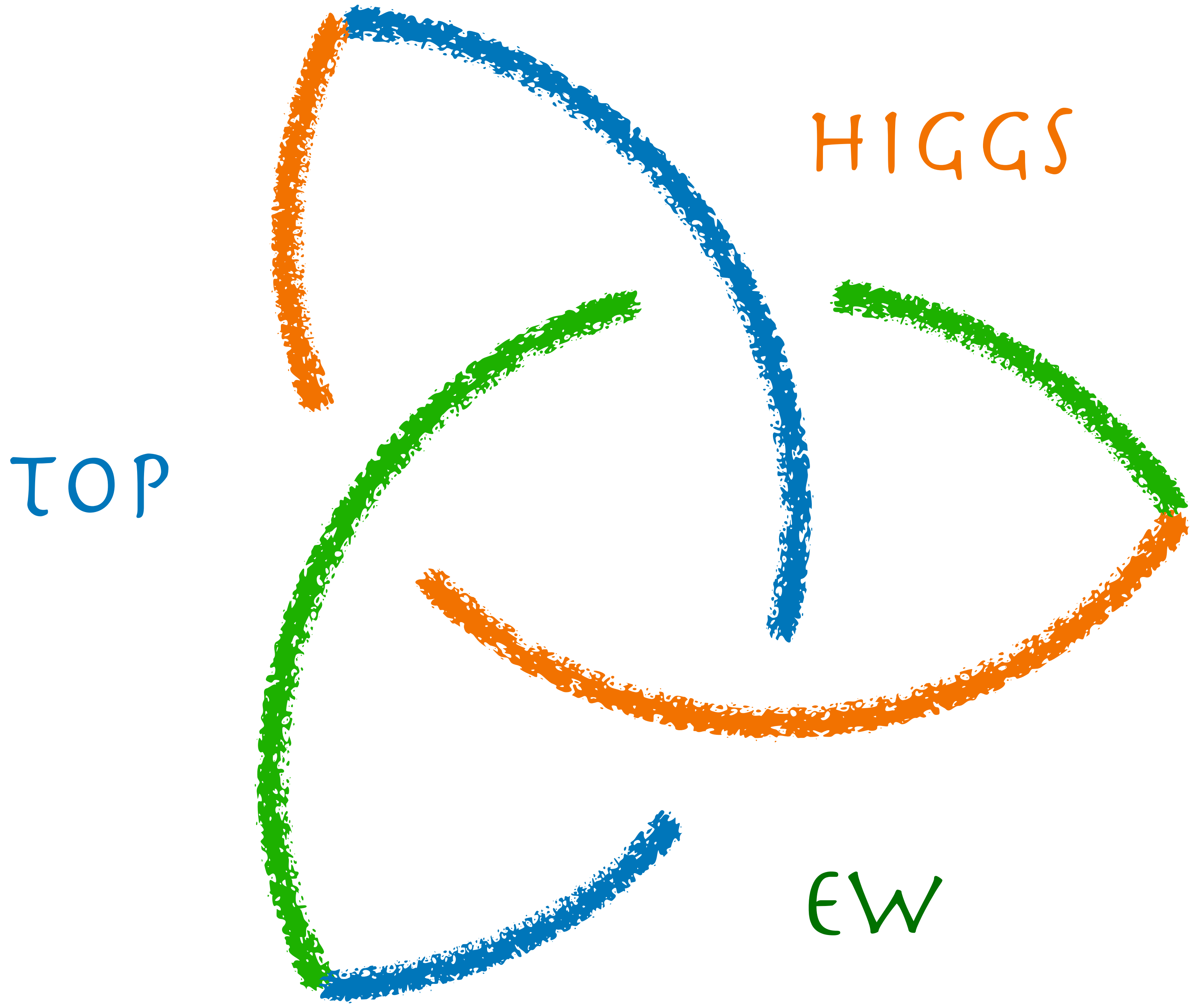
Theoretical issues of the SM and physics at the TeV scale



Fabio Maltoni
Università di Bologna
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SM@TeV

Thanks to all contributors

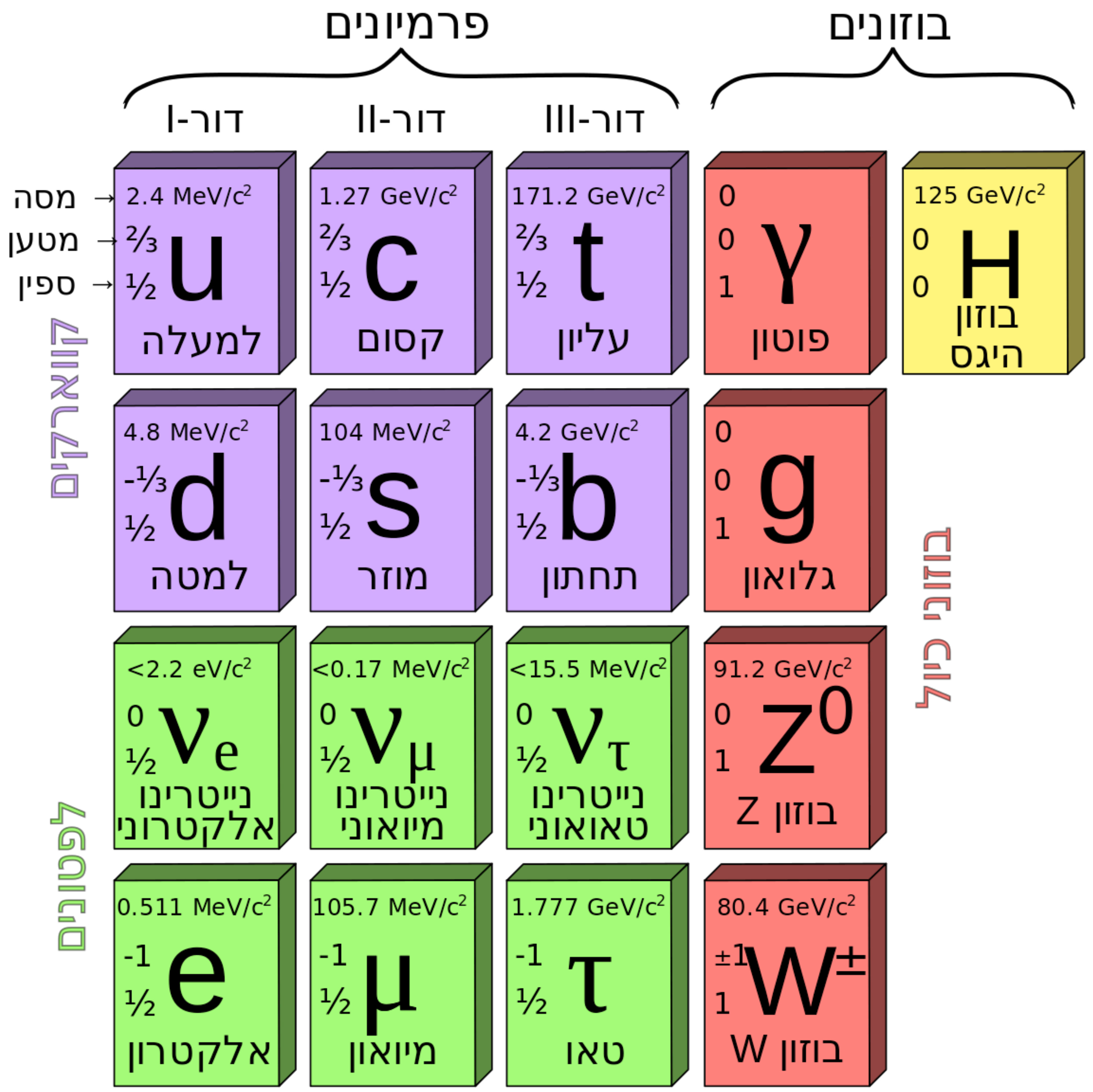
Status and future prospects of precision computations for Higgs Physics at the LHC	*Prof. Fabrizio Caola*	
Online		13:00 - 13:25
Measurement of Higgs differential distributions at the LHC	*Arun Kumar*	
Online		13:25 - 13:45
Higgs couplings to fermions and bosons (including inclusive cross sections, coupling combinations, spin/CP measure…	*Serhat Ördek*	
Probing Higgs couplings to light quarks via Higgs pair production	*Lina Alasfar*	
Online		14:05 - 14:25
Combined SMEFT interpretation of Higgs, diboson, and top quark data from the LHC	*Juan Rojo*	
Online		14:45 - 15:05
Higgs rare and exotic decays at the LHC	*Miha Muskinja*	
Online		15:05 - 15:25
Full NLO QCD corrections to Higgs-pair production in the Standard Model and beyond	*Dr Julien Baglio*	
Online		15:25 - 15:45
Double Higgs production at the LHC	*Louis Portales*	
Online		15:45 - 16:05
Perspectives for Higgs measurements at Future Colliders	*Ang Li*	
Online		16:20 - 16:40
ILC Higgs Physics Potential	*Dr Shin-ichi Kawada*	
Online		16:40 - 17:00
Nailing Higgs Couplings at Future Colliders	*Ayan Paul*	
Online		17:00 - 17:20
Single boson production overview (W, Z, ɣ) at the LHC	*Mario Pellicciono*	
Online		17:20 - 17:40

Status of NNLO QCD corrections for process with one or more jets in the final state at the LHC	*João Pires*	
Online		13:00 - 13:25
V+jets/+heavy flavour production at the LHC	*Alexandre Laurier*	
Online		13:25 - 13:45
Jet substructure and fragmentation (including TOP) at the LHC	*Andy Buckley*	
Online		13:45 - 14:05
Modelling the data at the LHC: status and issues (overview including soft QCD and TOP)	*Efe Yazgan*	
Online		14:05 - 14:25
Status of VBS measurements at the LHC	*Shu Li*	
Online		14:40 - 15:00
Four-lepton production in gluon fusion at NLO matched to parton showers	*Dr Silvia Ferrario Ravasio*	
Online		15:00 - 15:20
Precise predictions for photon pair production	*Alessandro Broggio*	
Online		15:20 - 15:40
Multibosons production at the LHC (diboson, triboson)	*Oleg Kuprash*	
Online		15:40 - 16:00
Overview of precision measurements (angular coefficients, charge asymmetry, sin2ϴ, mW, etc) at the LHC	*Vladislav Shalaev*	
Top quark Cross sections overview (including re-interpretation) at the LHC		
Online		16:35 - 16:55
Status of single top measurements at the LHC	*Víctor Rodríguez Bouza*	
Online		16:55 - 17:15
Top quark mass measurements at the LHC	*Christoph Garbers*	
Online		17:15 - 17:35
Top quark properties overview (asymmetries, CP violation, spin correlations, FCNC) at the LHC	*Dr Jacob Kempster*	
Online		17:35 - 17:55
Associated productions with top (t+X, tt+X with X=W,Z,ɣ, heavy-flavours, tt) at the LHC	*Tomas Dado*	
Online		17:55 - 18:15

The Standard Model

Simplicity

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



- $SU(3)_c \times SU(2)_L \times U(1)_Y$ 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
- Neutrino masses can be easily accommodated.

- **Renormalisable = valid to “arbitrary” high scales.**

- **A number of accidental symmetries,**

$$U(1)_L, U(1)_B, SU(2)_L \times SU(2)_R, SU(N)_f, GIM, \ldots$$

which allow to explain what we see and we don’t see in our exps.

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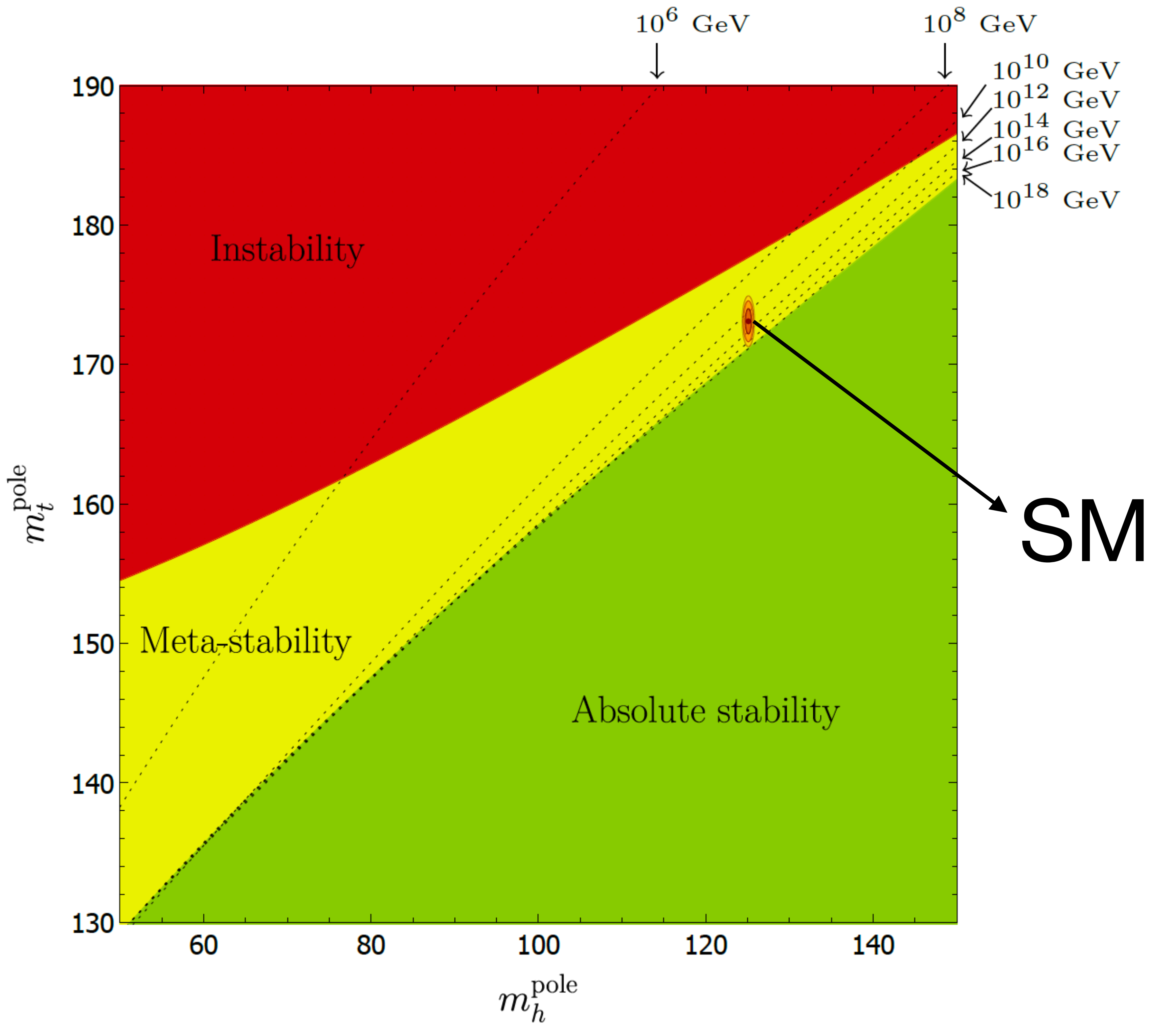

[Andreassen et al. 1707.08124]

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Naturalness:

t V H

- **Higgs** $m_H^2 = m_{H0}^2 \quad - \frac{3}{8\pi^2} y_t \Lambda^2 + \frac{1}{16\pi^2} g^2 \Lambda^2 + \frac{1}{16\pi^2} \lambda^2 \Lambda^2$

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Observations:

- No EWBG (Higgs too light, not enough CPV,…)
- No Dark Matter ?

} cosmo

- (g-2)μ ?
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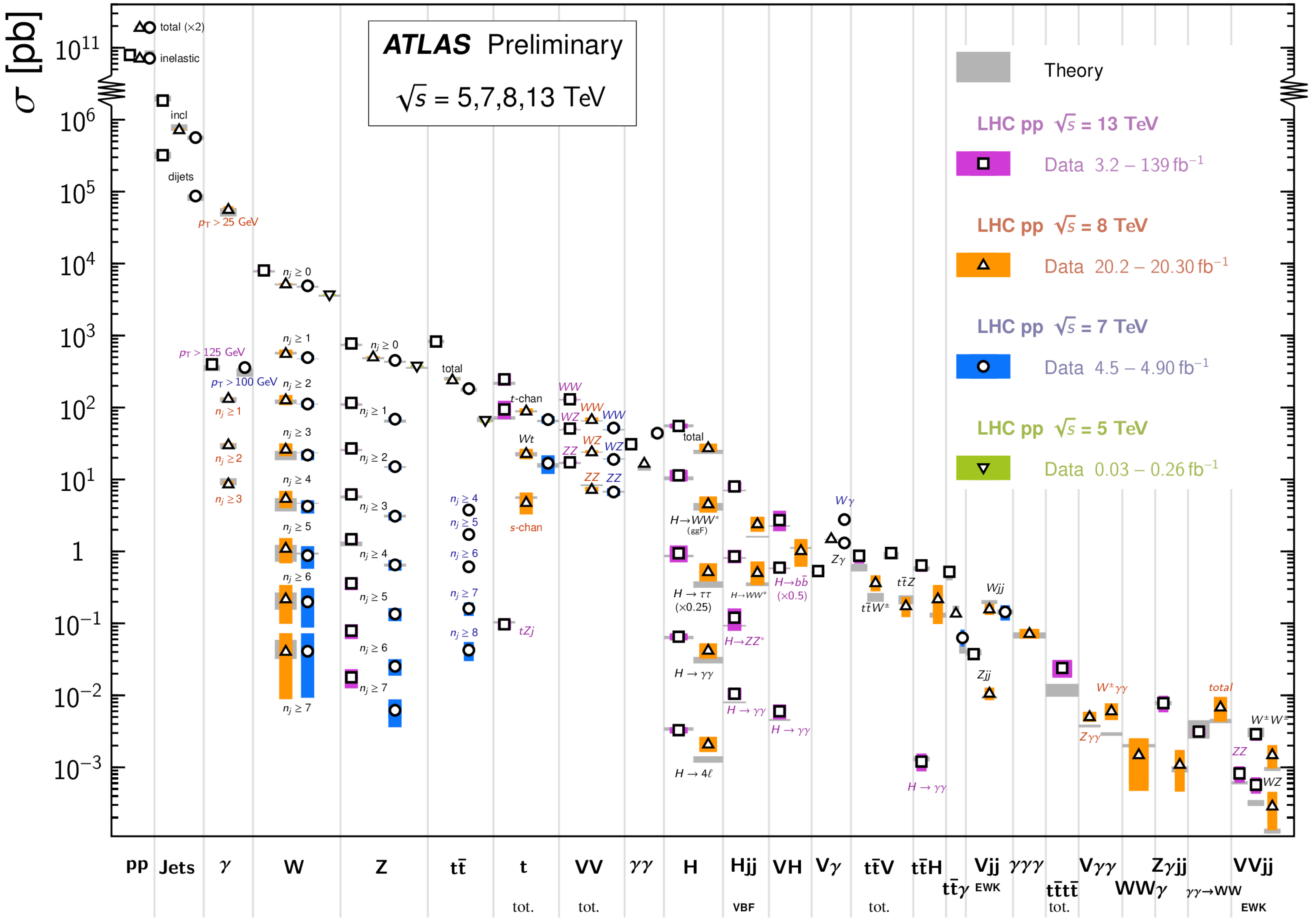
…and at the TeV scale?

The Standard Model at the TeV

Theory vs exp



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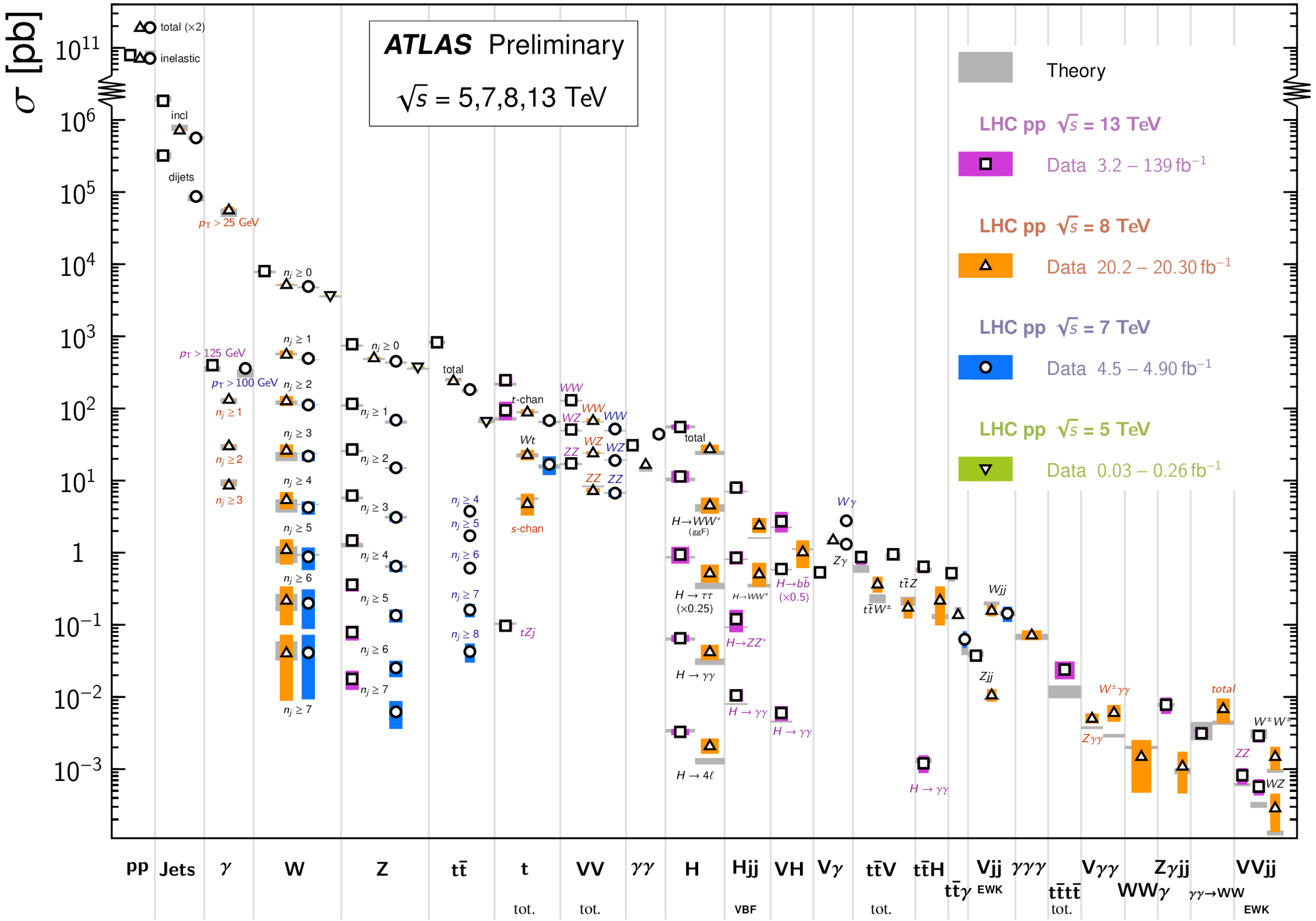

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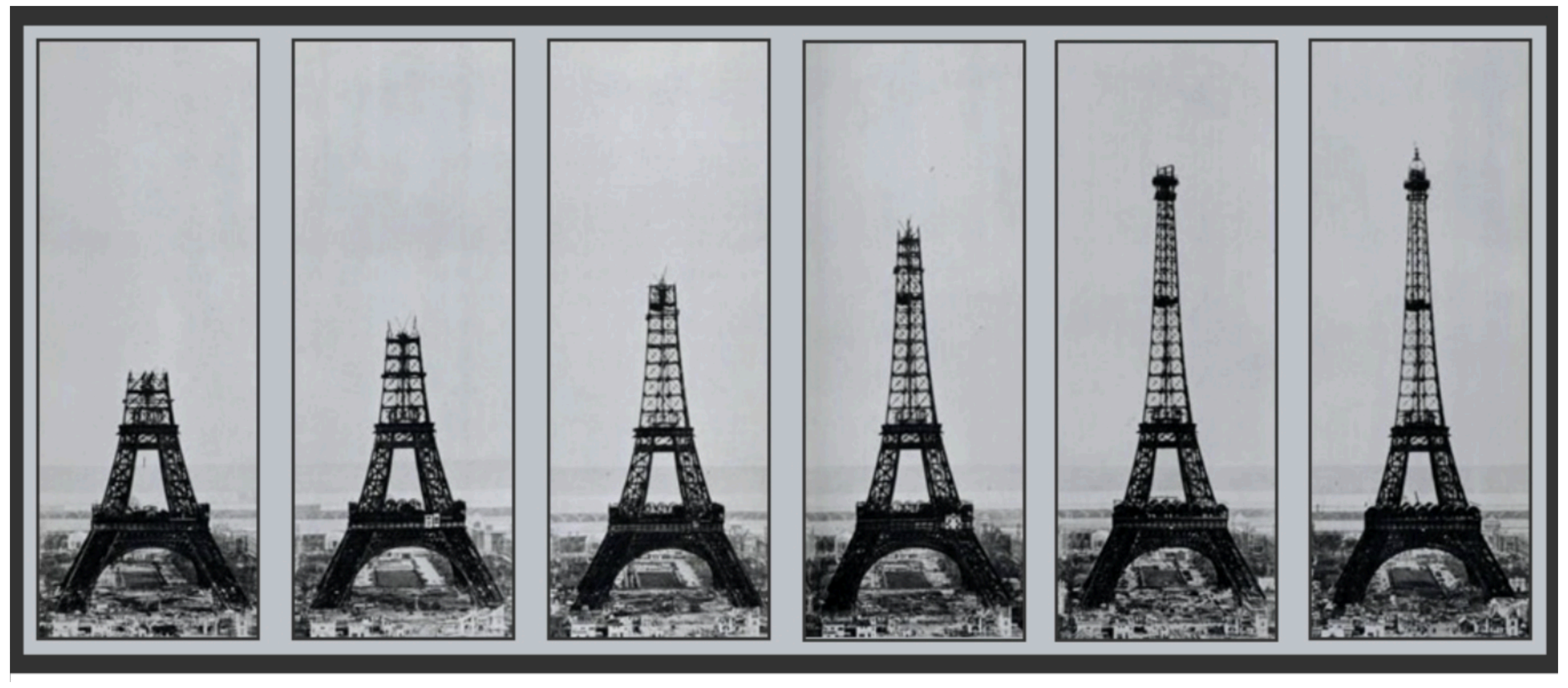

The Standard Model at the TeV

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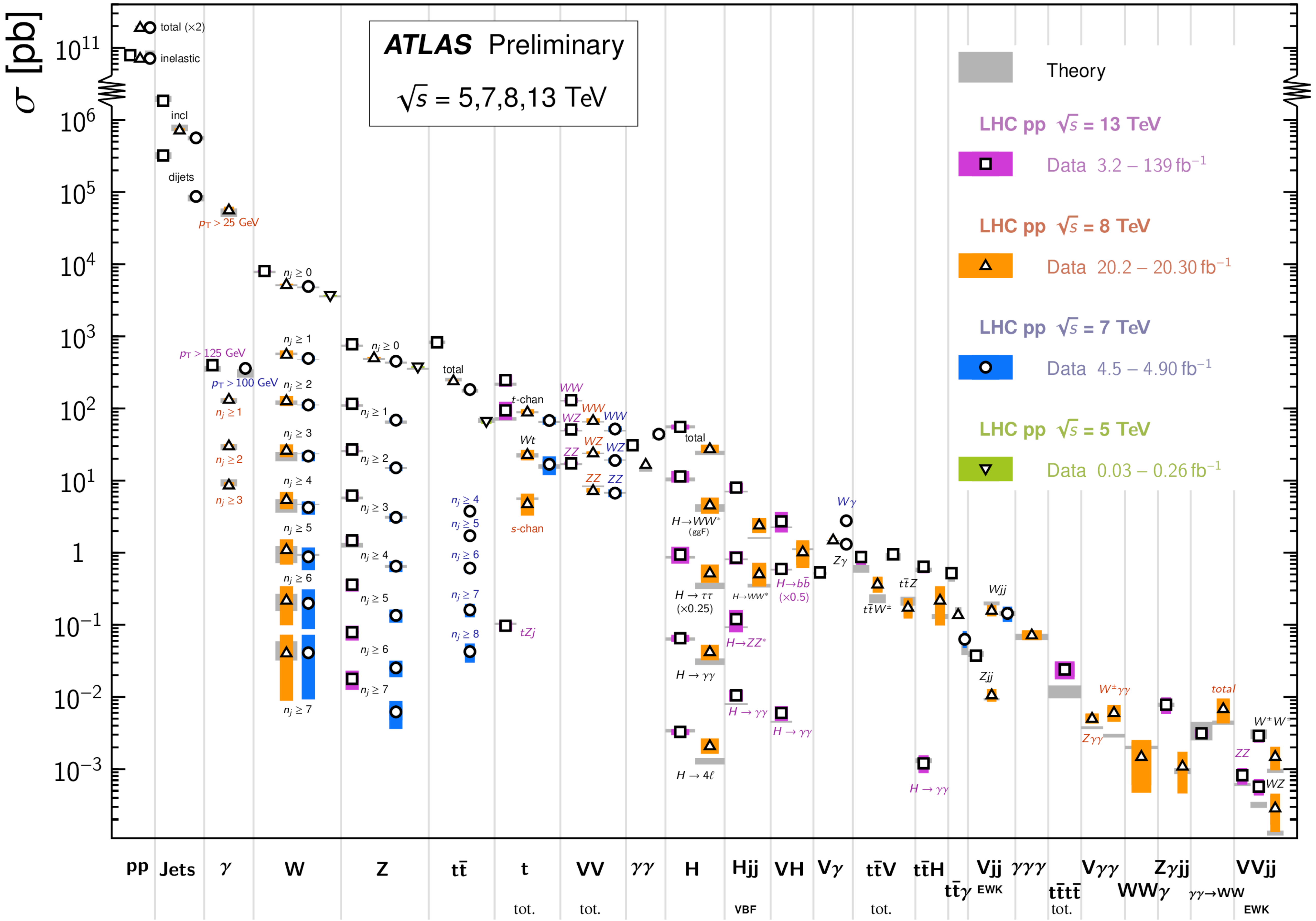

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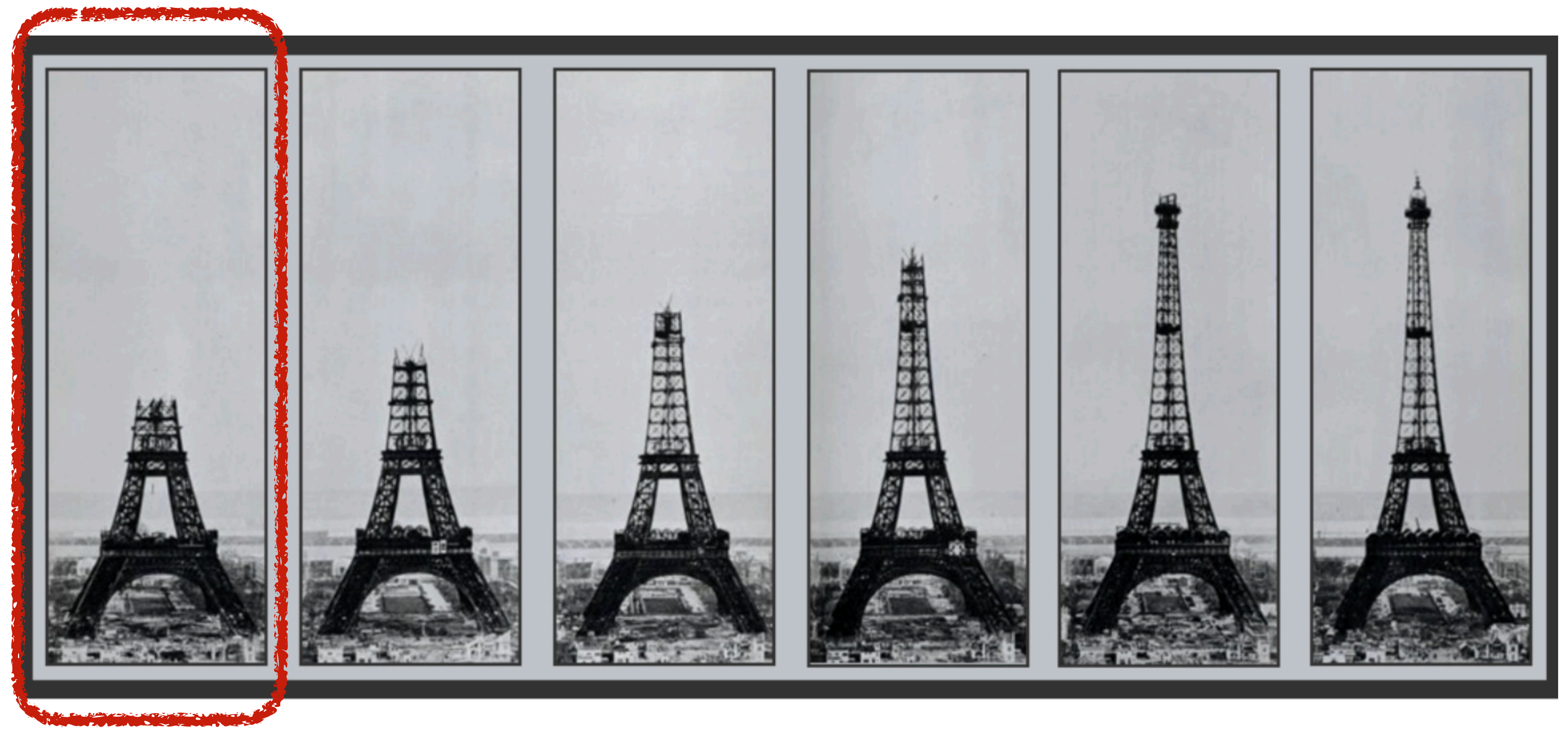

The Standard Model at the TeV

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.

The Standard Model at the TeV

Theory vs exp

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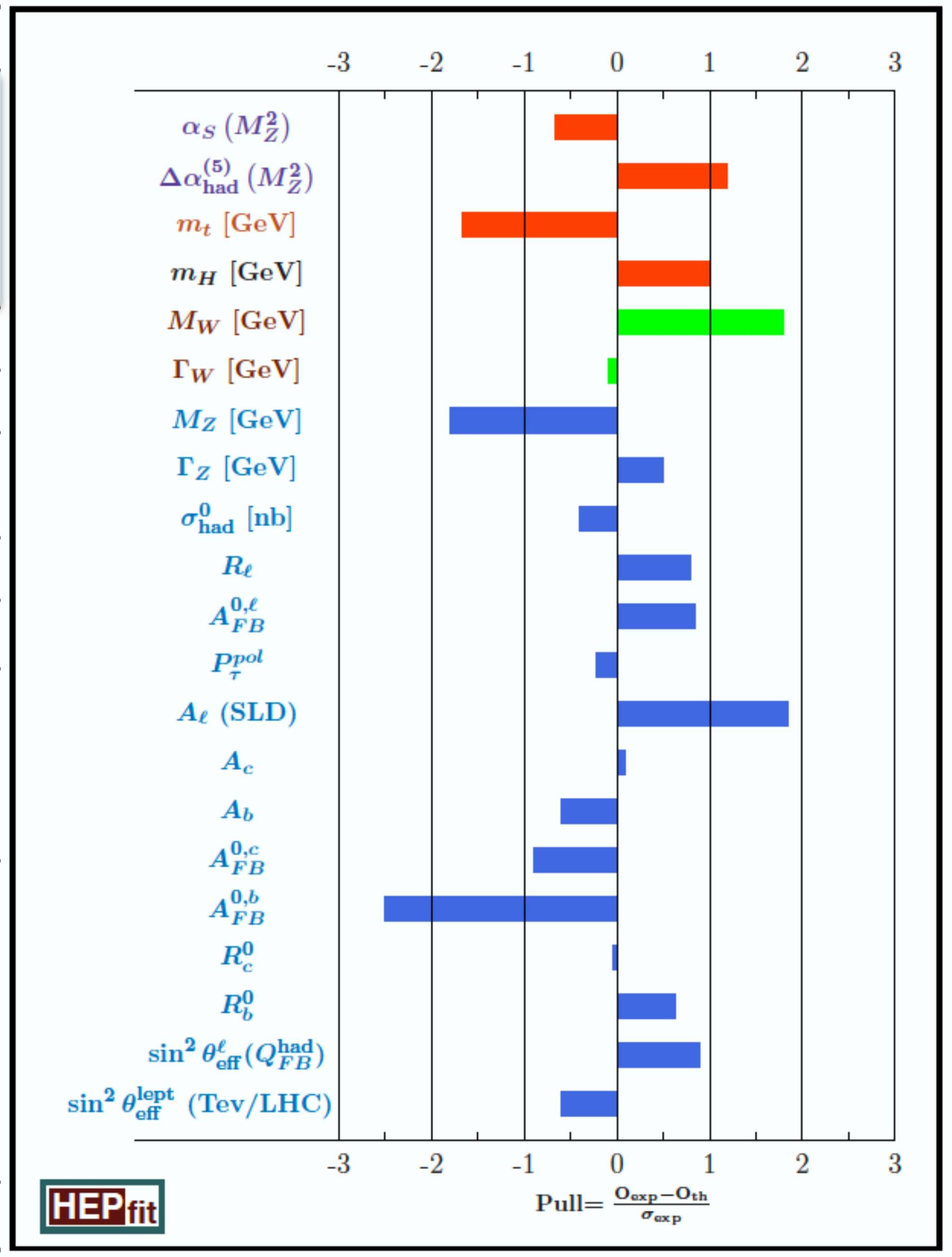
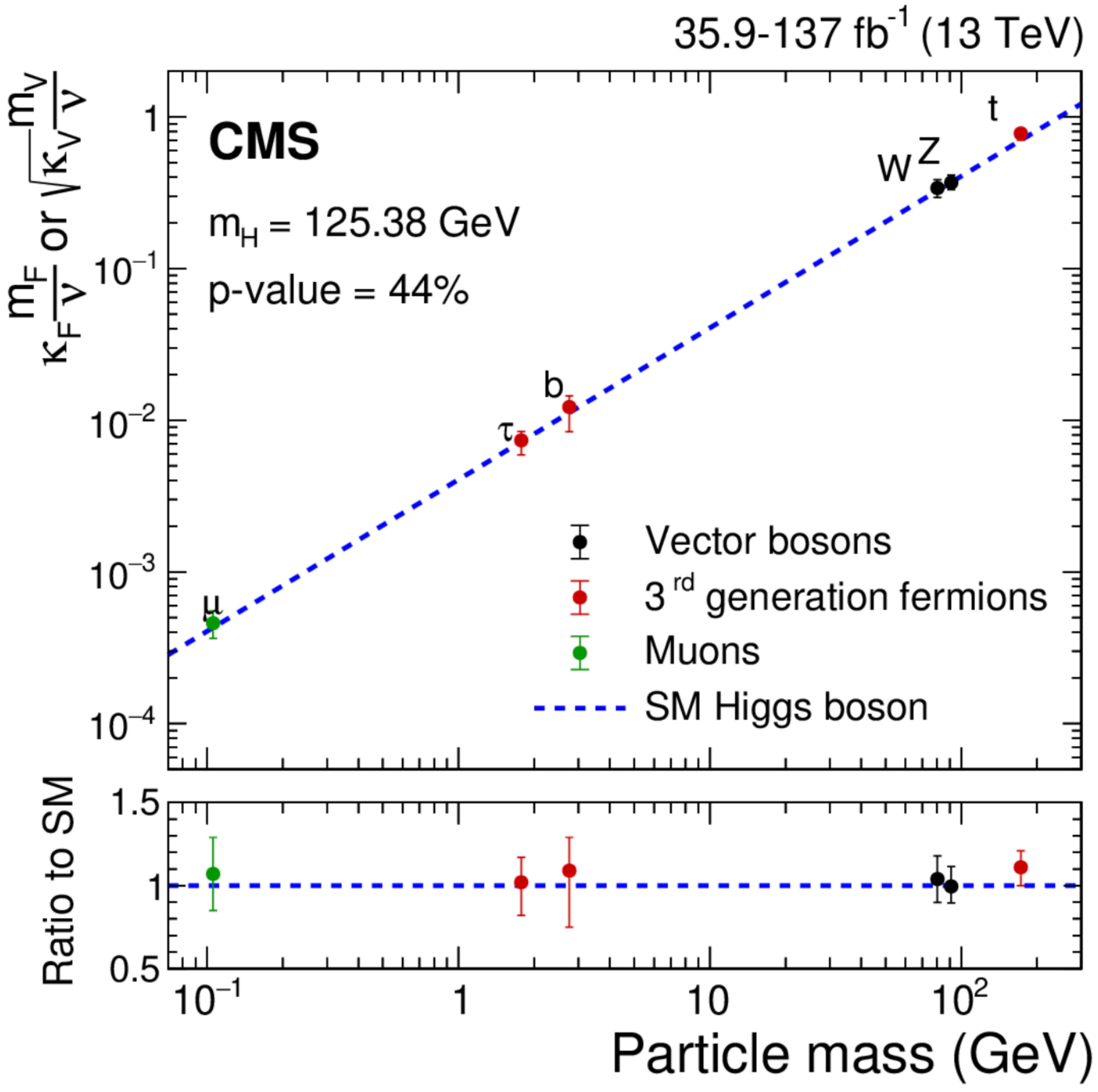
	Measurement	Posterior	Prediction	Pull
$\alpha_s(M_Z)$	0.1177 ± 0.0010	0.1179 ± 0.0009	0.1197 ± 0.0028	-0.7
$\Delta\alpha^{(5)}_{\rm had}(M_Z)$	0.027611 ± 0.000111	0.027572 ± 0.000106	0.027168 ± 0.000355	1.2
M_Z [GeV]	91.1875 ± 0.0021	91.1880 ± 0.0020	91.2038 ± 0.0087	-1.8
m_t [GeV]	172.59 ± 0.45	172.76 ± 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
$\mathrm{BR}_{W\to\mathrm{had}}$	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
$P_\tau^{\rm pol}=\mathcal{A}_\ell$	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
$\mathcal{A}_\ell$ (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
$\mathcal{A}_b$	0.923 ± 0.020	0.93475 ± 0.00004	0.93475 ± 0.00004	-0.59
$\mathcal{A}_c$	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

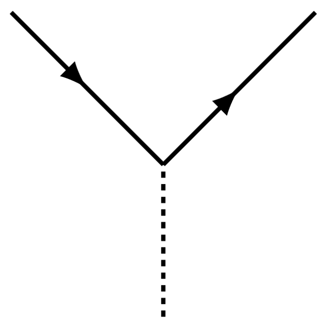


[Courtesy of De Blas et al., work in progress]

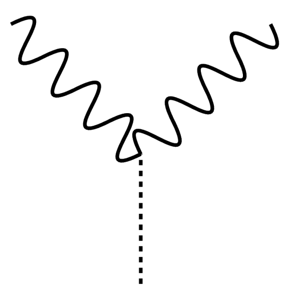
The Standard Model

Explored vs unexplored





$i\, m_f / v$



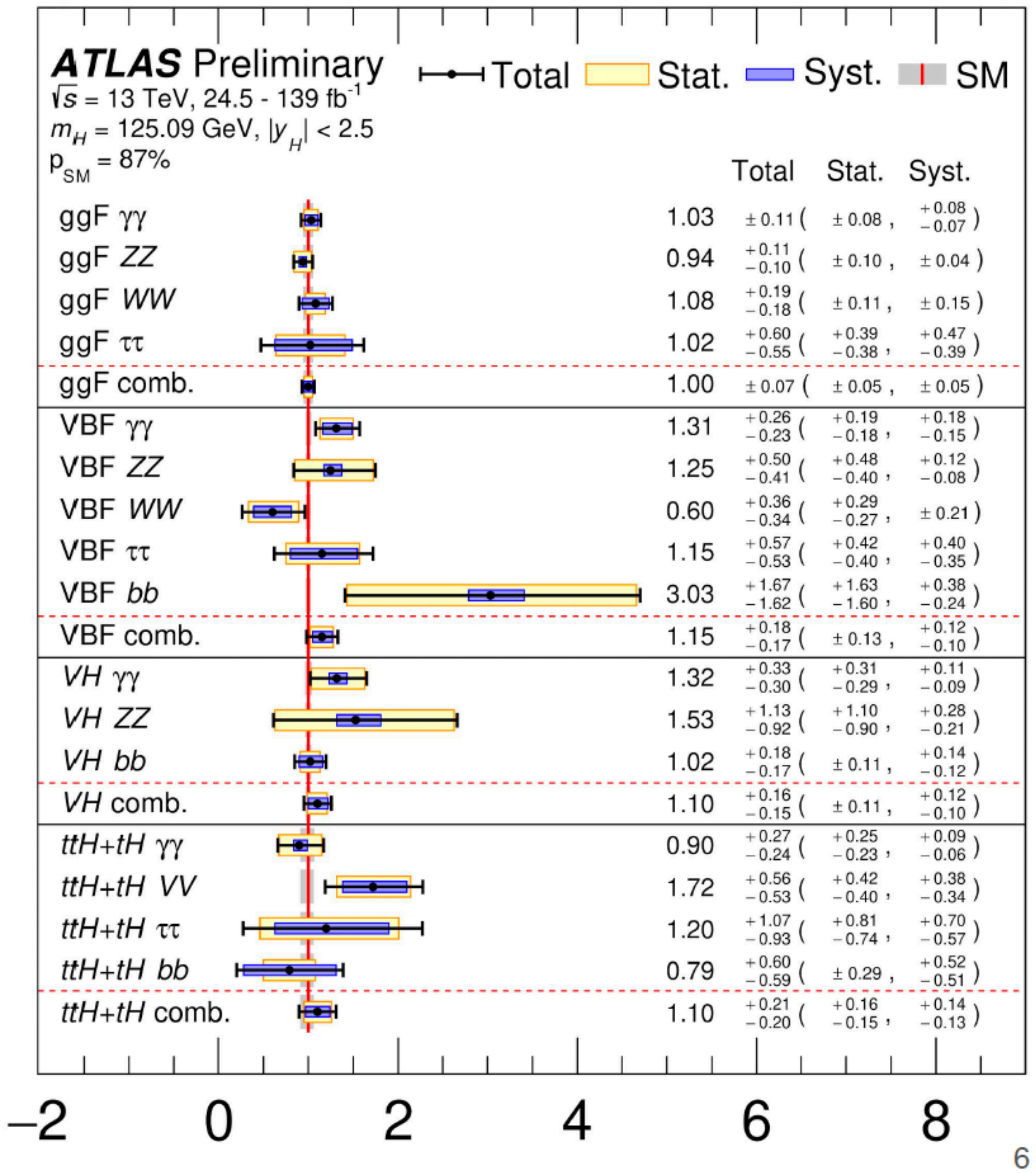
$$i g m_W g_{\mu\nu} = 2 i v g_{\mu\nu} \cdot m_W^2 / v^2$$

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

Unique mass generation mechanism for fermions and vectors.

Constrained system.

[ATLAS 2020]



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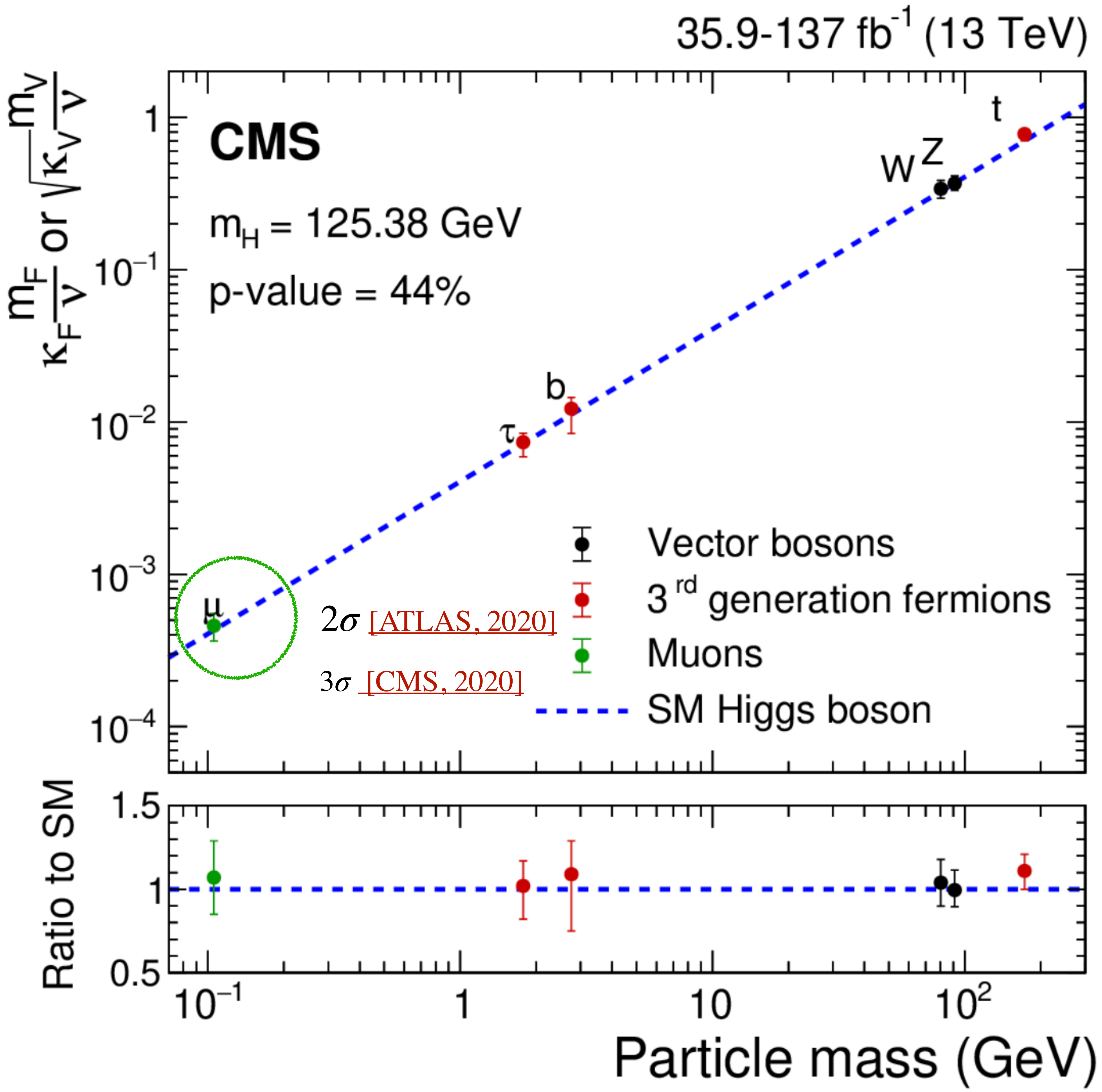
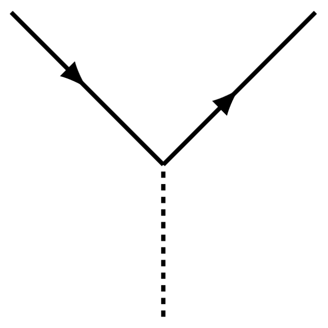
The Standard Model

Explored vs unexplored





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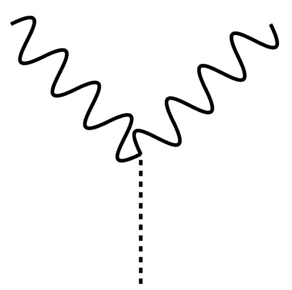

$$ig m_W g_{\mu\nu} = 2i v g_{\mu\nu} \cdot m_W^2/v^2$$

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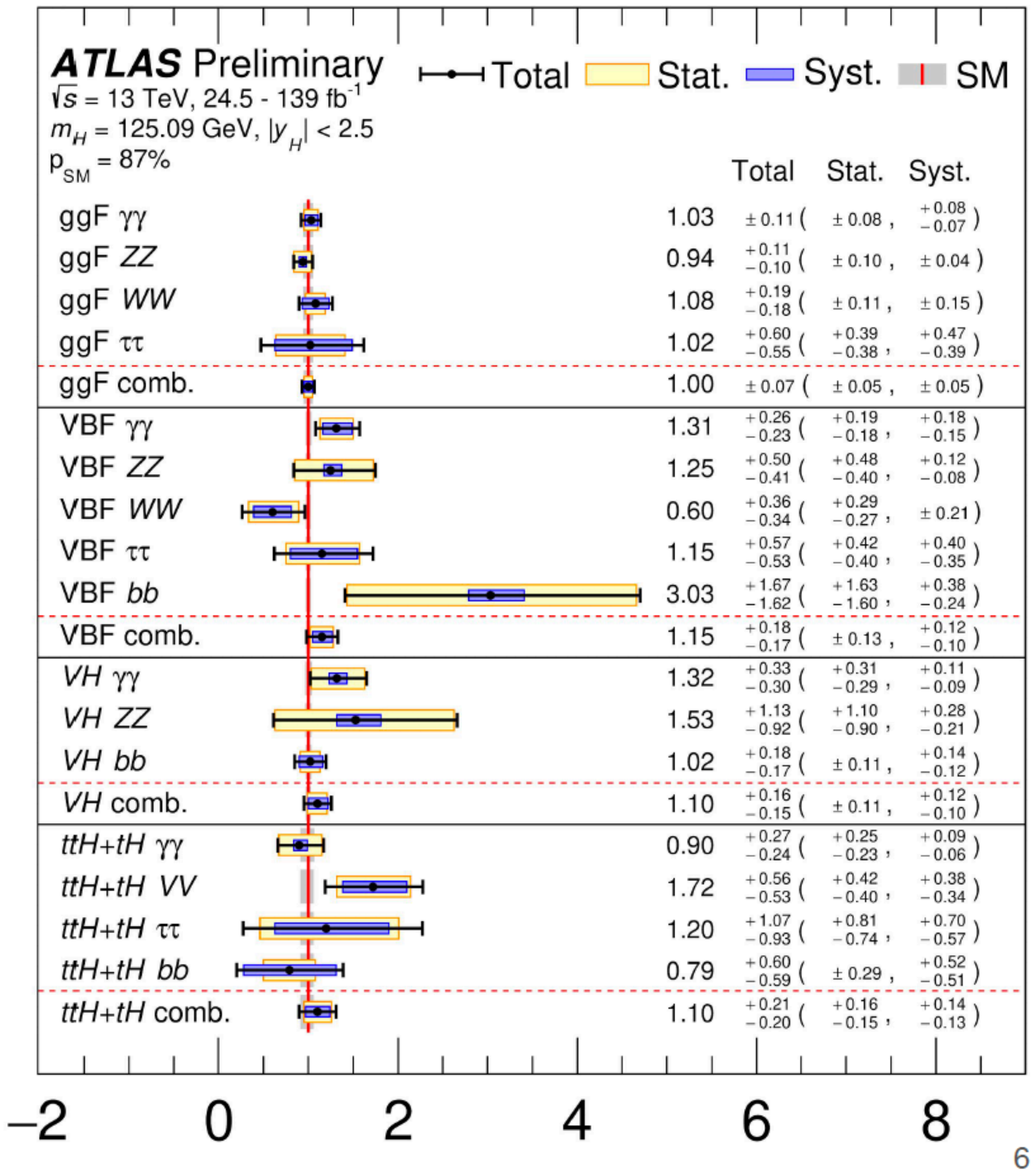

The Standard Model

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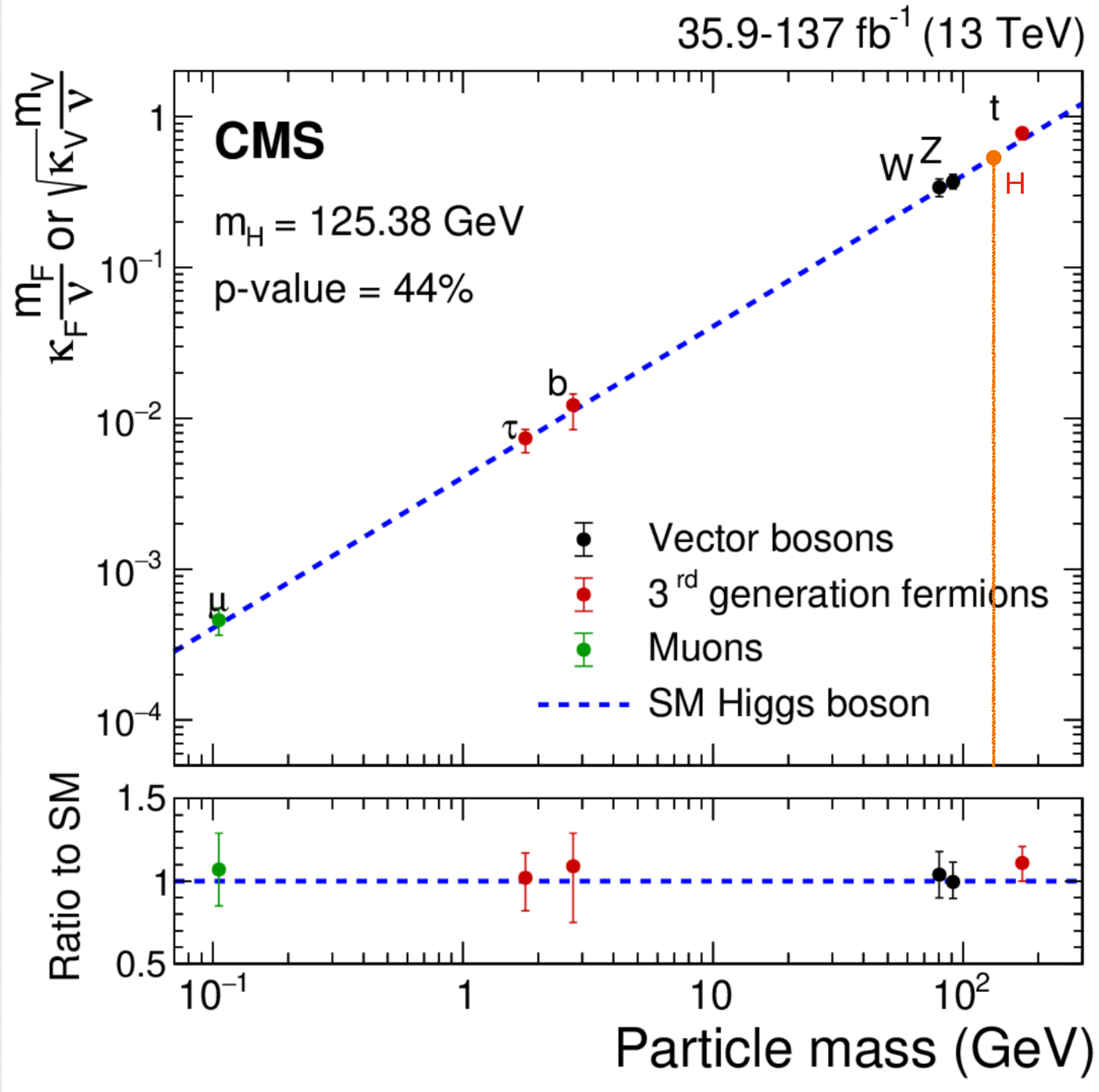

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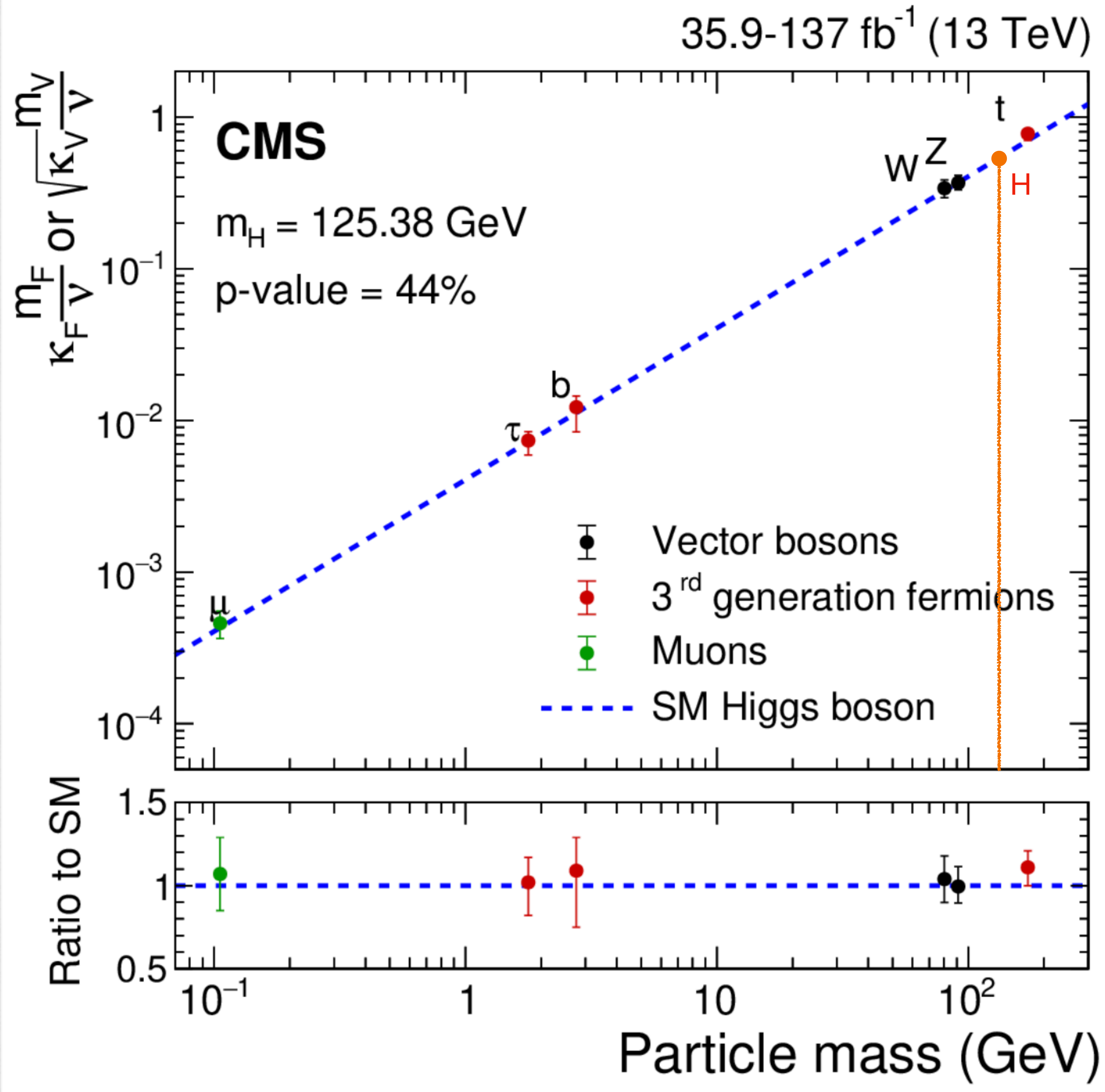

$$V(H) = \frac{m_H^2}{2} H^2 + \lambda_3 v H^3 + \frac{\lambda_4}{4} H^4 + \ldots$$

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

The Standard Model

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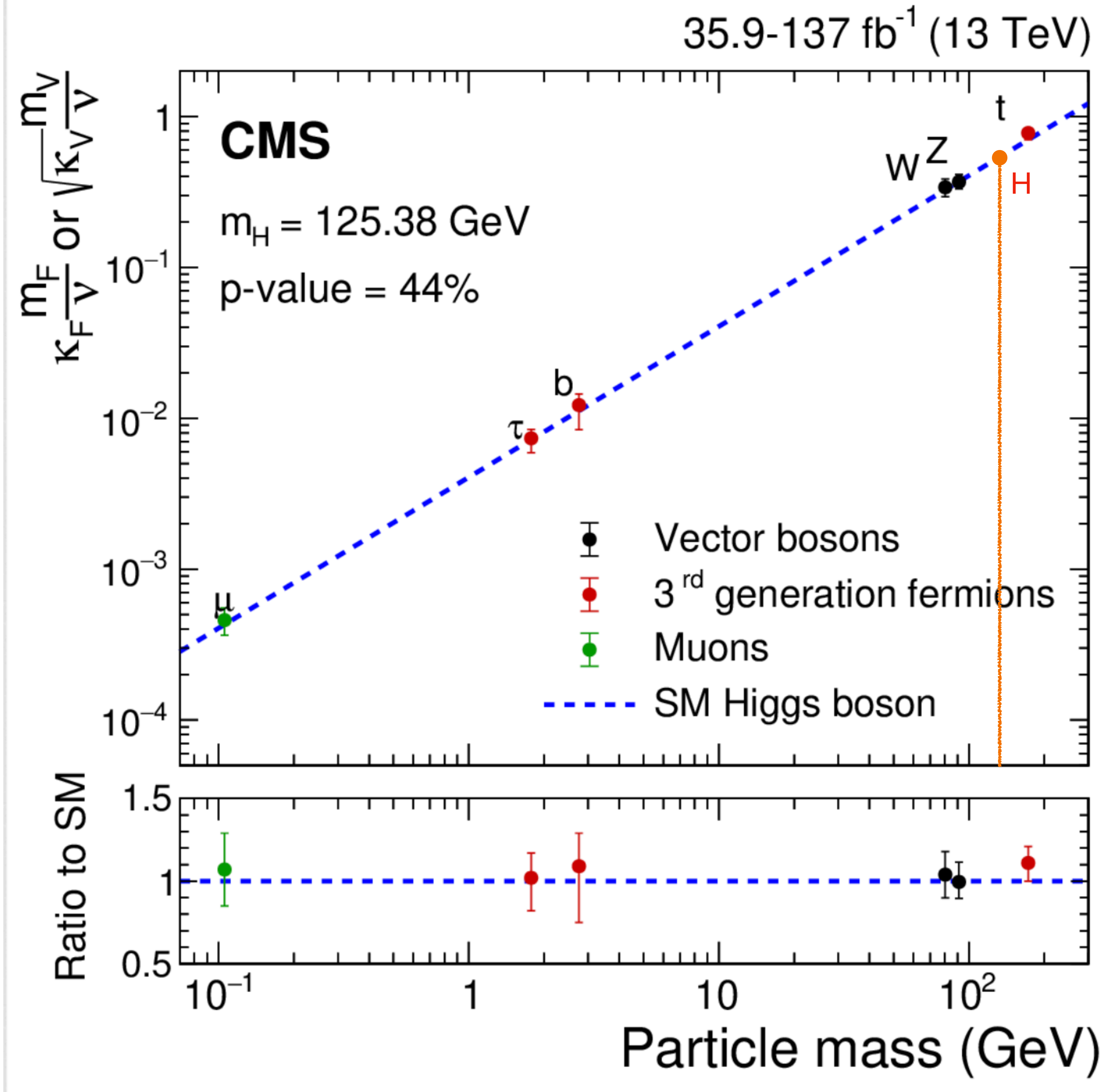

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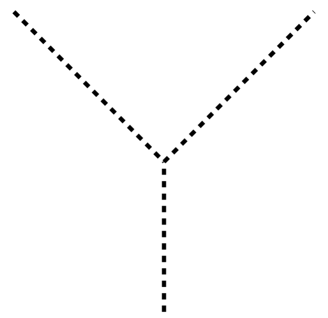

$$-3\, iv \cdot m_h^2/v^2$$

The Standard Model

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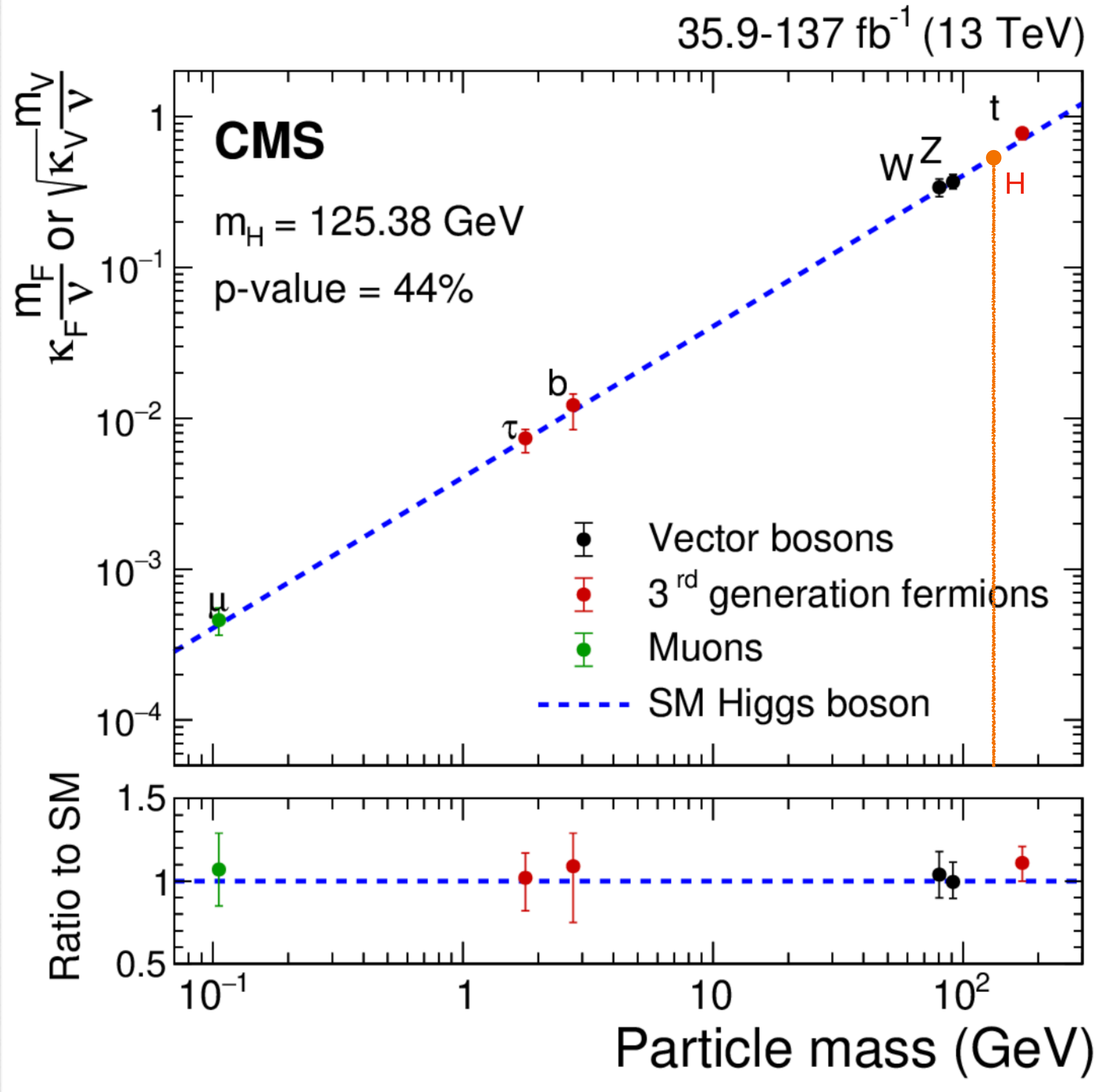

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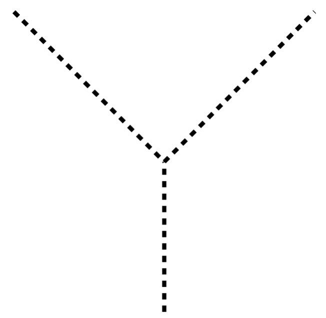

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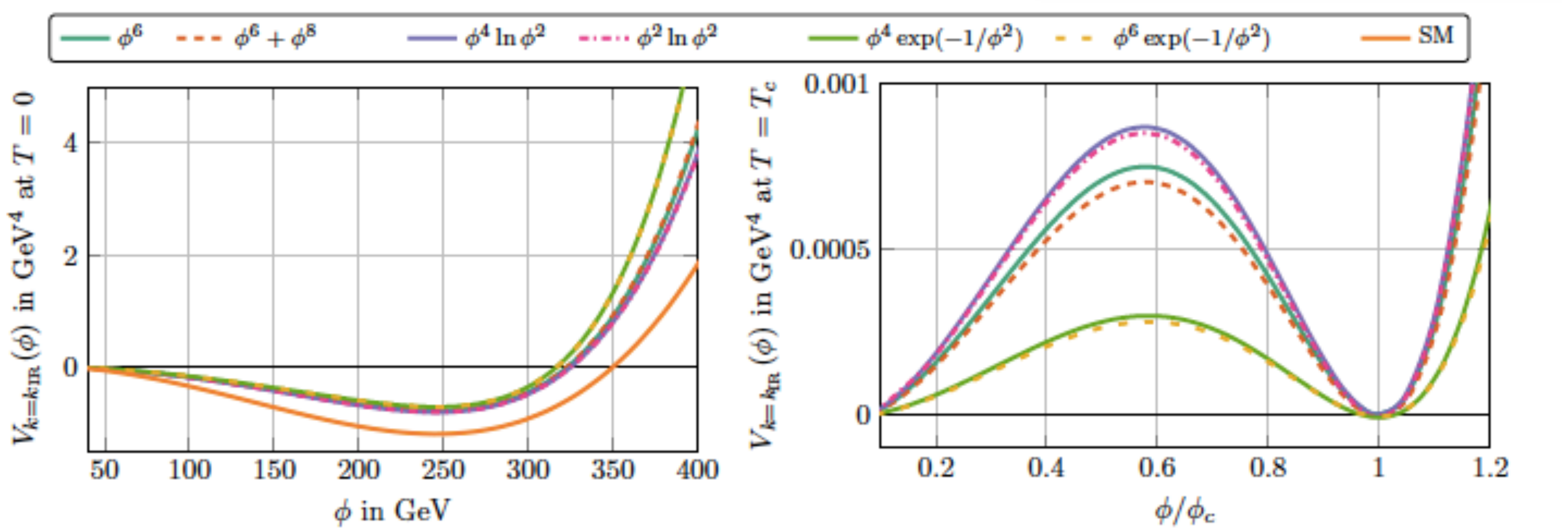

Reichert et al. 1711.00019

The Standard Model

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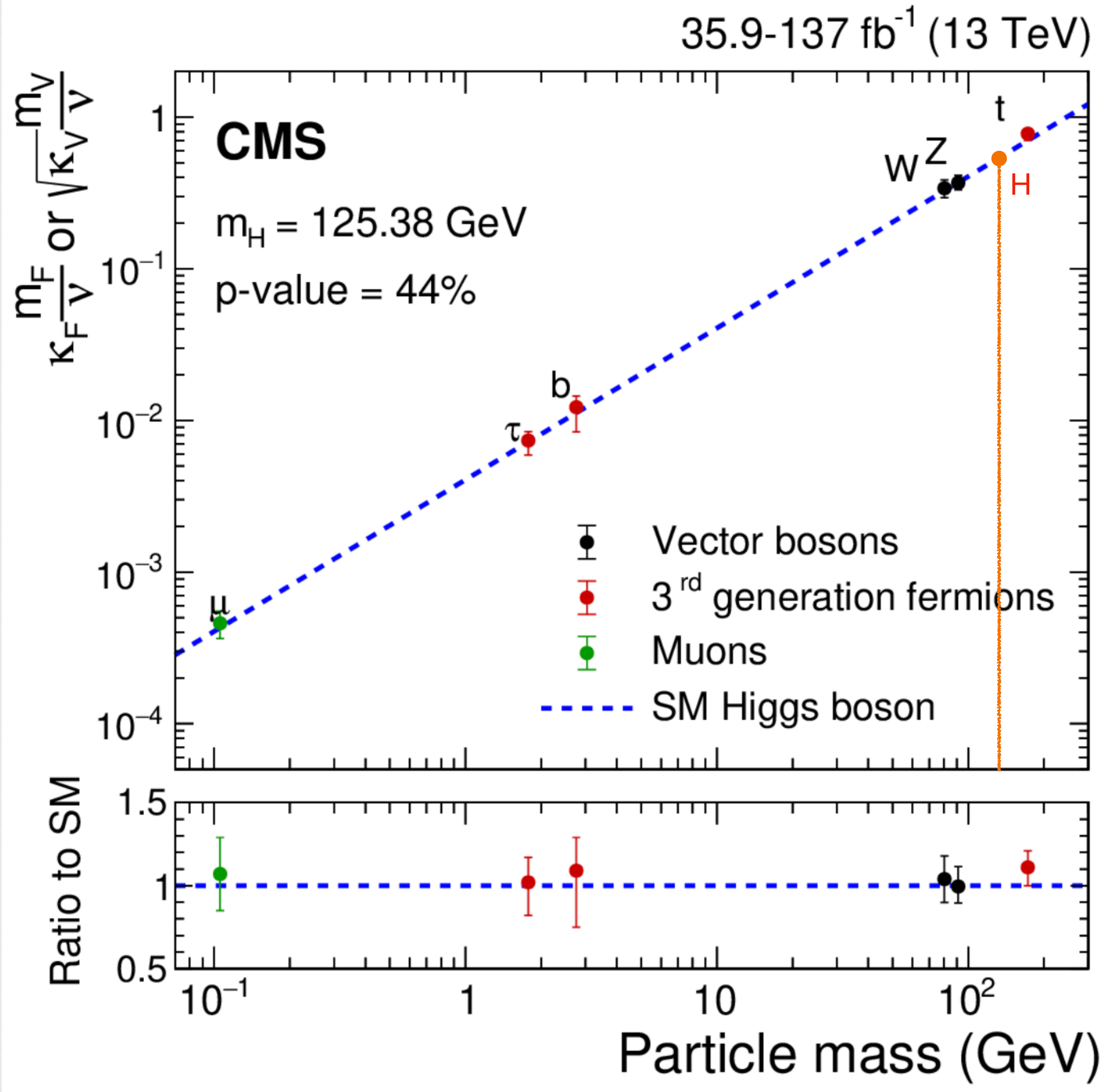

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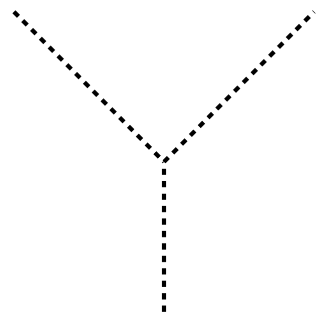

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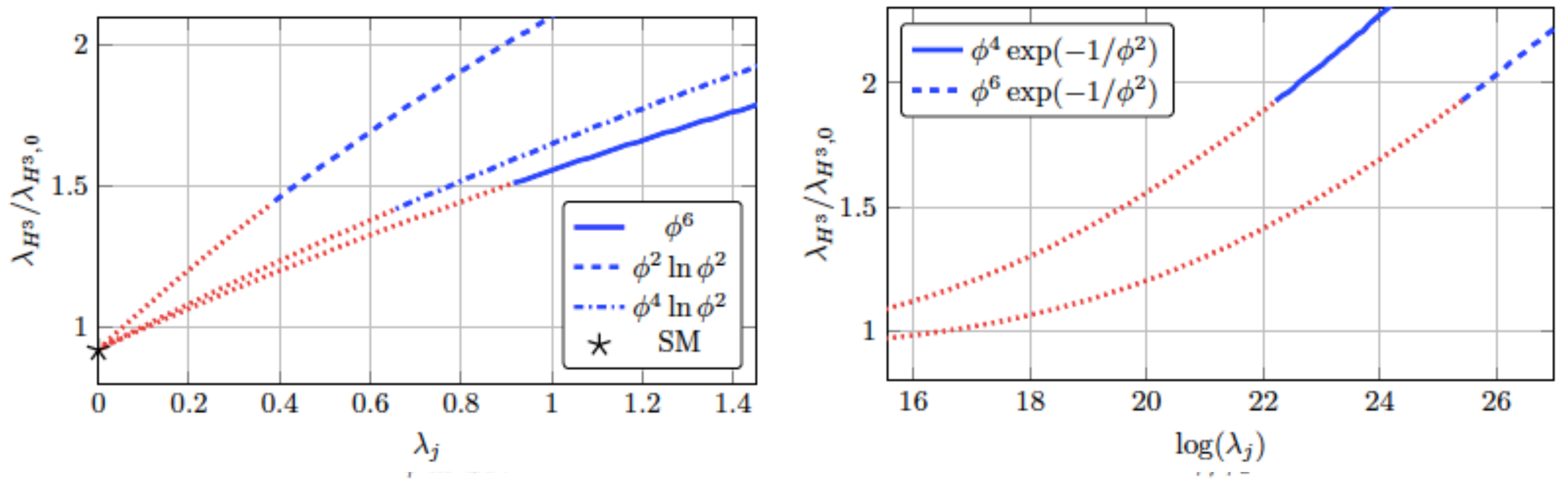

Reichert et al. 1711.00019

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

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

The Standard Model

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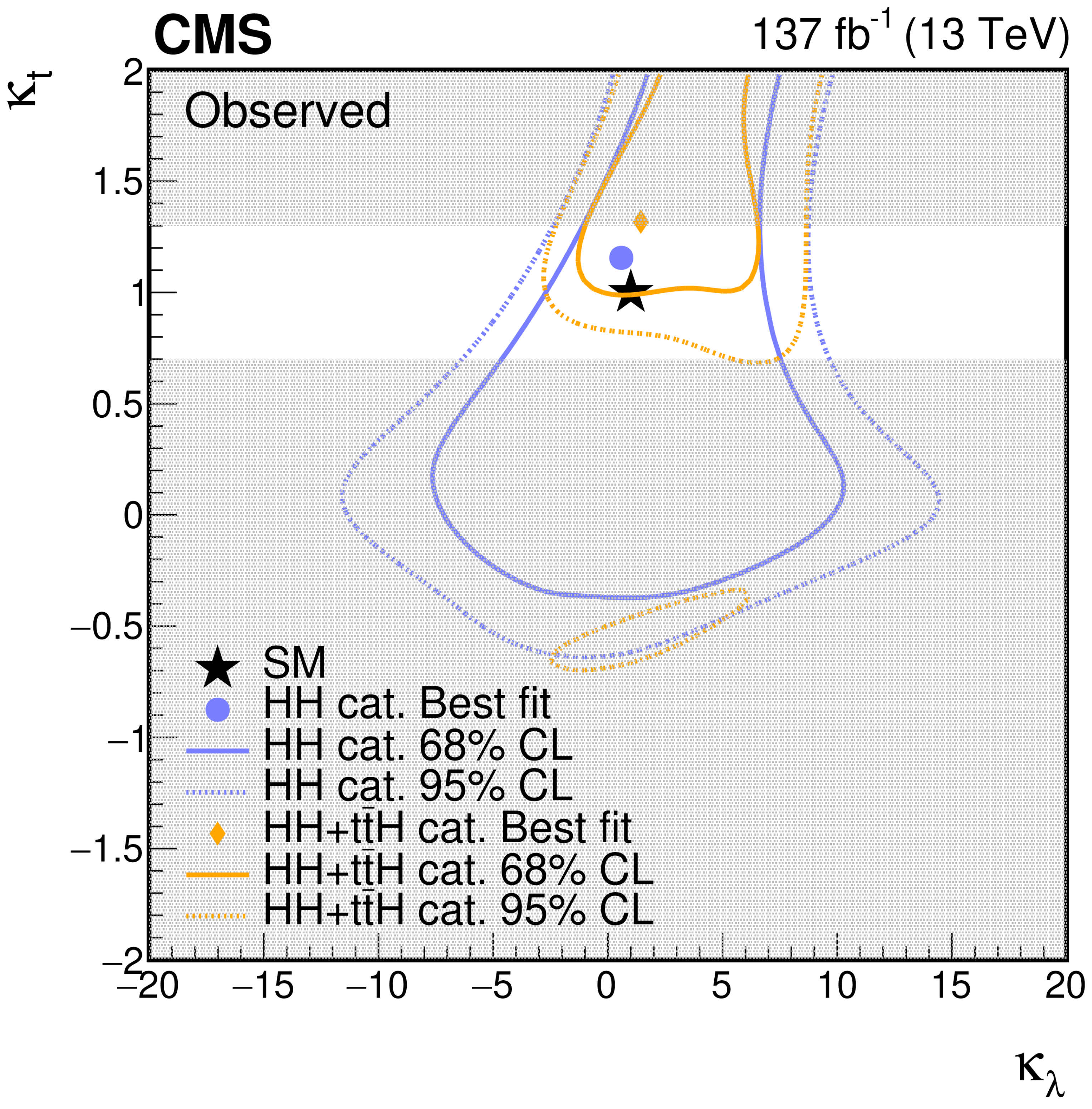
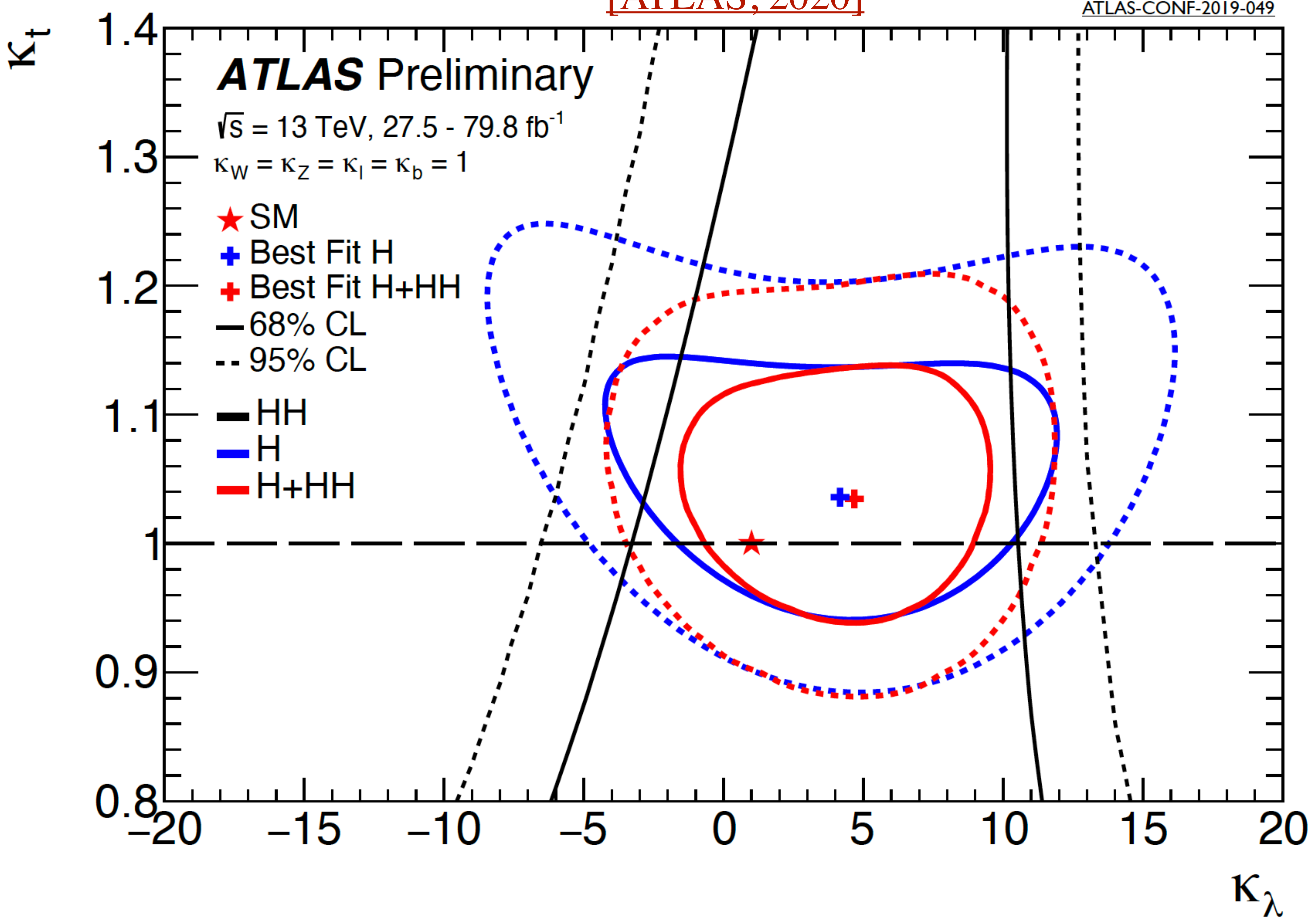


[ATLAS, 2020]



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

The precision path

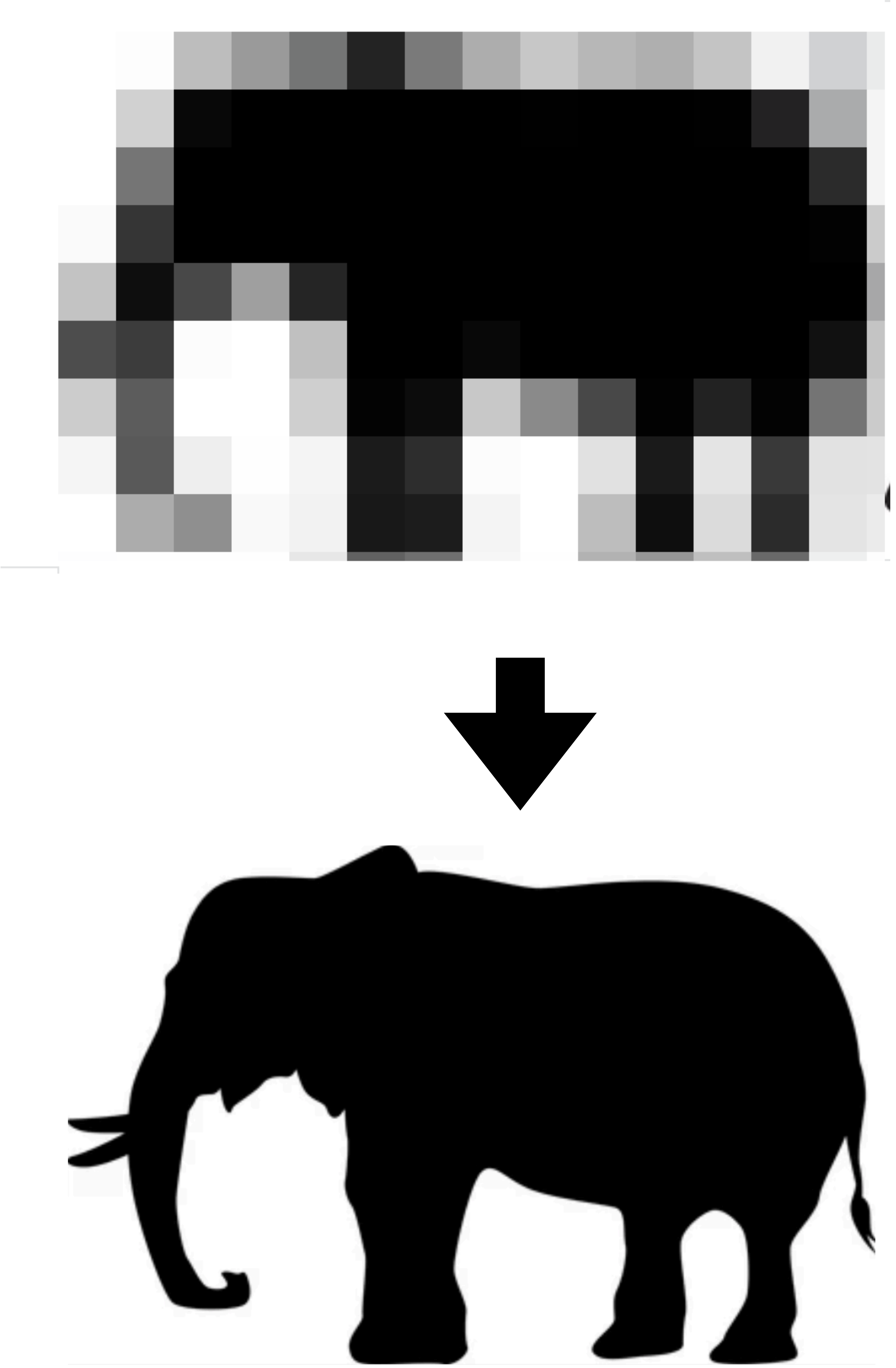
Two questions

1. What is the expected experimental precision on key SM measurements at the TeV scale and a reasonable goal for the corresponding TH predictions? Are we there yet?

2. How to frame and interpret our results to maximise the sensitivity to New Physics?

Towards the HL-LHC

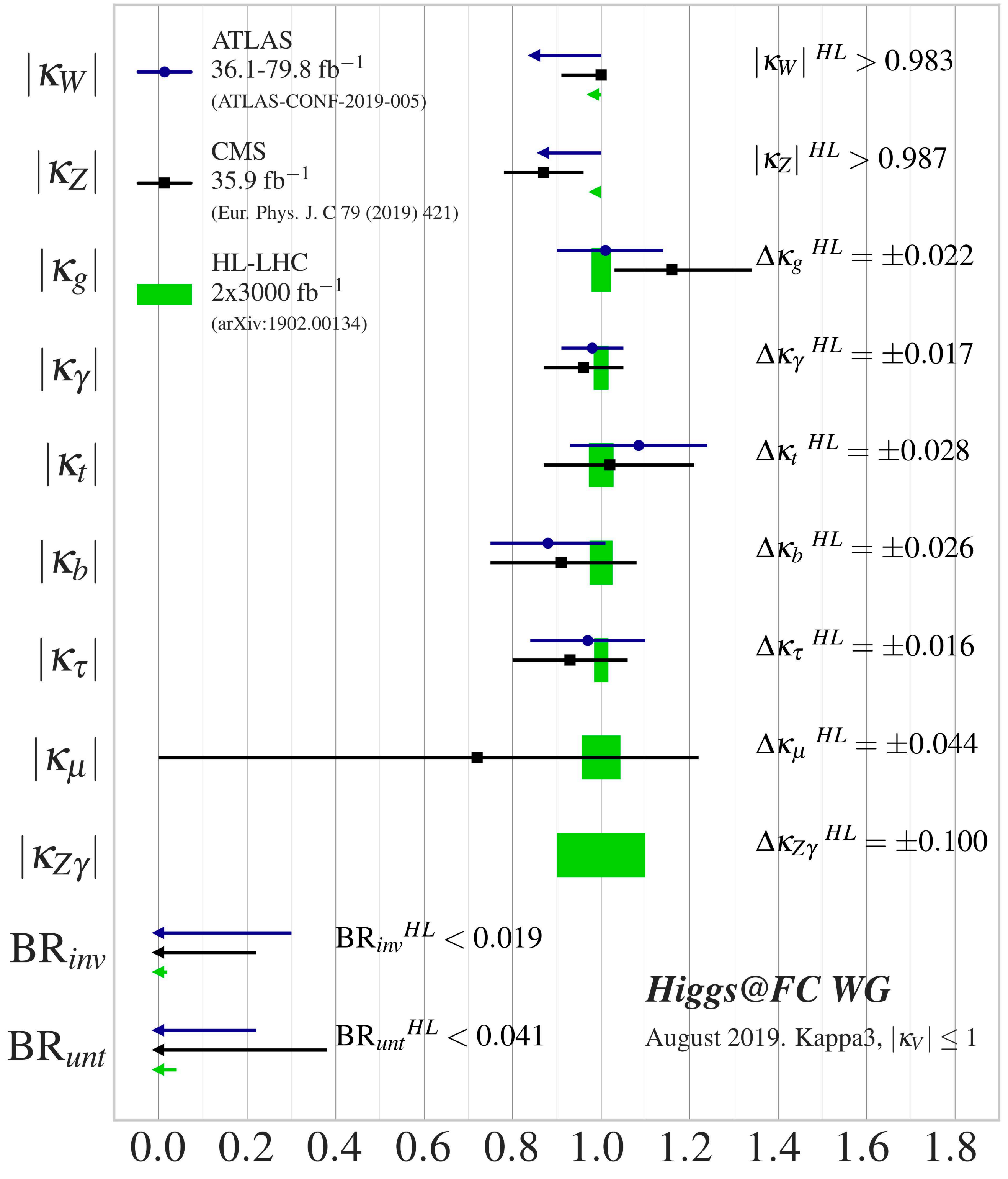
- 20-fold data sample
- 1/5 statistical uncertainties
- Comparable reduction of systematic uncertainties?
- Definition of tails and access to rare processes



HL-LHC projections

Higgs couplings

[De Blas et al., 2020]



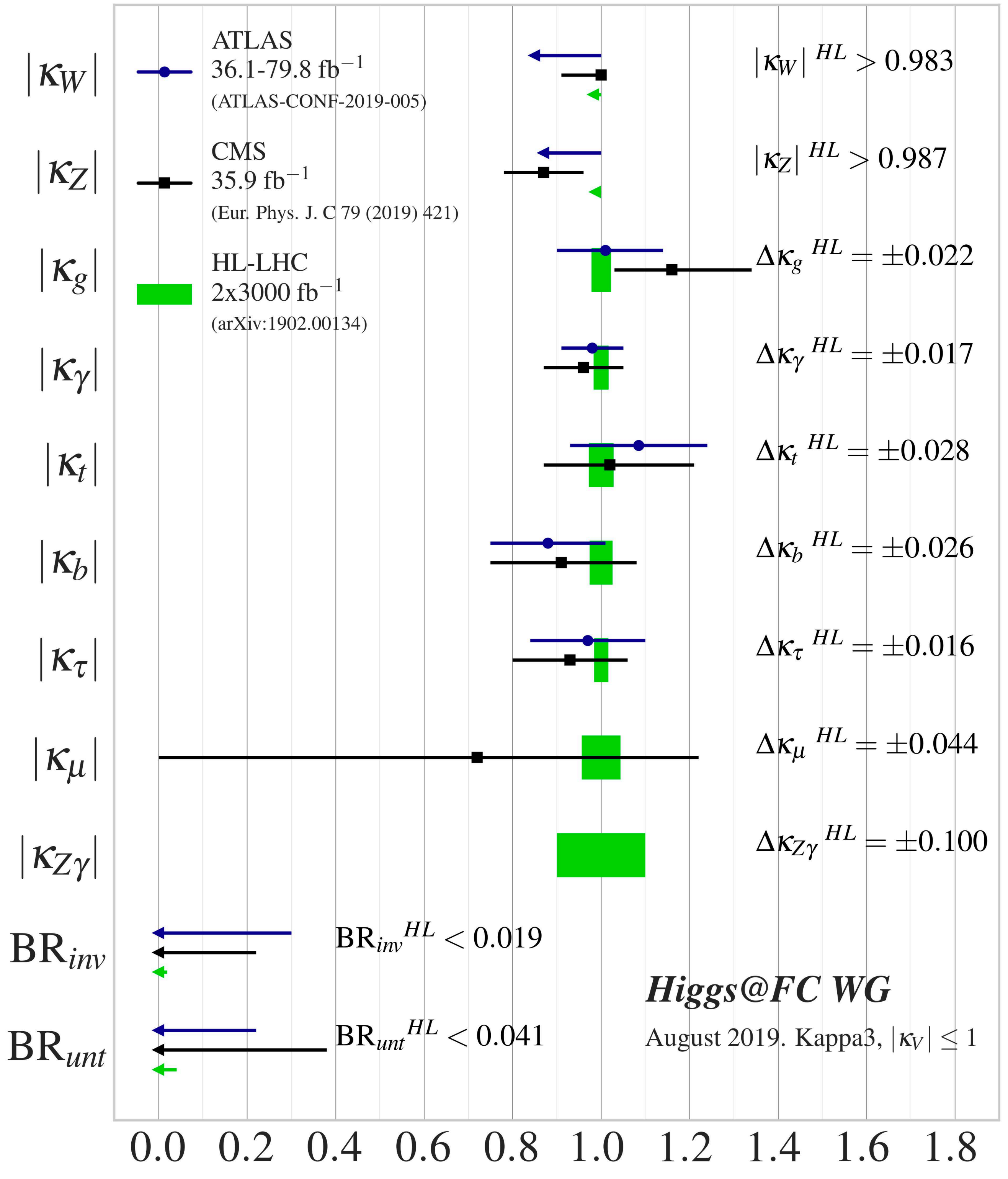
10-20%

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

HL-LHC projections

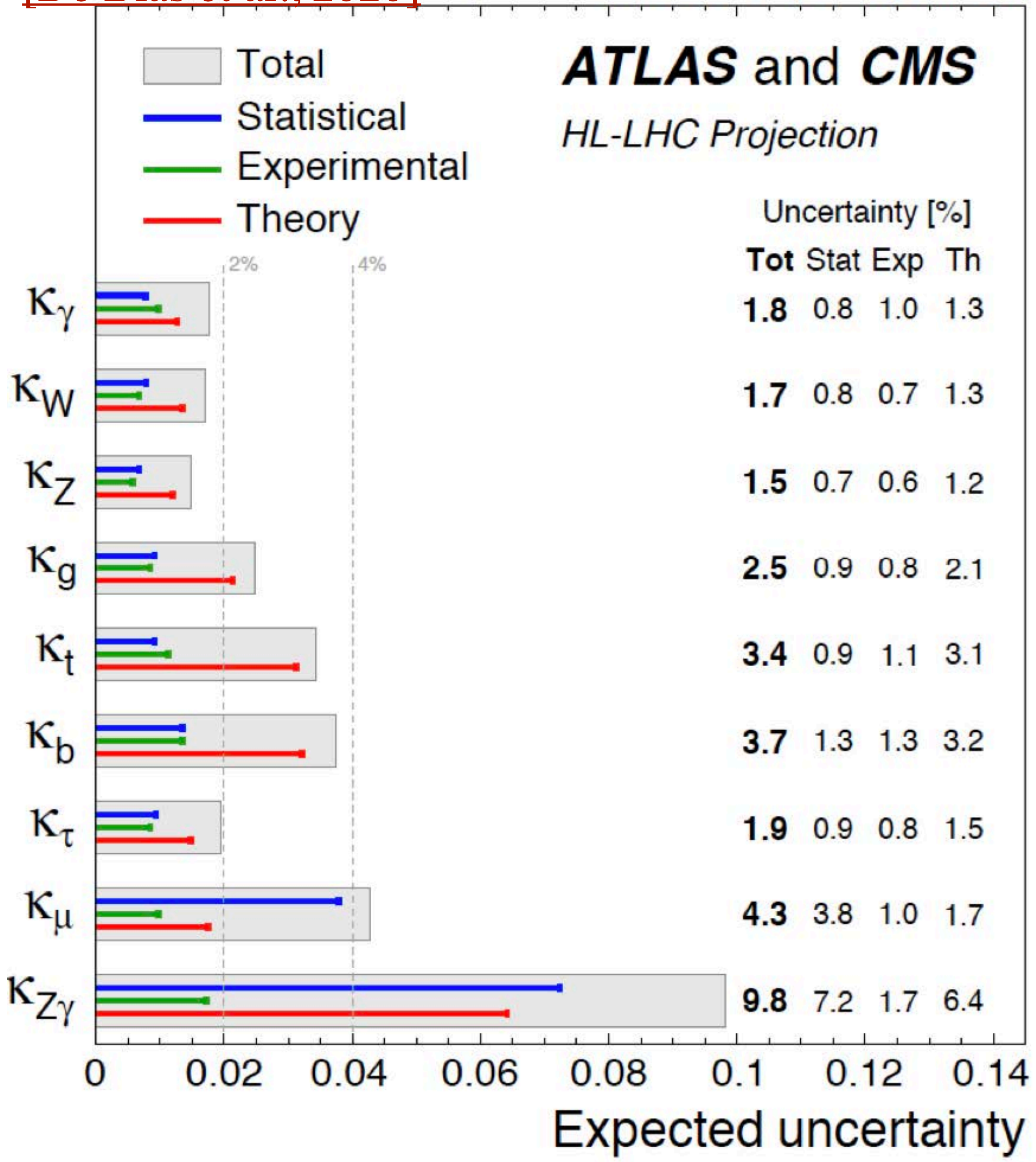
Higgs couplings

[De Blas et al., 2020]



10-20% → 2-4%

[De Blas et al., 2020]



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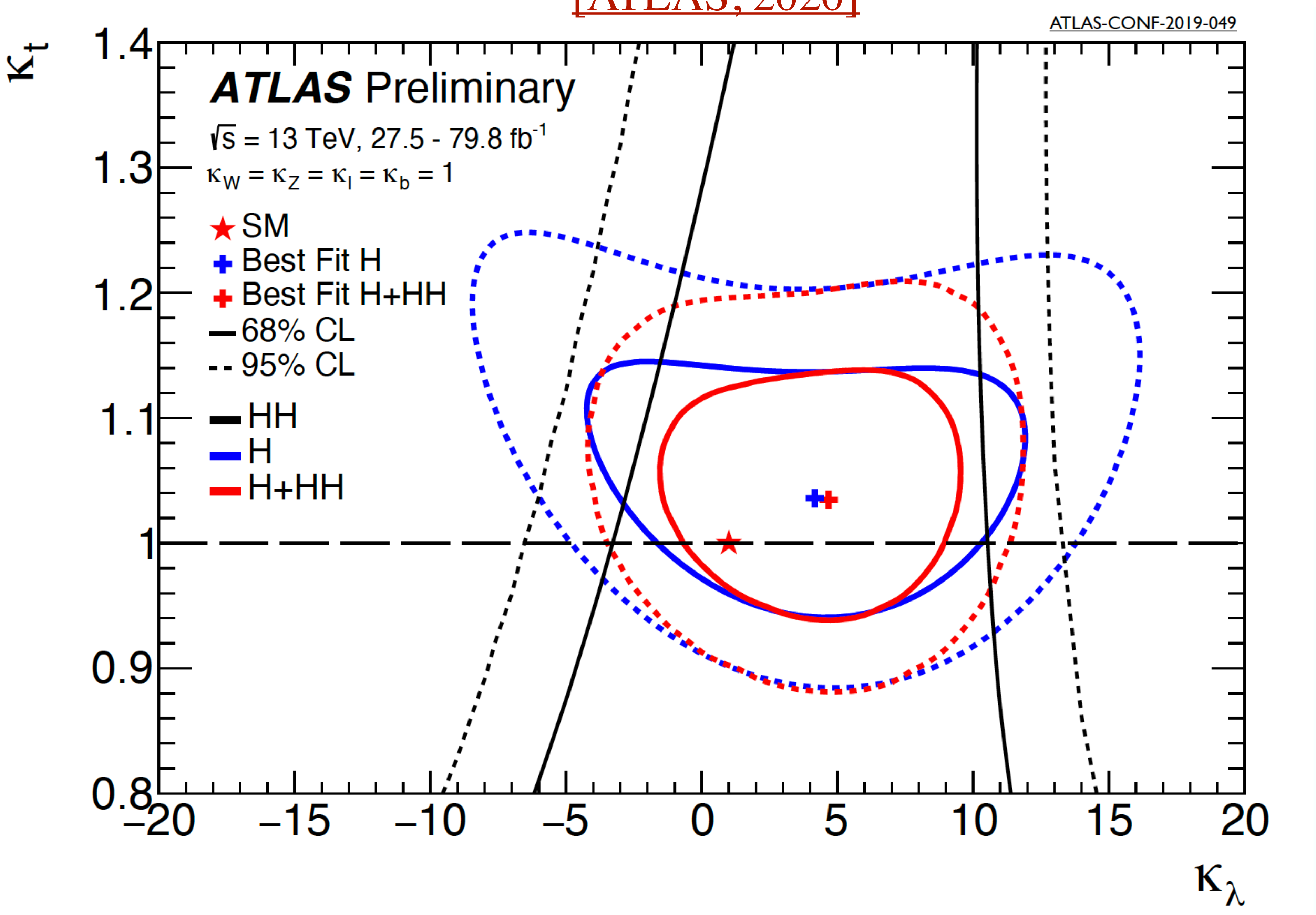
HL-LHC projections

Higgs couplings

Now

[ATLAS, 2020]

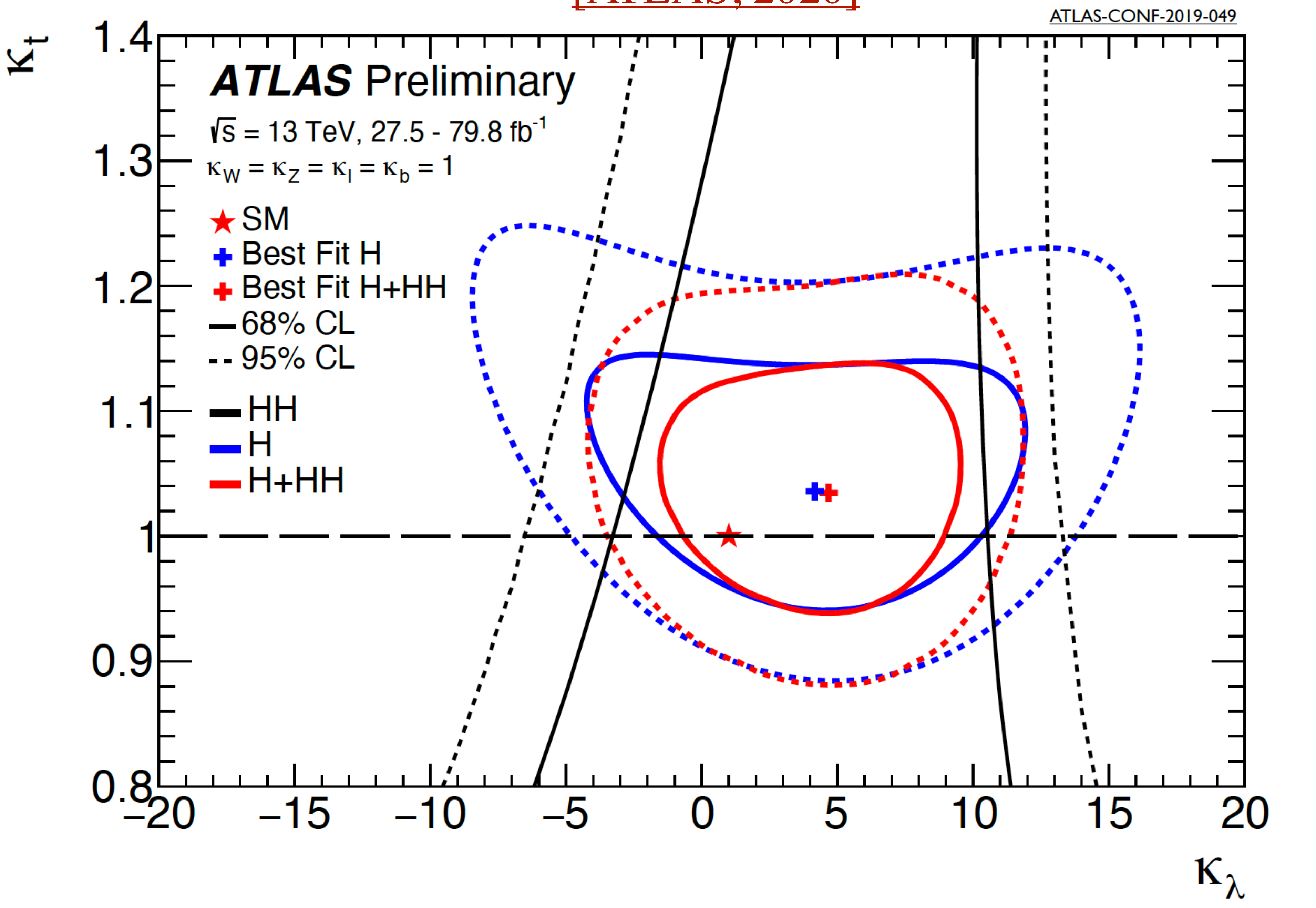


HL-LHC projections

Higgs couplings

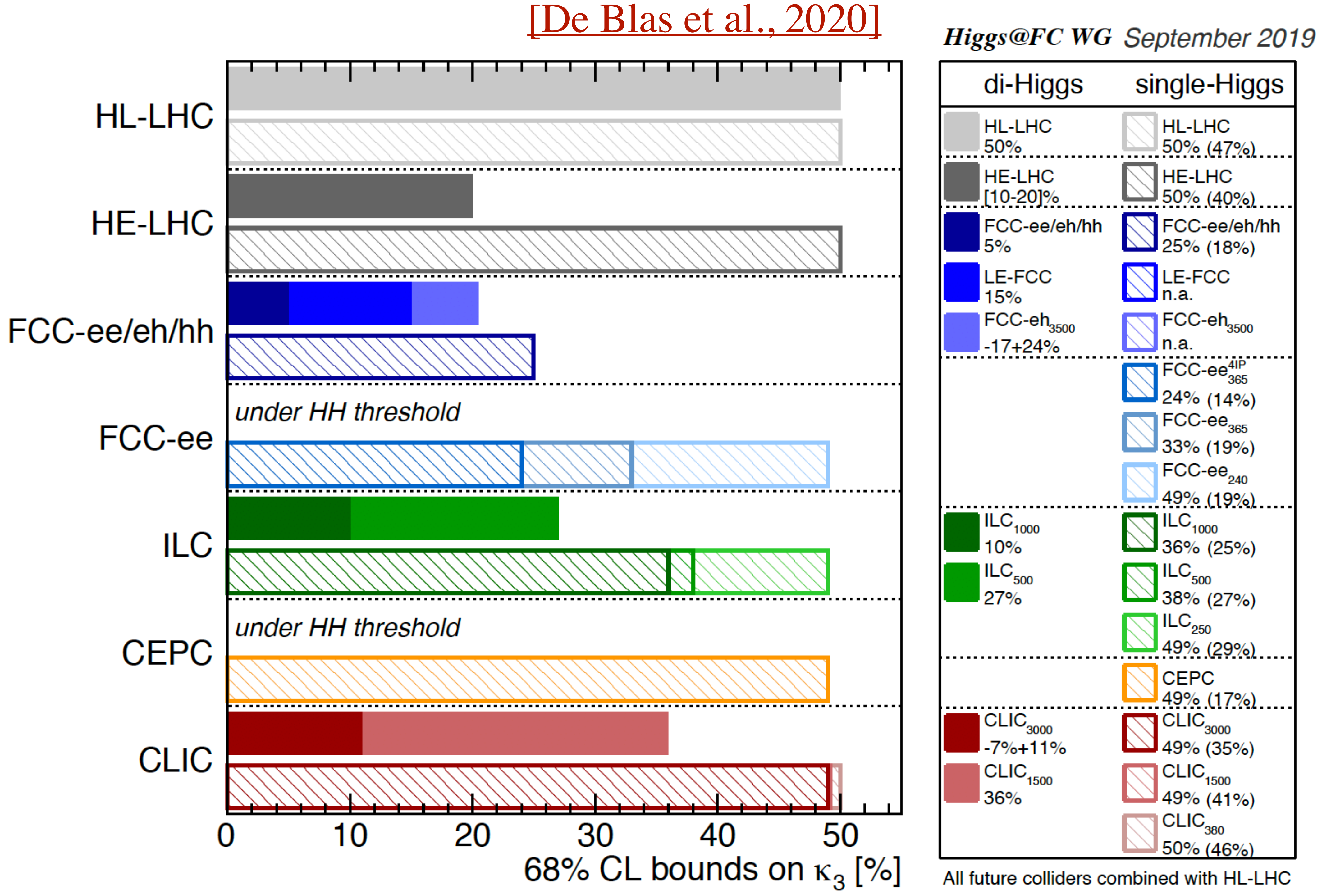
Now

[ATLAS, 2020]



Future

[De Blas et al., 2020]

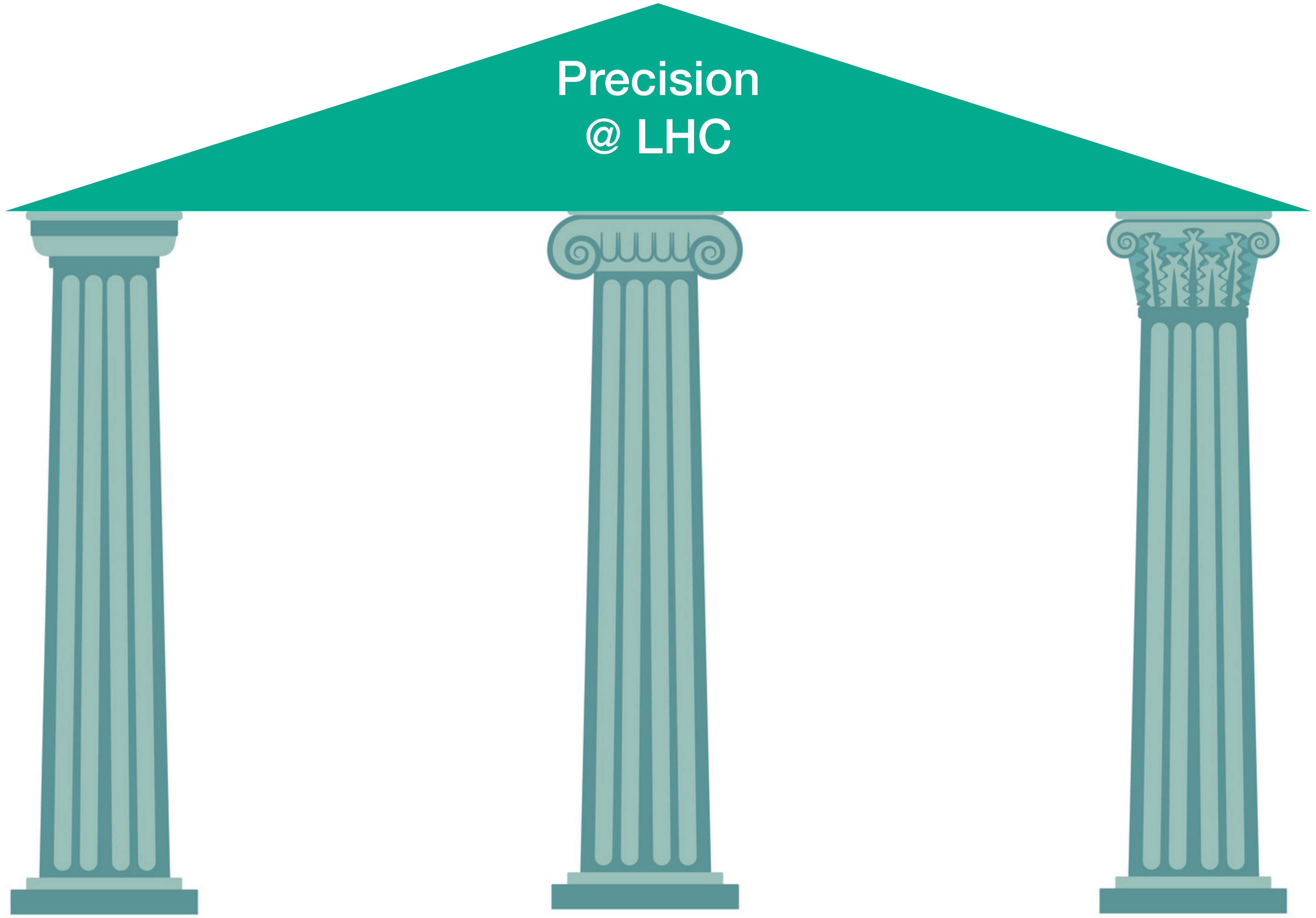


Currently limits on k_λ from H and HH are comparable and will stay so at the HL-LHC.

Borderline sensitivity to say something about EW baryogenesis…

Precision calculations for the LHC

Status



Fixed Order
LO, NLO,…
QCD EW

Resummation
LL, NLL,…
Parton Showers

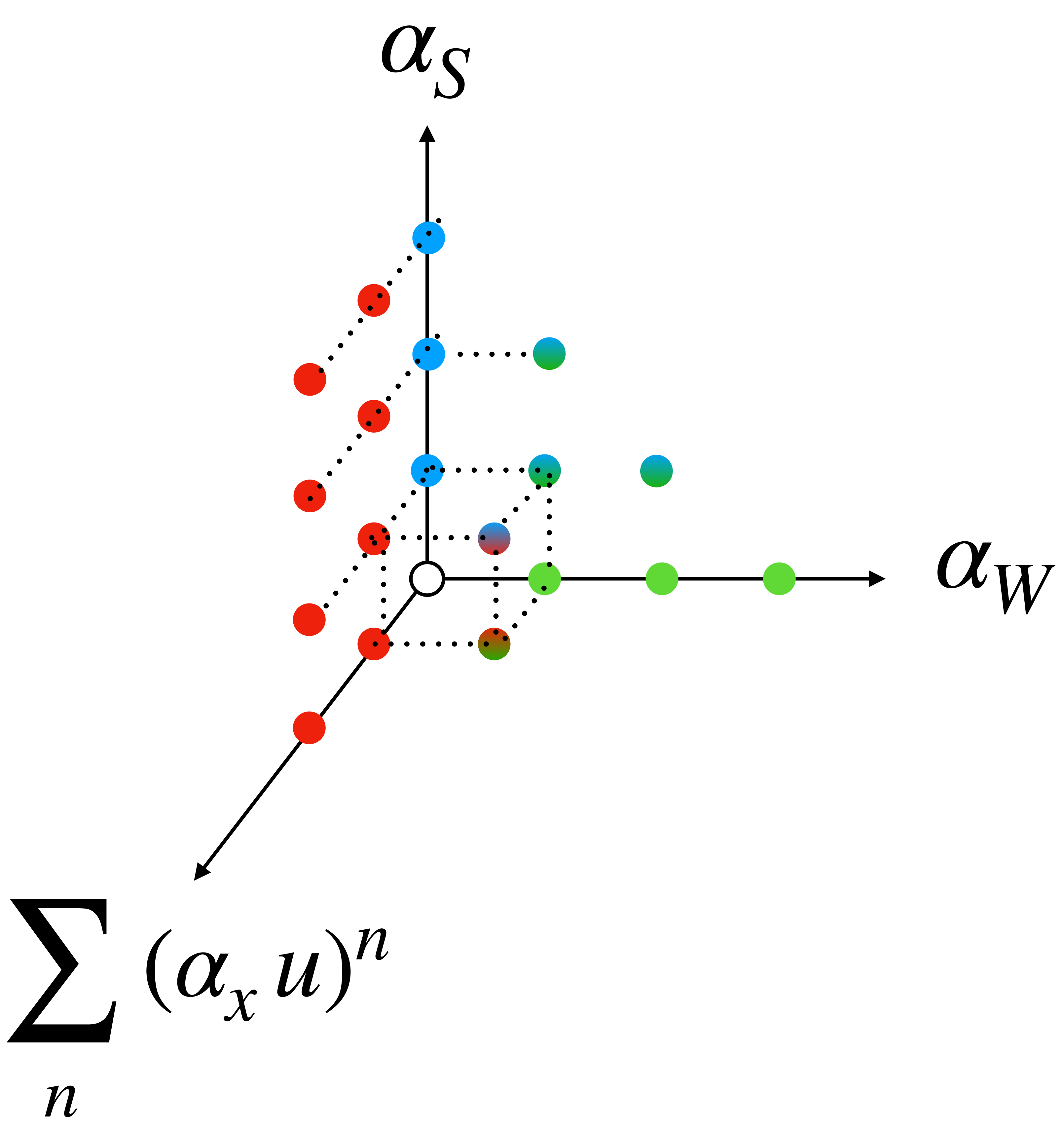
PDF’s
LO,NLO,..Evolution
Fits

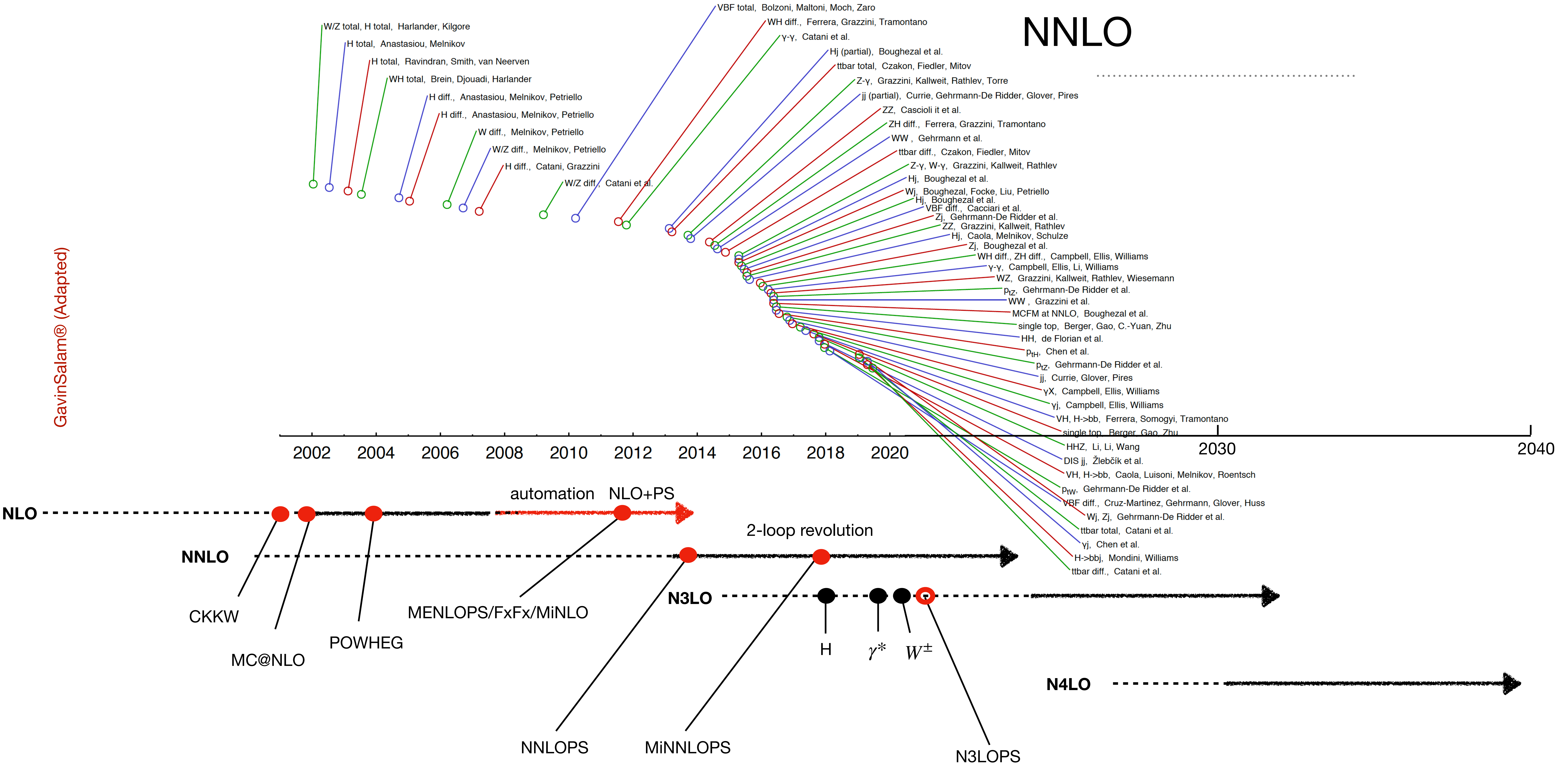
Precision calculations for the LHC

The path

"Rules of thumb at the LHC":

- Predictions must be calculated at least to **NLO QCD** to control the central value at 10-20%.
- **N2LO QCD** provides control at 5% level and on the uncertainties stabilizing the perturbative expansion.
- **N2LO QCD** is expected to be of the **same order** as **NLO EW** $\alpha_S^2 \sim \alpha_W$**, yet EW** corrections grow large and negative at high energies (Sudakov logs).
- **N3LO QCD** is the frontier of precision aiming ~1% of MHO uncertainties.
- **Resummation** Universal, all-order terms that are potentially large for some observables (logs or 1PI loops for propagators) need to be resummed. They might refer to global or non-global observables. Resummation leads to mprovements in precision and accuracy.

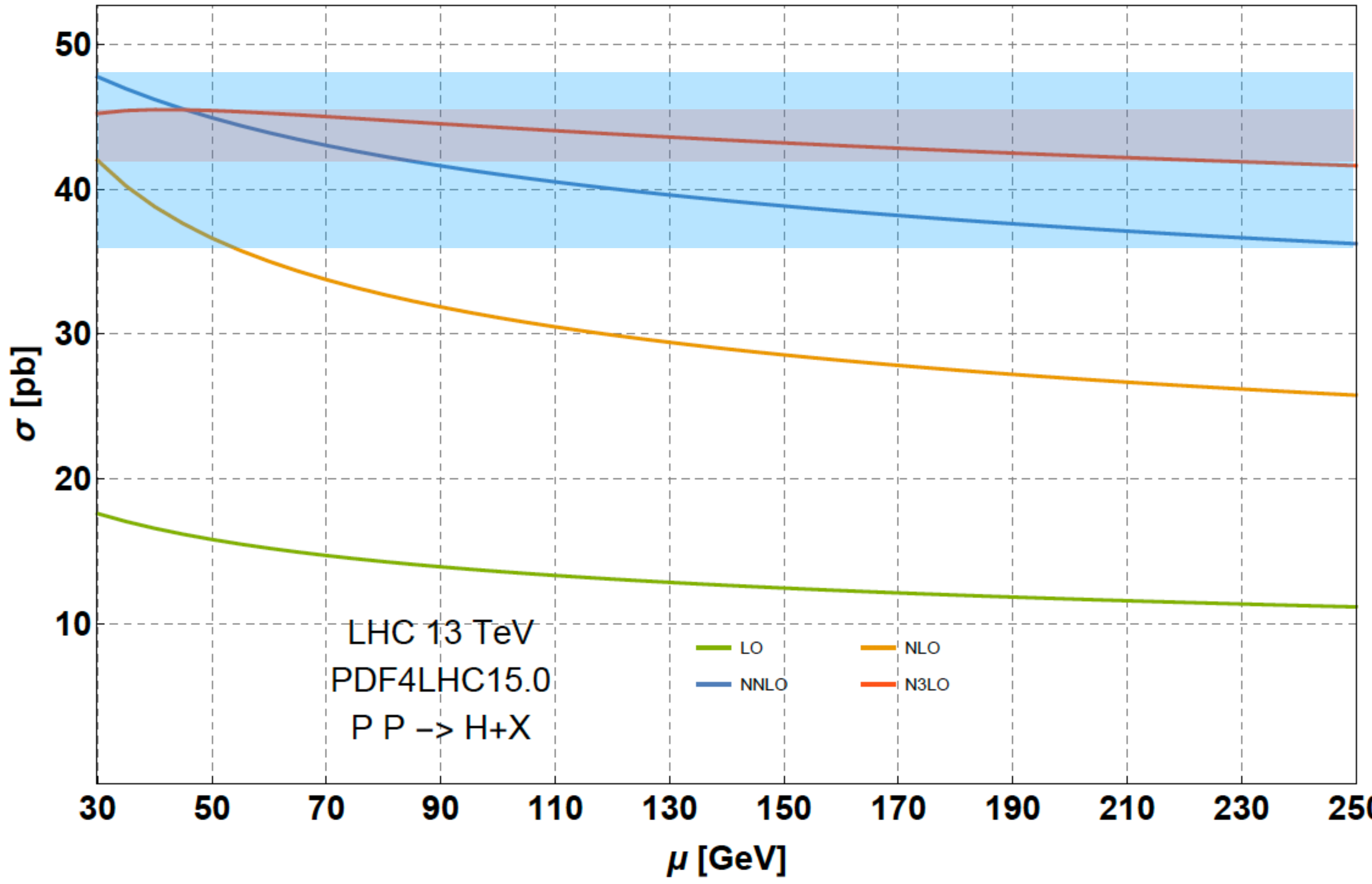



GavinSalam® (Adapted)
NNLO
W/Z total, H total, Harlander, Kilgore
H total, Anastasiou, Melnikov
H total, Ravindran, Smith, van Neerven
WH total, Brein, Djouadi, Harlander
H diff., Anastasiou, Melnikov, Petriello
H diff., Anastasiou, Melnikov, Petriello
W diff., Melnikov, Petriello
W/Z diff., Melnikov, Petriello
H diff., Catani, Grazzini
W/Z diff., Catani et al.
VBF total, Bolzoni, Maltoni, Moch, Zaro
WH diff., Ferrera, Grazzini, Tramontano
γ-γ, Catani et al.
Hj (partial), Boughezal et al.
ttbar total, Czakon, Fiedler, Mitov
Z-γ, Grazzini, Kallweit, Rathlev, Torre
jj (partial), Currie, Gehrmann-De Ridder, Glover, Pires
ZZ, Cascioli it et al.
ZH diff., Ferrera, Grazzini, Tramontano
WW , Gehrmann et al.
ttbar diff., Czakon, Fiedler, Mitov
Z-γ, W-γ, Grazzini, Kallweit, Rathlev
Hj, Boughezal et al.
Wj, Boughezal, Focke, Liu, Petriello
Hj, Boughezal et al.
VBF diff., Cacciari et al.
Zj, Gehrmann-De Ridder et al.
ZZ, Grazzini, Kallweit, Rathlev
Hj, Caola, Melnikov, Schulze
Zj, Boughezal et al.
WH diff., ZH diff., Campbell, Ellis, Williams
γ-γ, Campbell, Ellis, Li, Williams
WZ, Grazzini, Kallweit, Rathlev, Wiesemann
p_{TZ}, Gehrmann-De Ridder et al.
WW , Grazzini et al.
MCFM at NNLO, Boughezal et al.
single top, Berger, Gao, C.-Yuan, Zhu
HH, de Florian et al.
p_{tH}, Chen et al.
p_{tZ}, Gehrmann-De Ridder et al.
jj, Currie, Glover, Pires
γX, Campbell, Ellis, Williams
γj, Campbell, Ellis, Williams
VH, H->bb, Ferrera, Somogyi, Tramontano
single top, Berger, Gao, Zhu
HHZ, Li, Li, Wang
DIS jj, Žlebčík et al.
VH, H->bb, Caola, Luisoni, Melnikov, Roentsch
p_{tW}, Gehrmann-De Ridder et al.
VBF diff., Cruz-Martinez, Gehrmann, Glover, Huss
Wj, Zj, Gehrmann-De Ridder et al.
ttbar total, Catani et al.
γj, Chen et al.
H->bbj, Mondini, Williams
ttbar diff., Catani et al.
2002
2004
2006
2008
2010
2012
2014
2016
2018
2020
2030
2040
NLO
automation
NLO+PS
CKKW
MC@NLO
POWHEG
MENLOPS/FxFx/MiNLO
NNLO
2-loop revolution
NNLOPS
MiNNLOPS
N3LO
H
γ^*
$W^\pm$
N3LOPS
N4LO

Precision calculations for the LHC

N3LO revolution

[Anastasiou et al. , 1602.00695]

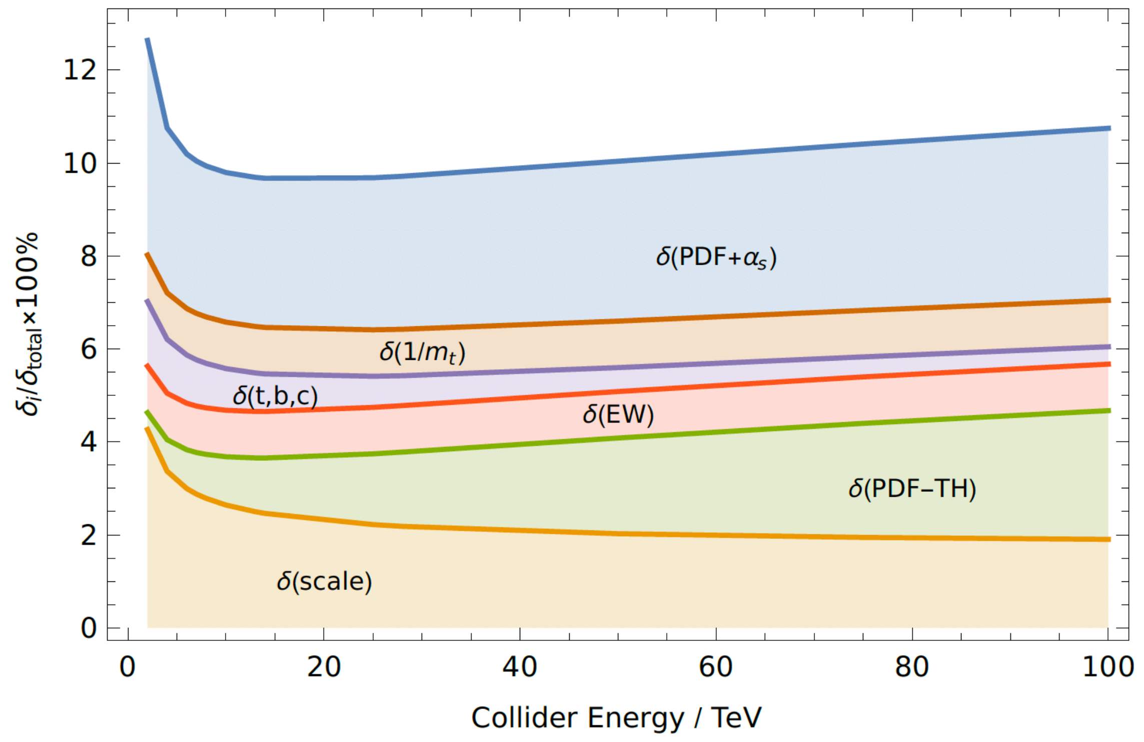


<5%

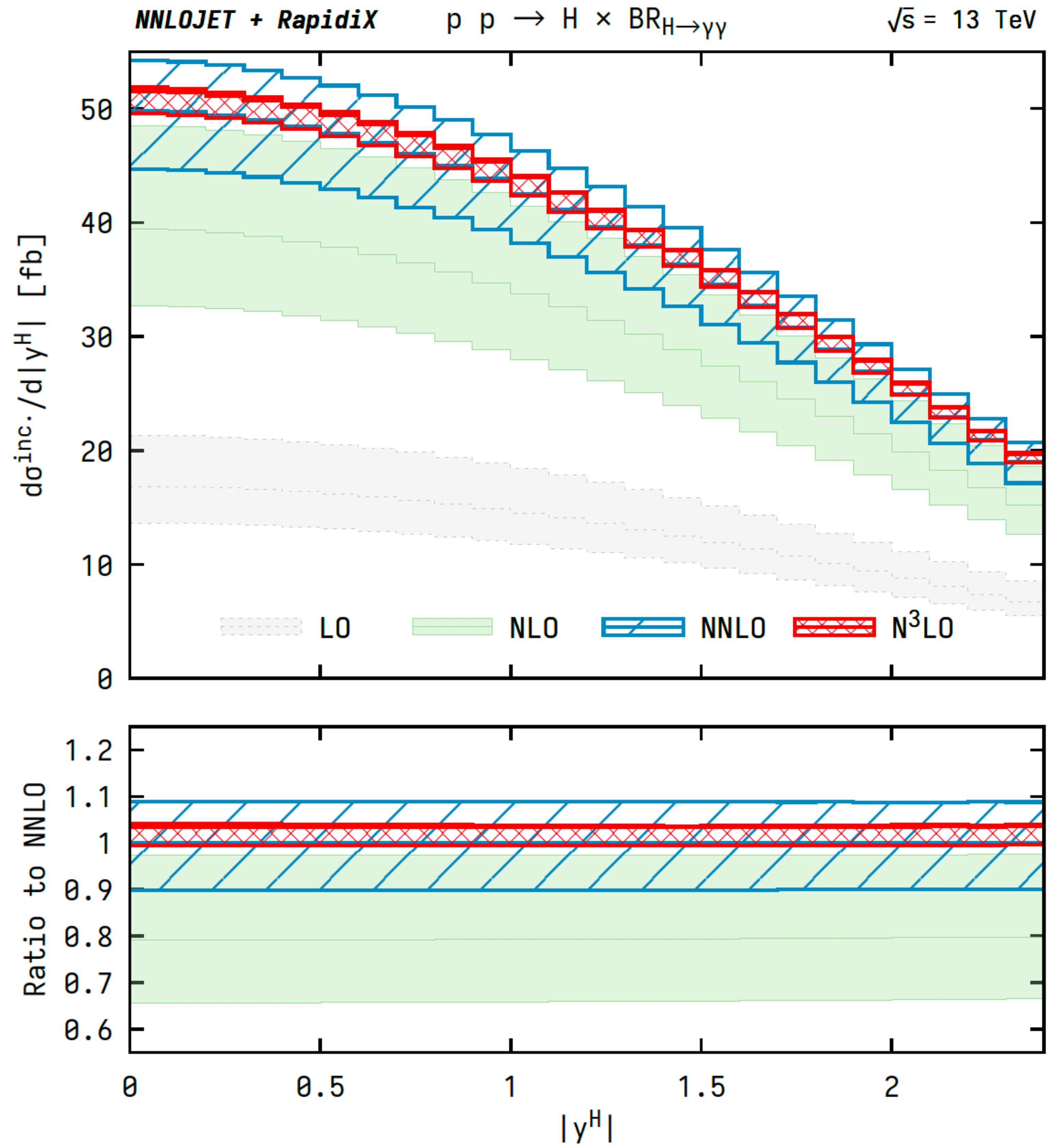
Table 2: Gluon fusion Higgs boson production cross sections and uncertainties as a function of the pp collider energy.

$\sqrt{s}$	σ	δ(theory)		δ(PDF)	$\delta(\alpha_s)$	
13 TeV	48.61 pb	$^{+2.08\text{pb}}_{-3.15\text{pb}}$	$\left(^{+4.27\%}_{-6.49\%}\right)$	± 0.89 pb $(\pm 1.85\%)$	$^{+1.24\text{pb}}_{-1.26\text{pb}}$	$\left(^{+2.59\%}_{-2.62\%}\right)$
14 TeV	54.72 pb	$^{+2.35\text{pb}}_{-3.54\text{pb}}$	$\left(^{+4.28\%}_{-6.46\%}\right)$	± 1.00 pb $(\pm 1.85\%)$	$^{+1.40\text{pb}}_{-1.41\text{pb}}$	$\left(^{+2.60\%}_{-2.62\%}\right)$
27 TeV	146.65 pb	$^{+6.65\text{pb}}_{-9.44\text{pb}}$	$\left(^{+4.53\%}_{-6.43\%}\right)$	± 2.81 pb $(\pm 1.95\%)$	$^{+3.88\text{pb}}_{-3.82\text{pb}}$	$\left(^{+2.69\%}_{-2.64\%}\right)$

- Very significant reduction of MHO uncertainties.
- Differential distributions are available.
- Uncertainty budget points to PDF as the main source of error.



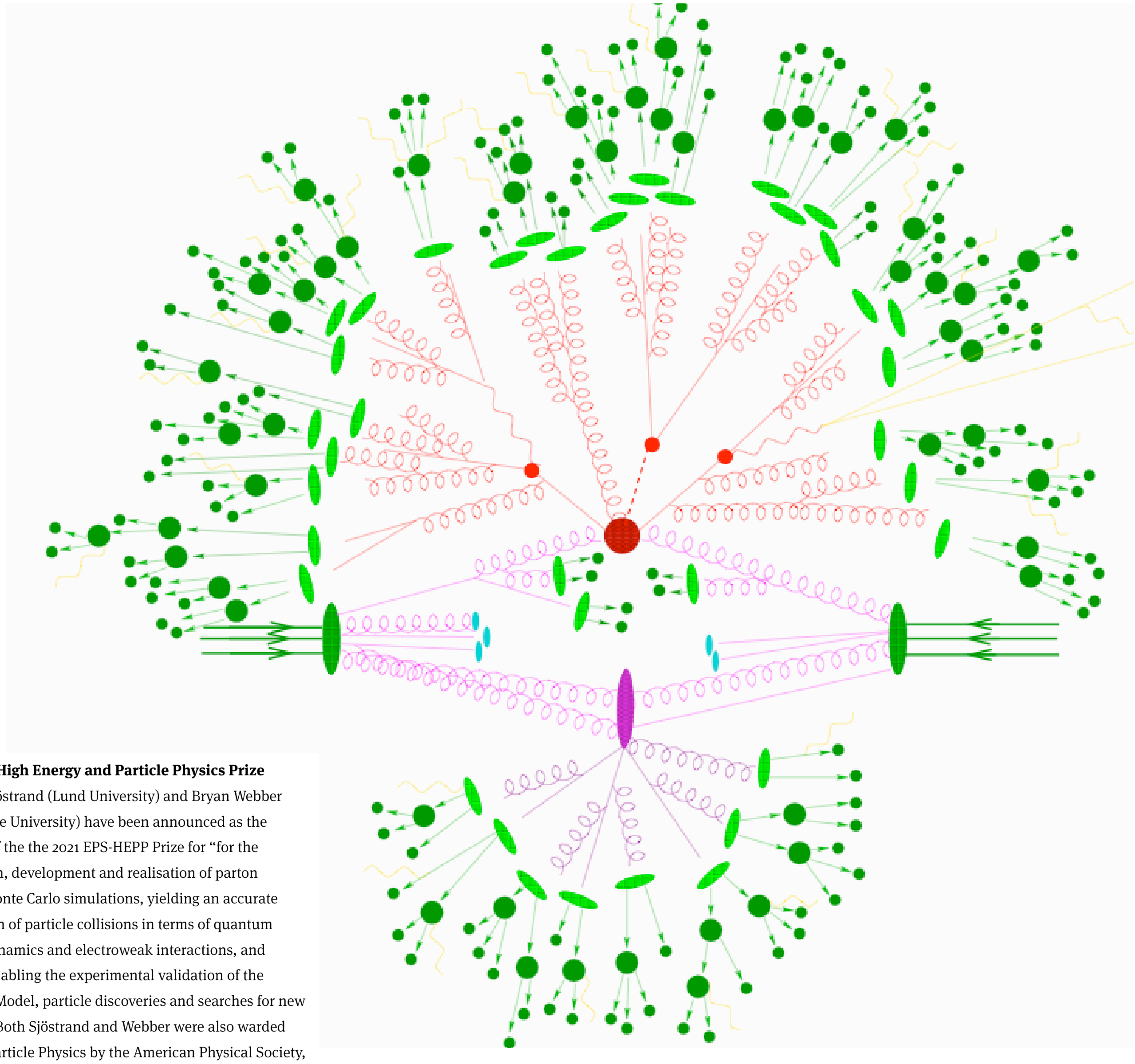
[Chen et al , 2102.07607]



- Drell-Yan now available [Duhr, Dulat and Mistelberger, 2001.07717] [Duhr, Dulat and Mistelberger, 2007.13313]

Precision calculations for the LHC

Fully exclusive simulations



Bryan Webber (left) and Torbjörn Sjöstrand (right). Credit: Lund University, T Sjöstrand

2021 EPS High Energy and Particle Physics Prize
Torbjrn Sjöstrand (Lund University) and Bryan Webber (Cambridge University) have been announced as the winners of the the 2021 EPS-HEPP Prize for "for the conception, development and realisation of parton shower Monte Carlo simulations, yielding an accurate description of particle collisions in terms of quantum chromodynamics and electroweak interactions, and thereby enabling the experimental validation of the Standard Model, particle discoveries and searches for new physics." Both Sjöstrand and Webber were also warded the 2012 Sakurai Prize for Theoretical Particle Physics by the American Physical Society, along with the late Guido Altarelli.

[Mazzitelli et al. , 2012.14267]

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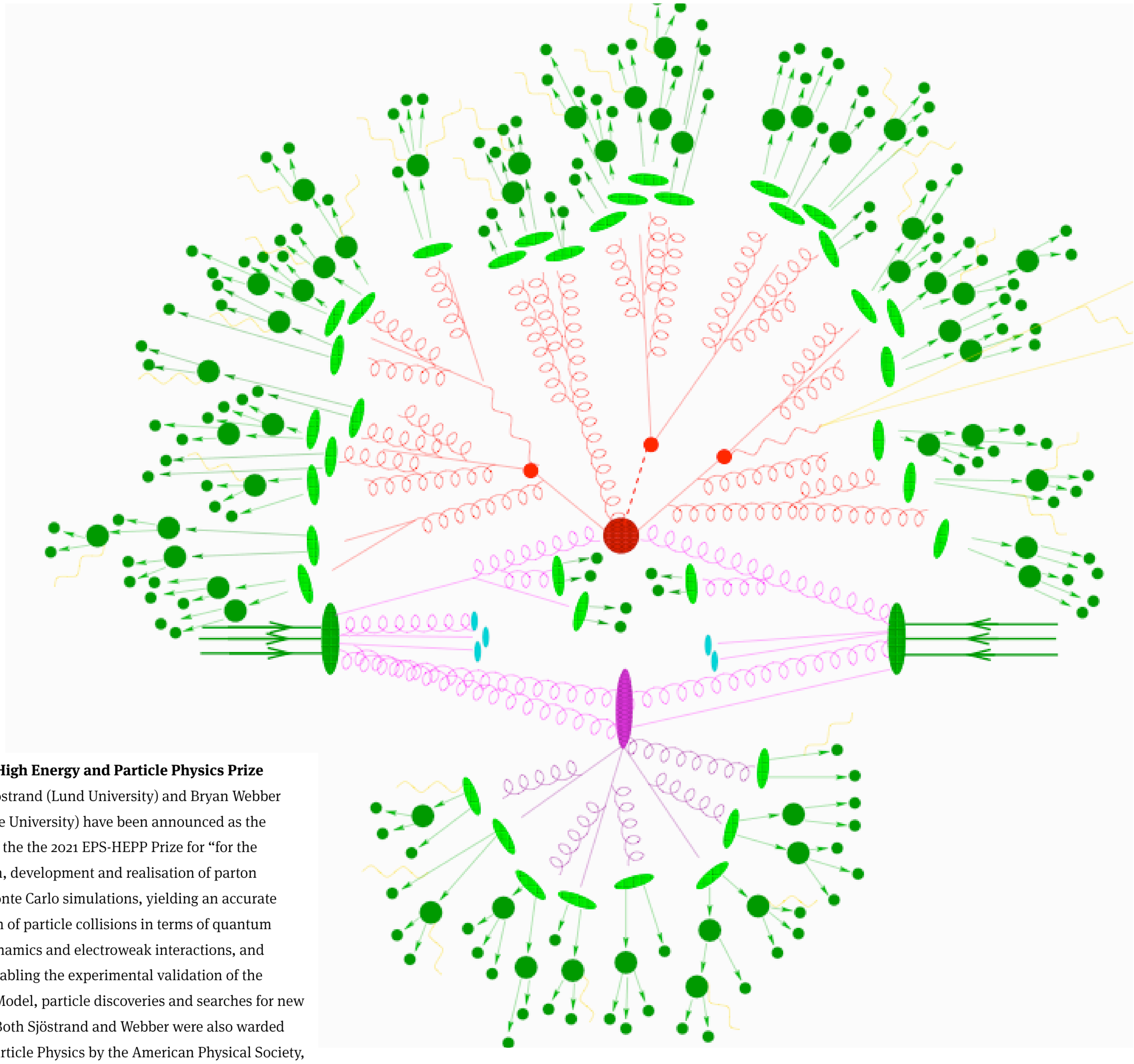

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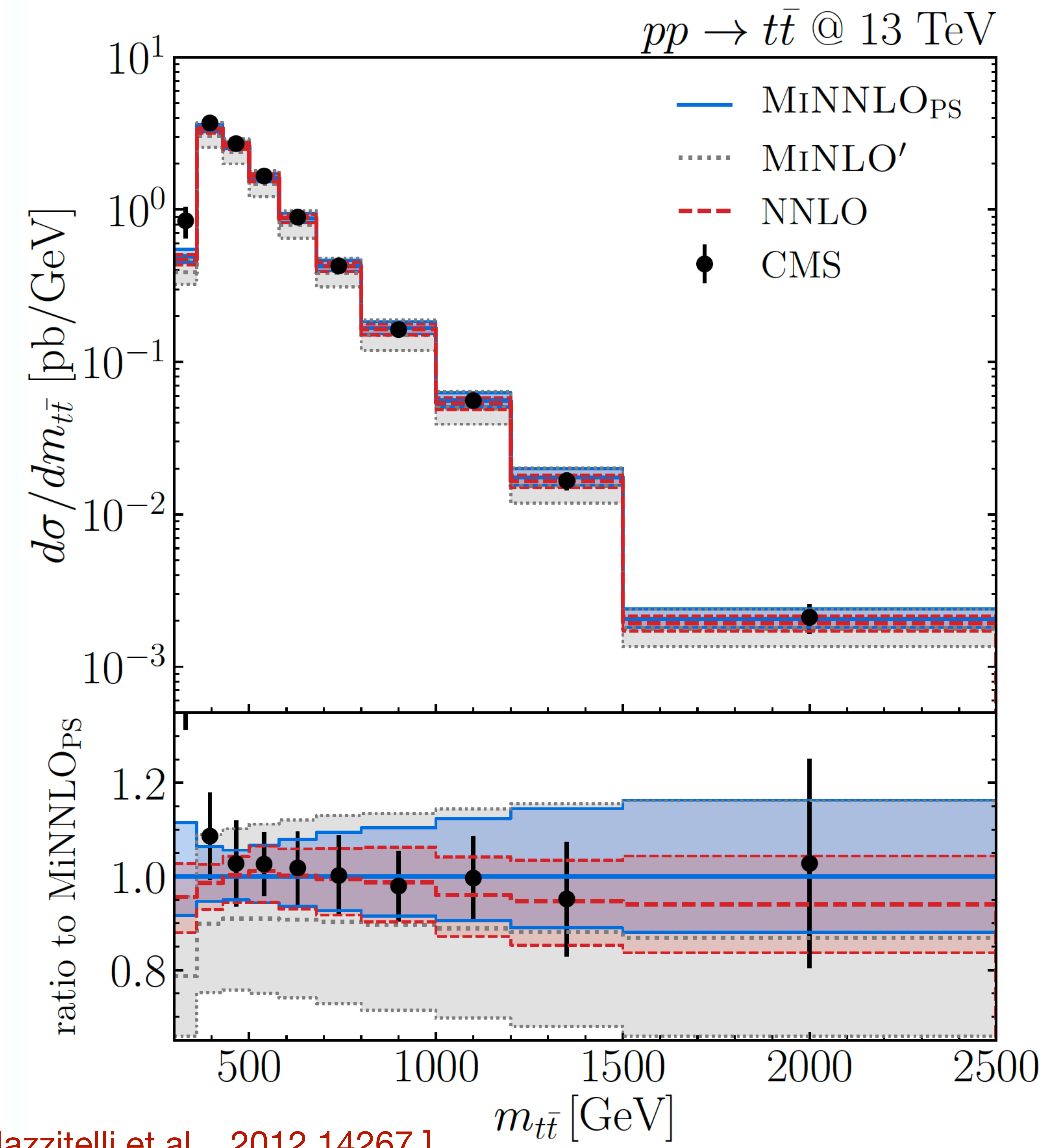
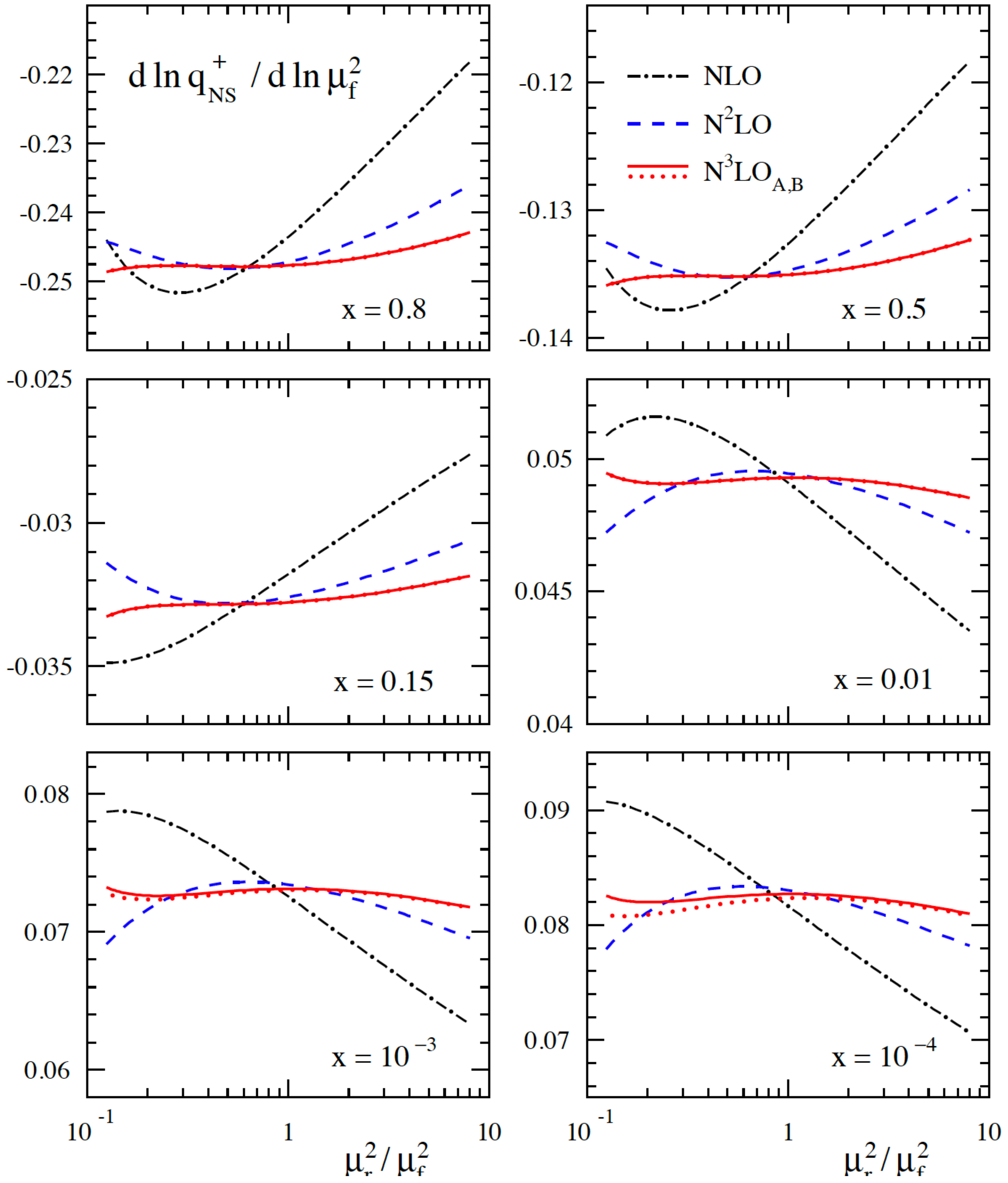


[Mazzitelli et al. , 2012.14267]

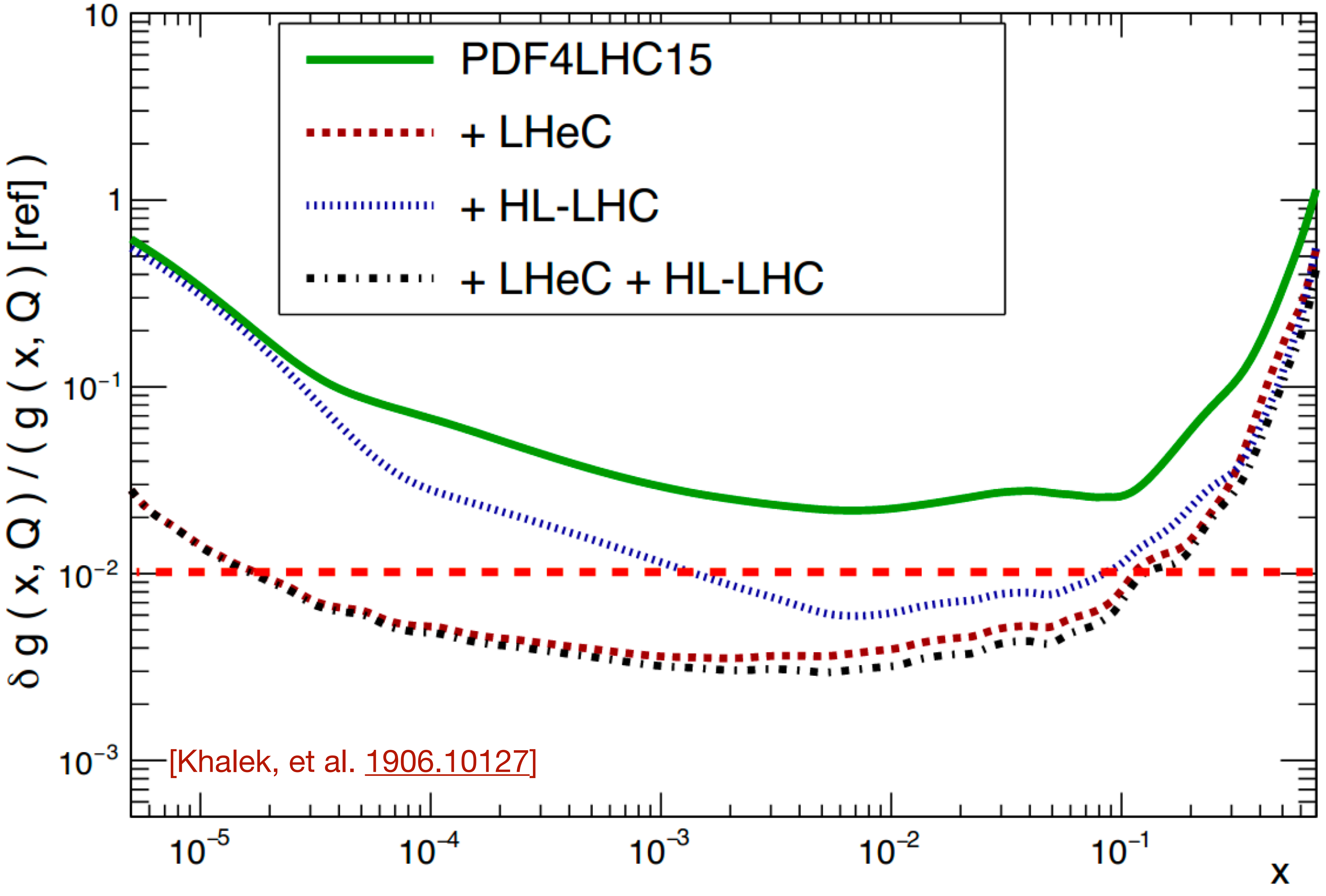
Precision calculations for the LHC

Status: PDF's



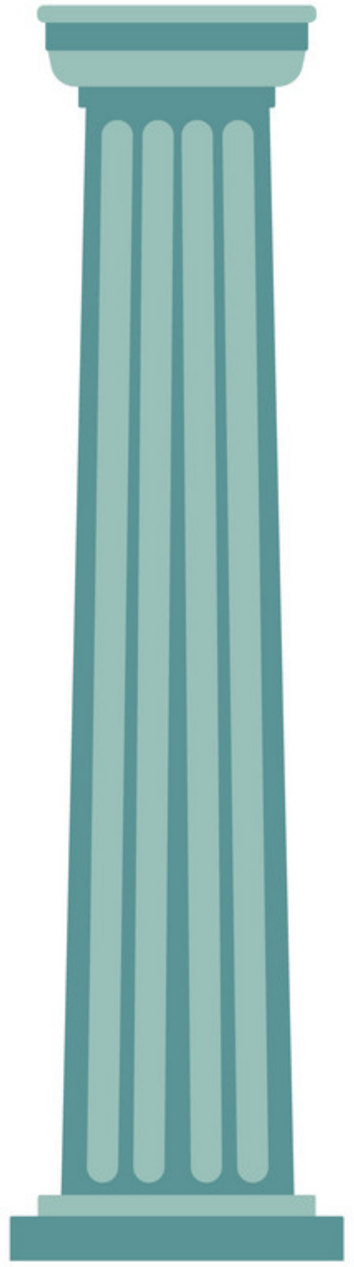
[Moch et al. , 1707.08315]

- Complete N3LO PDF's evolution not available yet. Non-singlet evolution available at 4 loops already.
- 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 calculations for the LHC

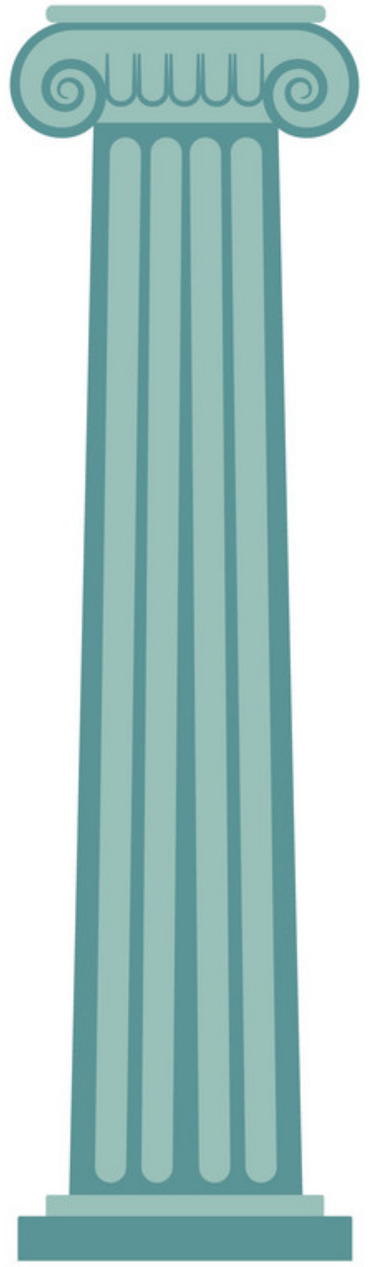
The challenges towards the “1% goal”



Fixed Order

LO, NLO,…

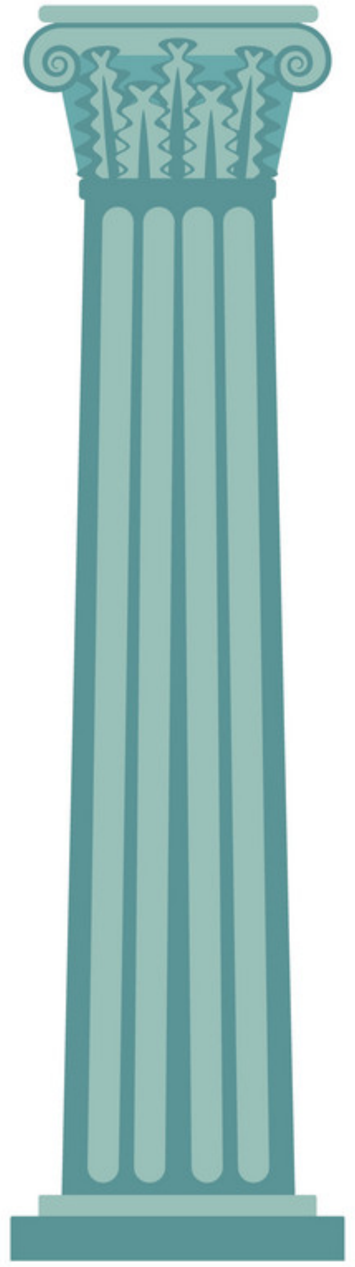
QCD/EW



Resum

LL, NLL,…

PS



PDF’s

LO,NLO,..

Fits

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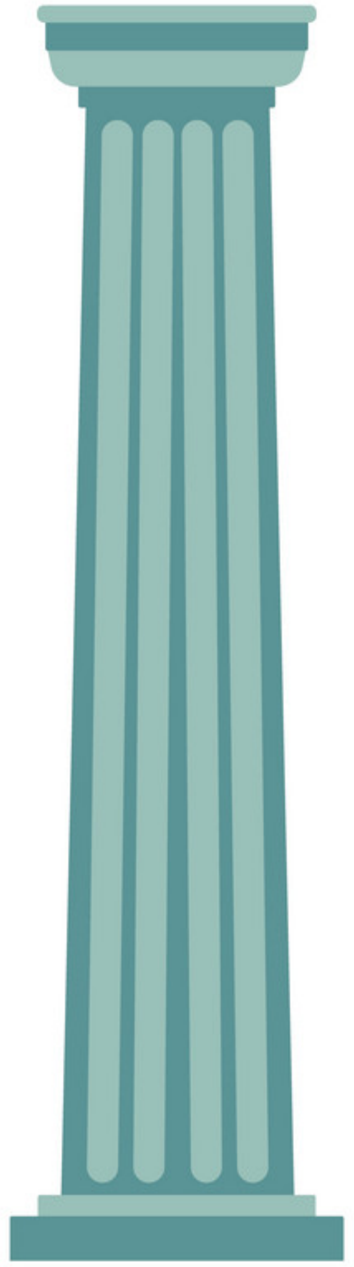

- Very fast progress in conceptual as well as technical aspects.
- Tight and consolidated community, with high momentum.
- Considering the status of 20 years ago seems clear that NNLO will be completed and N3LO will start to become available for 2→2 (see 3-loop $q\bar{q} \to \gamma\gamma$ results)
-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

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LO, NLO,…

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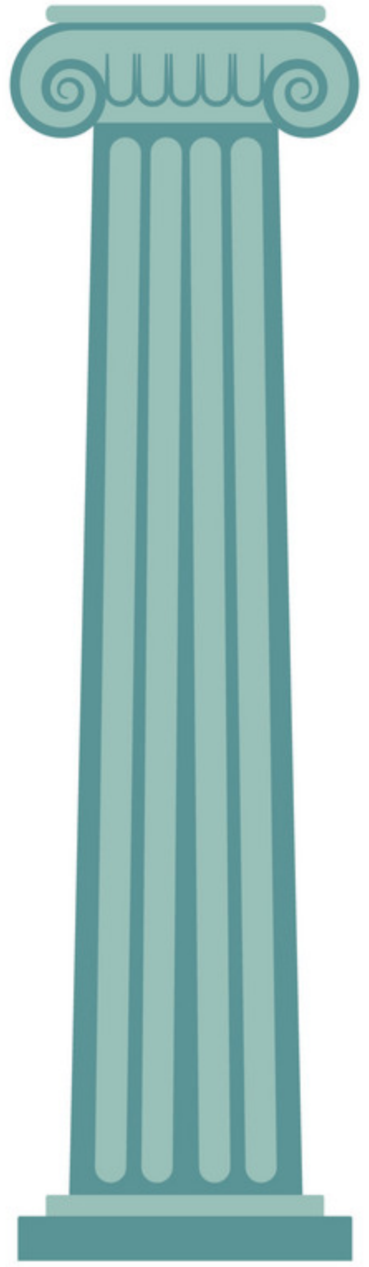

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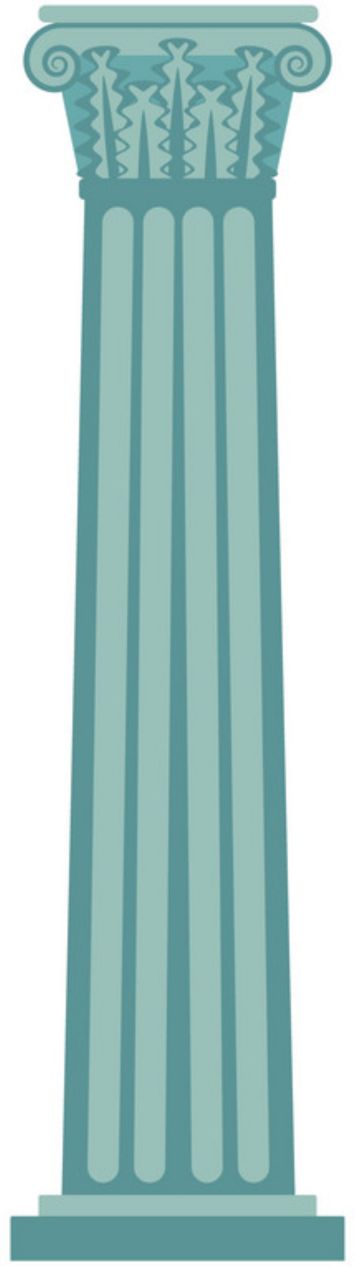

PDF’s

LO,NLO,..

Fits

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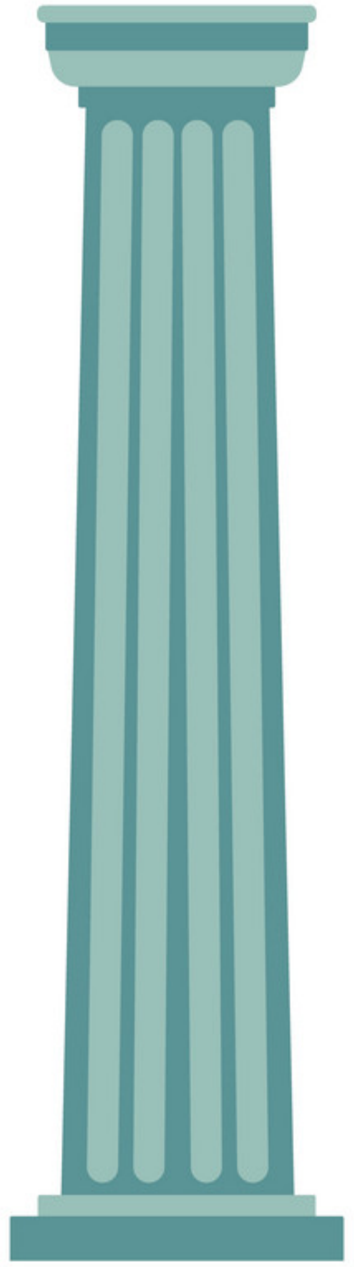

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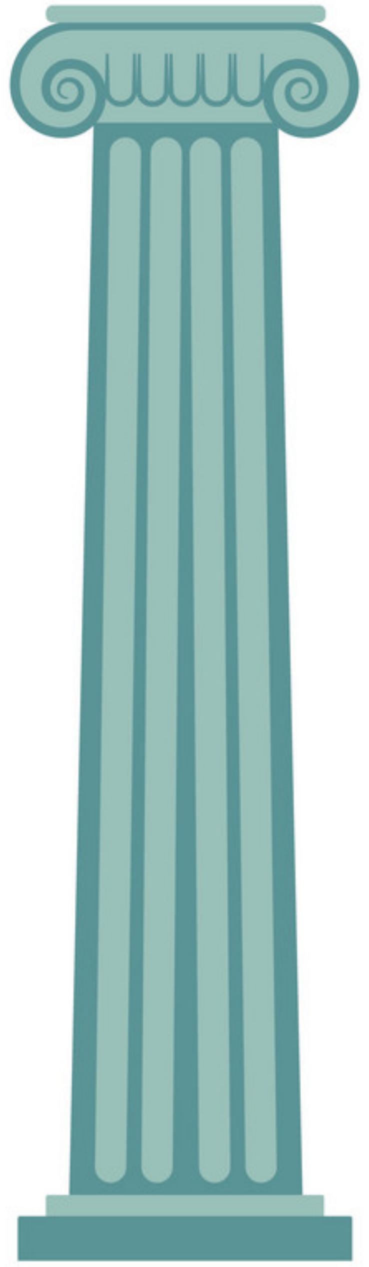
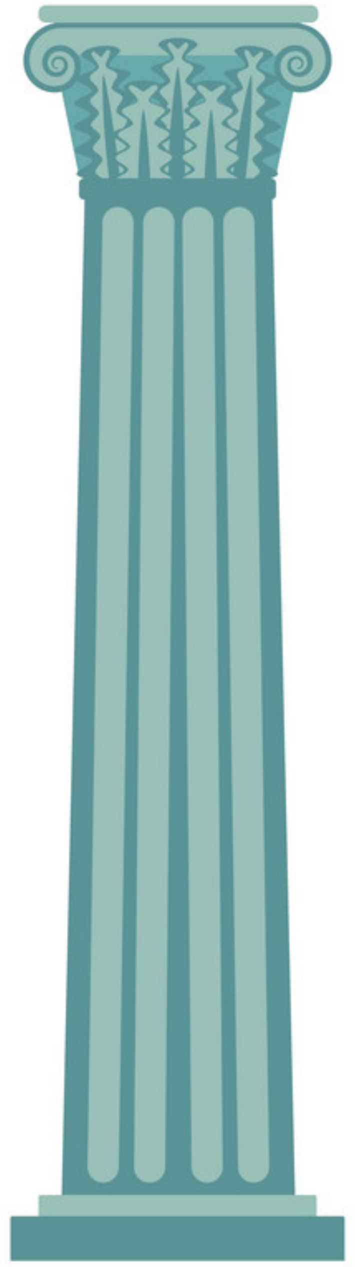


Resum

LL, NLL,…

PS

- A variety of approaches available, both analytical and numerical.
- Analytically historically matching the FO accuracy.
- NNLO+PS will be the new standard. (N3LO+PS already being explored)
- Having a NLL and beyond PS, is being explored now. To be seen.
- Not clear whether one can reach 1%.



PDF’s

LO,NLO,..

Fits

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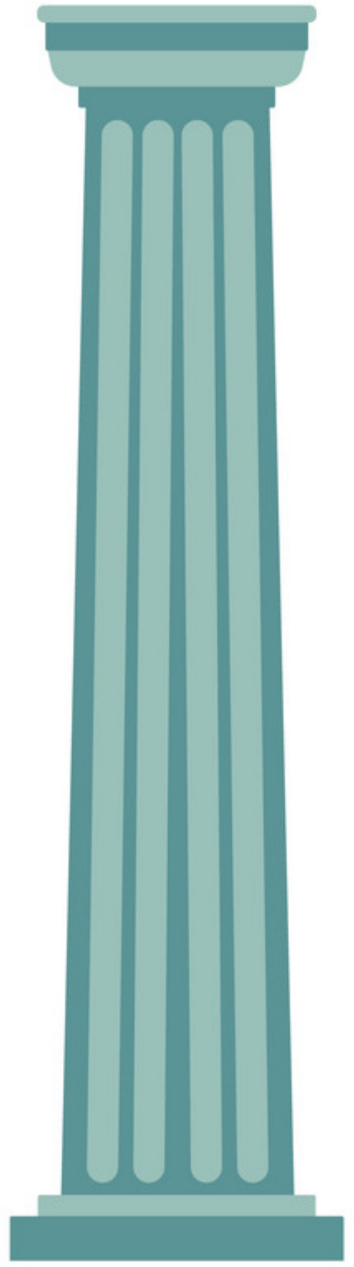

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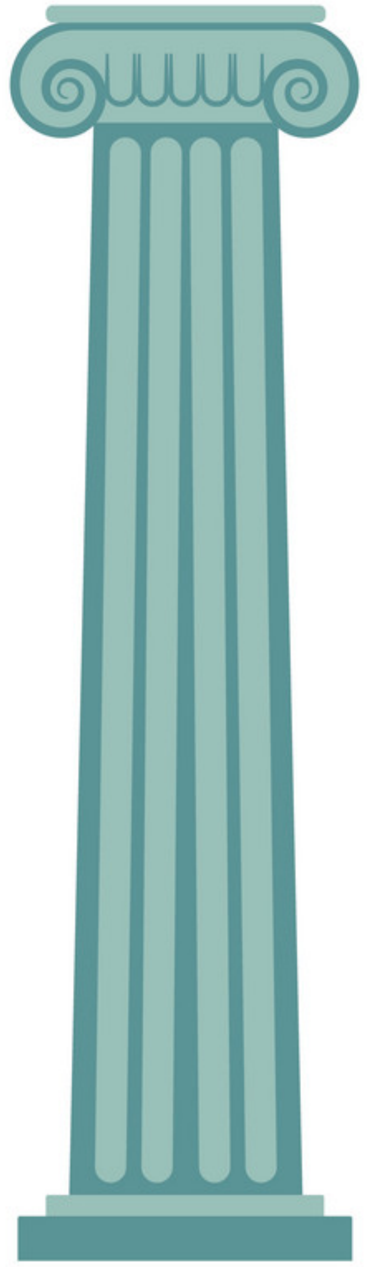

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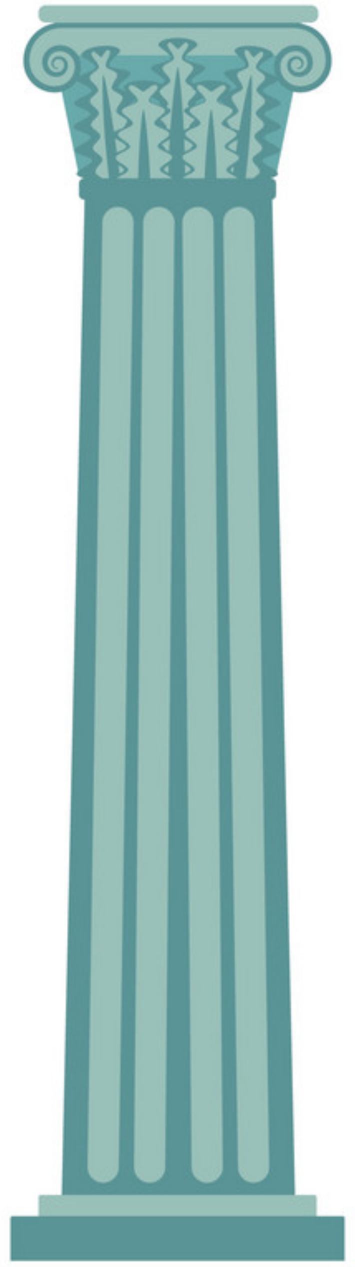

PDF’s

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.

The precision path
Two questions

1. What is the expected experimental precision on key SM measurements at the TeV scale and a reasonable goal for the corresponding TH predictions? Are we there yet?

2. How to frame and interpret our results to maximise the sensitivity to New Physics?

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

The way of SMEFT

Going beyond the SM

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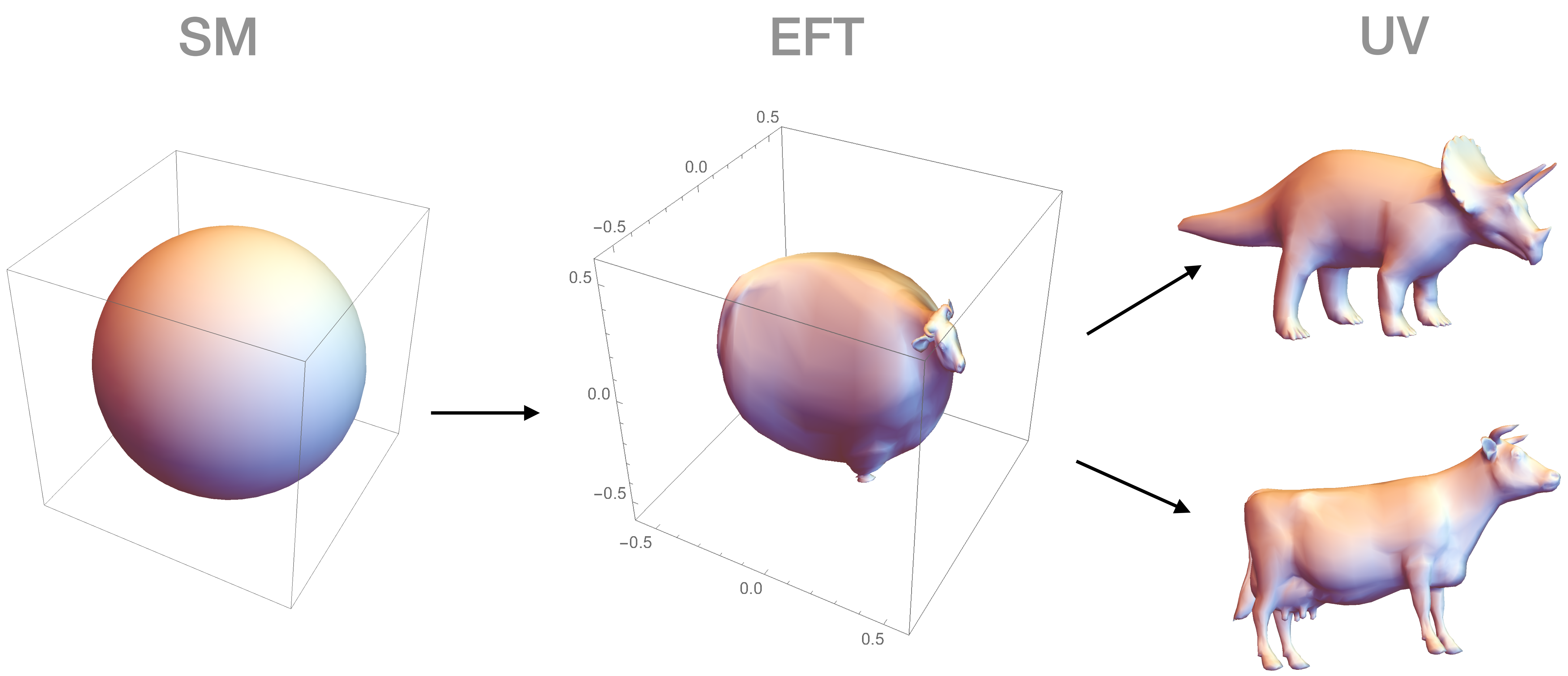
Is it possible to "minimally" deform the SM in a way to encompass “all” New Physics and without losing any of the above?

The way of SMEFT

Going beyond the SM



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Rattazzi® adapted

The way of SMEFT

Going beyond the SM

$$\mathscr{L} = \mathscr{L}^{(2)} + \mathscr{L}^{(4)} + \frac{1}{\Lambda}\mathscr{L}^{(5)} + \frac{1}{\Lambda^2}\mathscr{L}^{(6)} + \dots$$

The way of SMEFT

Going beyond the SM

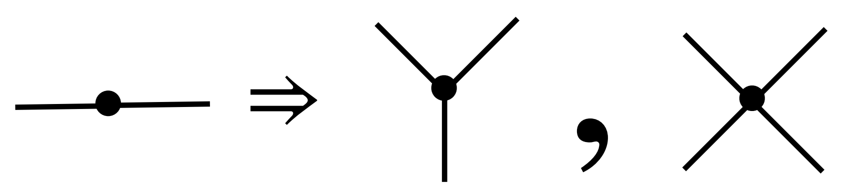
$$\mathscr{L} = \mathscr{L}^{(2)} + \mathscr{L}^{(4)} + \frac{1}{\Lambda}\mathscr{L}^{(5)} + \frac{1}{\Lambda^2}\mathscr{L}^{(6)} + \ldots$$

$$m_\nu = 0$$

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

GIM

$$Y_u, Y_d, Y_l \Rightarrow \cancel{\text{Flavor}}\ \&\ \cancel{CP}$$



The way of SMEFT

Going beyond the SM

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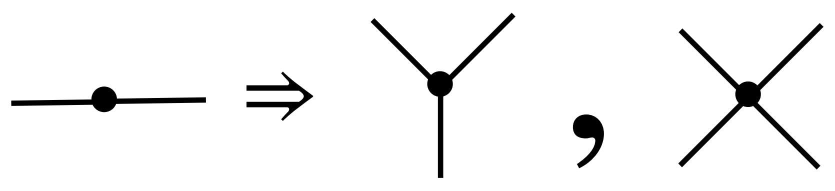


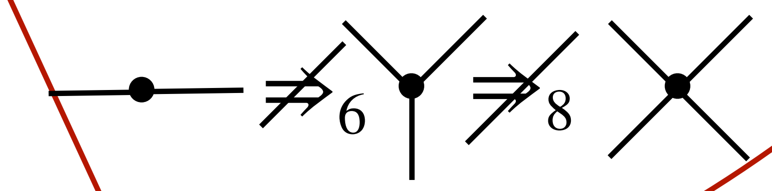
$\cancel{U(1)}_L \to m_\nu \neq 0$

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

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

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

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



Rattazzi® adapted

The way of SMEFT

Going beyond the SM

$$\mathcal{L} = \mathcal{L}^{(2)} + \mathcal{L}^{(4)} + \frac{1}{\Lambda}\mathcal{L}^{(5)} + \frac{1}{\Lambda^2}\mathcal{L}^{(6)} + \dots$$

$m_h^2 \simeq \Lambda^2$

$m_\nu = 0$

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

GIM

$Y_u, Y_d, Y_l \Rightarrow \cancel{\text{Flavor}} \;\&\; \cancel{CP}$

$\cancel{U(1)}_L \to m_\nu \neq 0$

$\cancel{\text{Flavor}} \Rightarrow \mu \to e\gamma, \Delta m_K, \dots$

$\cancel{CP} \Rightarrow$ edm's

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

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

The way of SMEFT

Going beyond the SM

$$\mathscr{L} = \mathscr{L}^{(2)} + \mathscr{L}^{(4)} + \frac{1}{\Lambda}\mathscr{L}^{(5)} + \frac{1}{\Lambda^2}\mathscr{L}^{(6)} + \dots$$

$m_h^2 \simeq \Lambda^2$

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

$m_\nu = 0$

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

GIM

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

$\Rightarrow$,

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

~~Flavor~~ $\Rightarrow \mu \to e\gamma, \Delta m_K, \dots$ $\quad \Rightarrow \Lambda \geq 10^{6}$ GeV

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

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

$U(1)_B \Rightarrow p \to \pi^0 e^+$ $\quad \Rightarrow \Lambda \geq 10^{15}$ GeV

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

Rattazzi® adapted

The way of SMEFT

Going beyond the SM

Λ_{UV}

TeV

Simplicity 🙂

Naturalness ☹️

TeV Λ_{UV}

Naturalness 🙂

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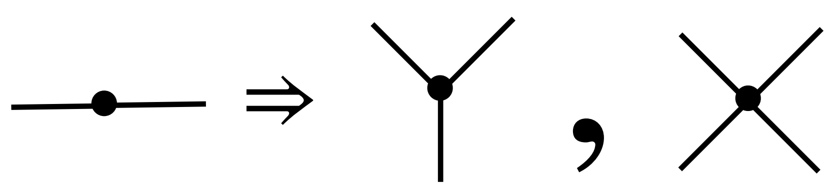

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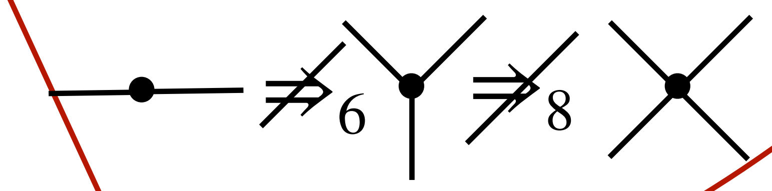


$\Rightarrow \Lambda \geq 10^{3}$ GeV

A powerful approach

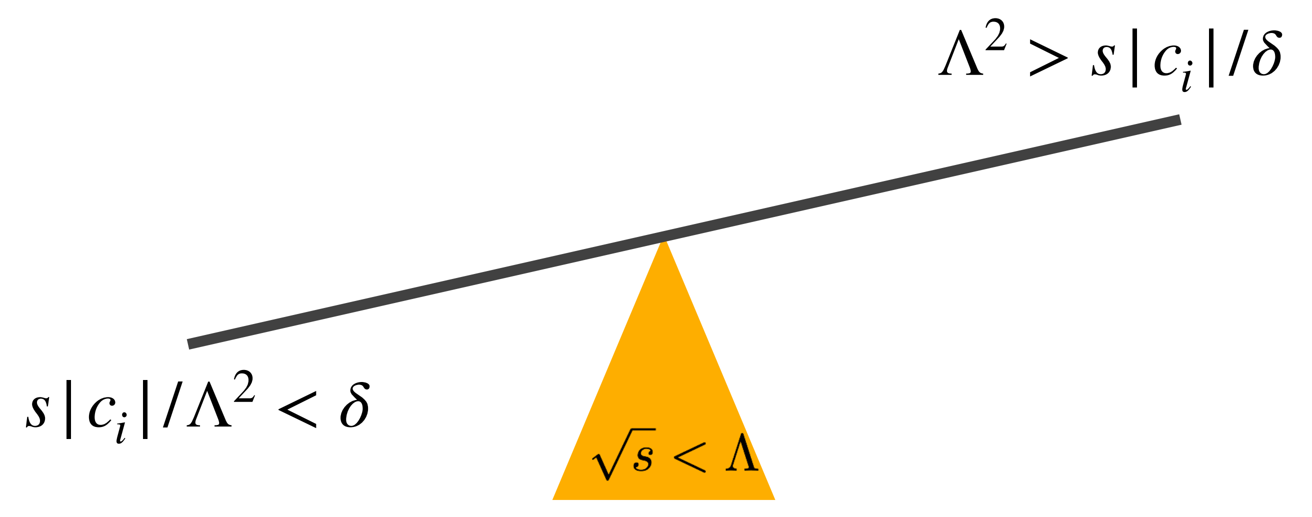
Searching for new interactions with an EFT

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

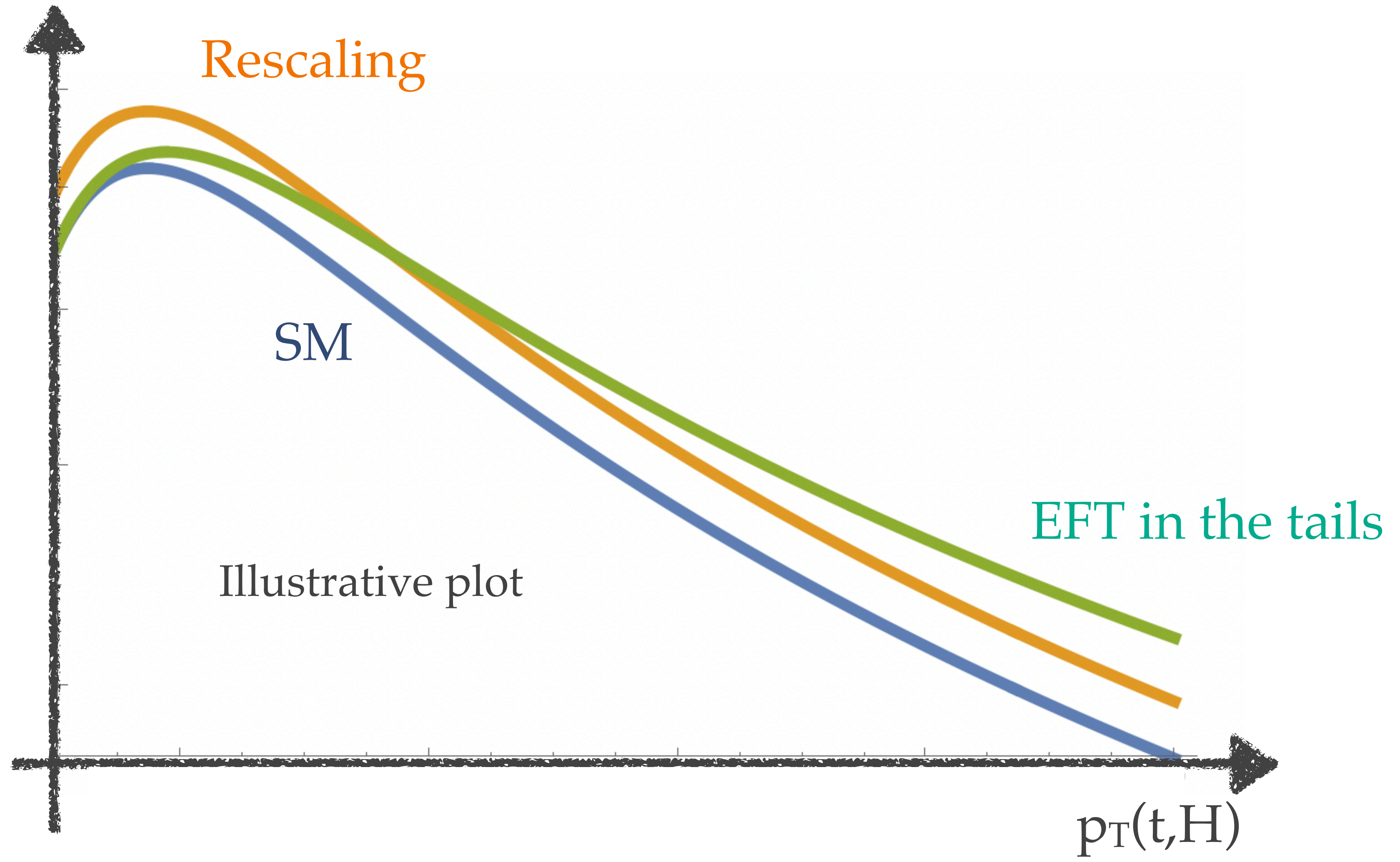
$$\mathscr{L}_{\text{SMEFT}} = \mathscr{L}^{(4)}_{\text{SM}} + \frac{1}{\Lambda^2}\sum_i^{N_6} c_i \mathscr{O}_i^{(6)} + \frac{1}{\Lambda^4}\sum_j^{N_8} c_j \mathscr{O}_i^{(8)} + \ldots$$

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:

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

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Most precise/accurate experimental measurements
with uncertainties and correlations

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

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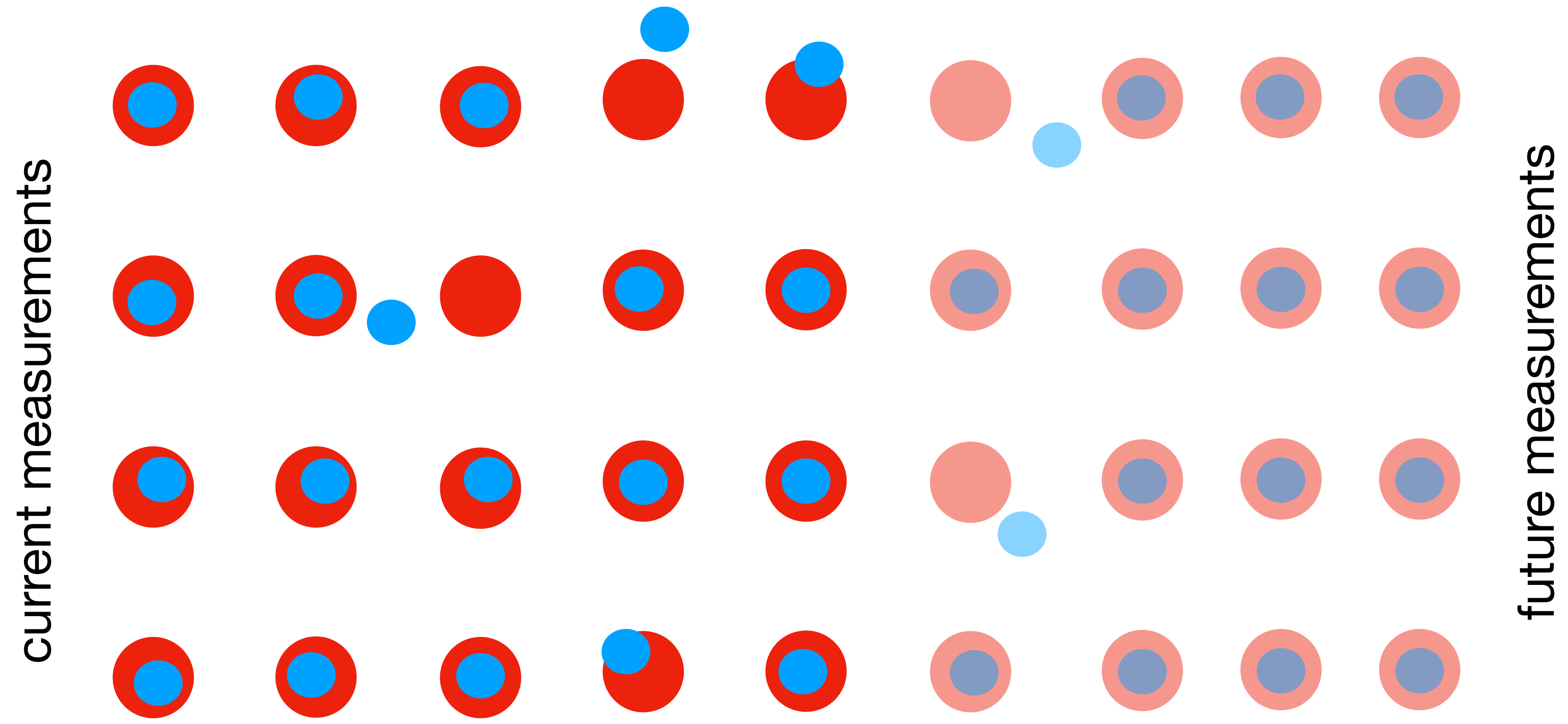

$\Rightarrow$ increased NP Sensitivity

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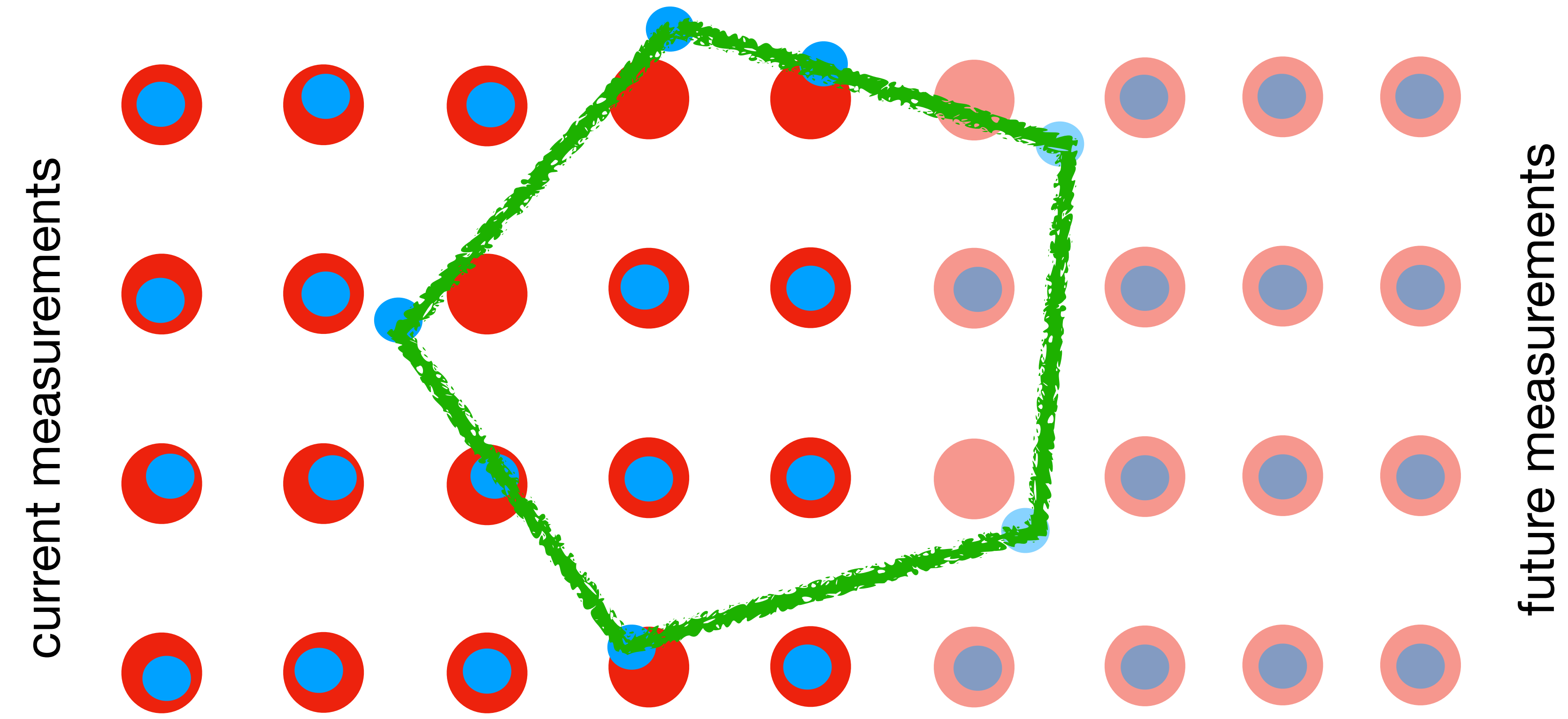

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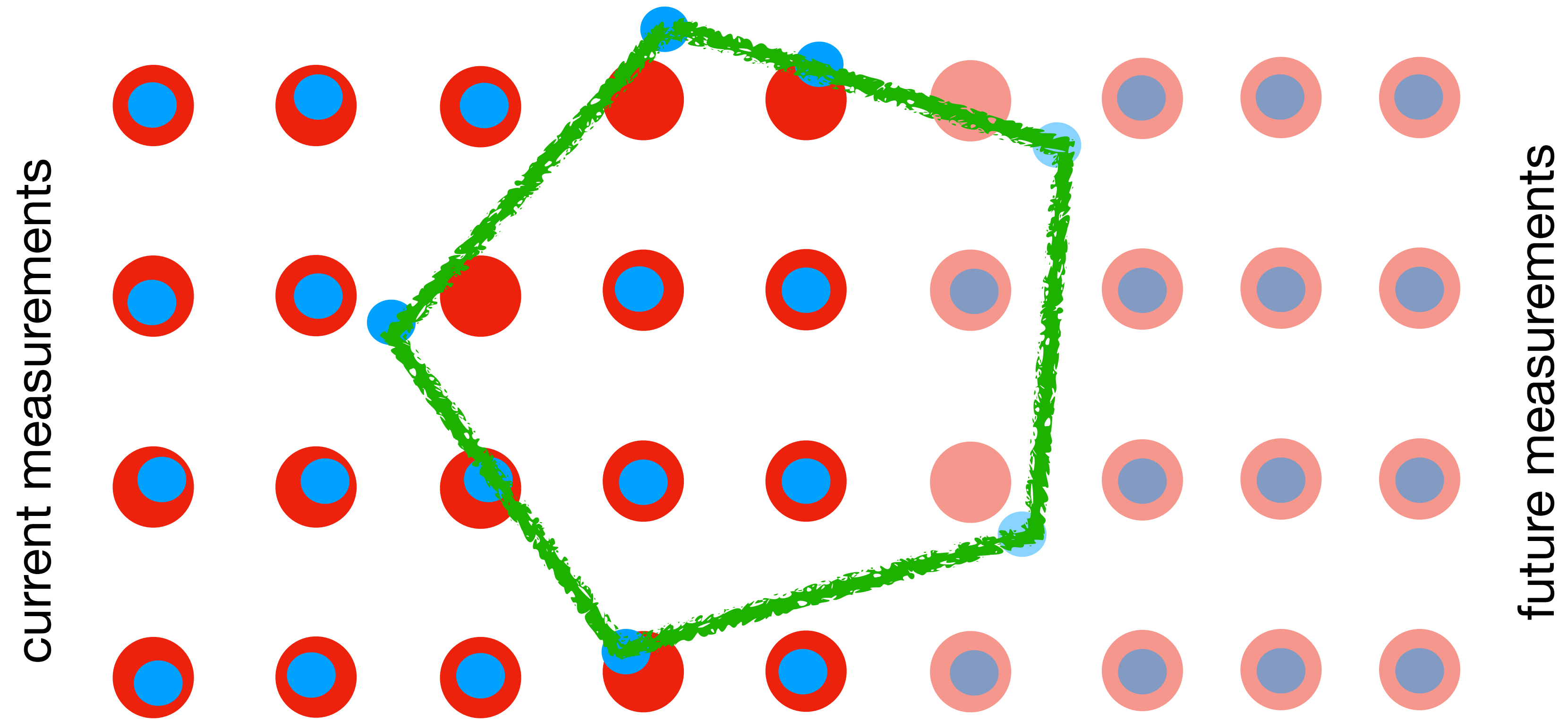
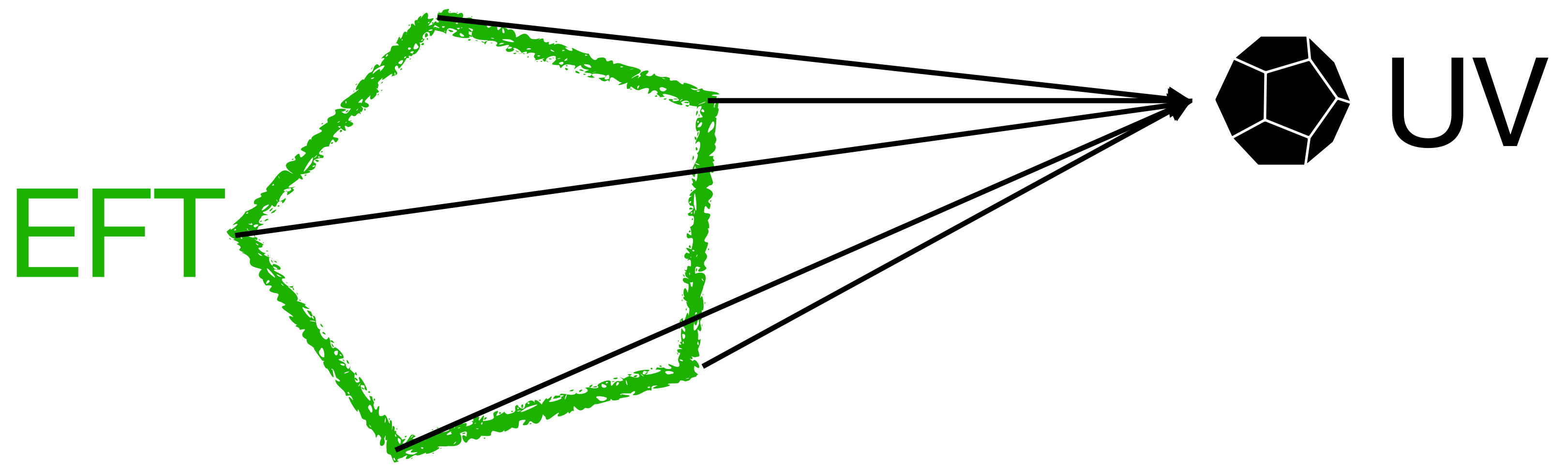


$\Rightarrow$ increased NP Sensitivity

$\Rightarrow$ increased UV identification power

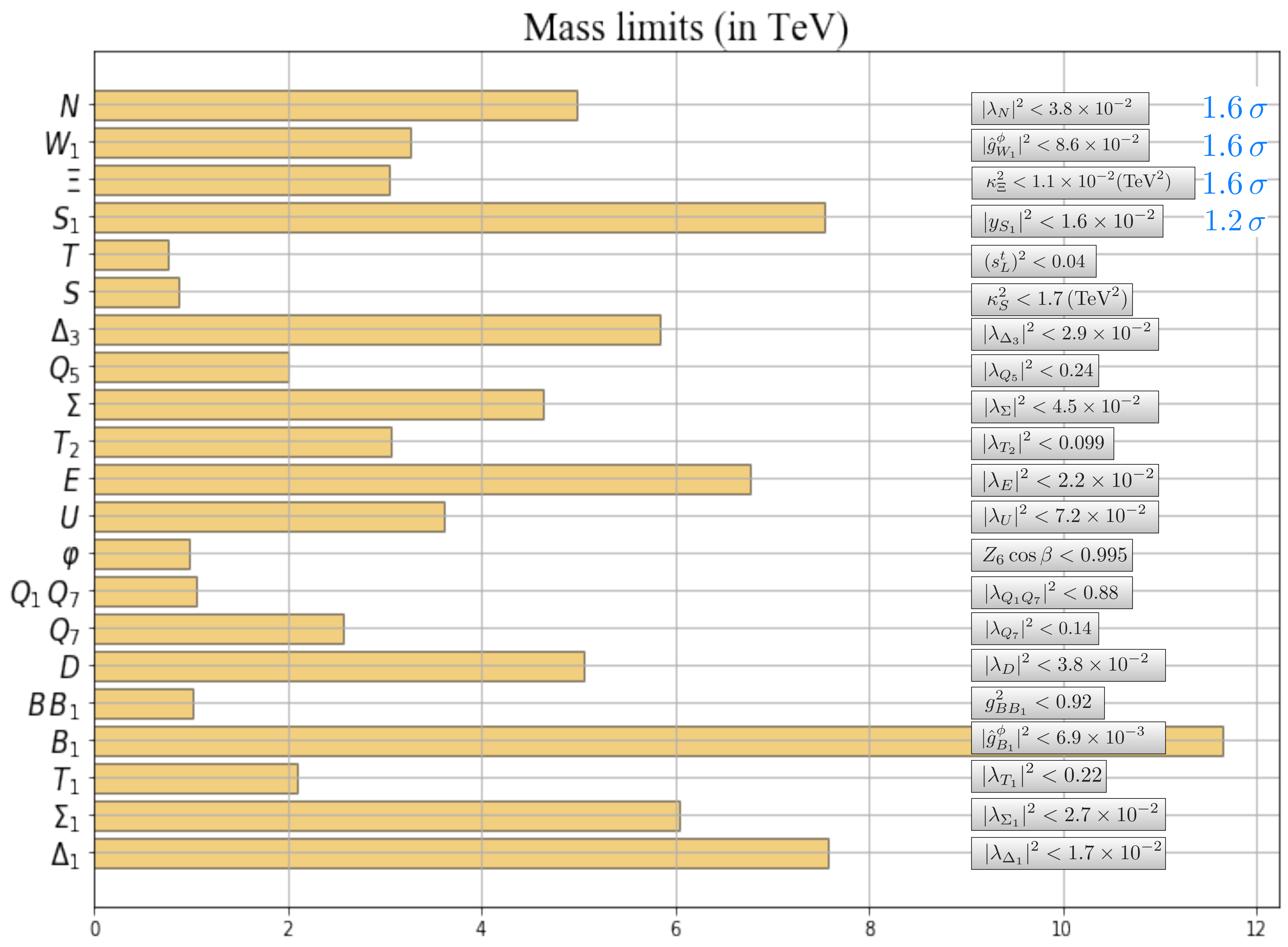


The way of SMEFT

A simple approach

EFT bounds translate to constraints on parameters of UV models

Simplest case: single-field extensions of the SM



[Ellis et al. 2012.02779]

A powerful approach

Is this easy?

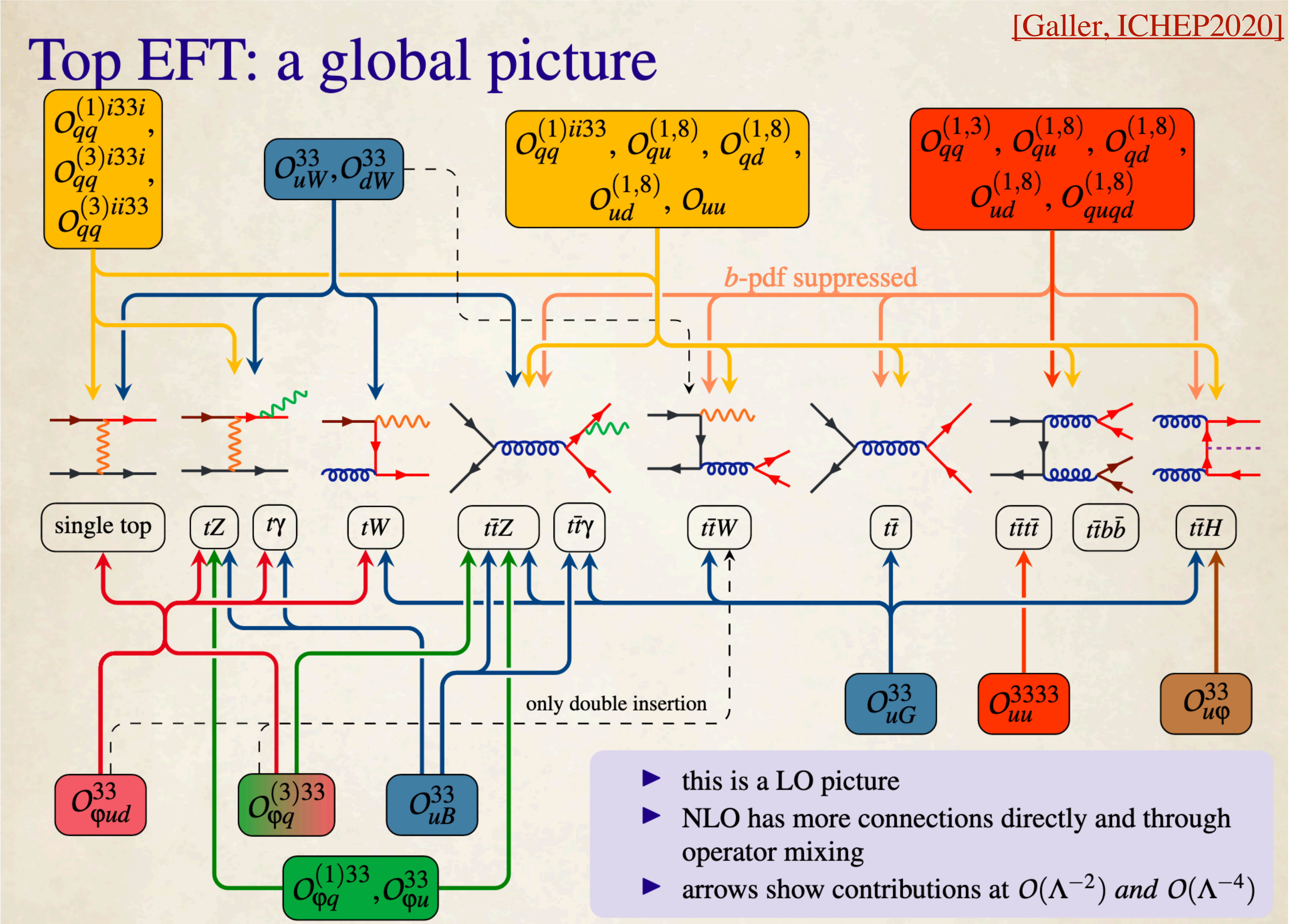
It's as exciting as challenging. Pattern of deformations enter many observables in a correlated way.

Needs to manage complexity, uncertainties and correlations.

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

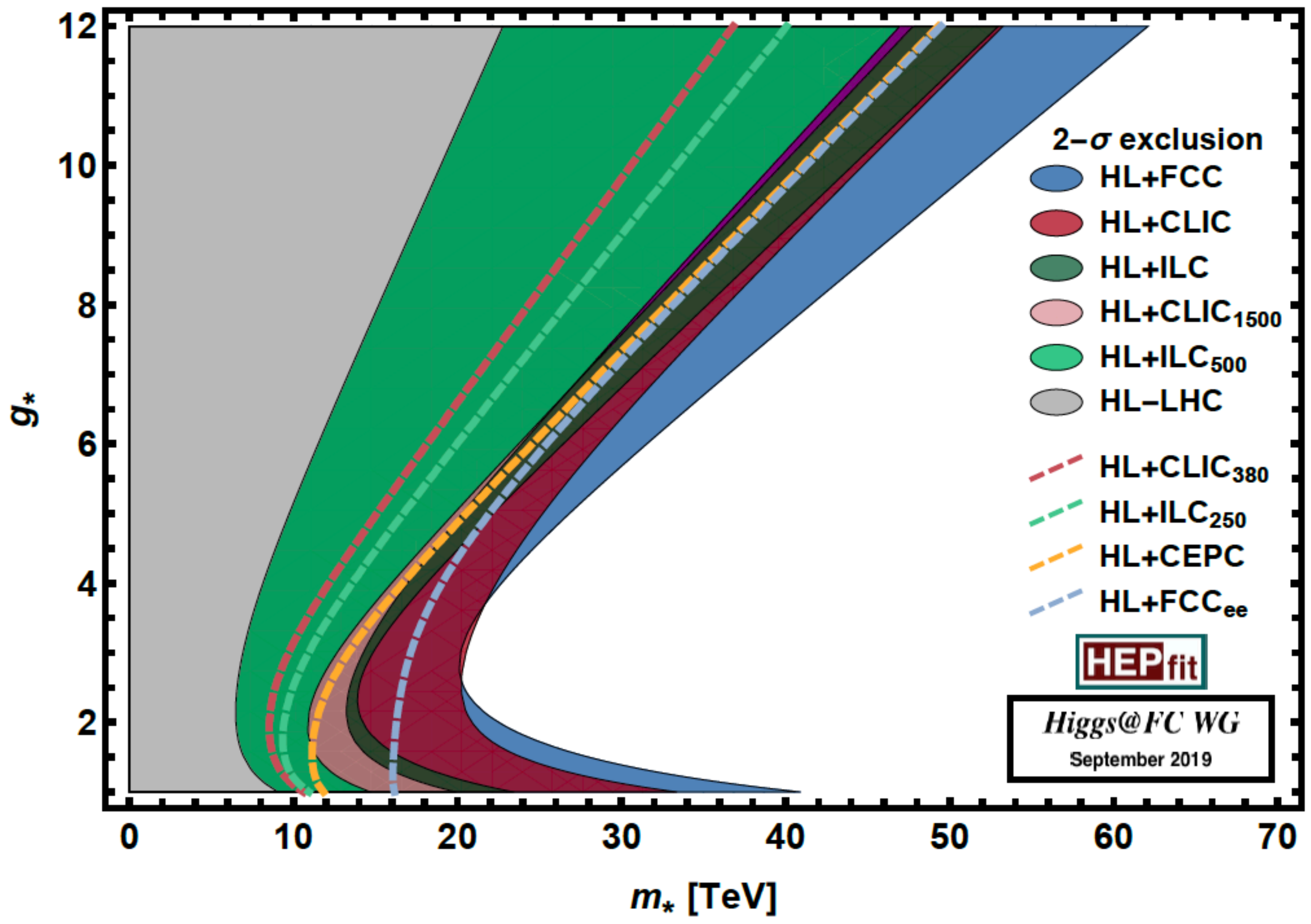
Needs coordinated work between theorists and experimentalists (model dependence, validity, interpretations, matching to the UV).

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

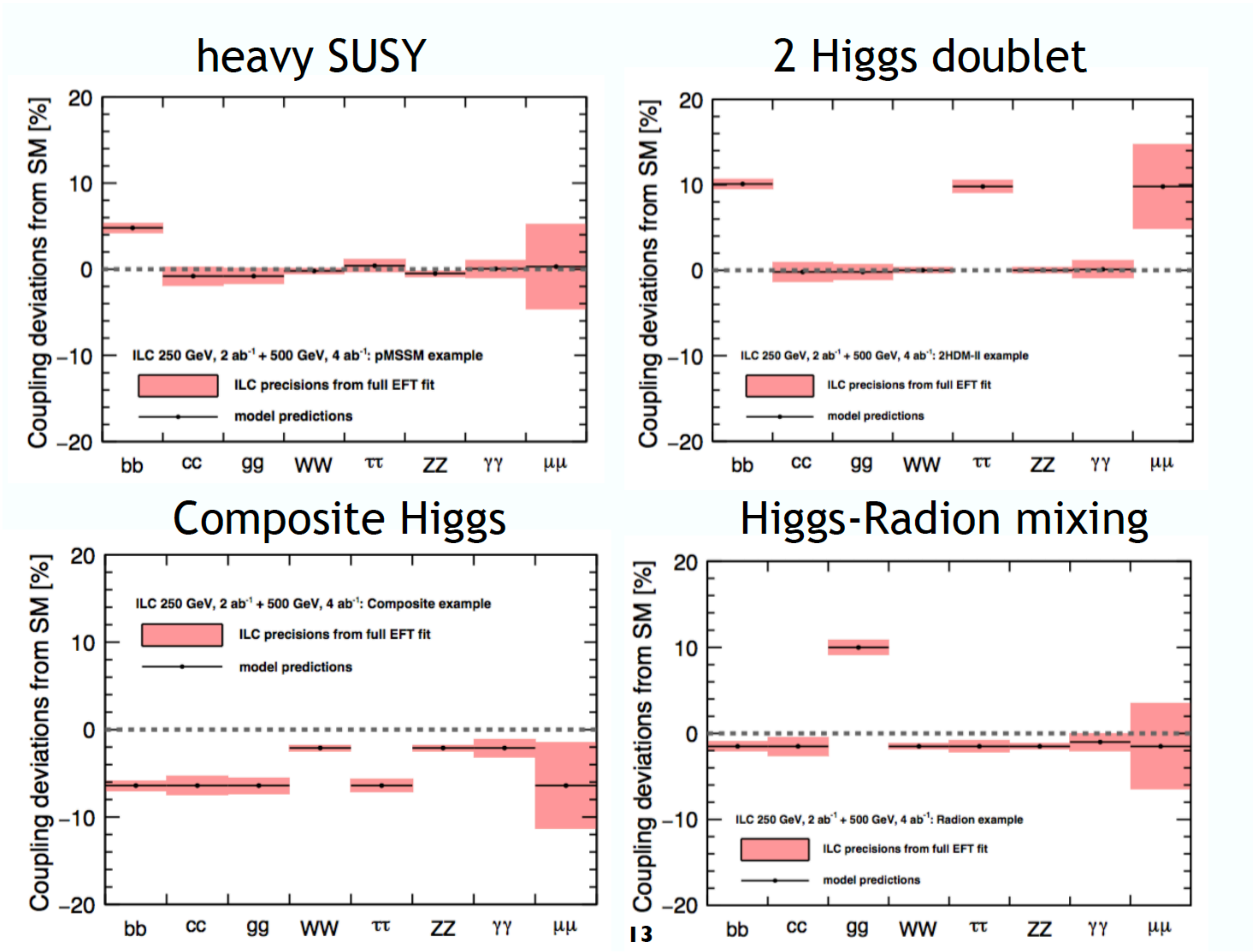


A powerful approach

What are we going to learn?



[De Blas et al., 2020]



[Peskin, ICHEP2020]

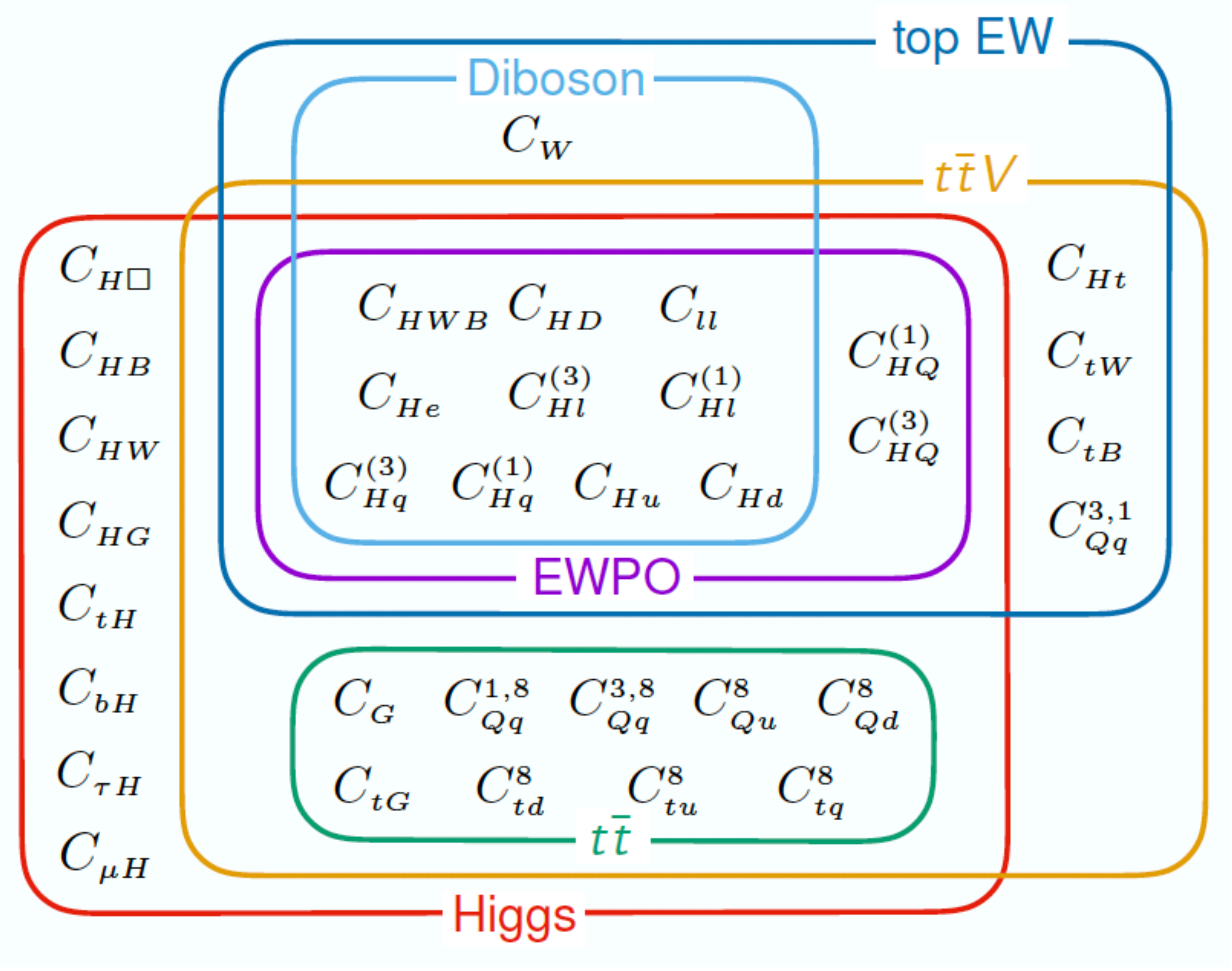
Full mapping at tree level to SMEFT : [de Blas et al. 2018]

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

EleniVryonidou®

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

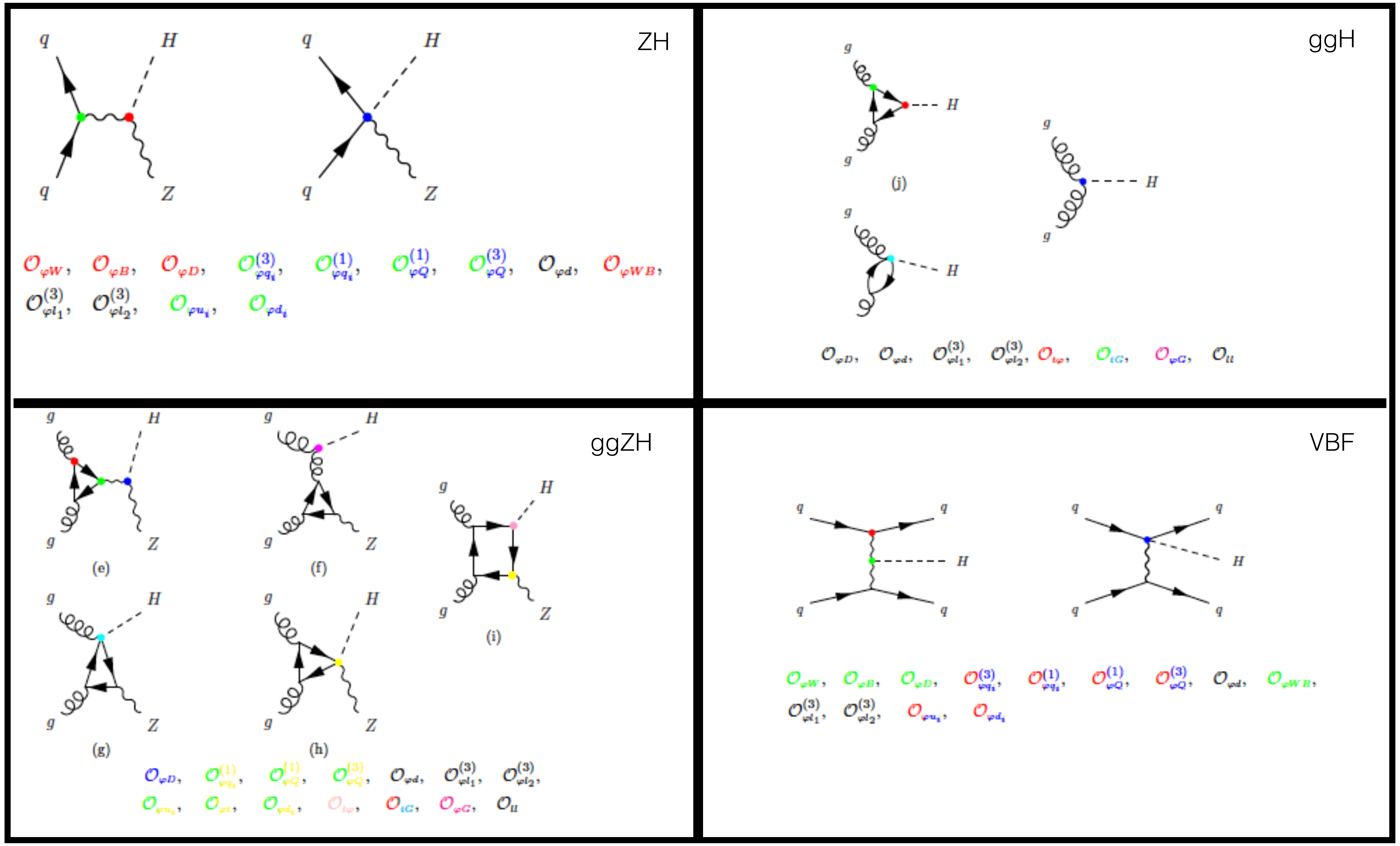
Faithful uncertainty estimate
Avoid under- and over-fitting
Validated on pseudo-data (closure test)

Output

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

Global fits

Operators vs processes

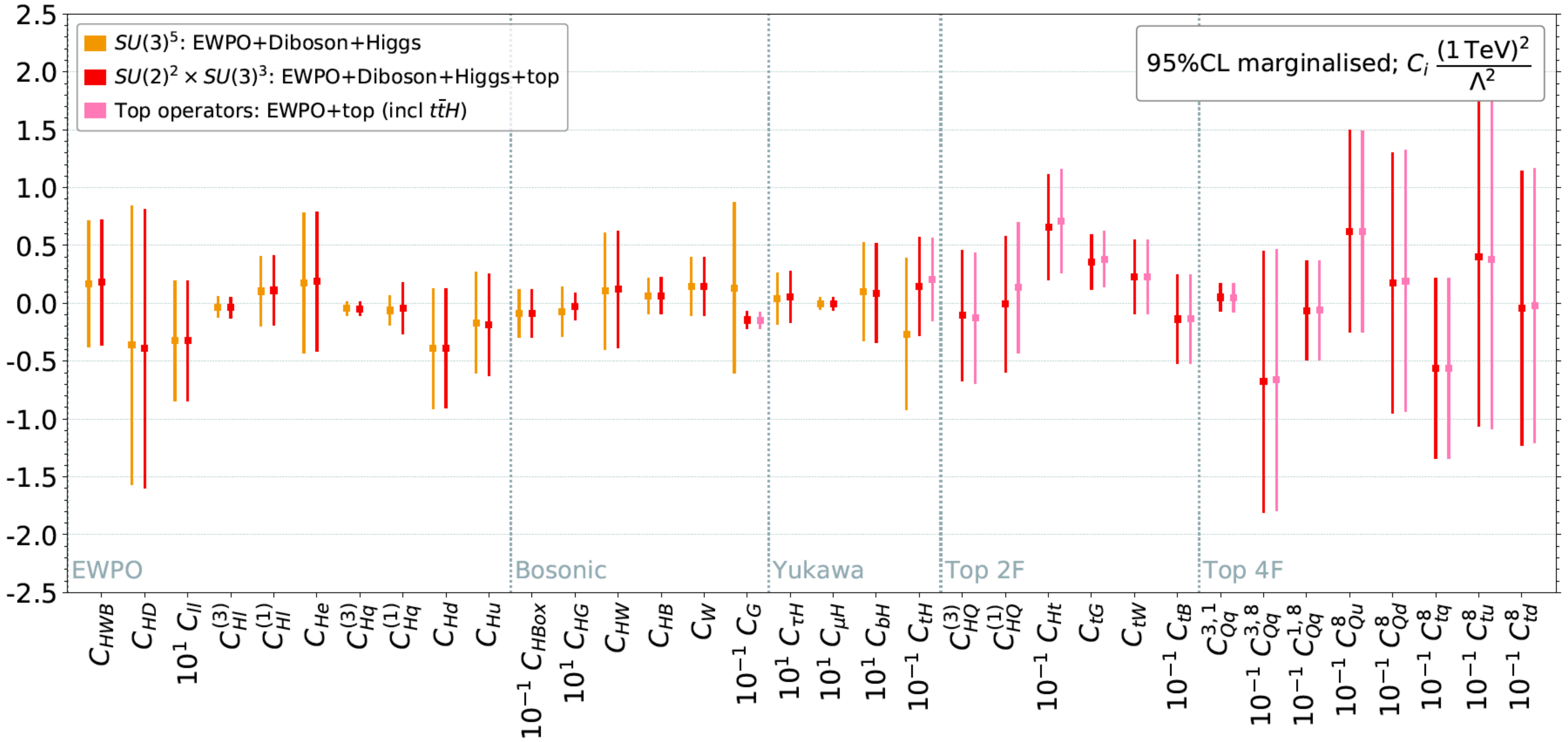


Luca Mantani®

Global EW(PO)+H+Top

Examples

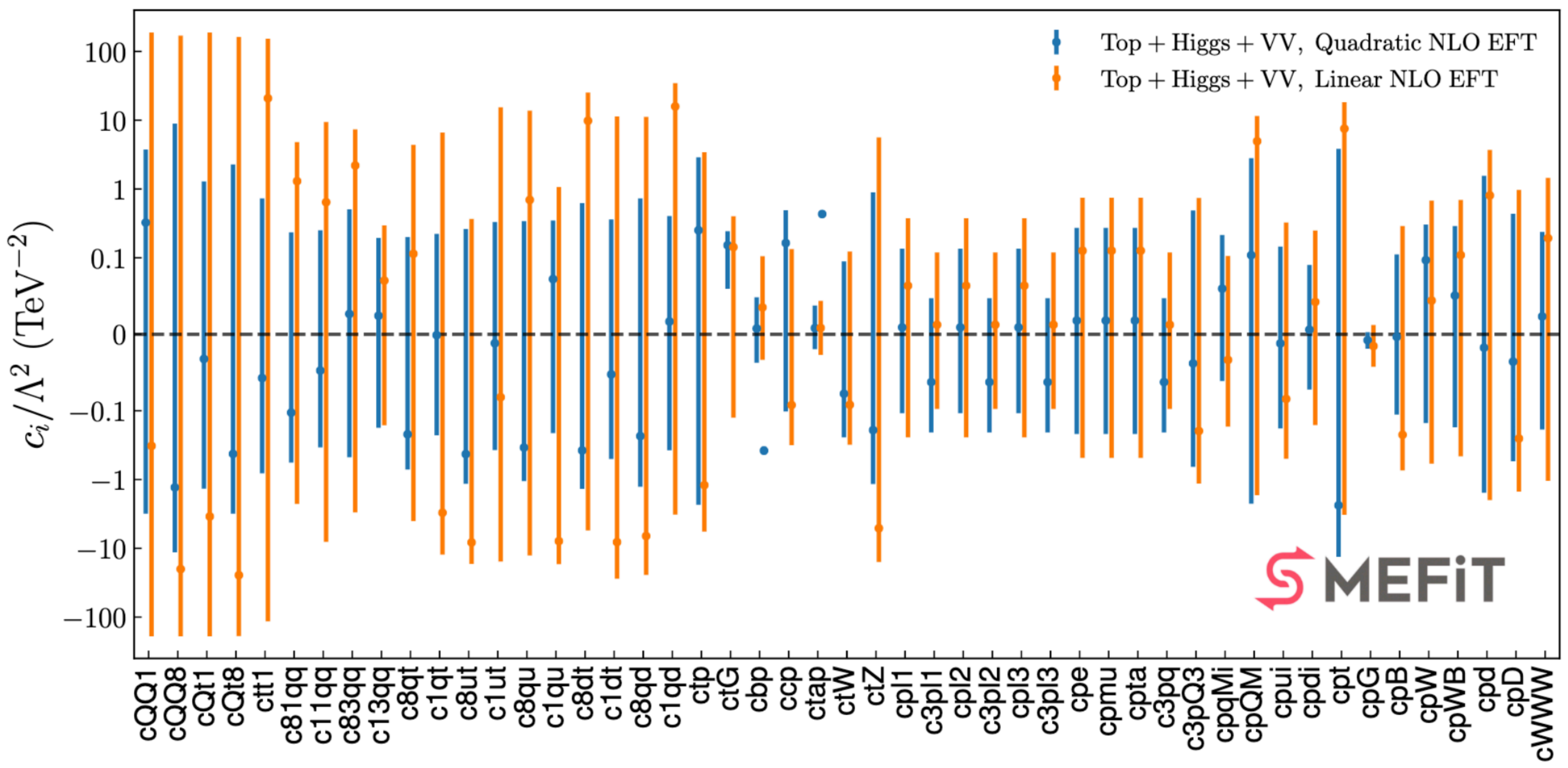
[Ellis et al. 2012.02779]



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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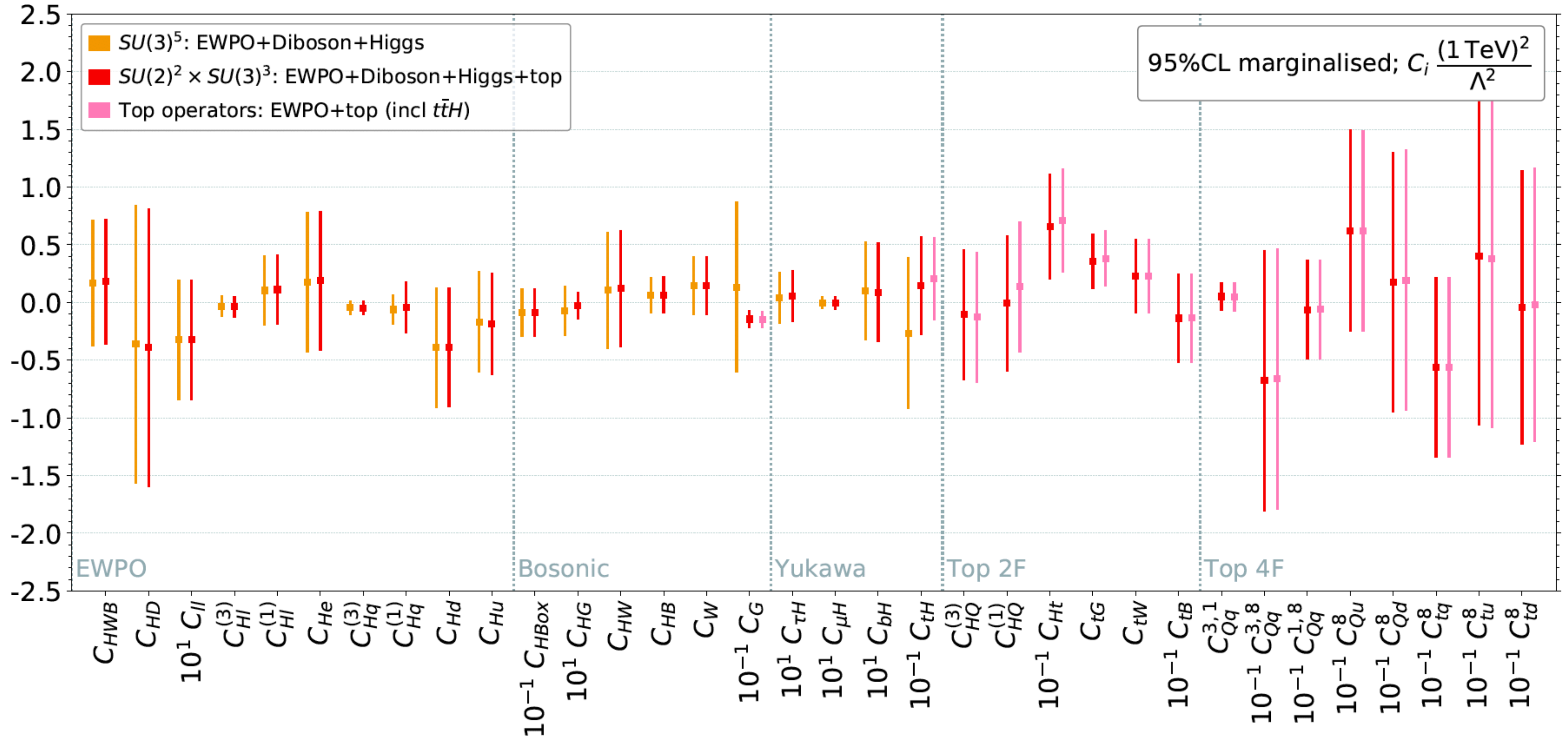
Global EW(PO)+H+Top

Examples

[Ellis et al. 2012.02779]



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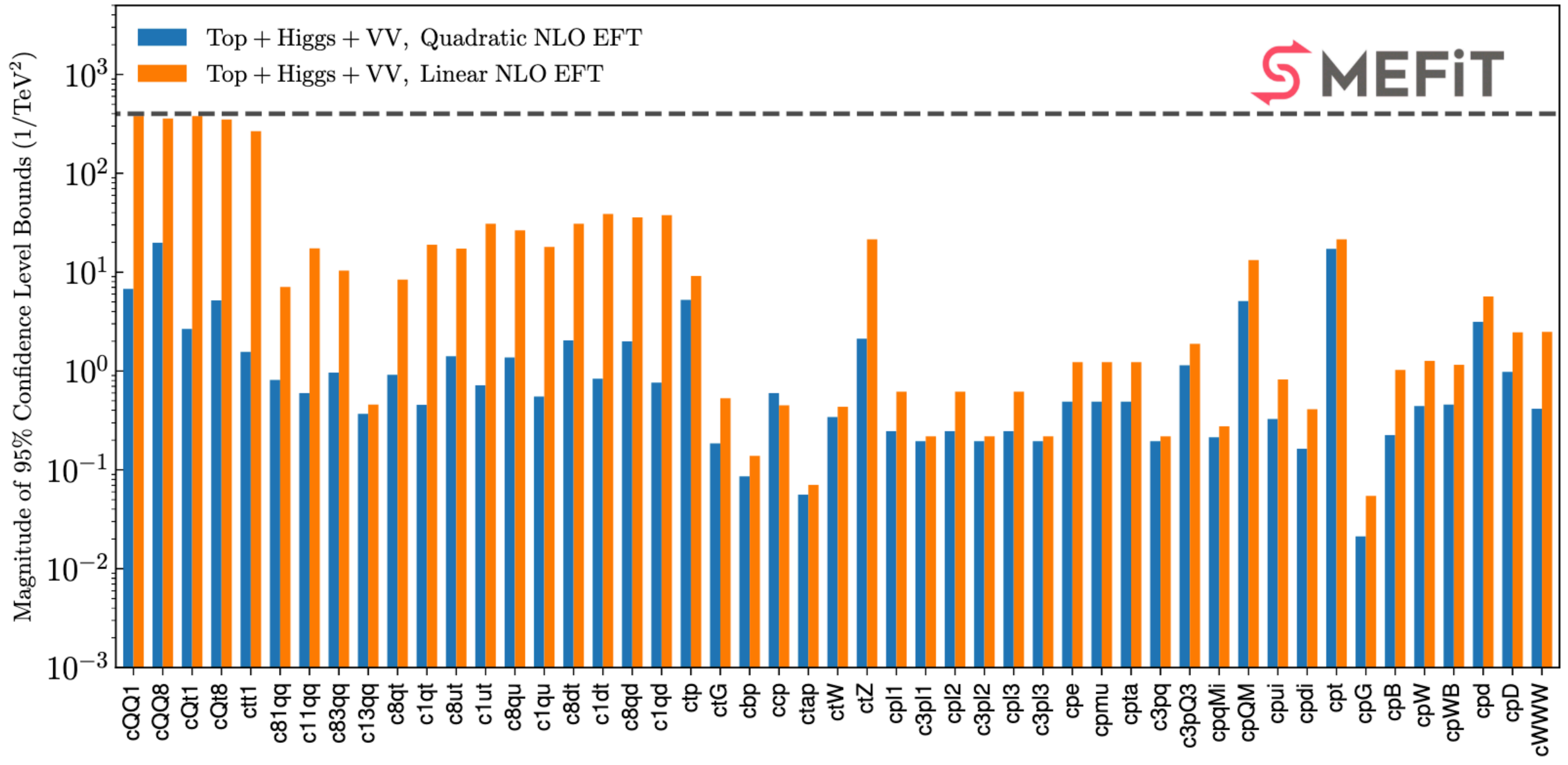

36 operators, $SU(2)^2 \times SU(3)^3$

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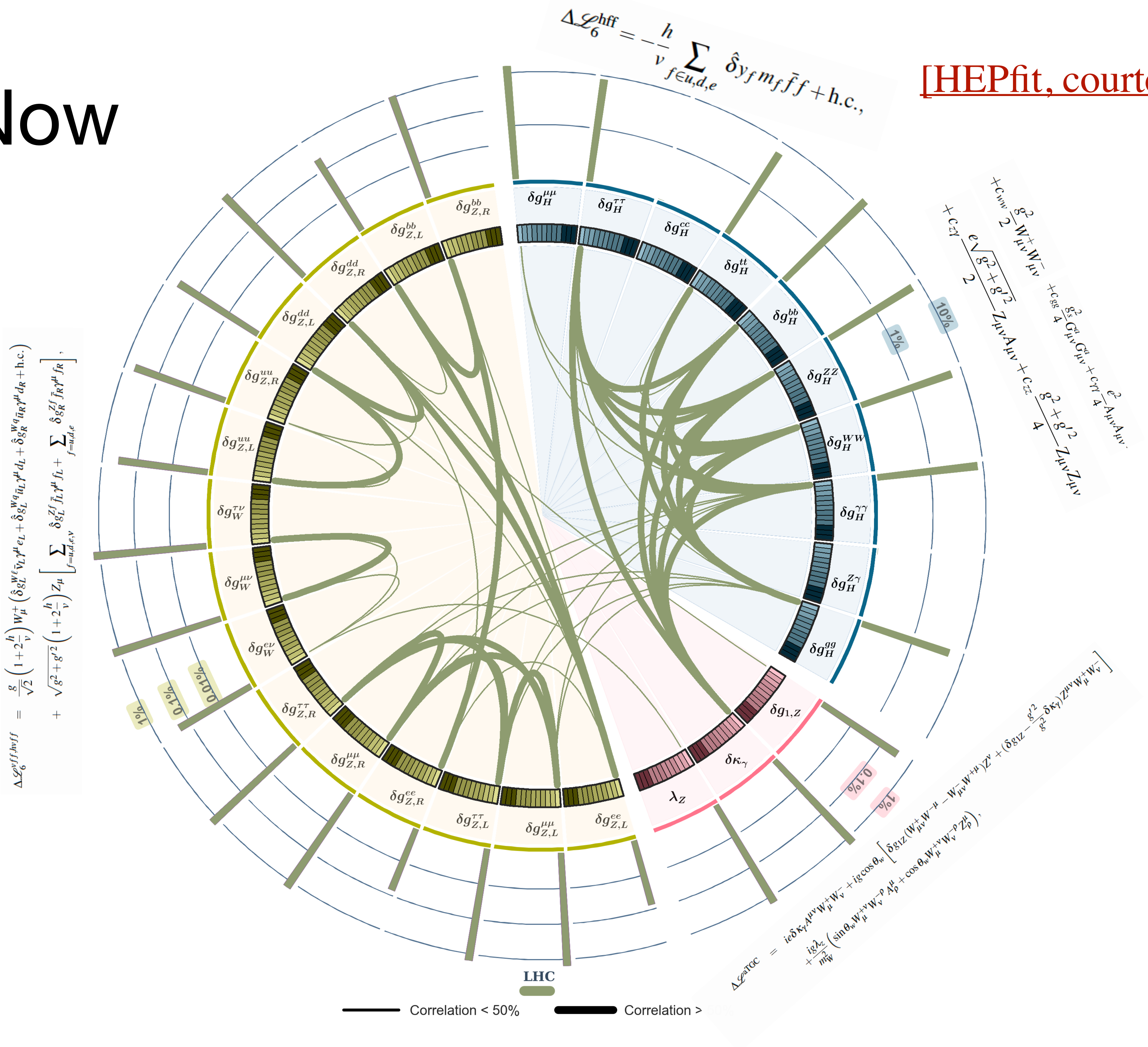
Global fits: now vs future

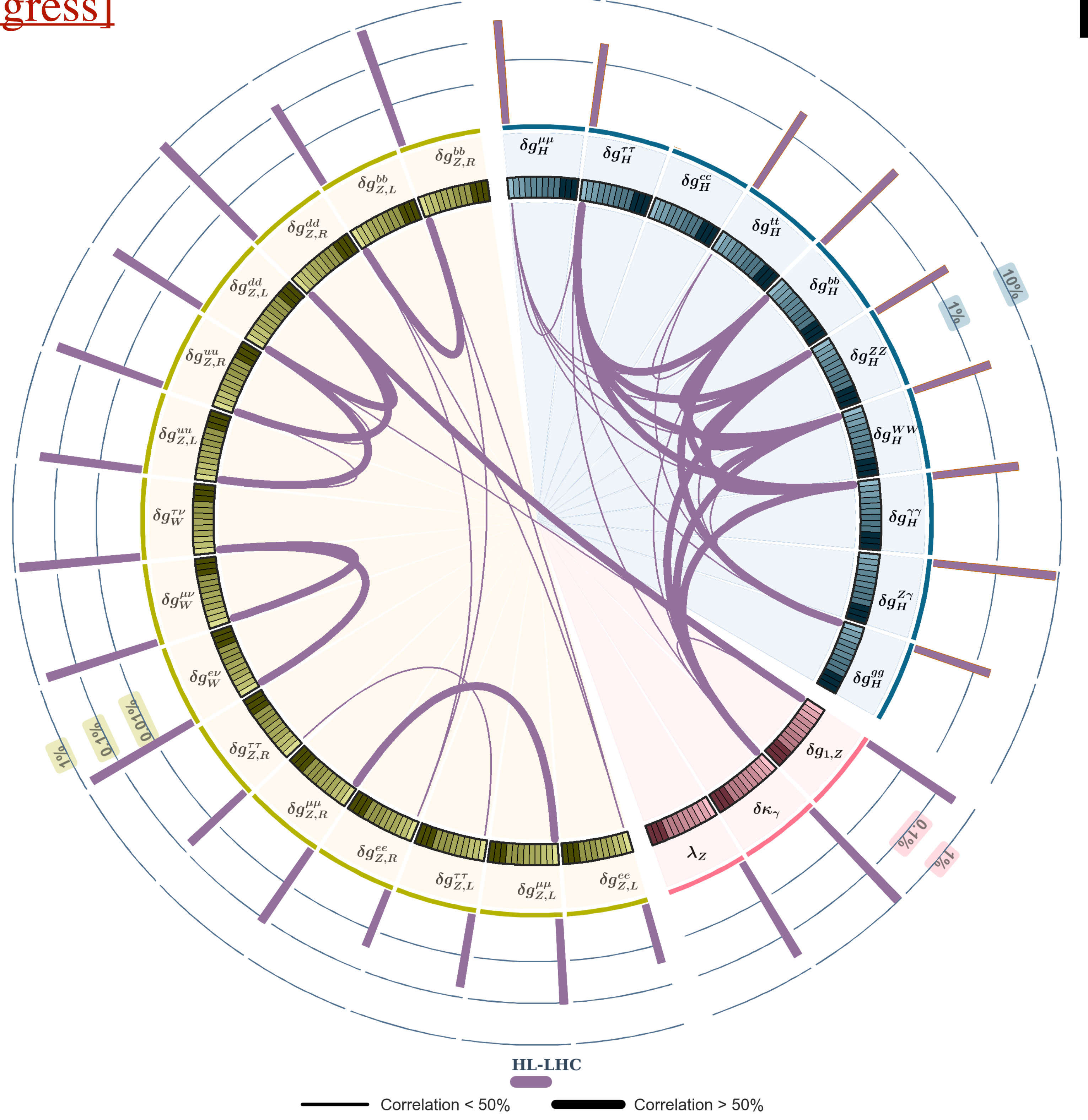
EWPO+EW+Higgs

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

Now



HL-LHC

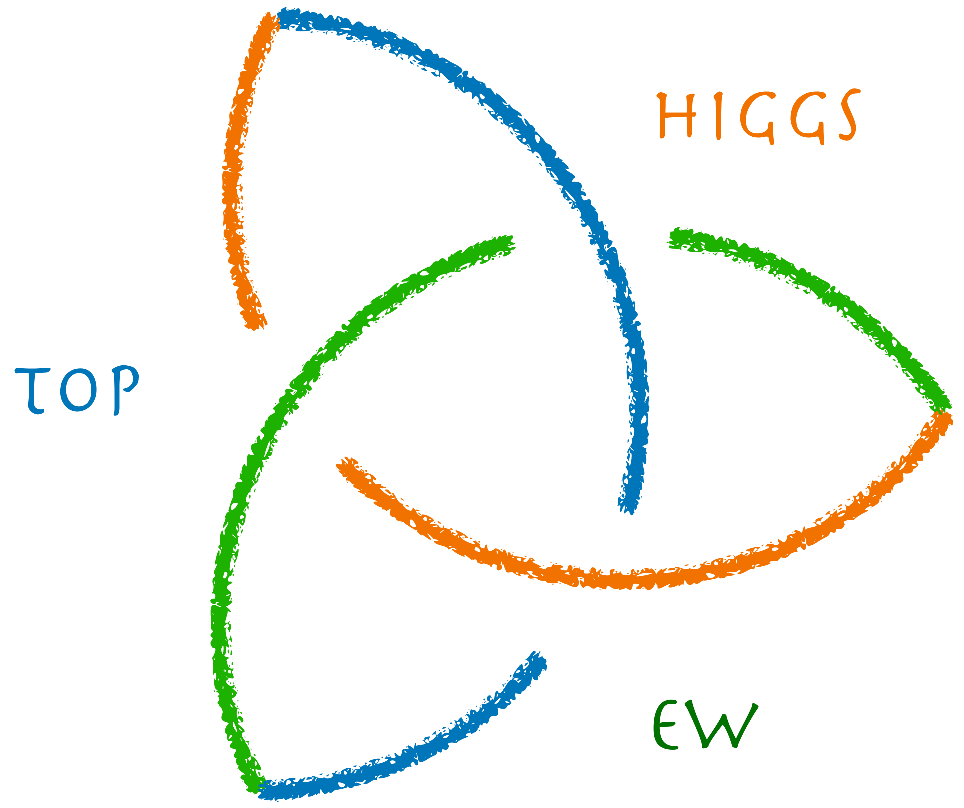


EW known at 0.1%
TGC known at 1%
Higgs known at 10%

As constraints improve for the TGC and Higgs correlations increase.

The SM at the TeV

Conclusions



- SM at the TeV scale is in an extremely good shape. No signs of significant deviations have been detected.
- 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 SM interactions at the TeV scale (and beyond) 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.