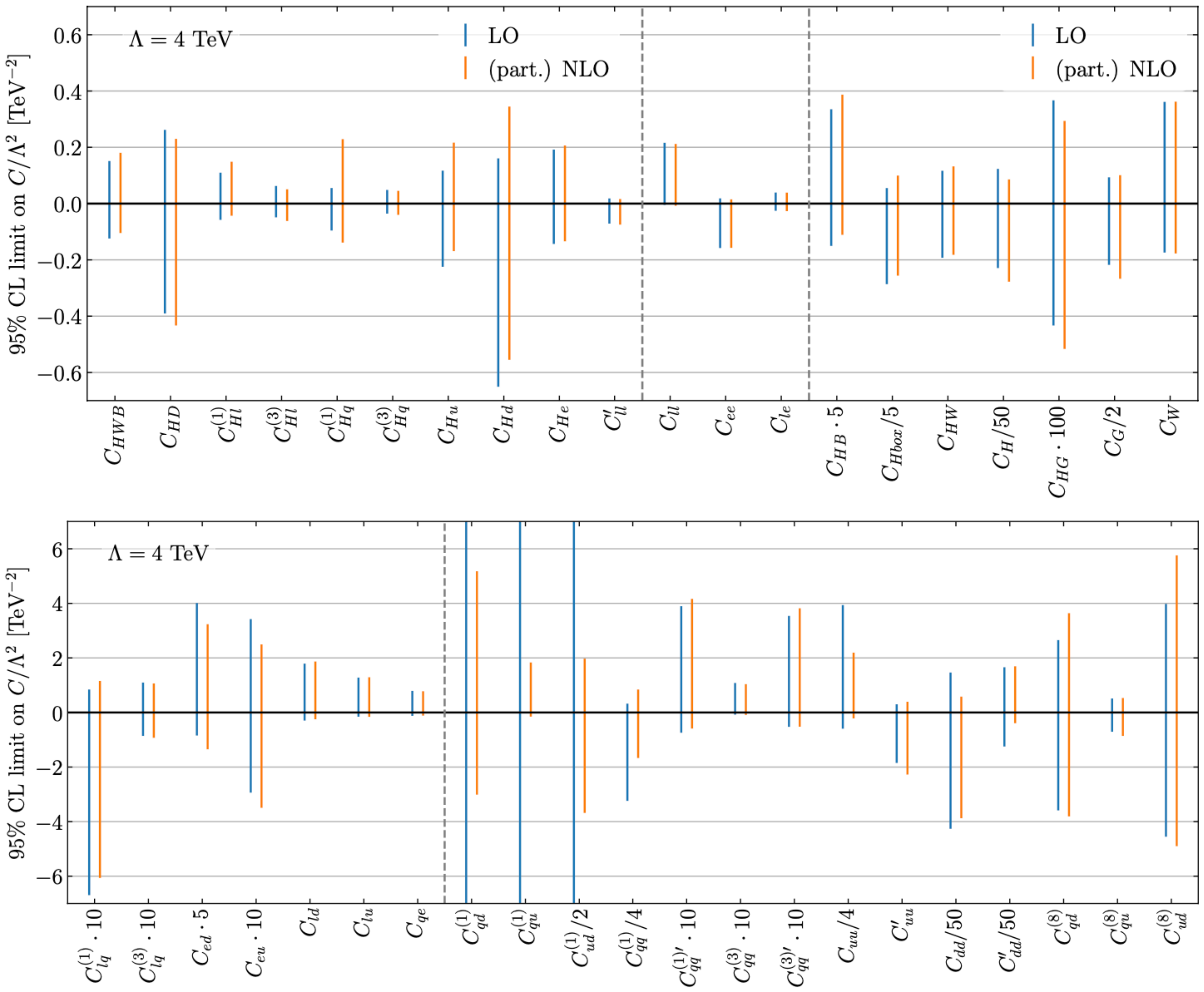
$$\mathcal{L}_{\varphi_2} = \mathcal{L}_{\rm SM}^{d\leq 4} + (D_\mu \varphi_2)^\dagger (D^\mu \varphi_2) - m_{\varphi_2}^2 \varphi_2^\dagger \varphi_2 - \eta_{\varphi_2} H^\dagger H \varphi_2^\dagger \varphi_2 - \lambda_{\varphi_2} \left(\varphi_2^\dagger \varphi_2\right)^2 + \left\{ y_{\varphi_2} \varphi_2^{\alpha\dagger}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

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

Correlation matrix

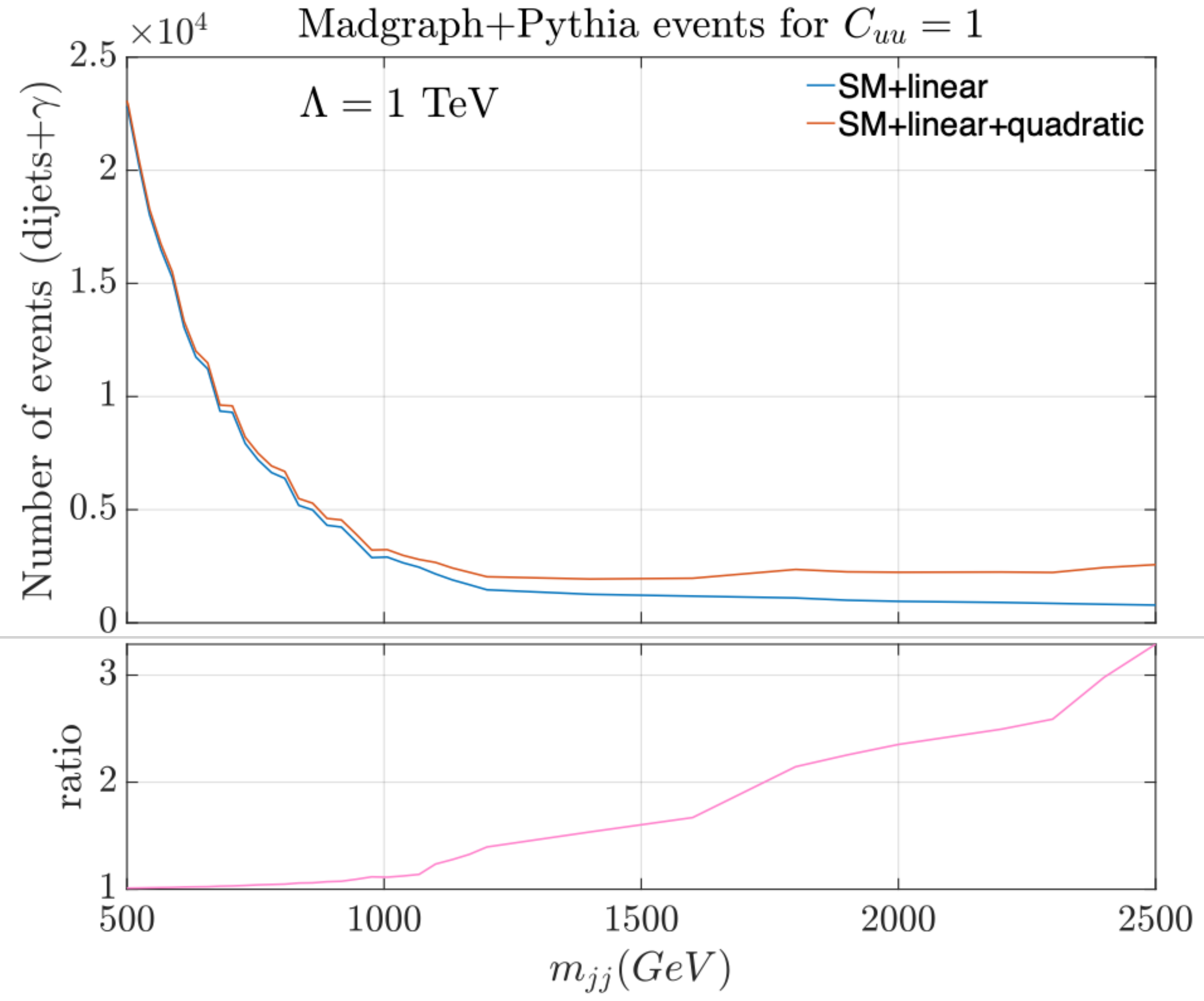


Full LO vs NLO results



Dijets+γ

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

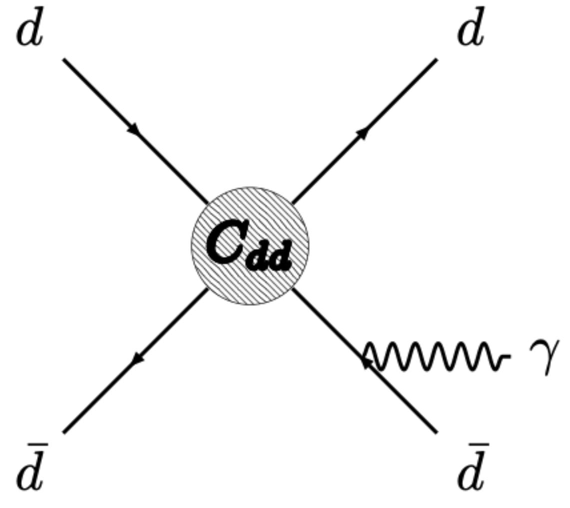


$$\sigma \propto \frac{|C_{dd}|^2}{\Lambda^4} s$$

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**.

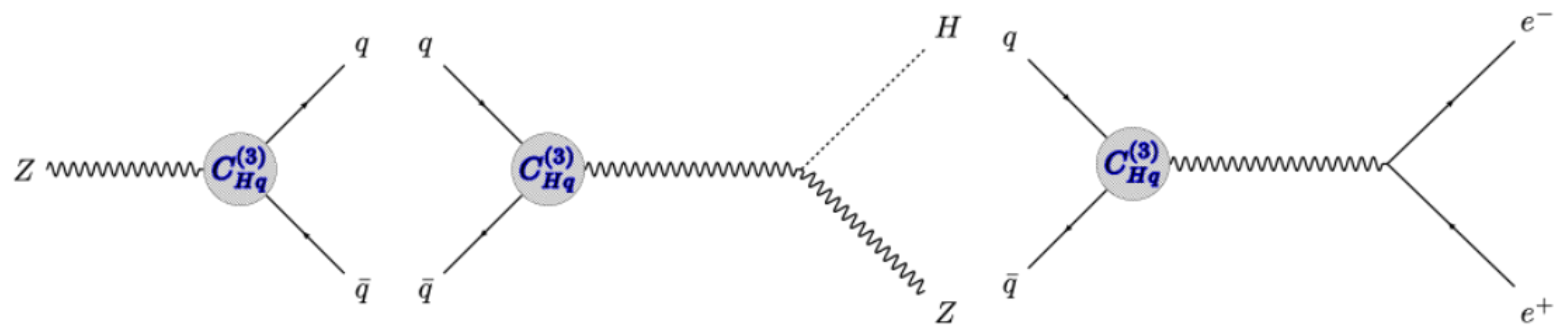


[1901.10917, ATLAS]

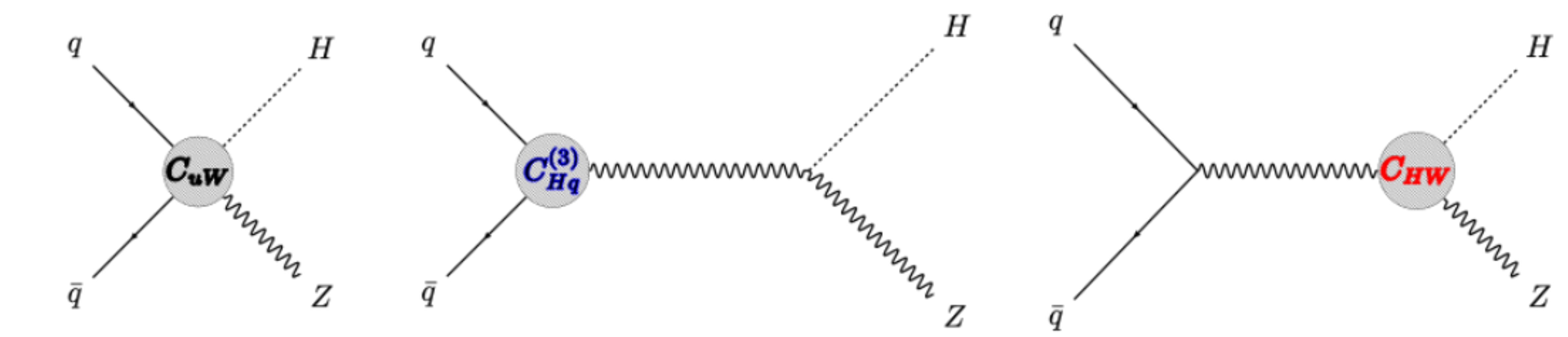
Global analyses in the SMEFT

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

One operator influences different observables:



One observable is influenced by many different operators:



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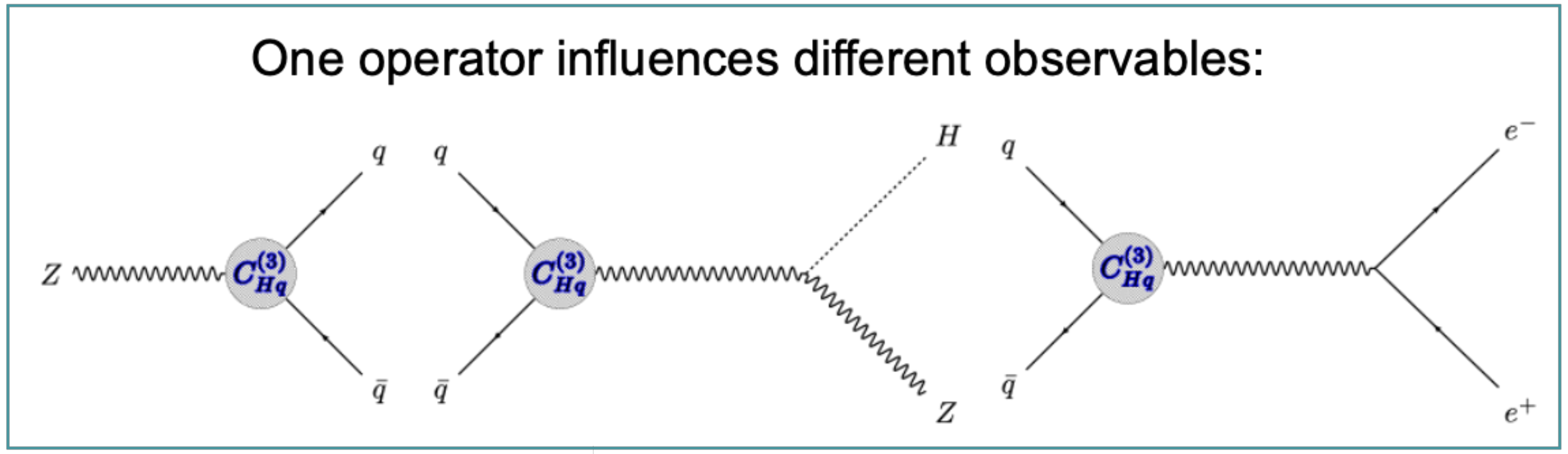

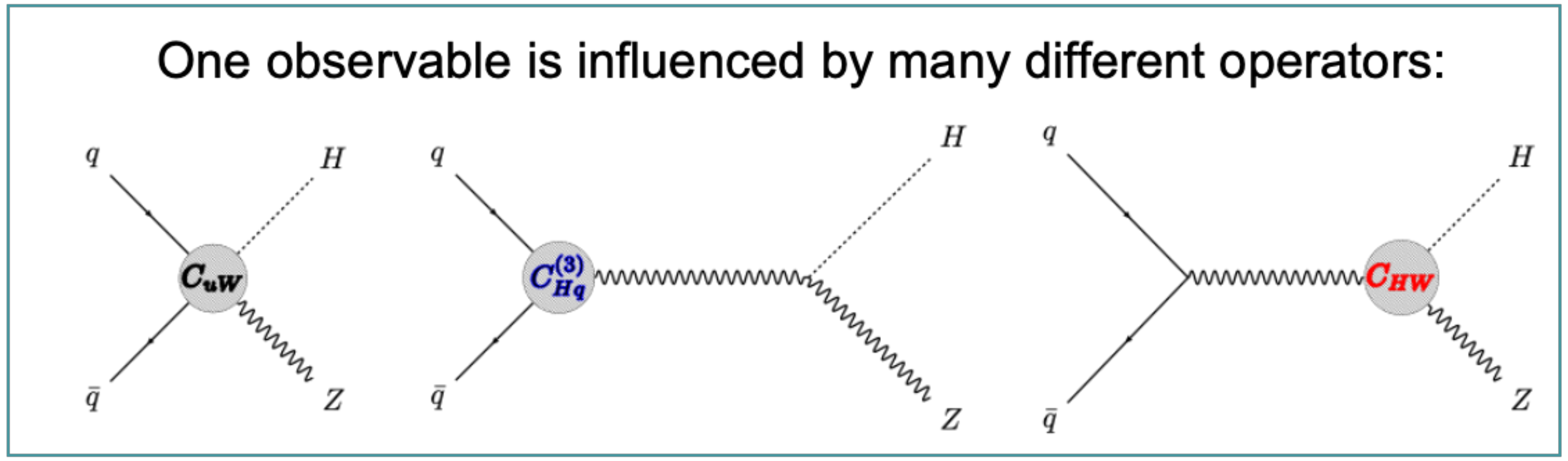

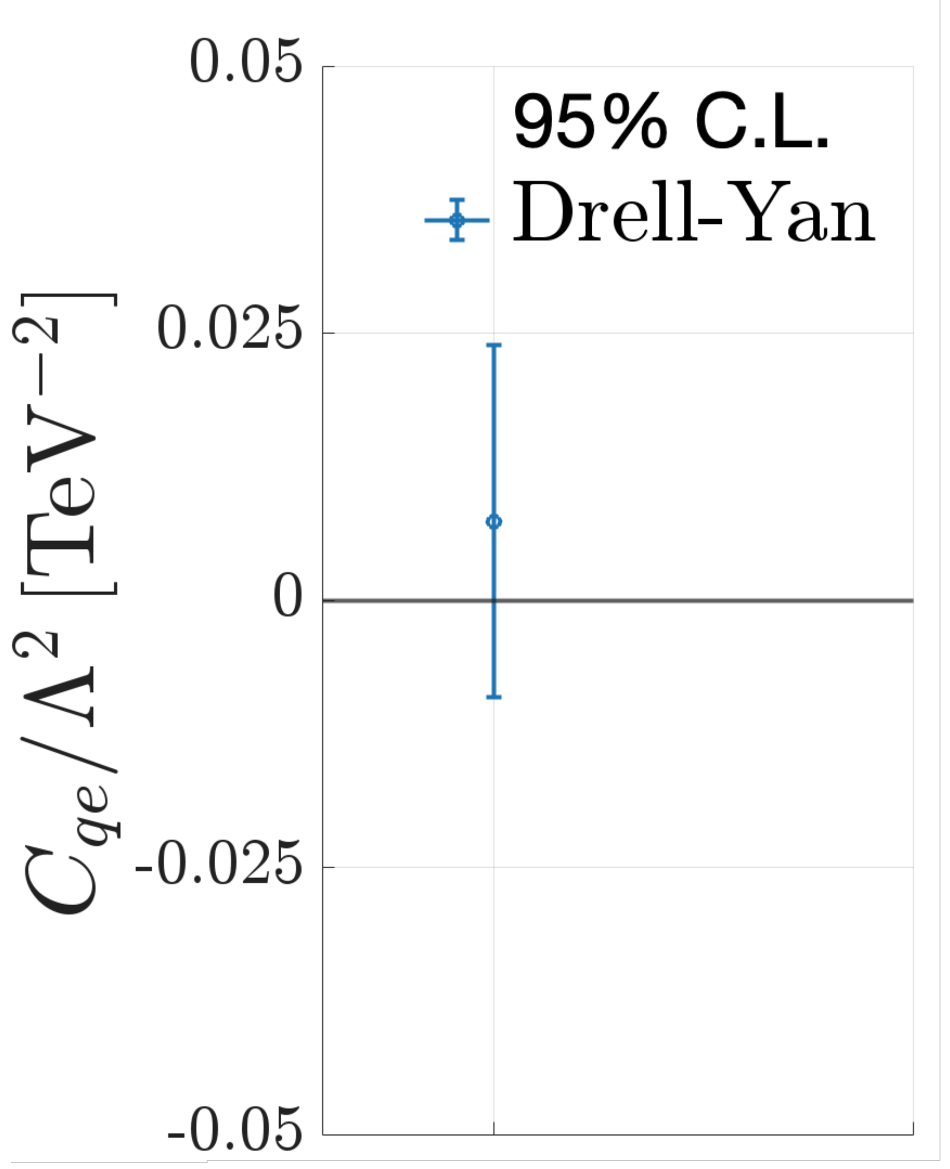

[2311.04963: RB, Biekötter, Hurth]
[1706.03783: Falkowski et al.]
[2207.10714: Allwicher et al.]

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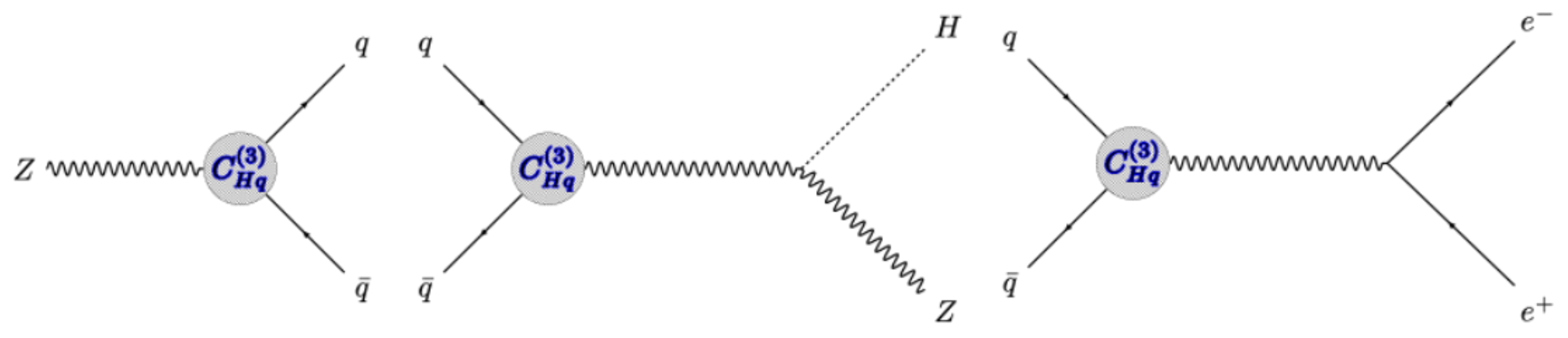

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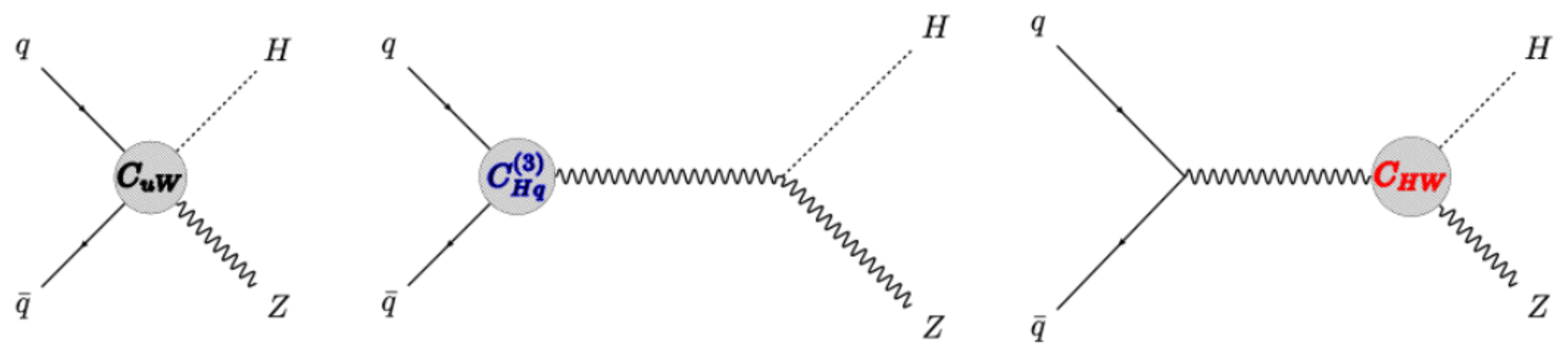

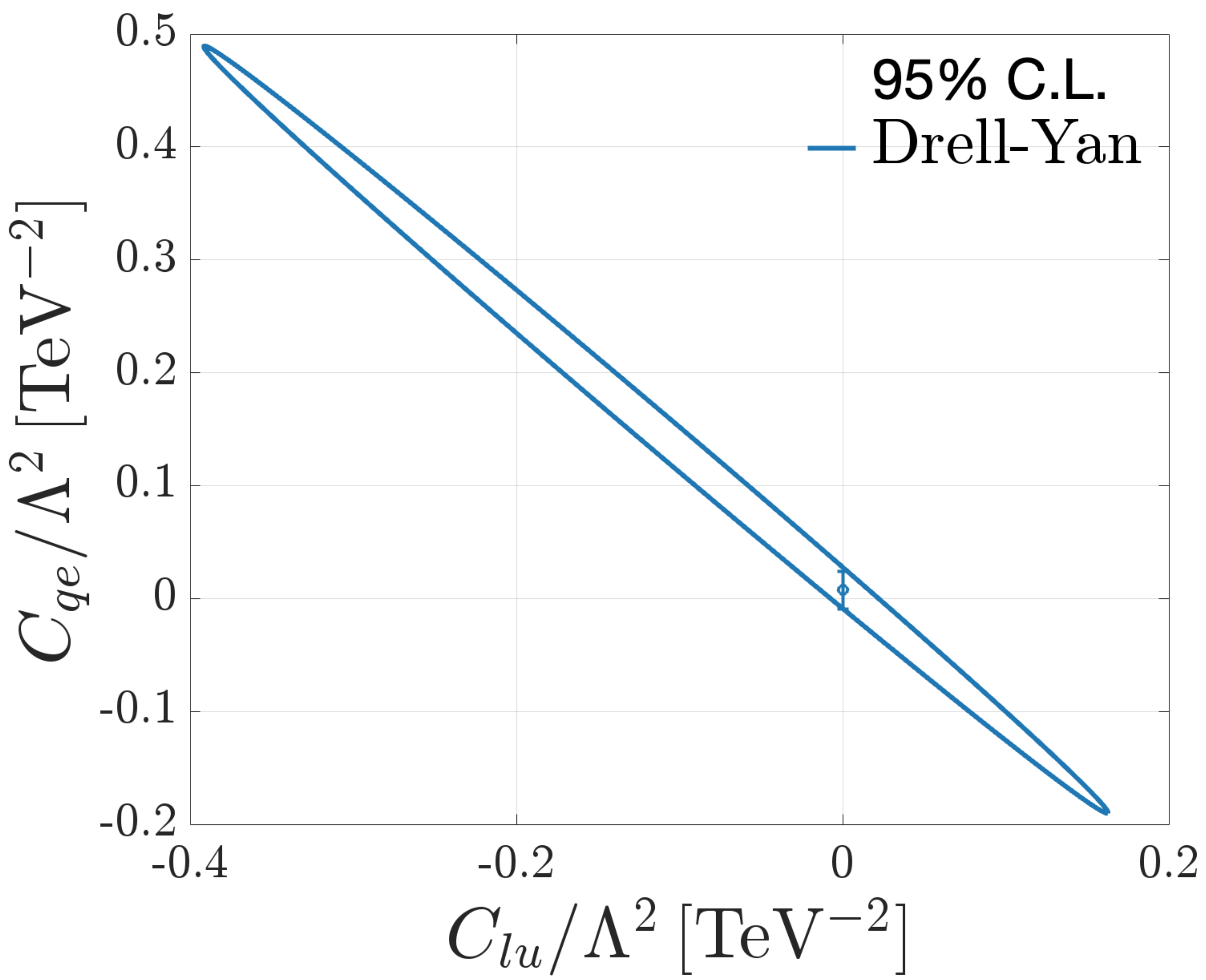

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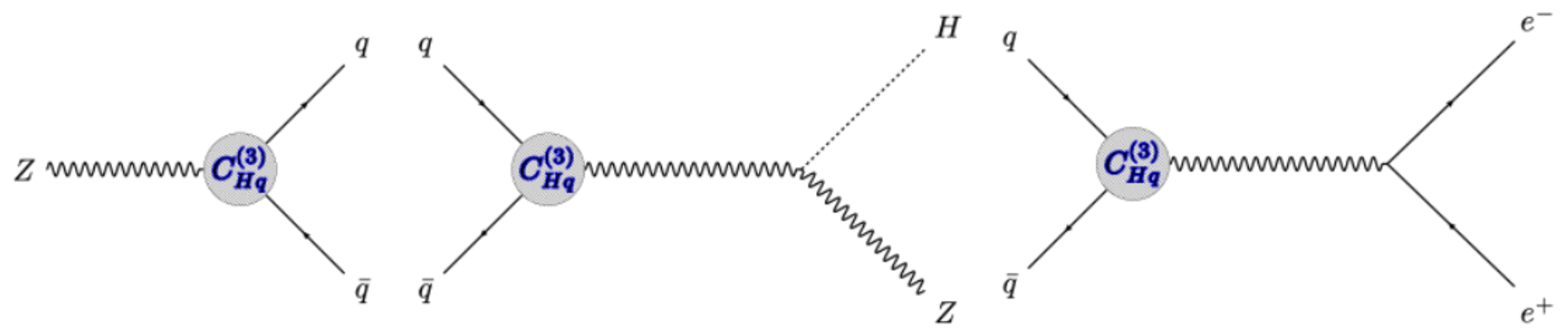

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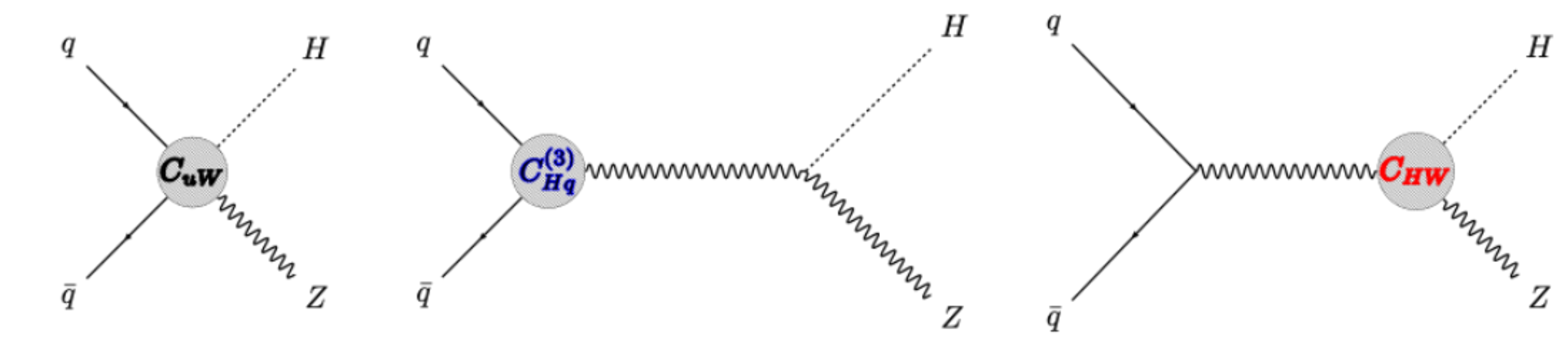

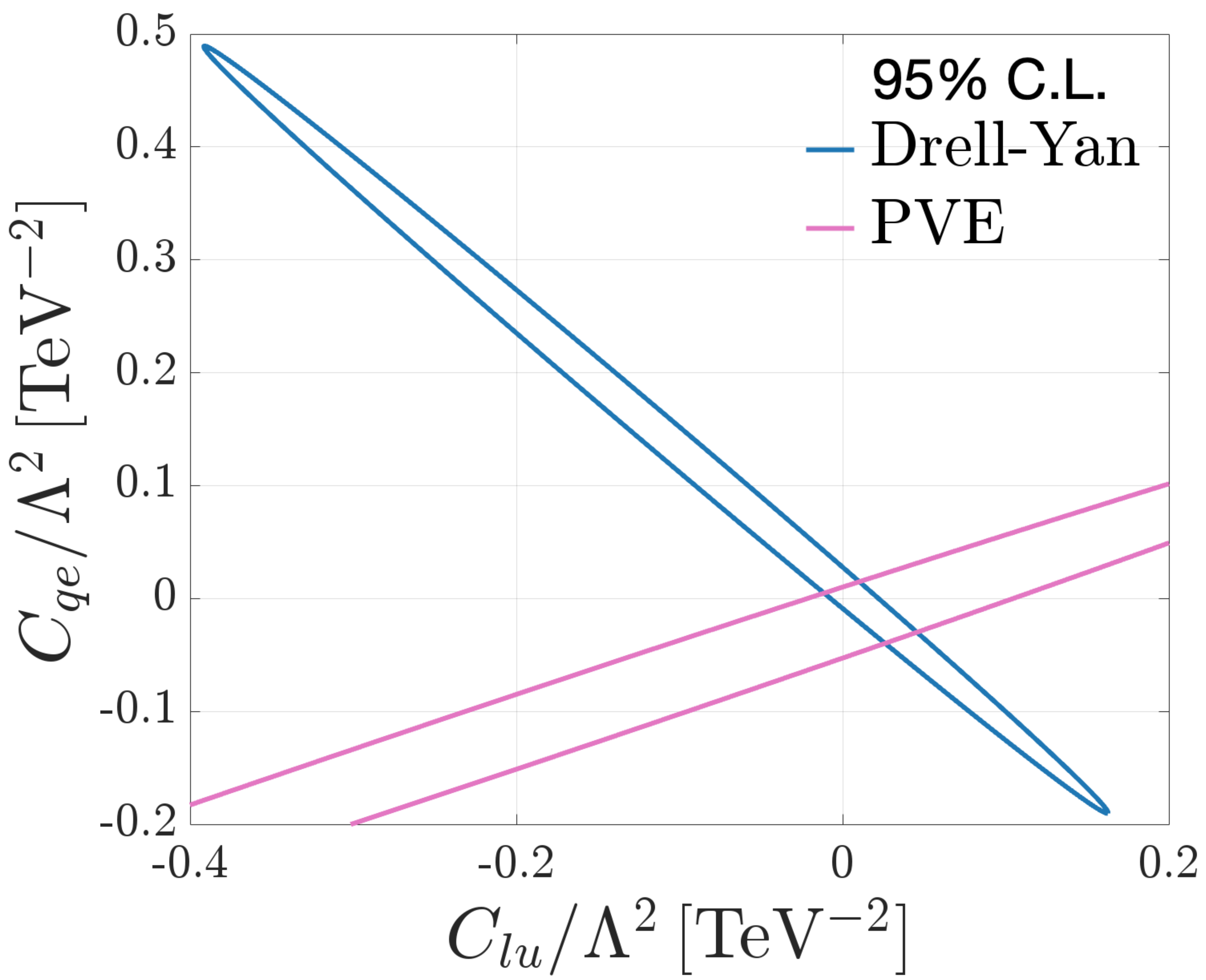

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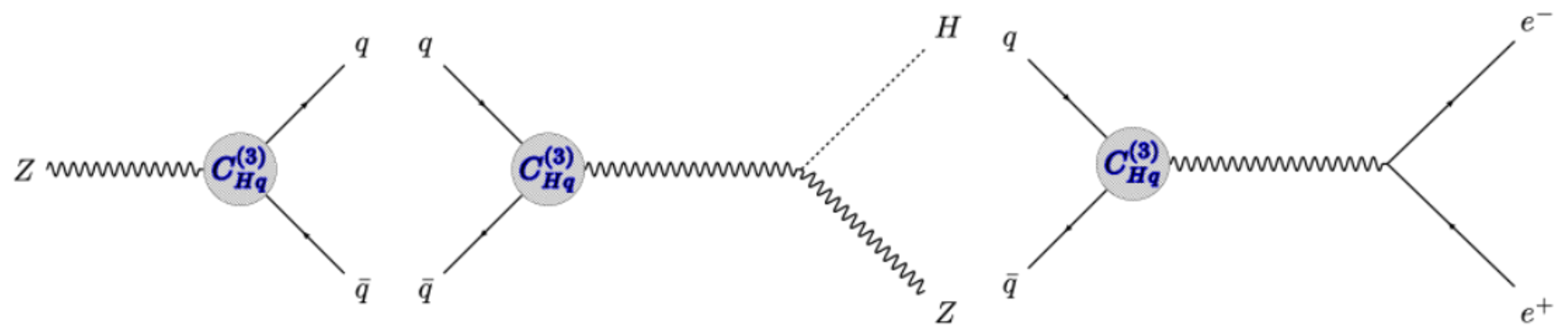

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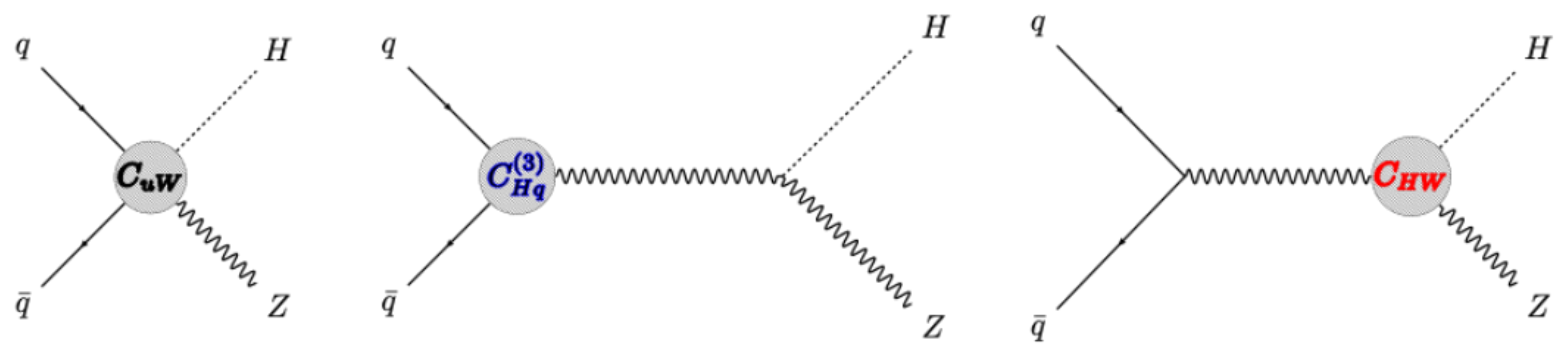

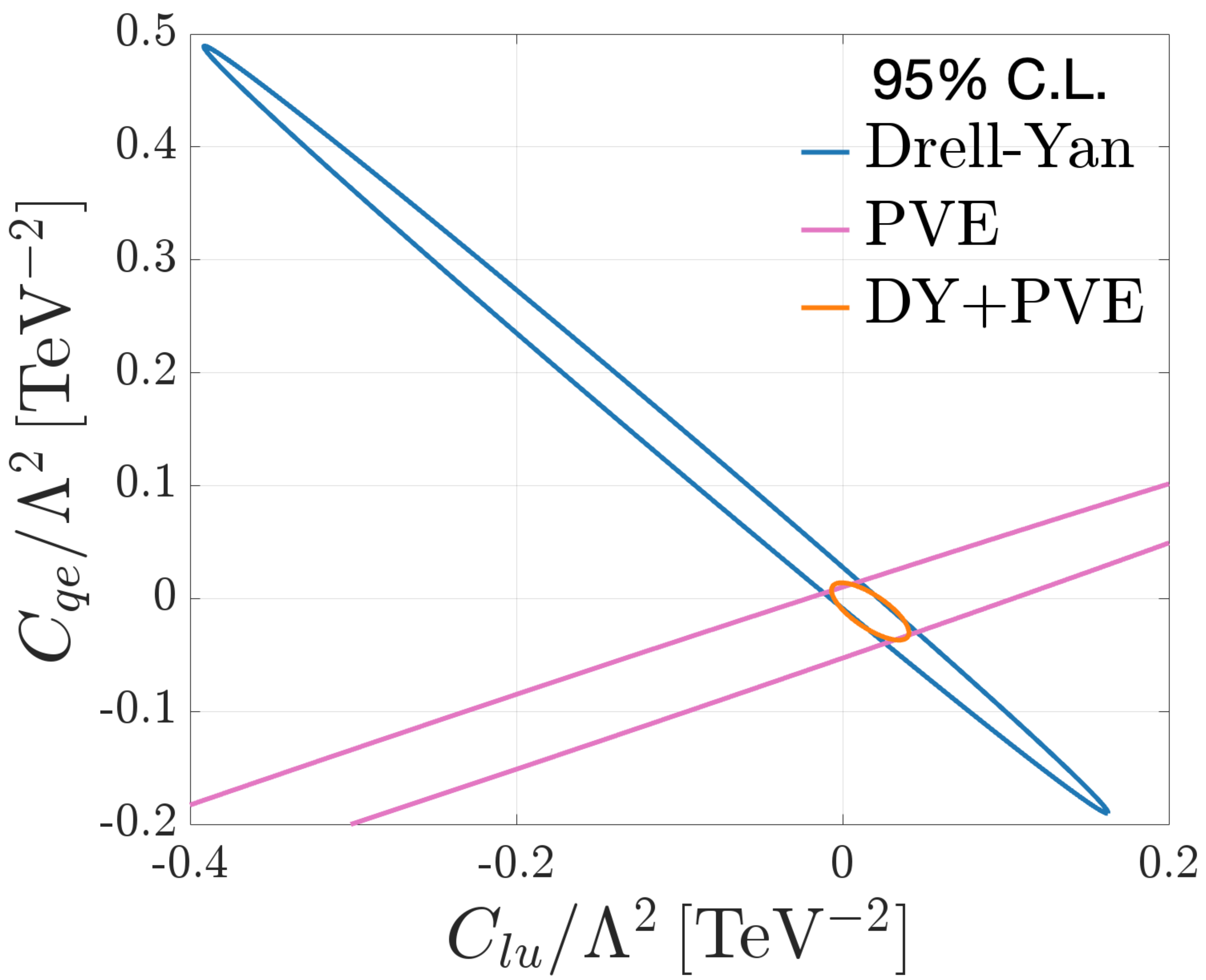

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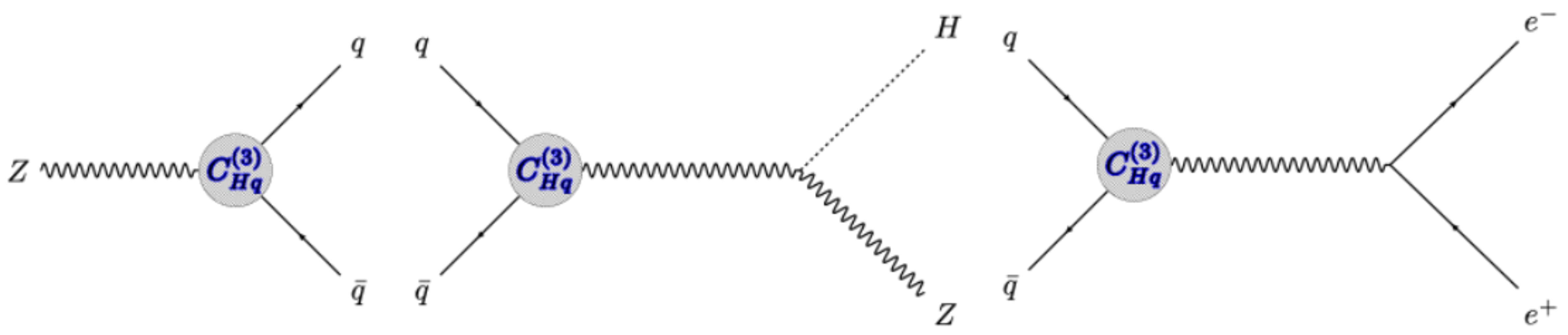

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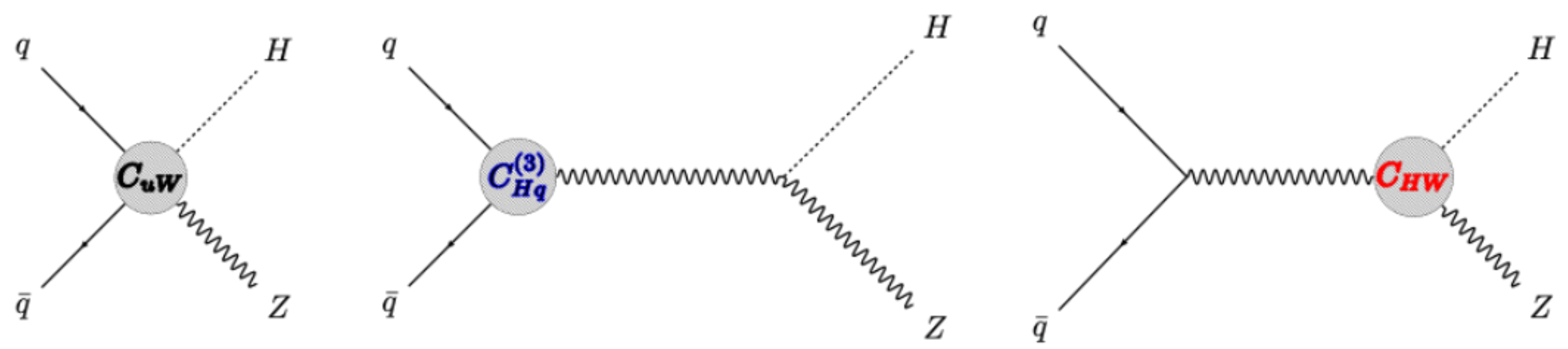

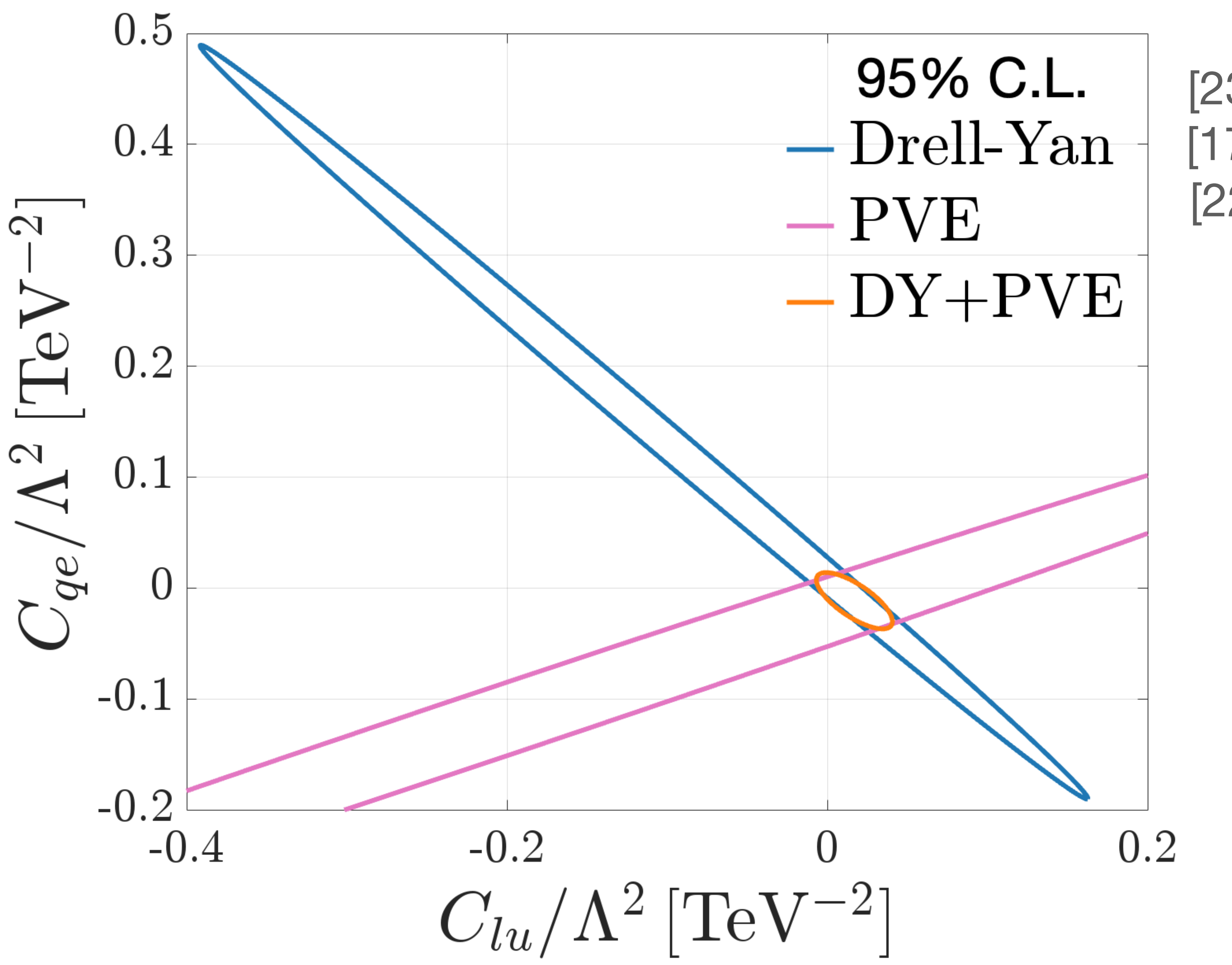

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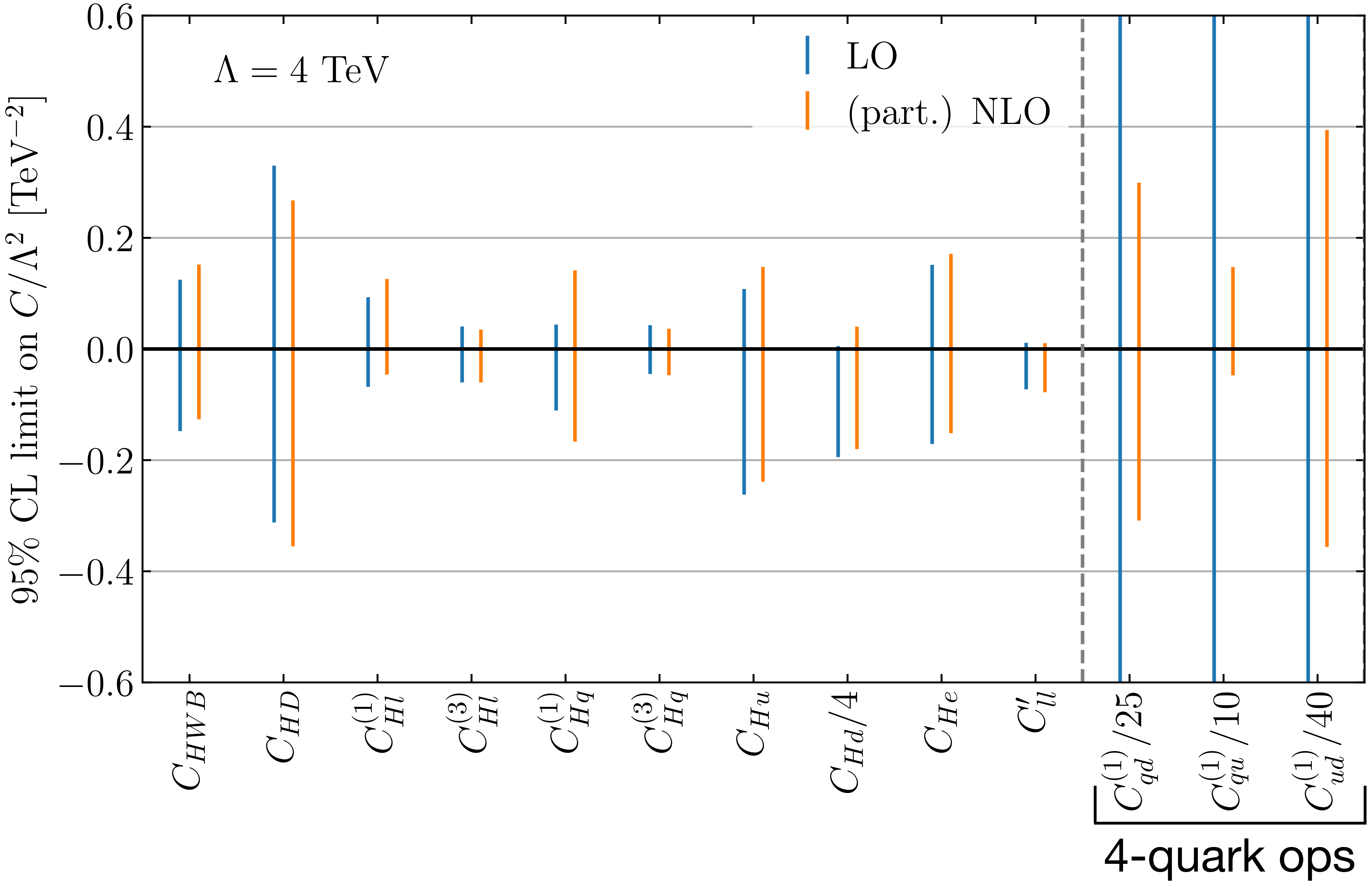
Goal: Constrain all the possible directions (linear combinations of Wilson coefficients)

High and low energy data

Identify correlations

LO vs NLO fit

[2311.04963: RB, Biekötter, Hurth]



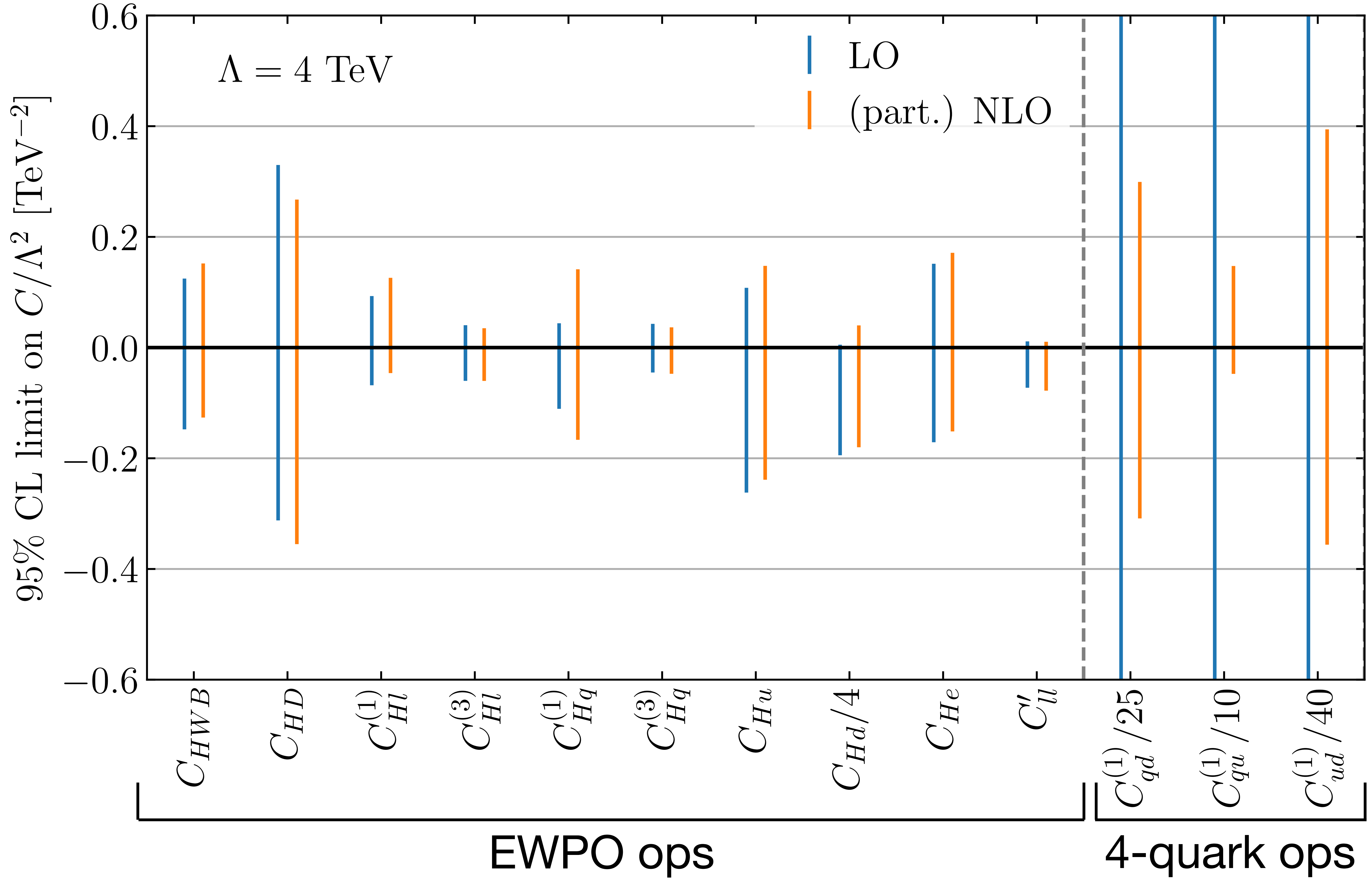
- Some operators, poorly constrained using only LO observables, result much better bounded when NLO observables are included.

  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 impact on 1D bounds