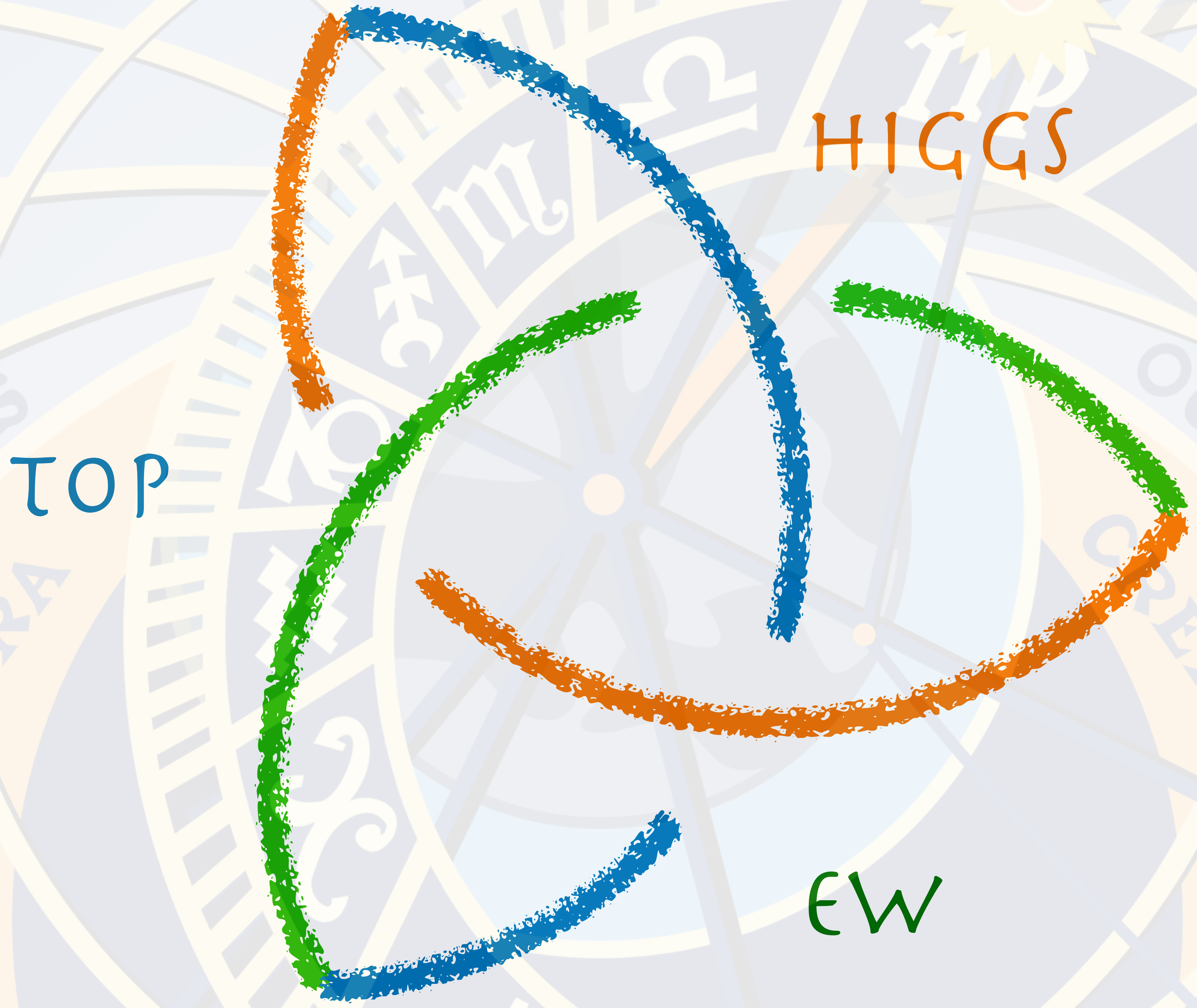
EW/Top/Higgs Theory review



Fabio Maltoni
Università di Bologna
Université catholique de Louvain

EW/Top/Higgs

Thanks to all the speakers in the Top/EW and Higgs sessions!

Production of heavy particle pairs via photon-photon processes at the LHC in proton-proton scattering	*Marta Luszczak*
KKMC-hh for Precision EW Phenomenology at the LHC — *virtual conference*	*Scott Alan Yost* — 19:05 - 19:30
The electro-weak couplings of the top quark: current constraints, prospects and impact in a combined top-Higgs EFT fit	*Martín Perelló Roselló*
New results from TopFitter — *virtual conference*	*Dr Peter Galler* — 10:15 - 10:40
NLO QCD corrections to the electroweak top-pair production beyond the Standard Model — *virtual conference*	*Mohammad Mahdi AlTakach* — 10:40 - 11:05
Enhancing fits of SMEFT Wilson coefficients in the top-quark sector — *virtual conference*	*Cornelius Grunwald* — 19:55 - 20:20
$\gamma \gamma \to \gamma \gamma$ in heavy ion collisions -- new results and prospects	*Mariola Kłusek-Gawenda et al.*

Two-loop corrections to the Higgs trilinear coupling in models with extended scalar sectors — *virtual conference*	*Johannes Braathen* — 12:24 - 12:42
Higgs boson pair production at N3LO QCD — *virtual conference*	*Hua-Sheng Shao* — 12:42 - 13:00
Searching for Light Boson via the Yukawa Process at Lepton Colliders — *virtual conference*	*Dr Tanmoy Mondal* — 08:36 - 08:54
A new way of understanding the role of each measurement at future Higgs factories in SMEFT — *virtual conference*	*Dr Junping Tian* — 08:54 - 09:12
Expectations for Precision Tests of the Standard Model at the ILC" — *virtual conference*	*Michael Peskin* — 08:00 - 08:18
Constraining resonances by using the EW effective theory — *virtual conference*	*Ignasi Rosell* — 12:42 - 13:00
Top and quark contributions to electroweak-boson elastic-scattering at the LHC — *virtual conference*	*Mr Carlos Quezada Calonge* — 11:12 - 11:30
JHU generator framework: new features for Higgs boson studies — *virtual conference*	*Meng Xiao* — 11:30 - 11:48
Flavor Changing Neutral Higgs Boson Meets the Top and the Tau at Hadron Colliders — *virtual conference*	*Prof. Chung Kao* — 17:00 - 17:18
Suppression of fermionic operators in the HEFT — *virtual conference*	*Juan José Sanz-Cillero* — 17:18 - 17:36
Higgs decay into a lepton pair and a photon revisited — *virtual conference*	*Mr Aliaksei Kachanovich et al.* — 17:36 - 17:54

36 talks, 6 theory

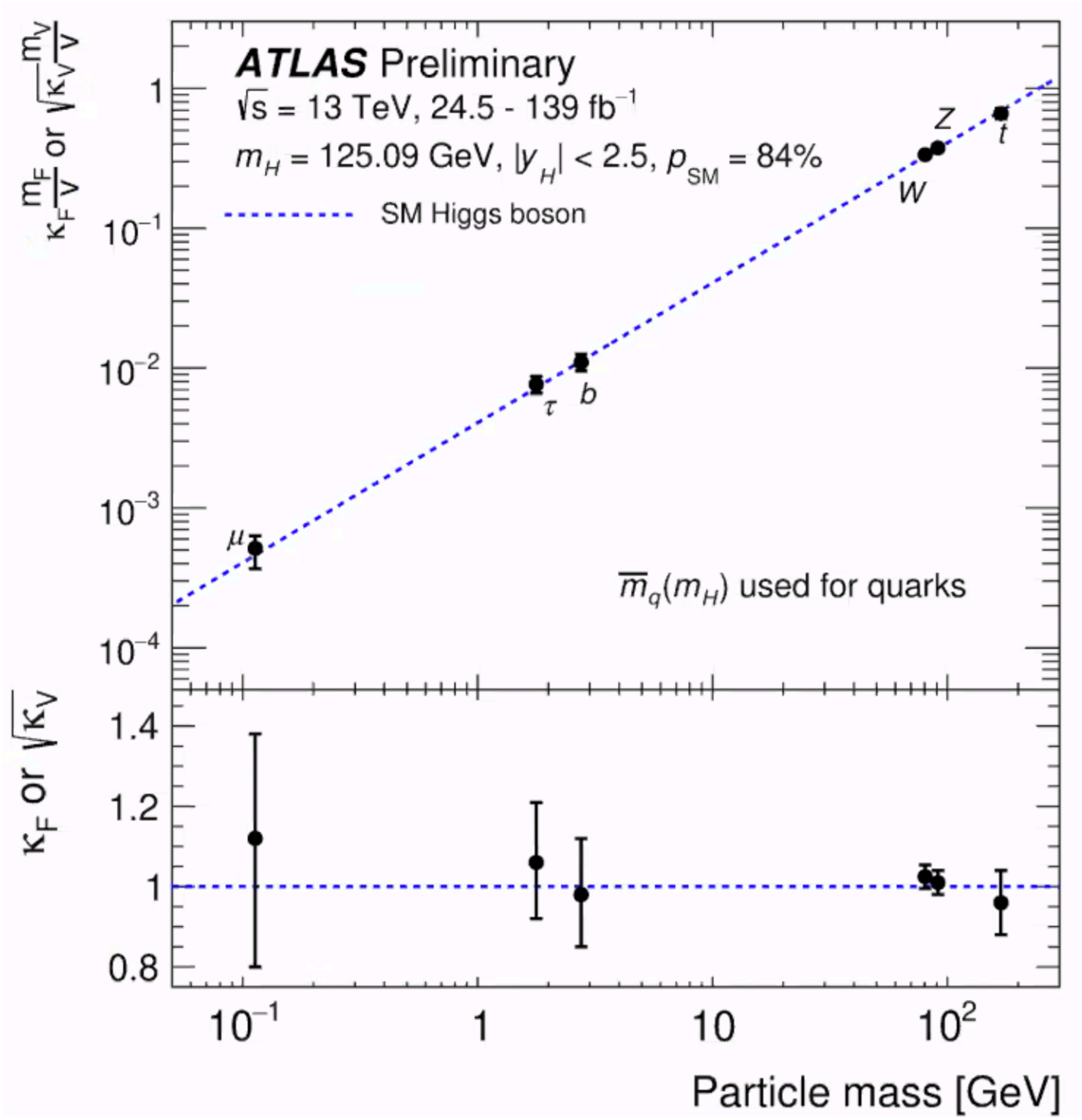
>50% theory talks on EFT’s

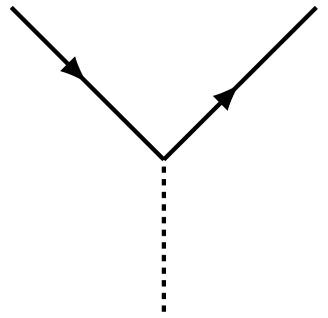
45 talks, 11 theory

SM 101

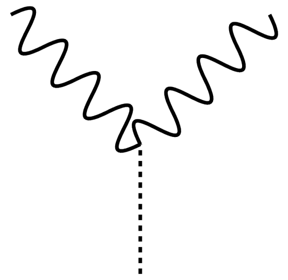
Mass generation with gauge invariance

[ATLAS 2020]





$i\, m_f / v$



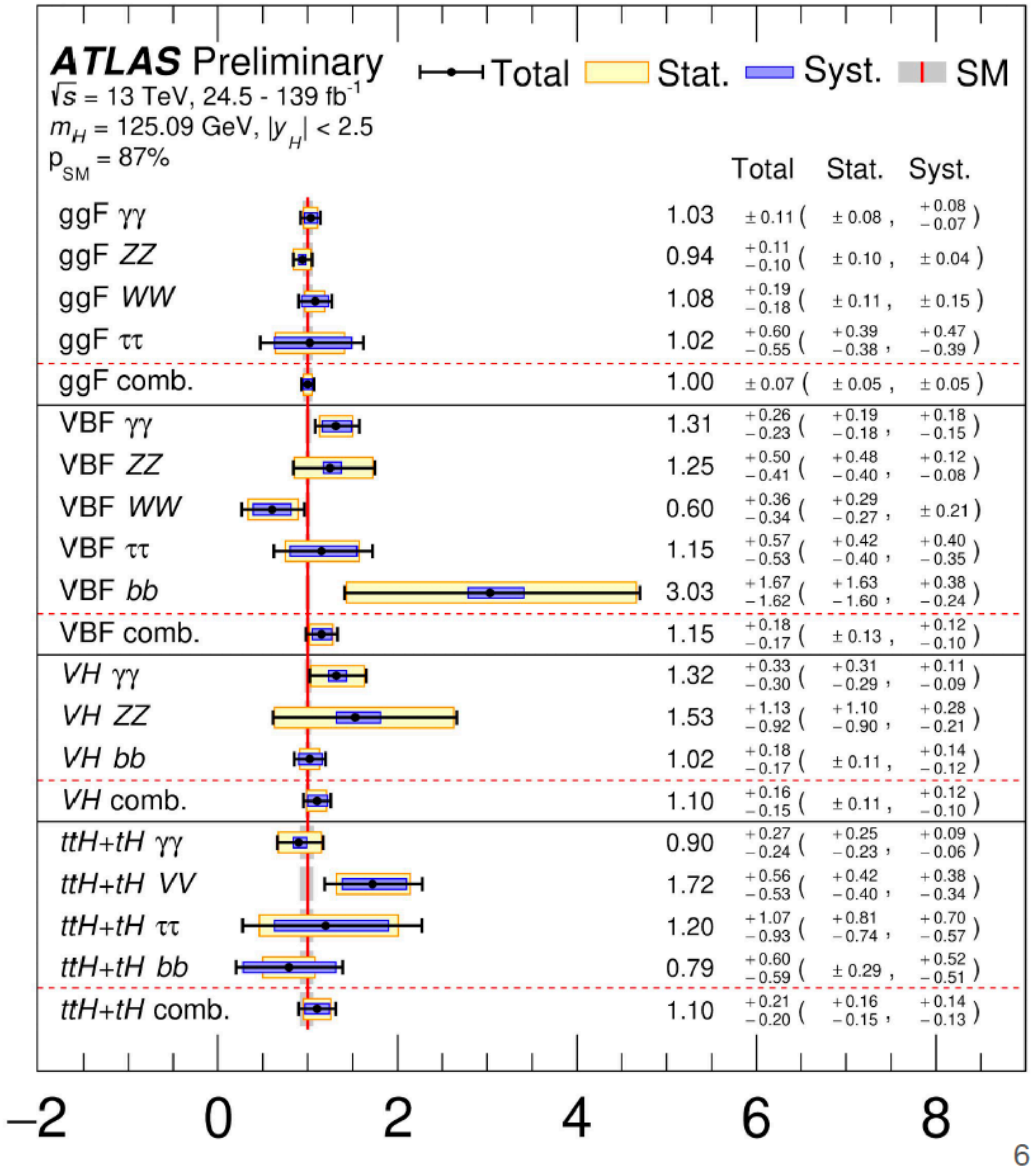
$$i g m_W g_{\mu\nu} = 2 i v g_{\mu\nu} \cdot m_W^2 / v^2$$

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

Unique mass generation mechanism for fermions and vectors.

Constrained system.

[ATLAS 2020]



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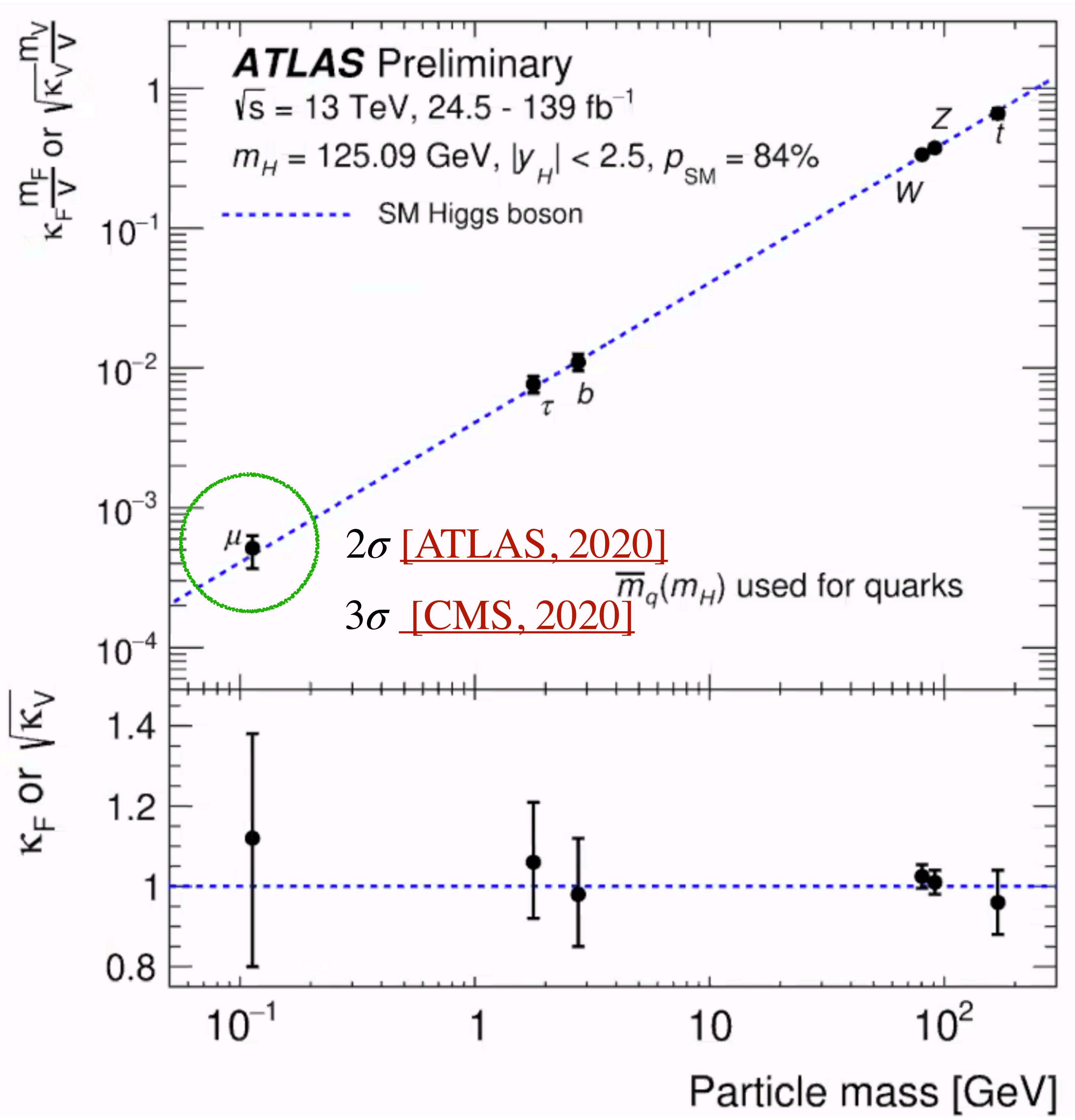
SM 101

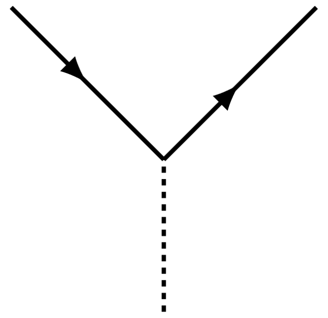
Mass generation with gauge invariance

[ATLAS 2020]



2σ [ATLAS, 2020]

3σ [CMS, 2020]



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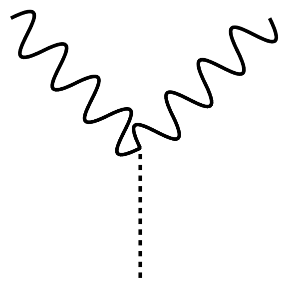

$$ig m_W g_{\mu\nu} = 2i\, v g_{\mu\nu} \cdot m_W^2/v^2$$

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

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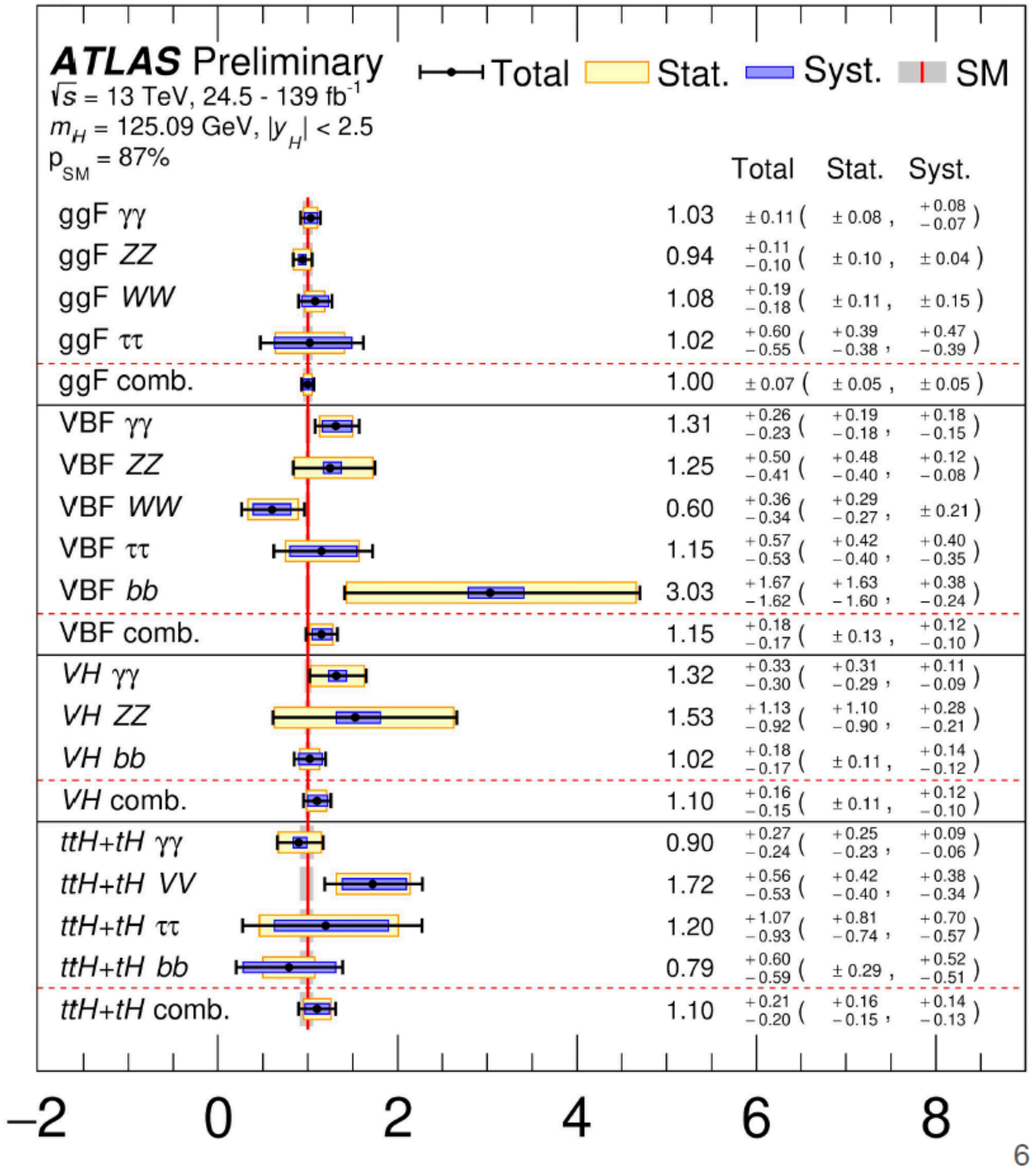

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SM 101

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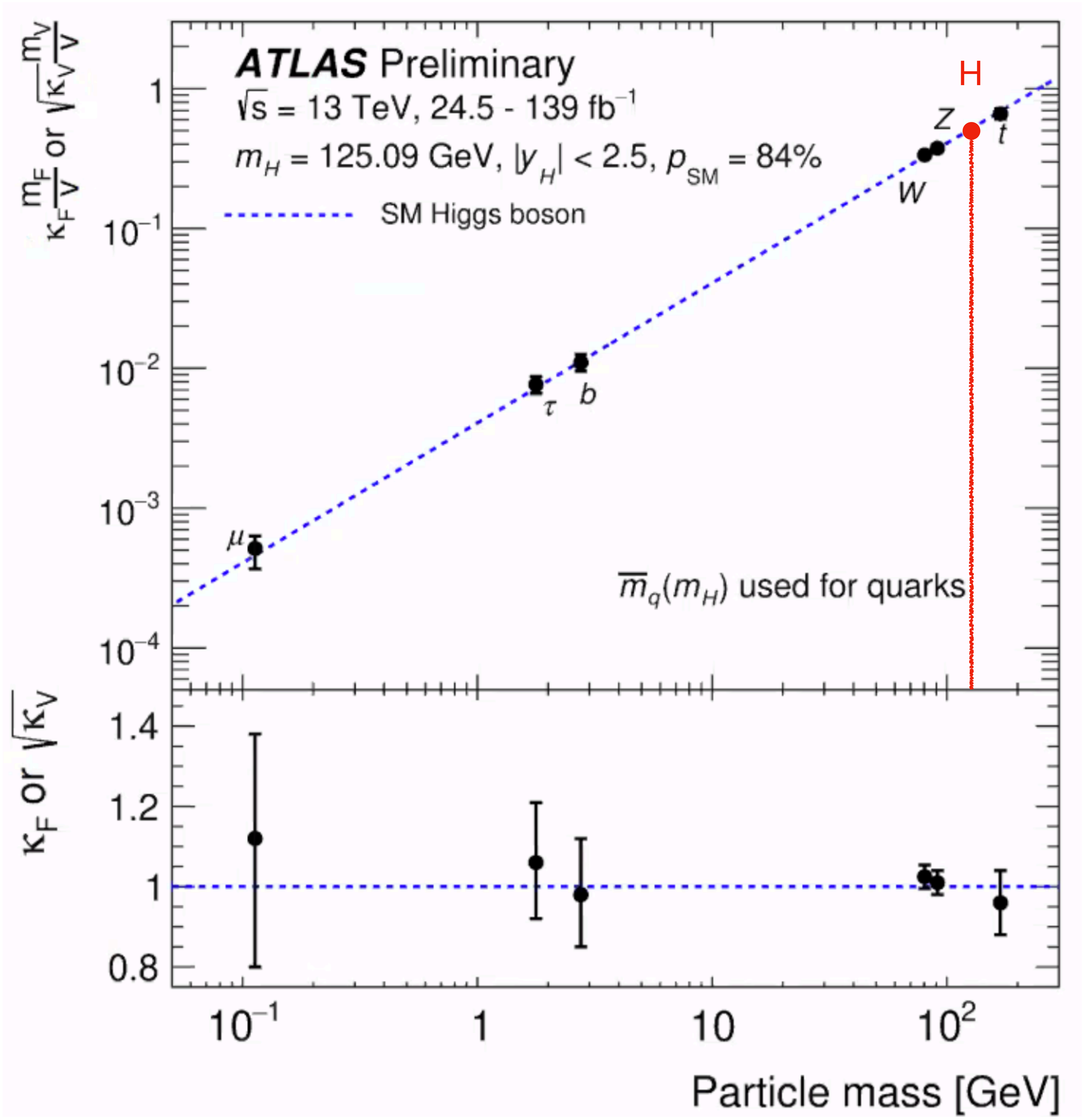
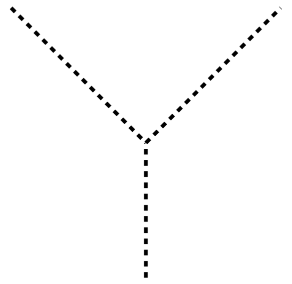


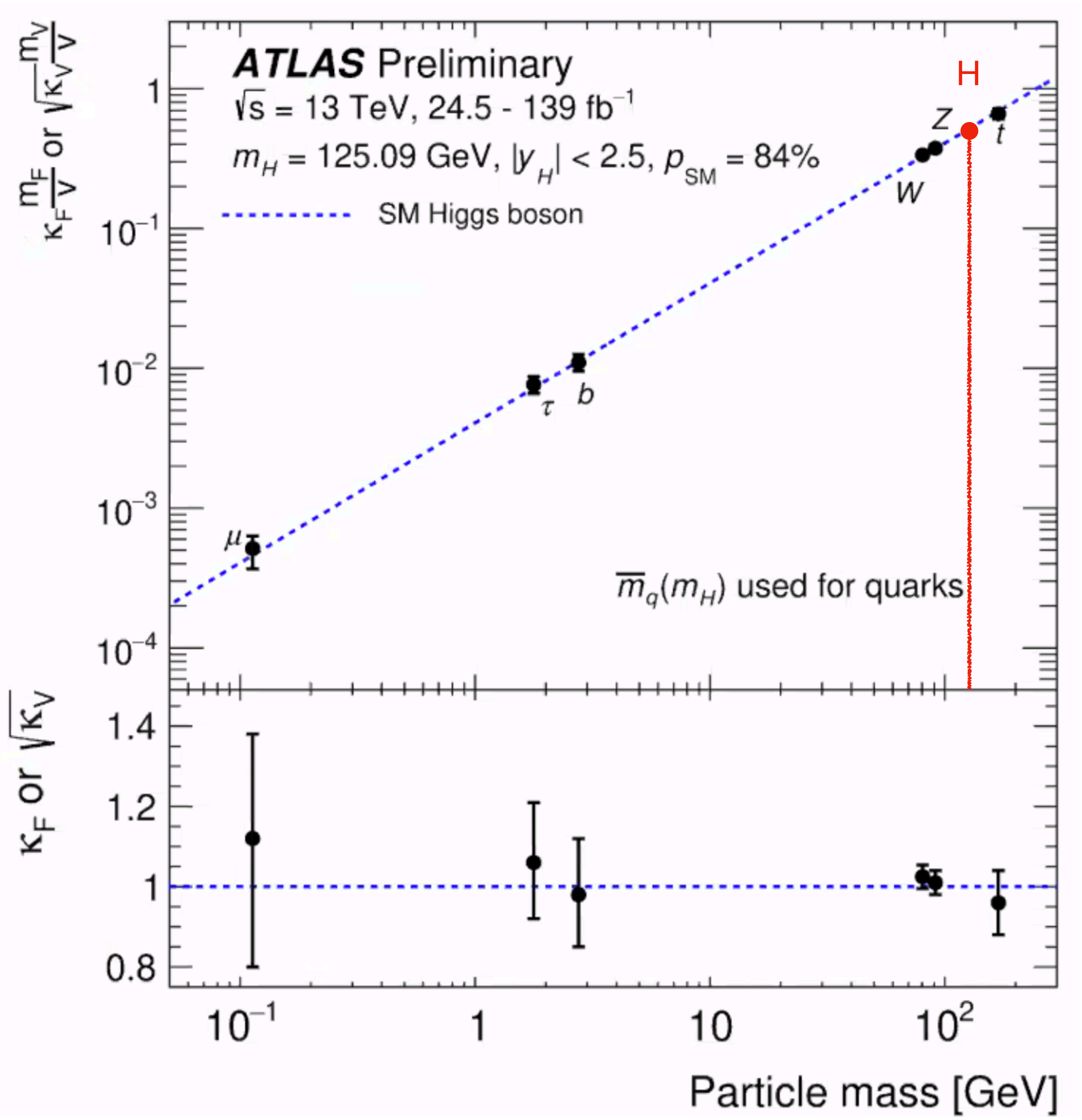


$-3\, iv \cdot m_h^2/v^2$

SM 101

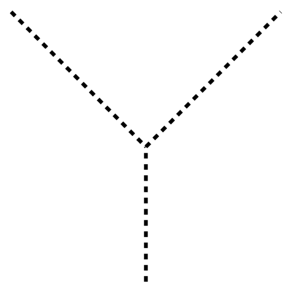
Mass generation with gauge invariance

[ATLAS 2020]



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

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



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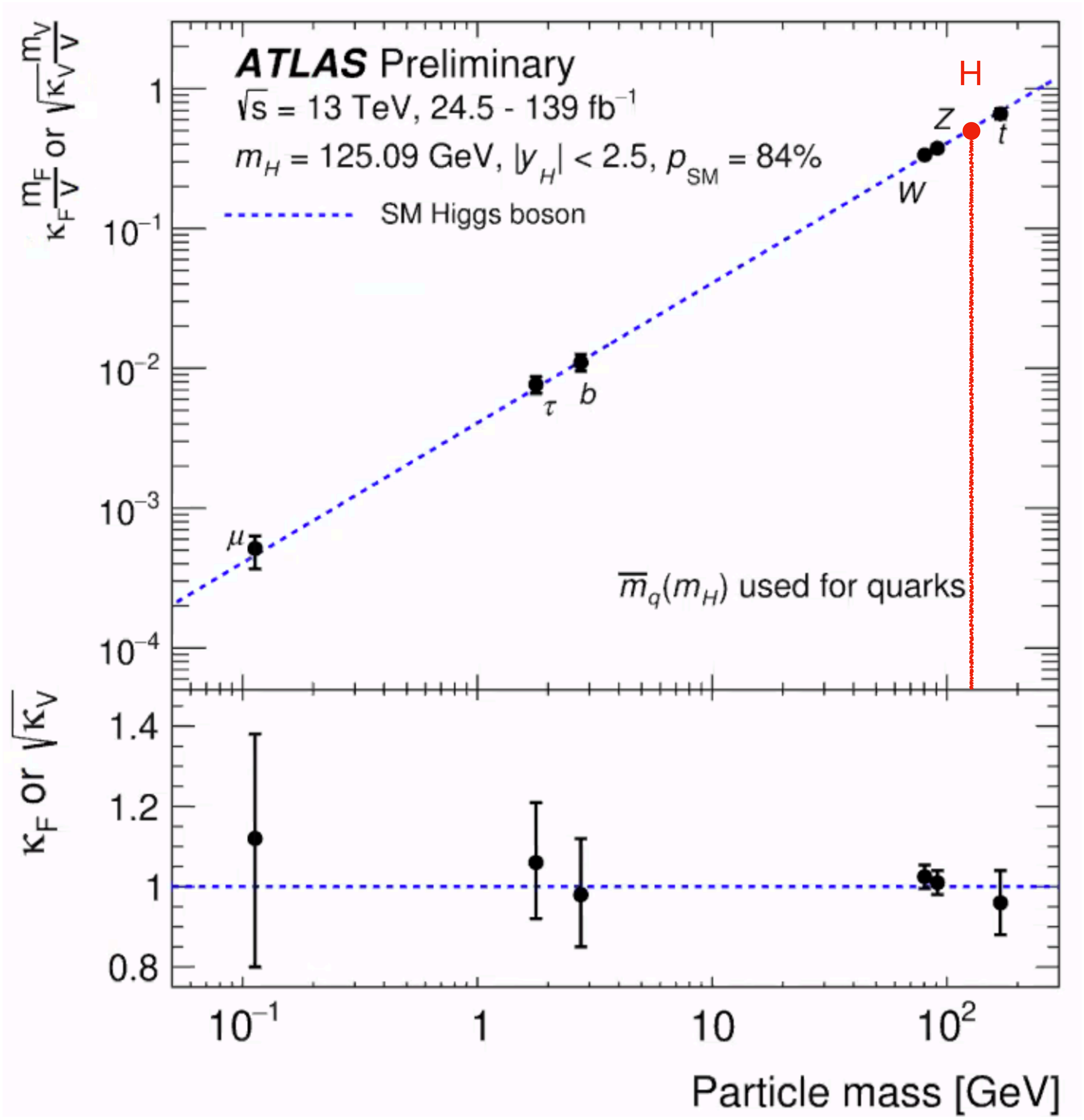

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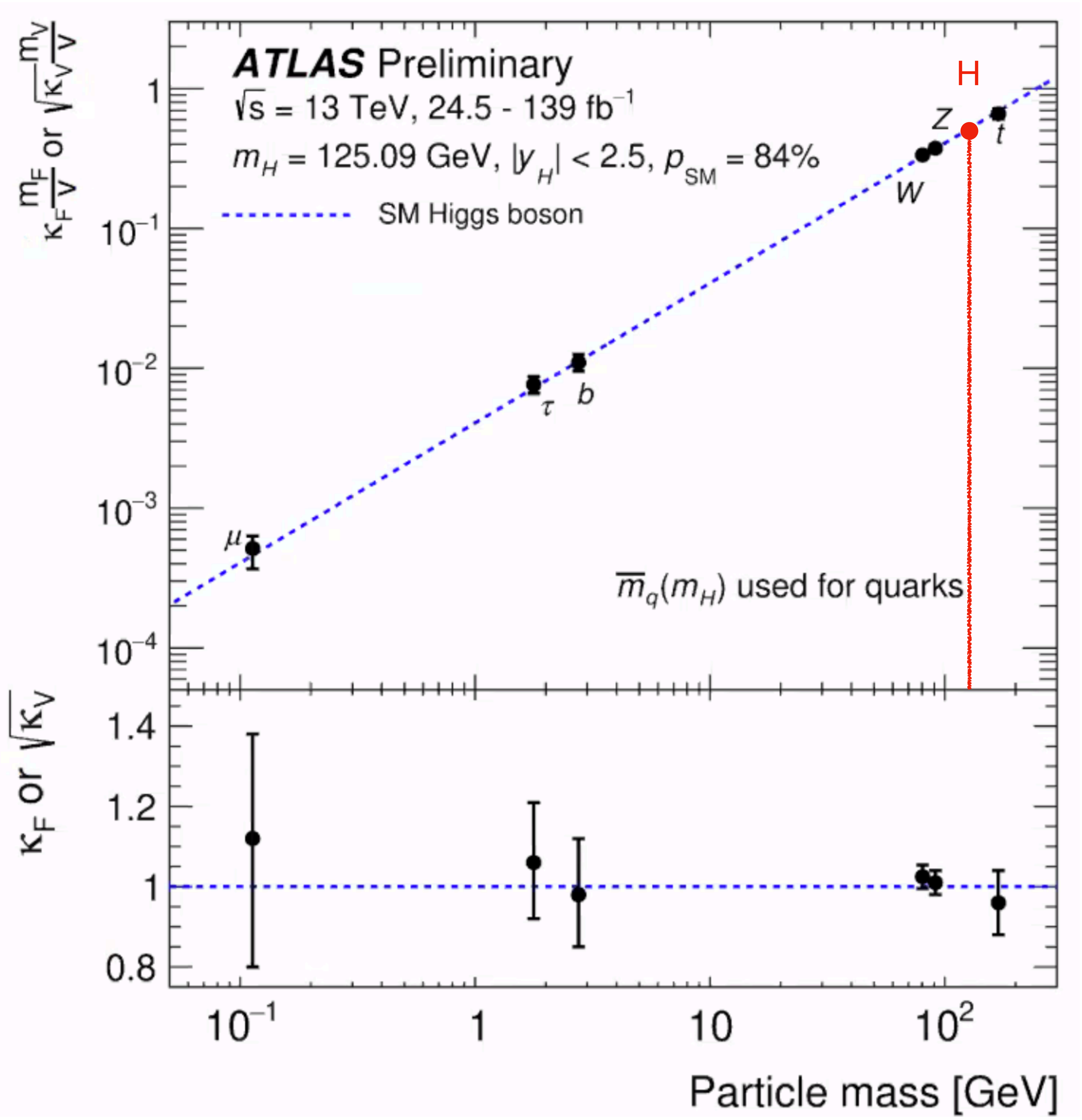

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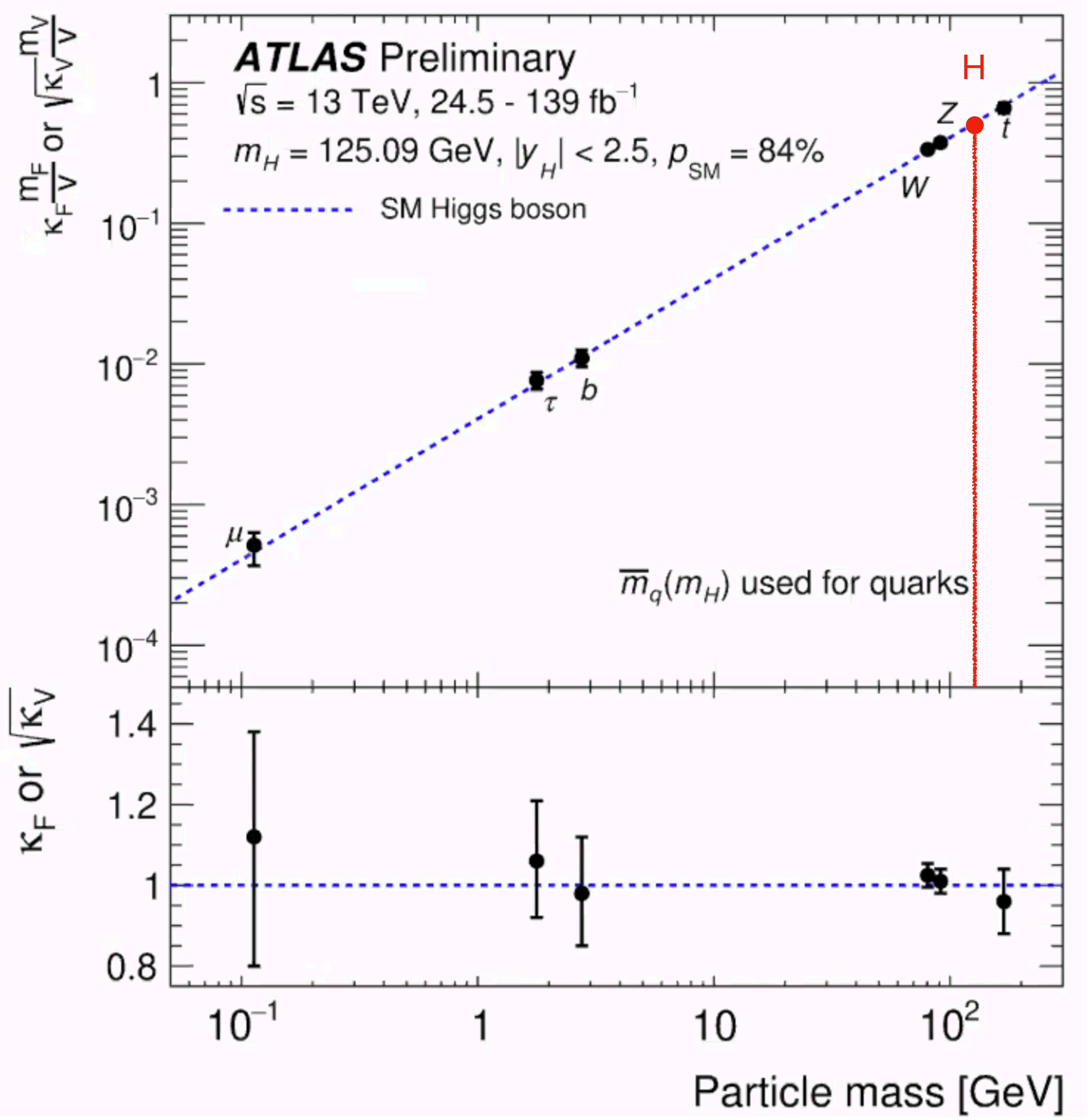
SM 101

Mass generation with gauge invariance

[ATLAS 2020]



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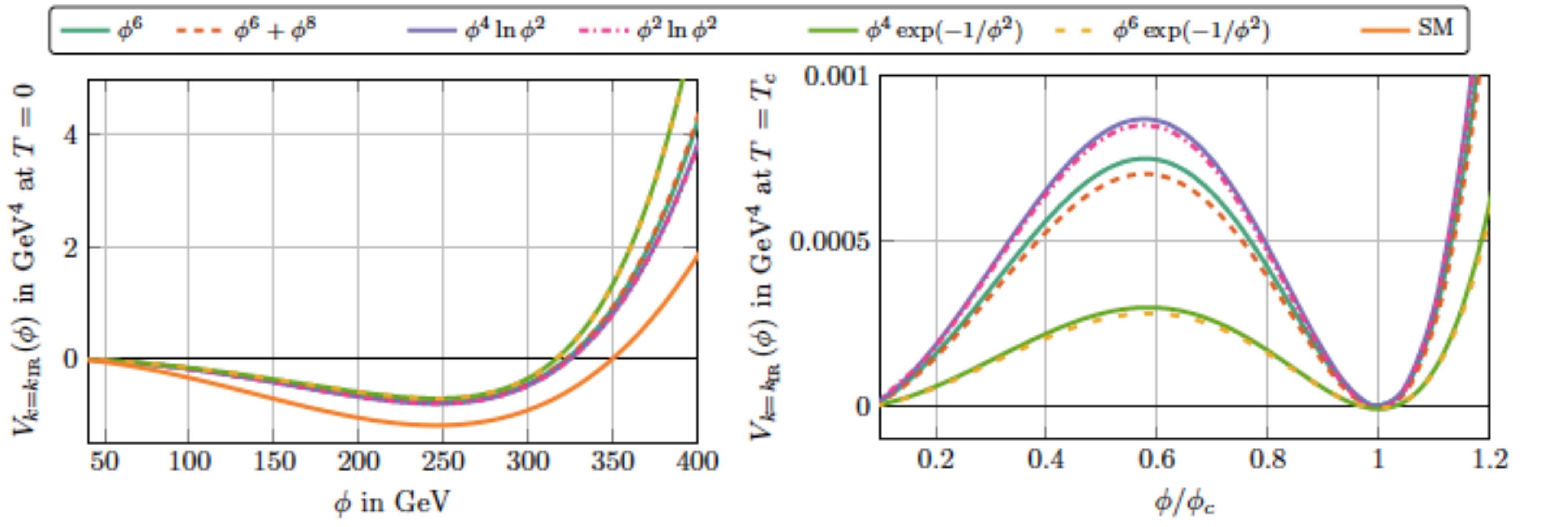
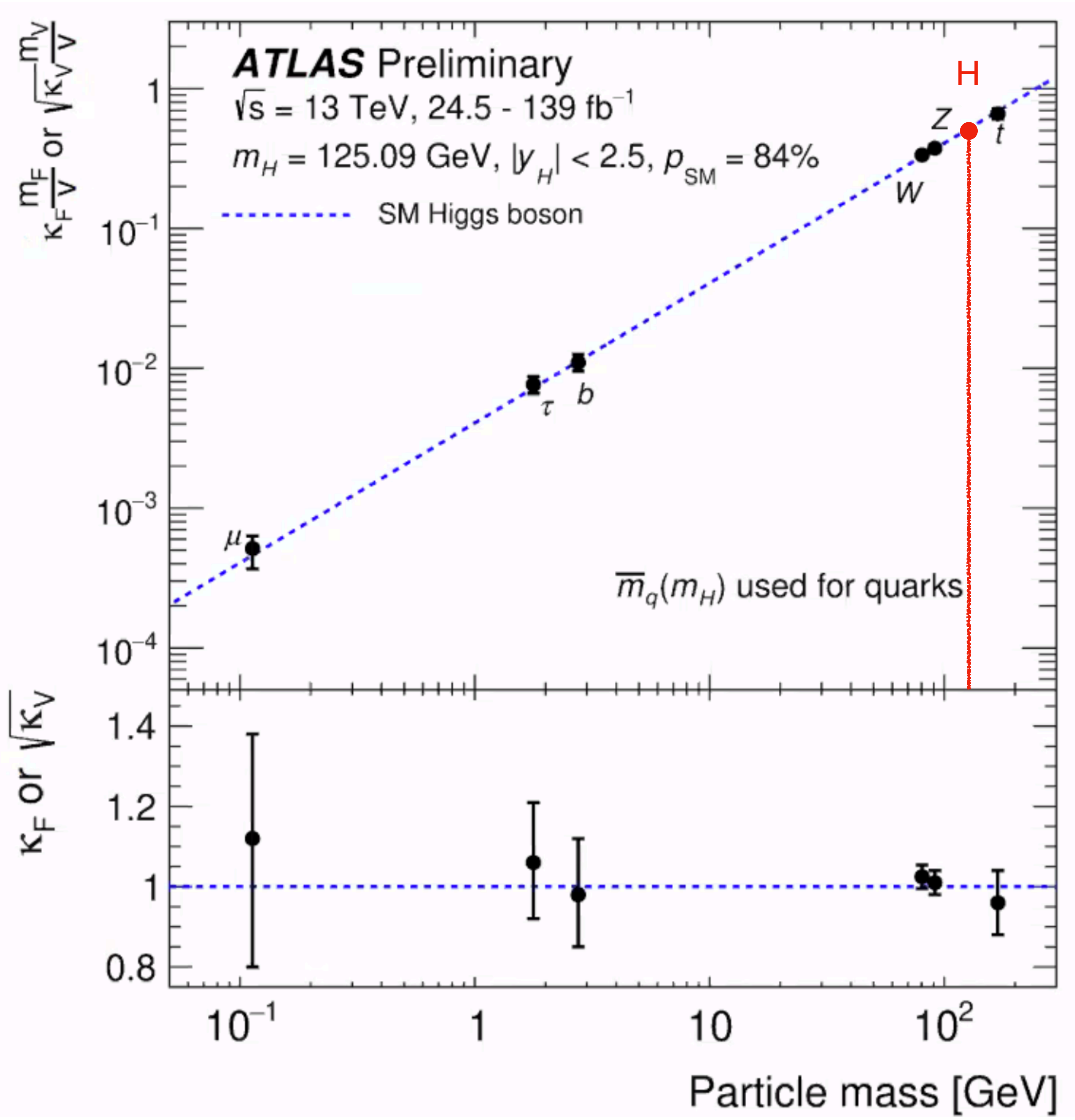


Reichert et al. 1711.00019

SM 101

Mass generation with gauge invariance

[ATLAS 2020]



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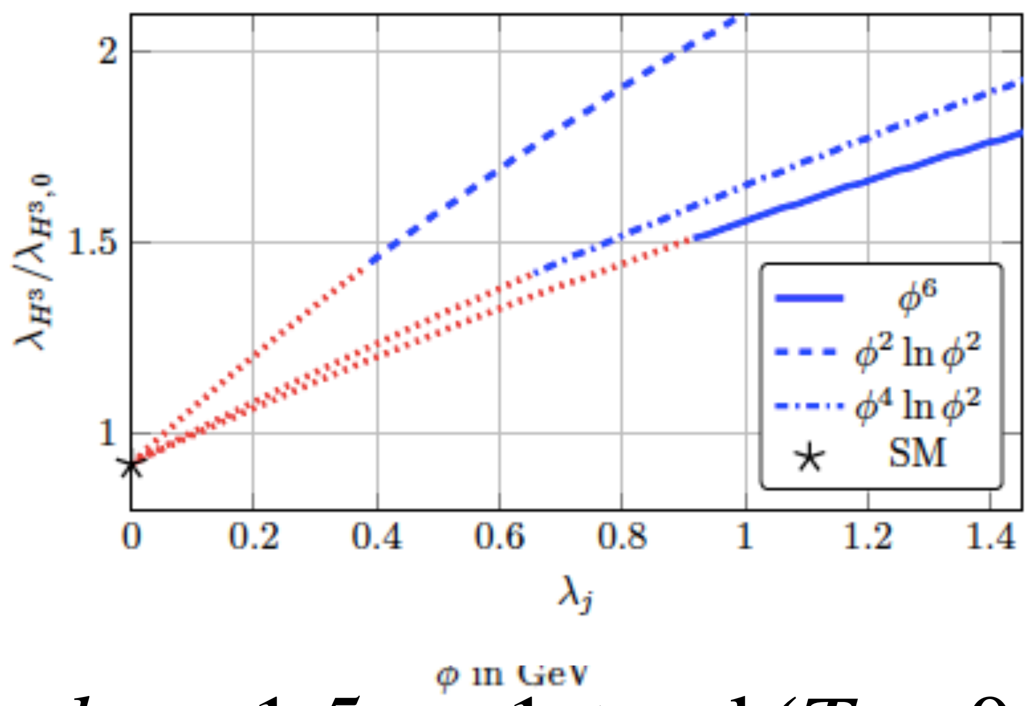
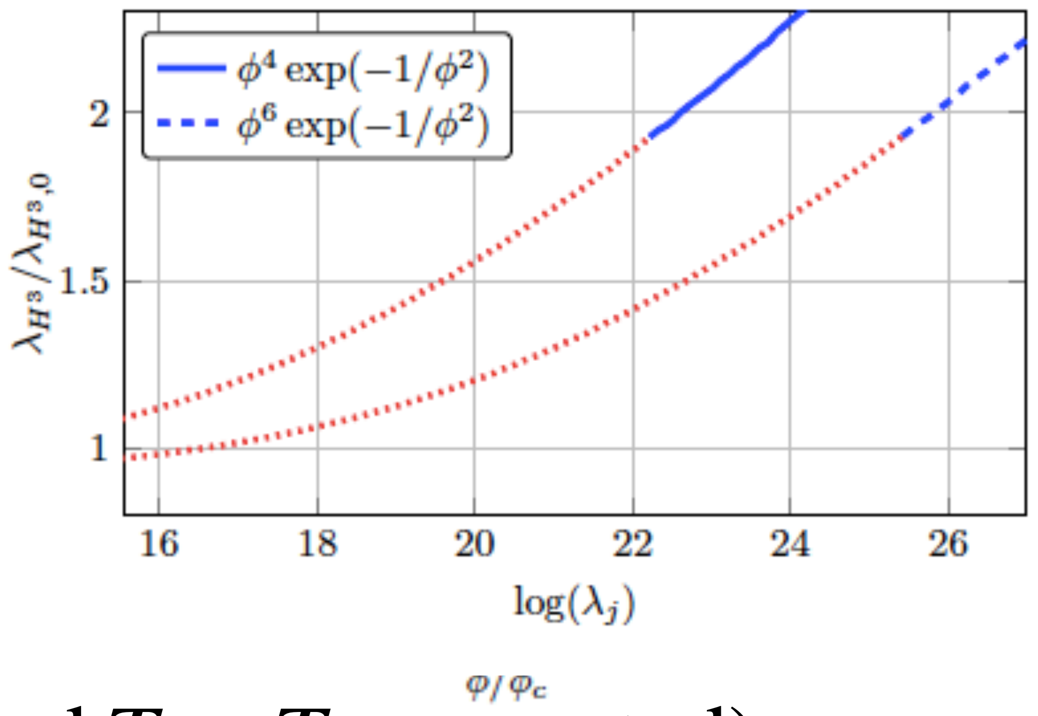




Reichert et al. 1711.00019

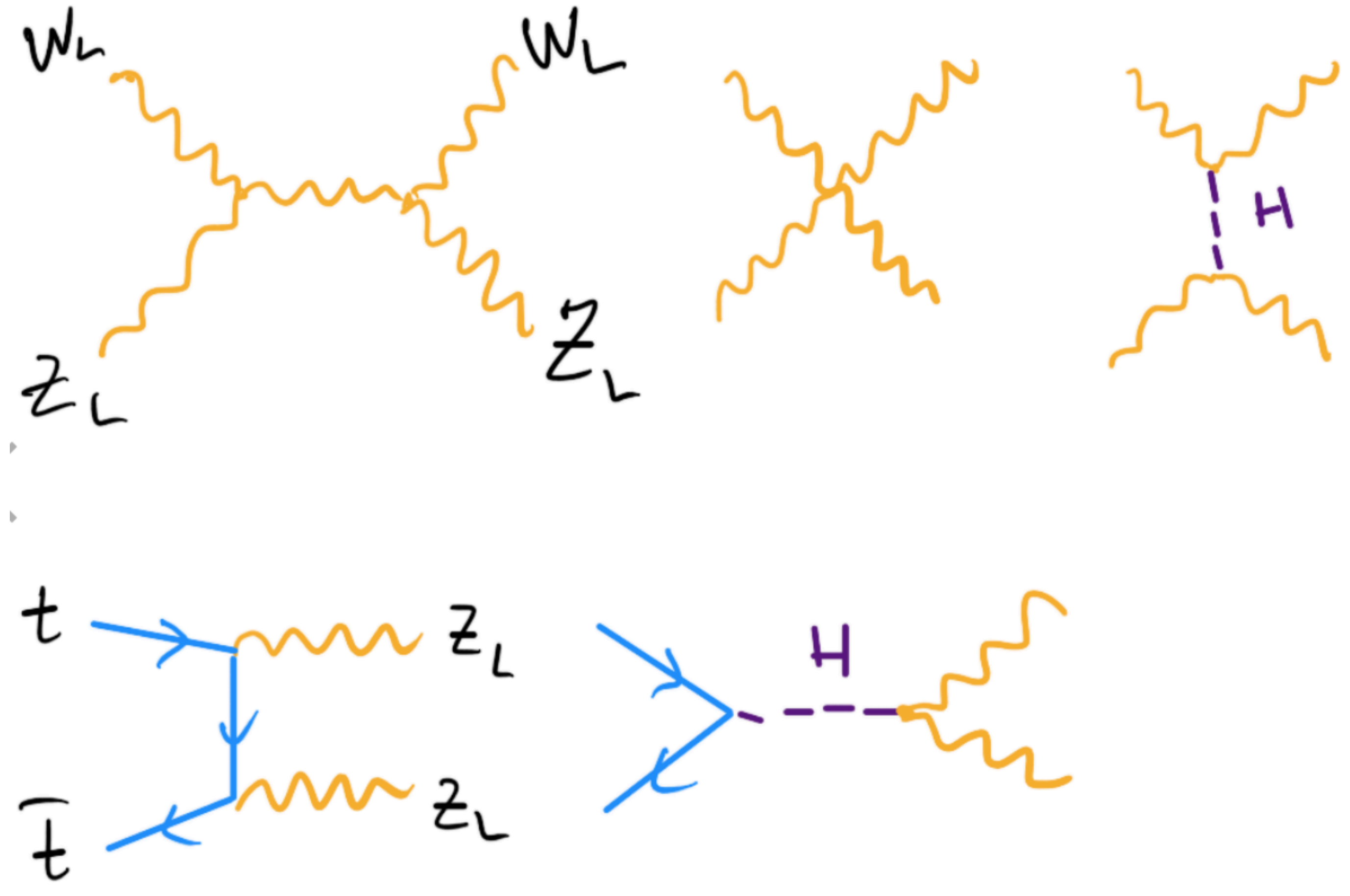
$k_\lambda > 1.5 \Rightarrow$ 1st ord ($T = 0$ and $T = T_c$ connected)

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

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.



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

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

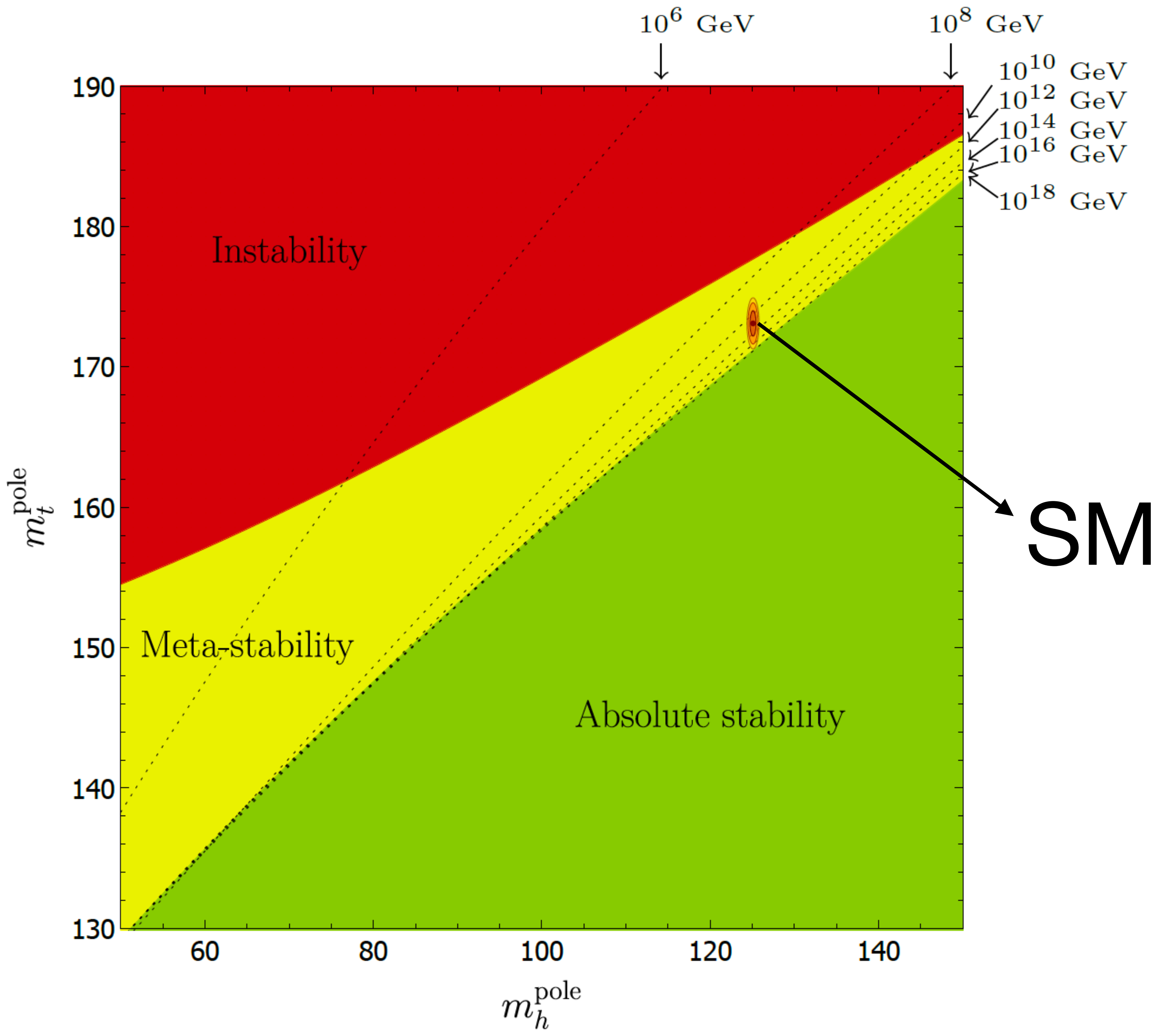
Arbitrary modifications of couplings respecting Lorentz, $U(1)_{EM}$ and SU(3) symmetries generally lead to unitarity violations at low scales.

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

SM 101

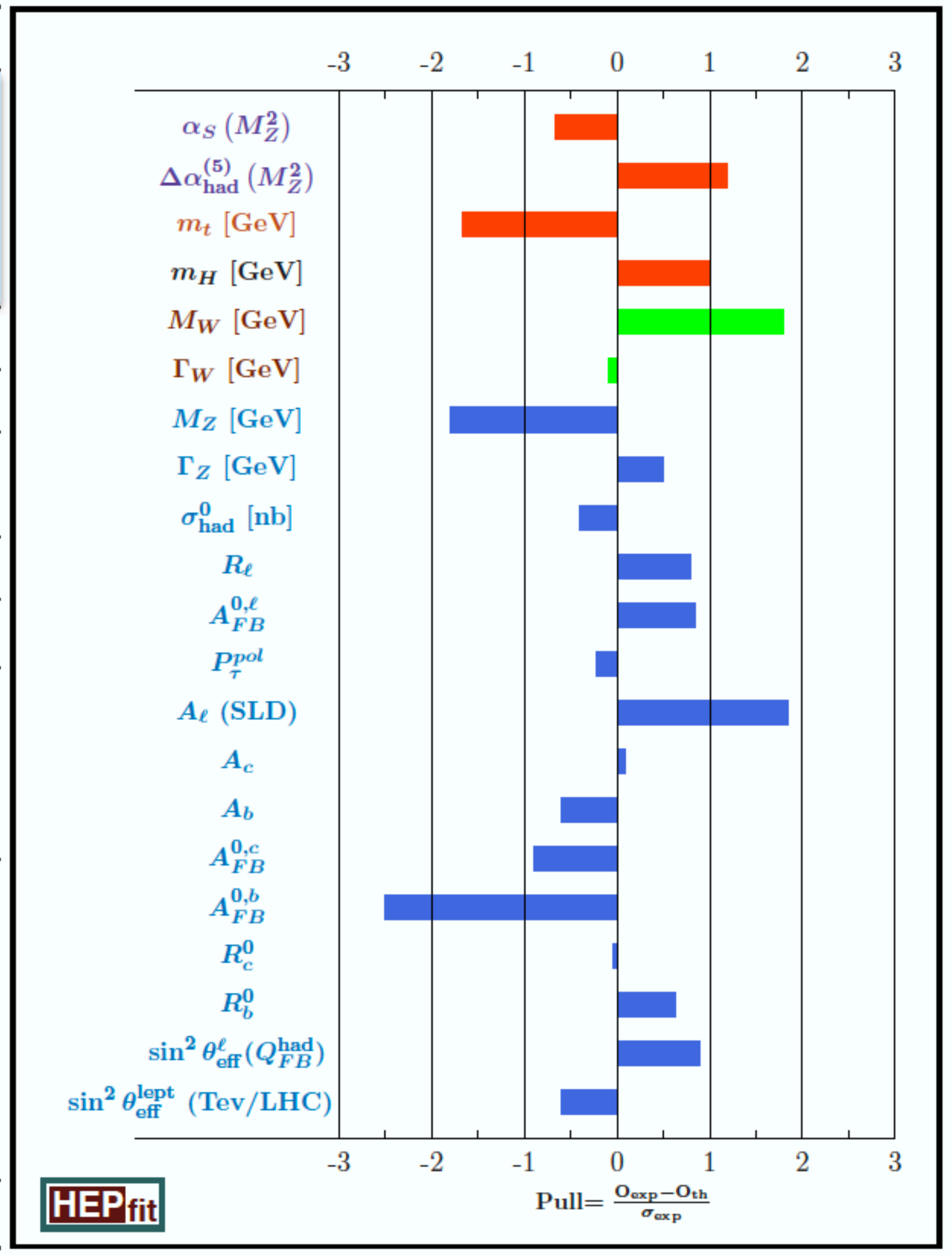
Perturbativity/Loops

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
${\rm BR}_{W\to{\rm had}}$	0.6741±0.0027	0.67486±0.00007	0.67486±0.00007	-0.28
${\rm BR}_{W\to\ell\nu}$	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

SM 101

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Three key properties of the SM:

- Mass generation with gauge invariance
- Unitarity (up to a predefined Λ)
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Is it possible to "minimally" deform the SM without losing any of the above?

A powerful approach

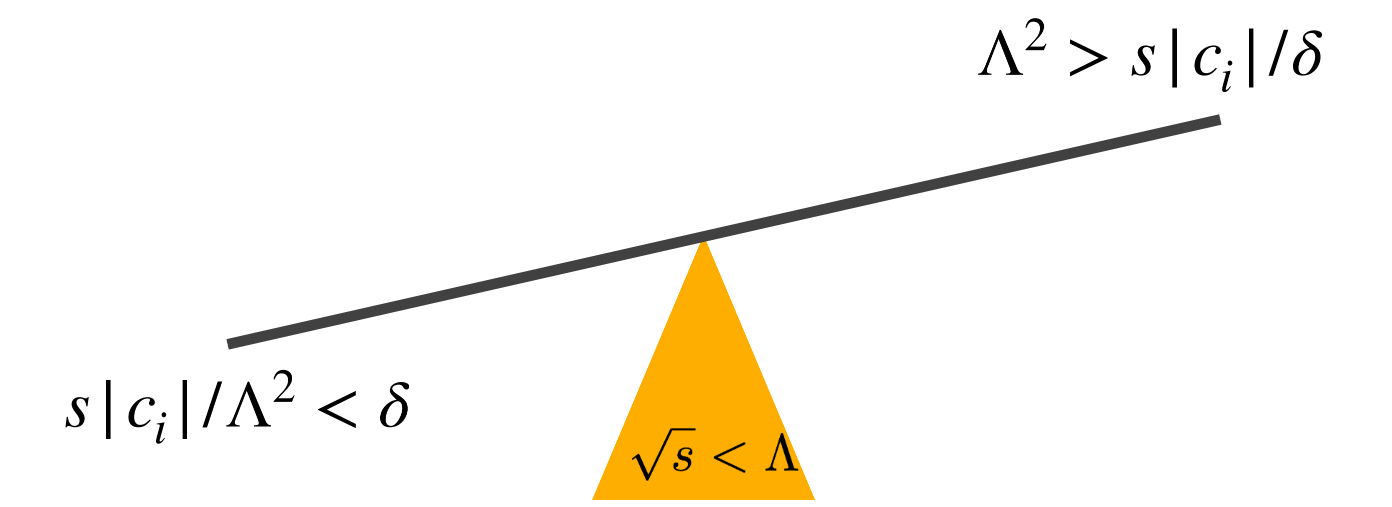
Searching for new interactions with an EFT

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

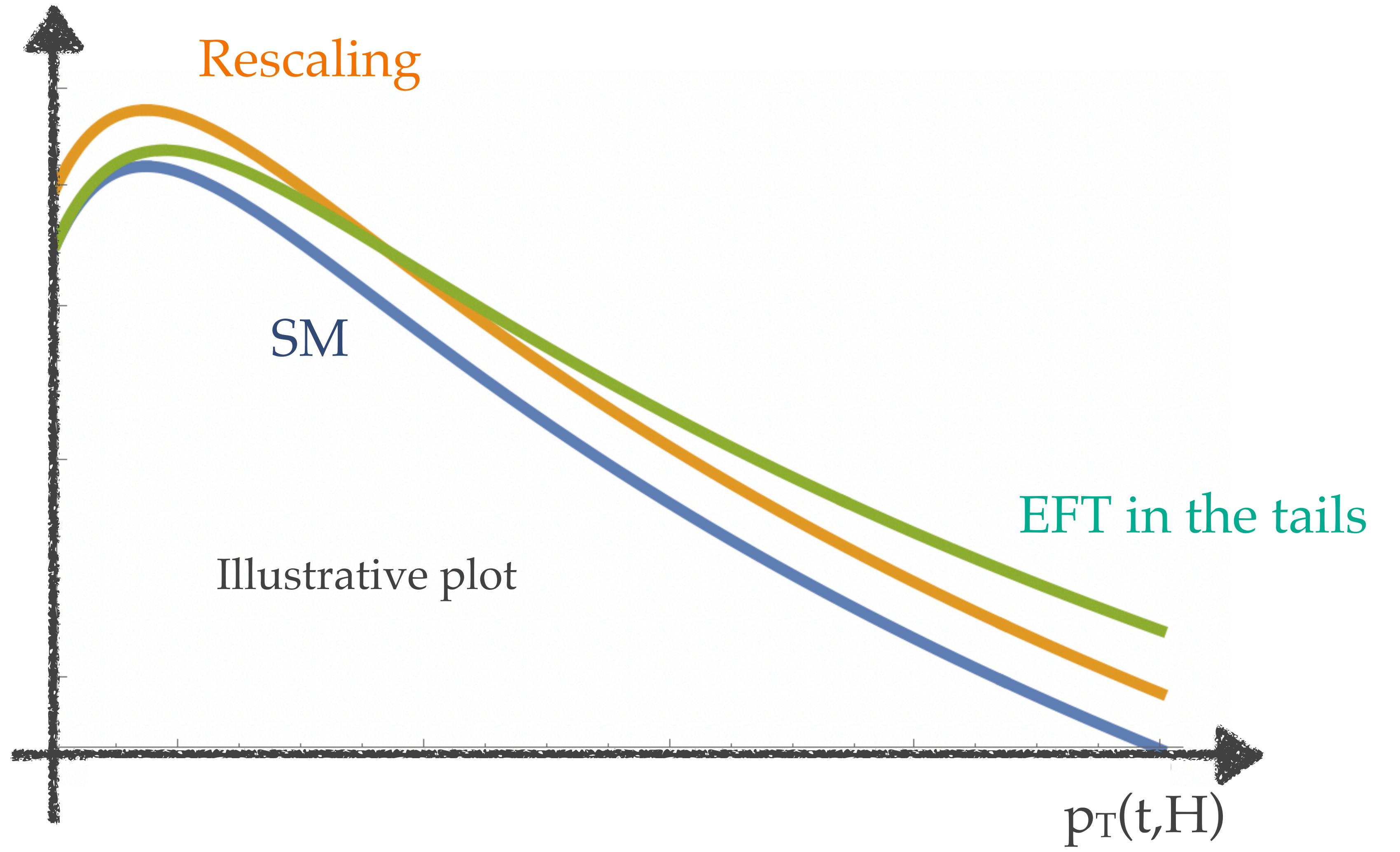
$$\mathcal{L}_{SM}^{(6)} = \mathcal{L}_{SM}^{(4)} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i + \dots$$

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:

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

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→ Most precise/accurate experimental measurements with uncertainties and correlations

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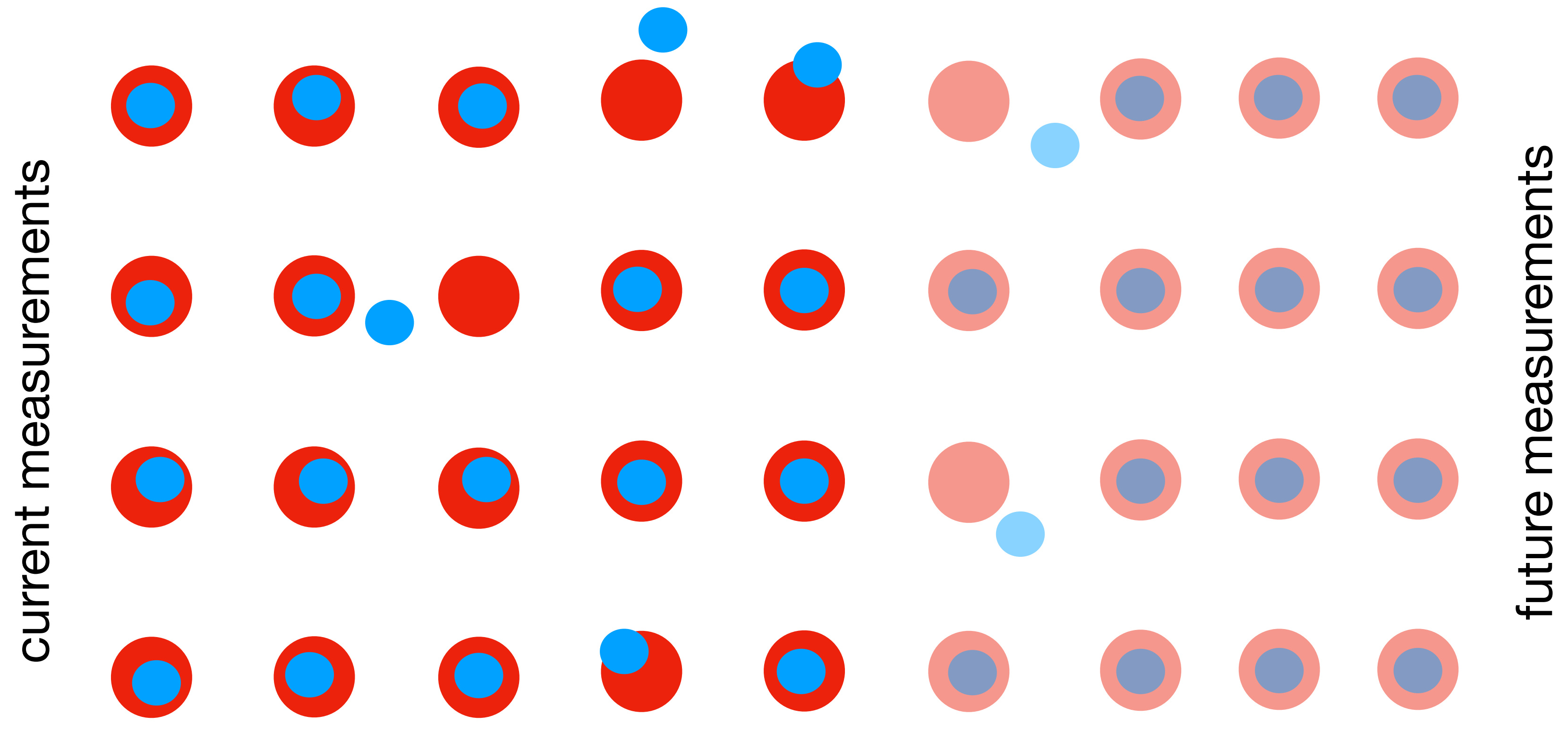

$\Rightarrow$ increased NP Sensitivity

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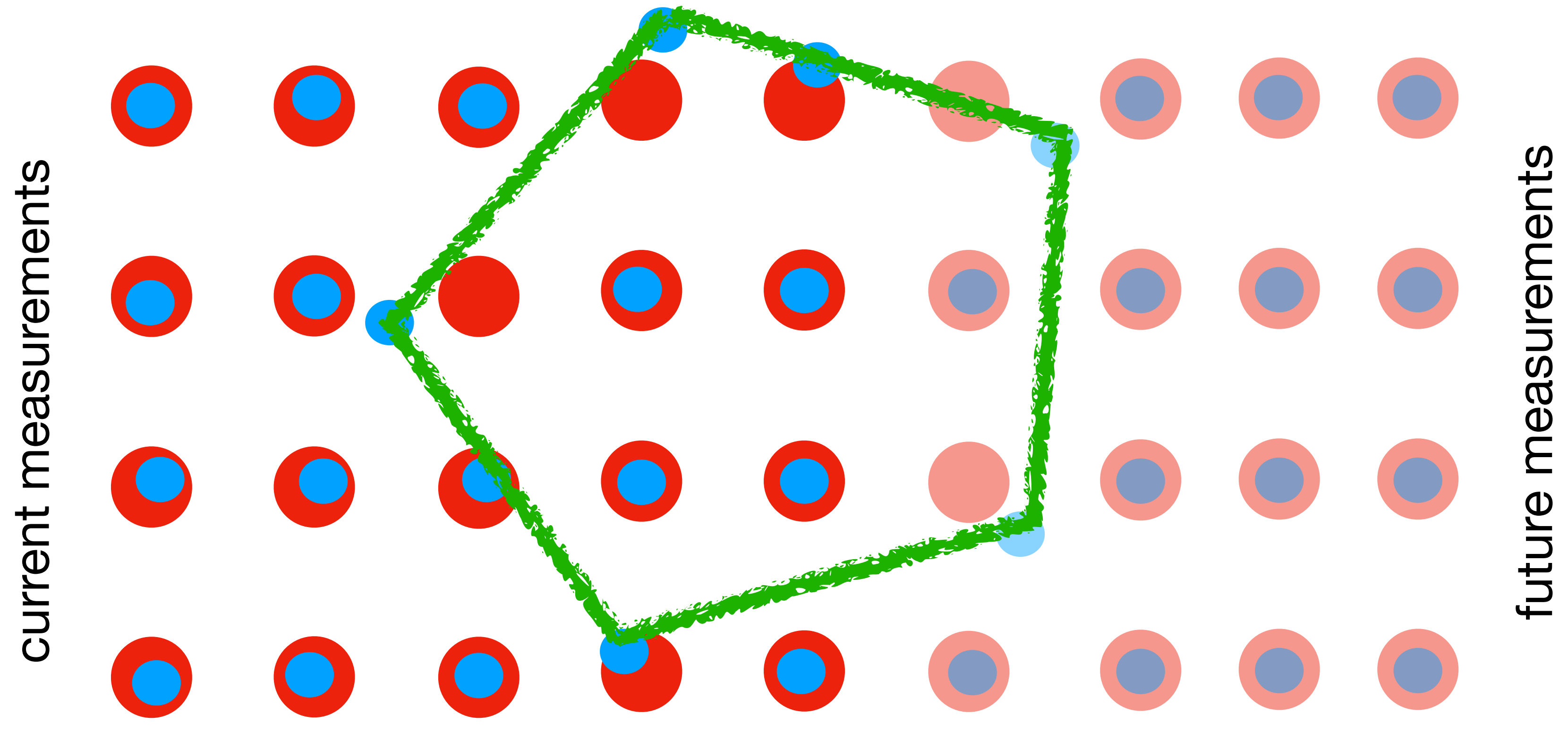

⇒ increased NP Sensitivity

Most precise EFT predictions

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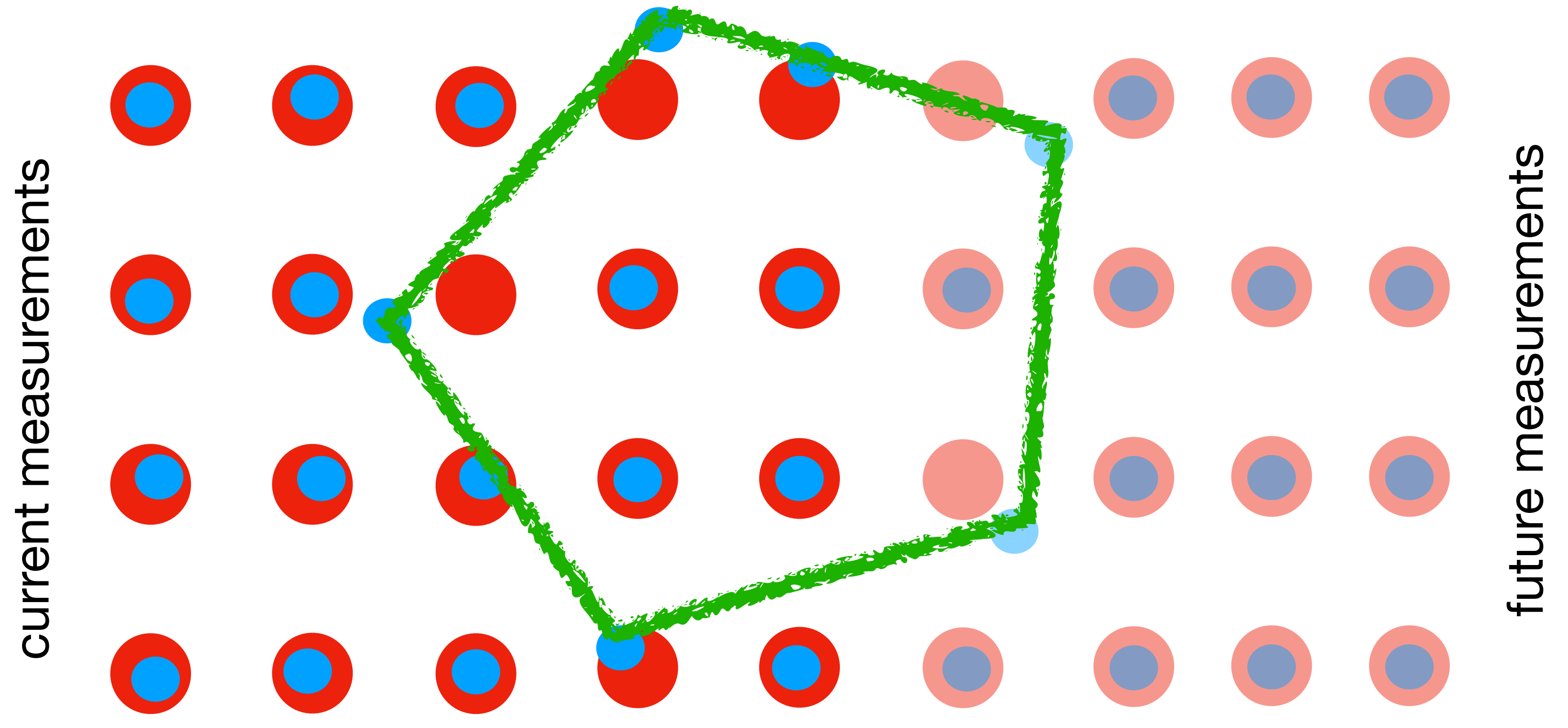
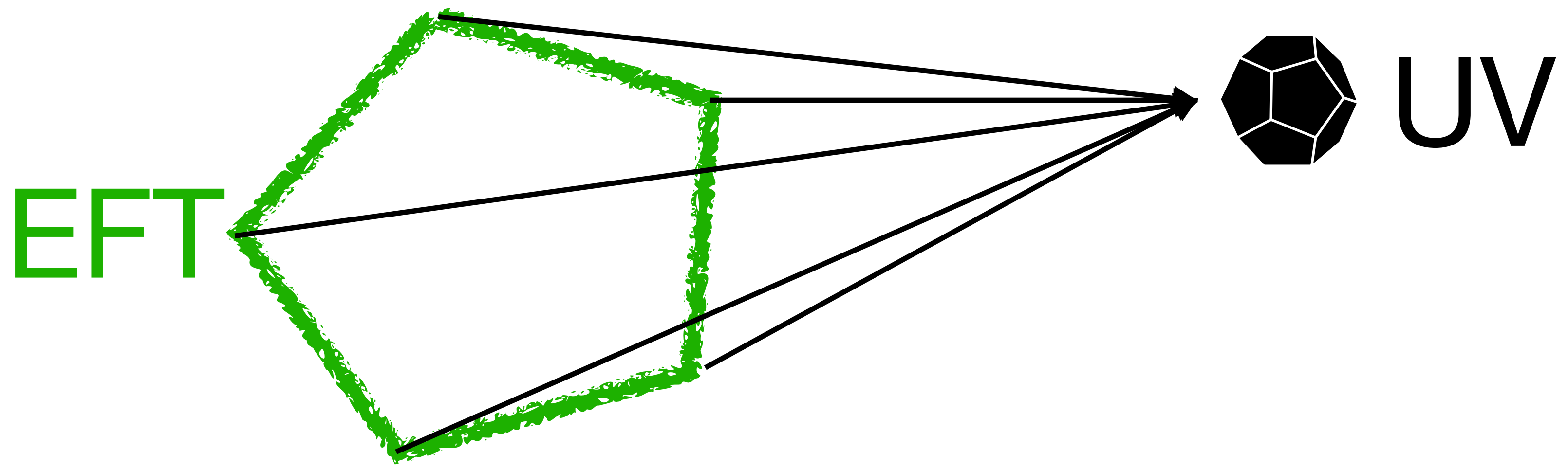


⇒ increased NP Sensitivity

⇒ increased UV identification power

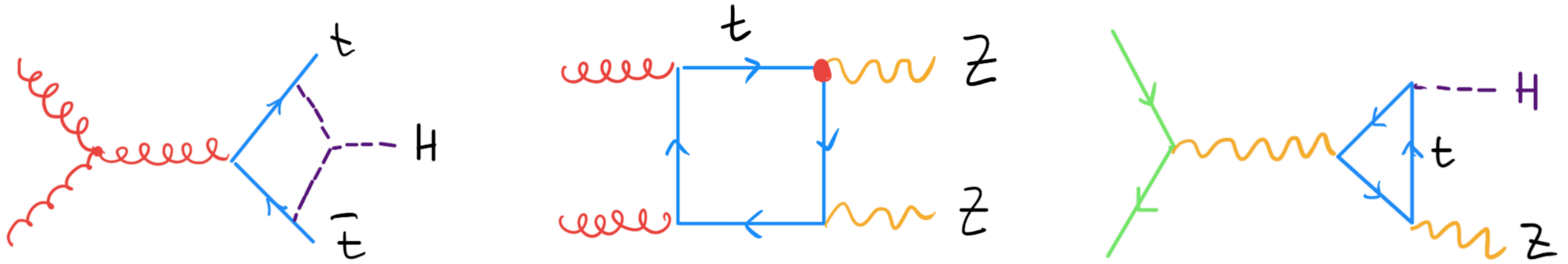


A powerful approach

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:



Many results available. Automation of 1-loop computations in the SMEFT available for QCD corrections, SMEFT@NLO .

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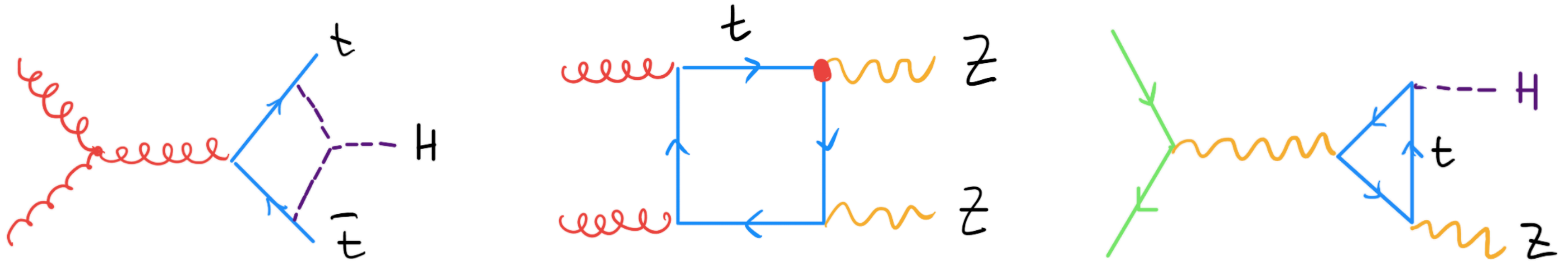
- K-factors (accuracy)
- Scale uncertainties (precision)
- Exploit loop sensitivity:



Many results available. Automation of 1-loop computations in the SMEFT available for QCD corrections, SMEFT@NLO .

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]

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.

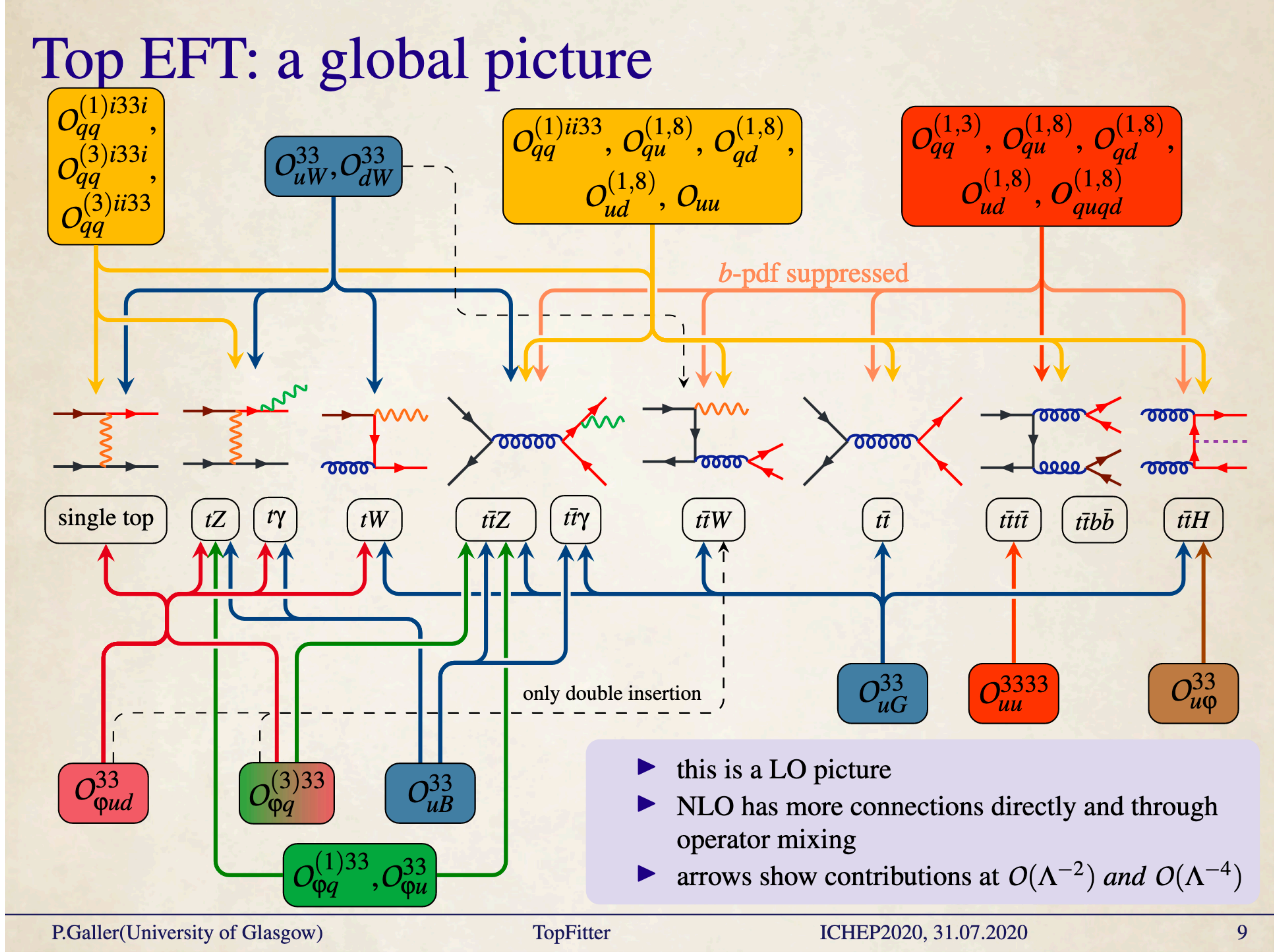
Needs coordinated work among analysis groups in collaborations traditionally working separately (top, Higgs, EW,…)

Needs coordinated work between theorists and experimentalists (model dependence, validity, interpretations, matching to the UV).

A New LHC EFT WG has just been set up.

Tremendous community progress…

[Galler, ICHEP2020]



A powerful approach

What are we going to learn?

[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

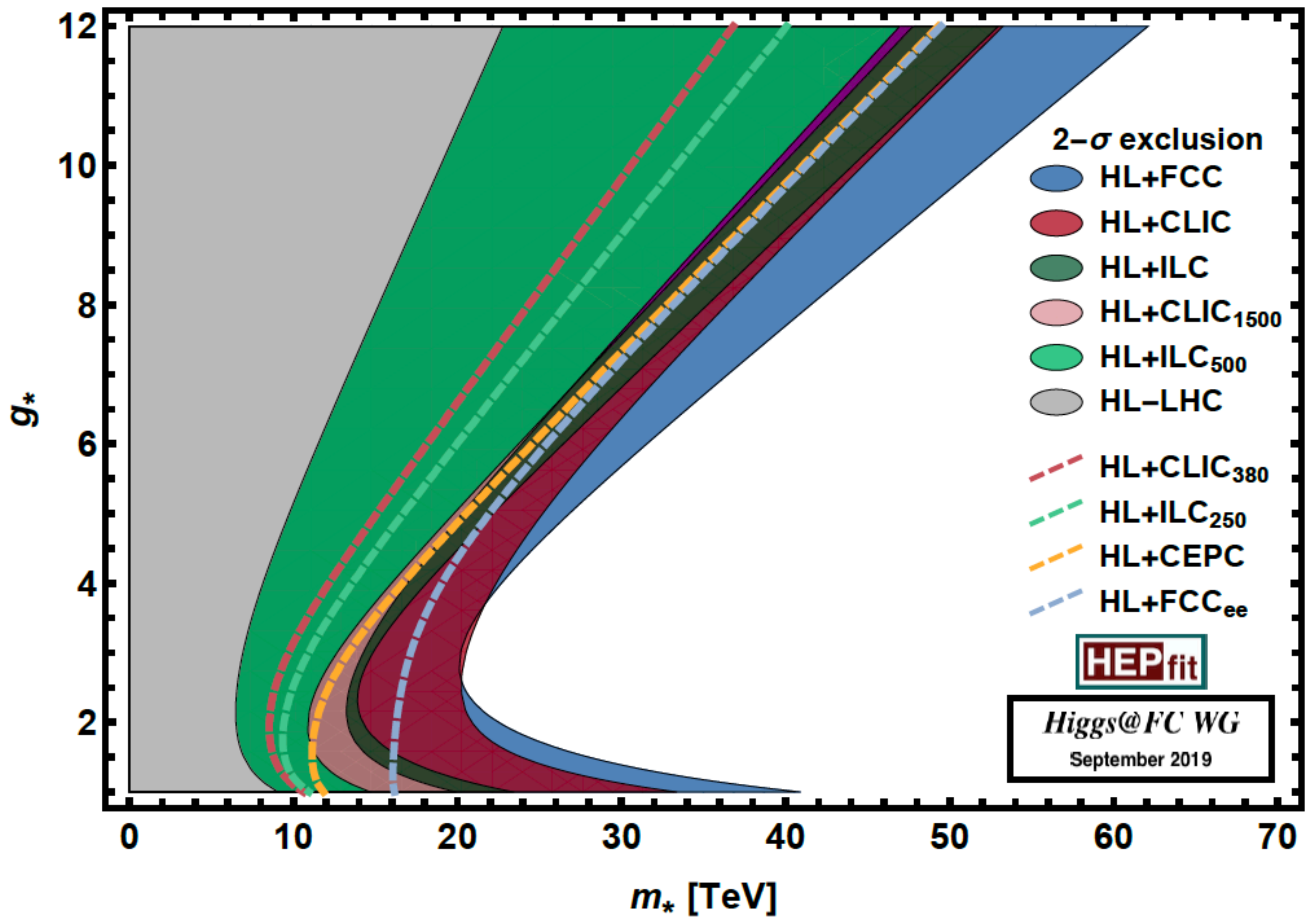
$\varepsilon \equiv m_H^2 / \Delta m_H^2$

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

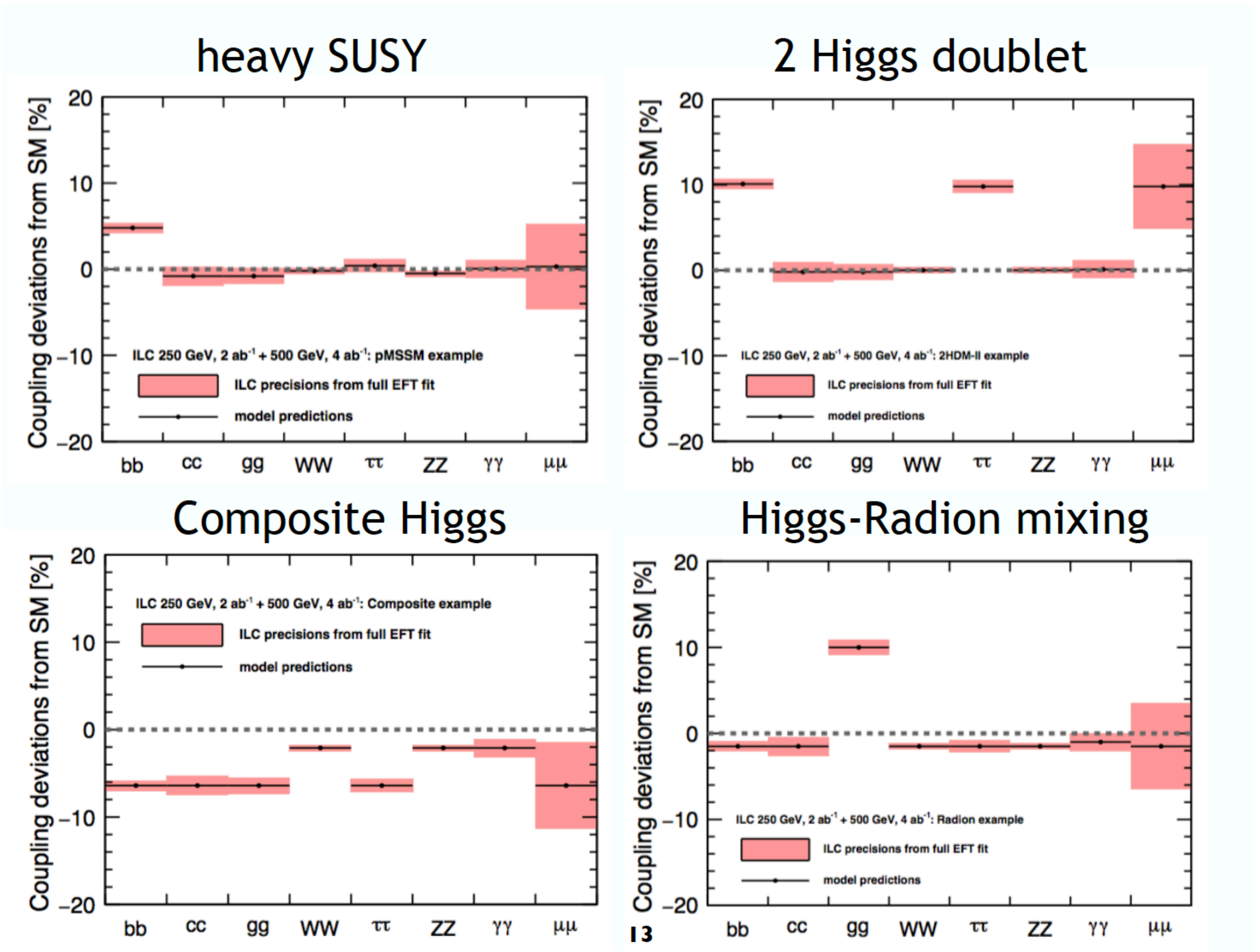
Direct searches	Higgs couplings	EWPT
$\epsilon = (10^{-4}, 10^{-3}, 10^{-2})$	$\delta g_H / g_H{}^{SM} \sim c\,\varepsilon$	$\widehat{S} \sim (\alpha_W/4\pi)(m_{weak}^2/m_*^2)$

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]

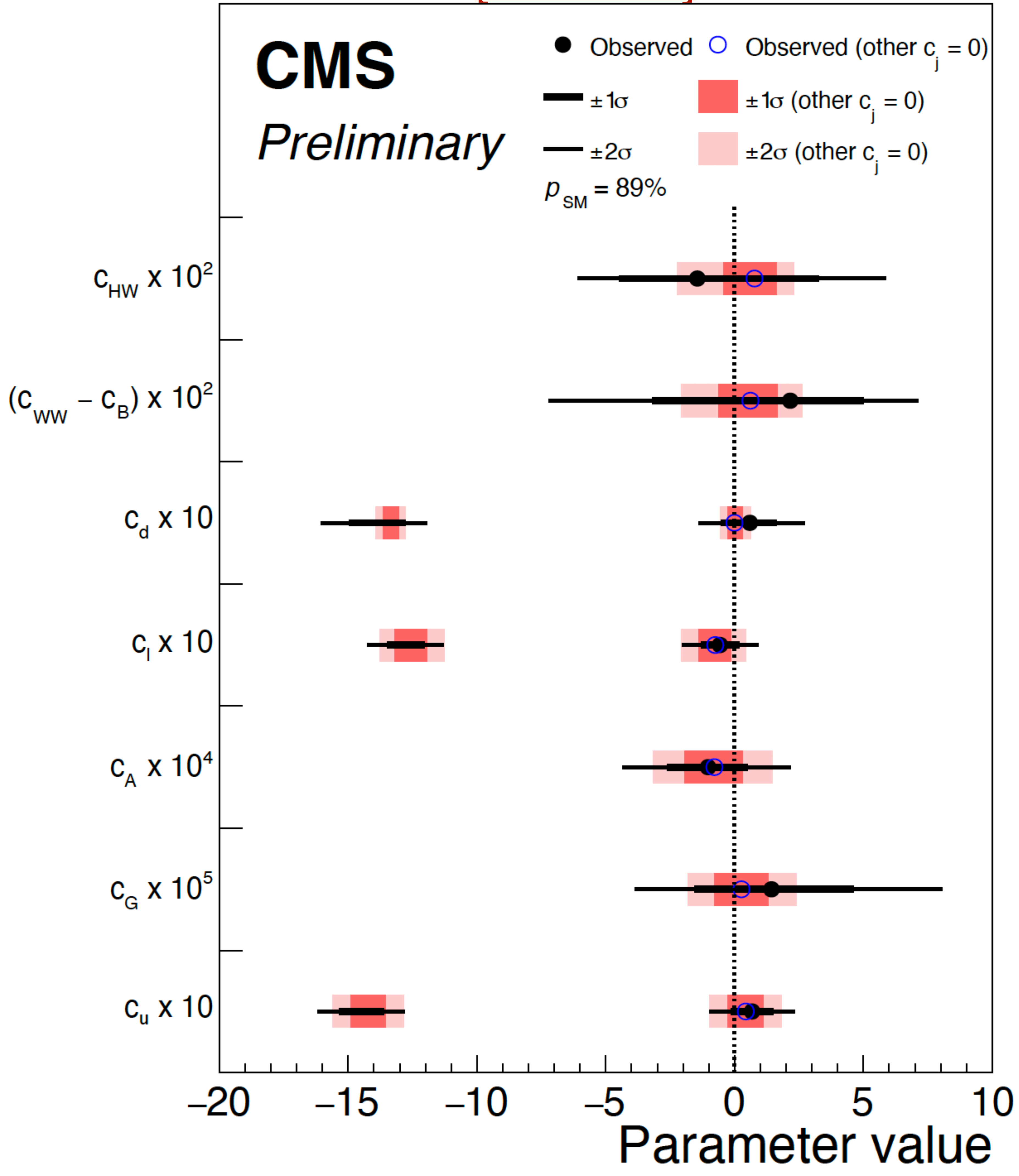
Experimental fits

CMS Higgs combination fit

- SILH basis, HEL implementation. Warsaw mapping.
- 8 operators, 7 d.o.f (1 fixed by EWPO).
- Production gg, VBF, VH, ttH.
- Decay to $\gamma\gamma$,ZZ,WW,$\tau\tau$, $\mu\mu$, bb.
- Single operators and marginalised fit.

Fit at the quadratic level in the SMEFT. No corrections for EFT acceptance. Very close to $k-$framework.

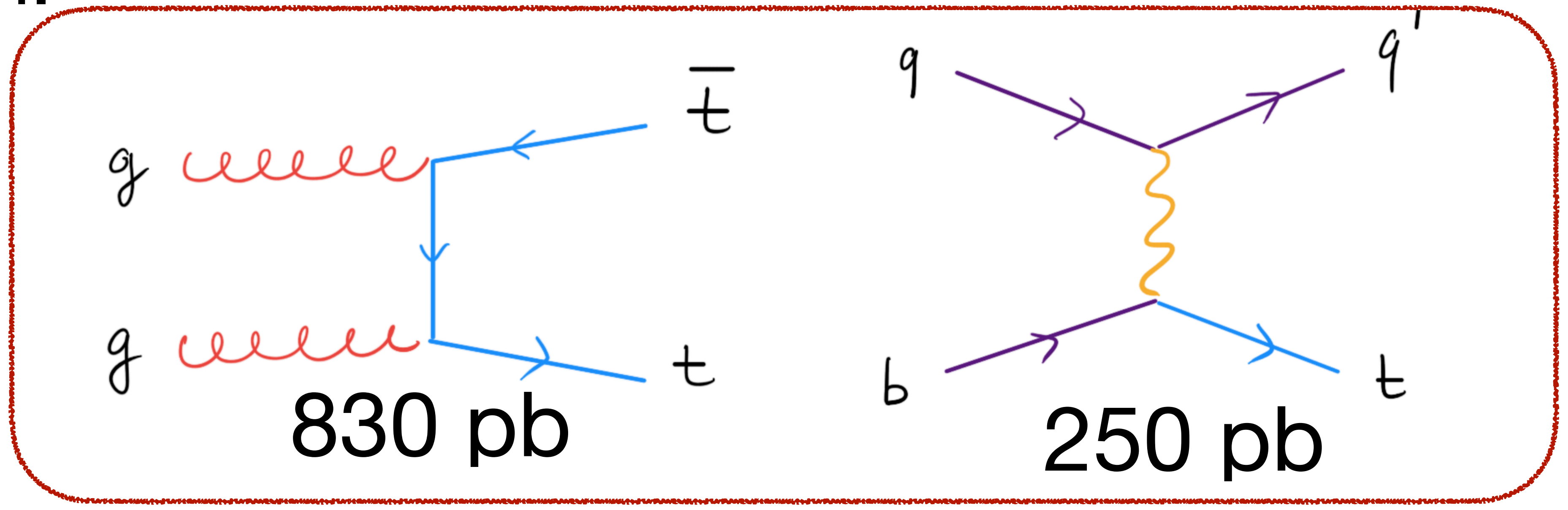
[CMS 2020] 35.9-137 fb^{-1} (13 TeV)

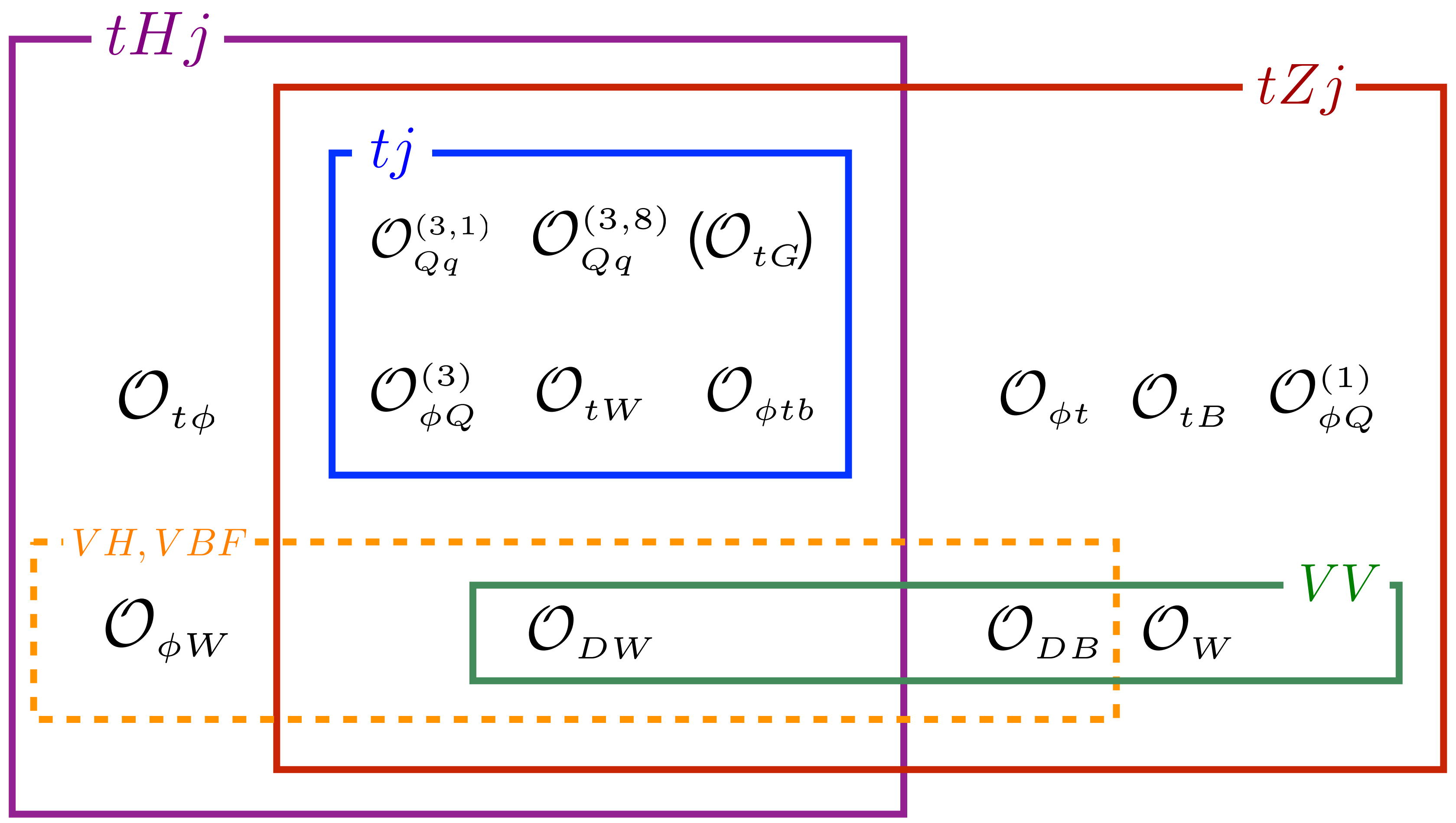


Experimental fits

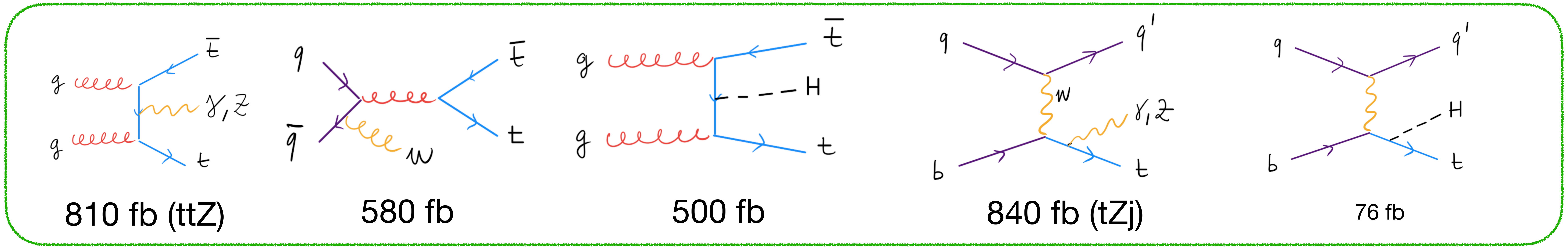
CMS top fit

Main top quark production channels are top pair and single top production.





Selecting multi-lepton final state starting from 2ssl, 3lept, 4lept and focusing on operators that can be especially bounded through these channels:



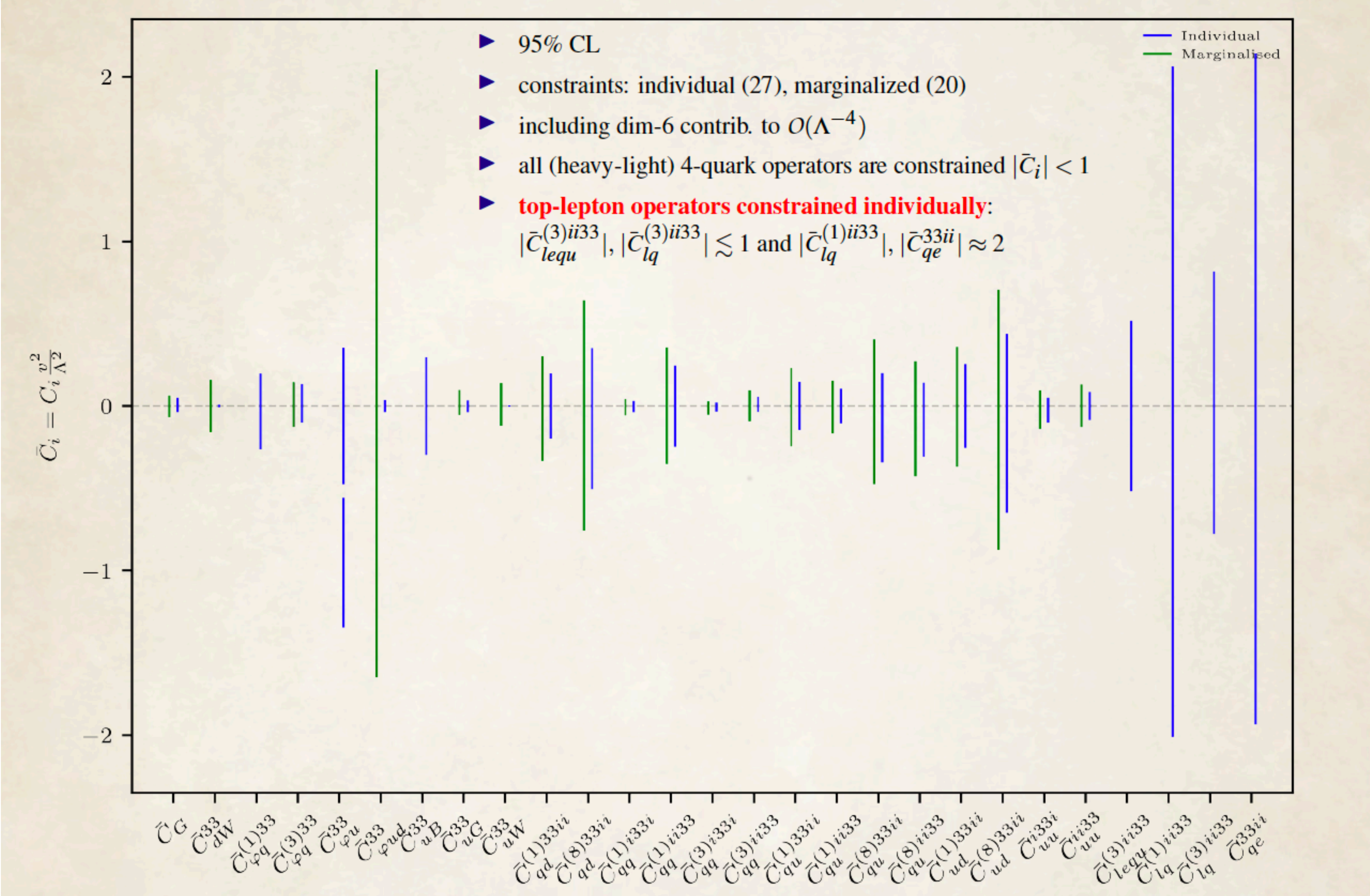
Built-in assumption: operators entering in tt and tj are considered to be bound.

Experimental fits

CMS top fit

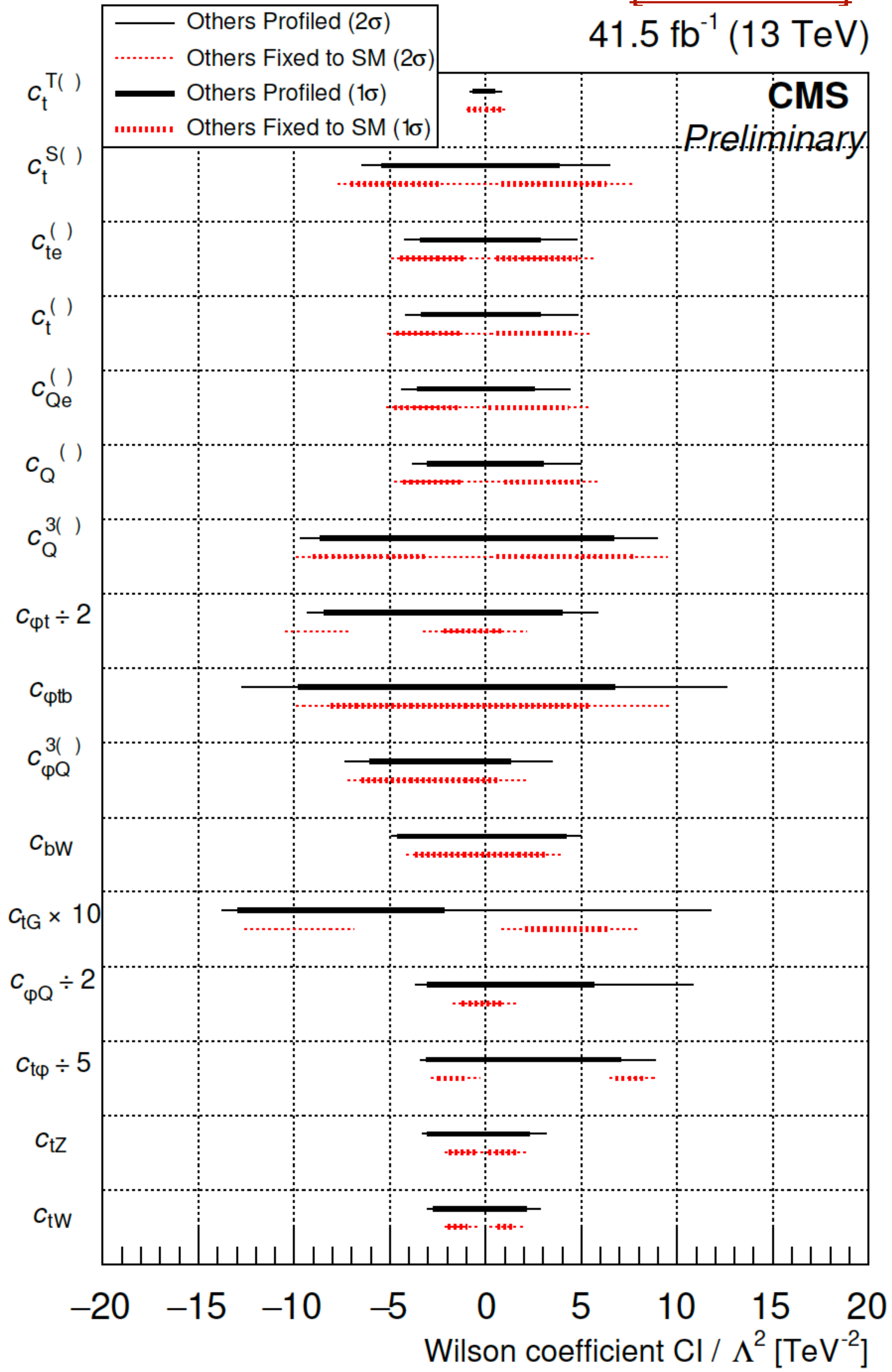
- 35 signal regions, 16 operators, including ttll ones.

- Limits for operators only appearing here comparable with global TH fits, see, e.g., top fitter:



[Galler, ICHEP2020]

[CMS 2020]

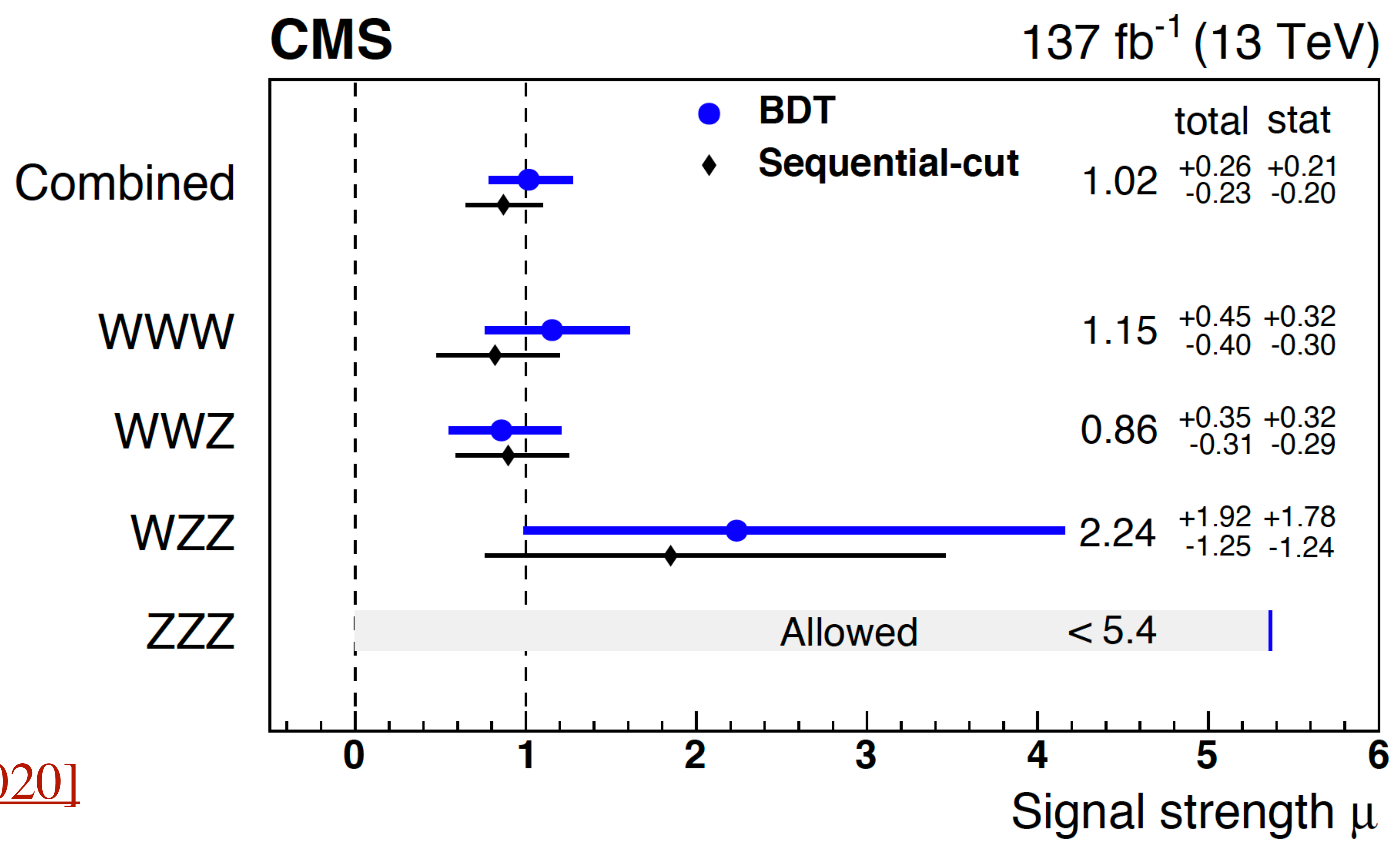


- Great example of top-down EFT analysis.

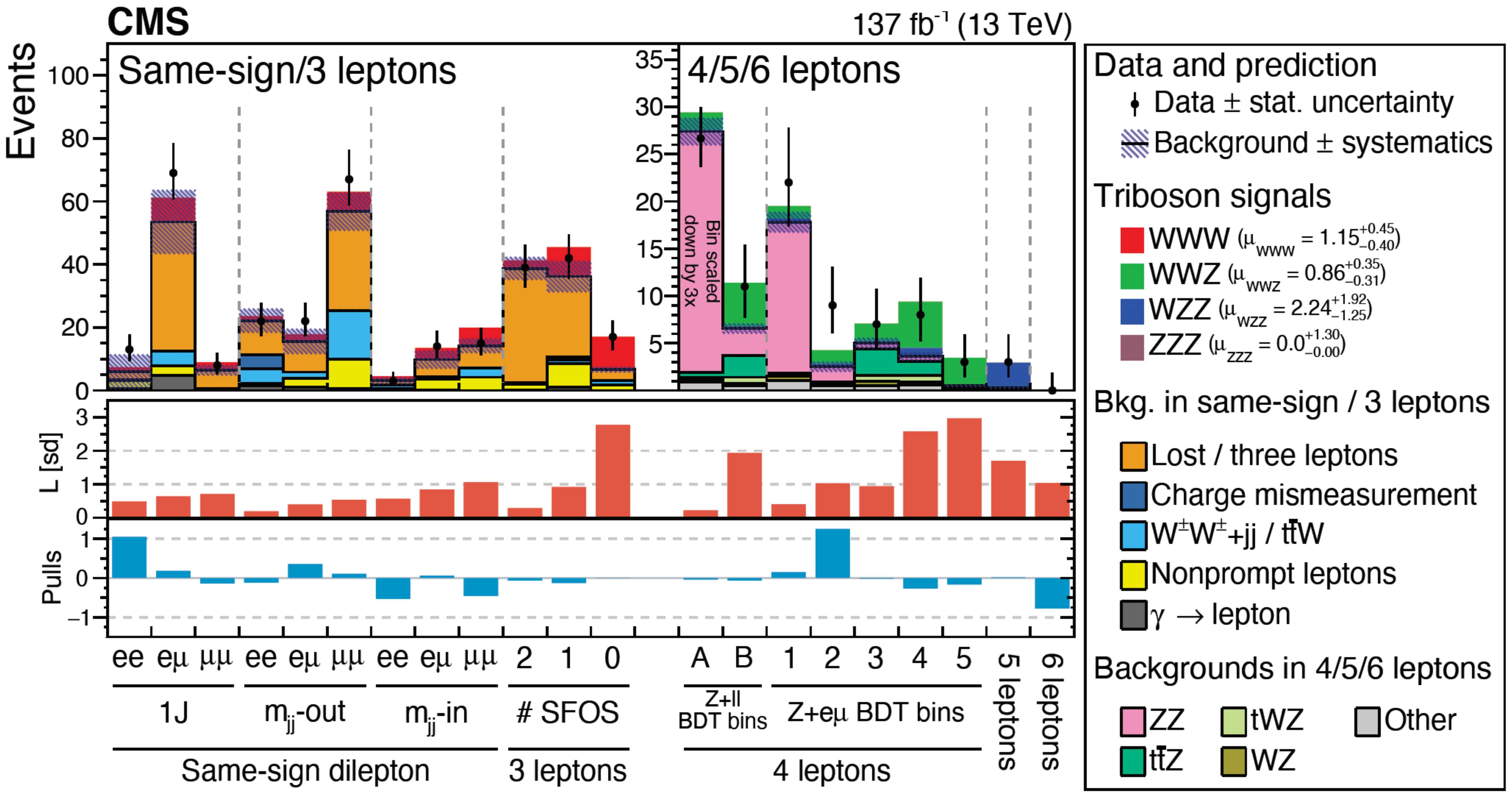
VVV measurement

the 1000th CMS paper

- 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.



[CMS, 2020]



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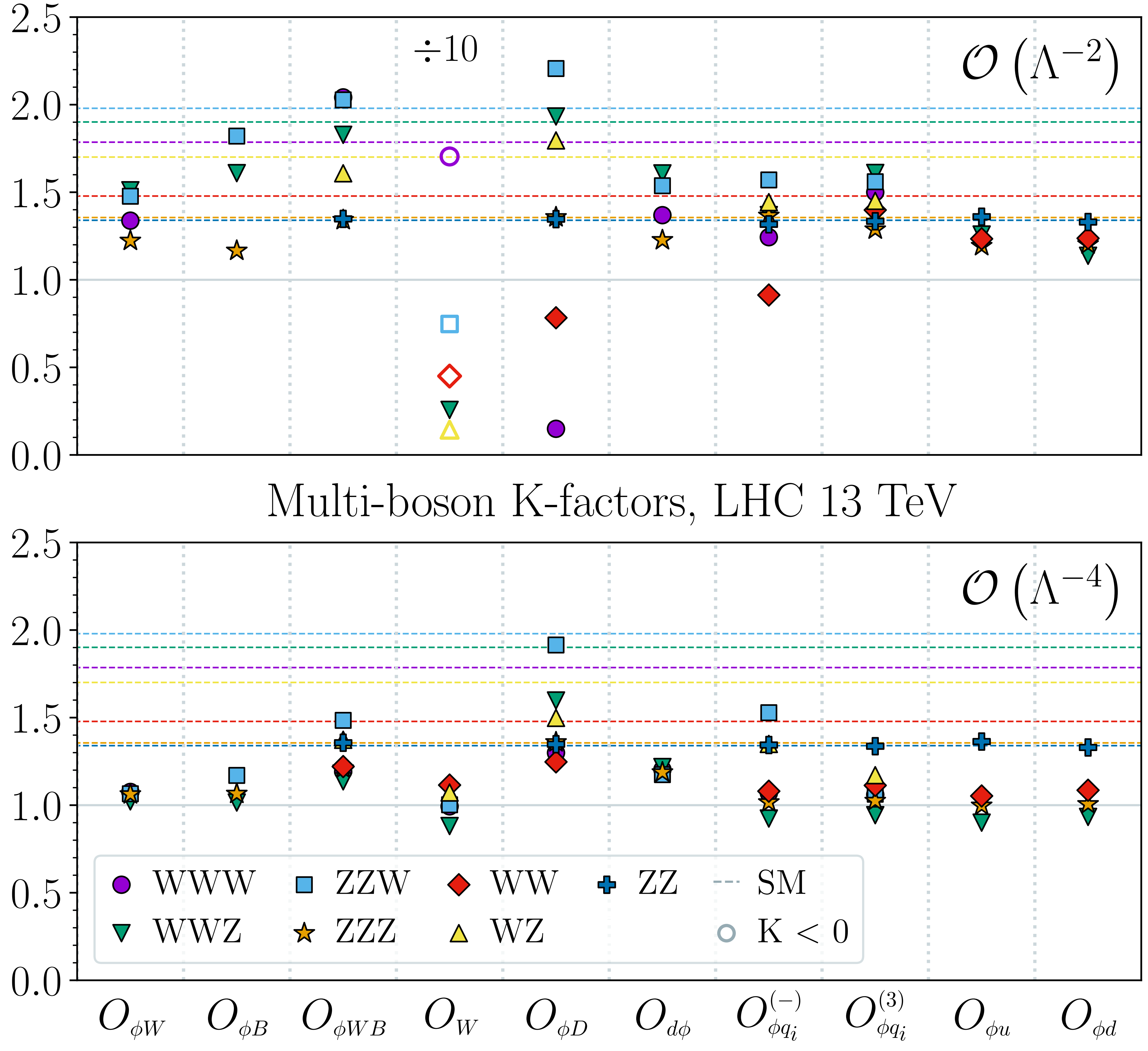
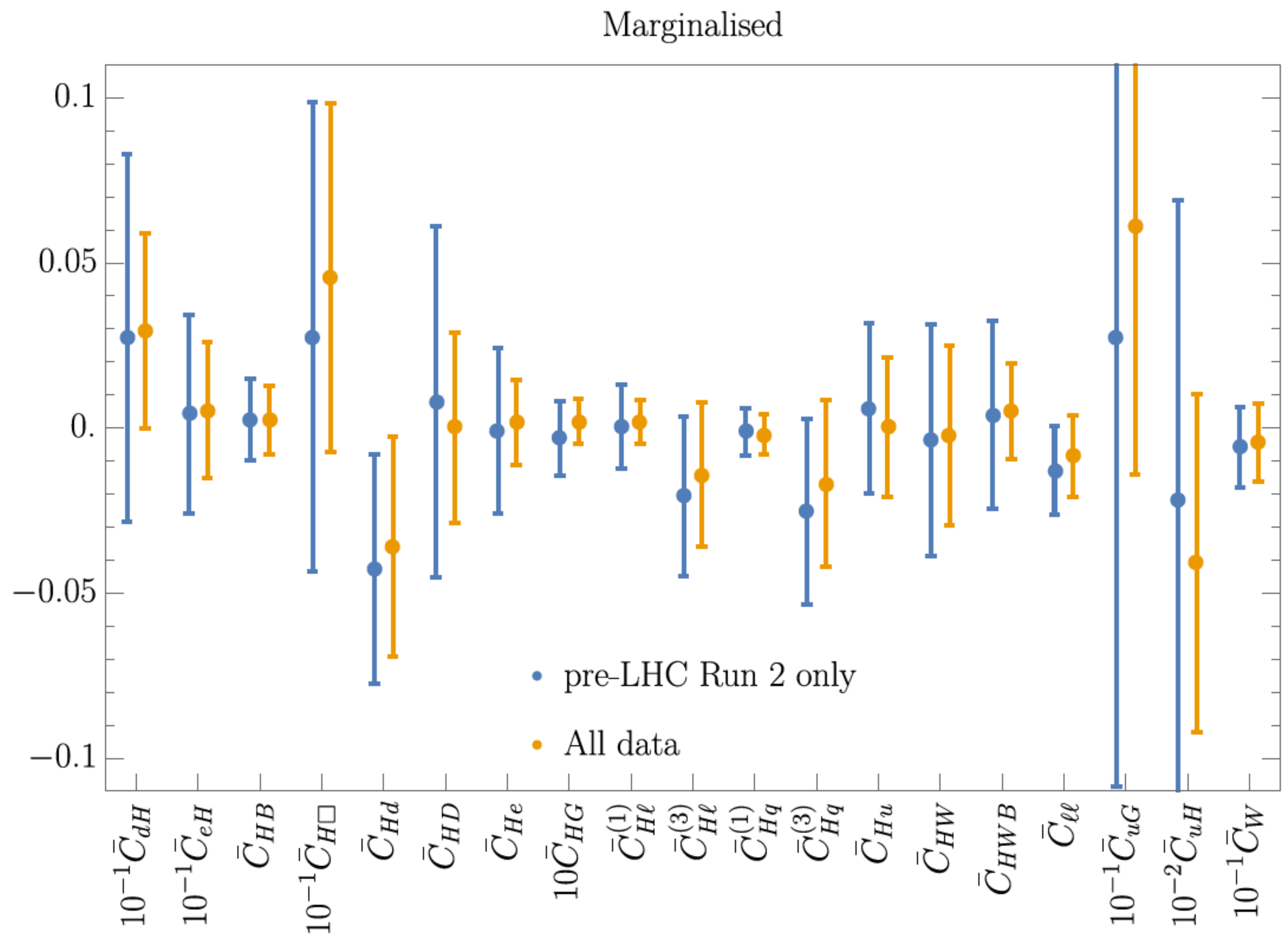
[Courtesy of Degrande et al., work in progress]



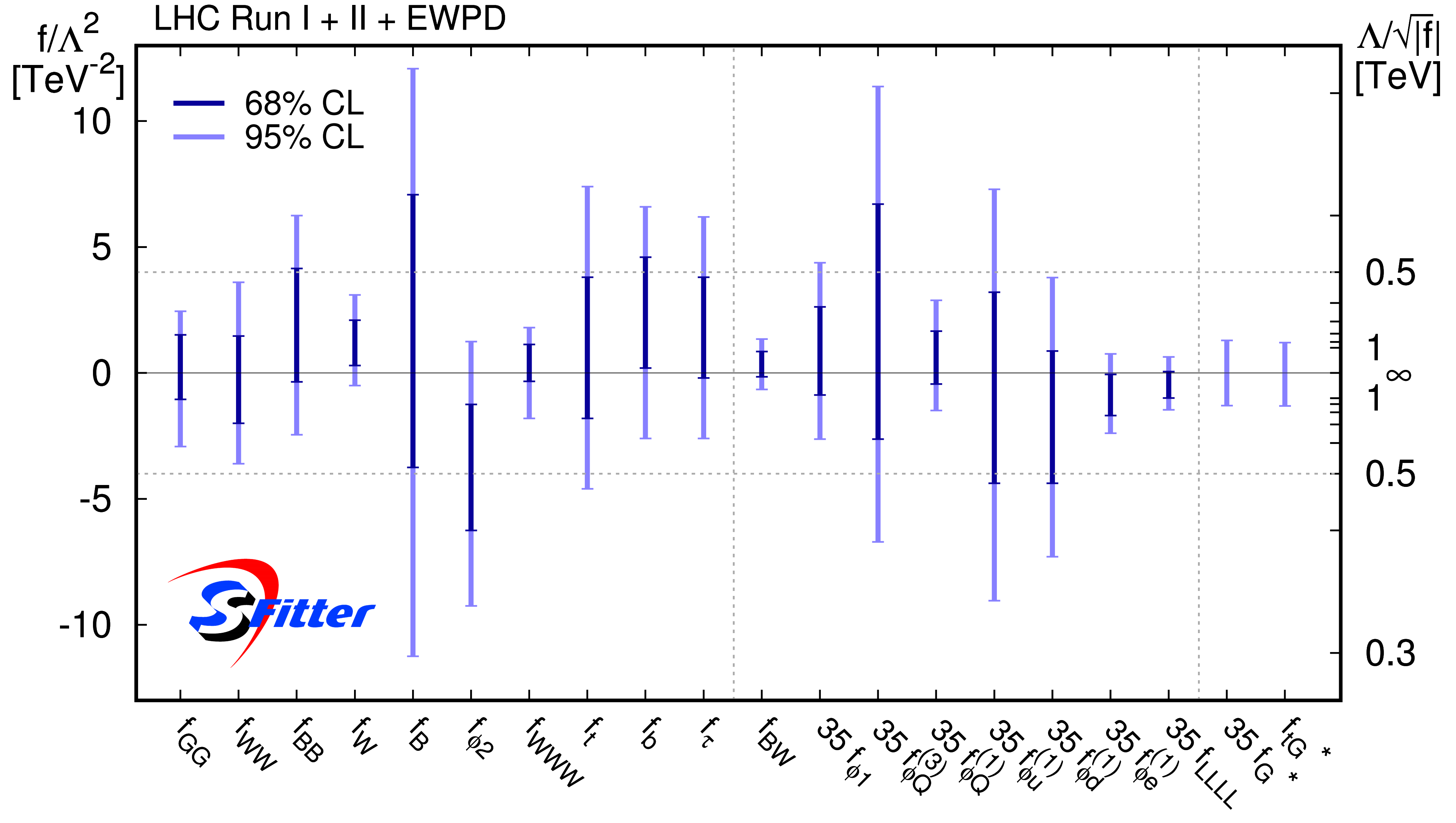
SMEFT

Global fits: EW+H+WW

- 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.



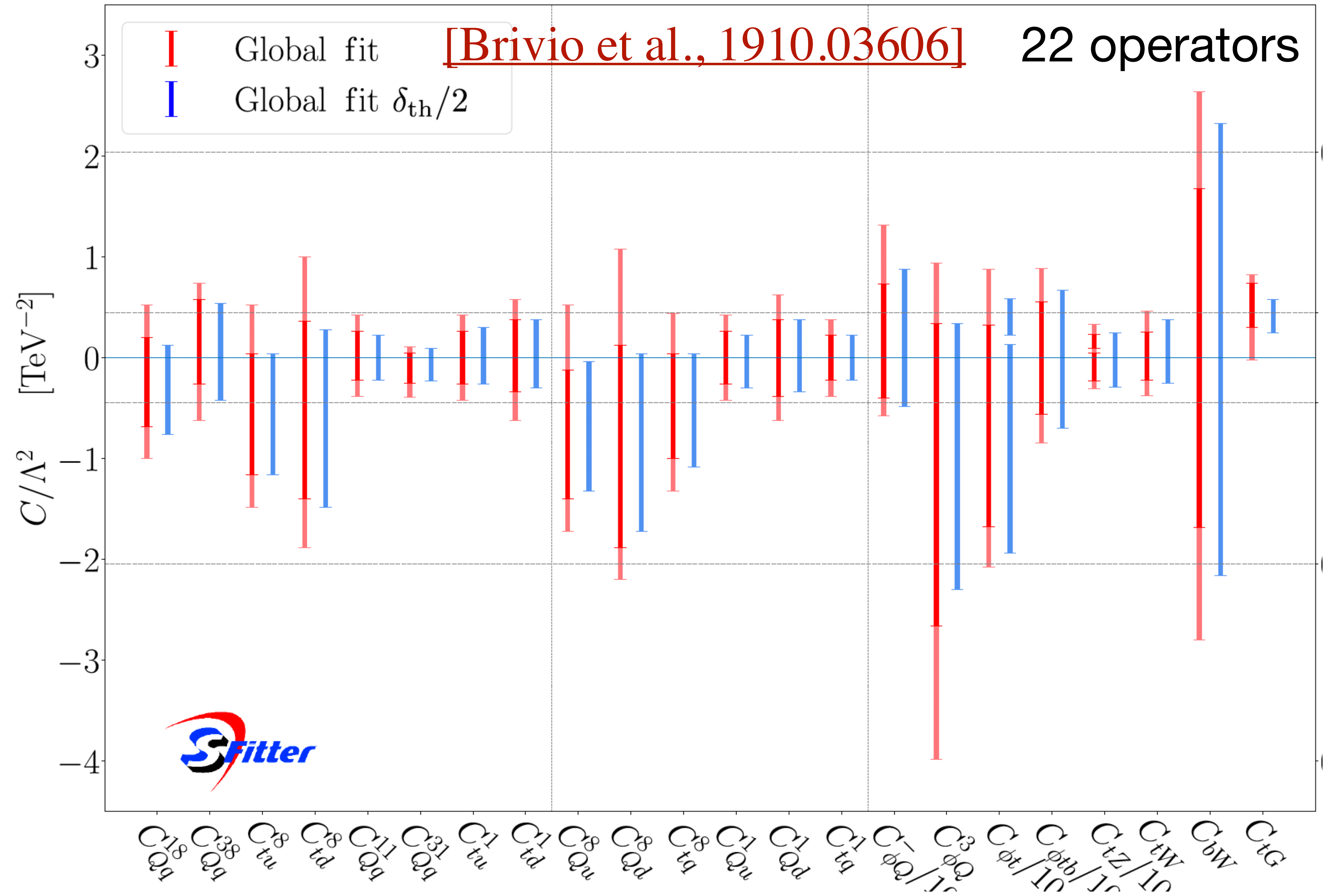
[Ellis, Murphy, Sanz, You '18]

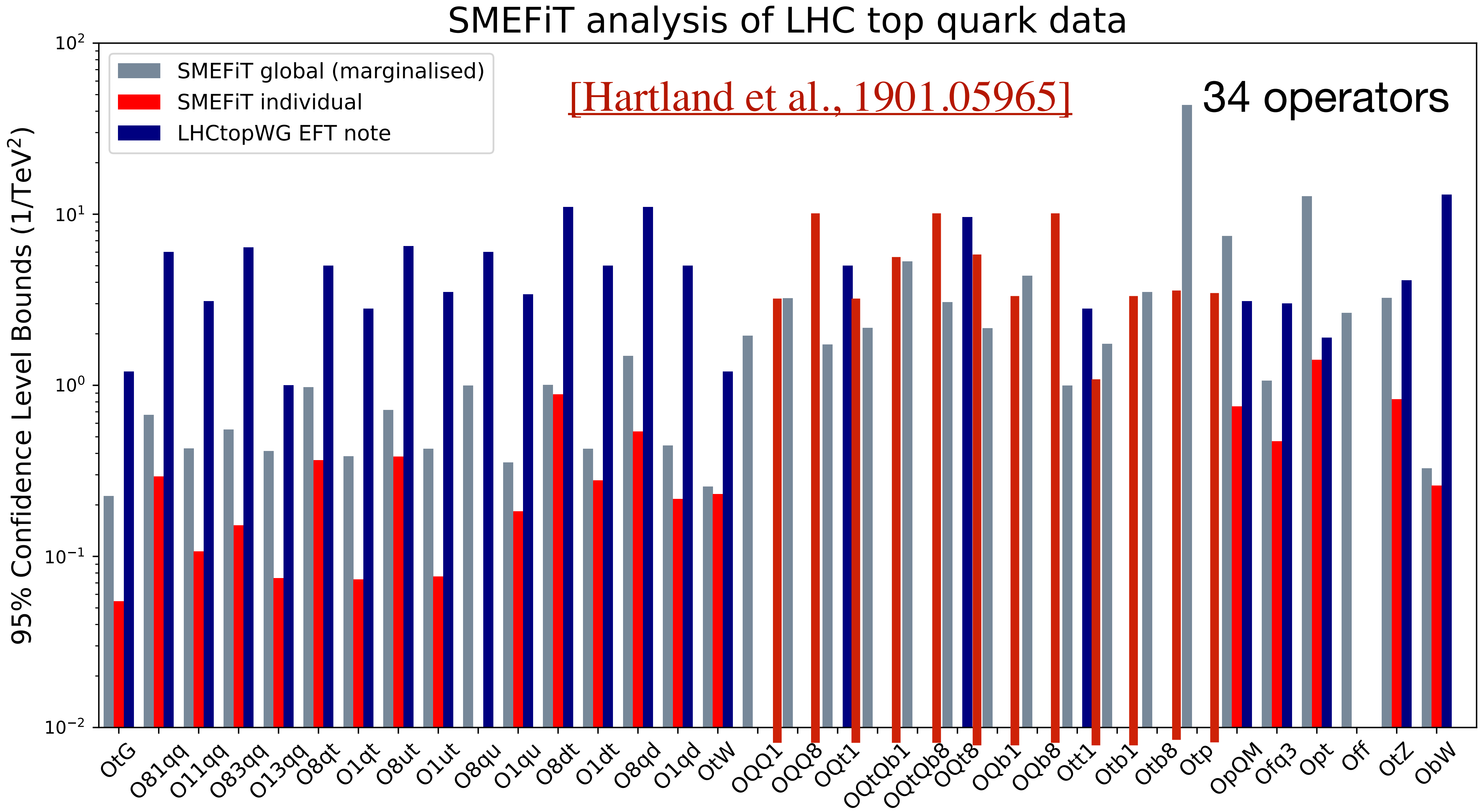


[Biekötter, Corbett, Plehn '18]

SMEFT
Global fits: Top

- 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.



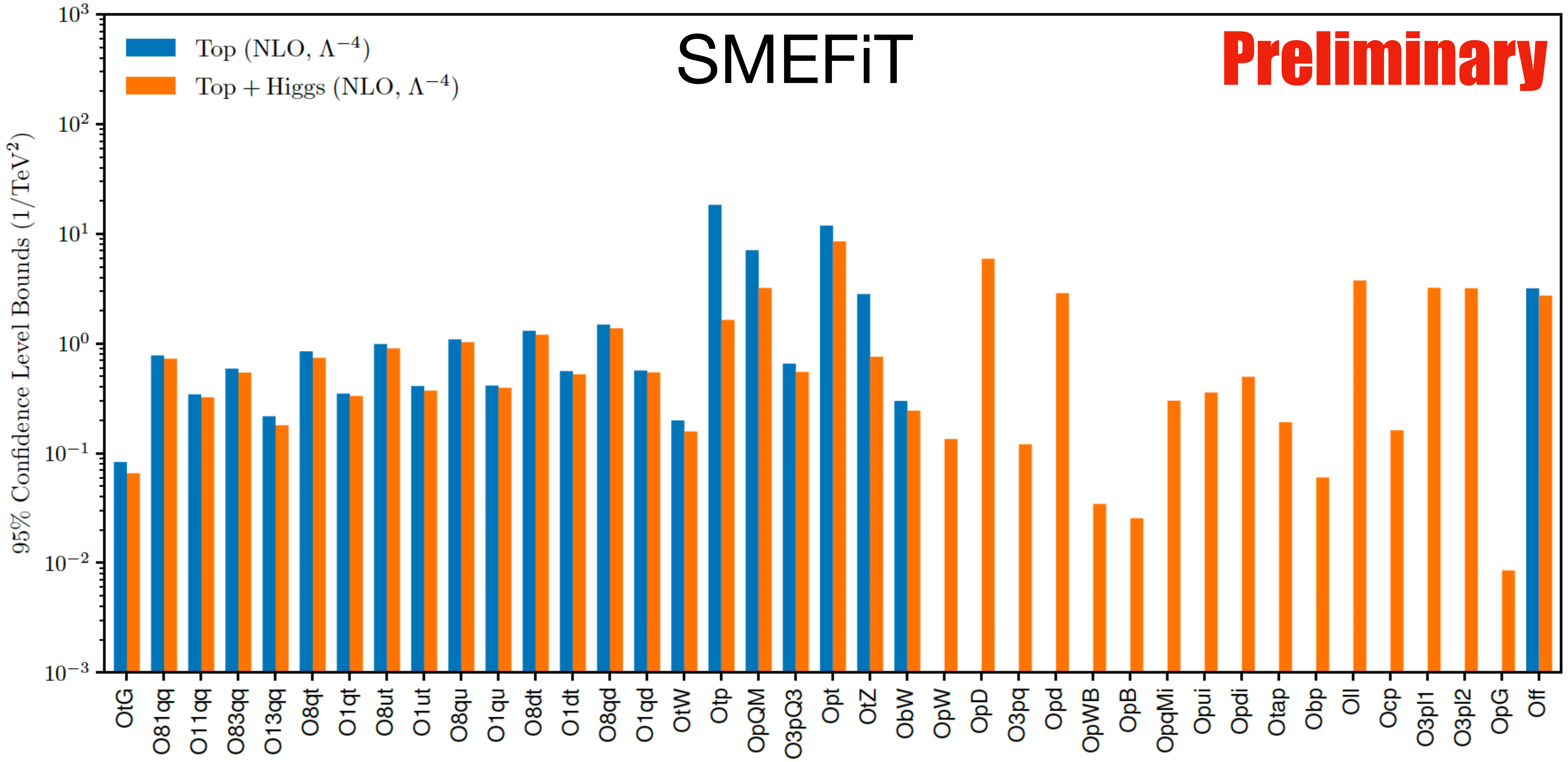


SMEFT

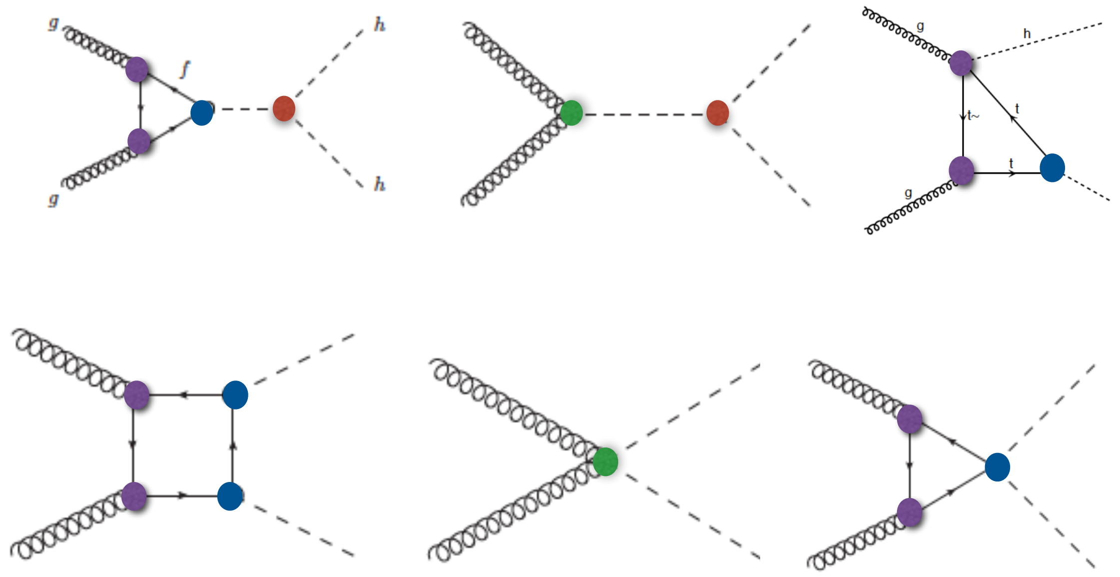
Global fits: Top + Higgs

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

The top sector is connected to both the EW and Higgs sectors and therefore a really global approach is needed. A total of 24 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).



SMEFT
Global fit Top + Higgs: application

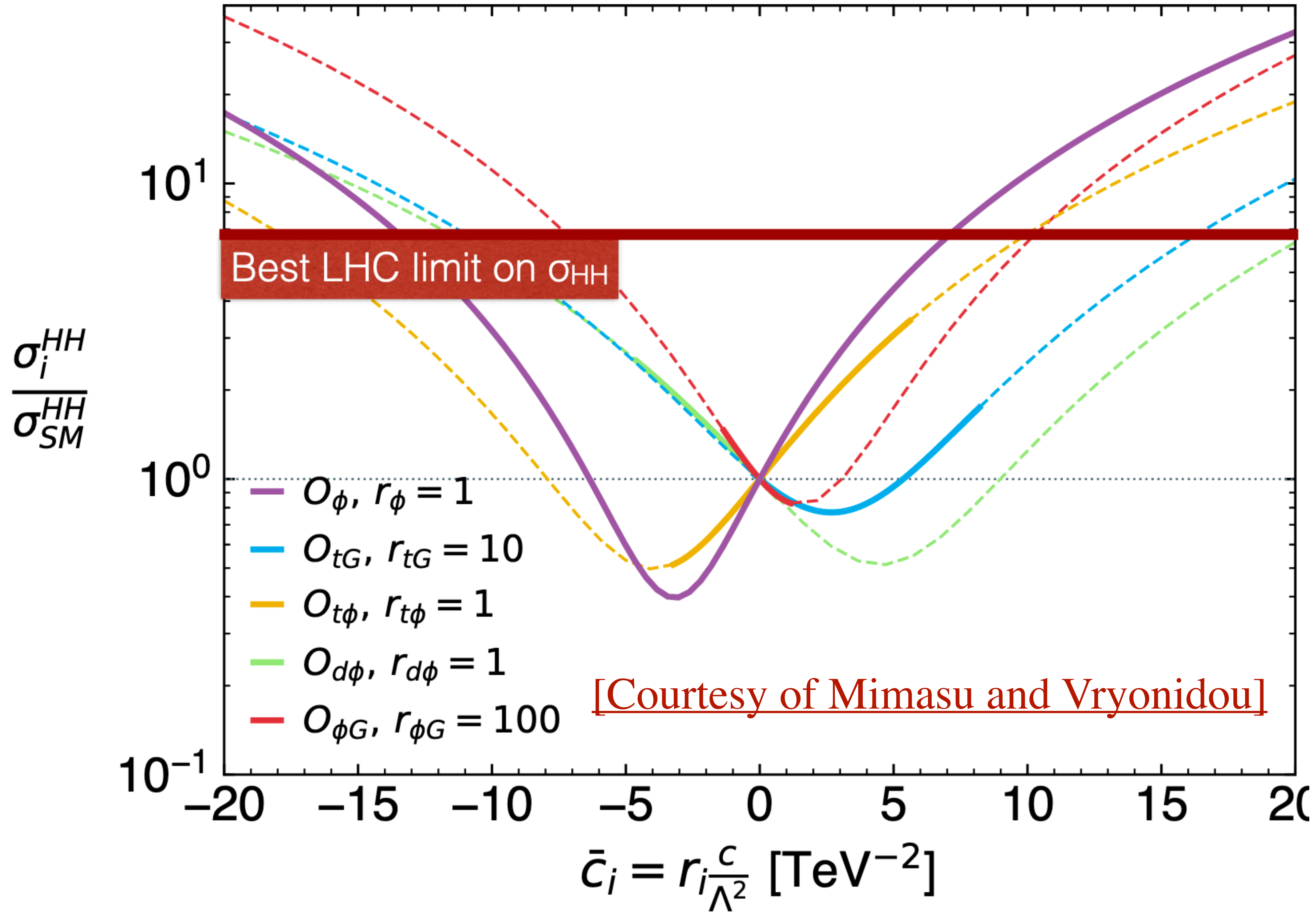


Double Higgs production is sensitive to 5 top-Higgs operators at 1-loop level:

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

Determination of self-coupling will depend SM Theory uncertainties (see [Shao, ICHEP2020]) but also how well the other EFT couplings will be constrained.

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.

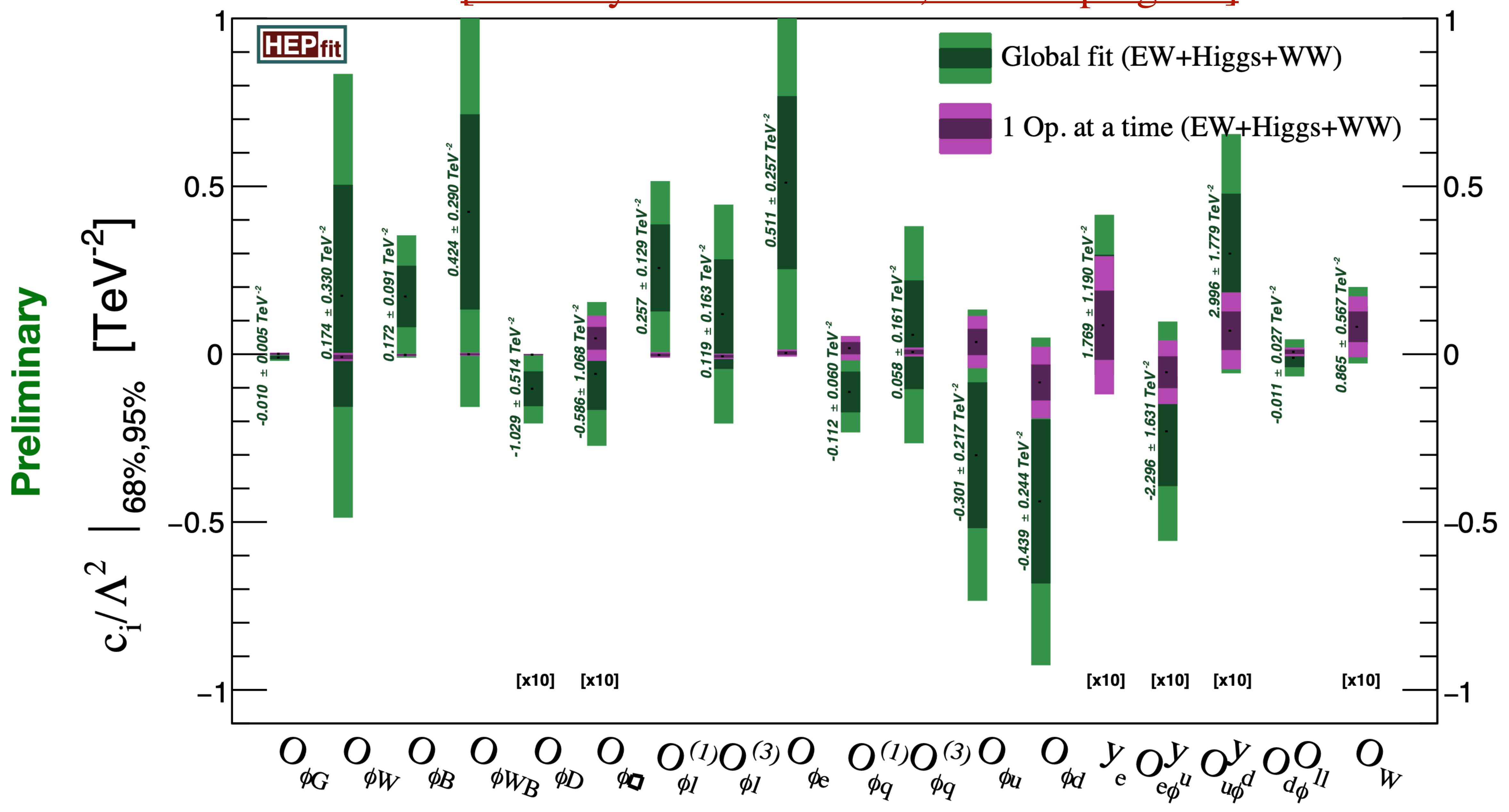


Future improvements

EW+Higgs+EWPO

Now

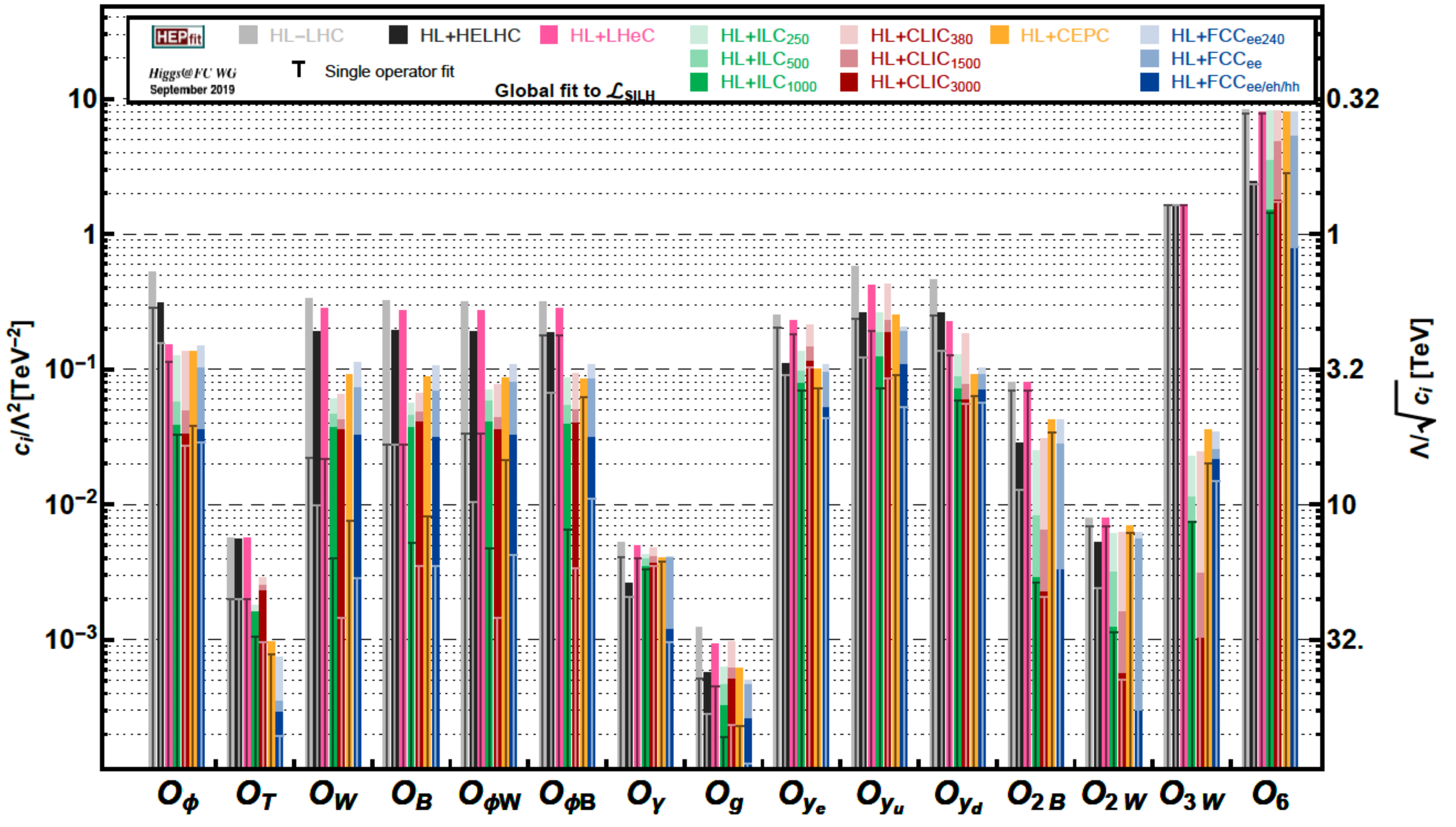
[Courtesy of De Blas et al., work in progress]



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

Future

[De Blas et al., 2020]



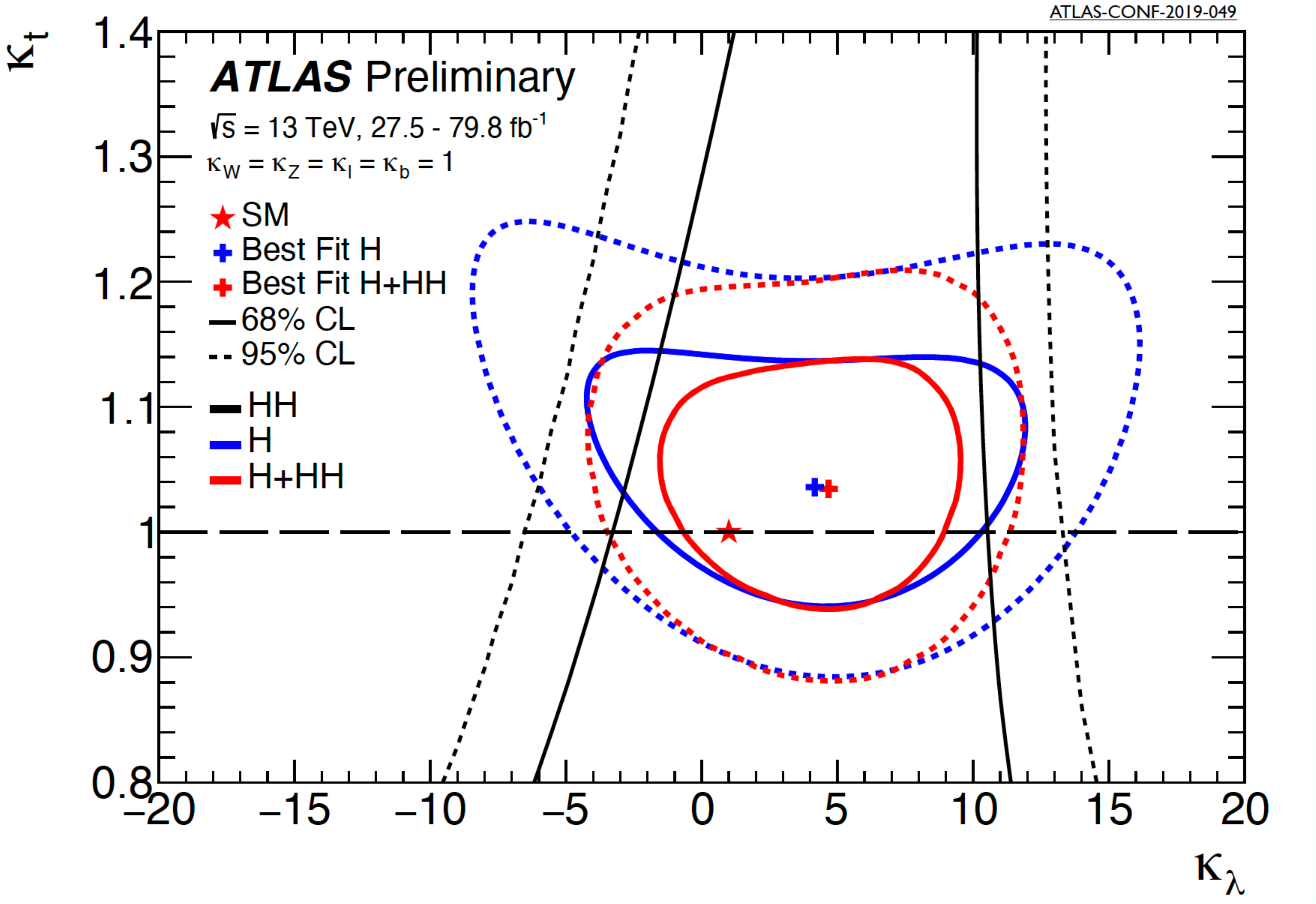
Expected more than 1 order of magnitude improvements

Future improvements

Higgs self couplings : tree-level and loops

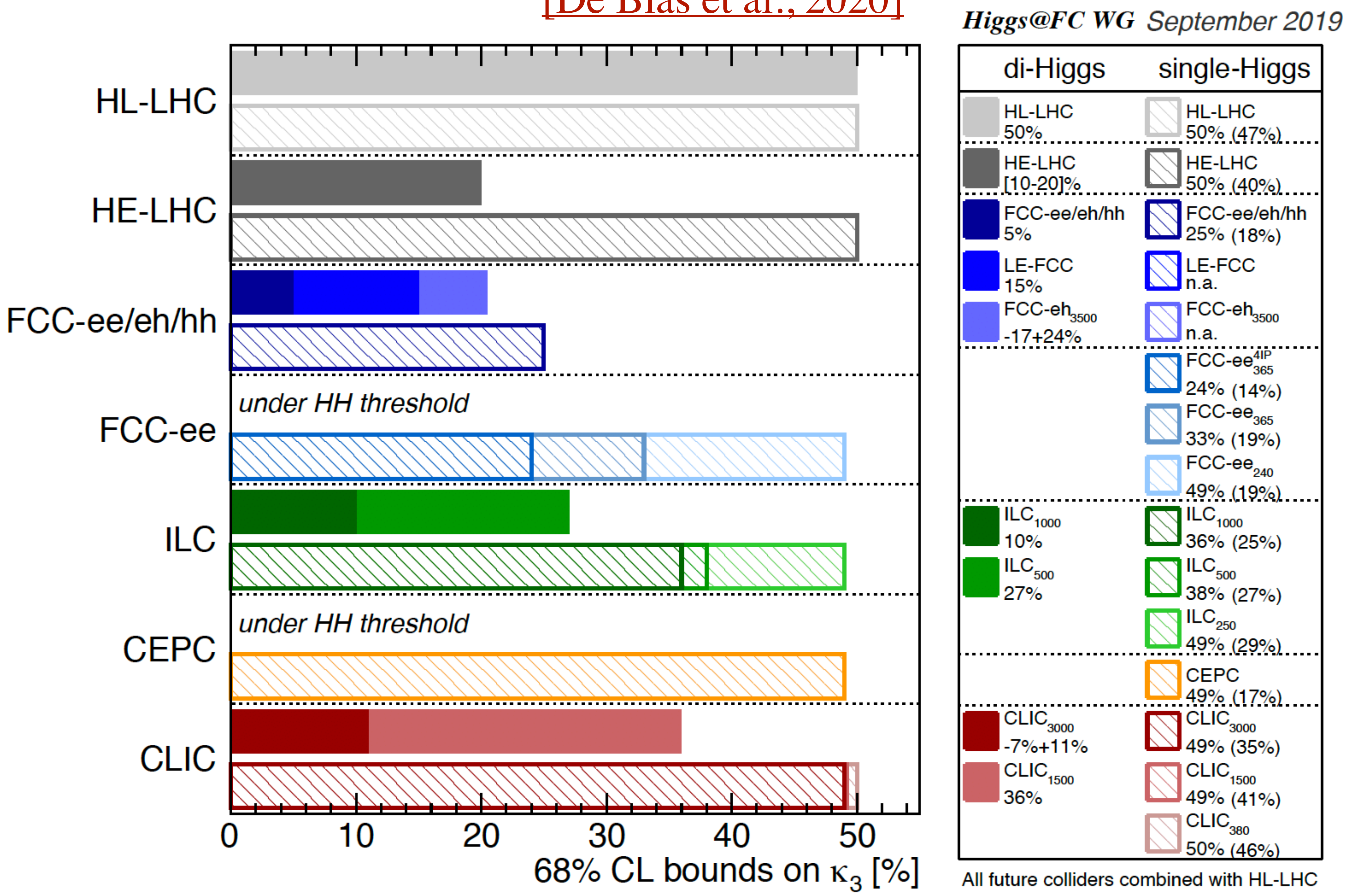
Now

[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.

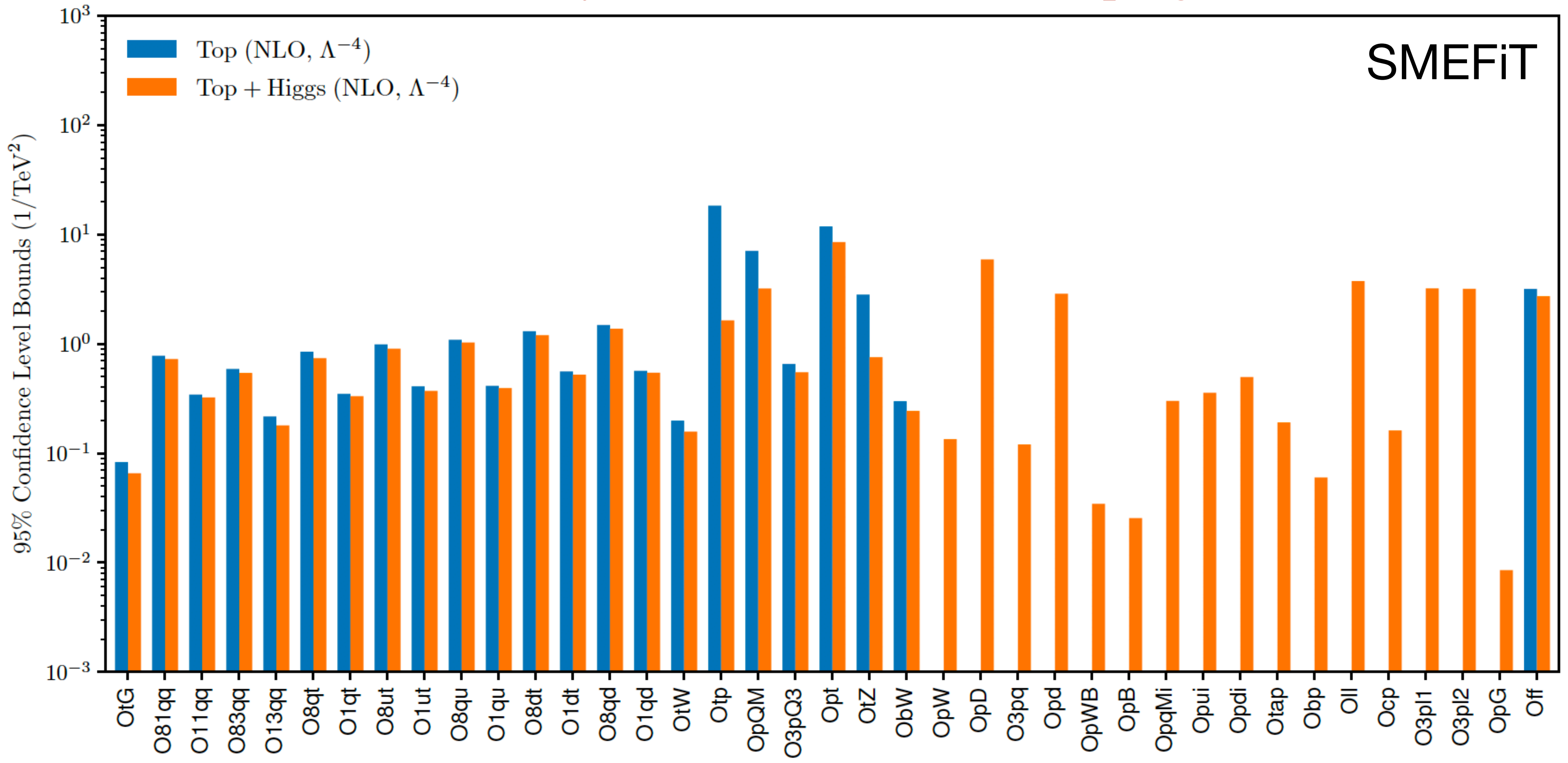
At high-energy pp and ee, HH will be more sensitive.

Future improvements

Top+Higgs

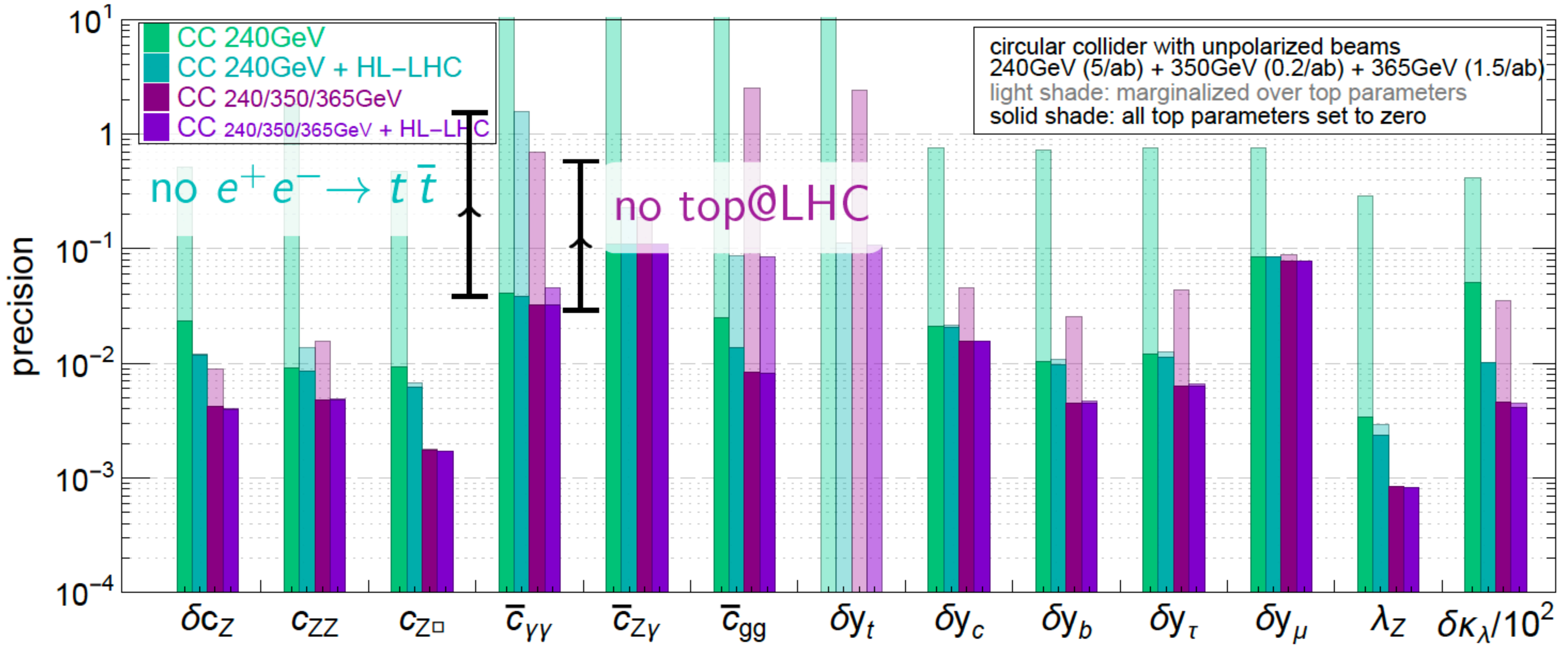
Now

[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.

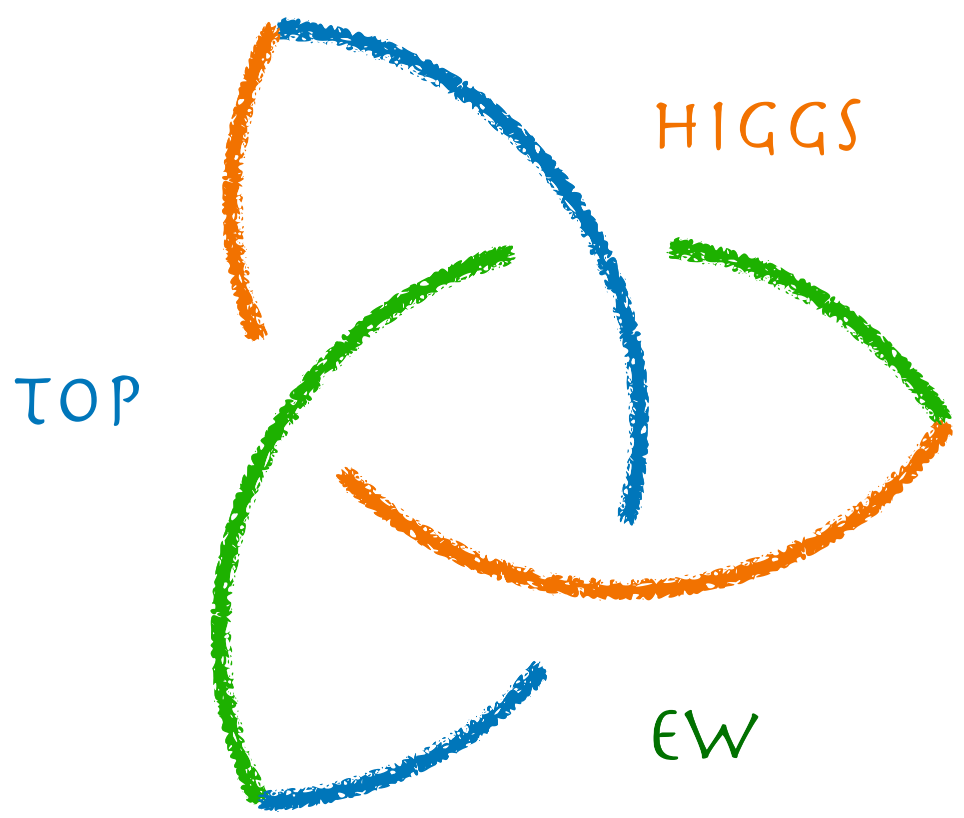
Future improvements
Theory

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.
- 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.

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Acknowledgements

I am thankful to organisers for having given me the opportunity to give this talk.

I am in debt with E. Vryonidou, K. Mimasu, G. Durieux for sharing with me many insights and precious material used in this presentation.

Backup Slides

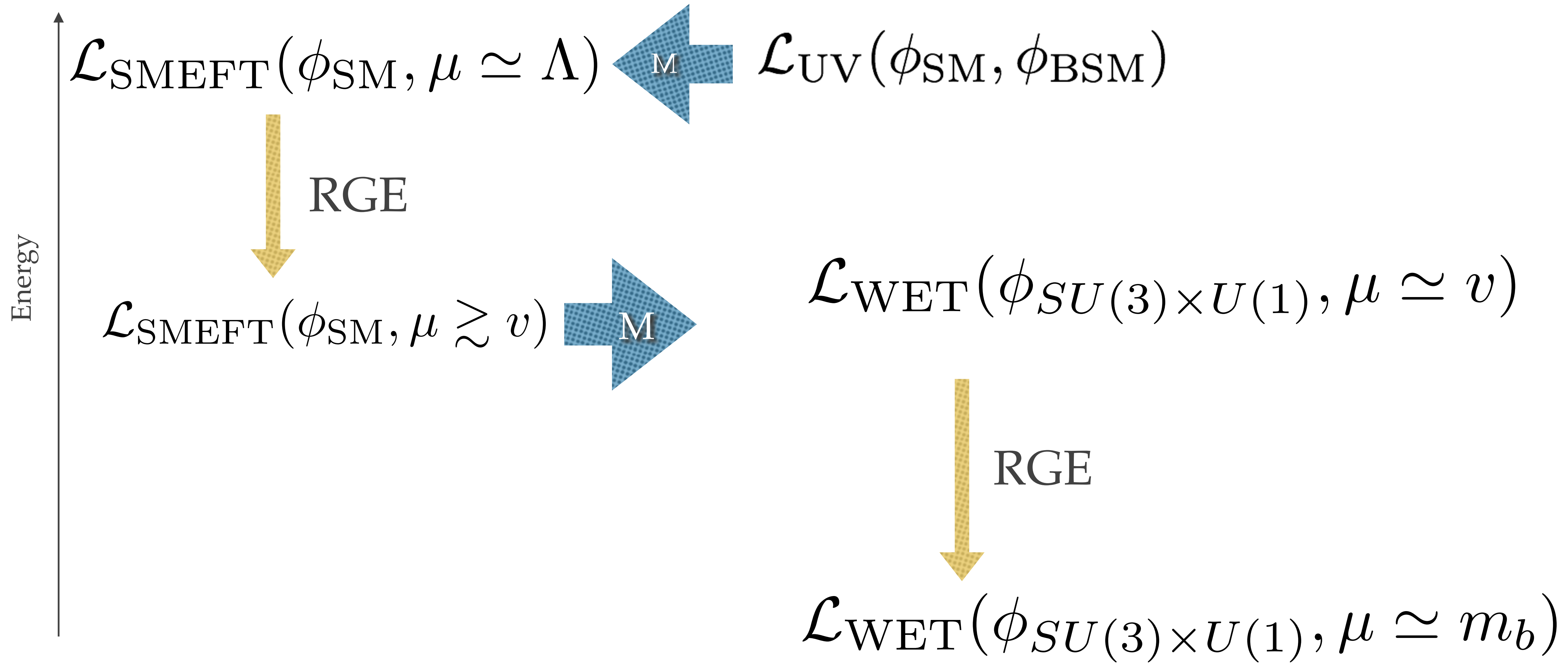
SMEFT
Adding flavour constraints

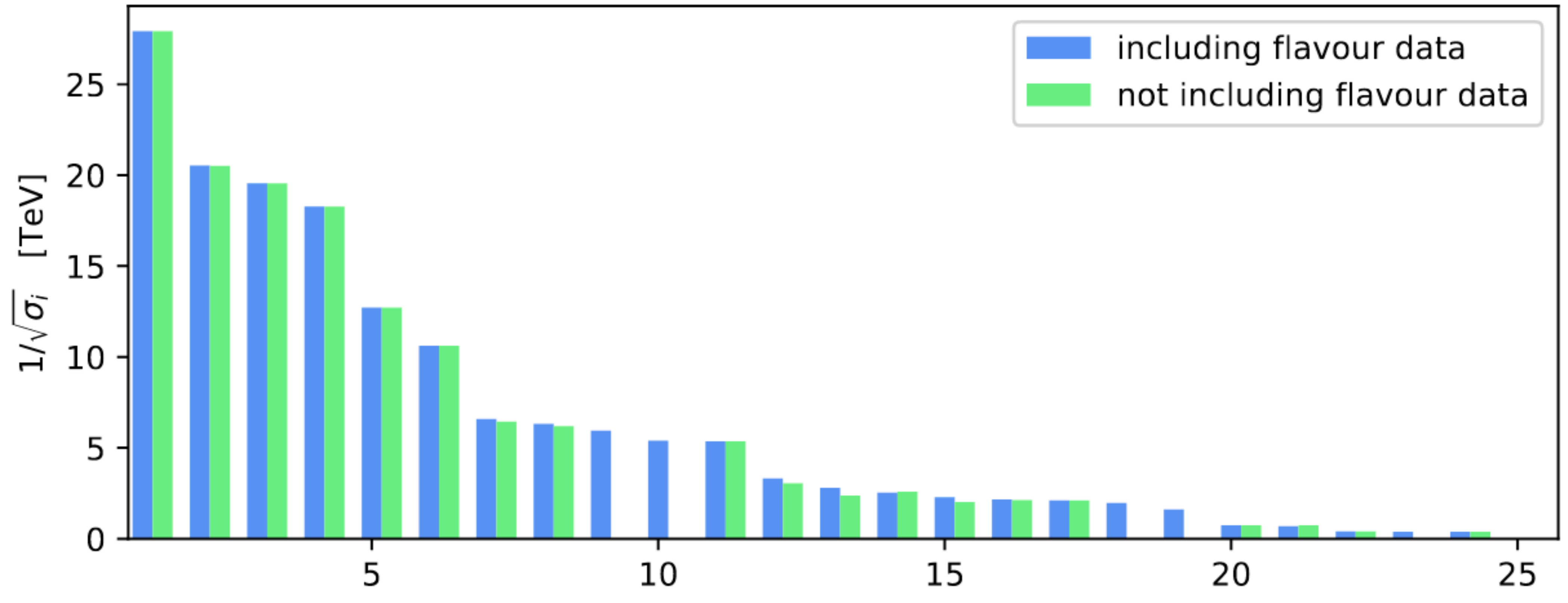
[Aoude et al,; arXiv:2003.05432]
[Hurth et al,; JHEP 06 (2019) 029]
[Bissmann at al. , 2020]

- 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
- See also [Grunwald, ICHEP2020].





SMEFT

High energy & multiplicity

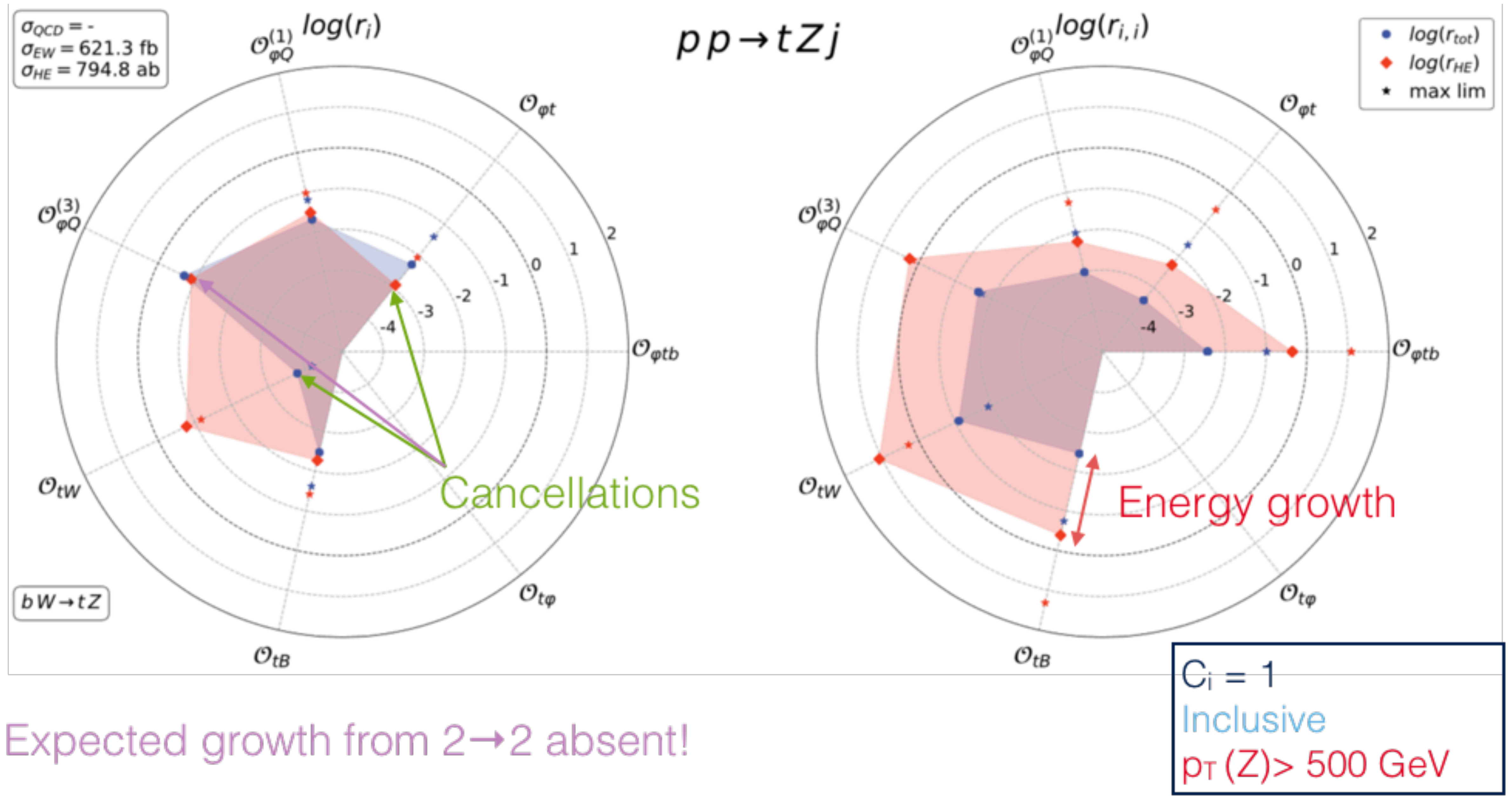
[Mantani, Mimasu, FM, 2019]

- 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]

SMEFT

High energy & multiplicity



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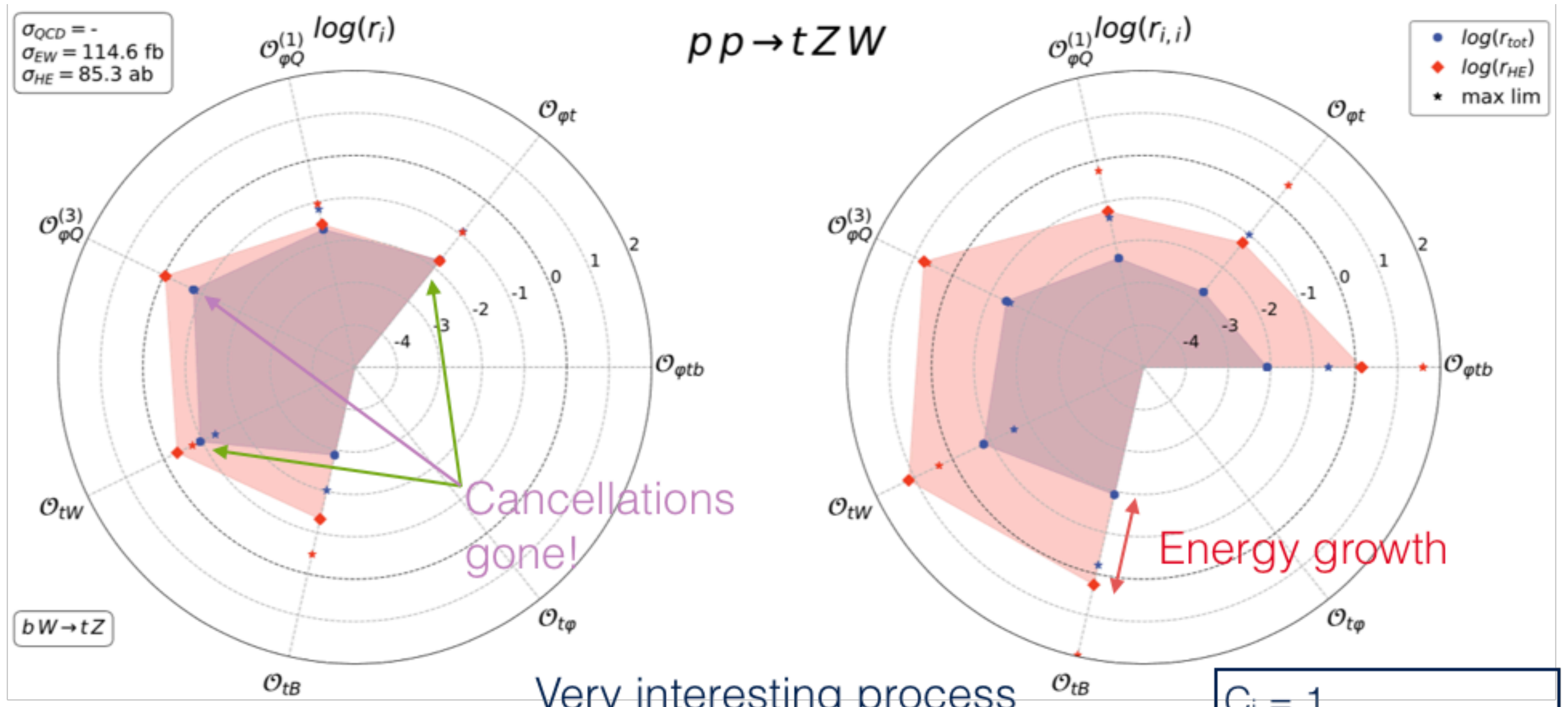


Expected growth is there!

Very interesting process that should be measured at the LHC

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

[Henning et al. 2019]
[Mantani, Mimasu, FM, 2019]
[Costantini et al. 2020]

SMEFT

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

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

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

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

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

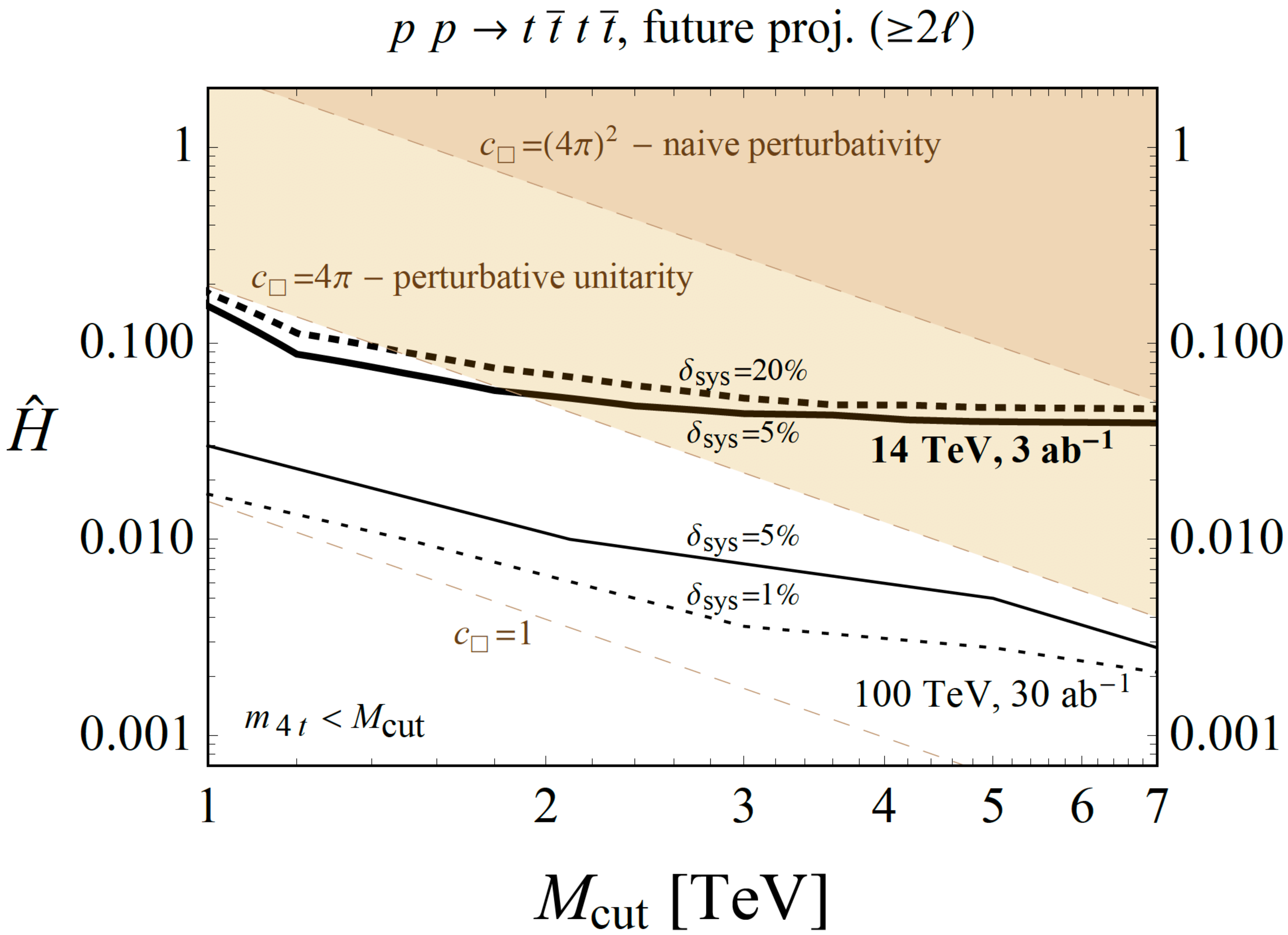
$$\mathcal{O}_W = \frac{ig c_W}{2M^2}(H^\dagger \sigma^a \overleftrightarrow{D}^\mu H) D^\nu W^a_{\mu\nu}$$

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

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

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

[Englert et al., 1903.07725]



SMEFT

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

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

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

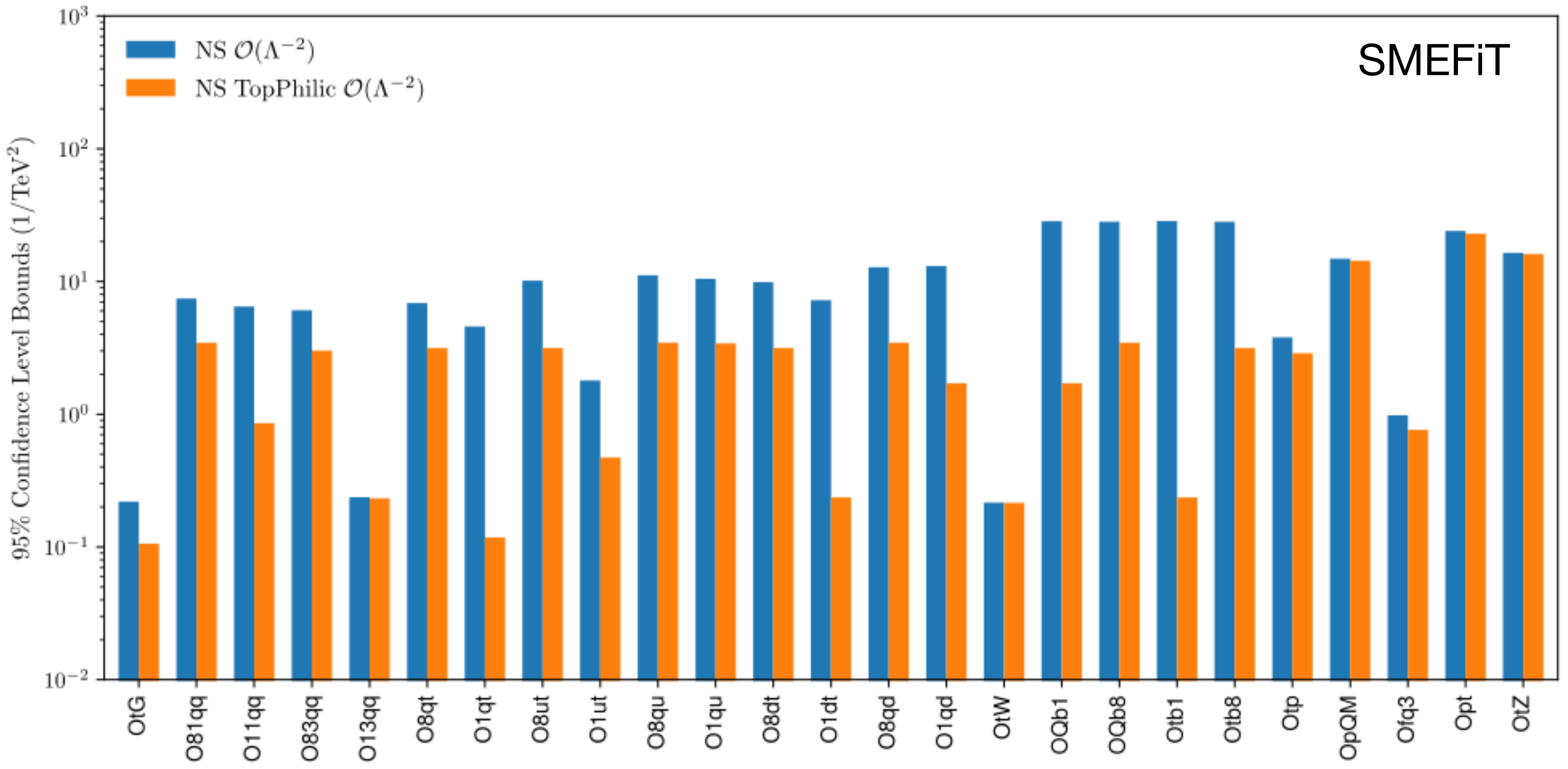
$$c_{QDB} = 6c_{Qq}^{1,1} = \frac{3}{2}c_{Qu}^{1} = -3c_{Qd}^{1} = -3c_{Qb}^{1} = -2c_{Ql}^{1(\ell)} = -c_{Qe}^{(\ell)},$$

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

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

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

- 34 parameter basis reduced to 19 free parameters



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