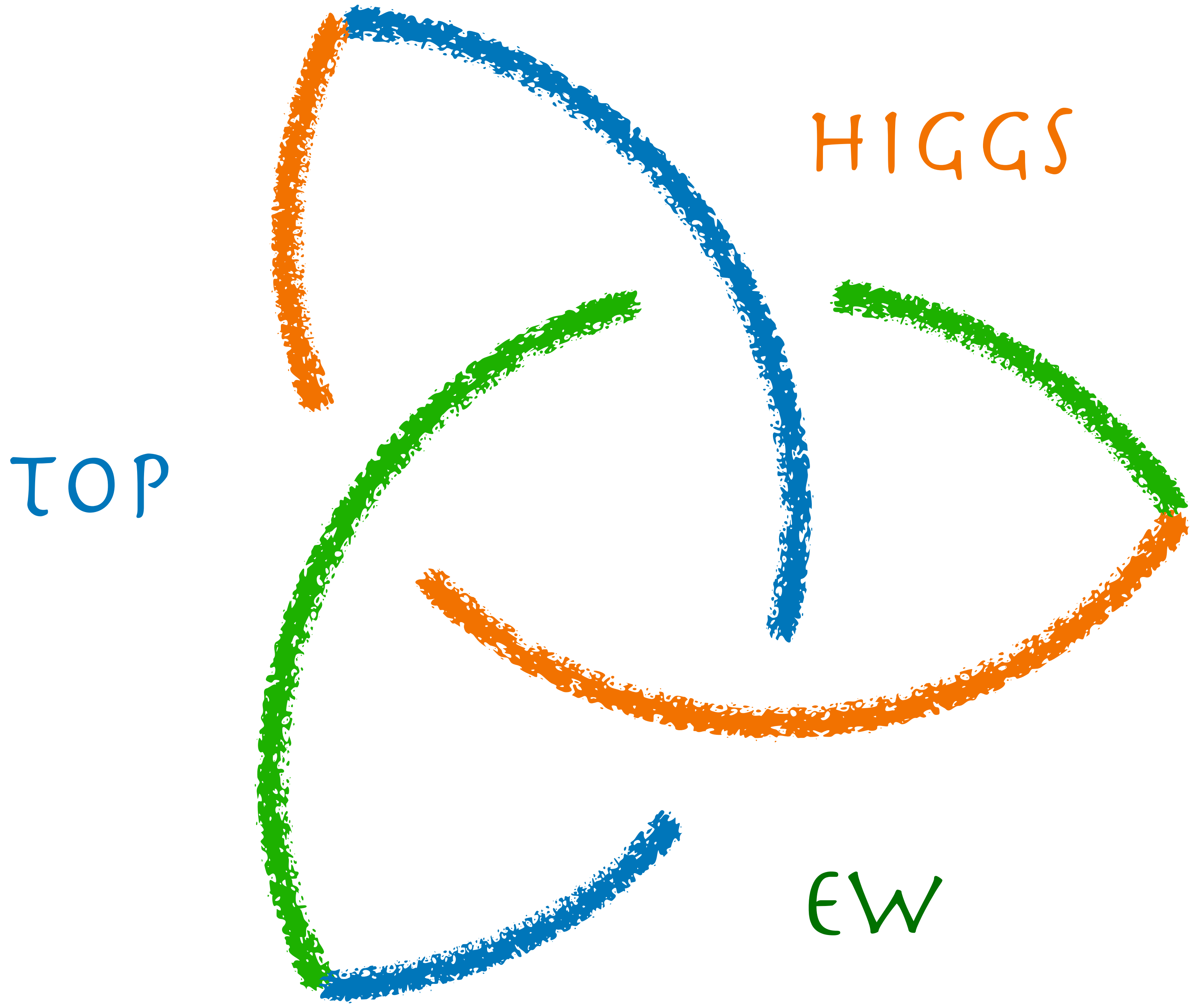
The Higgs/Top/EW gateway to new physics



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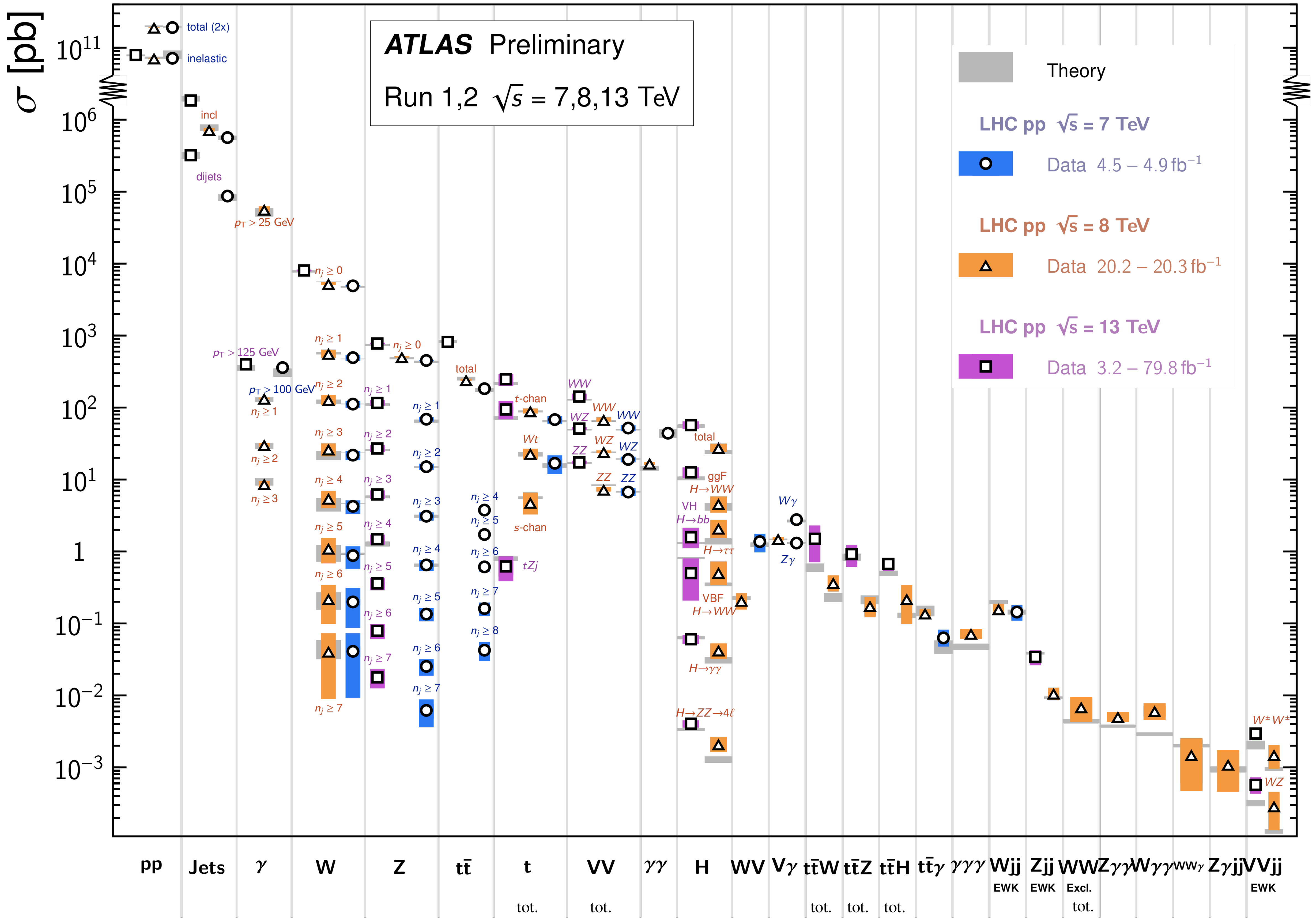
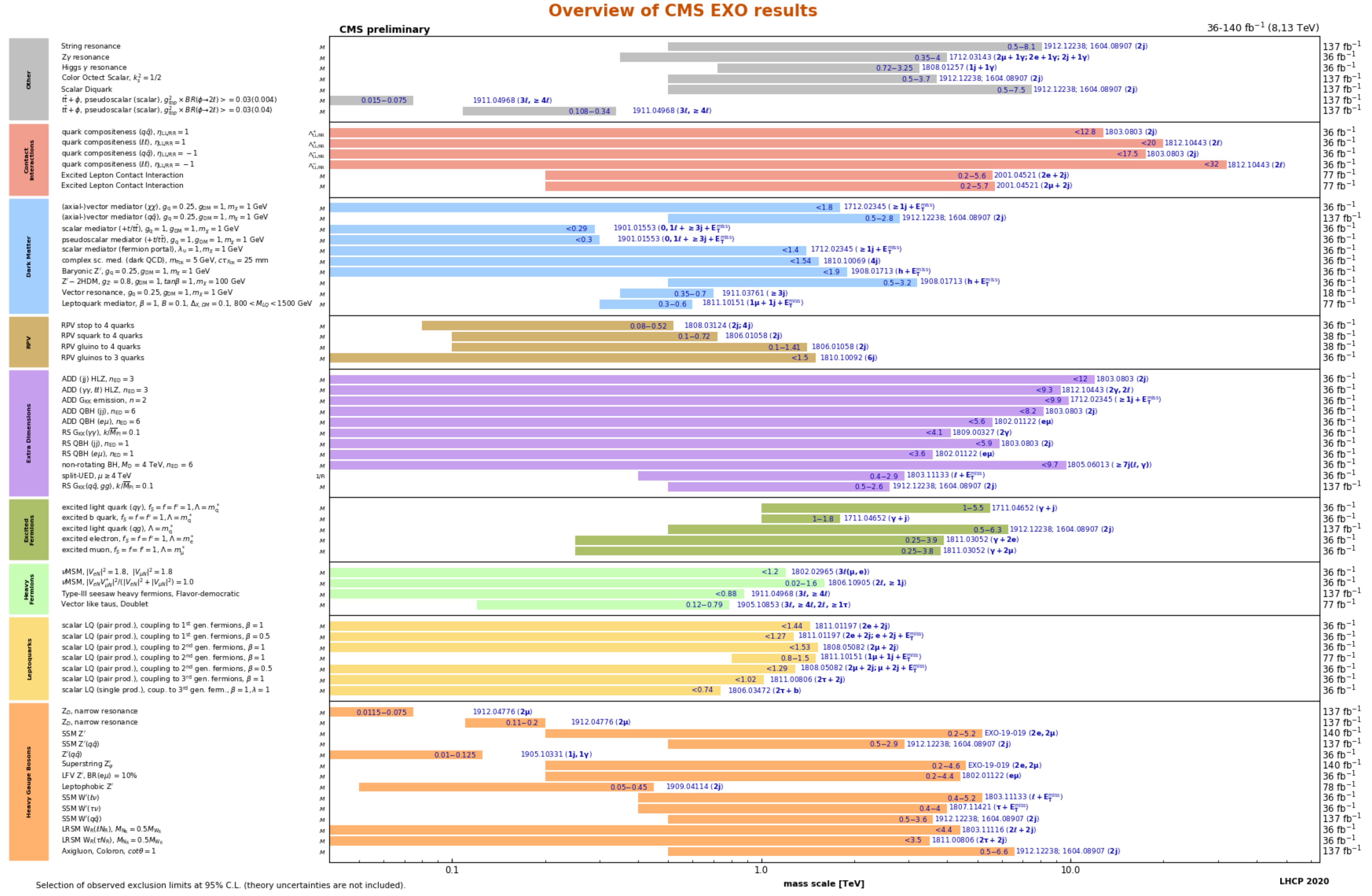
LHC Physics : status

Standard Model



(absence of) New Physics



Searching for new physics

Model-dependent	⟷	Model-independent
SUSY, 2HDM, ED,…		simplified models, EFT, …
Search for new states	⟷	Search for new interactions
specific models, simplified models		anomalous couplings, EFT…
Exotic signatures	⟷	Standard signatures
precision measurements		rare processes

The hedgehog and the fox

Archilocus (-650), Erasmo (1500), Berlin (1953)

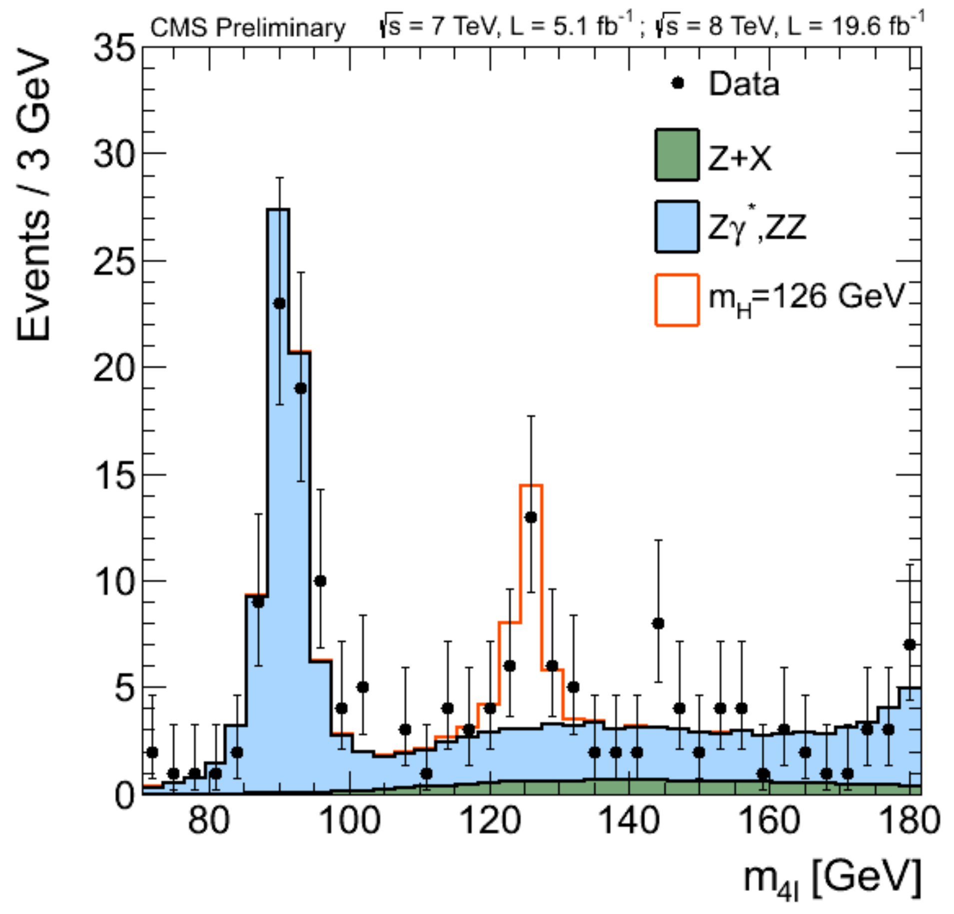
Multa novit vulpes, verum echinus unum magnum

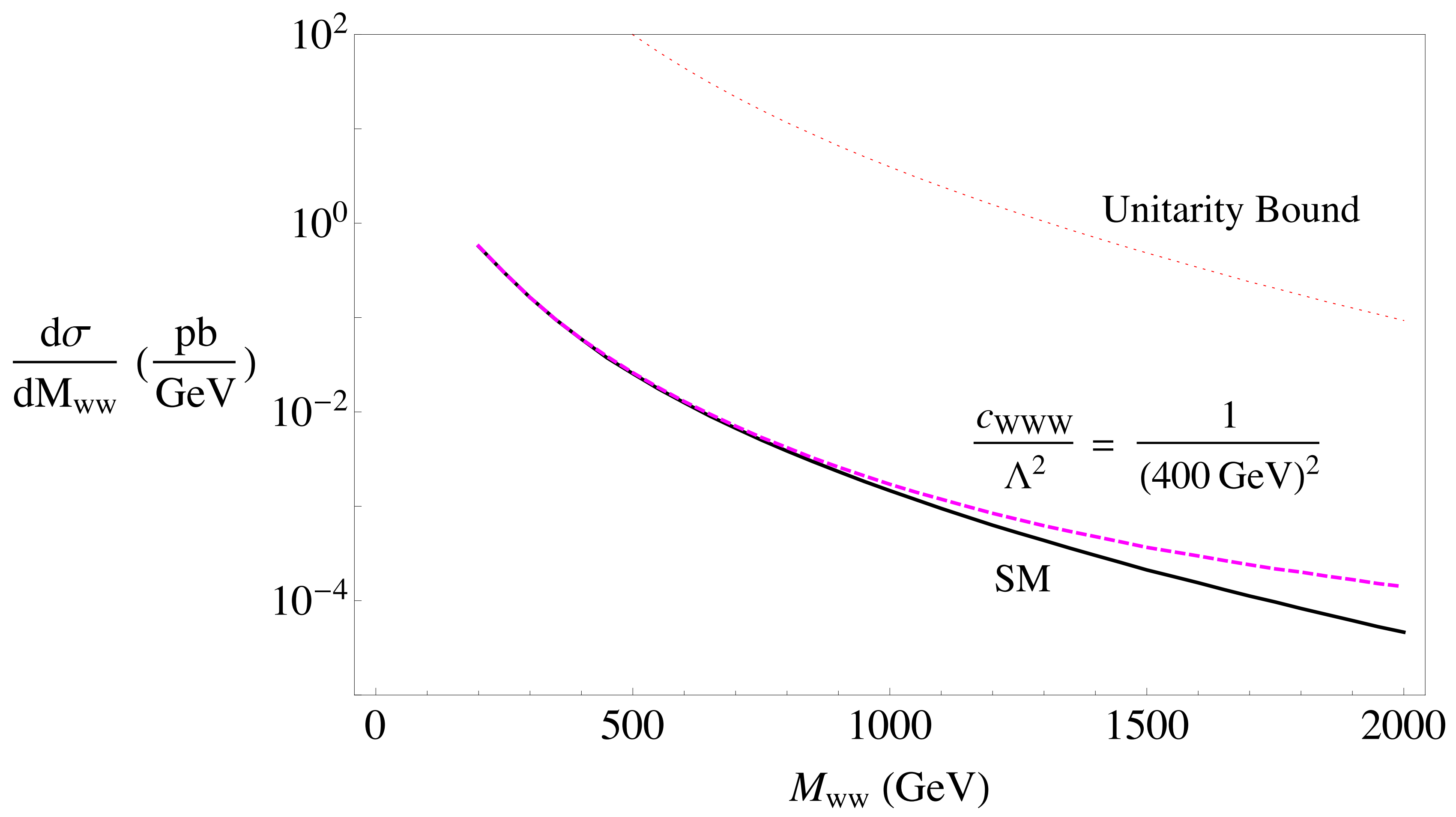
the hedgehogs view the world through the lens of a single defining idea

the foxes draw on a variety of experiences and for them the world cannot be boiled down to a single idea

Searching for new physics

Search for new states ⟷ Search for new interactions





"Peak" or more complicated structures searches. Need for **descriptive simulations** for discovery = Discovery is data driven.

Need precision for characterisation.

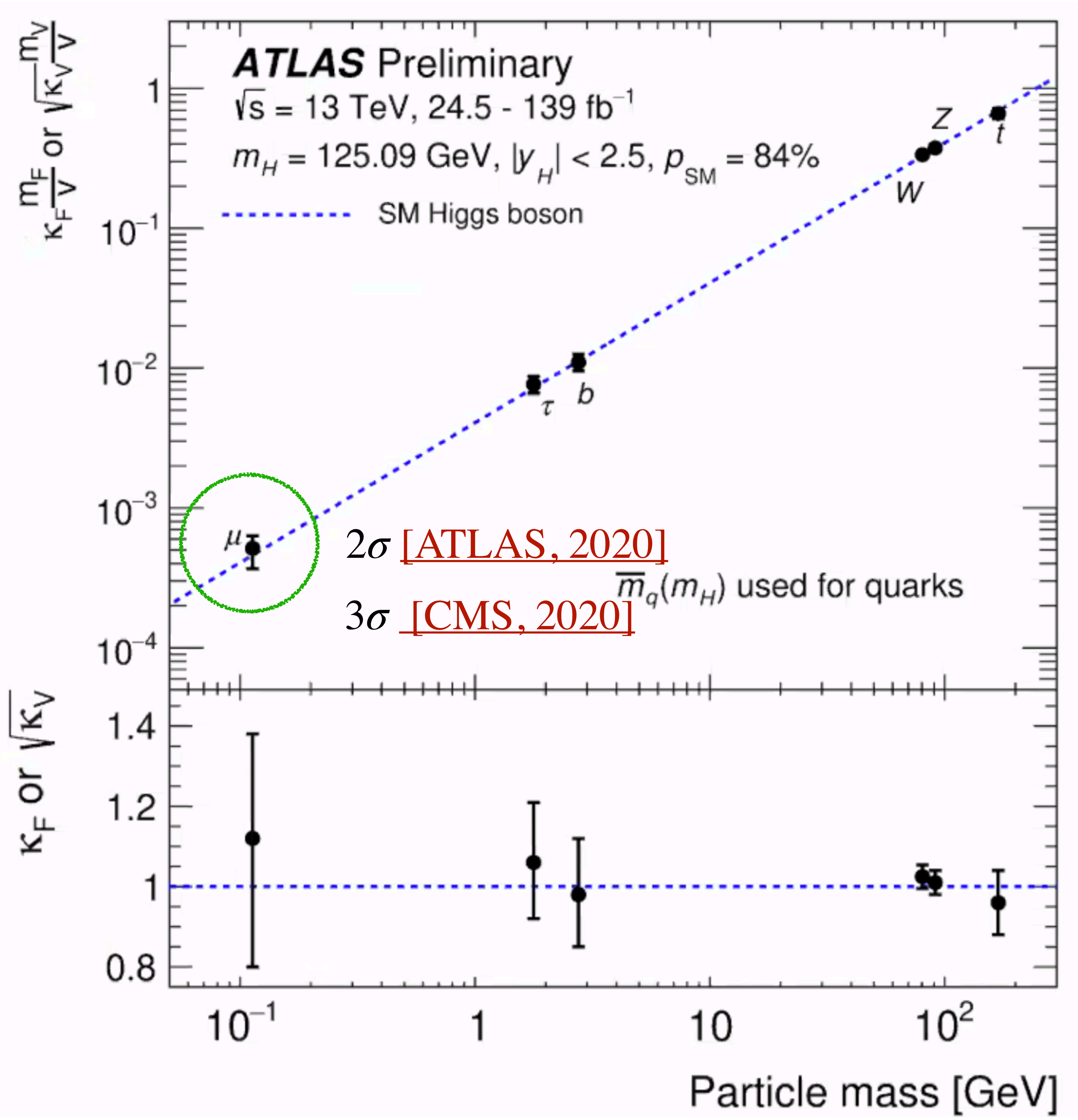
Deviations are expected to be small. Intrinsically a precision measurement.

Need for accurate predictions for SM (assess deviations) and for interpretations.

SM 101

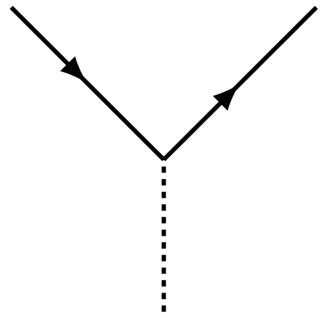
Mass generation with gauge invariance

[ATLAS 2020]

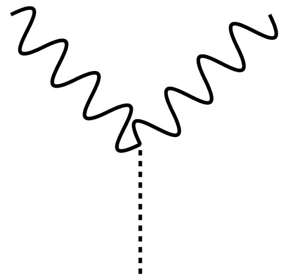


2σ [ATLAS, 2020]

3σ [CMS, 2020]



$i\, m_f/v$



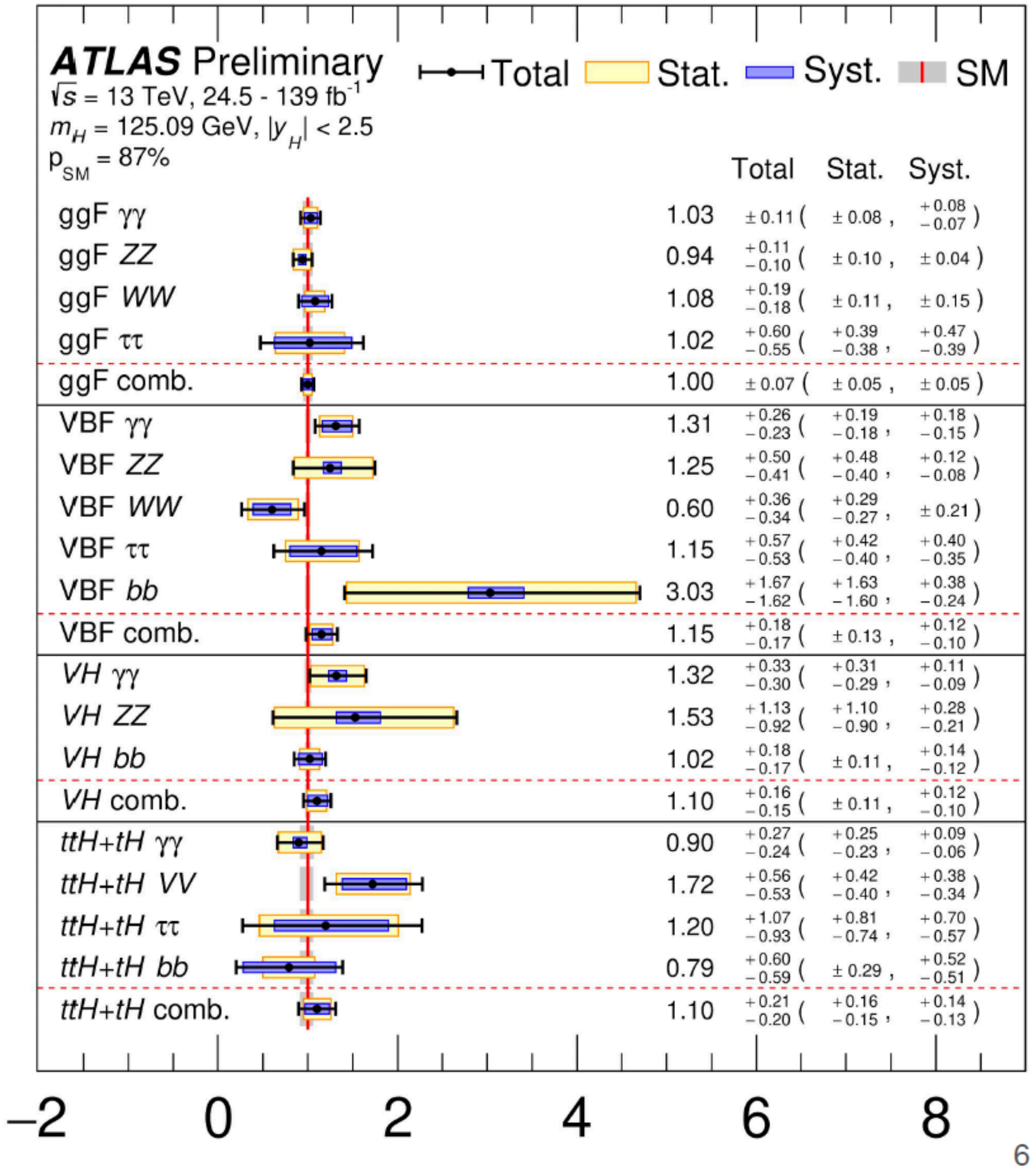
$igm_W g_{\mu\nu} = 2i\, v g_{\mu\nu} \cdot m_W^2/v^2$

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

Unique mass generation mechanism for fermions and vectors.

Constrained system.

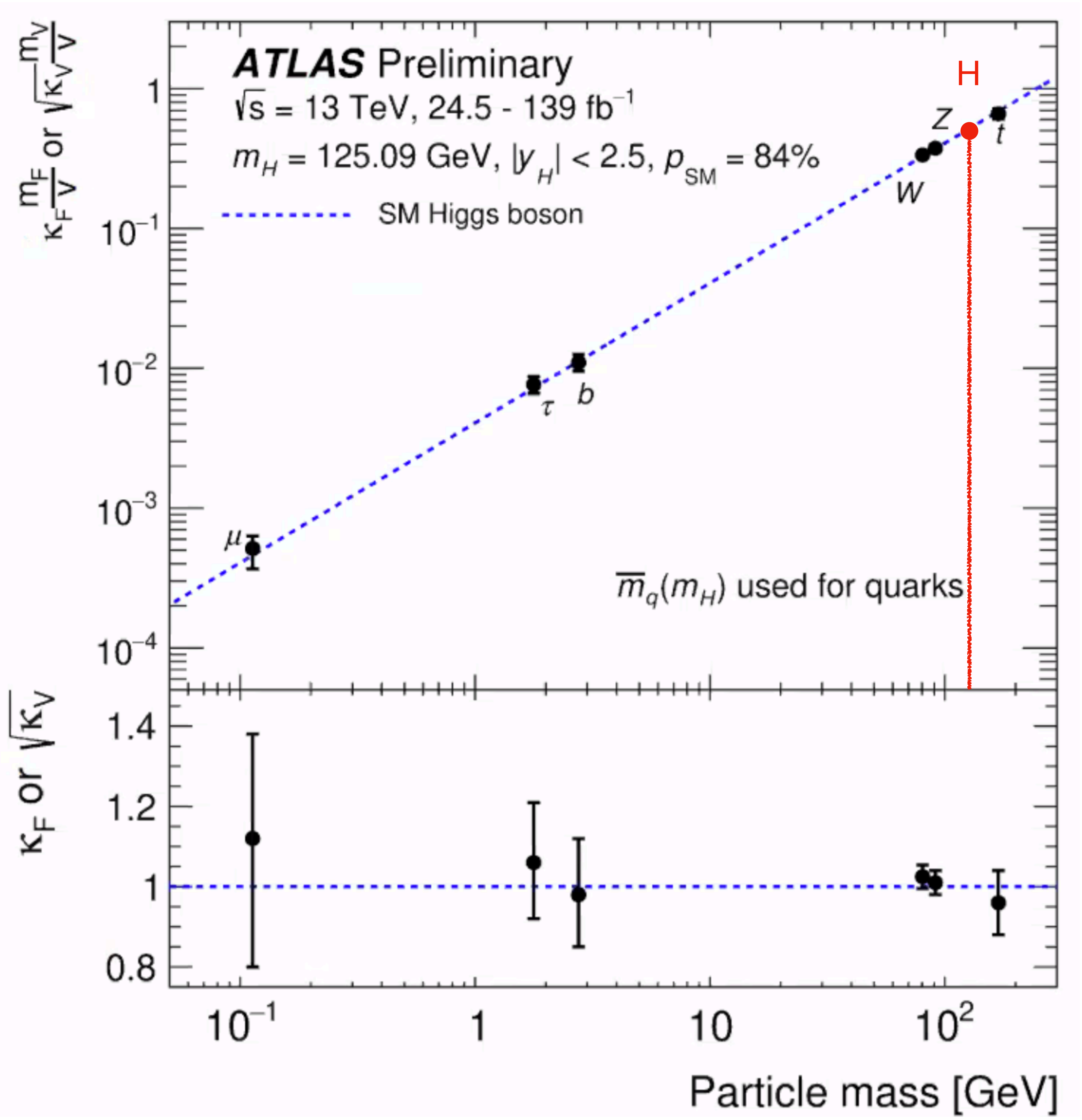
[ATLAS 2020]



SM 101

Mass generation with gauge invariance

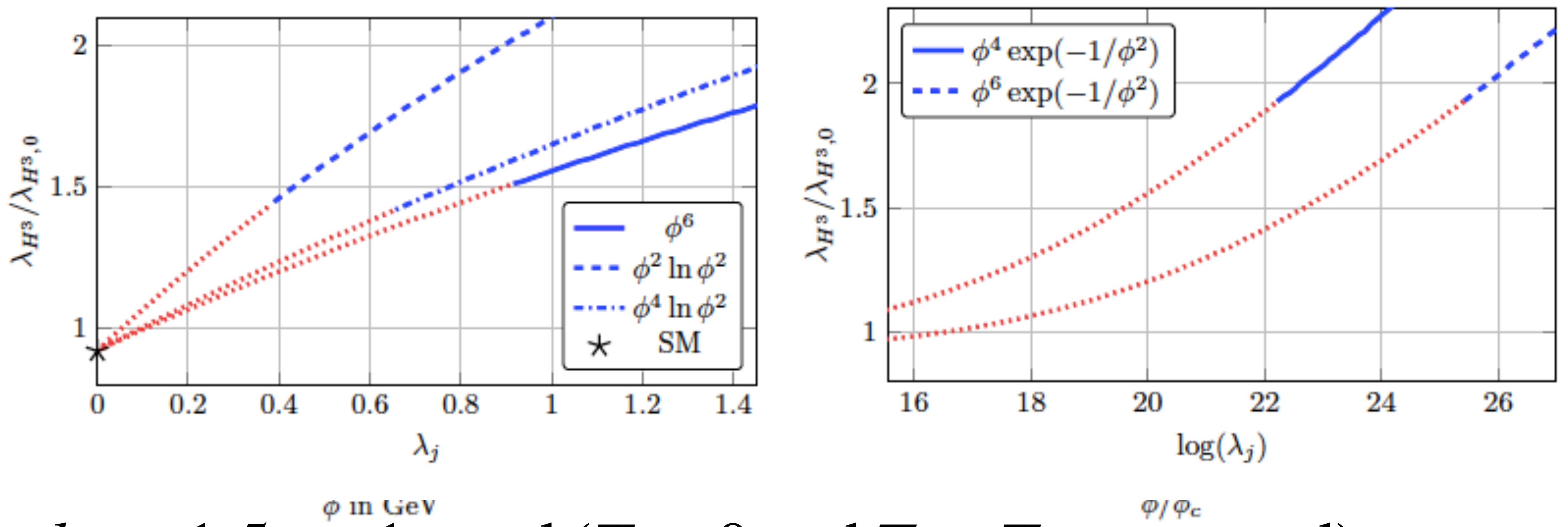
[ATLAS 2020]



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

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

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



Reichert et al. 1711.00019

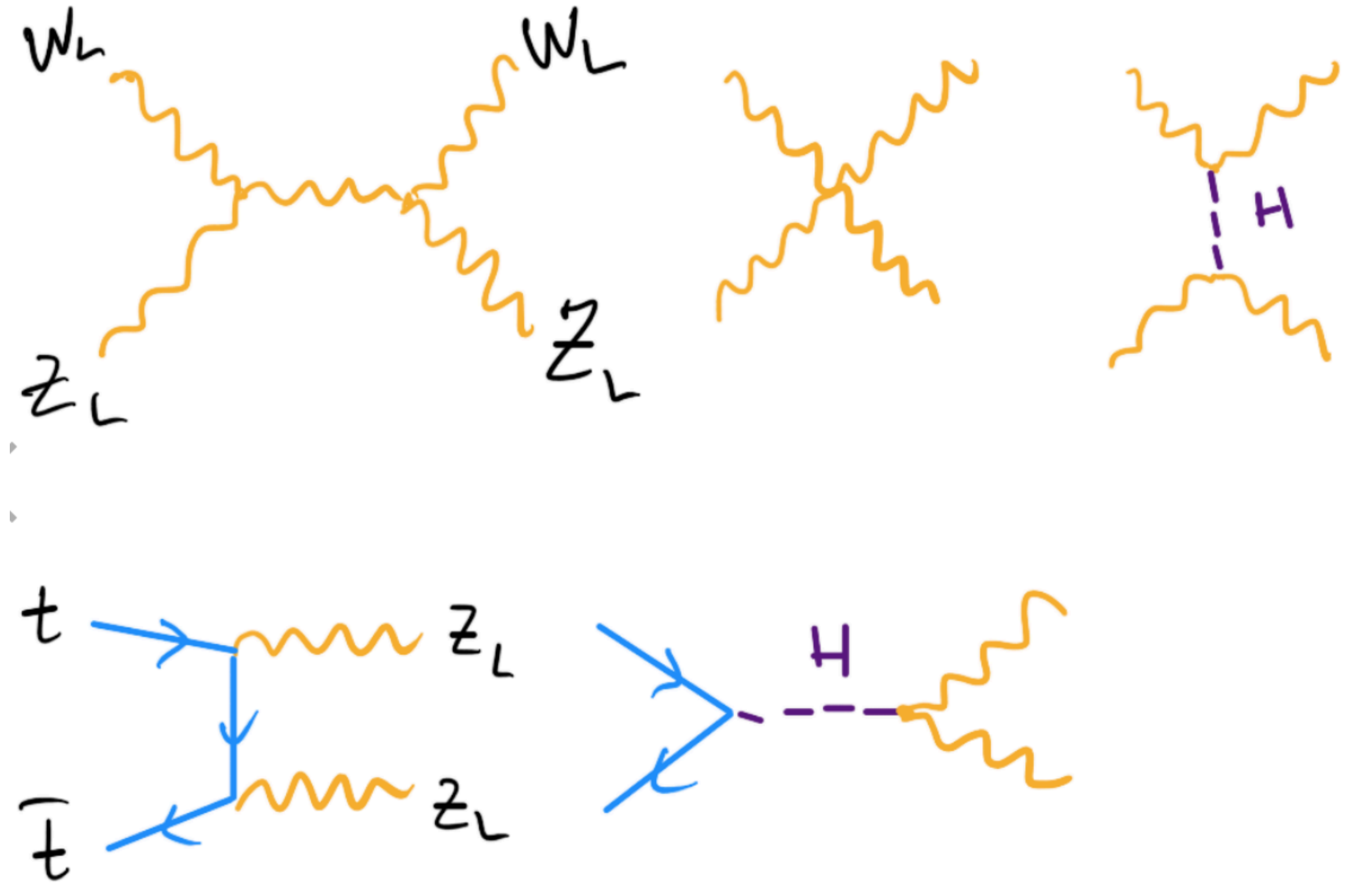
$k_\lambda > 1.5 \Rightarrow$ 1st ord ($T = 0$ and $T = T_c$ connected)

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

SM 101
Unitarity

Unitarity dictates that amplitudes cannot grow with energy.

Energy violating behaviours signal the existence of a scale $\Lambda > v$ where new phenomena occur.



$$a_0 \sim \frac{s}{v^2} - \frac{s}{v^2} \sim \frac{m_H^2}{v^2}$$

$$a_0 \sim \frac{\sqrt{s} m_f}{v^2} - \frac{\sqrt{s} m_f}{v^2} \sim \frac{m_f^2}{v^2}$$

Arbitrary modifications of couplings respecting Lorentz, $U(1)_{EM}$ and SU(3) symmetries generally lead to unitarity violations at low scales.

see, e.g., [Abu-Ajameieh, Chang, Chen, Luty, 2009.11293]

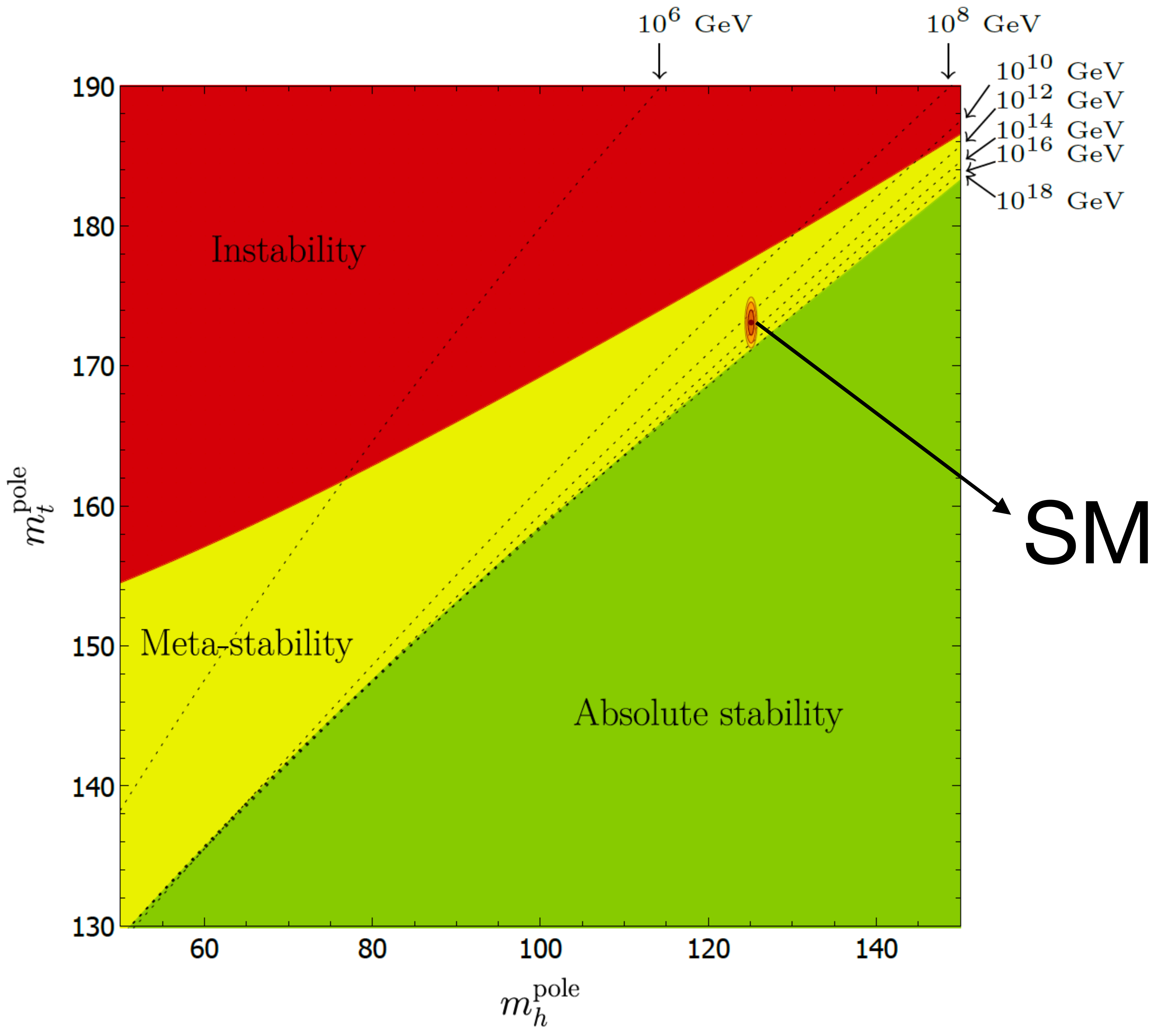
Imposing full SU(3) x SU(2) x U(1) in the deformations moves unitarity violations at higher scales.

see, e.g., [Mantani, Mimasu, FM, 2019]

SM 101

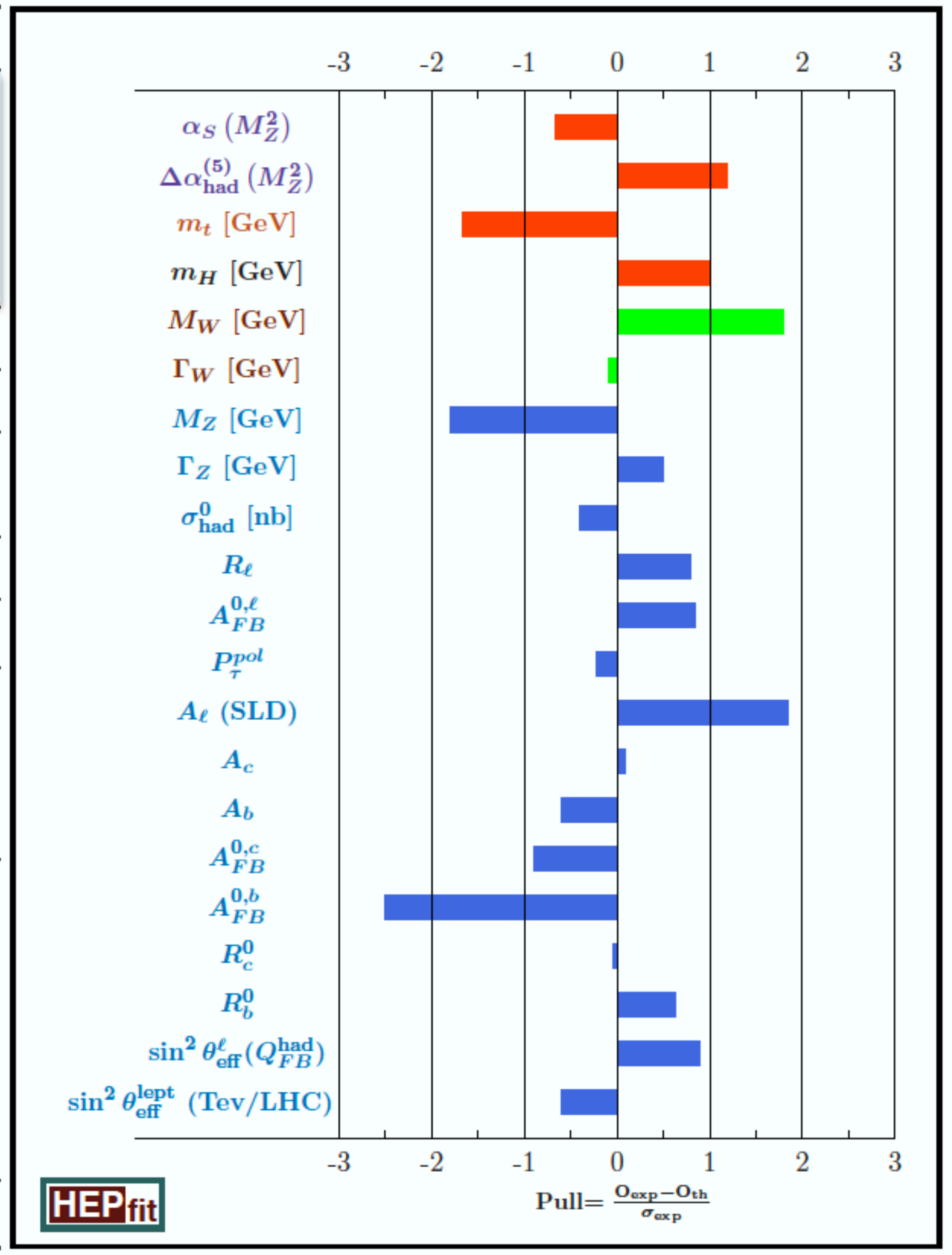
Perturbativity/Loops

Being renormalisable the SM allows to consistently perform loop computations and to **test** the theory at a high degree of precision.



[Andreassen et al. 1707.08124]

	Measurement	Posterior	Prediction	Pull
$\alpha_s(M_Z)$	0.1177±0.0010	0.1179±0.0009	0.1197±0.0028	-0.7
$\Delta\alpha^{(5)}_{\rm had}(M_Z)$	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
$\mathrm{BR}_{W\to \rm had}$	0.6741±0.0027	0.67486±0.00007	0.67486±0.00007	-0.28
$\mathrm{BR}_{W\to \ell\nu}$	0.1086±0.0009	0.10838±0.00002	0.10838±0.00002	0.24
$P_\tau^{\rm pol} = A_\ell$	0.1465±0.0033	0.1473±0.0004	0.1473±0.0005	-0.23
$\sin^2\theta_{\rm eff}^{\rm lept}(Q_{\rm FB}^{\rm had})$	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_h^0 [nb]	41.4802±0.0325	41.4910±0.0076	41.4930±0.0080	-0.38
R_ℓ^0	20.7666±0.0247	20.750±0.0080	20.7460±0.0087	0.79
$A_{\rm FB}^{0,\ell}$	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_b^0	0.21629±0.00066	0.21588±0.00010	0.21587±0.00010	0.63
R_c^0	0.1721±0.0030	0.17221±0.00005	0.17221±0.00005	-0.04
$A_{\rm FB}^{0,b}$	0.0992±0.0016	0.1032±0.0003	0.10327±0.00033105	-2.5
$A_{\rm FB}^{0,c}$	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
$\sin^2\theta_{\rm eff}^{\rm lept}$(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]

SM 101
Going beyond

Three key properties of the SM:

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

Is it possible to "minimally" deform the SM without losing any of the above?

A powerful approach

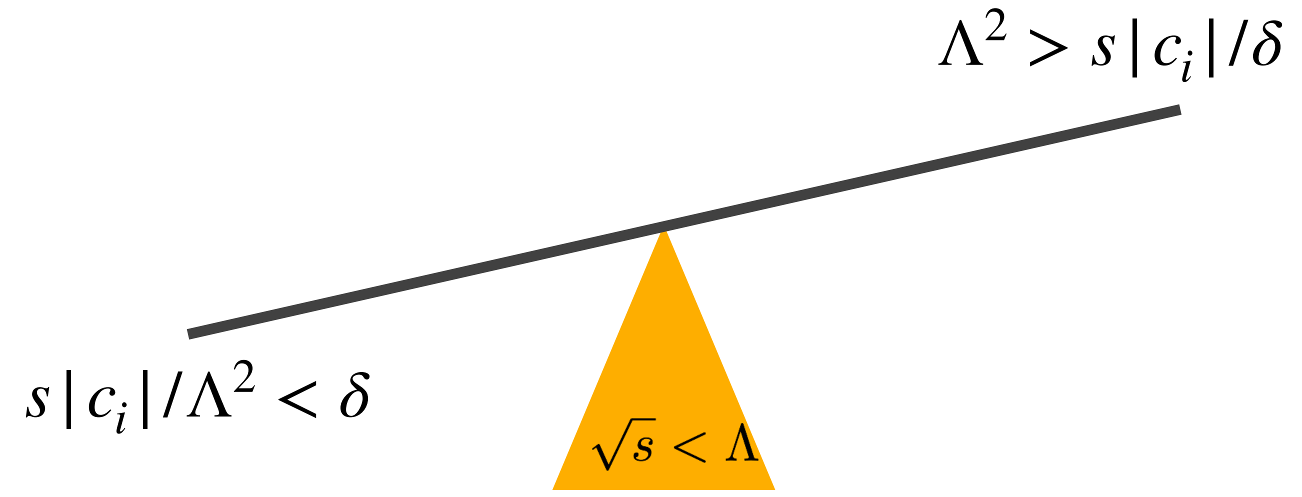
Searching for new interactions with an EFT

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

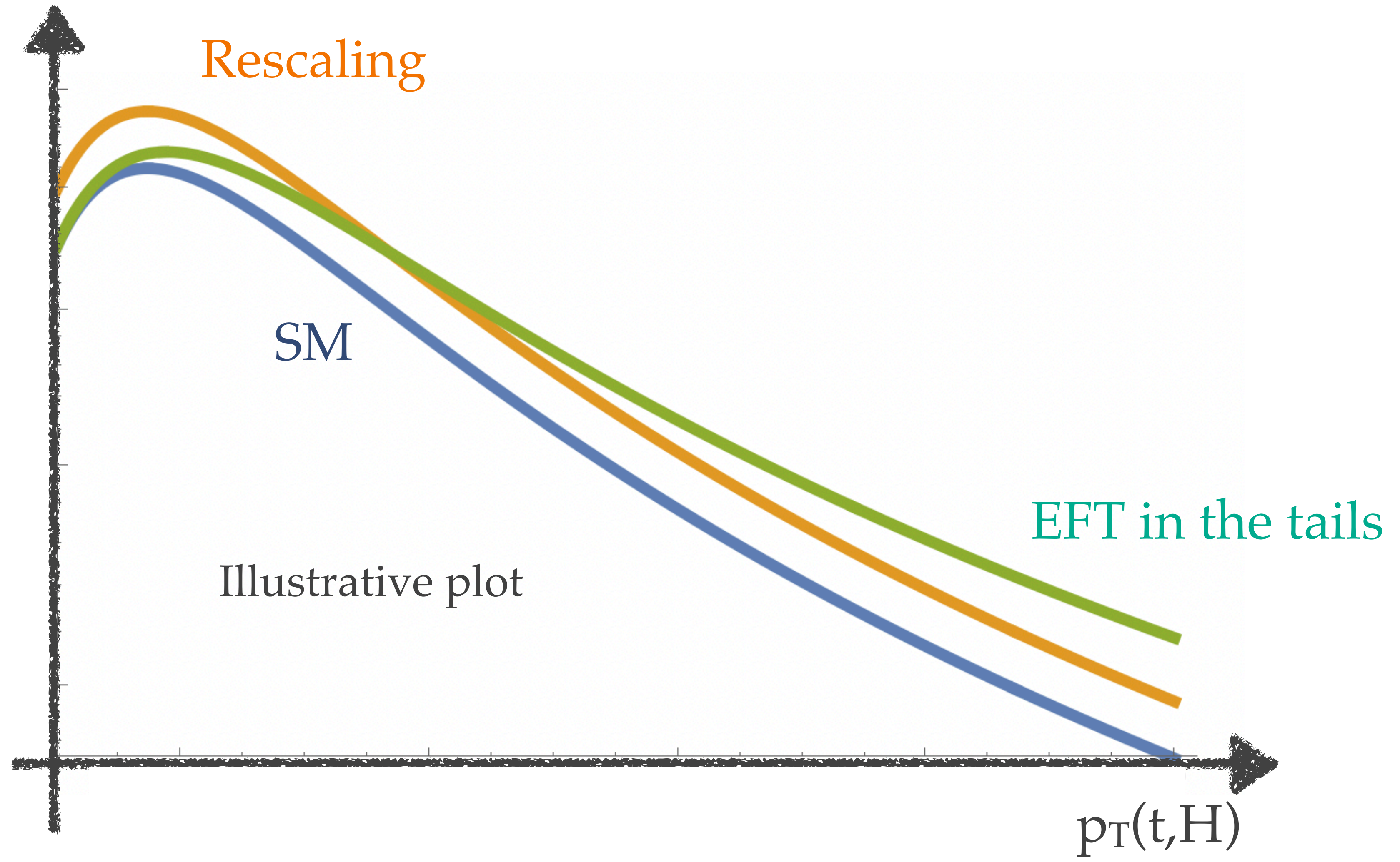
$$\mathcal{L}_{SM}^{(6)} = \mathcal{L}_{SM}^{(4)} + \sum_i \frac{c_i}{\Lambda^2} \mathcal{O}_i + \dots$$

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.

A powerful approach

Searching for new interactions with an EFT

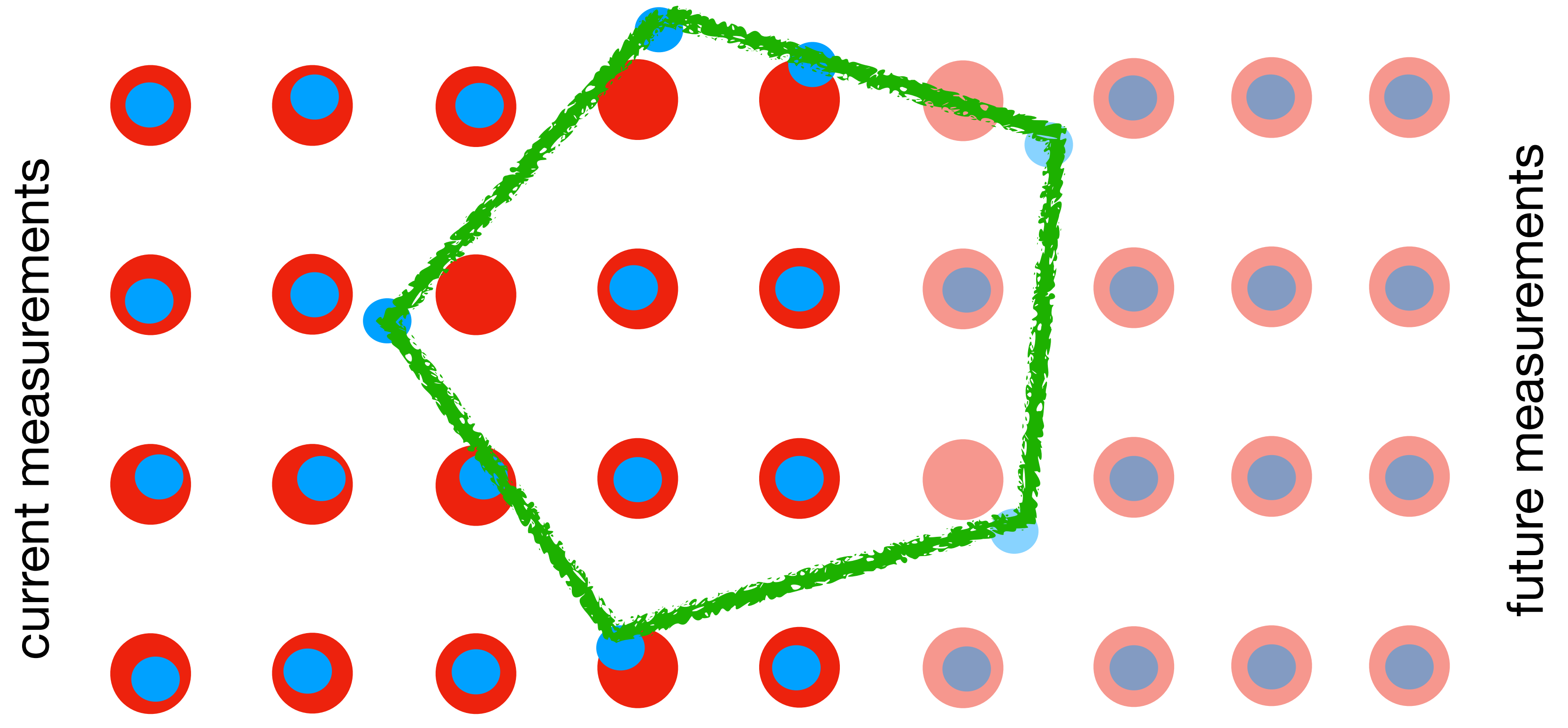
The master equation of an EFT approach has three key elements:

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

Most precise EFT predictions

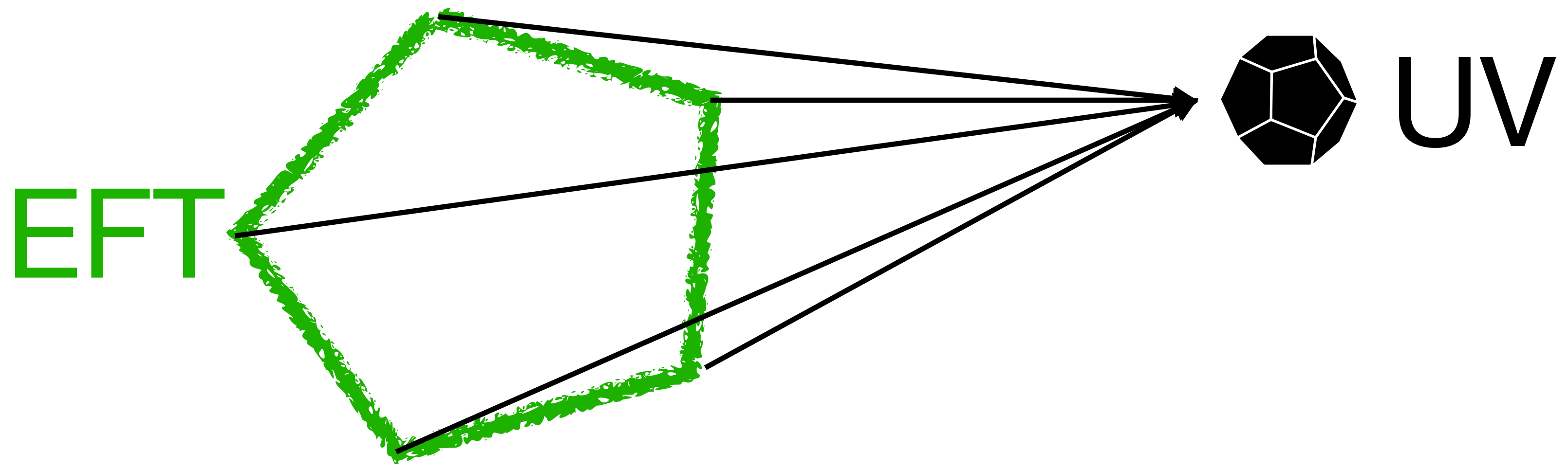
Most precise SM predictions for observables: NLO, NNLO, N3LO…

Most precise/accurate experimental measurements with uncertainties and correlations



⇒ increased NP Sensitivity

⇒ increased UV identification power



A powerful approach

What are we going to learn?

[Grojean and Rattazzi in De Blas et al., 2020]

IR Simplicity:	Naturalness:
$M_{UV} \gg m_{weak}$, new physics effects decouple (B&L, $m_\nu \ll v$, GIM, no FCNC,..)	$M_{UV} \sim m_H$,
In the SM: simplicity ⇒ not natural	In BSM : natural ⇒ not simple

Fine tuning

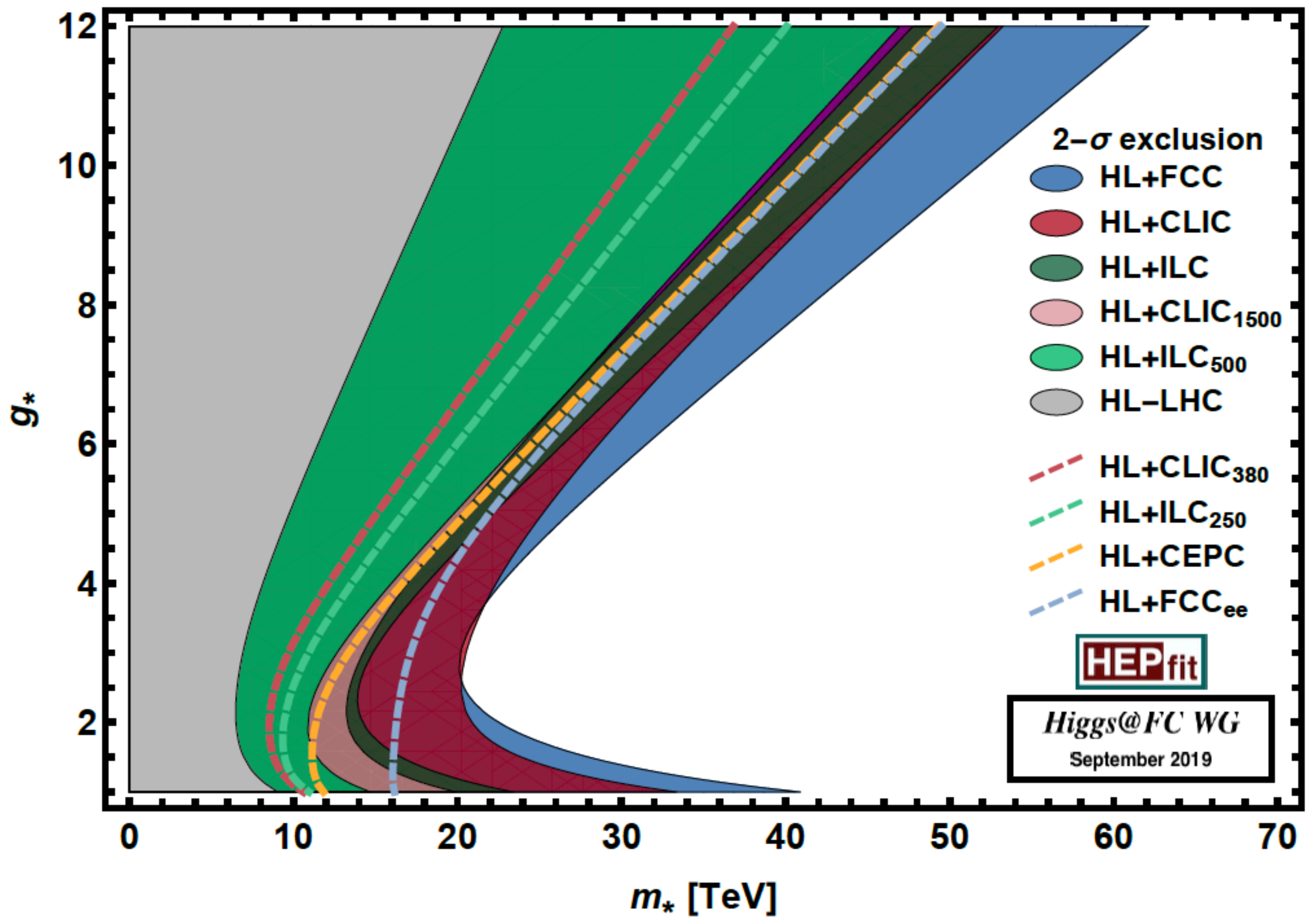
$\varepsilon \equiv m_H^2 / \Delta m_H^2$

$m_T = 10\,\text{TeV}$

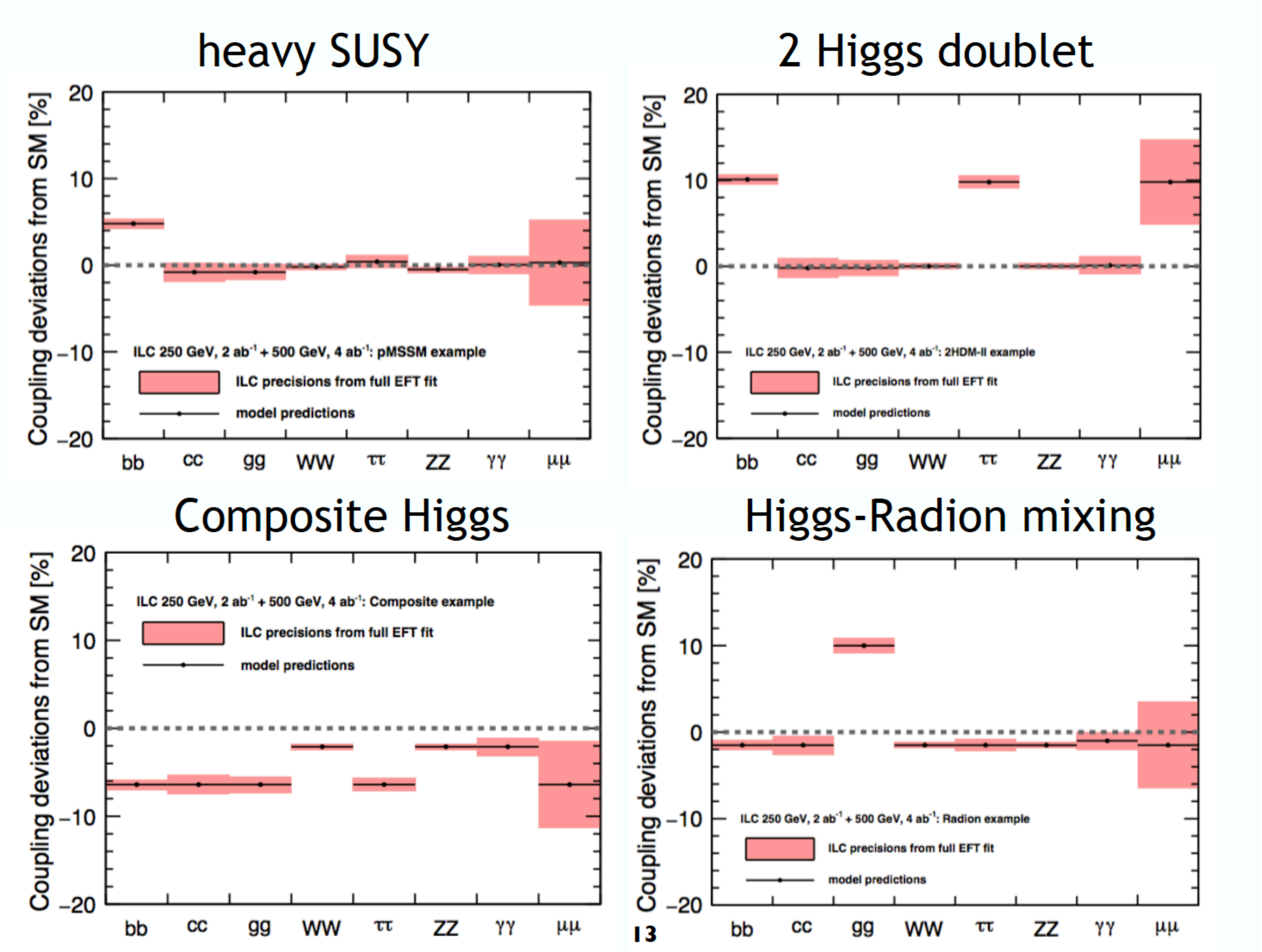
Direct searches	Higgs couplings	EWPT
$\epsilon = (10^{-4}, 10^{-3}, 10^{-2})$	$\delta g_H / g_H{}^{SM} \sim c\,\varepsilon$	$\widehat{S} \sim (\alpha_W / 4\pi)(m_{weak}^2 / m_*^2)$

A powerful approach

What are we going to learn?



[De Blas et al., 2020]



[Peskin, ICHEP2020]

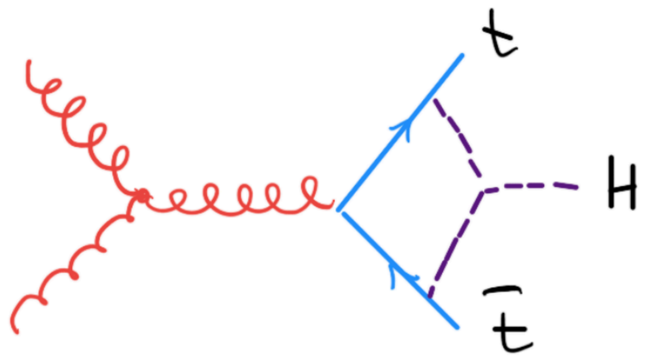
Full mapping at tree level to SMEFT : [de Blas et al. 2018]

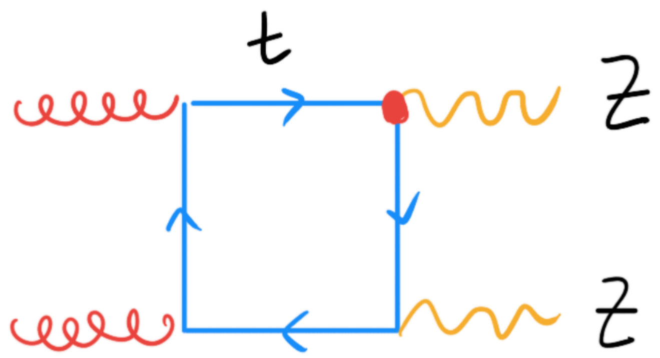
Precision EFT

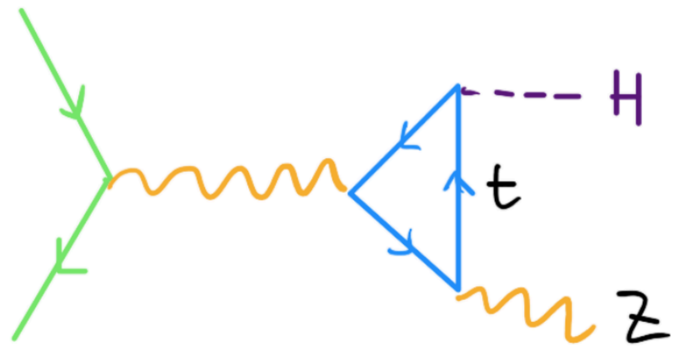
SMEFT at 1-loop level

1-loop accuracy allows:

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







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]

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

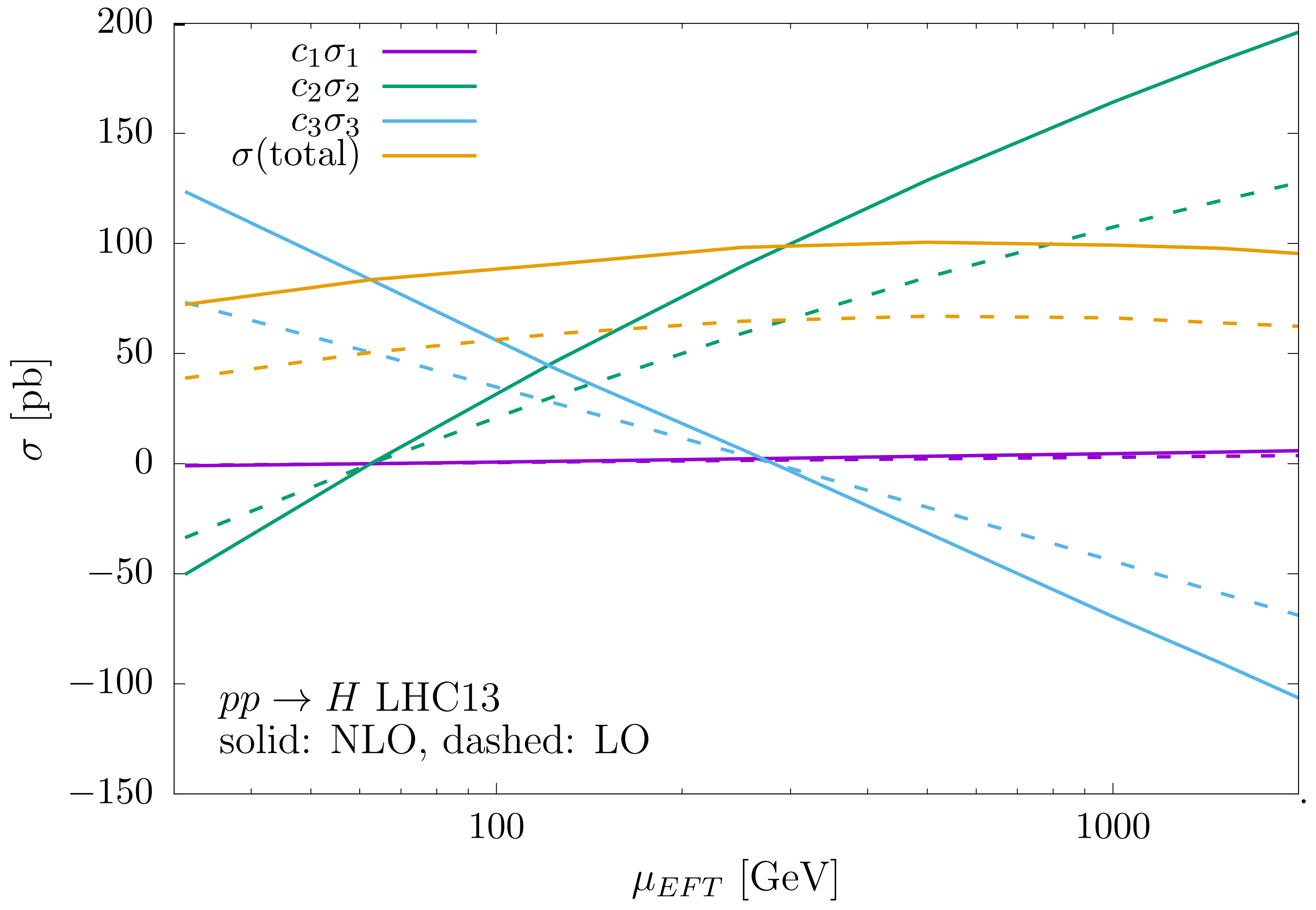
· EWPO [Zhang, Greiner, Willenbrock '12] [Dawson, Giardino ,2020]

Precision EFT

Three motivations for NLO

1. EFT scale dependence

[Deutschmann, Duhr, FM, Vryonidou, 17]



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

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

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

$$\frac{dC_i(\mu)}{d\log\mu} = \frac{\alpha_s}{\pi}\gamma_{ij}C_j(\mu),$$

$$\gamma = \begin{pmatrix} -2 & 16 & 8 \\ 0 & -7/2 & 1/2 \\ 0 & 0 & 1/3 \end{pmatrix}$$

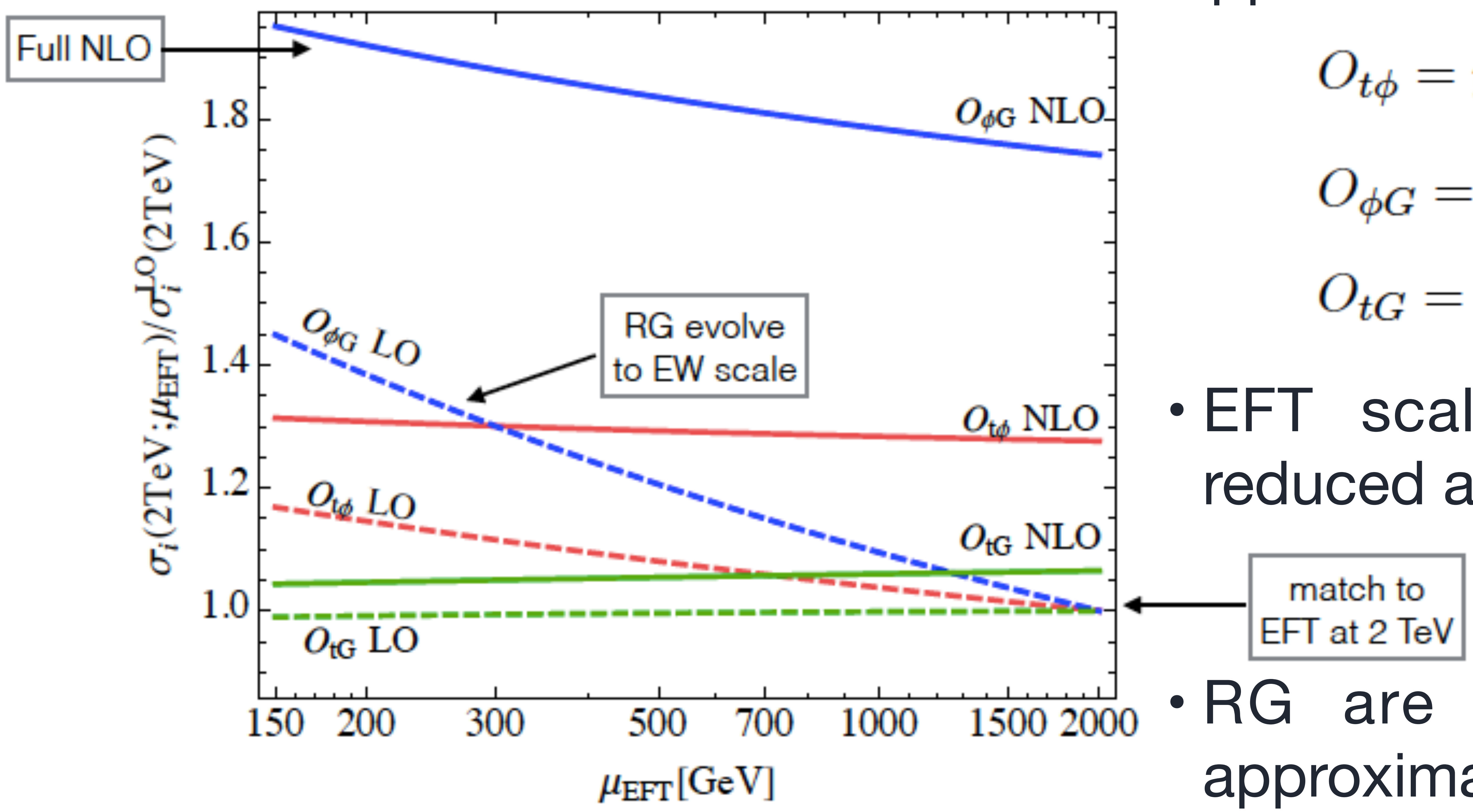
By including the mixing, the overall scale dependence at LO, is very much reduced with respect to the single ones. A global point of view is required: contribution from each coupling may not make sense; only their sum is meaningful.

Precision EFT

Three motivations for NLO

2. 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.

Precision EFT

Three motivations for NLO

3. New operators arise

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.

[Ghezzi, Gomez-Ambrosio, Passarino, Uccirati, 2015a]

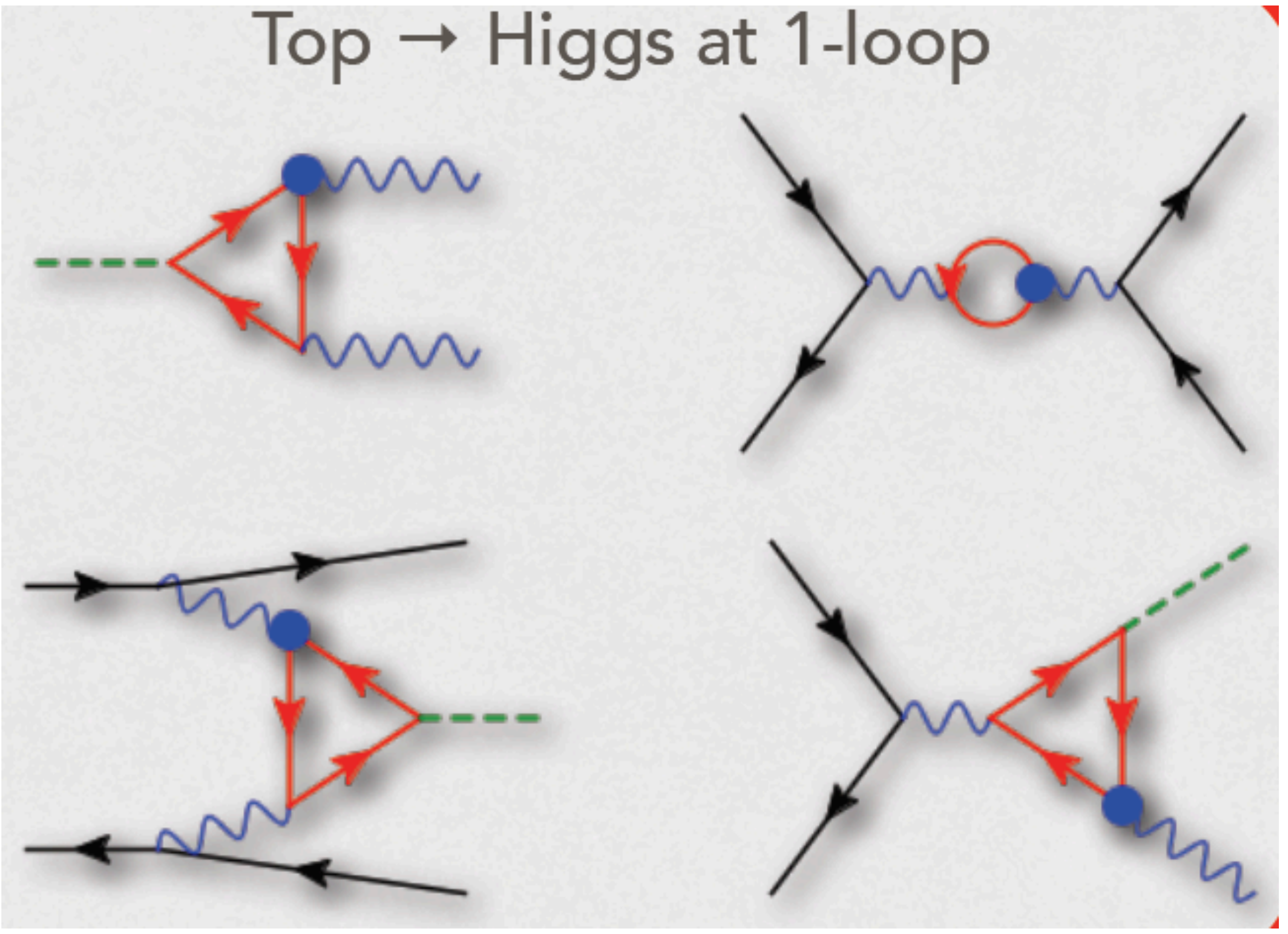
[Hartmann and Trott, 2015]

[Ghezzi, Gomez-Ambrosio, Passarino, Uccirati, 2015b]

[Dawson, Giardino, 2018, 2019]

[Dedes et al, 2018]

[Vryonidou and Zhang, 2018]

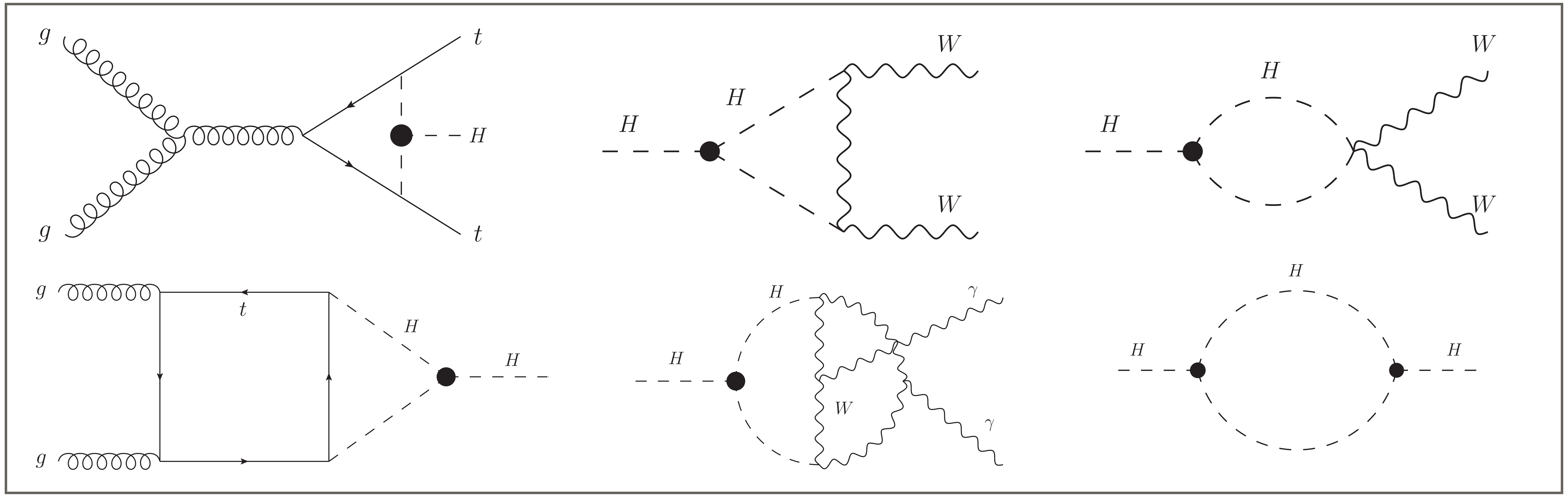


Precision EFT

Three motivations for NLO

3. New operators arise

Example: the dependence of single-Higgs (total and differential) cross sections and decay rates on the self couplings at NLO (EW) level:



$\mathcal{O}_{\varphi d}$	cdp	$\partial_\mu(\varphi^\dagger\varphi)\partial^\mu(\varphi^\dagger\varphi)$
$\mathcal{O}_{\varphi}$	cp	$\left(\varphi^\dagger\varphi - \frac{v^2}{2}\right)^3$

[Degrassi, Giardino, FM, Pagani, Shivaji, Zhao, 2016-2018]

Precision EFT
SMEFT@NLO

Aim to fully automate NLO calculations in the SMEFT within public Monte Carlo generators based on:

- Warsaw basis of dimension-6 operators

Current status:

- NLO in QCD
- 73 degrees of freedom (top, Higgs, gauge):
  - CP-conserving
  - Flavour assumption: $U(2)_Q \times U(2)_u \times U(3)_d \times U(3)_L \times U(3)_e$
- Successful validation with LO implementations
- 0/2/4F@NLO validated and released: **http://feynrules.irmp.ucl.ac.be/wiki/SMEFTatNLO**

Paves the way for a precise SMEFT programme at the LHC

[Degrande et al.,2008.11743]

Top sector

Interactions

- New interactions among SM particles can be systematically parametrized in the context of the SMEFT. Directly related to the top fields, at dim=6

$$\mathcal{L}_{SM}^{(6)} = \mathcal{L}_{SM}^{(4)} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i + \dots \quad \Rightarrow \quad \mathrm{Obs}_i = \mathrm{Obs}_i^{\mathrm{SM}} + M_{ij}\cdot\frac{s}{\Lambda^2}c_j$$

[Aguilar-Saavedra et al. 1802.07237]

2QBs

$$\begin{aligned}
{}^\ddagger O_{u\varphi}^{(ij)} &= \bar q_i u_j \tilde\varphi\,(\varphi^\dagger\varphi),\\
O_{\varphi q}^{1(ij)} &= (\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar q_i\gamma^\mu q_j),\\
O_{\varphi q}^{3(ij)} &= (\varphi^\dagger i\overleftrightarrow{D}^I_\mu\varphi)(\bar q_i\gamma^\mu\tau^I q_j),\\
O_{\varphi u}^{(ij)} &= (\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar u_i\gamma^\mu u_j),\\
{}^\ddagger O_{\varphi ud}^{(ij)} &= (\tilde\varphi^\dagger iD_\mu\varphi)(\bar u_i\gamma^\mu d_j),\\
{}^\ddagger O_{uW}^{(ij)} &= (\bar q_i\sigma^{\mu\nu}\tau^I u_j)\,\tilde\varphi W^I_{\mu\nu},\\
{}^\ddagger O_{dW}^{(ij)} &= (\bar q_i\sigma^{\mu\nu}\tau^I d_j)\,\varphi W^I_{\mu\nu},\\
{}^\ddagger O_{uB}^{(ij)} &= (\bar q_i\sigma^{\mu\nu} u_j)\quad\tilde\varphi B_{\mu\nu},\\
{}^\ddagger O_{uG}^{(ij)} &= (\bar q_i\sigma^{\mu\nu}T^A u_j)\,\tilde\varphi G^A_{\mu\nu},
\end{aligned}$$

2Q2L

$$\begin{aligned}
O_{lq}^{1(ijkl)} &= (\bar l_i\gamma^\mu l_j)(\bar q_k\gamma^\mu q_l),\\
O_{lq}^{3(ijkl)} &= (\bar l_i\gamma^\mu\tau^I l_j)(\bar q_k\gamma^\mu\tau^I q_l),\\
O_{lu}^{(ijkl)} &= (\bar l_i\gamma^\mu l_j)(\bar u_k\gamma^\mu u_l),\\
O_{eq}^{(ijkl)} &= (\bar e_i\gamma^\mu e_j)(\bar q_k\gamma^\mu q_l),\\
O_{eu}^{(ijkl)} &= (\bar e_i\gamma^\mu e_j)(\bar u_k\gamma^\mu u_l),\\
{}^\ddagger O_{lequ}^{1(ijkl)} &= (\bar l_i e_j)\;\varepsilon\;(\bar q_k u_l),\\
{}^\ddagger O_{lequ}^{3(ijkl)} &= (\bar l_i\sigma^{\mu\nu} e_j)\;\varepsilon\;(\bar q_k\sigma_{\mu\nu} u_l),\\
{}^\ddagger O_{ledq}^{(ijkl)} &= (\bar l_i e_j)(\bar d_k q_l),
\end{aligned}$$

2Q2q-4Q

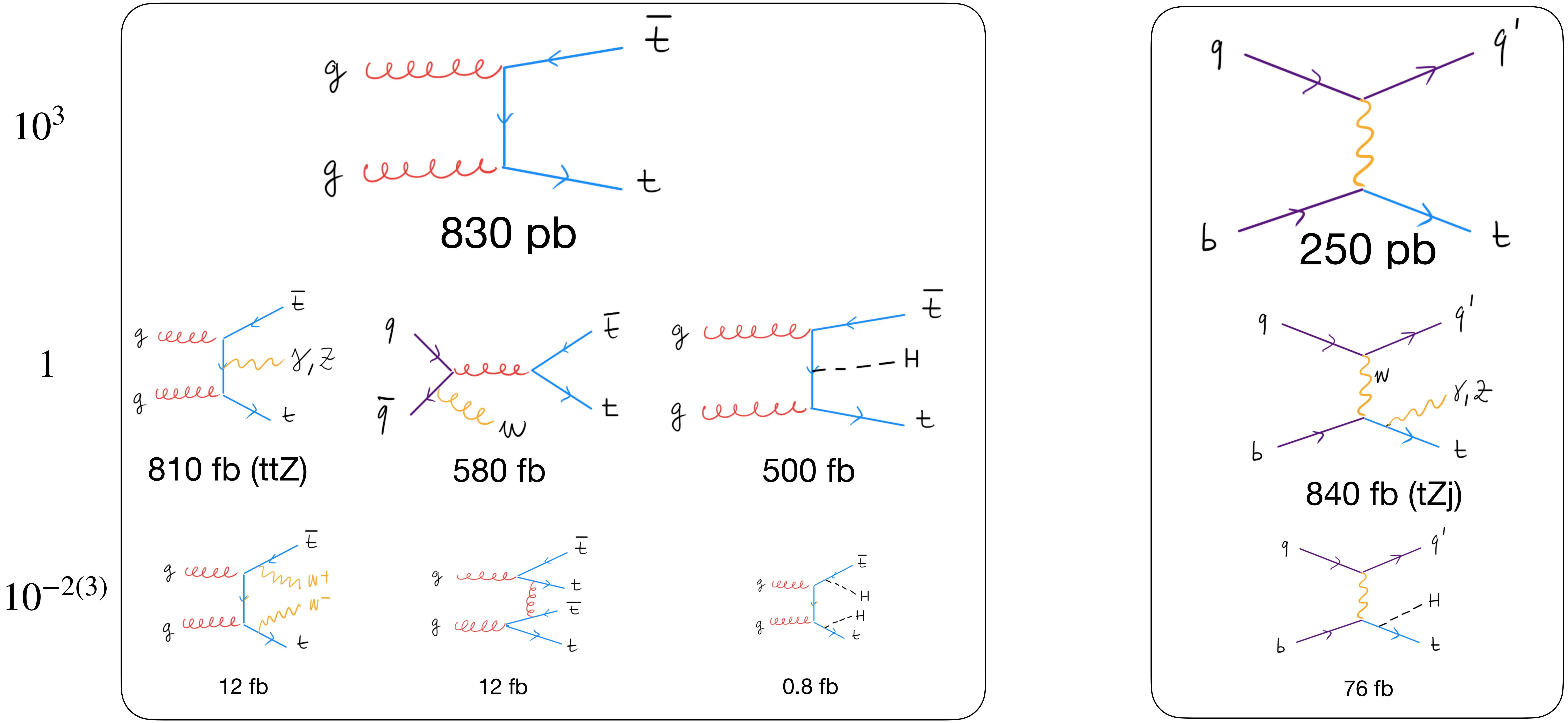
$$\begin{aligned}
O_{qq}^{1(ijkl)} &= (\bar q_i\gamma^\mu q_j)(\bar q_k\gamma_\mu q_l),\\
O_{qq}^{3(ijkl)} &= (\bar q_i\gamma^\mu\tau^I q_j)(\bar q_k\gamma_\mu\tau^I q_l),\\
O_{qu}^{1(ijkl)} &= (\bar q_i\gamma^\mu q_j)(\bar u_k\gamma_\mu u_l),\\
O_{qu}^{8(ijkl)} &= (\bar q_i\gamma^\mu T^A q_j)(\bar u_k\gamma_\mu T^A u_l),\\
O_{qd}^{1(ijkl)} &= (\bar q_i\gamma^\mu q_j)(\bar d_k\gamma_\mu d_l),\\
O_{qd}^{8(ijkl)} &= (\bar q_i\gamma^\mu T^A q_j)(\bar d_k\gamma_\mu T^A d_l),\\
O_{uu}^{(ijkl)} &= (\bar u_i\gamma^\mu u_j)(\bar u_k\gamma_\mu u_l),\\
O_{ud}^{1(ijkl)} &= (\bar u_i\gamma^\mu u_j)(\bar d_k\gamma_\mu d_l),\\
O_{ud}^{8(ijkl)} &= (\bar u_i\gamma^\mu T^A u_j)(\bar d_k\gamma_\mu T^A d_l),\\
{}^\ddagger O_{quqd}^{1(ijkl)} &= (\bar q_i u_j)\;\varepsilon\;(\bar q_k d_l),\\
{}^\ddagger O_{quqd}^{8(ijkl)} &= (\bar q_i T^A u_j)\;\varepsilon\;(\bar q_k T^A d_l),
\end{aligned}$$

which, assuming $U(2)_q \times U(2)_u \times U(2)_d$,corresponds to 42 degrees of freedom (11x4Q, 14x2Q2q, 9x2QBs, 8x2Q2L)

Top sector

LHC channels

- A large number of final states to study:



Top sector

LHC data sets

Large number of datasets available from the LHC involving tops in the final state.

Dataset	$\sqrt{s}, \mathcal{L}$	Info	Observables	$N_{\rm dat}$	Ref
ATLAS_tt_8TeV_ljets	8 TeV, 20.3 fb^{-1}	lepton+jets	$d\sigma/d\vert y_t\vert$, $d\sigma/dp_t^T$, $d\sigma/dm_{t\bar{t}}$, $d\sigma/d\vert y_{t\bar{t}}\vert$	5, 8, 7, 5	[32]
CMS_tt_8TeV_ljets	8 TeV, 20.3 fb^{-1}	lepton+jets	$d\sigma/dy_t$, $d\sigma/dp_t^T$, $d\sigma/dm_{t\bar{t}}$, $d\sigma/dy_{t\bar{t}}$	10, 8, 7, 10	[33]
CMS_tt2D_8TeV_dilep	8 TeV, 20.3 fb^{-1}	dileptons	$d^2\sigma/dy_t dp_t^T$, $d^2\sigma/dy_t dm_{t\bar{t}}$, $d^2\sigma/dp_{t\bar{t}}^T dm_{t\bar{t}}$, $d^2\sigma/dy_{t\bar{t}} dm_{t\bar{t}}$	16, 16, 16, 16	[34]
CMS_tt_13TeV_ljets	13 TeV, 2.3 fb^{-1}	lepton+jets	$d\sigma/d\vert y_t\vert$, $d\sigma/dp_t^T$, $d\sigma/dm_{t\bar{t}}$, $d\sigma/d\vert y_{t\bar{t}}\vert$	7, 9, 8, 6	[35]
CMS_tt_13TeV_ljets2	13 TeV, 35.8 fb^{-1}	lepton+jets	$d\sigma/d\vert y_t\vert$, $d\sigma/dp_t^T$, $d\sigma/dm_{t\bar{t}}$, $d\sigma/d\vert y_{t\bar{t}}\vert$	11, 12, 10, 10	[36]
CMS_tt_13TeV_dilep	13 TeV, 2.1 fb^{-1}	dileptons	$d\sigma/dy_t$, $d\sigma/dp_t^T$, $d\sigma/dm_{t\bar{t}}$, $d\sigma/dy_{t\bar{t}}$	8, 6, 6, 8	[37]
ATLAS_WhelF_8TeV	8 TeV, 20.3 fb^{-1}	W hel. fract	F_0, F_L, F_R	3	[38]
CMS_WhelF_8TeV	8 TeV, 20.3 fb^{-1}	W hel. fract	F_0, F_L, F_R	3	[39]

$$t\bar{t}$$

Dataset	$\sqrt{s}, \mathcal{L}$	Info	Observables	$N_{\rm dat}$	Ref
CMS_ttbb_13TeV	13 TeV, 2.3 fb^{-1}	total xsec	$\sigma_{\rm tot}(t\bar{t}b\bar{b})$	1	[40]
CMS_ttbb_13TeV_2016 (*)	13 TeV, 35.9 fb^{-1}	total xsec	$\sigma_{\rm tot}(t\bar{t}b\bar{b})$	1	[41]
CMS_tttt_13TeV	13 TeV, 35.9 fb^{-1}	total xsec	$\sigma_{\rm tot}(t\bar{t}t\bar{t})$	1	[42]
CMS_tttt_13TeV_run2 (*)	13 TeV, 137 fb^{-1}	total xsec	$\sigma_{\rm tot}(t\bar{t}t\bar{t})$	1	[43]
CMS_ttZ_8TeV	8 TeV, 19.5 fb^{-1}	total xsec	$\sigma_{\rm tot}(t\bar{t}Z)$	1	[44]
CMS_ttZ_13TeV	13 TeV, 35.9 fb^{-1}	total xsec	$\sigma_{\rm tot}(t\bar{t}Z)$	1	[45]
CMS_ttZ_ptZ_13TeV (*)	13 TeV, 77.5 fb^{-1}	total xsec	$\sigma_{\rm tot}(t\bar{t}Z)$, $d\sigma(t\bar{t}Z)/dp_T^Z$	1, 4	[45]
ATLAS_ttZ_8TeV	8 TeV, 20.3 fb^{-1}	total xsec	$\sigma_{\rm tot}(t\bar{t}Z)$	1	[46]
ATLAS_ttZ_13TeV	13 TeV, 3.2 fb^{-1}	total xsec	$\sigma_{\rm tot}(t\bar{t}Z)$	1	[47]
CMS_ttW_8_TeV	8 TeV, 19.5 fb^{-1}	total xsec	$\sigma_{\rm tot}(t\bar{t}W)$	1	[44]
CMS_ttW_13TeV	13 TeV, 35.9 fb^{-1}	total xsec	$\sigma_{\rm tot}(t\bar{t}W)$	1	[45]
ATLAS_ttW_8TeV	8 TeV, 20.3 fb^{-1}	total xsec	$\sigma_{\rm tot}(t\bar{t}W)$	1	[46]
ATLAS_ttW_13TeV	13 TeV, 3.2 fb^{-1}	total xsec	$\sigma_{\rm tot}(t\bar{t}W)$	1	[47]

$$t\bar{t}+V, t\bar{t}b\bar{b}, t\bar{t}t\bar{t}$$

Dataset	$\sqrt{s}, \mathcal{L}$	Info	Observables	$N_{\rm dat}$	Ref
CMS_t_tch_8TeV_inc	8 TeV, 19.7 fb^{-1}	t-channel	$\sigma_{\rm tot}(t), \sigma_{\rm tot}(\bar{t})$ (R_t)	2 (1)	[48]
CMS_t_sch_8TeV	8 TeV, 19.7 fb^{-1}	s-channel	$\sigma_{\rm tot}(t+\bar{t})$	1	[49]
ATLAS_t_sch_8TeV	8 TeV	s-channel	$\sigma_{\rm tot}(t+\bar{t})$	1	[50]
ATLAS_t_tch_8TeV	8 TeV	t-channel	$d\sigma(tq)/dp_T^t, d\sigma(\bar{t}q)/dp_T^{\bar{t}}$, $d\sigma(tq)/dy_t, d\sigma(\bar{t}q)/dy_t$	5, 4, 4, 4	[51]
ATLAS_t_tch_13TeV	13 TeV	t-channel	$\sigma_{\rm tot}(t), \sigma_{\rm tot}(\bar{t})$ (R_t)	2 (1)	[52]
CMS_t_tch_13TeV_inc	13 TeV	t-channel	$\sigma_{\rm tot}(t+\bar{t})$ (R_t)	1 (1)	[53]
CMS_t_tch_8TeV_dif	8 TeV	t-channel	$d\sigma/dp_T^{(t+\bar{t})}$, $d\sigma/d\vert y^{(t+\bar{t})}\vert$	6, 6	[54]
CMS_t_tch_13TeV_dif	13 TeV	t-channel	$d\sigma/dp_T^{(t+\bar{t})}$, $d\sigma/d\vert y^{(t+\bar{t})}\vert$	4, 4	[55]
ATLAS_tW_inc_8TeV	8 TeV	inclusive	$\sigma_{\rm tot}(tW)$	1	[56]
CMS_tW_inc_8TeV	8 TeV	inclusive	$\sigma_{\rm tot}(tW)$	1	[57]
ATLAS_tW_inc_13TeV	13 TeV	inclusive	$\sigma_{\rm tot}(tW)$	1	[58]
CMS_tW_inc_13TeV	13 TeV	inclusive	$\sigma_{\rm tot}(tW)$	1	[59]
CMS_tZ_inc_13TeV	13 TeV	inclusive	$\sigma_{\rm fid}(Wbl^+l^-q)$	1	[60]
ATLAS_tZ_inc_13TeV	13 TeV	inclusive	$\sigma_{\rm tot}(tZq)$	1	[61]

$$t+X$$

Top sector

$t\bar{t}Z$ operators: trees and loops $gg \to HZ, gg \to ZZ, t\bar{t}$

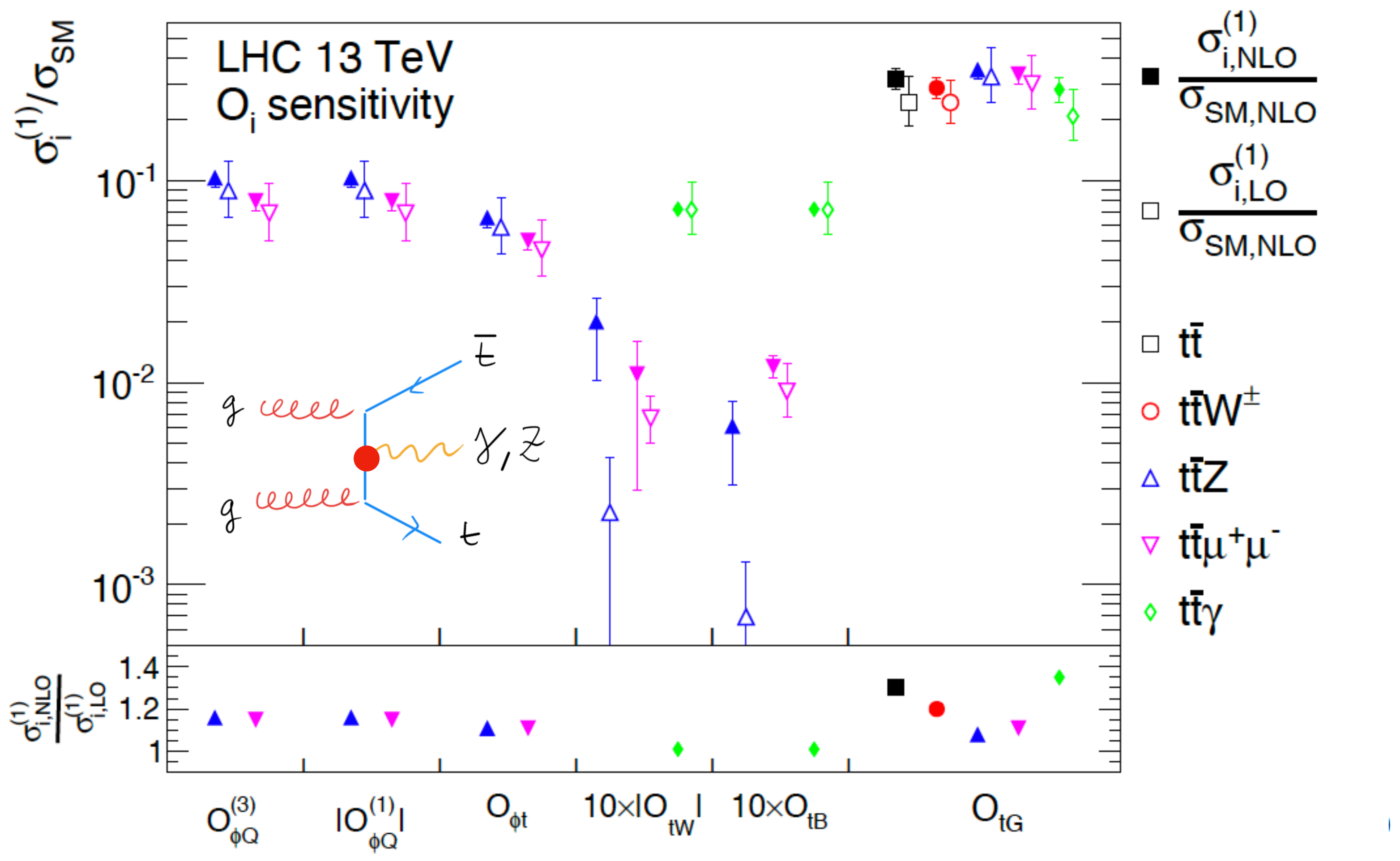
SMEFT computations at NLO in QCD are available for $t\bar{t}Z$ too. A natural way to test the couplings of the Z-boson to the top. However, comparable sensitivity can be obtained from high p_T tails in loop induced processes such as $gg \to HZ$, where only the top loop contributes, $gg \to ZZ$ and also $t\bar{t}$ close to threshold, as recently suggested.

$$O^1_{\phi Q} = (\phi^\dagger \, i \, \overleftrightarrow{D}_\mu \, \phi)(\bar{Q}\gamma^\mu Q)$$

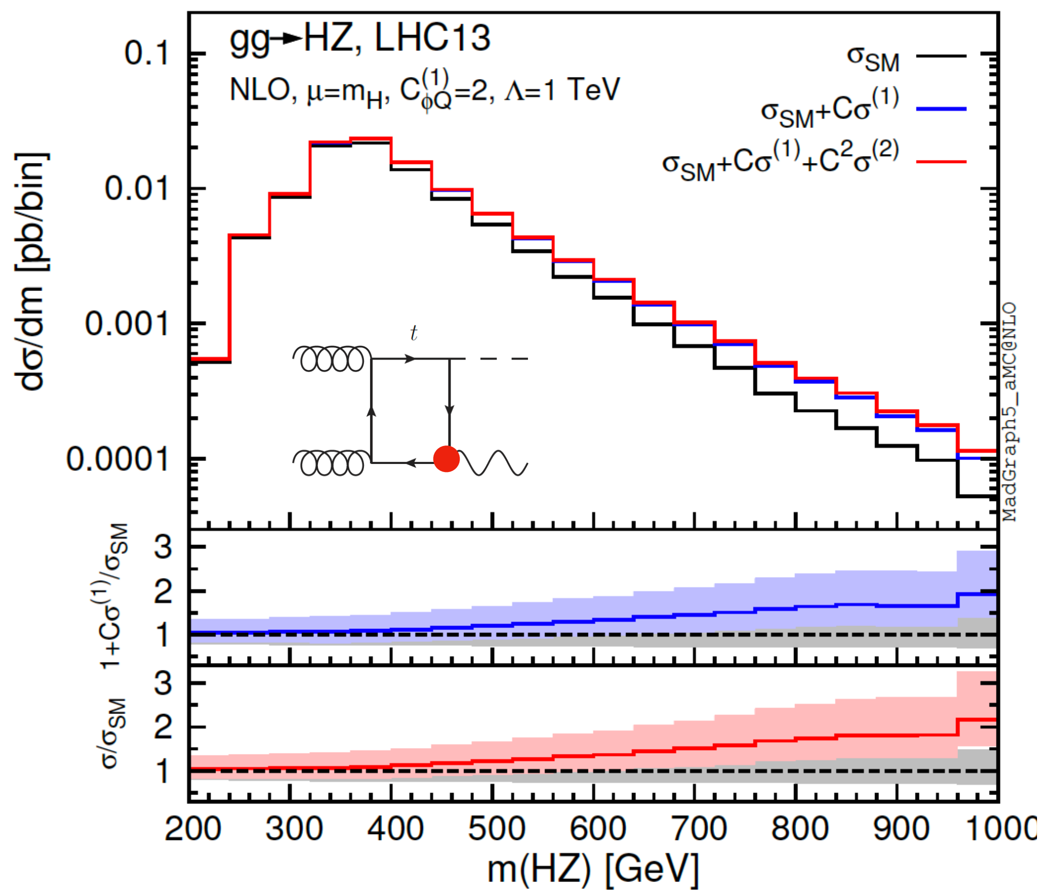
$$O^3_{\phi Q} = (\phi^\dagger \, i \, \overleftrightarrow{D}^I_\mu \, \phi)(\bar{Q}\gamma^\mu \tau^I Q)$$

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

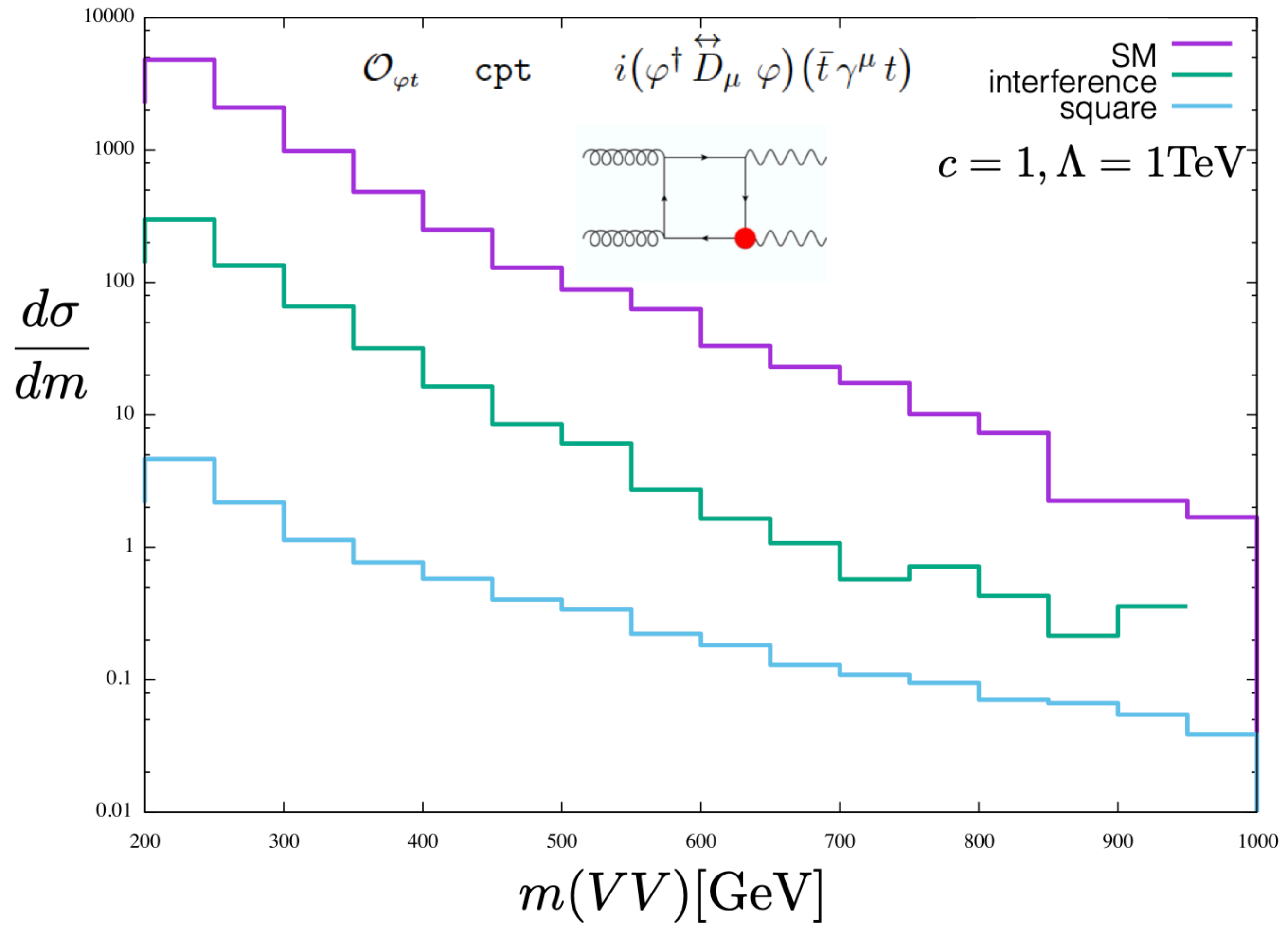
[Bylund et al., 1601.08193]



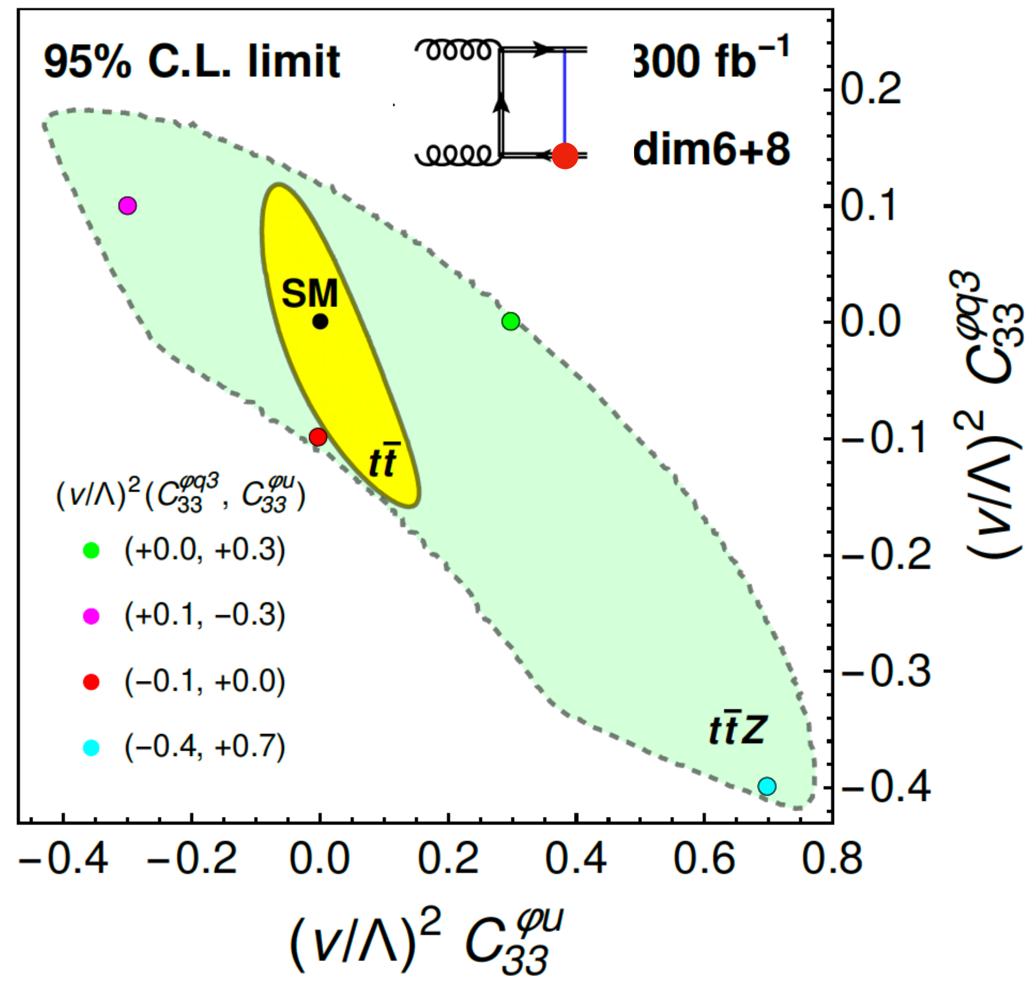
[Bylund et al., 1601.08193]



[Vryonidou at HEFT2020]



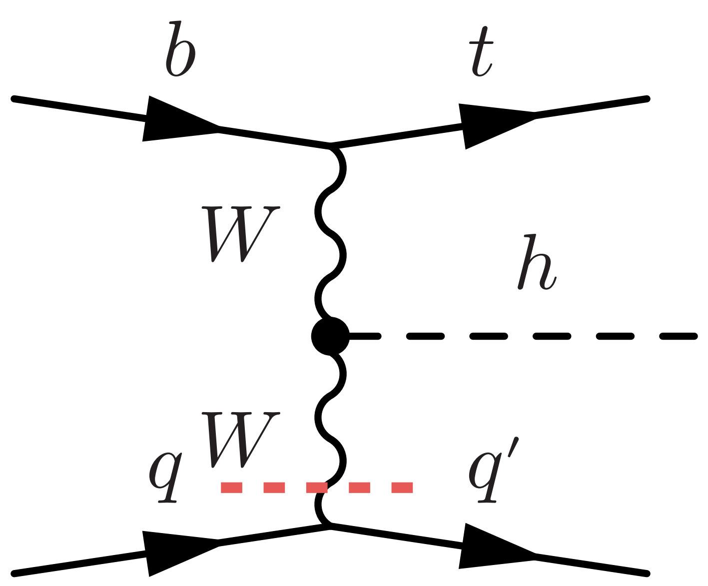
[Martini and Schultze, 1911.11244]



See also [Englert et al. 1410.5440] [Englert et al., 1603.05304] [Azatov et al., 1608.00977]

Top sector

tZj and *tHj* : the interplay of operators/processes

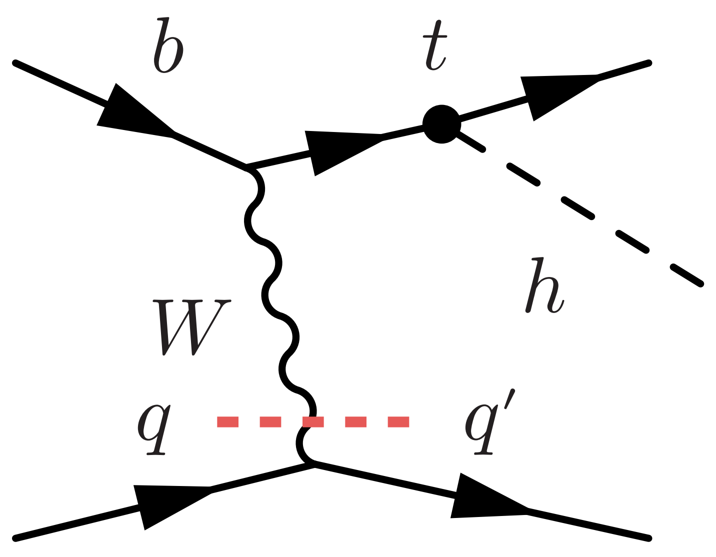


$\mathcal{O}_{\varphi W} : \varphi^\dagger \varphi\, W_i^{\mu\nu} W^i_{\mu\nu}$

HWW

TGC

$\mathcal{O}_W \;:\; \epsilon^{ijk} W_{i,\,\mu\nu} W_j^{\nu\rho} W^{\mu}_{k,\,\rho}$

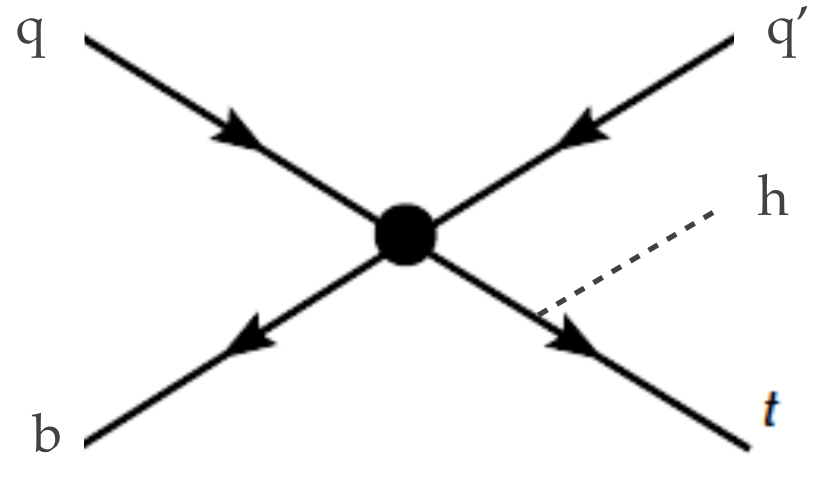


$\mathcal{O}_{t\varphi} \;:\; (\varphi^\dagger\varphi)\,(\bar{Q}\,t)\,\tilde{\varphi}$

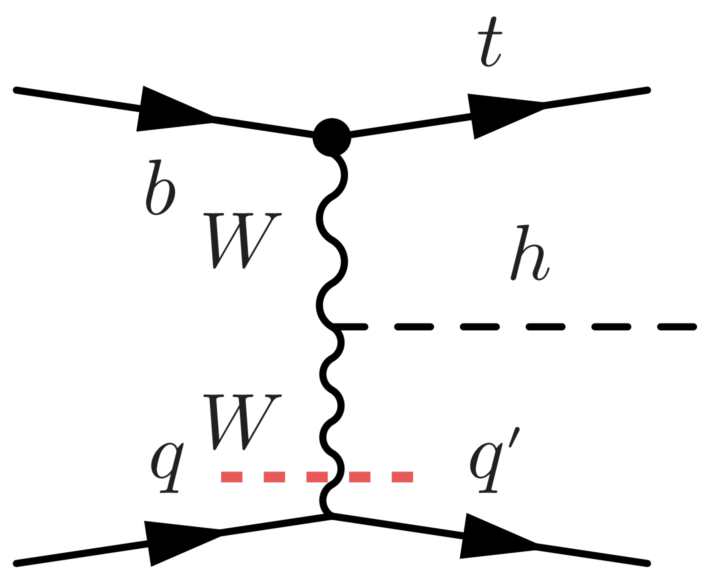
top Yukawa

ttZ coupling

$\mathcal{O}_{\varphi t} \;:\; i(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi)(\bar{t}\gamma^\mu t)$



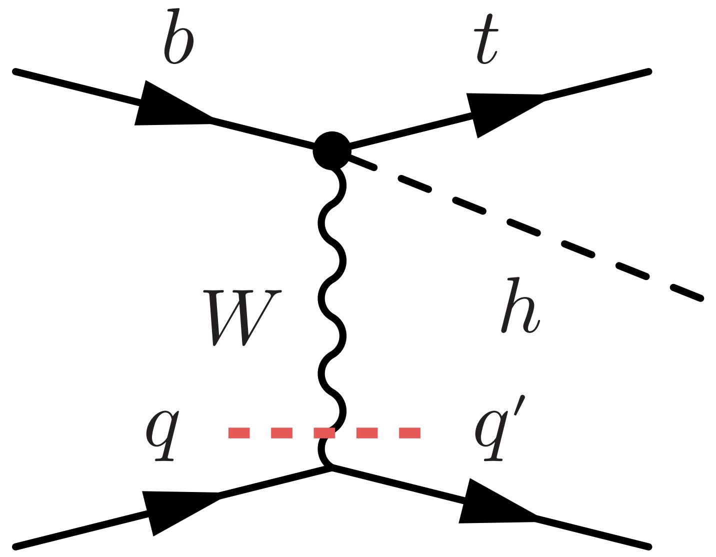
Four fermion



$\mathcal{O}^{(3)}_{\varphi Q} \;:\; i(\varphi^\dagger \overleftrightarrow{D}^i_\mu \varphi)(\bar{Q}\gamma^\mu \sigma_i Q)$

Wtb vertex

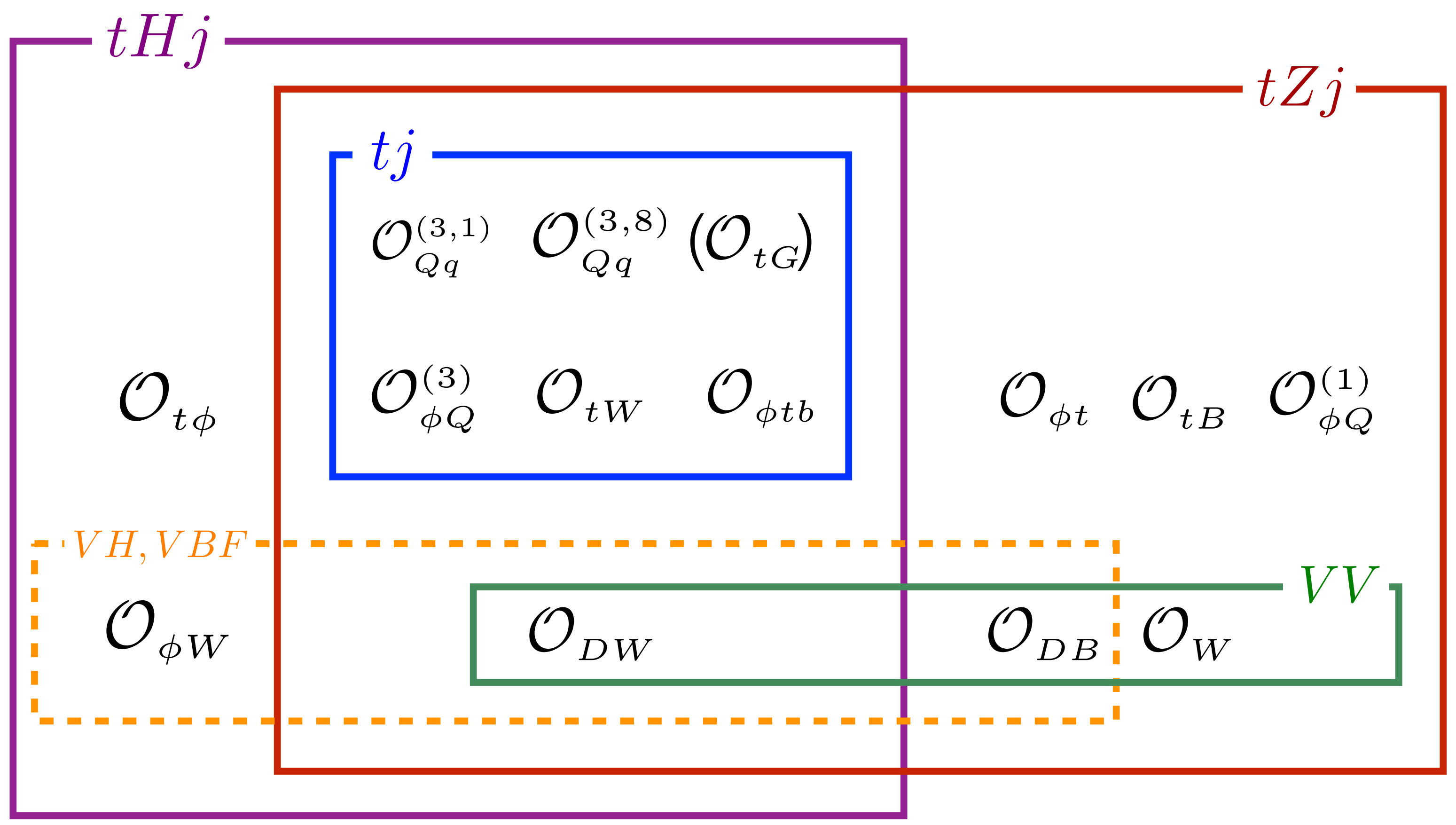
$\mathcal{O}_{\varphi tb} \;:\; i(\tilde{\varphi}\, D_\mu \varphi)(\bar{b}\gamma^\mu t)$



$\mathcal{O}^{(3)}_{\varphi Q} \;:\; i(\varphi^\dagger \overleftrightarrow{D}^i_\mu \varphi)(\bar{Q}\gamma^\mu \sigma_i Q)$

Contact terms

$\mathcal{O}_{tB} \;:\; (\bar{Q}\,\sigma_{\mu\nu}\,t)\,\tilde{\varphi}\,B^{\mu\nu}$



Accessing the bW→tH & bW→tZ sub-amplitudes

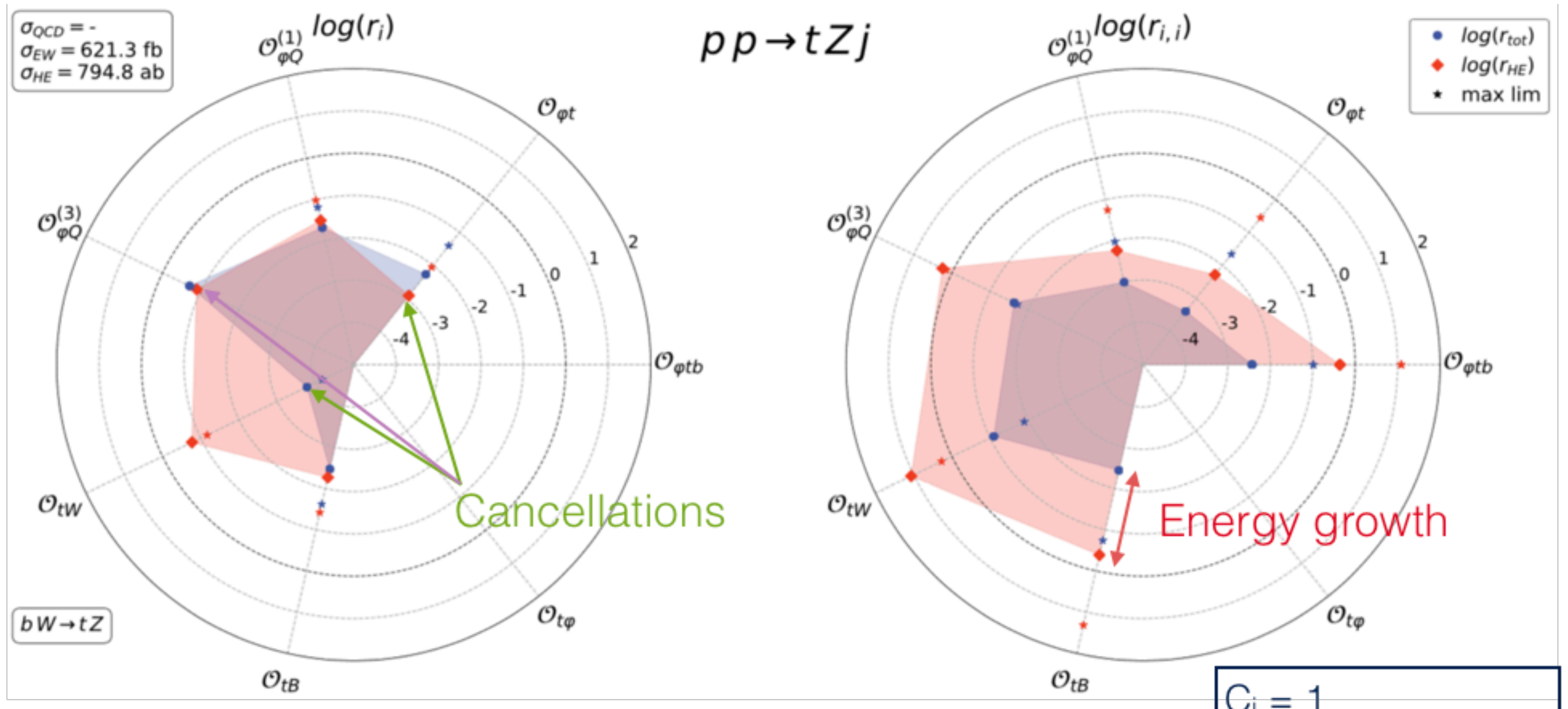
- Rich interplay between EFT operators from different sectors.
- Different energy growth and interference with the SM.
- Four fermion interactions also present.

Top sector

High energy & multiplicity

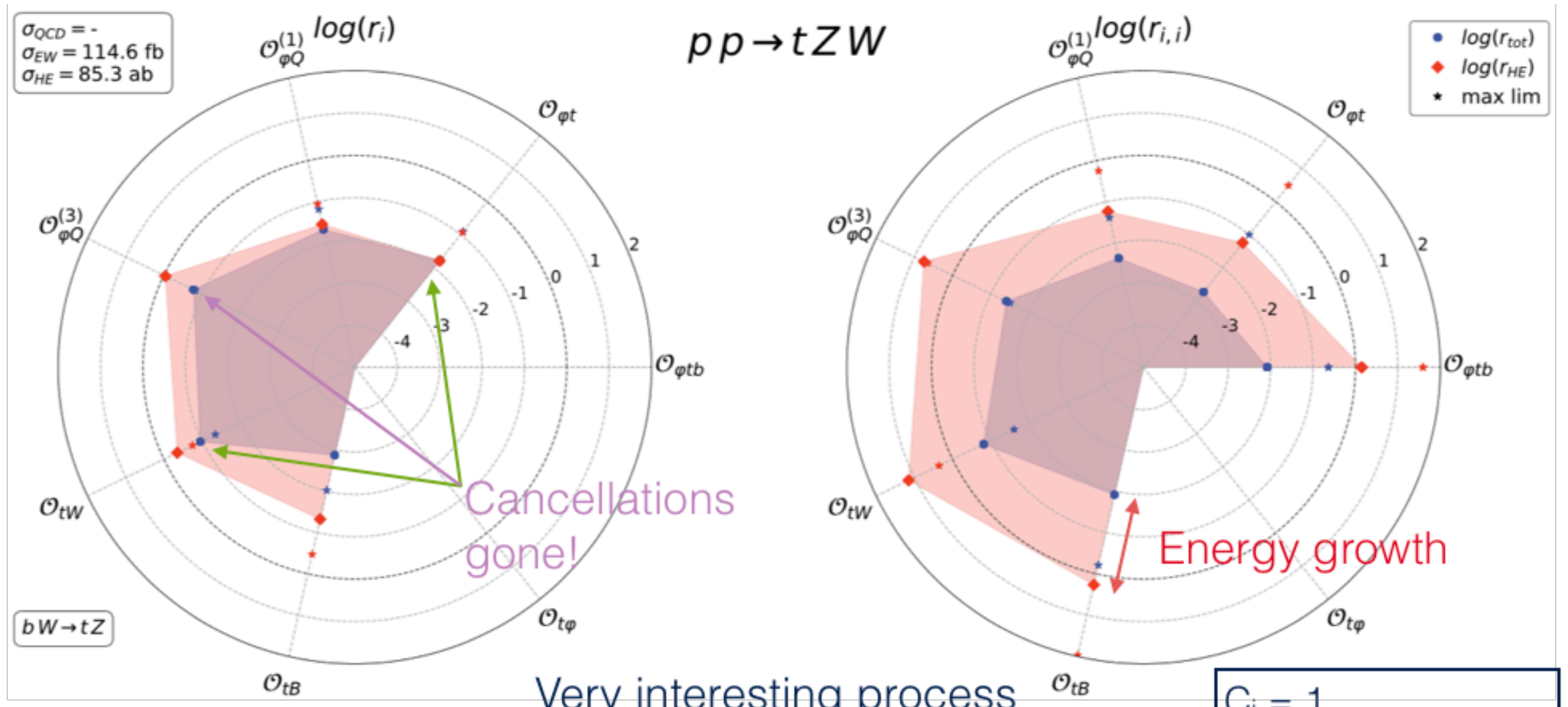
- Due to unitarity violating behaviours amplitudes can be enhanced by s/Λ^2 terms even if the operators themselves don't grow with energy.
- The final scaling of the interference terms can be enhanced or not depending on the SM amplitude behaviour.
- Non-trivial patterns can be arise. Amplitudes $2 \to n$ can lead to maximal growth.

[Henning et al. 2019]
[Mantani, Mimasu, FM, 2019]
[Costantini et al. 2020]
[El Faham, FM, Mimasu, Zaro, Work in progress]



Expected growth from 2→2 absent!

$C_i = 1$
Inclusive
p_T (Z)> 500 GeV



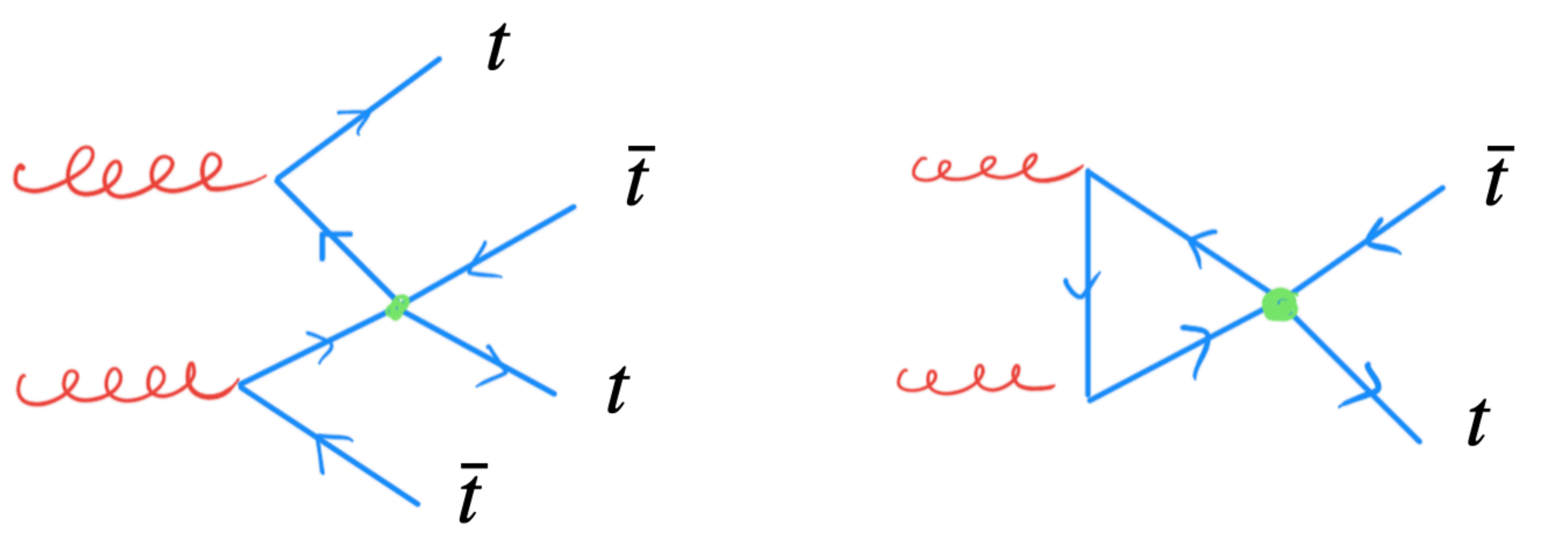
Expected growth is there!

Very interesting process that should be measured at the LHC

$C_i = 1$
Inclusive
p_T (W,Z)> 500 GeV

Top sector

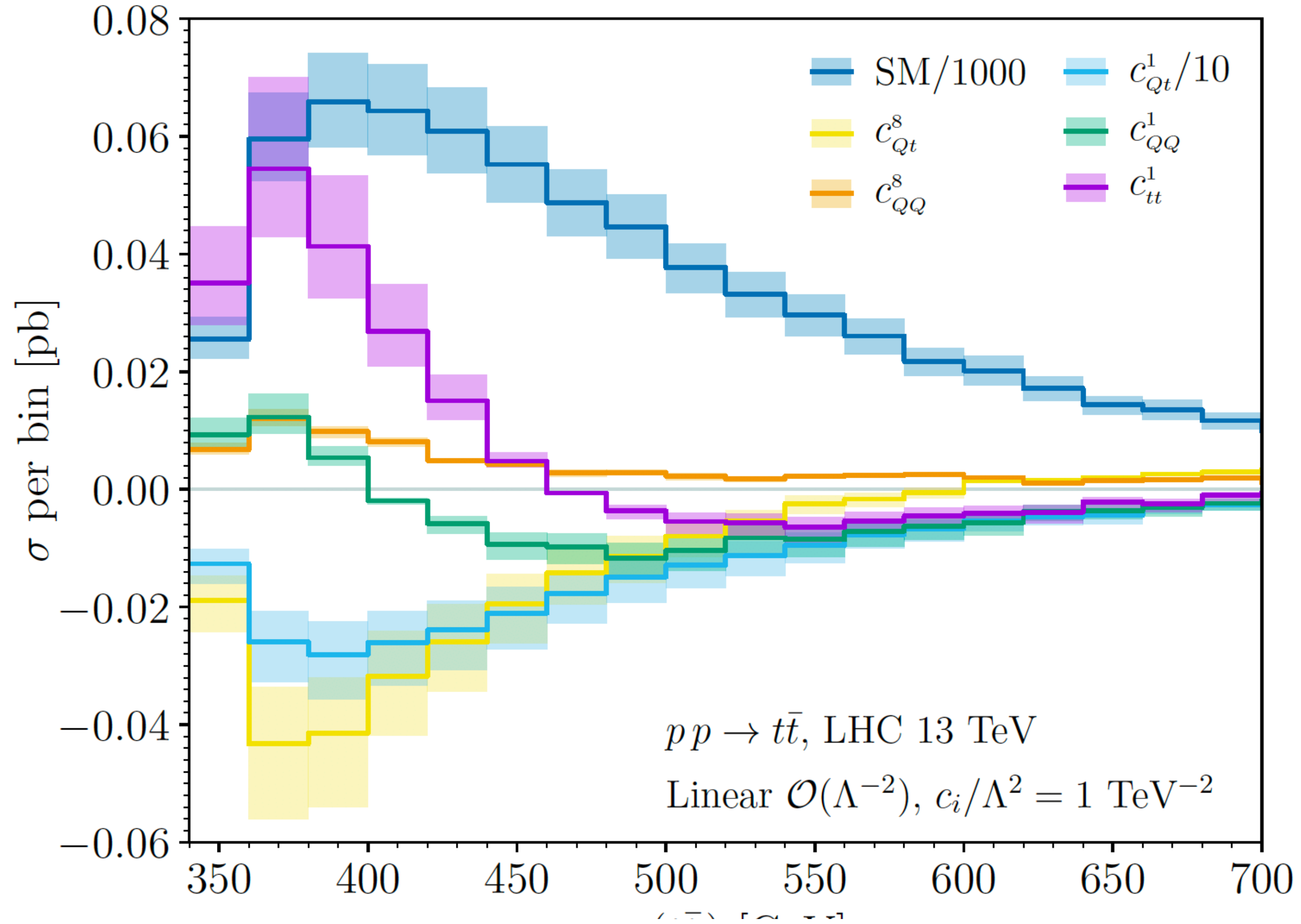
Self-interactions



- Four-top interactions and in particular those involving t_R are quite unconstrained.
- 4-top production observed with almost 3σ significance, 12.6+-5 fb vs 12+-2 fb prediction of the SM.
- SMEFT cross sections for 4-tops evaluated at NLO in QCD for the first time with SMEFT@NLO:

c_i	$\mathcal{O}(\Lambda^{-2})$ LO	$\mathcal{O}(\Lambda^{-2})$ NLO	$\mathcal{O}(\Lambda^{-2})$ K	$\mathcal{O}(\Lambda^{-4})$ LO	$\mathcal{O}(\Lambda^{-4})$ NLO	$\mathcal{O}(\Lambda^{-4})$ K
c^8_{QQ}	$0.126^{+61\%}_{-35\%}$	$0.089^{+8\%}_{-66\%}$	0.71	$0.170^{+53\%}_{-32\%}$	$0.165^{+3\%}_{-26\%}$	0.97
c^8_{Qt}	$0.421^{+63\%}_{-35\%}$	$0.295^{+9\%}_{-69\%}$	0.70	$0.498^{+52\%}_{-32\%}$	$0.333^{+15\%}_{-75\%}$	0.67
c^1_{QQ}	$0.373^{+62\%}_{-35\%}$	$0.20(1)^{+23\%}_{-115\%}$	0.53	$1.513^{+53\%}_{-32\%}$	$1.40^{+3\%}_{-32\%}$	0.93
c^1_{Qt}	$-0.007(1)^{+88\%}_{-84\%}$	$-0.14(3)^{+83\%}_{-40\%}$	21	$2.061^{+53\%}_{-32\%}$	$1.89^{+3\%}_{-33\%}$	0.92
c^1_{tt}	$0.741^{+61\%}_{-35\%}$	$0.42(3)^{+18\%}_{-101\%}$	0.57	$6.08^{+53\%}_{-32\%}$	$5.65^{+3\%}_{-30\%}$	0.93

- Four-top interactions enter $t\bar{t}$ production at one loop.

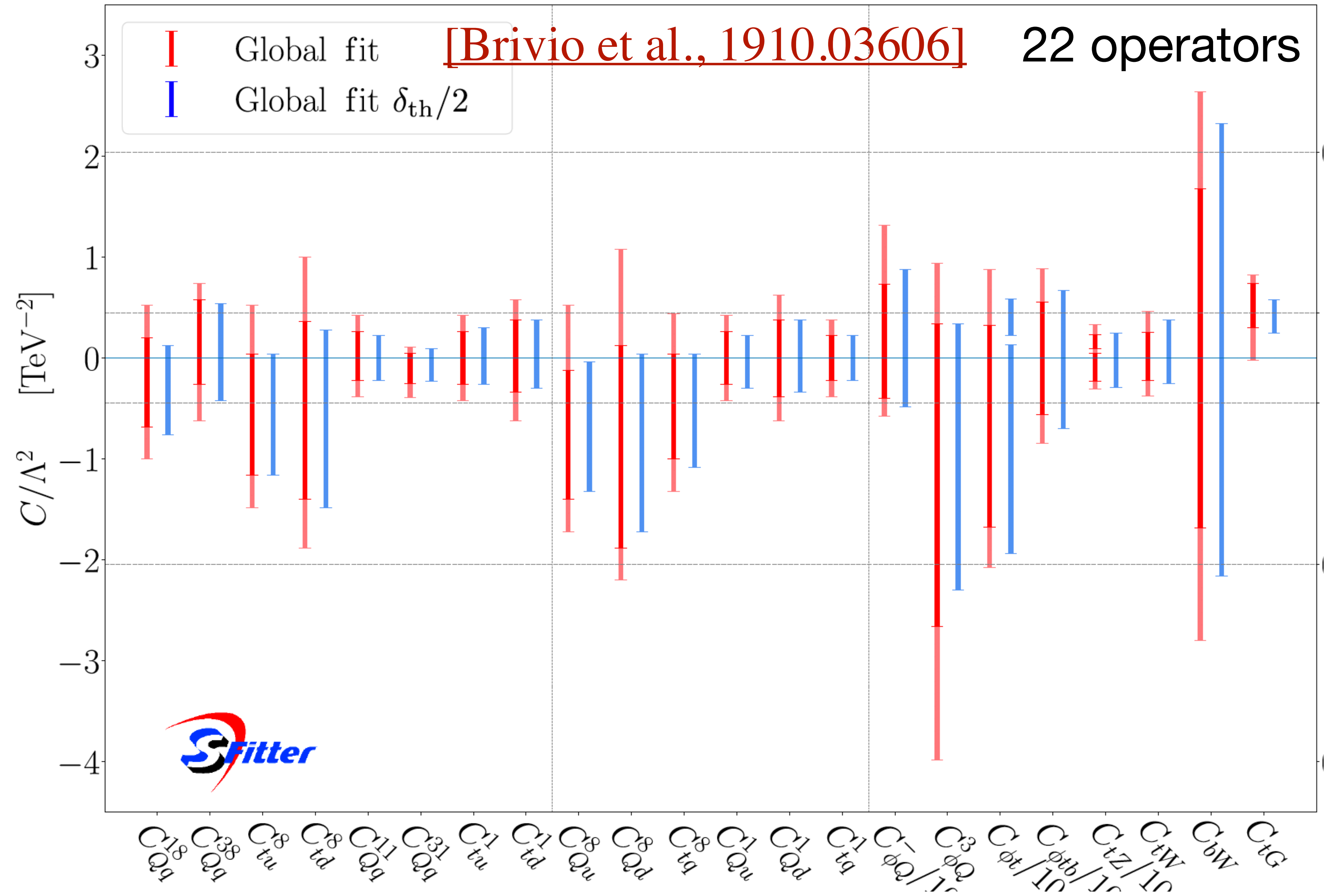


c_i	$\mathcal{O}(\Lambda^{-2})$ LO	$\mathcal{O}(\Lambda^{-2})$ NLO		$\mathcal{O}(\Lambda^{-4})$ LO	$\mathcal{O}(\Lambda^{-4})$ NLO
c^8_{QQ}	$0.0586^{+27\%}_{-25\%}$	$0.125^{+10\%}_{-11\%}$		$0.00628^{+13\%}_{-16\%}$	$0.0133^{+7\%}_{-5\%}$
c^8_{Qt}	$0.0583^{+27\%}_{-25\%}$	$-0.107(6)^{+40\%}_{-33\%}$		$0.00619^{+13\%}_{-16\%}$	$0.0118^{+8\%}_{-5\%}$
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}	×	$0.215^{+23\%}_{-18\%}$		×	×

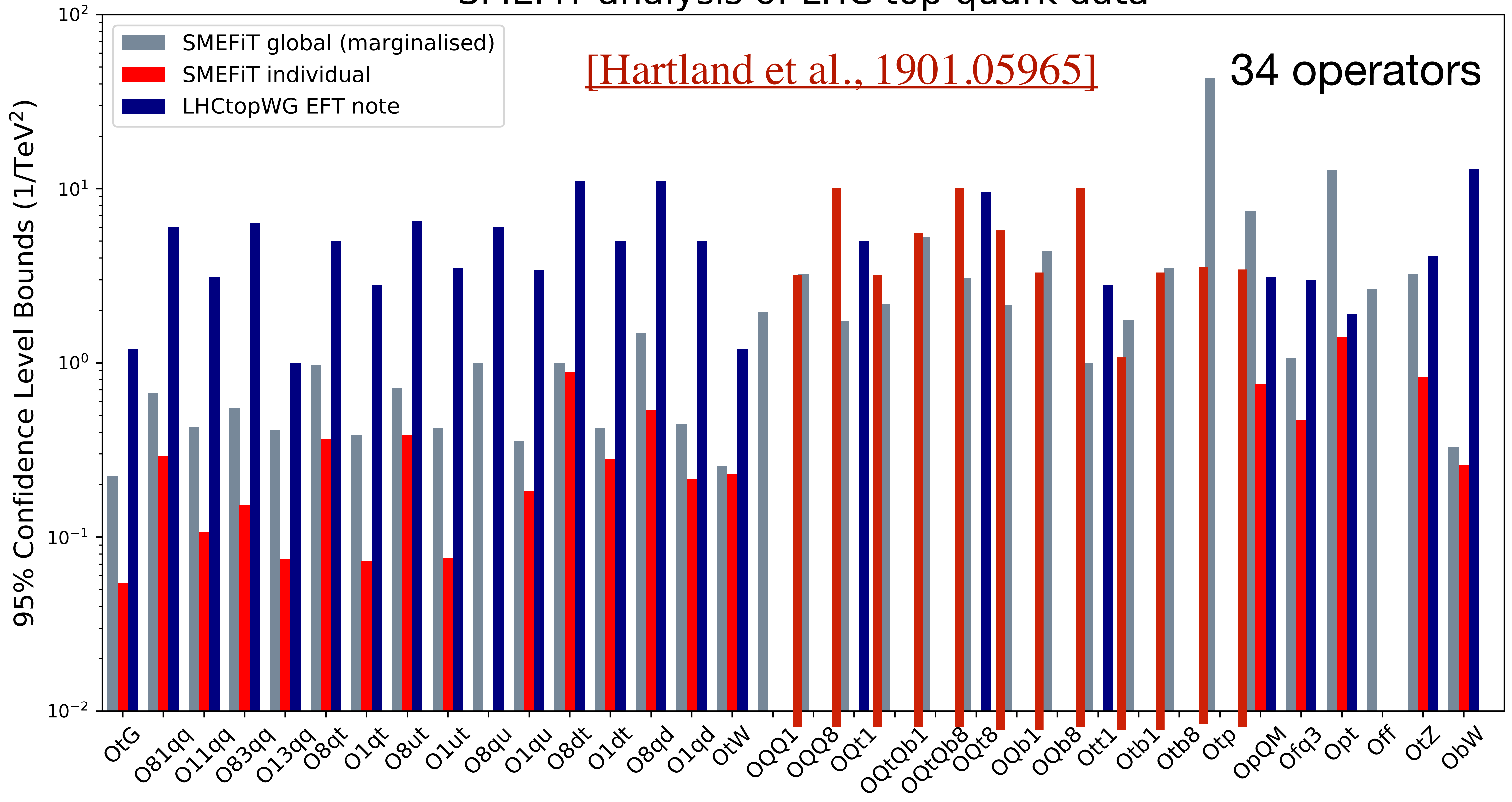
[Degrande et al., SMEFT@NLO, 2008.11743]

Top sector

Global fits



- Already now and without a dedicated experimental effort there is considerable information that can be used to set limits. Fits dedicated to the top sector:
  - TopFitter (Global, LHC+Tevatron, LO) [Buckley et al. 1506.08845]
  - SMEFiT (Global, LHC,NLO) [Hartland et al., 1901.05965]
  - EFTfitter (Partial, LHC+Flavor, LO) [Bissmann et al., 1909.13632]
  - SFitter* (Global, LHC,NLO) [Brivio et al., 1910.03606]
- Several flat directions can be lifted with specific observables, also exploiting NLO effects.
- Combination with EW and Higgs data is needed to constrain all operators entering all processes.



*see the excellent talk by Susanne Westhoff at Top 2020!

Top sector

Global fits: top-philic scenario

- Same flavour symmetries as baseline scenario
- Assumes new physics couples more strongly to 3rd-generation LH doublet and RH up-type singlet (+ bosons)

$$c_{t\varphi}^{[I]}, \quad c_{\varphi Q}^{-}, \quad c_{\varphi Q}^{3}, \quad c_{\varphi t}, \quad c_{tW}^{[I]}, \quad c_{tZ}^{[I]}, \quad c_{tG}^{[I]},$$

$c_{\varphi tb}^{[I]}$ and $c_{bW}^{[I]}$ appear proportional to y_b

$$c_{QQ}^{1}, \quad c_{QQ}^{8}, \quad c_{Qt}^{1}, \quad c_{Qt}^{8}, \quad c_{tt}^{1},$$

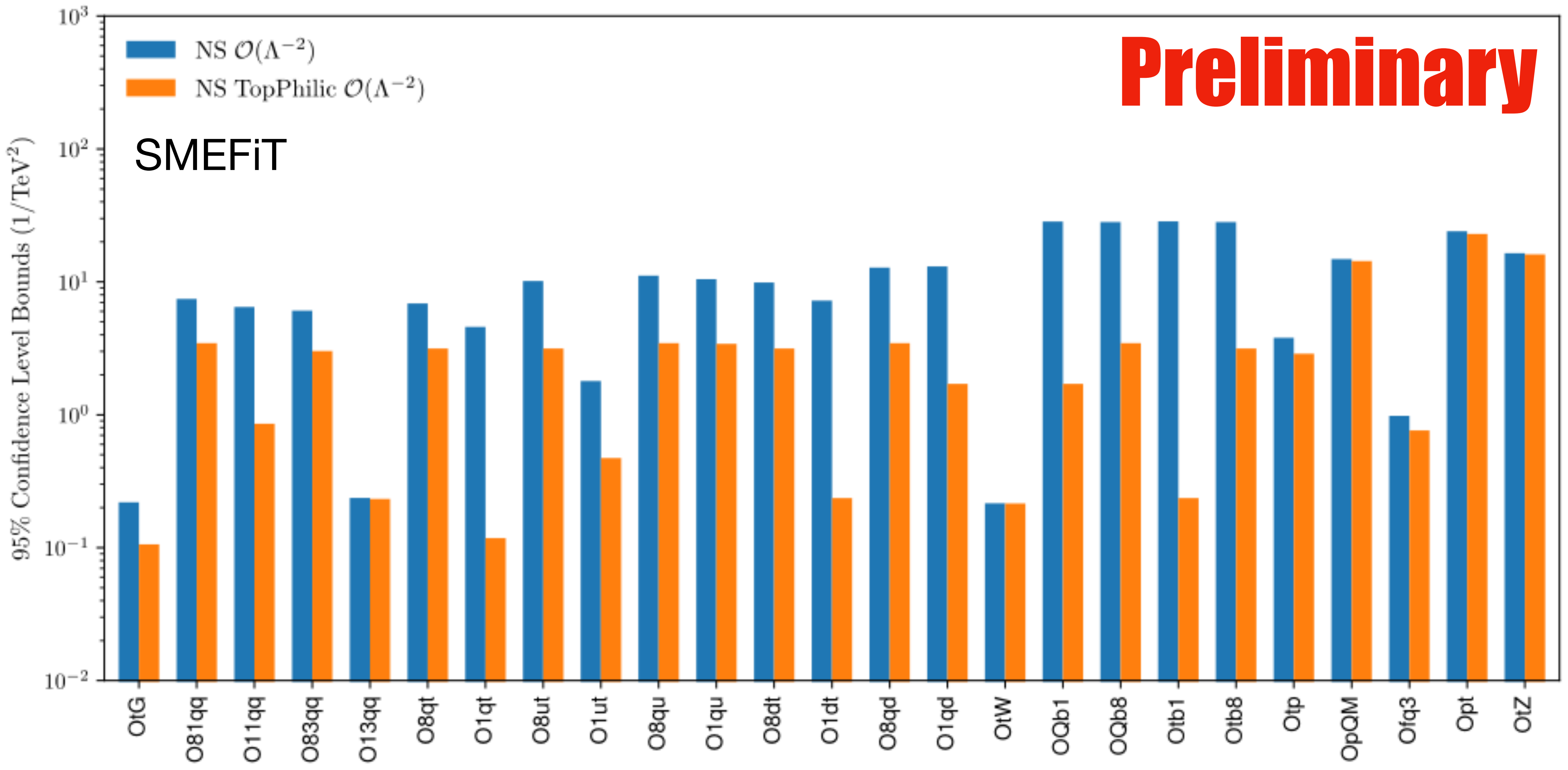
$$c_{QDW} = c_{Qq}^{3,1} = c_{Ql}^{3(\ell)},$$

$$c_{QDB} = 6c_{Qq}^{1,1} = \frac{3}{2}c_{Qu}^{1} = -3c_{Qd}^{1} = -3c_{Qb}^{1} = -2c_{Ql}^{1(\ell)} = -c_{Qe}^{(\ell)},$$

$$c_{tDB} = 6c_{tq}^{1} = \frac{3}{2}c_{tu}^{1} = -3c_{td}^{1} = -3c_{tb}^{1} = -2c_{tl}^{(\ell)} = -c_{te}^{(\ell)},$$

$$c_{QDG} = c_{Qq}^{1,8} = c_{Qu}^{8} = c_{Qd}^{8} = c_{Qb}^{8},$$

$$c_{tDG} = c_{tq}^{8} = c_{tu}^{8} = c_{td}^{8} = c_{tb}^{8}.$$



Reducing the number of dofs leads to an improvement of the bounds as could be expected. The pattern, however is not always trivial.

- 34 parameter basis reduced to 19 free parameters

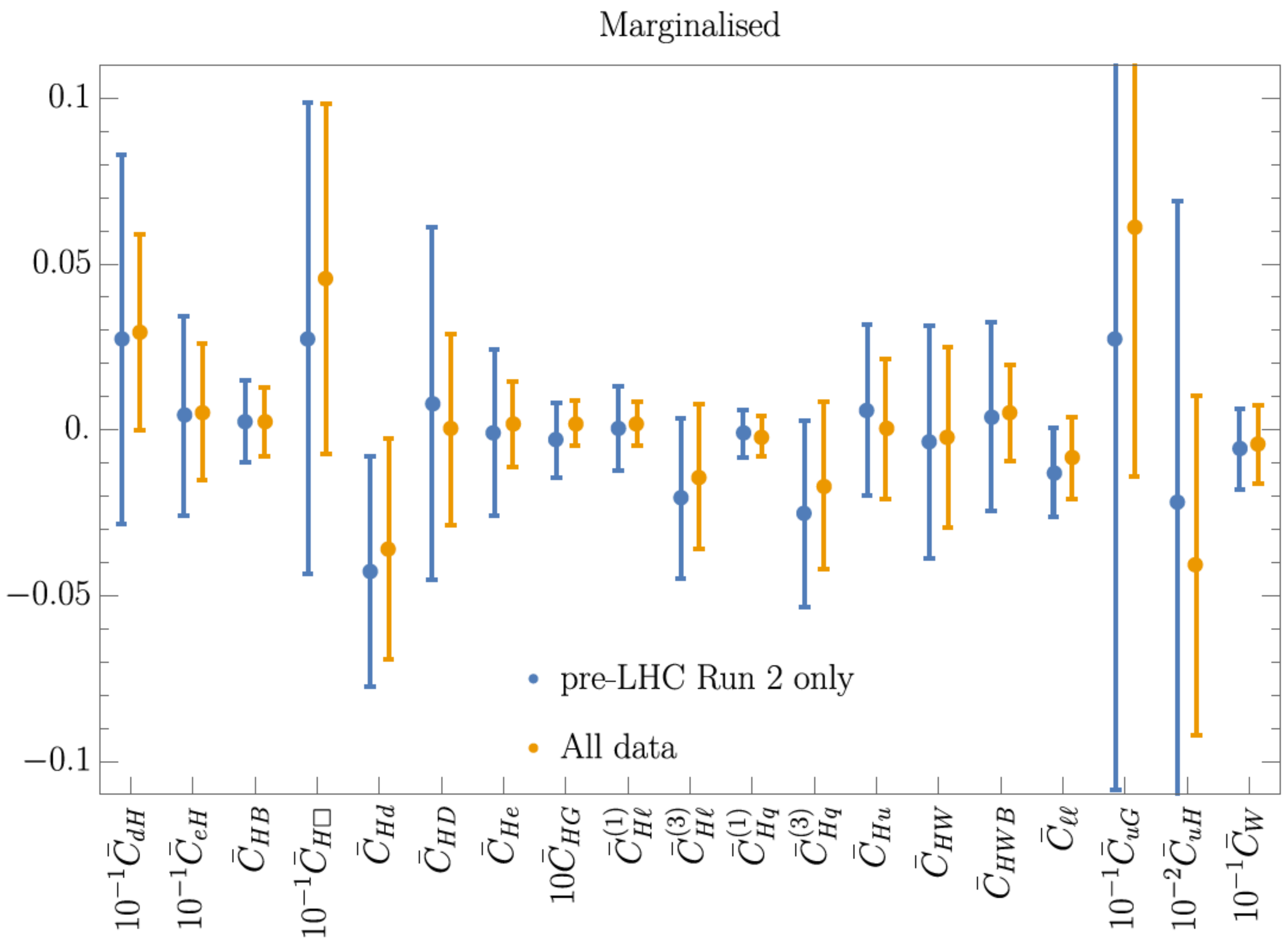
EW+Higgs sector

Global fits

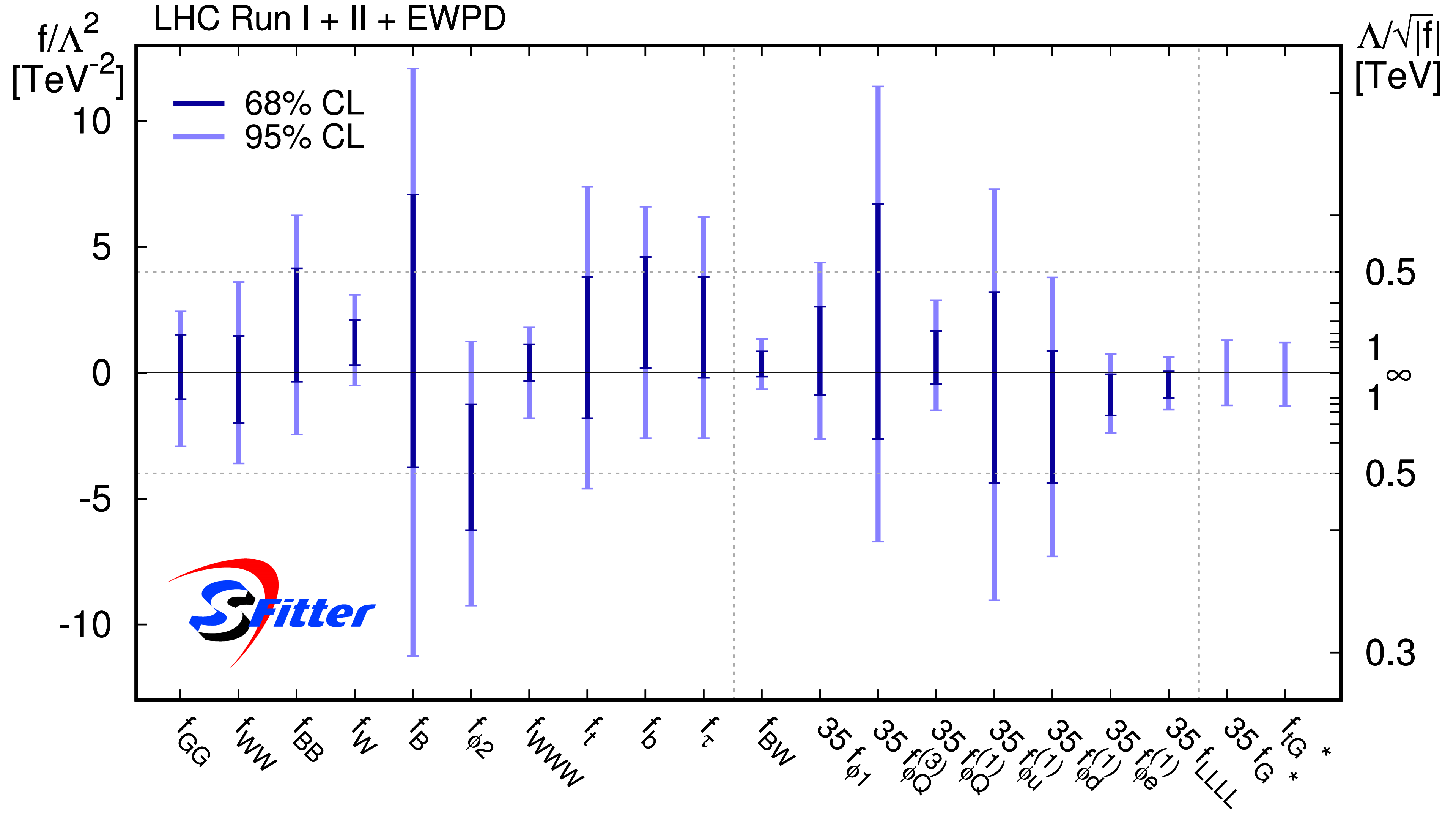
- Already now and without a dedicated experimental effort there is considerable information that can be used to set limits:
  - Ellis et al. [Ellis, Murphy, Sanz, You 2018]
  - Almeida et al. [Almeida, Alves, Rosa-Agostinho, Eboli, Gonzalez-Garcia, 2018]
  - SFitter [Biekötter, Corbett, Plehn, 2018]
  - HEPfit [de Blas, et al. 20XX]

- 18 operators, linear and quadratic fits, Higgs at LHC, WW at LEP (and LHC), EWPO (8 constraints/10 ops)

- Top not included. Not special in this scenario.



[Ellis, Murphy, Sanz, You '18]

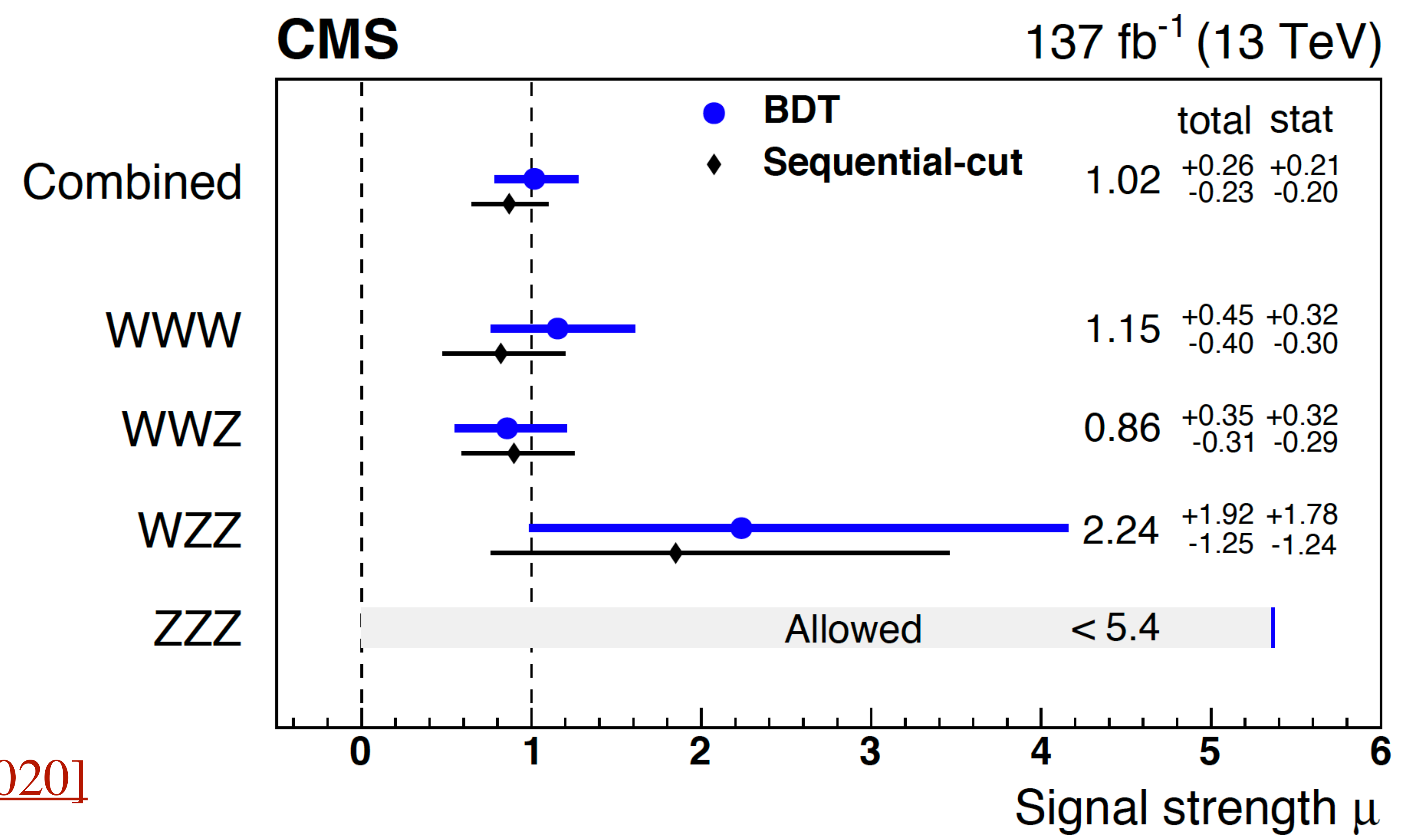


[Biekötter, Corbett, Plehn '18]

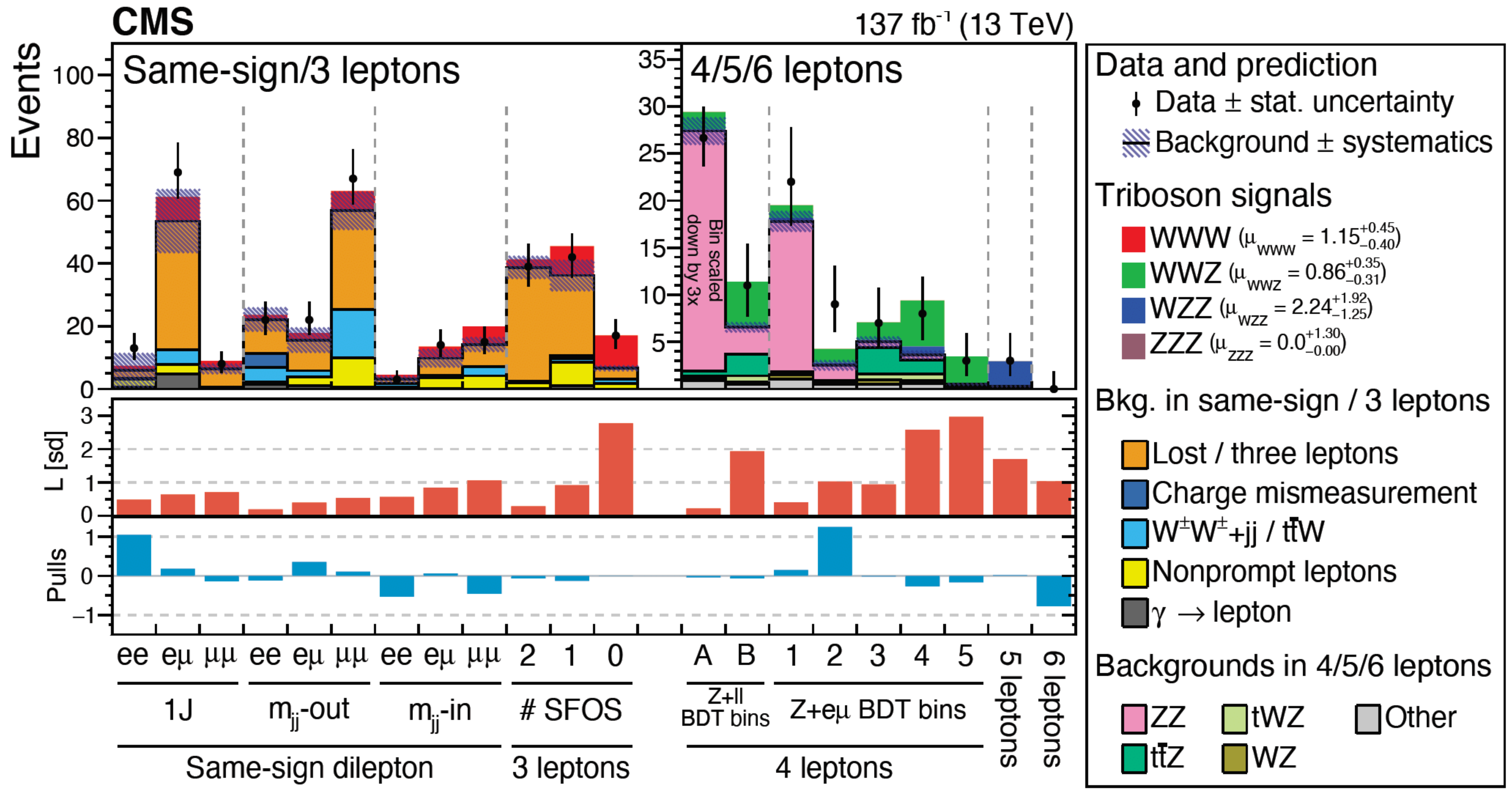
EW+Higgs sector

VVV measurement

- VVV observed by CMS in the multi-lepton final state by combining various channels.



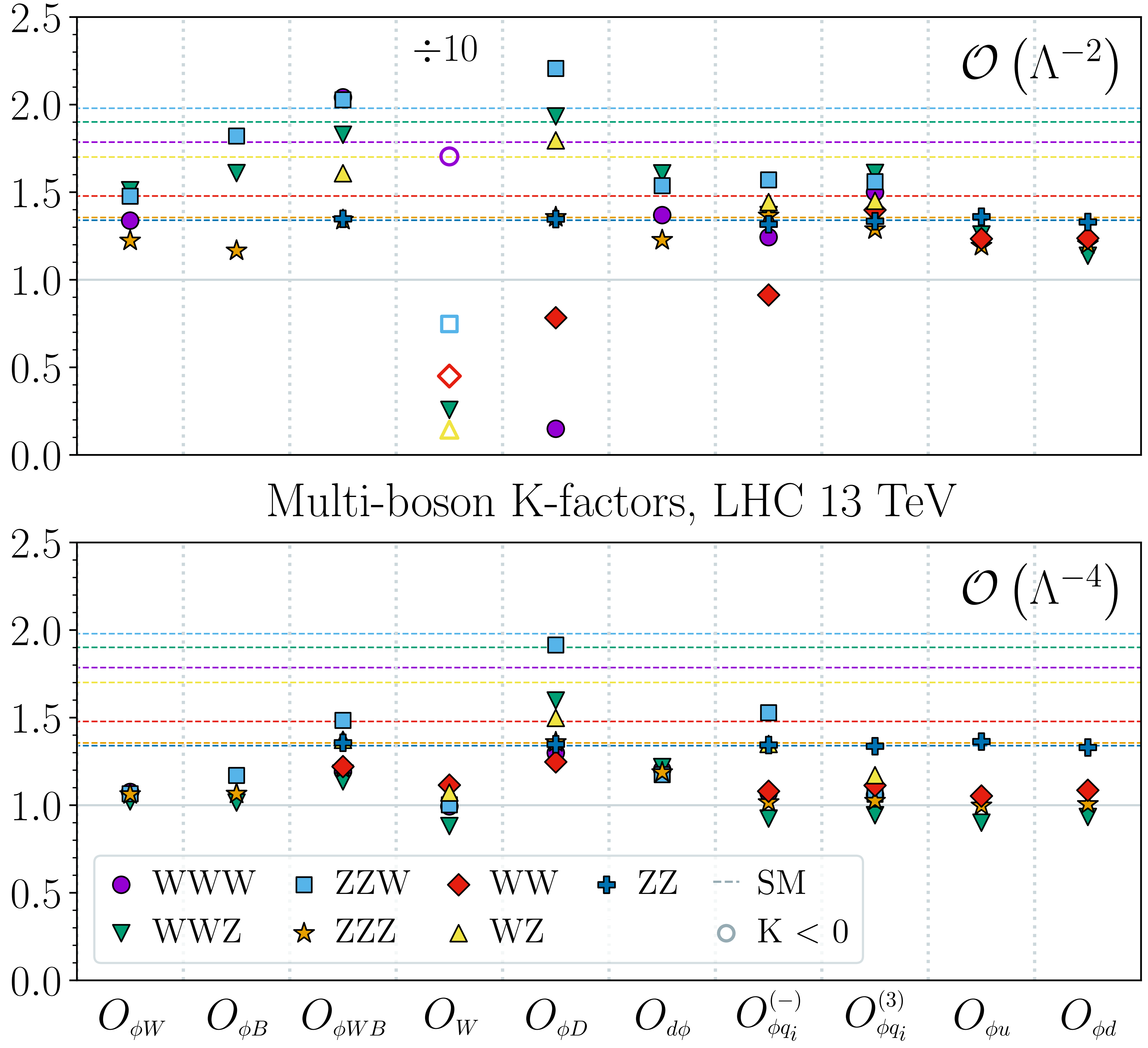
[CMS, 2020]



EW+Higgs sector

VVV measurement

- VVV observed by CMS in the multi-lepton final state by combining various channels.
- VVV known at NLO in QCD in the SM.
- Now prediction at NLO QCD in the SMEFT for VVV production at the LHC are available.
- K-factors show a non-trivial behaviour.
- An interesting outcome is the large K-factor of O_W opening the possibility of bounding it here, instead of by using differential distributions in WW. Work is ongoing, preliminary results promising.



[Degrande et al., SMEFT@NLO, 2008.11743]

SMEFT

Global fits: Top + Higgs

Dataset	$\sqrt{s}$, $\mathcal{L}$	Info	Observables	$N_{\rm dat}$	Ref
ATLAS_tt_8TeV_ljets	**8 TeV, 20.3 fb^{-1}**	lepton+jets	$d\sigma/d\|y_t\|$, $d\sigma/dp_t^T$, $d\sigma/dm_{t\bar{t}}$, $d\sigma/d\|y_{t\bar{t}}\|$	5, 8, 7, 5	[32]
CMS_tt_8TeV_ljets	**8 TeV, 20.3 fb^{-1}**	lepton+jets	$d\sigma/dy_t$, $d\sigma/dp_t^T$, $d\sigma/dm_{t\bar{t}}$, $d\sigma/dy_{t\bar{t}}$	10, 8, 7, 10	[33]
CMS_tt2D_8TeV_dilep	**8 TeV, 20.3 fb^{-1}**	dileptons	$d^2\sigma/dy_t dp_t^T$, $d^2\sigma/dy_t dm_{t\bar{t}}$, $d^2\sigma/dp_{t\bar{t}}^T dm_{t\bar{t}}$, $d^2\sigma/dy_{t\bar{t}} dm_{t\bar{t}}$	16, 16, 16, 16	[34]
CMS_tt_13TeV_ljets	**13 TeV, 2.3 fb^{-1}**	lepton+jets	$d\sigma/d\|y_t\|$, $d\sigma/dp_t^T$, $d\sigma/dm_{t\bar{t}}$, $d\sigma/d\|y_{t\bar{t}}\|$	7, 9, 8, 6	[35]
CMS_tt_13TeV_ljets2	**13 TeV, 35.8 fb^{-1}**	lepton+jets	$d\sigma/d\|y_t\|$, $d\sigma/dp_t^T$, $d\sigma/dm_{t\bar{t}}$, $d\sigma/d\|y_{t\bar{t}}\|$	11, 12, 10, 10	[36]
CMS_tt_13TeV_dilep	**13 TeV, 2.1 fb^{-1}**	dileptons	$d\sigma/dy_t$, $d\sigma/dp_t^T$, $d\sigma/dm_{t\bar{t}}$, $d\sigma/dy_{t\bar{t}}$	8, 6, 6, 8	[37]
ATLAS_WhelF_8TeV	**8 TeV, 20.3 fb^{-1}**	W hel. fract	F_0, F_L, F_R	3	[38]
CMS_WhelF_8TeV	**8 TeV, 20.3 fb^{-1}**	W hel. fract	F_0, F_L, F_R	3	[39]

Dataset	$\sqrt{s}$, $\mathcal{L}$	Info	Observables	$N_{\rm dat}$	Ref
ATLAS_Vh_hbb_13TeV	**13 TeV, 79.8 fb^{-1}**	Wh , Zh	$d\sigma^{\rm (fid)}/dp_T^W$, $d\sigma^{\rm (fid)}/dp_T^Z$	2, 3	[69]
ATLAS_ggF_13TeV	**13 TeV, 79.8 fb^{-1}**	ggF	$\sigma_{\rm ggF}(p_T^h, N_{\rm jets})$	6	[64]

Dataset	$\sqrt{s}$, $\mathcal{L}$	Info	Observables	$N_{\rm dat}$	Ref
CMS_ttbb_13TeV	**13 TeV, 2.3 fb^{-1}**	total xsec	$\sigma_{\rm tot}(t\bar{t}b\bar{b})$	1	[40]
CMS_ttbb_13TeV_2016 (*)	**13 TeV, 35.9 fb^{-1}**	total xsec	$\sigma_{\rm tot}(t\bar{t}b\bar{b})$	1	[41]
CMS_tttt_13TeV	**13 TeV, 35.9 fb^{-1}**	total xsec	$\sigma_{\rm tot}(t\bar{t}t\bar{t})$	1	[42]
CMS_tttt_13TeV_run2 (*)	**13 TeV, 137 fb^{-1}**	total xsec	$\sigma_{\rm tot}(t\bar{t}t\bar{t})$	1	[43]
CMS_ttZ_8TeV	**8 TeV, 19.5 fb^{-1}**	total xsec	$\sigma_{\rm tot}(t\bar{t}Z)$	1	[44]
CMS_ttZ_13TeV	**13 TeV, 35.9 fb^{-1}**	total xsec	$\sigma_{\rm tot}(t\bar{t}Z)$	1	[45]
CMS_ttZ_ptZ_13TeV (*)	**13 TeV, 77.5 fb^{-1}**	total xsec	$\sigma_{\rm tot}(t\bar{t}Z)$, $d\sigma(t\bar{t}Z)/dp_T^Z$	1, 4	[45]
ATLAS_ttZ_8TeV	**8 TeV, 20.3 fb^{-1}**	total xsec	$\sigma_{\rm tot}(t\bar{t}Z)$	1	[46]
ATLAS_ttZ_13TeV	**13 TeV, 3.2 fb^{-1}**	total xsec	$\sigma_{\rm tot}(t\bar{t}Z)$	1	[47]
CMS_ttW_8_TeV	**8 TeV, 19.5 fb^{-1}**	total xsec	$\sigma_{\rm tot}(t\bar{t}W)$	1	[44]
CMS_ttW_13TeV	**13 TeV, 35.9 fb^{-1}**	total xsec	$\sigma_{\rm tot}(t\bar{t}W)$	1	[45]
ATLAS_ttW_8TeV	**8 TeV, 20.3 fb^{-1}**	total xsec	$\sigma_{\rm tot}(t\bar{t}W)$	1	[46]
ATLAS_ttW_13TeV	**13 TeV, 3.2 fb^{-1}**	total xsec	$\sigma_{\rm tot}(t\bar{t}W)$	1	[47]

Dataset	$\sqrt{s}$, $\mathcal{L}$	Info	Observables	$N_{\rm dat}$	Ref
ATLAS_CMS_SSinc_RunI	**7+8 TeV, 20 fb^{-1}**	Incl. μ_i^f	ggF, VBF, Vh, $t\bar{t}h$; $h\to\gamma\gamma, VV, \tau\tau, b\bar{b}$	20	[62]
ATLAS_SSinc_RunI	**8 TeV, 20 fb^{-1}**	Incl. μ^f	$h\to Z\gamma, \mu\mu$	2	[63]
ATLAS_SSinc_RunII	**13 TeV, 80 fb^{-1}**	Incl. μ_i^f	ggF, VBF, Vh, $t\bar{t}h$; $h\to\gamma\gamma, WW, ZZ, \tau\tau, b\bar{b}$	16	[64]
CMS_SSinc_RunII	**13 TeV, 36.9 fb^{-1}**	Incl. μ_i^f	ggF, VBF, Wh, Zh $t\bar{t}h$; $h\to\gamma\gamma, WW, ZZ, \tau\tau, b\bar{b}$	24	[65]

Dataset	$\sqrt{s}$, $\mathcal{L}$	Info	Observables	$N_{\rm dat}$	Ref
CMS_t_tch_8TeV_inc	**8 TeV, 19.7 fb^{-1}**	t-channel	$\sigma_{\rm tot}(t), \sigma_{\rm tot}(\bar{t})$ (R_t)	2 (1)	[48]
CMS_t_sch_8TeV	**8 TeV, 19.7 fb^{-1}**	s-channel	$\sigma_{\rm tot}(t+\bar{t})$	1	[49]
ATLAS_t_sch_8TeV	**8 TeV**	s-channel	$\sigma_{\rm tot}(t+\bar{t})$	1	[50]
ATLAS_t_tch_8TeV	**8 TeV**	t-channel	$d\sigma(tq)/dp_T^t, d\sigma(\bar{t}q)/dp_T^{\bar{t}}$, $d\sigma(tq)/dy_t, d\sigma(\bar{t}q)/dy_t$	5, 4, 4, 4	[51]
ATLAS_t_tch_13TeV	**13 TeV**	t-channel	$\sigma_{\rm tot}(t), \sigma_{\rm tot}(\bar{t})$ (R_t)	2 (1)	[52]
CMS_t_tch_13TeV_inc	**13 TeV**	t-channel	$\sigma_{\rm tot}(t+\bar{t})$ (R_t)	1 (1)	[53]
CMS_t_tch_8TeV_dif	**8 TeV**	t-channel	$d\sigma/dp_T^{(t+\bar{t})}$, $d\sigma/d\|y^{(t+\bar{t})}\|$	6, 6	[54]
CMS_t_tch_13TeV_dif	**13 TeV**	t-channel	$d\sigma/dp_T^{(t+\bar{t})}$, $d\sigma/d\|y^{(t+\bar{t})}\|$	4, 4	[55]
ATLAS_tW_inc_8TeV	**8 TeV**	inclusive	$\sigma_{\rm tot}(tW)$	1	[56]
CMS_tW_inc_8TeV	**8 TeV**	inclusive	$\sigma_{\rm tot}(tW)$	1	[57]
ATLAS_tW_inc_13TeV	**13 TeV**	inclusive	$\sigma_{\rm tot}(tW)$	1	[58]
CMS_tW_inc_13TeV	**13 TeV**	inclusive	$\sigma_{\rm tot}(tW)$	1	[59]
CMS_tZ_inc_13TeV	**13 TeV**	inclusive	$\sigma_{\rm fid}(Wbl^+l^-q)$	1	[60]
ATLAS_tZ_inc_13TeV	**13 TeV**	inclusive	$\sigma_{\rm tot}(tZq)$	1	[61]

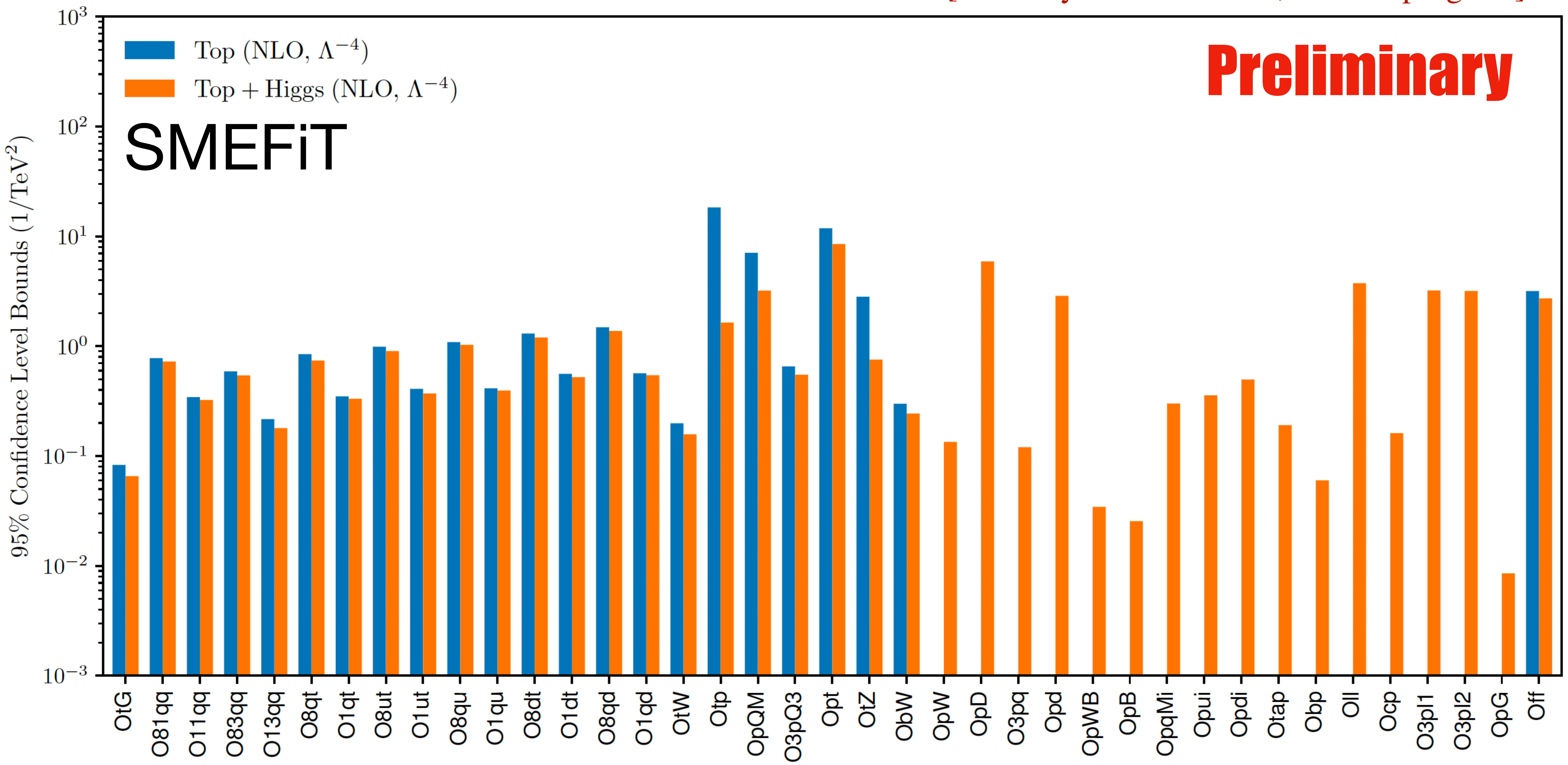
Dataset	$\sqrt{s}$, $\mathcal{L}$	Info	Observables	$N_{\rm dat}$	Ref
LEP2_WW_diff	[182, 296] GeV	LEP-2 comb	$d^2\sigma(WW)/dE_{\rm cm}d\cos\theta_{W^-}$	40	[70]
ATLAS_WZ_13TeV_2016	**13 TeV, 36.1 fb^{-1}**	fully leptonic	$d\sigma^{\rm (fid)}/dp_T^Z$, $d\sigma^{\rm (fid)}/dp_T^W$, $d\sigma^{\rm (fid)}/dm_T^{WZ}$, $d\sigma^{\rm (fid)}/d\phi(WZ)$, $d\sigma^{\rm (fid)}/dm_T^{\nu}$, $d\sigma^{\rm (fid)}/dm_{jj}$	7,6, 6,6, 4,5	[71]
ATLAS_WW_13TeV_2016	**13 TeV, 36.1 fb^{-1}**	fully leptonic	$d\sigma^{\rm (fid)}/dp_T^{\rm lead\ 1}$, $d\sigma^{\rm (fid)}/dm_{e\mu}$, $d\sigma^{\rm (fid)}/dm_T^{e\mu}$, $d\sigma^{\rm (fid)}/d\|y_{e\mu}\|$	14,13, 15,11	[71]
CMS_WW_13TeV_2016	**13 TeV, 36.1 fb^{-1}**	fully leptonic	$d\sigma^{\rm (fid)}/dp_T^Z$, $d\sigma^{\rm (fid)}/dm_{WZ}$, $d\sigma^{\rm (fid)}/dp_T^W$, $d\sigma^{\rm (fid)}/dp_T^{\rm jet,lead}$	11,5, 11,9	[72]

SMEFT

Global fits: Top + Higgs

The top sector is connected to both the EW and Higgs sectors and therefore a really global approach is needed. A total of 16 additional operators are needed in addition to the top ones. Robustness and convergence of the fitting procedure is being explored (starting with a smaller number of operators, i.e. no 4Q ops).

[Courtesy of Ethier et al., work in progress]



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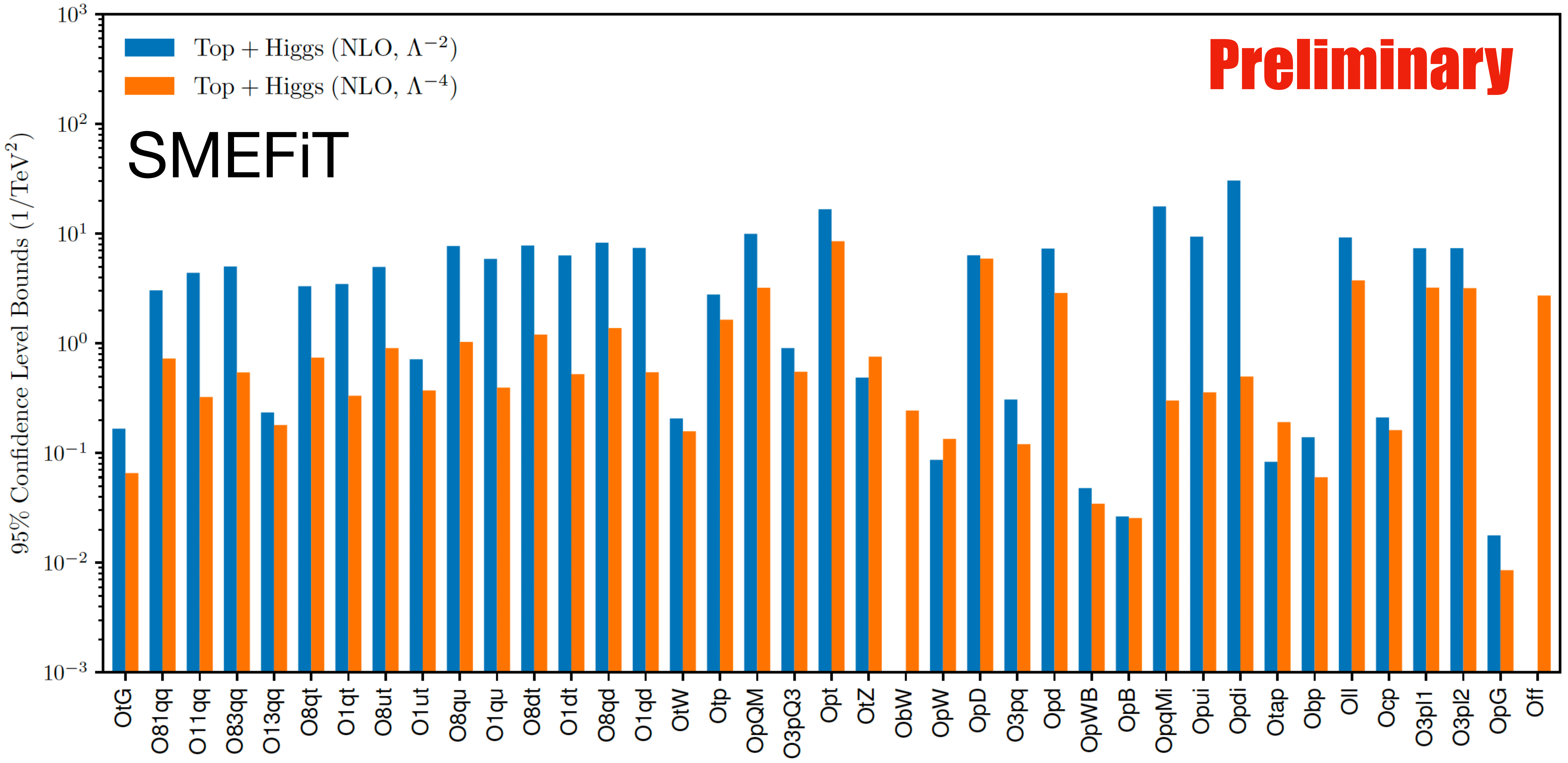
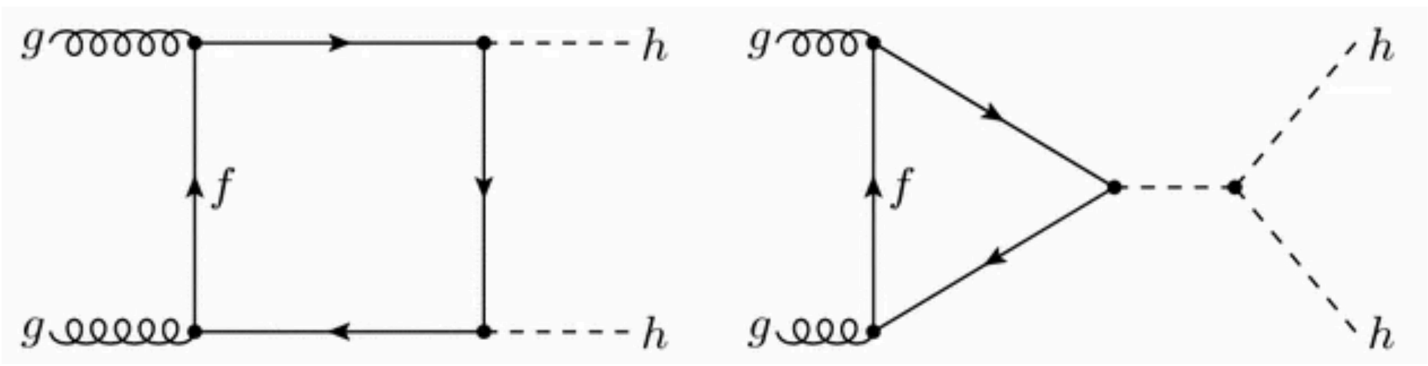


Global fits: Application

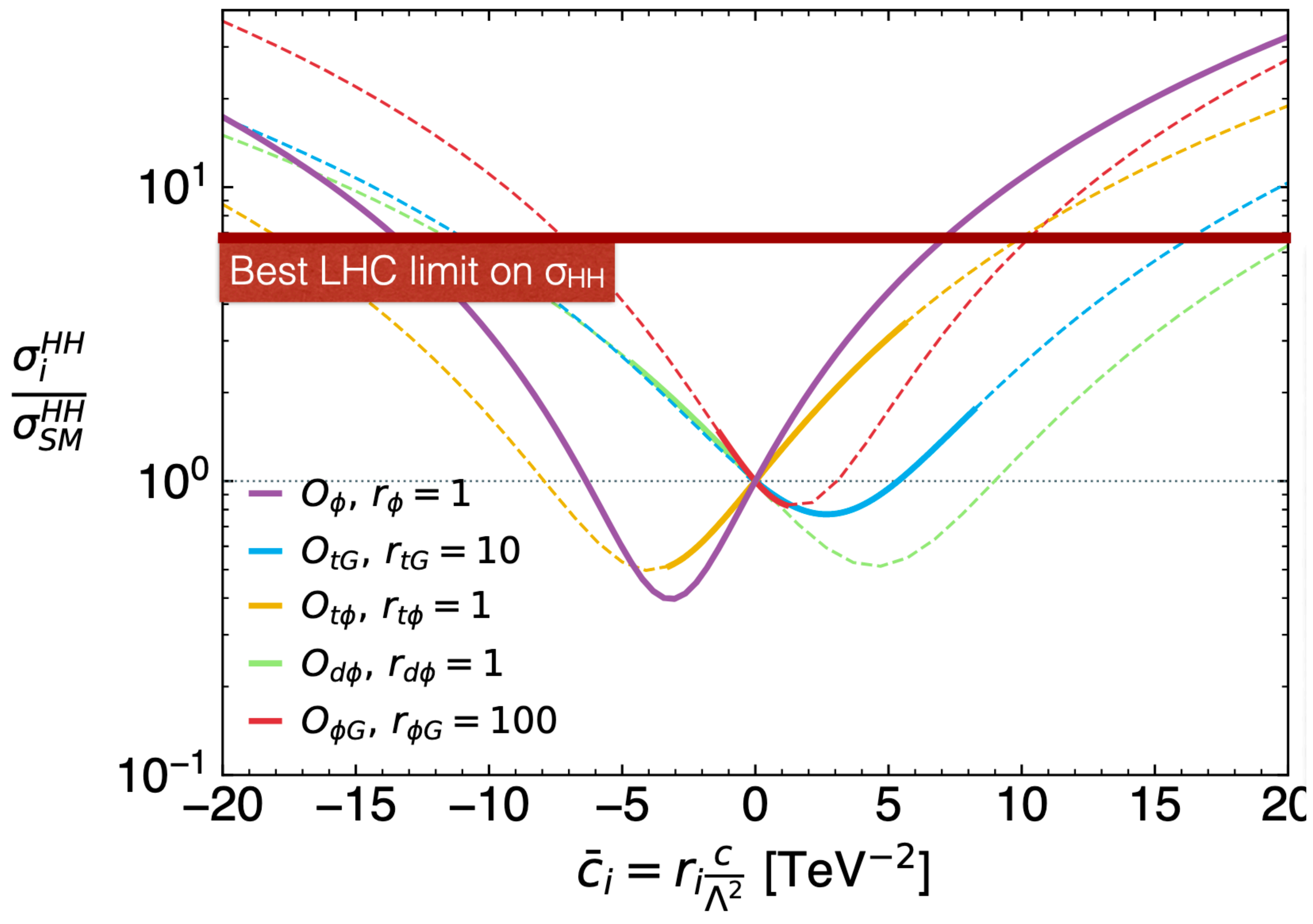
Higgs self-couplings



$\mathcal{O}_{t\varphi}$	ctp	$\left(\varphi^\dagger\varphi - \frac{v^2}{2}\right)\bar{Q}\,t\,\tilde{\varphi} + \text{h.c.}$
$\mathcal{O}_{tG}$	ctG	$ig_S\,(\bar{Q}\tau^{\mu\nu}\,T_A\,t)\,\tilde{\varphi}\,G^A_{\mu\nu} + \text{h.c.}$
$\mathcal{O}_{\varphi d}$	cdp	$\partial_\mu(\varphi^\dagger\varphi)\partial^\mu(\varphi^\dagger\varphi)$
$\mathcal{O}_{\varphi G}$	cpG	$\left(\varphi^\dagger\varphi - \frac{v^2}{2}\right)G^{\mu\nu}_A\,G^A_{\mu\nu}$
$\mathcal{O}_{\varphi}$	cp	$\left(\varphi^\dagger\varphi - \frac{v^2}{2}\right)^3$

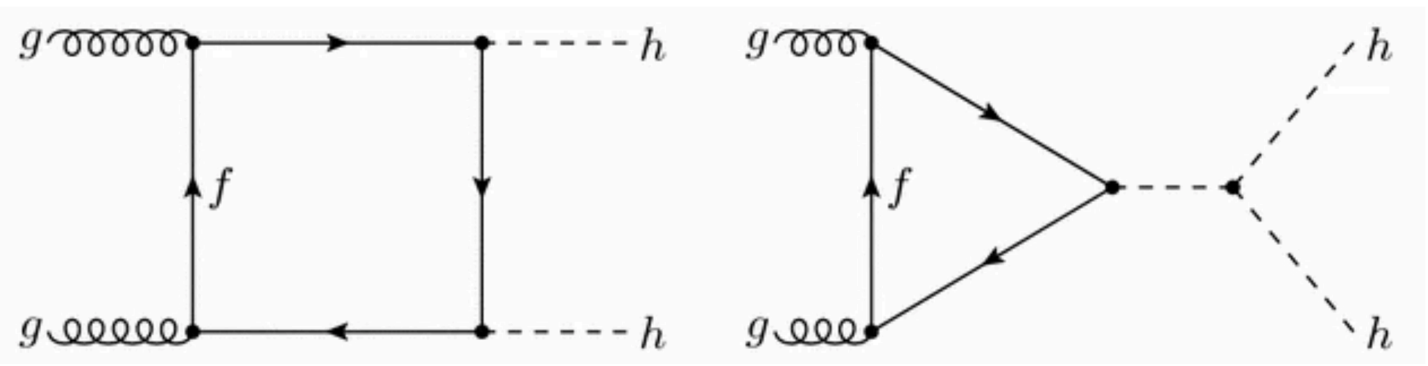
- Five operators modify gg to HH and HHH cross sections at the hadron colliders.
- Determination of self-coupling will depend SM Theory uncertainties but also how well the other EFT couplings will be constrained.
- Allowed range from the global fit are shown as continuous lines. Currently no limitation, as bounds on c_φ are very weak. We also see that most of contributions are far from the the linear EFT regime.

[Courtesy of Mimasu and Vryonidou]

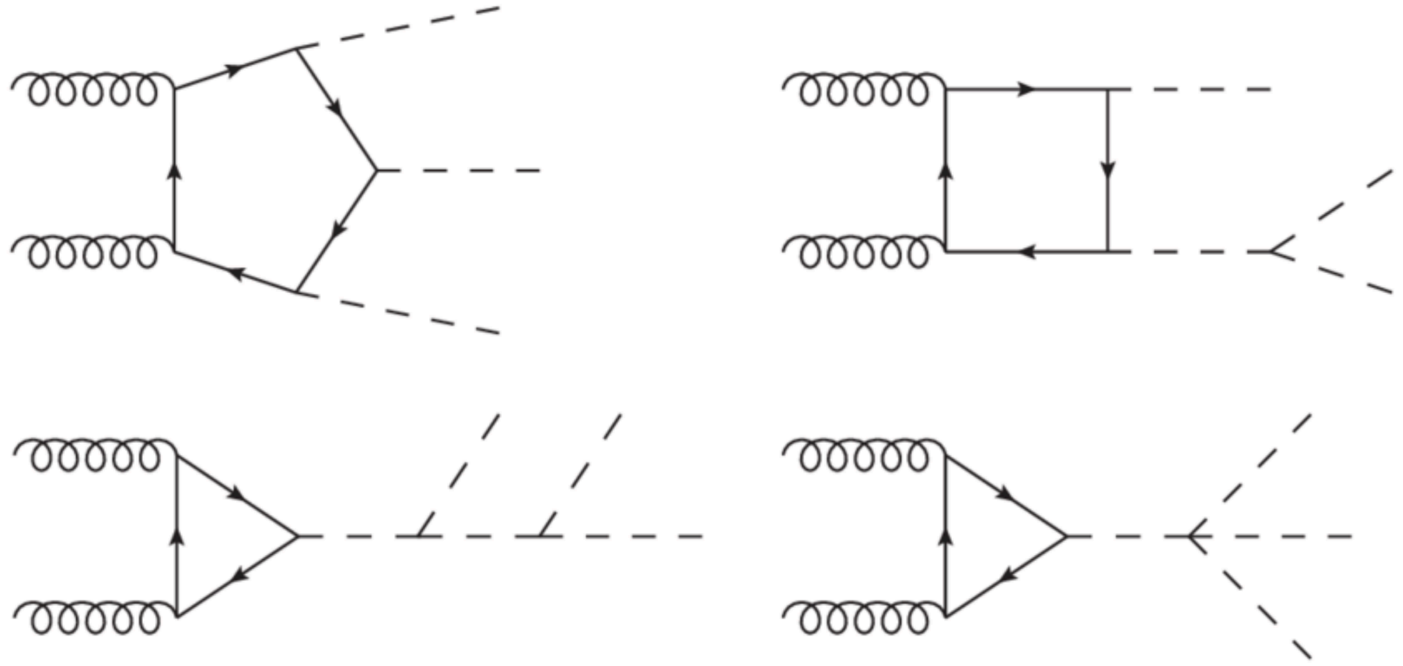


Global fits: Application

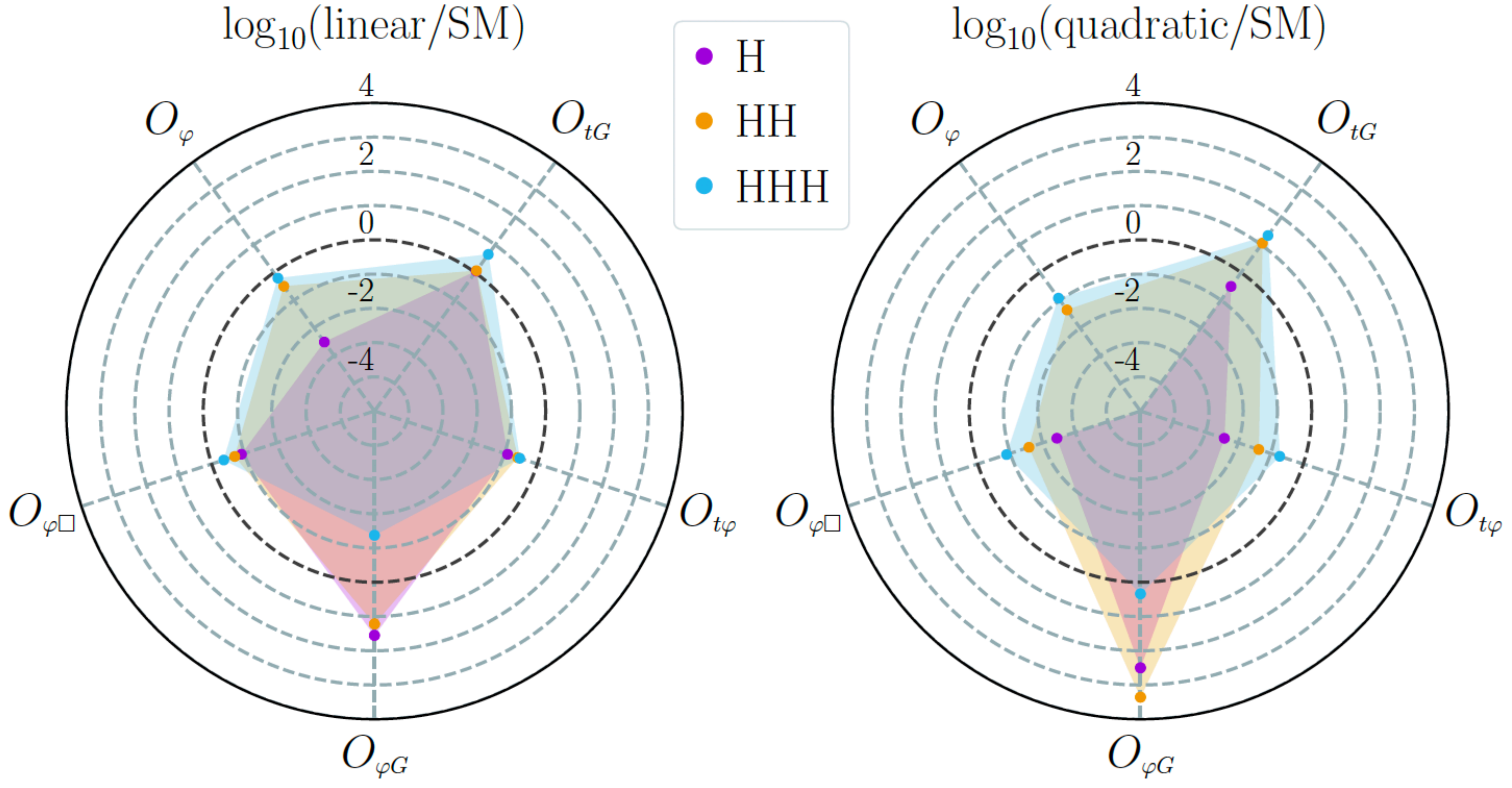
Higgs self-couplings



$\mathcal{O}_{t\varphi}$	ctp	$\left(\varphi^\dagger\varphi - \frac{v^2}{2}\right)\bar{Q}\,t\,\tilde{\varphi} + \text{h.c.}$
$\mathcal{O}_{tG}$	ctG	$ig_s\,(\bar{Q}\tau^{\mu\nu}\,T_A\,t)\,\tilde{\varphi}\,G^A_{\mu\nu} + \text{h.c.}$
$\mathcal{O}_{\varphi d}$	cdp	$\partial_\mu(\varphi^\dagger\varphi)\partial^\mu(\varphi^\dagger\varphi)$
$\mathcal{O}_{\varphi G}$	cpG	$\left(\varphi^\dagger\varphi - \frac{v^2}{2}\right)G^{\mu\nu}_A\,G^A_{\mu\nu}$
$\mathcal{O}_{\varphi}$	cp	$\left(\varphi^\dagger\varphi - \frac{v^2}{2}\right)^3$



- First computation of $gg \to HHH$ within the SMEFT [Degrande et al., SMEFT@NLO, 2008.11743] allows to compare sensitivities with $gg \to HH$ and $gg \to H$ (trilinear at two loops).
- At pp@100 TeV, increased sensitivity of HHH final state partially compensate its limited statistical power.

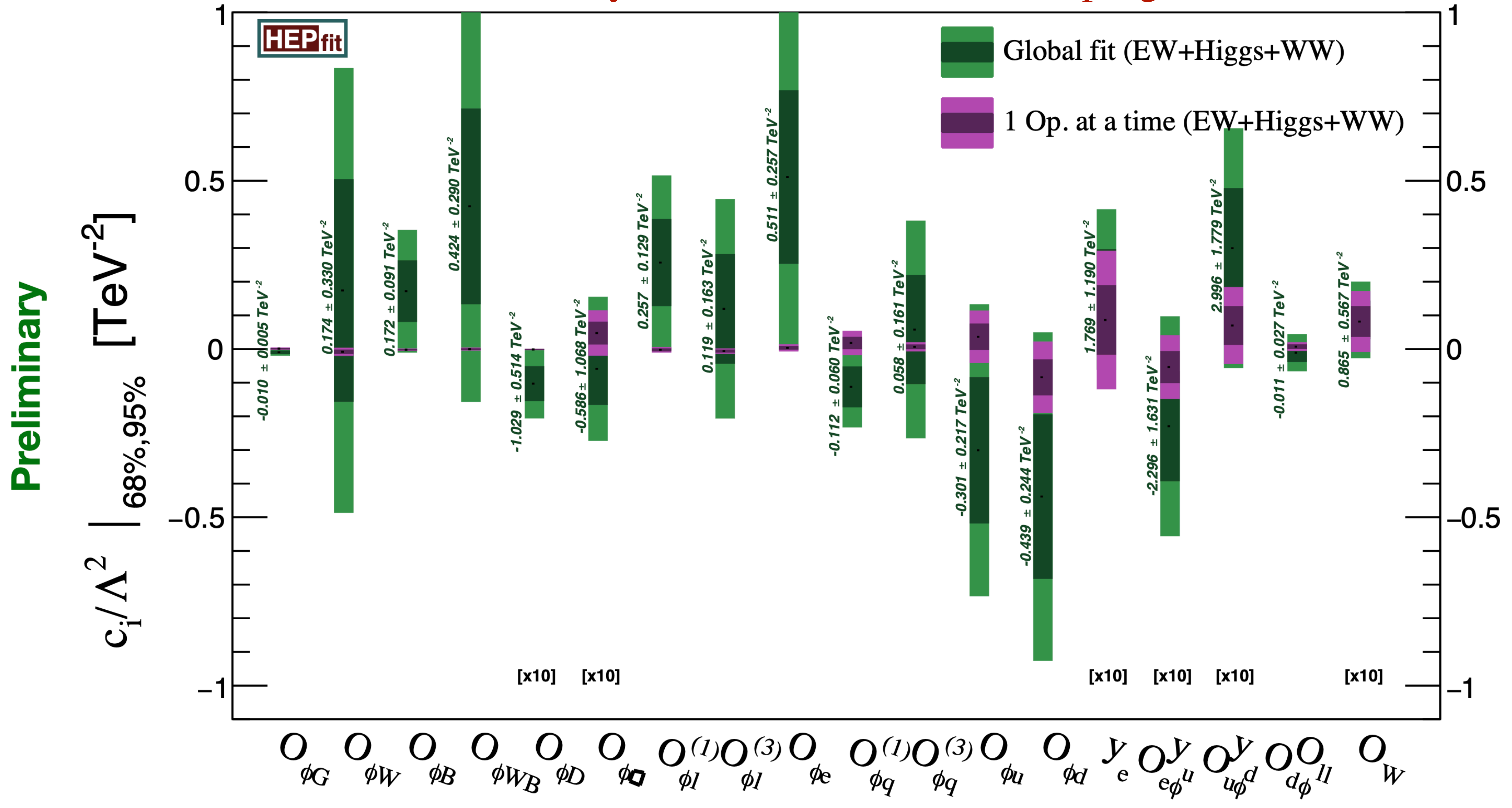


Future improvements

EW+Higgs+EWPO

Now

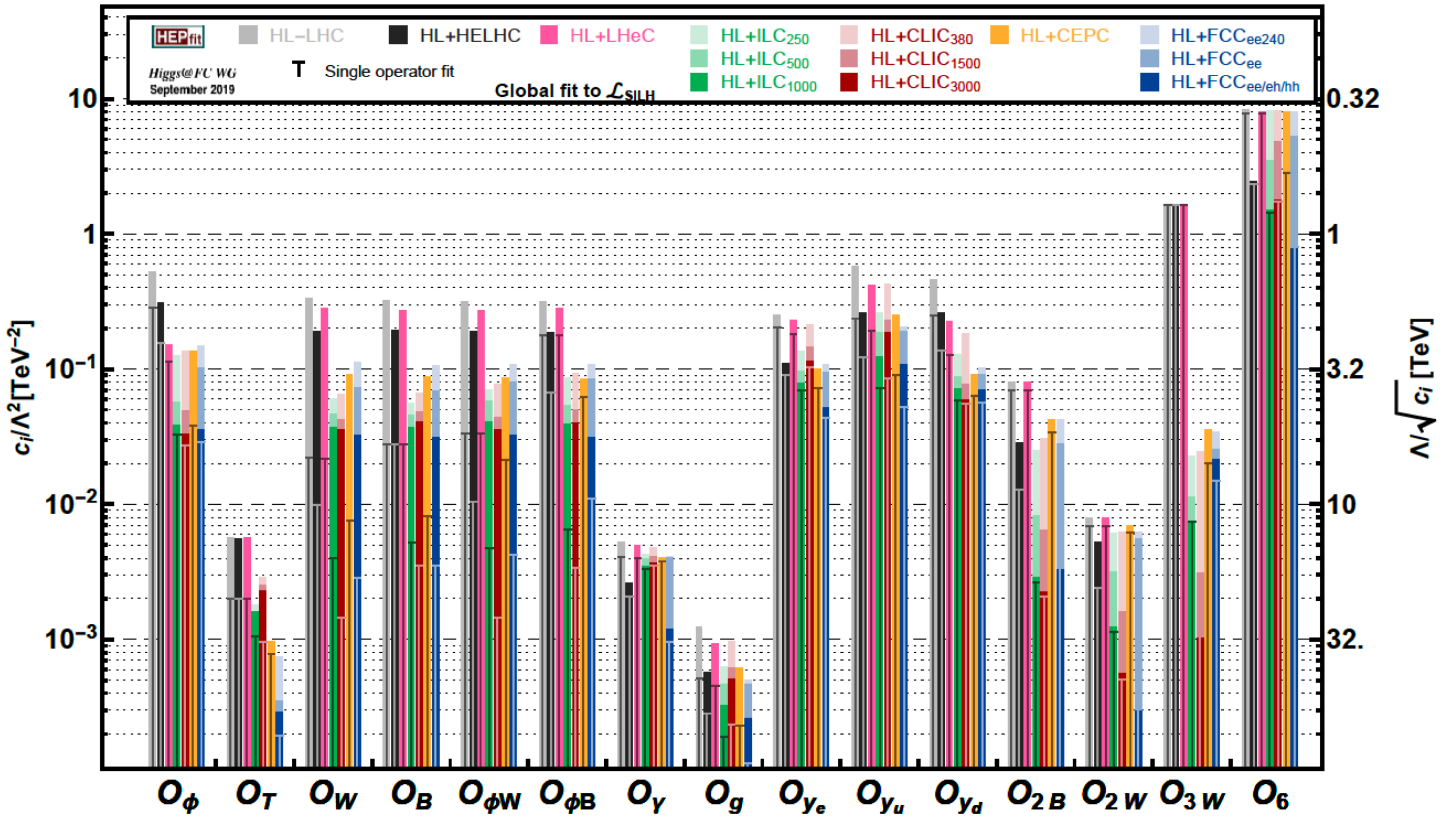
[Courtesy of De Blas et al., work in progress]



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

Future

[De Blas et al., 2020]



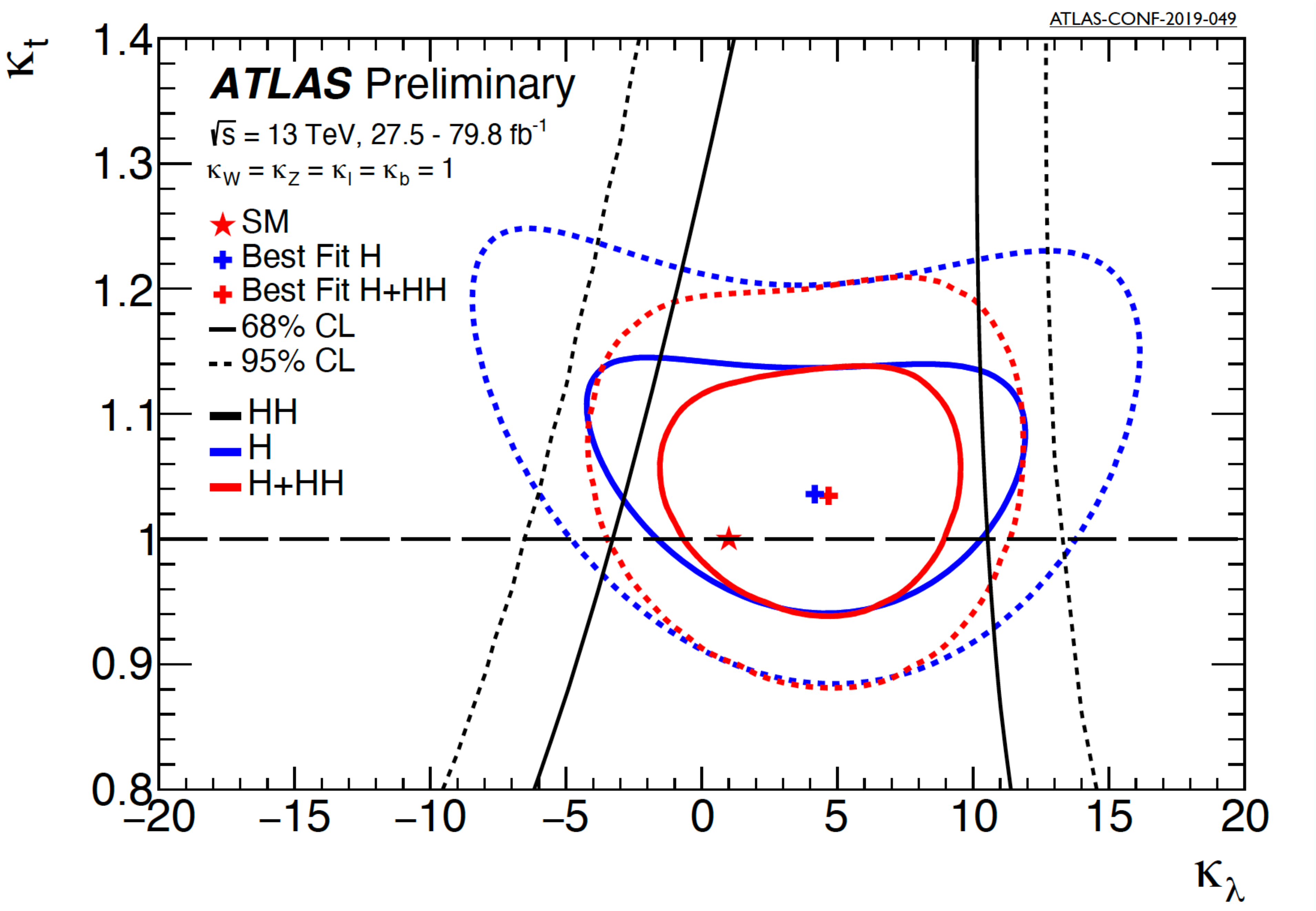
Expected more than 1 order of magnitude improvements

Future improvements

Higgs self couplings : tree-level and loops

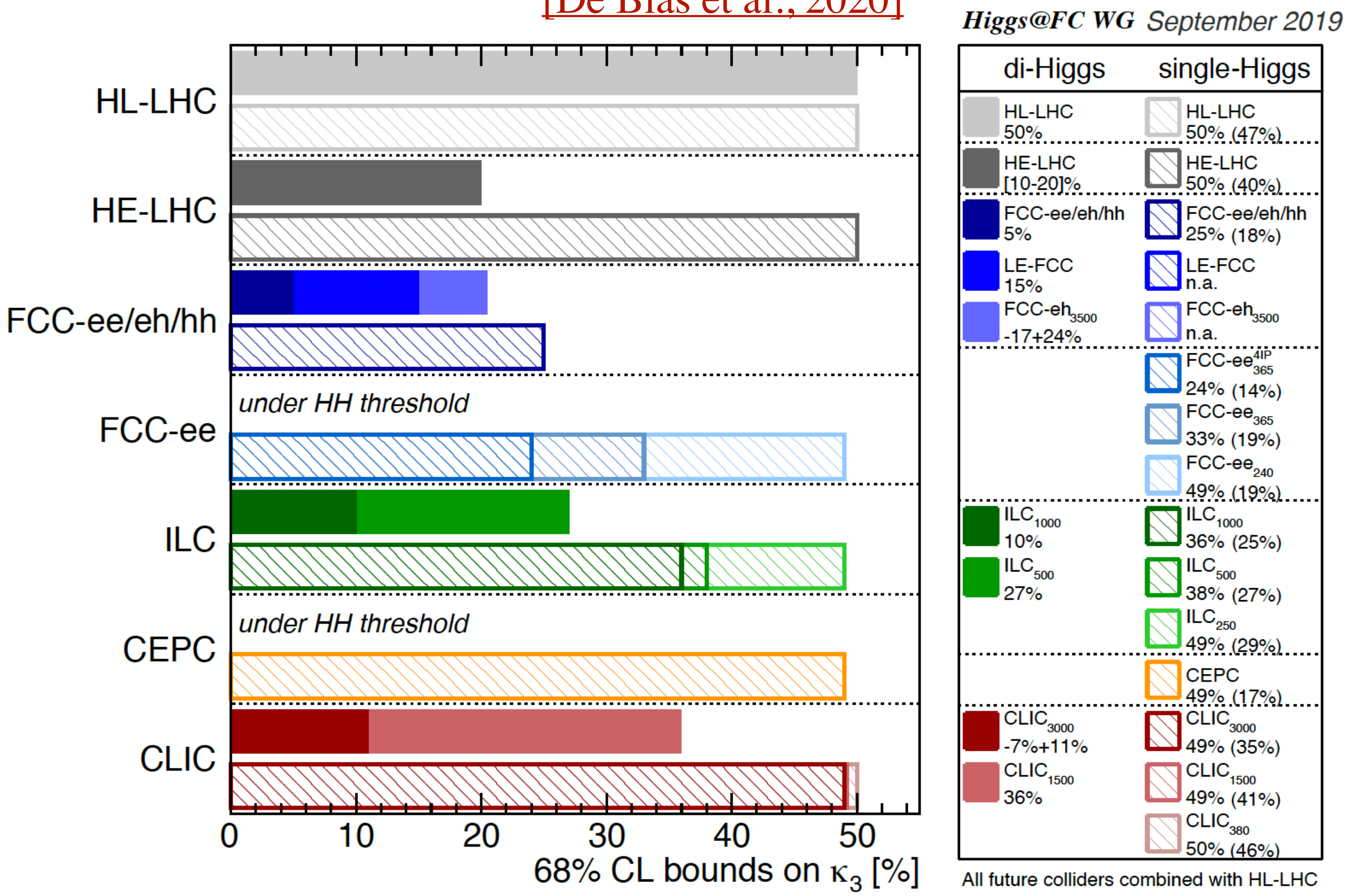
Now

[ATLAS, 2020]



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.

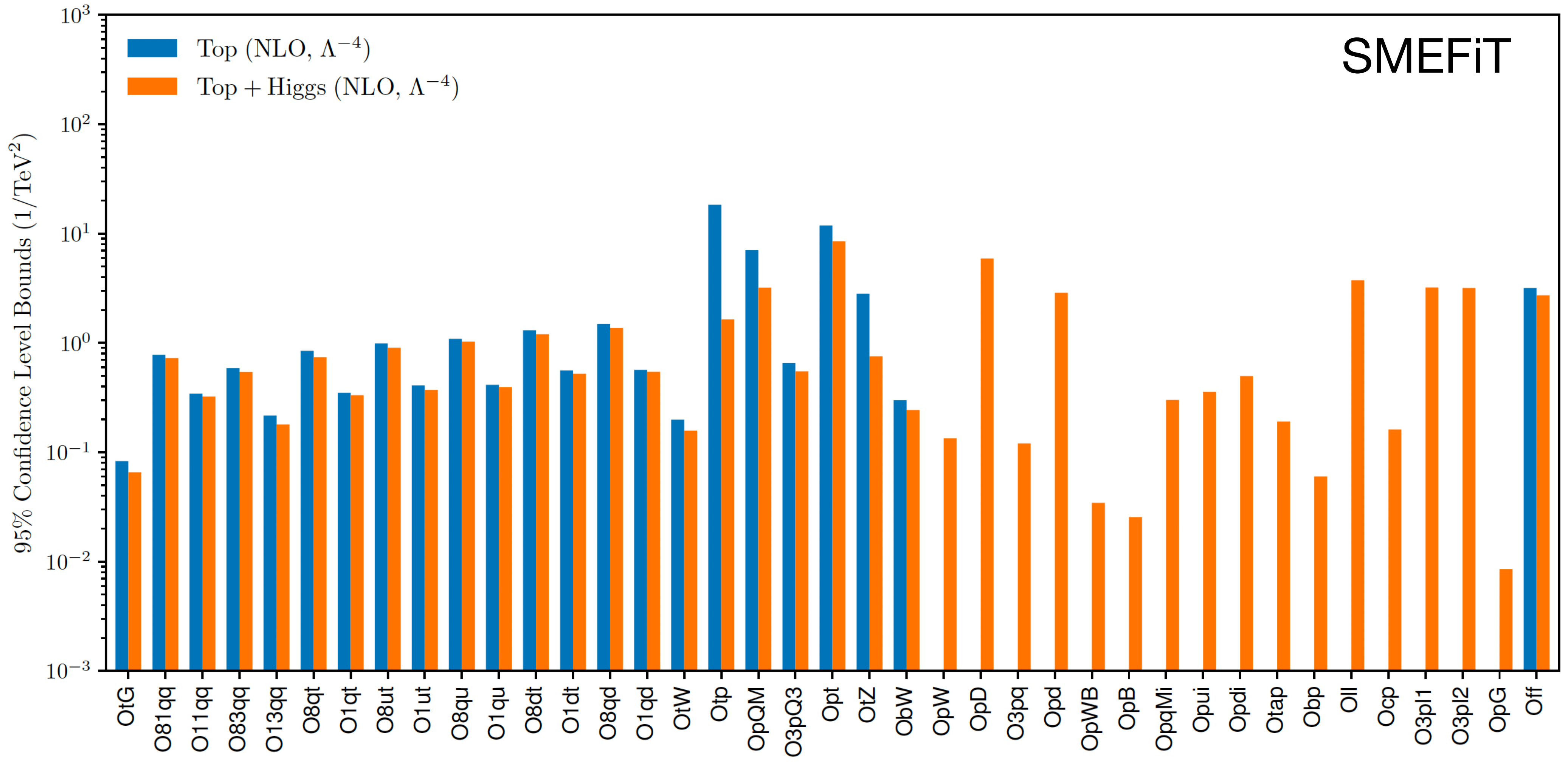
At high-energy pp and ee, HH will be more sensitive.

Future improvements

Top+Higgs

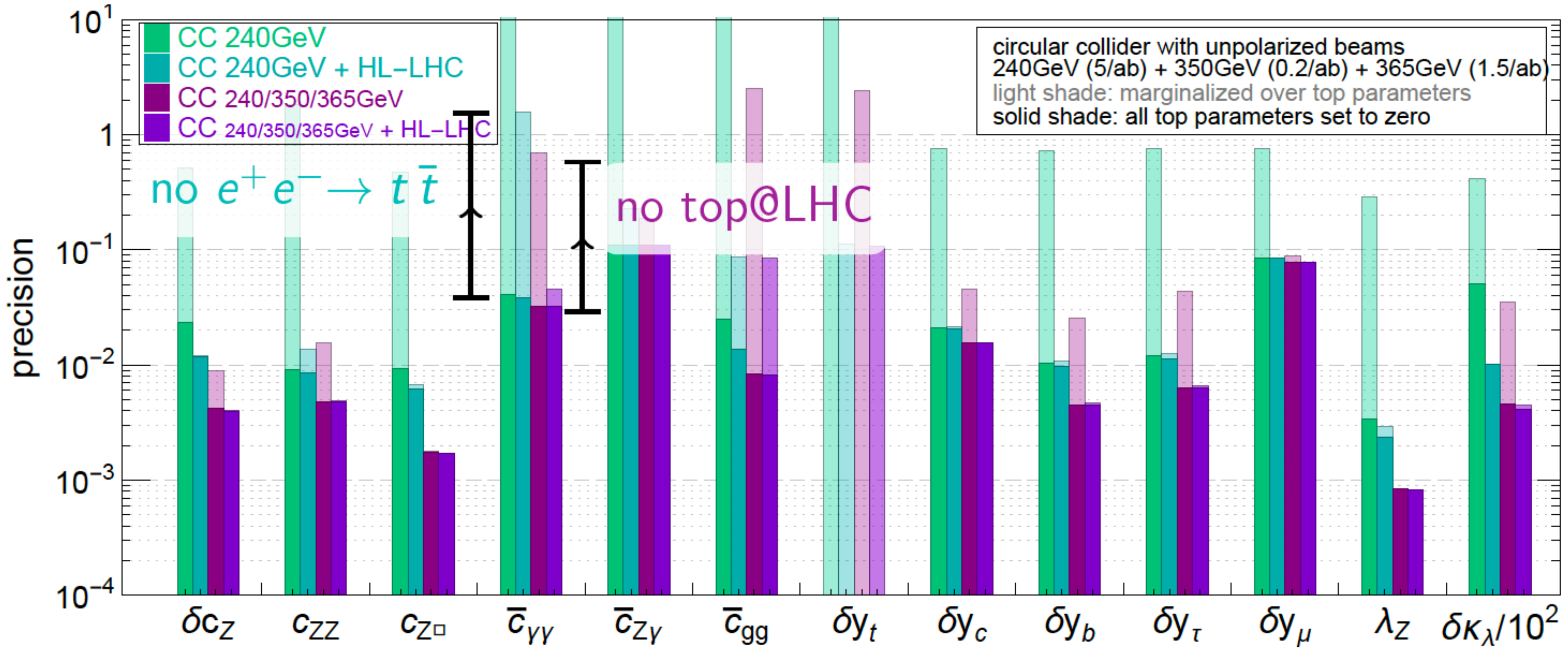
Now

[Courtesy of Ethier et al., work in progress]



Future

[Durieux et al., 2018]



Multiple energy runs below the tt threshold can give competitive determination of the yukawa of the top.

In the future the uncertainties on the top couplings could become a limitation for Higgs and EW measurements.

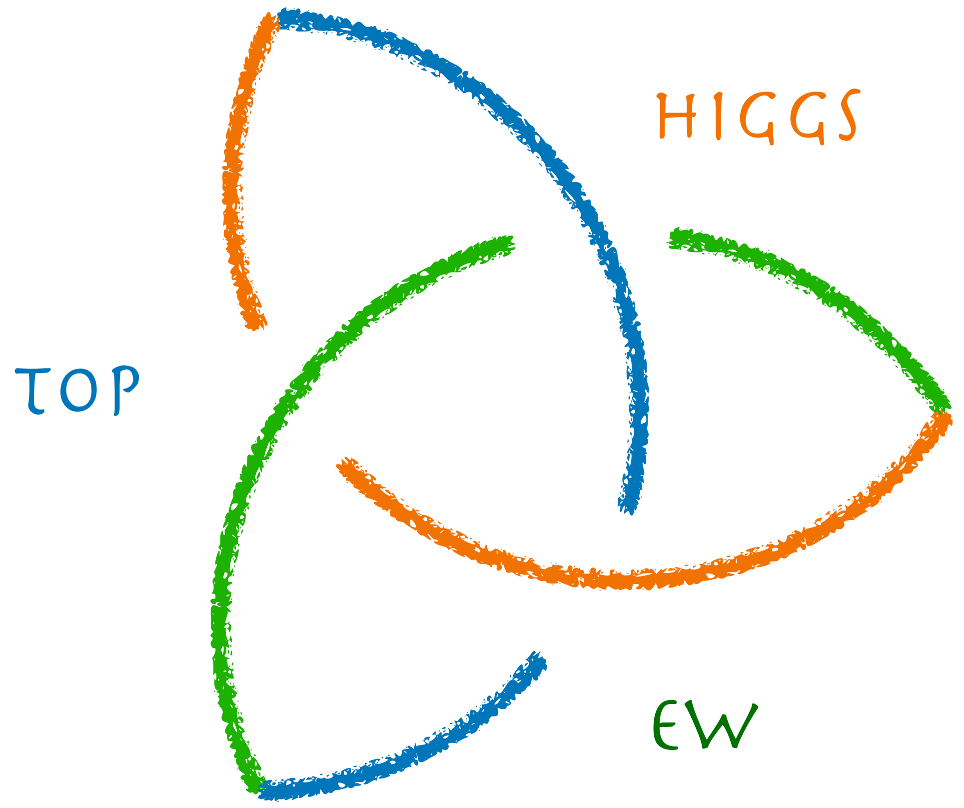
TH improvements

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

- Evaluation of the theory uncertainties and their correlations in the SMEFT still at its infancy. [Lot to learn here from PDF fits]. These come from missing higher orders (in gauge couplings and $1/\Lambda$ expansion).
- Currently, K-factors included in some fits, but theory uncertainties not accounted for.
- Development of restricted UV-inspired benchmarks to set limits in specific scenarios (including flavor data).
- Optimal observables for maximal sensitivity.
- Systematically including flavor constraints in global collider fits.
- Constraints from general QFT arguments: basis independent formulations (e.g. amplitudes), positivity, convexity,…

EW/Top/Higgs

Conclusions



- Tremendous improvements in the accuracy/precision of SM predictions have been achieved, opening a new realm of opportunities.
- The LHC campaign of precision measurements is entering a new phase measuring at unprecedented precision a large number of channels and accessing for the first time rare final states.
- A far reaching approach to interpreting SM measurements is to constrain the top/Higgs/EW interactions by employing the SMEFT, maximising sensitivity to heavy new physics.
- Considerable theory effort going on, being matched by the experimental work.
- EFT’s are also being used to gauge sensitivity to NP at future colliders.
- Busy future ahead with even more integrated TH/EXP activities.

A quote
Final Wisdom

[S]He who knows the art of
the direct and the indirect approaches
will be victorious.

Sun Tzu, The Art of War

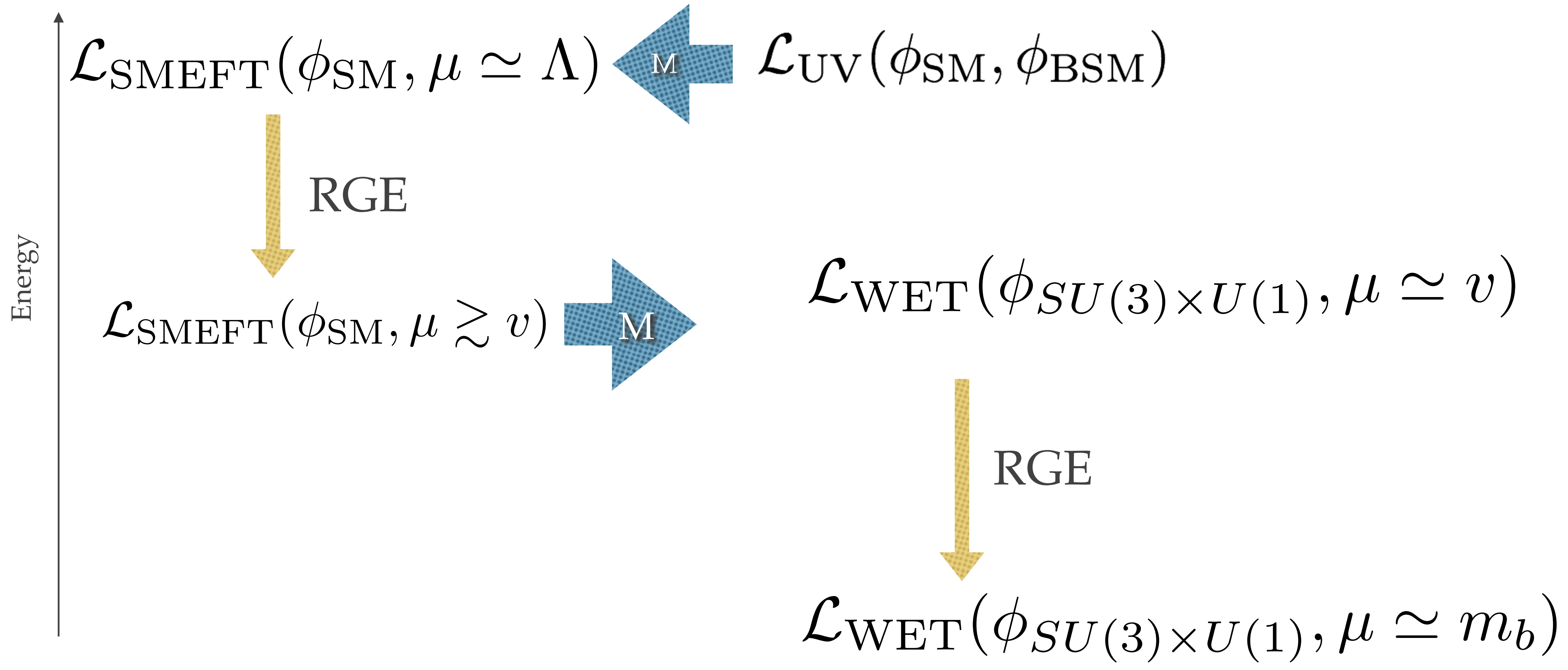
SMEFT
Flavour

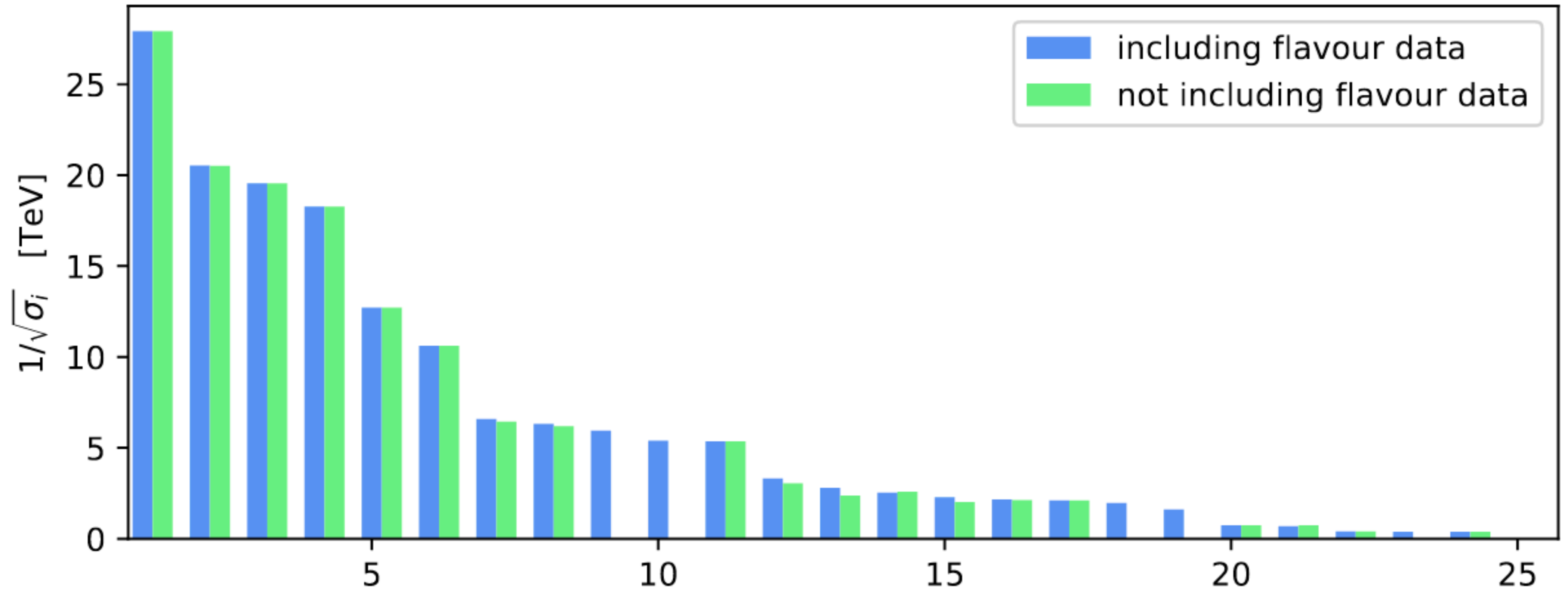
[Aoude et al,; arXiv:2003.05432]
[Hurth et al,; JHEP 06 (2019) 029]
[Bissmann at al. , 2020]

- Imposing flavor symmetry in SMEFT avoids tree-FCNC
- Flavor violation induced by SM interactions at loop level
- Down type FCNC processes at low energy: B-decay/mixing and some Kaon

SMEFT (Λ) → WET (v) → Flavour experiments

- Translate existing constraints on WET coefficients to SMEFT
- Combined with fit to EWPO/diboson/Higgs
- Constrain new directions

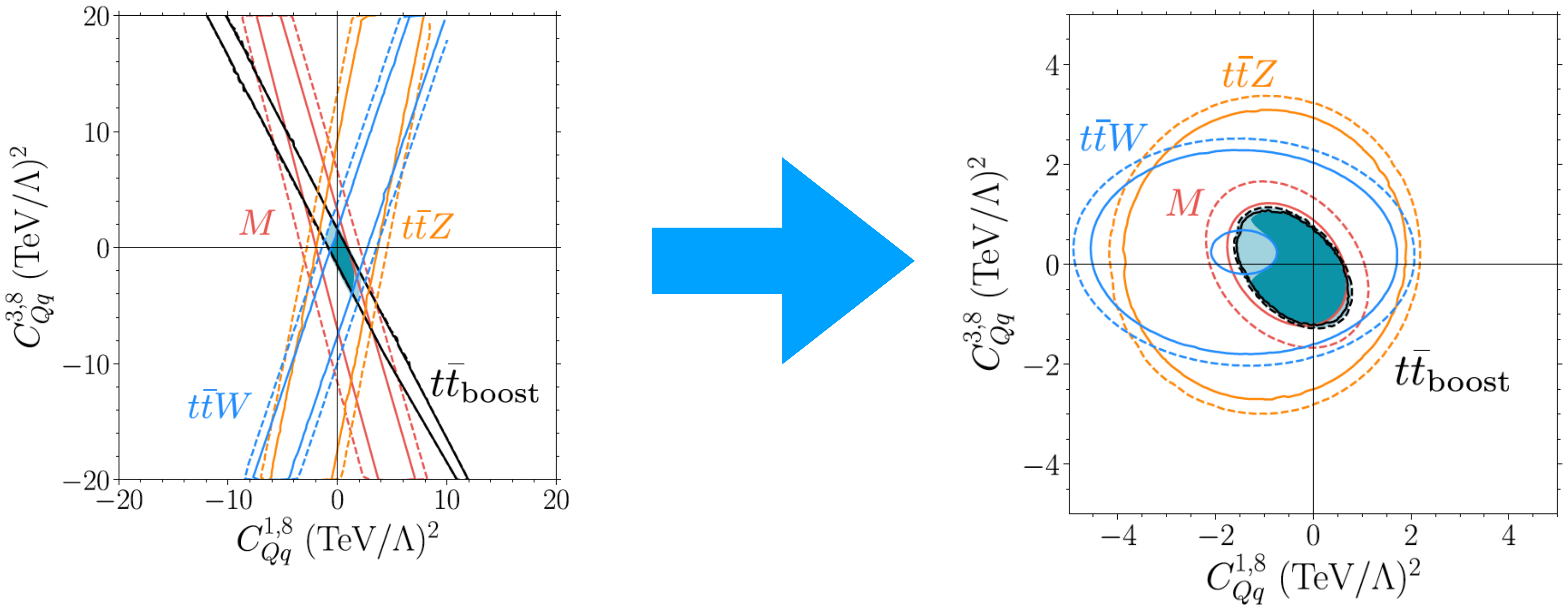




SMEFT

Linear vs quadratic

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 meaning/reliabilty of the fit.

Always provide constraints using i) linear and ii) linear+squared terms

SMEFT

$t\bar{t}t\bar{t}$: the power of 4

$$\mathcal{O}_T = \frac{c_T}{2M^2}(H^\dagger \overleftrightarrow{D}^\mu H)^2 \qquad \mathcal{O}_{2W} = -\frac{c_{2W}}{4M^2}(D_\rho W^a_{\mu\nu})^2$$

$$\mathcal{O}_{WB} = \frac{gg' c_{WB}}{M^2} H^\dagger \sigma^a H B^{\mu\nu} W^a_{\mu\nu} \qquad \mathcal{O}_{2B} = -\frac{c_{2B}}{4M^2}(\partial_\rho B_{\mu\nu})^2$$

$$\mathcal{O}_\Box = \frac{c_\Box}{M^2}|\Box H|^2 \qquad \mathcal{O}_{2G} = -\frac{c_{2G}}{4M^2}(D_\rho G^a_{\mu\nu})^2$$

$$\mathcal{O}_B = \frac{ig' c_B}{2M^2}(H^\dagger \overleftrightarrow{D}^\mu H)\partial^\nu B_{\mu\nu}$$

$$\mathcal{O}_W = \frac{ig c_W}{2M^2}(H^\dagger \sigma^a \overleftrightarrow{D}^\mu H) D^\nu W^a_{\mu\nu}$$

$$\hat{S} = 4\left(c_{WB} + \frac{c_W + c_B}{4}\right)\frac{m_W^2}{M^2} \qquad \hat{T} = c_T \frac{v^2}{M^2}$$

$$\hat{W} = c_{2W}\frac{m_W^2}{M^2} \qquad \hat{Y} = c_{2B}\frac{m_W^2}{M^2}$$

$$\hat{Z} = c_{2G}\frac{m_W^2}{M^2} \qquad \hat{H} = c_\Box \frac{m_h^2}{M^2}$$

[Englert et al., 1903.07725]