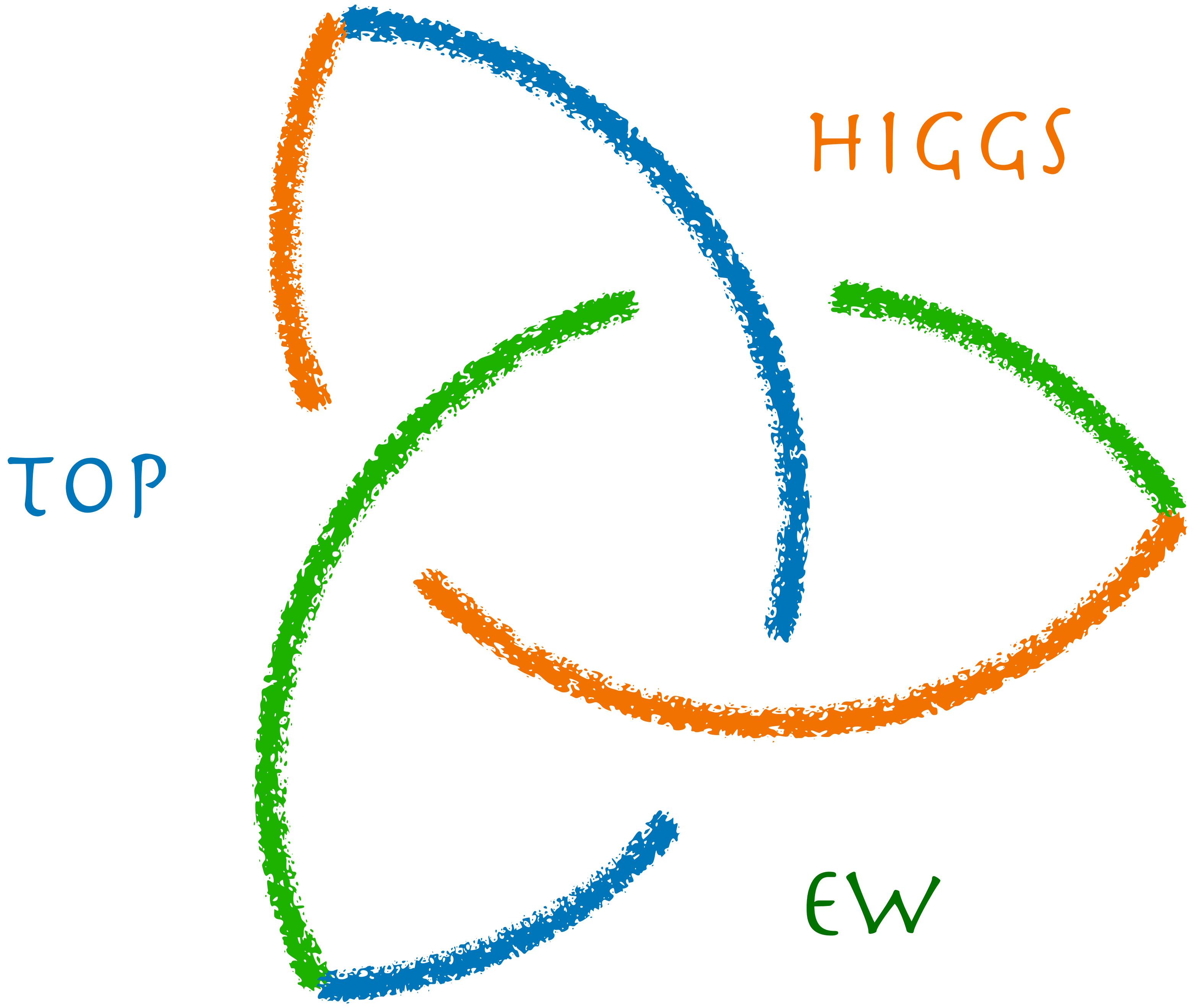
The way of SMEFT



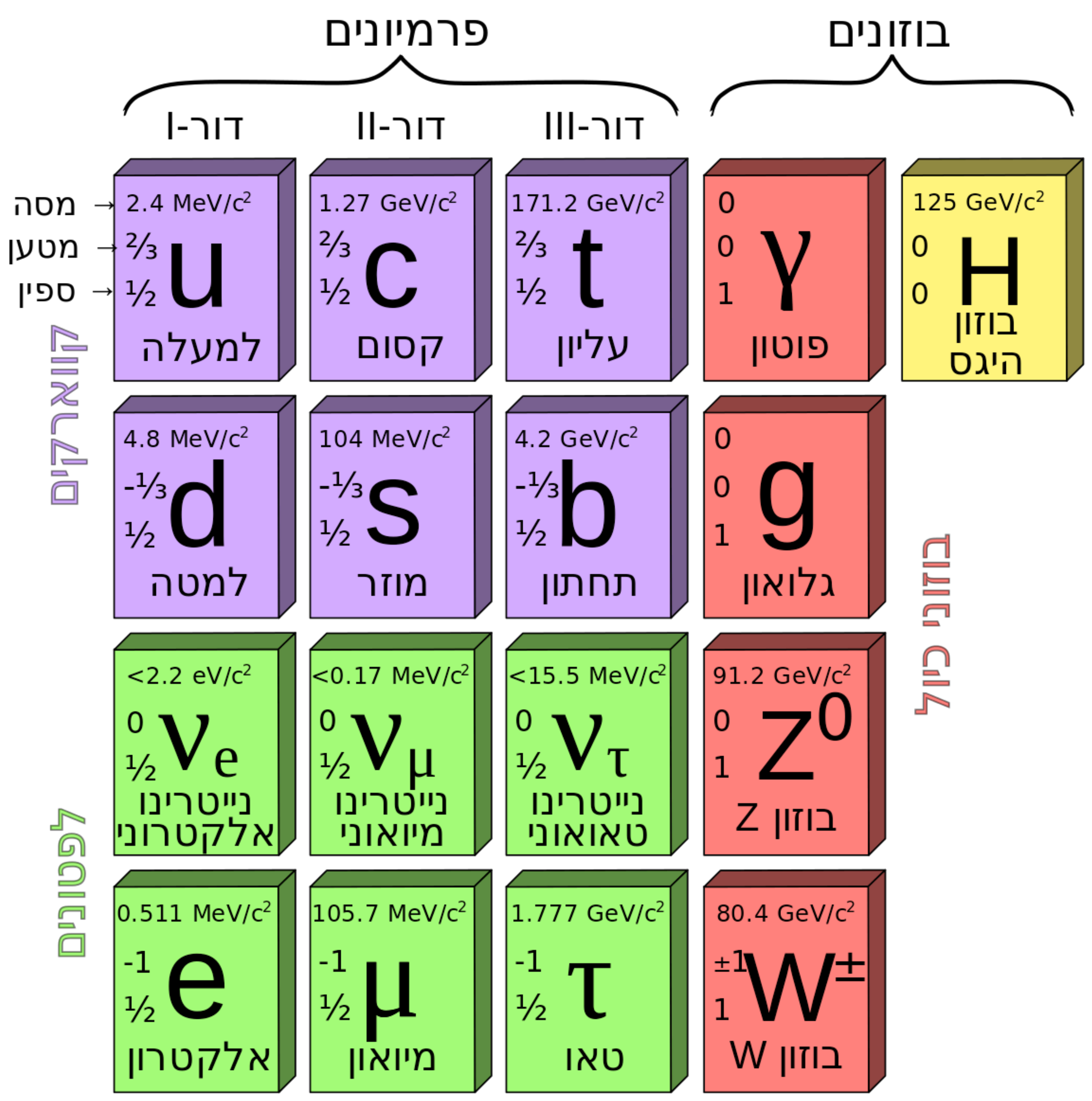
Fabio Maltoni
Università di Bologna
Université catholique de Louvain


visititaly.eu
Post pandemic blues? Italy is just what the doctor ordered!
eu
www.eurid.eu
JCDecaux
WELCOME

Where do we stand?

The SM

$$\mathscr{L}_{SM}^{(4)} = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} + \bar{\psi} i \not{D} \psi + (y_{ij}\bar{\psi}_L^i \phi \psi_R^j + \mathrm{h.c.}) + |D_\mu \phi|^2 - V(\phi)$$



- $SU(3)_c \times SU(2)_L \times U(1)_Y$ gauge symmetries.
- Matter is organised in chiral multiplets of the fund. representation.
- The $SU(2) \times U(1)$ symmetry is spontaneously broken to $U(1)_{EM}$.
- Yukawa interactions lead to fermion masses, mixing and CP violation.
- Matter+gauge group => Anomaly free
- Renormalisable = valid to “arbitrary” high scales.
- **A number of accidental global symmetries seen in Nature.**
- Neutrino masses can be accommodated in two distinct ways.

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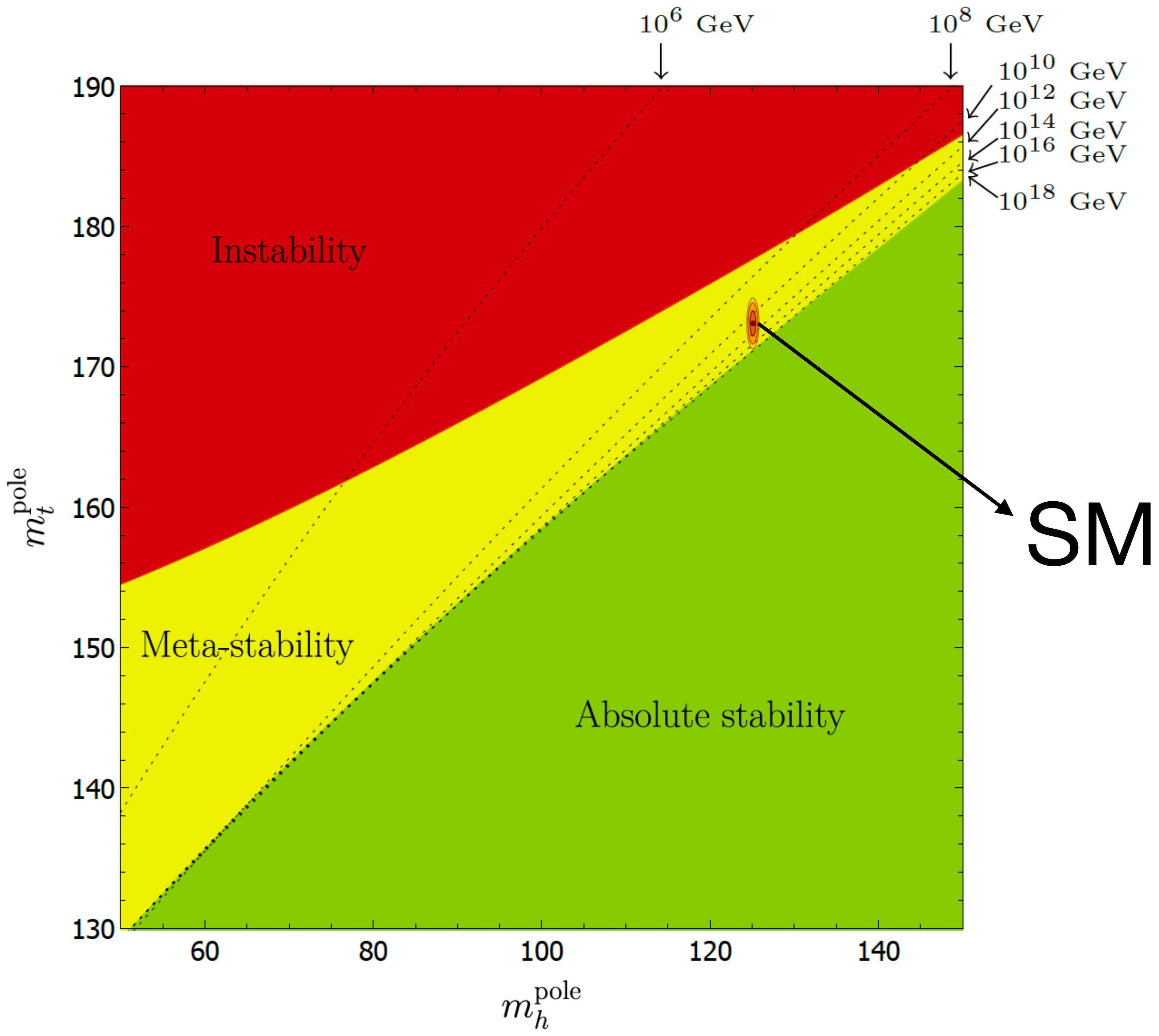

[Andreassen et al. 1707.08124]

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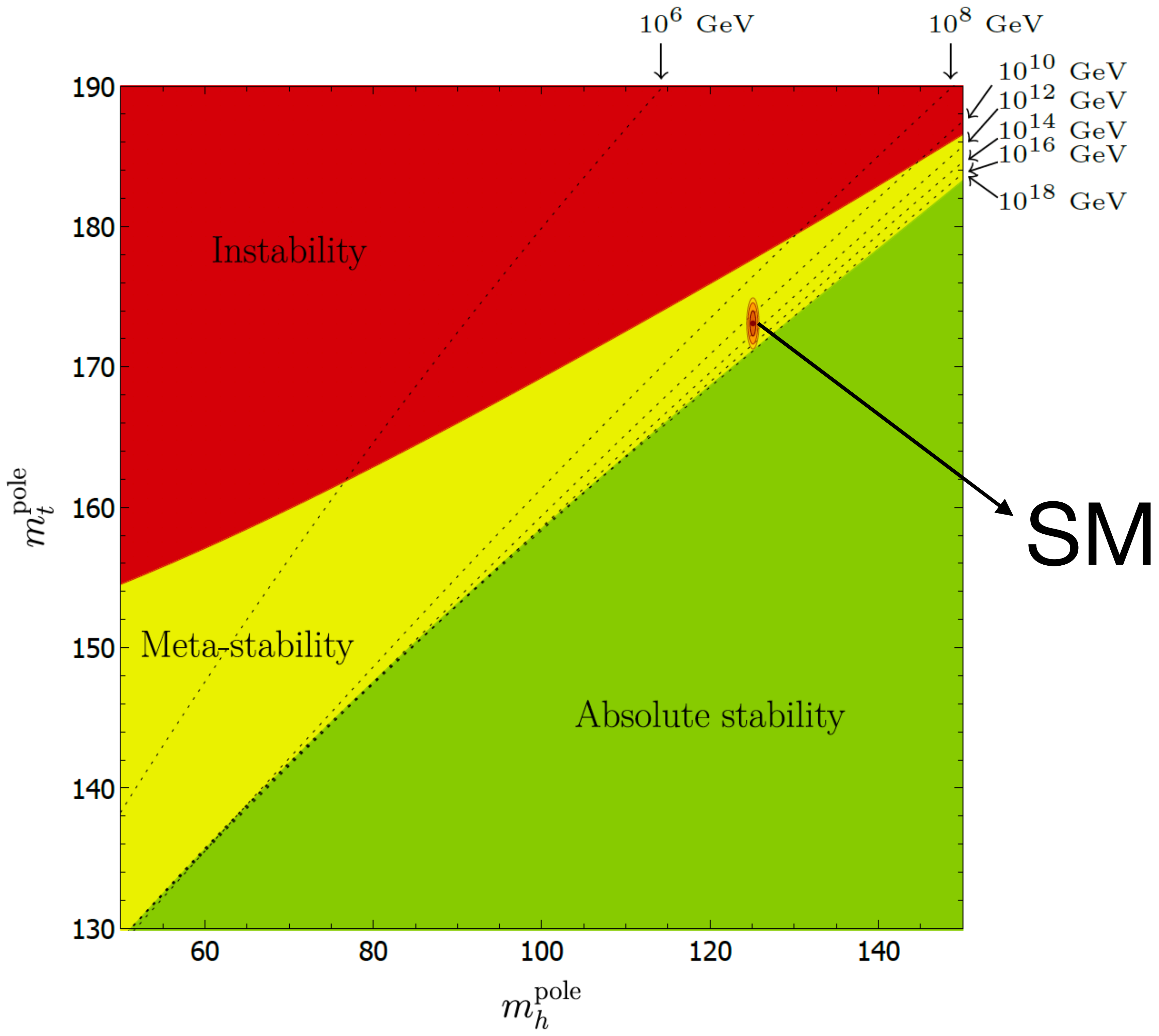

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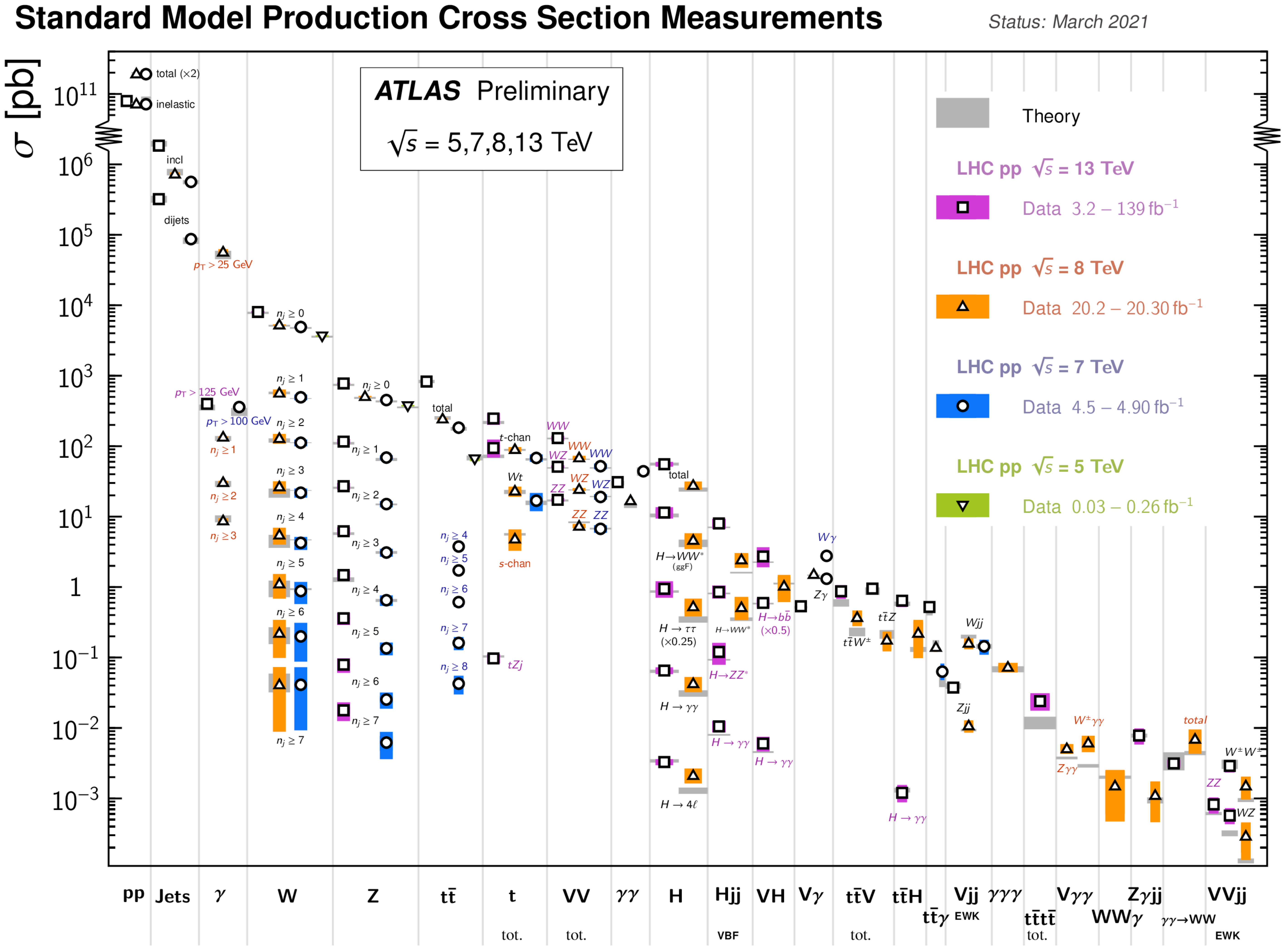
Simple and powerful

yet unnatural, incomplete…

Where do we stand?



- Tangible results of an amazing experimental effort over a 10+ year span, accessing a wide range of final states, each with very different challenges.
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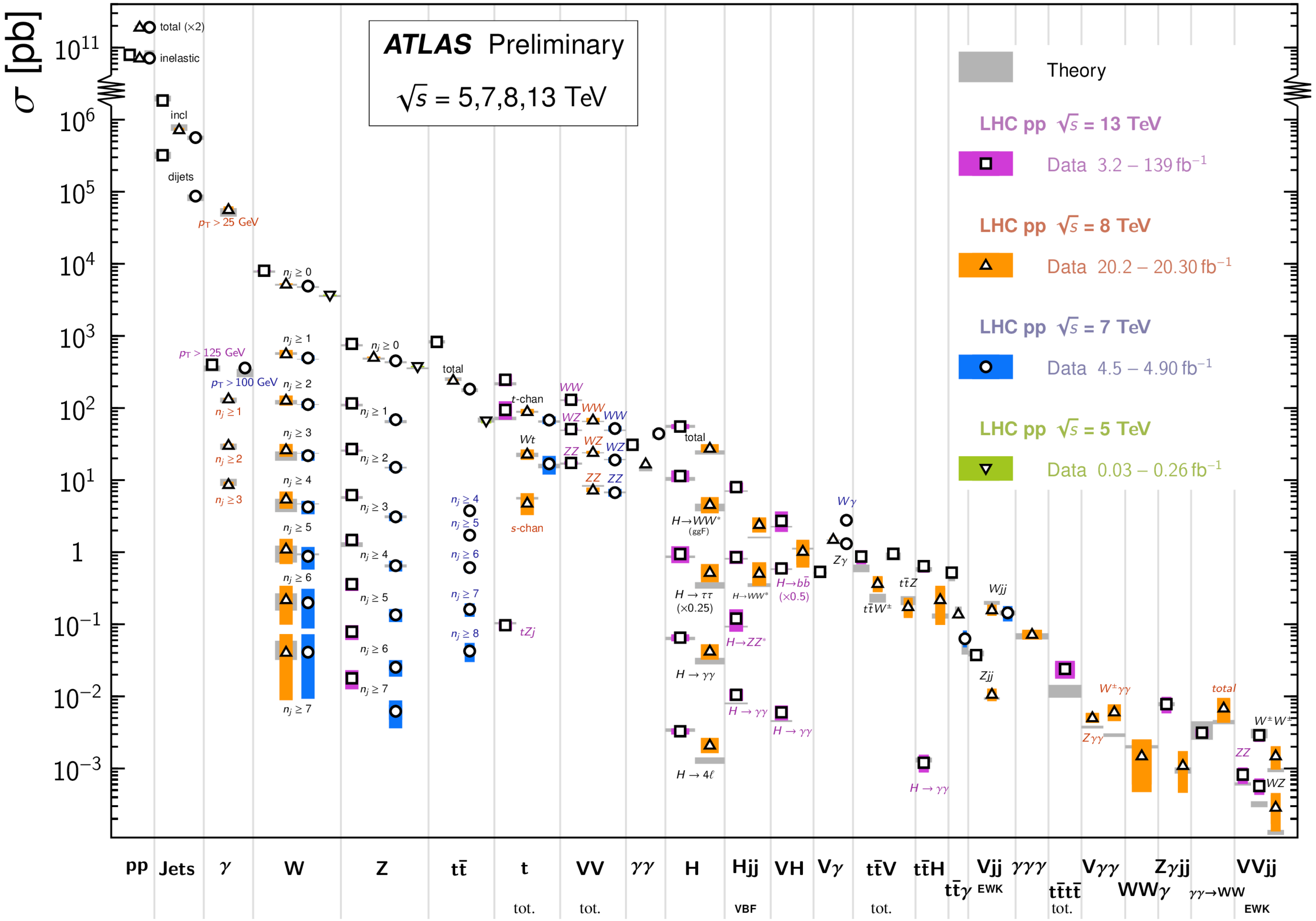
Where do we stand?

Standard Model Production Cross Section Measurements

Status: March 2021



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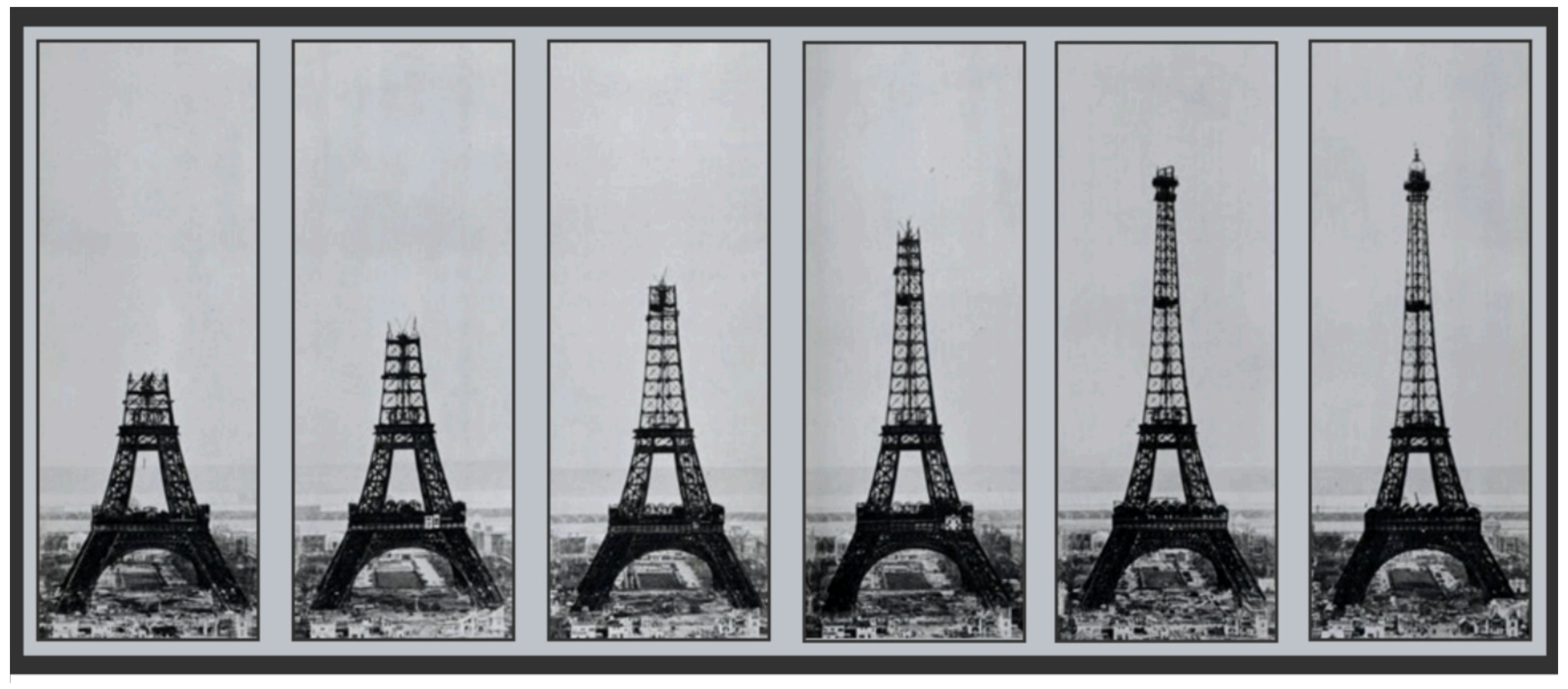

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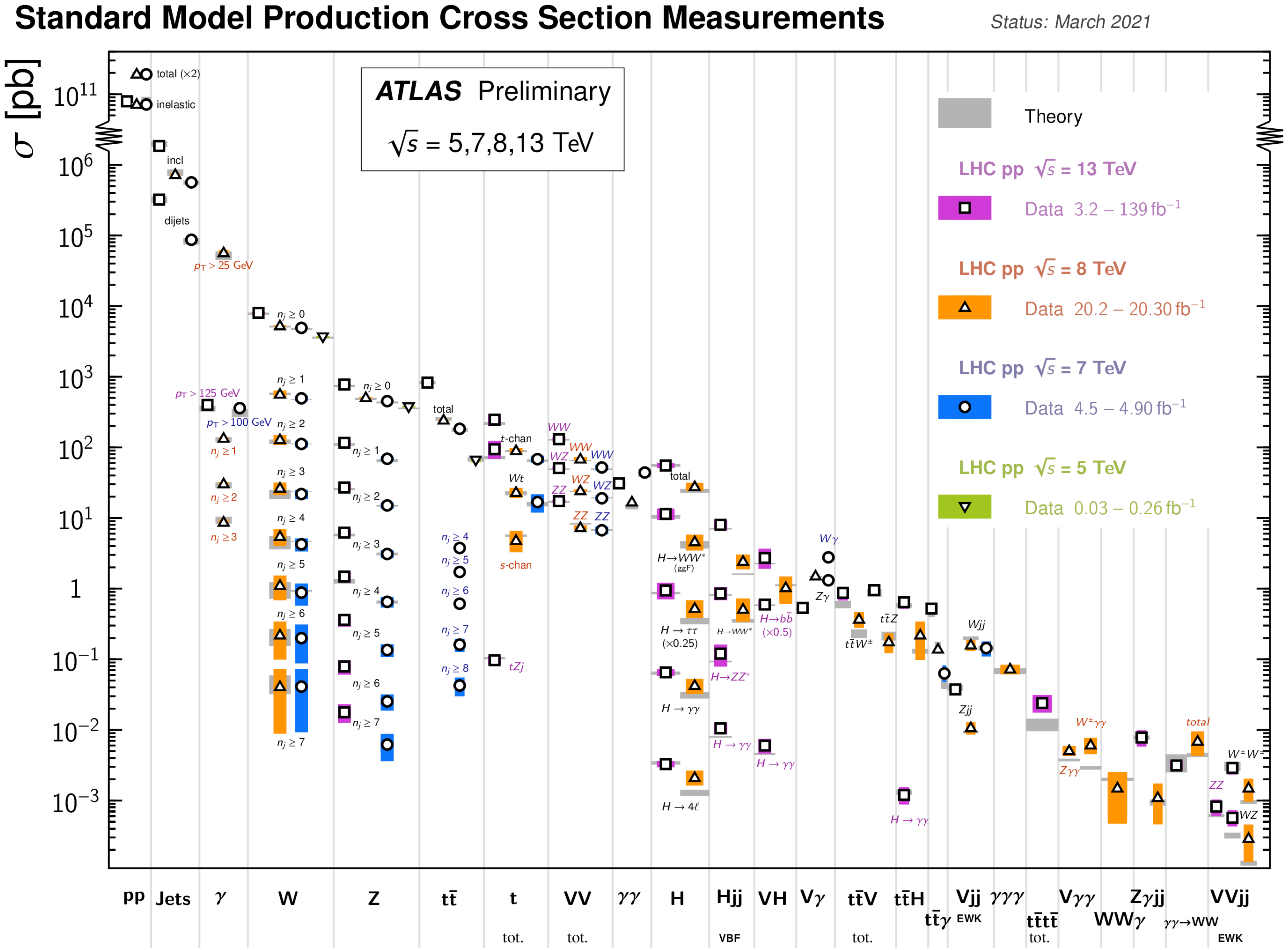

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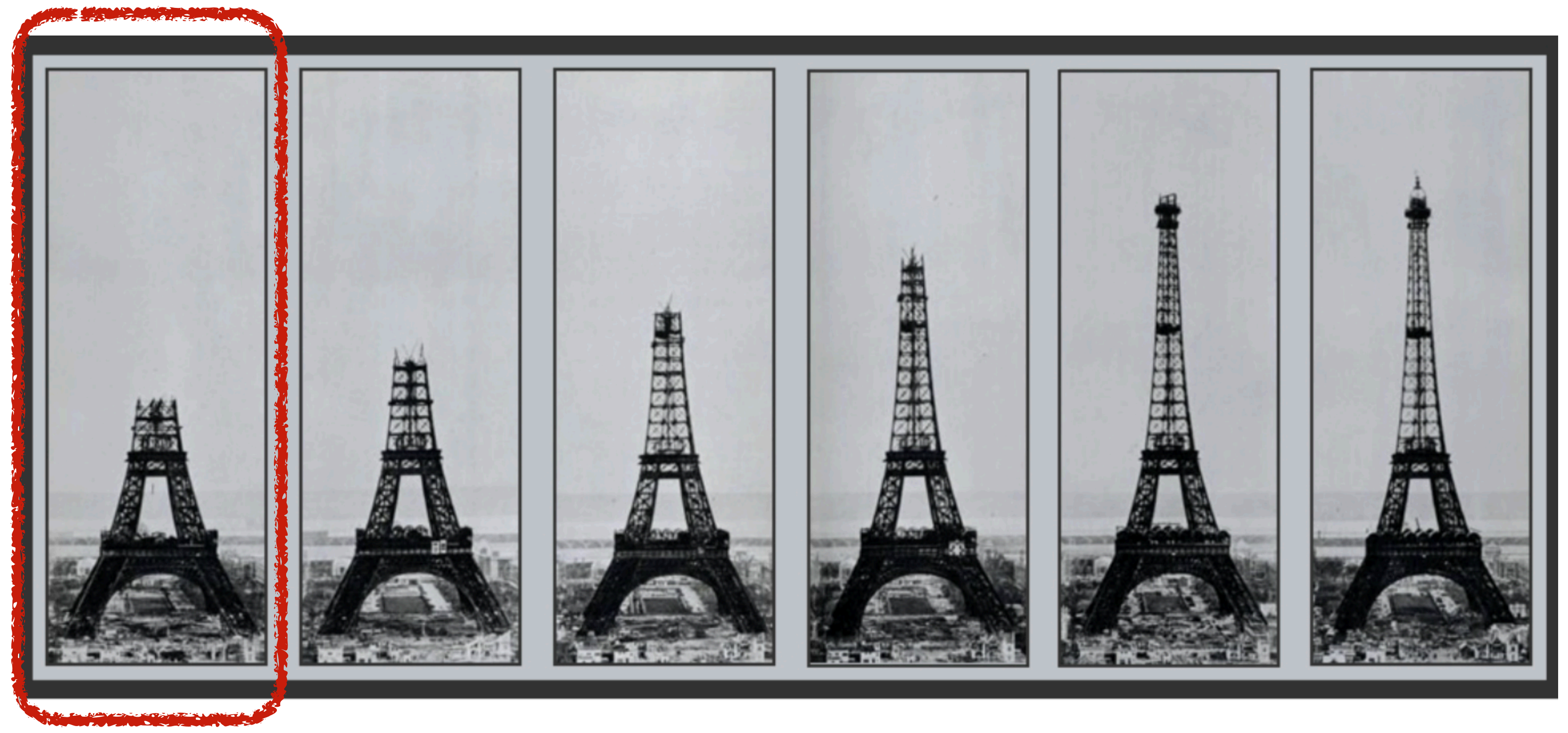

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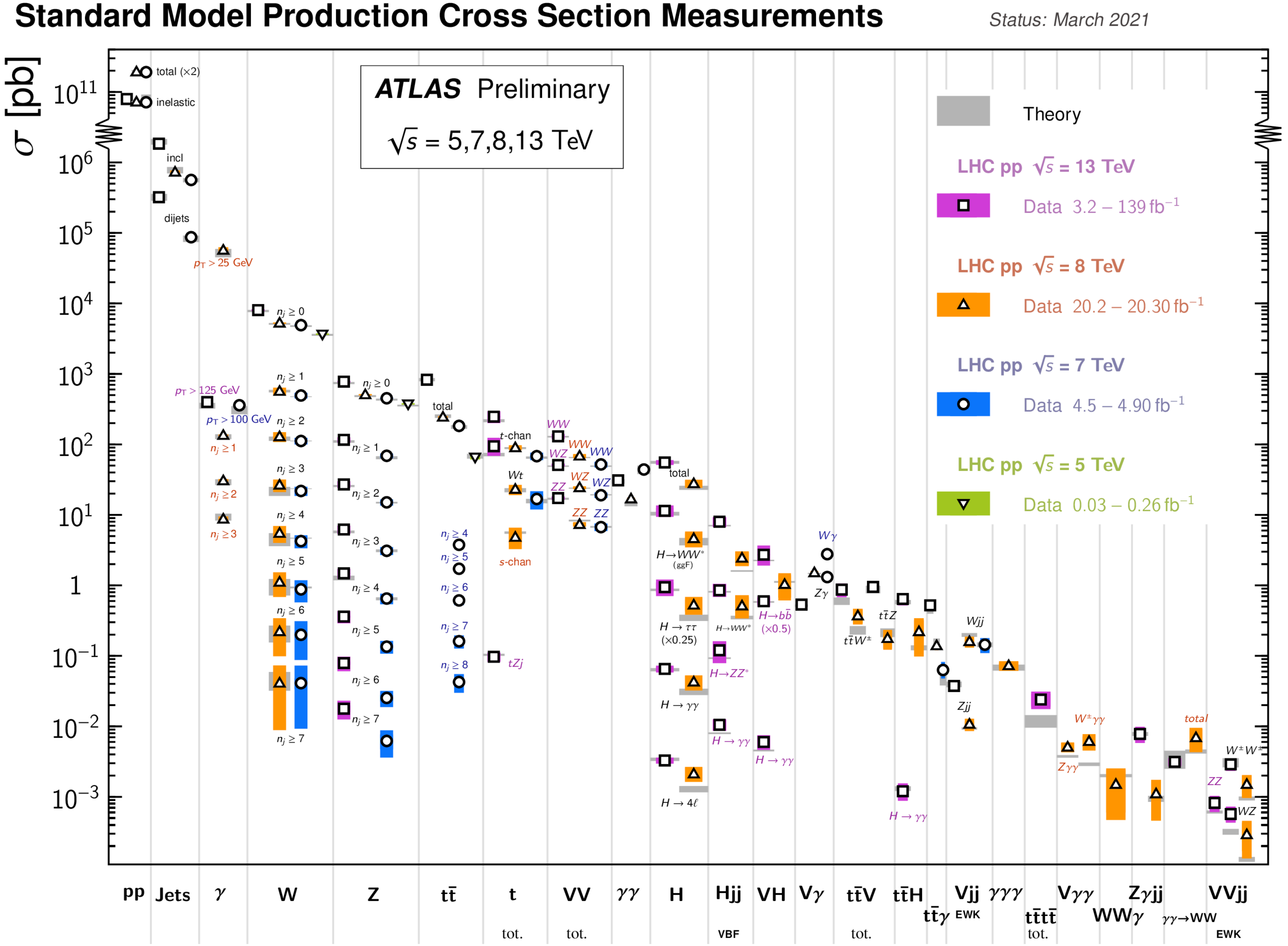

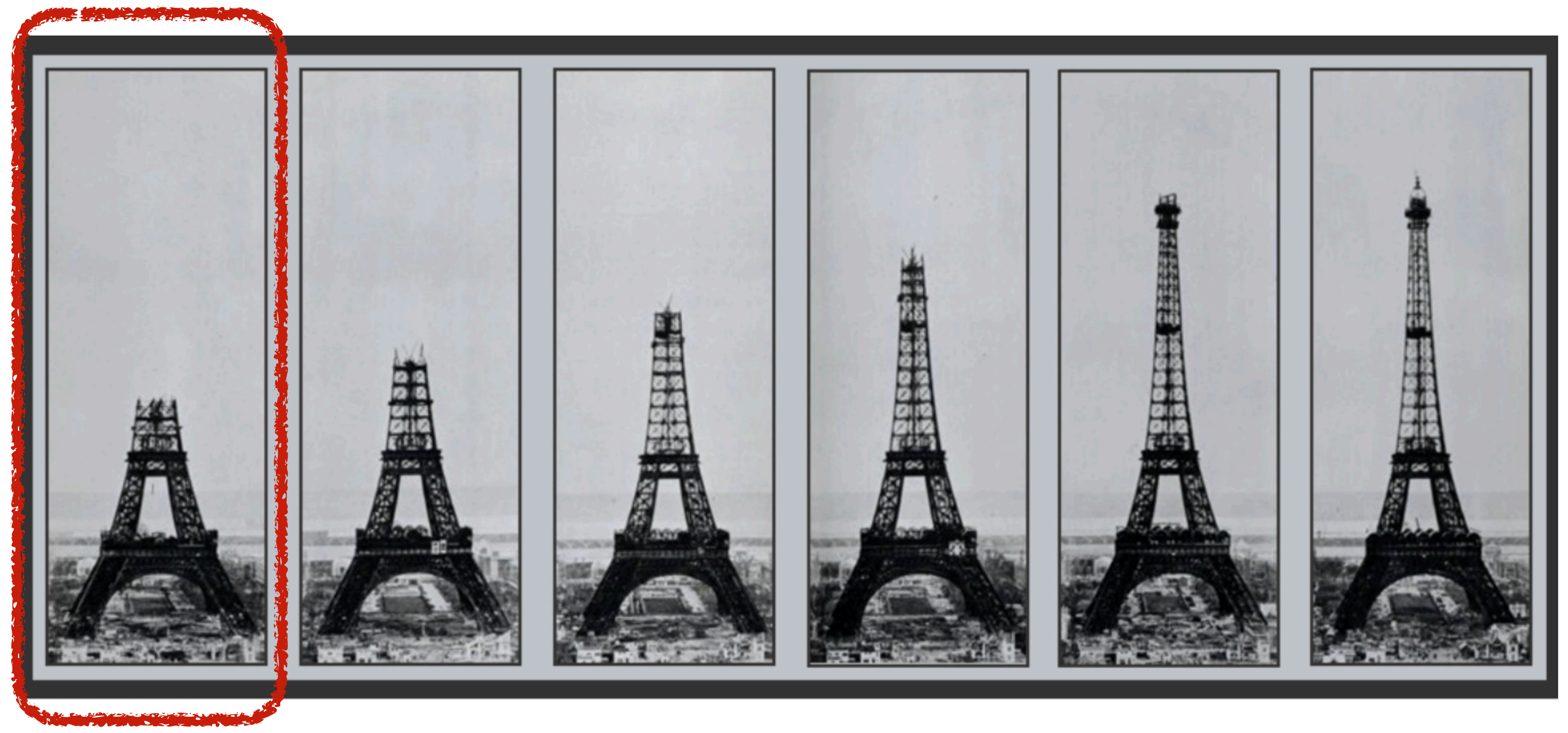

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note: Eiffel Tower was meant to last for 20 years max

Where do we stand?
Theory vs exp

Precision observables do not point to any clear deviation either.

The most puzzling experimental "issue" of the SM is that we don't really understand why it works so well…

Whatever New Physics might exist to address the SM theoretical shortcomings, its effects must be "small" so that have gone undetected so far.

The main path ahead is twofold

1] Explore the unexplored

2] Increase the precision of TH and EXP to identify possible deviations.

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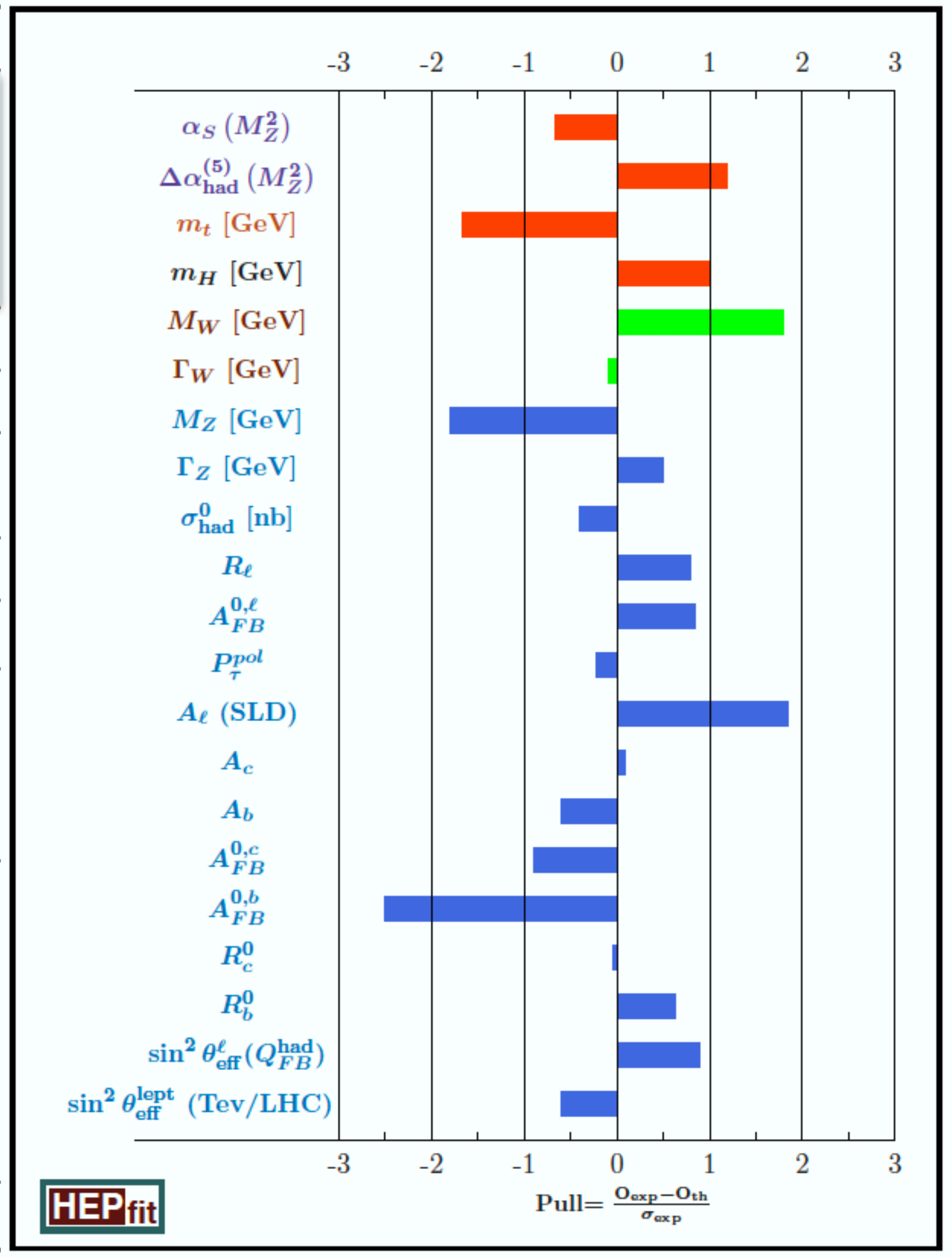
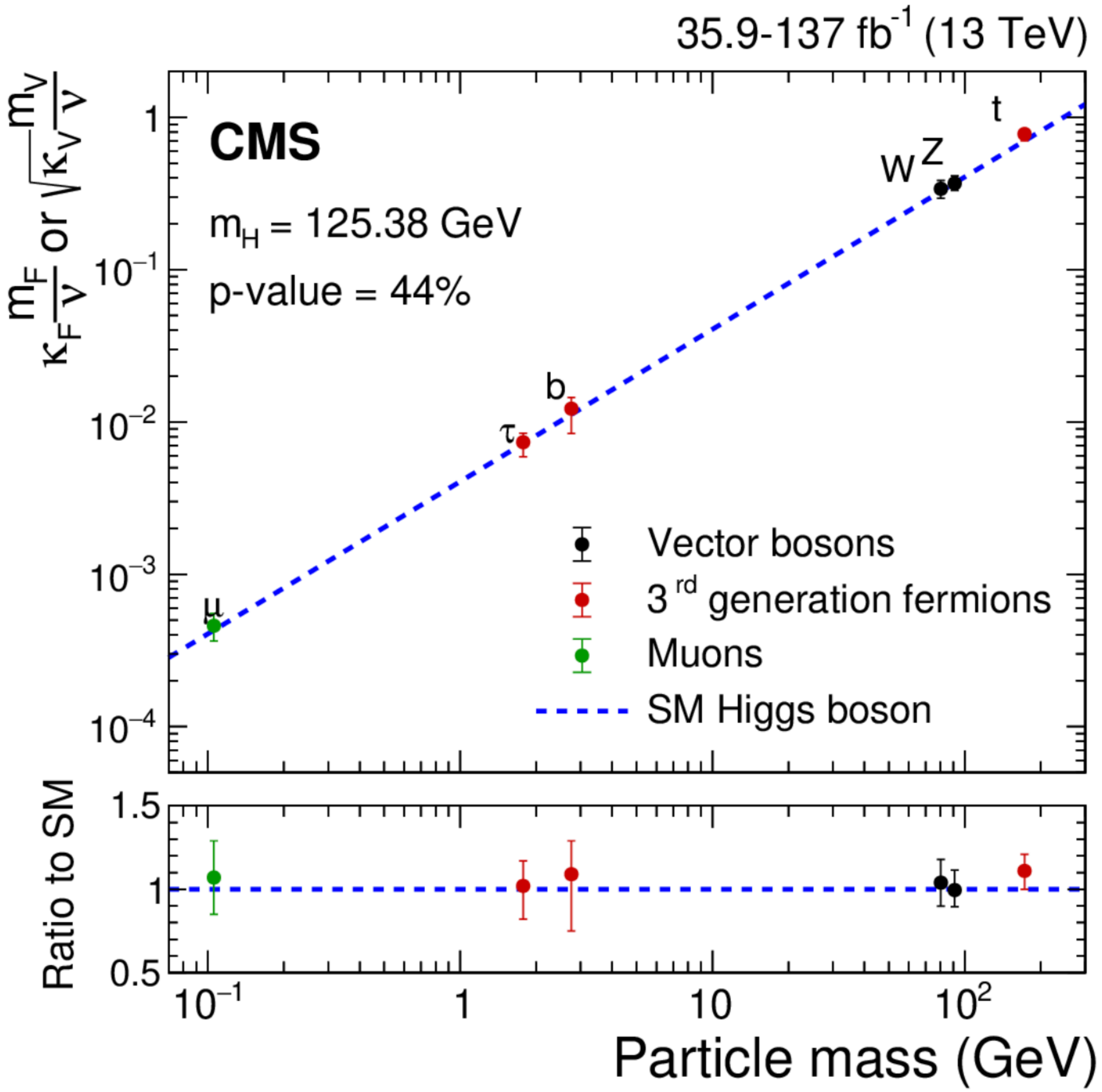
	Measurement	Posterior	Prediction	Pull
$\alpha_s(M_Z)$	0.1177 ± 0.0010	0.1179 ± 0.0009	0.1197 ± 0.0028	-0.7
$\Delta\alpha^{(5)}_{\text{had}}(M_Z)$	0.027611 ± 0.000111	0.027572 ± 0.000106	0.027168 ± 0.000355	1.2
M_Z [GeV]	91.1875 ± 0.0021	91.1880 ± 0.0020	91.2038 ± 0.0087	-1.8
m_t [GeV]	172.59 ± 0.45	172.76 ± 0.44	175.97 ± 1.98	-1.7
m_H [GeV]	125.30 ± 0.13	125.30 ± 0.13	112.68 ± 12.89	0.98
M_W [GeV]	80.379 ± 0.012	80.360 ± 0.005	80.355 ± 0.006	1.8
Γ_W [GeV]	2.085 ± 0.042	2.0883 ± 0.0006	2.0883 ± 0.0006	-0.08
$\text{BR}_{W\to\text{had}}$	0.6741 ± 0.0027	0.67486 ± 0.00007	0.67486 ± 0.00007	-0.28
$\text{BR}_{W\to\ell\nu}$	0.1086 ± 0.0009	0.10838 ± 0.00002	0.10838 ± 0.00002	0.24
$P^{\text{pol}}_\tau = A_\ell$	0.1465 ± 0.0033	0.1473 ± 0.0004	0.1473 ± 0.0005	-0.23
$\sin^2\theta^{\text{lept}}_{\text{eff}}(Q^{\text{had}}_{\text{FB}})$	0.2324 ± 0.0012	0.23149 ± 0.00006	0.23149 ± 0.00006	0.91
Γ_Z [GeV]	2.4955 ± 0.0023	2.4945 ± 0.0006	2.4943 ± 0.0007	0.50
σ^0_h [nb]	41.4802 ± 0.0325	41.4910 ± 0.0076	41.4930 ± 0.0080	-0.38
R^0_ℓ	20.7666 ± 0.0247	20.750 ± 0.0080	20.7460 ± 0.0087	0.79
$A^{0,\ell}_{\text{FB}}$	0.0171 ± 0.0010	0.01627 ± 0.00010	0.01626 ± 0.00010	0.84
A_ℓ (SLD)	0.1513 ± 0.0021	0.14727 ± 0.00045	0.14731 ± 0.00047	1.9
R^0_b	0.21629 ± 0.00066	0.21588 ± 0.00010	0.21587 ± 0.00010	0.63
R^0_c	0.1721 ± 0.0030	0.17221 ± 0.00005	0.17221 ± 0.00005	-0.04
$A^{0,b}_{\text{FB}}$	0.0992 ± 0.0016	0.1032 ± 0.0003	0.10327 ± 0.00033105	-2.5
$A^{0,c}_{\text{FB}}$	0.0707 ± 0.0035	0.0738 ± 0.0002	0.0738 ± 0.0002	-0.88
A_b	0.923 ± 0.020	0.93475 ± 0.00004	0.93475 ± 0.00004	-0.59
A_c	0.670 ± 0.027	0.6679 ± 0.0002	0.6679 ± 0.0002	0.08
$\sin^2\theta^{\text{lept}}_{\text{eff}}$(Tev/LHC)	0.23137 ± 0.00022	0.23149 ± 0.00006	0.23150 ± 0.00006	-0.57

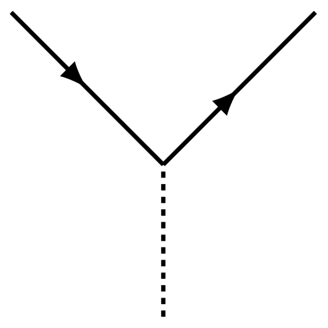


[Courtesy of De Blas et al., work in progress]

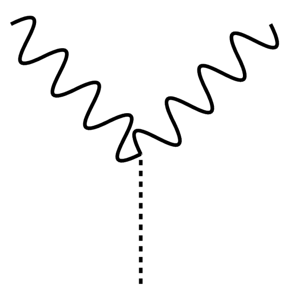
Where do we stand?

Higgs





$i\, m_f/v$



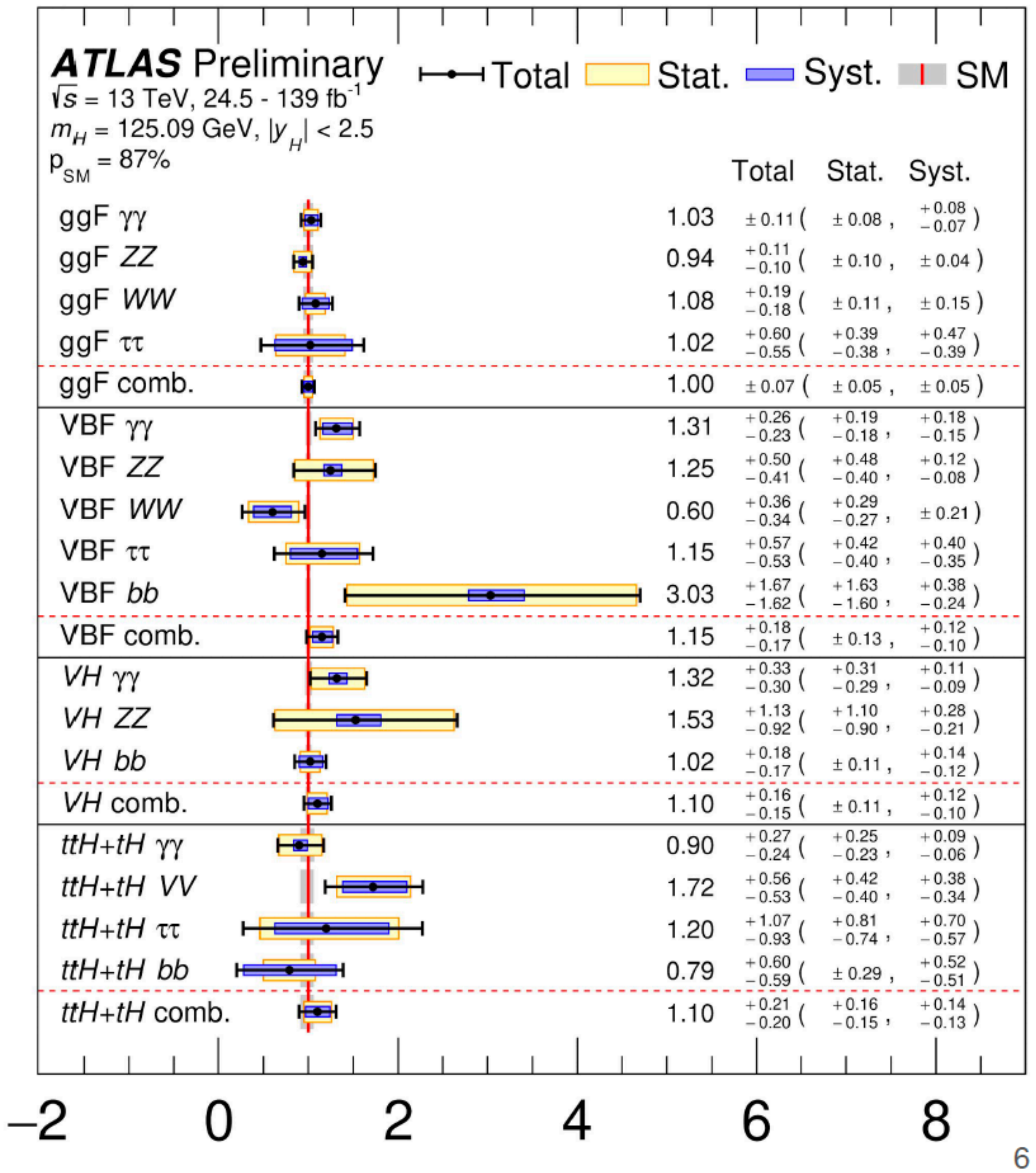
$igm_W g_{\mu\nu} = 2iv g_{\mu\nu} \cdot m_W^2/v^2$

$ig\frac{m_Z}{\cos\theta_W} g_{\mu\nu} = 2iv g_{\mu\nu} \cdot m_Z^2/v^2$

Unique mass generation mechanism for fermions and vectors.

Constrained system.

[ATLAS 2020]



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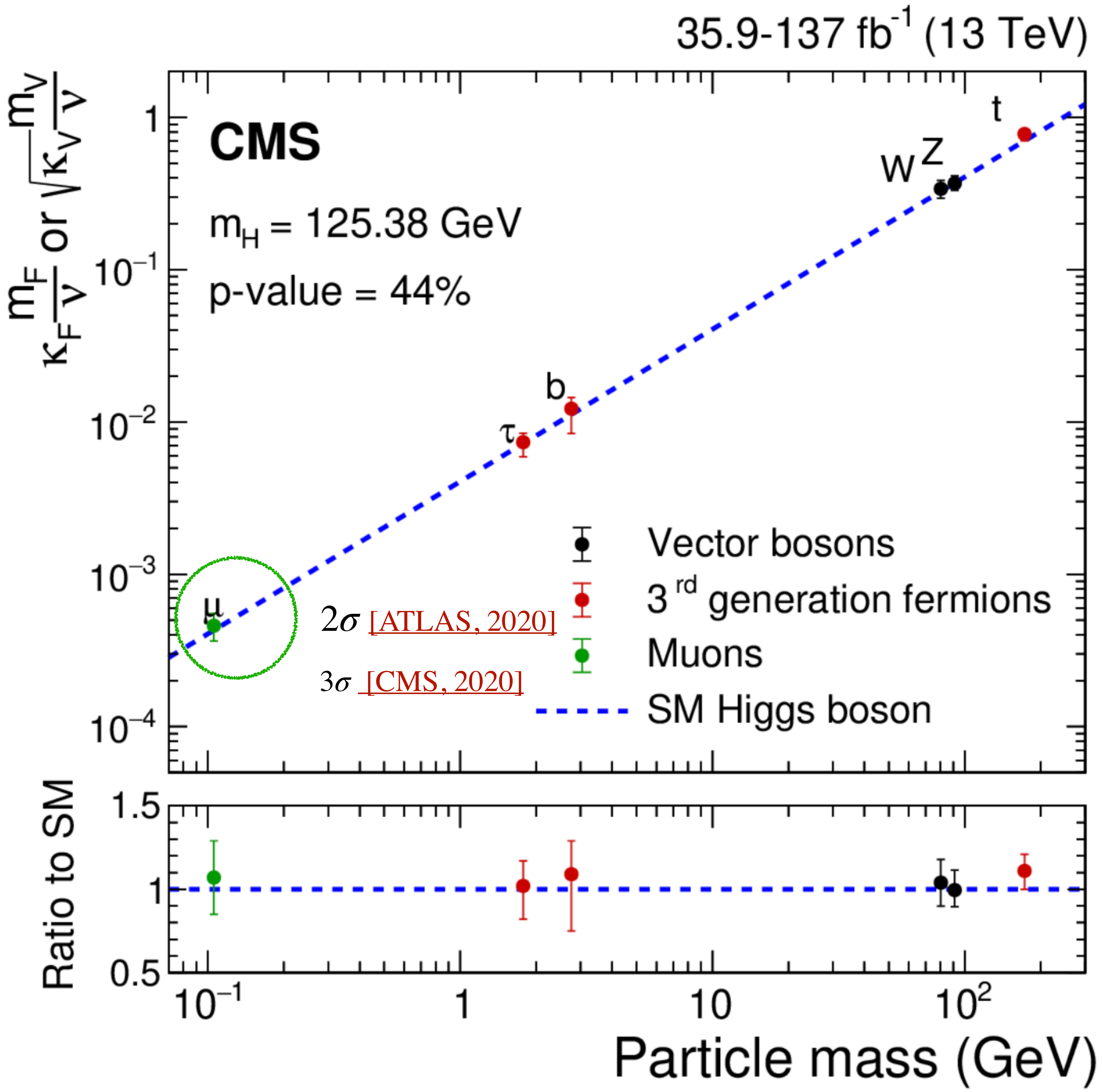
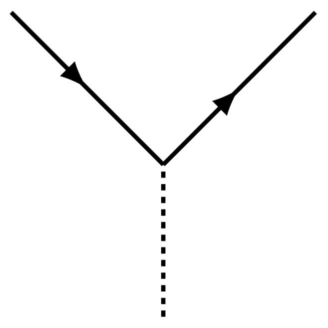


2σ [ATLAS, 2020]

3σ [CMS, 2020]



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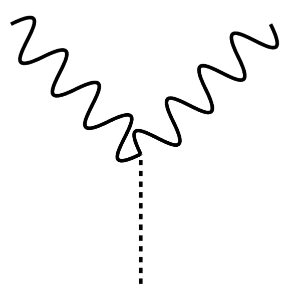

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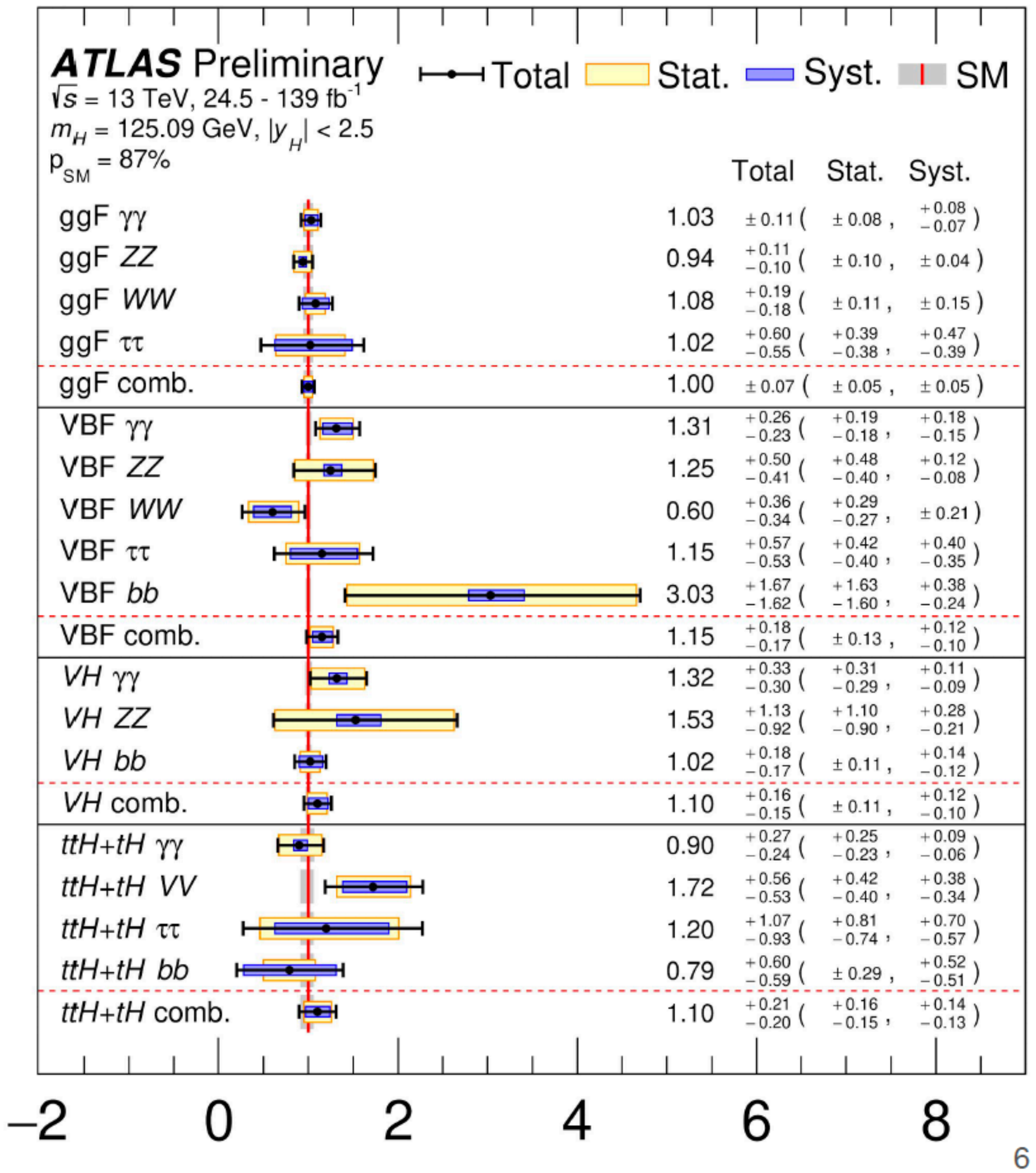
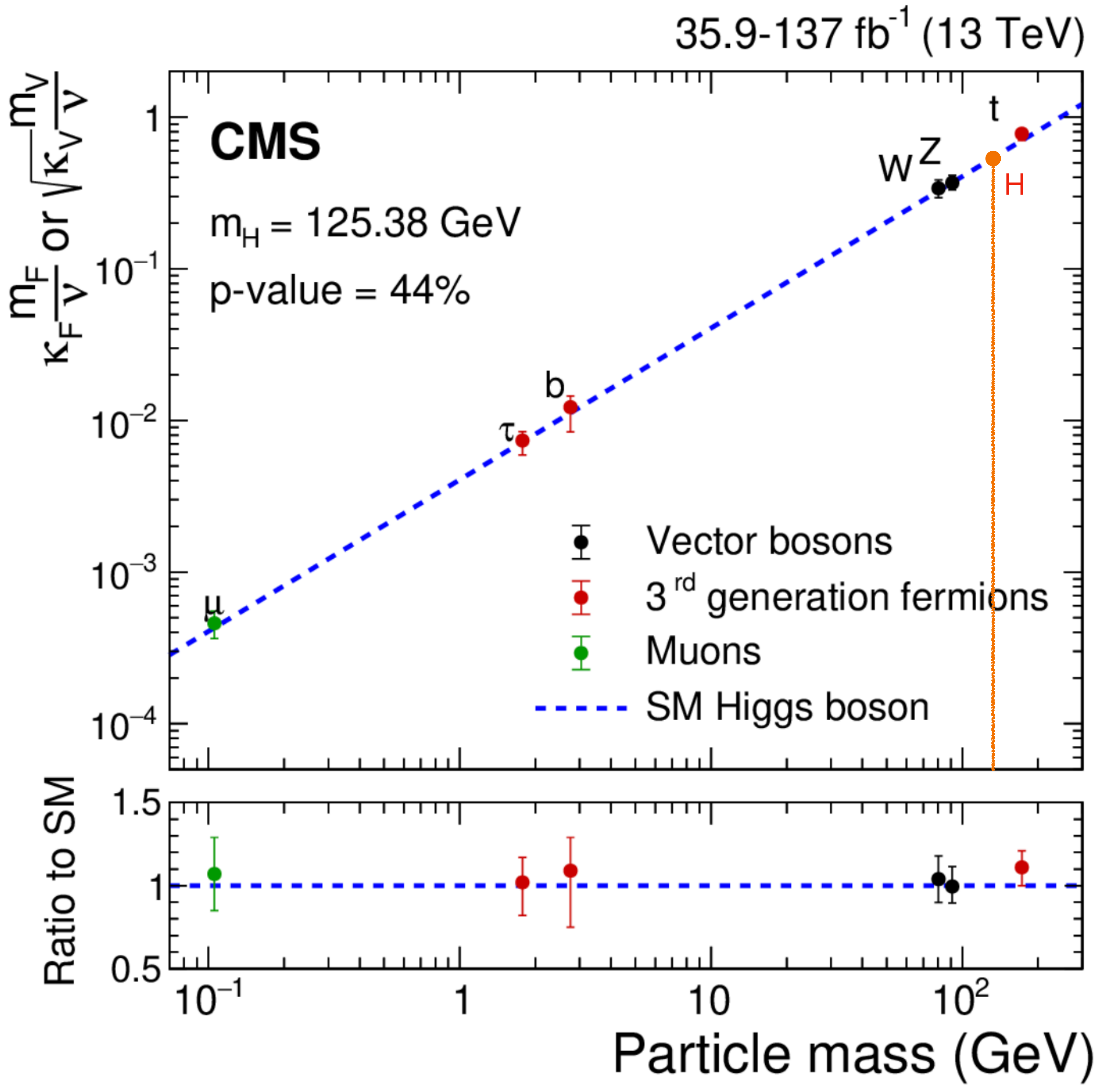


Where do we stand?

Higgs self interactions



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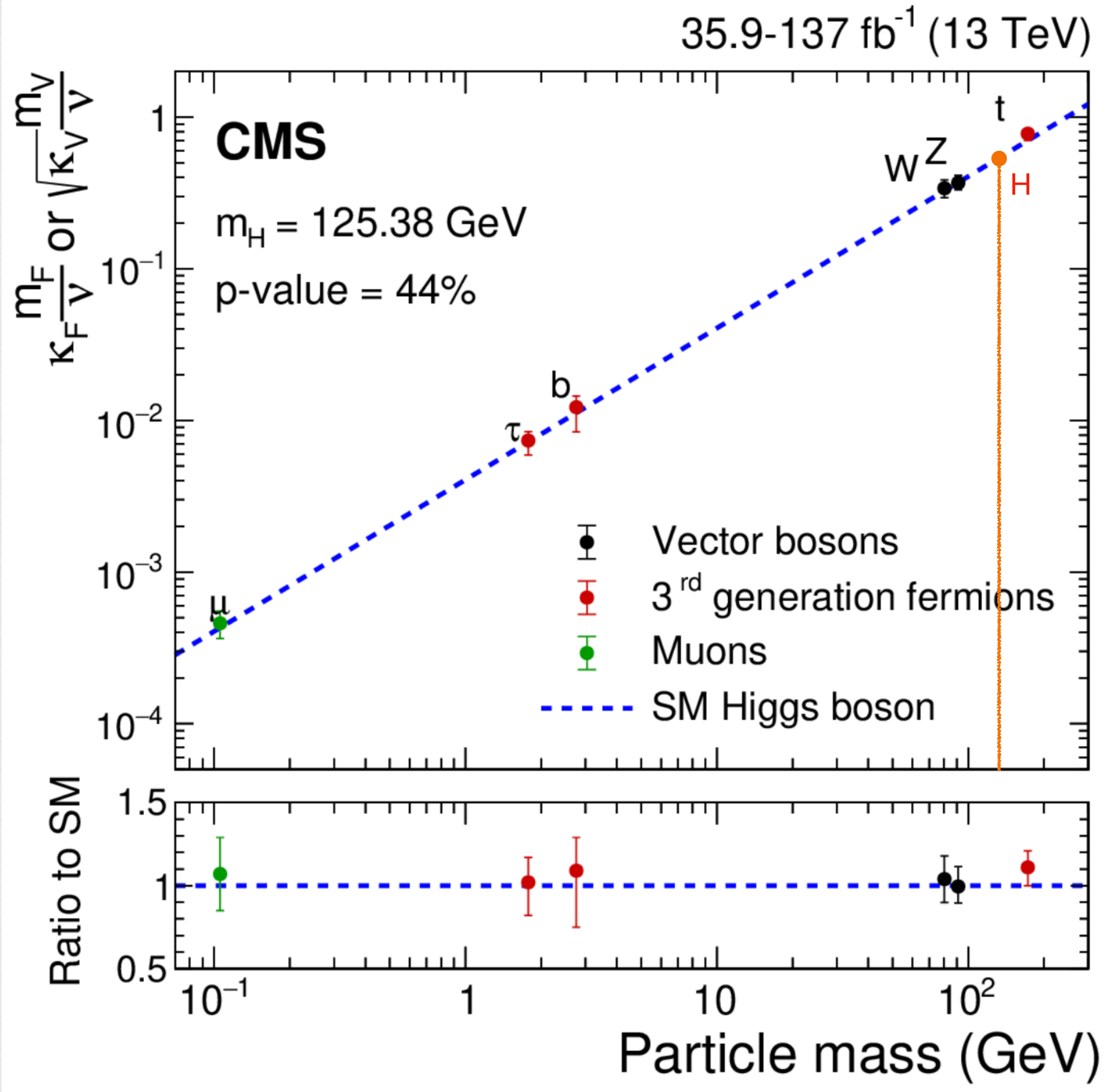

$$V(H) = \frac{m_H^2}{2} H^2 + \lambda_3 v H^3 + \frac{\lambda_4}{4} H^4 + \dots$$

$$V^{\rm SM}(\Phi) = -\mu^2(\Phi^\dagger\Phi) + \lambda(\Phi^\dagger\Phi)^2 \Longrightarrow \begin{cases} v^2 = \mu^2/\lambda \\ m_H^2 = 2\lambda v^2 \end{cases} \qquad \begin{cases} \lambda_3^{\rm SM} = \lambda \\ \lambda_4^{\rm SM} = \lambda \end{cases}$$

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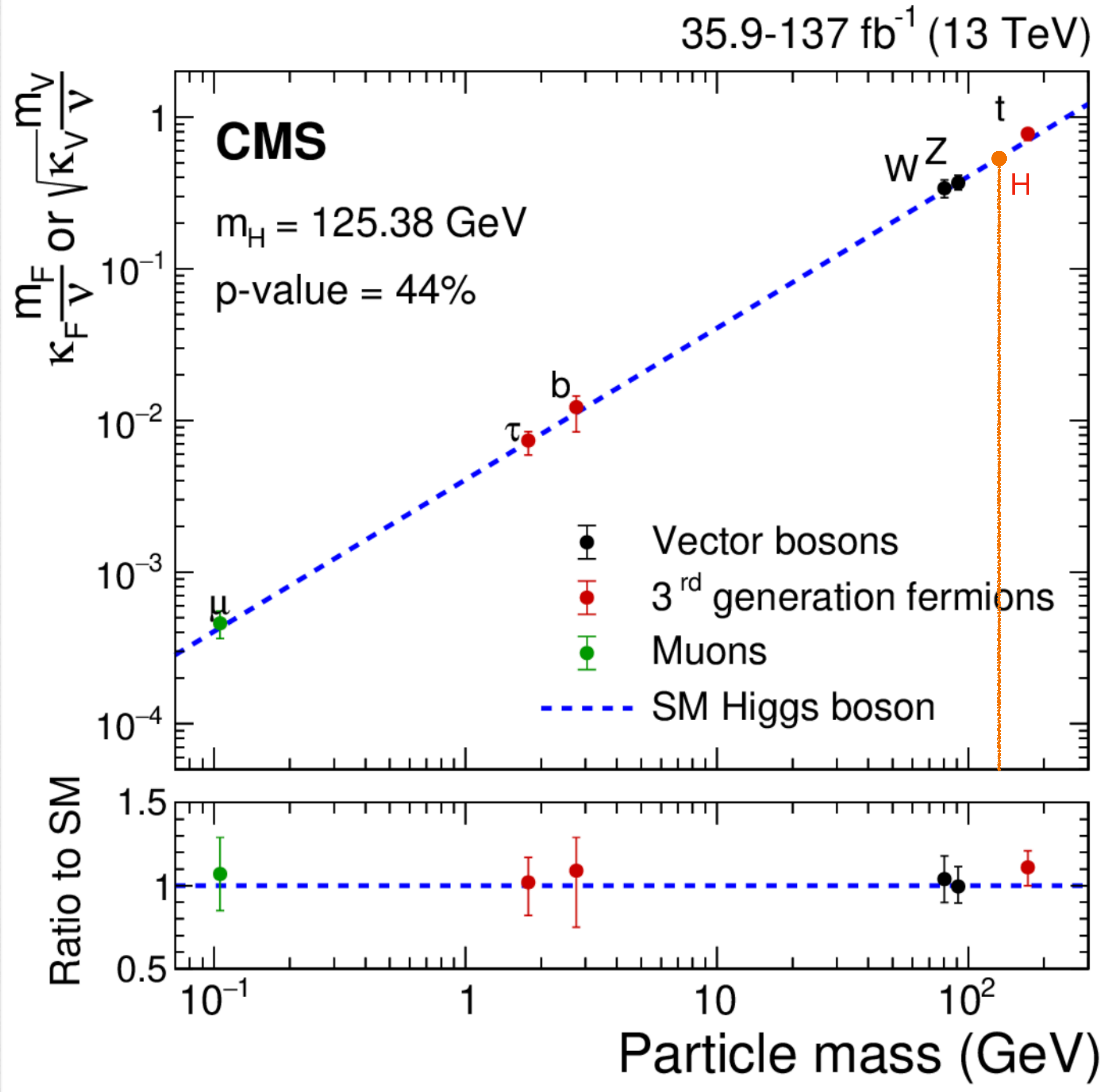

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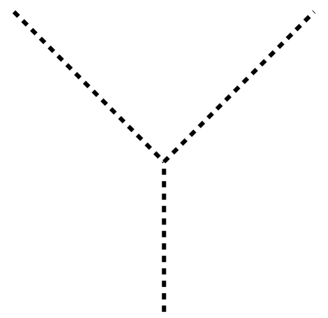

$$-3\, iv \cdot m_h^2/v^2$$

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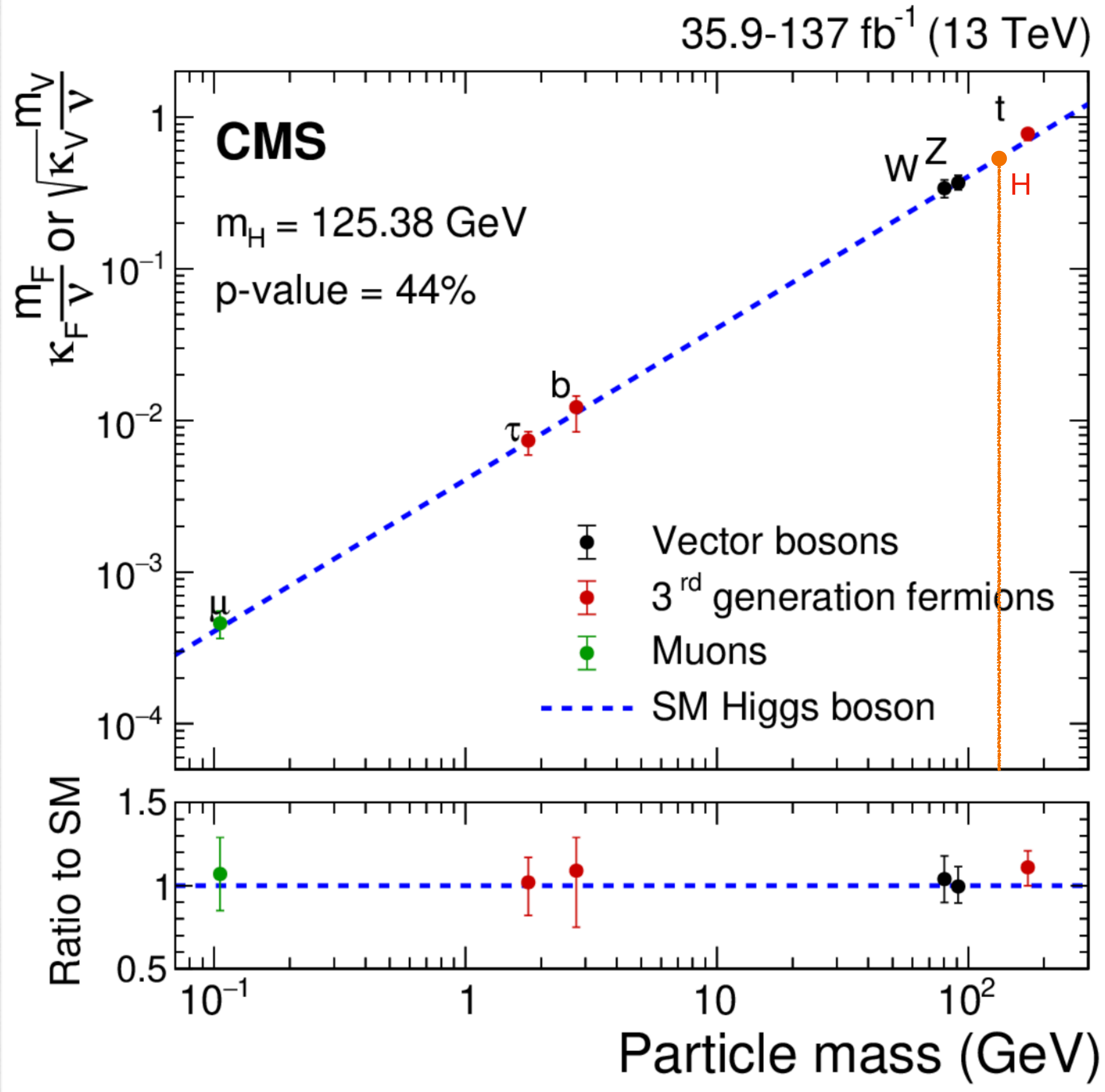

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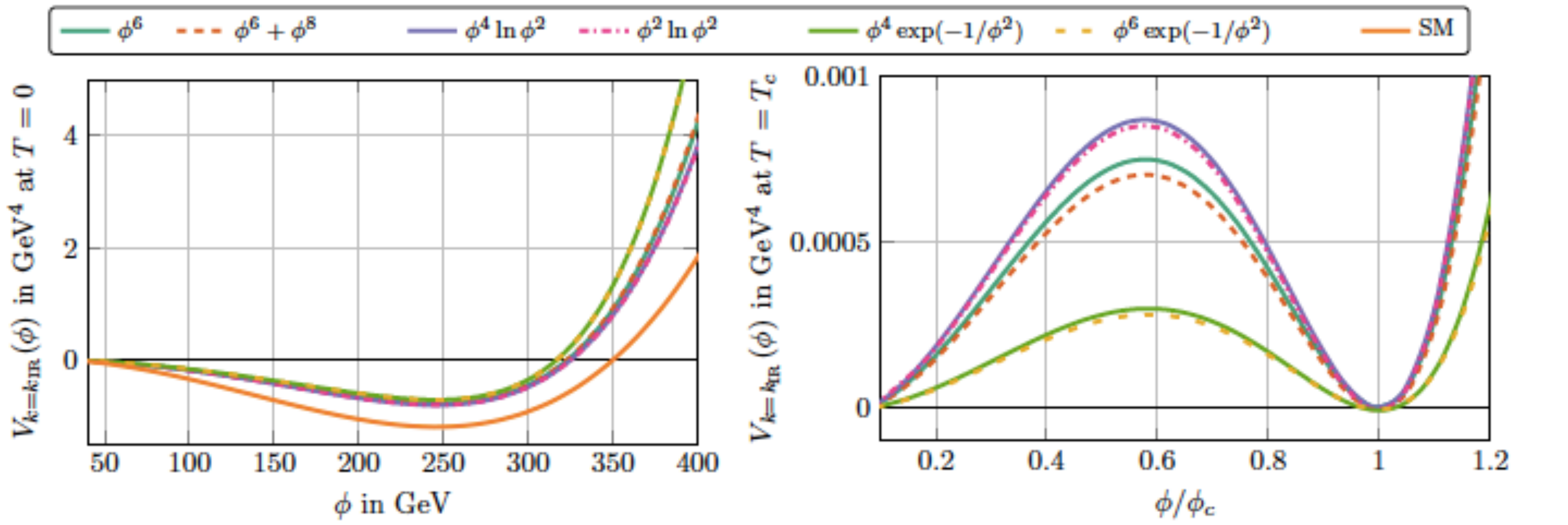

Reichert et al. 1711.00019

Where do we stand?

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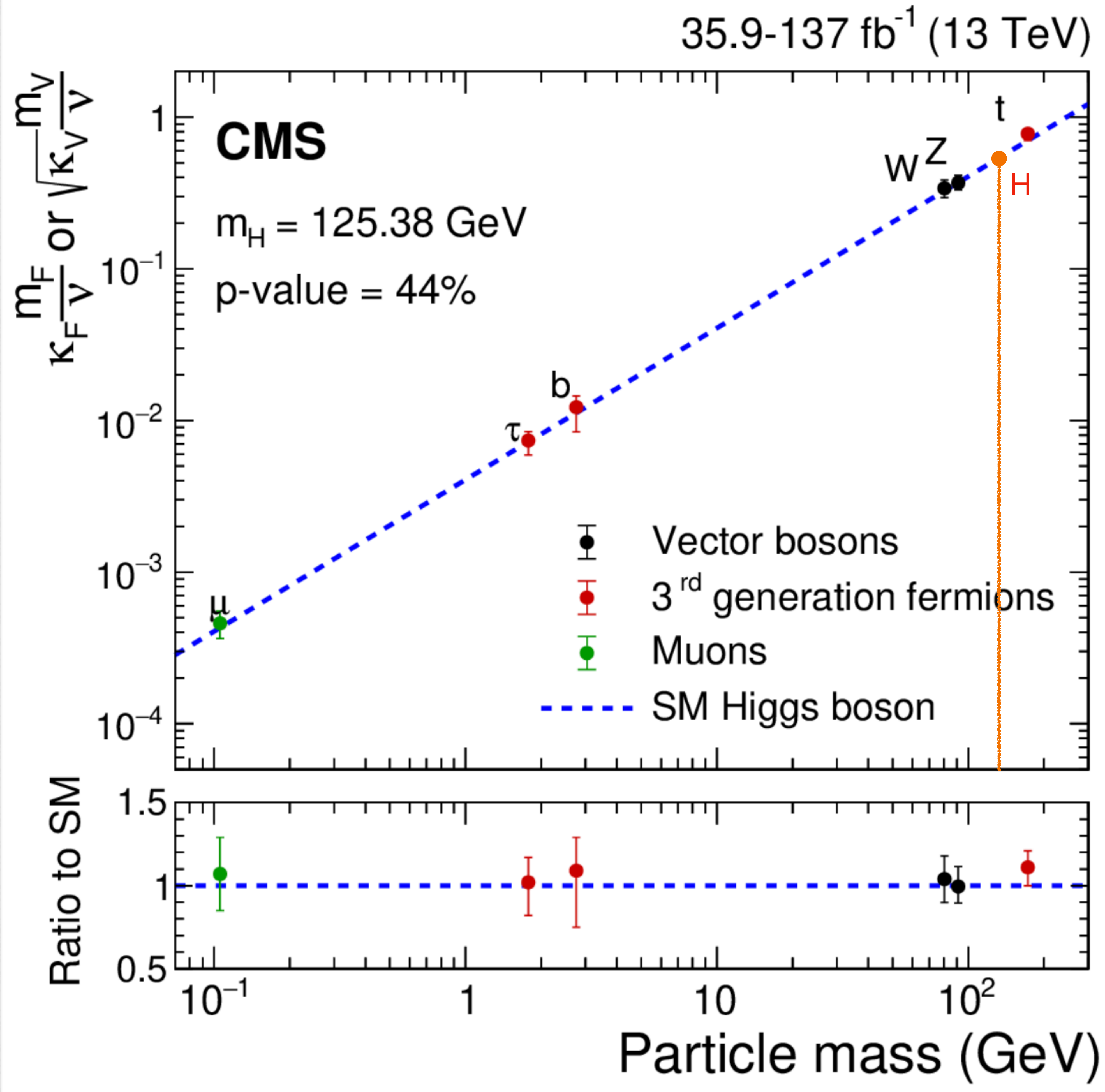

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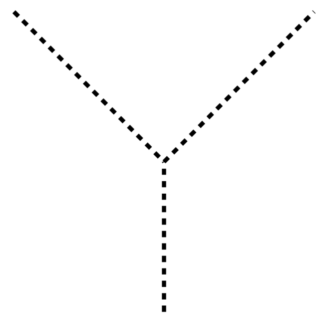

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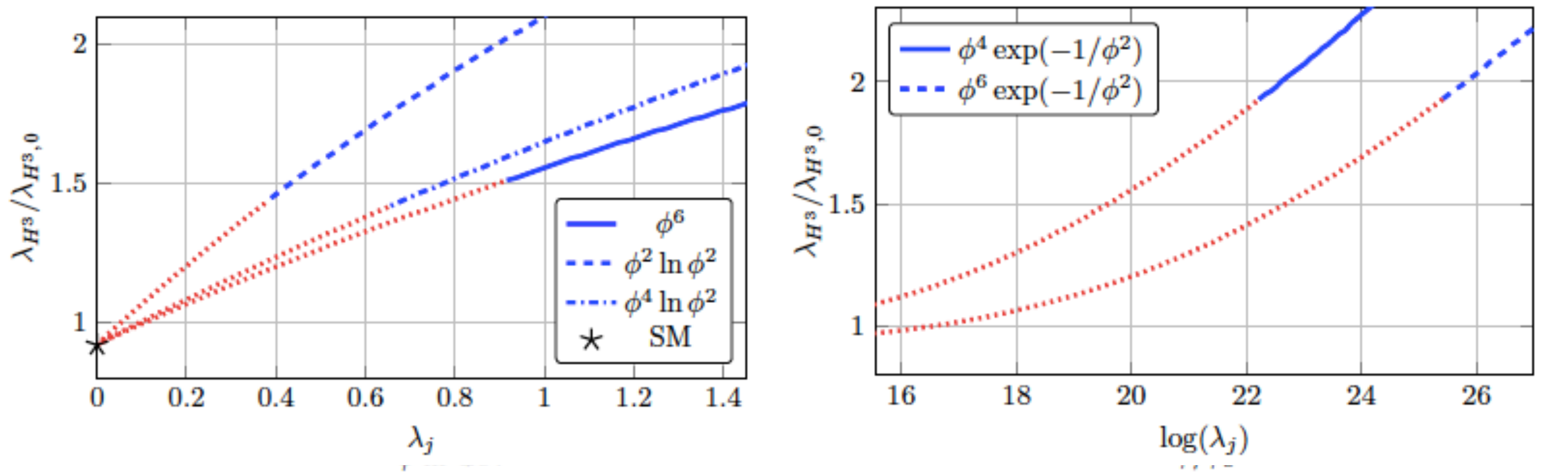


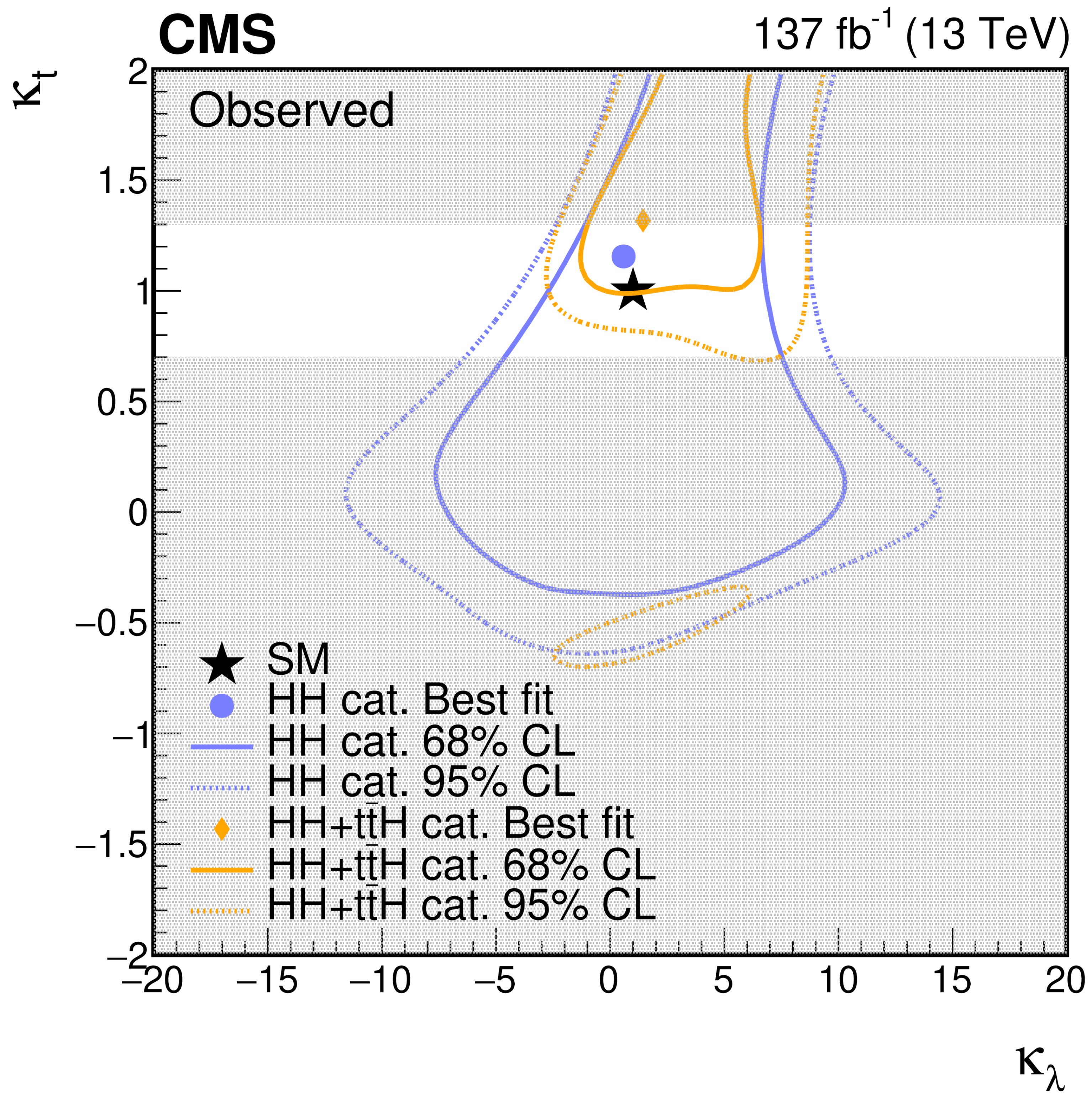
Reichert et al. 1711.00019

$k_\lambda > 1.5 \Rightarrow$ 1st ord ($T = 0$ and $T = T_c$ connected)

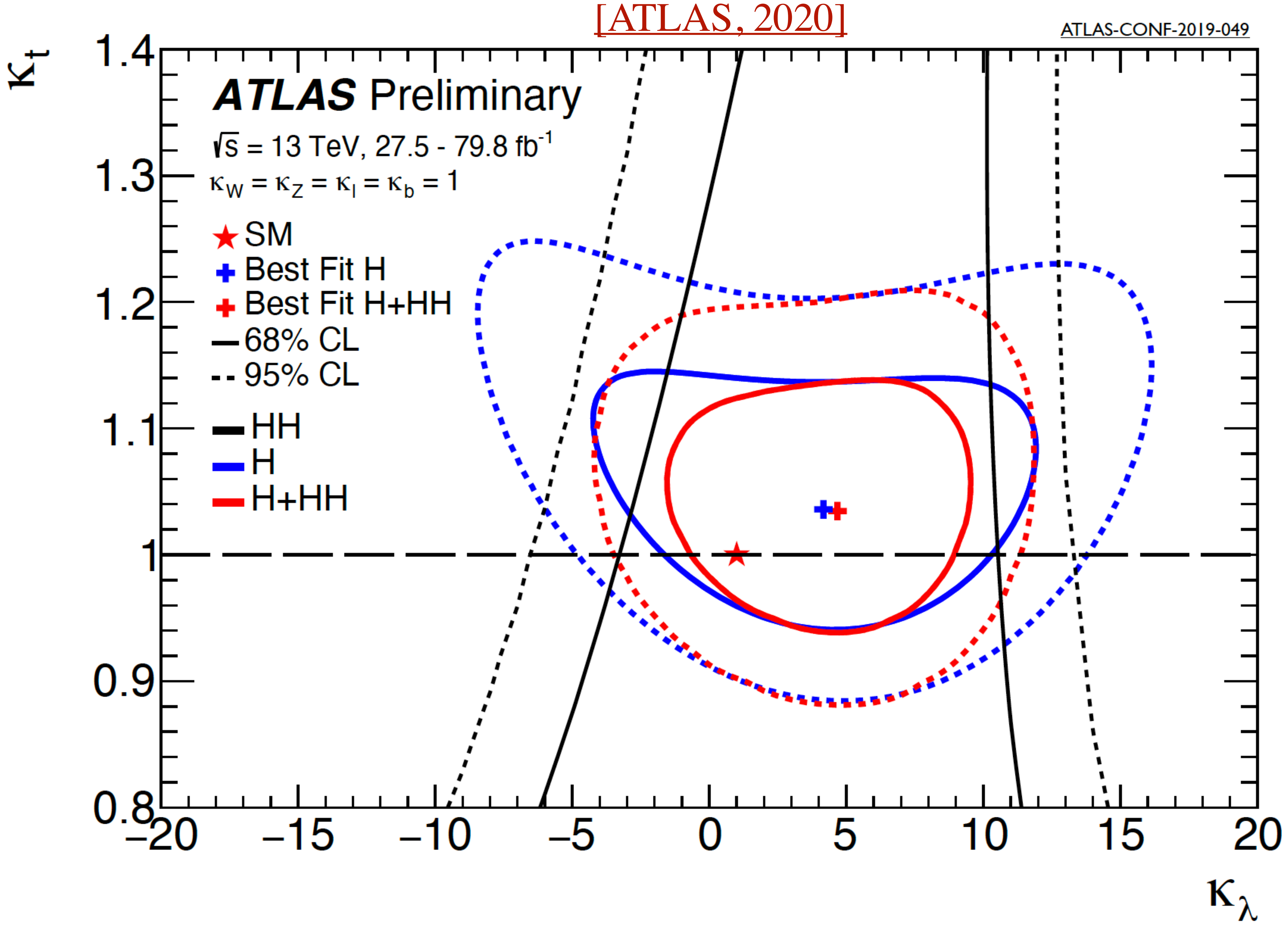
$\delta k_\lambda \sim 5\,\% \Rightarrow$ 1st ord ($T = 0$ and $T = T_c$ not connected)

Where do we stand?

Higgs self interactions



[ATLAS, 2020]



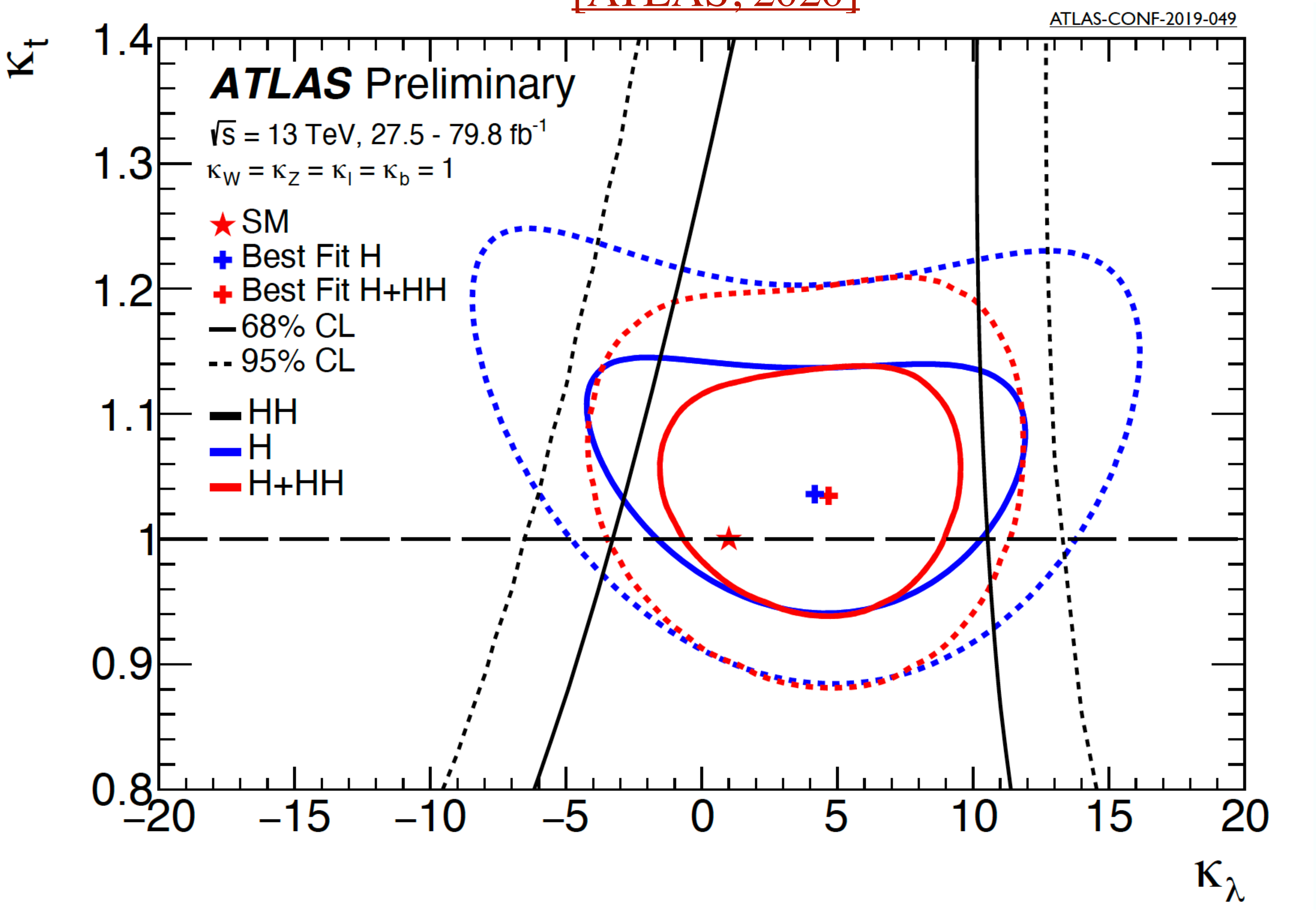
One of the flagship measurements foreseen for the HL-LHC. [Di Micco et al., 1910.00012]

HL-LHC projections

Higgs self interactions

Now

[ATLAS, 2020]



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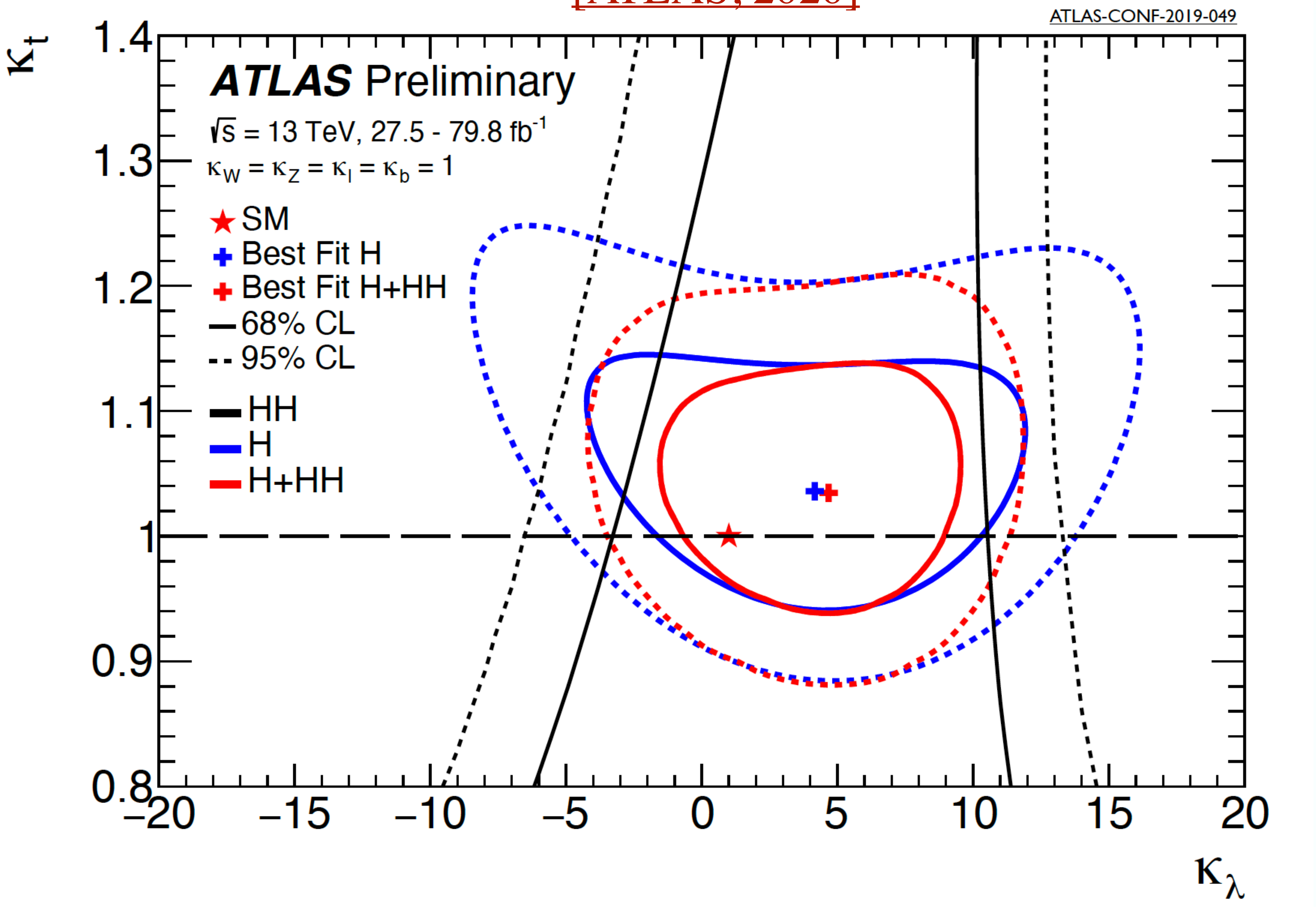
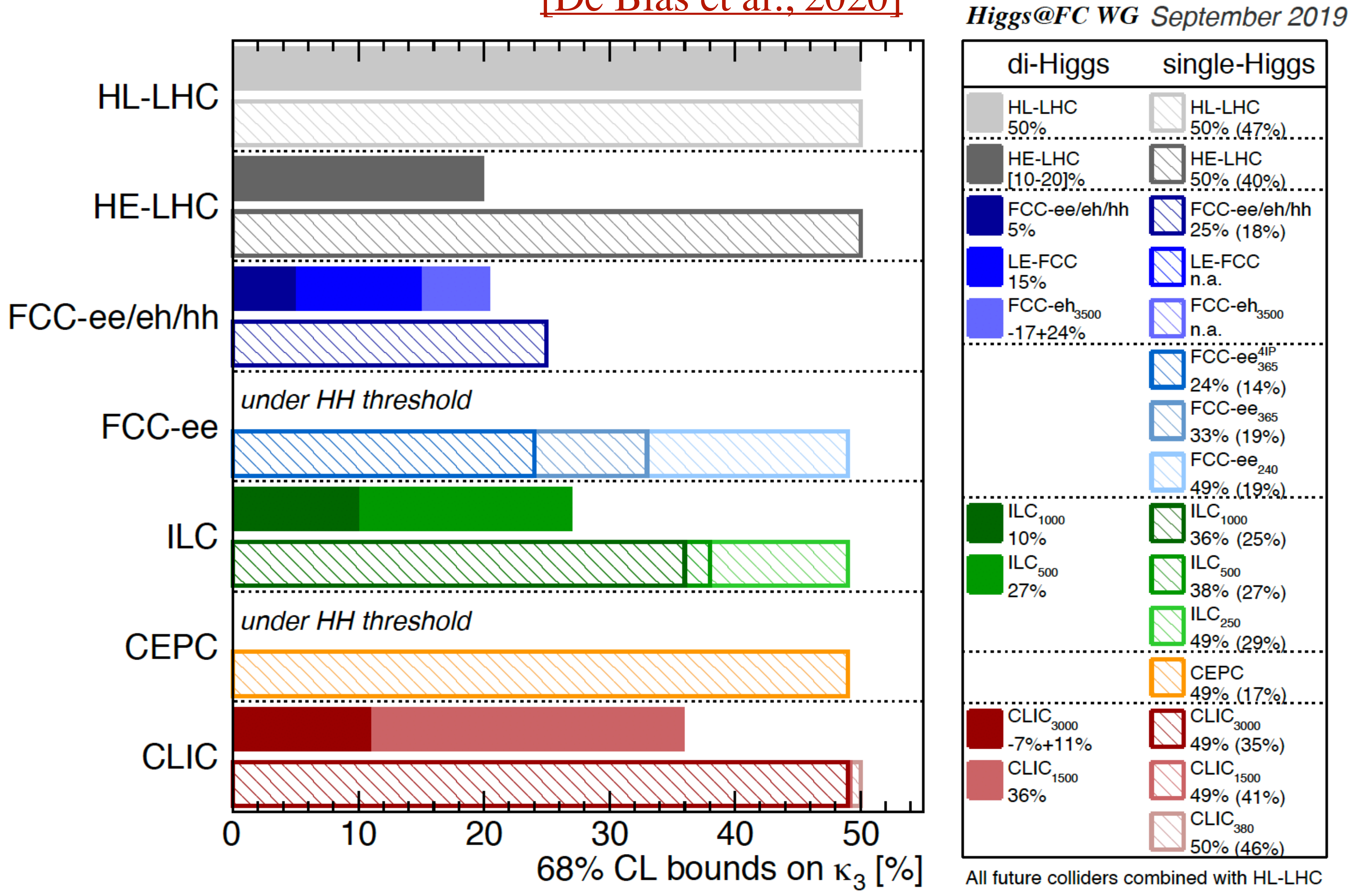


Future

[De Blas et al., 2020]



Currently limits on k_λ from H and HH are comparable and will stay so at the HL-LHC.
Borderline sensitivity to say something about EW baryogenesis…

Precision physics at the HL-LHC

The main questions

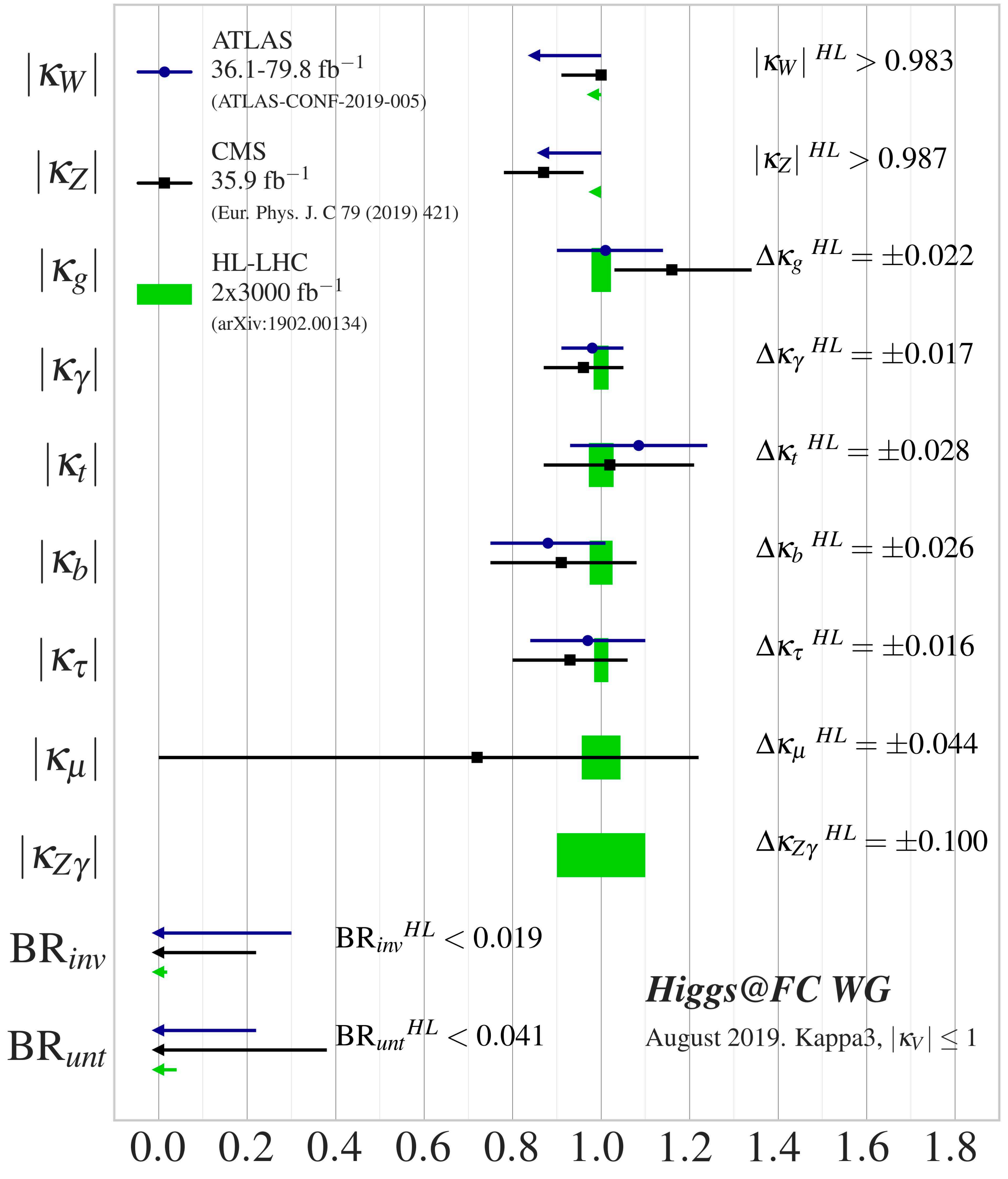
Given the statistics increase of a factor ~20 with respect to what we currently have and the expected experimental precision on key EW/top/Higgs measurements:

1. What is the precision goal for TH predictions?

2. How to frame and interpret our results so to maximally exploit the LHC data?

HL-LHC projections

Higgs couplings

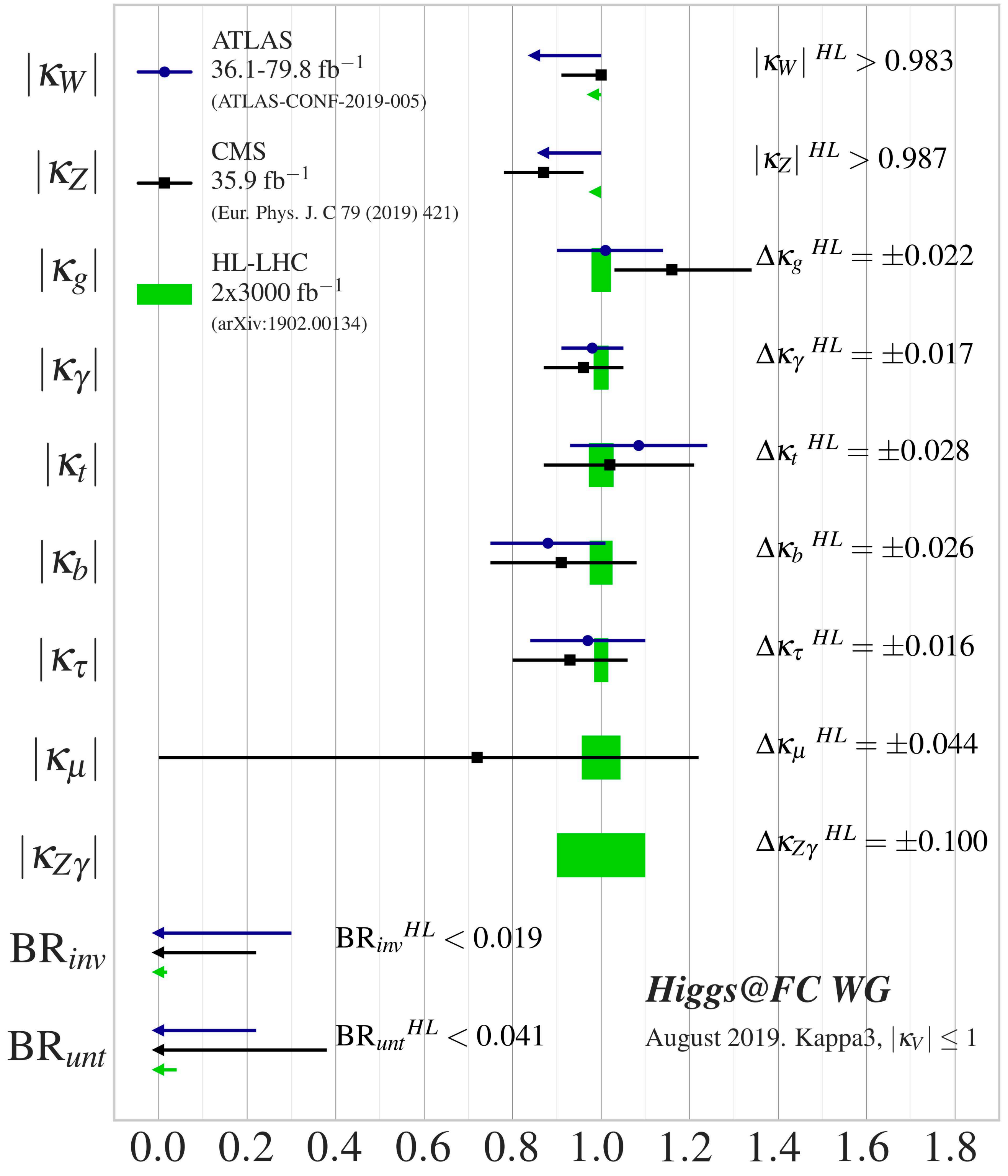


10-20%

$$(\sigma \cdot \mathrm{BR})(i \to \mathrm{H} \to f) = \frac{\sigma_i^{SM} \kappa_i^2 \cdot \Gamma_f^{SM} \kappa_f^2}{\Gamma_H^{SM} \kappa_H^2} \quad \to \quad \mu_i^f \equiv \frac{\sigma \cdot \mathrm{BR}}{\sigma_{\mathrm{SM}} \cdot \mathrm{BR}_{\mathrm{SM}}} = \frac{\kappa_i^2 \cdot \kappa_f^2}{\kappa_H^2}$$

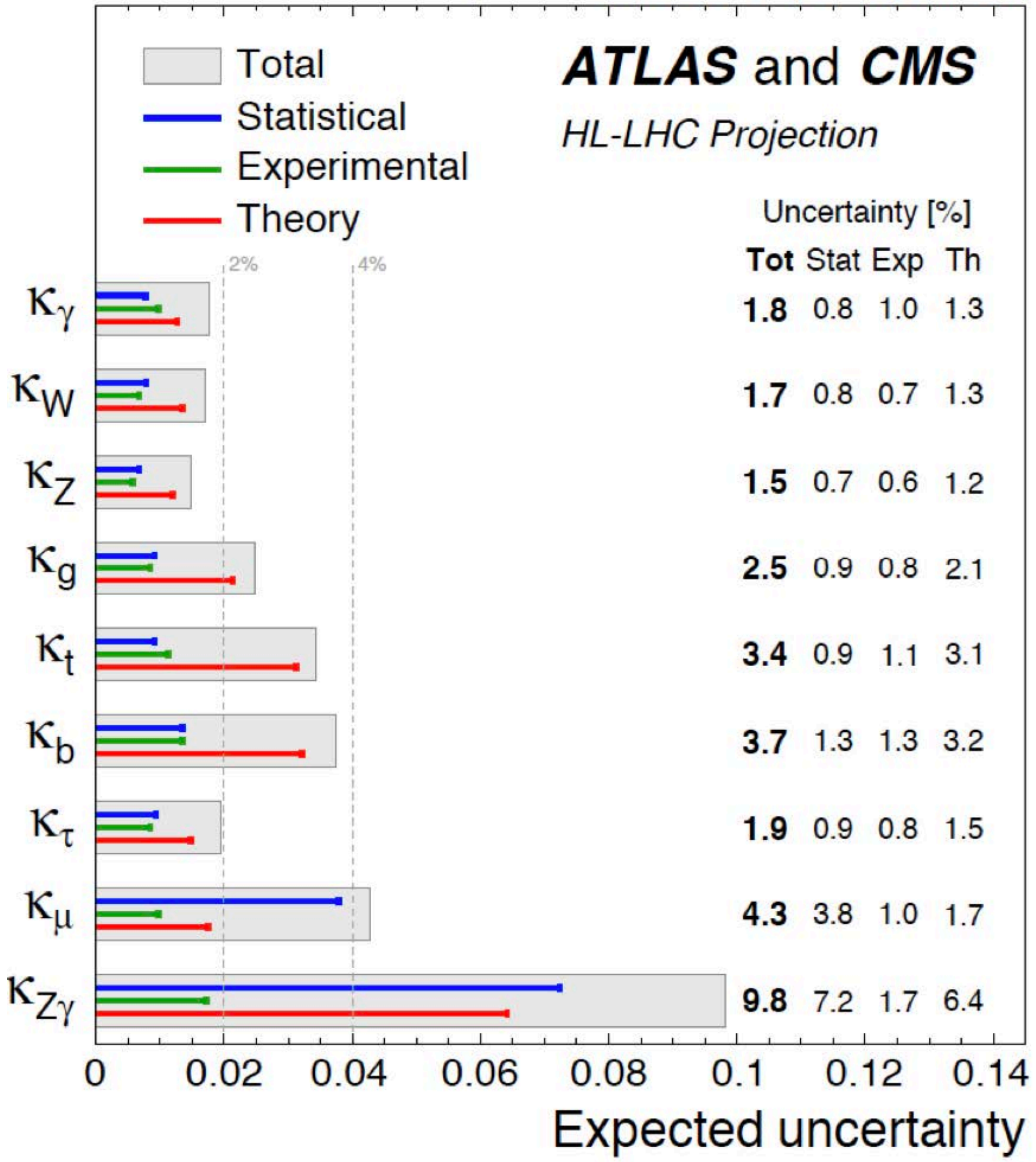
HL-LHC projections

Higgs couplings



10-20% → 2-4%

[De Blas et al., 2020]



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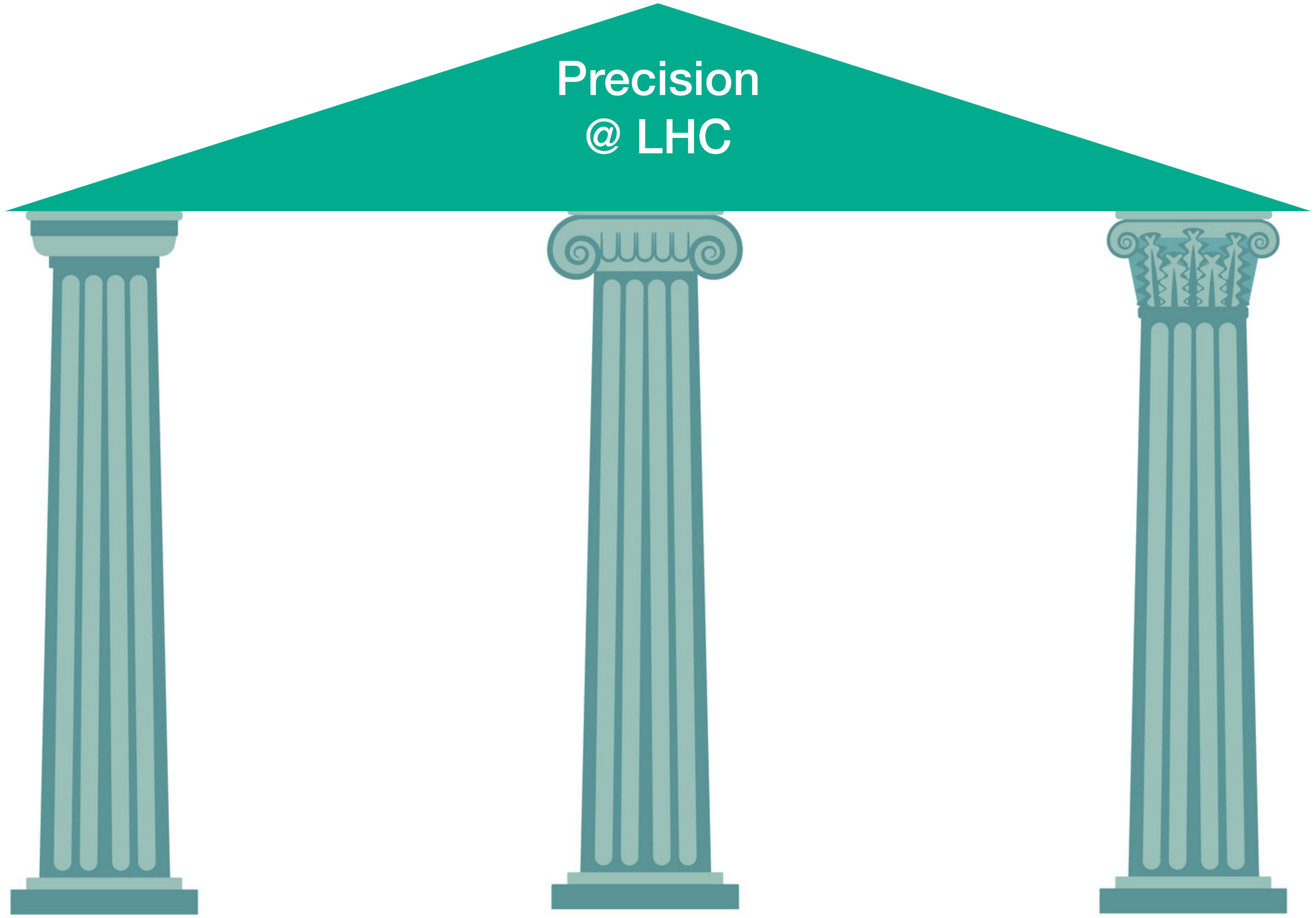
Precision physics at the LHC

Moving towards the "1% goal"



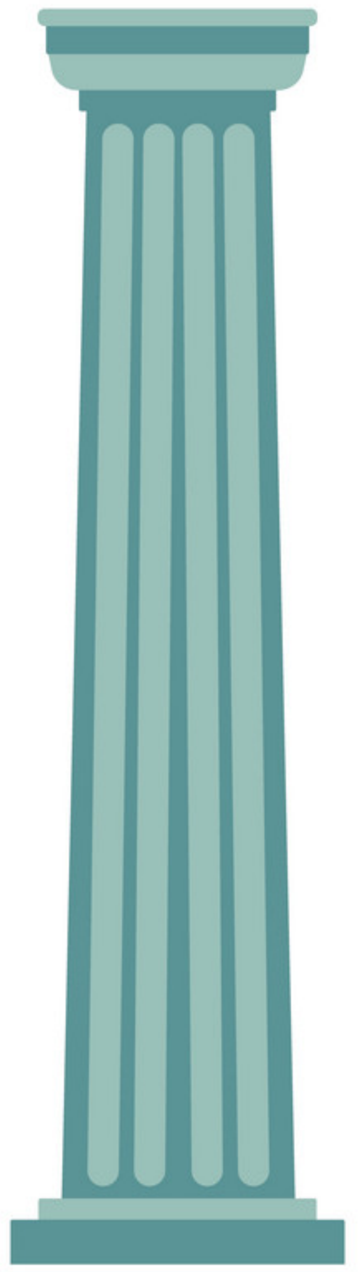
Fixed Order
LO, NLO,…
QCD EW

Resummation
LL, NLL,…
Parton Showers

PDF's
LO,NLO,..Evolution
Fits

Precision physics at the LHC

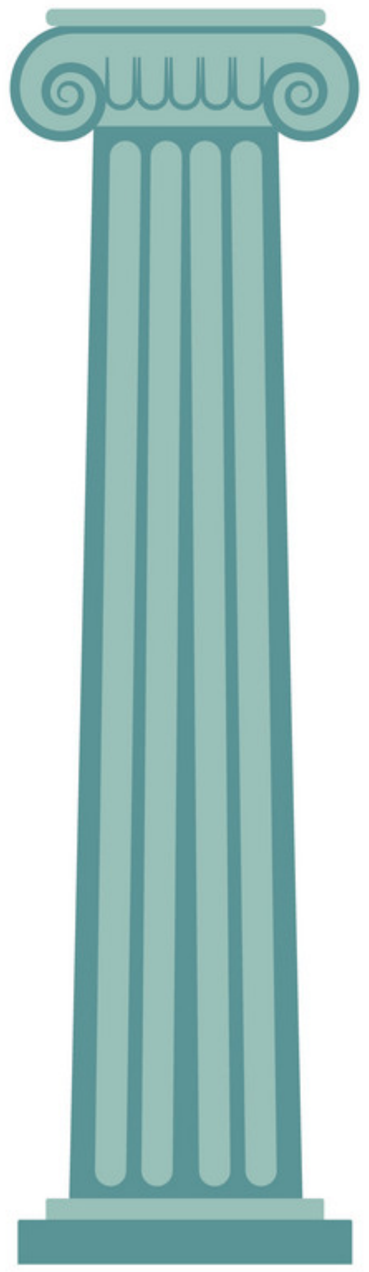
Moving towards the "1% goal"



Fixed Order

LO, NLO,…

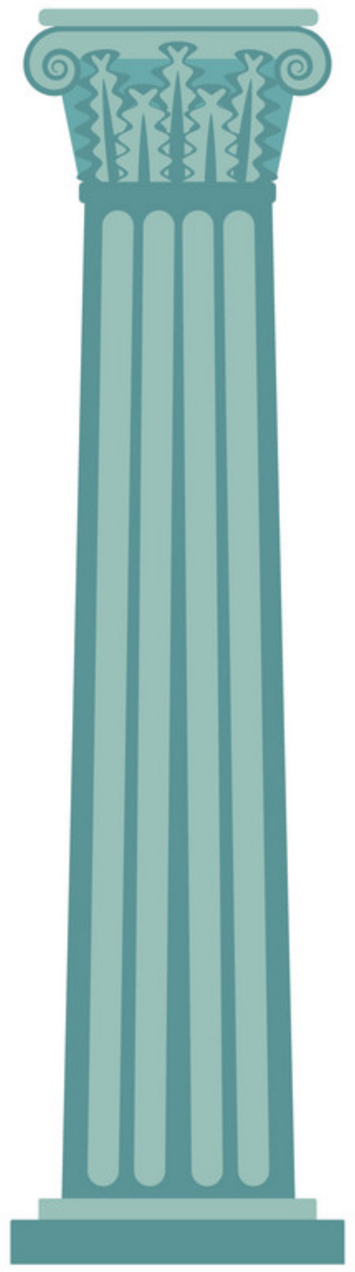
QCD/EW



Resum

LL, NLL,…

PS



PDF's

LO,NLO,..

Fits

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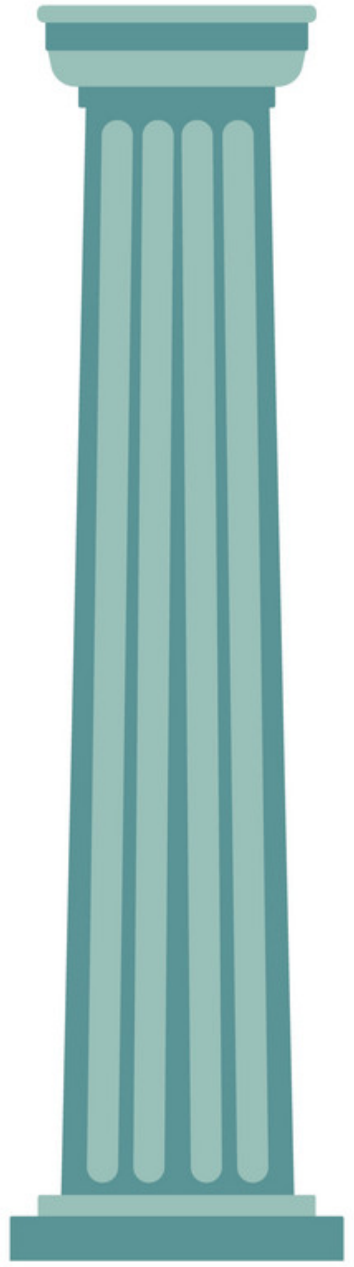
Doric



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- Very fast progress in conceptual as well as technical aspects.
- Tight and consolidated community, with high momentum.
- Considering the status of 20 years ago seems clear that NNLO will be completed and N3LO will start to become available for 2→2 (see 3-loop $q\bar{q} \to \gamma\gamma$ results)
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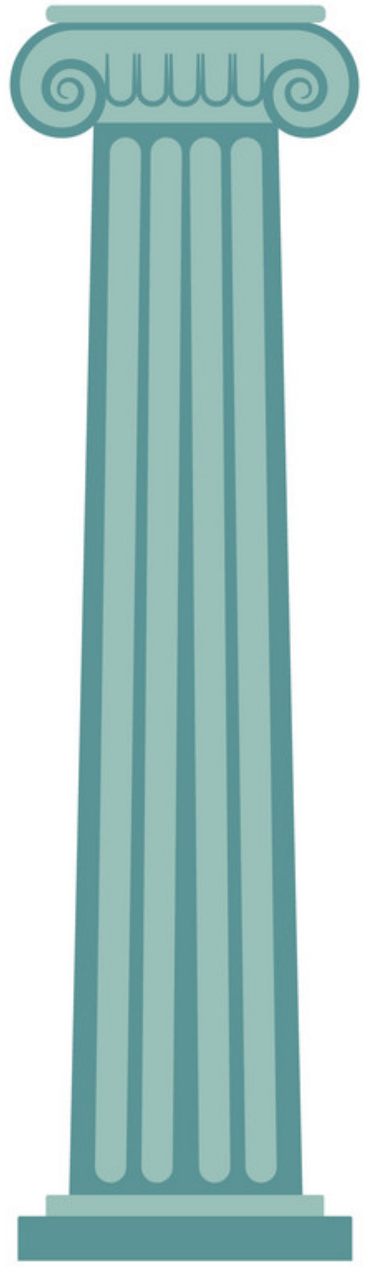
Ionic



Resum

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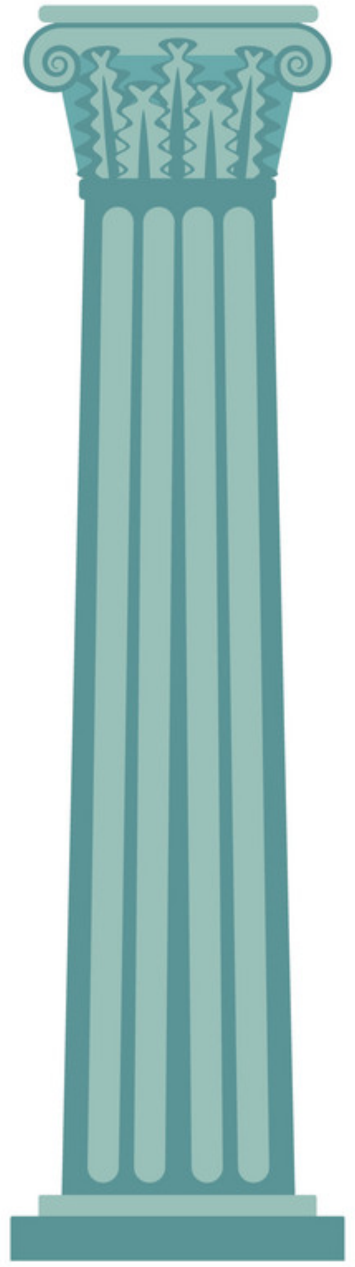
PS

Corinthian



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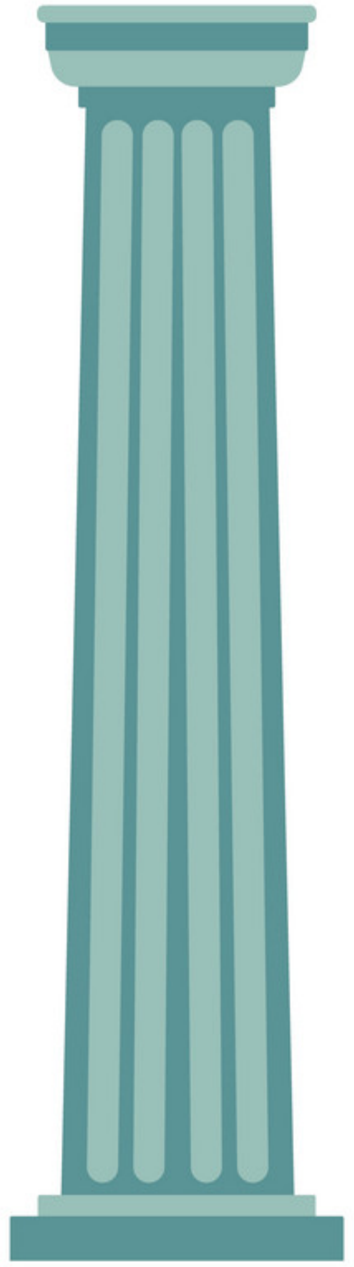

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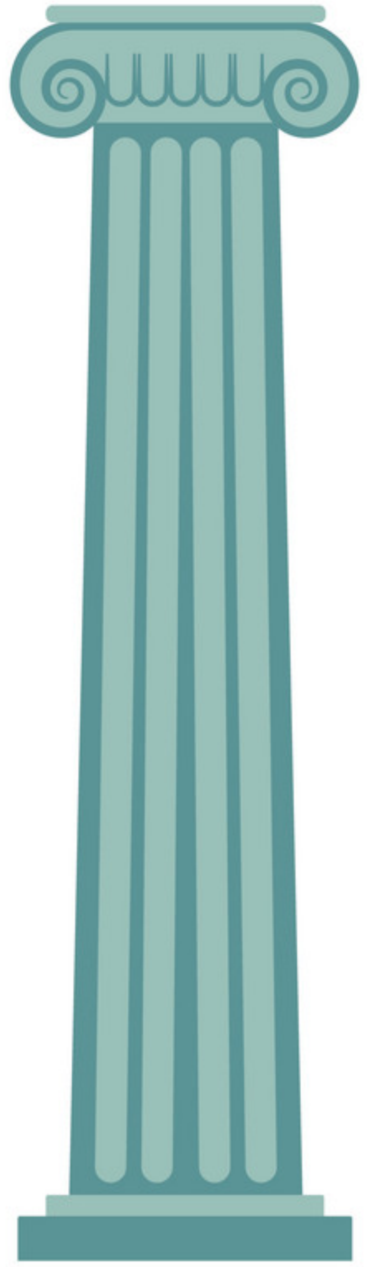

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- A variety of approaches available, both analytical and numerical.
- Analytically historically matching the FO accuracy.
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- Having a NLL and beyond PS, is being explored now. To be seen.
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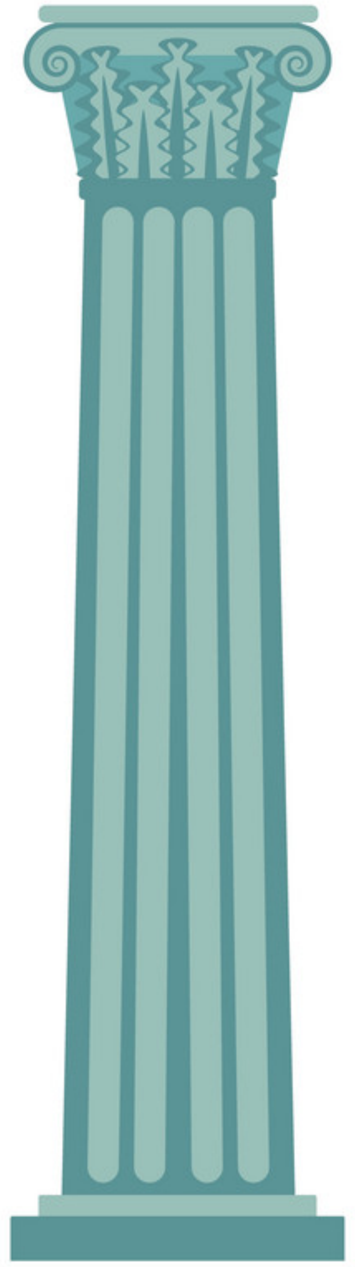

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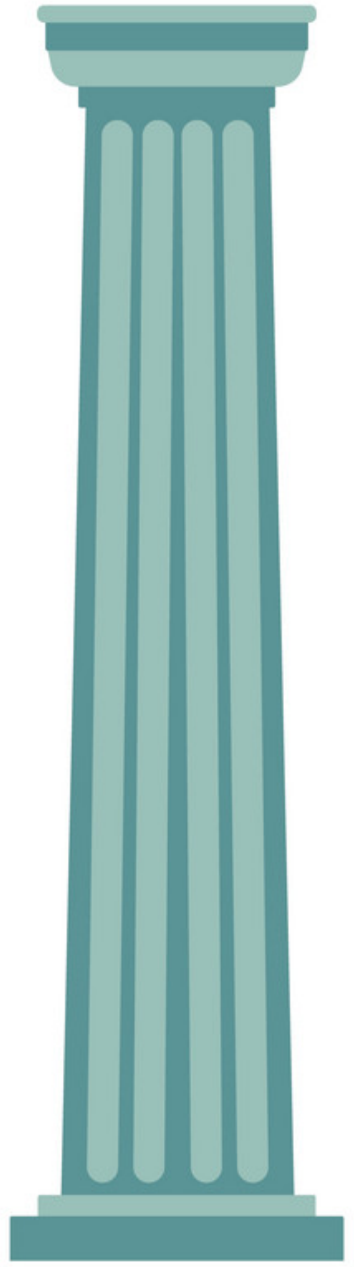

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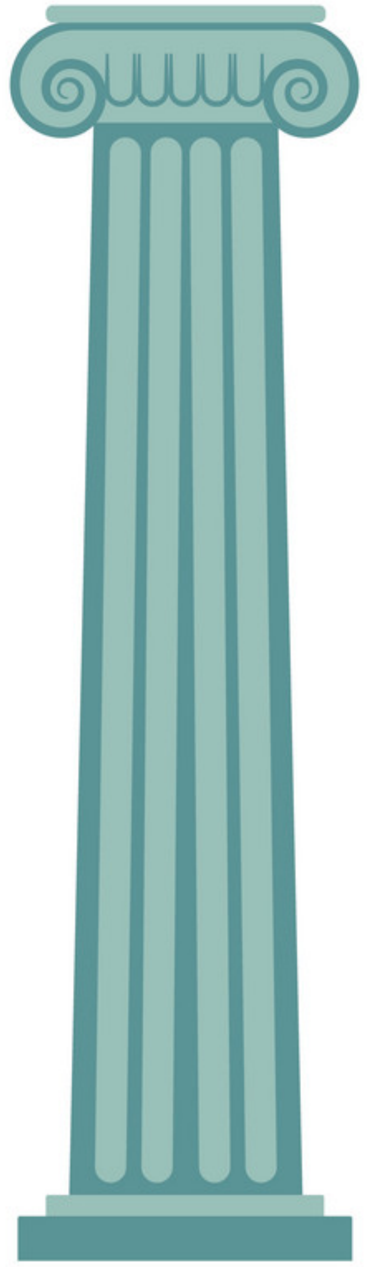

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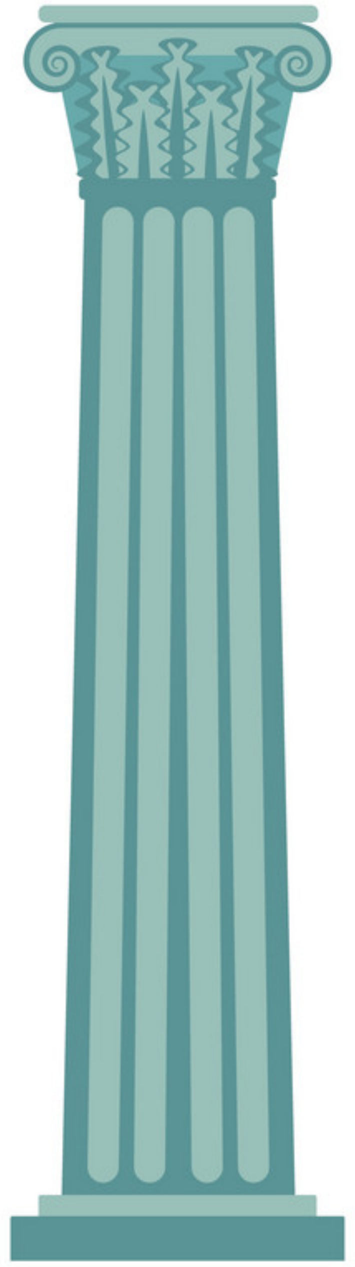

PDF's

LO,NLO,..

Fits

- Complete N3LO PDF's evolution not available yet.
- PDF determination from fitting large set of data. Final quality depends on measurements.
- Error budget with many sources. MHO uncertainties yet to be included in the final assessment.
- Reaching 1% will be very challenging.
- Room for a breakthrough from lattice.

Precision physics at the HL-LHC

The main questions

Given the statistics increase of a factor ~20 with respect to what we currently have and the expected experimental precision on key EW/top/Higgs measurements:

1. What is the precision goal for TH predictions?

2. How to frame and interpret our results so to maximally exploit the LHC data?

The way of SMEFT

Going beyond the SM

Three key properties of the SM:

- Mass generation with gauge invariance
- Unitarity (up to a predefined Λ)
- Perturbativity/renormalizability

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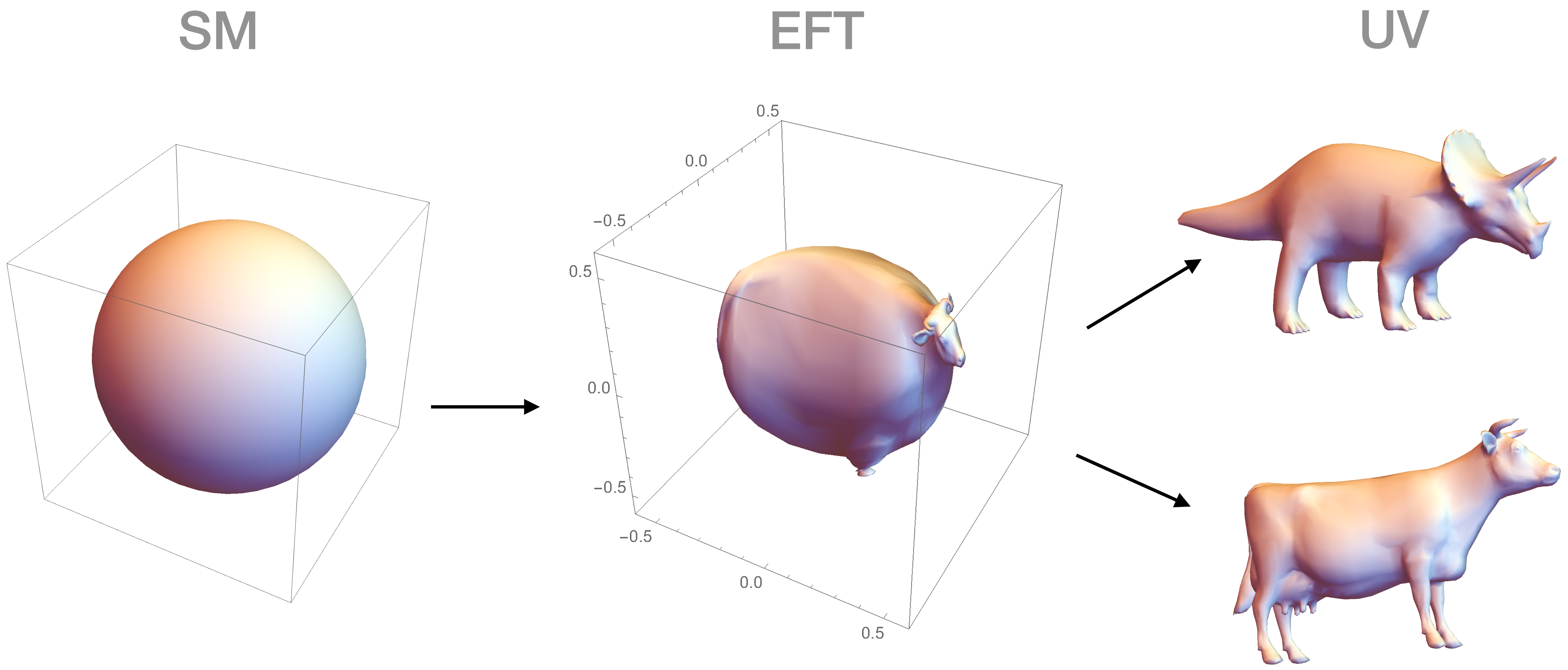

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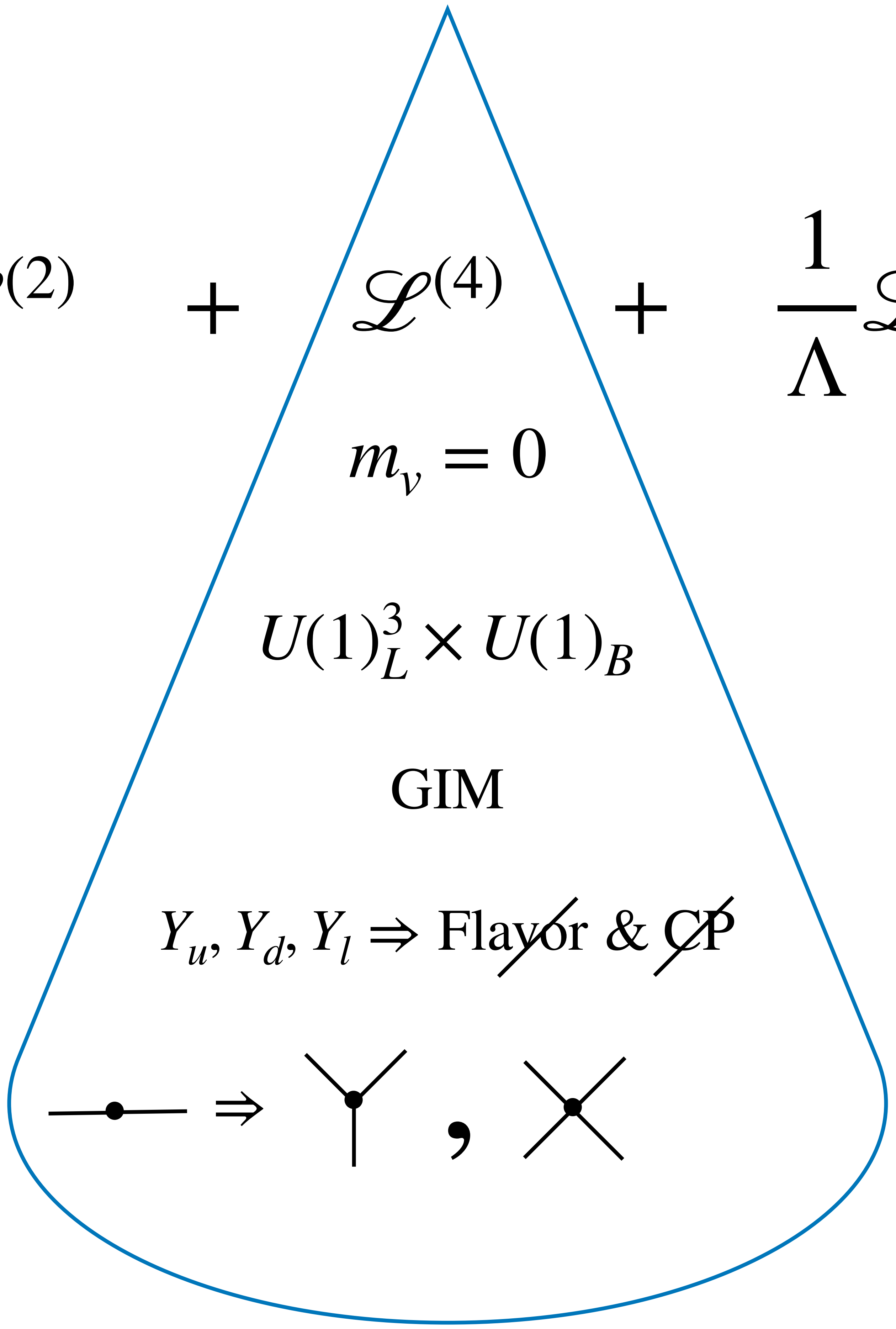

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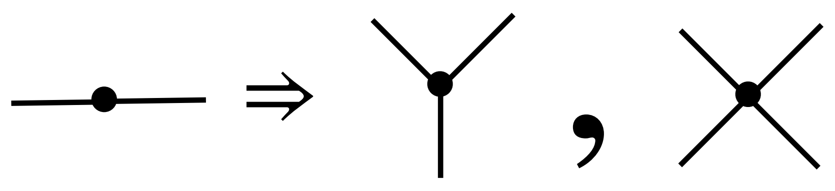
$m_\nu = 0$

$U(1)^3_L \times U(1)_B$

GIM

$Y_u, Y_d, Y_l \Rightarrow$ ~~Flavor~~ & ~~CP~~



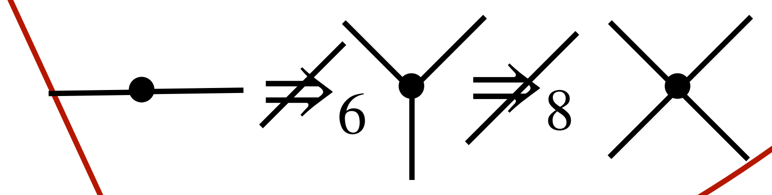
$\not{U(1)}_L \rightarrow m_\nu \neq 0$

~~Flavor~~ $\Rightarrow \mu \rightarrow e\gamma, \Delta m_K, \dots$

~~CP~~ $\Rightarrow$ edm's

Dipoles $\Rightarrow (g-2)_\mu$

$U(1)_B \Rightarrow p \rightarrow \pi^0 e^+$



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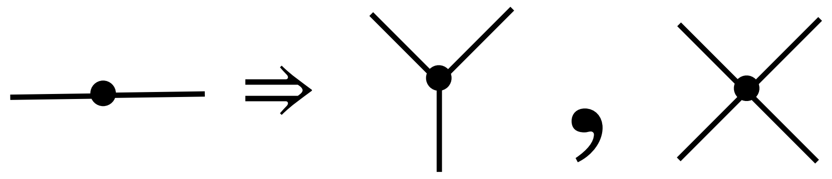

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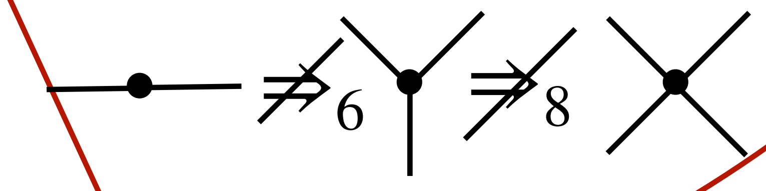

Rattazzi® adapted

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$\mathcal{L}^{(2)}$:

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$\Rightarrow \Lambda \simeq 10^3$ GeV

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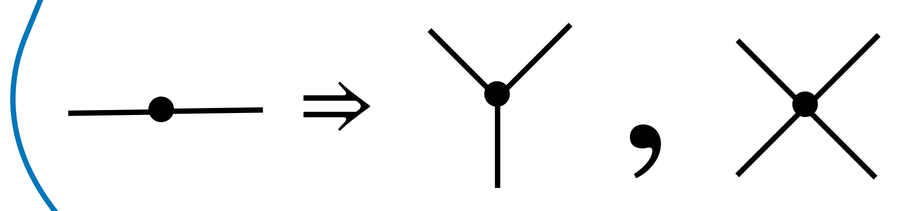

$\frac{1}{\Lambda}\mathcal{L}^{(5)} + \frac{1}{\Lambda^2}\mathcal{L}^{(6)} + \dots$:

~~$U(1)_L$~~ $\rightarrow m_\nu \neq 0$ $\quad \Rightarrow \Lambda \geq 10^{14}$ GeV

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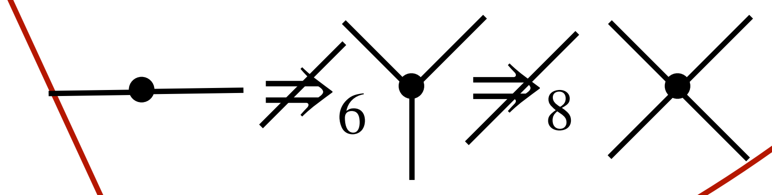

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Λ_{UV}

TeV

Simplicity 🙂

Naturalness ☹️

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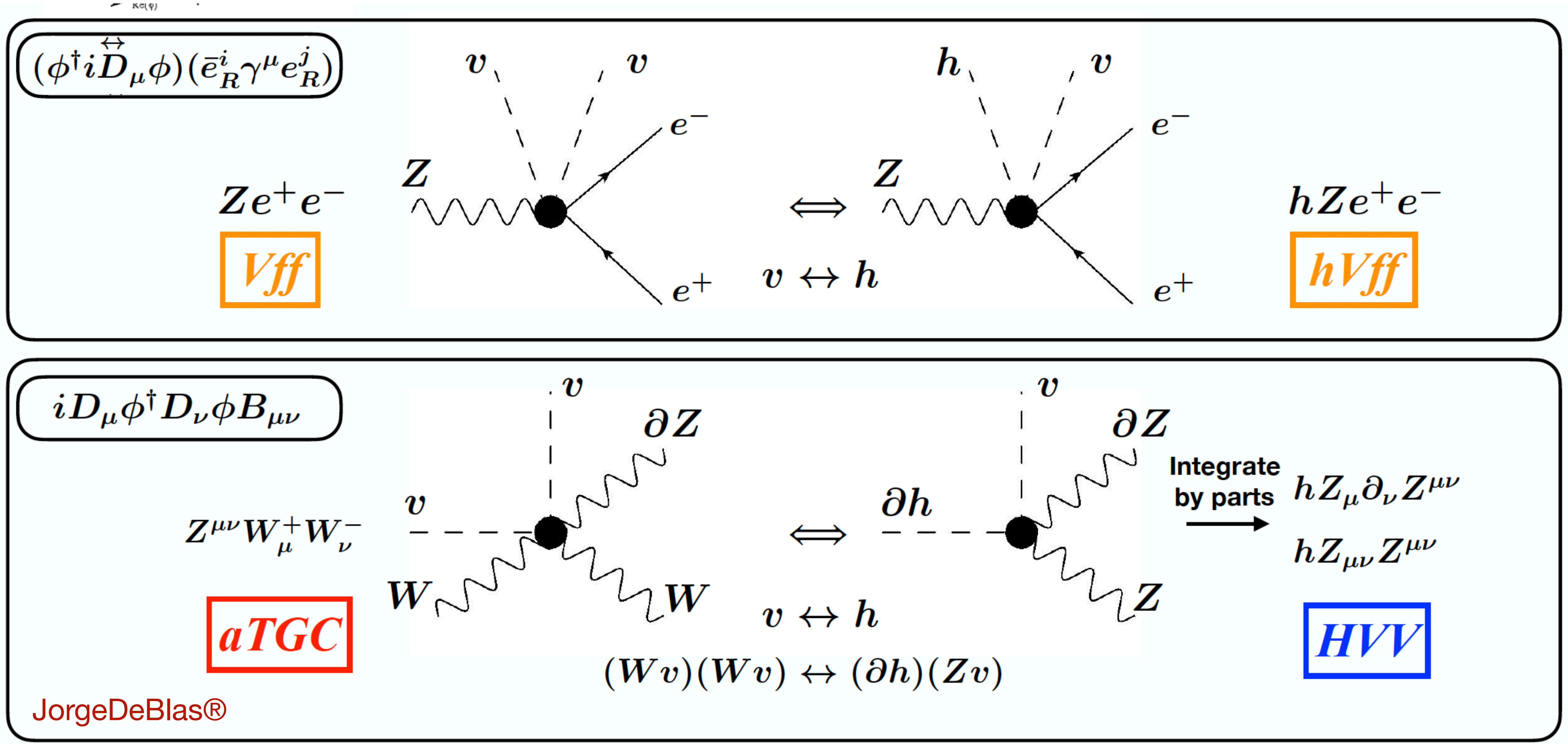
$\not\Rightarrow_6$ $\not\Rightarrow_8$ $\Rightarrow \Lambda \geq 10^3$ GeV

The way of SMEFT

Unlocking at dim=8

dim=6 : 3-point ⇒ 4-point

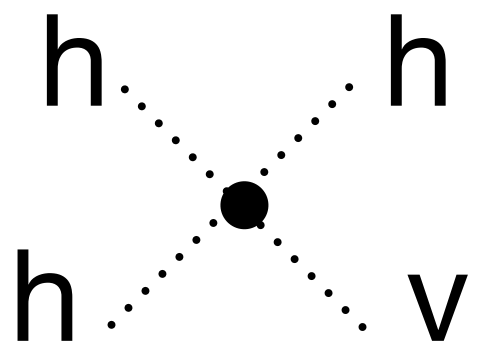
dim=8 : 3-point and 4-point independent (cfr HEFT)

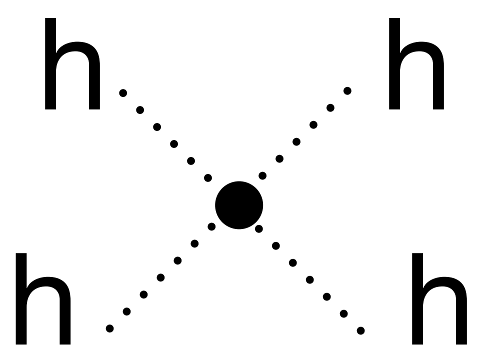


$$V^{\rm BSM}(\Phi) = -\mu^2(\Phi^\dagger\Phi) + \lambda(\Phi^\dagger\Phi)^2 + \sum_n \frac{c_{2n}}{\Lambda^{2n-4}}(\Phi^\dagger\Phi - \frac{v^2}{2})^n$$

$n = 3\,(\dim = 6) \Rightarrow$ $\quad \kappa_\lambda = 1 + \frac{c_6 v^2}{\lambda\Lambda^2} \quad \kappa_{\lambda_4} = 1 + \frac{6c_6 v^2}{\lambda\Lambda^2}$

$n = 4\,(\dim = 8) \Rightarrow$ $\quad k_{\lambda_3}$ and k_{λ_4} independent





The way of SMEFT

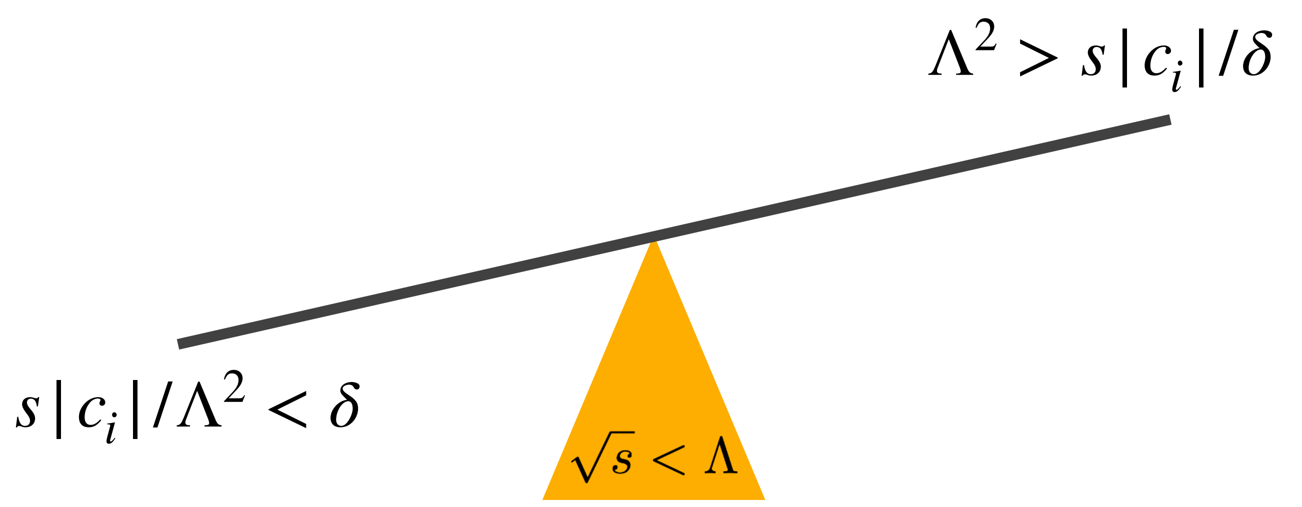
A simple approach

One can satisfy all the previous requirements, by building an EFT on top of the SM that respects the gauge symmetries:

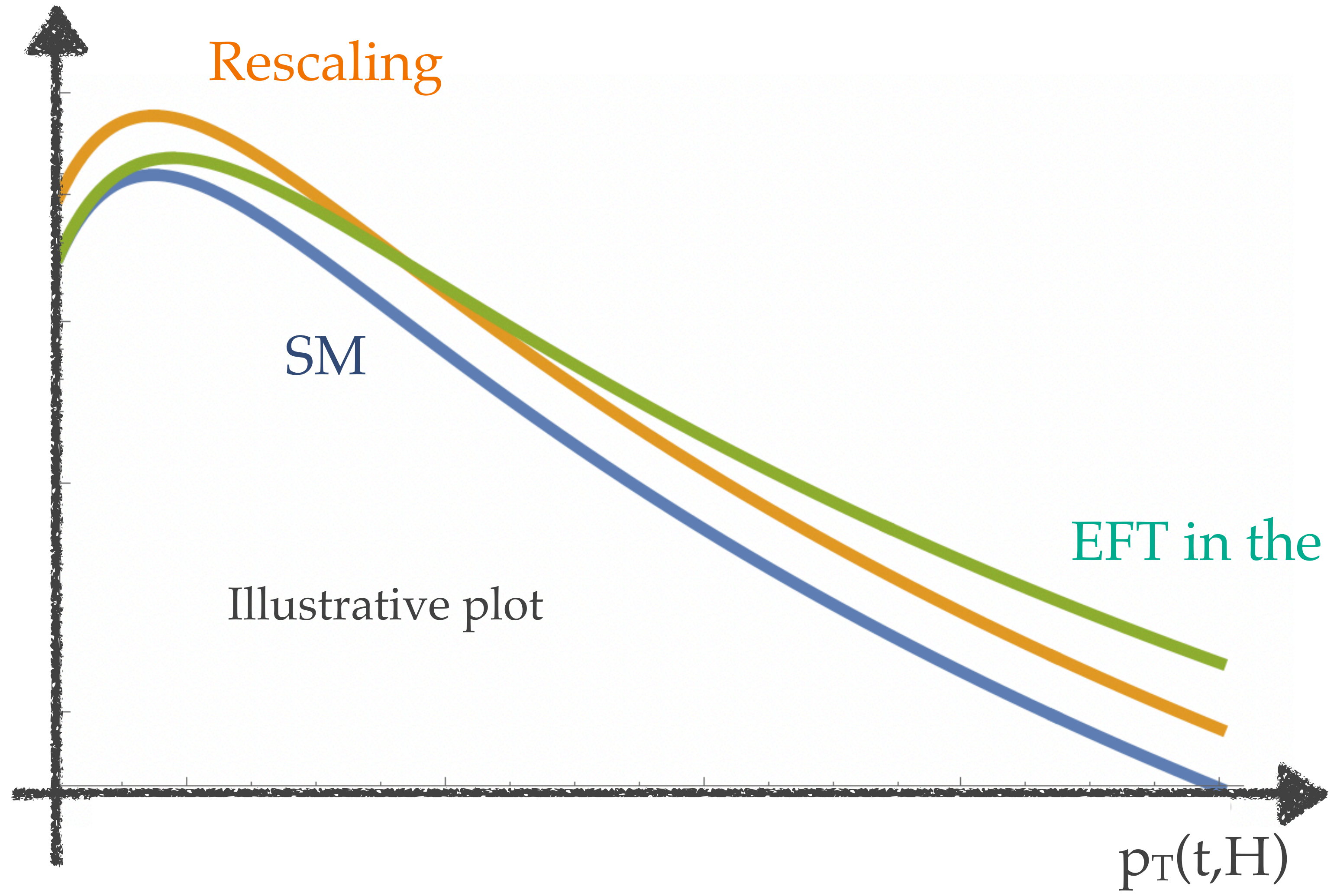
$$\mathscr{L}_{\text{SMEFT}} = \mathscr{L}_{\text{SM}}^{(4)} \quad + \quad \frac{1}{\Lambda^2}\sum_i^{N_6} c_i \mathcal{O}_i^{(6)} \quad + \quad \frac{1}{\Lambda^4}\sum_j^{N_8} c_j \mathcal{O}_j^{(8)} \quad + \quad \dots$$

With the "only" assumption that all new states are heavier than energy probed by the experiment $\sqrt{s} < \Lambda$.

The theory is renormalizable order by order in $1/\Lambda$, perturbative computations can be consistently performed at any order, and the theory is predictive, i.e., well defined patterns of deviations are allowed, that can be further limited by adding assumptions from the UV. Operators can lead to larger effects at high energy (for different reasons).



Energy helps precision



* Sufficiently weakly interacting states may also exist without spoiling the EFT.

The way of SMEFT

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The master equation of an EFT approach has three key elements:

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

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NLO, NNLO, N3LO…

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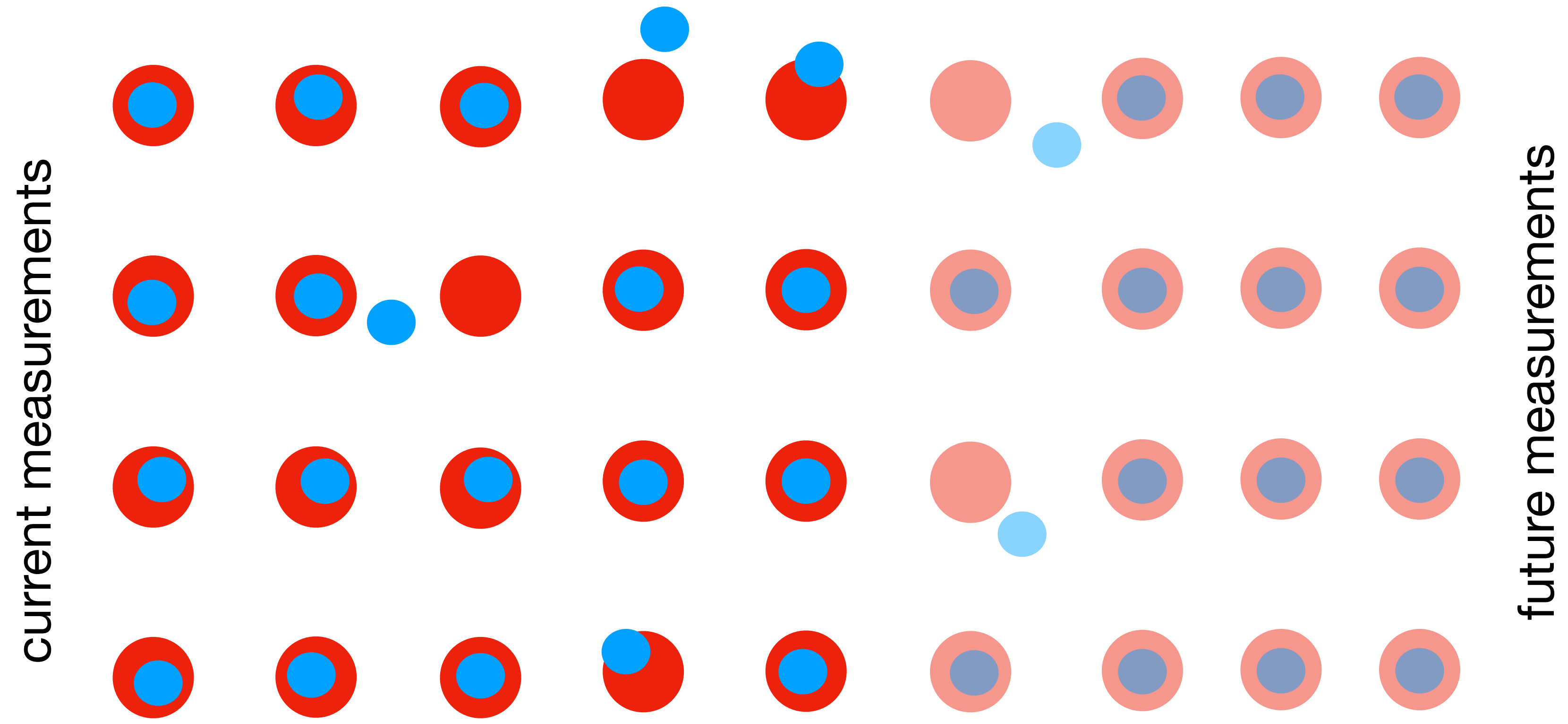

$\Rightarrow$ increased NP Sensitivity

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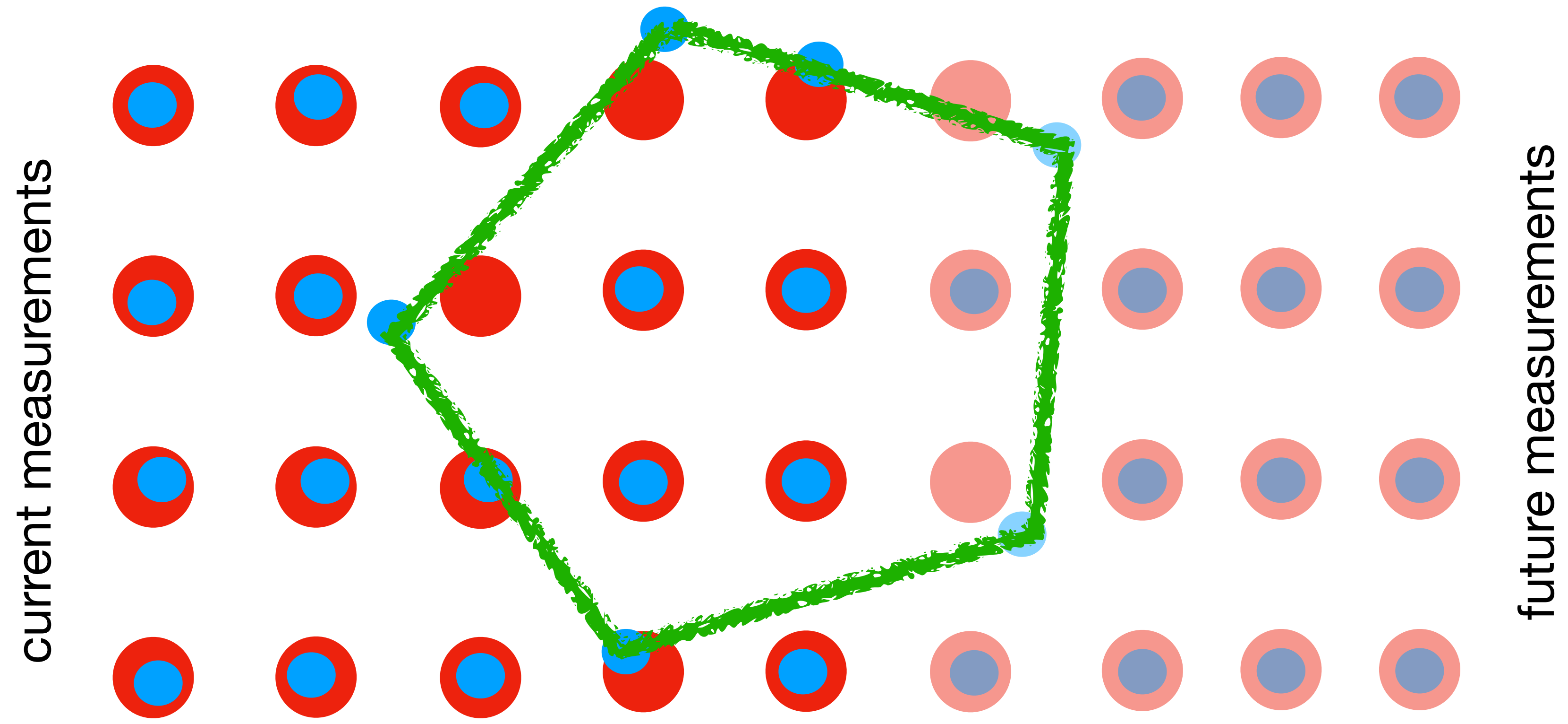

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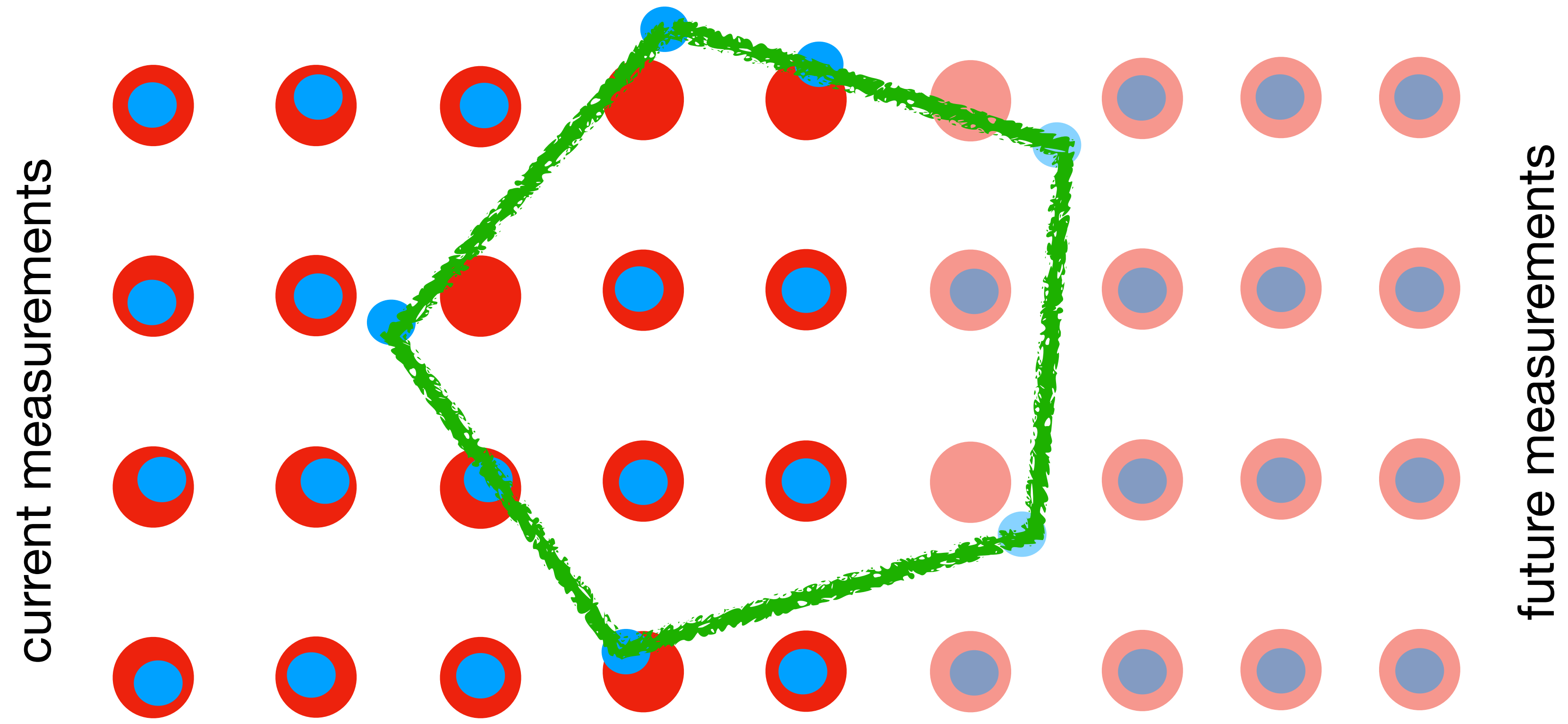
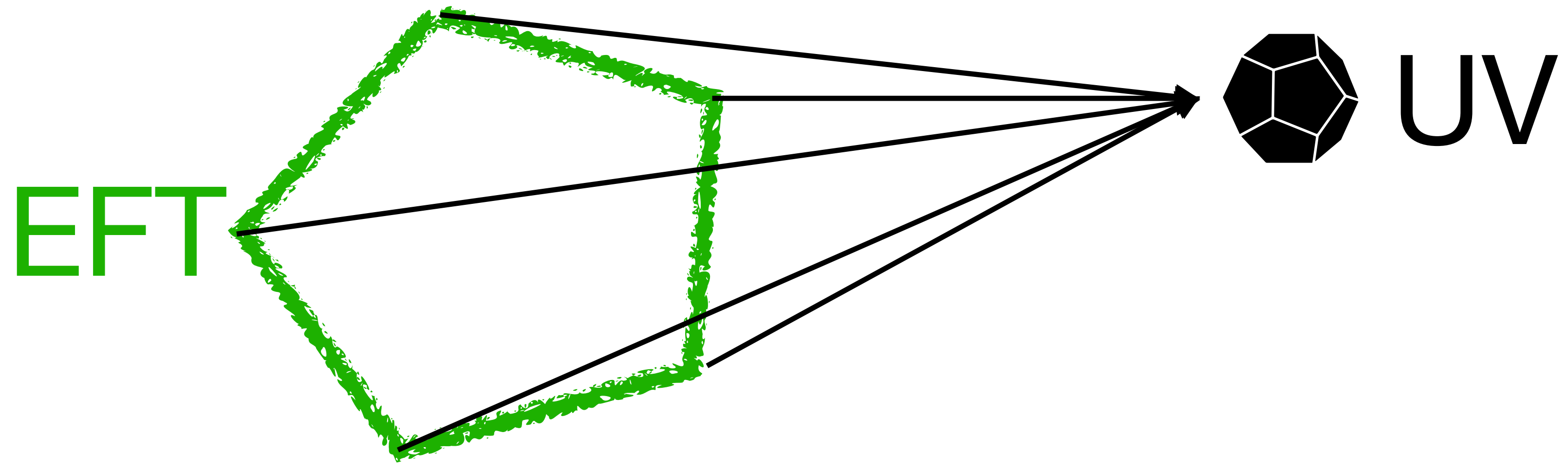


⇒ increased NP Sensitivity

⇒ increased UV identification power



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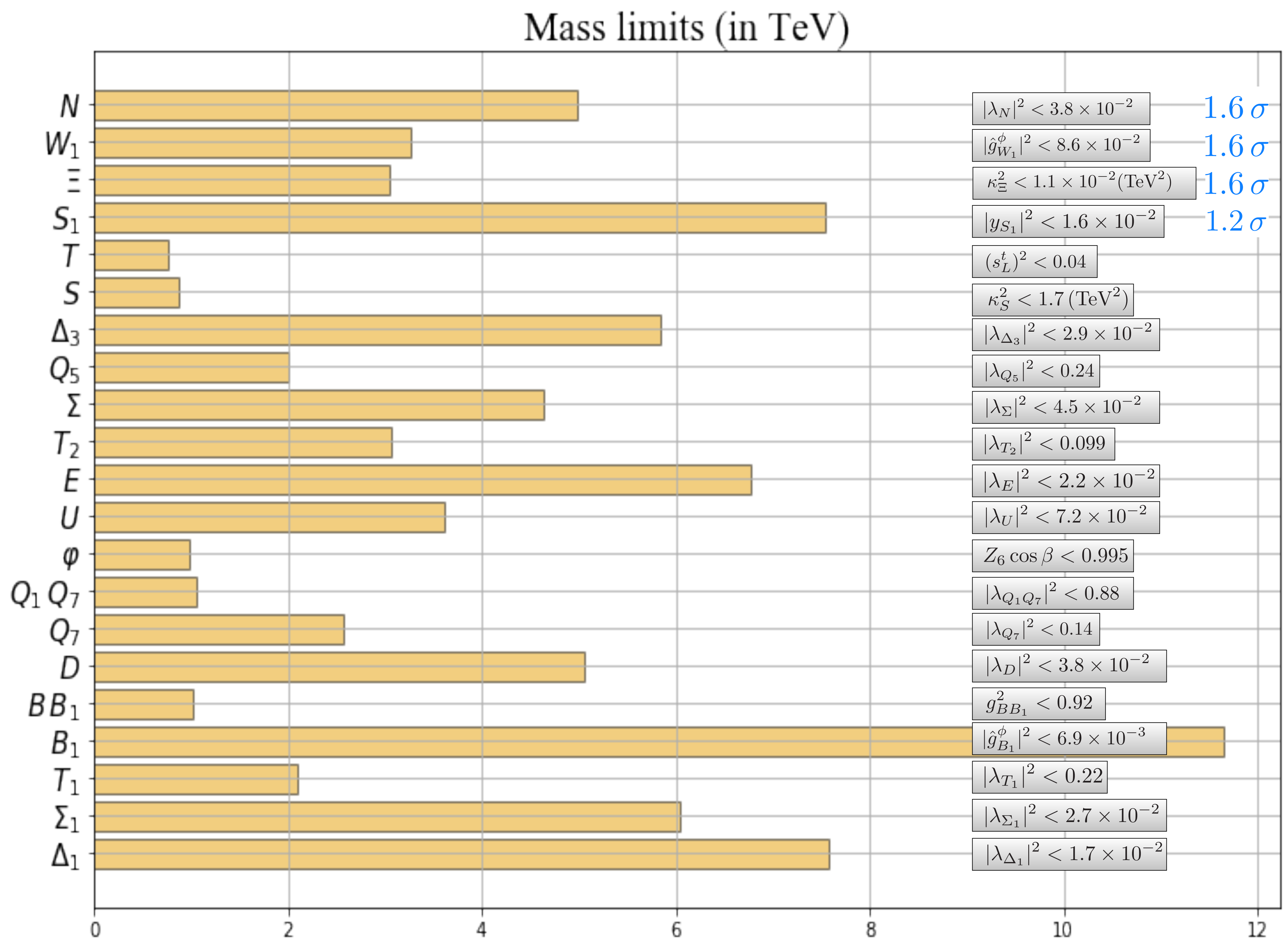
EFT bounds translate to constraints on parameters of UV models

Simplest case: single-field extensions of the SM



[Ellis et al. 2012.02779]

Need for NLO

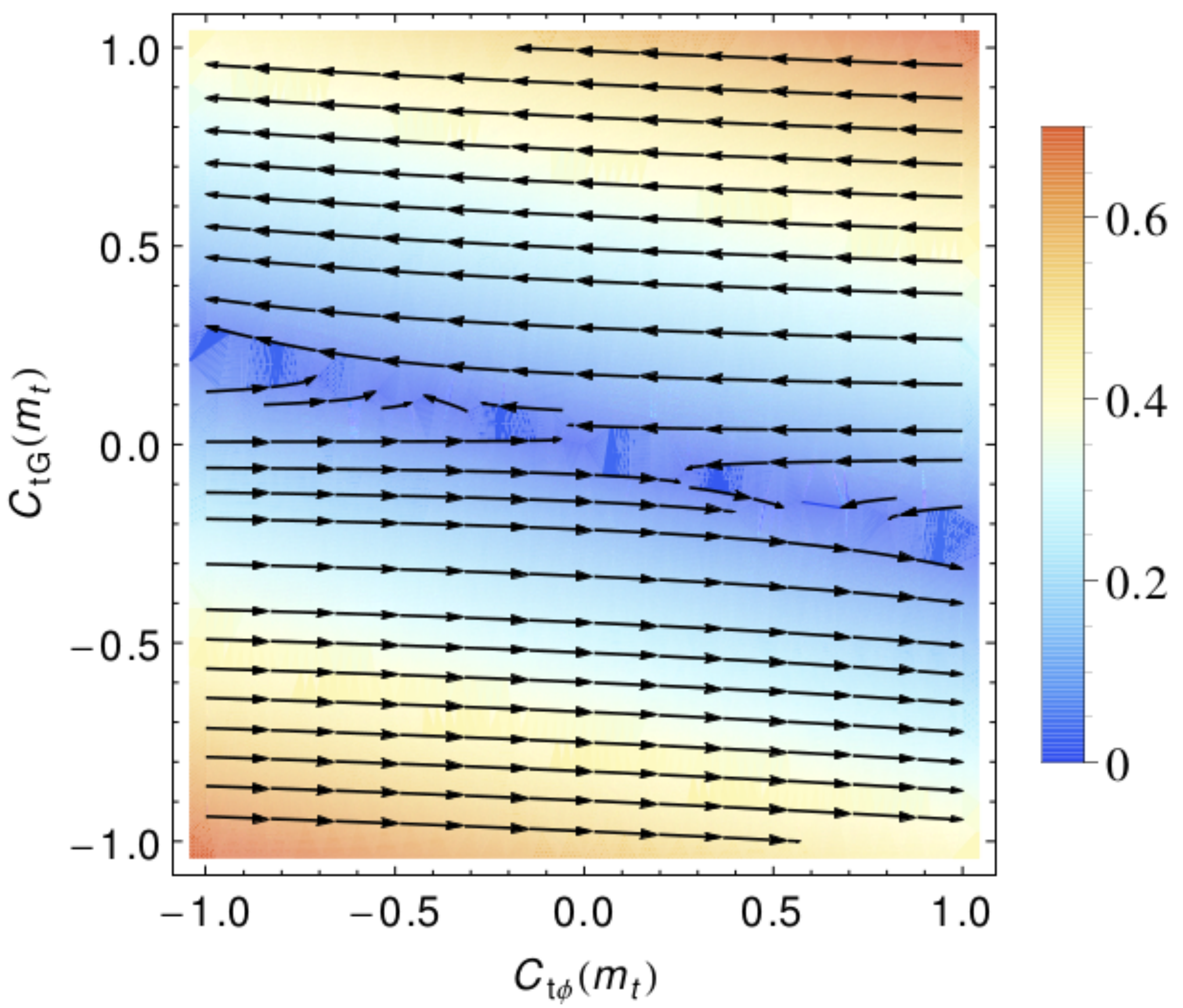
1. Operators run and mix under RGE

Running means that the Wilson coefficients depend on the scale where they are measured (as the couplings in the SM). Note that this introduces also an additional uncertainty in the perturbative computations.

Mixing means that in general the Wilson coefficients at low scale (=where the measurements happen) are related. One immediate consequence is that assumptions about some coefficients being zero at low scales are in general not valid (and in any case have to be consistent with the RGEs). Note also that operator mixing is not symmetric: Op1 can mix into Op2, but not viceversa.

Need for NLO

1. Operators run and mix under RGE



Scale corresponds to the change from mt to 2 TeV.

$$O_{t\phi} = y_t^3 \left(\phi^\dagger\phi\right) \left(\bar{Q}t\right) \tilde{\phi}\,,$$

$$O_{\phi G} = y_t^2 \left(\phi^\dagger\phi\right) G^A_{\mu\nu} G^{A\mu\nu}\,,$$

$$O_{tG} = y_t g_s (\bar{Q}\sigma^{\mu\nu} T^A t)\tilde{\phi} G^A_{\mu\nu}\,.$$

$$\frac{dC_i(\mu)}{d\log\mu} = \frac{\alpha_s}{\pi}\gamma_{ij}C_j(\mu), \quad \gamma = \begin{pmatrix} -2 & 16 & 8 \\ 0 & -7/2 & 1/2 \\ 0 & 0 & 1/3 \end{pmatrix}$$

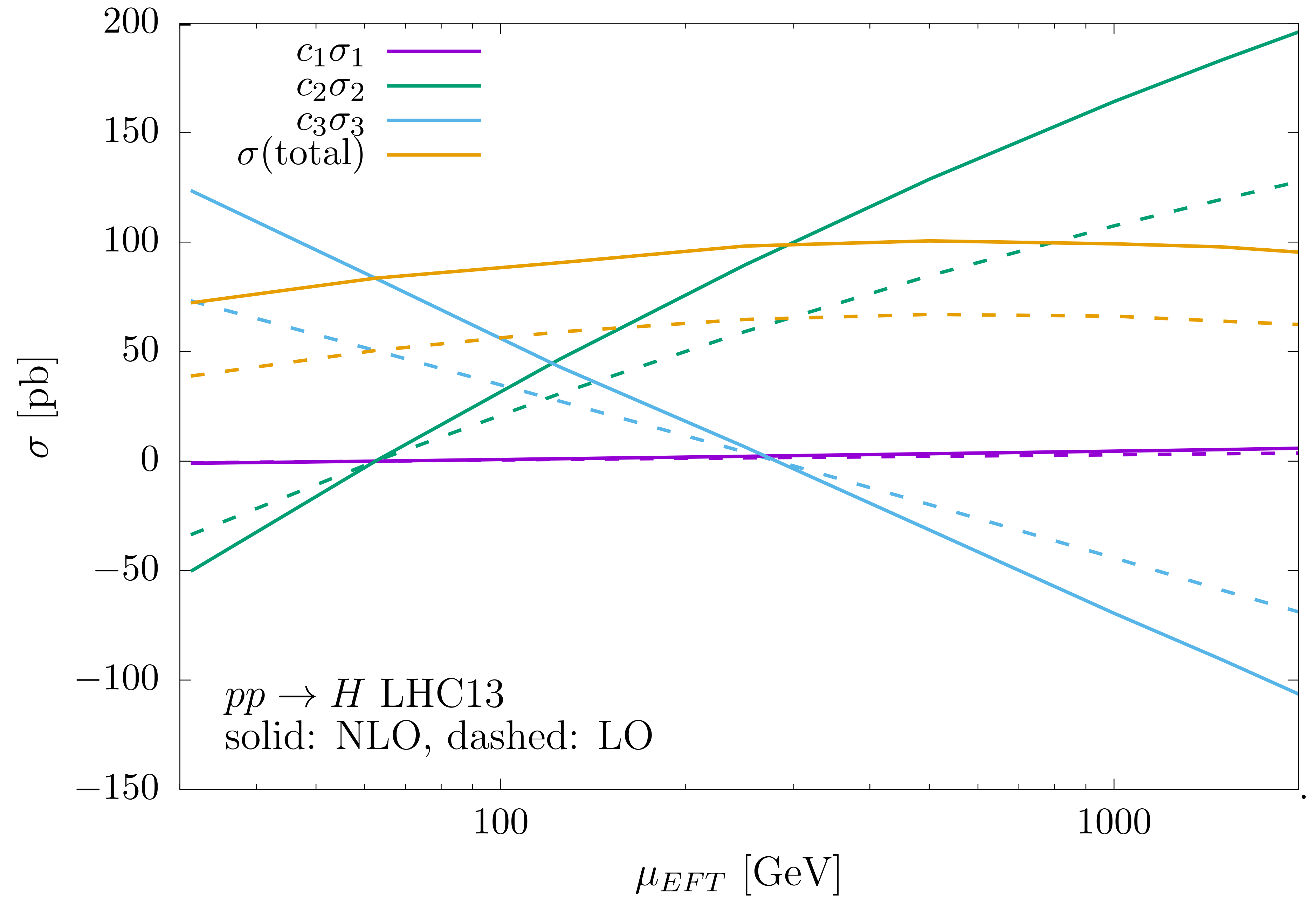
At = 1 TeV: C_{tG} = 1, $C_{t\phi}$ = 0;

At = 173 GeV: C_{tG} = 0.98, $C_{t\phi}$= 0.45

Need for NLO

2. EFT scale dependence

[Deutschmann, Duhr, FM, Vryonidou, 17]



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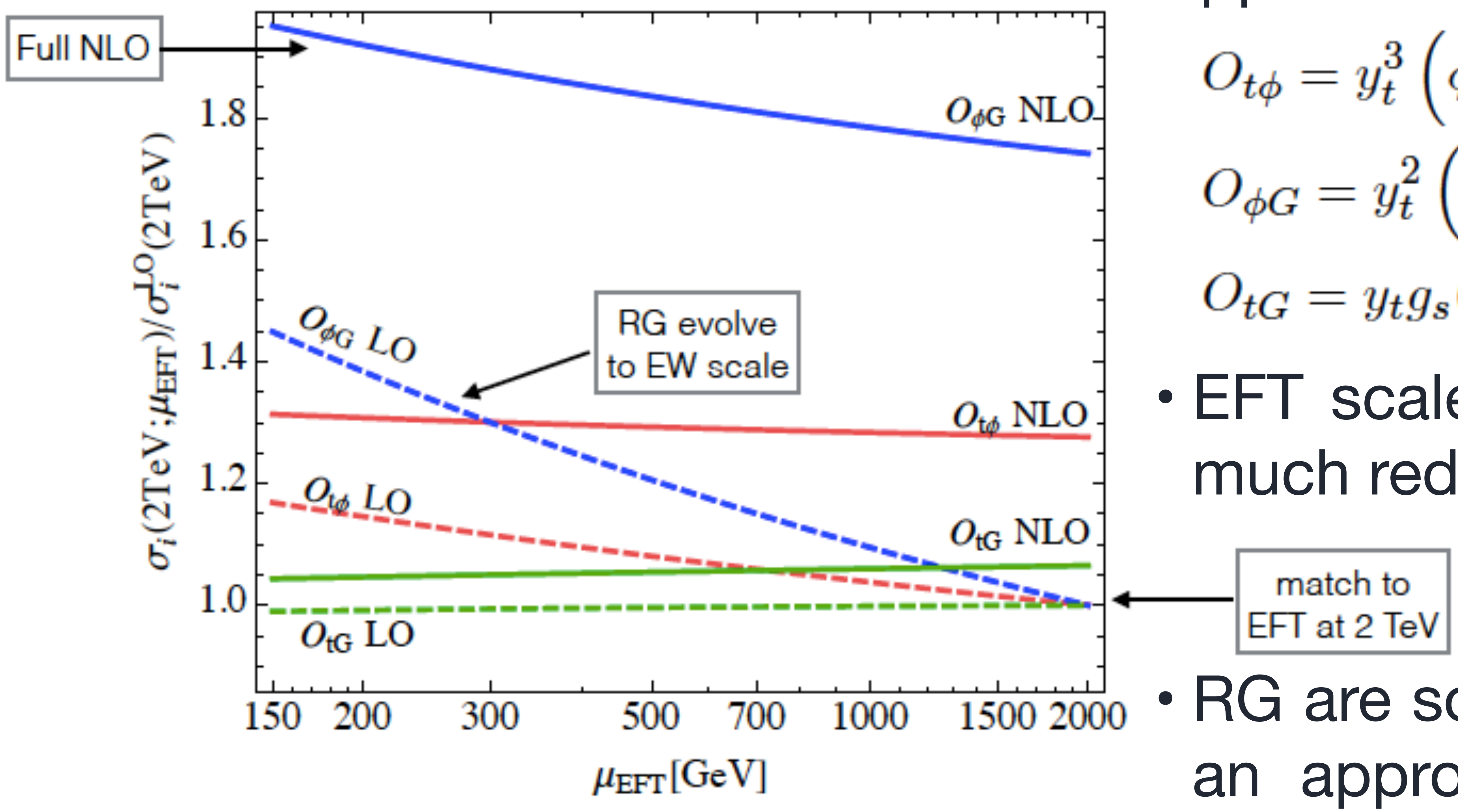
By including the mixing, the overall scale dependence at LO, is very much reduced with respect to the single ones. A global point of view is required: contribution from each coupling may not make sense; only their sum is meaningful.

Need for NLO

3. Genuine NLO corrections (finite terms) are important

[FM, Vryonidou, Zhang, 16]

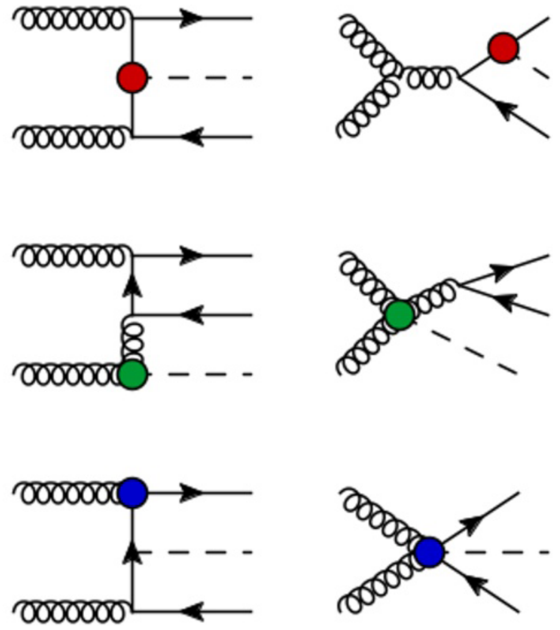


- pp → ttH

$$O_{t\phi} = y_t^3 \left(\phi^\dagger\phi\right)\left(\bar{Q}t\right)\tilde{\phi}\,,$$

$$O_{\phi G} = y_t^2 \left(\phi^\dagger\phi\right) G^A_{\mu\nu} G^{A\mu\nu}\,,$$

$$O_{tG} = y_t g_s (\bar{Q}\sigma^{\mu\nu}T^A t)\tilde{\phi} G^A_{\mu\nu}$$



- EFT scale uncertainties are very much reduced at NLO.
- RG are sometimes thought to be an approximation for full NLO, but it is often not the case.

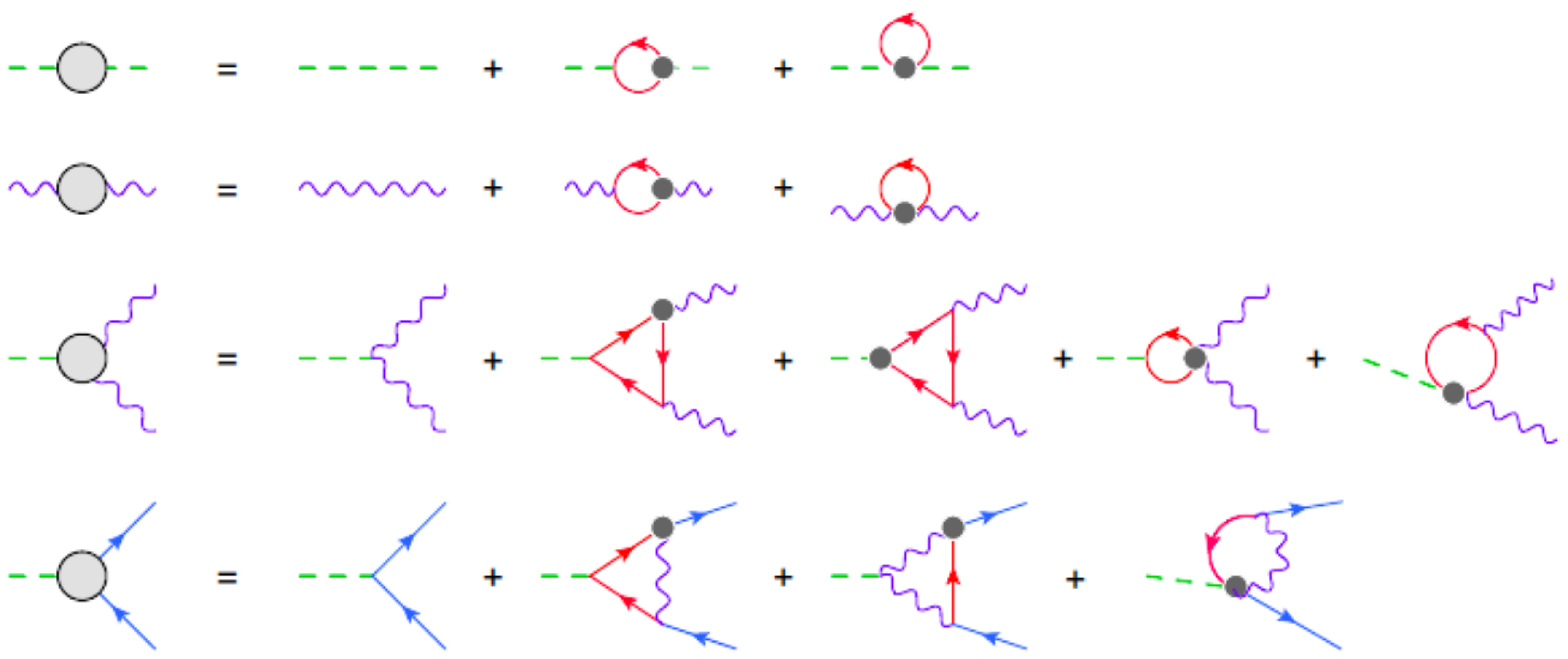
Need for NLO

4. New operators arise

[Ghezzi, Gomez-Ambrosio, Passarino, Uccirati, 15a]
[Hartmann and Trott, 15]
[Ghezzi, Gomez-Ambrosio, Passarino, Uccirati, 15b]
[Dawson, Giardino, 2018]
[Dedes et al, 2018]
[Vryonidou and Zhang, 2018]
[Dawson, Giardino, 2018]
[Vryonidou and Zhang, 2018]

New operators can arise at one-loop or via real corrections.

- At variance with the SM, loop-induced processes might not be finite.
- Including the full set of operators at a given order implies that no extra UV divergences appear (closure check).
- Use tree-level, loop-level, hierarchy but not gauge couplings.

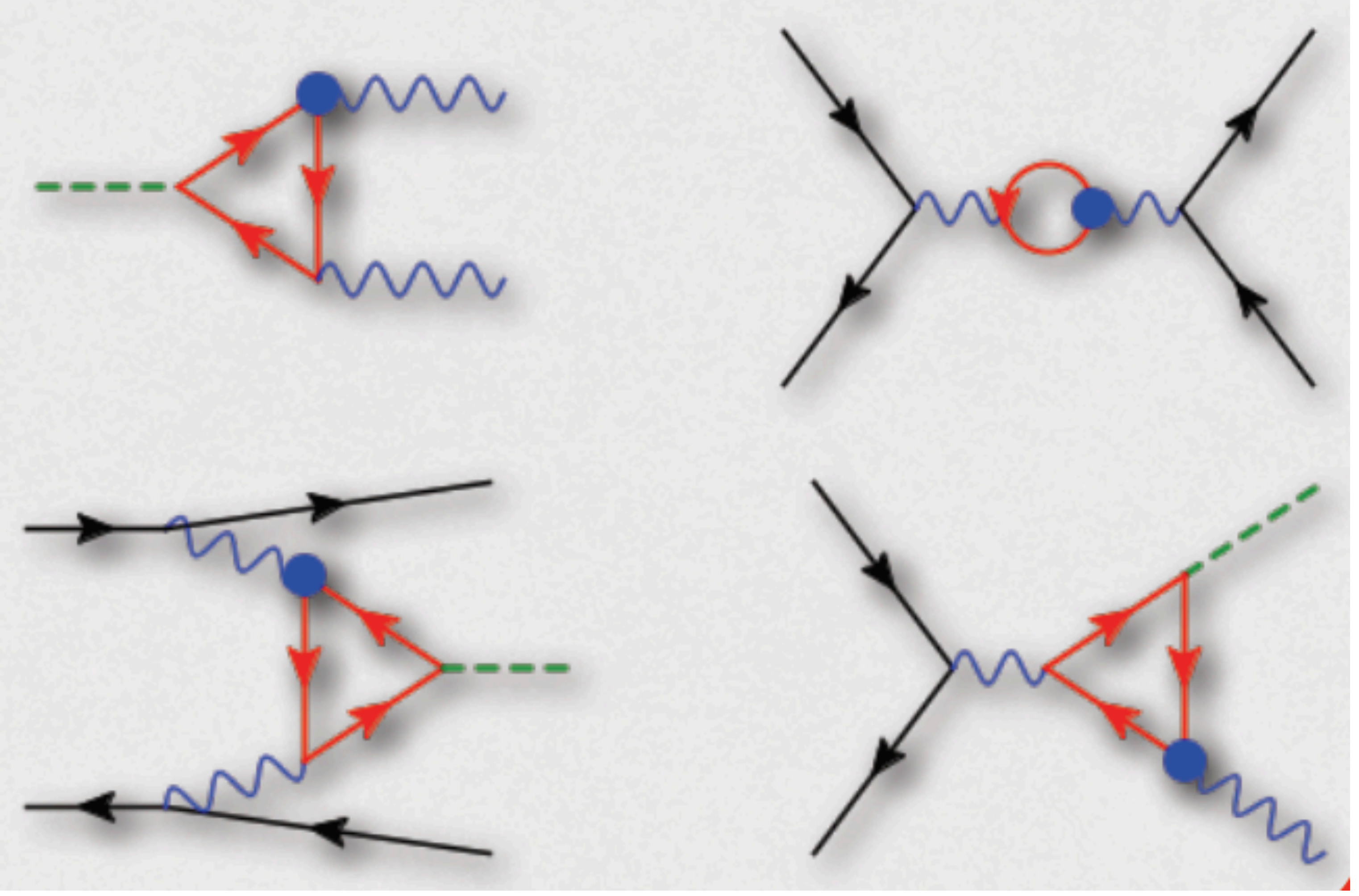


Need for NLO

4. New operators arise

[Vryonidou and Zhang, 2018]

- VBF, ZH, WH at LHC
- ZH, WWF, ZZF at e^+e^-
- H decay to γγ, γZ, Zll, Wlν, bb, ττ, μμ
- ggH is known



	$\gamma\gamma$	γZ	bb	WW*	ZZ*	$\tau\tau$	$\mu\mu$
gg	(-100%,1980%)	(-88%,200%)	(-40%,48%)	(-40%,47%)	(-40%,46%)	(-40%,48%)	(-40%,48%)
VBF	(-100%,1880%)	(-88%,170%)	(-6.1%,5.3%)	(-6.8%,6.7%)	(-8.8%,9.2%)	(-6.2%,5.9%)	(-6.2%,5.9%)
WH	(-100%,1880%)	(-88%,170%)	(-5.5%,4.2%)	(-6.1%,5.6%)	(-7.8%,7.9%)	(-5.8%,5.1%)	(-5.8%,5.1%)
ZH	(-100%,1880%)	(-87%,170%)	(-6.5%,5.9%)	(-7.1%,7.1%)	(-9.4%,9.9%)	(-6.8%,6.7%)	(-6.8%,6.7%)

Operator	Top Fitter	RHCC tree	$\sigma_{t\bar{t}H}$ [33]
$C_{\varphi tb}$		[-5.28,5.28]	
$C_{\varphi Q}^{(3)}$	[-2.59,1.50]		
$C_{\varphi Q}^{(1)}$	[-3.10,3.10]		
$C_{\varphi t}$	[-9.78,8.18]		
C_{tW}	[-2.49,2.49]		
C_{tB}	[-7.09,4.68]		
$C_{t\varphi}$			[-6.5,1.3]

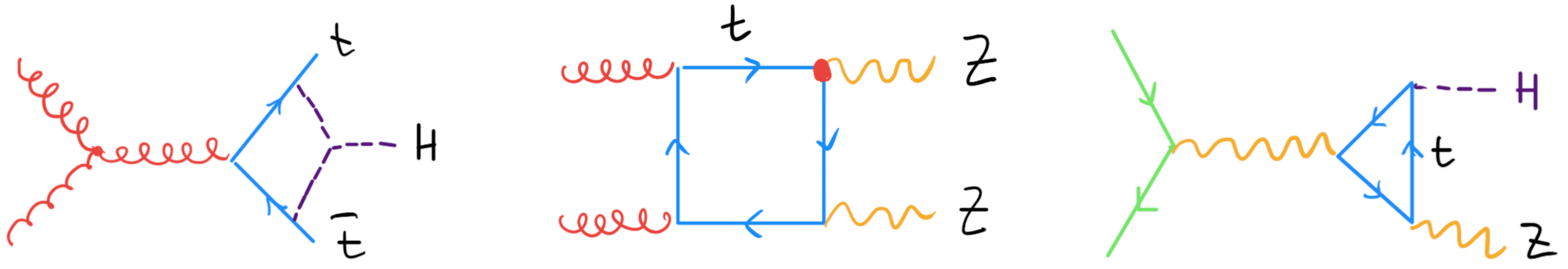
Possible deviations using current constraints on the relevant operators

Accurate SMEFT

Progress in SMEFT at 1-loop level

1-loop accuracy allows:

- Unveil the SMEFT structure (mixing)
- K-factors (accuracy)
- Scale uncertainties (precision)
- Exploit loop sensitivity:



"same strategy" as in SM@dim4

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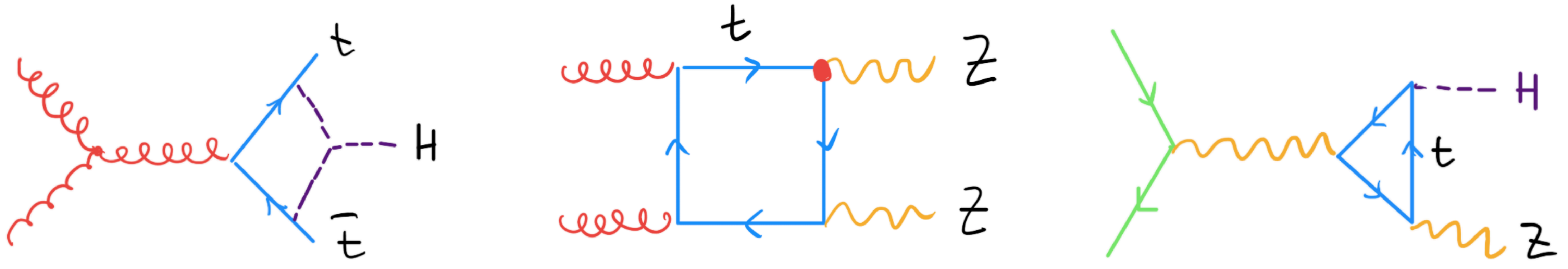


"same strategy" as in SM@dim4

RGE

· Anomalous dimension matrix [Jenkins, Manohar and Trott, 2013,2014,2014]

Production

· pp→jj (4F) [Gao, Li, Wang, Zhu, Yuan, 2011]
· pp→tt (4F) [Shao, Li, Wang, Gao, Zhang, Zhu, 2011]
· pp →VV [Dixon, Kunszt, Signer ,1999] [Melia, Nason, Röntsch, Zanderighi ,2011] [Baglio, Dawson, Lewis ,2017,2018,2019][Chiesa et al., 2018]
· top FCNCs [Degrande, FM, Wang, Zhang ,2014] [Durieux, FM, Zhang ,2014]
· pp →tt (chromo) [Franzosi, Zhang ,2015]
· pp →tj [Zhang ,2016] [de Beurs, Laenen, Vreeswijk, Vryonidou ,2018]
· pp → ttZ [Rontsch and Schulze,2015] [Bylund, FM, Tsinikos, Vryonidou, Zhang ,2016]
· pp → ttH [FM, Vryonidou, Zhang ,2016]
· pp →HV,Hjj [Greljo, Isidori, Lindert, Marzocca, 2015][Degrande, Fuks, Mawatari, Mimasu, Sanz ,2016], [Alioli, Dekens, Girard, Mereghetti ,2018]
· pp→H [Grazzini, Ilnicka, Spira, Wiesemann ,2016] [Deutschmann, Duhr, FM, Vryonidou ,2017]
· pp → tZj,tHj [Degrande, FM, Mimasu, Vryonidou, Zhang ,2018]
· pp → jets [Hirschi, FM, Tsinikos, Vryonidou ,2018]
· pp → VVV [Degrande, Durieux, FM, Mimasu, Vryonidou, Zhang, 20xx]
· gg → ZH,Hj,HH [Bylund, FM, Tsinikos, Vryonidou, Zhang ,2016]
· Higgs self-couplings [McCullough, 2014][Degrassi, Giardino, FM, Pagani, Shivaji, Zhao, 2016-2018][Borowka et al. 2019][FM,Pagani, Zhao, 2019]
· EW loops in tt [Kuhn et al.,1305.5773], [Martini 1911.11244]
· EW top loops in Higgs & EW [Vryonidou, Zhang ,2018][Durieux, Gu, Vryonidou, Zhang ,2018] [Boselli et al. 2019]
· Drell-Yan (EW corrections) [Dawson and Giardino, 2021]

Decay

· Top [Zhang ,2014] [Boughezal, Chen, Petriello, Wiegand ,2019]
· h → VV [Hartmann, Trott ,2015] [Ghezzi, Gomez-Ambrosio, Passarino, Uccirati ,2015, 2015] [Dawson, Giardino ,2018,2018][Dedes, et al. ,2018] [Dedes, Suxho, Trifyllis ,2019]
· h → ff [Gauld, Pecjak, Scott ,2016] [Cullen, Pecjak, Scott ,2019][Cullen, Pecjak, ,2020]
· Z,W [Hartmann, Shepherd, Trott ,2016] [Dawson, Ismail, Giardino ,2018,2018,2019]

EWPO

· EWPO [Zhang, Greiner, Willenbrock '12] [Dawson, Giardino ,2020]

Accurate SMEFT

SMEFT@NLO

Automated one-loop computations in the SMEFT

Céline Degrande,[1,*] Gauthier Durieux,[2,†] Fabio Maltoni,[1,3,‡]
Ken Mimasu,[1,§] Eleni Vryonidou,[4,¶] and Cen Zhang[5,6,**]

We present the automation of one-loop computations in the standard-model effective field theory at dimension six. Our implementation, dubbed SMEFT@NLO, contains ultraviolet and rational counterterms for bosonic, two- and four-fermion operators. It presently allows for fully differential predictions, possibly matched to parton shower, up to one-loop accuracy in QCD. We illustrate the potential of the implementation with novel loop-induced and next-to-leading order computations relevant for top-quark, electroweak, and Higgs-boson phenomenology at the LHC and future colliders.

Standard Model Effective Theory at One-Loop in QCD

Céline Degrande, Gauthier Durieux, Fabio Maltoni, Ken Mimasu, Eleni Vryonidou & Cen Zhang, arXiv:2008.11743

The implementation is based on the Warsaw basis of dimension-six SMEFT operators, after canonical normalization. Electroweak input parameters are taken to be G_F, M_Z, M_W. The CKM matrix is approximated as a unit matrix, and a $U(2)_q \times U(2)_u \times U(3)_d \times (U(1)_l \times U(1)_e)^3$ flavor symmetry is enforced. It forbids all fermion masses and Yukawa couplings except that only of the top quark. The model therefore implements the five-flavor scheme for PDFs.

A new coupling order, `NP=2`, is assigned to SMEFT interactions. The cutoff scale `Lambda` takes a default value of 1 TeV^{-2} and can be modified along with the Wilson coefficients in the `param_card`. Operators definitions, normalisations and coefficient names in the UFO model are specified in definitions.pdf. The notations and normalizations of top-quark operator coefficients comply with the LHC TOP WG standards of 1802.07237. Note however that the flavor symmetry enforced here is slightly more restrictive than the baseline assumption there (see the dim6top page for more information). This model has been validated at tree level against the `dim6top` implementation (see 1906.12310 and the comparison details).

Current implementation

UFO model: SMEFTatNLO_v1.0.tar.gz

- 2020/08/24 - v1.0: Official release including notably four-quark operators at NLO.

Support

Please direct any questions to smeftatnlo-dev**[at]**cern**[dot]**ch.

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

[Degrande, et al. arXiv:2008.11743]

Accurate SMEFT

SMEFT@NLO

What's in the 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 LHC Top WG ones
CP & Flavour conserving

Developments
CP-violation
RGE

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]
```

Higgs production

loop-induced

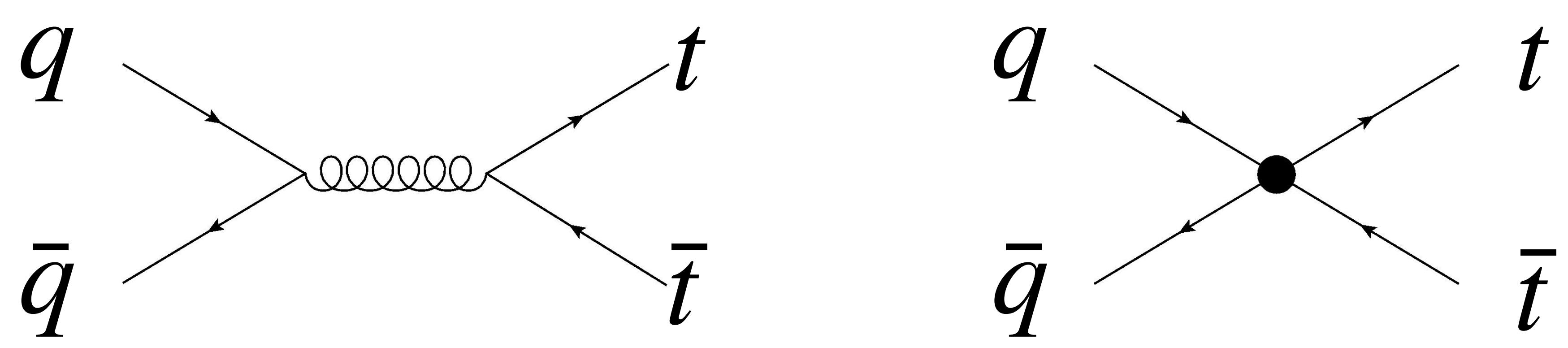
```
> g g > H         QED=1 QCD=2 NP=2 [QCD]
> g g > H H       QED=2 QCD=2 NP=2 [QCD]
> g g > H H H     QED=3 QCD=2 NP=2 [QCD]
> g g > H j       QED=1 QCD=3 NP=2 [QCD]
```

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]
```

Accurate SMEFT

SMEFT@NLO



14 4-fermion operators

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

$$O_{Qq}^{3,8} = (\bar{Q}\gamma_\mu T^A \tau^I Q)(\bar{q}_i\gamma^\mu T^A \tau^I q_i) \qquad O_{Qq}^{3,1} = (\bar{Q}\gamma_\mu \tau^I Q)(\bar{q}_i\gamma^\mu \tau^I q_i)$$

$$O_{tu}^{8} = (\bar{t}\gamma_\mu T^A t)(\bar{u}_i\gamma^\mu T^A u_i) \qquad O_{tu}^{1} = (\bar{t}\gamma_\mu t)(\bar{u}_i\gamma^\mu u_i)$$

$$O_{td}^{8} = (\bar{t}\gamma^\mu T^A t)(\bar{d}_i\gamma_\mu T^A d_i) \qquad O_{td}^{1} = (\bar{t}\gamma^\mu t)(\bar{d}_i\gamma_\mu d_i)\ ;$$

$$O_{Qu}^{8} = (\bar{Q}\gamma^\mu T^A Q)(\bar{u}_i\gamma_\mu T^A u_i) \qquad O_{Qu}^{1} = (\bar{Q}\gamma^\mu Q)(\bar{u}_i\gamma_\mu u_i)$$

$$O_{Qd}^{8} = (\bar{Q}\gamma^\mu T^A Q)(\bar{d}_i\gamma_\mu T^A d_i) \qquad O_{Qd}^{1} = (\bar{Q}\gamma^\mu Q)(\bar{d}_i\gamma_\mu d_i)$$

$$O_{tq}^{8} = (\bar{q}_i\gamma^\mu T^A q_i)(\bar{t}\gamma_\mu T^A t) \qquad O_{tq}^{1} = (\bar{q}_i\gamma^\mu q_i)(\bar{t}\gamma_\mu t)\ ;$$

Octets Singlets

Different chiralities and colour structures

c_i	$\mathcal{O}(\Lambda^{-2})$ LO	$\mathcal{O}(\Lambda^{-2})$ NLO		$\mathcal{O}(\Lambda^{-4})$ LO	$\mathcal{O}(\Lambda^{-4})$ NLO
c_{tu}^{8}	$4.27^{+11\%}_{-9\%}$	$4.06^{+1\%}_{-3\%}$		$1.04^{+6\%}_{-5\%}$	$1.03^{+2\%}_{-2\%}$
c_{td}^{8}	$2.79^{+11\%}_{-9\%}$	$2.77^{+1\%}_{-3\%}$		$0.577^{+6\%}_{-5\%}$	$0.611^{+3\%}_{-2\%}$
c_{tq}^{8}	$6.99^{+11\%}_{-9\%}$	$6.67^{+1\%}_{-3\%}$		$1.61^{+6\%}_{-5\%}$	$1.29^{+3\%}_{-2\%}$
c_{Qu}^{8}	$4.26^{+11\%}_{-9\%}$	$3.93^{+1\%}_{-4\%}$		$1.04^{+6\%}_{-5\%}$	$0.798^{+3\%}_{-3\%}$
c_{Qd}^{8}	$2.79^{+11\%}_{-9\%}$	$2.93^{+0\%}_{-1\%}$		$0.58^{+6\%}_{-5\%}$	$0.485^{+2\%}_{-2\%}$
$c_{Qq}^{8,1}$	$6.99^{+11\%}_{-9\%}$	$6.82^{+1\%}_{-3\%}$		$1.61^{+6\%}_{-5\%}$	$1.69^{+3\%}_{-3\%}$
$c_{Qq}^{8,3}$	$1.50^{+10\%}_{-9\%}$	$1.32^{+1\%}_{-3\%}$		$1.61^{+6\%}_{-5\%}$	$1.57^{+2\%}_{-2\%}$
c_{tu}^{1}	$[0.67^{+1\%}_{-1\%}]$	$-0.078(7)^{+31\%}_{-23\%}$	$[0.41^{+13\%}_{-17\%}]$	$4.66^{+6\%}_{-5\%}$	$5.92^{+6\%}_{-5\%}$
c_{td}^{1}	$[-0.21^{+1\%}_{-2\%}]$	$-0.306^{+30\%}_{-22\%}$	$[-0.15^{+10\%}_{-13\%}]$	$2.62^{+6\%}_{-5\%}$	$3.46^{+5\%}_{-5\%}$
c_{tq}^{1}	$[0.39^{+0\%}_{-1\%}]$	$-0.47^{+24\%}_{-18\%}$	$[0.50^{+3\%}_{-2\%}]$	$7.25^{+6\%}_{-5\%}$	$9.36^{+6\%}_{-5\%}$
c_{Qu}^{1}	$[0.33^{+0\%}_{-0\%}]$	$-0.359^{+23\%}_{-17\%}$	$[0.57^{+6\%}_{-5\%}]$	$4.68^{+6\%}_{-5\%}$	$5.96^{+6\%}_{-5\%}$
c_{Qd}^{1}	$[-0.11^{+0\%}_{-1\%}]$	$0.023(6)^{+114\%}_{-75\%}$	$[-0.19^{+6\%}_{-5\%}]$	$2.61^{+6\%}_{-5\%}$	$3.46^{+5\%}_{-5\%}$
$c_{Qq}^{1,1}$	$[0.57^{+0\%}_{-1\%}]$	$-0.24^{+30\%}_{-22\%}$	$[0.39^{+9\%}_{-12\%}]$	$7.25^{+6\%}_{-5\%}$	$9.34^{+5\%}_{-5\%}$
$c_{Qq}^{1,3}$	$[1.92^{+1\%}_{-1\%}]$	$0.088(7)^{+28\%}_{-20\%}$	$[1.05^{+17\%}_{-22\%}]$	$7.25^{+6\%}_{-5\%}$	$9.32^{+5\%}_{-5\%}$

Interesting interference patterns

[Degrande, et al. arXiv:2008.11743]

Accurate SMEFT

SMEFT@NLO

4-heavy operators in top pair production

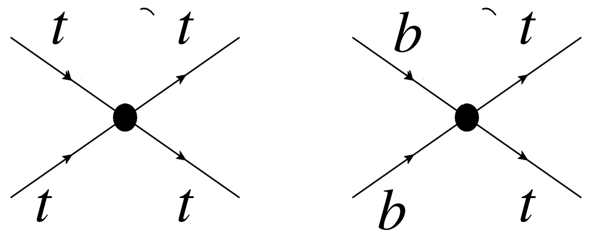
$$\mathcal{O}^8_{QQ} = (\bar{Q}\gamma^\mu T^A Q)(\bar{Q}\gamma_\mu T^A Q)$$

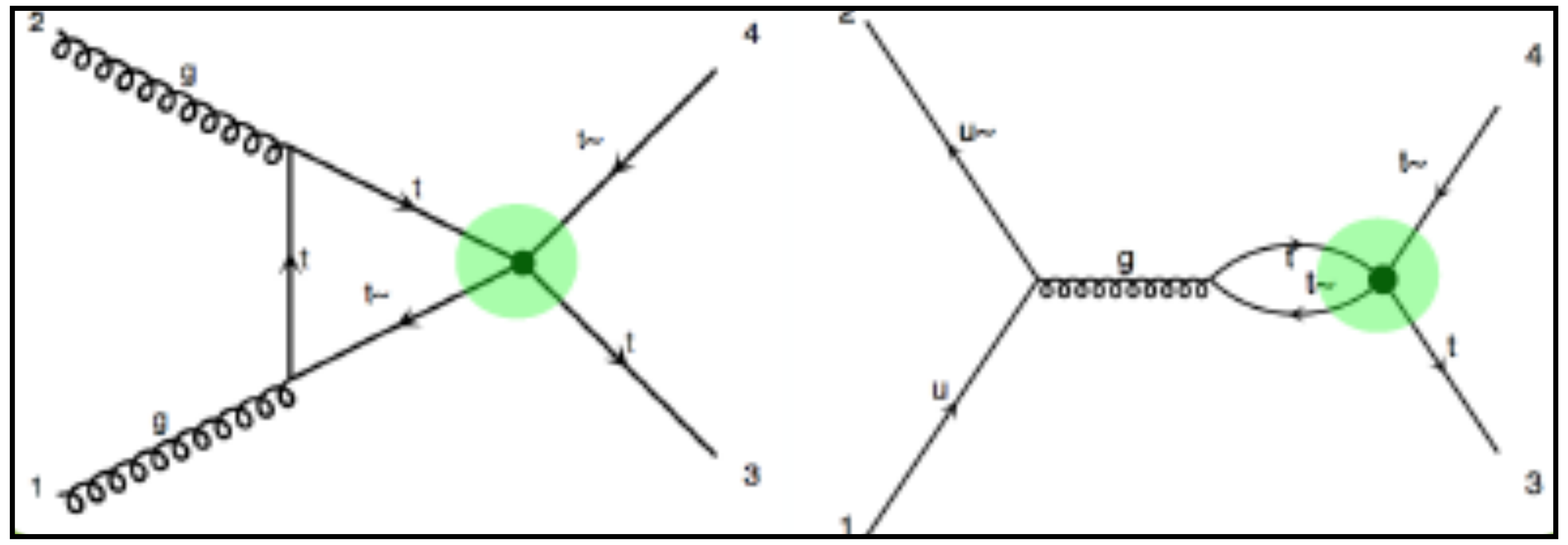
$$\mathcal{O}^1_{QQ} = (\bar{Q}\gamma^\mu Q)(\bar{Q}\gamma_\mu Q)$$

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

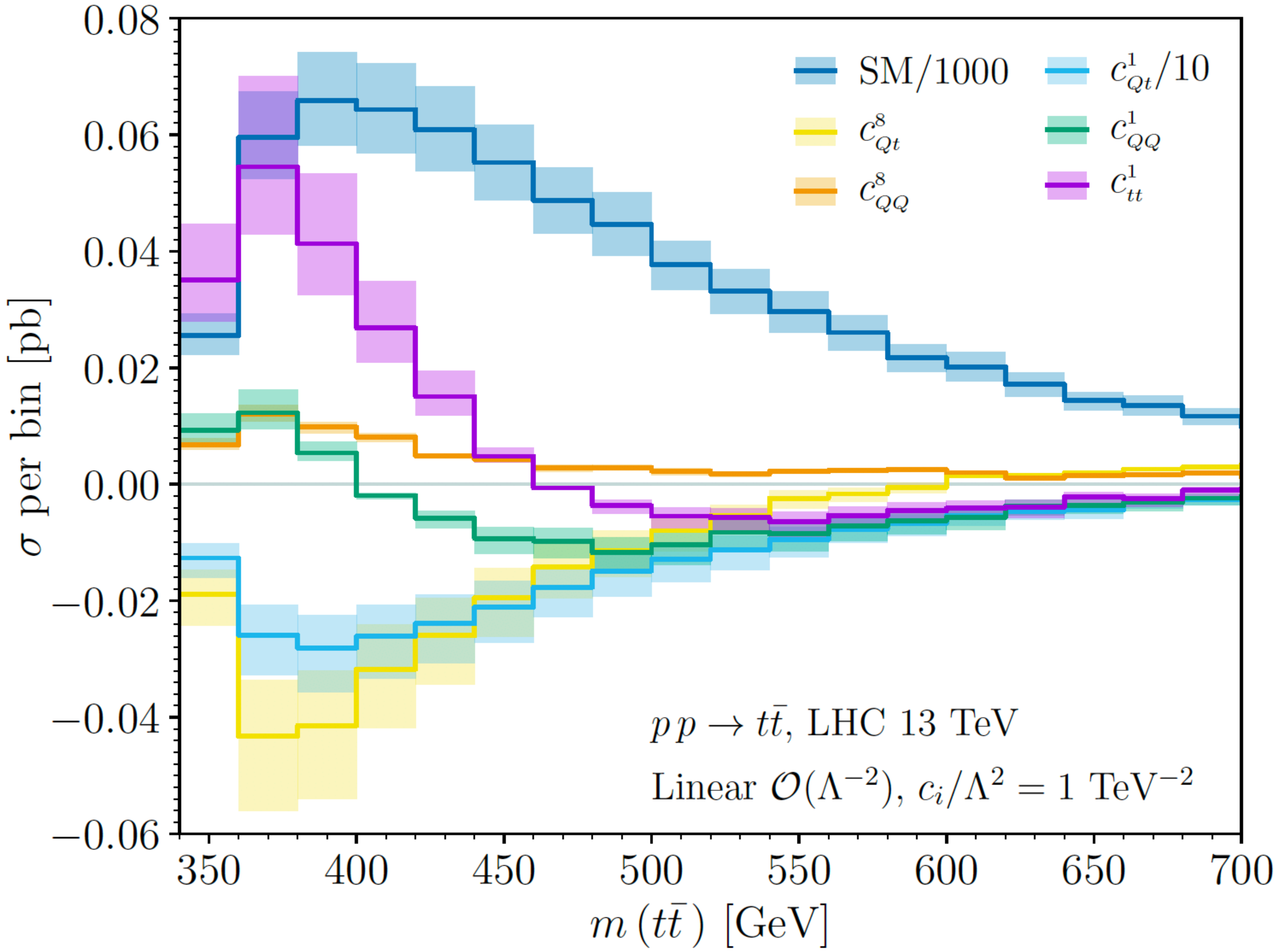
$$\mathcal{O}^1_{Qt} = (\bar{Q}\gamma^\mu Q)(\bar{t}\gamma_\mu t)$$

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





	LO	NLO		LO	NLO
c^8_{QQ}	$0.0586^{+27\%}_{-25\%}$	$0.125^{+10\%}_{-11\%}$		$0.00628^{+13\%}_{-16\%}$	$0.0133^{+7\%}_{-5\%}$
c^8_{Qt}	$0.0583^{+27\%}_{-25\%}$	$-0.107(6)^{+40\%}_{-33\%}$		$0.00619^{+13\%}_{-16\%}$	$0.0118^{+8\%}_{-5\%}$
c^1_{QQ}	$[-0.11^{+15\%}_{-18\%}]$	$-0.039(4)^{+51\%}_{-33\%}$	$[-0.12^{+7\%}_{-5\%}]$	$0.0282^{+13\%}_{-16\%}$	$0.0651^{+5\%}_{-6\%}$
c^1_{Qt}	$[-0.068^{+16\%}_{-18\%}]$	$-2.51^{+29\%}_{-21\%}$	$[-0.12^{+3\%}_{-6\%}]$	$0.0283^{+13\%}_{-16\%}$	$0.066^{+5\%}_{-6\%}$
c^1_{tt}	×	$0.215^{+23\%}_{-18\%}$		×	×



Loop-induced sensitivity

Complementary information to ttbb and 4top production

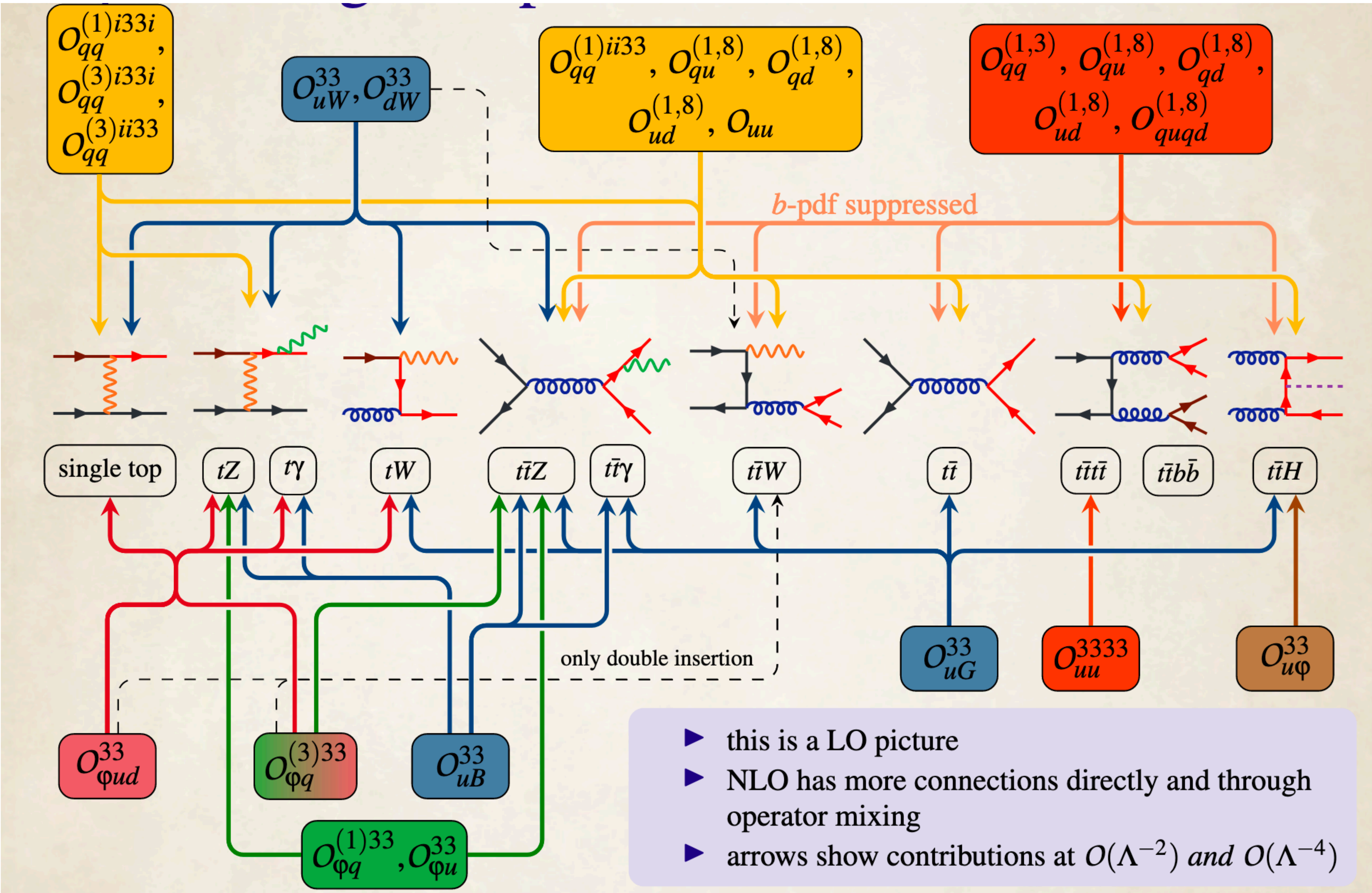
A powerful approach

Is this easy?

It's as exciting as challenging. Pattern of deformations enter many observables in a correlated way.

Needs to manage complexity, uncertainties and correlations.

[Galler, ICHEP2020]



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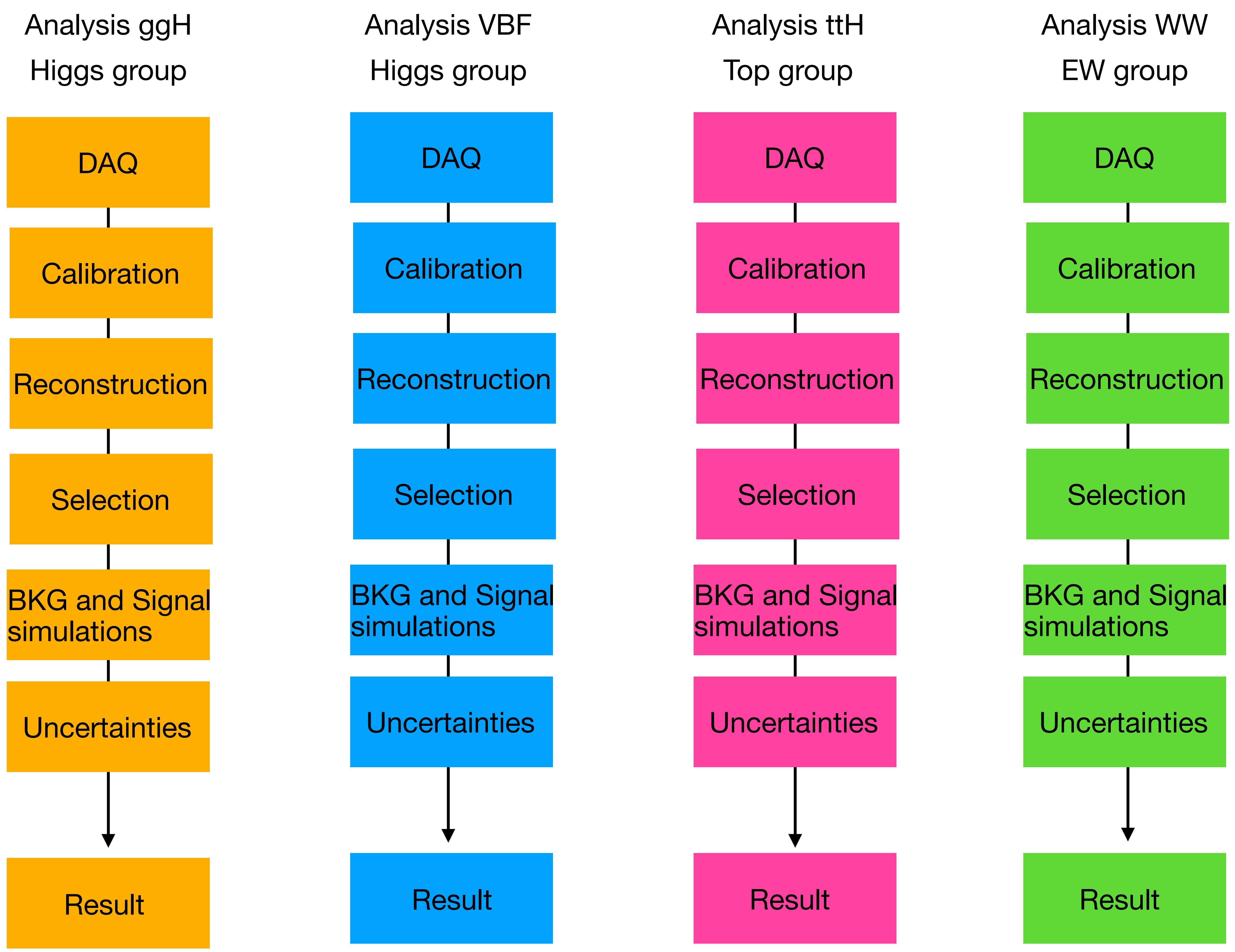
Naive TH view



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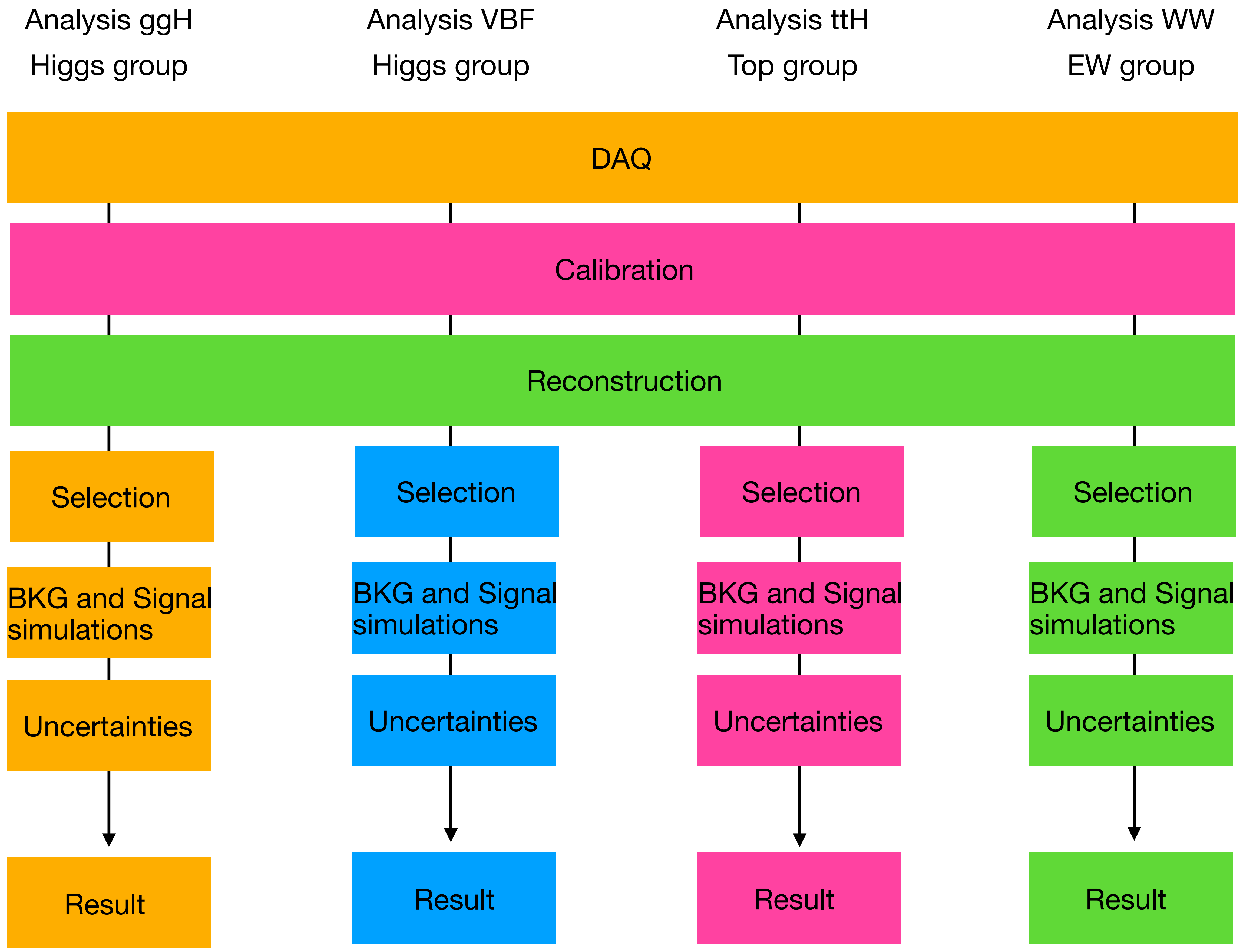

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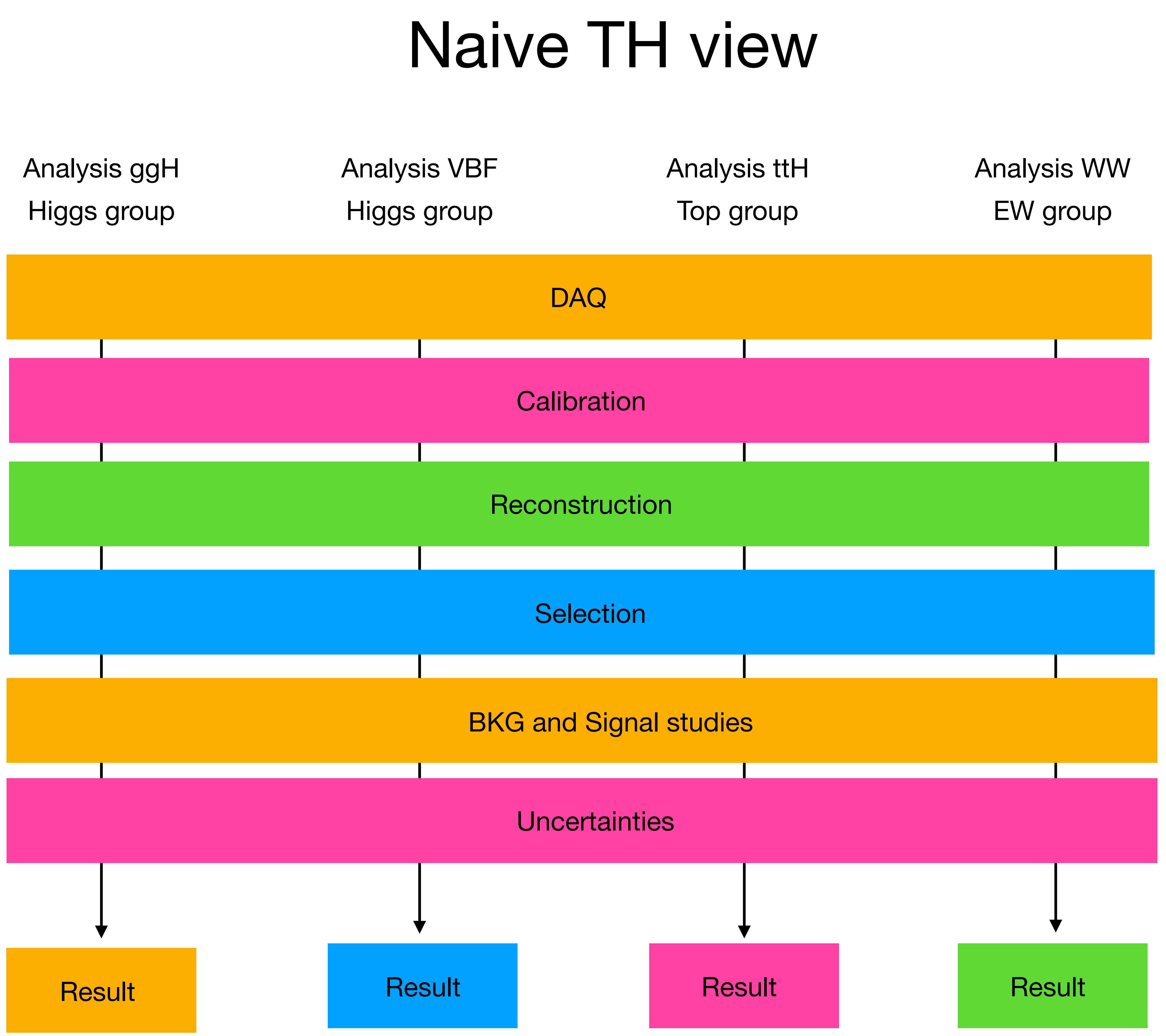

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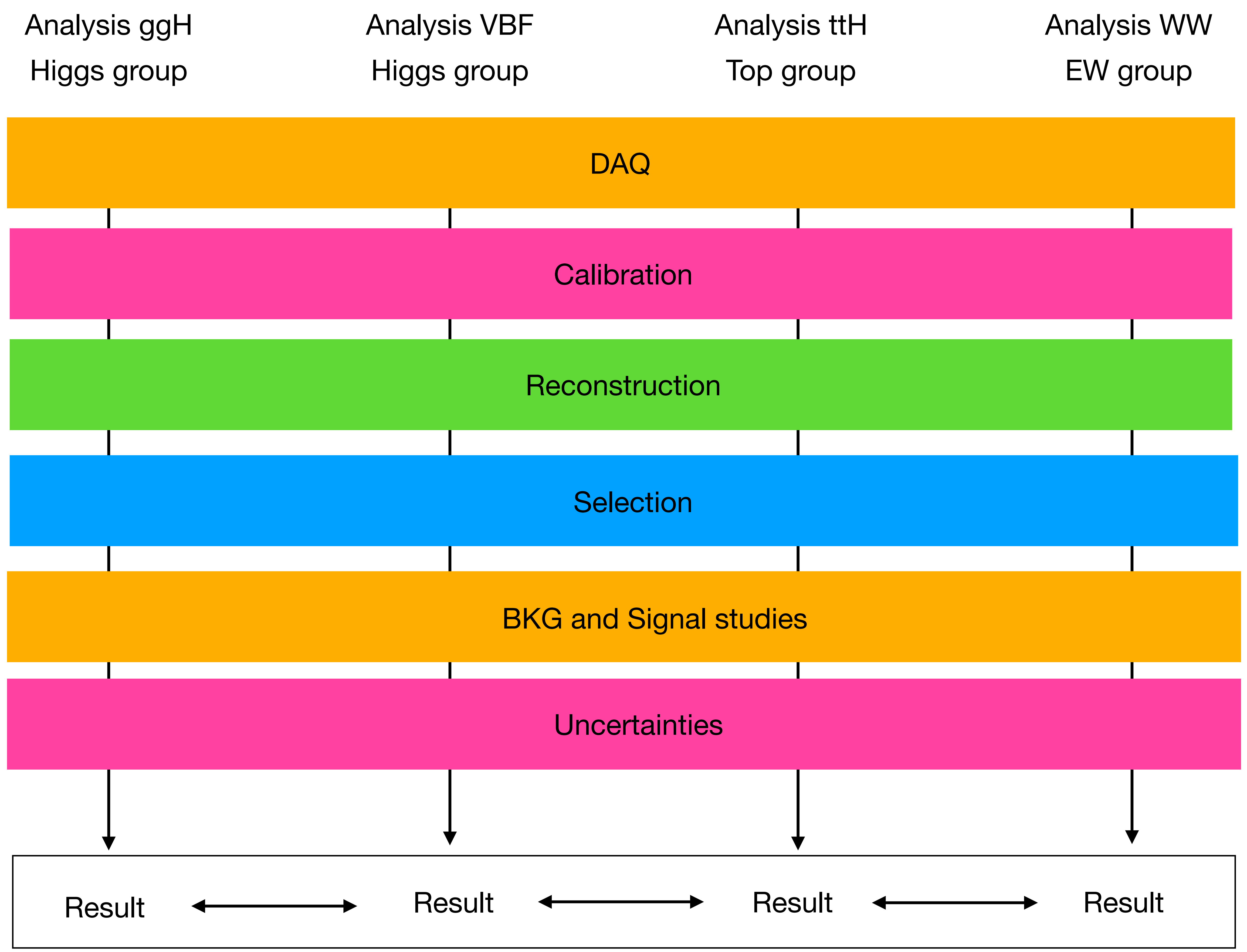
A new paradigm: shifting value from "the best single measurement" to "the best combinable measurement"!

Naive TH view



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A LHC EFT WG is working hard to move things forward in a joint TH/EXP effort (thanks to all contributing!!)

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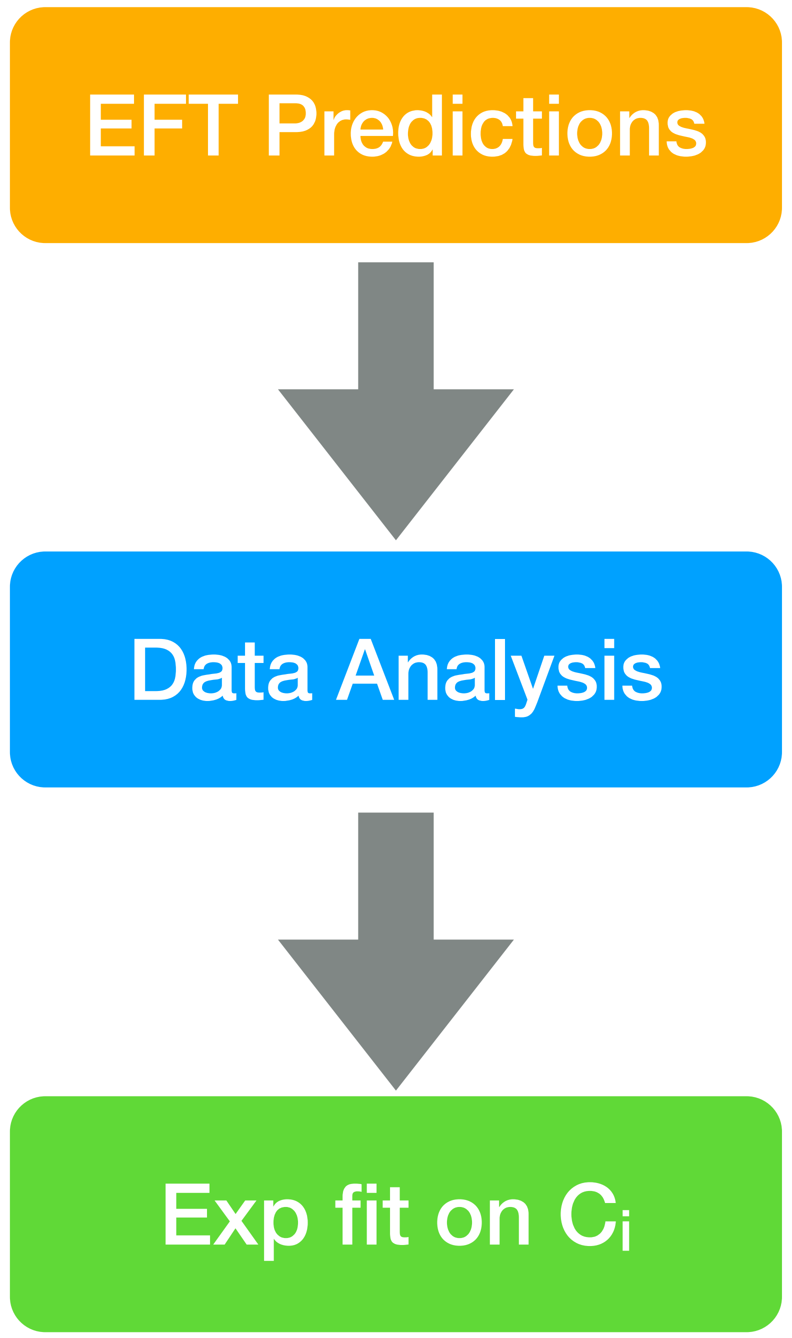
Top-down



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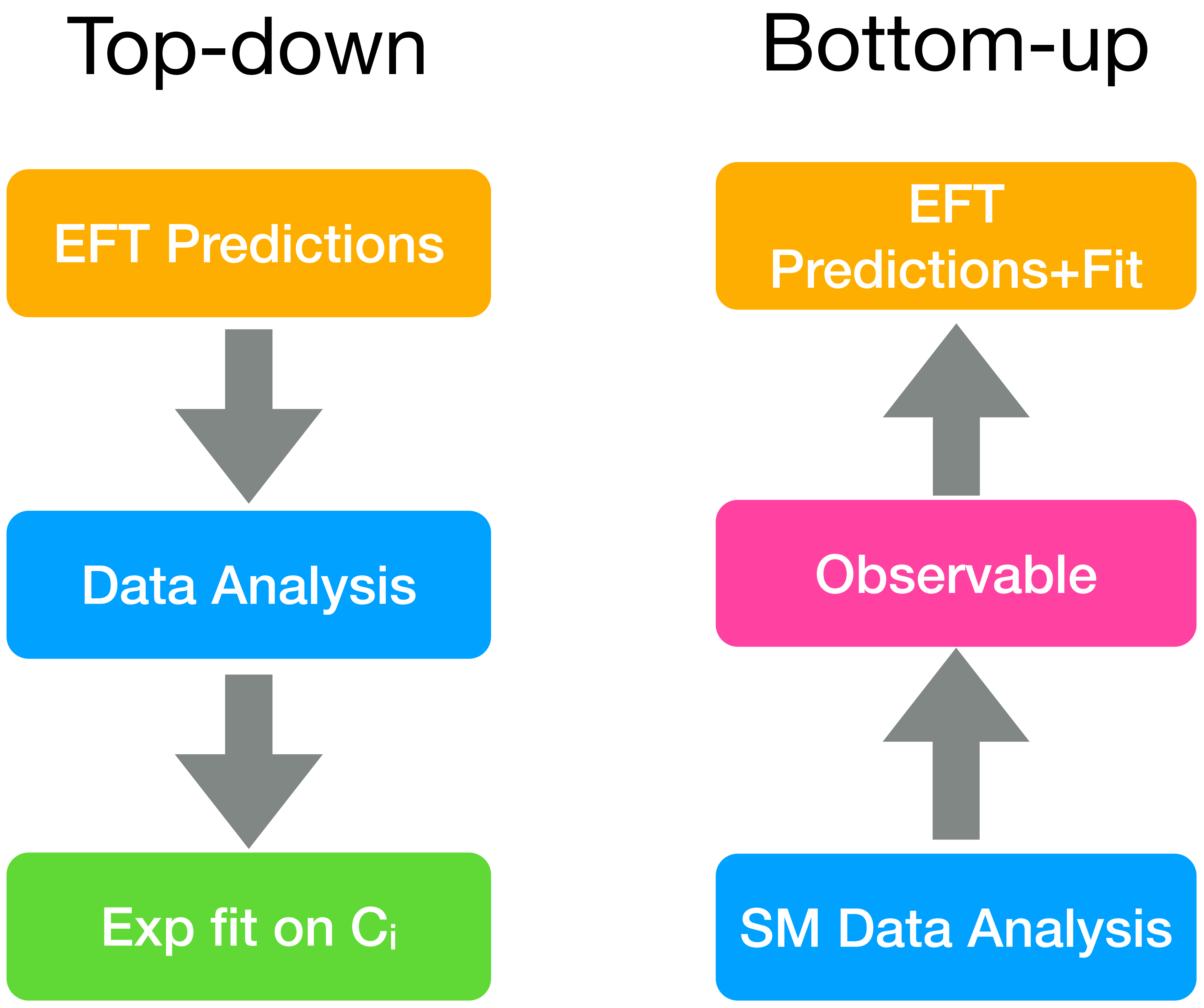

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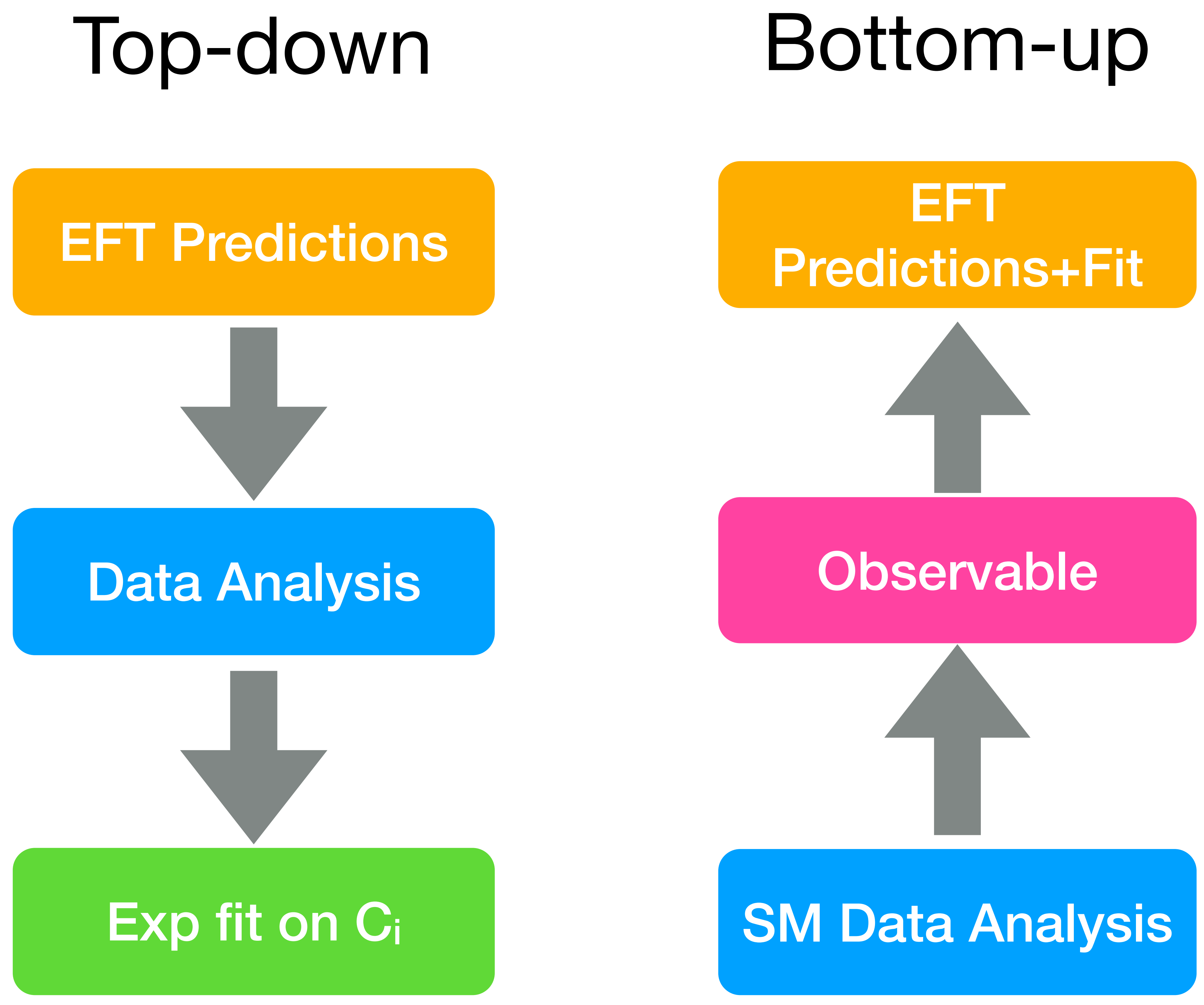
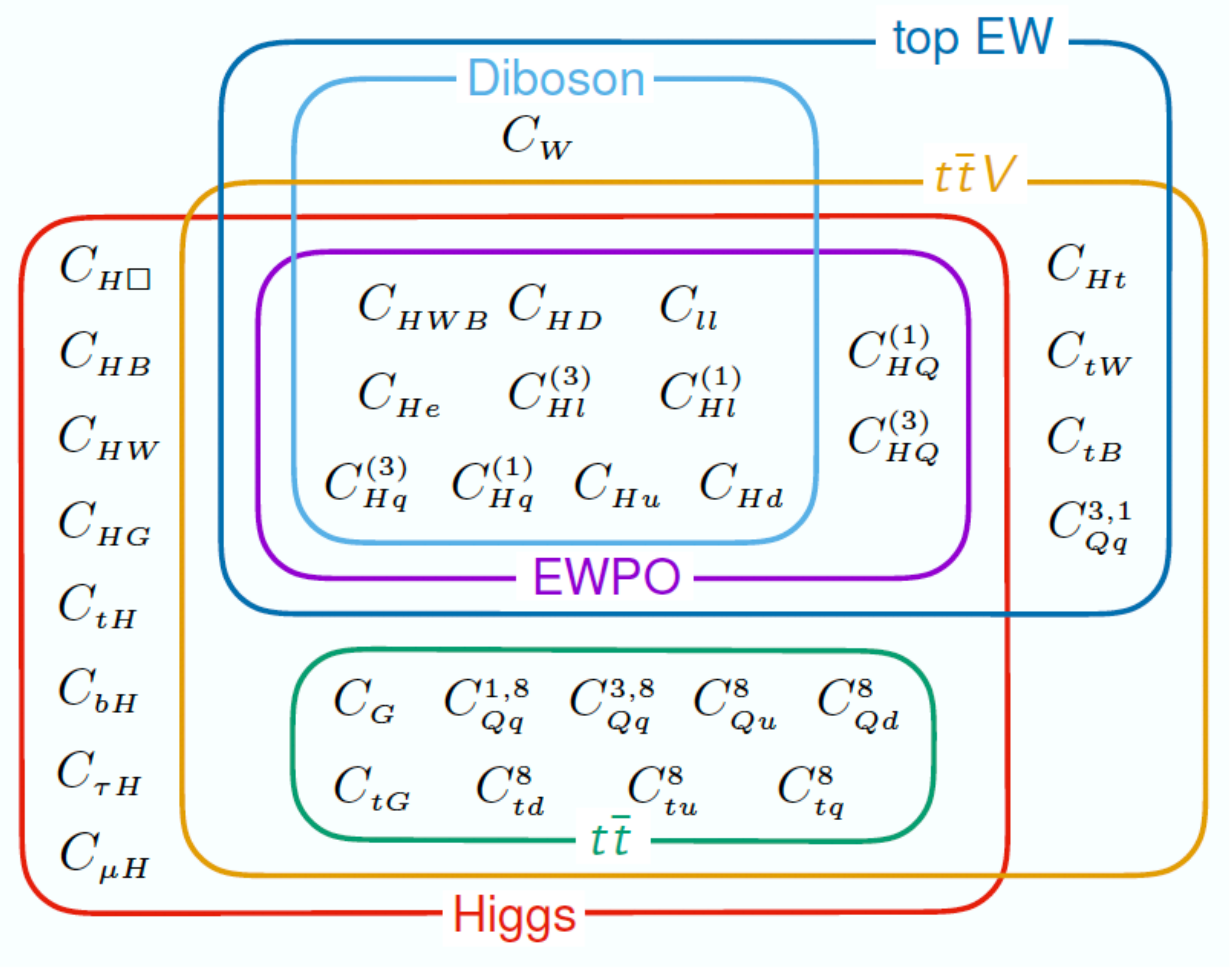
A LHC EFT WG is working hard to move things forward in a joint TH/EXP effort (thanks to all contributing!!)



Complementary!

Global fits
First explorations: EWPO+H+EW+Top

- Already now and without a dedicated experimental effort there is considerable information that can be used to set limits:
  - Fitmaker [J. Ellis, M. Madigan, K. Mimasu, V. Sanz, T. You 2012.02779]
  - SMEFiT [J. Either, G. Magni, F. M., L. Mantani, E. Nocera, J. Rojo, E. Slade, E. Vryonidou, C. Zhang, 2105.00006]
  - SFitter [Biekötter, Corbett, Plehn, 2018] + [I. Brivio, S. Bruggisser, F. M., R. Moutafis, T. Plehn, E. Vryonidou, S. Westhoff, C. Zhang, 1910.03606] (separated)
  - HEPfit [de Blas, et al. 2019]
- 30+ operators, linear and/or quadratic fits, Higgs/Top/EW at LHC, WW at LEP and EWPO.



[Ellis et al. 2012.02779]

Global fits

Workflow

Theory

(N)NLO QCD for SM
NLO QCD for SMEFT
State-of-the-art PDFs without top data

Data

317 data points: Top: ttbar, single-top, associated top production, distributions.
Higgs production and decay, differential distributions, STXS.
Diboson production, distributions

Global EW/Top/Higgs SMEFT fit

Methodology

Faithful uncertainty estimate
Avoid under- and over-fitting
Validated on pseudo-data (closure test)

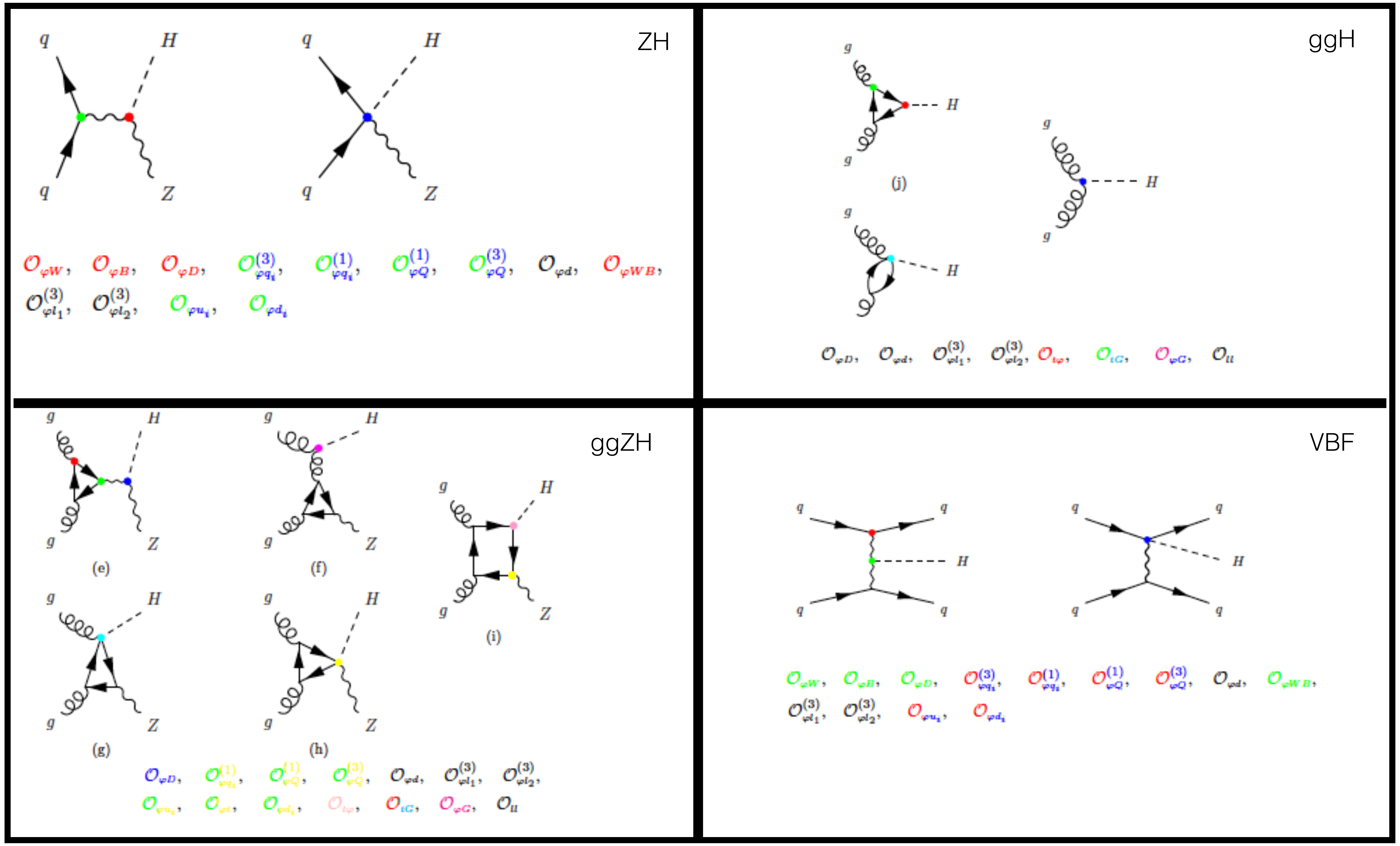
Output

Fit results can be used to bound specific UV complete models
New data can be straightforwardly added

EleniVryonidou®

Global fits

Operators vs processes

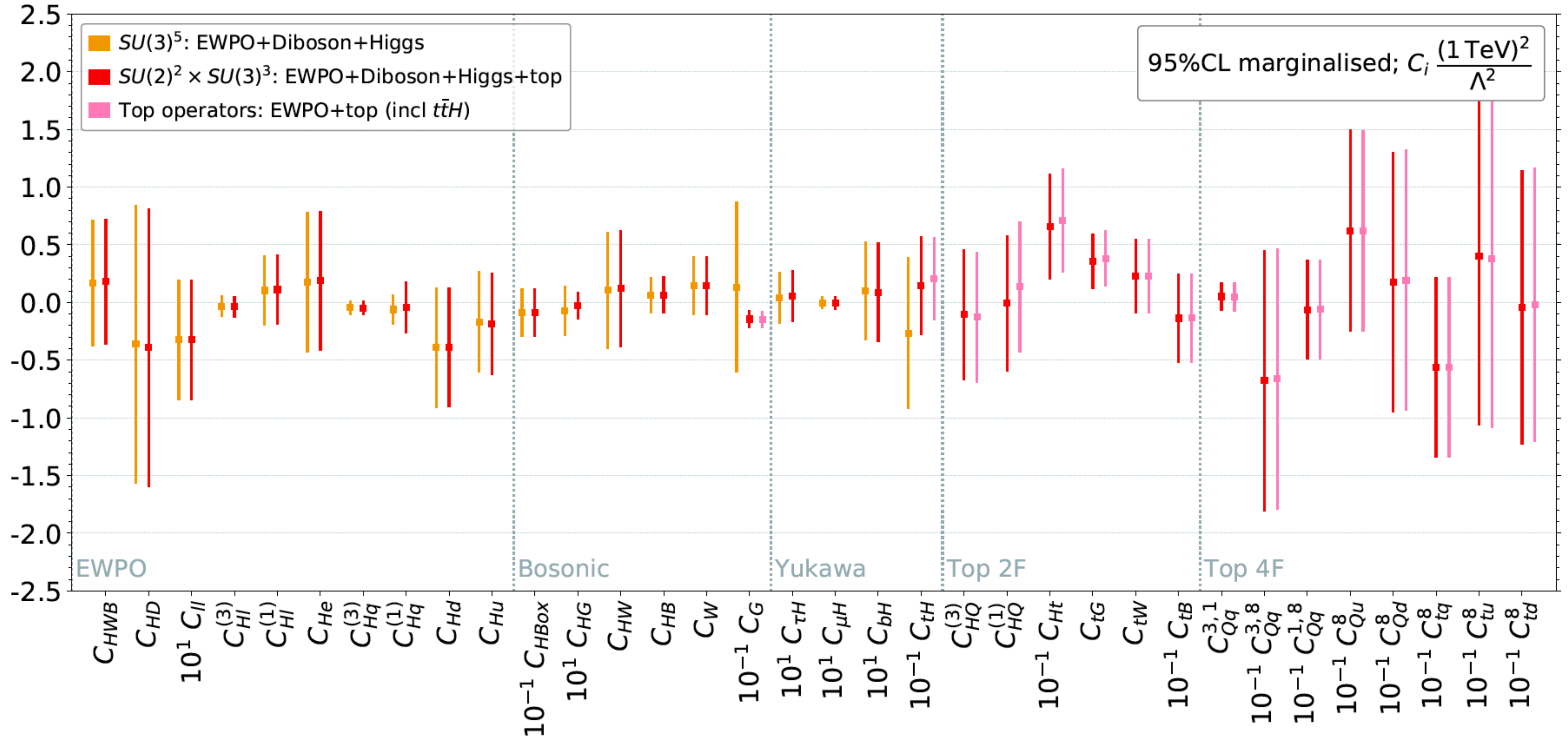


Luca Mantani®

Global EW(PO)+H+Top

Examples

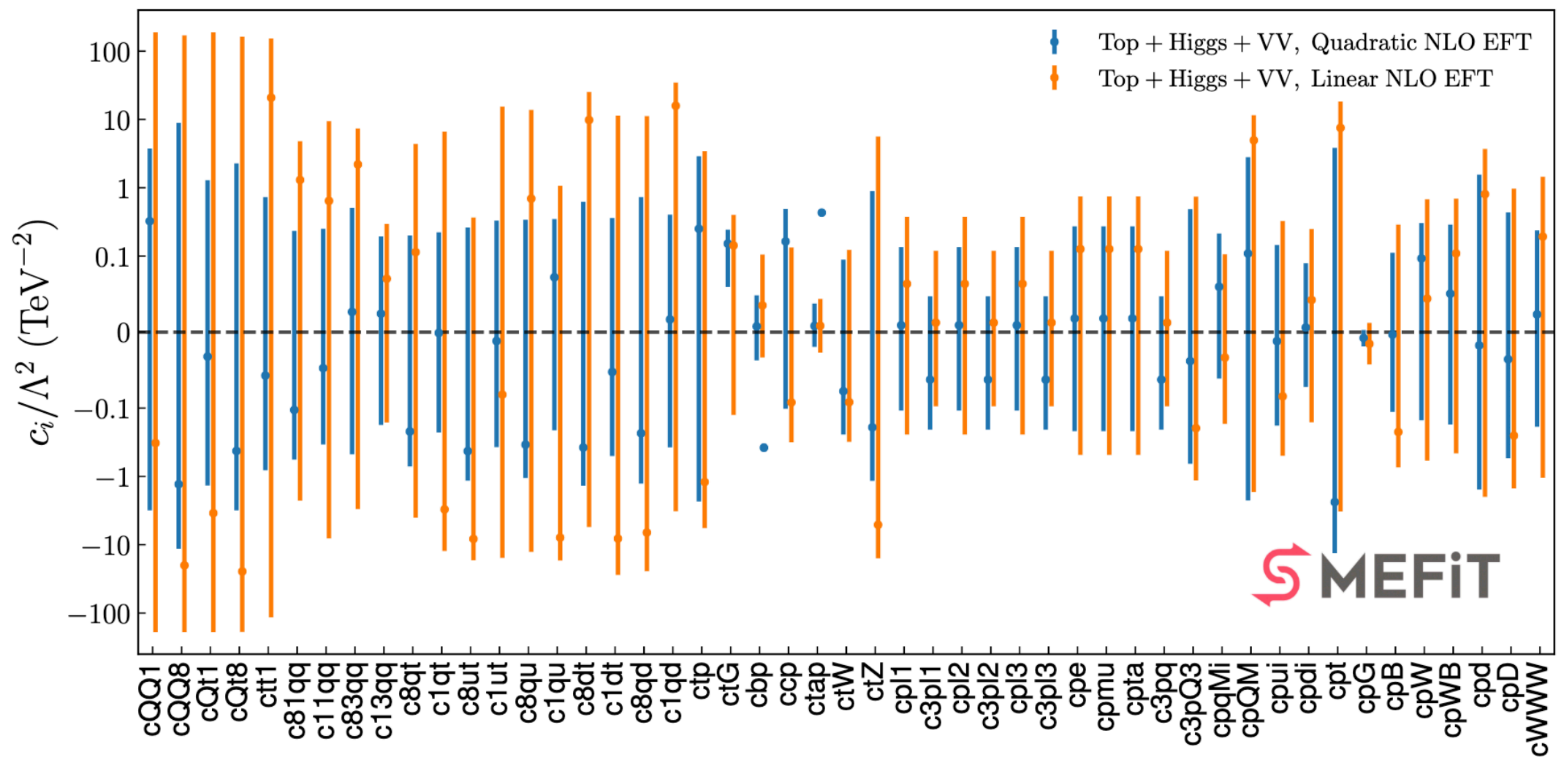
[Ellis et al. 2012.02779]



34 operators, $SU(2)^2 \times SU(3)^3$

EWPO fitted, 341 data points

[Either et al. (SMEFiT) 2105.00006]



36 operators, $SU(2)^2 \times SU(3)^3$

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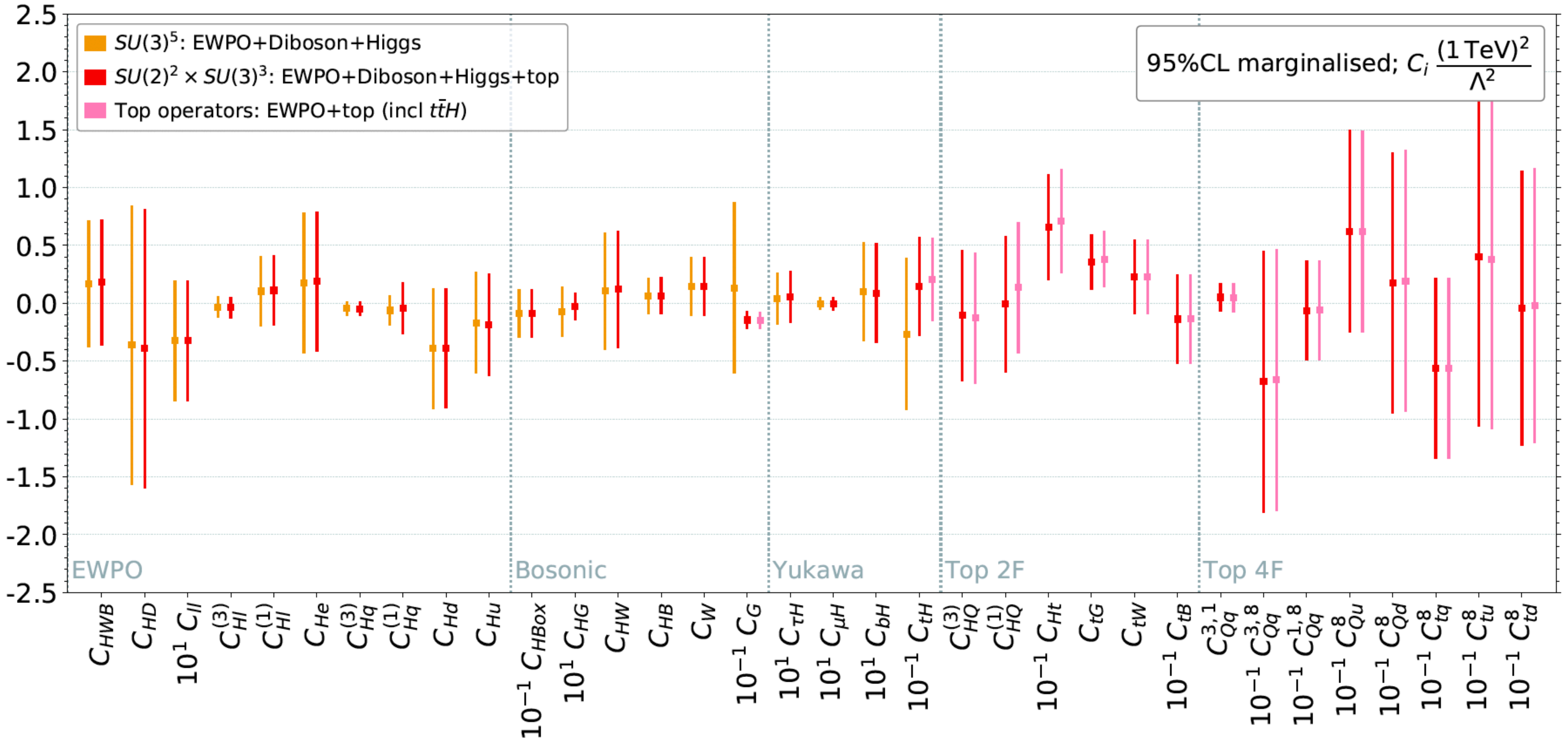
Global EW(PO)+H+Top

Examples

[Ellis et al. 2012.02779]



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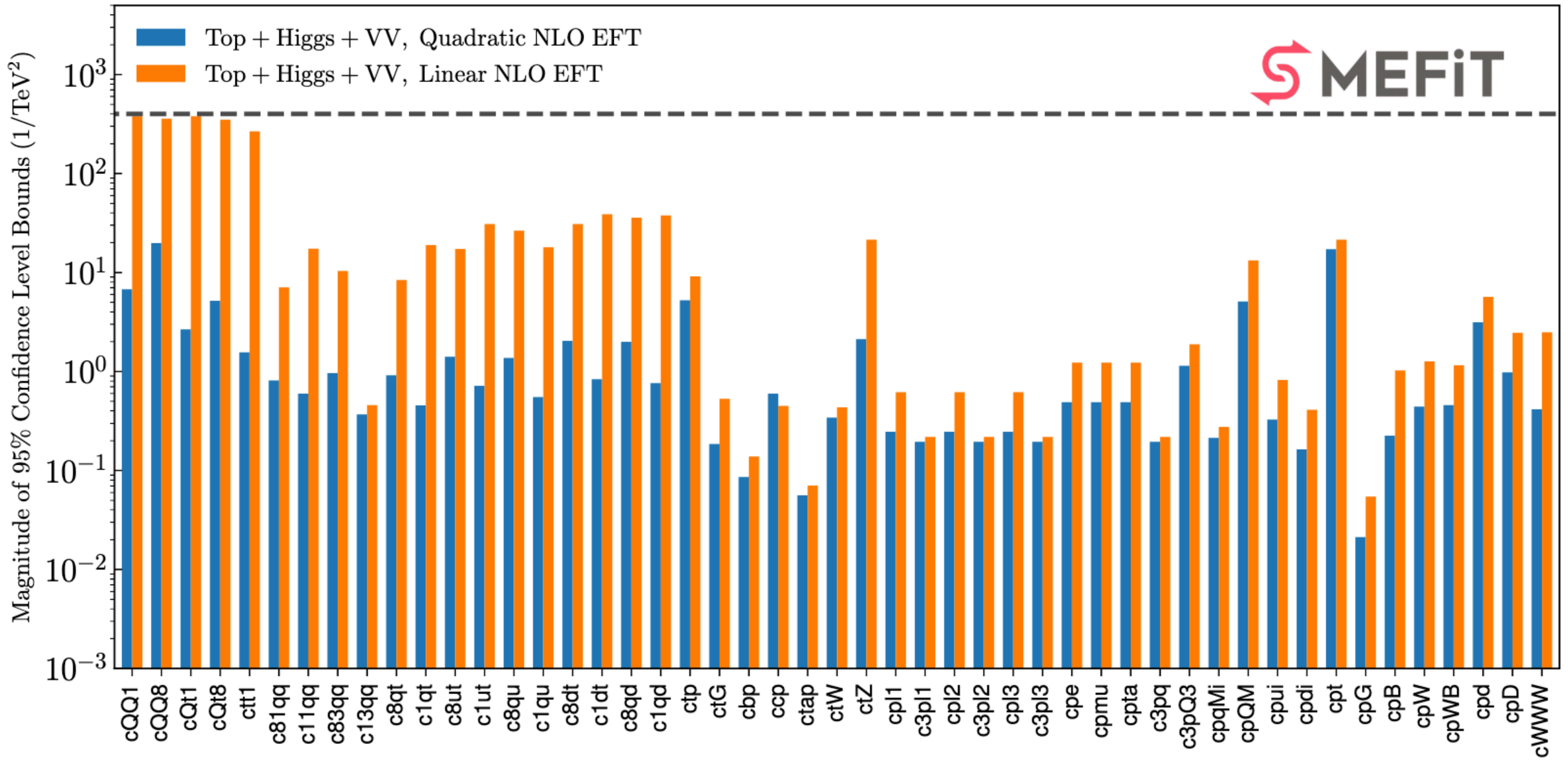
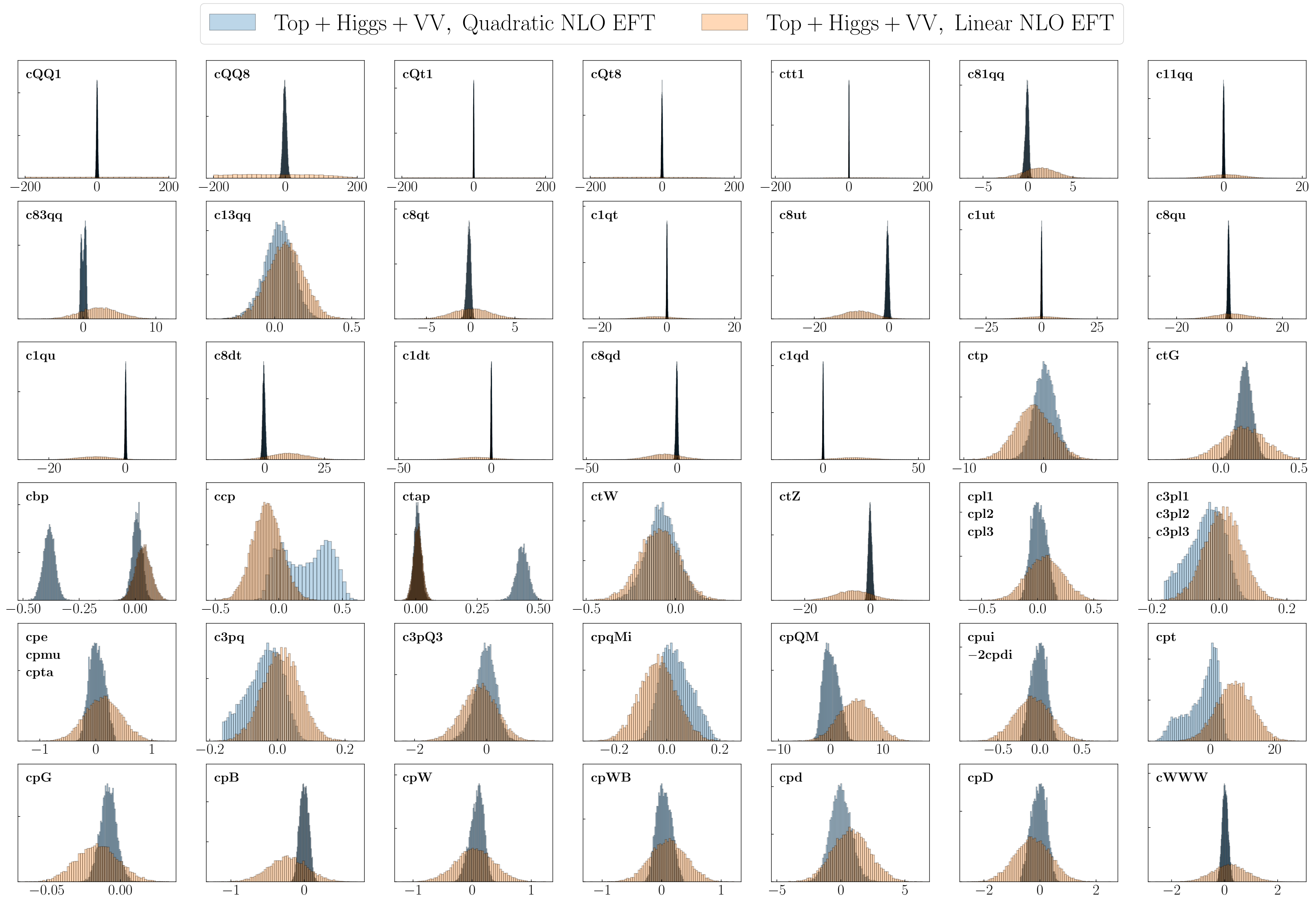


36 operators, $SU(2)^2 \times SU(3)^3$

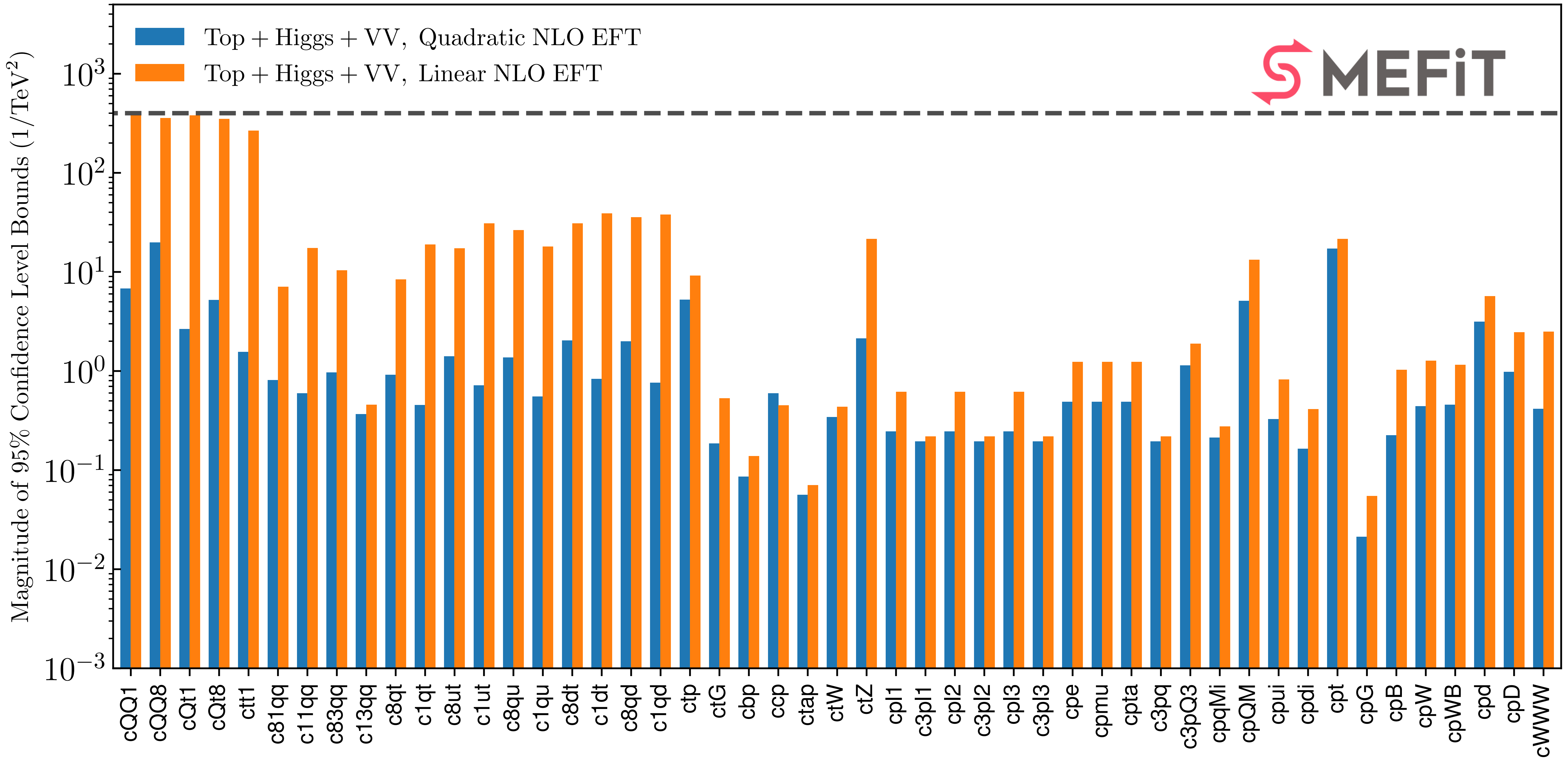
EWPO fixed, 317 data points

Global EW(PO)+H+Top

Linear vs quadratic



Posterior distributions

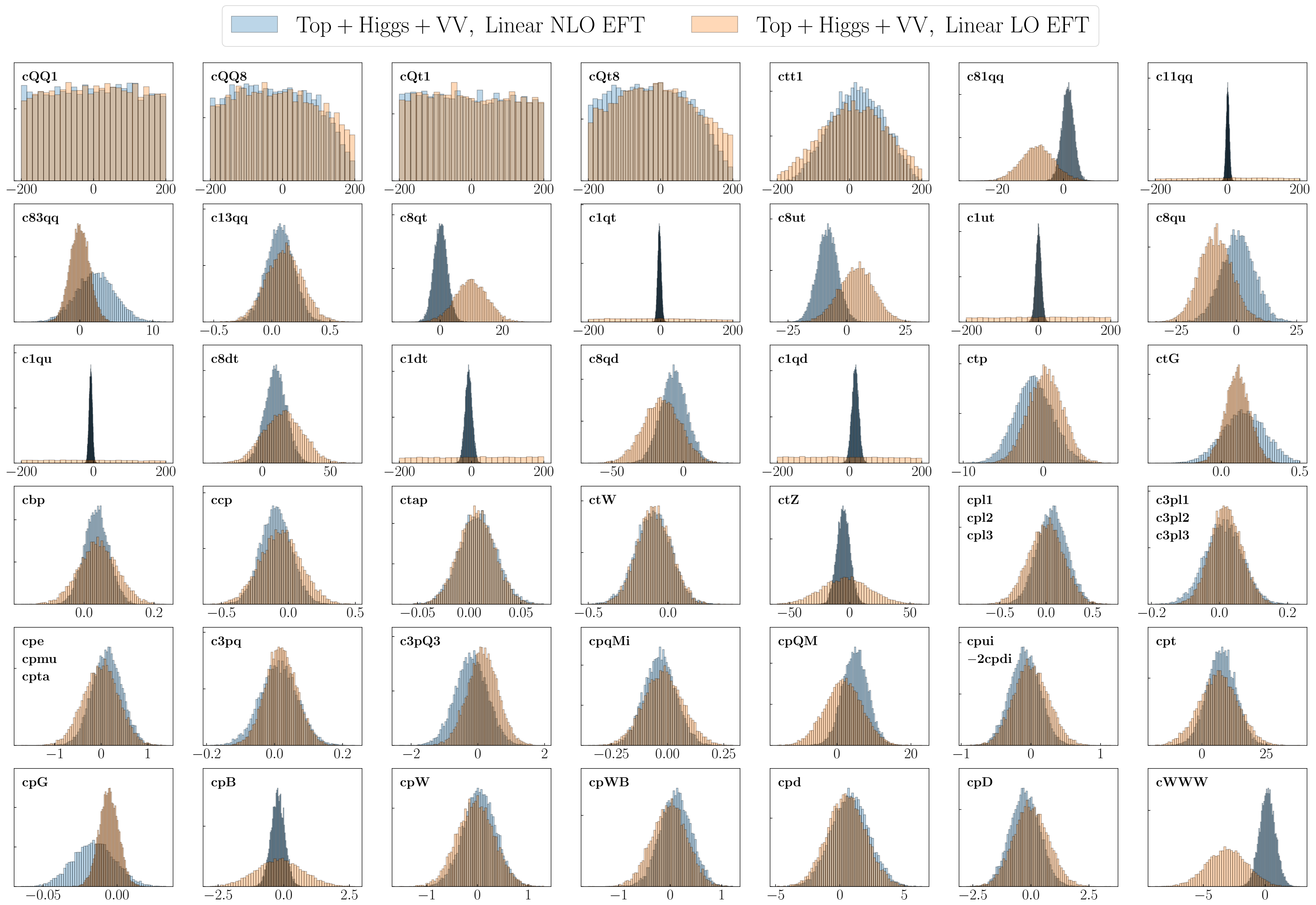


Significant impact for most operators
in particular 4-fermion operators

[Either et al. (SMEFiT) 2105.00006]

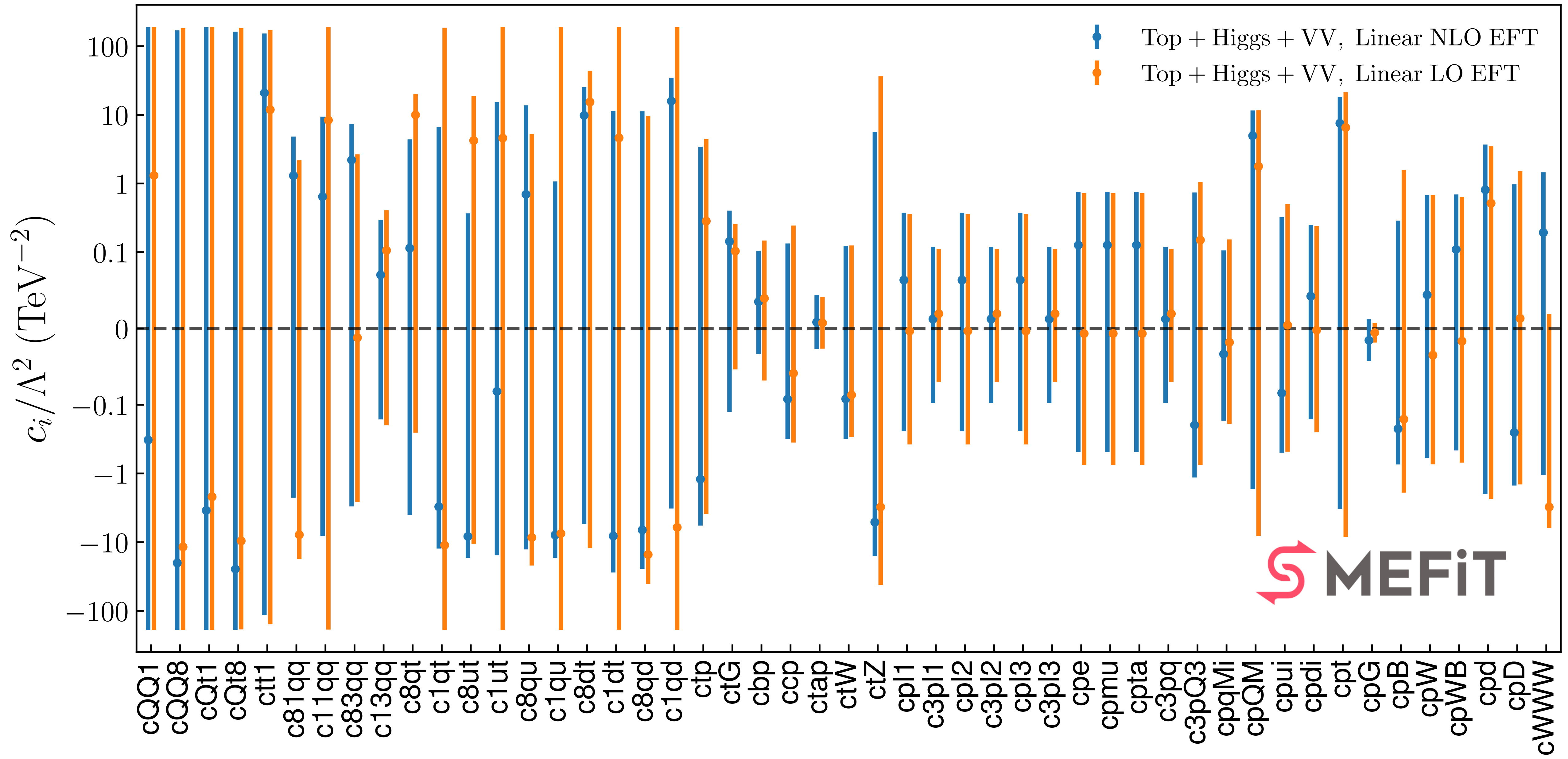
Global EW(PO)+H+Top

LO vs NLO : linear



Posterior distributions for Wilson coefficients

[Either et al. (SMEFiT) 2105.00006]

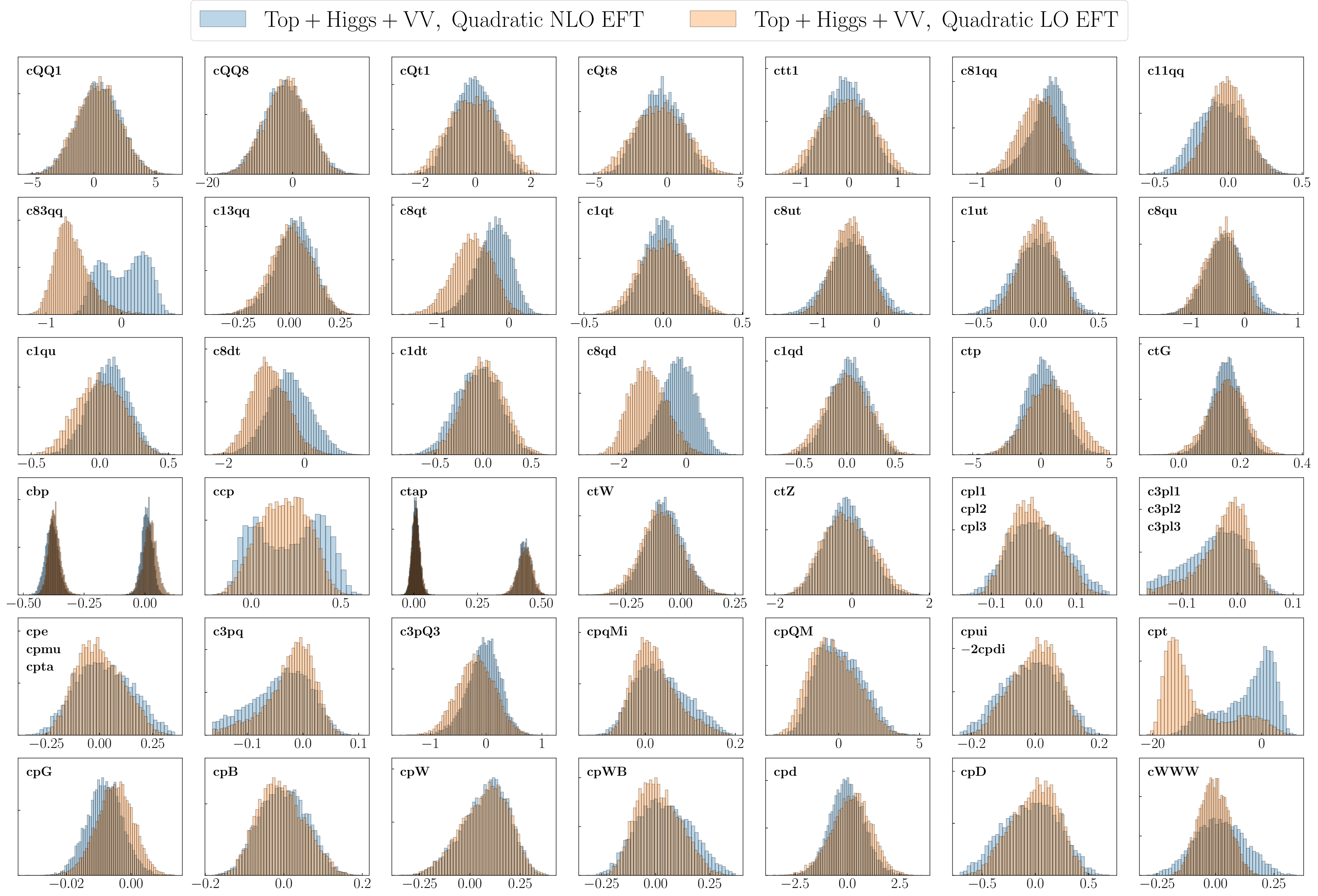


Significant impact of NLO for some operators

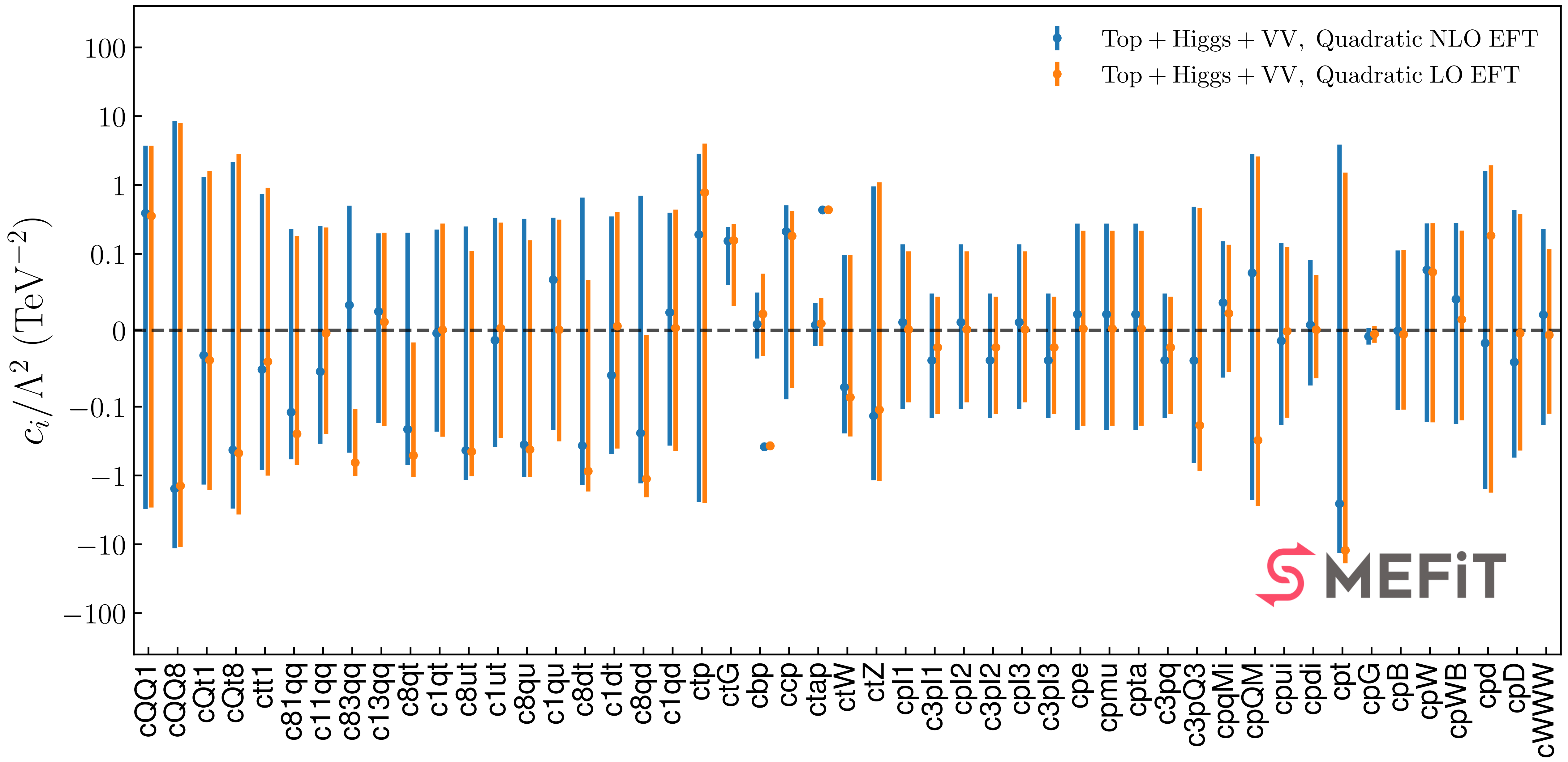
NLO resolves non-interference problem for colour singlet 4F operators

Global EW(PO)+H+Top

LO vs NLO : quadratic



Posterior distributions



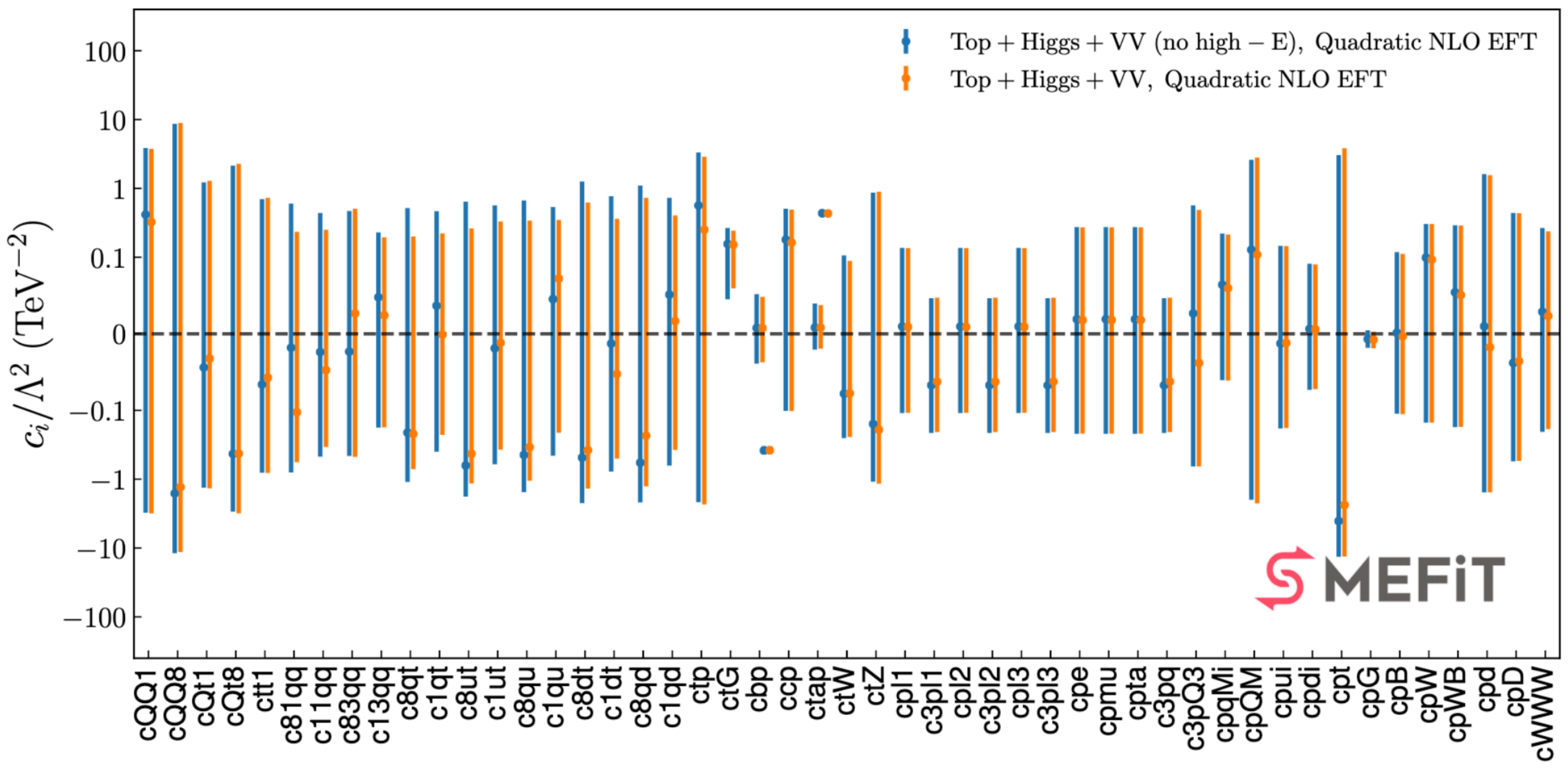
Significant impact of NLO for some operators

[Either et al. (SMEFiT) 2105.00006]

Global EW(PO)+H+Top

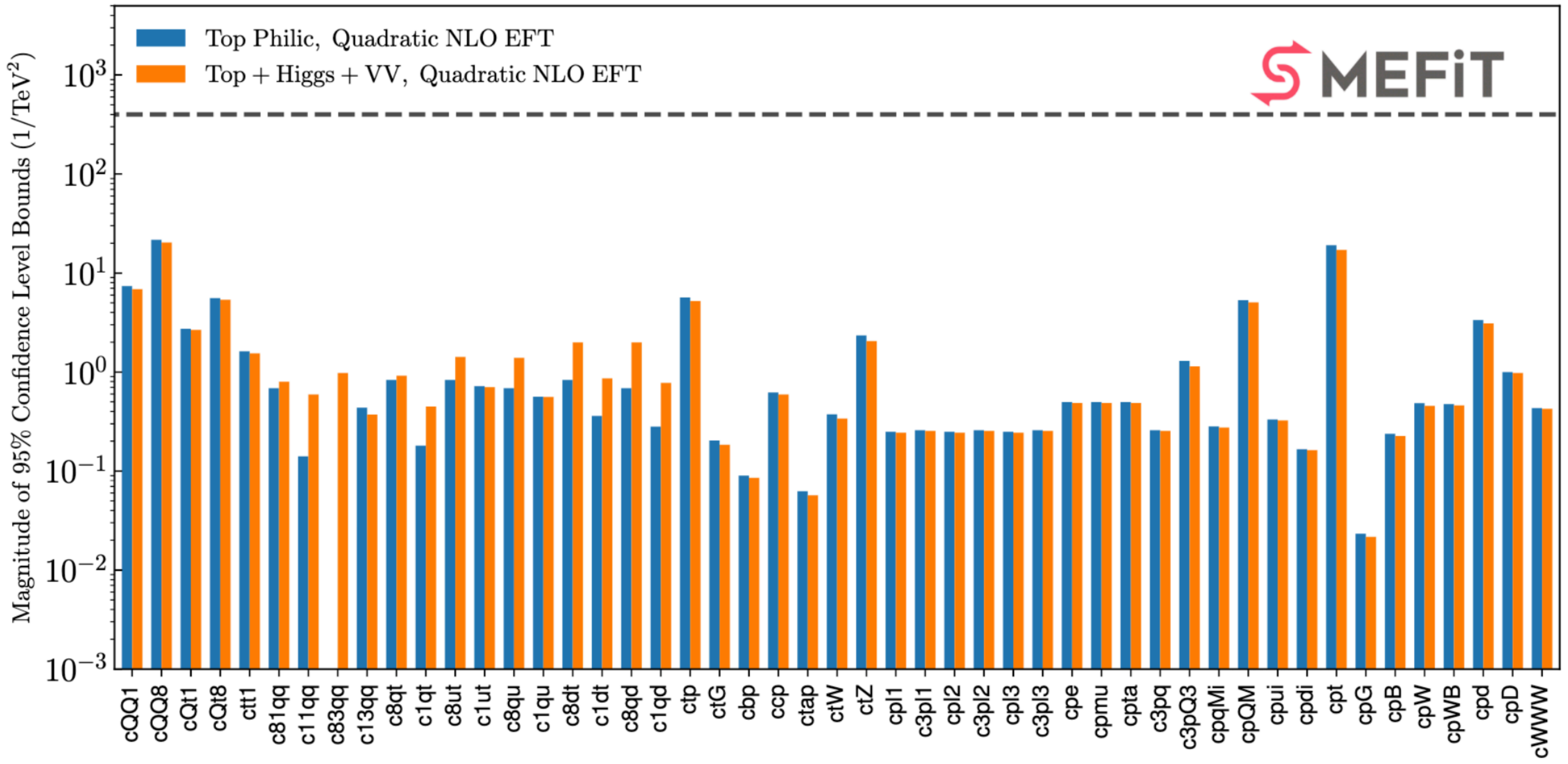
Restrictions

Data restriction



The limited role of the high energy tails (so far)

Theory restriction

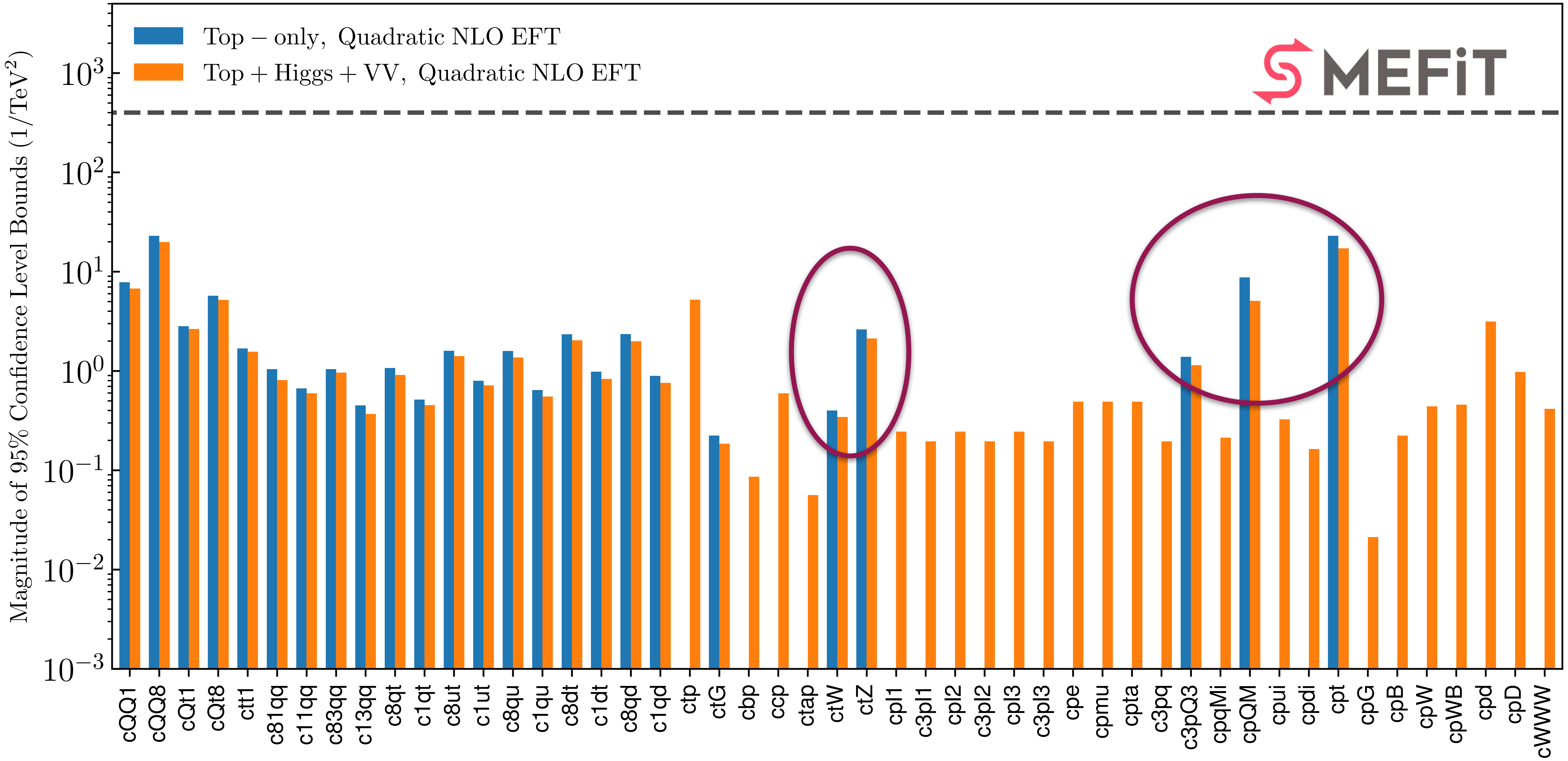


Top-Philic scenario (14 → 5 dof in the 2Q2q)

[Either et al. (SMEFiT) 2105.00006]

Global EW(PO)+H+Top

Top and Higgs

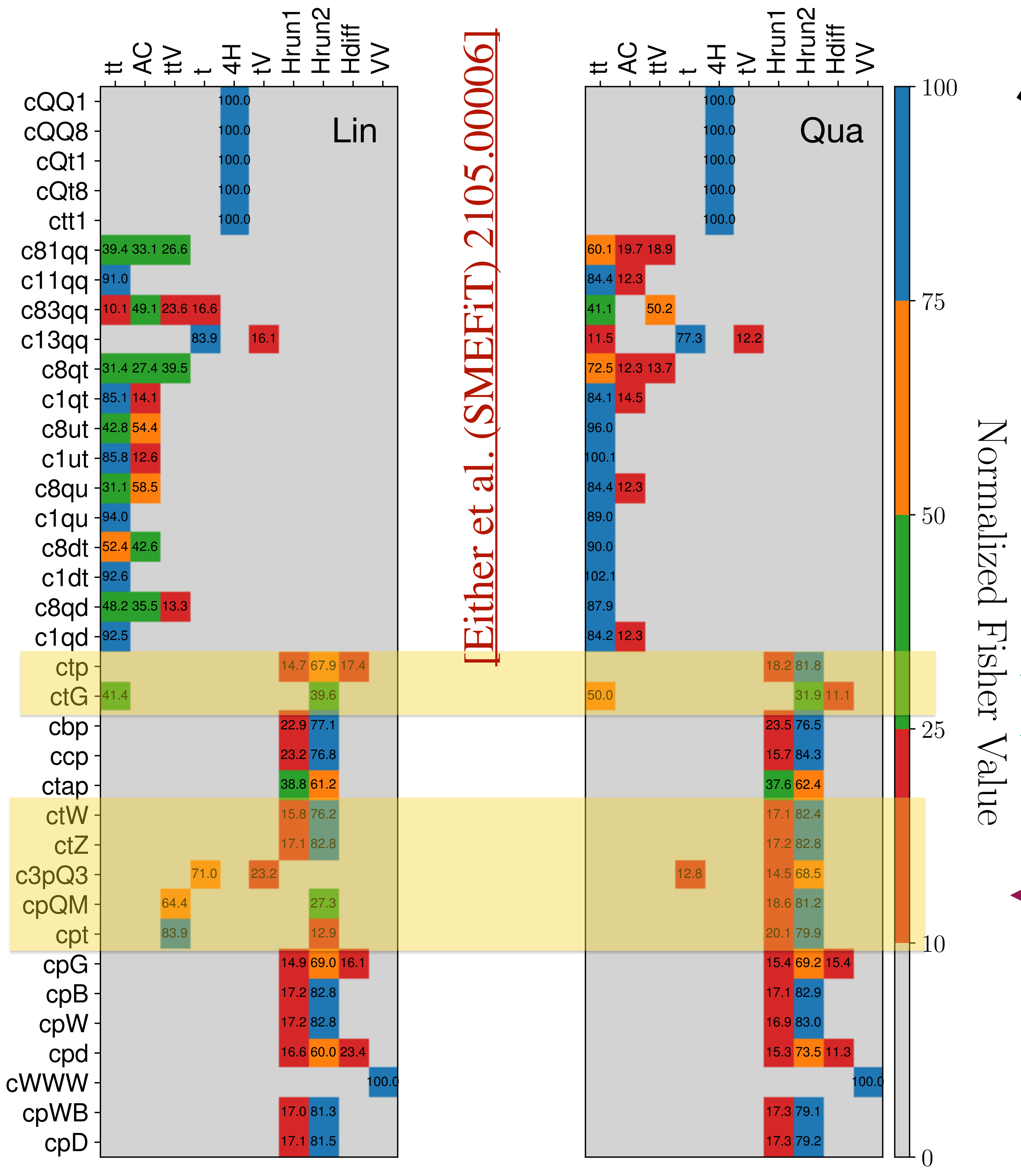


[Either et al. (SMEFiT) 2105.00006]

Higgs data improves certain top operator bounds

Global EW(PO)+H+Top

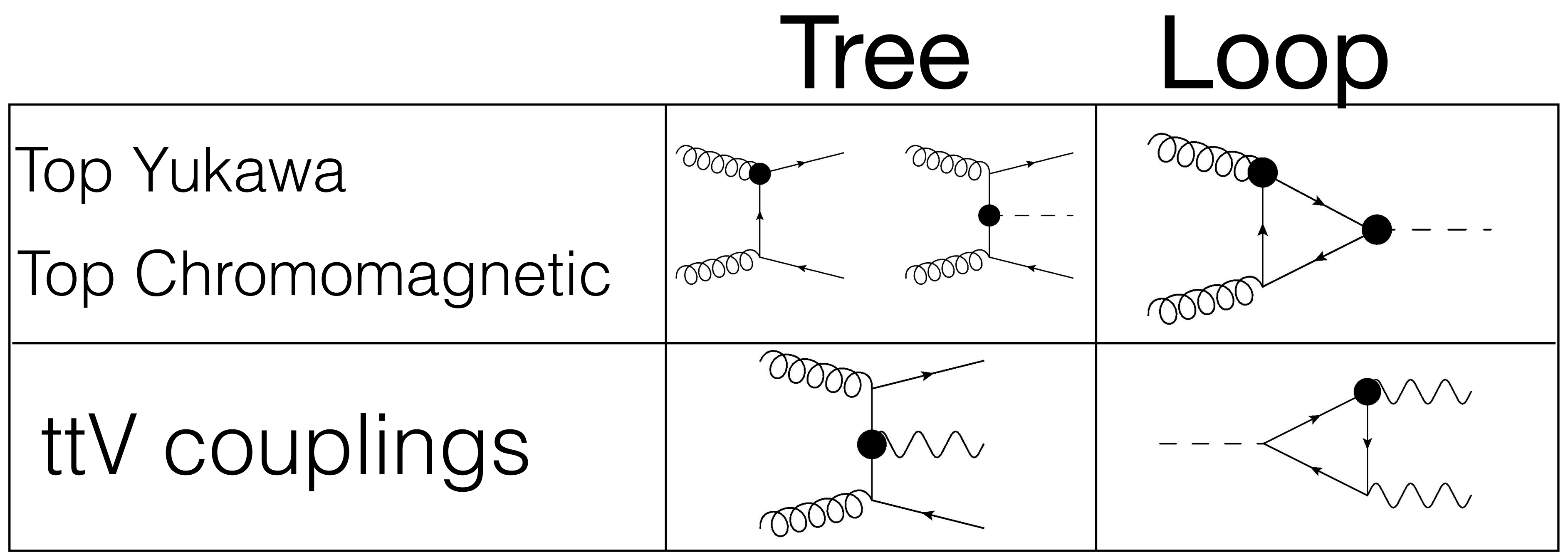
Top and Higgs



[Either et al. (SMEFiT) 2105.00006]

Fisher information table

4F mostly top

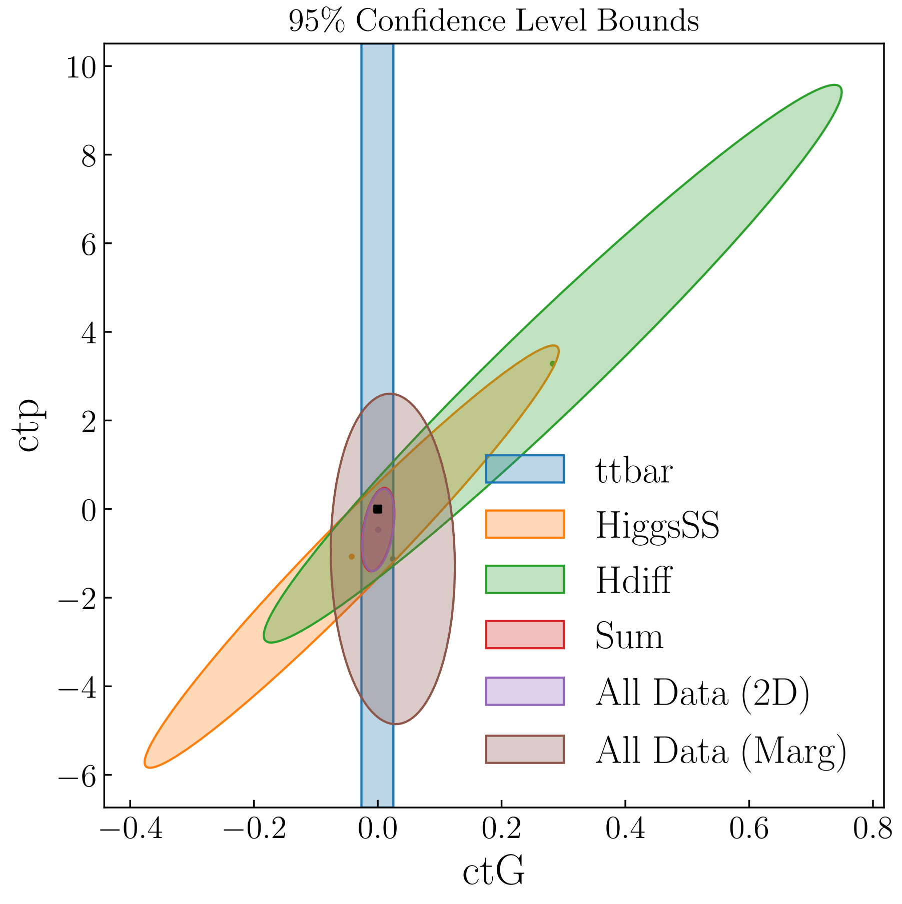


Tree-loop interface

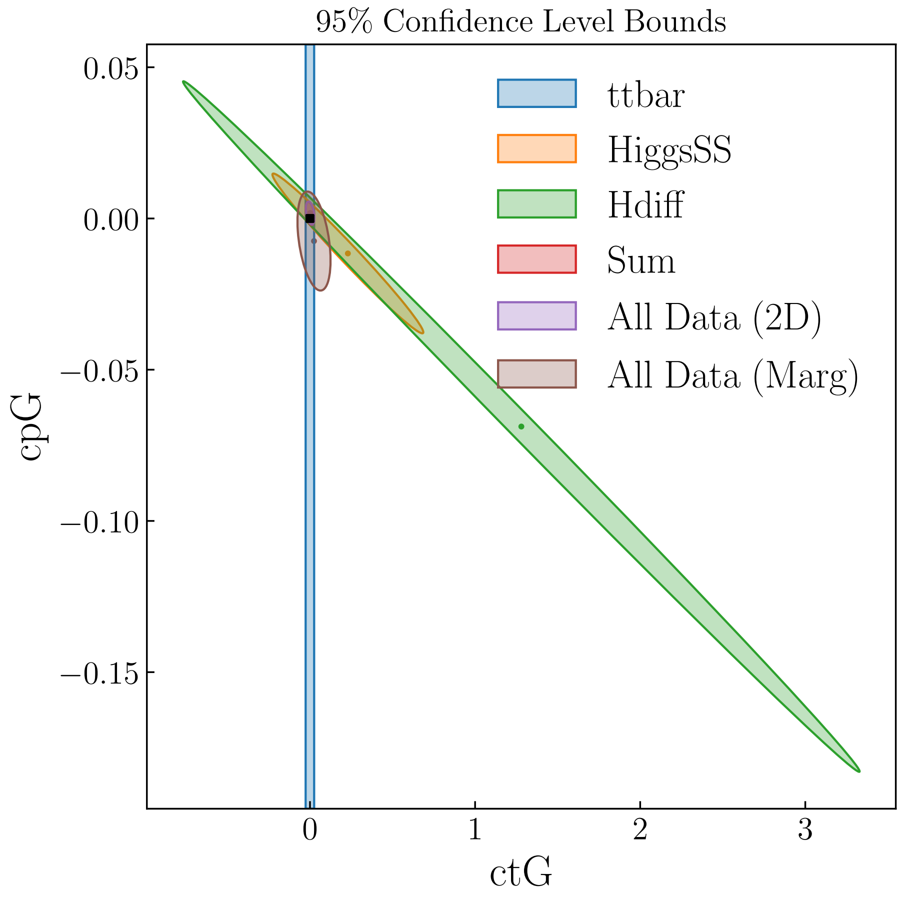
Global EW(PO)+H+Top

Top and Higgs

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



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



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

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

[Either et al. (SMEFiT) 2105.00006]

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

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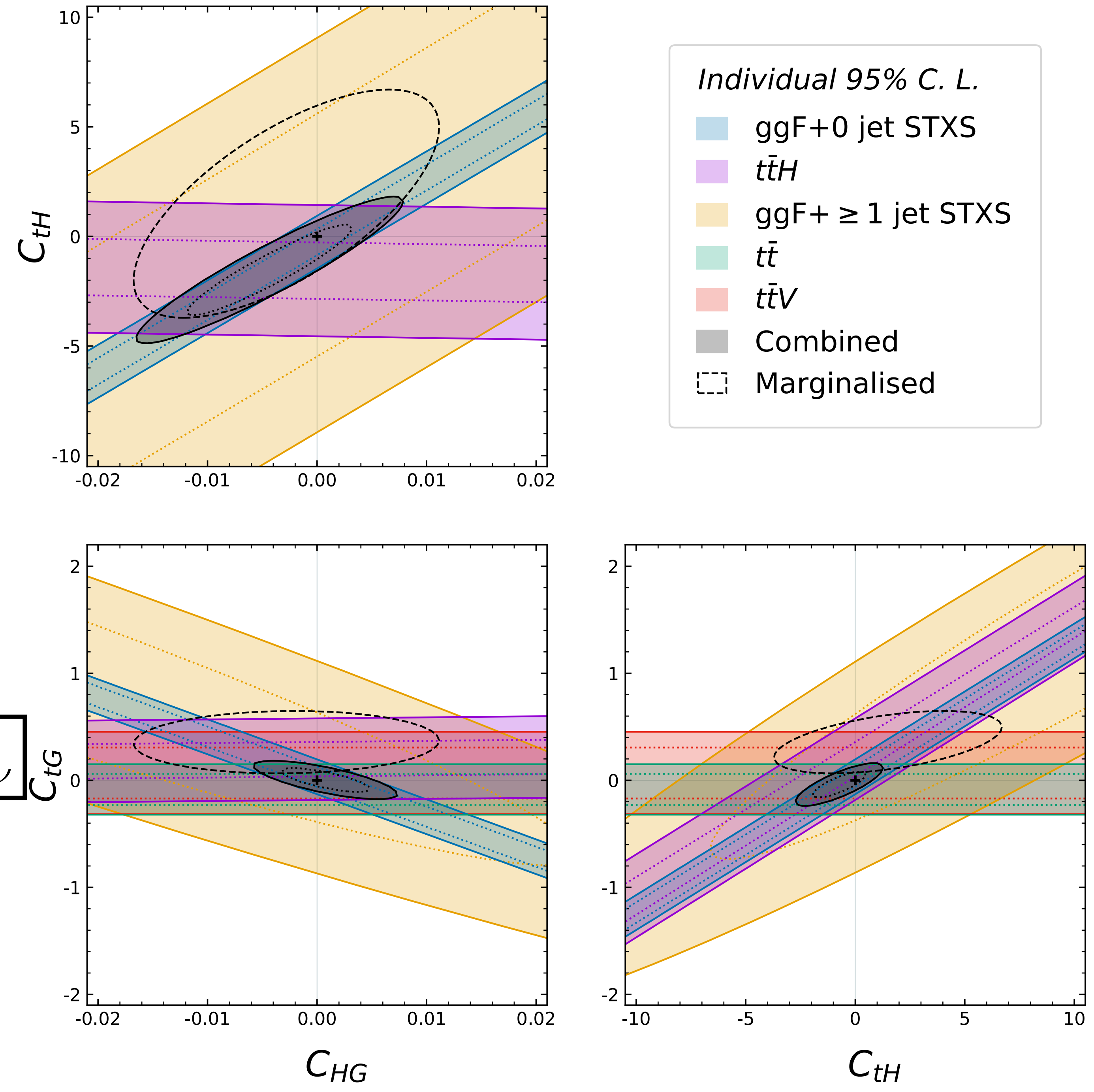


[Ellis et al. 2012.02779]

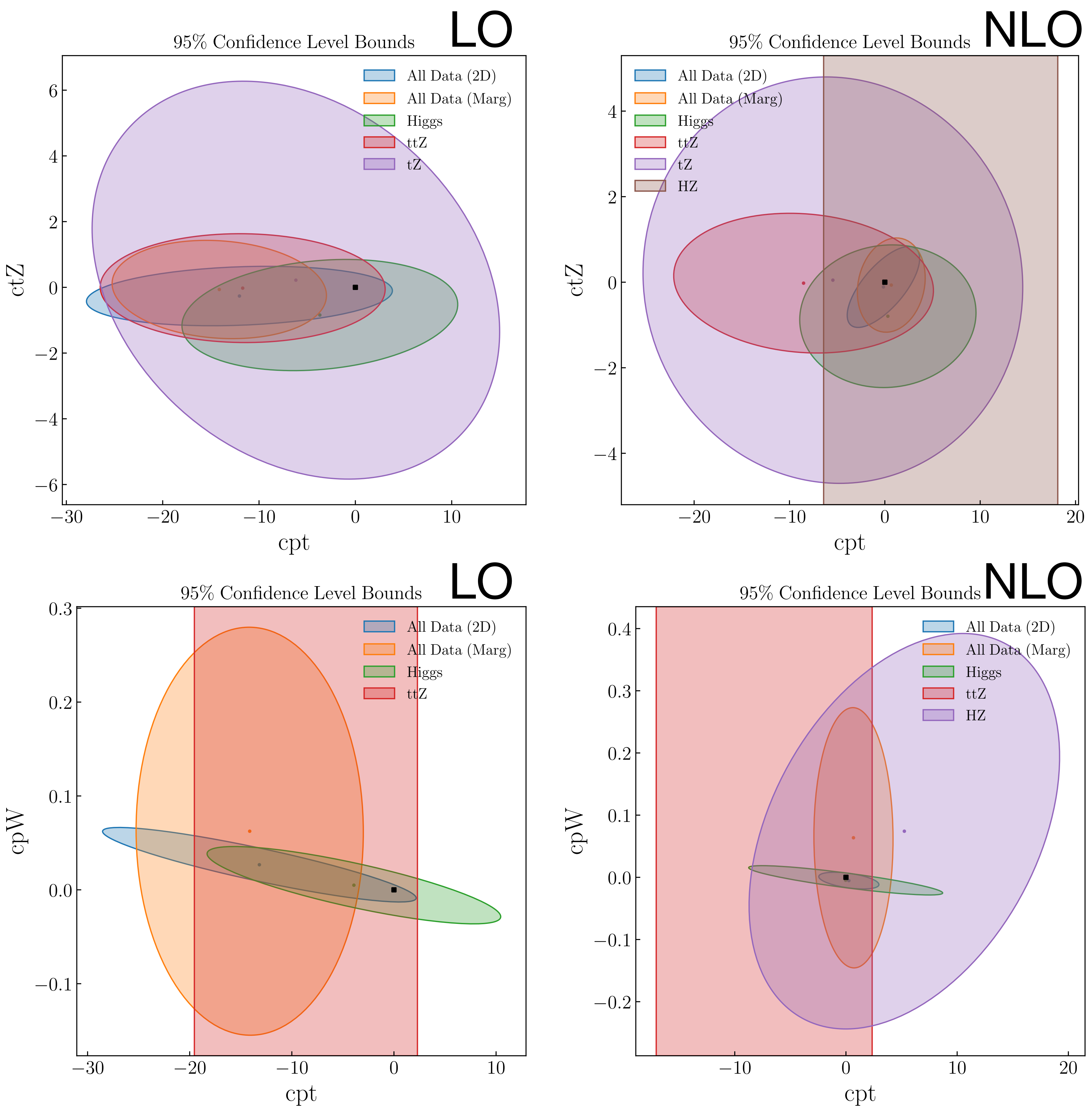
$$\left(\varphi^\dagger\varphi\right)G^{\mu\nu}_A\,G^A_{\mu\nu}$$

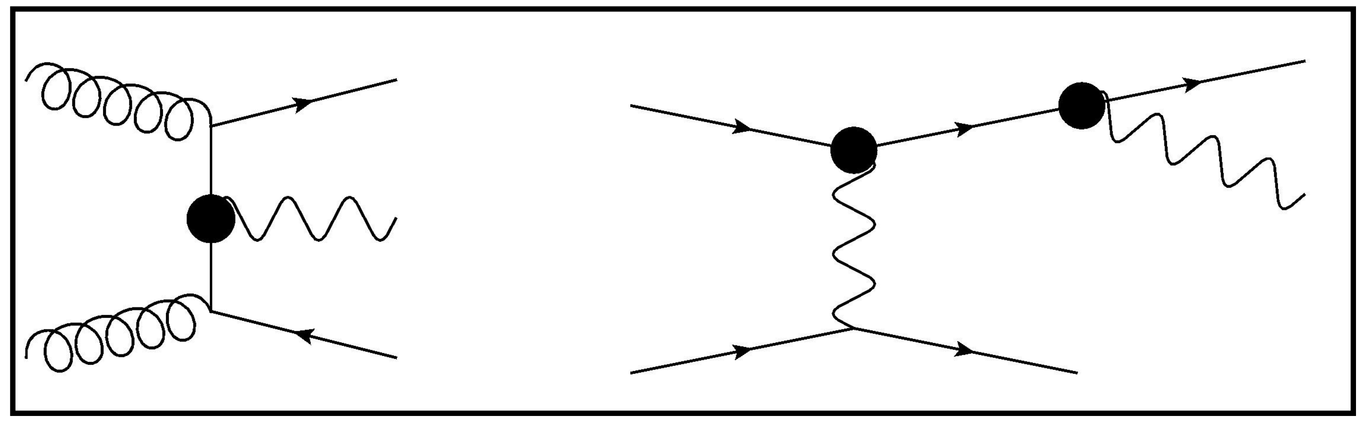
$$\left(\varphi^\dagger\varphi\right)\bar{Q}\,t\,\tilde{\varphi}$$

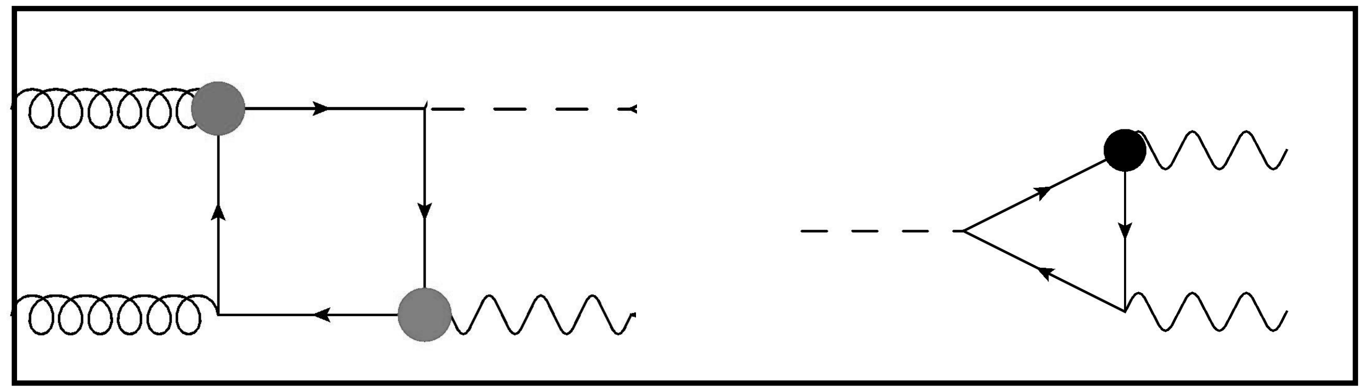
Top measurements break the degeneracy between Higgs operators

Global EW(PO)+H+Top

Top and Higgs







$\mathcal{O}_{\varphi t}$	`cpt`	$i\big(\varphi^\dagger \overleftrightarrow{D}_\mu\, \varphi\big)\big(\bar{t}\,\gamma^\mu\, t\big)$
$\mathcal{O}_{\varphi W}$	`cpW`	$\left(\varphi^\dagger\varphi - \frac{v^2}{2}\right) W_I^{\mu\nu}\, W^I_{\mu\nu}$
$\mathcal{O}_{tW}$	-	$i\big(\bar{Q}\tau^{\mu\nu}\,\tau_I\, t\big)\,\tilde{\varphi}\, W^I_{\mu\nu} + \text{h.c.}$
$\mathcal{O}_{tB}$	-	$i\big(\bar{Q}\tau^{\mu\nu}\, t\big)\,\tilde{\varphi}\, B_{\mu\nu} + \text{h.c.}$

[Either et al. (SMEFiT) 2105.00006]

Global EW(PO)+H+Top

3 points to take home

1. Current fits are at an exploratory state, yet prove feasibility.

2. Dedicated EFT studies/observables needed to improve sensitivity.

3. Shift towards combinable measurements is needed.

Global EW(PO)+H+Top

Work in progress

1. RGE effects

2. Complete-LO

3. Comparisons with UV models

Global EW(PO)+H+Top

Work in progress

1. RGE effects

2. Complete-LO

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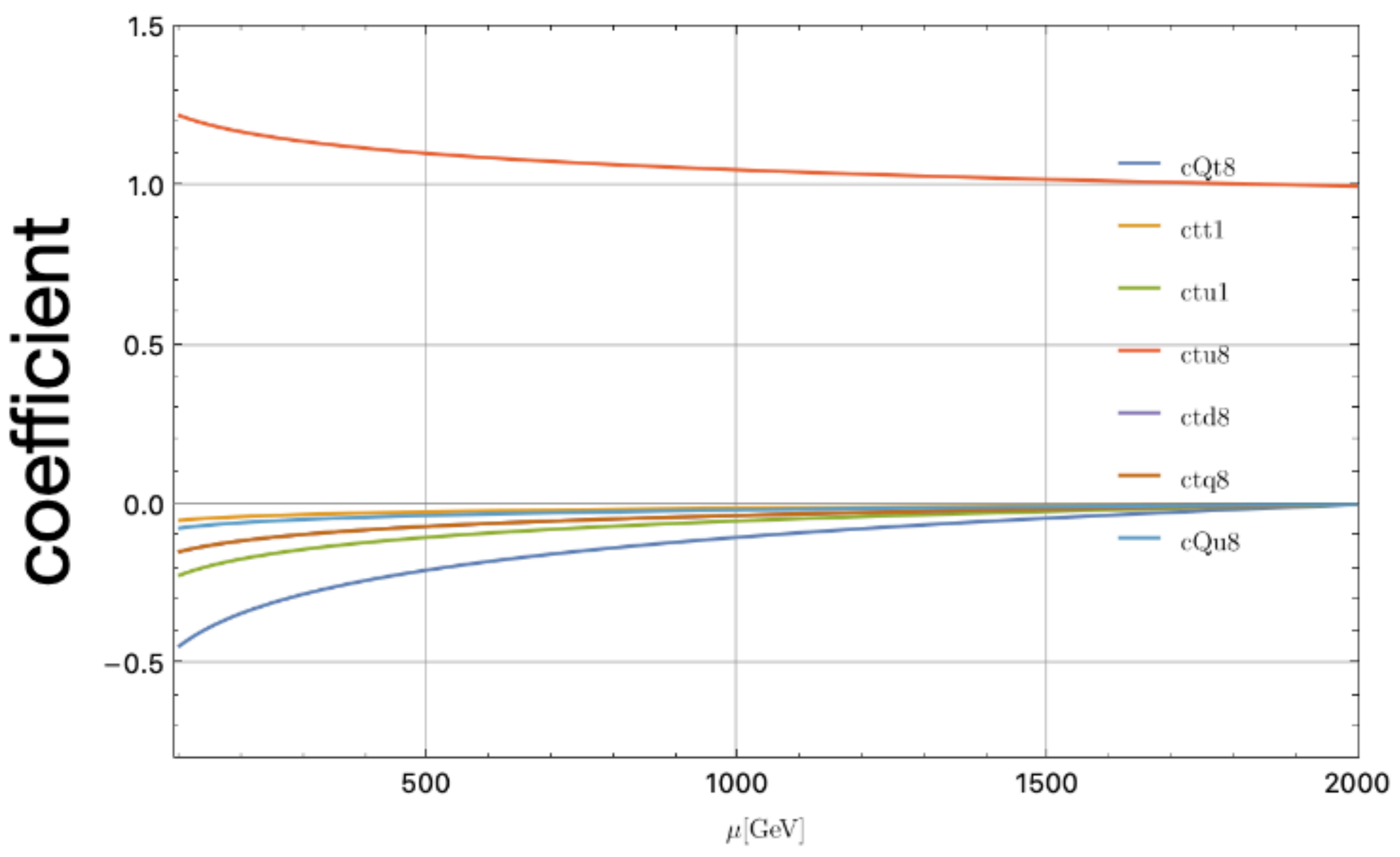

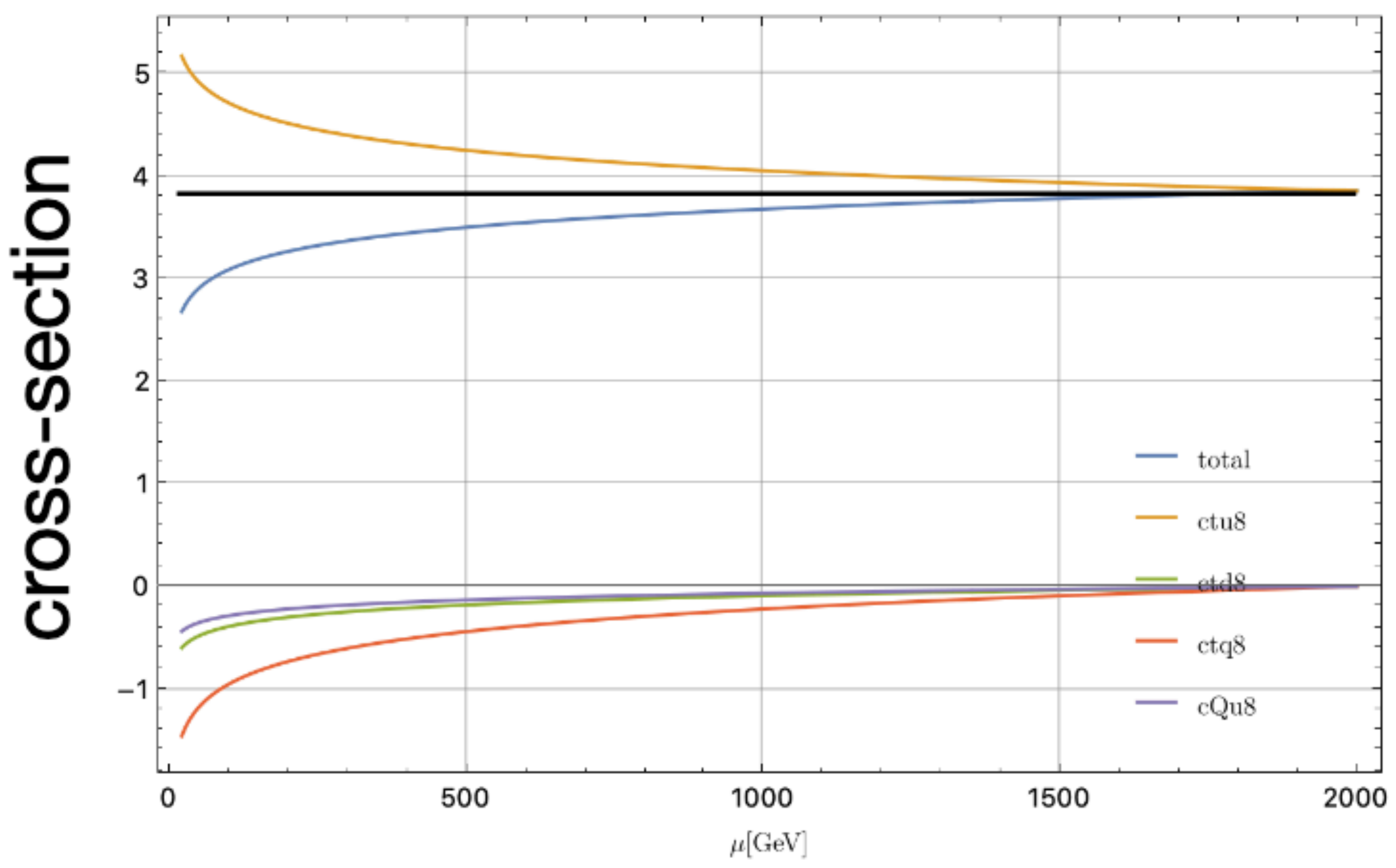

Global EW(PO)+H+Top

Work in progress

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Global EW(PO)+H+Top

Work in progress

[Darme, Fuks, FM, 2104.09512]

1. RGE effects

2. Complete-LO

3. Comparisons with UV models

	LO			NLO	
	$\lvert\text{new physics}\rvert^2$	Int. QCD only	Int. EW only	QCD [40]	via $K_{\rm SM}$
$\mathcal{O}^1_{LL}/2$	$0.8^{+44\%}_{-28\%}$ fb	$0.20^{+47\%}_{-31\%}$ fb	$-0.80^{+41\%}_{-28\%}$ fb	$1.6^{+3\%}_{-10\%}$ fb	$0.62^{+18\%}_{-22\%}$ fb
$\mathcal{O}^1_{LR}$	$1.1^{+45\%}_{-27\%}$ fb	$-0.02^{+32\%}_{-16\%}$ fb	$0.60^{+44\%}_{-28\%}$ fb	$1.84^{+3\%}_{-10\%}$ fb	$3.9^{+21\%}_{-26\%}$ fb
$\mathcal{O}^1_{RR}$	$3.4^{+44\%}_{-28\%}$ fb	$0.39^{+55\%}_{-29\%}$ fb	$-1.42^{+40\%}_{-30\%}$ fb	$6.14^{+3\%}_{-10\%}$ fb	$5.5^{+20\%}_{-22\%}$ fb
$\mathcal{O}^8_{LR}$	$0.28^{+44\%}_{-29\%}$ fb	$0.22^{+52\%}_{-35\%}$ fb	$-0.49^{+42\%}_{-28\%}$ fb	$0.69^{+3\%}_{-8\%}$ fb	$0.01^{+0.10}_{-0.04}$ fb
SM	/	$4.7^{+66\%}_{-38\%}$ fb	$0.50^{+0.95}_{-0.87}$ fb	/	$11.97^{+18\%}_{-21\%}$ fb

Global EW(PO)+H+Top

Work in progress

1. RGE effects

2. Complete-LO

3. Comparisons with UV models

Global EW(PO)+H+Top

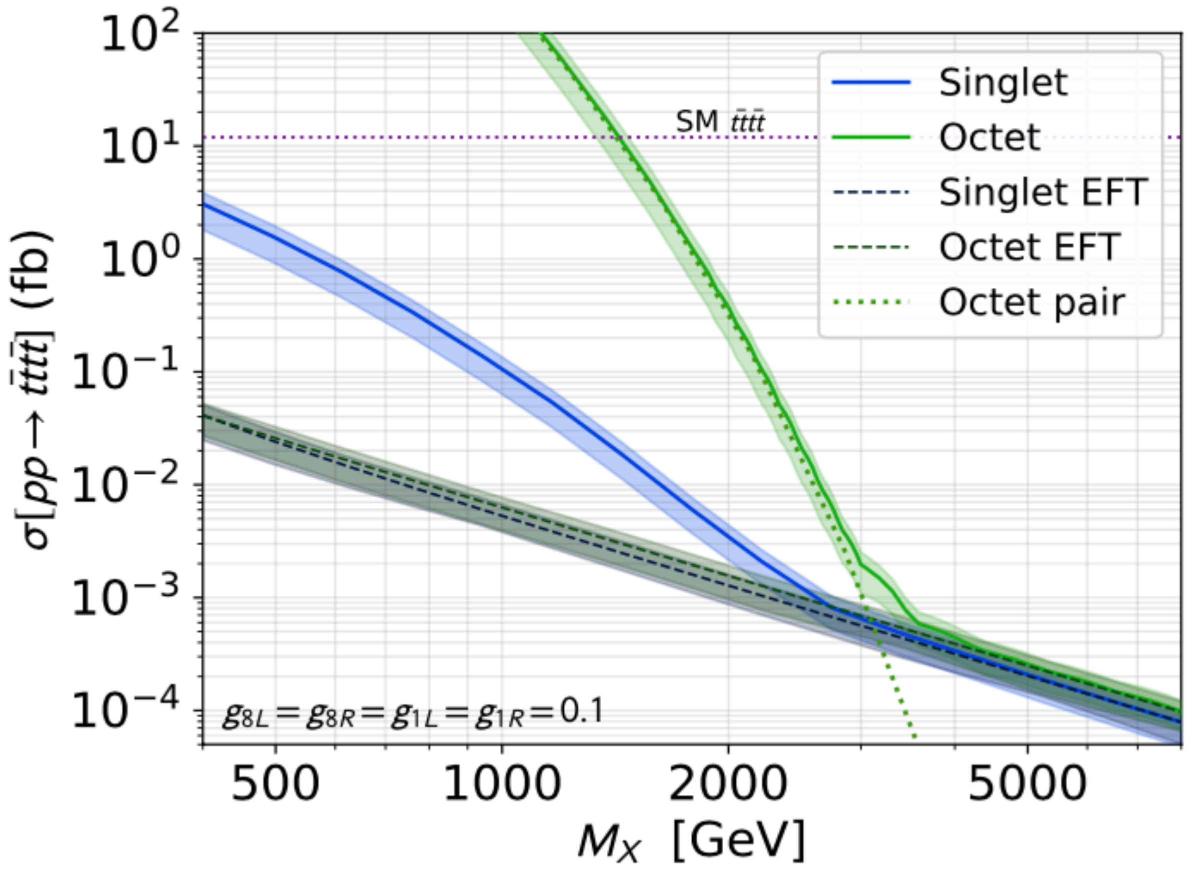
Work in progress

1. RGE effects

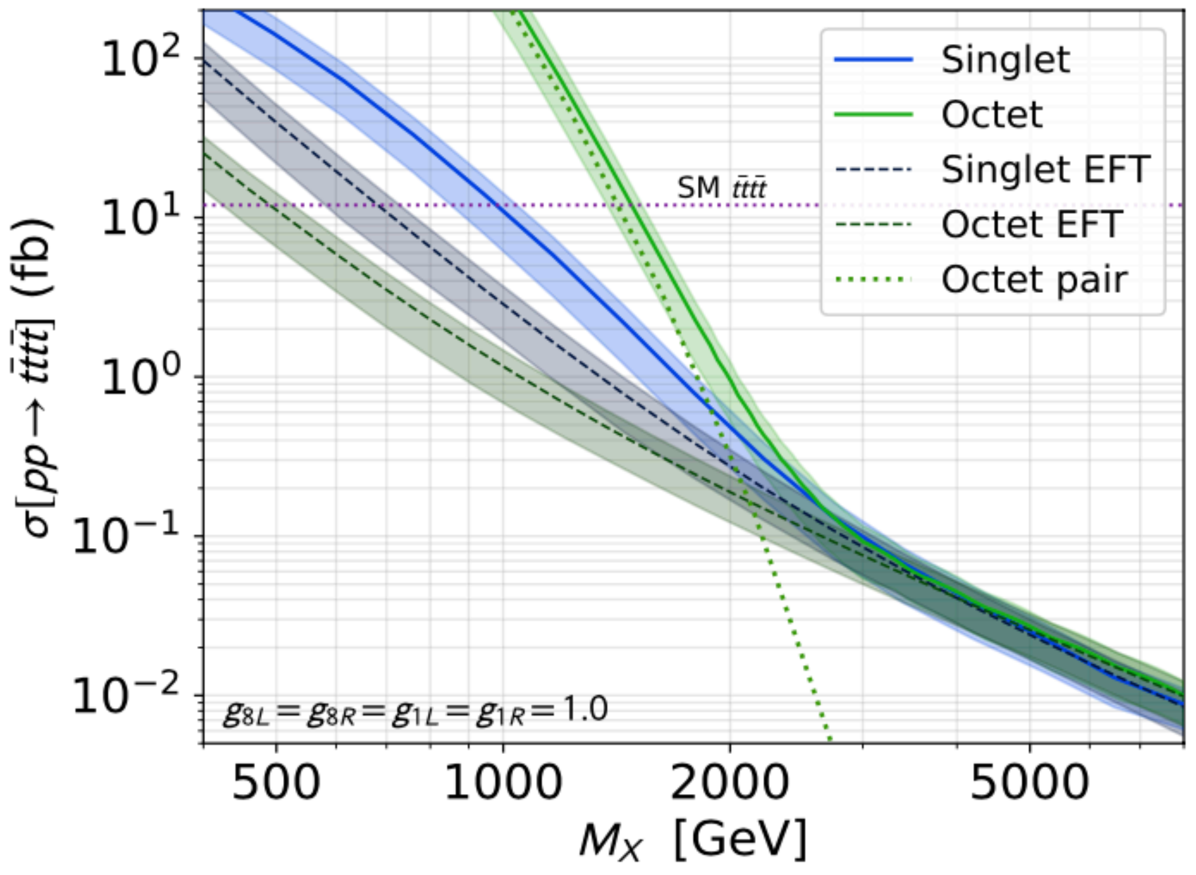
2. Complete-LO

3. Comparisons with UV models

[Darme, Fuks, FM, 2104.09512]



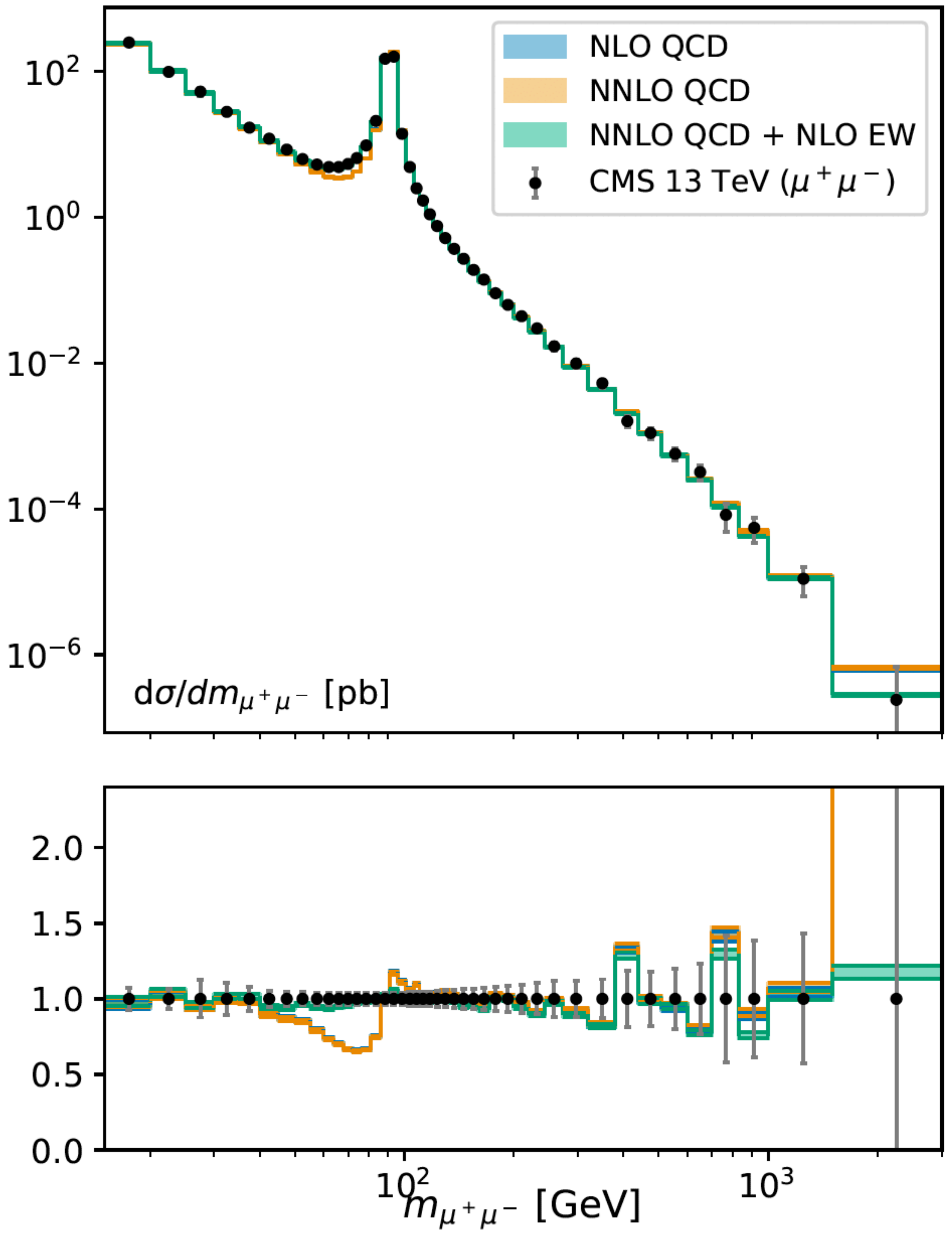
(b)

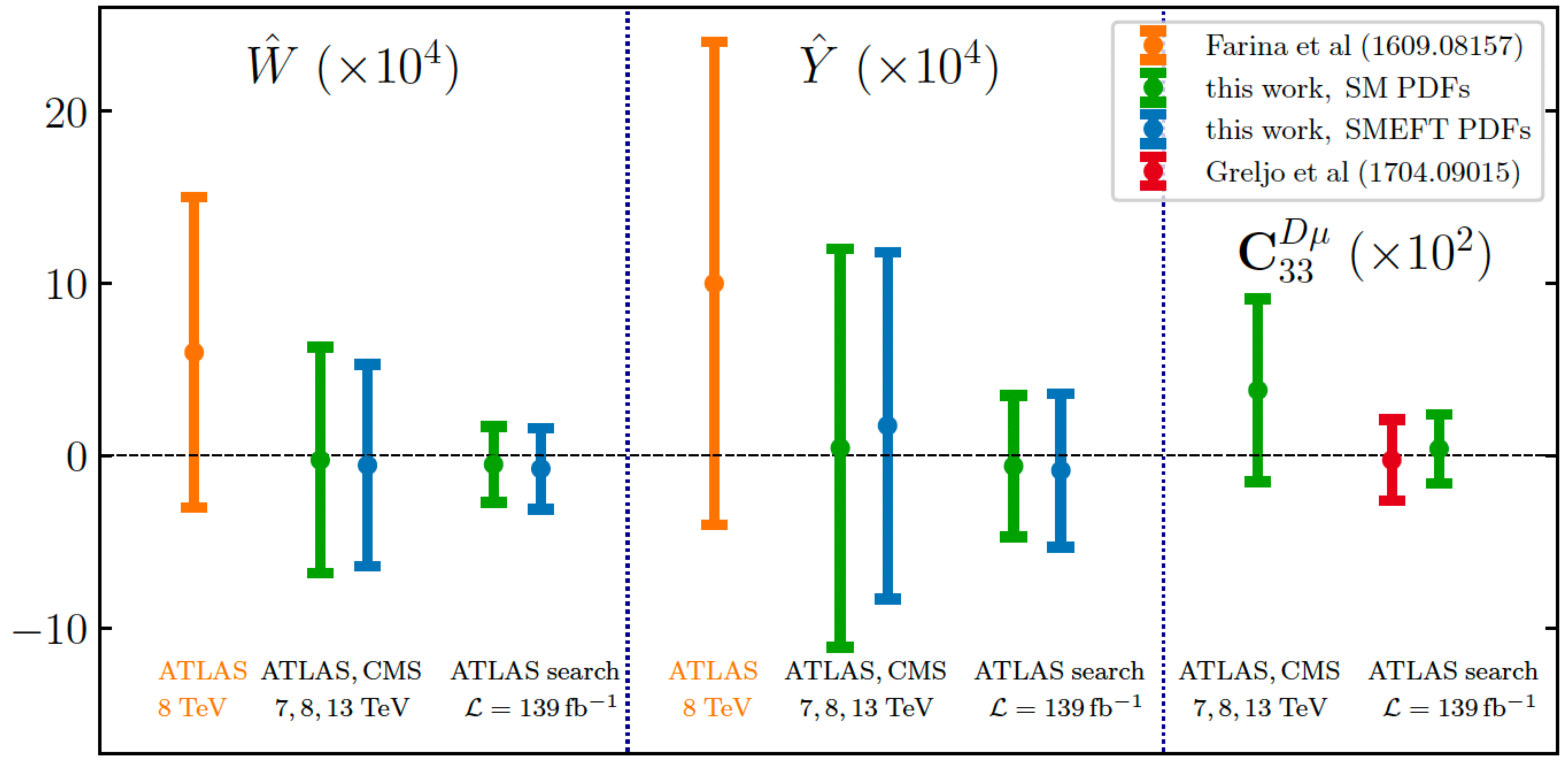


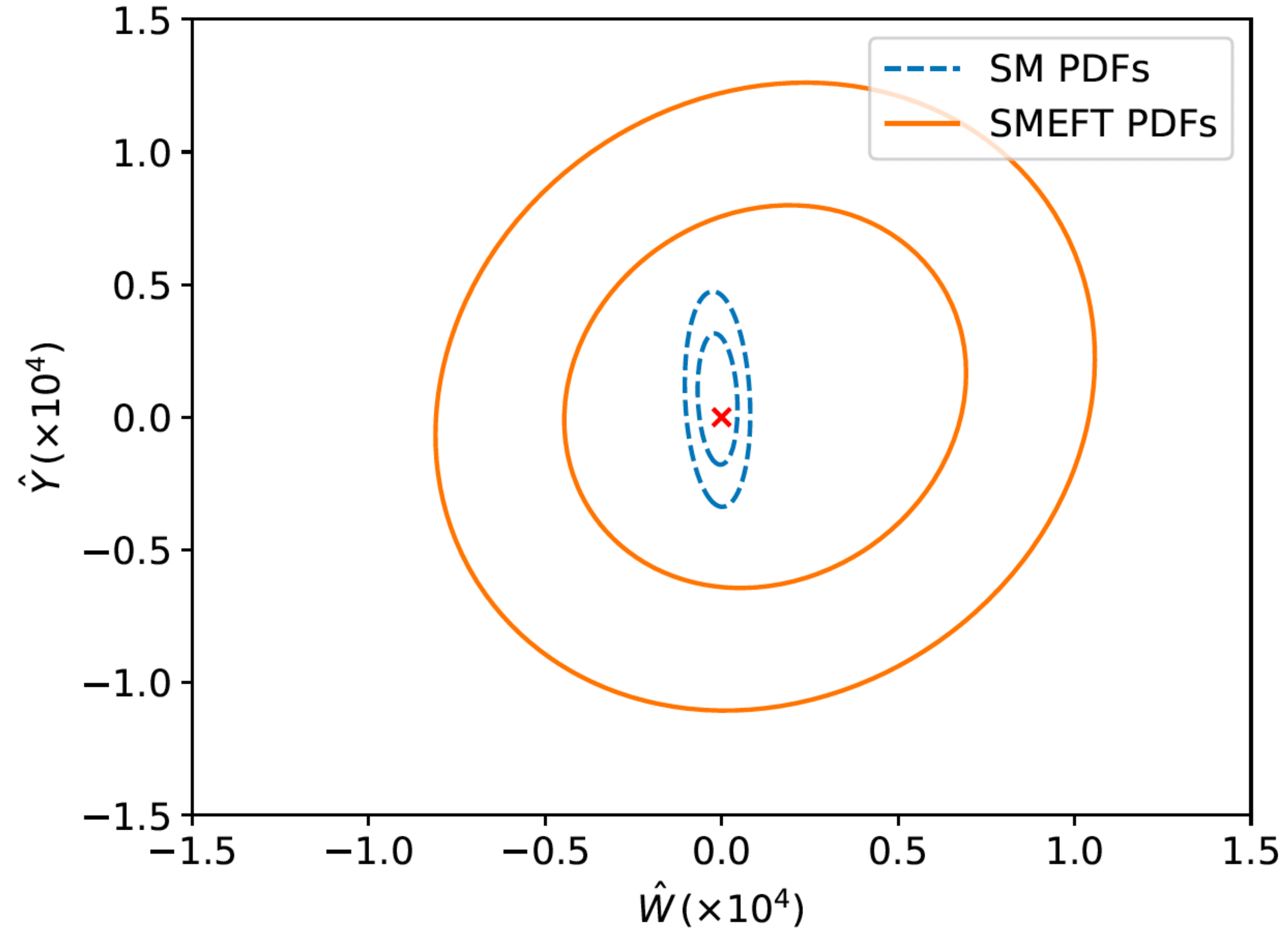
(b)

Theory trends

EFT and PDF fits







[Greljo et al. 2104.02723]

What's next
TH trends

Many directions of development and improvements in the fits are being pursued in TH:

- [Global] Extension to data sets from other (lower-energy) experiments.
- [NLO] Improvement at NLO (QCD+EW) in the SMEFT on-going. RGE at two loops needed to maintain NLO accuracy at different scales. Inclusion of theory uncertainties.
- [Unlocking] Effects and constraints at dim=8 or HEFT.
- [UV] Constraints from and to UV models, systematic studies of applicability/validity. Mixing.
- [PDF] Evaluation of the theory uncertainties to interplay with the PDF fits.
- [MaxSensitivity] Optimal observables, "energy helps accuracy", "X without the X"….
- [QFT] General QFT arguments: resummation of higher-order terms, basis independent formulations (e.g. amplitudes), positivity/convexity.

TRUE or FALSE?

10 questions you always wanted to know about the SMEFT and never dared to ask

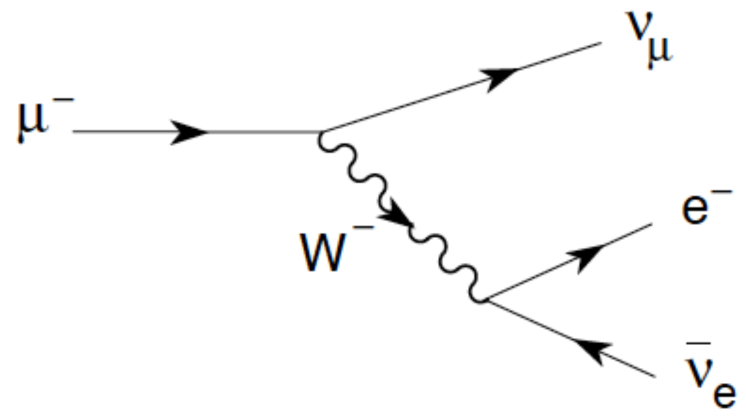
[Contino et al. , 1604.06444] [Aguilar-Saavedra ,1802.07237] [Many discussions…]

Λ is the scale of New Physics

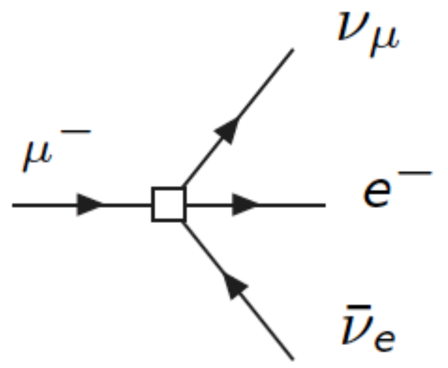
1

Λ is the scale of New Physics

Consider the case of the Fermi theory of the muon decay:



$$\mathbf{g^2}\,\frac{-g_{\mu\nu}+\frac{q_\mu q_\nu}{M_W^2}}{q^2-M_W^2}\ \xrightarrow{q^2\ll M_W^2}\ \frac{g_{\mu\nu}}{M_W^2}\,\mathbf{g^2}$$



$$\frac{G_F}{\sqrt{2}}\ \psi\,\psi\,\psi\,\psi$$

From the measured value of the Fermi constant G_F

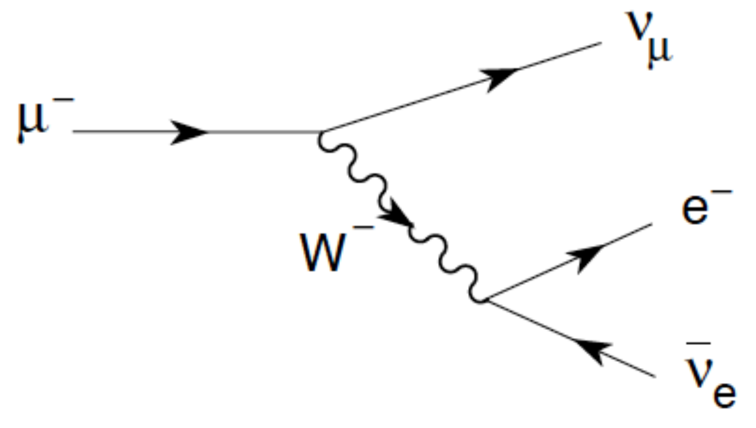
$$\frac{G_F}{\sqrt{2}}=\left(\frac{g}{2\sqrt{2}}\right)^2\frac{1}{m_W^2}=\frac{1}{2v^2}$$

So (4 pi) v is the upper bound on the scale of New Physics. If the theory is weakly interacting the first massive state will have mass of the order g v << v. If the theory is strongly interacting, g ~4 pi, (4 pi) v will coincide with the scale of NP.

Λ is the scale of New Physics

False

Consider the case of the Fermi theory of the muon decay:



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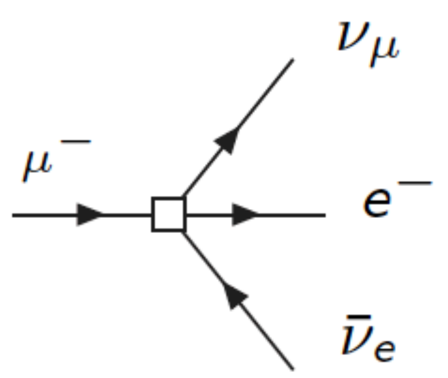

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1

Note: Reinstating dimensions

$$\mathcal{L}_i^{\mathrm{dim}=6} = \frac{g^{n_i-4}}{\Lambda^2}\mathcal{O}_i$$

$$\mathrm{loop-factor} = \frac{g^2\hbar}{(4\pi)^2}$$

$$M = g\Lambda = \mathrm{GeV}$$

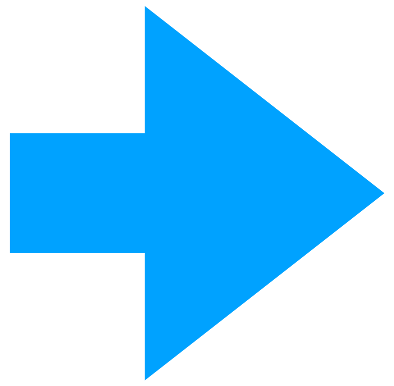
$$[G_{\mu\nu}] = \sqrt{\hbar}\,\mathrm{GeV}^2$$

$$[\phi] = [v] = [\Lambda] = \sqrt{\hbar}\,\mathrm{GeV}$$

$$[A_\mu] = \sqrt{\hbar}\,\mathrm{GeV}$$

$$[\psi] = \sqrt{\hbar}\,\mathrm{GeV}^{3/2}$$

$$[g] = [\sqrt{\lambda}] = 1/\sqrt{\hbar}$$



$$\mathcal{L} = \frac{g^2}{\Lambda^2}\phi^6 = \frac{g^4}{M^2}\phi^6$$

$$\mathcal{L} = \frac{g}{\Lambda^2}\phi\phi Q\phi u = \frac{g^3}{M^2}\phi\phi Q\phi u$$

$$\mathcal{L} = \frac{1}{\Lambda^2}\phi^2 GG = \frac{g^2}{M^2}\phi^2 GG$$

$$\mathcal{L} = \frac{1}{\Lambda^2}Q\phi u G = \frac{g^2}{M^2}Q\phi u G$$

$$\mathcal{L} = \frac{1}{\Lambda^2}\phi D\phi\psi\psi = \frac{g^2}{M^2}\phi D\phi\psi\psi$$

$$\mathcal{L} = \frac{1}{\Lambda^2}\psi\psi\psi\psi = \frac{g^2}{M^2}\psi\psi\psi\psi$$

$$\mathcal{L} = \frac{g^{-1}}{\Lambda^2}GGG = \frac{g}{M^2}GGG$$

The SMEFT is model independent

2

The SMEFT is model independent

The aim of an EFT is to reproduce the IR behaviour of (a possibly) wide set of UV theories. However, it always relies on (generic) assumptions on the UV dynamics. The SMEFT@dim6, for examples, assumes:

1. The upper bound on the scale of new physics is Λ.
2. The SU(2)xU(1) symmetry is linearly realised.
3. The expansion in $1/\Lambda$ is well-behaved, i.e. effects of dimension-8 operators are parametrically suppressed with respect to the dimension-6.

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2

In the SMEFT, the operator normalisation is meaningful

3

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Associating a “natural" normalisation to (class of) operators implies a UV bias, either some scaling rules and/or already an interpretation in mind. This is certainly legitimate, yet not necessary at the data analysis stage, if maximal flexibility/generality is desired.

At the SMEFT@dim6 one can work leaving the normalisation arbitrary (i.e. fixing the simplest convention) and just using data to constrain the coefficients. At the end only relations between observables as implied by the model are physically meaningful. And these do not depend on the normalisation.

3

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False

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3

The SMEFT is a non-renormalizable QFT and therefore it has no predictive power

The SMEFT is a non-renormalizable QFT and therefore it has no predictive power

Order by order in the $1/\Lambda$ expansion, the SMEFT is renormalisable, i.e. higher-order contributions can be computed as perturbative series in the gauge couplings. For example., amplitudes with one operator insertion (at order $1/\Lambda^2$) can be renormalised using a finite number of counter-terms at all order in PT.

4

The SMEFT is a non-renormalizable QFT and therefore it has no predictive power

False

Order by order in the $1/\Lambda$ expansion, the SMEFT is renormalisable, i.e. higher-order contributions can be computed as perturbative series in the gauge couplings. For example., amplitudes with one operator insertion (at order $1/\Lambda^2$) can be renormalised using a finite number of counter-terms at all order in PT.

4

Truncating the SMEFT at the dim=6 is always correct

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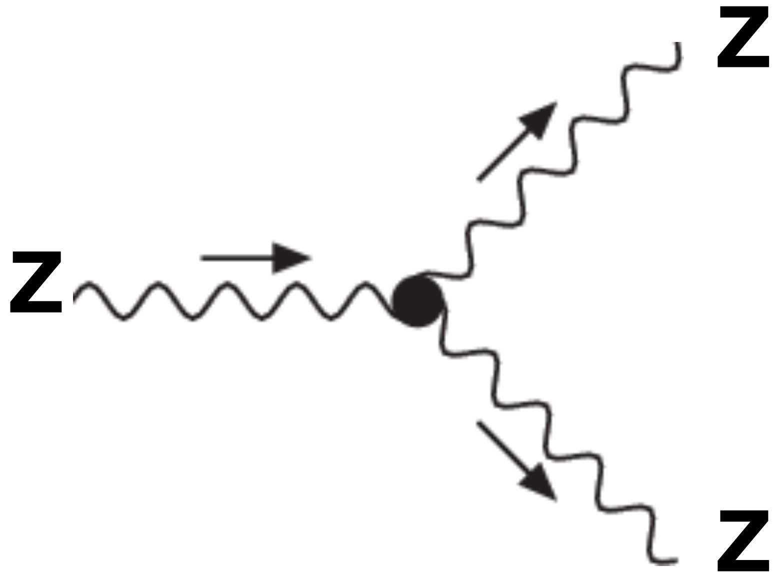
$$f_4^\gamma = -\frac{M_Z^2v^2\left(-c_ws_w\frac{C_{WW}}{\Lambda^4}+\frac{C_{BW}}{\Lambda^4}\left({c_w}^2-{s_w}^2\right)+4c_ws_w\frac{C_{BB}}{\Lambda^4}\right)}{4c_ws_w}$$



[Degrande, 1308.6323]

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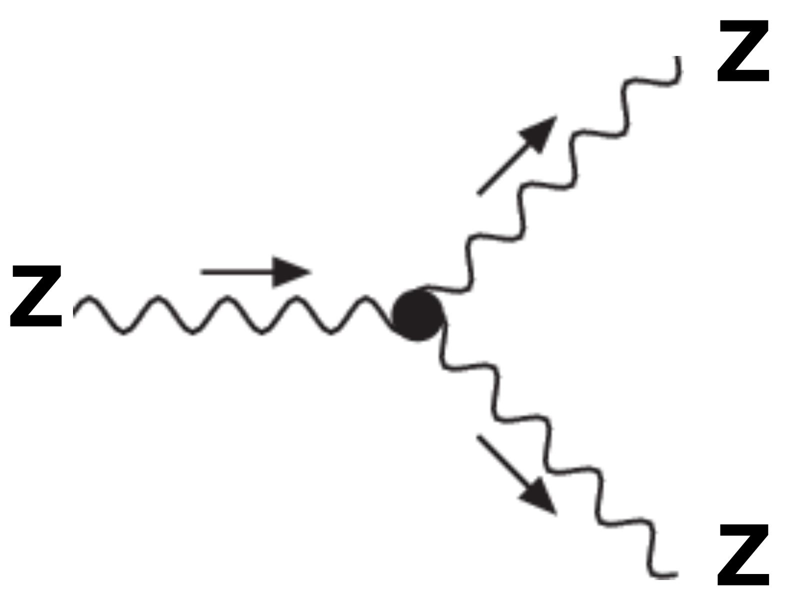

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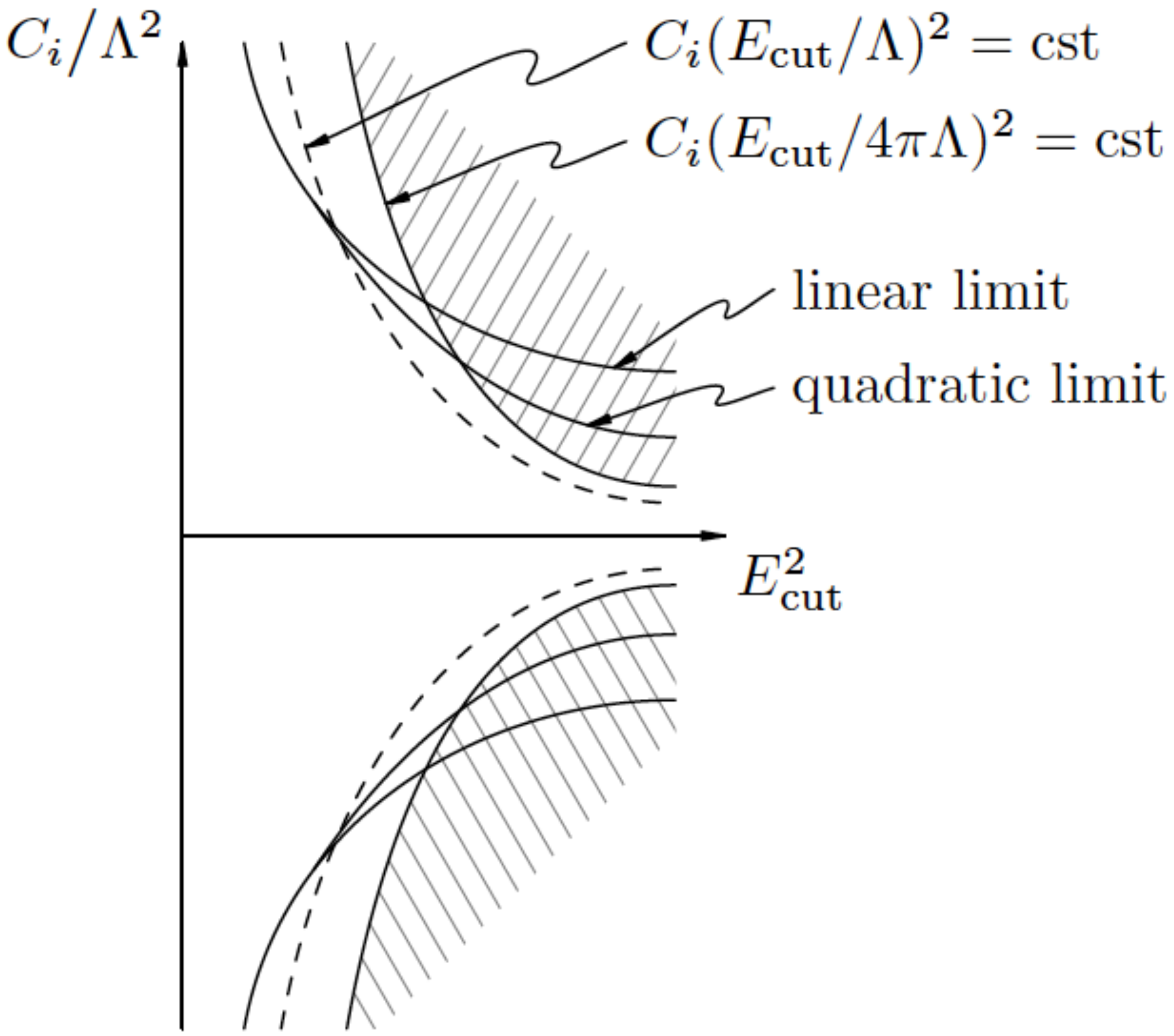

Figure 1: Illustration of the limit set on an EFT parameter as function of a cut on the characteristic energy scale of the process considered (see item 6). Qualitatively, one expects the limits to be progressively degraded as $E_{\rm cut}$ is pushed towards lower and lower values. At high cut values, beyond the energy directly accessible in the process considered, a plateau should be reached. The regions excluded when the dimension-six EFT is truncated to linear and quadratic orders are delimited by solid lines (see item 5c). The hatched regions indicate where the dimension-six EFT loses perturbativity (see item 7). In practice, curves will not be symmetric with respect to $C_i/\Lambda^2 = 0$.

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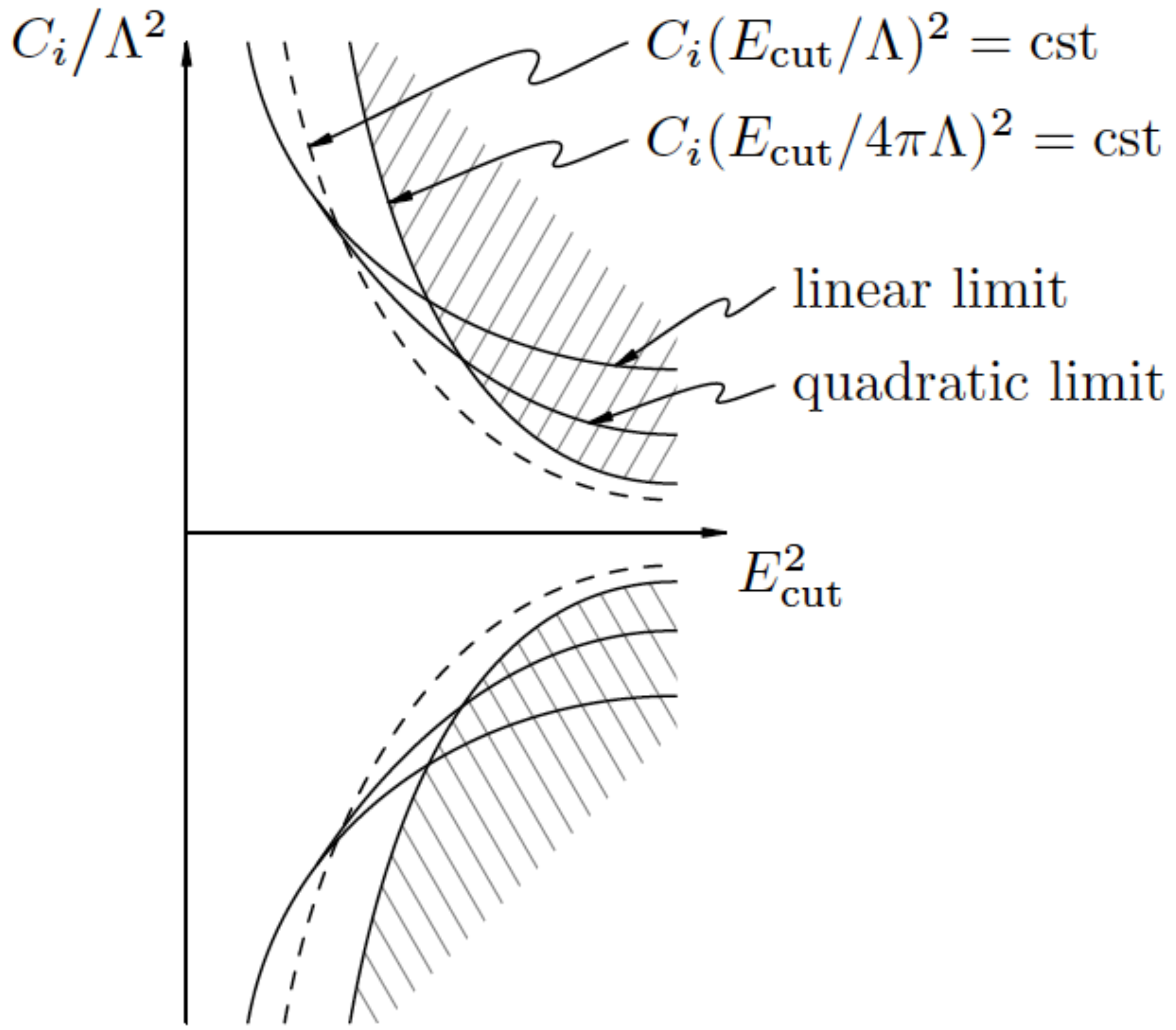

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Squared terms are not uniquely defined and should not be employed in pheno analyses

At the amplitude level:

$$A = A_{\rm SM} + \sum_i \tilde{c}_i^6 A_i^6 + \sum_k \tilde{c}_k^8 A_k^8 + \ldots$$

At $1/\Lambda^2$ level, the dim=6 term is uniquely defined. One can change the basis, perform field redifinitions, use the EOM, yet the full blue sum remains the same, generating however, corrections of order $1/\Lambda^4$, feeding into the red term . This means that

$$|A|^2 = |A_{\rm SM} + \sum_i \tilde{c}_i^6 A_i^6|^2$$
$$= |A_{\rm SM}|^2 + 2\sum_i \tilde{c}_i^6 \,{\rm Re}\left[A_{\rm SM}^* A_i^6\right] + \sum_{ij} \tilde{c}_i^6 \tilde{c}_j^{6*} A_i^{6*} A_j^6$$

is parametrisation invariant. The last term is order $1/\Lambda^4$, yet uniquely defined.

7

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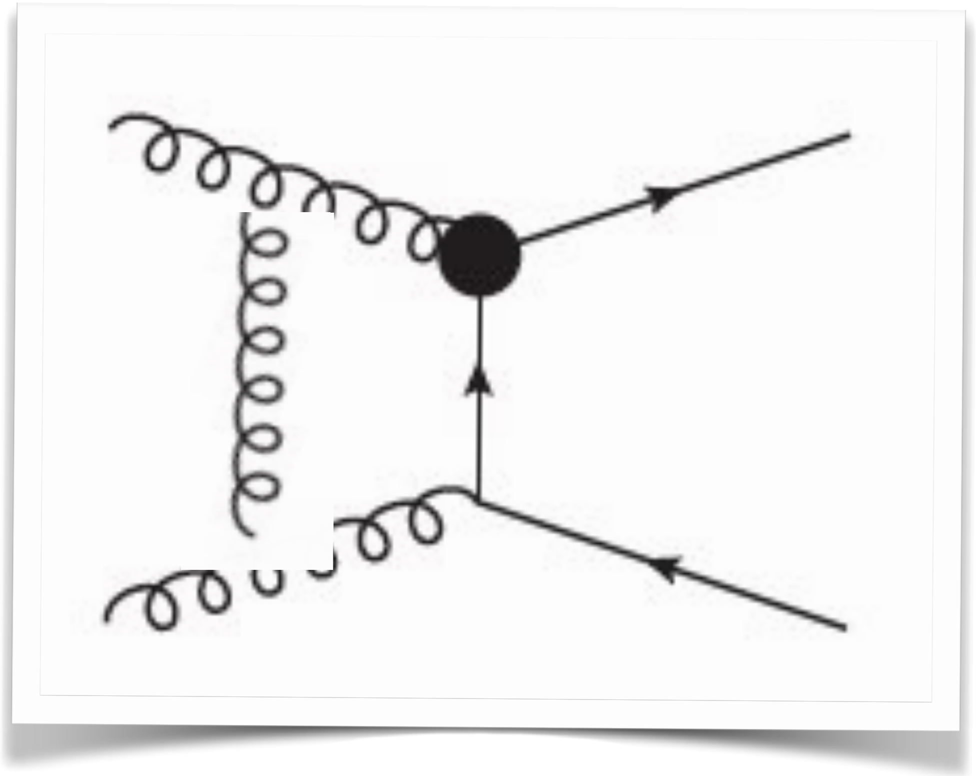
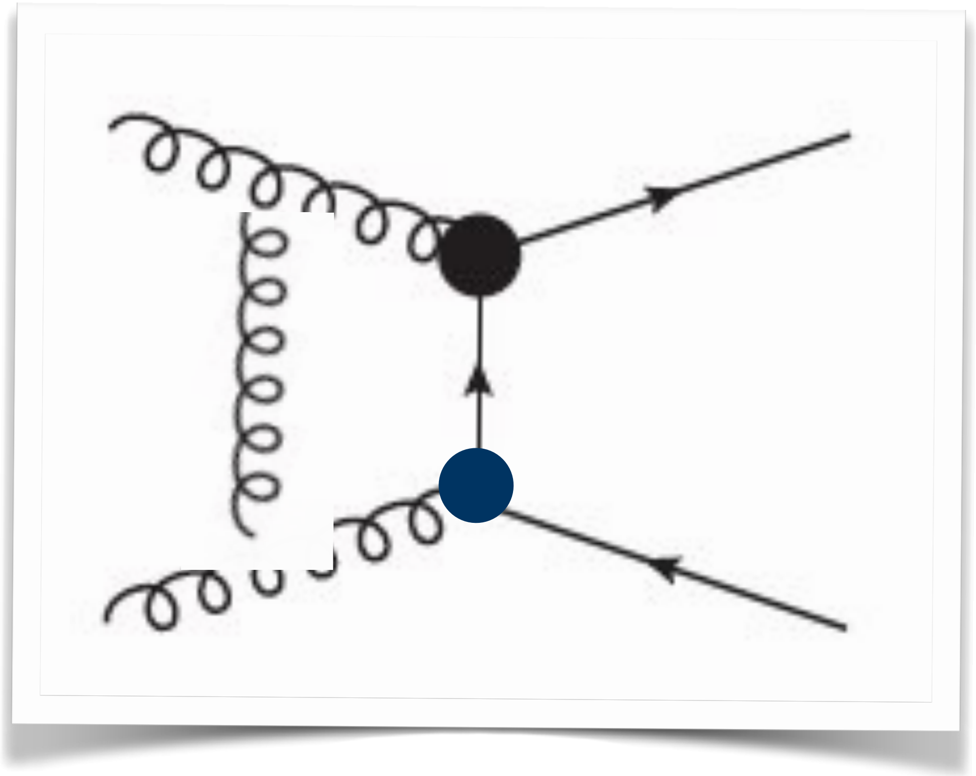


This amplitude will need max dim=6 operators for renormalisation



This amplitude will generically need dim=8 operators for renormalisation

Squared terms are not uniquely defined and should not be employed in pheno analyses

In many cases the squared term should be included and in any case can be included:

1) If the interference term is highly suppressed because of symmetries (such as absence of FCNC at the tree-level in the SM) or selection rules (helicity selection for VV productions, i.e. the GGG operator in gg→gg), the squared term is always the dominant contribution.

2) There are UV models, for which the squared terms are foreseen to be the dominant $1/\Lambda^4$ contributions:

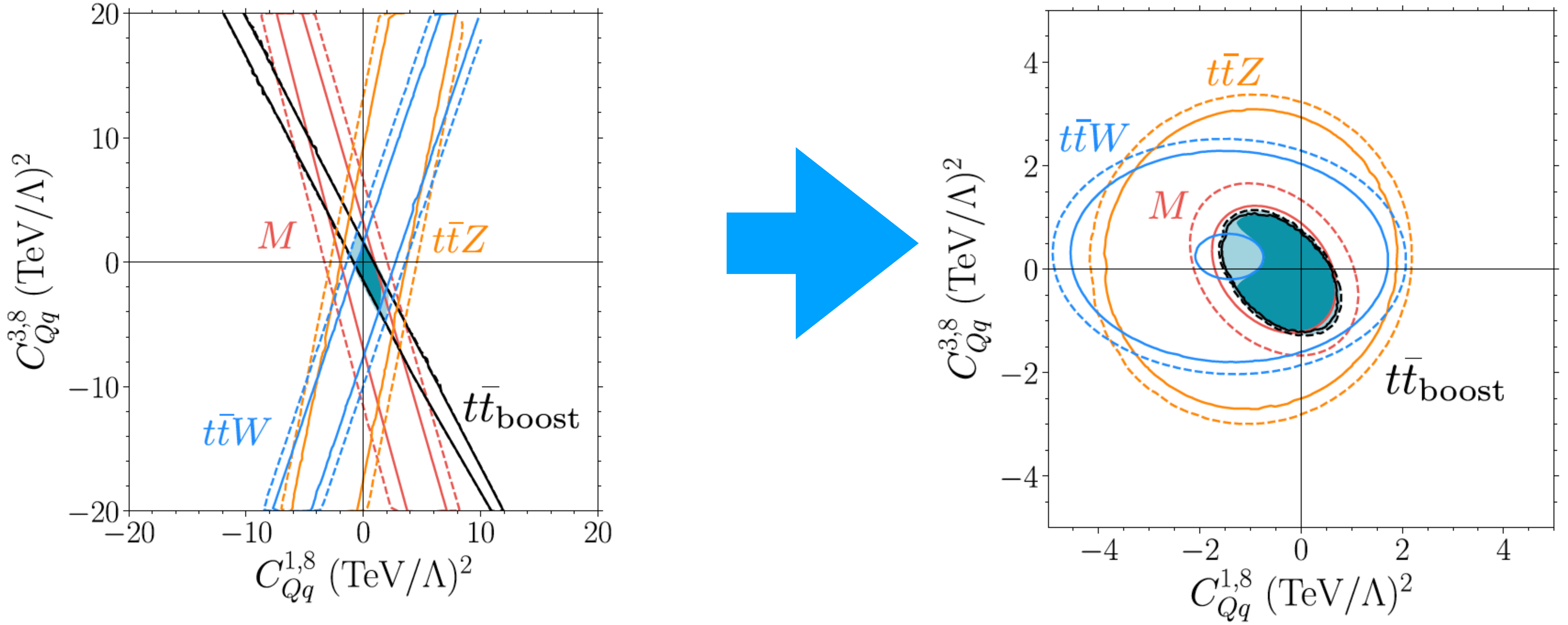
$$C_i^2 \frac{E^4}{\Lambda^4} > C_i \frac{E^2}{\Lambda^2} > 1 > \frac{E^2}{\Lambda^2}$$

EFT condition satisfied but $O(1/\Lambda^4)$ large for large operator coefficients

Squared terms are not uniquely defined and should not be employed in pheno analyses

At the fitting level the squared can have an important effect, as there are no flat directions in the fit with the squares:

[Brivio et al. , 1910.03606]



In general without knowing the effect of the squares one is left in the dark about the mean reliabilty of the fit.

Provide constraints using i) linear and ii) linear+squared terms

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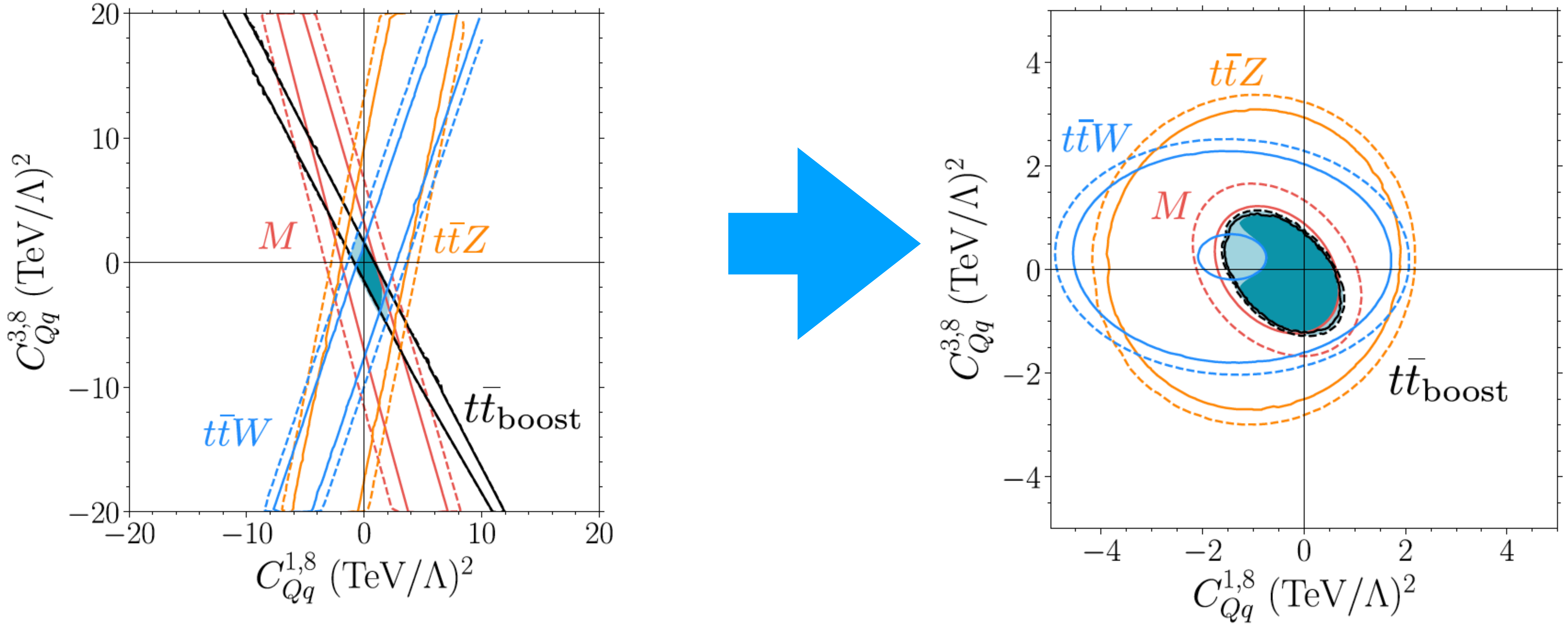

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There are at least two cases where this will not be the case:

1. The new resonance is quite heavy with respect to the collider energy and no other states are found ⇒ it could be the first of particle of a new heavy sector. EFT can include it and search for indirect effects of other states/phenomena.

2. The new resonance is light and very weakly interacting (like an axion) so that it does not impact collider phenomenology.

$$-\frac{g^2}{2M_W^2}+\frac{1}{f_a^2}\frac{q^2}{q^2-m_a^2}=-\frac{2}{v^2}\left[1+\frac{v^2}{2f_a^2}\frac{q^2/m_a^2}{q^2/m_a^2-1}\right]$$

$v = 246$ GeV, $f_a \sim 2\times10^{12}$ GeV, $v/f_a \sim 10^{-10}$, $m_a \sim 2\mu$eV. Need

$$\left|\frac{q^2}{m_a^2}-1\right| \sim \frac{v^2}{f_a^2} \sim 10^{-20} \implies \Delta q \sim 10^{-25}\,\text{GeV}$$

Ex. by Manohar

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It is true that the SMEFT approach is global in nature. This is due to RGE, reparametrisation invariance, and so on. However, individual constraints and constraints on subsets are extremely useful. For example:

1. To understand which process is the most constraining one (comparing the impact of an operator on different processes is normalisation independent) SENSITIVITY.

2. Using pairs or triplets to understand the correlations and the flat directions and how to break them.

3. Technically, it might be complicated to include all operators in an analysis. However, having previous knowledge about where the sensitivity of an operator comes from, bounds from other processes/experiments, RGE information and, if desired, also UV model dependent information, one can establish a hierarchy and make maximal use of experimental information.

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Understanding and quantifying the higher order effects in the SMEFT is needed because of many reasons:

1. The structure of the theory manifests itself when quantum corrections are known, such as for example mixing/running and relations between operators at different scales.

2. NLO brings more accurate central values (k-factors) and reduction of the uncertainties (which can be gauged with the scale dependence, including EFT.

3. NLO QCD effects are important at the LHC, due to the nature of the collision. Not only rates can be greatly affected but also distributions.

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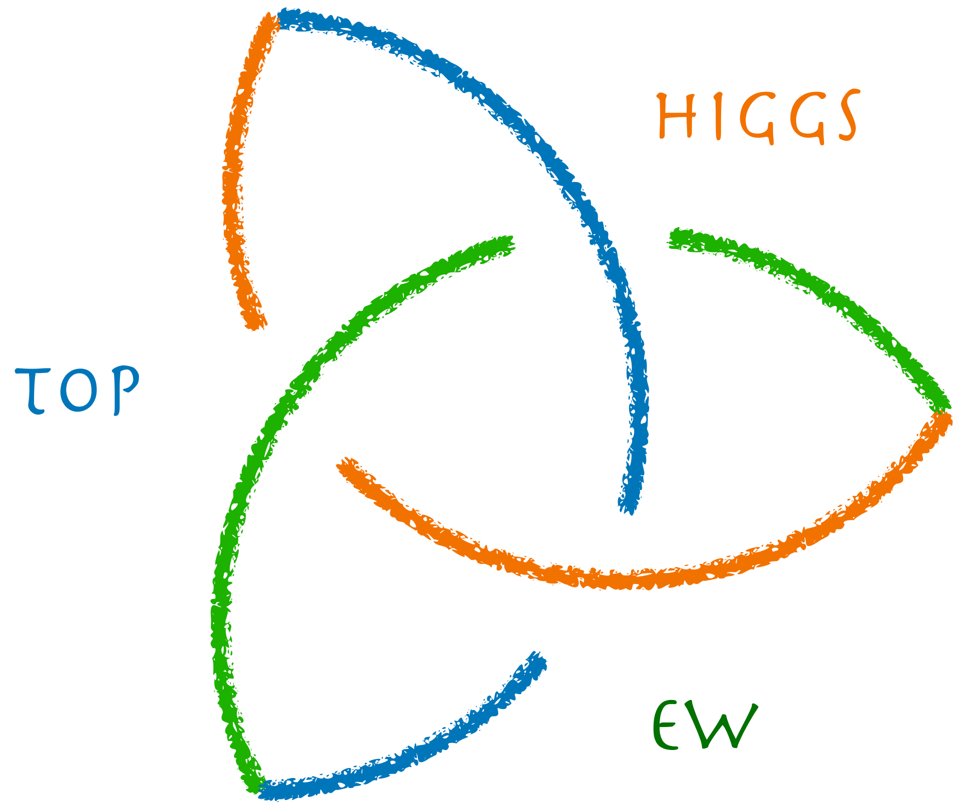
The way of SMEFT

Conclusions



- LHC precision physics programme has set clear and very challenging goals for the next years.
- A universal and very powerful approach to the interpretation of precision measurements is that of the SMEFT.
- The SMEFT provides challenges that force all of us go out of our confort zone, beyond our current TH/EXP workflows and value system.
- First explorations of the constraining power of present data in a global EW(PO)+Higgs+Top fit have appeared.
- A wonderful realm of opportunities and large room for improvement ⇒ many ways to contribute and learn about SM(EFT) physics.

Some extra material

The square story

$\mathscr{A}$ = a scattering amplitude (on shell external states). It's a complex number, gauge invariant and physical.

$$\mathscr{A}_{SMEFT} = \mathscr{A}_{\rm SM} + \frac{1}{\Lambda^2}\sum_i c_i^{(6)}\mathscr{A}_i^{(6)} + \frac{1}{\Lambda^4}\left[\sum_{kl} c_k^{(6)} c_l^{(6)} \mathscr{A}_{kl}^{(6x6)} + \sum_n c_n^{(8)}\mathscr{A}_n^{(8)}\right] + \ldots$$

The expansion is well defined (gauge invariant and reparametrization invariant) up to any given order.

Field transformation/basis change (keeping all terms up to $1/\Lambda^2$)$\Rightarrow$ $\mathscr{A}'_{SMEFT} = \mathscr{A}_{\rm SM} + \frac{1}{\Lambda^2}\sum_j c'_j \mathscr{A}'^{(6)}_j$

Now $\mathscr{A}'_{SMEFT} = \mathscr{A}_{\rm SMEFT}$ order by order in $1/\Lambda^2$ $\Rightarrow \sum_i c_i \mathscr{A}_i^{(6)} = \sum_j c'_j \mathscr{A}'^{(6)}_j$

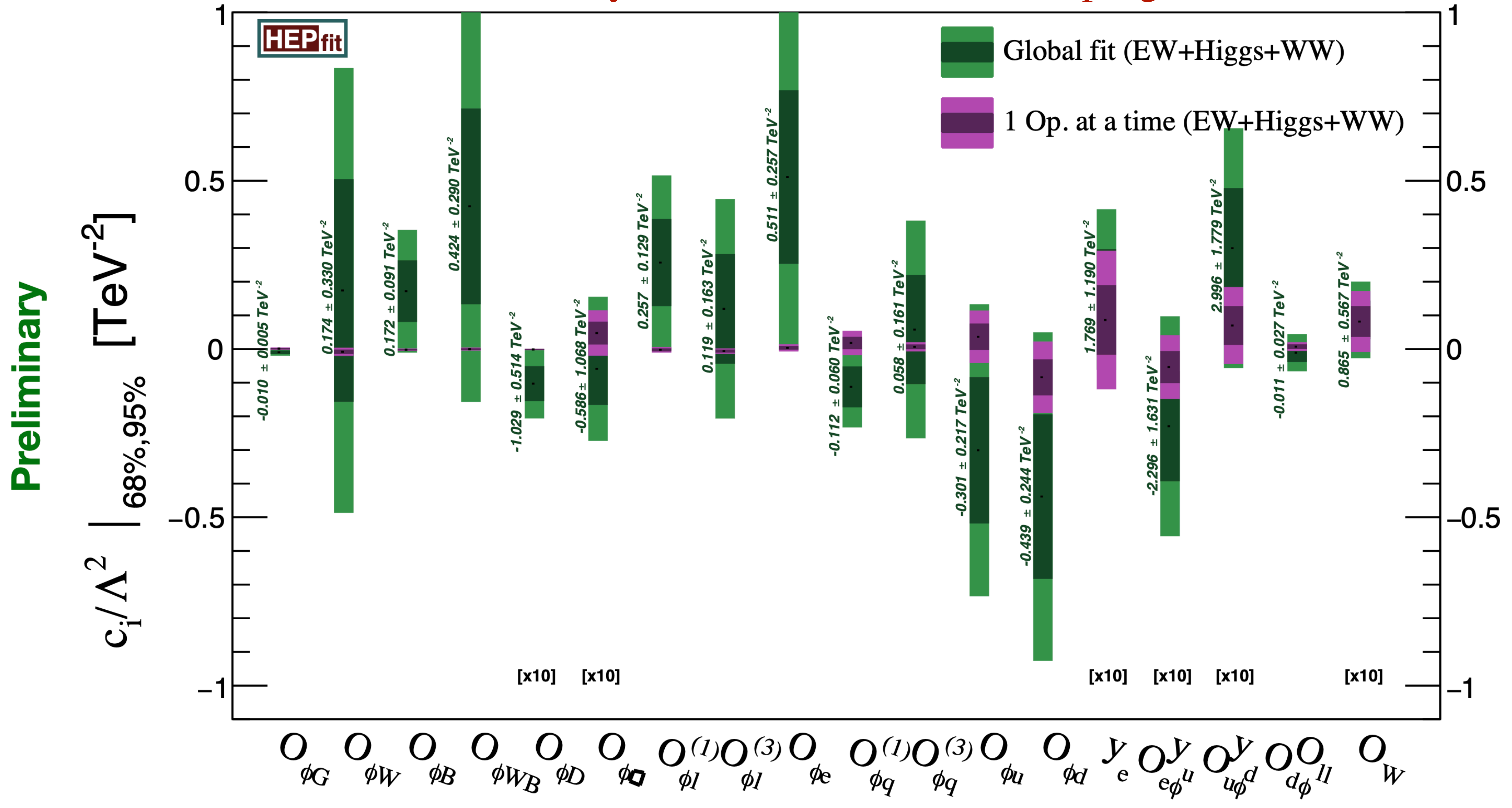
$$|\mathscr{A}_{SMEFT}|^2 = |\mathscr{A}_{\rm SM}|^2 + \frac{2}{\Lambda^2}{\rm Re}[\sum_i c_i \mathscr{A}_i^{(6)} \mathscr{A}^*_{\rm SM}] + \frac{1}{\Lambda^4}|\sum_i c_i \mathscr{A}_i^{(6)}|^2 + \frac{2}{\Lambda^4}{\rm Re}\left[[\ldots]\mathscr{A}^*_{\rm SM}\right]$$

Global fits: now vs Future

EW+Higgs+EWPO

Now

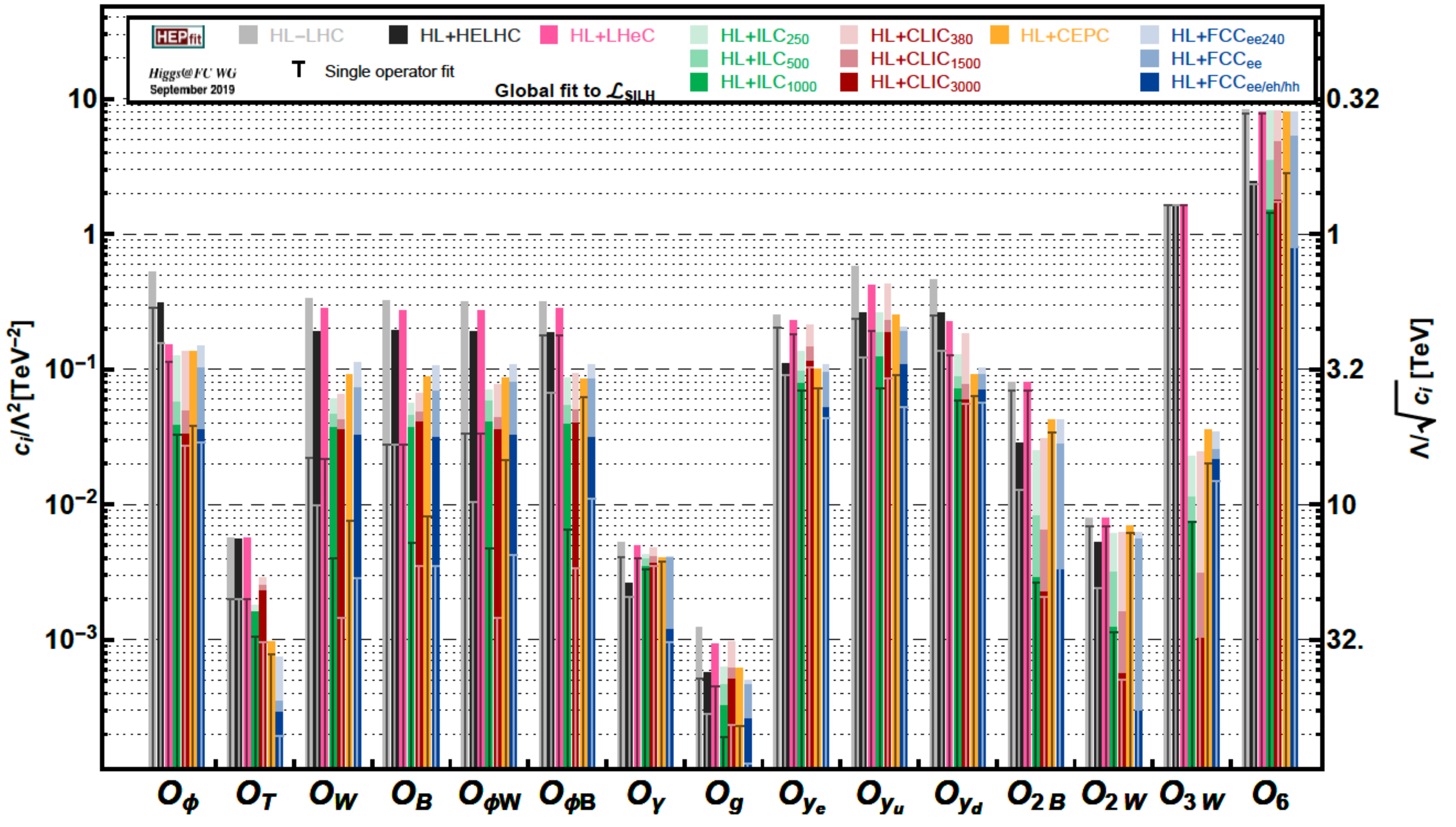
[Courtesy of De Blas et al., work in progress]



New Physics assumptions: CP-even, U(3)5

Future

[De Blas et al., 2020]



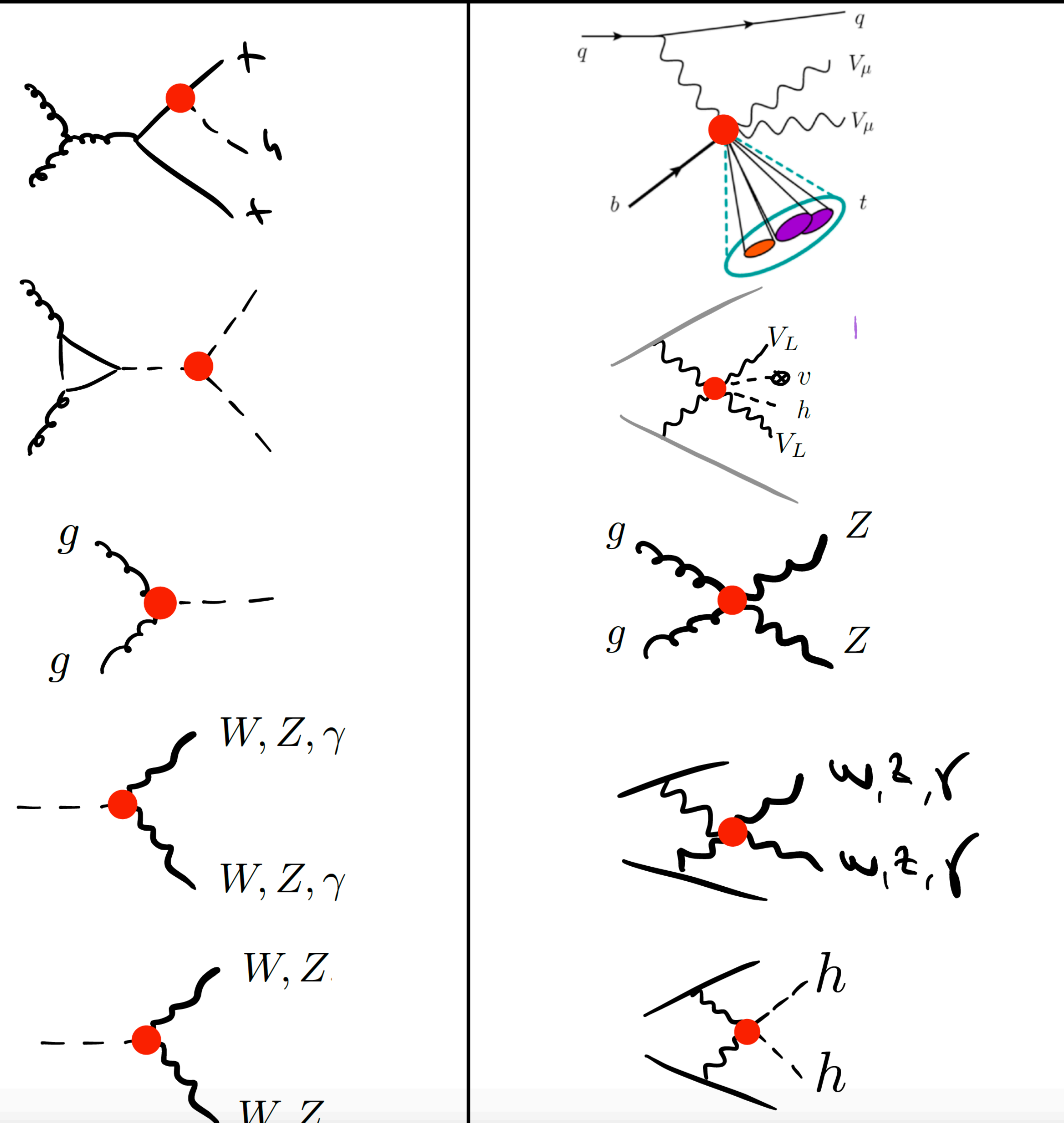
Expected more than 1 order of magnitude improvements

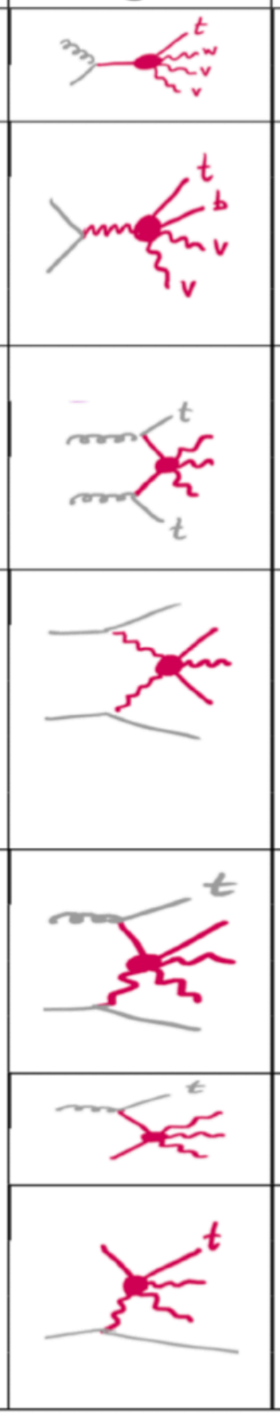
Theory trends

Higgs without the Higgs

$$\kappa_t \Longleftrightarrow \frac{|H|^2 Q\tilde{H}t_R}{\Lambda^2}$$

HwH Program		$\sim const$	$\sim E^2$
κ_t	$\lvert H\rvert^2 Q\tilde{H}t_R$		
κ_λ	$\lvert H\rvert^6$		
κ_G	$\lvert H\rvert^2 G^a_{\mu\nu}G^{a\,\mu\nu}$		
κ_γ $\kappa_{Z\gamma}$	$\lvert H\rvert^2 B_{\mu\nu}B^{\mu\nu}$ $\lvert H\rvert^2 W^a_{\mu\nu}W^{a\,\mu\nu}$		
κ_V	$\lvert H\rvert^2 \partial_\mu H^\dagger \partial^\mu H$		





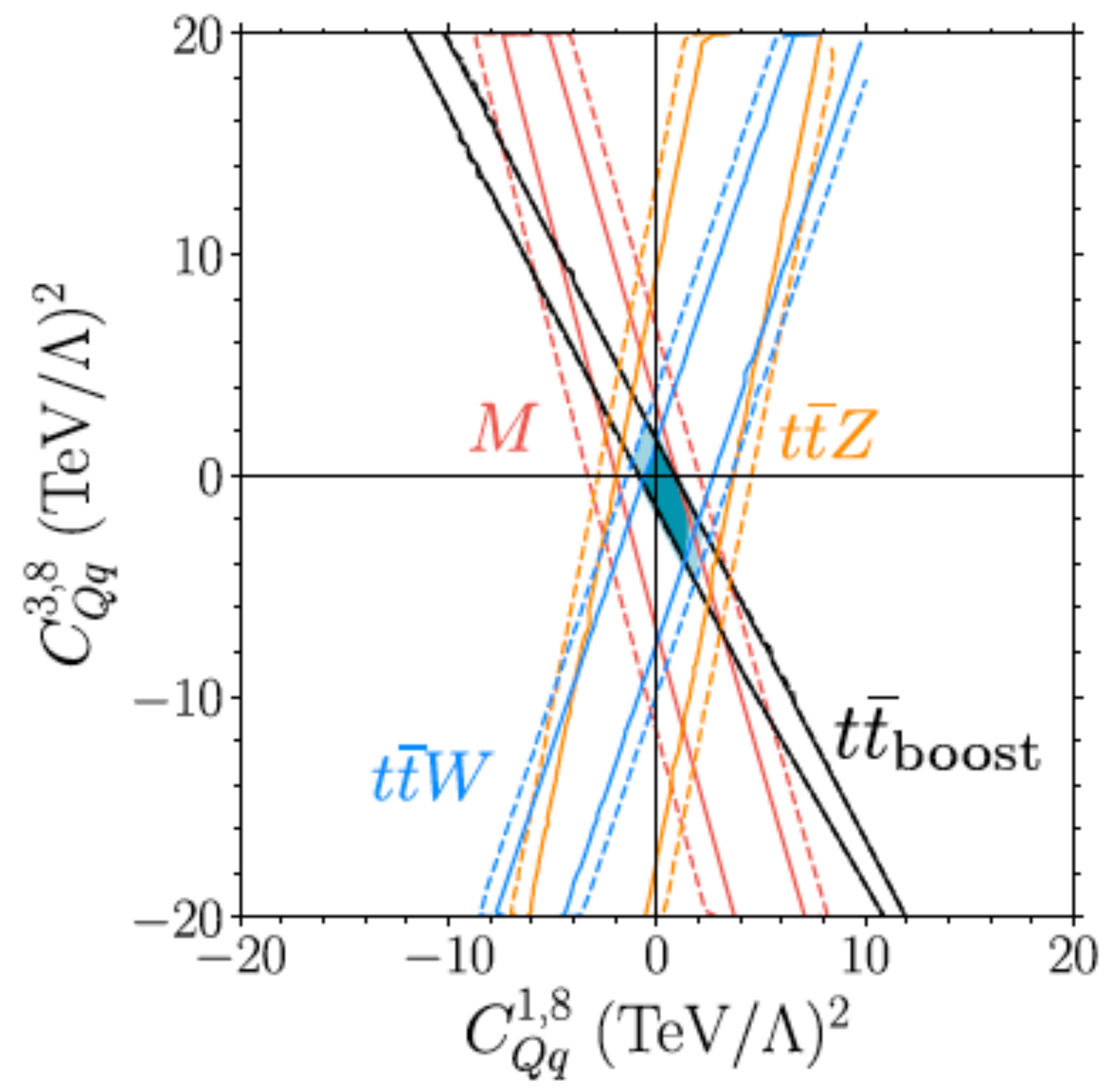
Legs	Order	Diagram	Channels	Xsec[fb]	QCD bgnd	L/T
$1 \to 4$	QCD		$tW^\pm W^\pm W^\mp$	0.7	/	0.03
			$tW^\pm ZZ$	0.4	/	0.03
	EW		$tbW^\pm W^\pm$	3.5	/	0.10
			$tbW^\pm W^\mp$	3.5	/	0.20
			$tbW^\pm Z$	3.8	/	0.11
			$tbZZ$	0.02	0	0.09
$2 \to 3$	QCD^2		$ttZWW$	0.083	/	0.03
			$ttZZZ$	0.008	/	0.04
			$tbWWW$	19	/	0.04
			$tbWZZ$	3.8	/	0.07
	EW^2		ttZ	0.1	/	0.29
			$ttW^\pm$	0.3	/	0.32
			tbZ	0.2	/	0.31
			$tbW^\pm(SS)$	0.9	2	0.29
			$tbW^\pm(OS)$	19	/	0.45
	EW $*$ QCD		$tbW^\pm W^\mp$	75	467	0.15
			$tbW^\pm W^\pm$	75	458	0.13
			$tbW^\pm Z$	26	215	0.15
			$tbZZ$	4	0	0.07
			$tW^\pm W^\mp W^\pm$	0.7	/	0.03
			$tW^\pm ZZ$	0.4	/	0.03
			$tW^\pm W^\mp$	9	7.15	0.09
			$tW^\pm W^\pm$	8	6.44	0.10
			$tW^\pm Z$	9	75.4	0.07
			tZZ	5	2.64	0.07

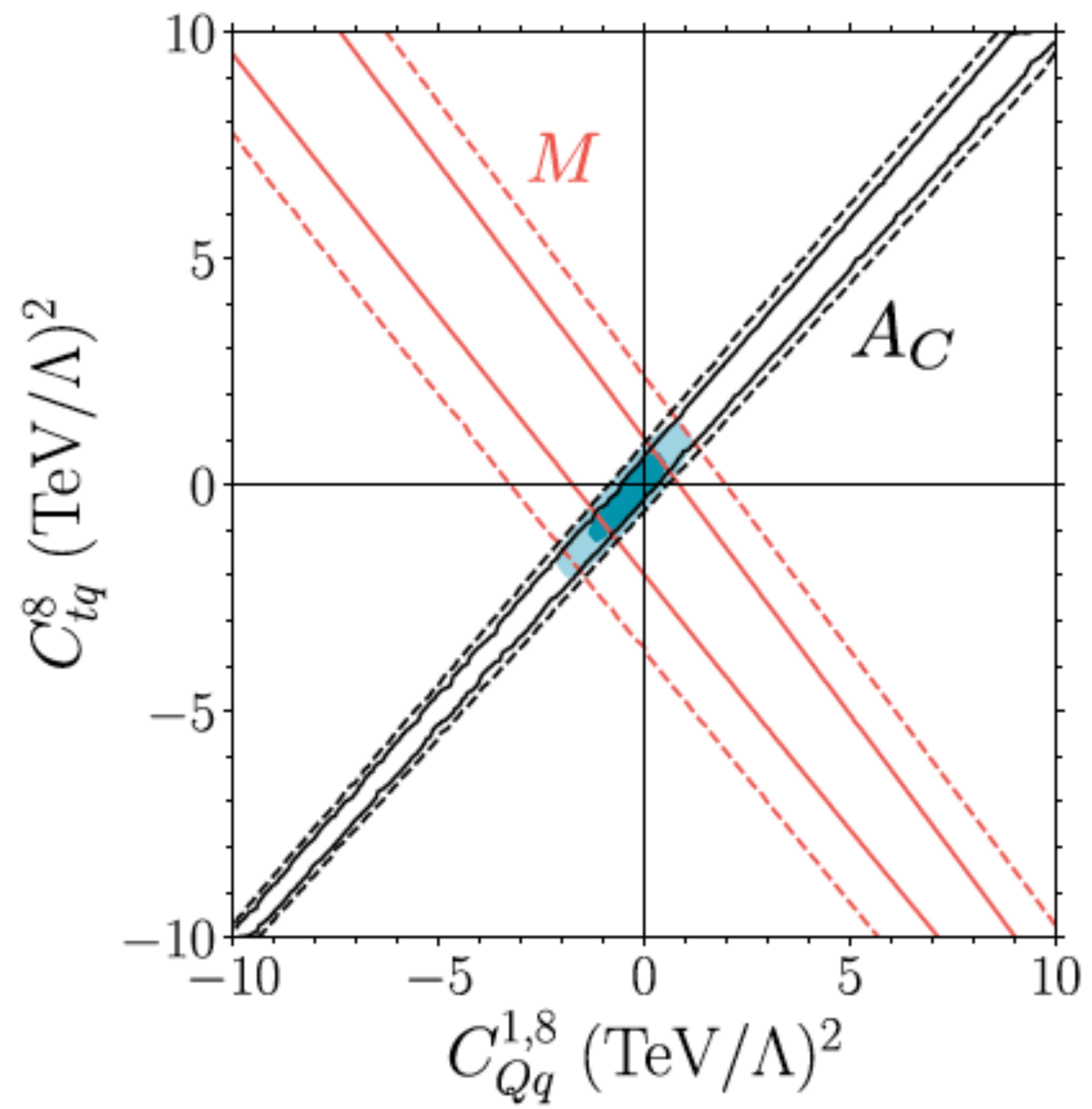
Disentagle SMEFT from HEFT!

[Henning et al. 1812.09299]

The impact of multiple measurements

Example in the top sector





$$O_{Qq}^{1,8} = (\bar{Q}\gamma_\mu T^A Q)(\bar{q}_i\gamma^\mu T^A q_i)$$
$$O_{Qq}^{3,8} = (\bar{Q}\gamma_\mu T^A \tau^I Q)(\bar{q}_i\gamma^\mu T^A \tau^I q_i)$$

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

[Brivio et al., 1910.03606]

Impact of quadratic terms in top production

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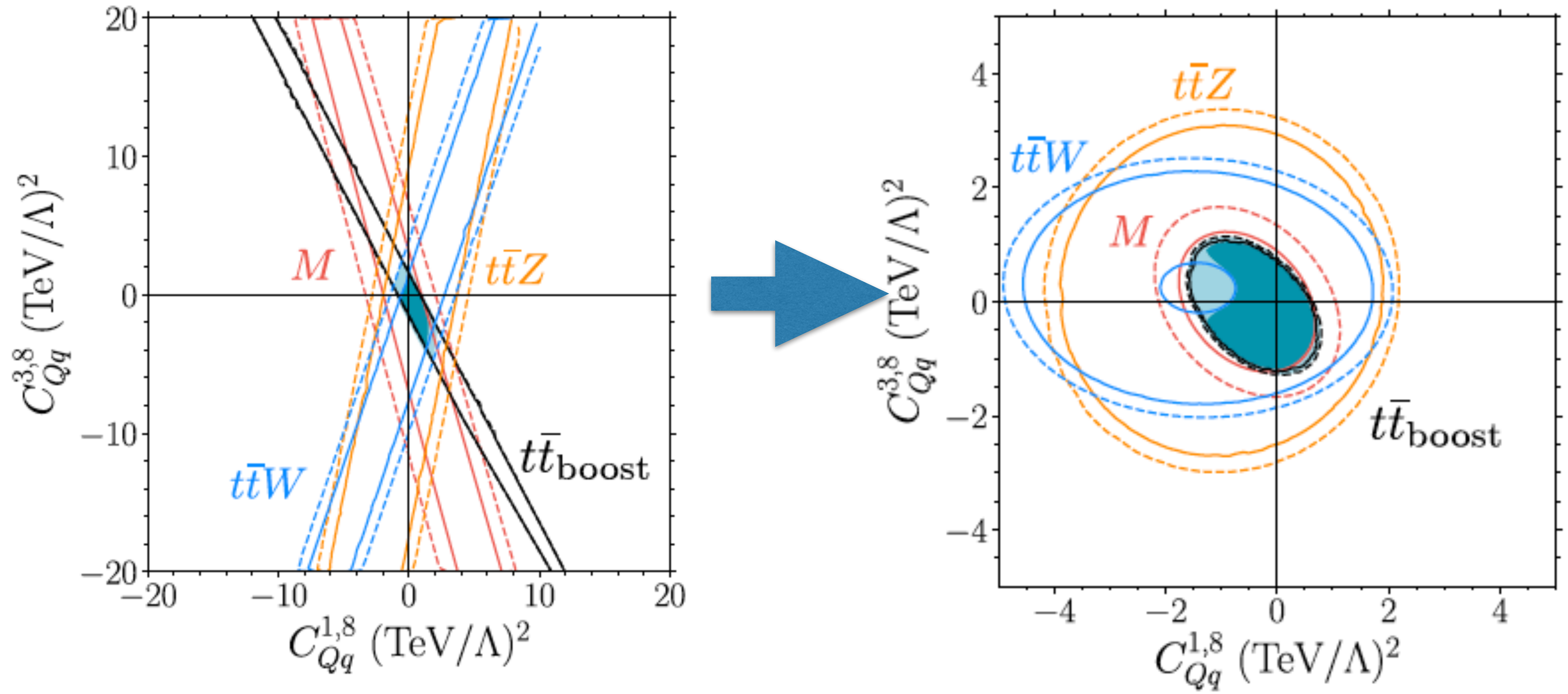

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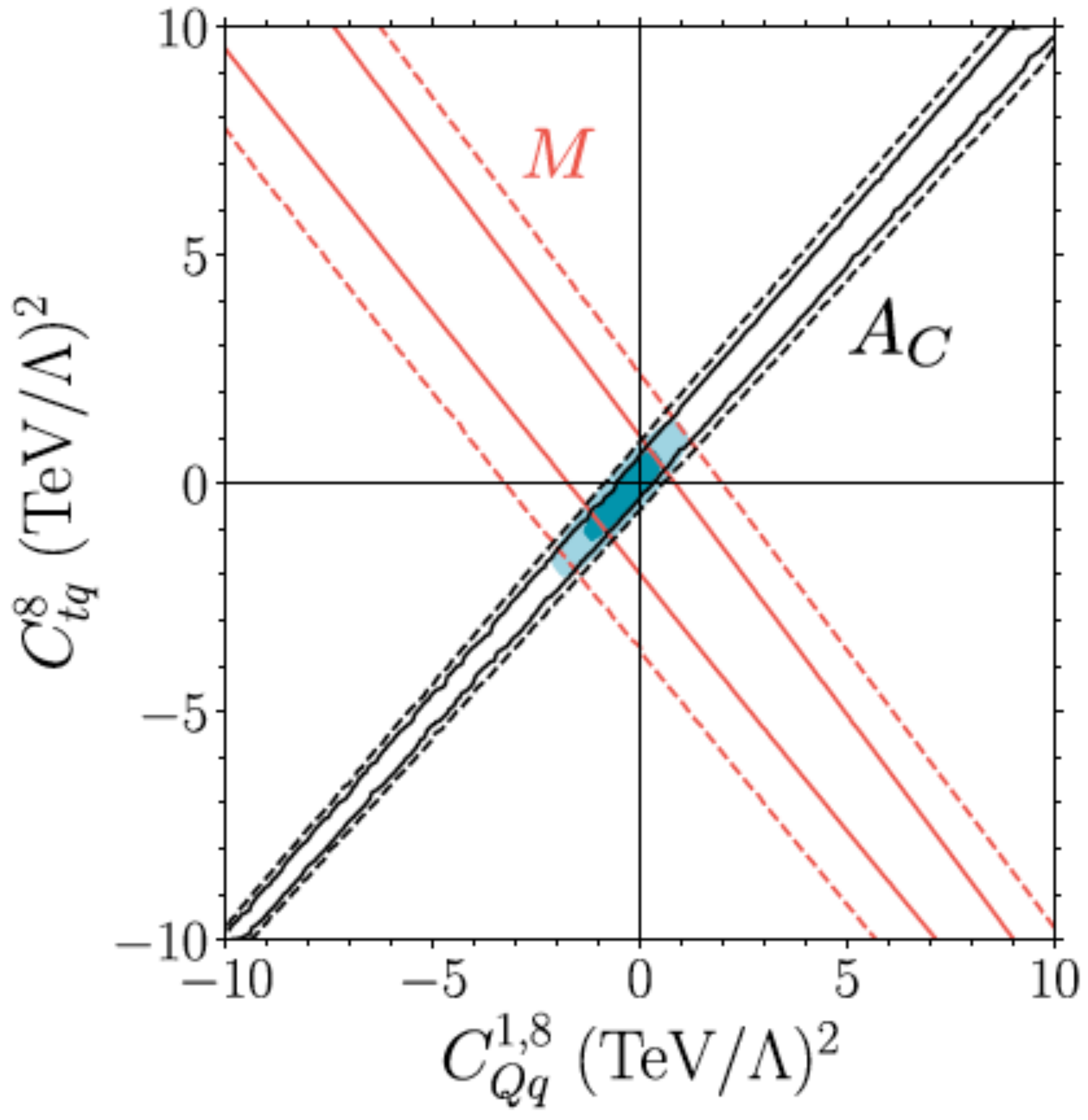

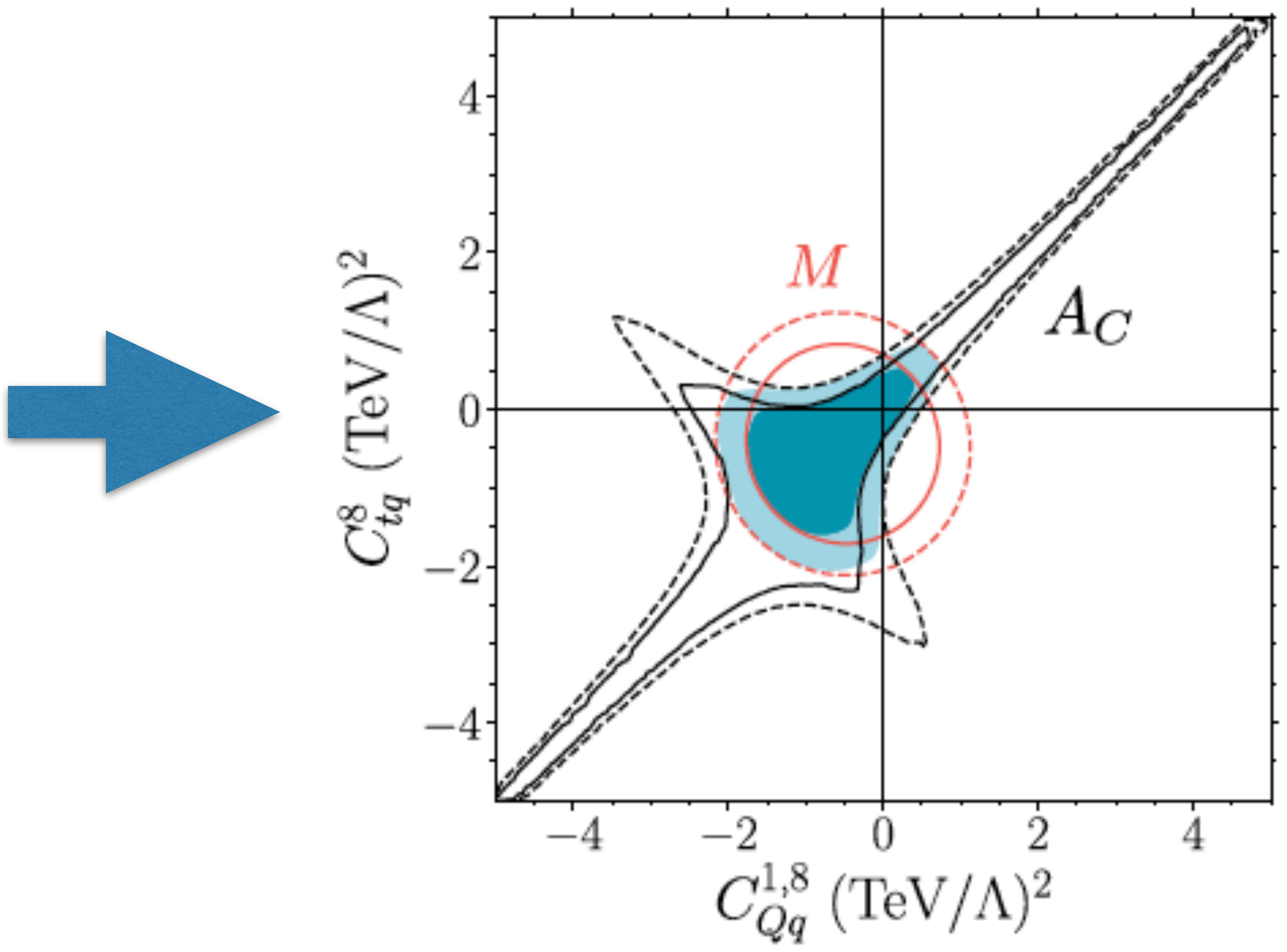

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