Precision in EFT predictions

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12/09/24

EFT

A model independent probe of heavy New Physics

Energy

Λ

UV physics (heavy particles) $\mathcal{L}_{NP}(\phi, \boldsymbol{Z'}, \boldsymbol{X}, \boldsymbol{Q}, \boldsymbol{S} \ldots)$

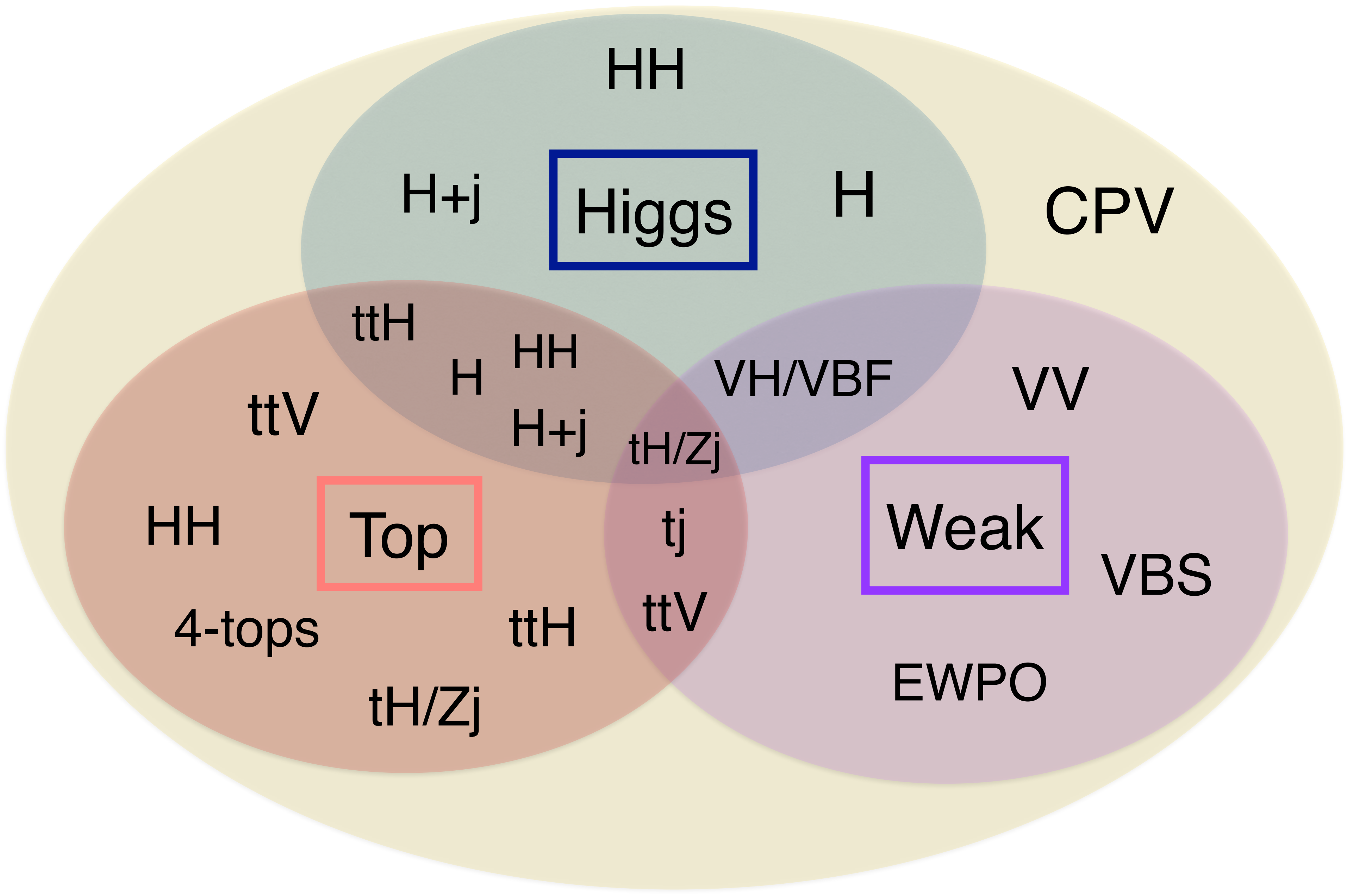
Effective Field Theory $\mathcal{L}_{SM}(\phi) + \boxed{\mathcal{L}_{dim6}(\phi)} + \ldots$

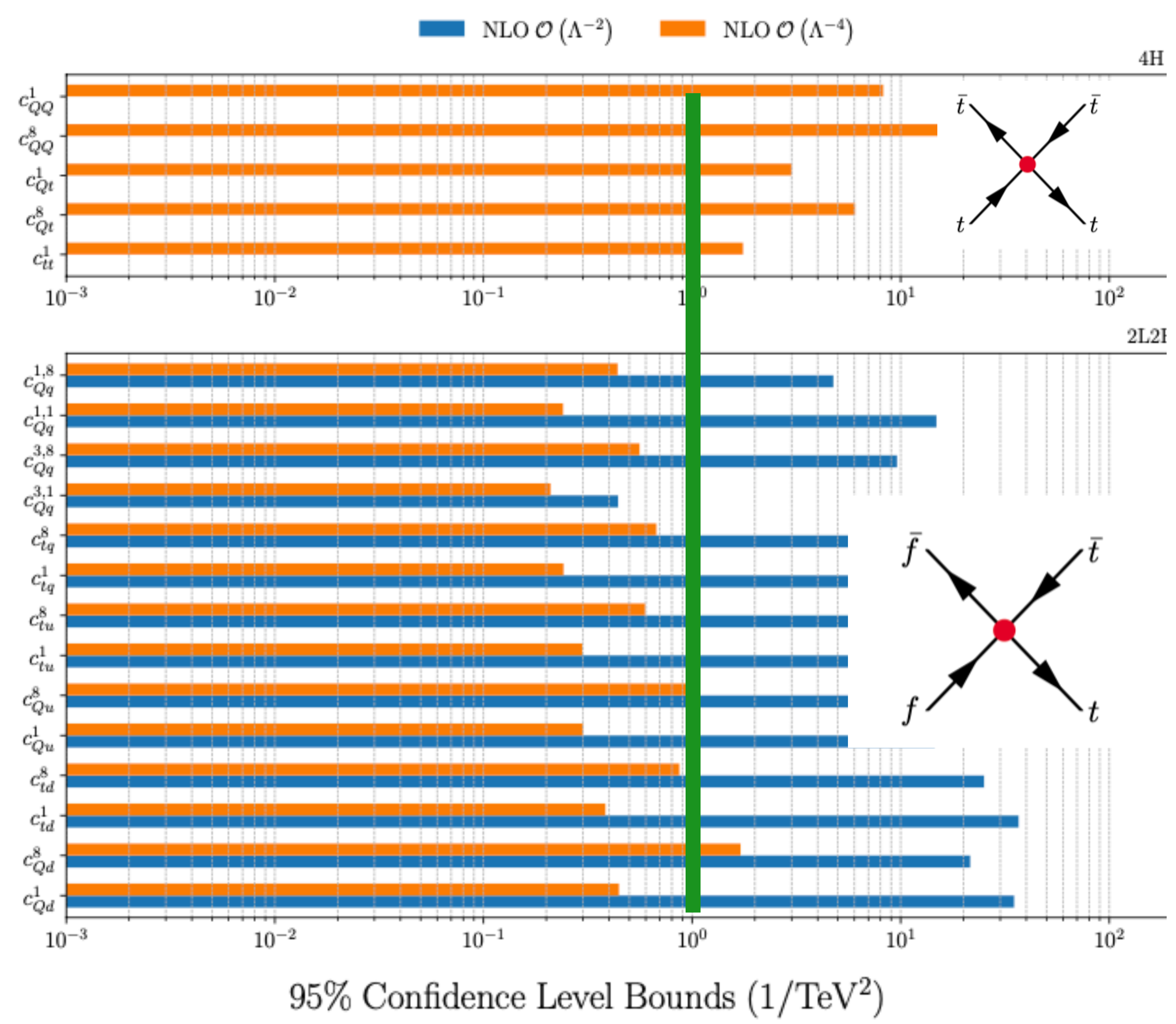
Standard Model $\mathcal{L}_{SM}(\phi)$

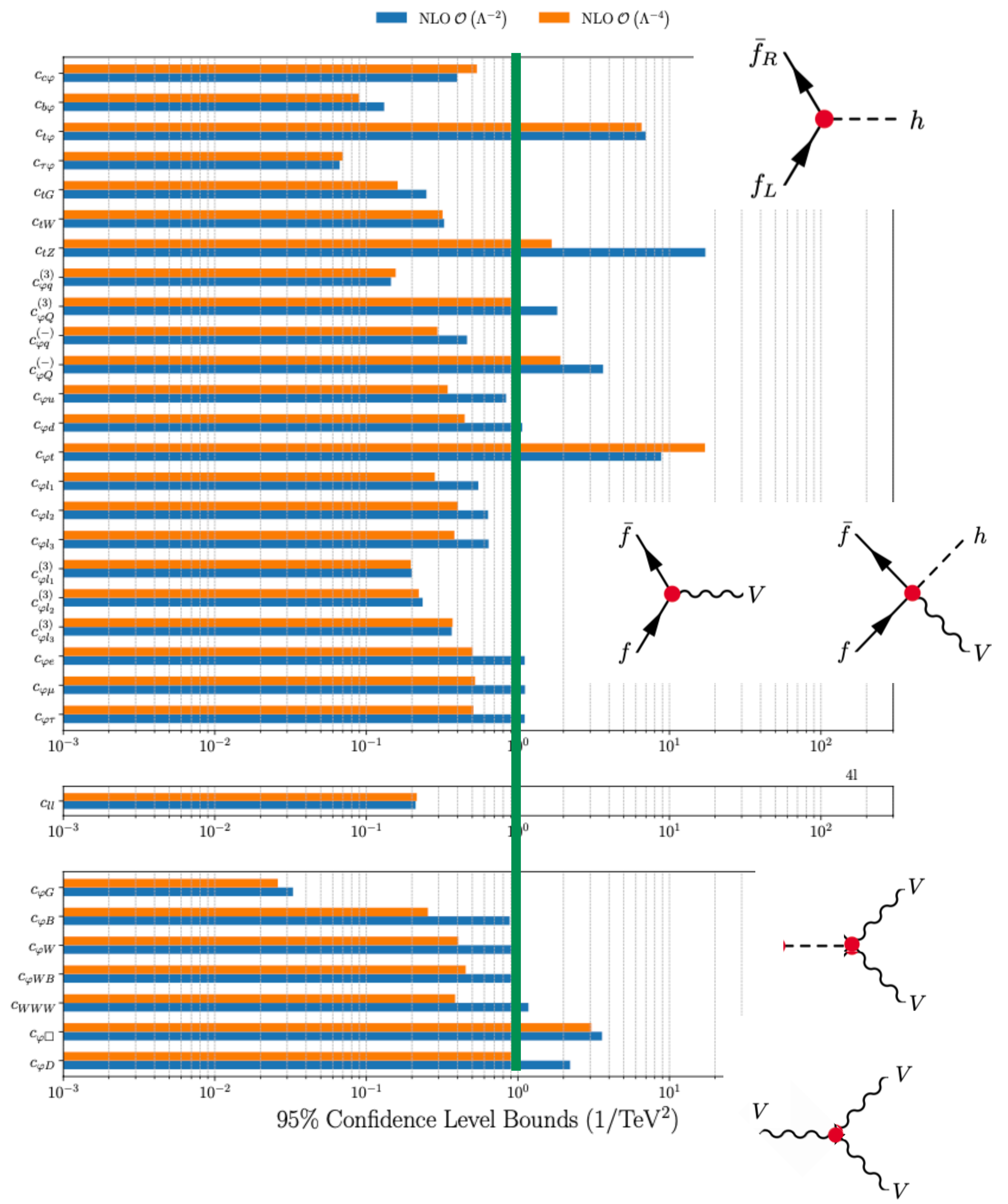
Effective Field Theory reveals high energy physics through **precise** measurements at low energy.

SMEFT

The global aspect







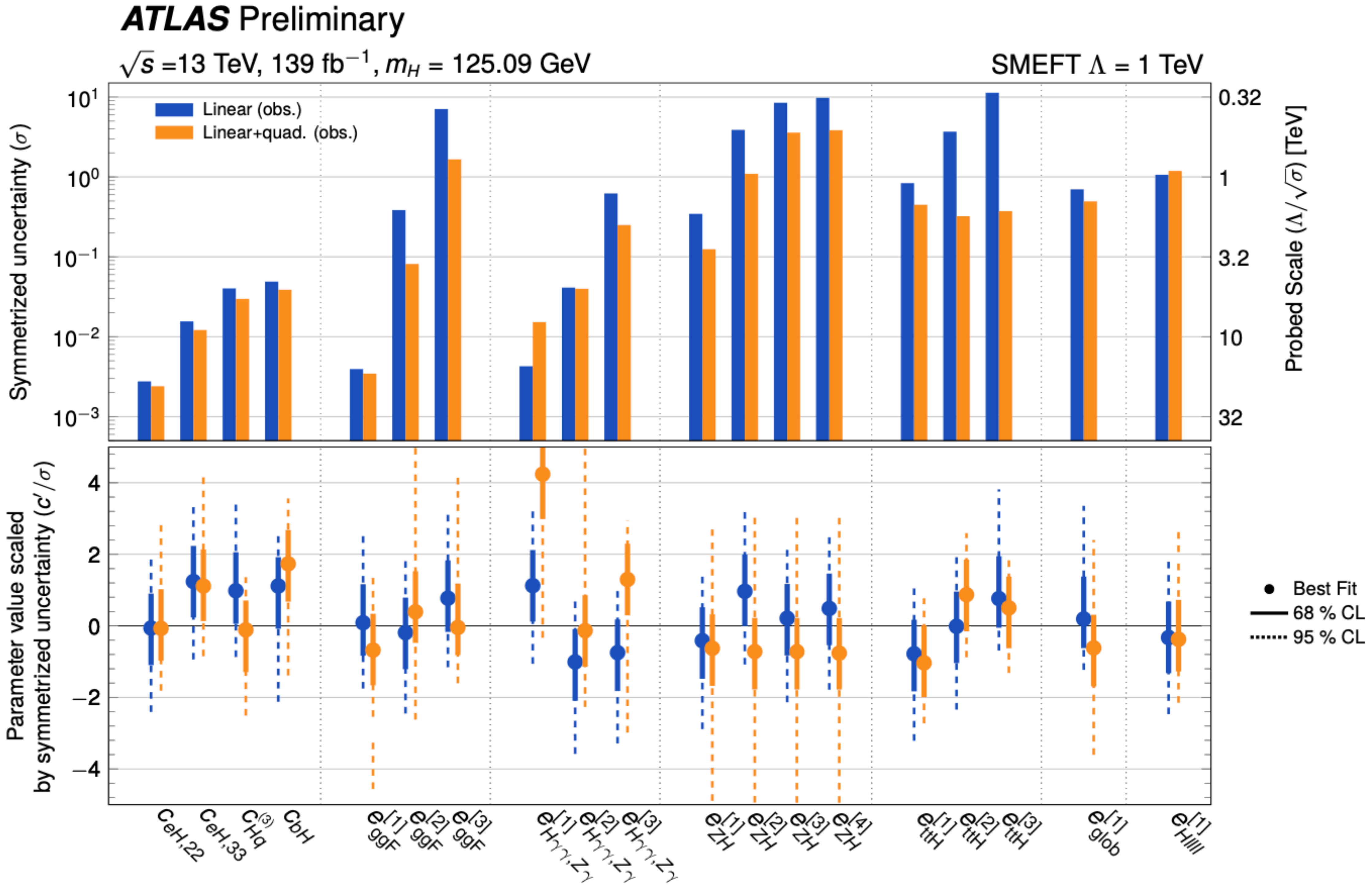
- 50 coefficients fitted: bounds varying between operators
- Most Wilson coefficient bounds below 1 for Λ=1 TeV
- No sign of significant deviations from the SM
- Least constrained coefficients are 4-top operators

SMEFiT3.0 Celada, Giani, Mantani, Rojo, Rossia, Thomas, EV, ter Hoeve arXiv:2404.12809

SMEFT

Not just a theorists' tool

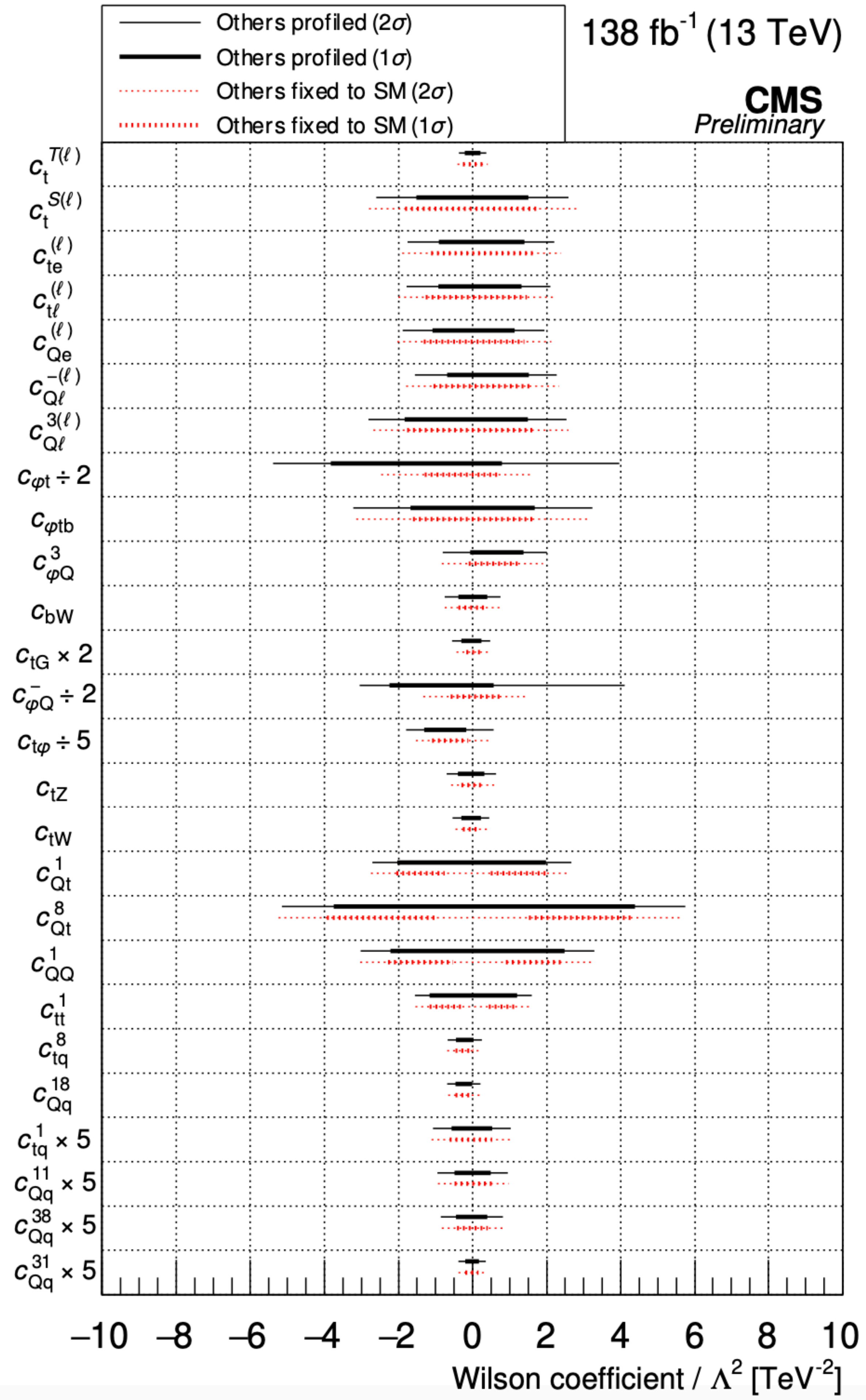
ATLAS CONF-2023-052



Higgs+EW

CMS-PAS-TOP-22-006

Top sector $t\bar{t}l\nu, t\bar{t}l\bar{l}, tl\bar{l}q, tHq$



EFT pathway to New Physics

$$\Delta \text{Obs}_n = \text{Obs}_n^{\text{EXP}} - \text{Obs}_n^{\text{SM}} = \frac{1}{\Lambda^2} \sum_i c_i^6(\mu) a_{n,i}^6(\mu) + \mathcal{O}\left(\frac{1}{\Lambda^4}\right)$$

Precise EFT predictions

Precise SM predictions

Precise experimental measurements

EFT pathway to New Physics

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Precise EFT predictions

Precise SM predictions ✔

Precise experimental measurements

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Precise EFT predictions

Precise SM predictions ✔

Precise experimental measurements

Constraints $\frac{1}{\Lambda^2} c_i^6(\mu)$

EFT pathway to New Physics

$$\Delta \text{Obs}_n = \text{Obs}_n^{\text{EXP}} - \text{Obs}_n^{\text{SM}} = \frac{1}{\Lambda^2}\sum_i c_i^6(\mu) a_{n,i}^6(\mu) + \mathcal{O}\left(\frac{1}{\Lambda^4}\right)$$

Precise EFT predictions

Precise SM predictions ✔

Precise experimental measurements

Constraints $\frac{1}{\Lambda^2} c_i^6(\mu)$ → UV

Aspects of EFT predictions

And how to improve them

- Higher Orders in $1/\Lambda^4$
  - squared dim-6 contributions
  - double insertions of dim-6
  - dim-8/10… contributions
- Higher Orders in QCD and EW
  - EFT is a QFT, renormalisable order-by-order $1/\Lambda^2$

$$\mathcal{O}(\alpha_s, \alpha_{ew}) + \mathcal{O}\left(\frac{1}{\Lambda^2}\right) + \mathcal{O}\left(\frac{\alpha_s}{\Lambda^2}\right) + \mathcal{O}\left(\frac{\alpha_{ew}}{\Lambda^2}\right)$$

Why bother with higher orders?

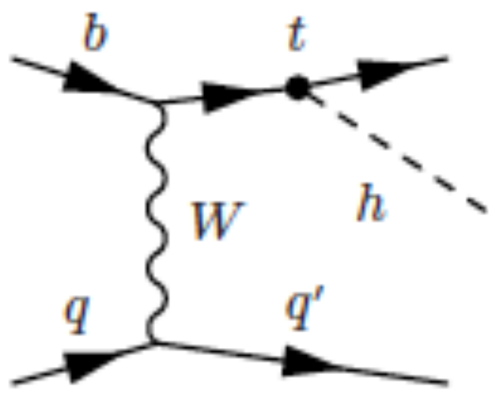
Higher orders in SMEFT bring:

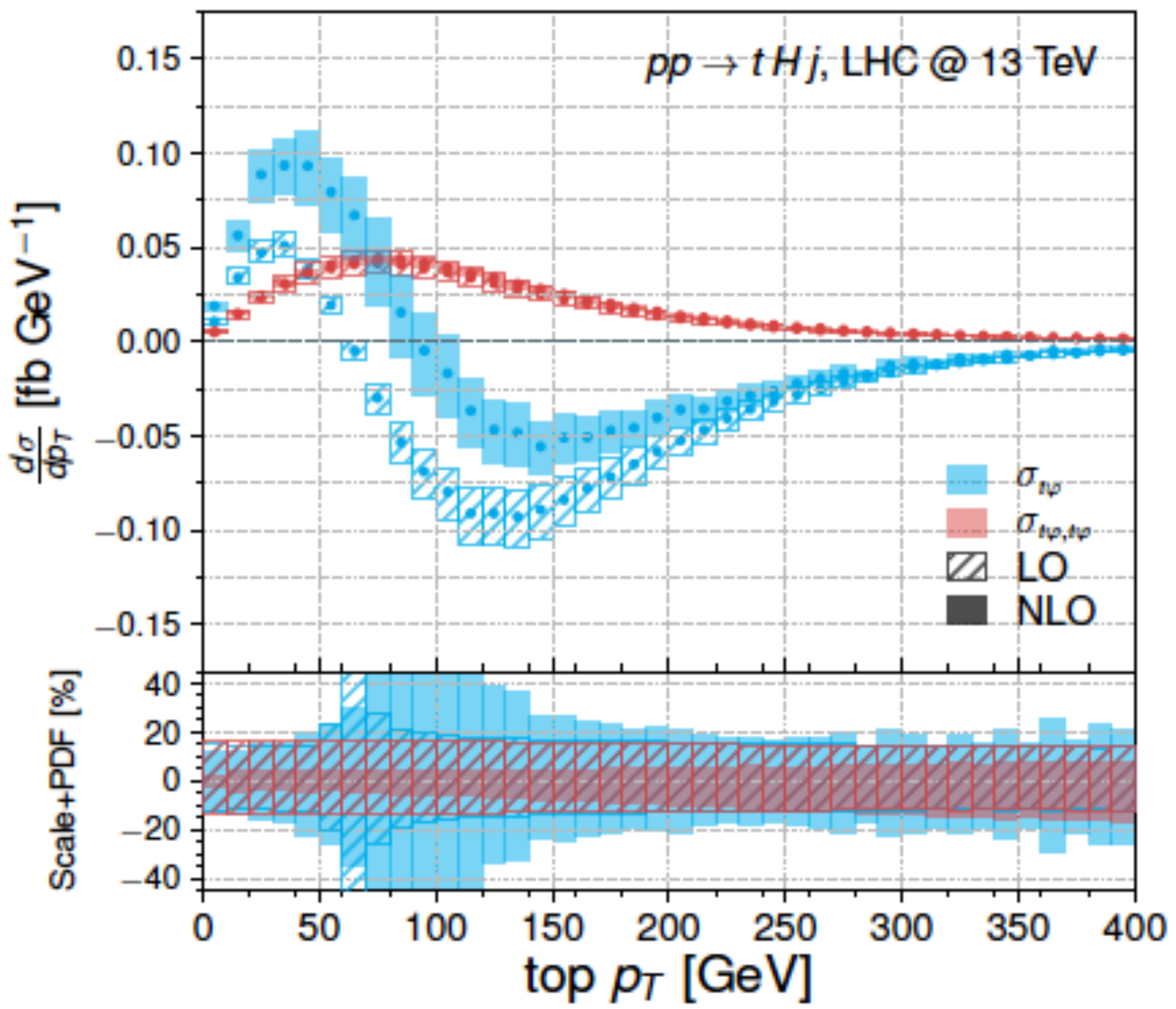
* Accuracy
* Precision
* Improved sensitivity
  * Accurate knowledge of the deviations (distribution shapes, correlations between observables, etc.) can be the key to disentangle them from the SM.
  * Loop-induced new sensitivity: operators entering at one-loop

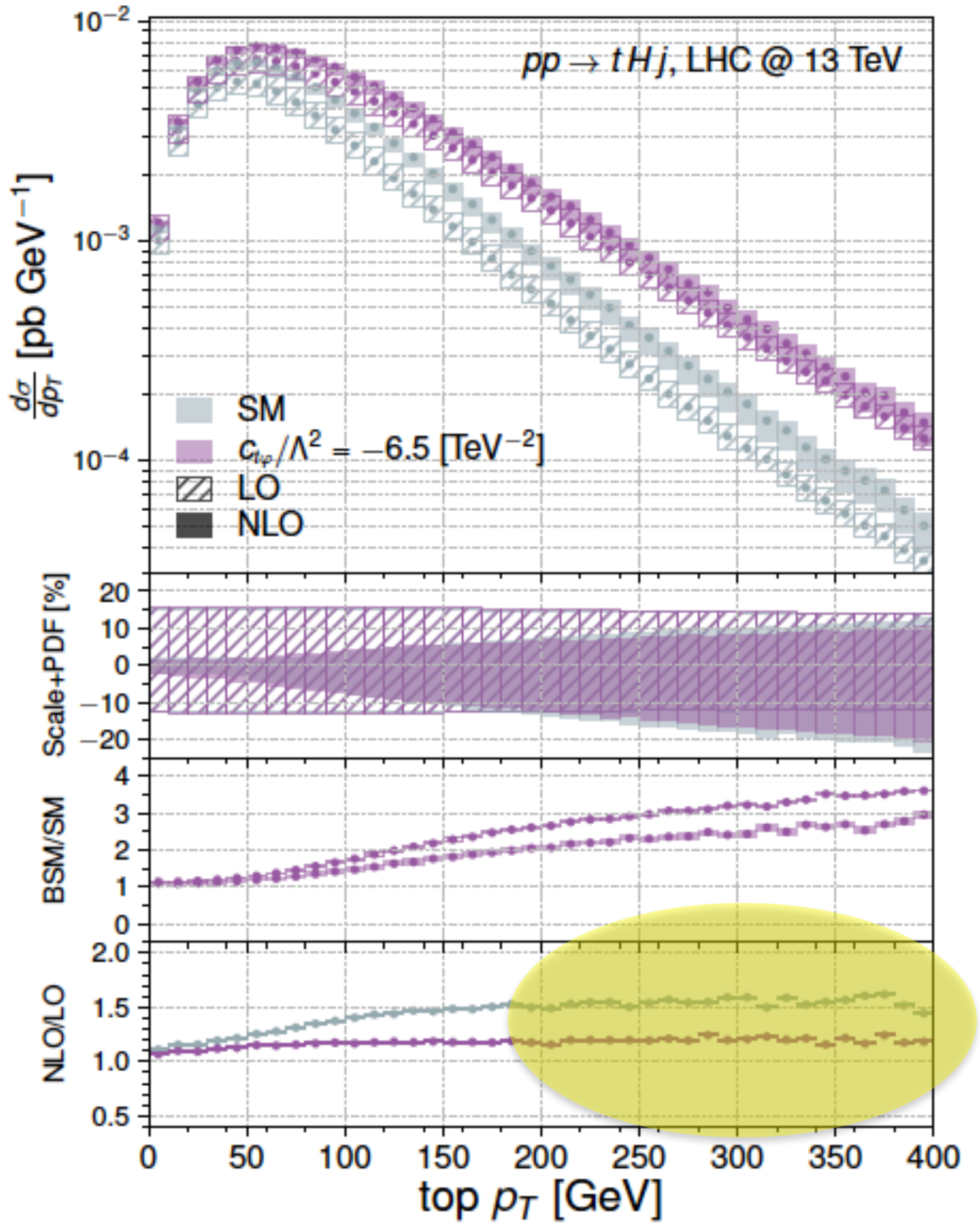
Accuracy and precision: QCD

Example 1: k-factors and shapes

tHj







Different shapes at NLO

Degrande, Maltoni, Mimasu, EV, Zhang arXiv:1804.07773

ttH

	13 TeV	σ NLO	K
	σ_{SM}	$0.507^{+0.030+0.000+0.007}_{-0.048-0.000-0.008}$	1.09
Linear	$\sigma_{t\phi}$	$-0.062^{+0.006+0.001+0.001}_{-0.004-0.001-0.001}$	1.13
Linear	$\sigma_{\phi G}$	$0.872^{+0.131+0.037+0.013}_{-0.123-0.035-0.016}$	1.39
Linear	σ_{tG}	$0.503^{+0.025+0.001+0.007}_{-0.046-0.003-0.008}$	1.07
Quadratic	$\sigma_{t\phi,t\phi}$	$0.0019^{+0.0001+0.0001+0.0000}_{-0.0002-0.0000-0.0000}$	1.17
Quadratic	$\sigma_{\phi G,\phi G}$	$1.021^{+0.204+0.096+0.024}_{-0.178-0.085-0.029}$	1.58
Quadratic	$\sigma_{tG,tG}$	$0.674^{+0.036+0.004+0.016}_{-0.067-0.007-0.019}$	1.04
Quadratic	$\sigma_{t\phi,\phi G}$	$-0.053^{+0.008+0.003+0.001}_{-0.008-0.004-0.001}$	1.42
Quadratic	$\sigma_{t\phi,tG}$	$-0.031^{+0.003+0.000+0.000}_{-0.002-0.000-0.000}$	1.10
Quadratic	$\sigma_{\phi G,tG}$	$0.859^{+0.127+0.021+0.017}_{-0.126-0.020-0.022}$	1.37

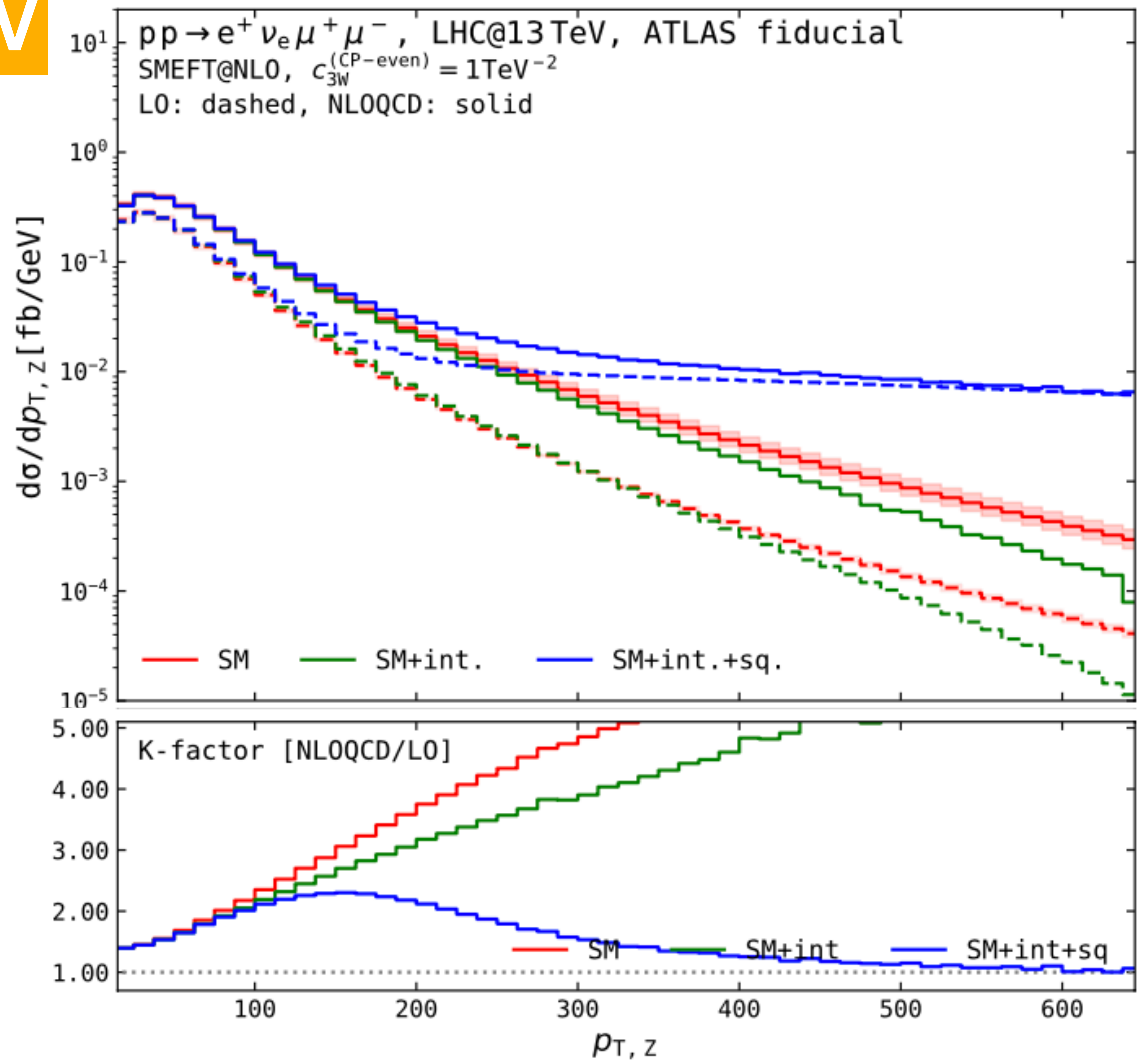
Different K-factors for different operators, different from the SM

Maltoni, EV, Zhang arXiv:1607.05330

Accuracy and precision: QCD

Example 2: more k-factors and shapes

VV



El Faham, Pellicciolі, EV arXiv:2405.19083

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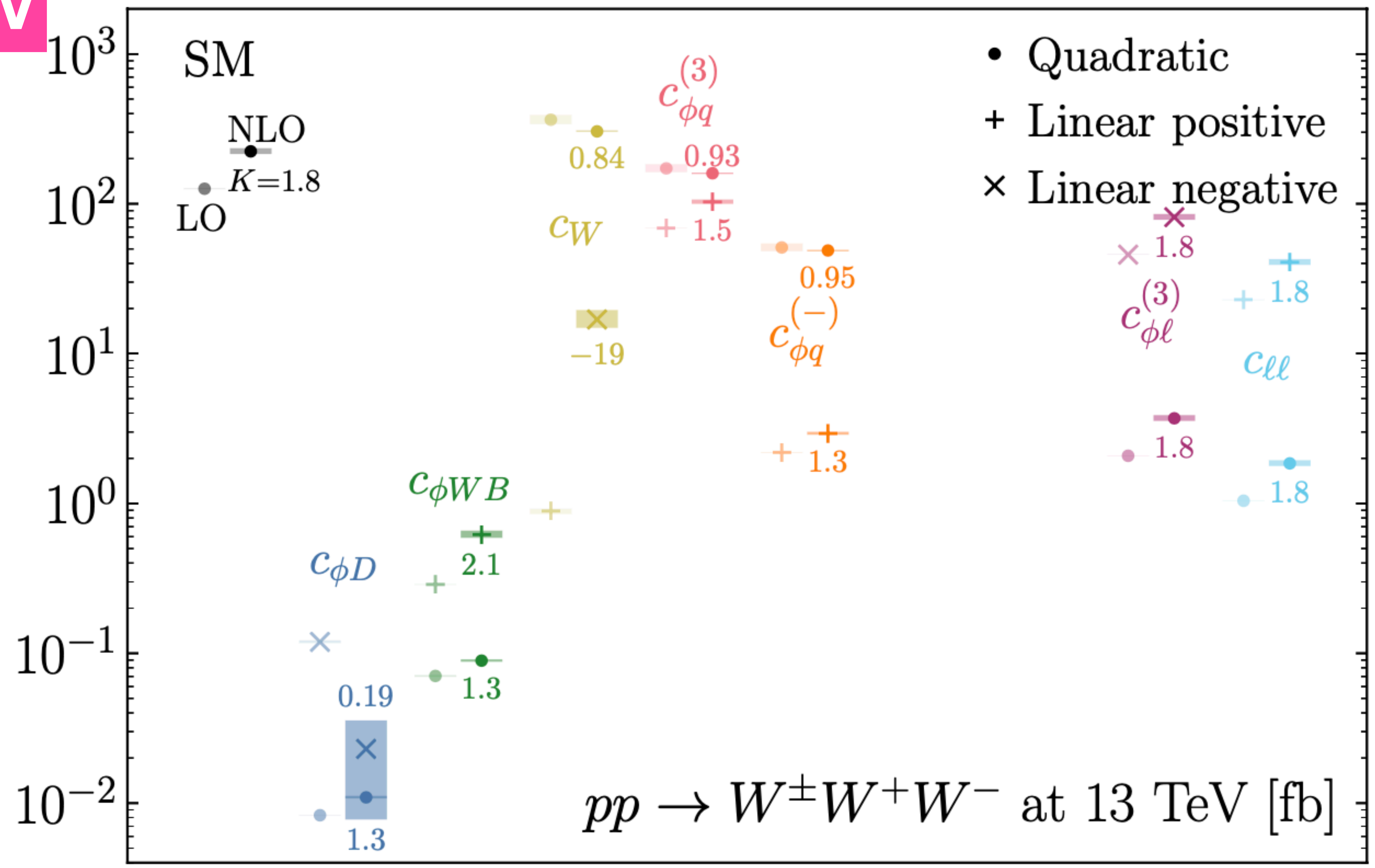

Celada, Durieux, Mimasu, EV arXiv:2407.09600

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Accuracy and precision: QCD

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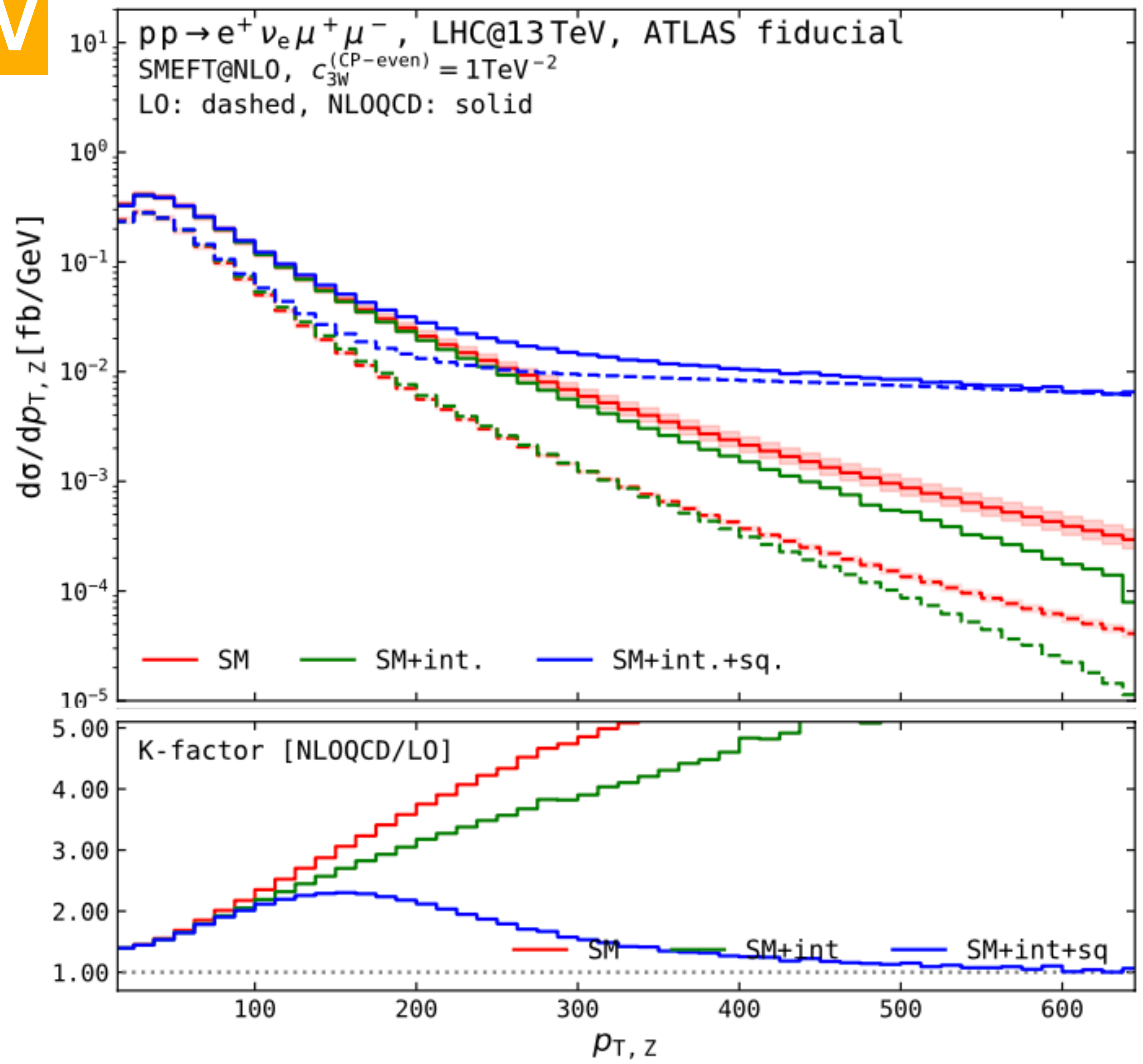

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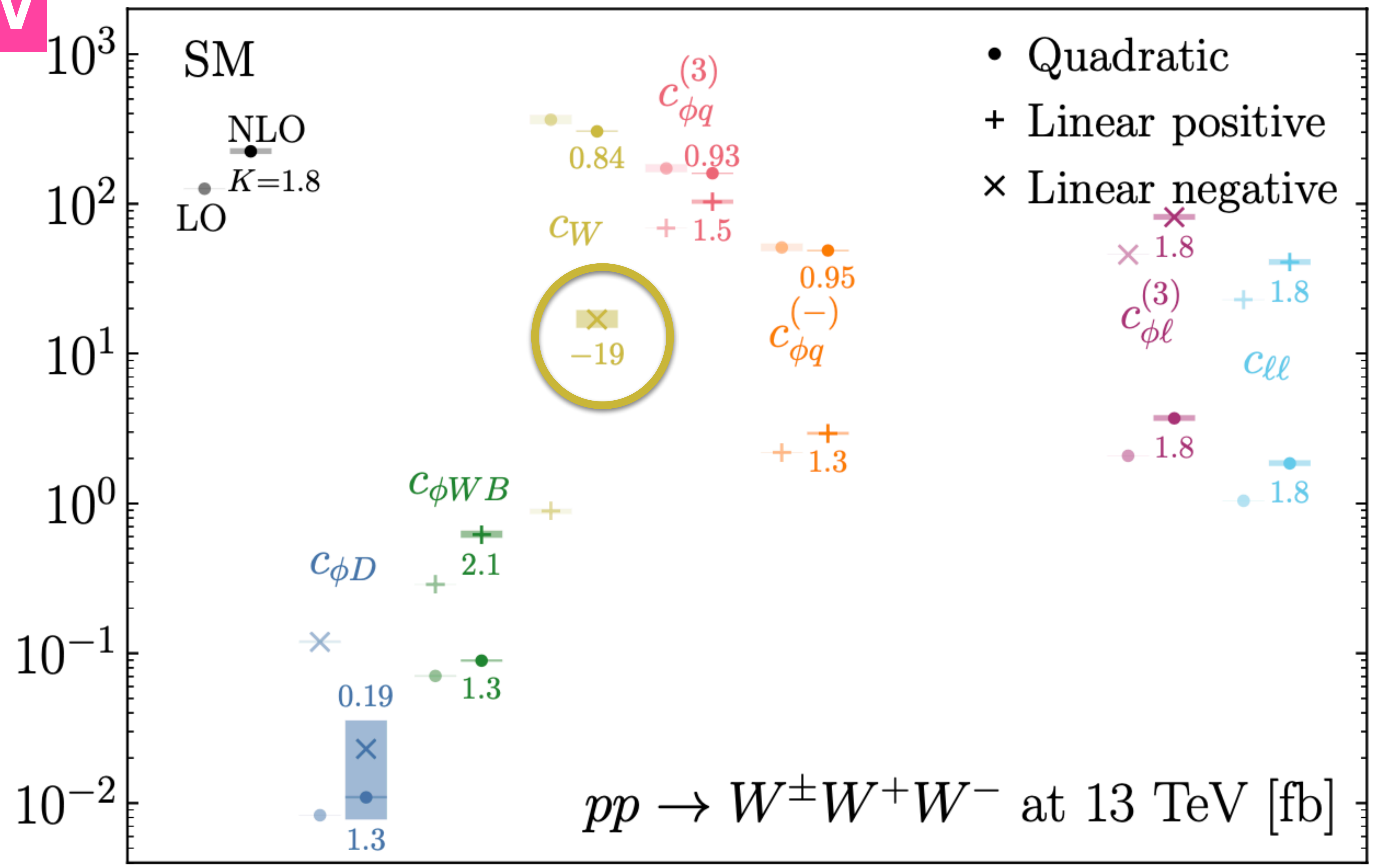

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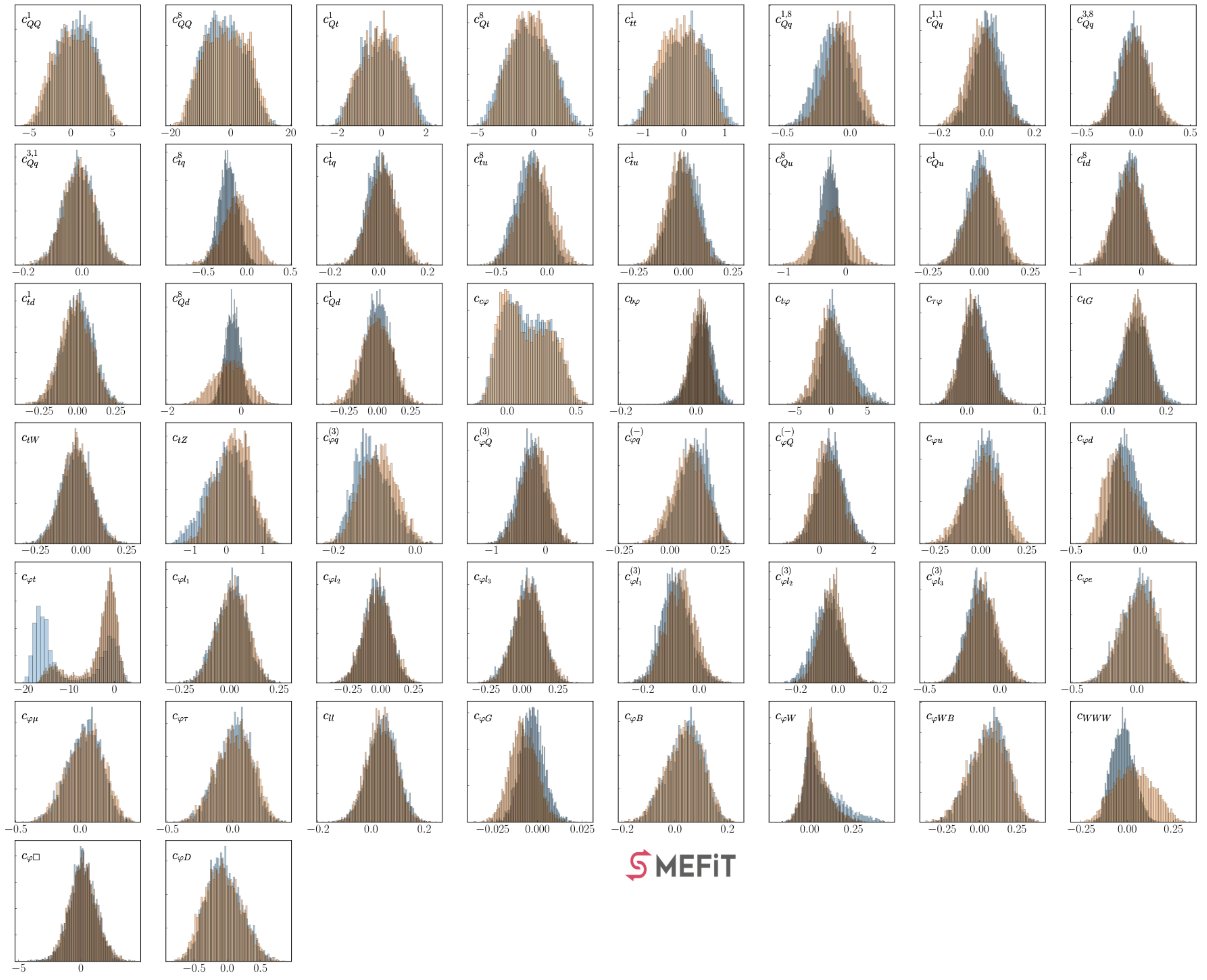
Does NLO QCD change global fits?

Global top fits



Posterior distributions for Wilson coefficients

Blue: LO

Orange: NLO

Significant impact of NLO for some operators

Linear level: NLO resolves non-interference problem for colour singlet 4-fermion operators

NLO is not necessarily more constraining but it is more reliable

SMEFiT3.0 Celada, Giani, Mantani, Rojo, Rossia, Thomas, EV, ter Hoeve arXiv:2404.12809

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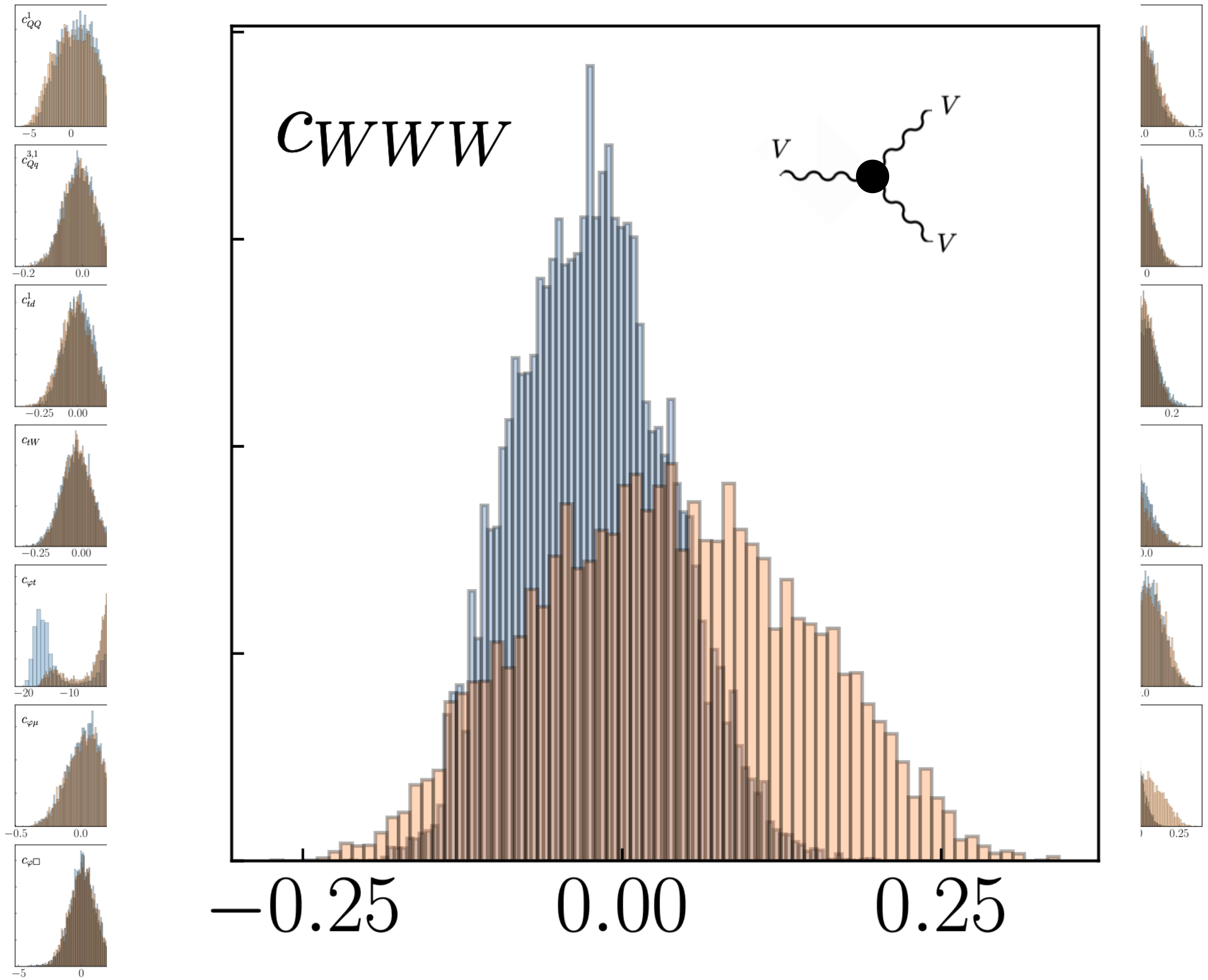

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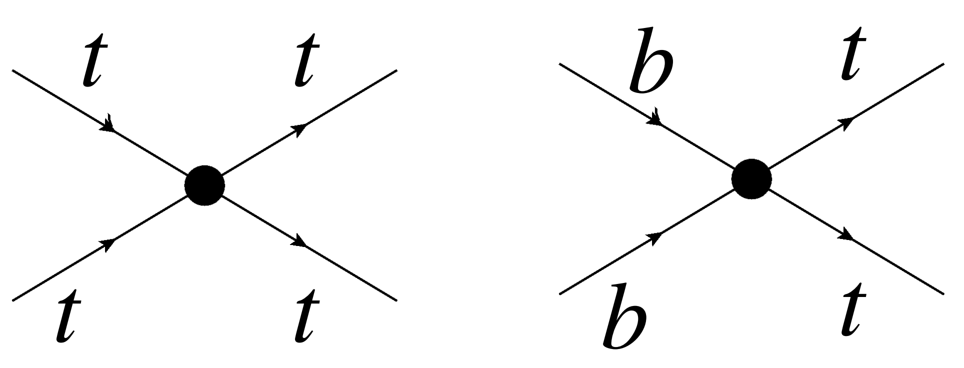
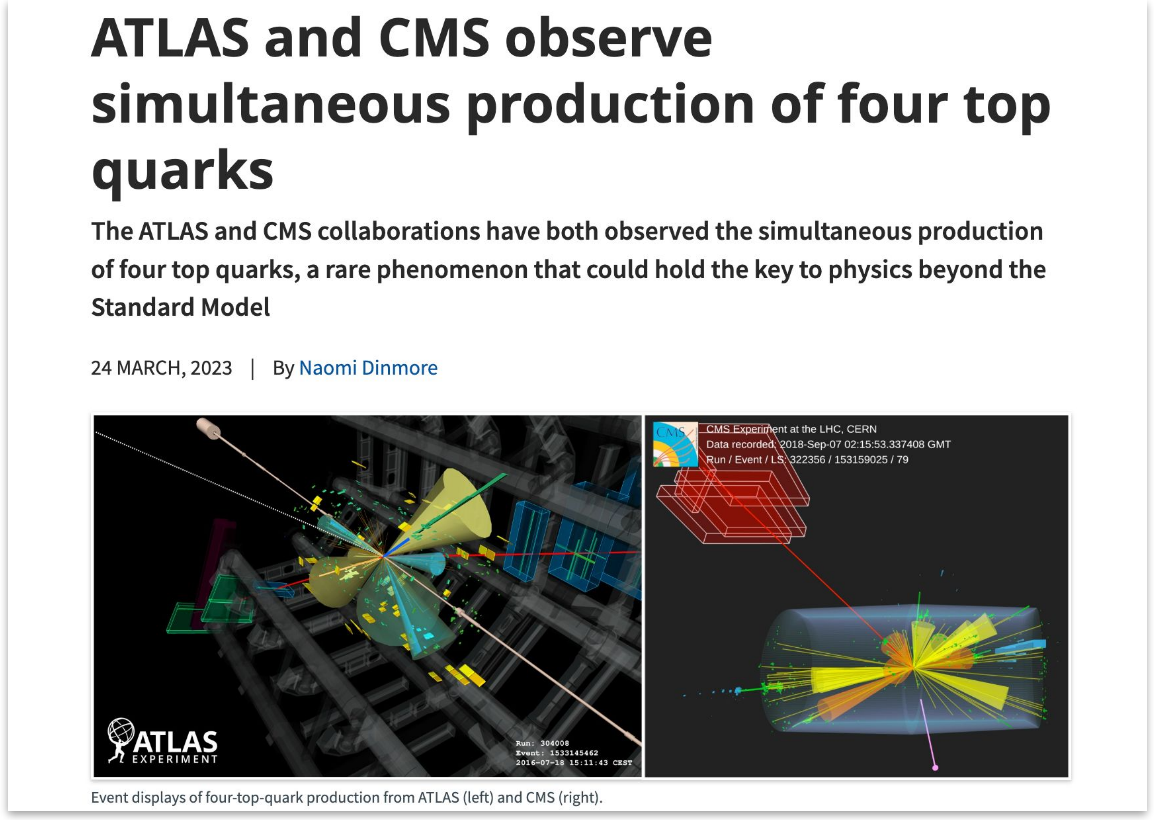
Where can higher orders help?

Poorly constrained operators

$$\mathcal{O}^8_{QQ} = (\bar{Q}\gamma^\mu T^A Q)(\bar{Q}\gamma_\mu T^A Q)$$
$$\mathcal{O}^1_{QQ} = (\bar{Q}\gamma^\mu Q)(\bar{Q}\gamma_\mu Q)$$
$$\mathcal{O}^8_{Qt} = (\bar{Q}\gamma^\mu T^A Q)(\bar{t}\gamma_\mu T^A t)$$
$$\mathcal{O}^1_{Qt} = (\bar{Q}\gamma^\mu Q)(\bar{t}\gamma_\mu t)$$
$$\mathcal{O}^1_{tt} = (\bar{t}\gamma^\mu t)(\bar{t}\gamma_\mu t)$$



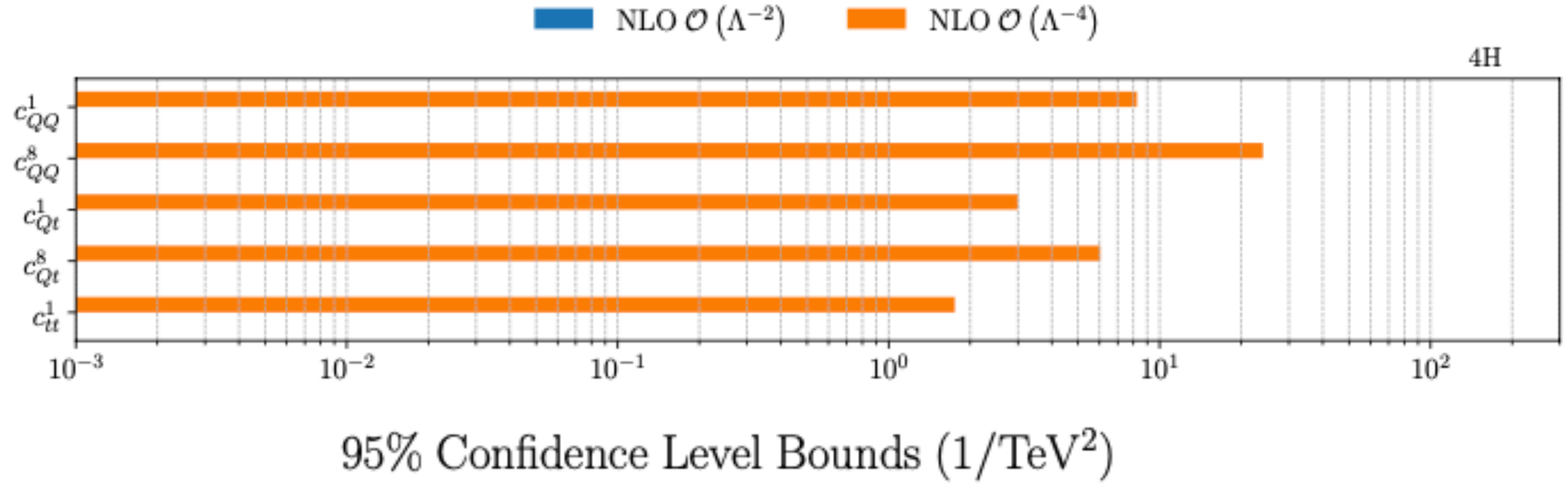
Only accessible through 4-top and $t\bar{t}b\bar{b}$ measurements


ATLAS and CMS observe simultaneous production of four top quarks

The ATLAS and CMS collaborations have both observed the simultaneous production of four top quarks, a rare phenomenon that could hold the key to physics beyond the Standard Model

24 MARCH, 2023 | By Naomi Dinmore

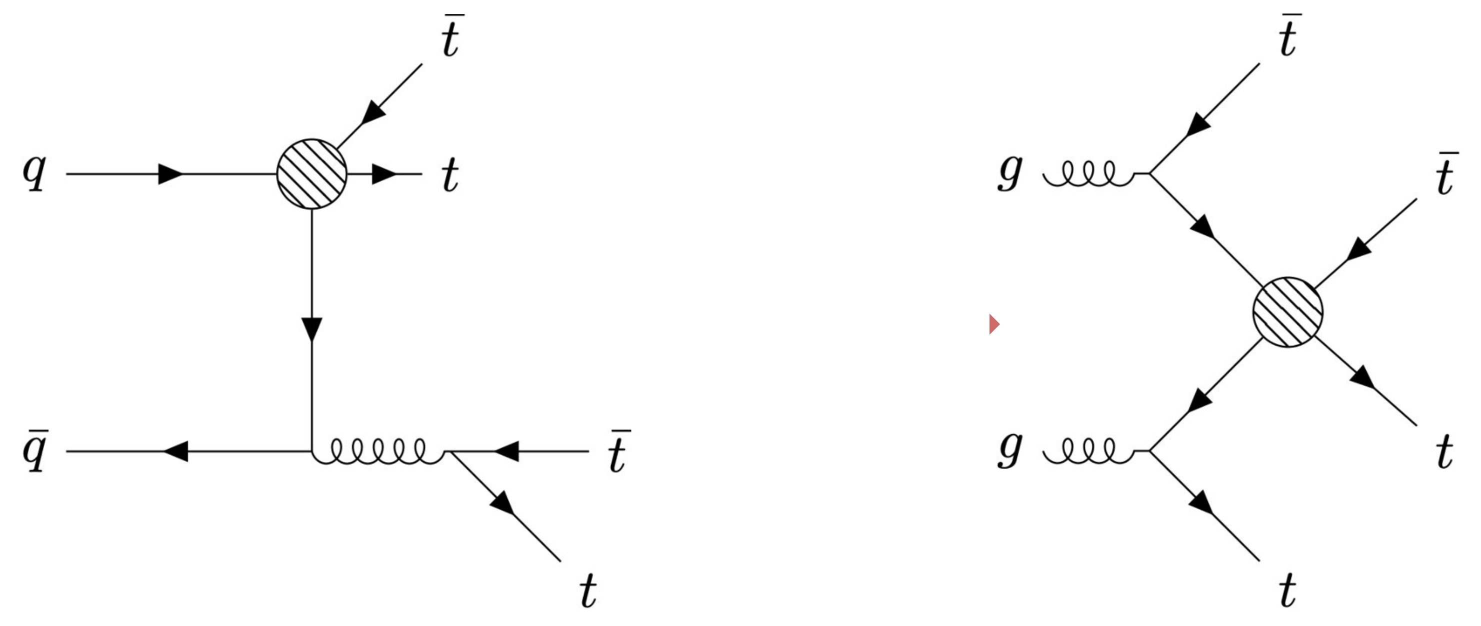
Event displays of four-top-quark production from ATLAS (left) and CMS (right).

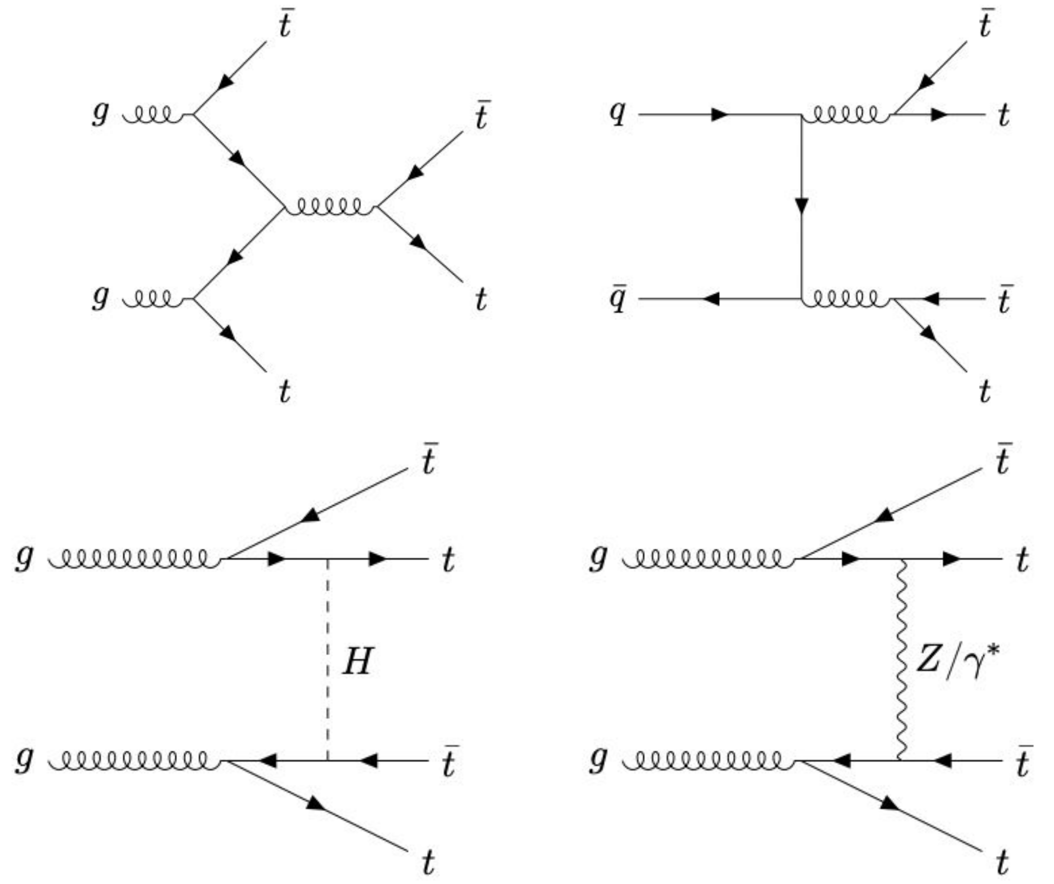


Can precision help improve this picture?

SMEFiT3.0 Celada, Giani, Mantani, Rojo, Rossia, Thomas, EV, ter Hoeve arXiv:2404.12809

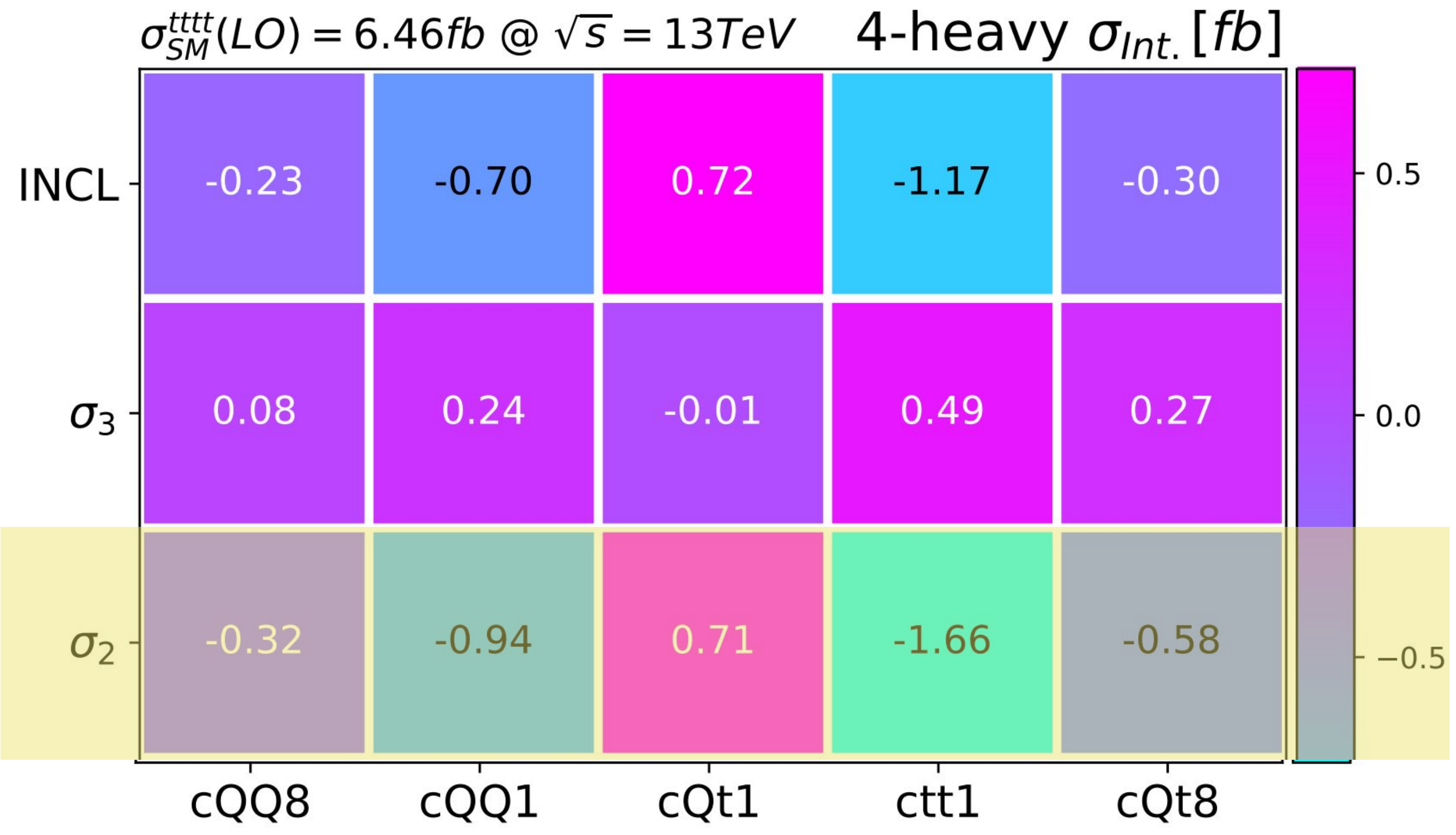
“Subleading” leading contributions





QCD

EW



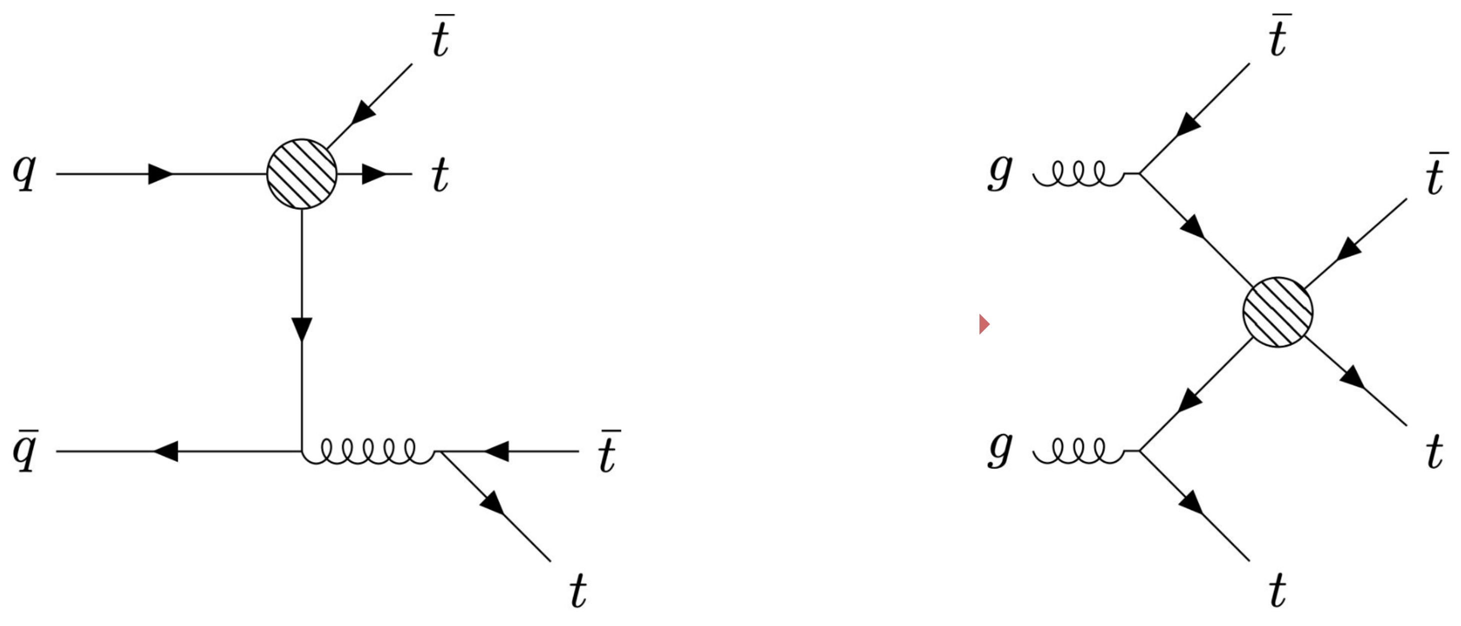
QCD

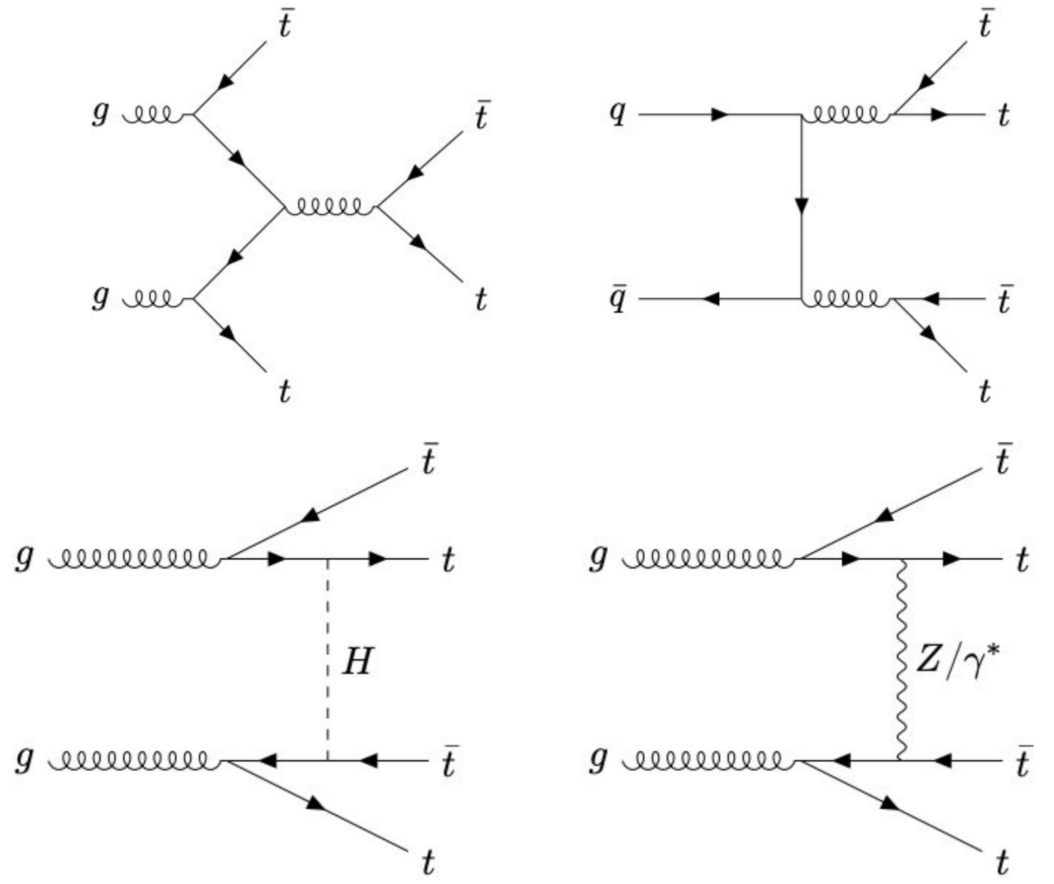
EW

Formally subleading EW effects are large and need to be taken into account

Aoude, El Faham, Maltoni, EV arXiv:2208.04962

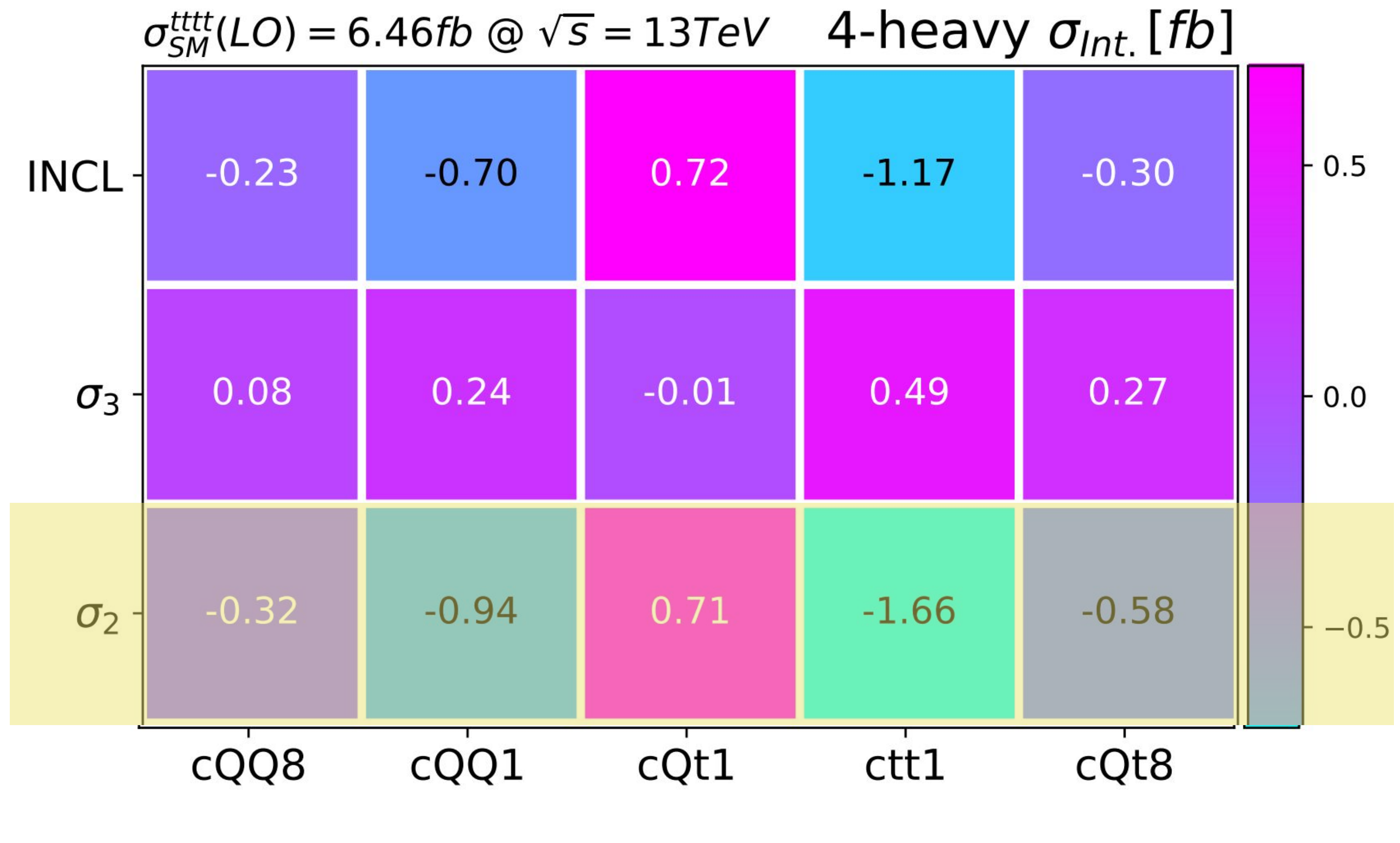
“Subleading” leading contributions





QCD

EW



QCD

EW

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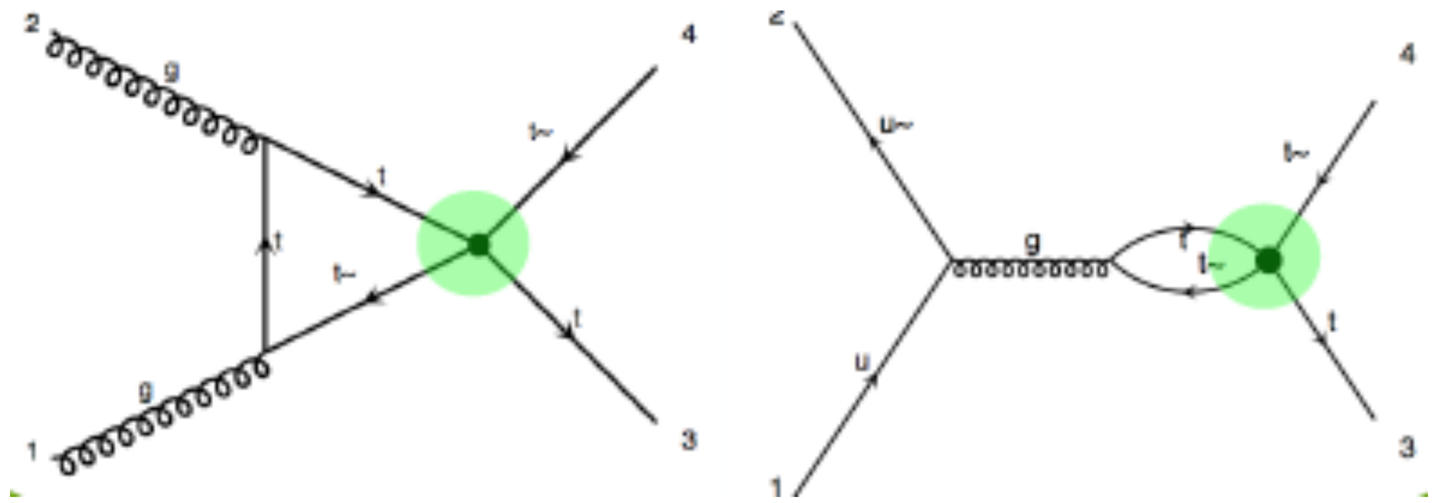
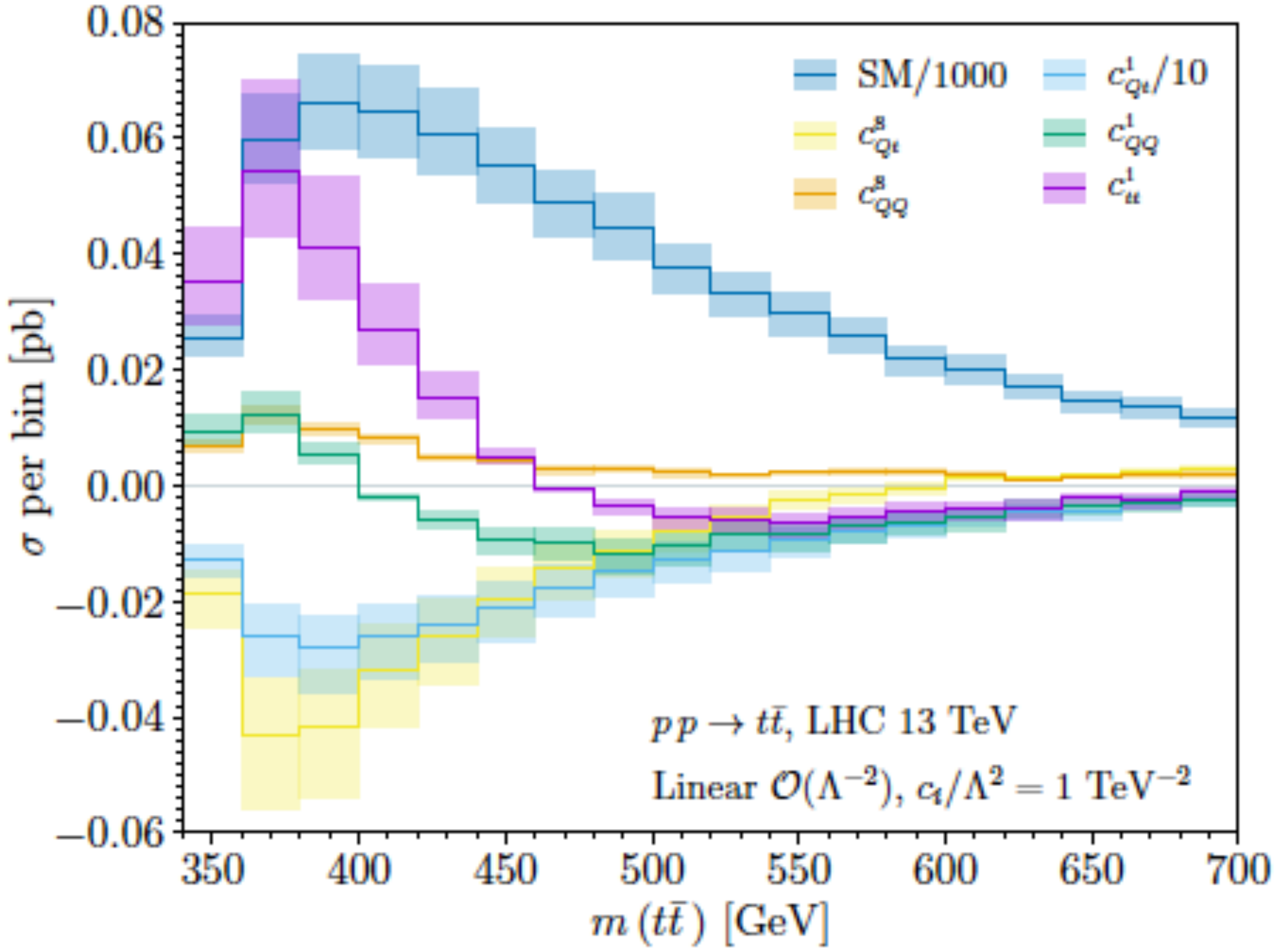
New probes

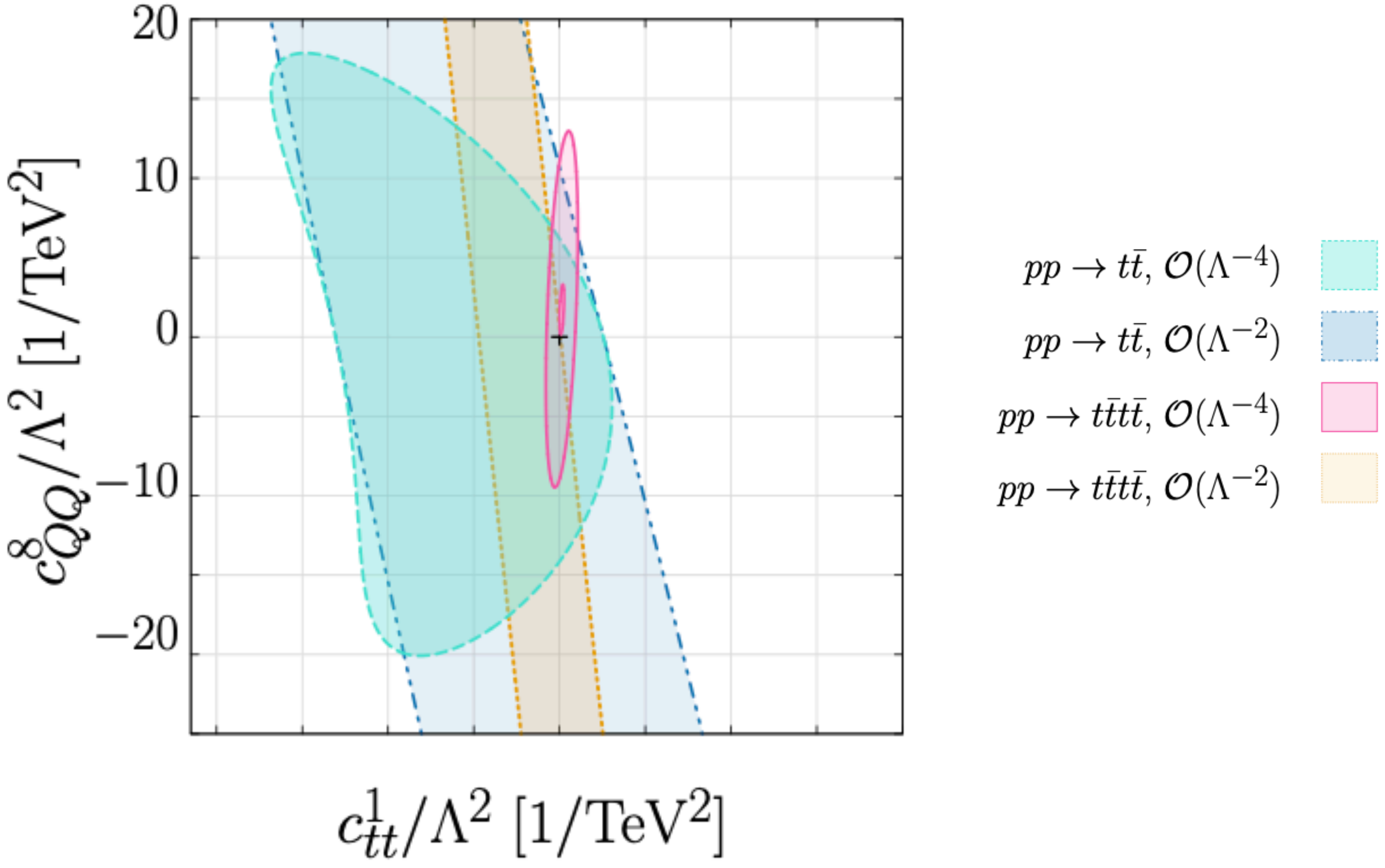
4-heavy operators in top pair production

At NLO:





Degrande, Durieux, Maltoni, Mimasu, EV, Zhang arXiv:2008.11743

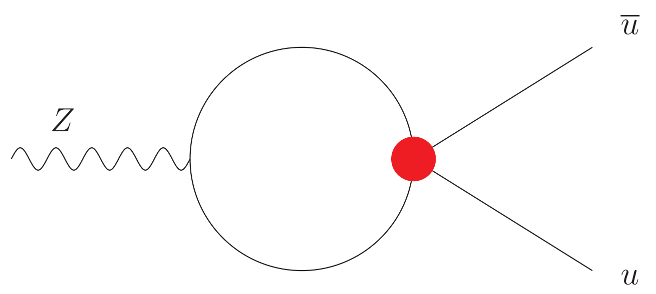


Degrande, Rosenfeld, Vasquez arXiv:2402.06528

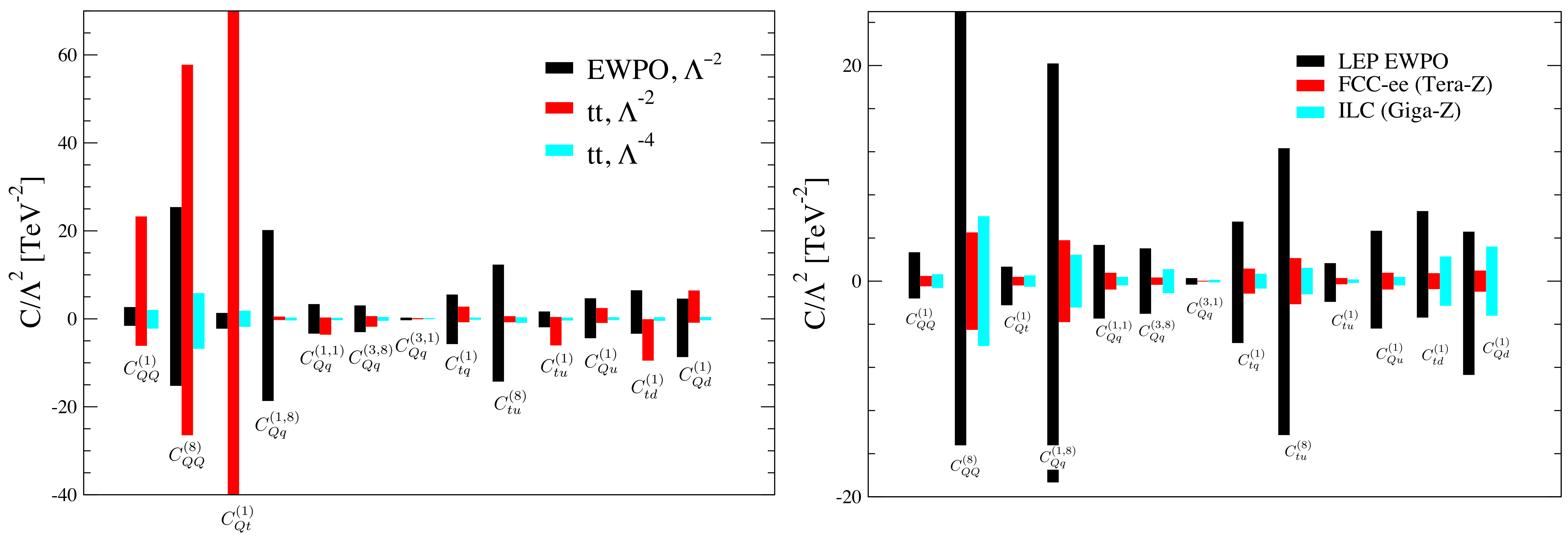
Complementary information to ttbb and 4top production

Improved sensitivity due to EW loops

4-heavy operators in EWPO

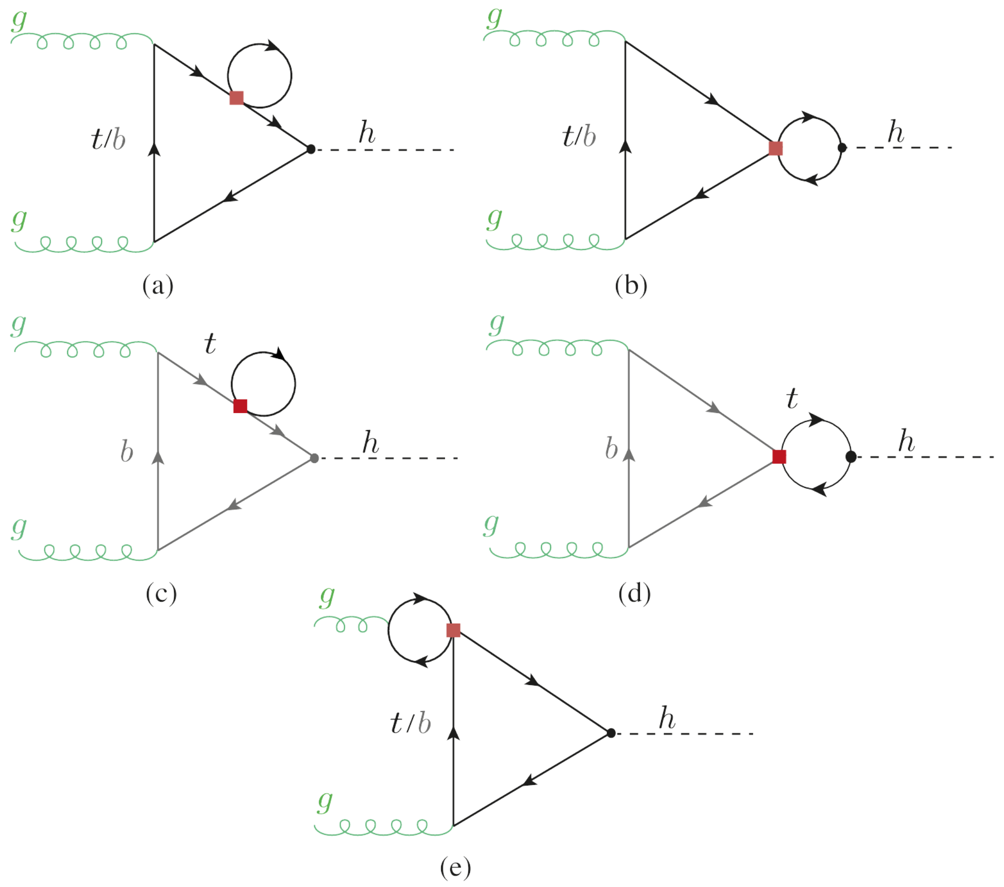


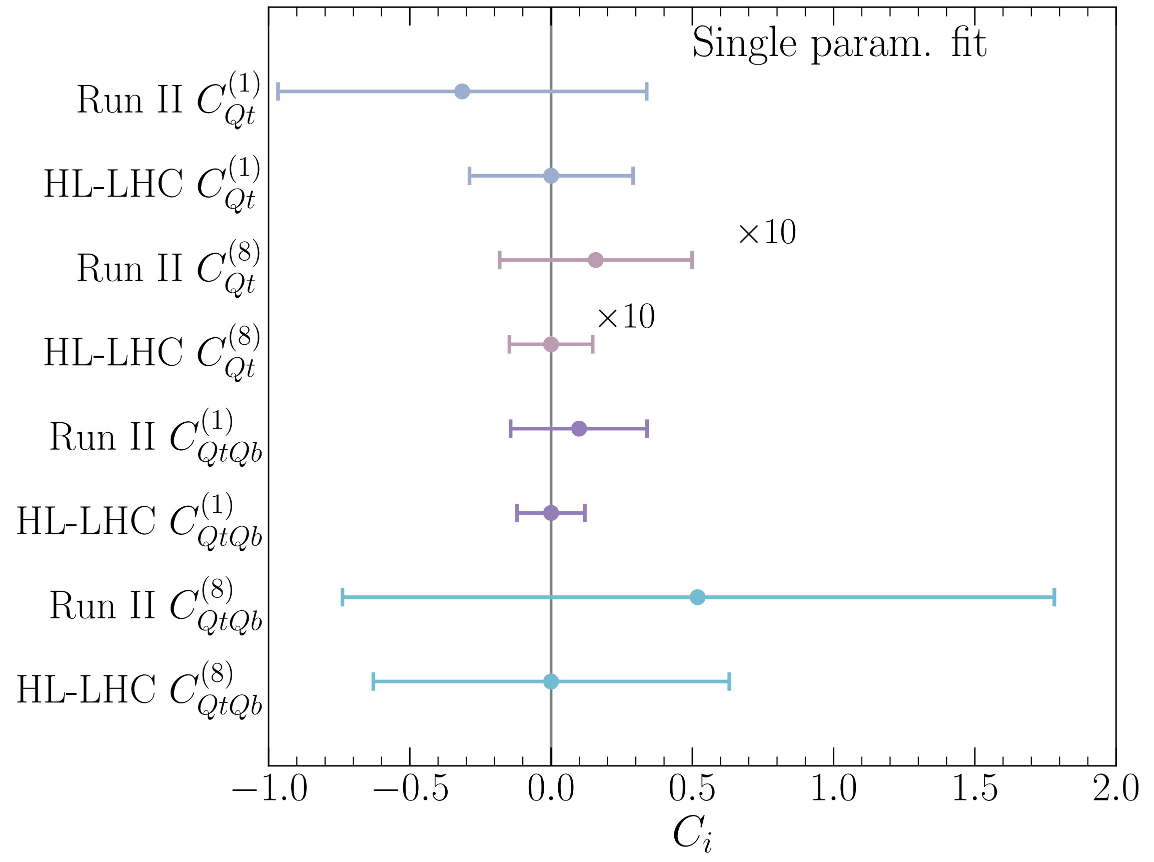
95% CL limits on 3[rd] generation 4-fermion operators



Dawson and Giardino arXiv: 2201.09887

4-heavy operators in Higgs production





Alasfar, de Blas, Gröber arXiv:2202.02333

New loop-induced sensitivities: EWPO and Higgs production

Bounds are competitive to 4top production

A combination of all probes can pin these coefficients down!

Towards NLO EW corrections

EFT effects often pronounced in the tails of distributions

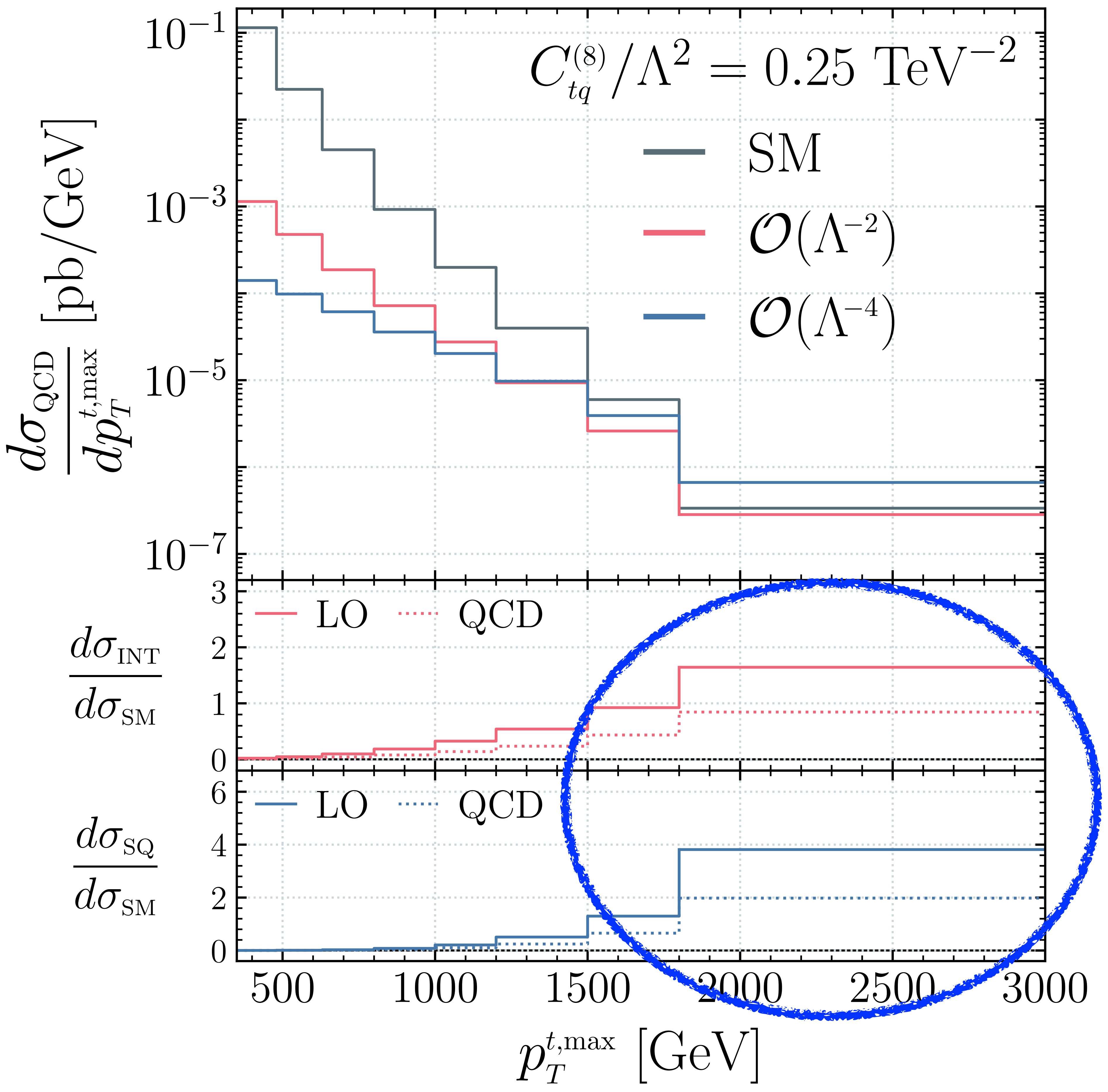
This is where EW corrections are important

In the SM NLO EW can be O(10%) at 1/2 TeV

Exact NLO EW corrections are not available in the SMEFT in general (some simple processes studied)

At high energy these are described by Sudakov logarithms ~$\log^2 (s/m_W^2)$ and ~$\log (s/m_W^2)$

Can Sudakov logs be computed and be a good approximation for EW corrections in the SMEFT?



EW corrections at high energy

Formalism

Denner-Pozzorini algorithm

Born logs

$$\lim_{M_W^2/s\to 0}(\mathcal{M}_{1,\mathrm{EW}}^{\mathrm{SM}})^{i_1\ldots i_n}(p_1,\ldots,p_n) = \sum_{i'_1\ldots i'_n}(\mathcal{M}_0^{\mathrm{SM}})^{i'_1\ldots i'_n}(p_1,\ldots,p_n)\,\delta^{\mathrm{SM}}_{\mathrm{EW},\,i'_1 i_1\ldots i'_n i_n}$$

$$\delta^{\mathrm{SM}}_{\mathrm{EW}} = \delta^{\mathrm{SM}}_{\mathrm{LSC}} + \delta^{\mathrm{SM}}_{\mathrm{SSC}} + \delta^{\mathrm{SM}}_{\mathrm{C}} + \delta^{\mathrm{SM}}_{\mathrm{PR}}$$

leading soft collinear | subleading soft collinear | collinear | parameter renormalisation

Only depends on Born amplitudes and the EW charges of the external legs

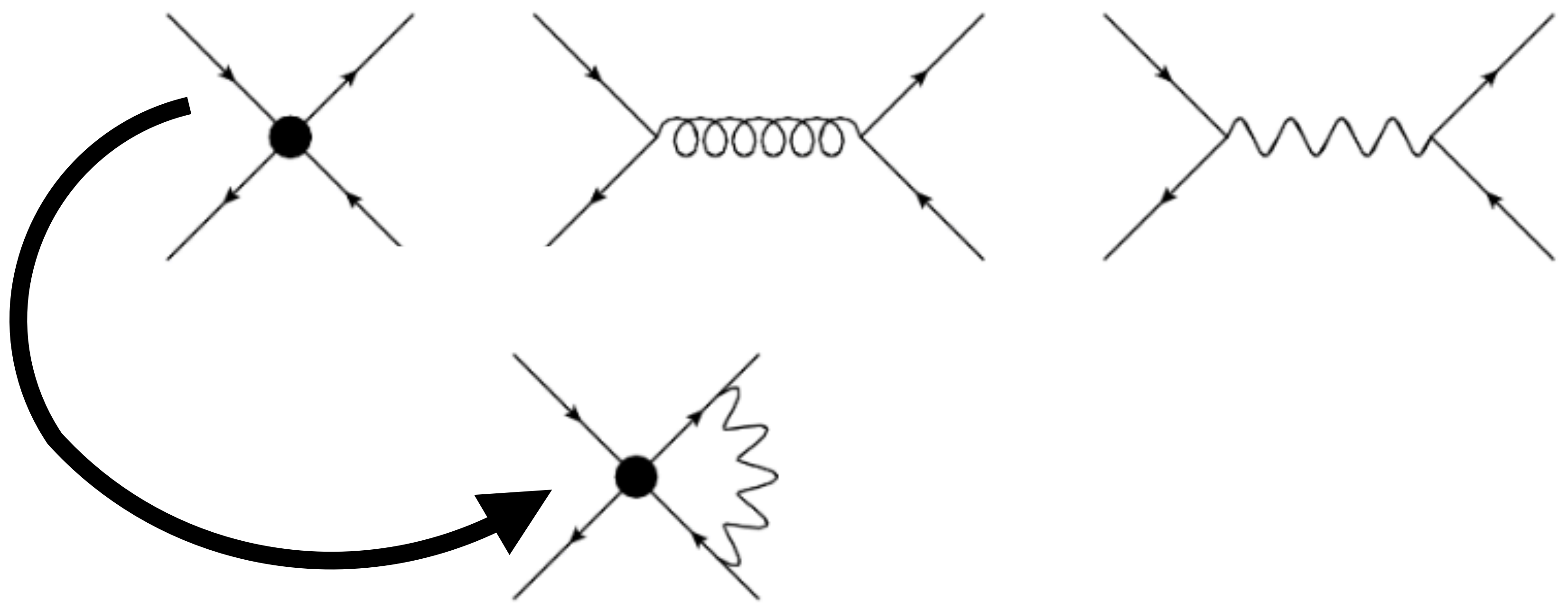
Denner and Pozzorini hep-ph/0010201 and hep-ph/0104127

How about the SMEFT?

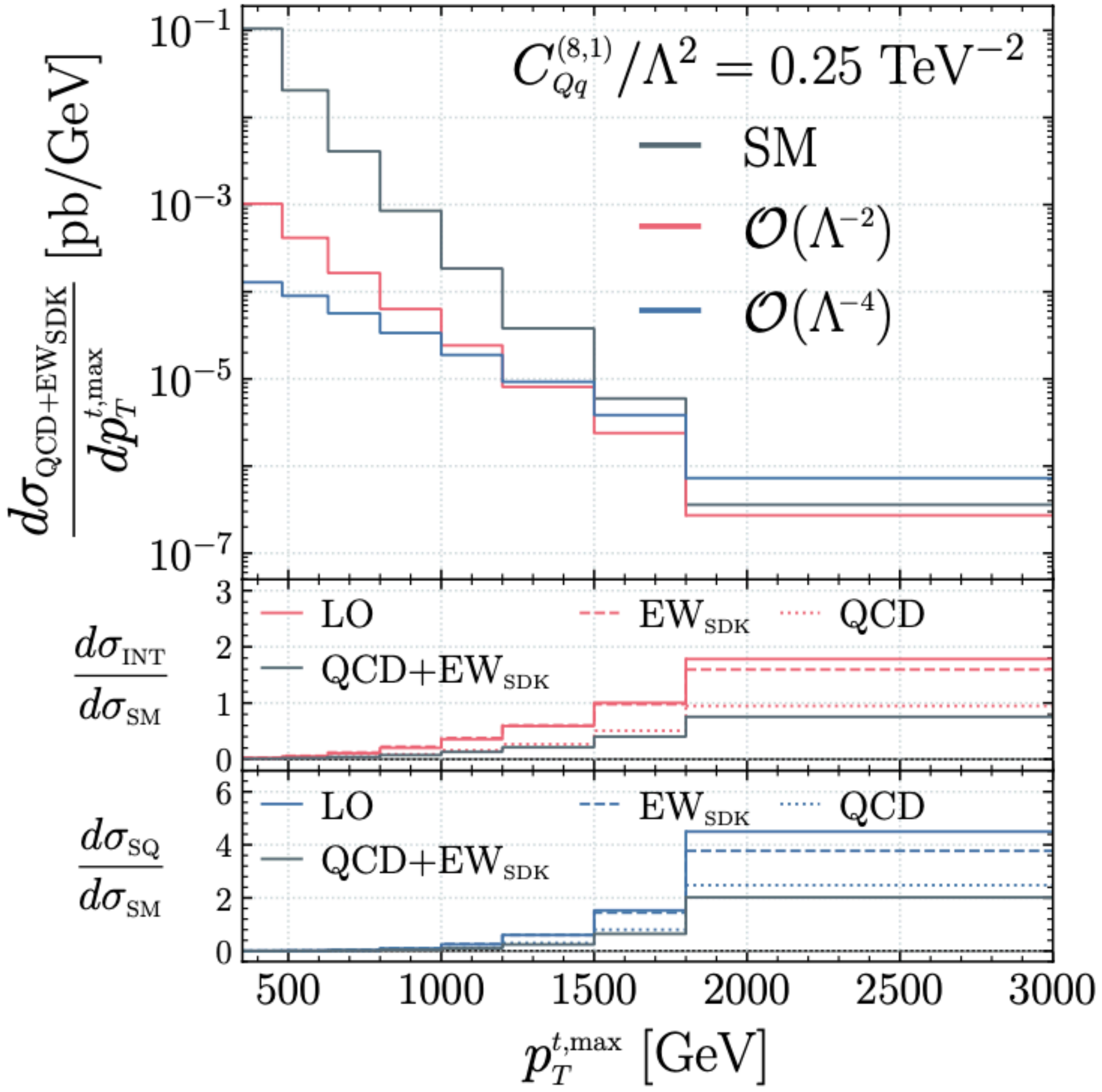
High-energy EW corrections

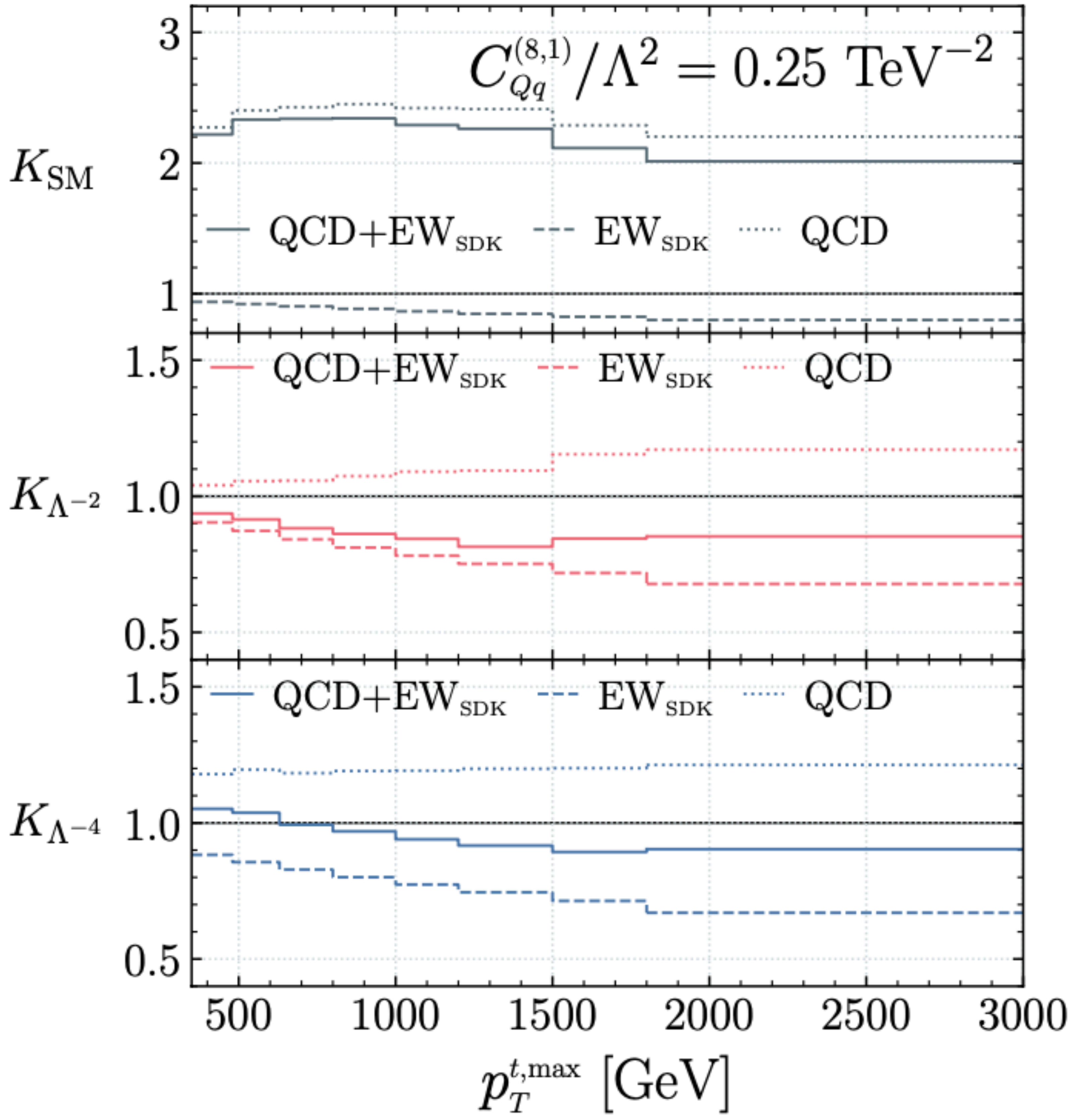
Top pair production@LHC

$$\mathcal{O}_{Qq}^{1,8} = (\overline{Q}\gamma^{\mu}T^{A}Q)(\overline{q}_i\gamma_{\mu}T^{A}q_i)$$



$$\lim_{M_W^2/s\to 0} \mathcal{M}_{1,\mathrm{EW}}^{\mathrm{NP}} = \mathcal{M}_0^{\mathrm{NP}}\delta_{\mathrm{EW}}^{\mathrm{SM}}$$





El Faham, Mimasu, Pagani, Severi, EV, Zaro in preparation

MC implementation based on Pagani, Zaro arXiv:2110.03714, see also Lindert, Mai 2312.07927

High-energy EW corrections

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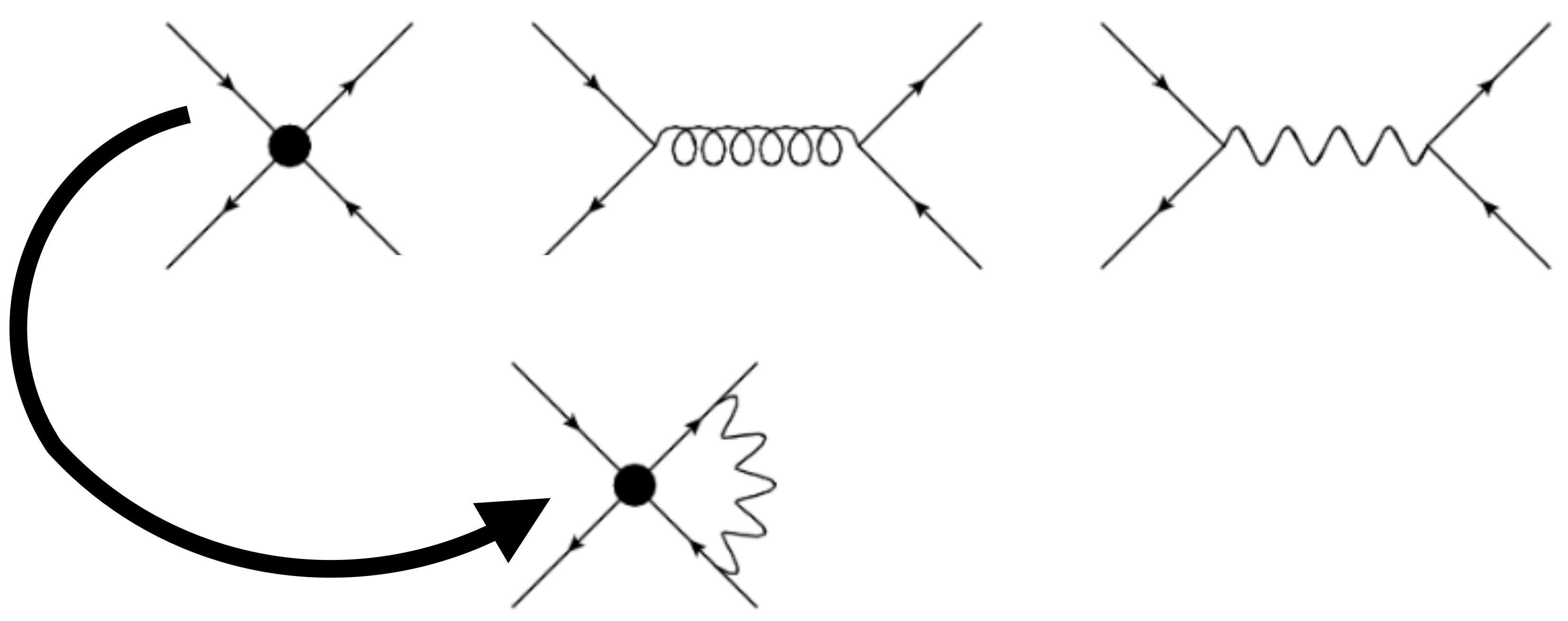
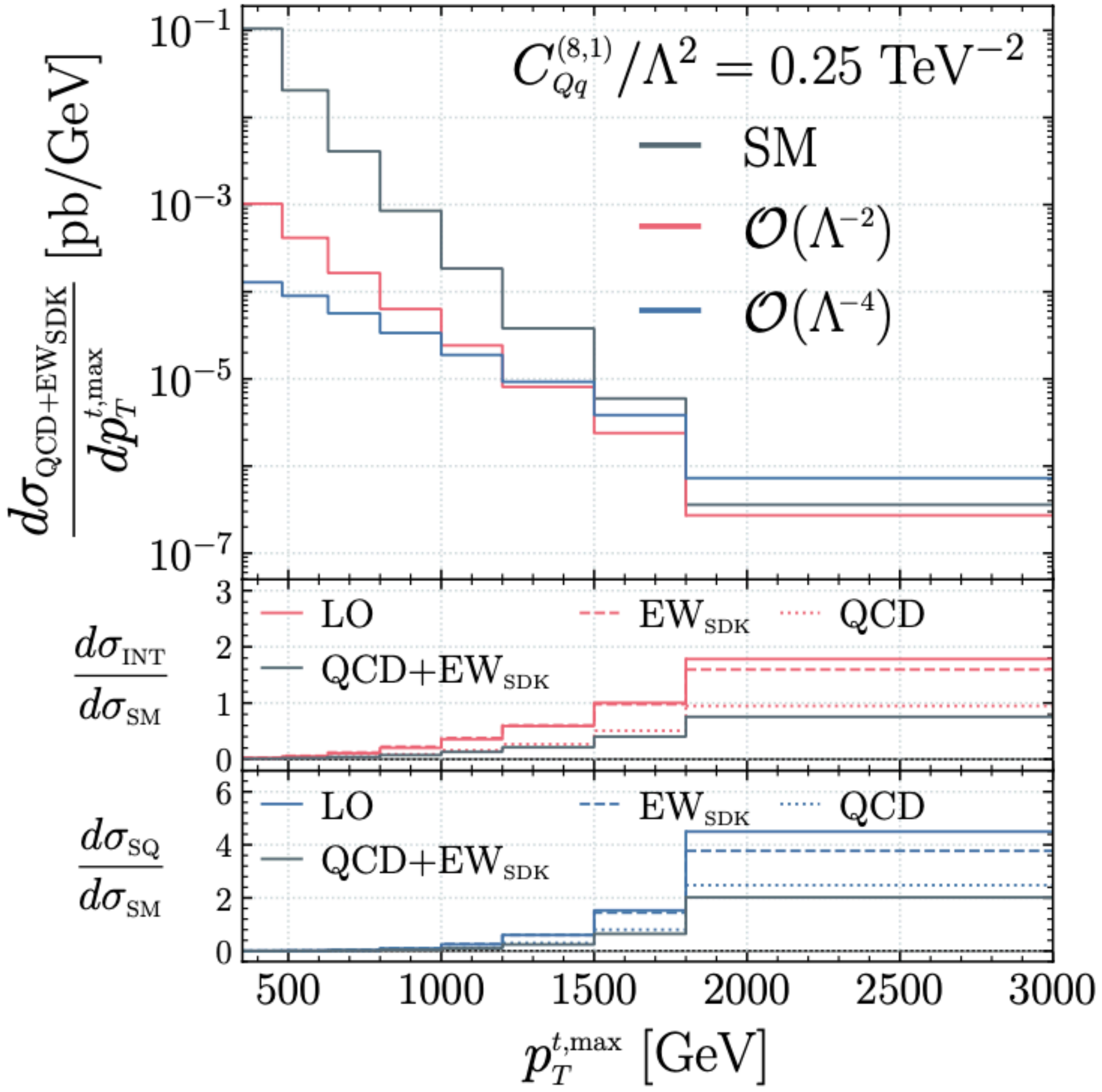
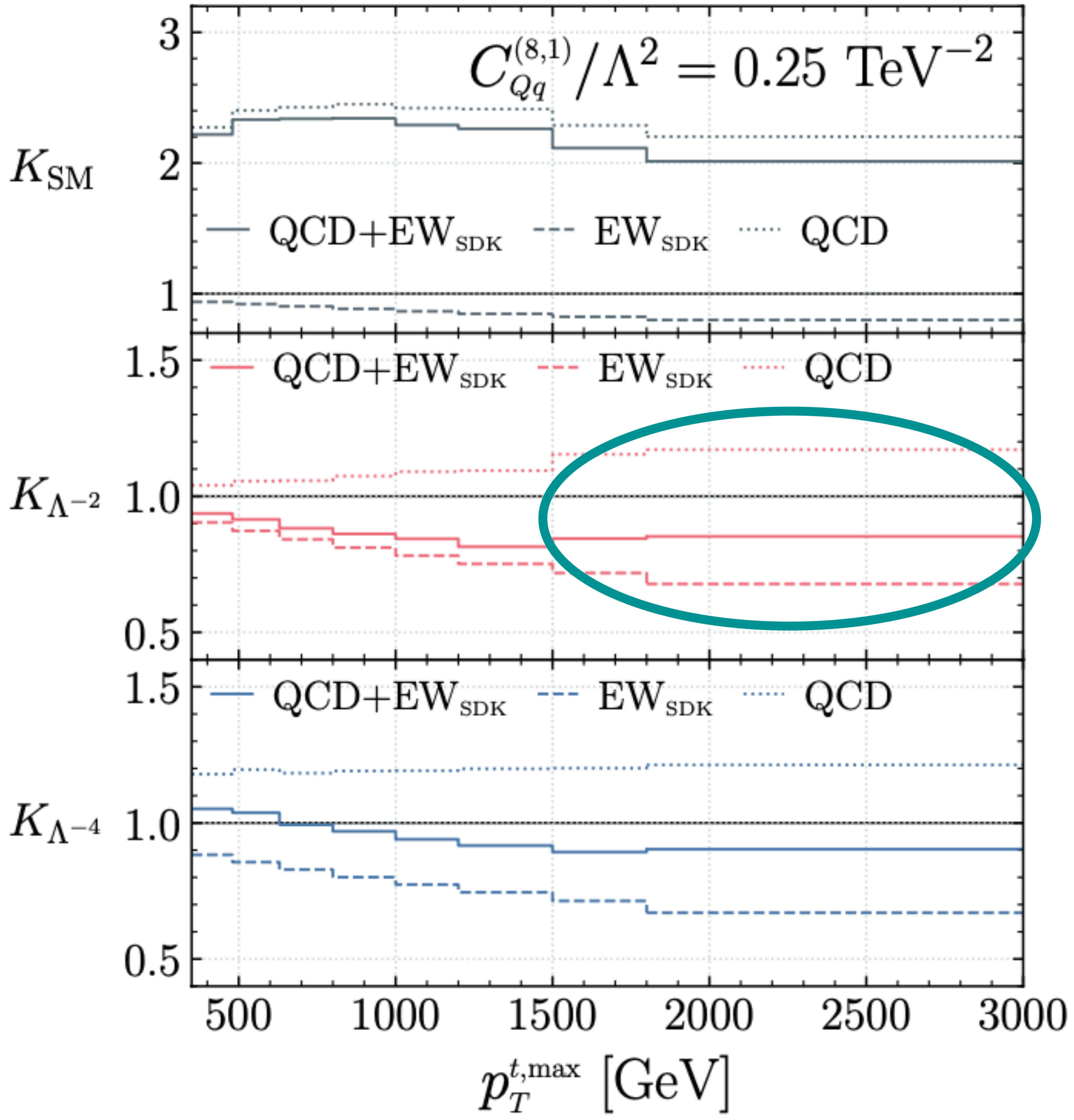


$$\lim_{M_W^2/s\to 0} \mathcal{M}_{1,\mathrm{EW}}^{\mathrm{NP}} = \mathcal{M}_0^{\mathrm{NP}}\delta_{\mathrm{EW}}^{\mathrm{SM}}$$

QCD corrections: +ve

EW corrections: -ve





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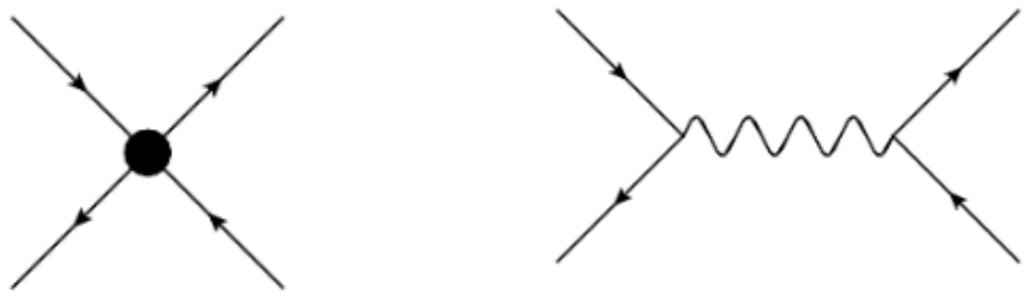
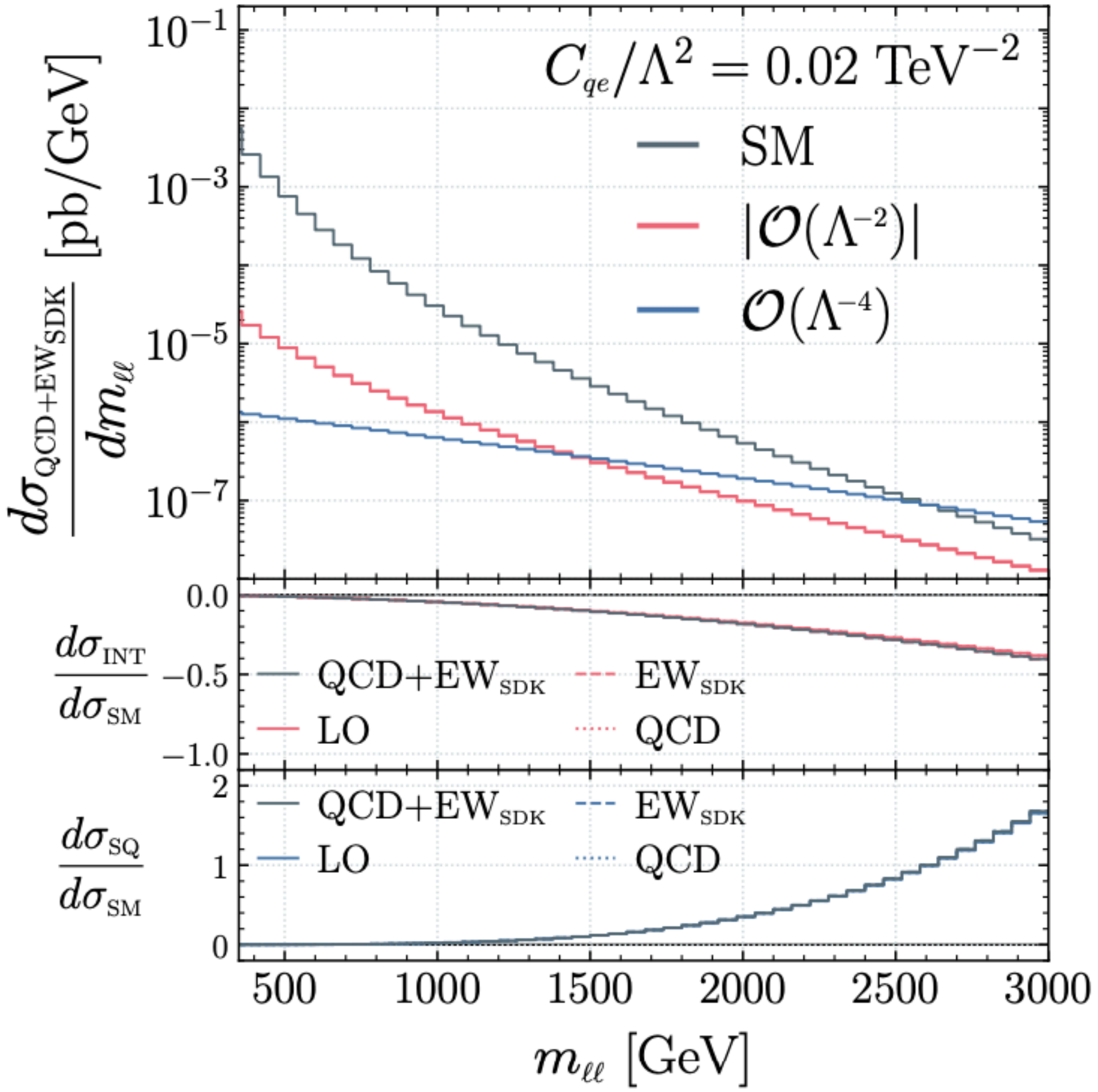
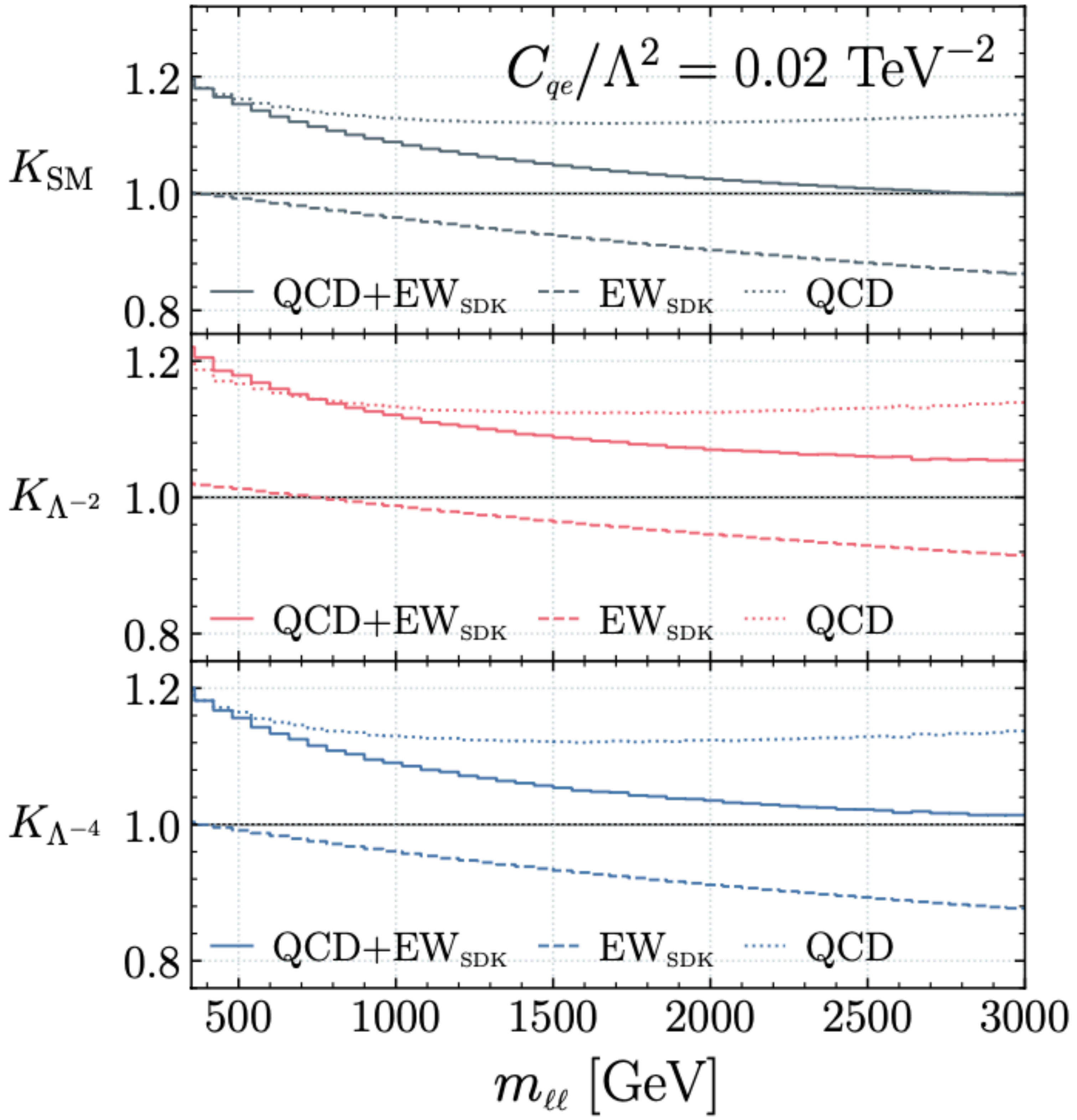
High-energy EW corrections

DY@LHC

$$\mathcal{O}_{qe} = \sum_{\mathrm{f}=1}^{2} (\bar{q}_\mathrm{f}\gamma_\mu q_\mathrm{f})(\bar{e}\gamma^\mu e)$$







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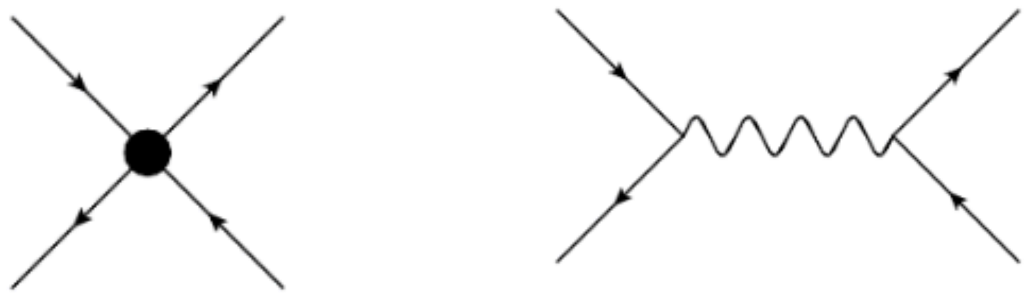
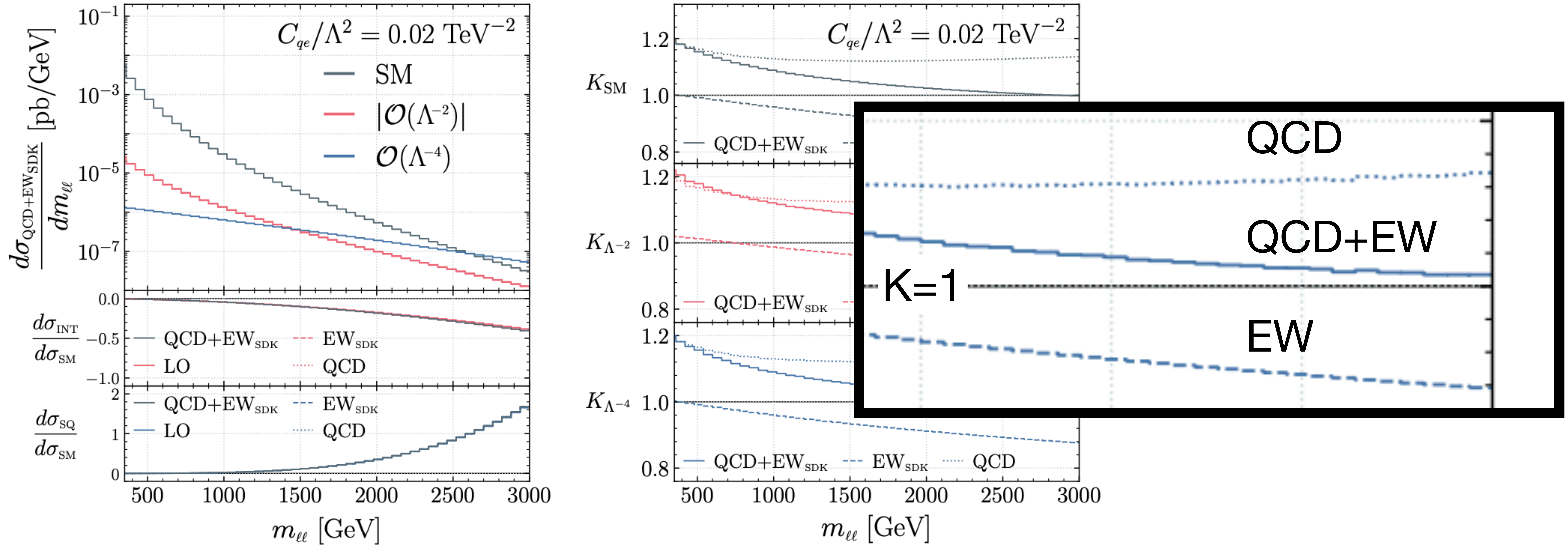
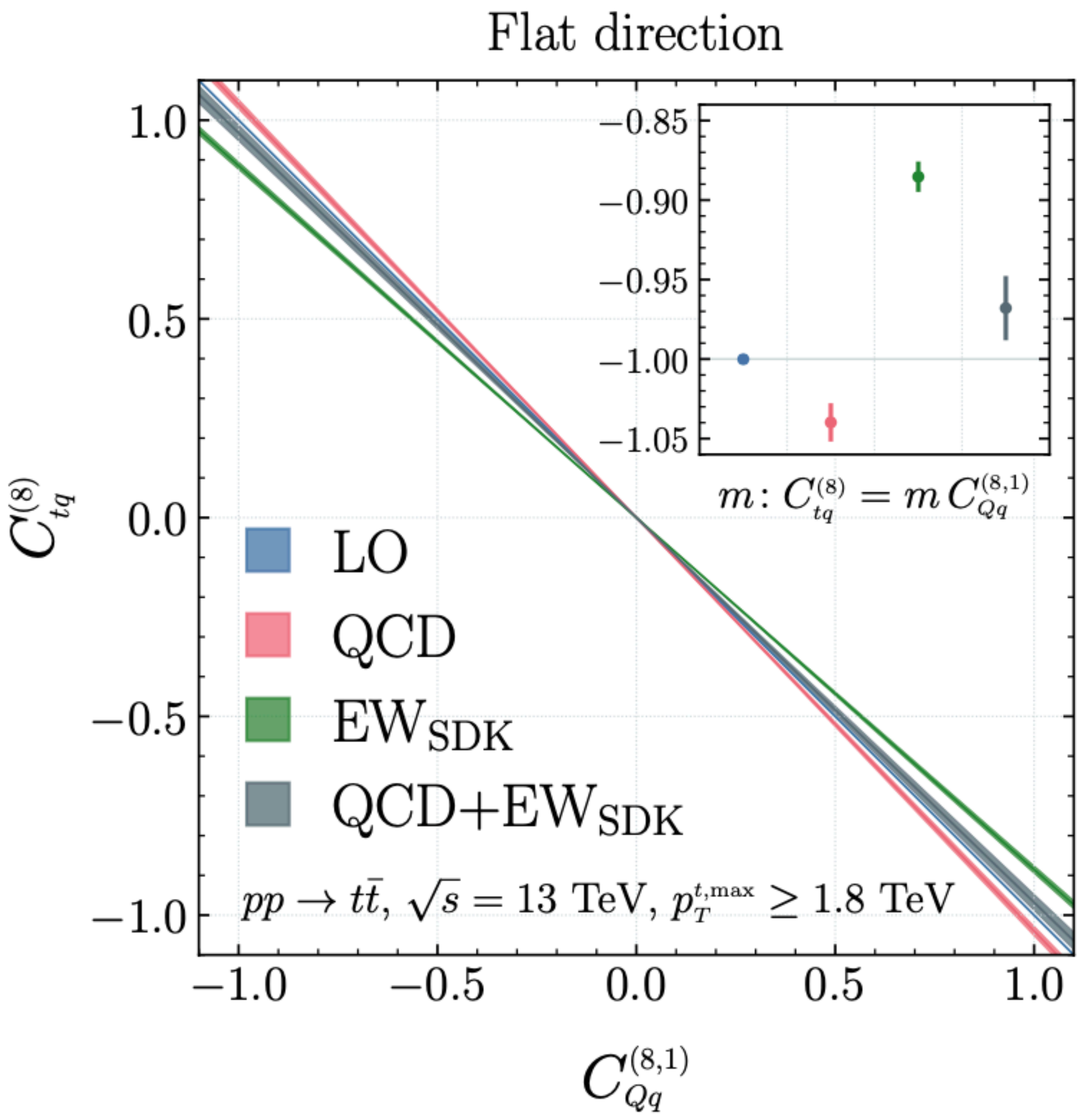




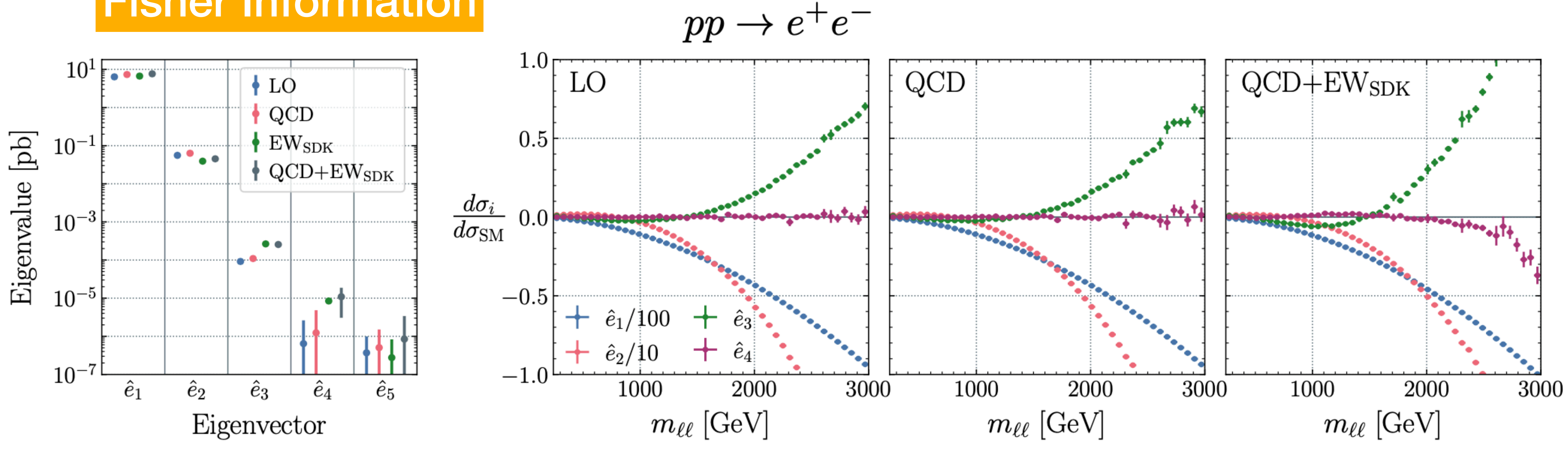
El Faham, Mimasu, Pagani, Severi, EV, Zaro in preparation

High-energy EW corrections

Breaking degeneracies



Fisher Information



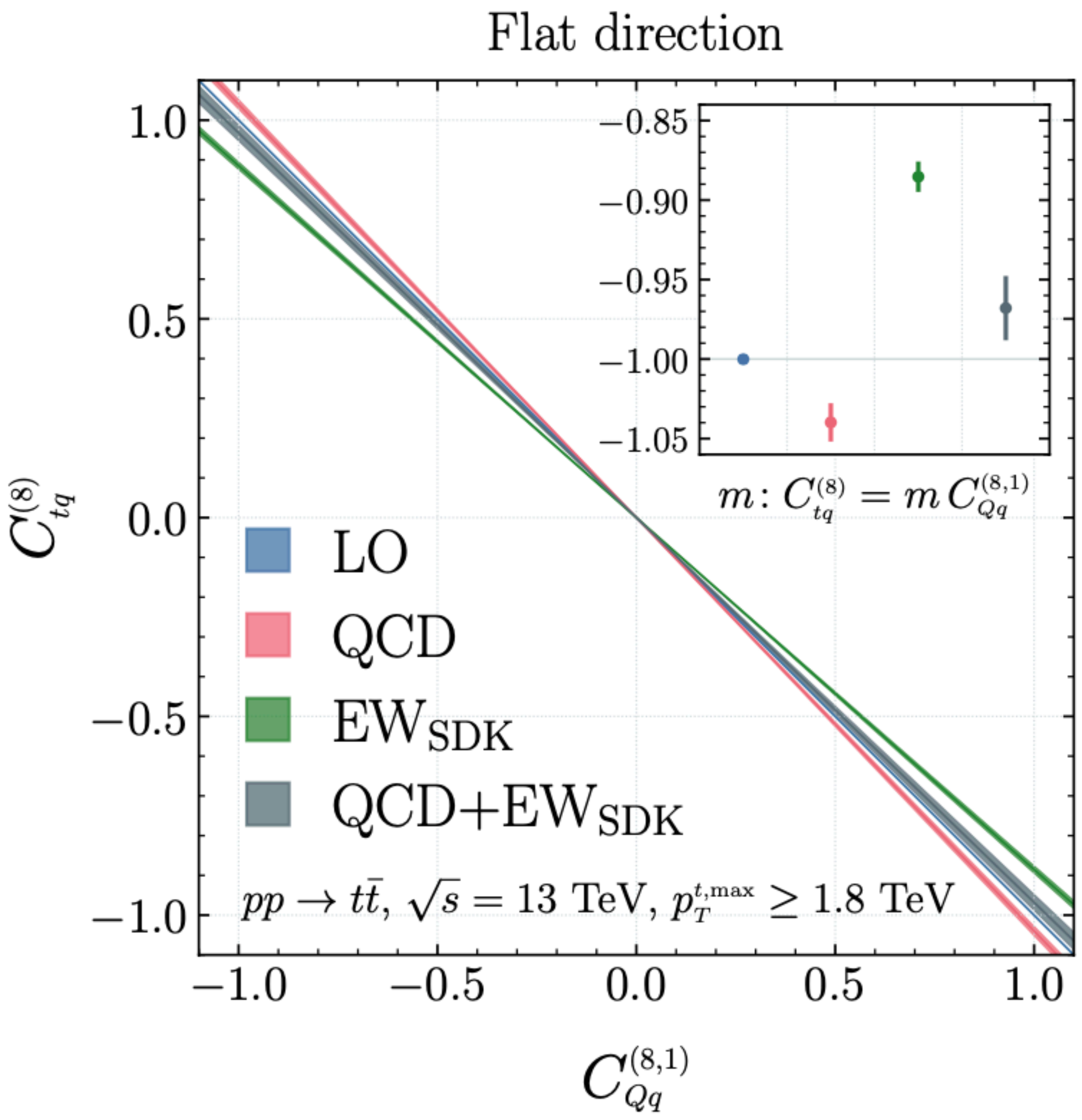
Adding EW corrections:

- Changes flat directions
- Lifts flat directions

El Faham, Mimasu, Pagani, Severi, EV, Zaro in preparation

High-energy EW corrections

Breaking degeneracies



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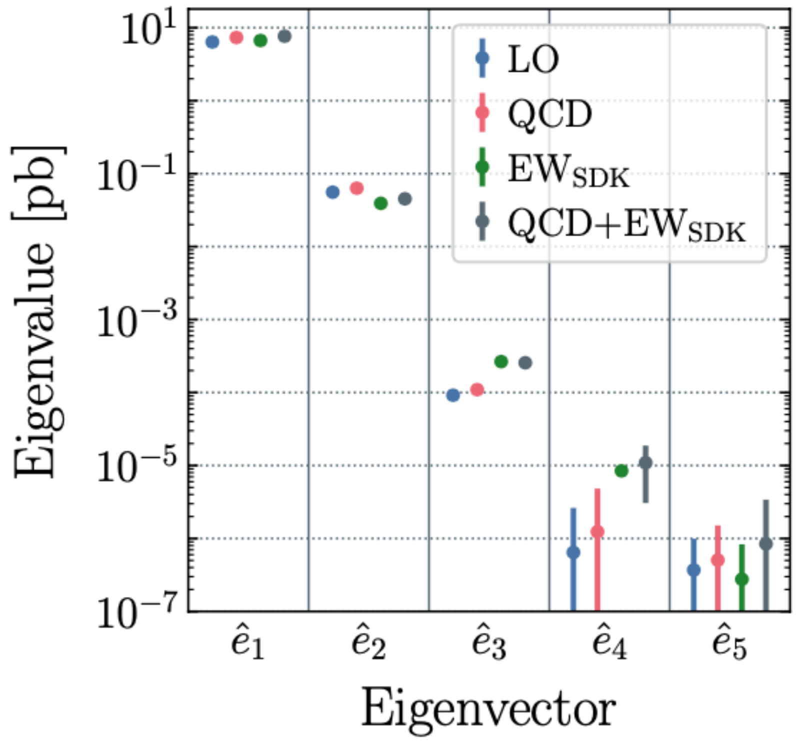

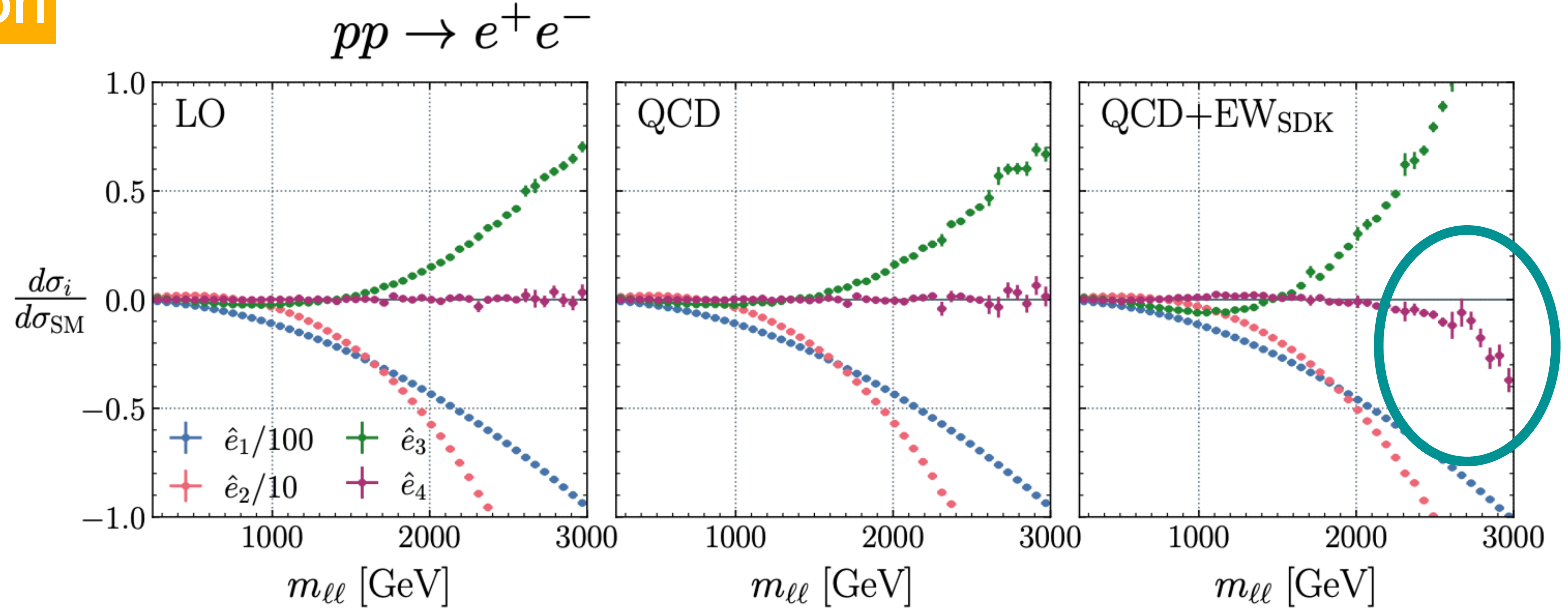

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Future of global fits

More observables:
- particle level observables
- new final states

More/less/different operators:
- different flavour assumptions
- UV inspired scenarios

Better EFT predictions

Higher Orders in $1/\Lambda^4$
- squared dim-6 contributions
- double insertions of dim-6
- dim-8 contributions

Higher Orders in QCD and EW

EFT is a QFT, renormalisable order-by order in $1/\Lambda^2$

$$\mathcal{O}(\alpha_s, \alpha_{ew}) + \mathcal{O}\left(\frac{1}{\Lambda^2}\right) + \mathcal{O}\left(\frac{\alpha_s}{\Lambda^2}\right) + \mathcal{O}\left(\frac{\alpha_{ew}}{\Lambda^2}\right)$$

SMEFT computations at dimension-6

$$\Delta \text{Obs}_n = \text{Obs}_n^{\text{EXP}} - \text{Obs}_n^{\text{SM}} = \sum_i \frac{c_i^6(\mu)}{\Lambda^2} \boxed{a_{n,i}^6(\mu)} + \mathcal{O}\left(\frac{1}{\Lambda^4}\right)$$

NLO QCD & loop-induced: Done (SMEFT@NLO)

Degrande, Durieux, Maltoni, Mimasu, EV, Zhang arXiv:2008.11743

http://feynrules.irmp.ucl.ac.be/wiki/SMEFTatNLO

NLO EW: Some examples available, progress towards automating these as well.

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How about this μ?

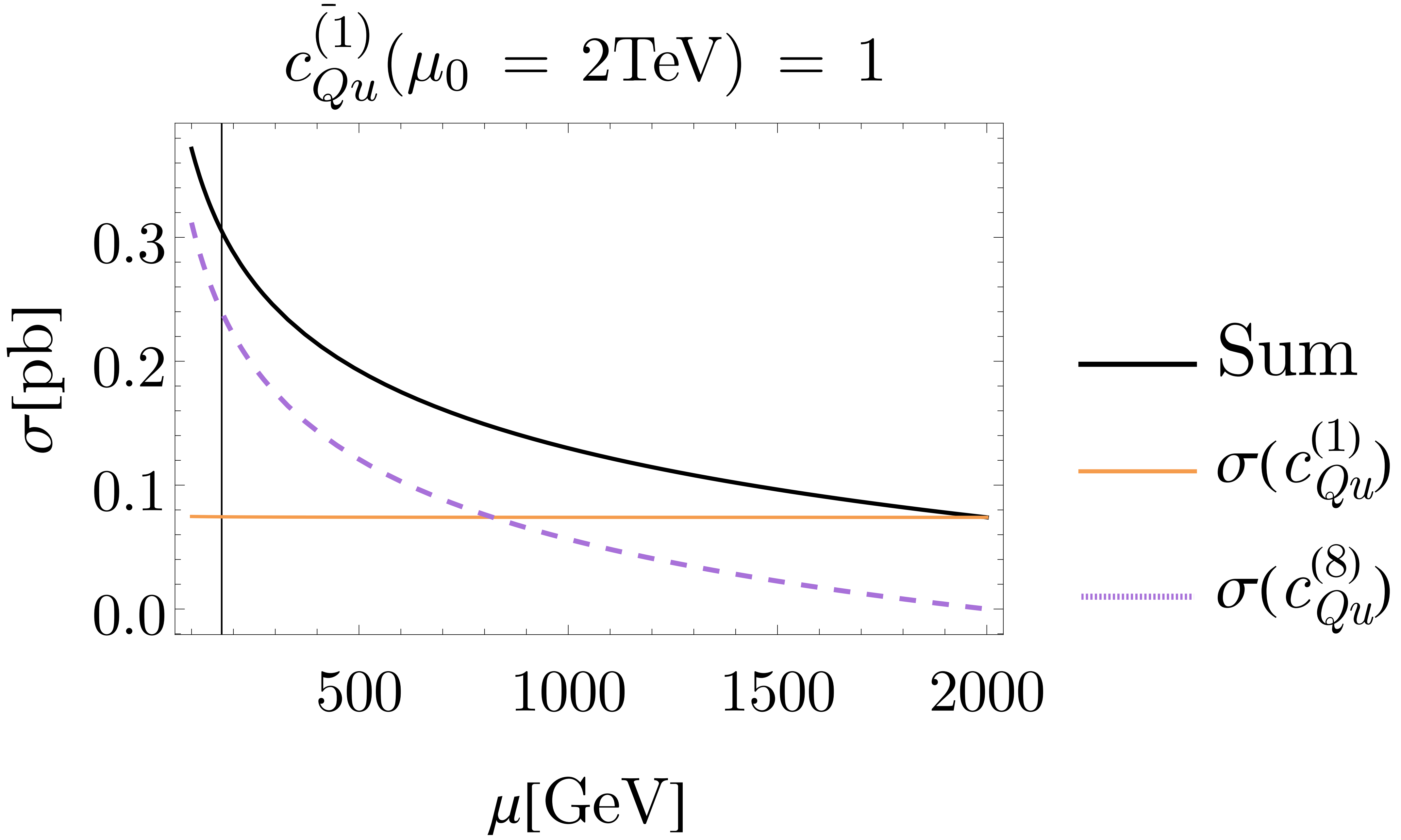
Running and mixing in SMEFT

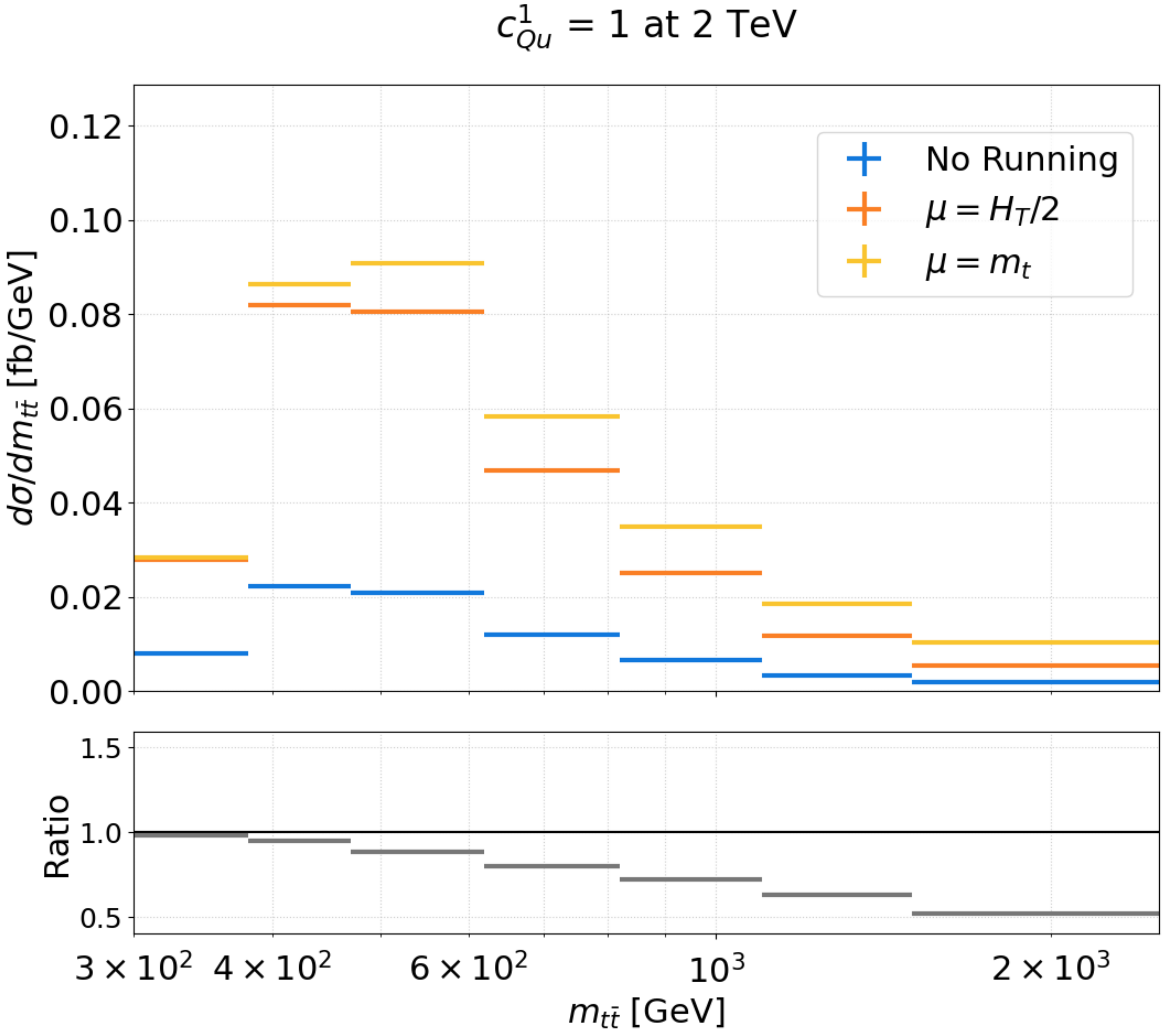
$$\frac{dc_i(\mu)}{d\log\mu} = \gamma_{ij}\, c_j(\mu)$$

One loop anomalous dimension known:
(Alonso) Jenkins et al arXiv:1308.2627, 1310.4838, 1312.2014

Example: Turn on 1 operator at high-scale

Compute effect on top pair cross-section



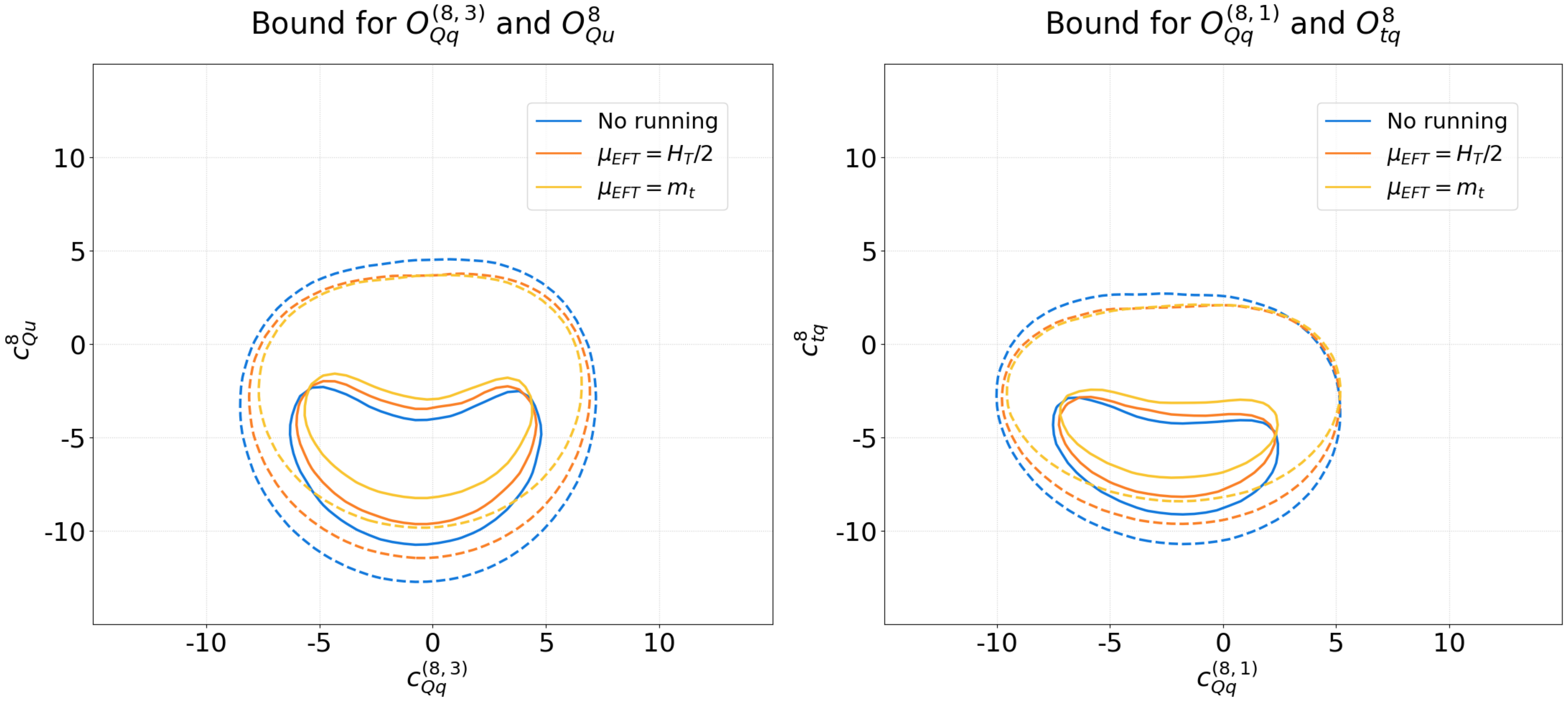


Aoude, Maltoni, Mattelaer, Severi, EV arXiv:2212.05067

Impact of RGE on constraints

How does running and mixing impacts the constraints?

Top sector fit:



RGE evolution within MC:

PS by PS point computation of coefficients: dynamical scale e.g. $H_T/2$

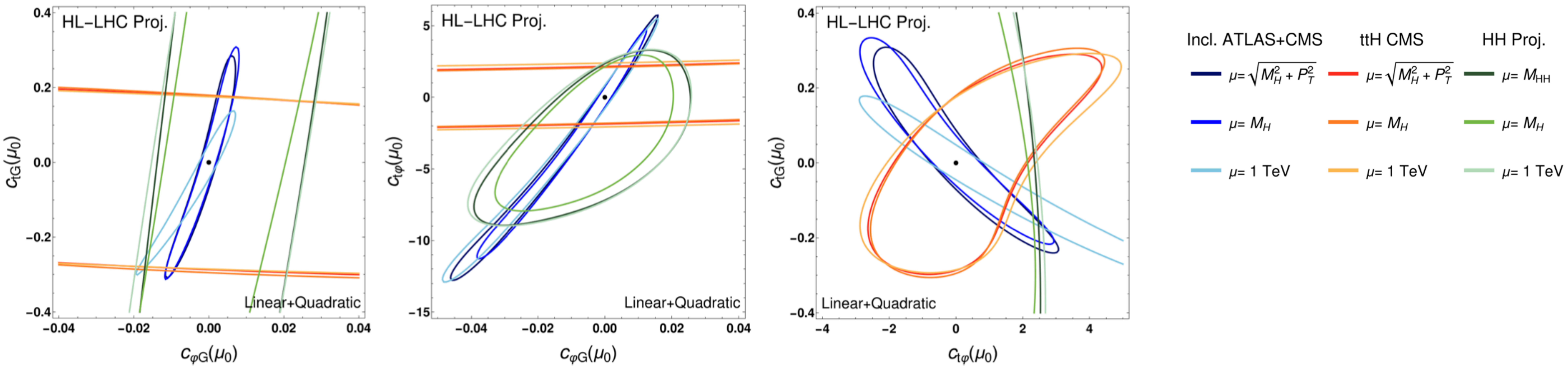
Aoude, Maltoni, Mattelaer, Severi, EV arXiv:2212.05067

More important for differential distributions & measurements with very different scales

Impact of RGE on constraints

How does running and mixing impacts the constraints?

Higgs sector fit



Maltoni, Ventura, EV arXiv:2406.06670

See also Battaglia, Grazzini, Spira, Wiesemann arXiv: 2109.02987
Di Noi, Grober arXiv:2312.11327
Di Noi, Grober, Mandal arXiv: 2408.03252

Eventually need to be taken into account in a global fit!

Summary

Precision computations important to enhance sensitivity (especially for unconstrained operators)

Global fit results affected by the precision of EFT predictions

Progress in computation of QCD and EW corrections, and inclusion of RGE effects in predictions

Aim to include more and more precise theory predictions in the fits