SMEFT in Monte Carlo

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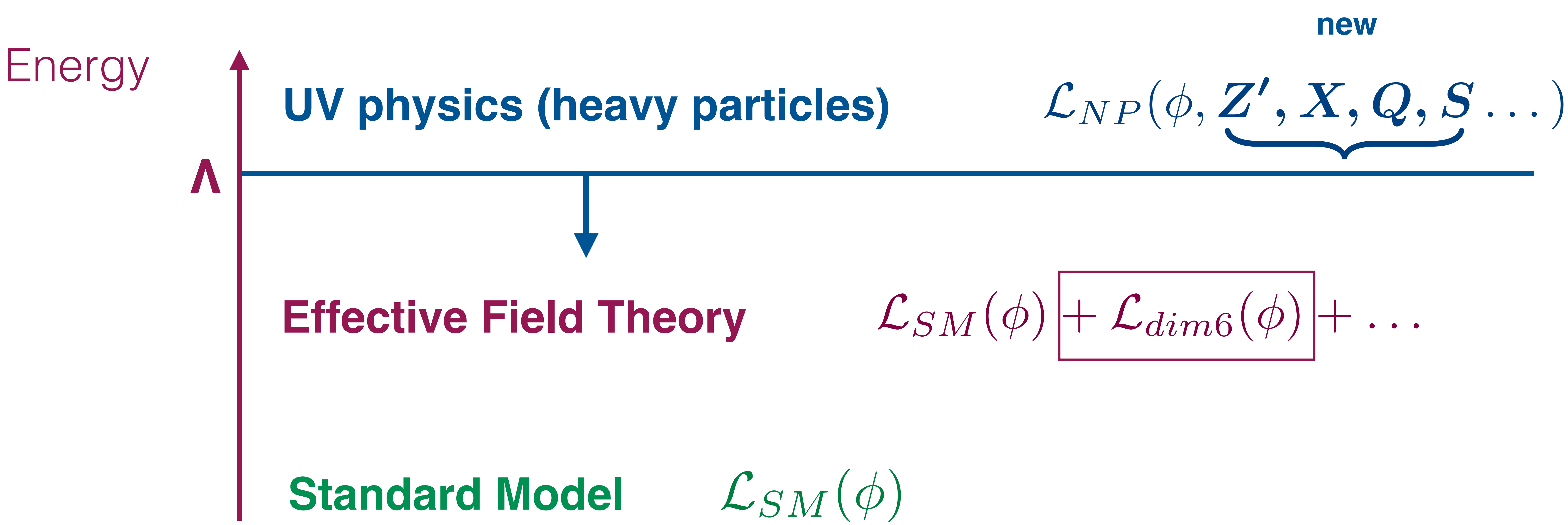
Workshop on Tools for High Precision LHC simulations
Castle Ringberg, 31/10-4/11/22

SMEFT: What is it all about?



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

A ~model-independent way of searching for new physics!

EFT pathway to New Physics

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

Precise EFT predictions

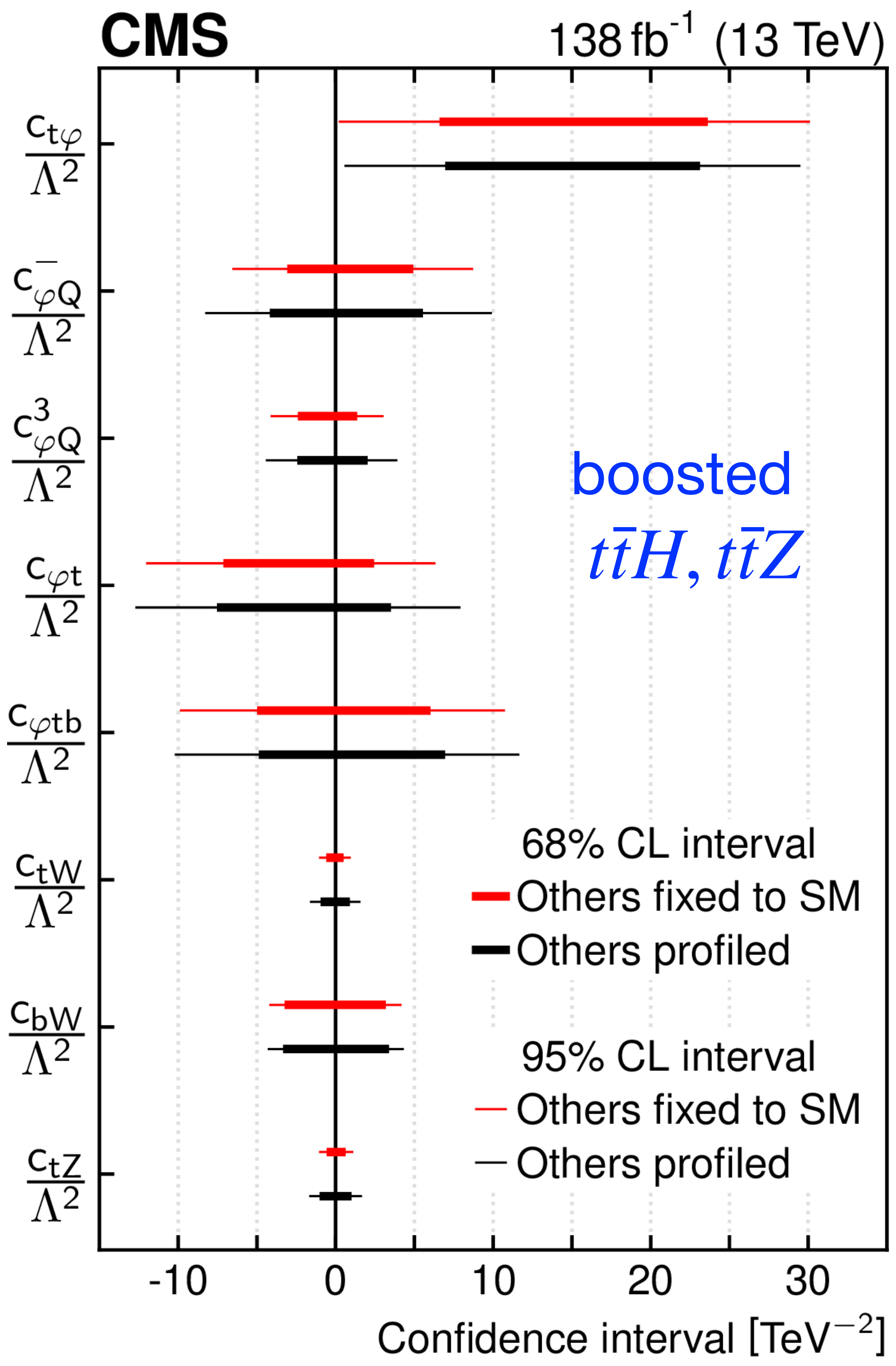
Precise SM predictions

Precise experimental measurements

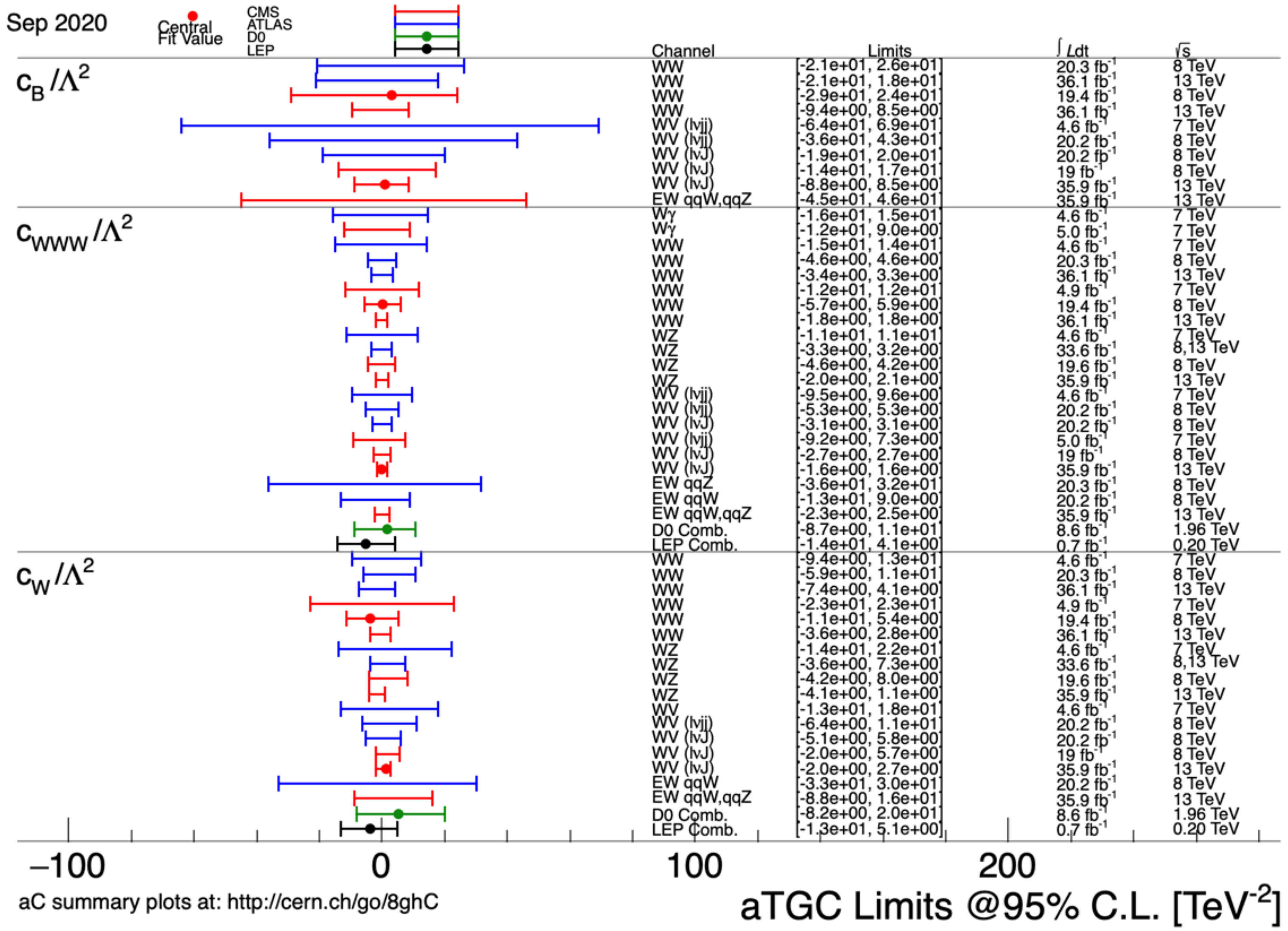
Introduction

EFT interpretations spreading in top, Higgs and EW sectors

CMS-TOP-21-003

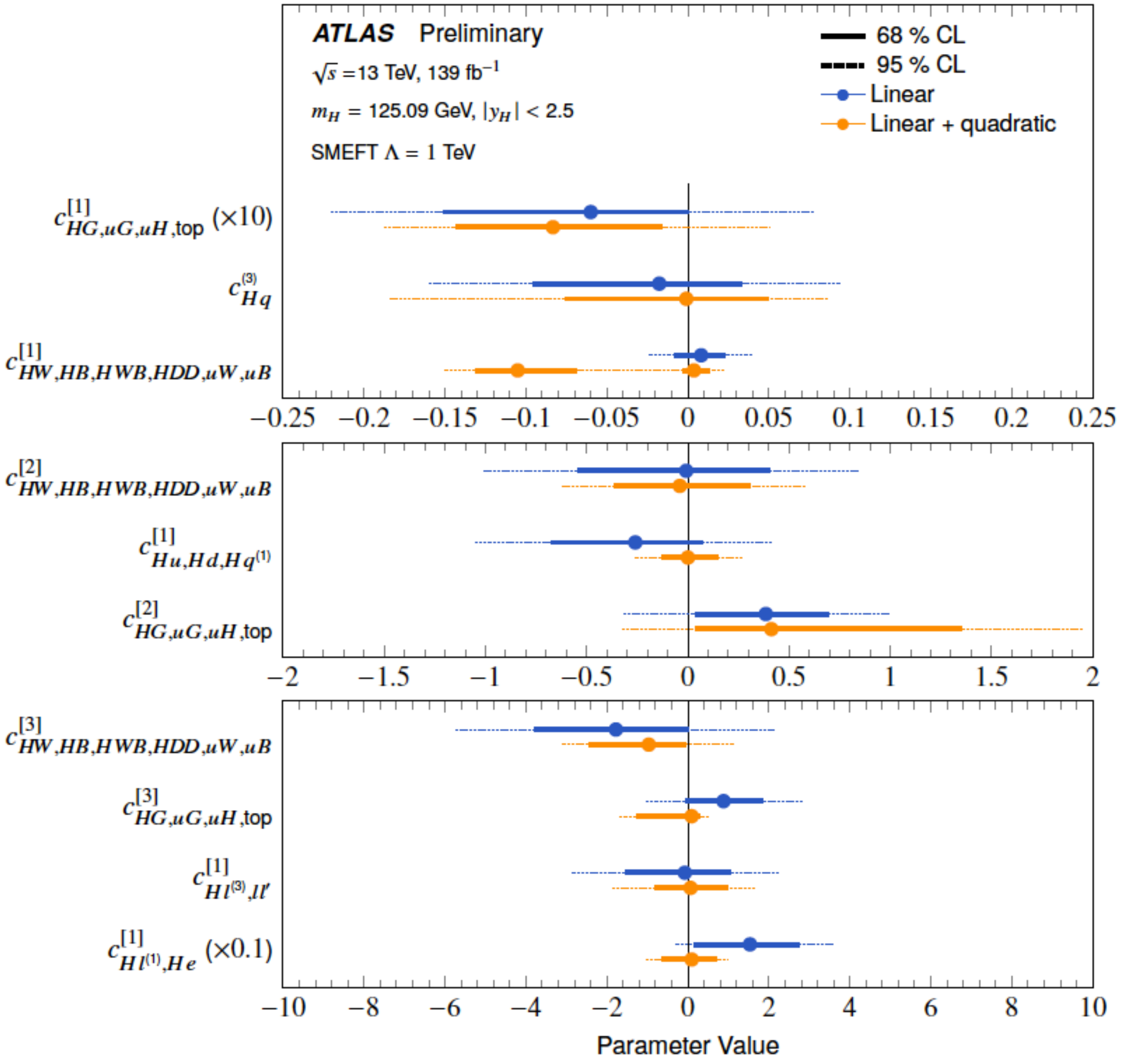


LHC EW Multiboson Subgroup

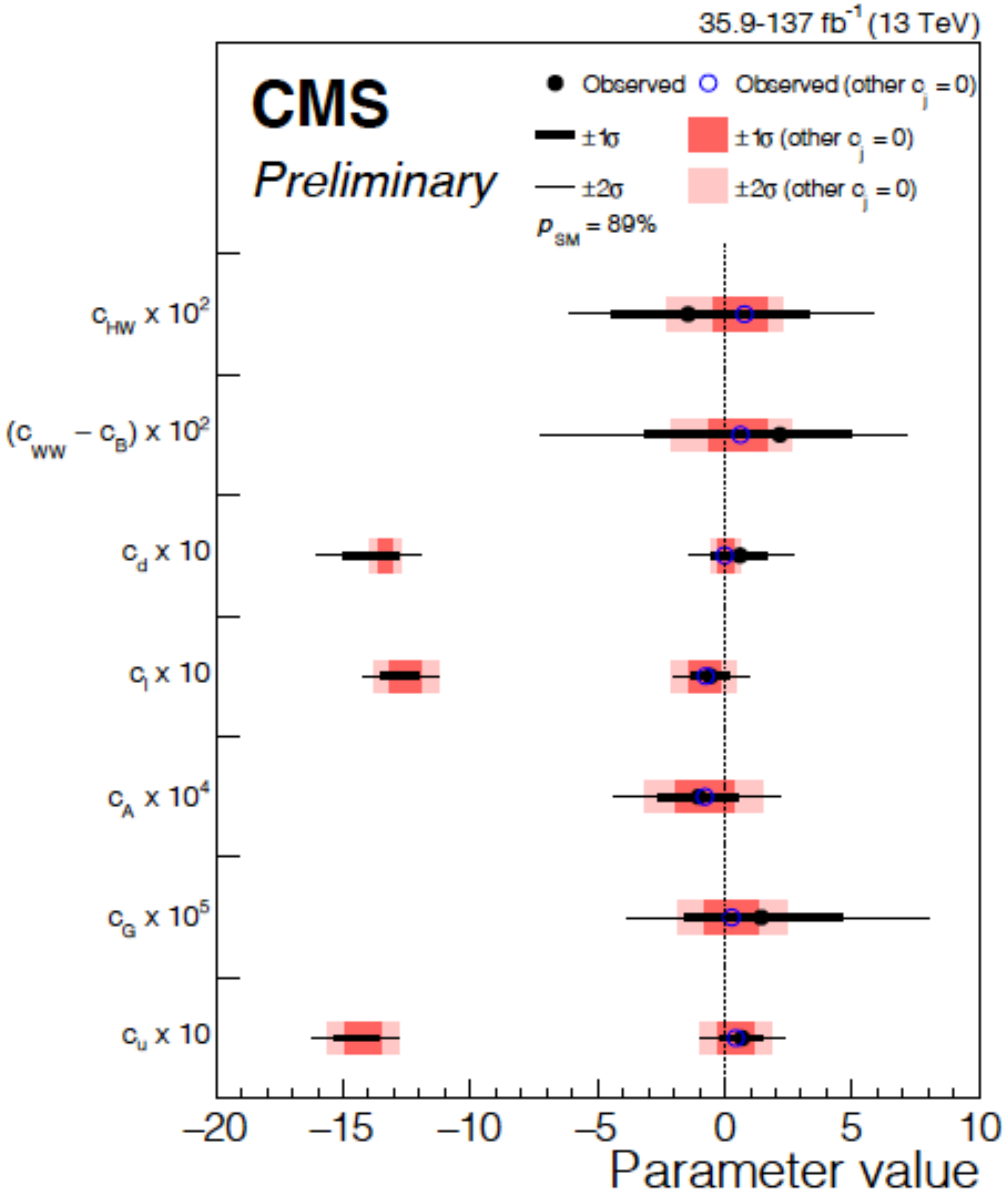


EFT in Higgs measurements

ATLAS CONF-2020-053



CMS PAS HIG-19-005



Issues and questions

Ingredients for combined/global analyses?

Need to address:

* (Choice of basis)
* Choice of flavour assumption: 2499 operators
* Choice of which operators to fit and which to ignore
* Precision of predictions
* Availability of tools

Basis and Flavour

Basis

ATLAS CONF-2020-053

Warsaw basis (smeftsim & SMEFT@NLO implementations)

c.f.

CMS PAS HIG-19-005

SILH basis (HEL implementation)

c.f.

CMS TOP-21-003

Warsaw basis (dim6top implementation)

Flavour assumption

	e.g. $Q_{Hu,pr} = (Hi\overleftrightarrow{D}_\mu H)(\bar{u}_p\gamma^\mu u_r)$		tot
general	$(C_{Hu})_{pr}$	9	2499
$U(3)^5$	$C_{Hu}\,\delta_{pr}$	1	~ 85
$U(3)^2_{\ell,e} \times U(2)^3_{q,u,d}$	$C_{Hu}\,\delta_{pr},\ p,r = 1,2$ $C_{Ht} \quad p = r = 3$	2	~ 180

ATLAS CONF-2020-053

CMS TOP-19-001

How to combine?

From I. Brivio

First attempts towards guidelines

The LHC Top WG EFT note

Interpreting top-quark LHC measurements
in the standard-model effective field theory

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F. Maltoni,[4] E. Vryonidou,[2] C. Zhang[5] (editors),
D. Barducci,[6] I. Brivio,[7] V. Cirigliano,[8] W. Dekens,[8,9] J. de Vries,[10] C. Englert,[11]
M. Fabbrichesi,[12] C. Grojean,[3,13] U. Haisch,[2,14] Y. Jiang,[7] J. Kamenik,[15,16]
M. Mangano,[2] D. Marzocca,[12] E. Mereghetti,[8] K. Mimasu,[4] L. Moore,[4] G. Perez,[17]
T. Plehn,[18] F. Riva,[2] M. Russell,[18] J. Santiago,[19] M. Schulze,[13] Y. Soreq,[20]
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Abstract

This note proposes common standards and prescriptions for the effective-field-theory interpretation of top-quark measurements at the LHC.

arXiv:1802.07237

- Warsaw basis
- 3 scenarios with different flavour assumptions
- Constraints from LHC, EWPO, indirect constraints
- Public UFO implementations and benchmark results already given for LHC13
- Separate discussion of FCNC

Monte Carlo tools and validation

A systematic effort to cross-validate different implementations

CERN-LPCC-2019-02

Proposal for the validation of Monte Carlo implementations of the standard model effective field theory

Gauthier Durieux[1] (ed.), Ilaria Brivio[2,3] (ed.), Fabio Maltoni[4,5] (ed. ex officio), Michael Trott[2] (ed. ex officio), Simone Alioli,[6] Andy Buckley,[7] Mauro Chiesa,[8] Jorge de Blas,[9,10] Athanasios Dedes,[11] Céline Degrande,[4] Ansgar Denner,[8] Christoph Englert,[7] James Ferrando,[12] Benjamin Fuks,[13,14] Peter Galler,[7] Admir Greljo,[15] Valentin Hirschi,[16] Gino Isidori,[17] Wolfgang Kilian,[18] Frank Krauss,[19] Jean-Nicolas Lang,[17] Jonas Lindert,[19] Michelangelo Mangano,[15] David Marzocca,[20] Olivier Mattelaer,[4] Kentarou Mawatari,[21] Emanuele Mereghetti,[22] David J. Miller,[7] Ken Mimasu,[4] Michael Paraskevas,[23] Tilman Plehn,[3] Laura Reina,[24] Janusz Rosiek,[23] Jürgen Reuter,[12] José Santiago,[25] Kristaq Suxho,[11] Lampros Trifyllis,[11] Eleni Vryonidou,[15] Christopher White,[27] Cen Zhang,[28,29] Hantian Zhang[17]

arXiv:1906.12310

Examples of implementations:

- DIM6TOP is a UFO implementation of top-quark interactions following the conventions of the LHC top Working Group [3]. It is available at this url[1].
- SMEFTSIM is a complete UFO implementation of the Warsaw basis [4] of dimension-six operators [5]. It is available at this url[2].
- SMEFT@NLO is a UFO implementation, to next-to-leading order in QCD, of of CP- and $U(2)_q \times U(2)_u \times U(3)_d \times U(3)_l \times U(3)_e$-conserving dimension-six interactions, available at this url[3].
- SMEFTFR [6, 7] is a package generating Feynman rules, in FEYNRULES and UFO formats, for the dimension-six operators of the Warsaw basis [4] (or any subset), in unitary or linear R_ξ gauges, in terms of physical fields (mass eigenstates), for general flavour structures. It is available at this url[4].
- HEL [8] is an implementation of dimension-six operators in the SILH basis [9] available at this url[5].
- BSMC [10] is an implementation of dimension-six operators in the Higgs basis [11] associated with the ROSETTA package (here[6]). It is available at this url[7].

Need for systematic comparison and validation

see also LHC EFT WG efforts

SMEFT Monte Carlo

Dim6top: arXiv:1802.07237

Warsaw basis: focusing on top interactions

Baseline flavour scenario singles out the 3rd generation

$$U(2)_q \times U(2)_u \times U(2)_d$$

four heavy quarks	$11 + 2$ CPV
two light and two heavy quarks	14
two heavy quarks and bosons	$9 + 6$ CPV
two heavy quarks and two leptons	$(8 + 3$ CPV$) \times 3$ lepton flavours

UFO also includes FCNC

Tree level Monte Carlo implementation of top interactions

Widely used by the top community

SMEFT Monte Carlo

SMEFTsim

	general		U35		MFV		top		topU31	
	all	~~CP~~	all	~~CP~~	all	~~CP~~	all	~~CP~~	all	~~CP~~
tot	2499	1149	85	25	120	-	275	71	182	53

Warsaw basis with

various flavour assumptions

Two possible input schemes (see Darren's talk):

$\{\alpha_{\text{em}}, m_Z, G_F\}$ $\{m_W, m_Z, G_F\}$

flavour and input scheme: 10 model variants!

EFT corrections to propagators: linearised corrections

Tree-level but most general and flexible implementation, and very nice manual

Brivio, Jiang, Trott 1709.06492, Brivio 2012.11343

SMEFT Monte Carlo

SMEFT@NLO

What's in this box?

Warsaw basis operators

Flavour assumption: $U(2)_q \times U(2)_u \times U(3)_d \times (U(1)_l \times U(1)_e)^3$

Includes Higgs, top, gauge boson interactions

Conventions matching dim6top

m_W input scheme

Limitations: CP conserving, no FCNC, just one flavour assumption

Advantage: Loops/NLO

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

What can SMEFT@NLO do?

Example processes

Multi-boson production

quark-initiated

```
> p p > W+ W-     QED=2 QCD=0 NP=2 [QCD]
> p p > W+ Z      QED=2 QCD=0 NP=2 [QCD]
> p p > Z  Z      QED=2 QCD=0 NP=2 [QCD]
```

loop-induced

```
> g g > W+ W-     QED=2 QCD=2 NP=2 [QCD]
> g g > Z  Z      QED=2 QCD=2 NP=2 [QCD]
> g g > W+ W- Z   QED=3 QCD=2 NP=2 [QCD]
> g g > Z  Z  Z   QED=3 QCD=2 NP=2 [QCD]
```

loop-induced

```
> g g > H         QED=1 QCD=2 NP=2 [QCD]
> g g > H H       QED=2 QCD=2 NP=2 [QCD]
> g g > H H H     QED=3 QCD=2 NP=2 [QCD]
> g g > H j       QED=1 QCD=3 NP=2 [QCD]
```

Top quark production

```
> e+ e- > t t~          QED=2 QCD=0 NP=2 [QCD]
> p p > t t~            QED=0 QCD=2 NP=2 [QCD]
> p p > t t~ h          QED=1 QCD=2 NP=2 [QCD]
> p p > t t~ Z          QED=1 QCD=2 NP=2 [QCD]
> p p > t t~ W+         QED=1 QCD=2 NP=2 [QCD]
> p p > t W-     $$ t~ QED=1 QCD=1 NP=2 [QCD]
> p p > t W- j   $$ t~ QED=1 QCD=2 NP=2 [QCD]
> p p > t j      $$ W- QED=2 QCD=0 NP=2 [QCD]
> p p > t h j    $$ W- QED=3 QCD=0 NP=2 [QCD]
> p p > t Z j    $$ W- QED=3 QCD=0 NP=2 [QCD]
> p p > t a j    $$ W- QED=3 QCD=0 NP=2 [QCD]
```

NLO QCD for tree level processes

Loop induced

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

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

Uncertainties in EFT predictions

* Missing Higher Orders in 1/Λ^4
  * squared dim-6 contributions
  * double insertions of dim-6
  * dim-8 contributions
* Missing 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 NLO (or 1-loop) for SMEFT?

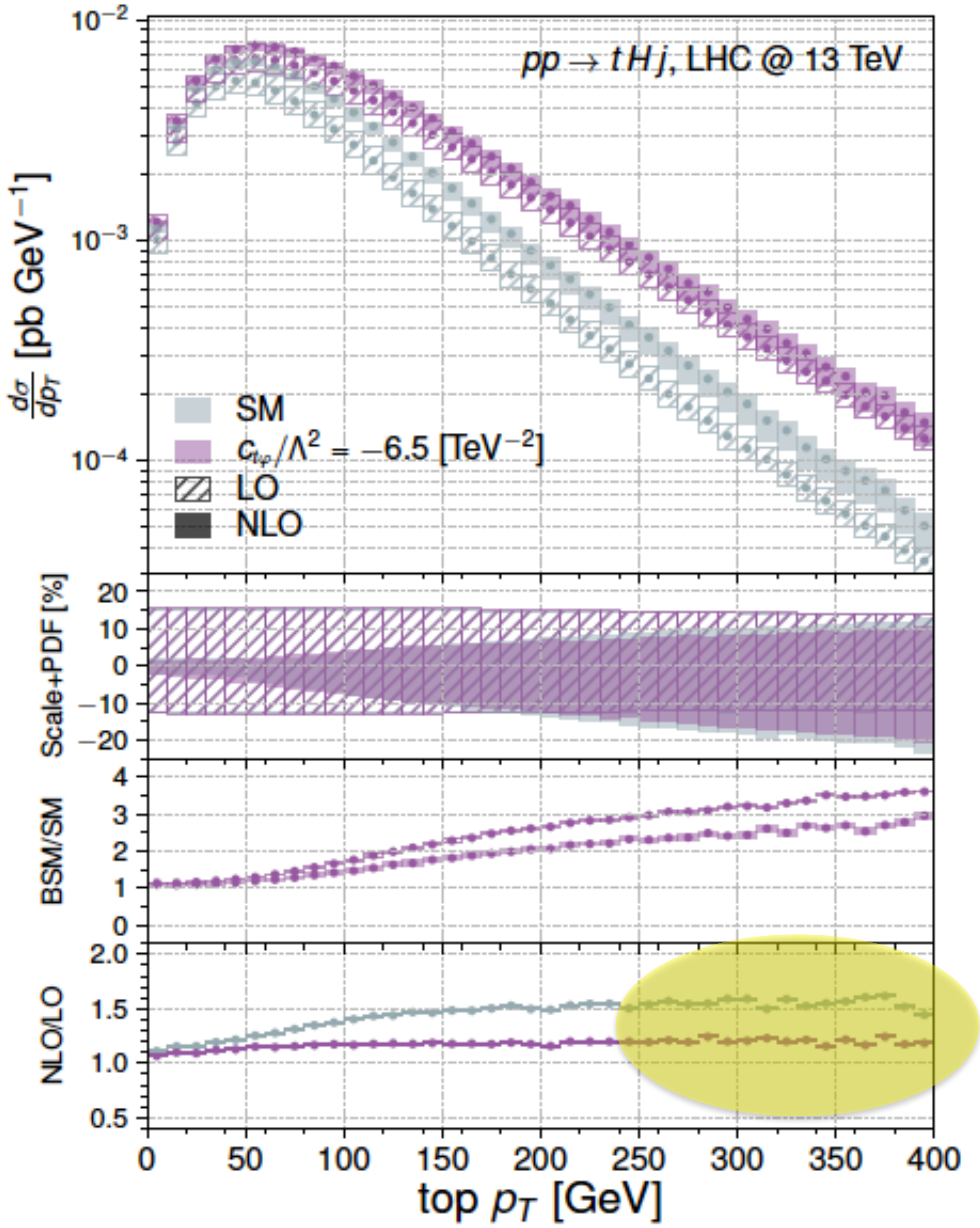
Higher orders in SMEFT bring:

* 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.

Accuracy and precision (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
$\sigma_{t\phi}$	$-0.062^{+0.006+0.001+0.001}_{-0.004-0.001-0.001}$	1.13
$\sigma_{\phi G}$	$0.872^{+0.131+0.037+0.013}_{-0.123-0.035-0.016}$	1.39
σ_{tG}	$0.503^{+0.025+0.001+0.007}_{-0.046-0.003-0.008}$	1.07

$$\sigma = \sigma_{\rm SM} + \sum_i \frac{1{\rm TeV}^2}{\Lambda^2} C_i \sigma_i$$

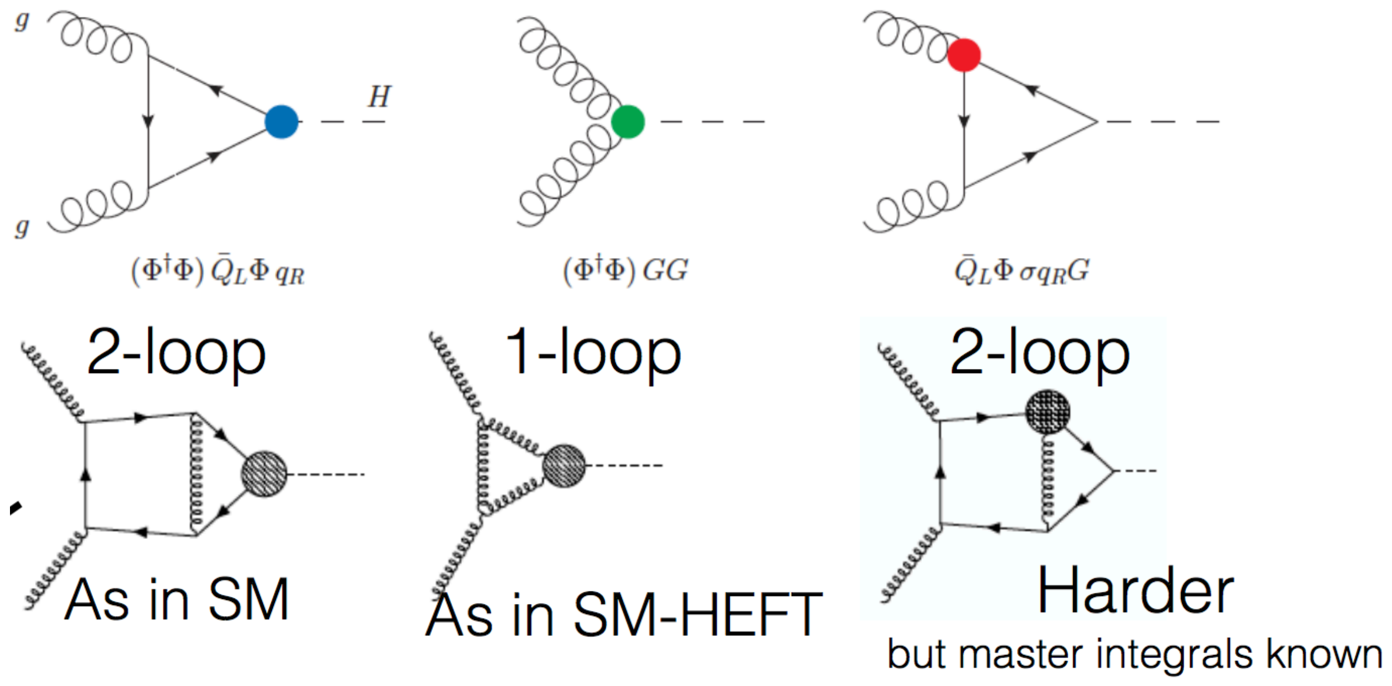
Different K-factors for different operators, different from the SM

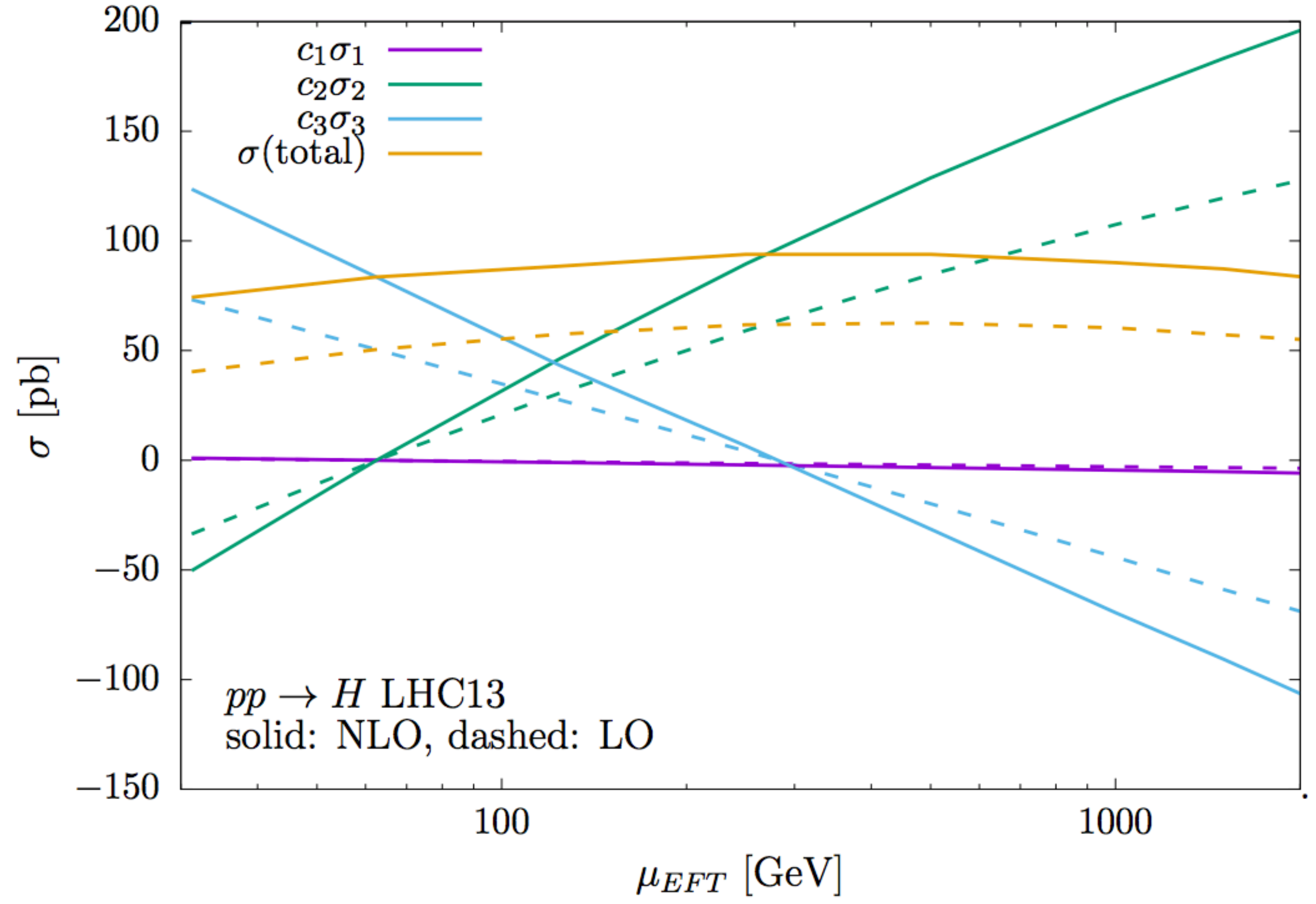
Maltoni, EV, Zhang arXiv:1607.05330

Accuracy and precision (2)

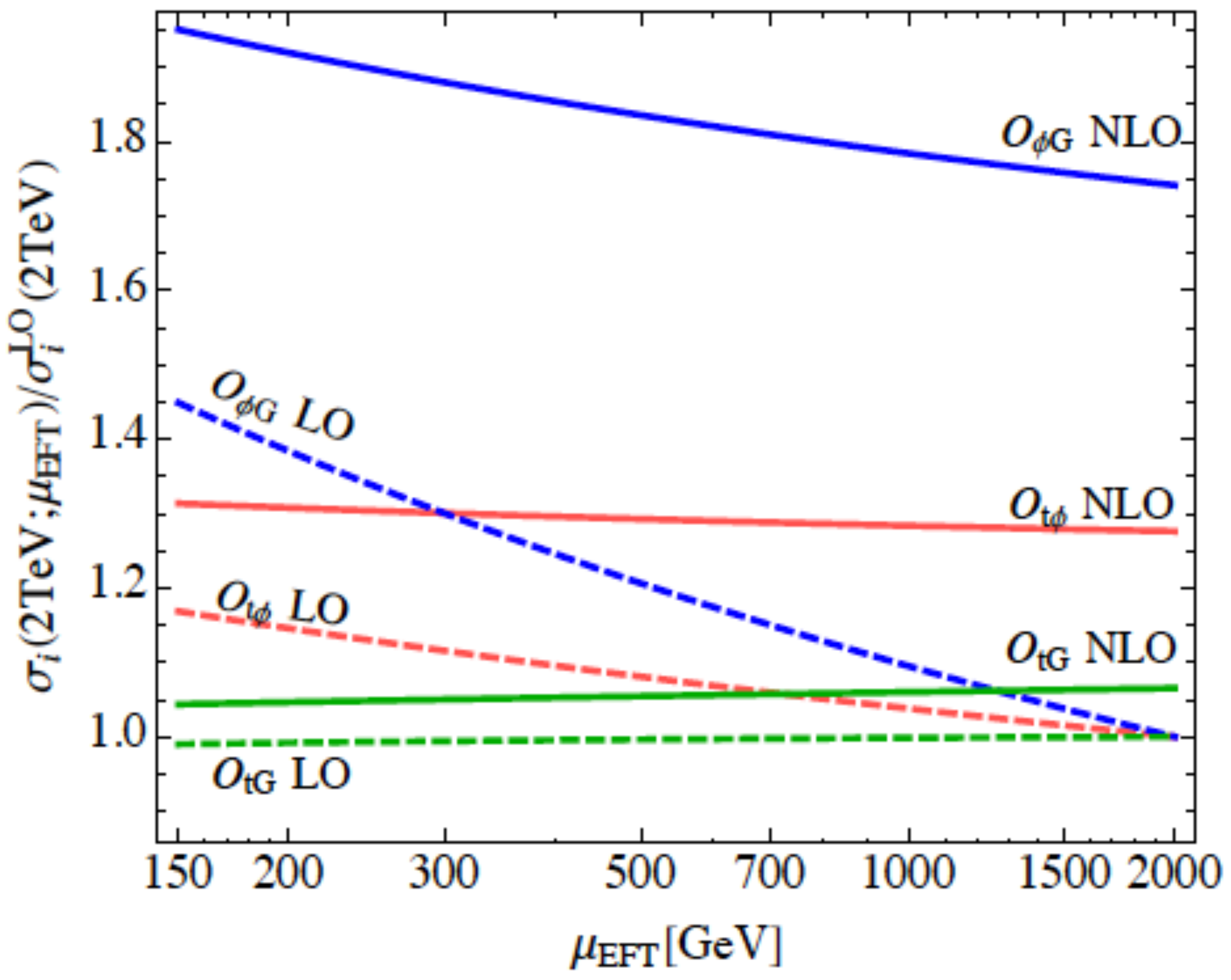
Reduction of scale uncertainty

ggH





ttH



RG corrections not a good approximation to the NLO result, underestimate the NLO corrections

Milder EFT scale dependence at NLO, when mixing effects also taken into account

Comparison of exact NLO with LO improved by 1-loop RG running

Deutschmann, Duhr, Maltoni, EV arXiv:1708.00460

Maltoni, EV, Zhang arXiv:1607.05330

Improved sensitivity (1)

New operators opening up at NLO

4-heavy operators in top pair production

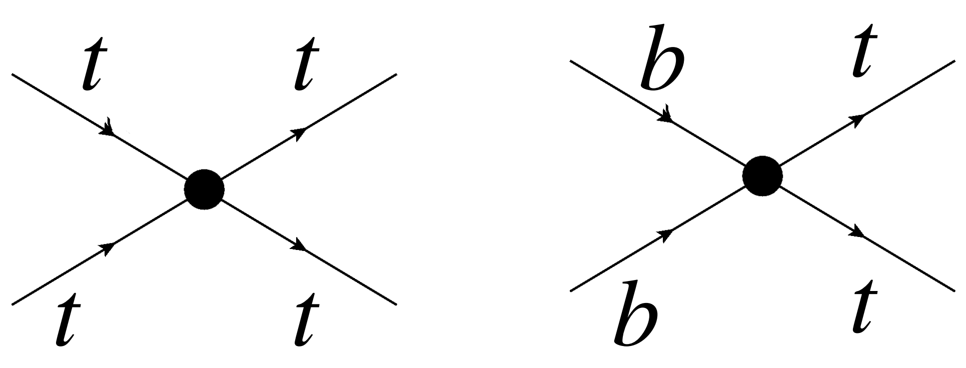
$$\mathcal{O}^8_{QQ} = (\bar{Q}\gamma^\mu T^A Q)(\bar{Q}\gamma_\mu T^A Q)$$

$$\mathcal{O}^1_{QQ} = (\bar{Q}\gamma^\mu Q)(\bar{Q}\gamma_\mu Q)$$

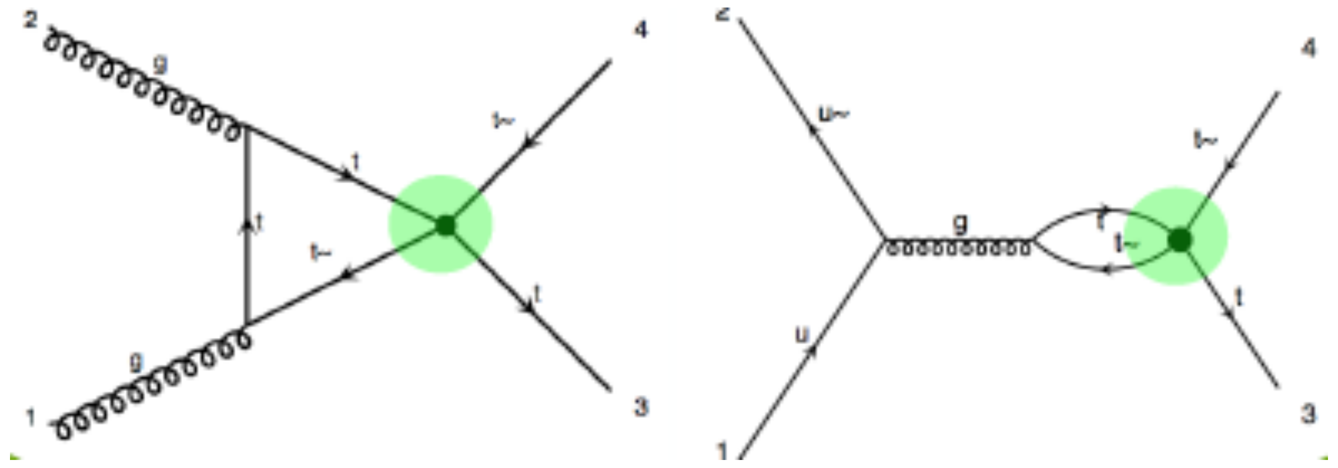
$$\mathcal{O}^8_{Qt} = (\bar{Q}\gamma^\mu T^A Q)(\bar{t}\gamma_\mu T^A t)$$

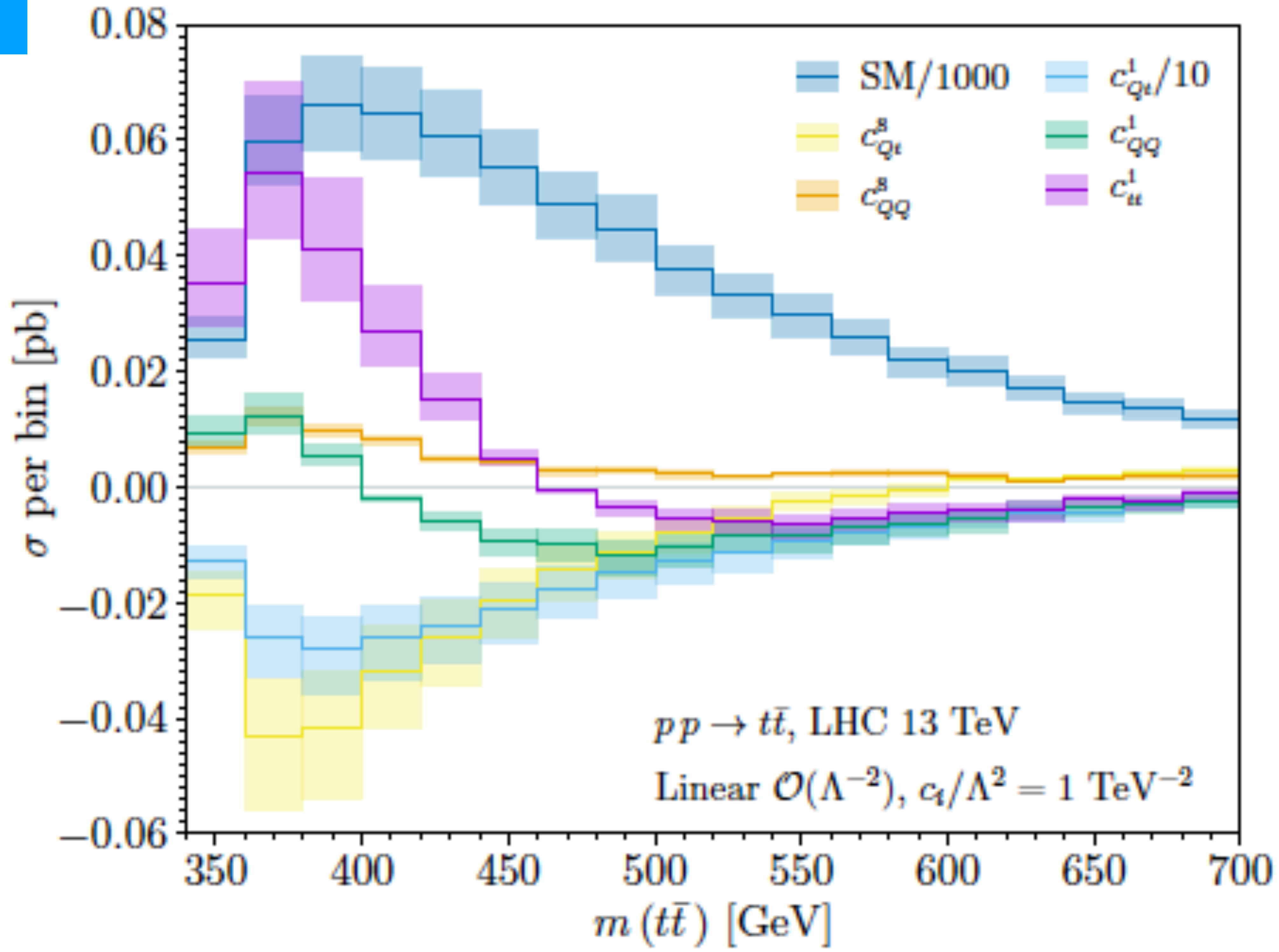
$$\mathcal{O}^1_{Qt} = (\bar{Q}\gamma^\mu Q)(\bar{t}\gamma_\mu t)$$

$$\mathcal{O}^1_{tt} = (\bar{t}\gamma^\mu t)(\bar{t}\gamma_\mu t)$$



Top pairs at NLO:



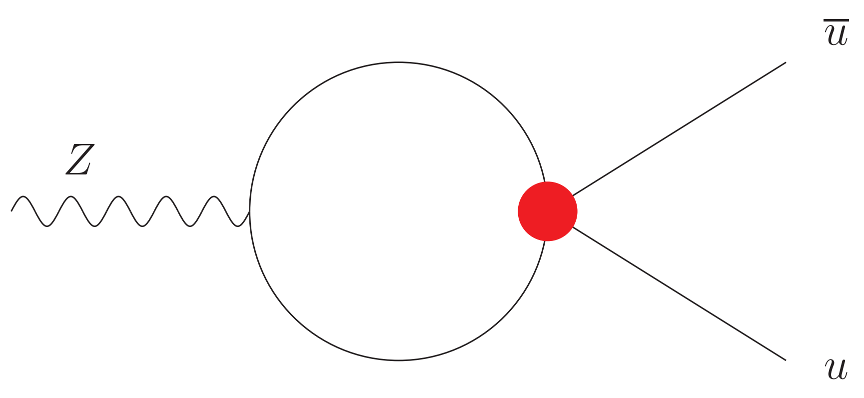


Complimentary information to ttbb and 4top production

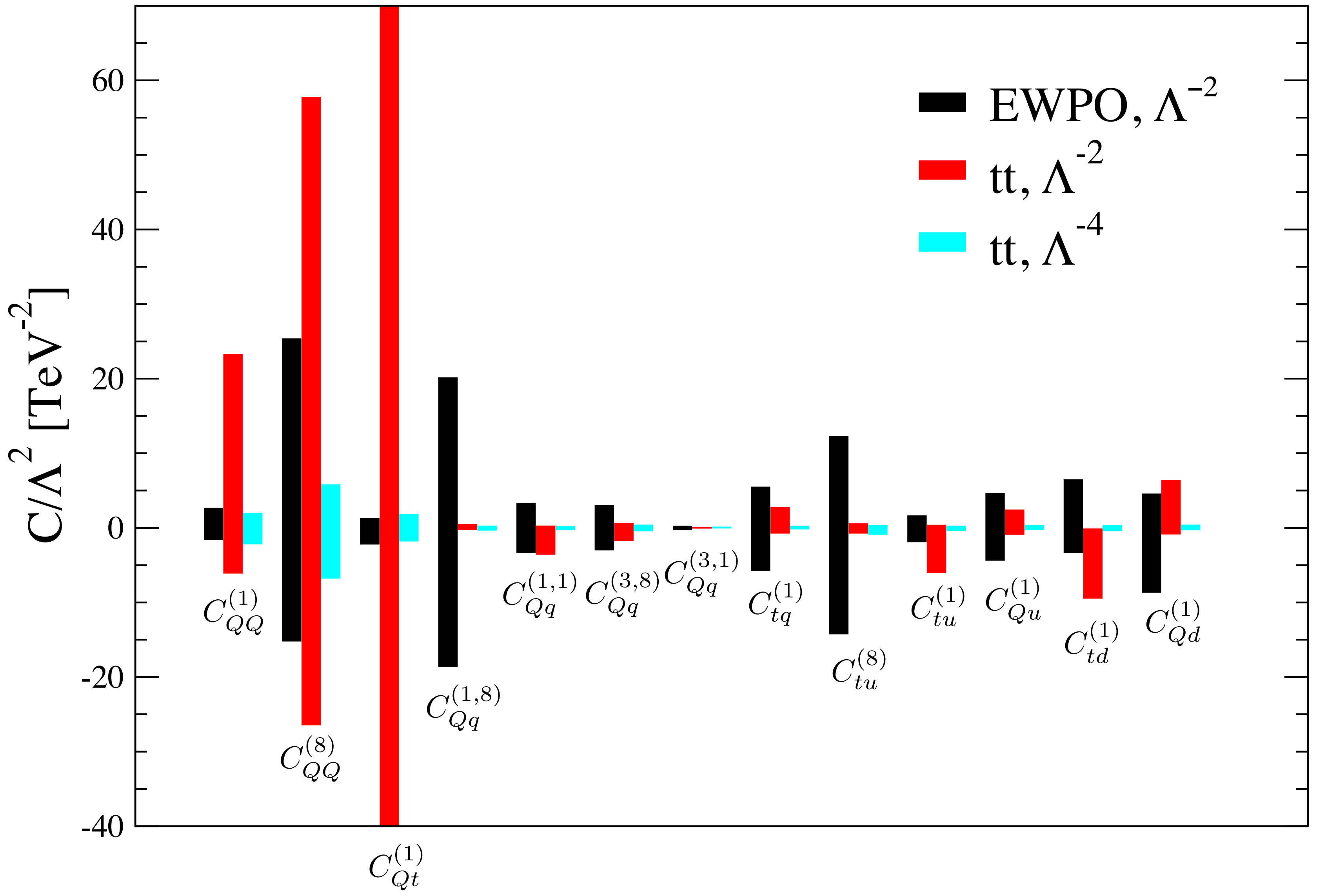
Degrande, Durieux, Maltoni, Mimasu, EV, Zhang arXiv:2008.11743

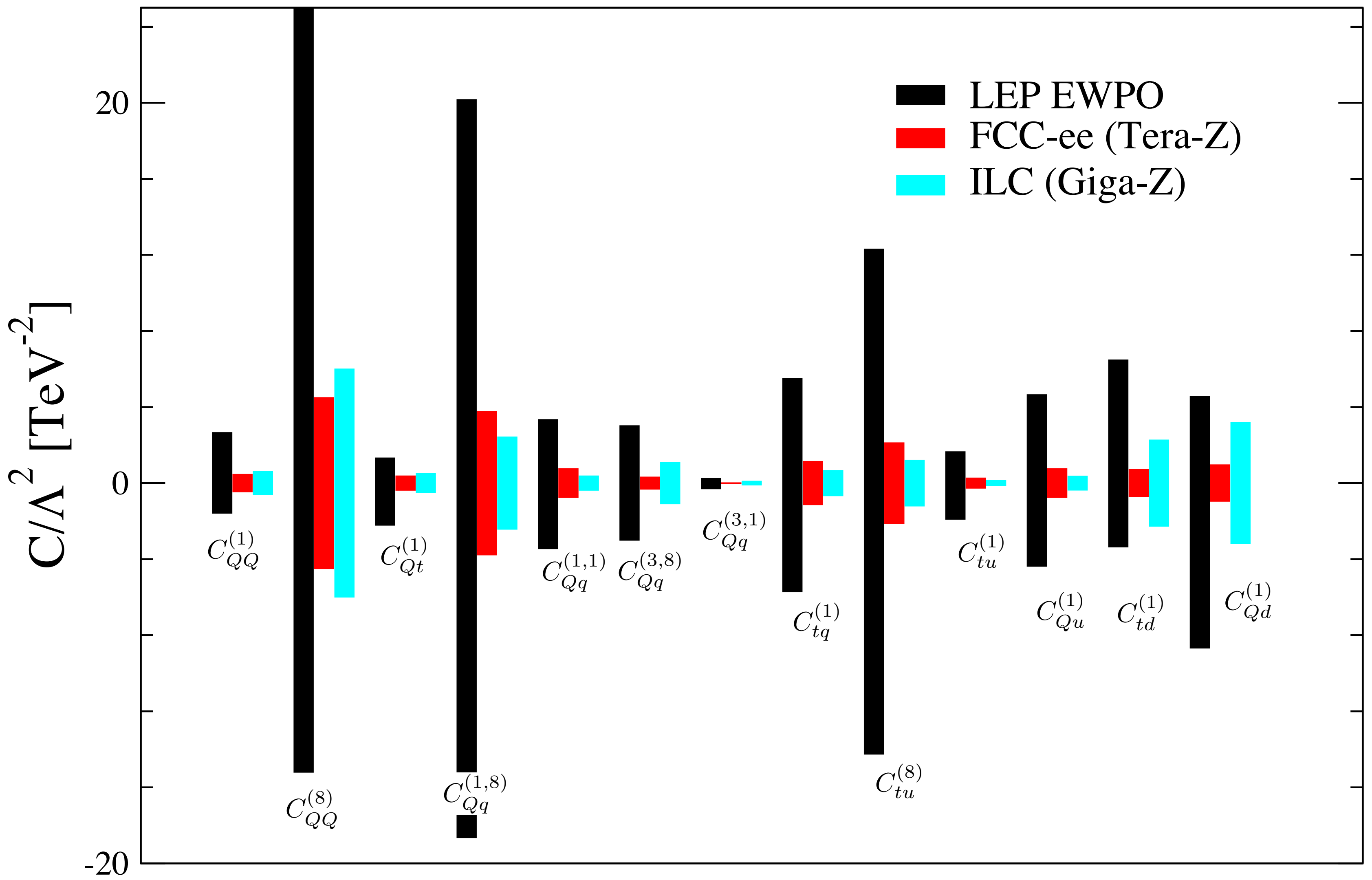
Improved sensitivity (2)

4-heavy operators in EWPO



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



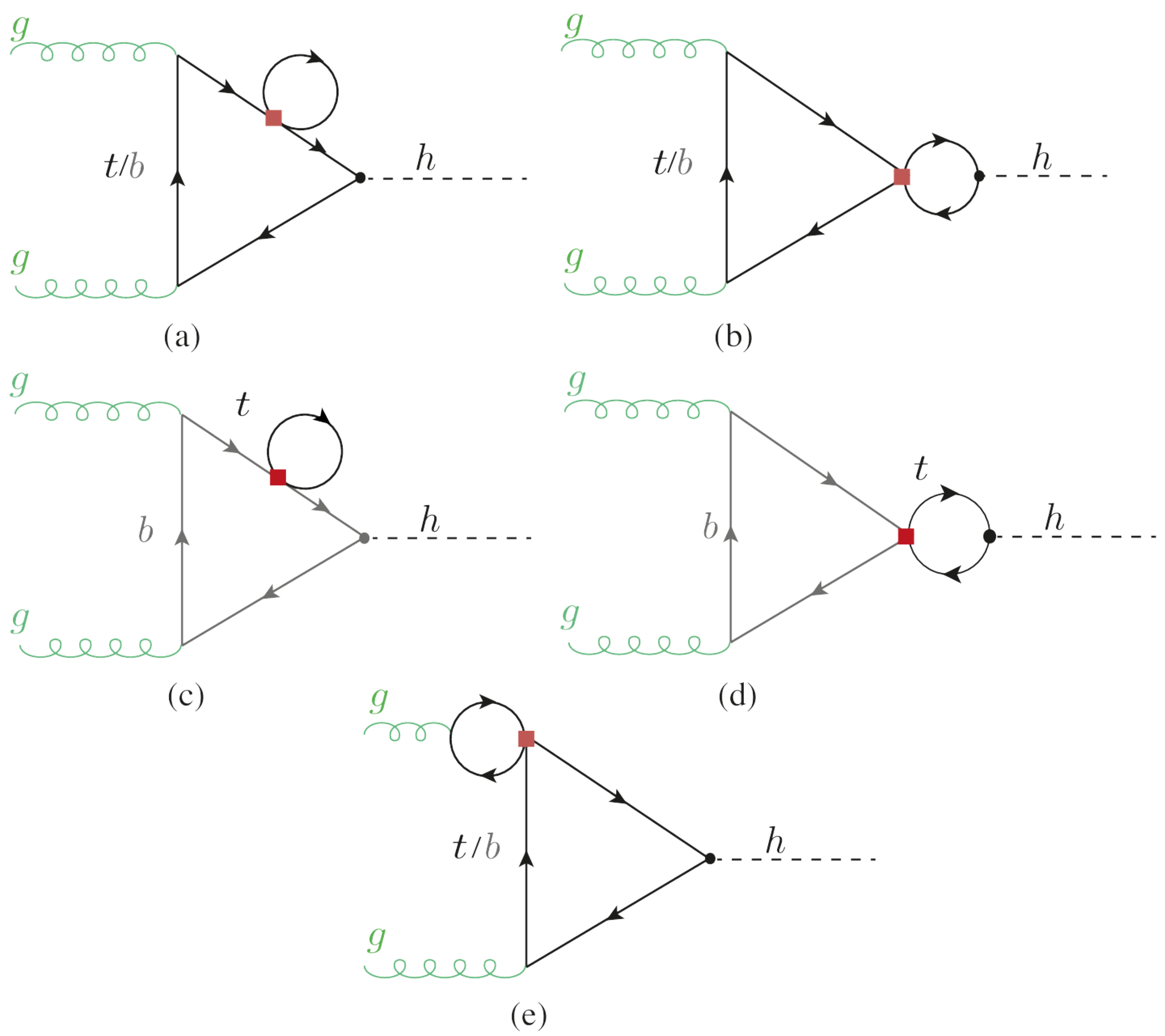


Dawson and Giardino arXiv: 2201.09887

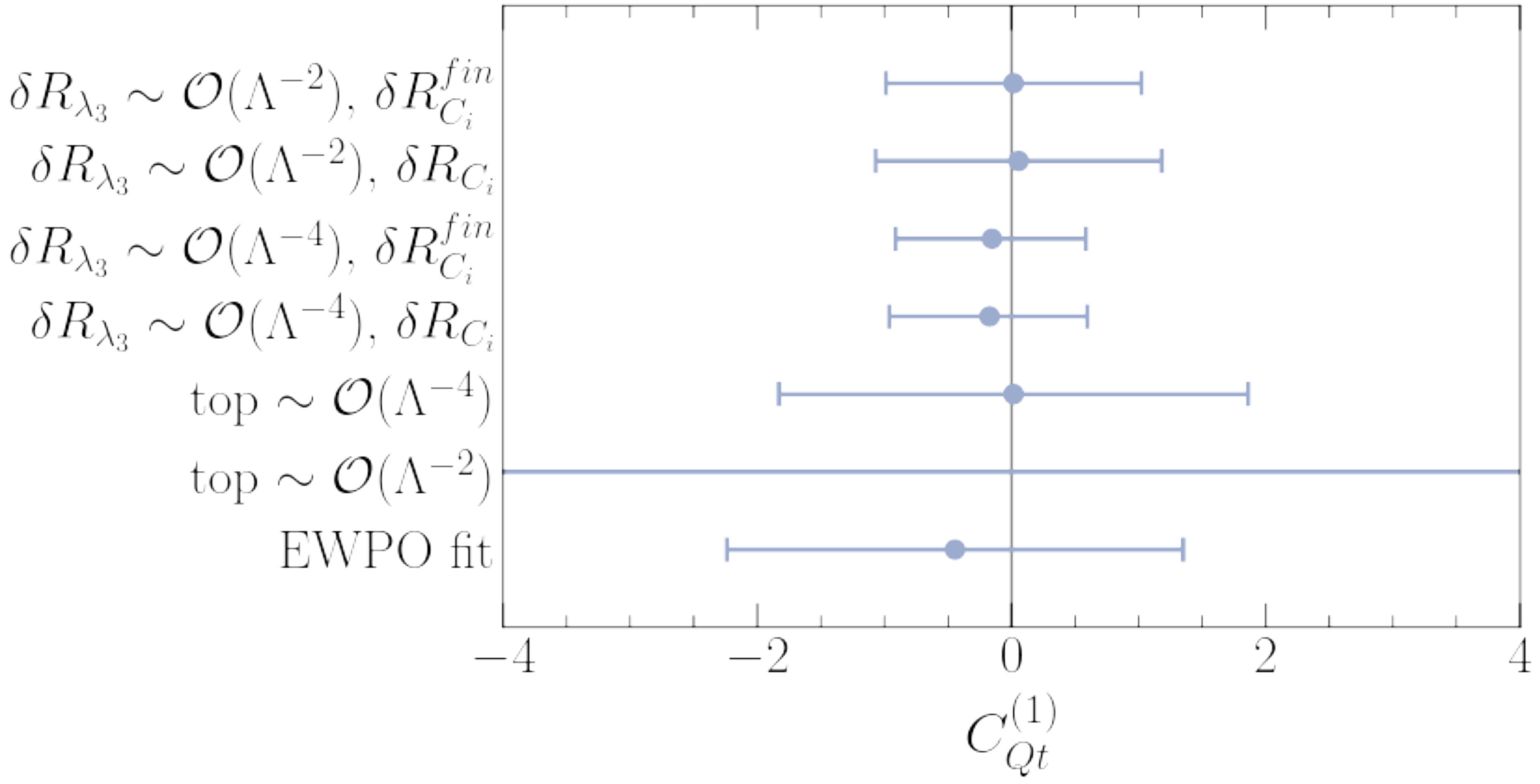
New loop-induced sensitivity
Competitive to 4top production

Improved sensitivity (3)

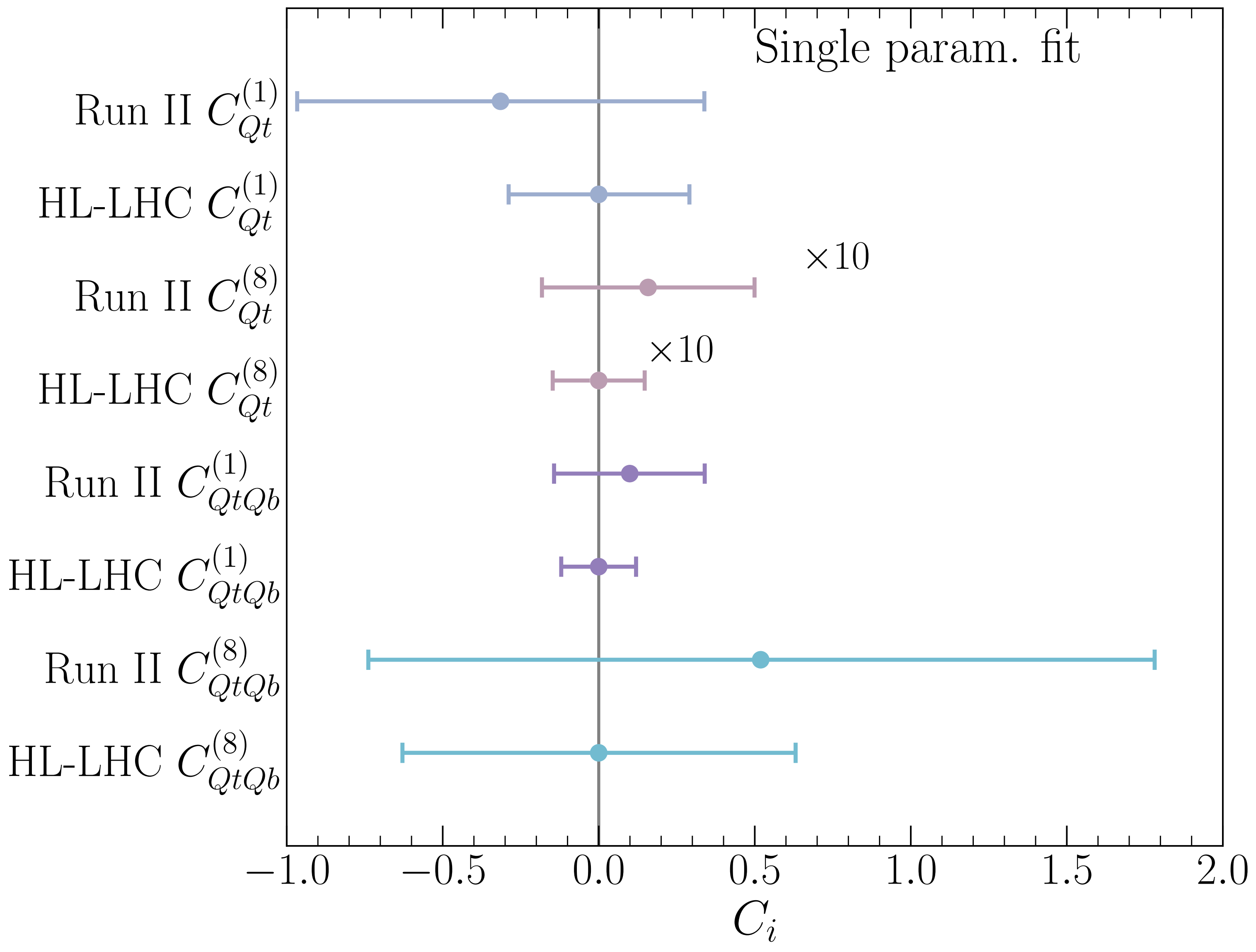
4-heavy operators in Higgs production



Alasfar, de Blas, Gröber arXiv:2202.02333



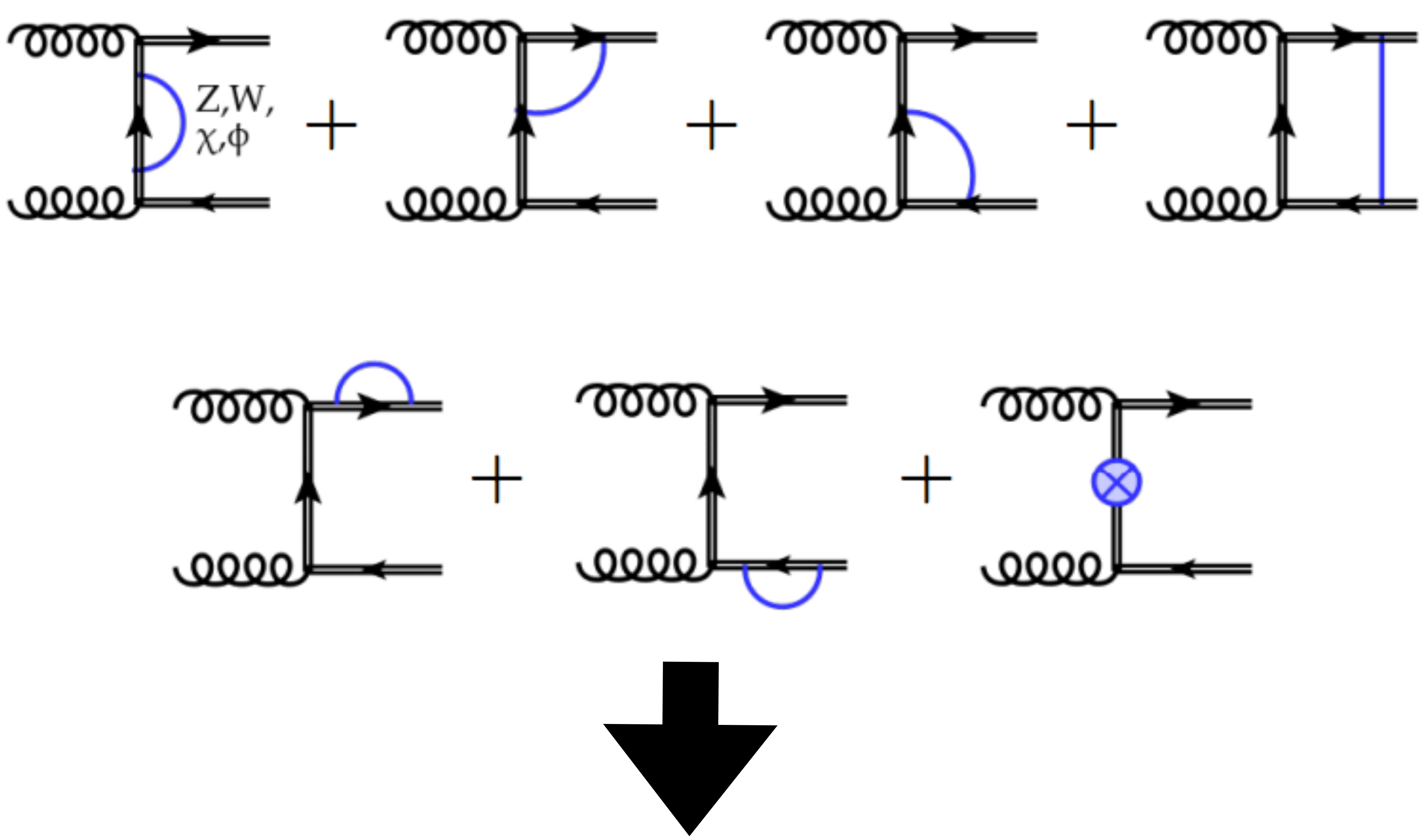
Again competitive with top fit bounds!



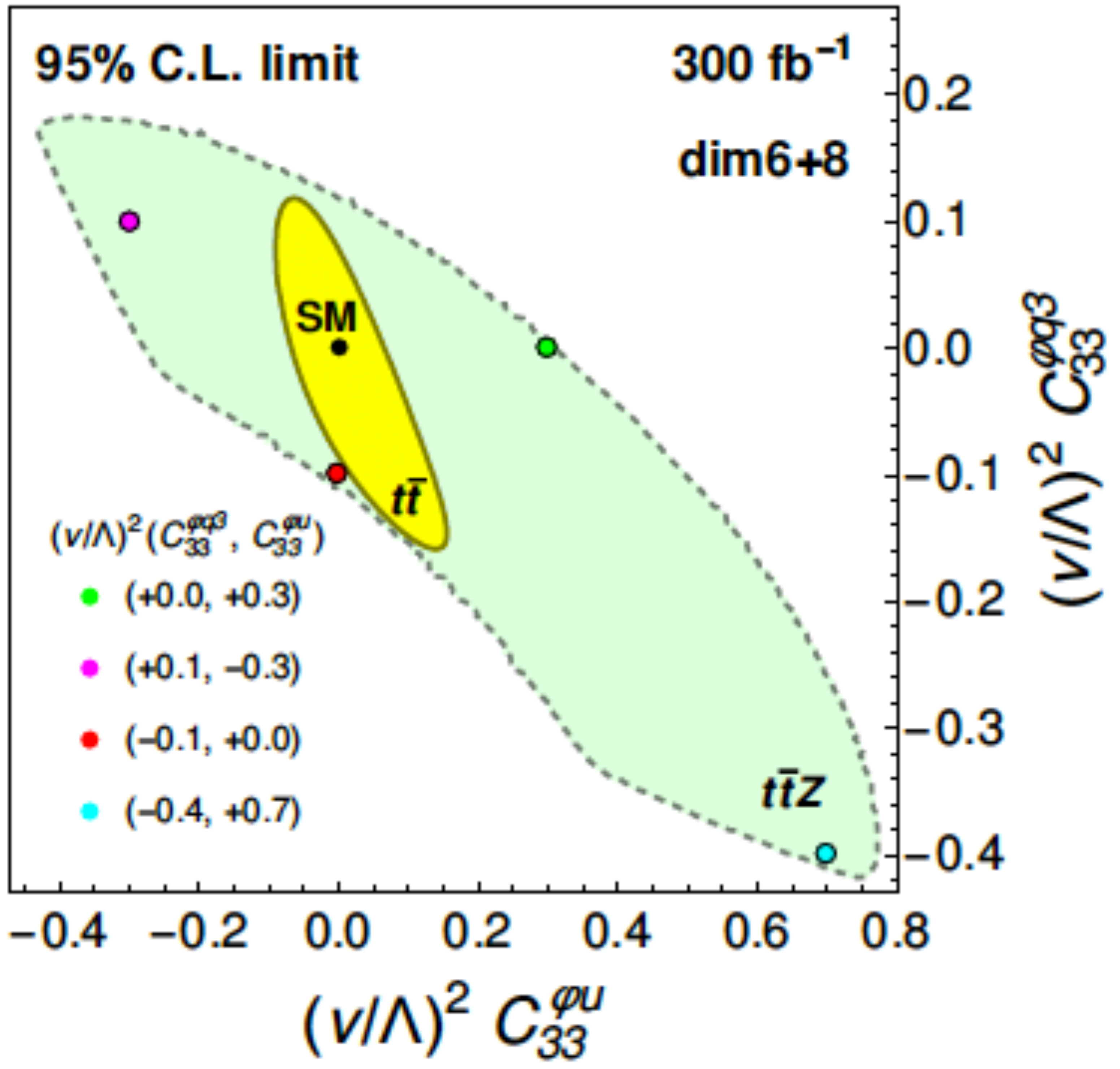
More loop-induced sensitivities

Top pair production sensitivity to EW top couplings

EW corrections to top pair production:



Top-Z couplings

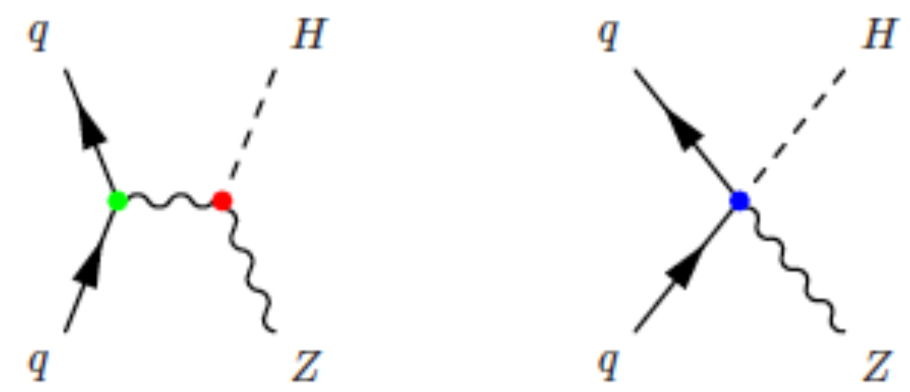


Martini and Schulze arXiv:1911.11244

Loop-induced sensitivity in Higgs

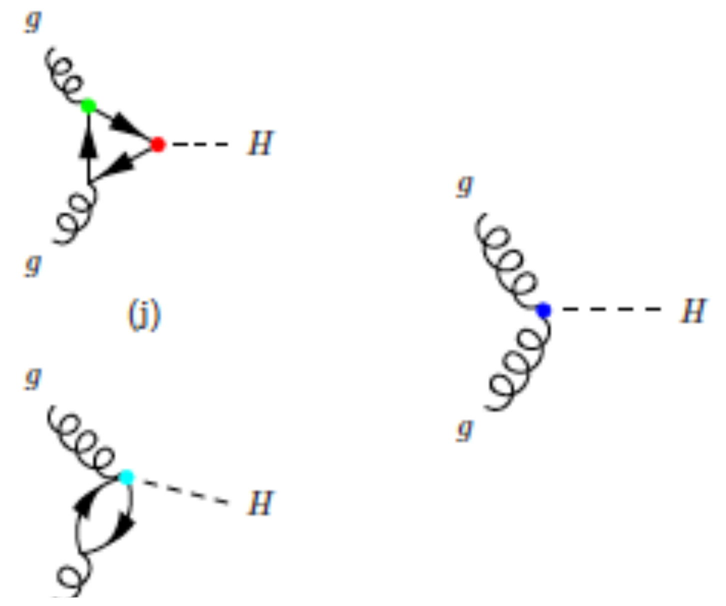
Top operators in Higgs observables

ZH



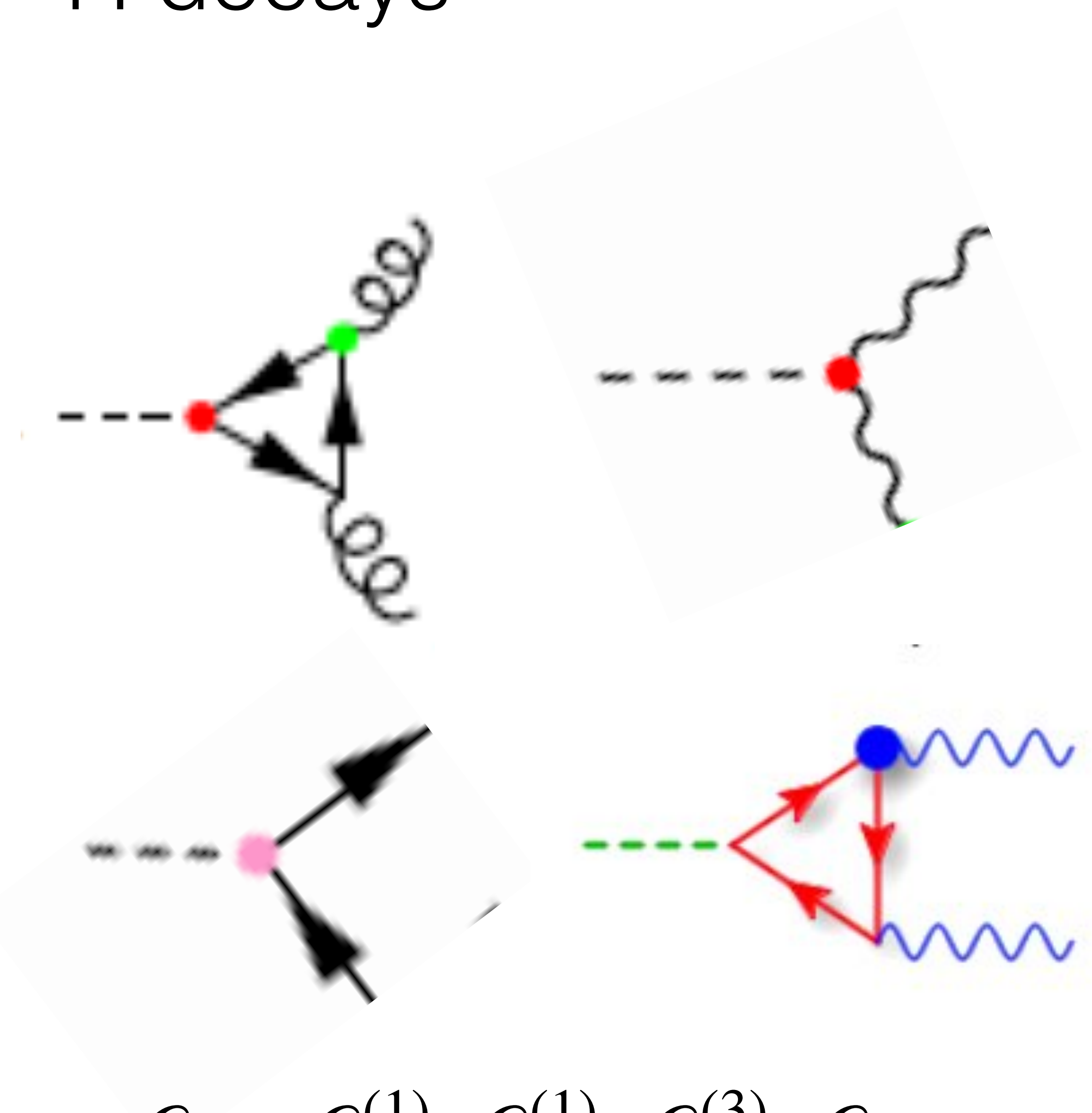
$\mathcal{O}_{\varphi W}$, $\mathcal{O}_{\varphi B}$, $\mathcal{O}_{\varphi D}$, $\mathcal{O}^{(3)}_{\varphi q_i}$, $\mathcal{O}^{(1)}_{\varphi q_i}$, $\mathcal{O}^{(1)}_{\varphi Q}$, $\mathcal{O}^{(3)}_{\varphi Q}$, $\mathcal{O}_{\varphi d}$, $\mathcal{O}_{\varphi WB}$, $\mathcal{O}^{(3)}_{\varphi l_1}$, $\mathcal{O}^{(3)}_{\varphi l_2}$, $\mathcal{O}_{\varphi u_i}$, $\mathcal{O}_{\varphi d_i}$

ggH



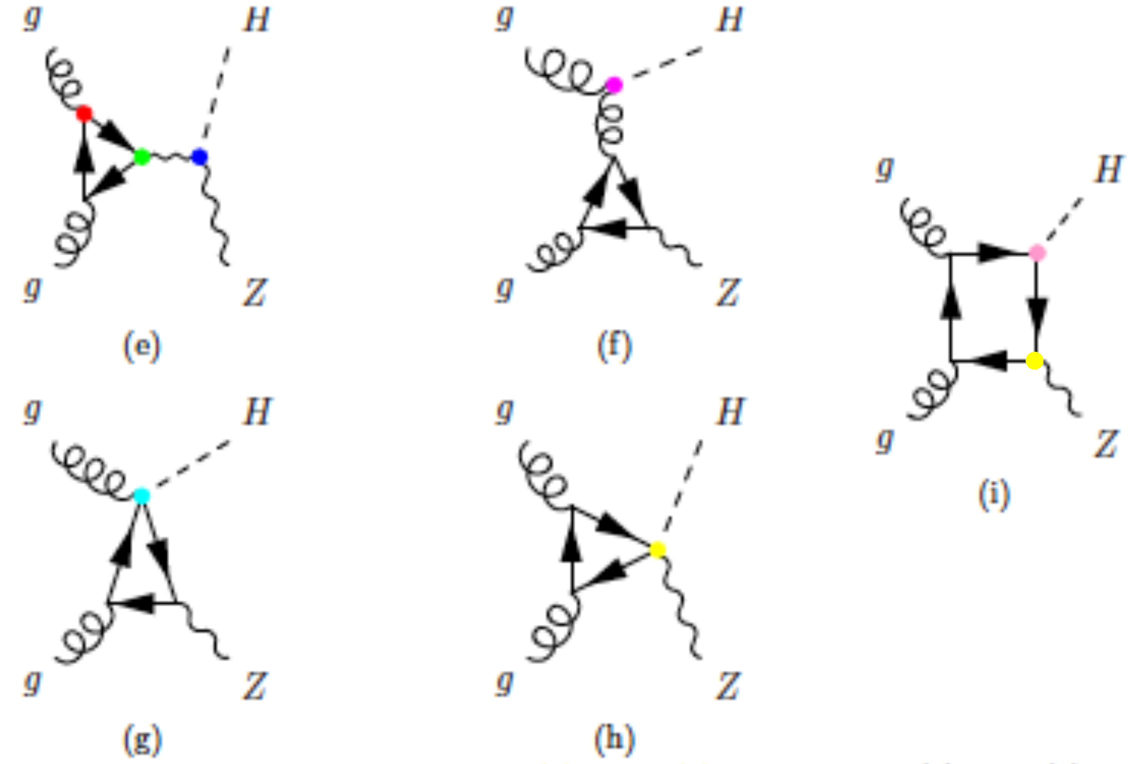
$\mathcal{O}_{\varphi D}$, $\mathcal{O}_{\varphi d}$, $\mathcal{O}^{(3)}_{\varphi l_1}$, $\mathcal{O}^{(3)}_{\varphi l_2}$, $\mathcal{O}_{t\varphi}$, $\mathcal{O}_{tG}$, $\mathcal{O}_{\varphi G}$, $\mathcal{O}_{ll}$

H decays



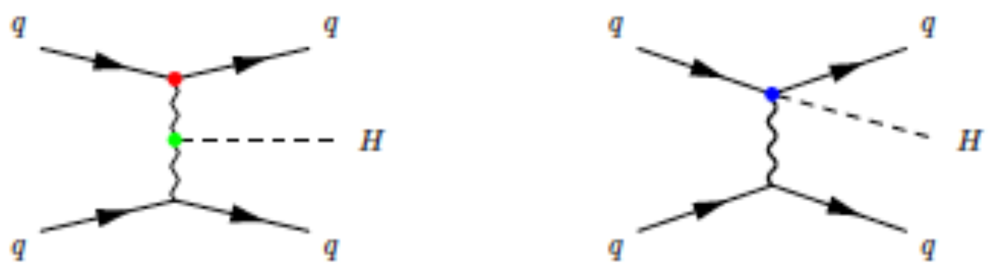
$\mathcal{O}_{\varphi D}, \mathcal{O}^{(1)}_{\varphi q_i}, \mathcal{O}^{(1)}_{\varphi Q}, \mathcal{O}^{(3)}_{\varphi Q}, \mathcal{O}_{\phi d} \cdots$

ZH



$\mathcal{O}_{\varphi D}$, $\mathcal{O}^{(1)}_{\varphi q_i}$, $\mathcal{O}^{(1)}_{\varphi Q}$, $\mathcal{O}^{(3)}_{\varphi Q}$, $\mathcal{O}_{\varphi d}$, $\mathcal{O}^{(3)}_{\varphi l_1}$, $\mathcal{O}^{(3)}_{\varphi l_2}$, $\mathcal{O}_{\varphi u_i}$, $\mathcal{O}_{\varphi t}$, $\mathcal{O}_{\varphi d_i}$, $\mathcal{O}_{t\varphi}$, $\mathcal{O}_{tG}$, $\mathcal{O}_{\varphi G}$, $\mathcal{O}_{ll}$

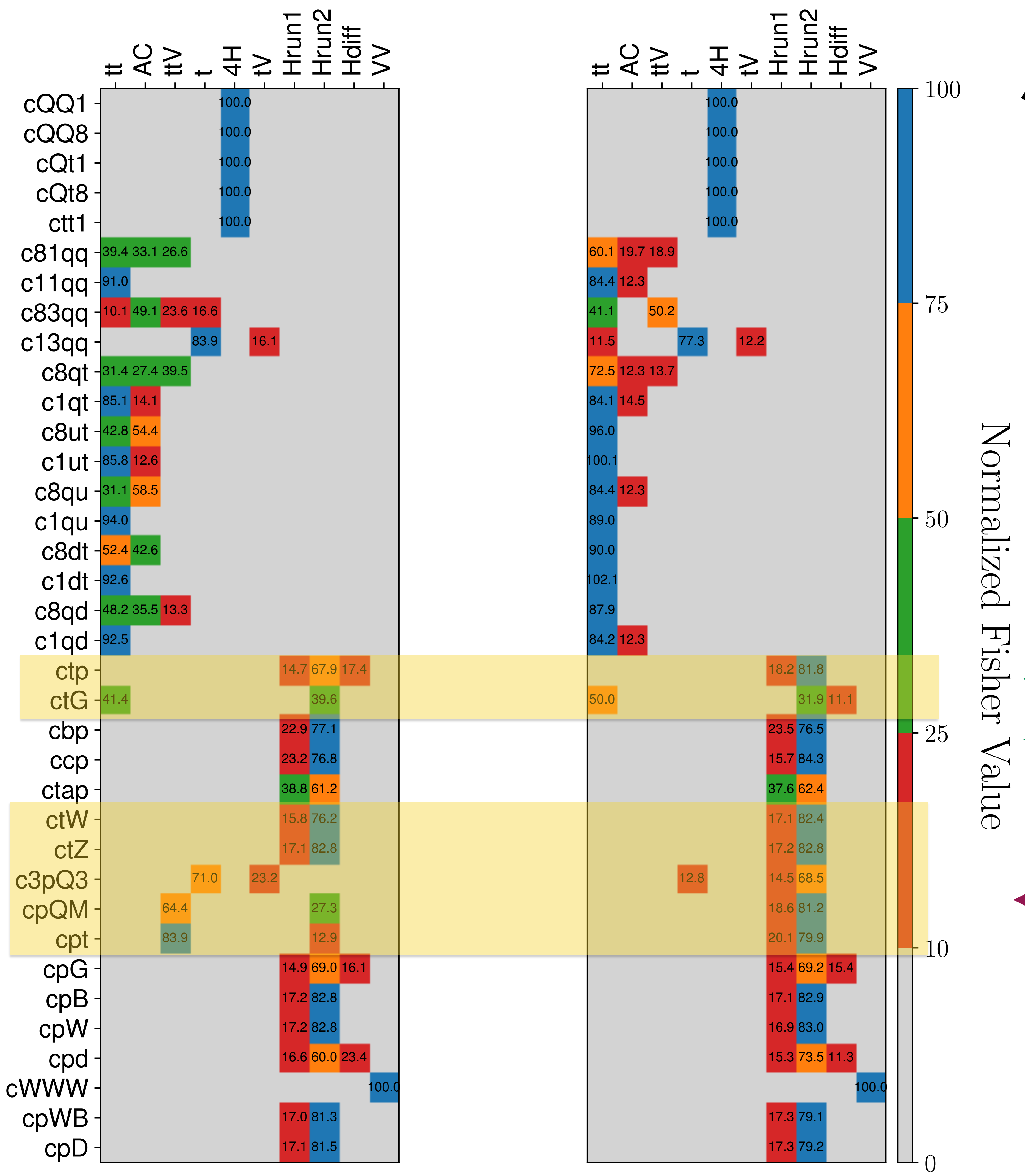
VBF



$\mathcal{O}_{\varphi W}$, $\mathcal{O}_{\varphi B}$, $\mathcal{O}_{\varphi D}$, $\mathcal{O}^{(3)}_{\varphi q_i}$, $\mathcal{O}^{(1)}_{\varphi q_i}$, $\mathcal{O}^{(1)}_{\varphi Q}$, $\mathcal{O}^{(3)}_{\varphi Q}$, $\mathcal{O}_{\varphi d}$, $\mathcal{O}_{\varphi WB}$, $\mathcal{O}^{(3)}_{\varphi l_1}$, $\mathcal{O}^{(3)}_{\varphi l_2}$, $\mathcal{O}_{\varphi u_i}$, $\mathcal{O}_{\varphi d_i}$

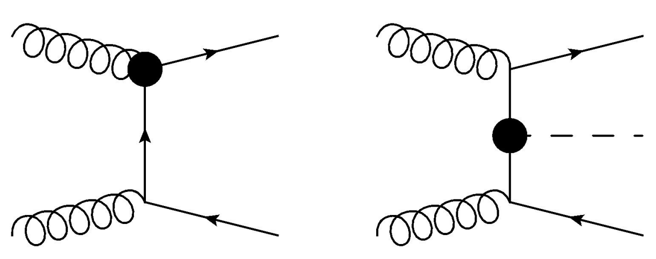
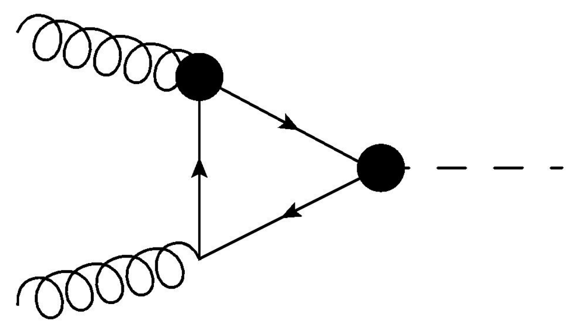
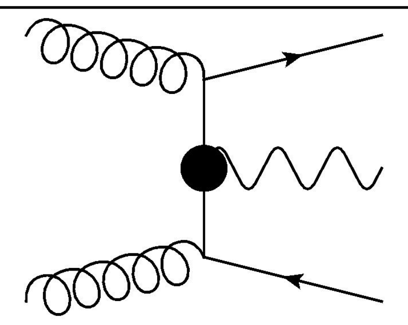
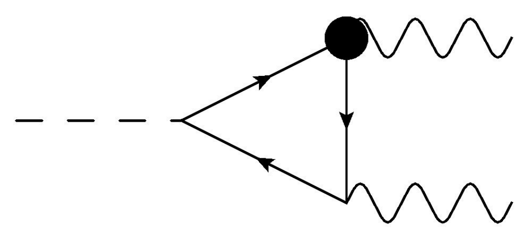
from L. Mantani

Tree-loop interplay in global fits



Fisher information table

4F mostly top

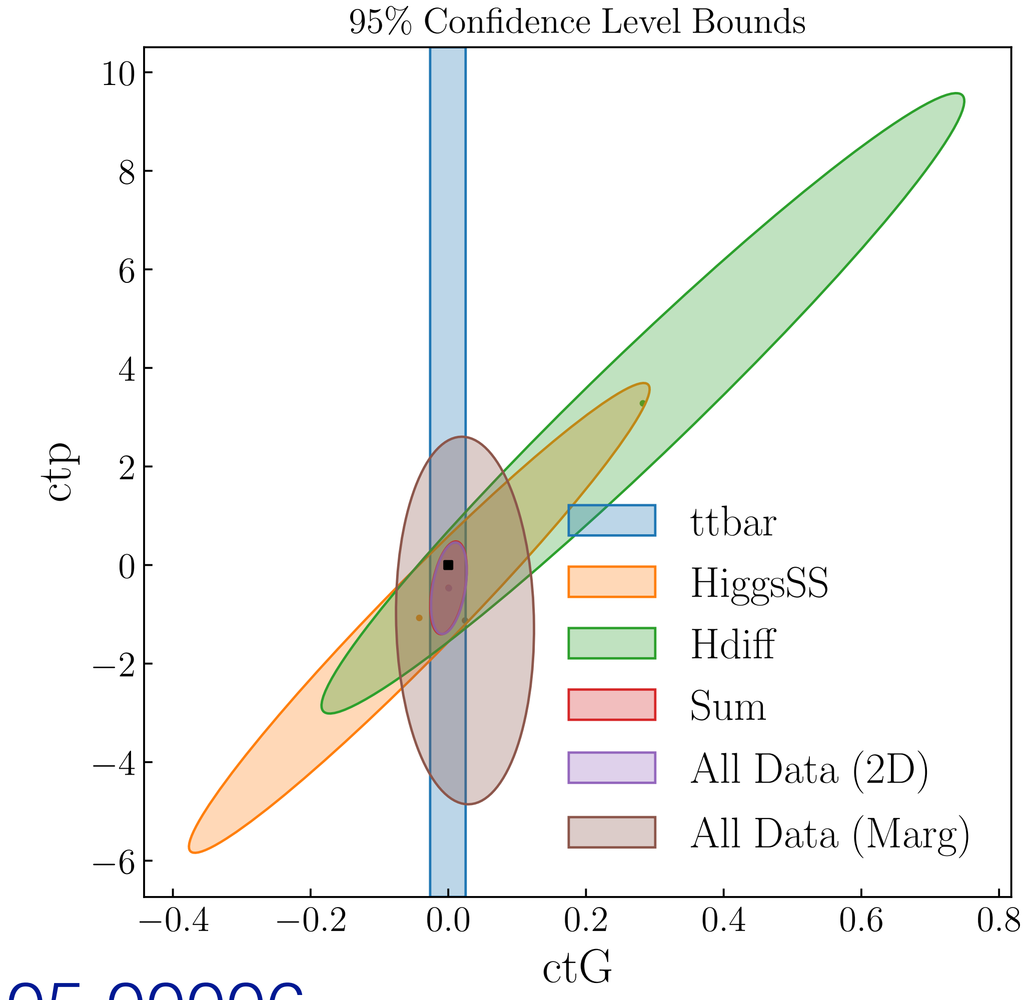
	Tree	Loop
Top Yukawa Top Chromomagnetic		
ttV couplings		

Tree-loop interface

Ethier, Maltoni, Mantani, Nocera, Rojo, Slade, EV and Zhang arXiv:2105.00006

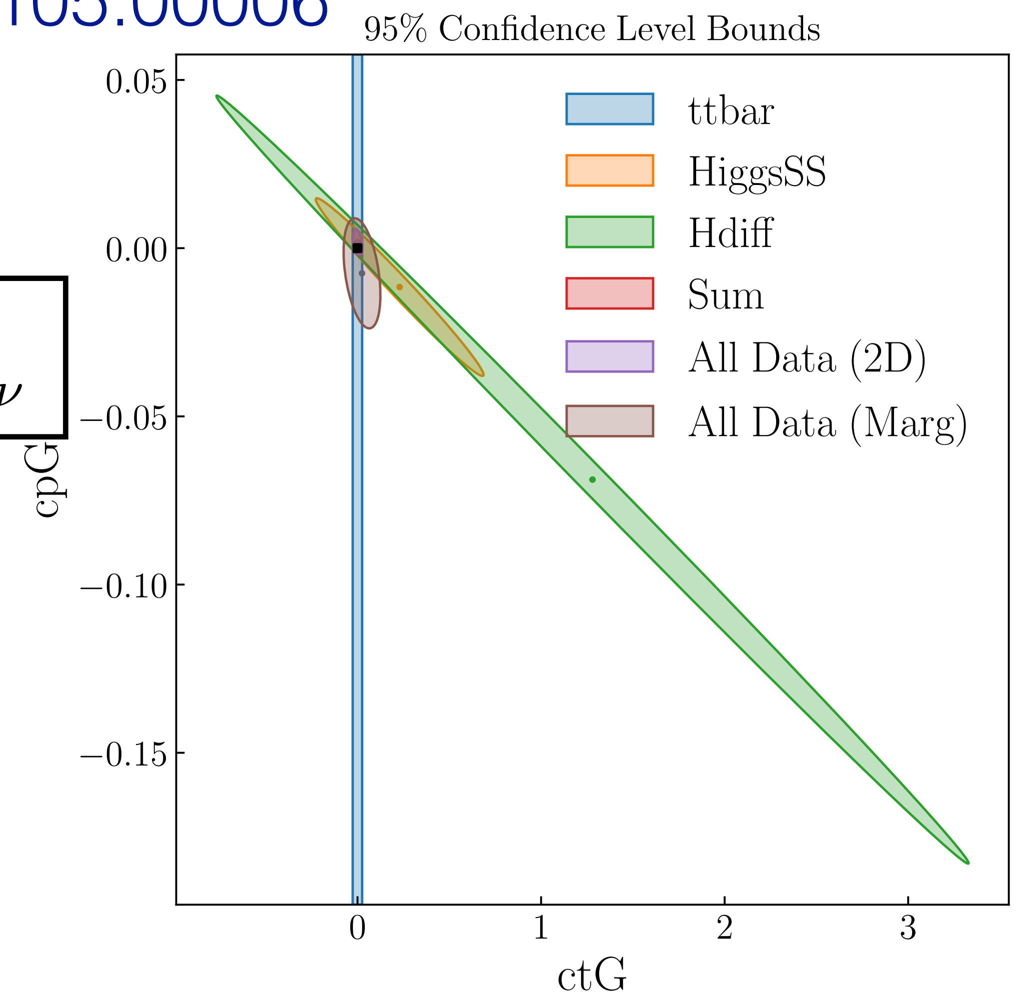
Breaking degeneracies

$\left(\varphi^\dagger\varphi\right)\bar{Q}\,t\,\tilde{\varphi}$



Ethier et al arXiv:2105.00006

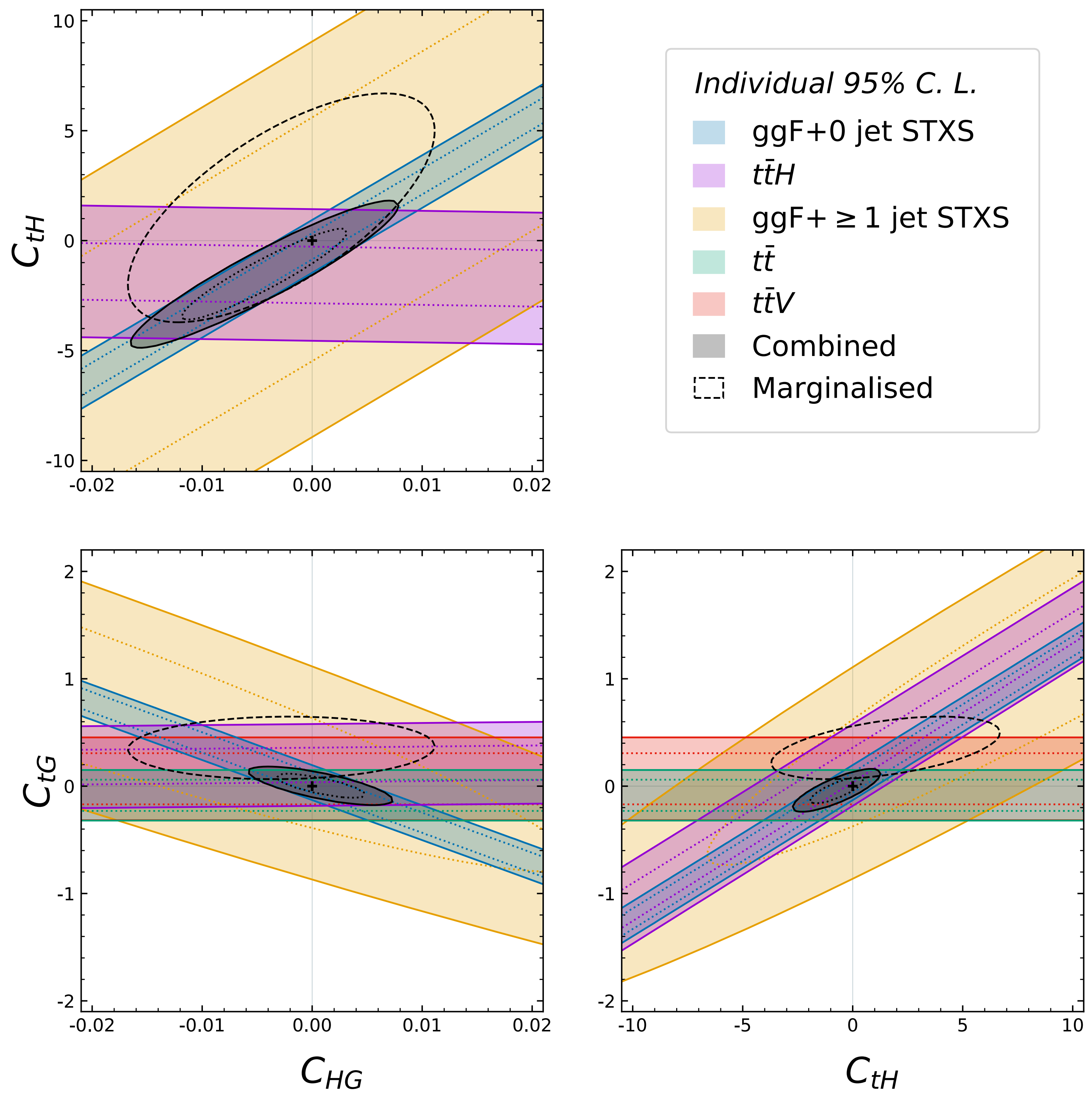
$\left(\varphi^\dagger\varphi\right)G_A^{\mu\nu}\,G^A_{\mu\nu}$



$(\bar{Q}\tau^{\mu\nu}\,T_A\,t)\,\tilde{\varphi}\,G^A_{\mu\nu}$

$\left(\varphi^\dagger\varphi\right)\bar{Q}\,t\,\tilde{\varphi}$

$(\bar{Q}\tau^{\mu\nu}\,T_A\,t)\,\tilde{\varphi}\,G^A_{\mu\nu}$



$\left(\varphi^\dagger\varphi\right)G_A^{\mu\nu}\,G^A_{\mu\nu}$ $\left(\varphi^\dagger\varphi\right)\bar{Q}\,t\,\tilde{\varphi}$

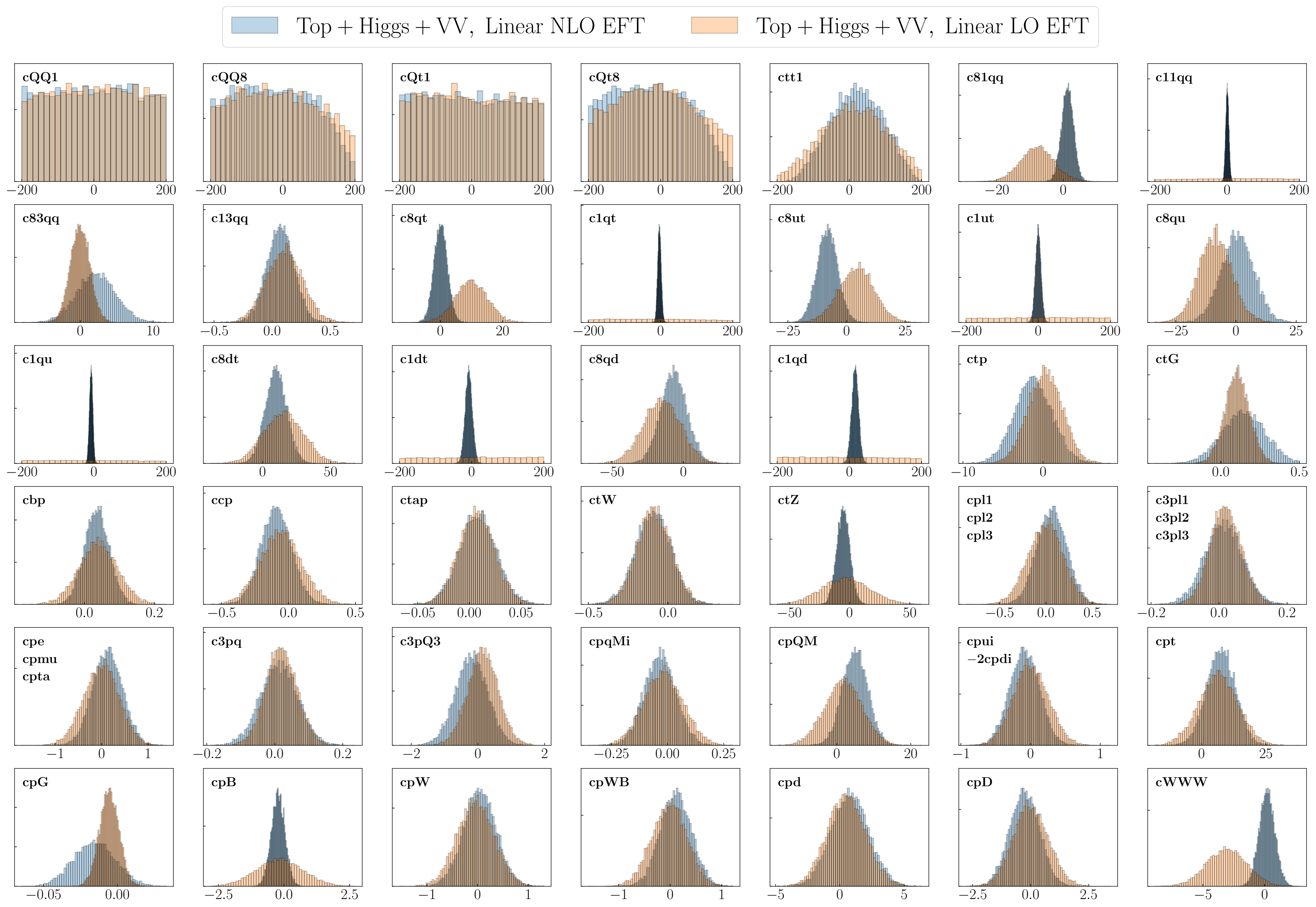
Ellis, Madigan, Mimasu, Sanz, You arXiv:2012.02779

Top measurements break the degeneracy between Higgs operators

Does NLO/1-loop change global fits?

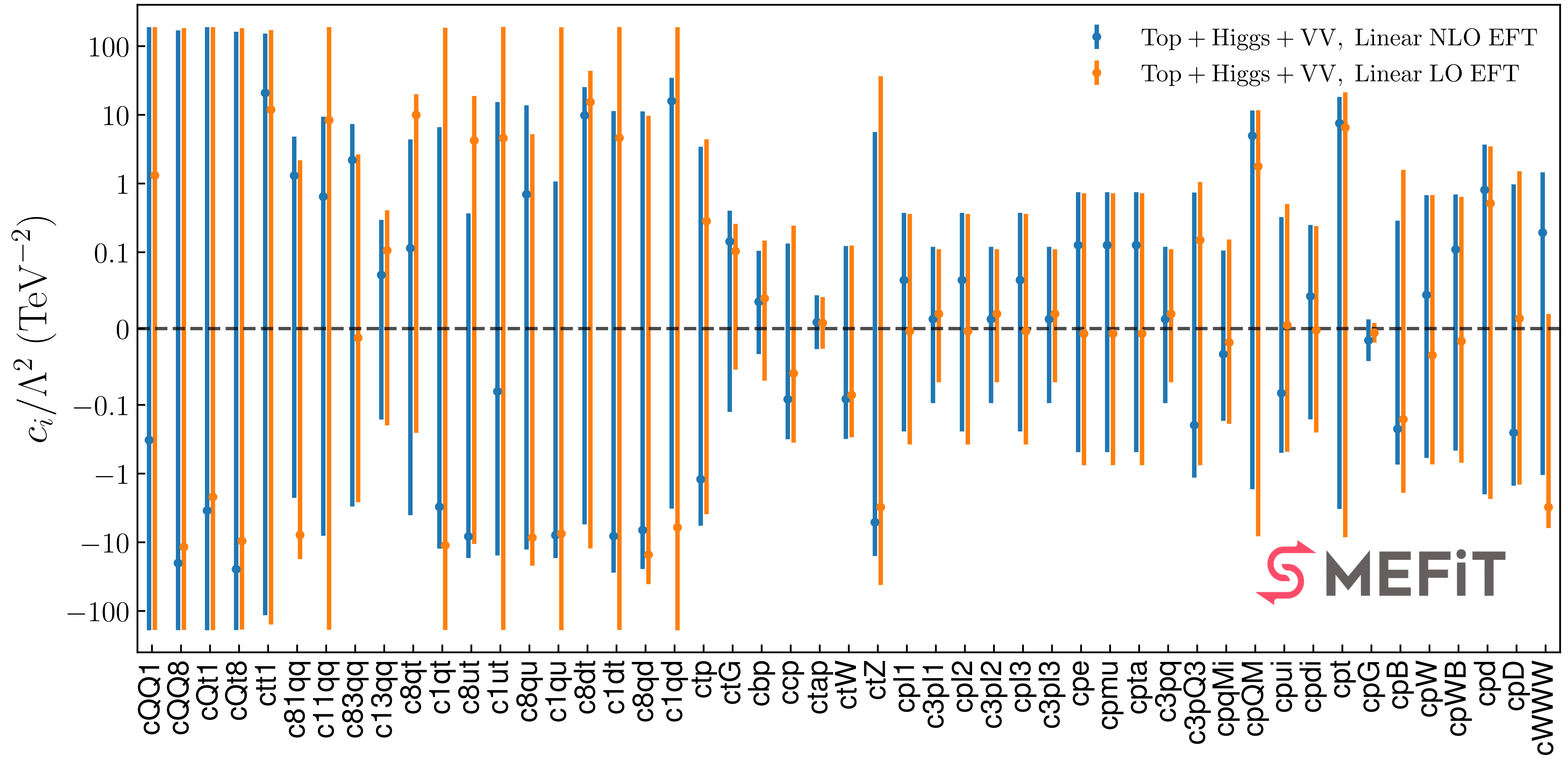
Global top fits

Linear fits:



Posterior distributions for Wilson coefficients

Ethier et al arXiv:2105.00006



Significant impact of NLO for some operators

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

Ongoing and future developments

Status of SMEFT computations at dimension-6:

Tree level Monte Carlo: Done

NLO QCD: ~Done

NNLO QCD: A couple of examples (Uli's talk)

NLO EW: Some examples available, needed to probe unconstrained operators.

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

How about this μ?

RGE in MC

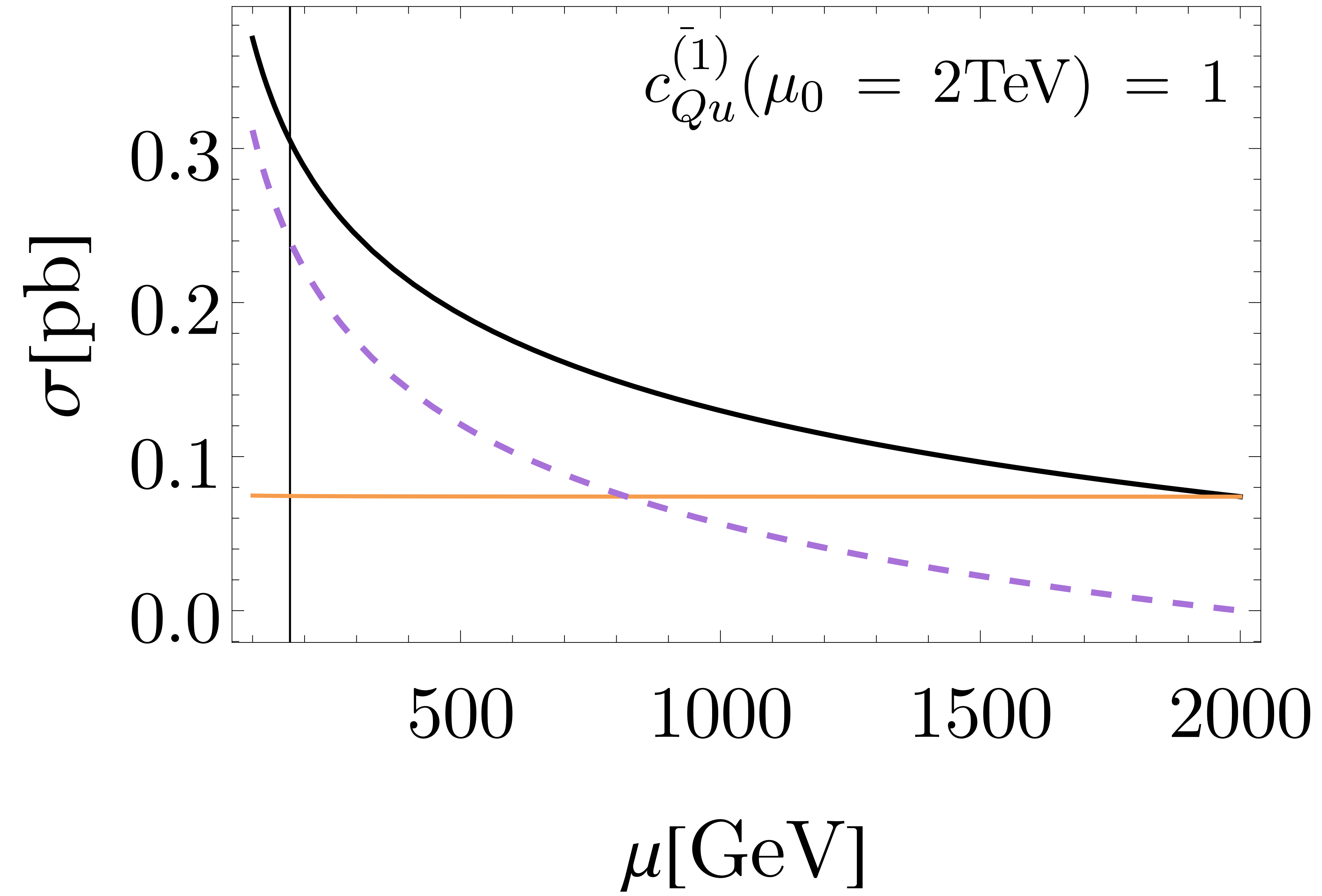
$$\frac{dc_i(\mu)}{d\log\mu} = \gamma_{ij}\, c_j(\mu)$$

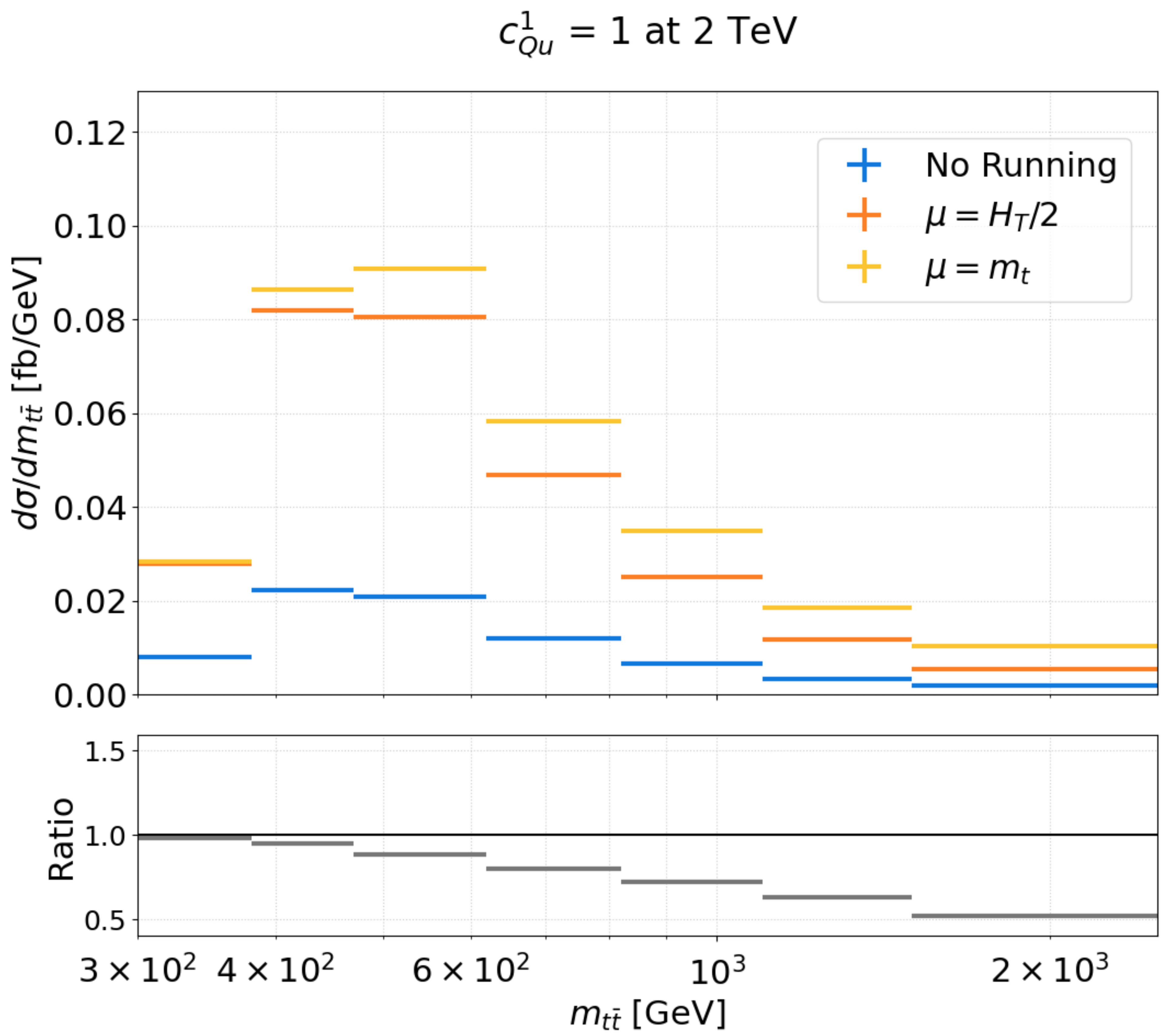
One loop known:

(Alonso) Jenkins et al arXiv:1308.2627, 1310.4838, 1312.2014

Example: Turn one 1 operator at high-scale

Compute effect on top pair cross-section

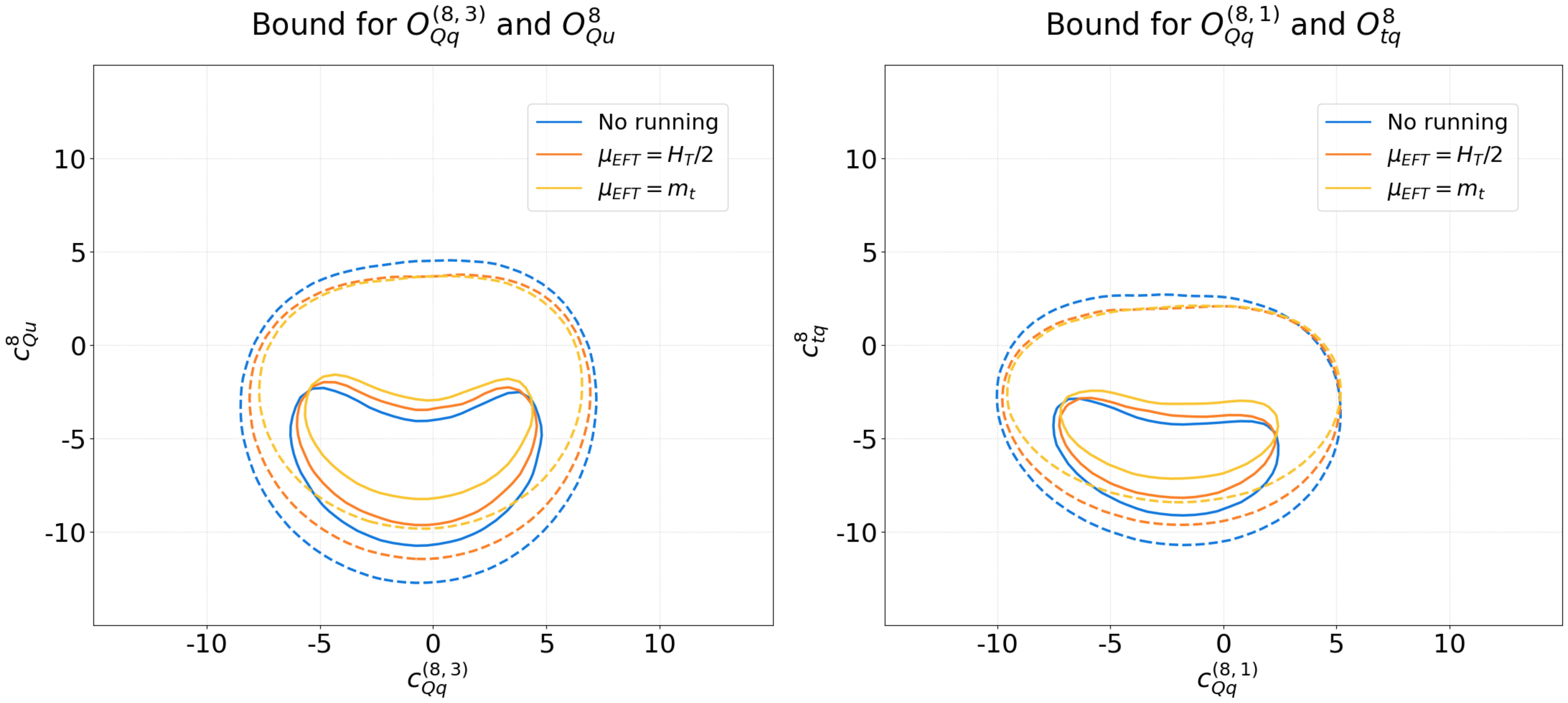




Aoude, Maltoni, Mattelaer, Severi, EV (soon)

Impact of RGE on constraints

Mini-fit in the top sector



Aoude, Maltoni, Mattelaer, Severi, EV (soon)

See also Battaglia, Grazzini, Spira, Wiesemann arXiv: 2109.02987

Conclusions

* Efforts towards EFT interpretations for the LHC are ongoing on both theory and experimental side.
* To allow combination of different analyses common conventions about bases, flavour assumptions etc are needed.
* Tools play an important role and their validation and comparison is crucial.
* Higher-order corrections in the EFT predictions can play a crucial role and including them as much as possible can improve our sensitivity.
* RGE effects included in the Monte Carlo, allowing on the fly computation of running and mixing effects

Thank you