Precision in EFT predictions and impact on EFT fits

Eleni Vryonidou

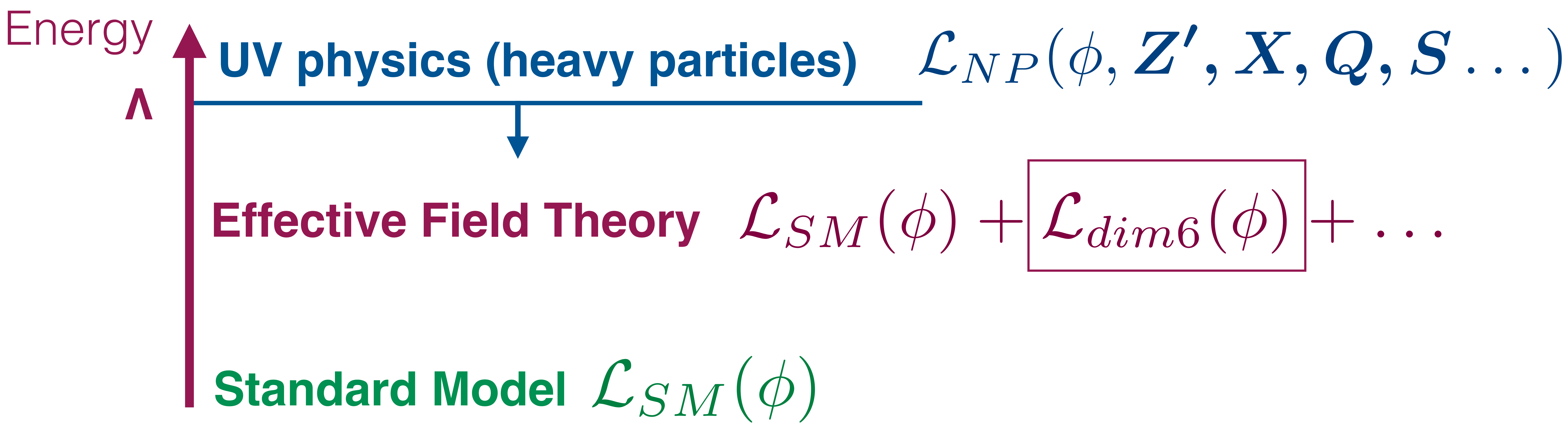
University of Manchester

The LHC precision programme

Benasque, 4/10/23

EFT

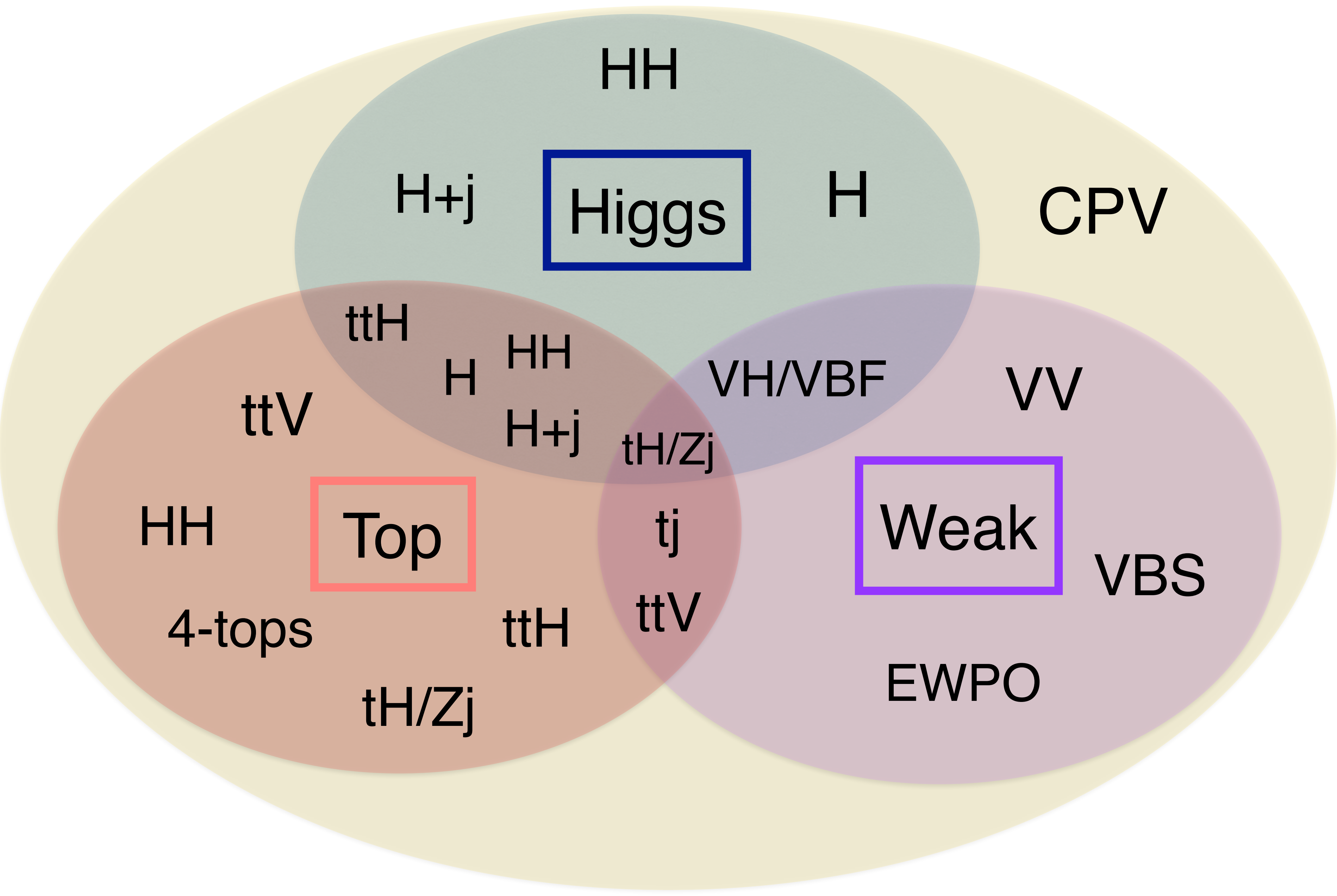
A model independent probe of heavy New Physics



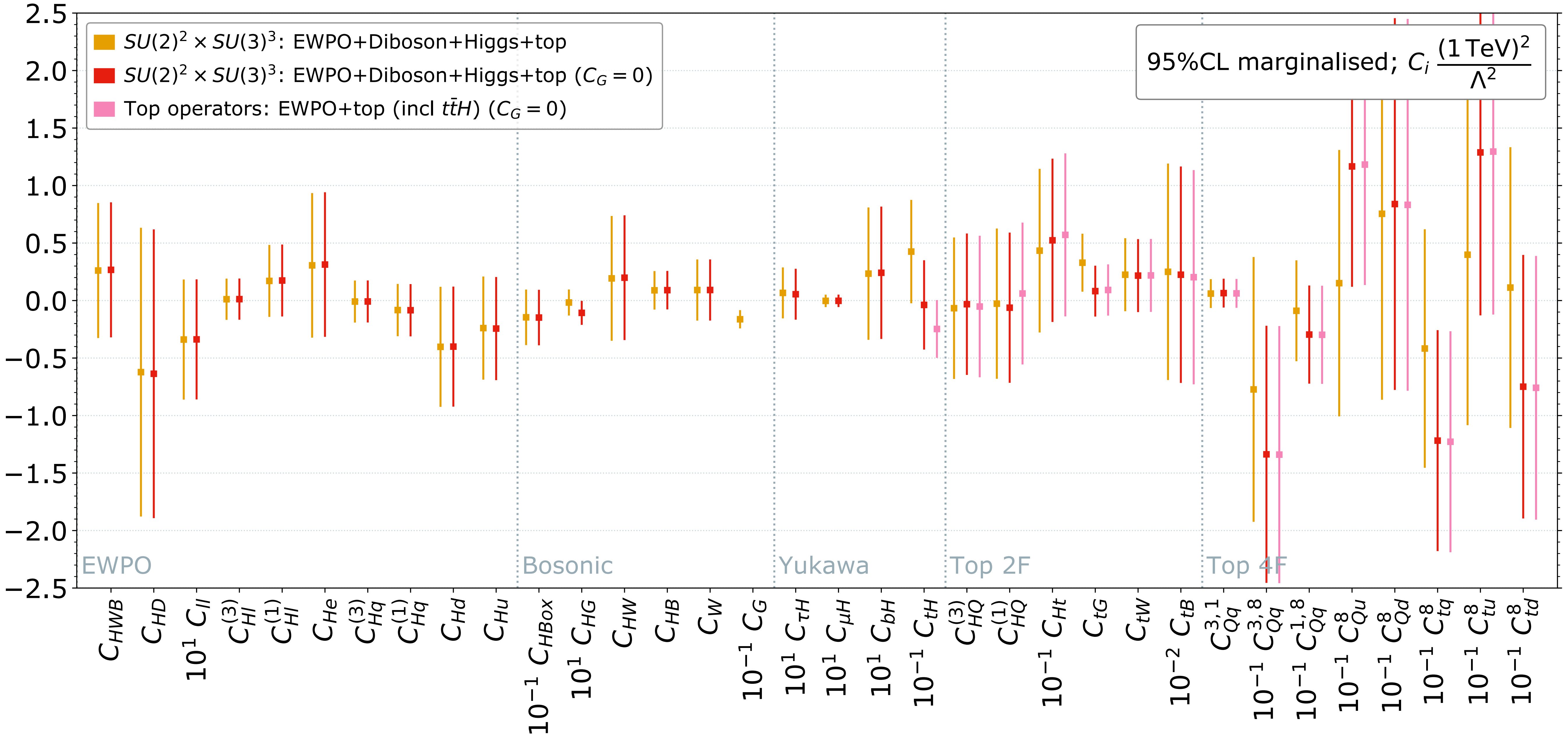
Effective Field Theory reveals high energy physics through precise measurements at low energy.

SMEFT

The global aspect



Adapted from K. Mimasu



First global fit of the top+Higgs+EW sectors

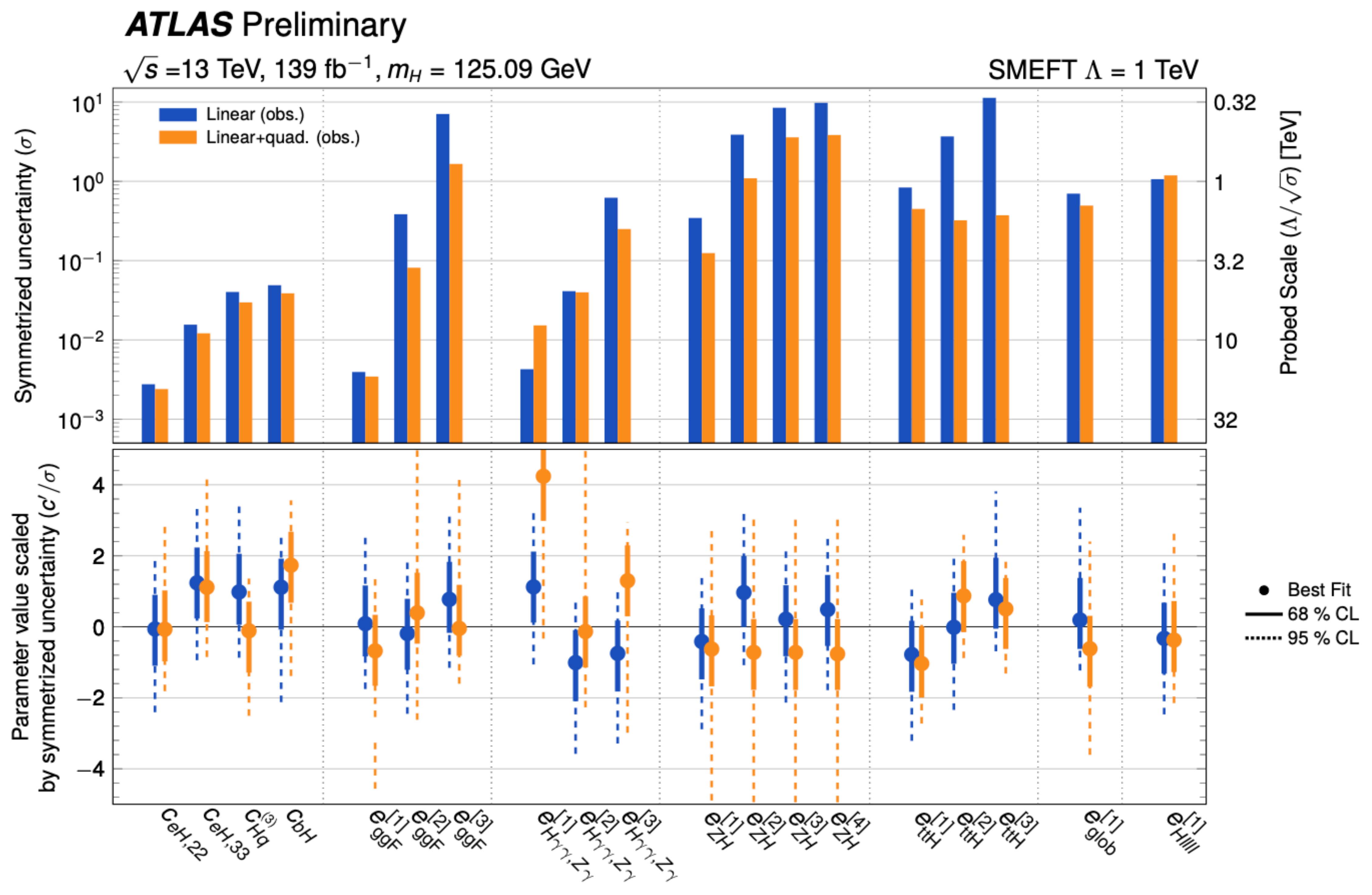
Ellis, Madigan, Mimasu, Sanz, You arXiv:2012.02779

SMEFT correlates different sectors: Global interpretations are needed

SMEFT

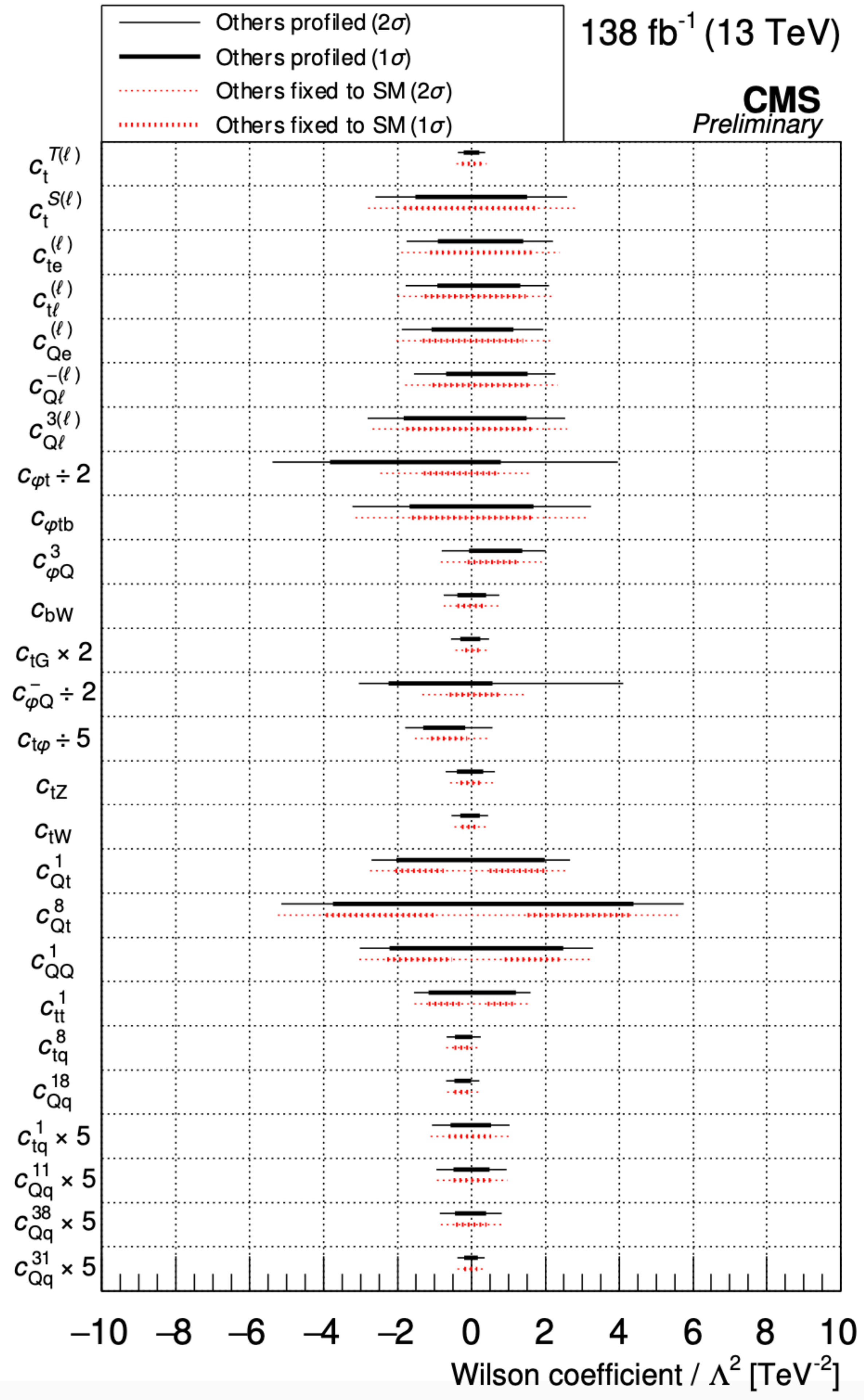
Not just a theorists' tool

ATLAS CONF-2023-052



CMS-PAS-TOP-22-006

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



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

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

EFT pathway to New Physics

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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 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?

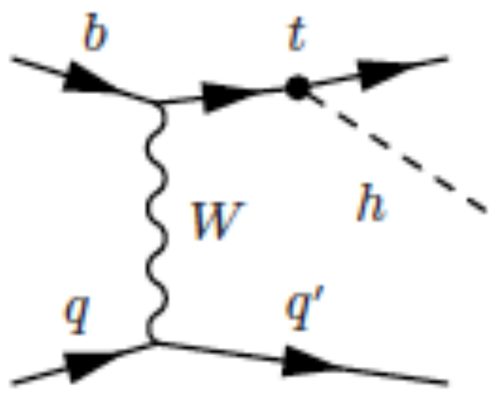
Higher orders in SMEFT bring:

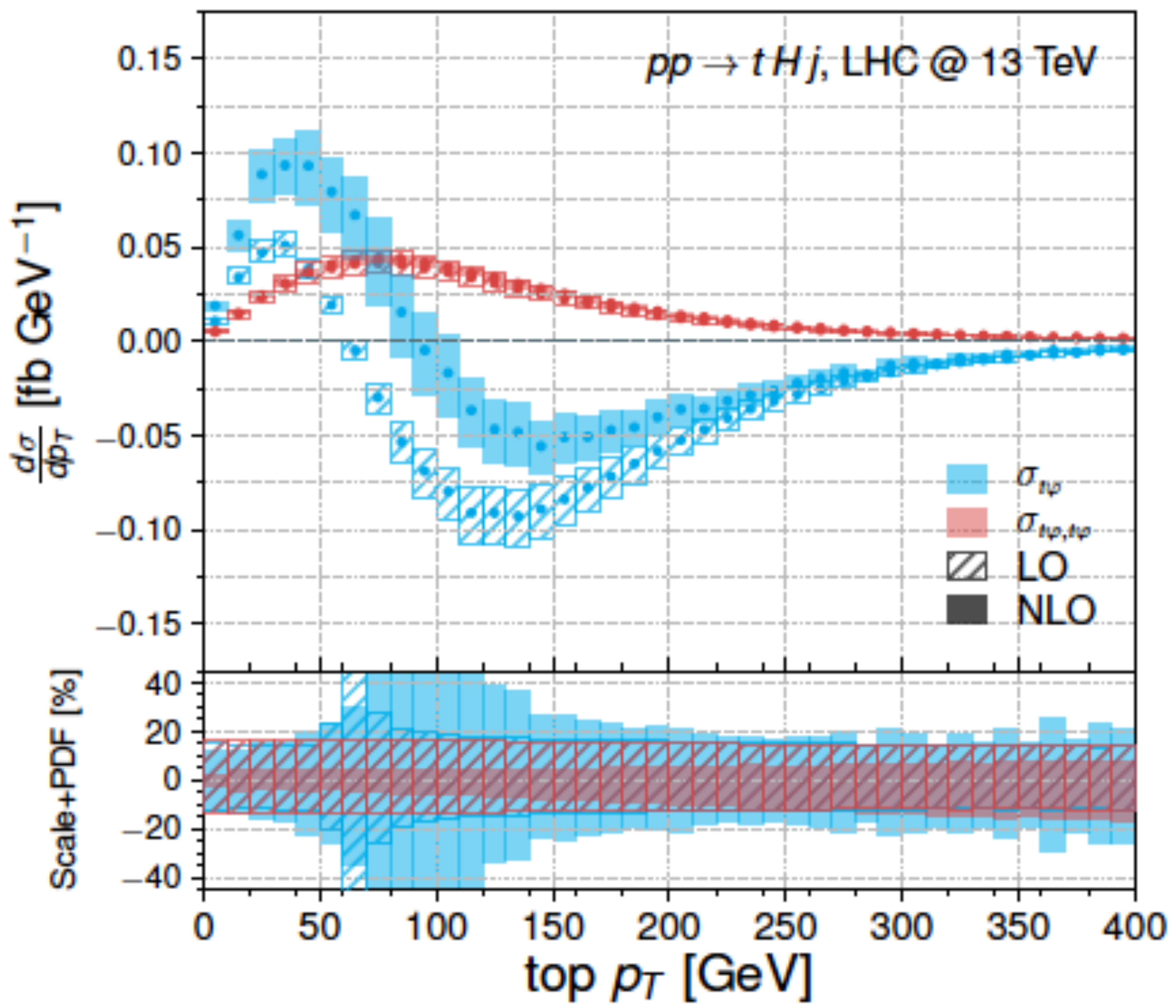
* Accuracy
* Precision
* Improved sensitivity
  * Accurate knowledge of the deviations (distribution shapes, correlations between observables, etc.) can be the key to disentangle them from the SM.
  * Loop-induced new sensitivity: operators entering at one-loop

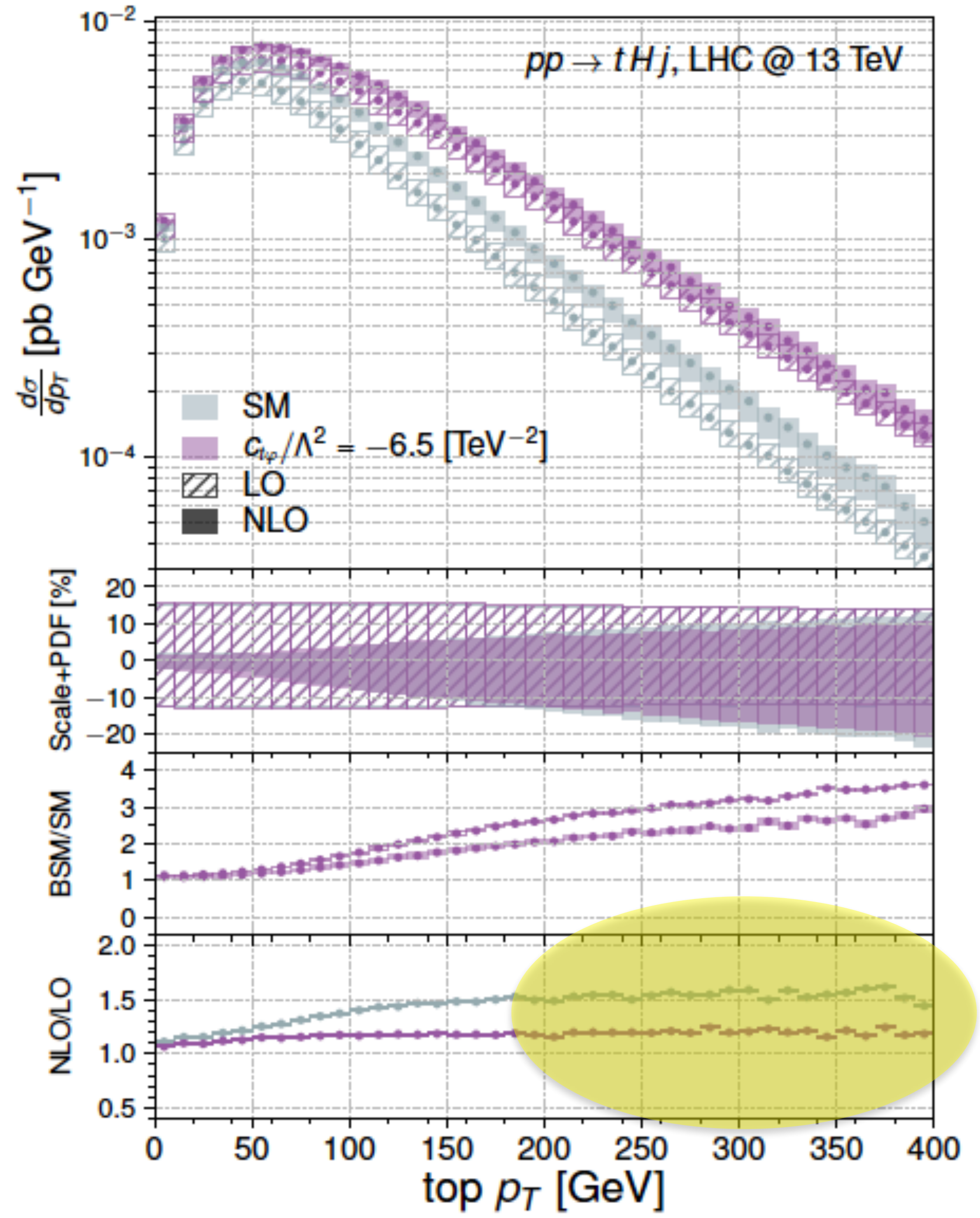
Accuracy and precision

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
$\sigma_{t\phi}$	$-0.062^{+0.006+0.001+0.001}_{-0.004-0.001-0.001}$	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
$\sigma_{t\phi,t\phi}$	$0.0019^{+0.0001+0.0001+0.0000}_{-0.0002-0.0000-0.0000}$	1.17
$\sigma_{\phi G,\phi G}$	$1.021^{+0.204+0.096+0.024}_{-0.178-0.085-0.029}$	1.58
$\sigma_{tG,tG}$	$0.674^{+0.036+0.004+0.016}_{-0.067-0.007-0.019}$	1.04
$\sigma_{t\phi,\phi G}$	$-0.053^{+0.008+0.003+0.001}_{-0.008-0.004-0.001}$	1.42
$\sigma_{t\phi,tG}$	$-0.031^{+0.003+0.000+0.000}_{-0.002-0.000-0.000}$	1.10
$\sigma_{\phi G,tG}$	$0.859^{+0.127+0.021+0.017}_{-0.126-0.020-0.022}$	1.37

Linear ($\sigma_{t\phi}$, $\sigma_{\phi G}$, σ_{tG})

Quadratic ($\sigma_{t\phi,t\phi}$ … $\sigma_{\phi G,tG}$)

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

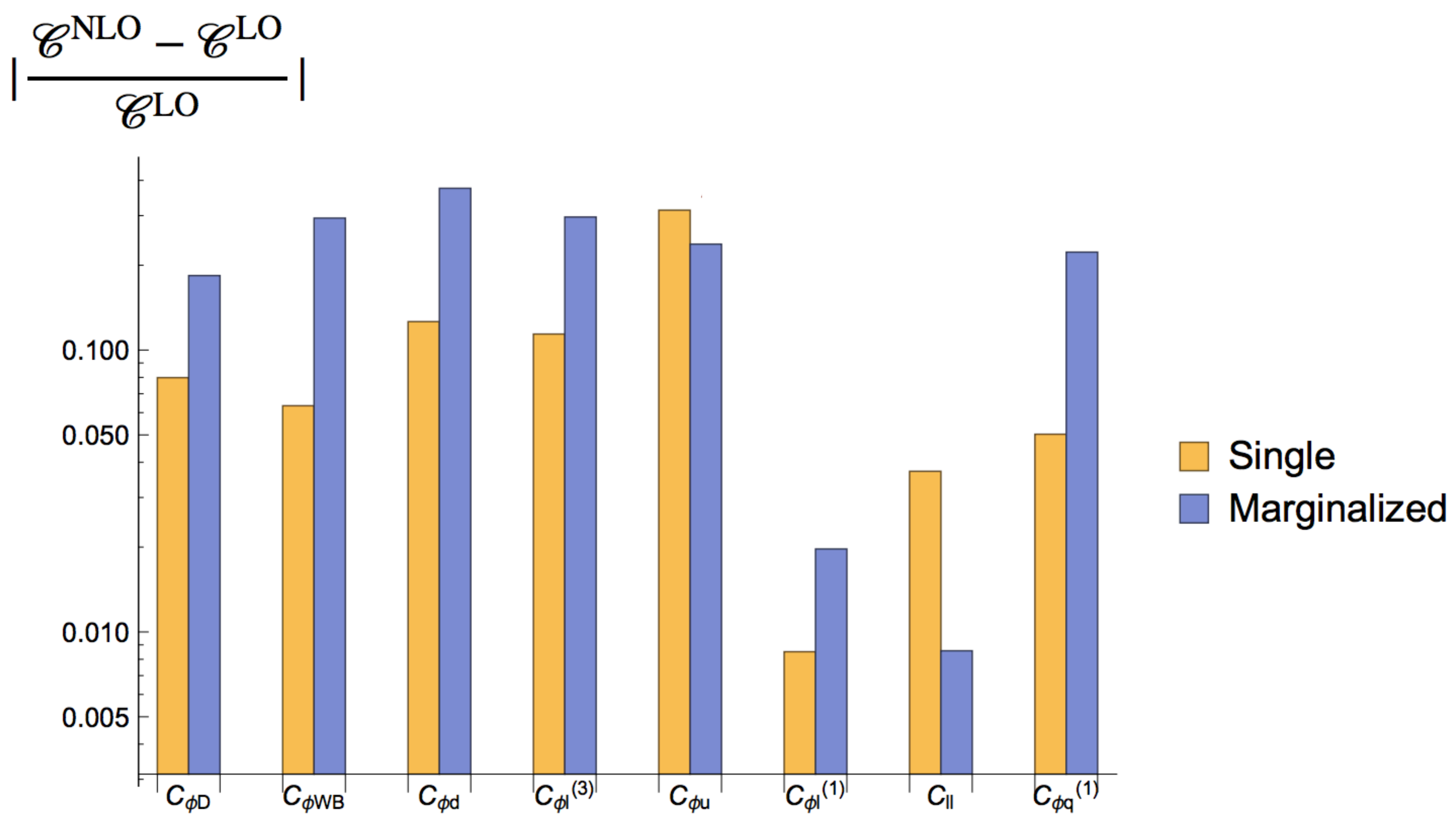
Maltoni, EV, Zhang arXiv:1607.05330

Accuracy and precision

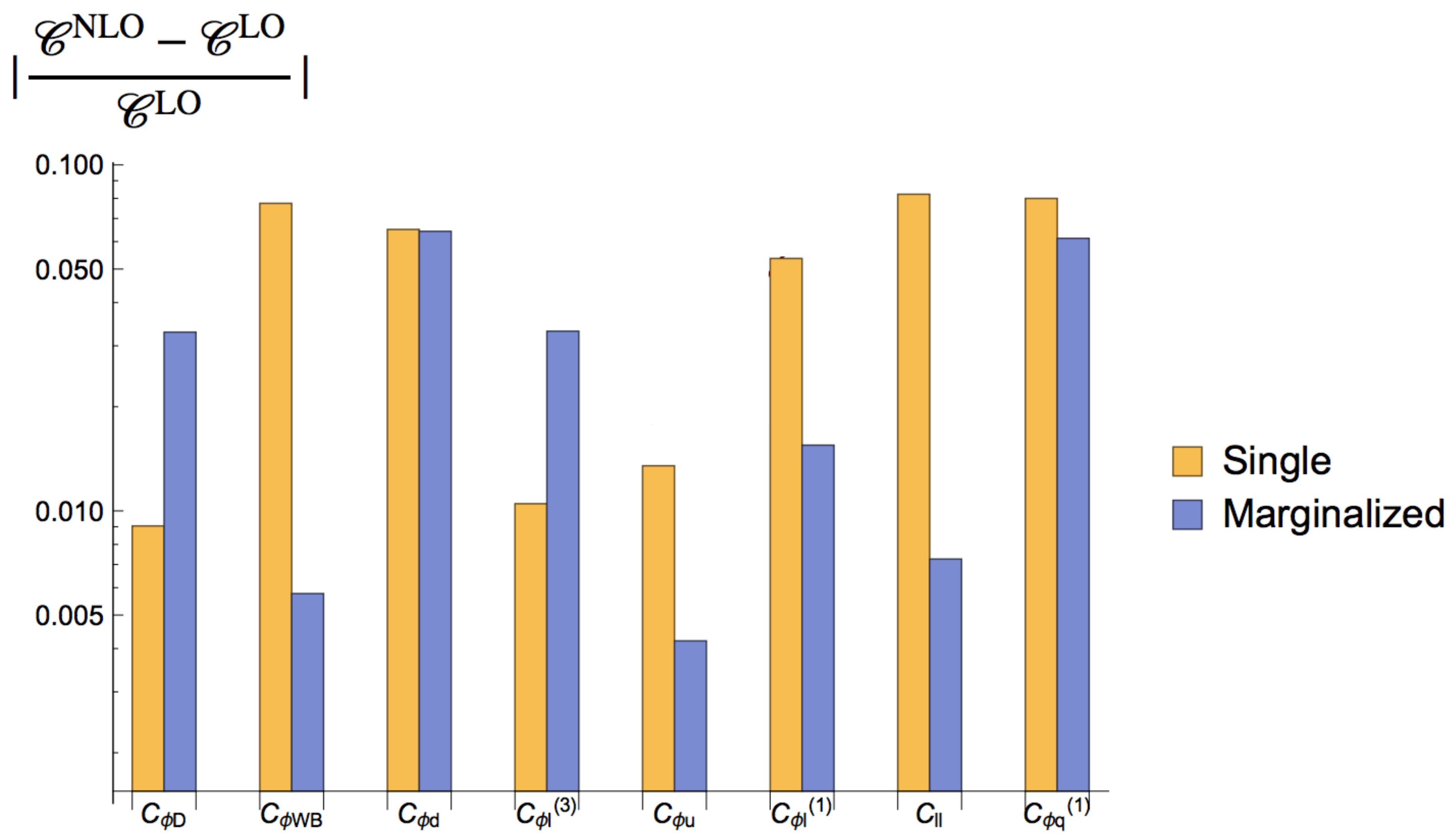
Example 2: EWPO

Impact of NLO corrections on W, Z pole observables:

LEP



ILC GigaZ [arXiv:1908.11299]



Dawson and Giardino arXiv:1909.02000 & Giardino@HEFT2020

Even EW corrections lead to ~20% difference

Improved sensitivity

New operators opening up at NLO

4-heavy operators in top pair production

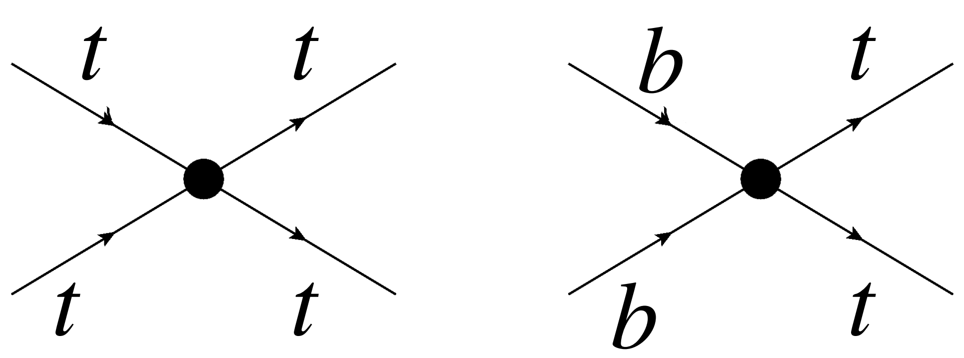
$$\mathcal{O}^8_{QQ} = (\bar{Q}\gamma^\mu T^A Q)(\bar{Q}\gamma_\mu T^A Q)$$

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

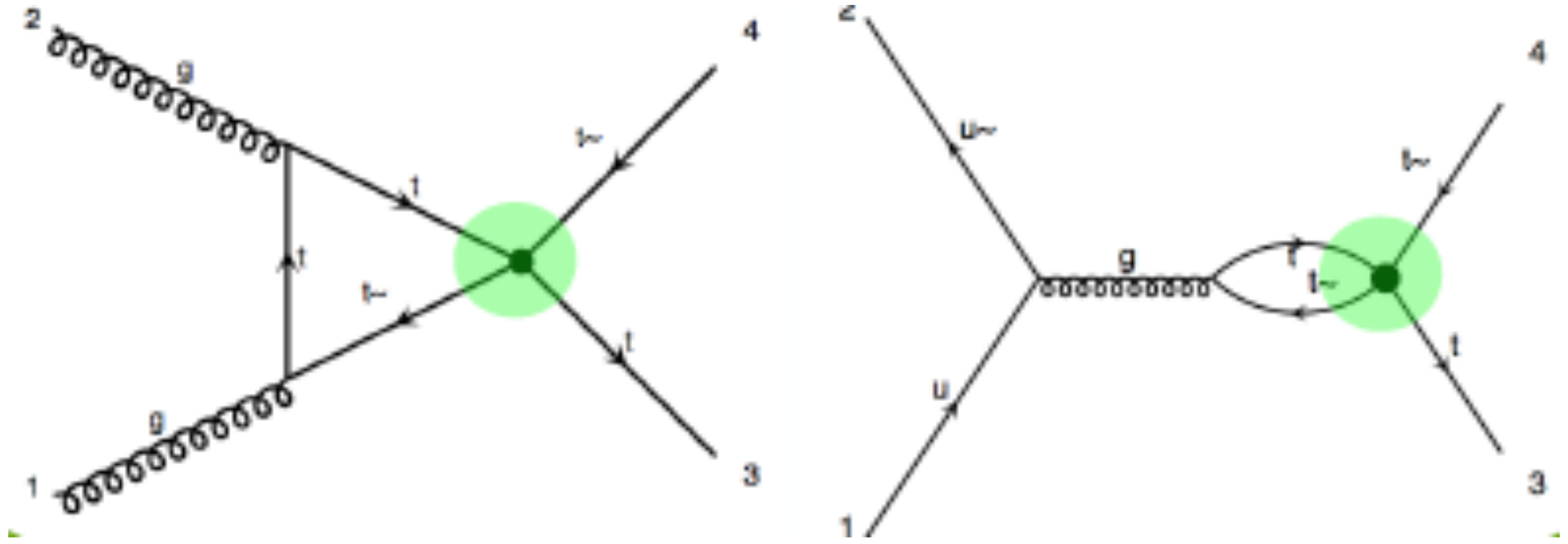
$$\mathcal{O}^8_{Qt} = (\bar{Q}\gamma^\mu T^A Q)(\bar{t}\gamma_\mu T^A t)$$

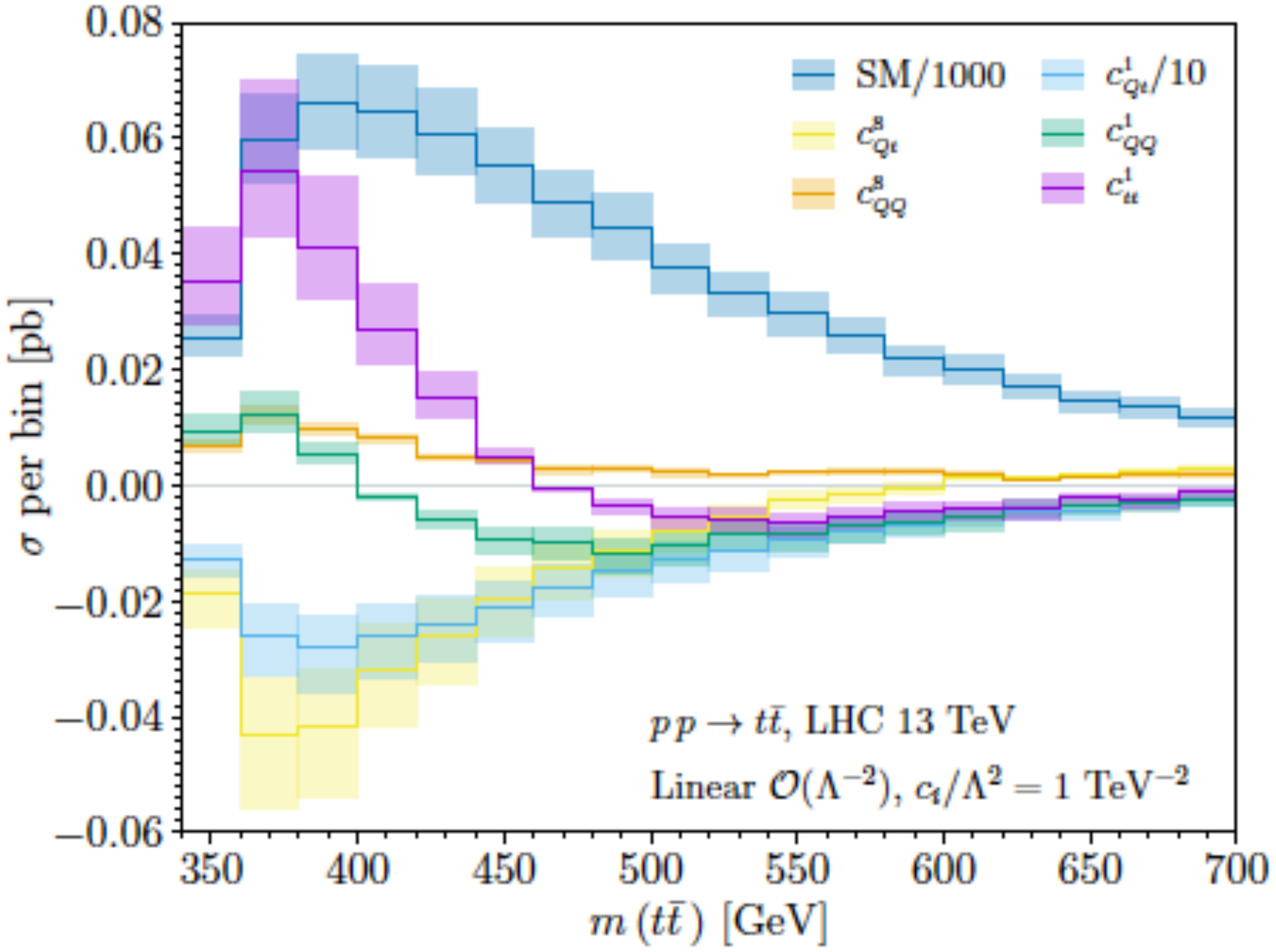
$$\mathcal{O}^1_{Qt} = (\bar{Q}\gamma^\mu Q)(\bar{t}\gamma_\mu t)$$

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



At NLO:



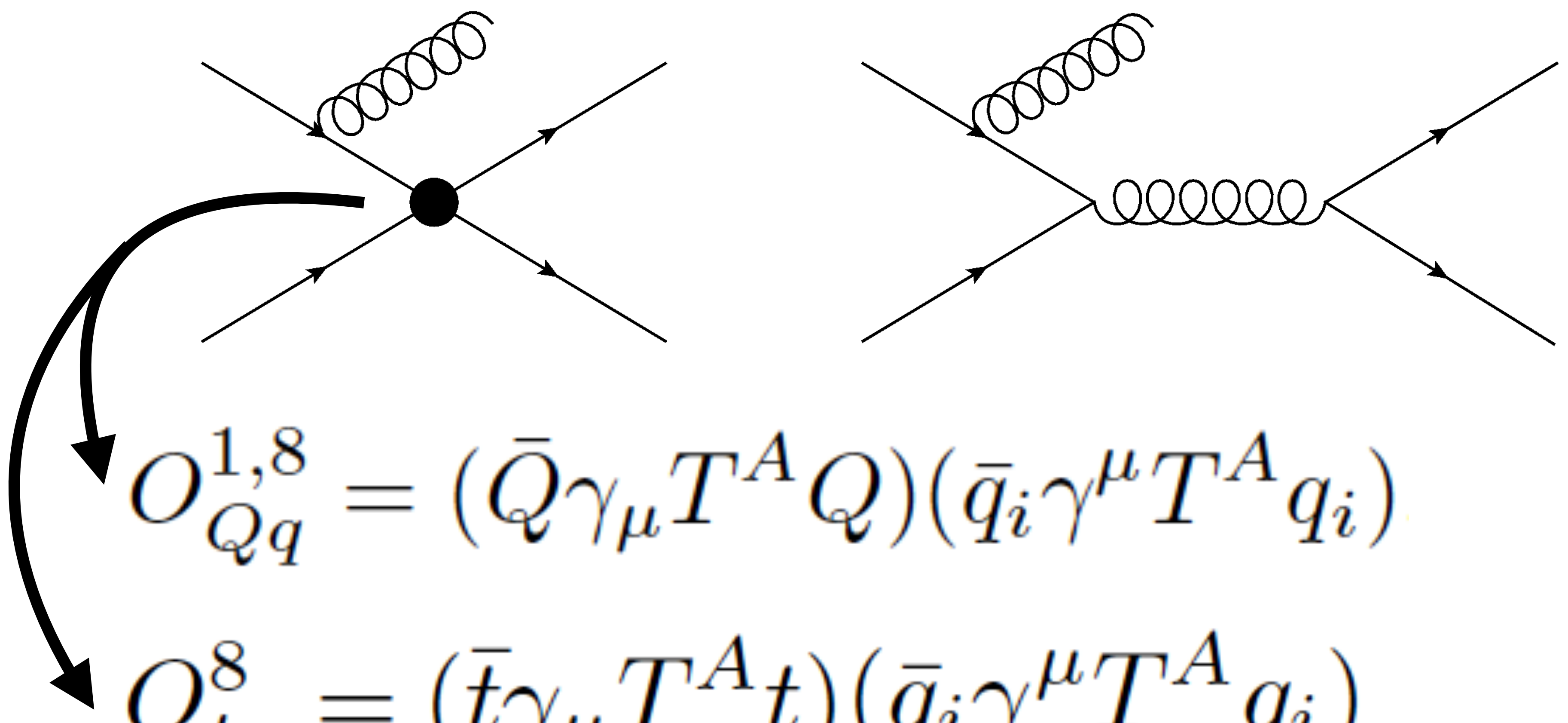


Degrande, Durieux, Maltoni, Mimasu, EV, Zhang arXiv:2008.11743

Complimentary information to ttbb and 4top production

Improved sensitivity

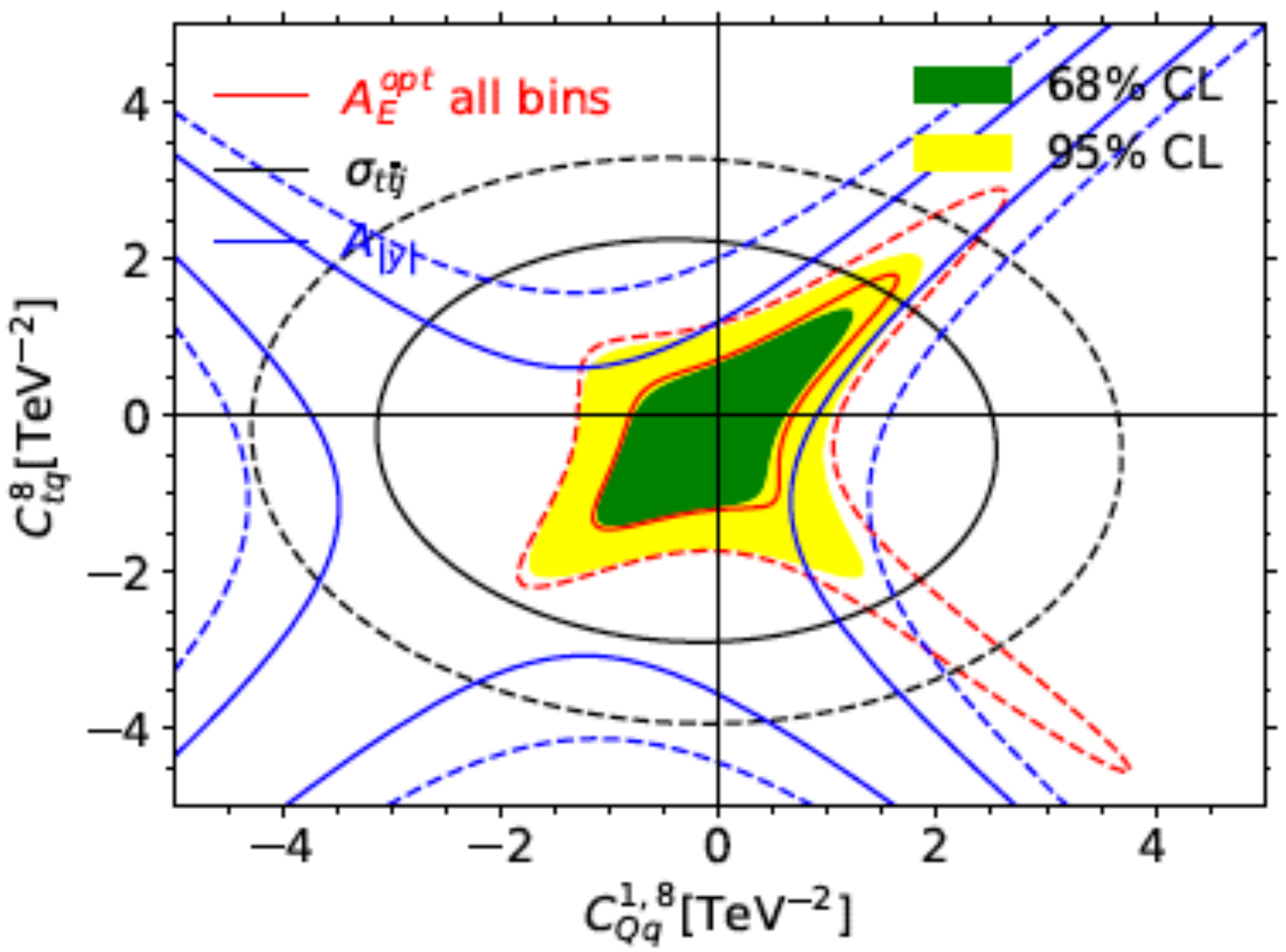
Breaking degeneracies by going beyond LO



$$O_{Qq}^{1,8} = (\bar{Q}\gamma_\mu T^A Q)(\bar{q}_i \gamma^\mu T^A q_i)$$

$$O_{tq}^{8} = (\bar{t}\gamma_\mu T^A t)(\bar{q}_i \gamma^\mu T^A q_i)$$

Different top chiralities

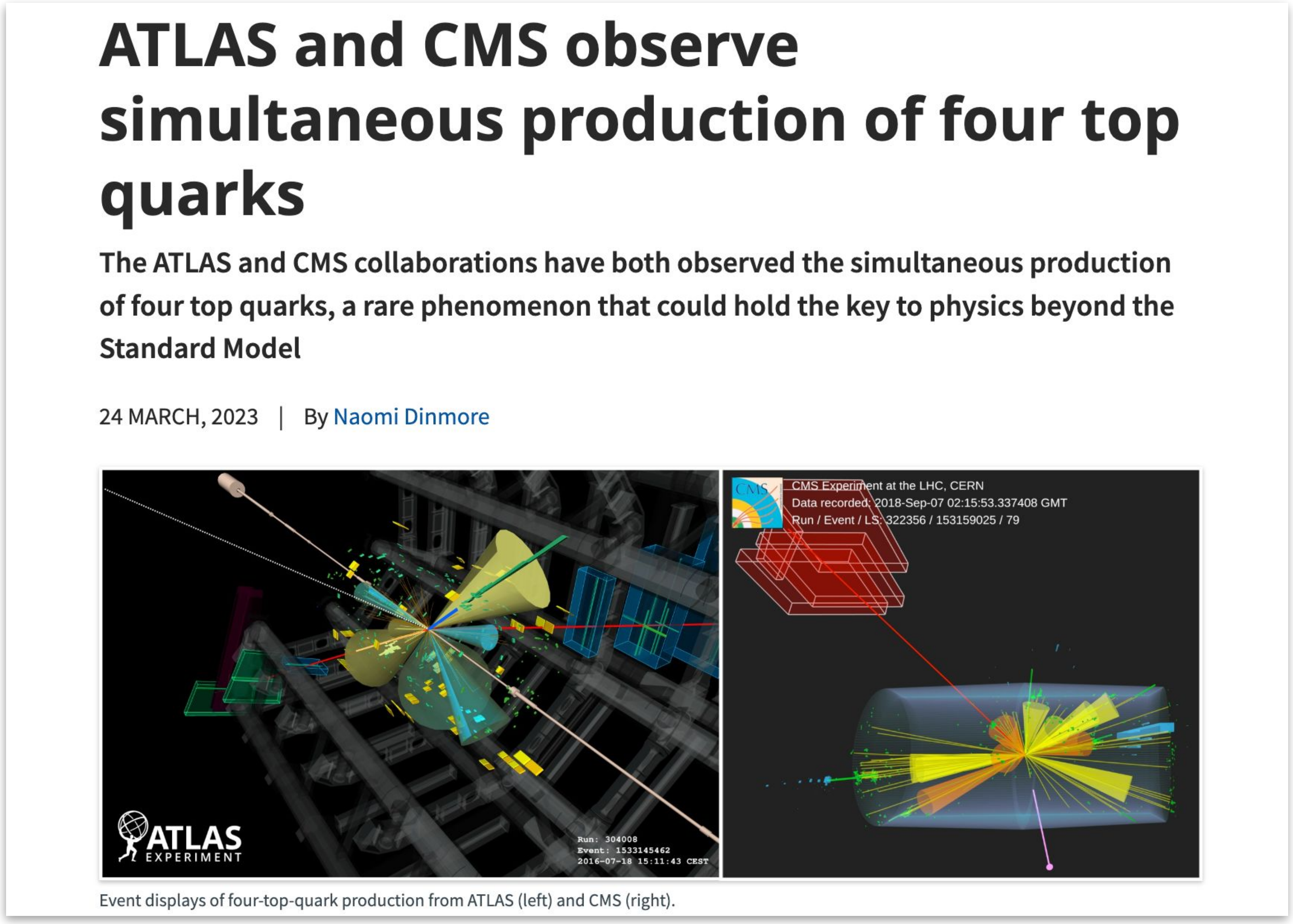


Basan, Berta, Masetti, EV, Westhoff arXiv:2001.07225

An asymmetry observable

$$A_E(\theta_j) = \frac{\sigma_{t\bar{t}j}(\theta_j, \Delta E > 0) - \sigma_{t\bar{t}j}(\theta_j, \Delta E < 0)}{\sigma_{t\bar{t}j}(\theta_j, \Delta E > 0) + \sigma_{t\bar{t}j}(\theta_j, \Delta E < 0)}$$

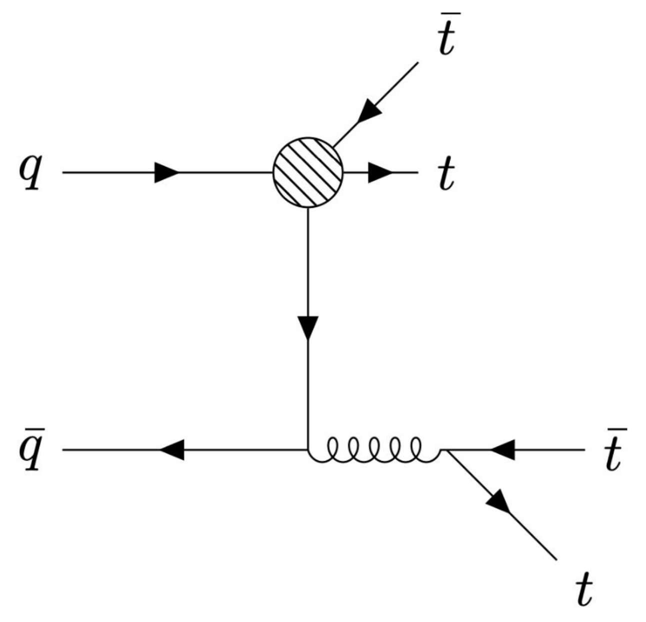
“Subleading” leading contributions

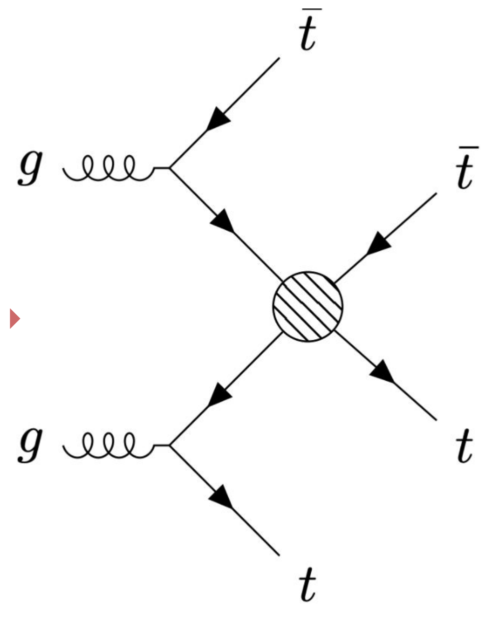

ATLAS and CMS observe simultaneous production of four top quarks

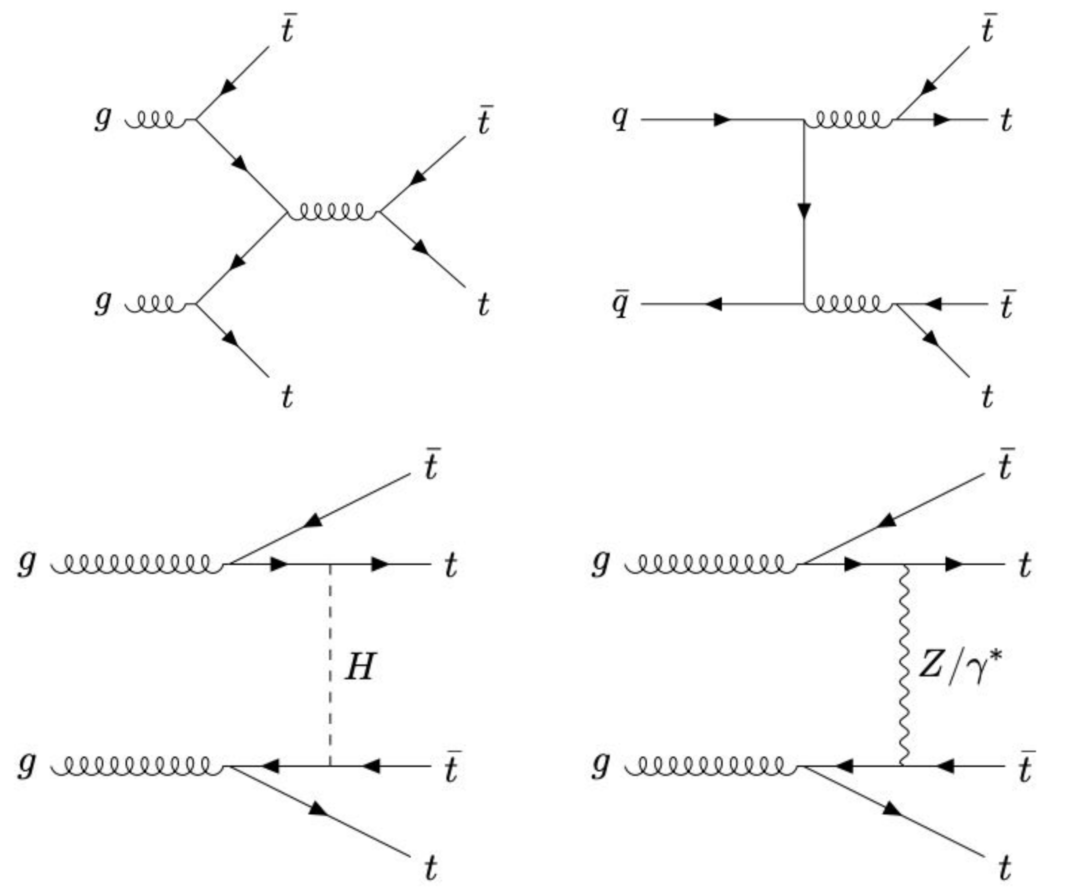
The ATLAS and CMS collaborations have both observed the simultaneous production of four top quarks, a rare phenomenon that could hold the key to physics beyond the Standard Model

24 MARCH, 2023 | By Naomi Dinmore

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

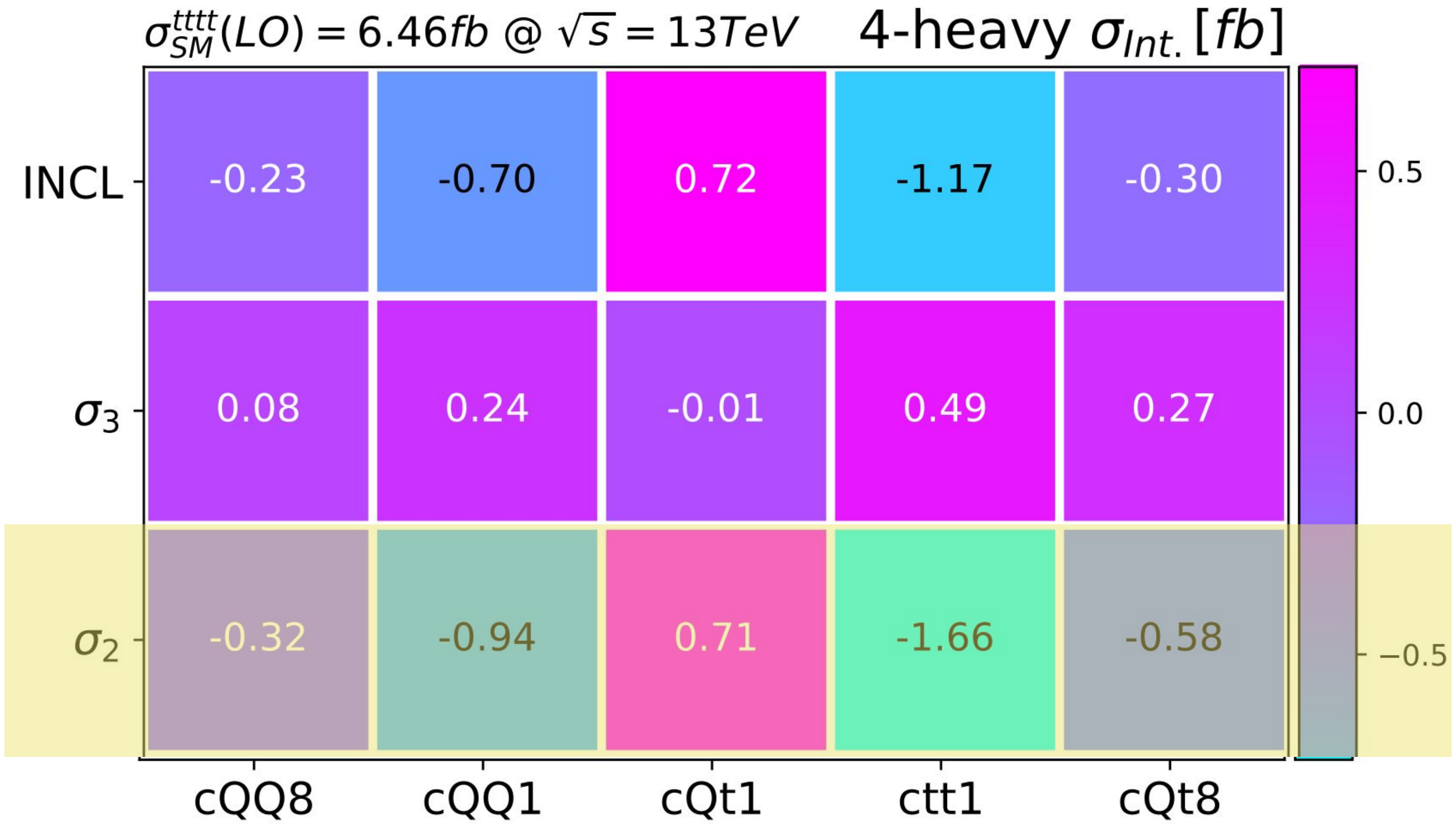






QCD

EW



QCD

EW

Aoude, El Faham, Maltoni, EV arXiv:2208.04962

Formally sub-leading EW effects are large

"Subleading" leading contributions

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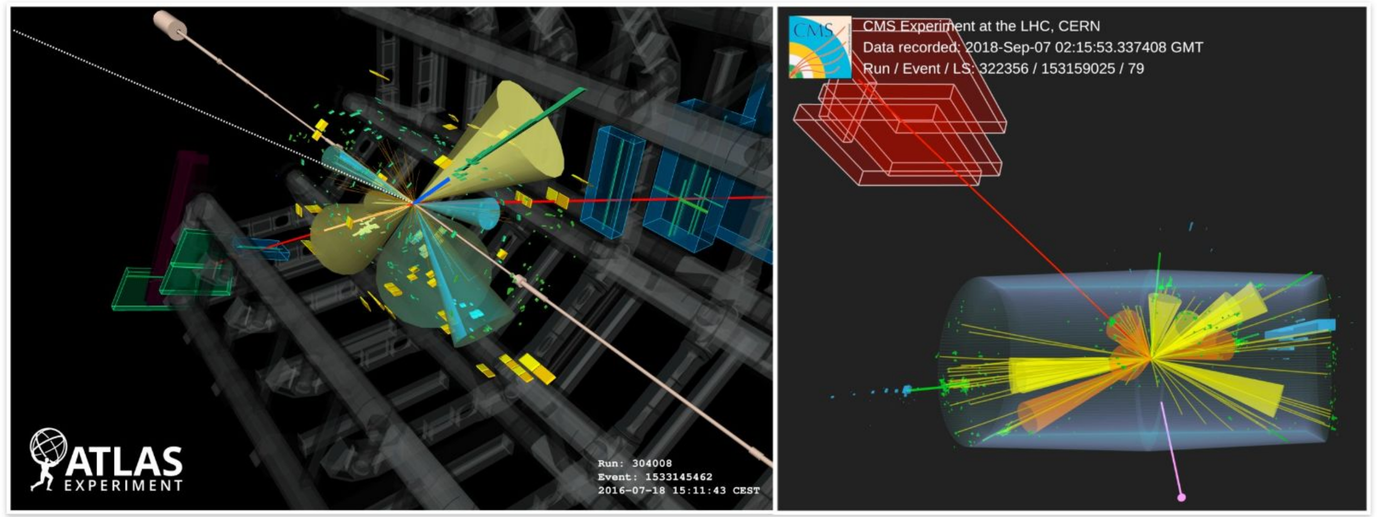

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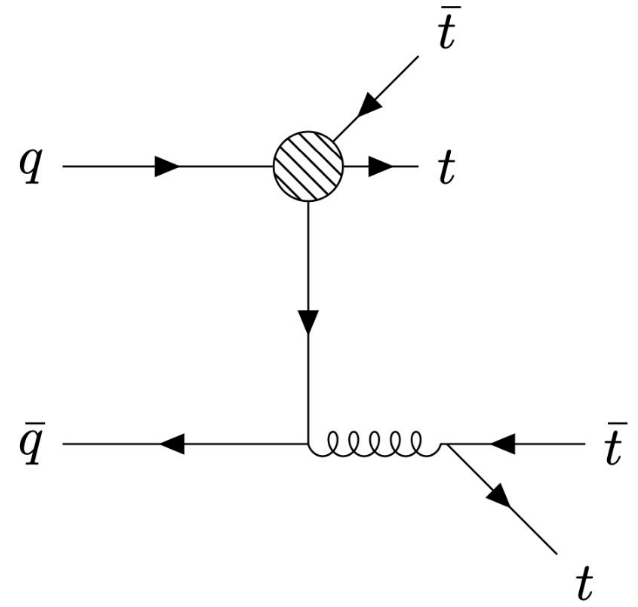
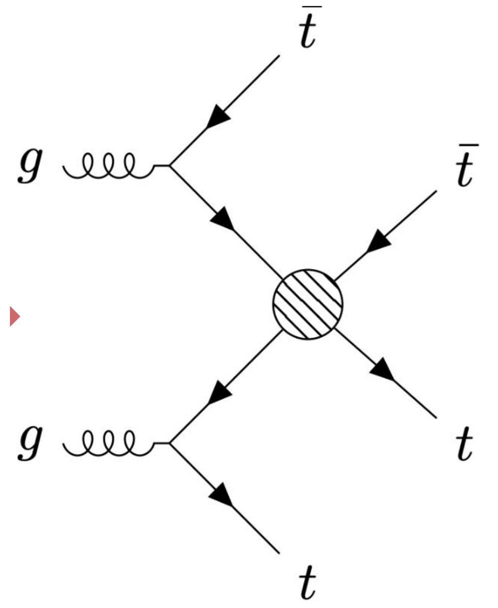
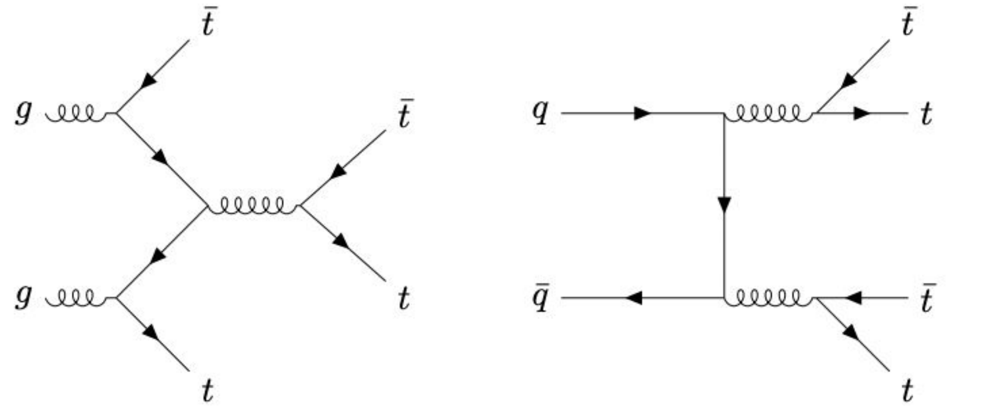
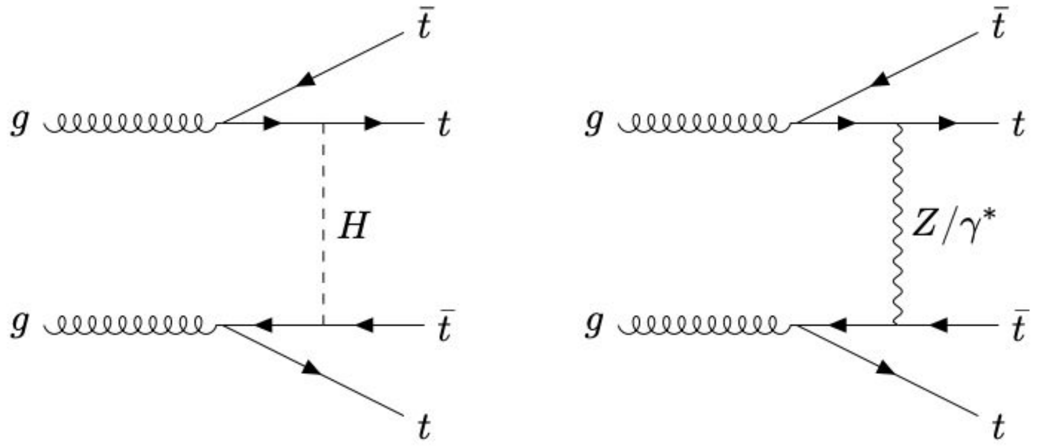


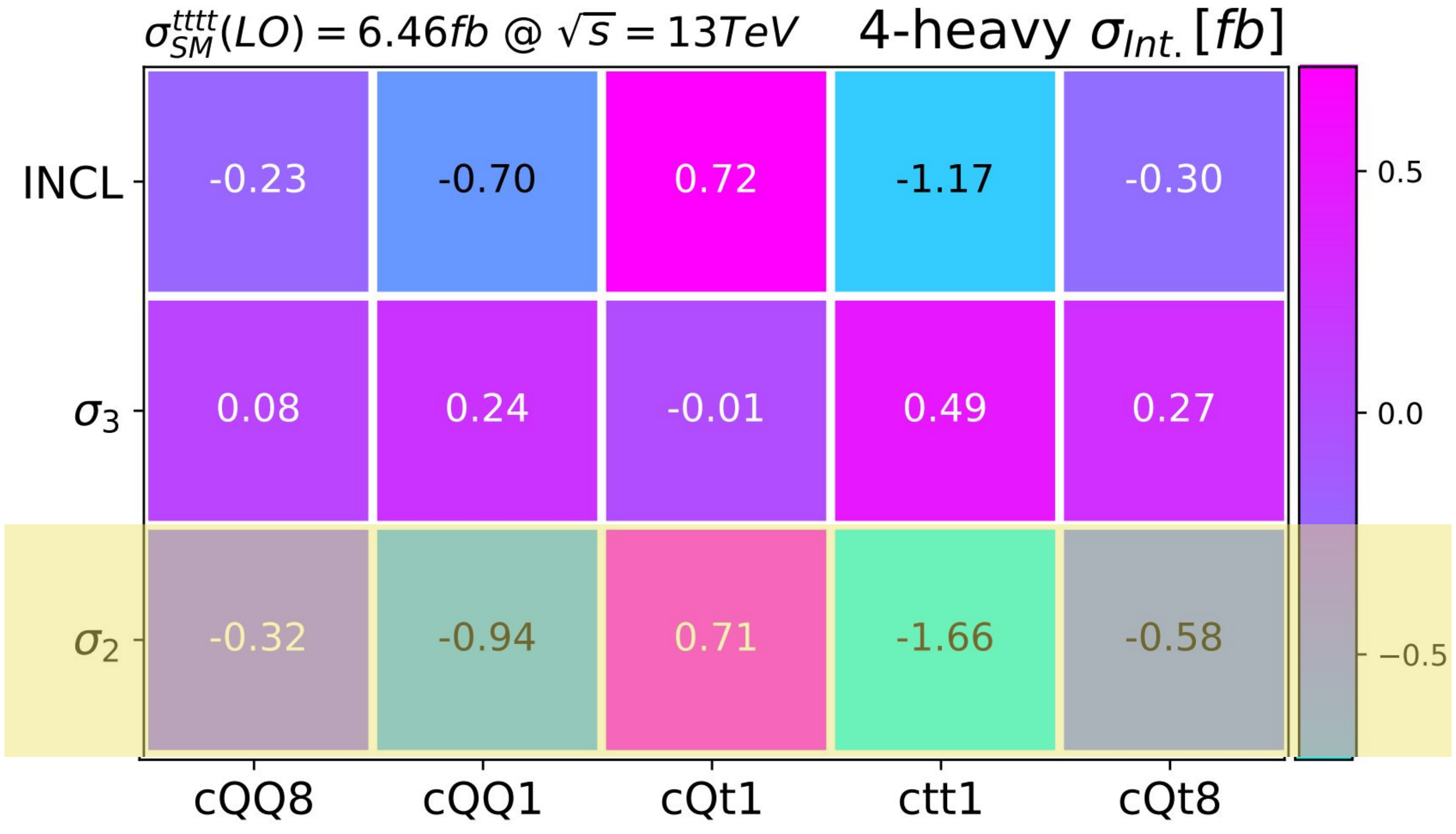




QCD



EW



QCD

EW

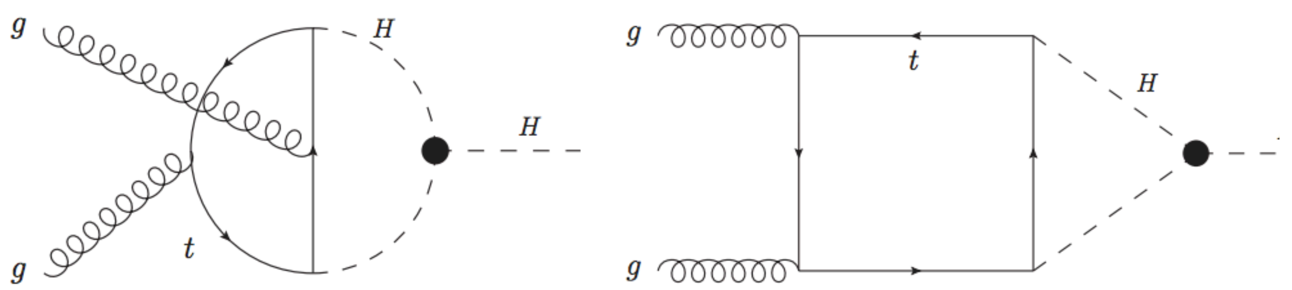
Aoude, El Faham, Maltoni, EV arXiv:2208.04962

Formally sub-leading EW effects are large

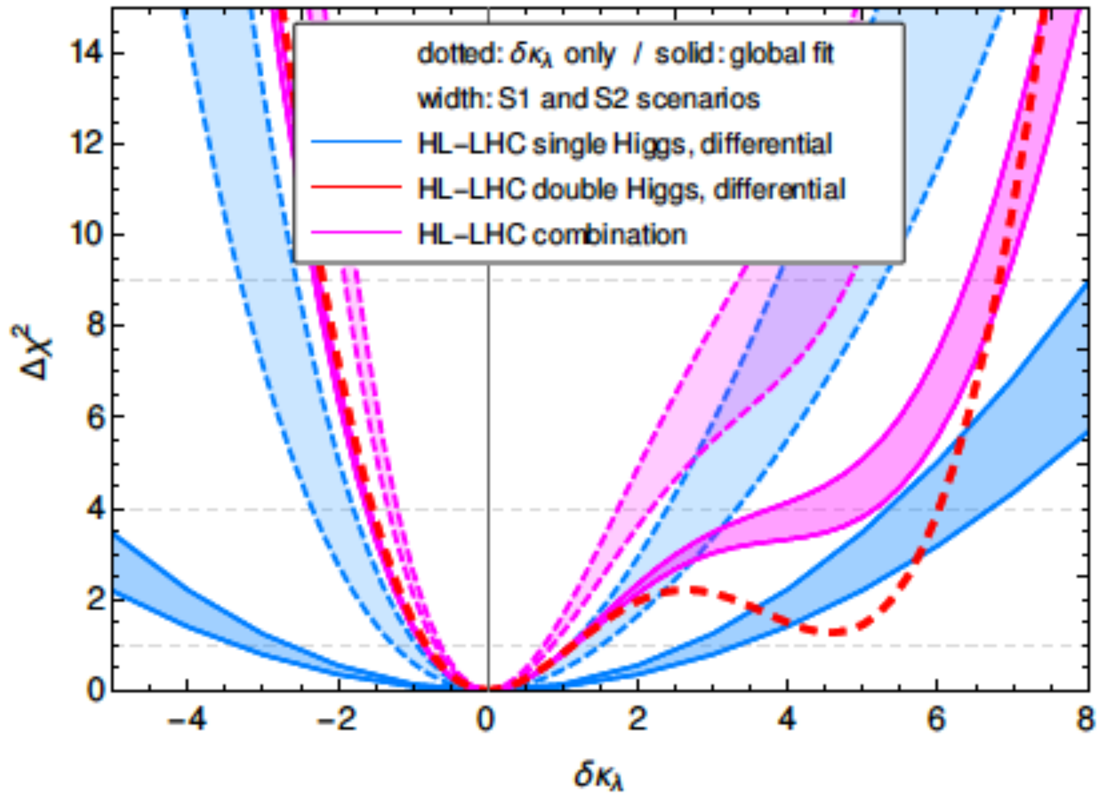
Loop-induced sensitivity

Trilinear H coupling

* Sensitivity through 1-loop EW corrections to single Higgs production.
* A new opportunity to extract information, beyond the typical probe of HH production.

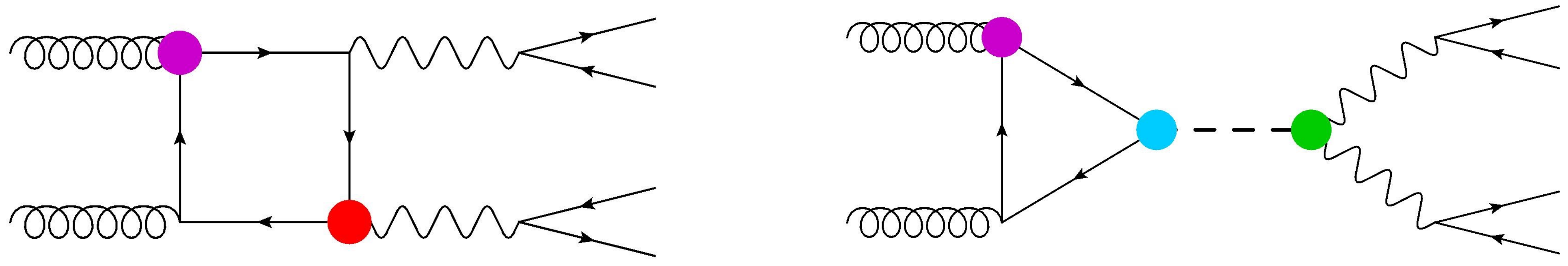


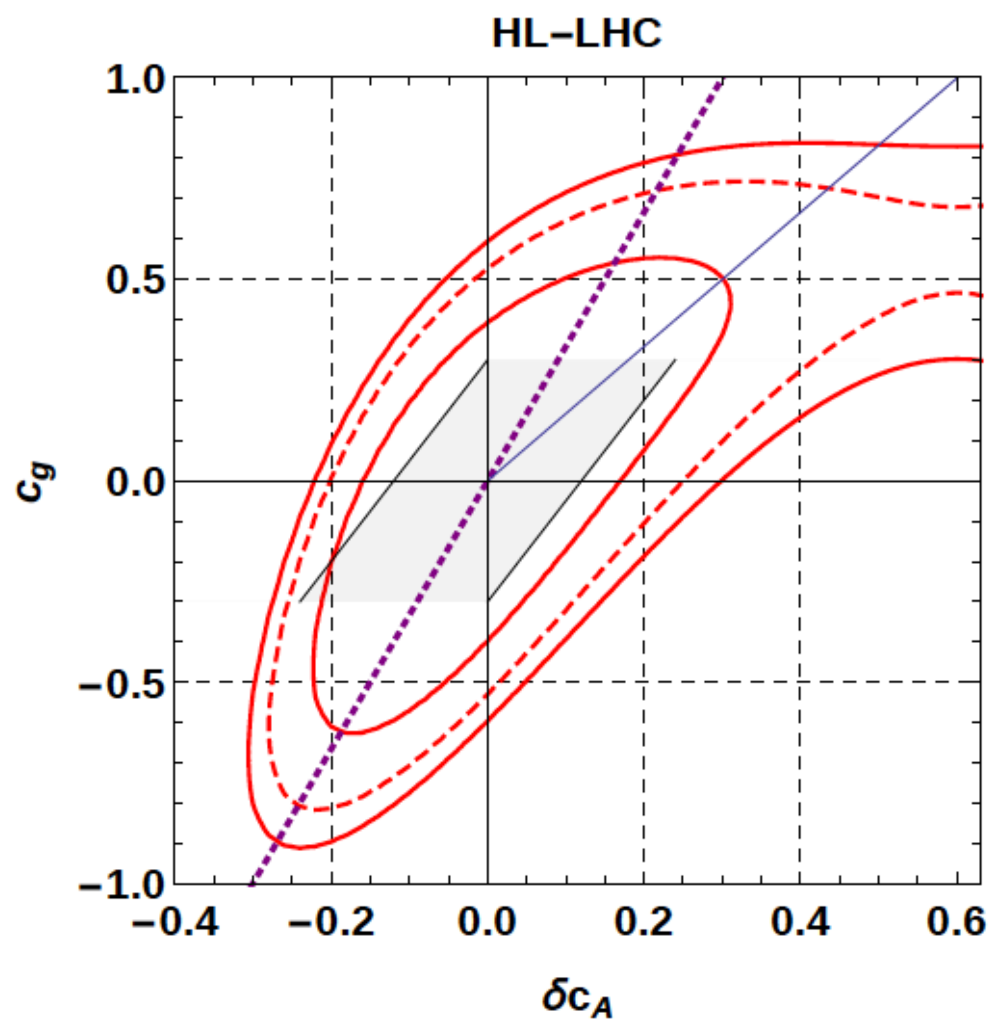
Degrassi et al. arXiv:1607.04251, Gorbahn, Haisch 1607.03773, Bizon et al 1610.05771, Maltoni et al 1709.08649



Di Vita et al. arXiv:1704.01953 and HH white paper

Diboson (off-shell Higgs) sensitivity to top couplings





4-parameter fit:

c_t, c_g, c_V, c_A

Constraint from gg to ZH
Englert et al arXiv:1603.05304

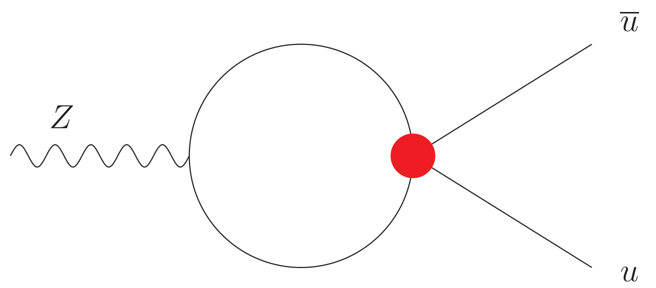
Constraints on ttZ couplings competitive with ttZ process

Azatov, Grojean, Paul, Salvioni arXiv:1608.00977

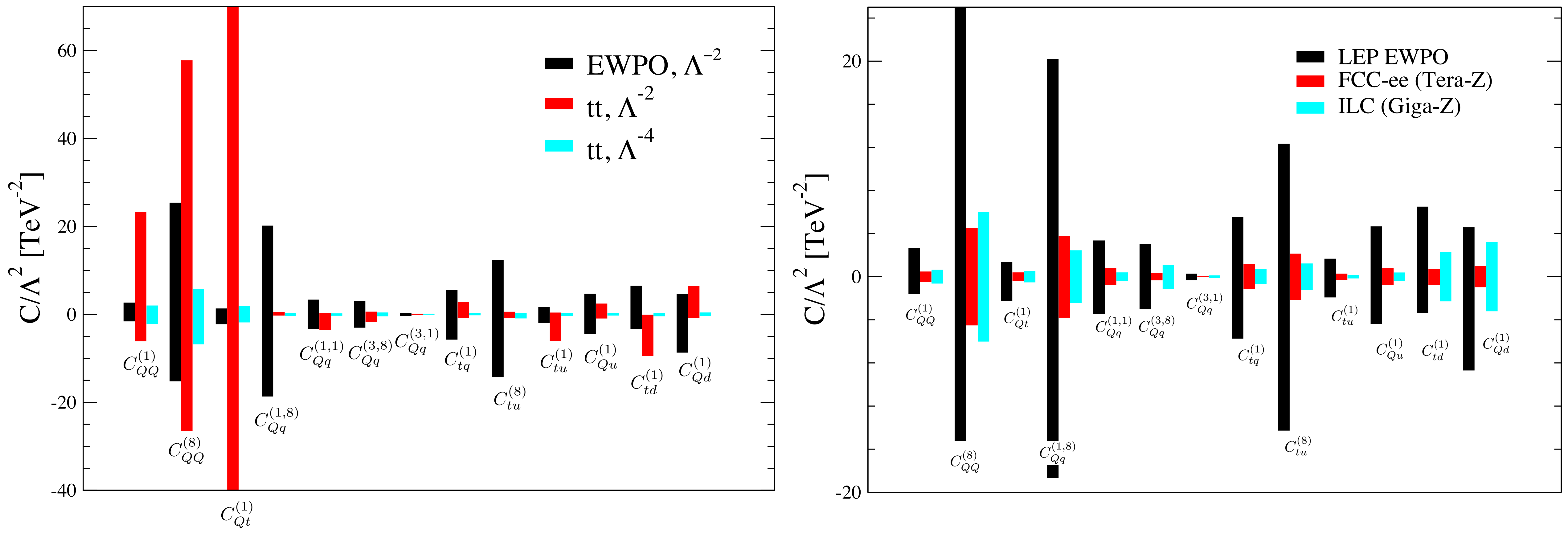
See also: Englert, Soreq, Spannowsky arXiv:1410.5440 and Cao et al 2004.02031

Improved sensitivity due to EW loops

4-heavy operators in EWPO



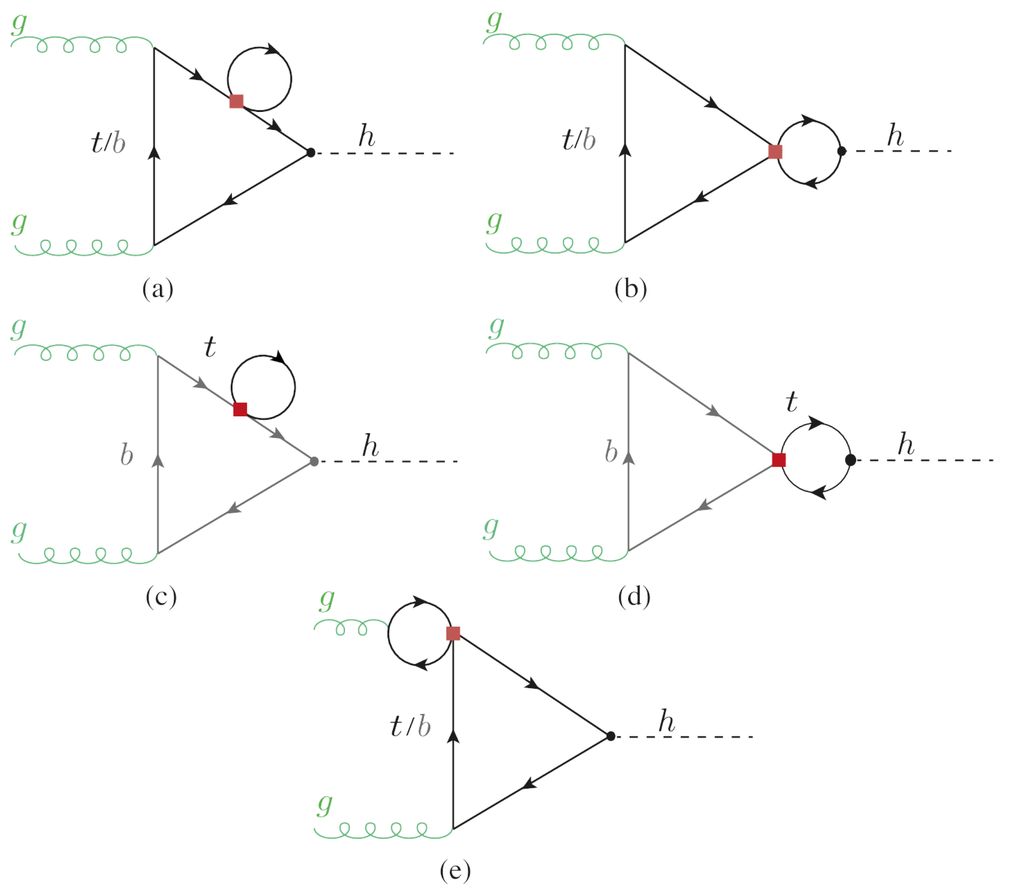
95% CL limits on 3rd generation 4-fermion operators

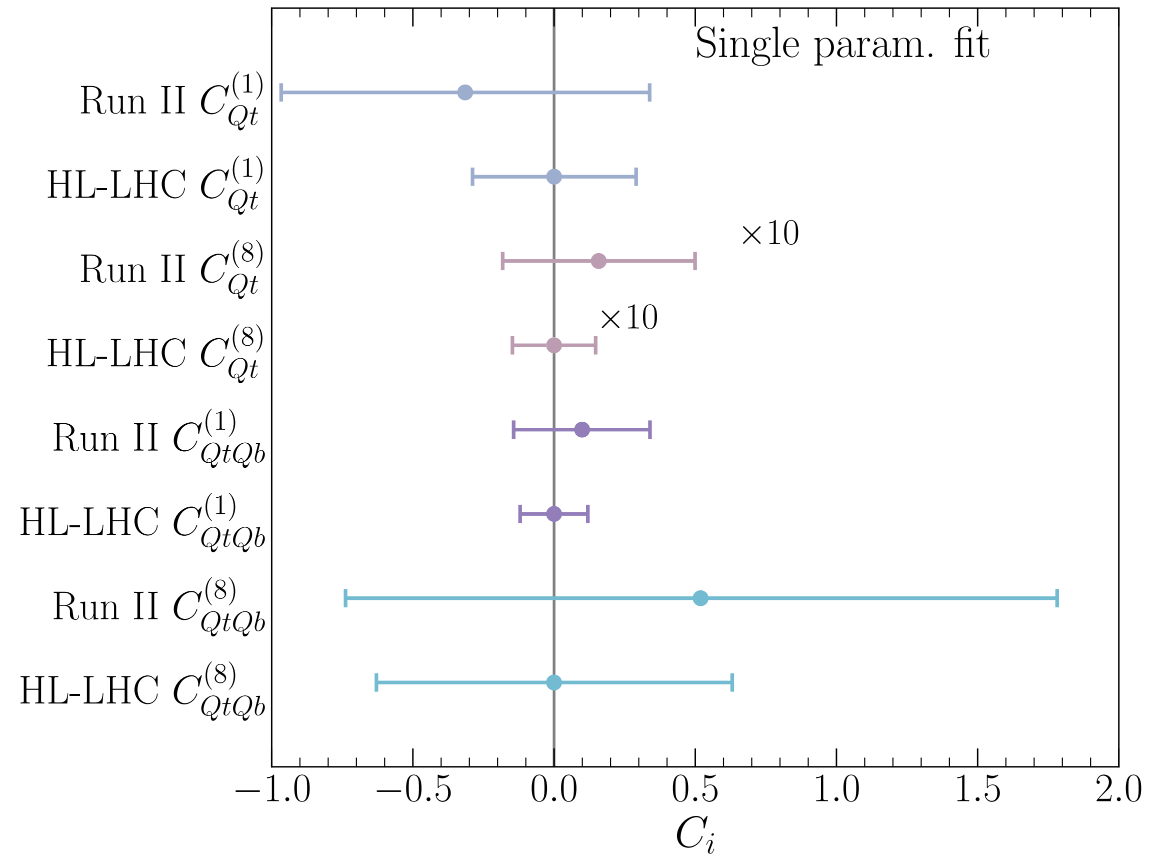


Dawson and Giardino arXiv: 2201.09887

New loop-induced sensitivity
Competitive to 4top production

4-heavy operators in Higgs production



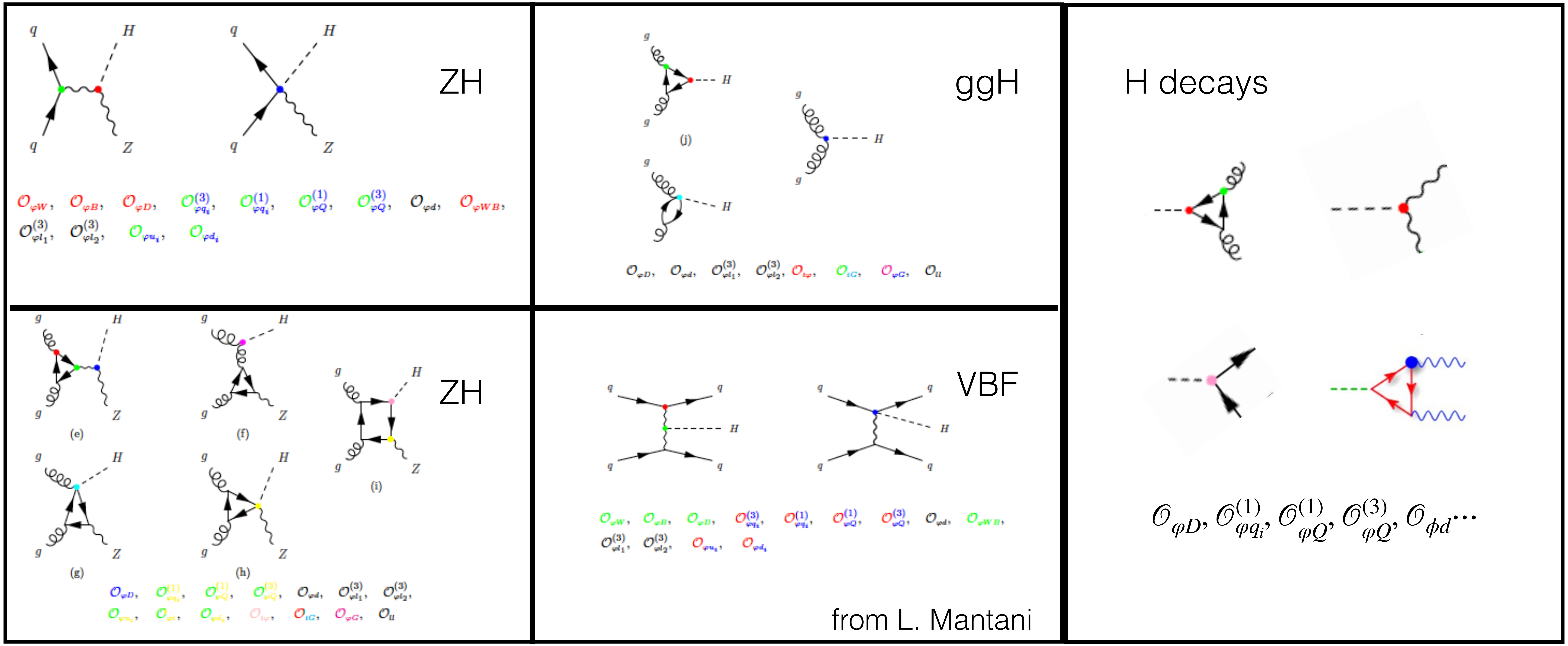


Alasfar, de Blas, Gröber arXiv:2202.02333

Again competitive with top fit bounds!

Loop & tree sensitivity in global fits

Higgs production and decay



Global fit observables

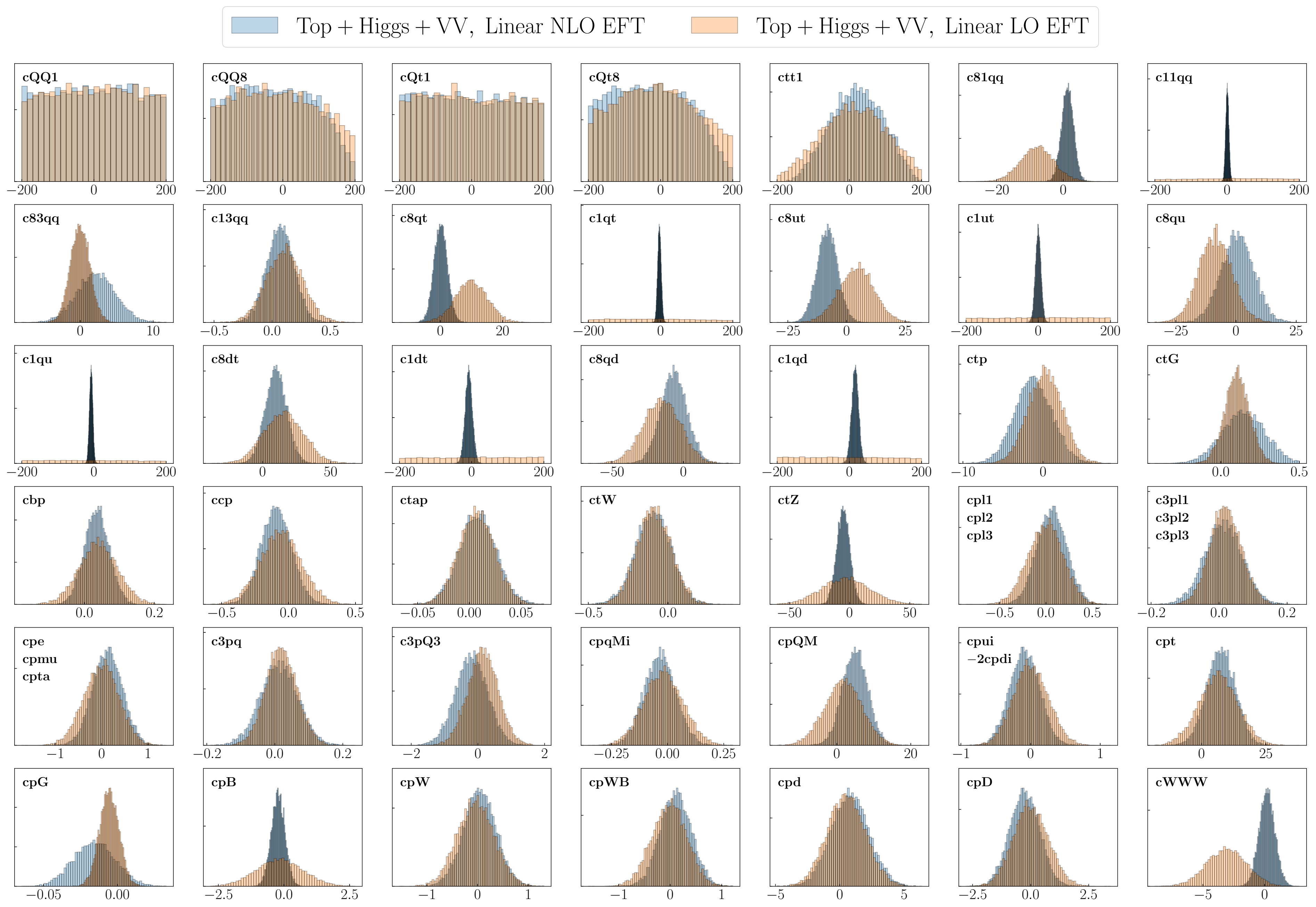
	Category	Processes	n_{dat}
Top	Top quark production	$t\bar{t}$ (inclusive)	94
		$t\bar{t}Z$, $t\bar{t}W$	14
		single top (inclusive)	27
		tZ, tW	9
		$t\bar{t}t\bar{t}$, $t\bar{t}b\bar{b}$	6
		Total	**150**
Higgs	Higgs production and decay	Run I signal strengths	22
		Run II signal strengths	40
		Run II, differential distributions & STXS	35
		Total	**97**
EW	Diboson production	LEP-2	40
		LHC	30
		Total	**70**
	Baseline dataset	**Total**	**317**

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

Does NLO/1-loop change global fits?

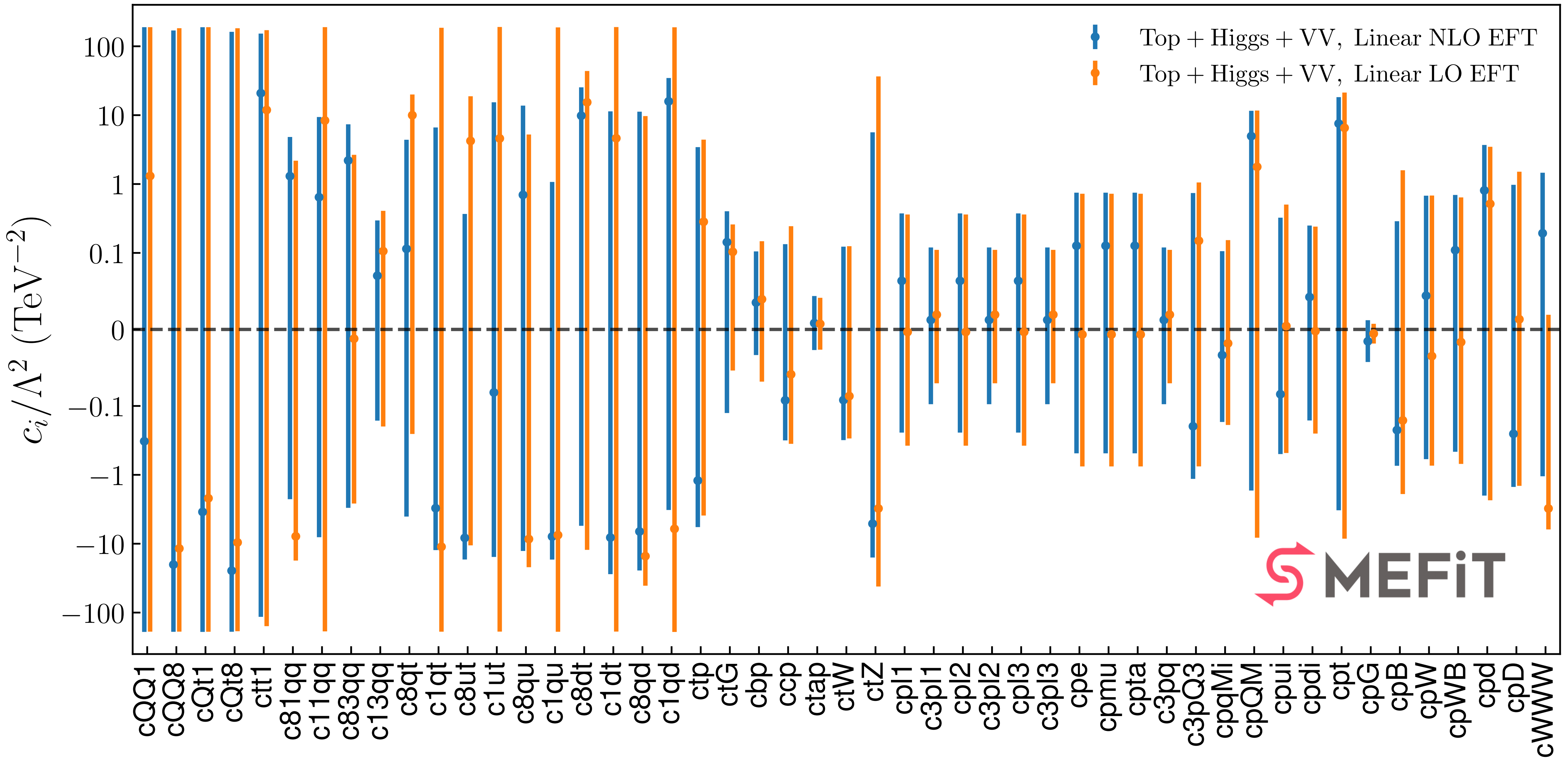
Global top fits

Linear fits:



Posterior distributions for Wilson coefficients

Ethier et al arXiv:2105.00006

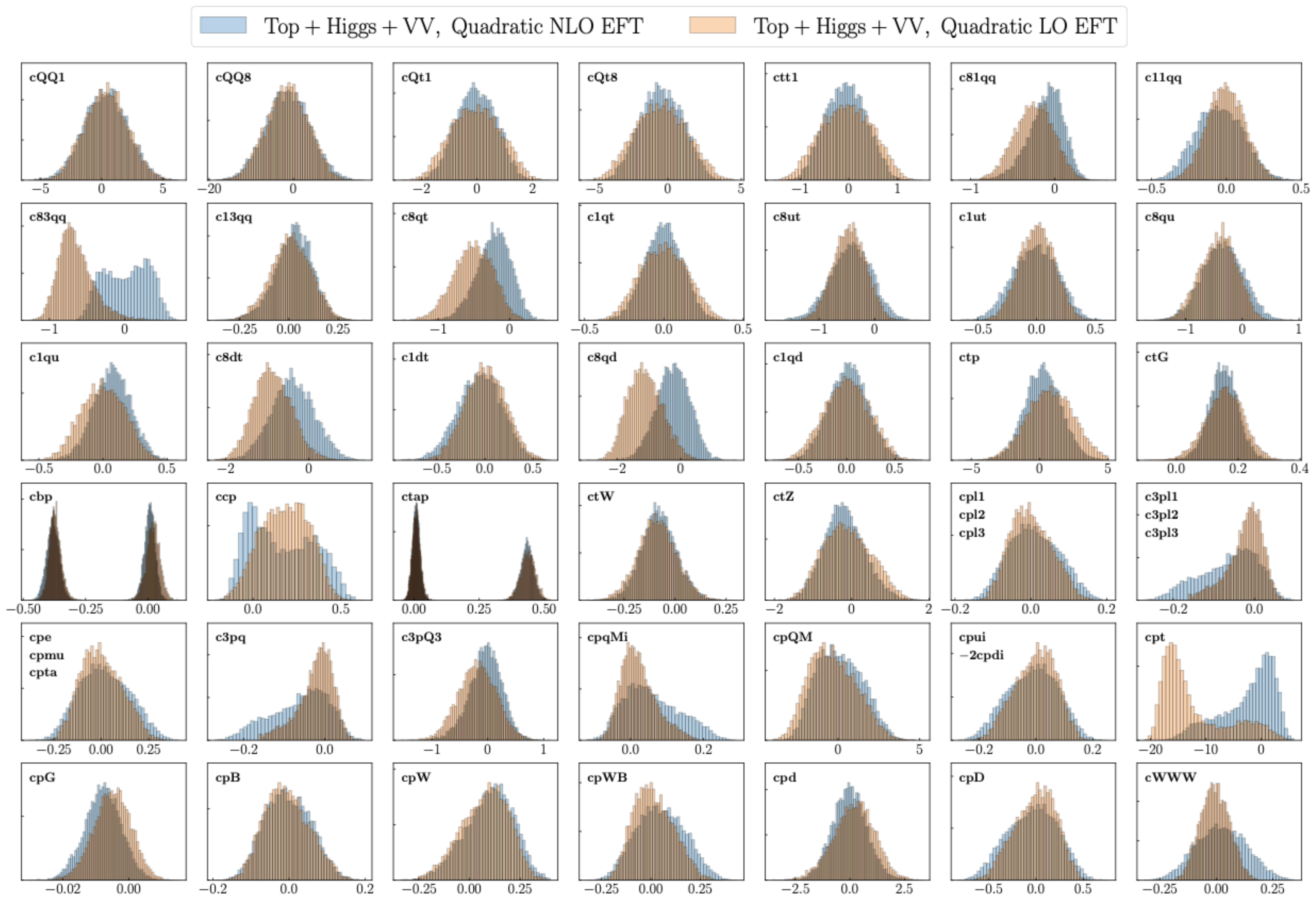


Significant impact of NLO for some operators

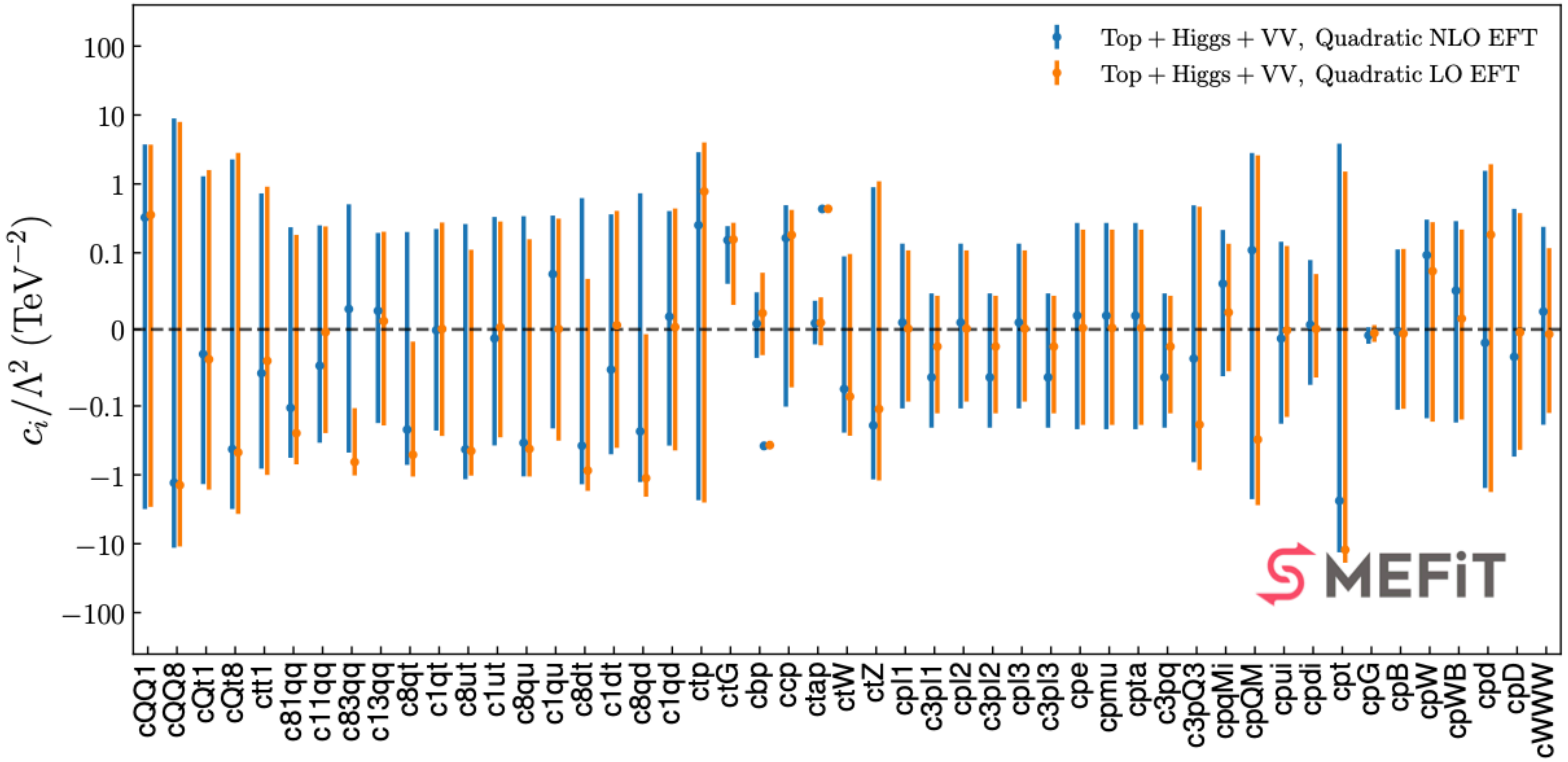
NLO resolves non-interference problem for colour singlet 4-fermion operators

Impact of NLO predictions in global fits

Marginalised constraints

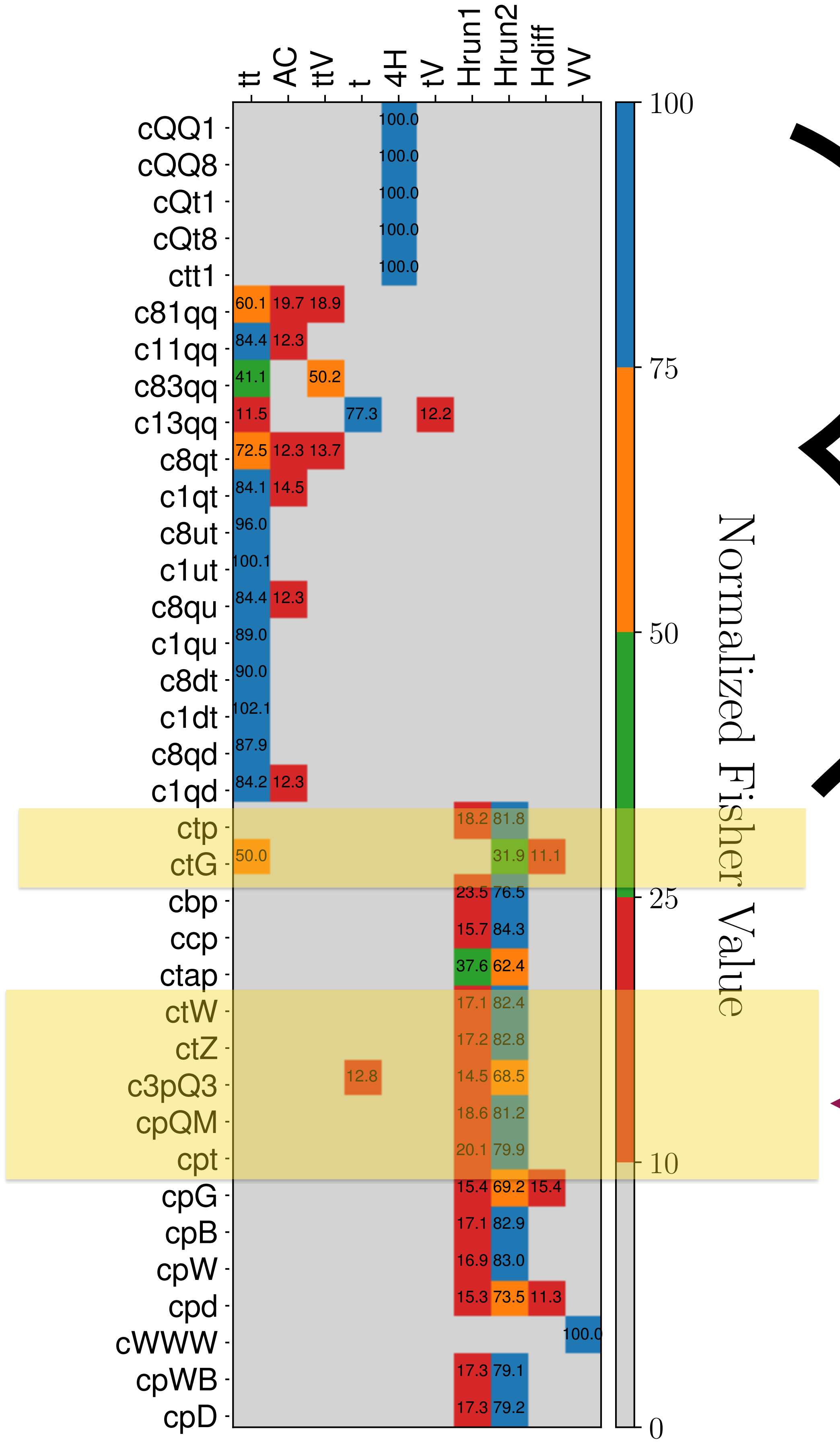


Posterior distributions

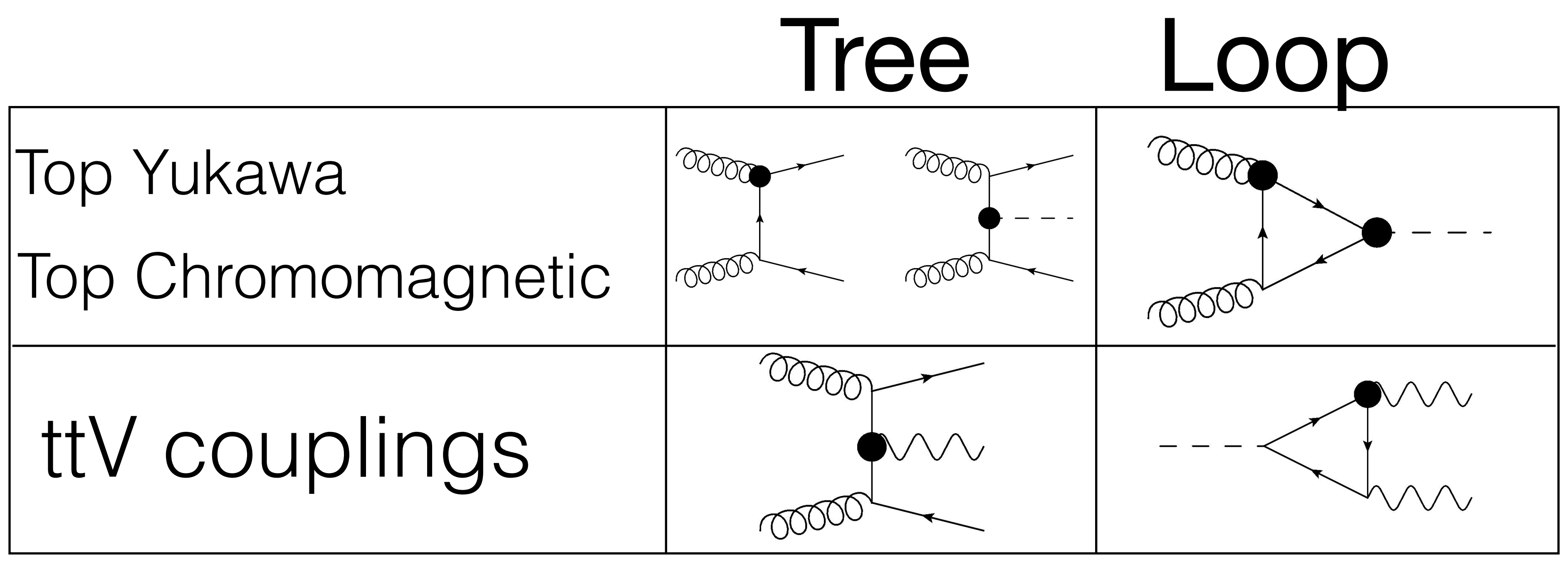


Significant impact of NLO for some operators

Where is most information from?



4-fermion operators: mostly top

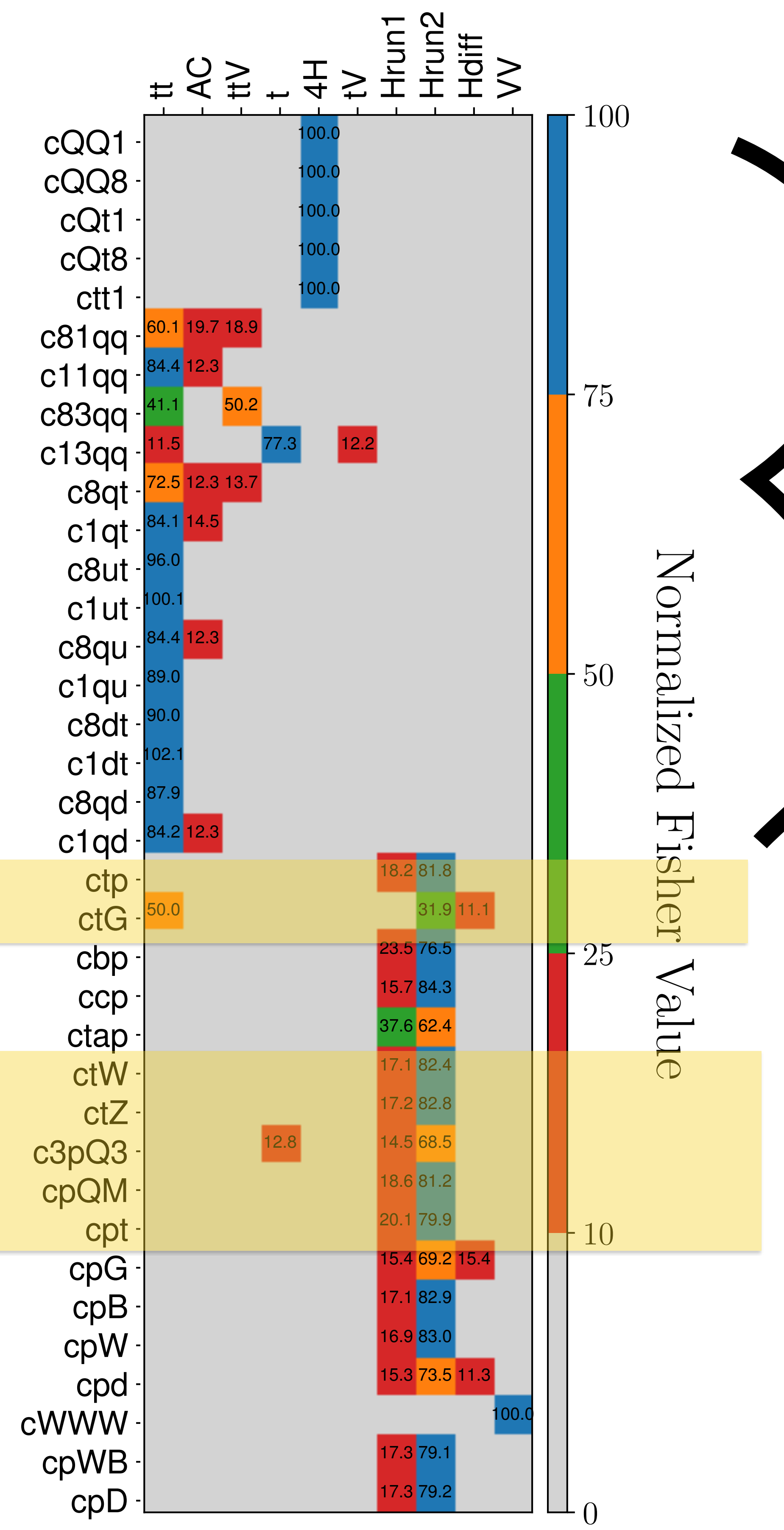


Higgs-Top interface

Fisher information table

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

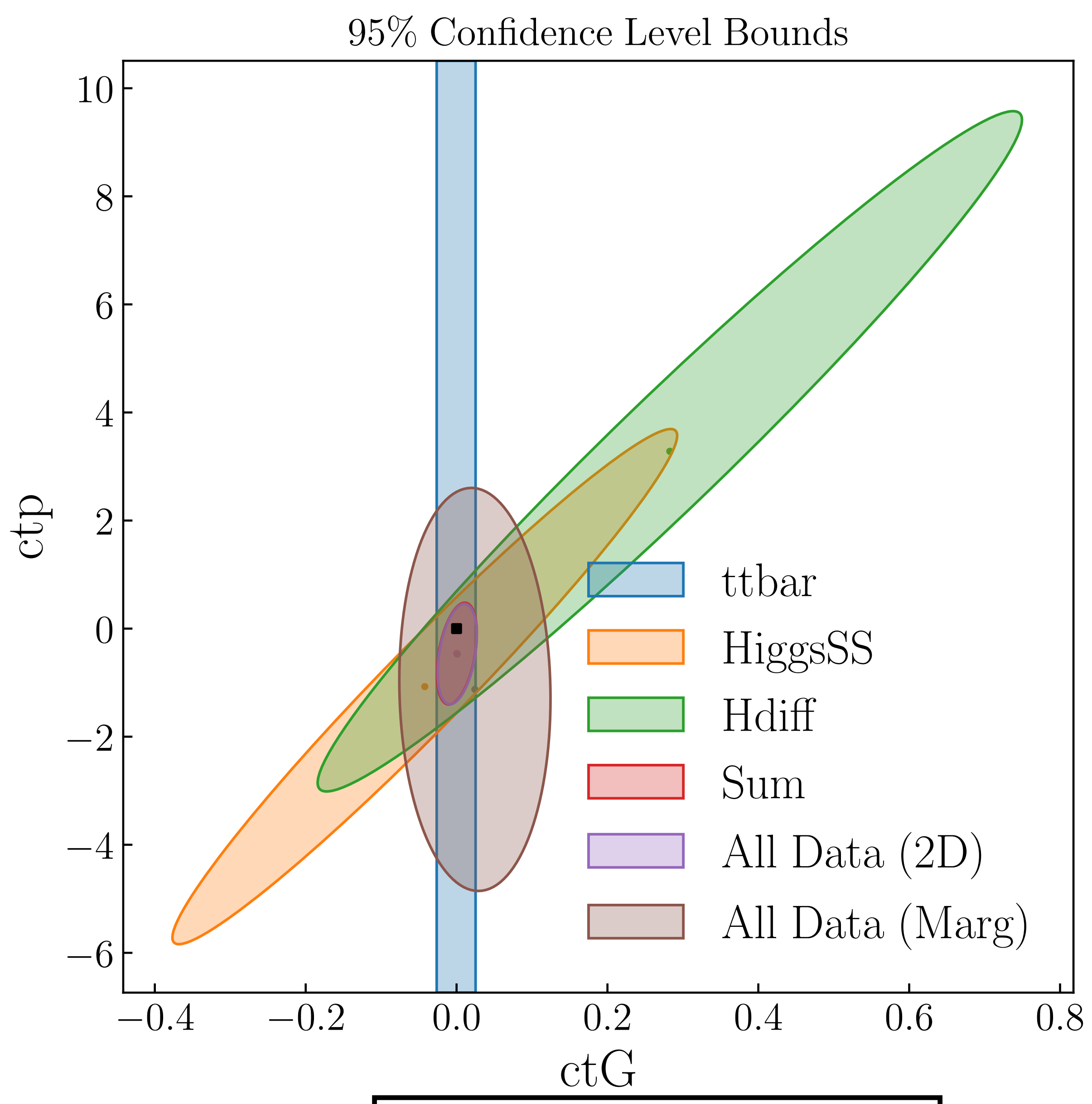
Where is most information from?



Fisher information table

4-fermion operators: mostly top

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

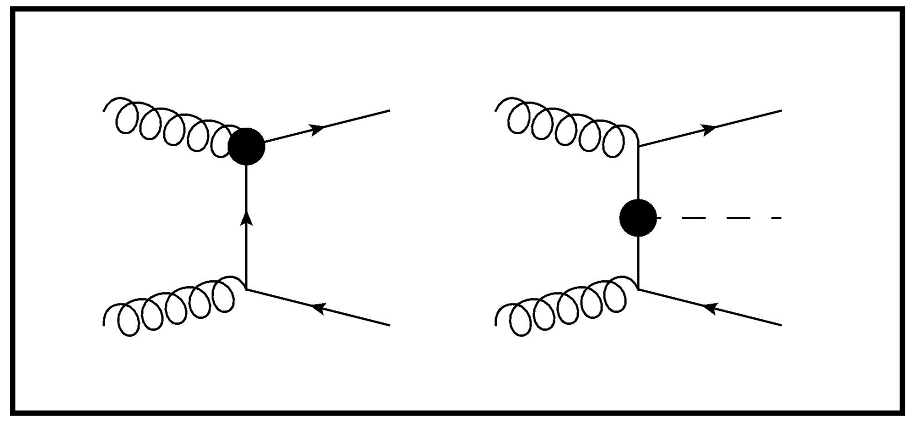


$$\left(\bar{Q}\tau^{\mu\nu}\,T_A\,t\right)\tilde{\varphi}\,G^{A}_{\mu\nu}$$

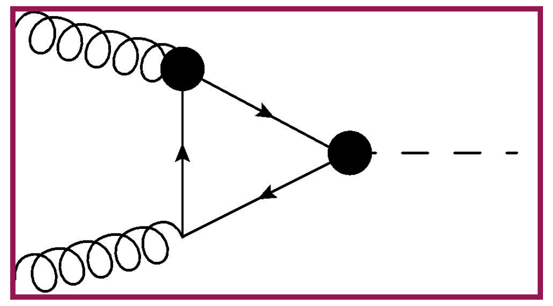
Ethier, Maltoni, Mantani, Nocera, Rojo, Slade, EV and Zhang arXiv:2105.00006

What did we learn from global fits?

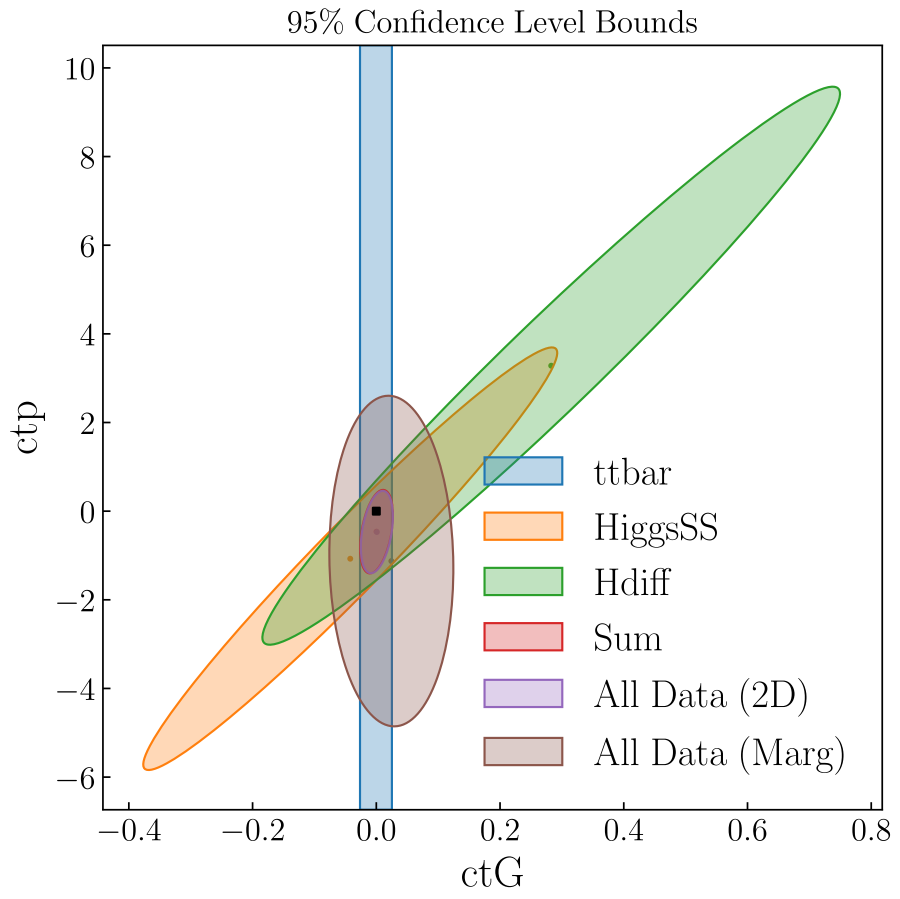
Tree-level



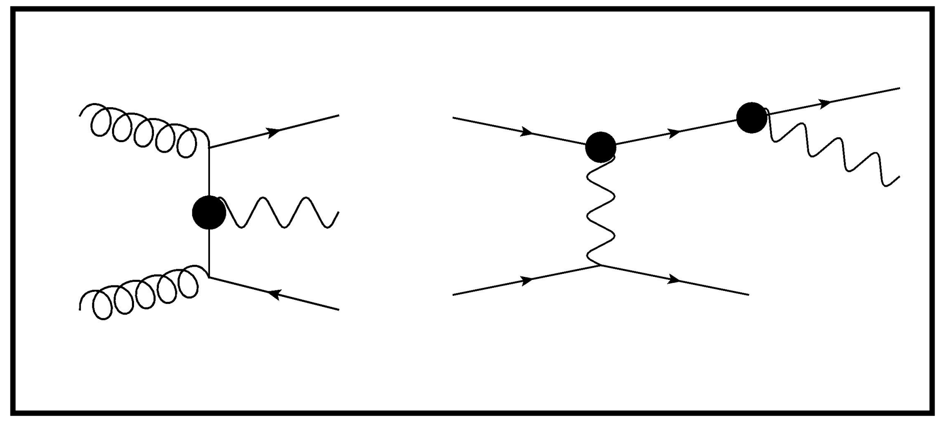
Loop-level

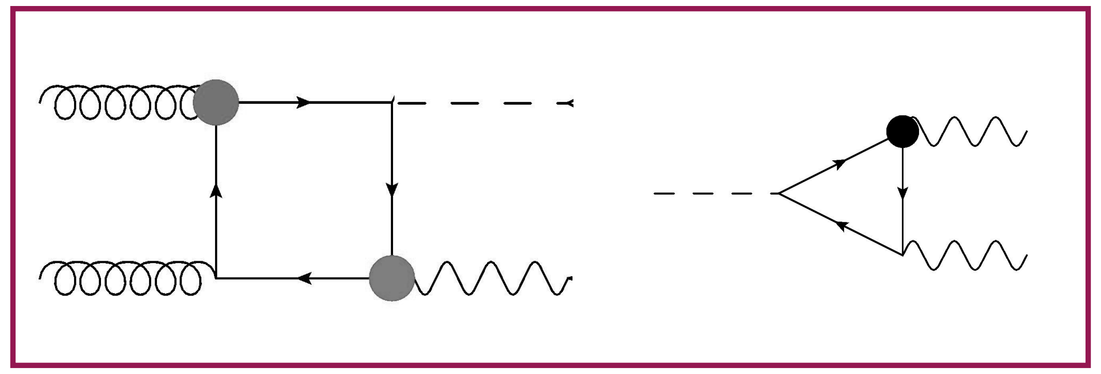


$(\varphi^\dagger\varphi)\,\bar{Q}\,t\,\tilde{\varphi}$

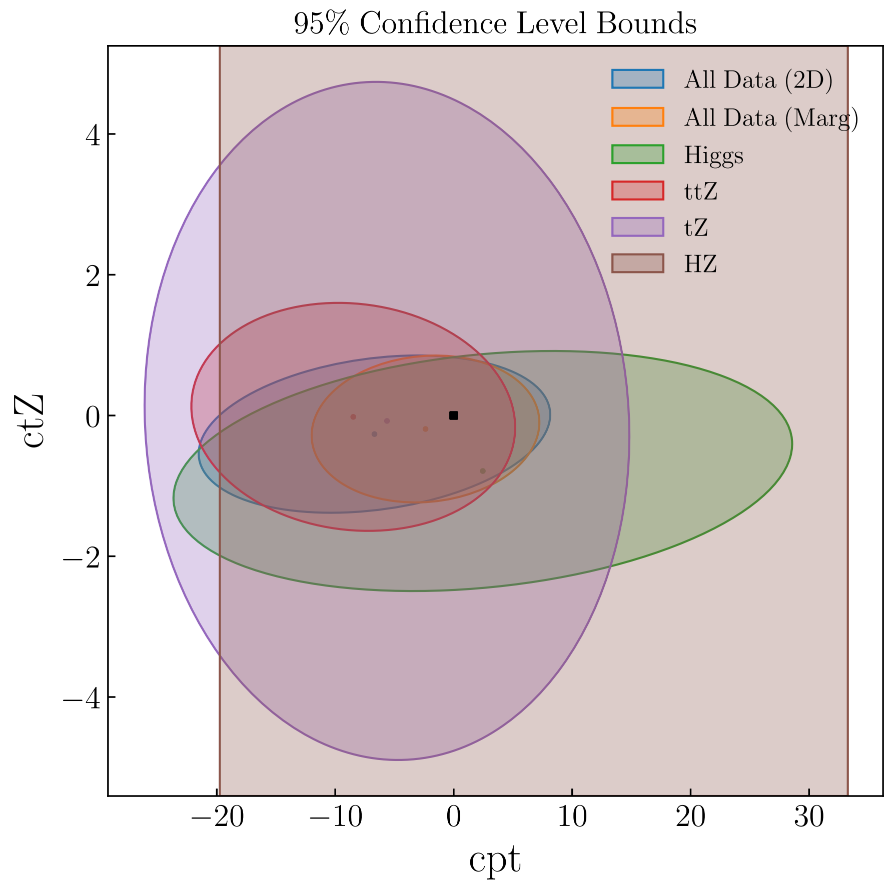


$(\bar{Q}\tau^{\mu\nu}\,T_A\,t)\,\tilde{\varphi}\,G^A_{\mu\nu}$





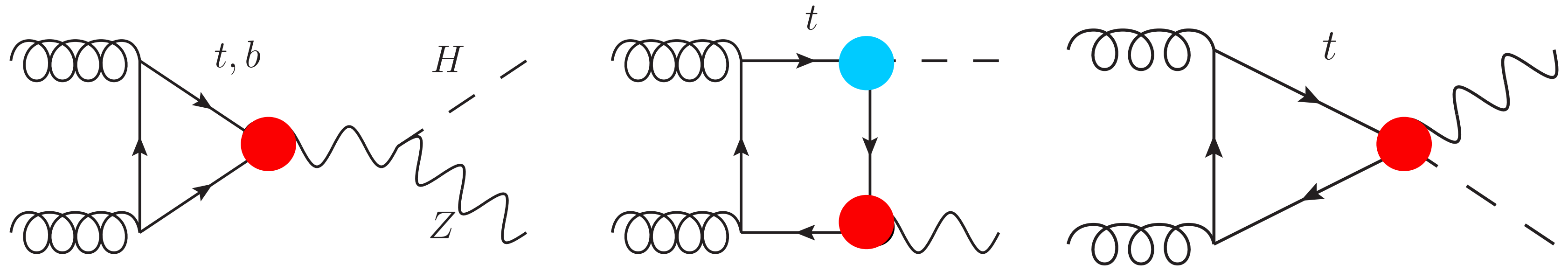
$i(\bar{Q}\tau^{\mu\nu}\,\tau_I\,t)\,\tilde{\varphi}\,W^I_{\mu\nu}$



$i(\varphi^\dagger \overleftrightarrow{D}_\mu\,\varphi)(\bar{t}\,\gamma^\mu\,t)$

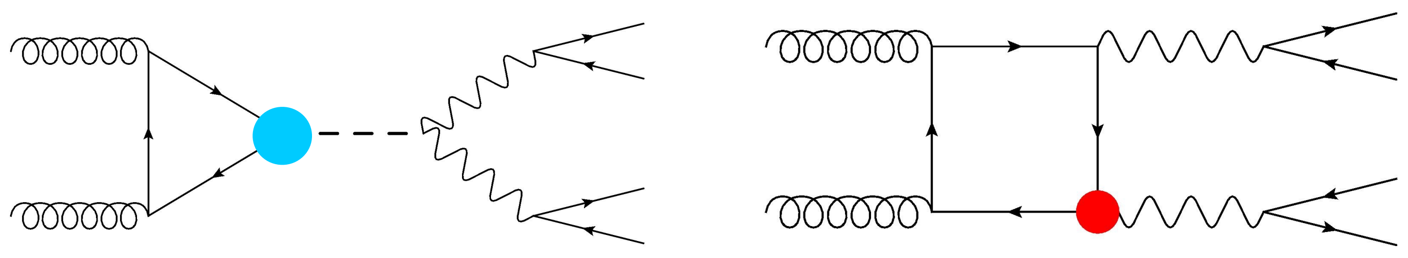
arXiv:2105.00006

Why are loop processes so important?



ZH production

	$\mathcal{O}_{\varphi t}$	$\mathcal{O}_{\varphi Q}^{(-)}$	$\mathcal{O}_{t\varphi}$
$\mathcal{M}_{++00} \sim$	$\frac{m_t^2\, v\, e\, g_s^2}{32\pi^2\, m_Z\, c_W\, s_W}\left[\log\left(\frac{s}{m_t^2}\right) - i\pi\right]^2$	$\frac{m_t^2\, v\, e\, g_s^2}{32\pi^2\, m_Z\, c_W\, s_W}\left[\log\left(\frac{s}{m_t^2}\right) - i\pi\right]^2$	$\frac{m_t\, v^2\, e\, g_s^2}{32\sqrt{2}\pi^2\, m_Z\, c_W\, s_W}\left[\log\left(\frac{s}{m_t^2}\right) - i\pi\right]^2$



ZZ production

	$\mathcal{O}_{t\varphi}$	$\mathcal{O}_{\varphi t}$	$\mathcal{O}_{\varphi Q}^{(-)}$
$\mathcal{M}_{++00} \sim$	$\frac{m_t\, v^3\, e^2\, g_s^2}{128\pi^2\, m_Z^2\, c_W^2\, s_W^2}\left[\log\left(\frac{s}{m_t^2}\right) - i\pi\right]^2$	$\frac{m_t^2\, v^2\, e^2\, g_s^2}{32\sqrt{2}\pi^2\, m_Z^2\, c_W^2\, s_W^2}\left[\log\left(\frac{s}{m_t^2}\right) - i\pi\right]^2$	$\frac{m_t^2\, v^2\, e^2\, g_s^2}{32\sqrt{2}\,\pi^2\, m_Z^2\, c_W^2\, s_W^2}\left[\log\left(\frac{s}{m_t^2}\right) - i\pi\right]^2$

Logarithmic energy growth in one-loop helicity amplitudes

POTENTIAL IMPACT@HL-LHC

Rossia, Thomas, EV arXiv:2306.09963

Future of global fits

More observables:
- particle level observables
- spin correlations
- new final states

More/less/different operators:
- different flavour assumptions
- UV inspired scenarios
- dimension-8 operators

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, needed to probe unconstrained operators.

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How about this μ?

Running and mixing in SMEFT

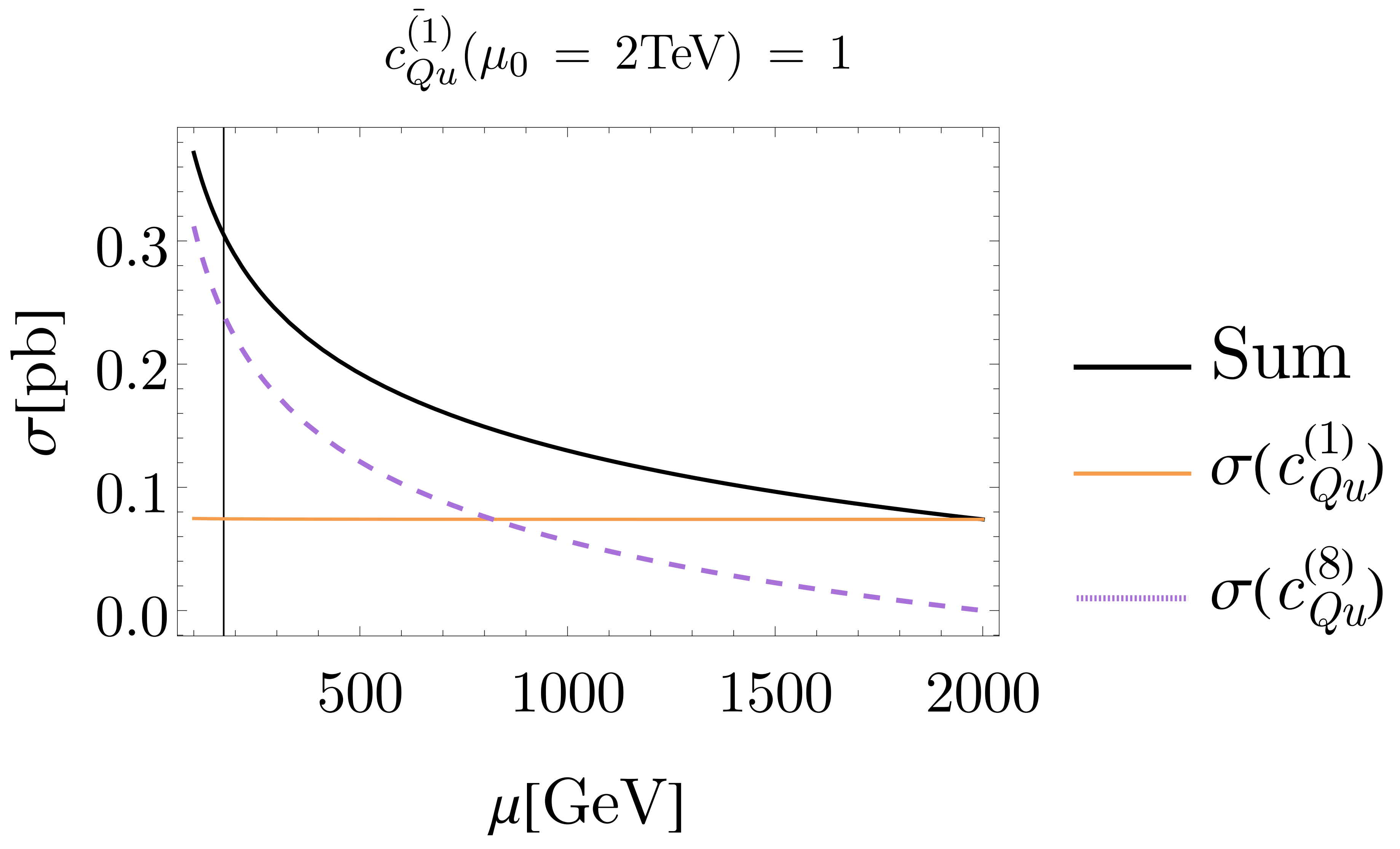
$$\frac{dc_i(\mu)}{d\log\mu} = \gamma_{ij}\, c_j(\mu)$$

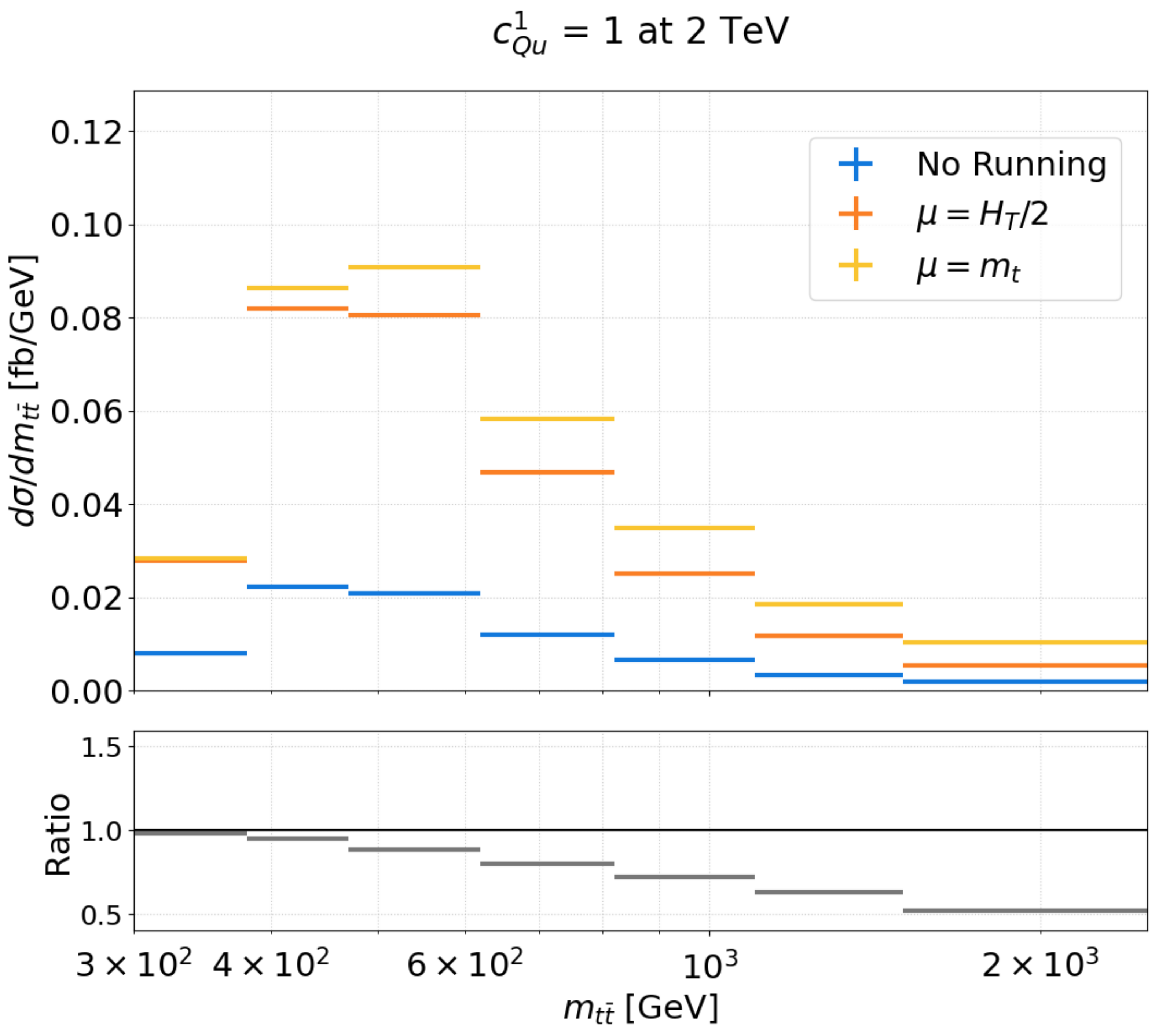
One loop anomalous dimension known:

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

Example: Turn one 1 operator at high-scale

Compute effect on top pair cross-section



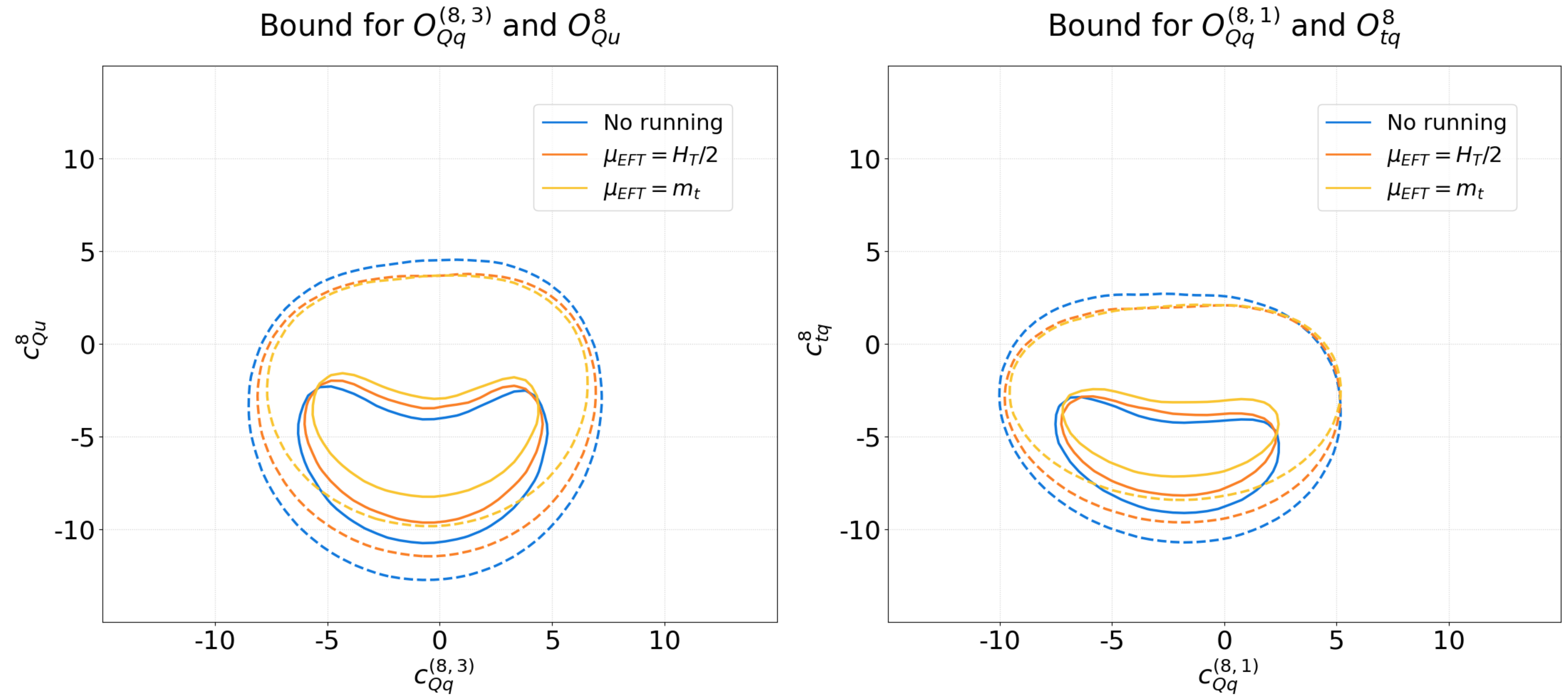


Aoude, Maltoni, Mattelaer, Severi, EV arXiv:2212.05067

Impact of RGE on constraints

How does running and mixing impacts the constraints?

Top sector fit:



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

Effect becomes more important for differential distributions & measurements with very different scales

Summary

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

Global fit results affected by the precision of EFT predictions

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