Karlsruher Institut für Technologie

Particle Physics Phenomenology after the Higgs Discovery

Theoretical Summary

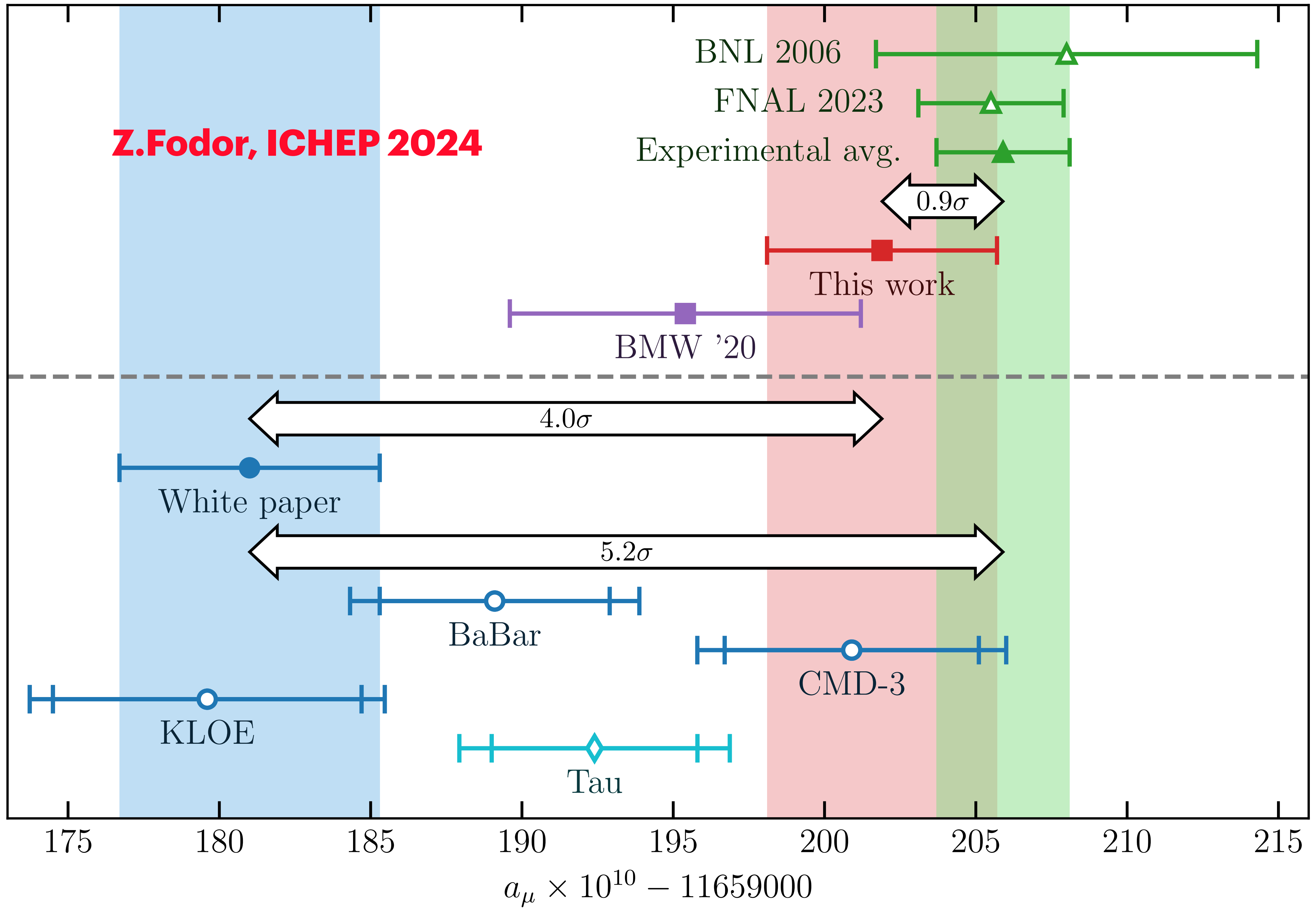
Higgs Hunting 2024, Paris, September 23-25, 2024

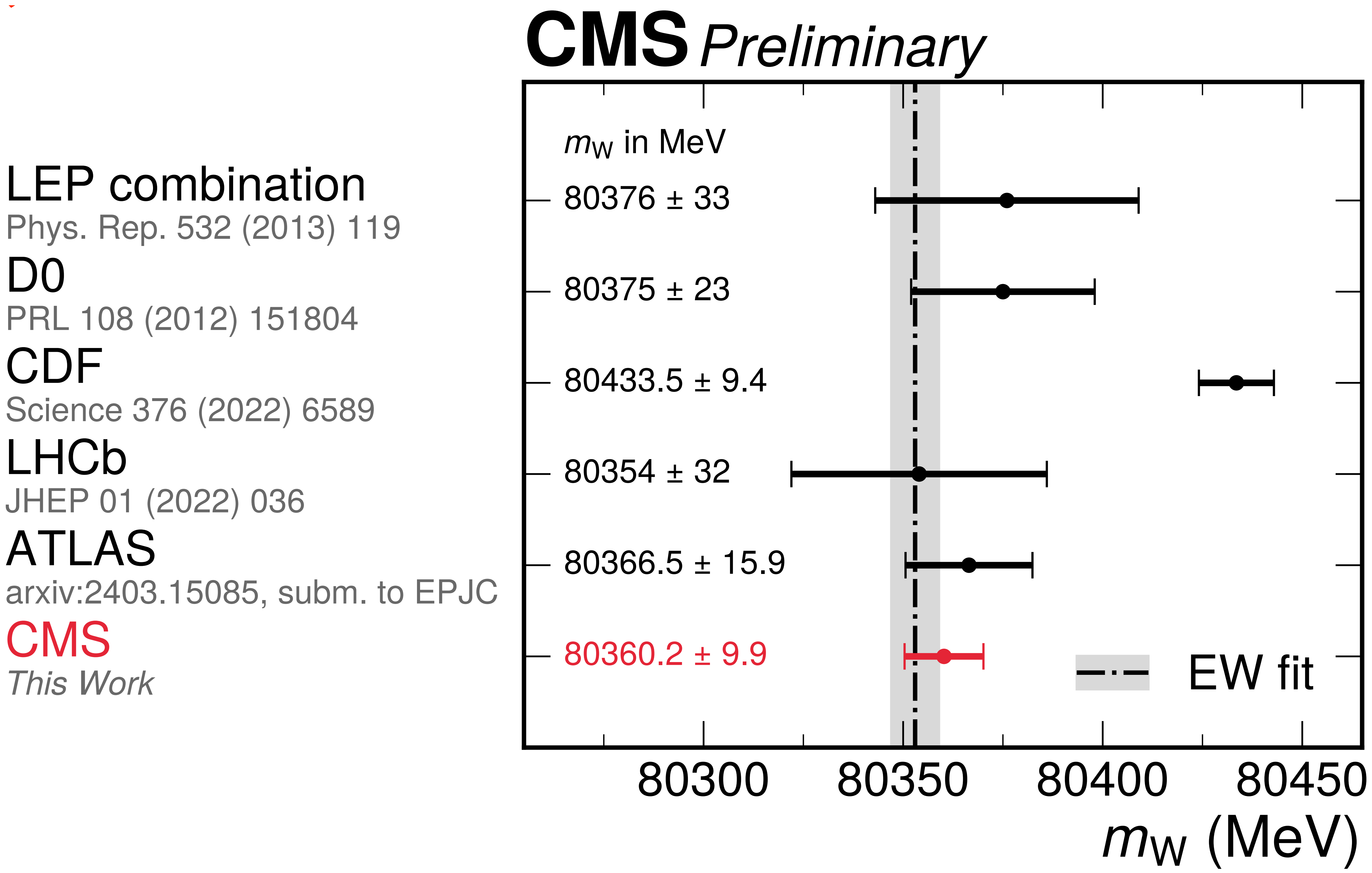
Kirill Melnikov

My only experience with theory summary talks at the Higgs Hunting was the talk by Guido Altarelli in 2013.
I don't remember what he said at all but I do remember that the talk was brilliant and inspiring.

When, on July 4th 2012, R.D. Hoyer cried to the world “I think we have it”, we all thought we finally got the elusive Higgs boson. In fact what we really got was the full Standard Model as the theory of Nature since, once the Higgs boson mass is fixed, the predictive power of the Standard Model becomes absolute. This is both a blessing and a curse.

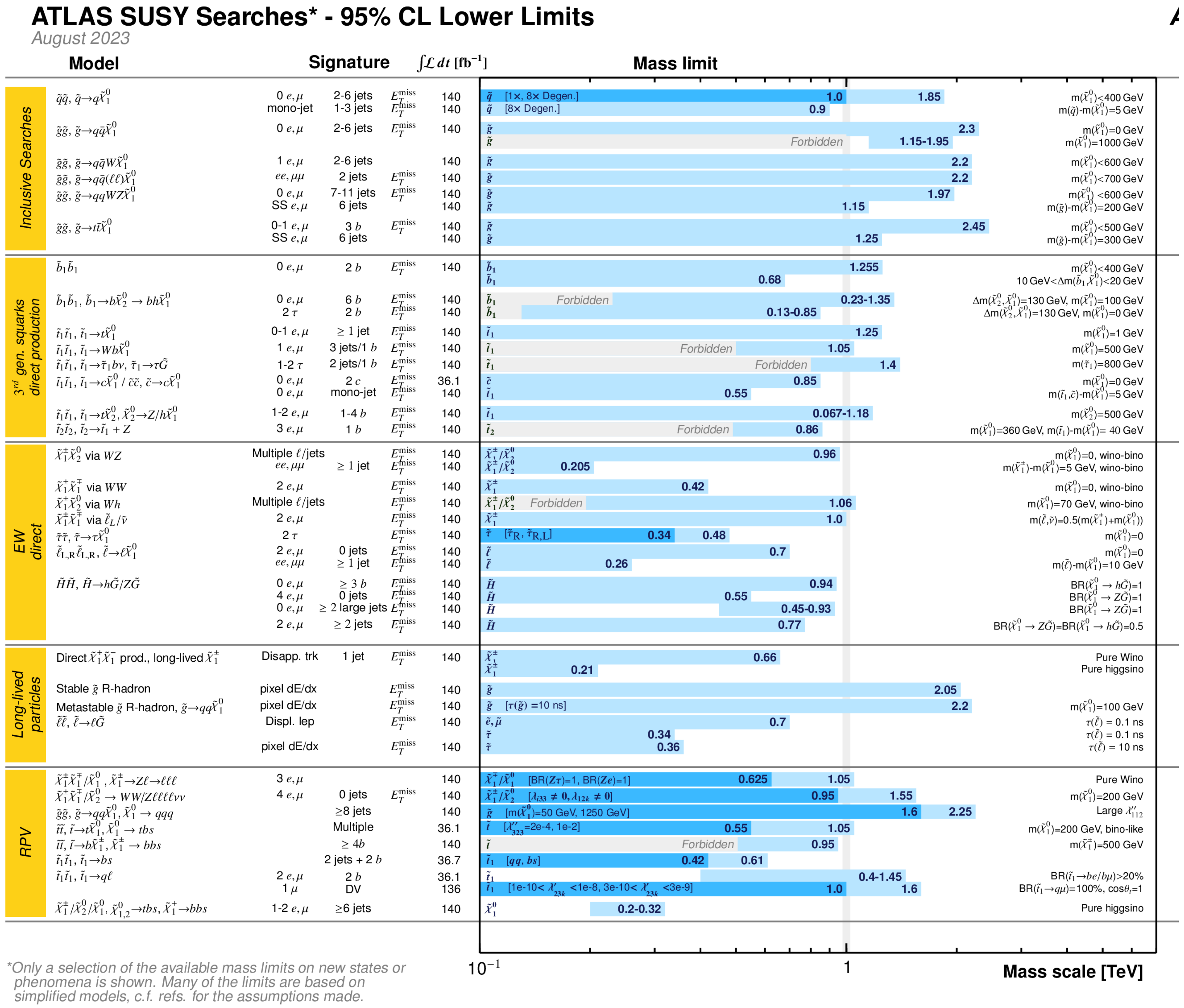
Just this summer, the superb ability of the Standard Model to describe Nature was again on full display, with BMW collaboration showing us the way out of the twenty-year-long muon g-2 crises, and the CMS collaboration measuring the W-mass in a spectacular agreement with predictions of the precision electroweak fit.

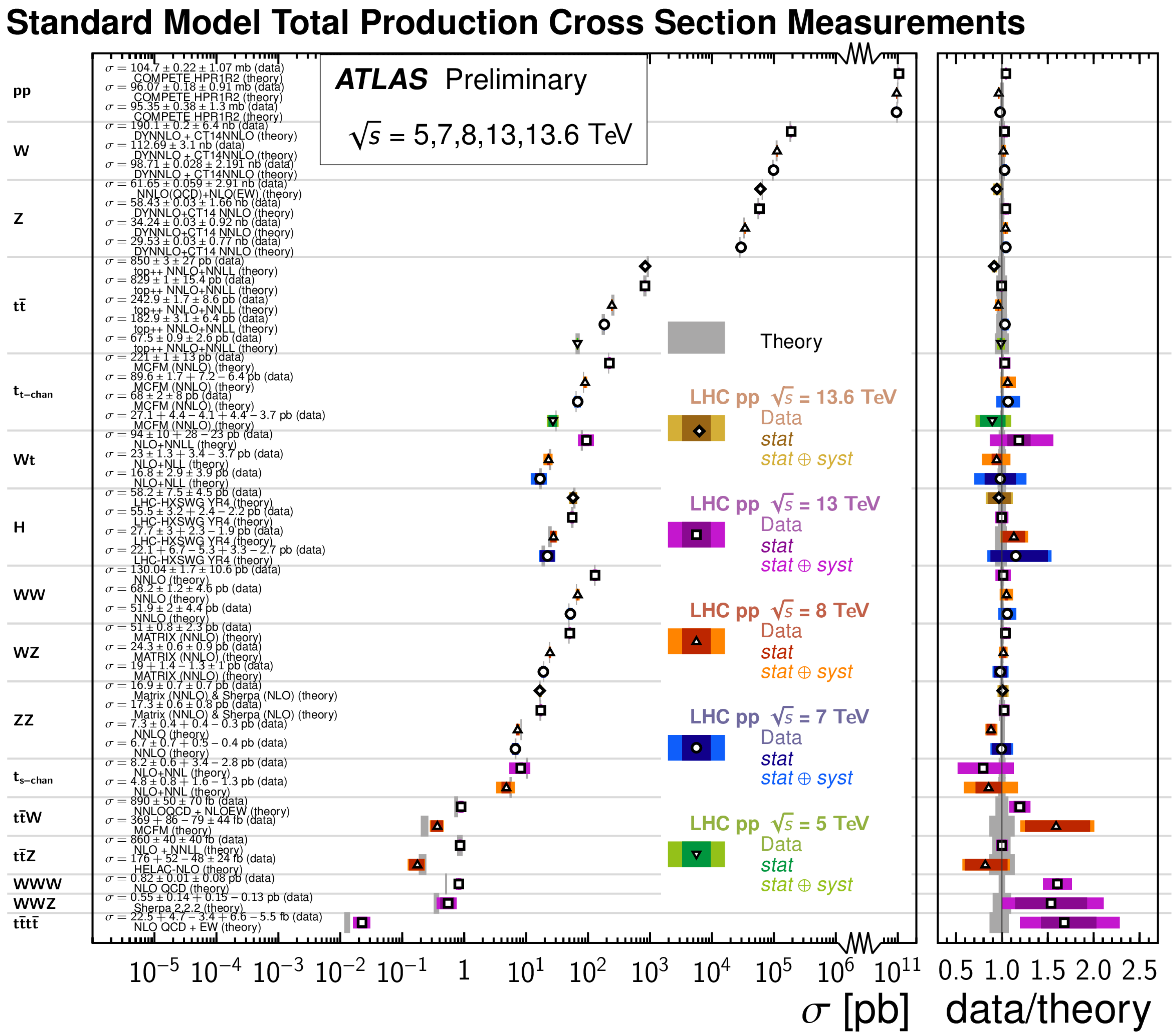




Talk by Andrew Gilbert

Combine this with null results from direct searches and with overall across-the-board agreement of many measured cross sections with theoretical predictions, and you certainly get a feeling that the Standard Model may indeed be the only game in town.





Even if the SM seems to be right at the moment, there are still important issues that it cannot address, at least not in a straightforward way. Several of them are related to the physics of Higgs field.

- unification of interactions
- nature of EW symmetry breaking
- origin of quark/lepton families
- masses and Yukawa couplings
- matter anti-matter asymmetry

$\Big\}\ H$

- nature of dark matter
- connection to gravity

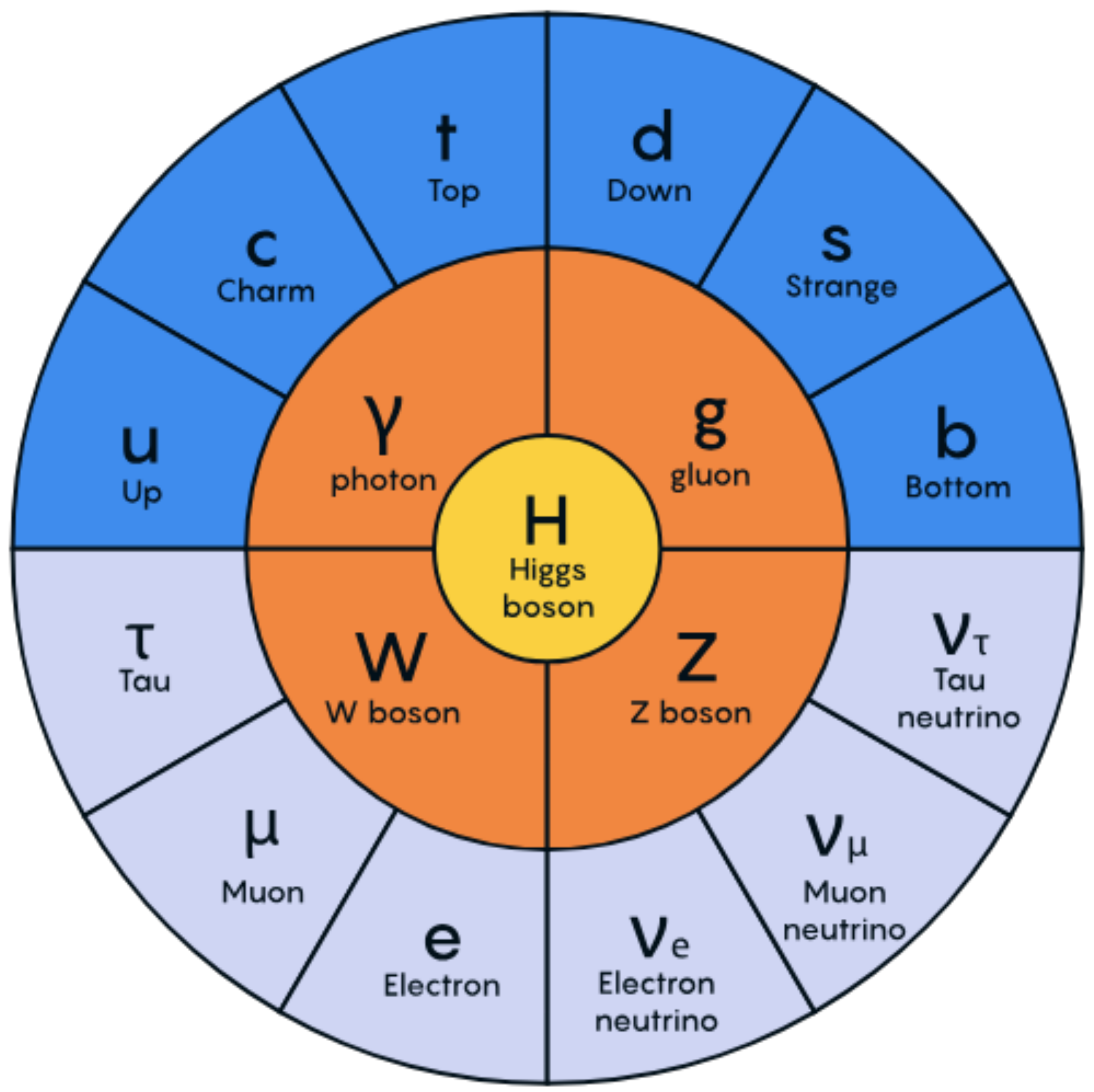
$\Big\}\ H$

Talk by Bibhushan Shakya

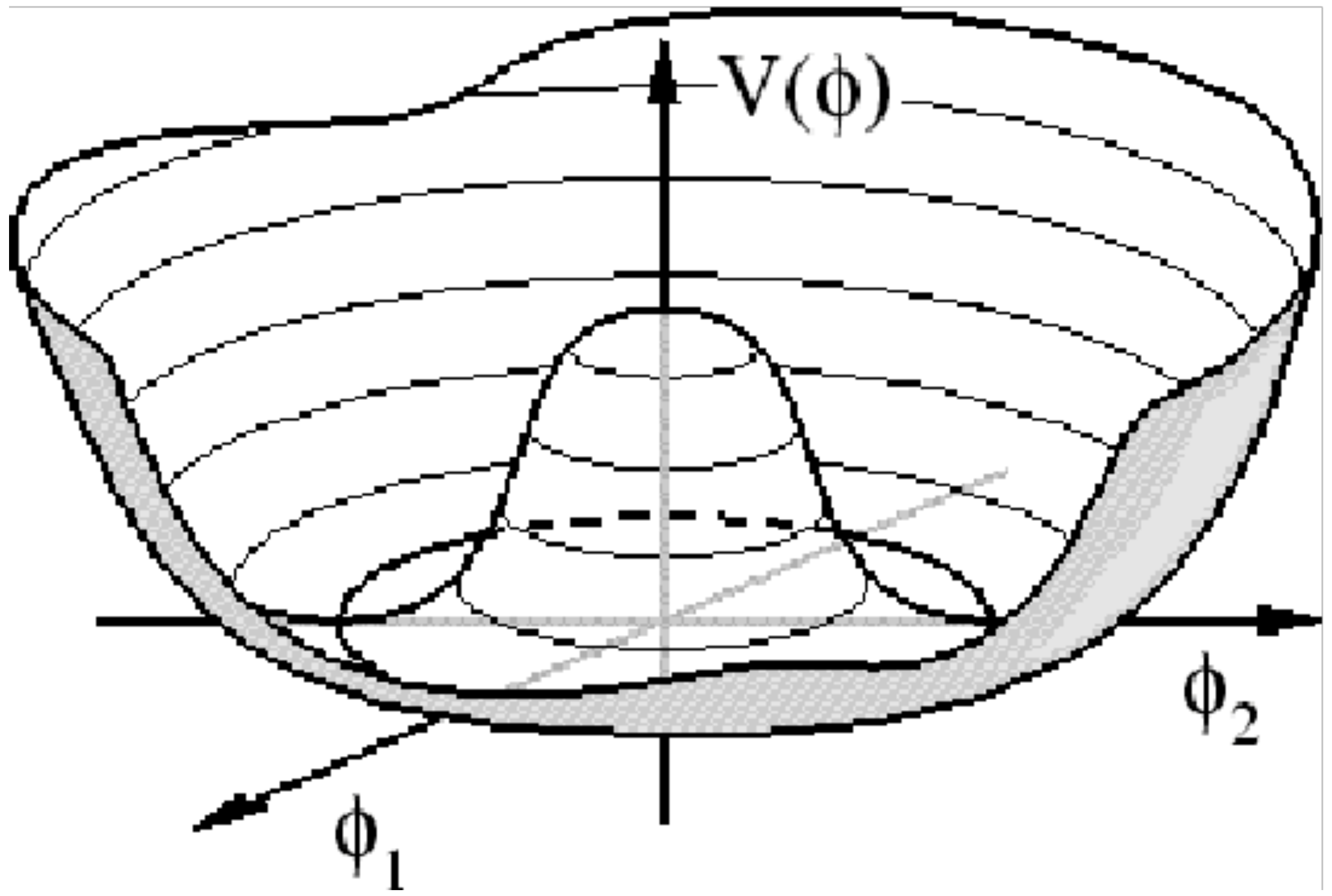
The Higgs boson is a crucial element of the SM, it would not work without it. Our fascination with the Higgs boson is related to two nearly exclusive features that this particle brings to the table.

On the one hand, it makes the Standard Model, augmented with general relativity, the first example of a complete (and correct!) theory of all known fundamental forces that does not require any ultraviolet completion.

On the other hand, the Higgs mechanism in the SM is embarrassingly simple and sort of ad hoc, but it seems to be doing what we want it to do. We keep coming to this conclusion over and again.



$$V(\phi) = -\lambda\left(\phi^{+}\phi - \frac{v^2}{2}\right)^2$$



We may not be too happy about the fact that the renormalizability of the SM — a direct consequence of the Higgs mechanism — ensures that there is no indication of an energy scale where the Standard Model gives way to something else. But it is quite obvious that the SM is a fantastic intellectual achievement of the 20th-century physics.

Core elements of the SM — the gauge principle and the idea of spontaneous symmetry breaking by the ground state of the theory — allow us to describe all fundamental interactions that we know about in a uniform way.

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i \bar{\Psi} \not{D} \psi + |D_\mu \phi|^2 - V(\phi)$$

The second point — a single Higgs field being a trigger of electroweak symmetry breaking — begs the question of the reason for the apparent simplicity especially because additional complexity would make the SM a "better theory".

$$\mathcal{L} = |D_\mu \phi|^2 - V(\phi) + \bar{\psi}_i y_{ij} \psi_j \phi + h.c.$$

For example:

1) additional Higgs fields can provide new (largely needed) sources of CP violation and make the electroweak phase transition stronger, allowing to generate the observed matter-anti-matter asymmetry.

$$V_{2\mathrm{HDM}}(\Phi_1,\Phi_2) = m_{11}^2\left(\Phi_1^\dagger\Phi_1\right) + m_{22}^2\left(\Phi_2^\dagger\Phi_2\right) - m_{12}^2\left[\left(\Phi_1^\dagger\Phi_2\right) + \left(\Phi_2^\dagger\Phi_1\right)\right] + \frac{\lambda_1}{2}\left(\Phi_1^\dagger\Phi_1\right)^2 + \frac{\lambda_2}{2}\left(\Phi_2^\dagger\Phi_2\right)^2 + \lambda_3\left(\Phi_1^\dagger\Phi_1\right)\left(\Phi_2^\dagger\Phi_2\right)$$

$$+ \lambda_4\left(\Phi_1^\dagger\Phi_2\right)\left(\Phi_2^\dagger\Phi_1\right) + \frac{\lambda_5}{2}\left[\left(\Phi_1^\dagger\Phi_2\right)^2 + \left(\Phi_2^\dagger\Phi_1\right)^2\right].$$

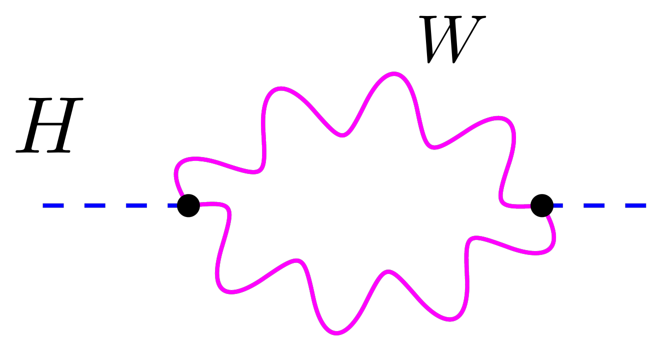
See talk of Wrishik Nascar for the implicatiions of the extended Higgs sector for multi-Higgs production at the LHC

2) if the Higgs boson is a composite particle its self-interaction potential would generically be described by the fourth-degree polynomial as in the SM. However, in contrast to the SM where his polynomial is the whole story, in composite models, these will be the first view terms in the expansion of a much more complex effective potential that we have not seen yet. This is what happens in the Landau theory of phase transitions where the analog of the vacuum value of the Higgs field is a generic "order parameter" which always has a microscopic origin.

$$\frac{F_L}{V} = \frac{1}{2}a(T-T_C)\vec{M}\cdot\vec{M} + \frac{1}{4}c\left(\vec{M}\cdot\vec{M}\right)^2 + \ldots$$

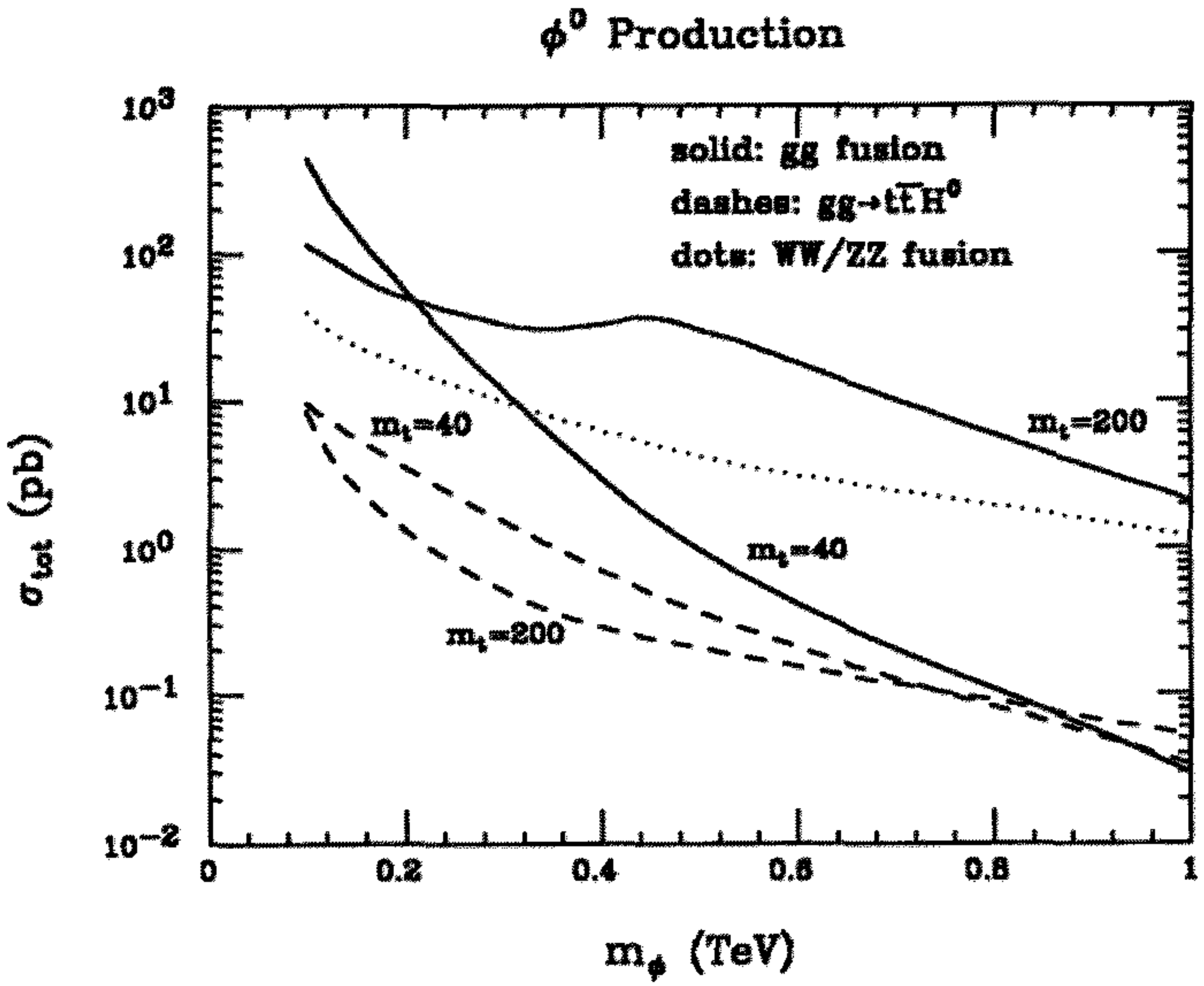
3) new particles with masses below a TeV make the Higgs mass, as measured at the LHC, much more natural. Supersymmetry is an example of a theory that can do this elegantly but, so far, Nature is not cooperating.

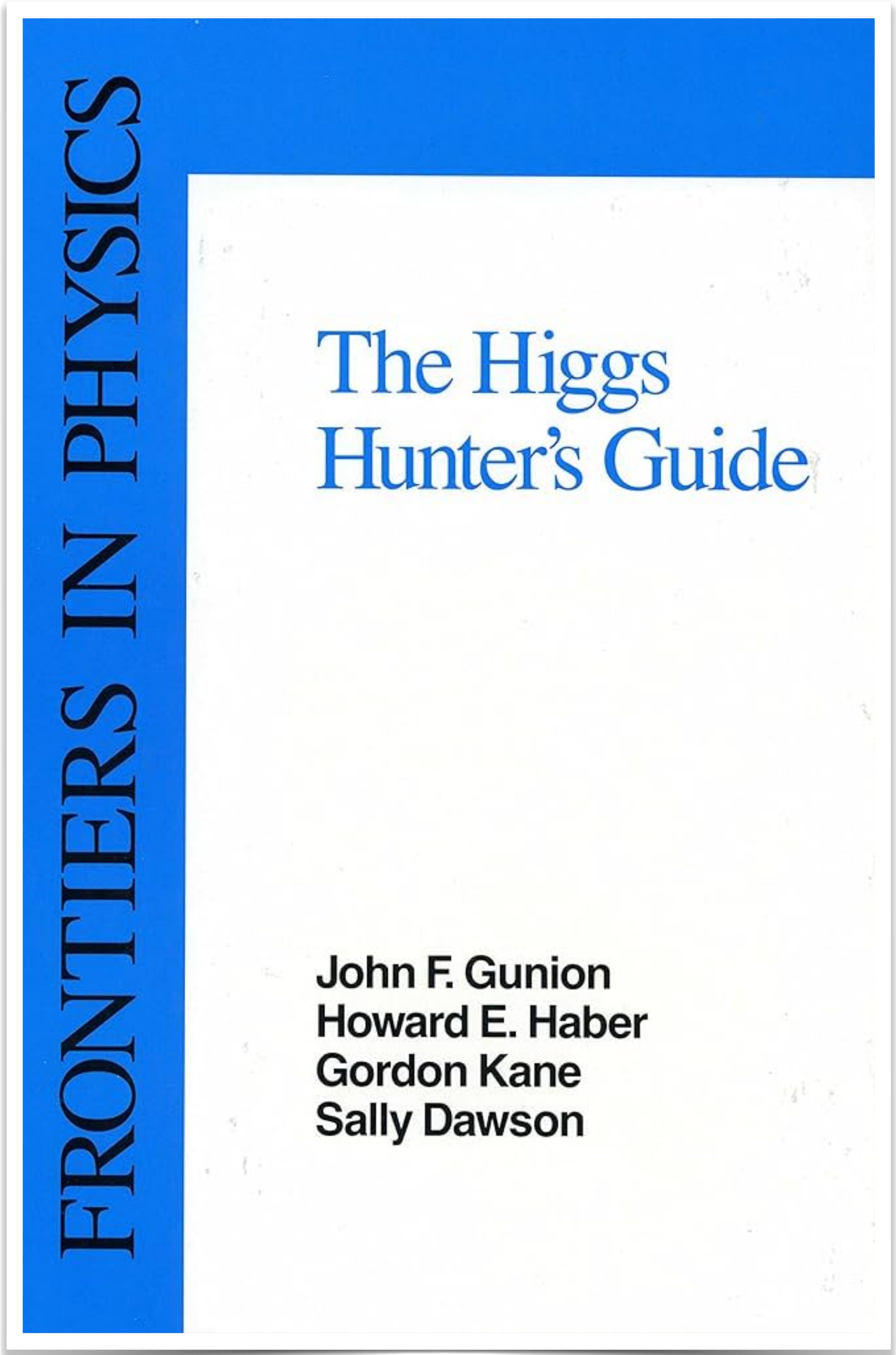
$$\delta m_H^2 = \frac{3G_F}{2\sqrt{2}\pi^2}\left(4m_t^2 - 2m_W^2 - m_Z^2 - m_H^2\right)\Lambda^2$$



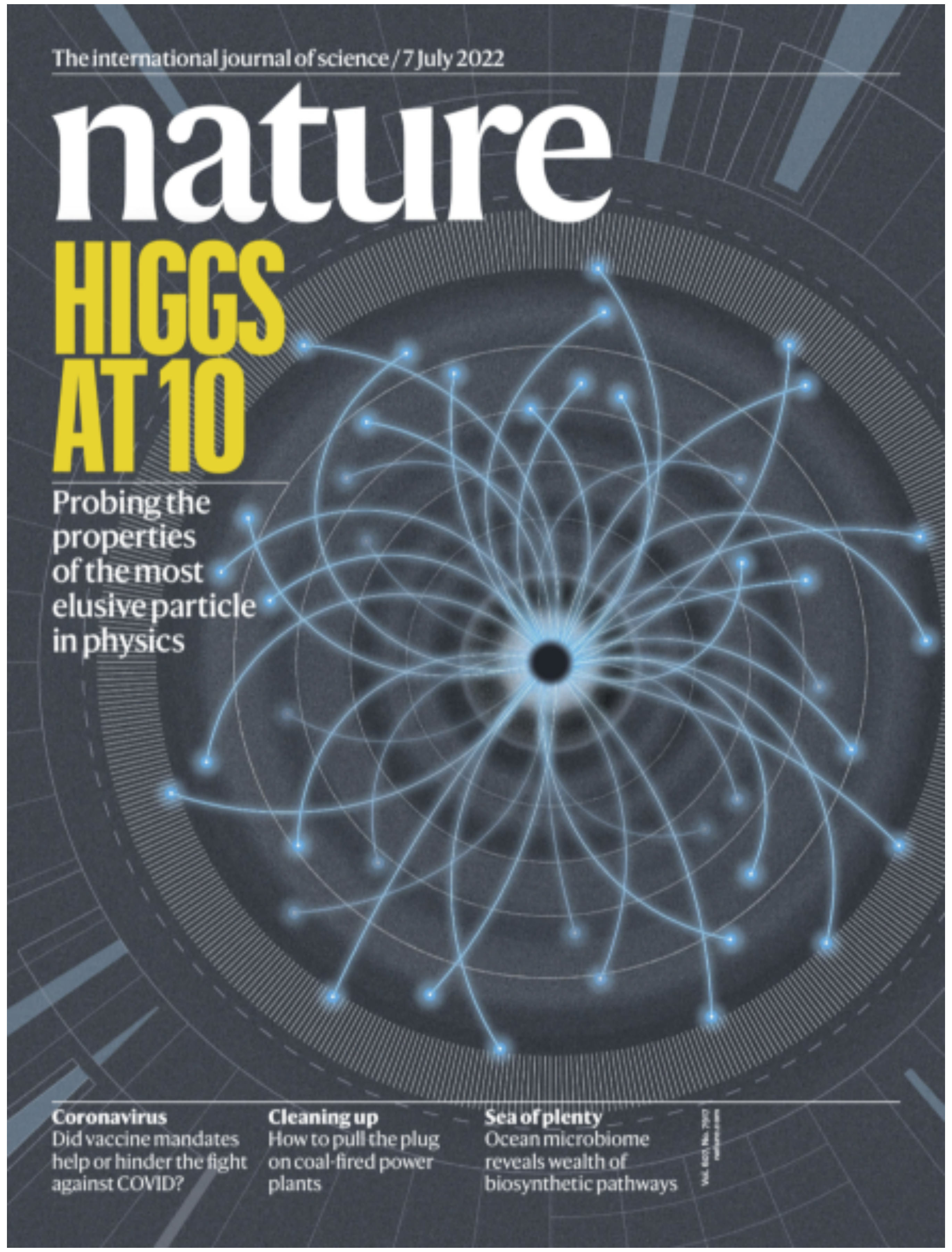
Hence, there were, and still are, good reasons to believe that the Higgs sector of the SM is just a placeholder for something much more fundamental, that we still have to discover.

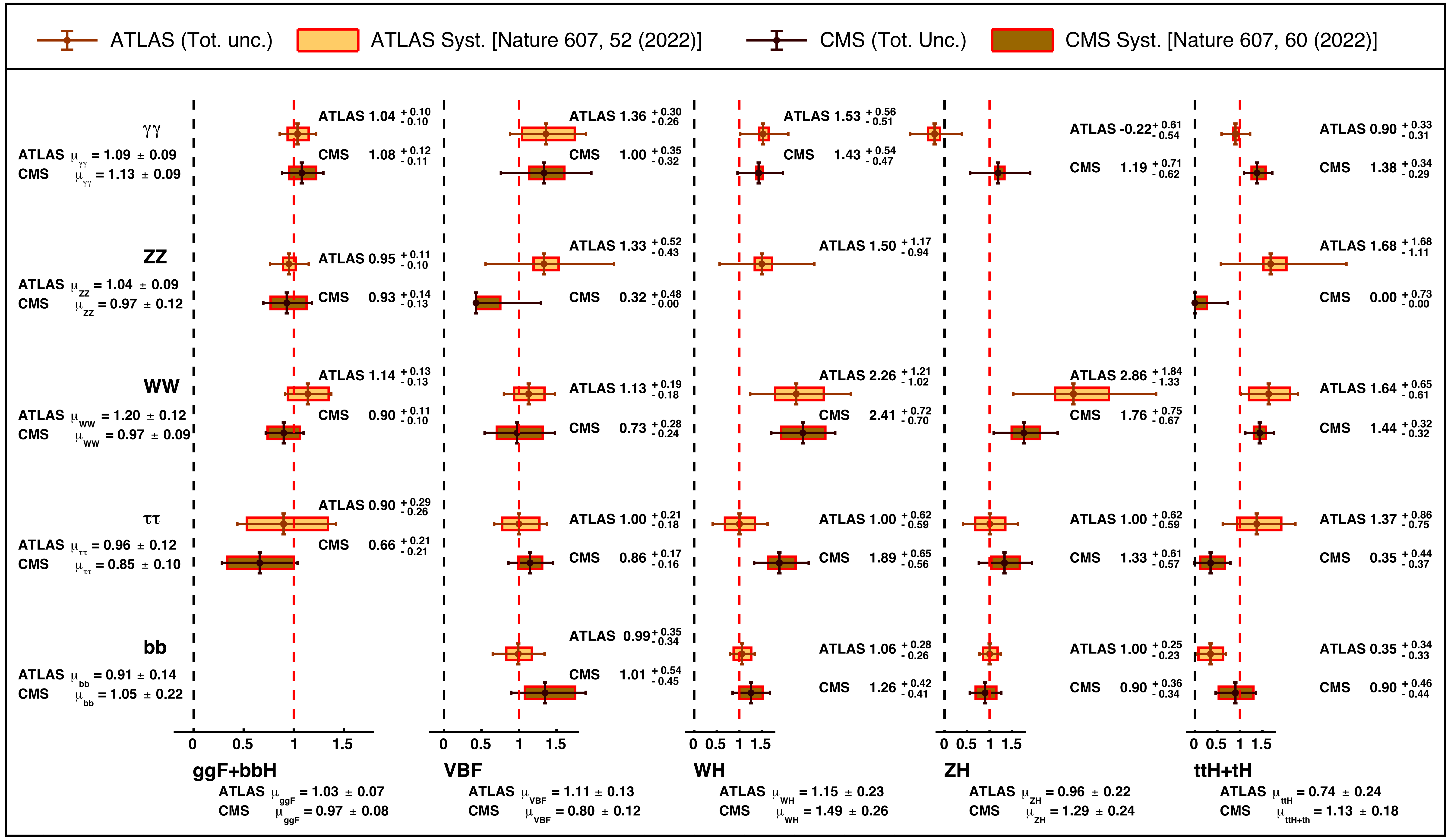
At the same time, the SM with its Higgs sector provides complete and calculable example of a fundamental theory of Nature which gave many of us an opportunity to discuss physics of the SM Higgs in great detail, before its discovery.





The discovery of the Higgs boson was followed by a period, during which our knowledge about this particle was consolidated. As the result of this, we seem to be coming to a conclusion that none of the more exciting things that we came to expect from the Higgs sector are being realised in Nature, at least not in grand style.

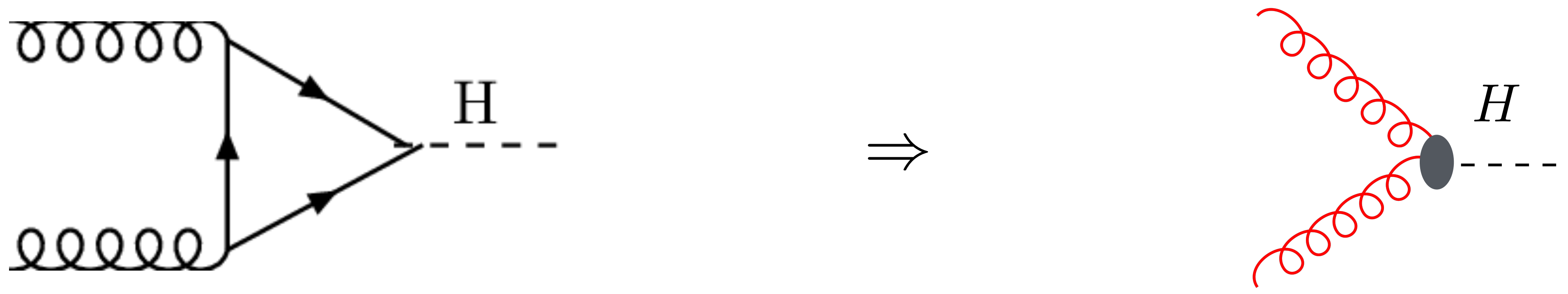




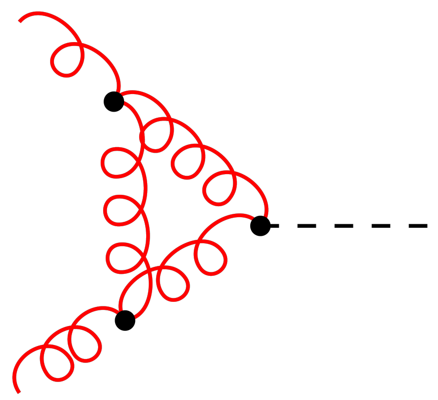
This (somewhat premature) conclusion has a somewhat negative connotation, but this is a very important scientific result that particle physicists, as a community, managed to achieve. The path towards this result was not particularly srtaightforward.

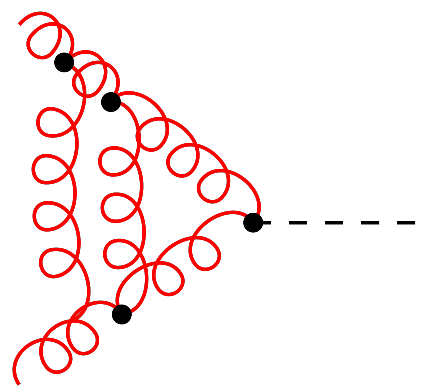
Precise prediction of the Higgs boson production cross section at the LHC is the important success story of particle theory. Without computed higher order corrections, we would be discussing n O(1) discrepancies between predictions and measurements, instead of celebrating their agreement at a few percent level.

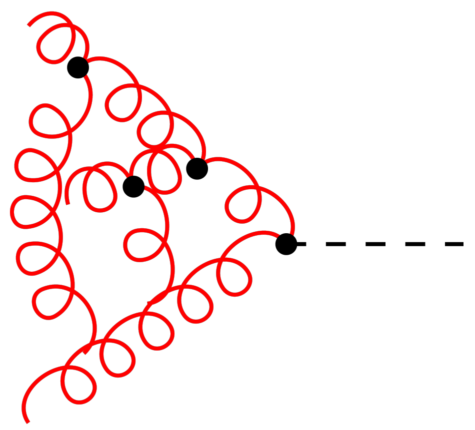
More details in the talk by Steve Jones



$$\sigma = 48.58\,\mathrm{pb}^{+2.22\,\mathrm{pb}\,(+4.56\%)}_{-3.27\,\mathrm{pb}\,(-6.72\%)}\;(\mathrm{theory}) \pm 1.56\,\mathrm{pb}\,(3.20\%)\;\;(\mathrm{PDF}{+}\alpha_s)\,.$$



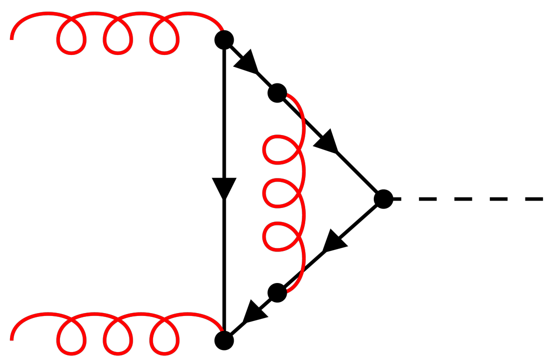


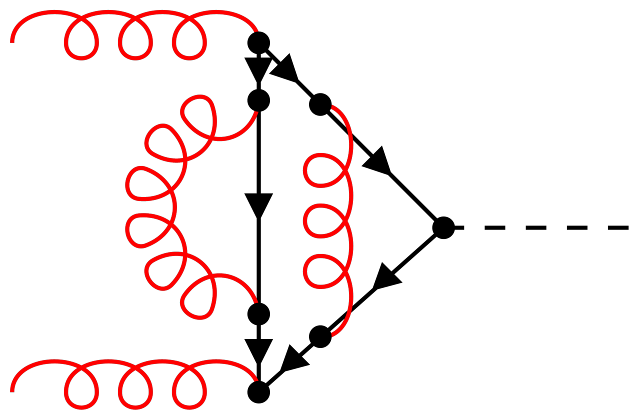


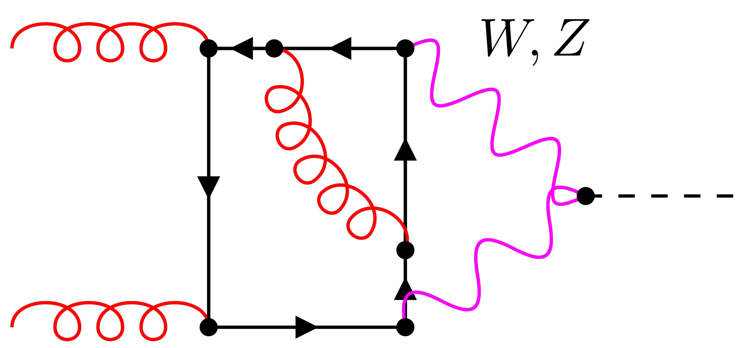
$$\begin{aligned}
48.58\,\mathrm{pb} = \;& 16.00\,\mathrm{pb} && (+32.9\%) && (\mathrm{LO,\ rEFT})\\
& +20.84\,\mathrm{pb} && (+42.9\%) && (\mathrm{NLO,\ rEFT})\\
& -\;\;2.05\,\mathrm{pb} && (-4.2\%) && ((t,b,c),\ \mathrm{exact\ NLO})\\
& +\;\;9.56\,\mathrm{pb} && (+19.7\%) && (\mathrm{NNLO,\ rEFT})\\
& +\;\;0.34\,\mathrm{pb} && (+0.7\%) && (\mathrm{NNLO},\ 1/m_t)\\
& +\;\;2.40\,\mathrm{pb} && (+4.9\%) && (\mathrm{EW,\ QCD\text{-}EW})\\
& +\;\;1.49\,\mathrm{pb} && (+3.1\%) && (\mathrm{N^3LO,\ rEFT})
\end{aligned}$$

Anastasiou, Duhr, Dulat, Furlan, Gehrmann, Herzog, Lazopoulos, Mistlberger

δ(scale)	δ(trunc)	δ(PDF-TH)	δ(EW)	$\delta(t,b,c)$	$\delta(1/m_t)$
$^{+0.10}_{-1.15}$ pb	±0.18 pb	±0.56 pb	±0.49 pb	±0.40 pb	±0.49 pb
$^{+0.21\%}_{-2.37\%}$	±0.37%	±1.16%	±1%	±0.83%	±1%

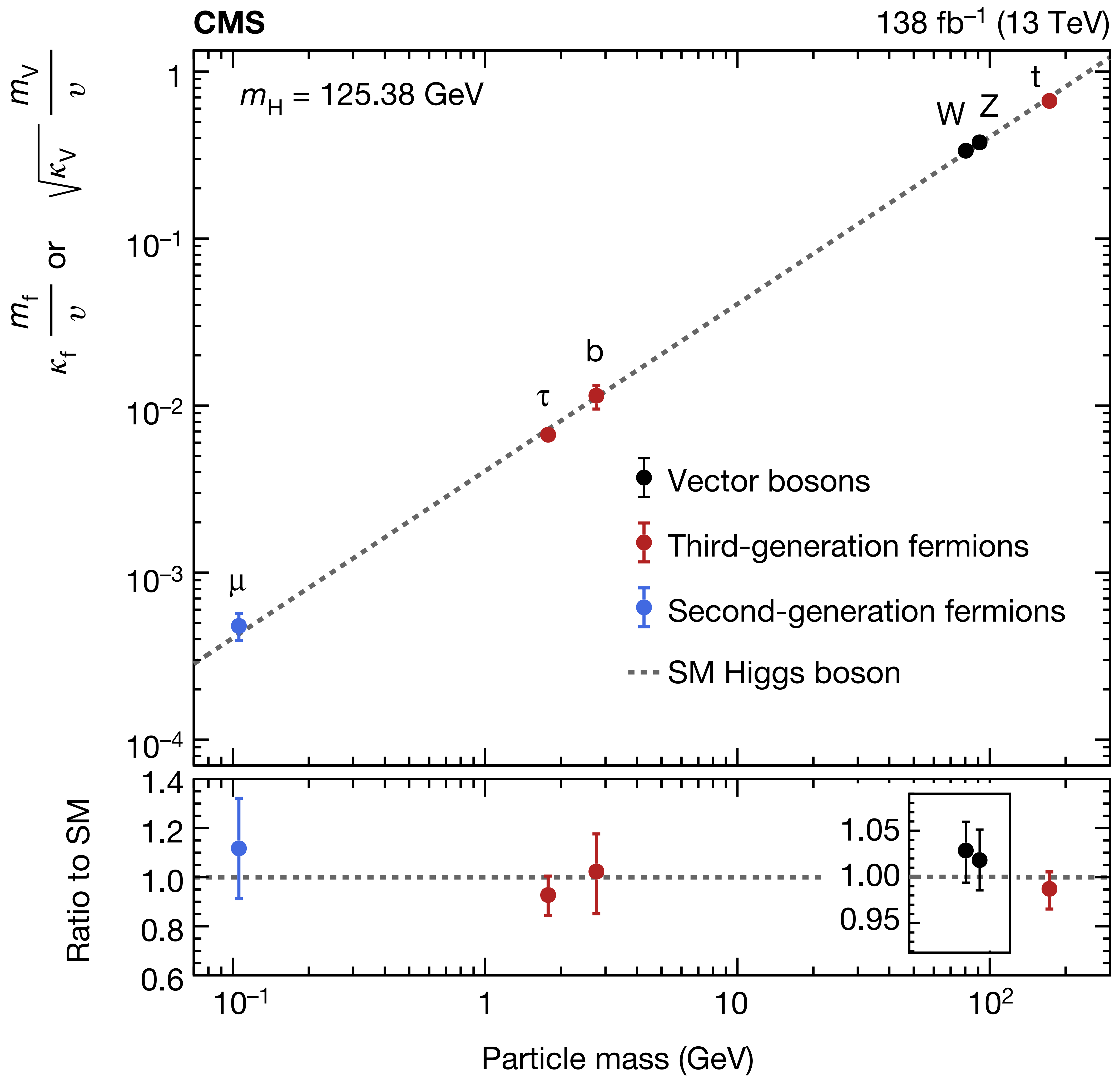


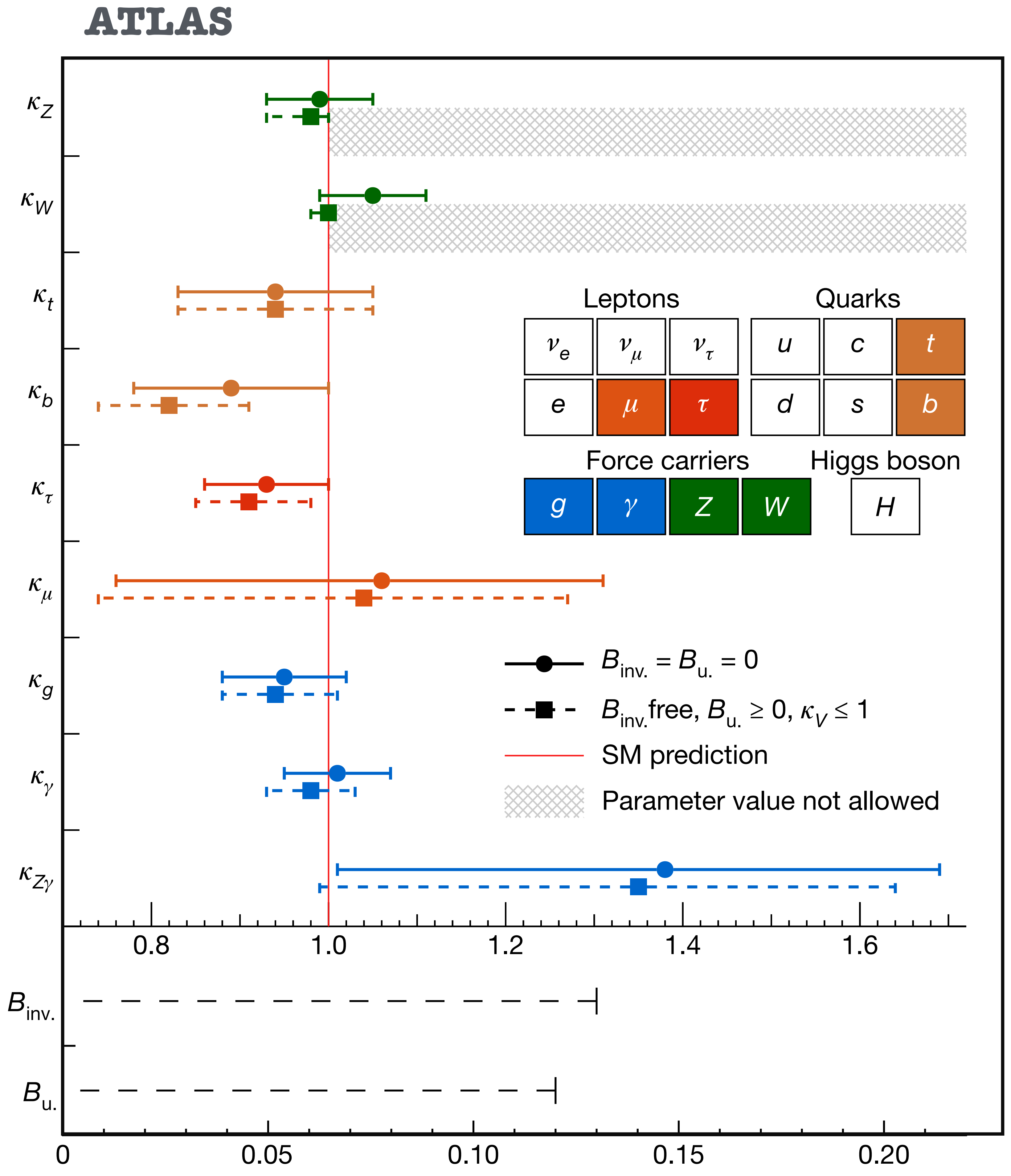




Mistlberger, Bonetti, Tancredi, K.M., Becchetti, Bonciani, Del Duca, Hirschi, Moriello, Czakon, Eschment, Schellenberger , Niggetiedt, Poncelet

As the result, we currently have a picture of the HIggs boson that is very consistent with the Standard Model. However, some elements in this picture are missing, for very practical reasons. Indeed, it was known since long that the exploration of some of the Higgs boson properties at a hadron collider is extremely difficult...





Before the start of the LHC, the general perception was that

- the measurement of the Higgs coupling to bottom and charm quarks are either very difficult or plain impossible;
- the measurement of the Higgs self-coupling will only give us an and order of magnitude estimates
- the measurement of the Higgs decay width with a precision that is better than a factor O(200) cannot happen at the LHC.

These expectations turned out to be too pessimistic and as of now

the bottom Yukawa coupling is measured to about 20 percent;

the Higgs boson width is measure to about 70 percent;

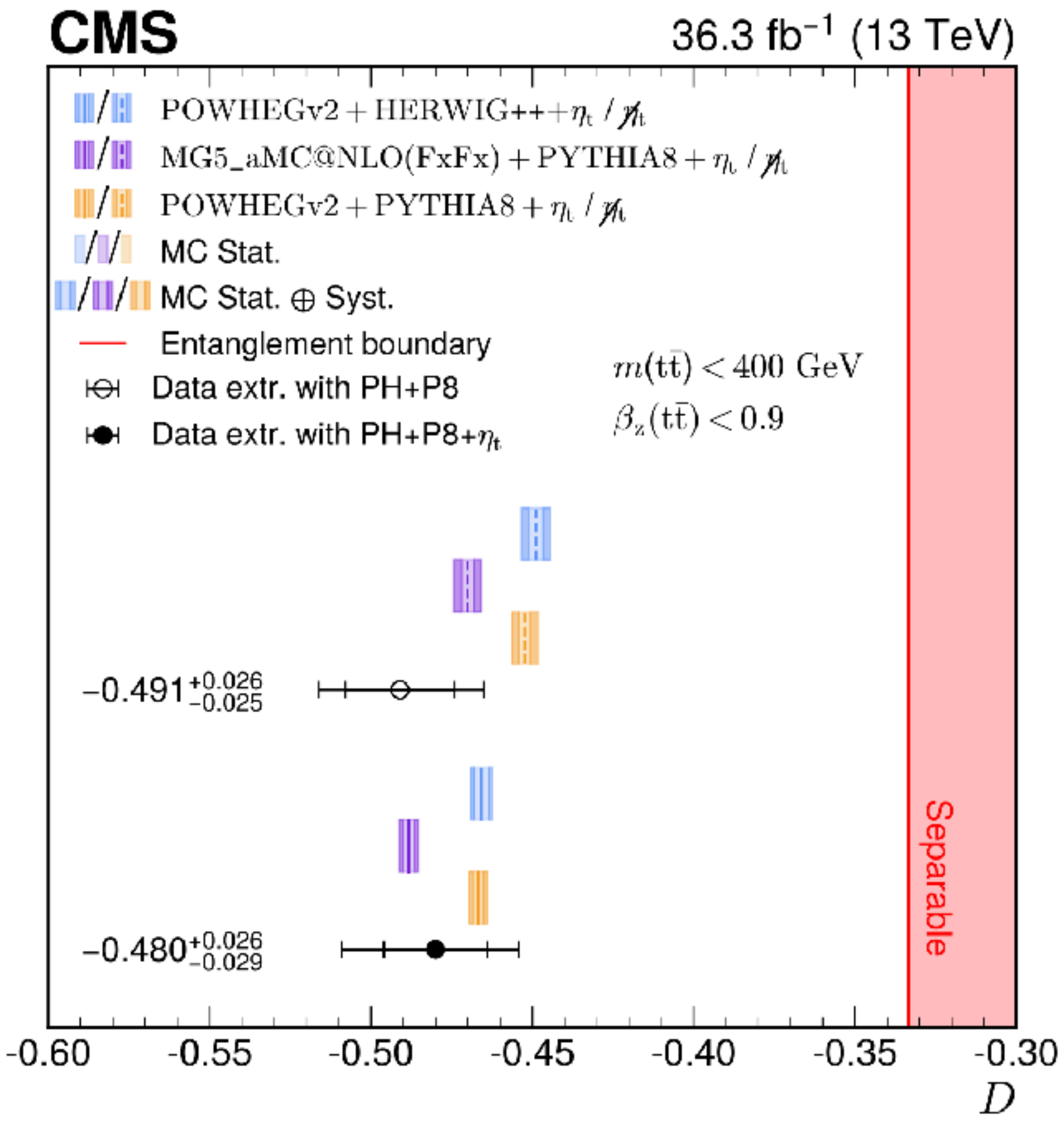
there are plenty of ideas on how to constrain the charm Yukawa coupling, so that we will certainly see this happening at the HL-LHC;

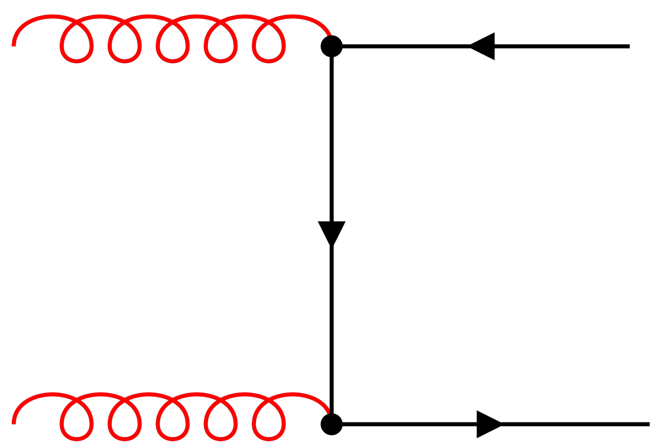
and there will be significant improvements in what is known about Higgs trilinear coupling by the end of HL-LHC.

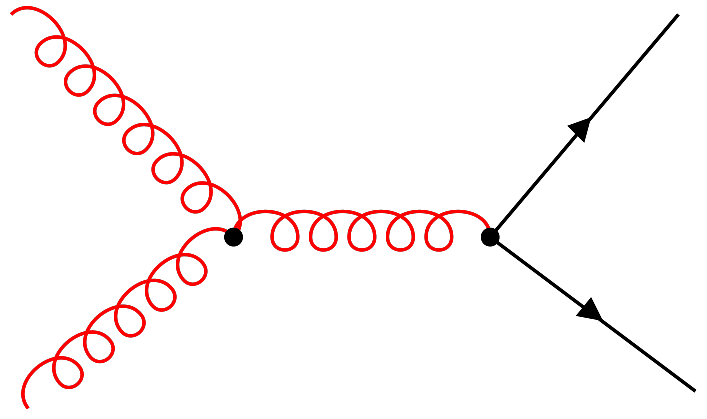
The key behind this progress was, amusingly, Quantum Mechanics.

Recently the correctness of Quantum Mechanics was confirmed in top quark pair production by the LHC collaborations, so we are going to use it with confidence.

- At production threshold in $t\bar{t} \to b\ell\nu b\ell\nu$ events







$$\Psi_{t\bar{t}} = \frac{1}{\sqrt{2}}\left(|+-\rangle - |-+\rangle\right)$$

At the threshold, top quarks in a color-singlet channel will have the zero-spin wave function which means that spins of top and anti-top are fully correlated.

A key feature of Quantum Mechnics is the interference of probability amplitudes. If an interesting final state can be reached from the initial state in two different ways, there must be an interference of quantum amplitudes. If the two amplitudes have drastically different magnitude, then the interferences is significantly larger than the square of the small amplitude.

$$\mathcal{A} = \mathcal{A}_1 + \delta \mathcal{A}_2 \qquad\qquad \delta \ll 1$$

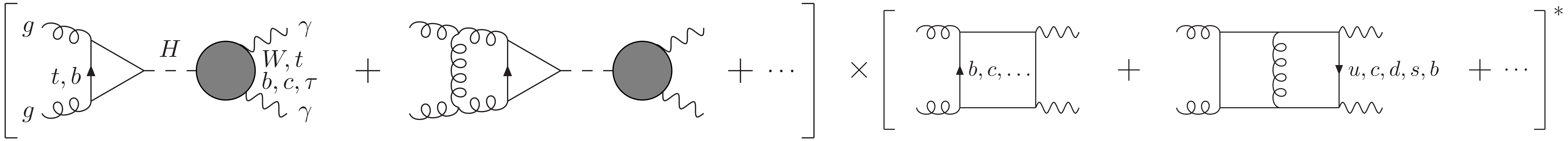
$$|\mathcal{A}|^2 = |\mathcal{A}_1|^2 + \delta\, \mathrm{Re}\left[\mathcal{A}_1 \mathcal{A}_2^* + \mathrm{c.c}\right] + \delta^2\, |\mathcal{A}_2|^2$$

Some ideas about measuring the charm Yukawa, and the Higgs width are based on the observation that the interference with a large quantum amplitude can lift up a tiny signal that otherwise would be impossible to observe.

Baron Münchhausen pulls himself and the horse he sits on from the swap by the hair.

A well-known example of the interference arises in the main discovery channel: Higgs production in gluon fusion followed by the Higgs decay to two photons. In this case, the amplitude is two-loop and the signal is one-loop, therefore the signal-background interference might be enhanced by a loop factor!

Dicus and Willenbrock (1988)



$$A_{i\to f} = \frac{R\, m_h^2}{s - m_h^2 + i m_h \Gamma_h} + B$$

$$|A_{i\to f}|^2 = \frac{|R|^2 \quad m_h^4}{(s-m_h^2)^2 + \Gamma_h^2 m_h^2}\left[1 + \frac{2(s-m_h^2)}{m^2}\mathrm{Re}\left(\frac{B^*}{R}\right) + \frac{2\Gamma_h}{m_h}\mathrm{Im}\left(\frac{B^*}{R}\right)\right] + |B|^2$$

$$R \sim \frac{\alpha_s \alpha m_h^2}{(4\pi v)^2}, \qquad B \sim \frac{g_s^2 e^2}{(4\pi)^2}$$

$$[\sigma_{\rm int}/\sigma_H]_{\rm naive} \approx \frac{2\Gamma_H}{m_H}\frac{(4\pi v)^2}{m_h^2} \approx 0.1$$

The estimate is way too naive. It turns out that all relevant one-loop amplitudes are real (equal helicity photons can not annihilate to massless fermions) and, for this reason, the interference does not occur at one-loop. At two-loops the interference is present, but it only affects Higgs production cross-section at a few percent level.

Dixon and Siu

See the talk byFederico Bunccioni about the role of the interference in Higgs decays to Z-gamma.

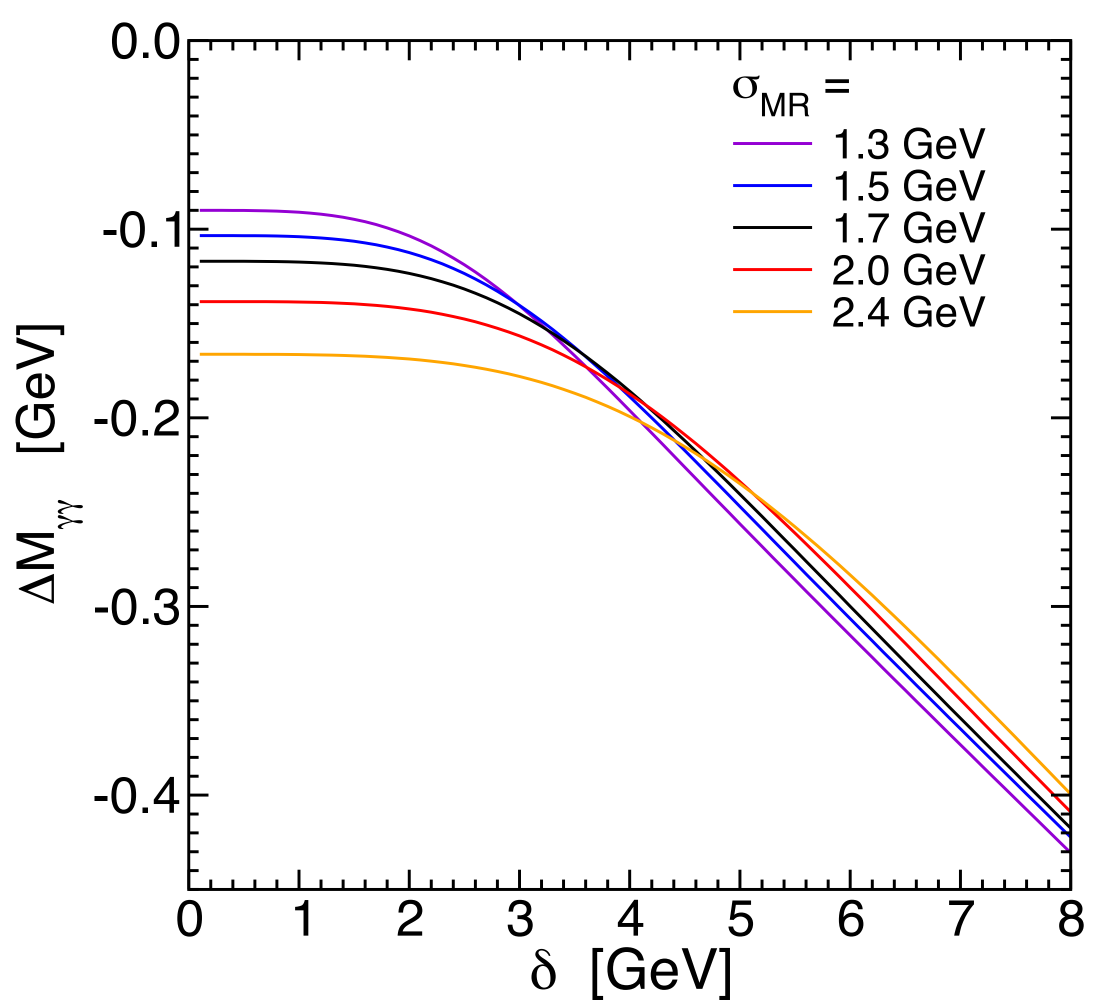
Although not very important for the total cross section, this interference introduces a process-dependent shift in the measured value of the Higgs boson mass. The shift is bigger in the di-photon channel than in the four-lepton one.

$$\frac{d\sigma}{ds} = \frac{R}{(s-m_h^2)^2 + m_h^2\Gamma_h^2} + \frac{(s-m_h^2)I}{(s-m_h)^2 + m_h^2\Gamma_h^2}$$

$$\langle M^2 \rangle = \frac{1}{\sigma_0}\int ds\; s\,\frac{d\sigma}{ds} = m_h^2 + \frac{I}{\sigma_0}\int_{s_-}^{s_+} ds = m_h^2 + \frac{I(s_+ - s_-)}{\sigma_0}$$

$$\delta m_h = \frac{2I\delta}{\sigma_0}, \qquad s_\pm = (m_h \pm \delta)^2$$

Martin



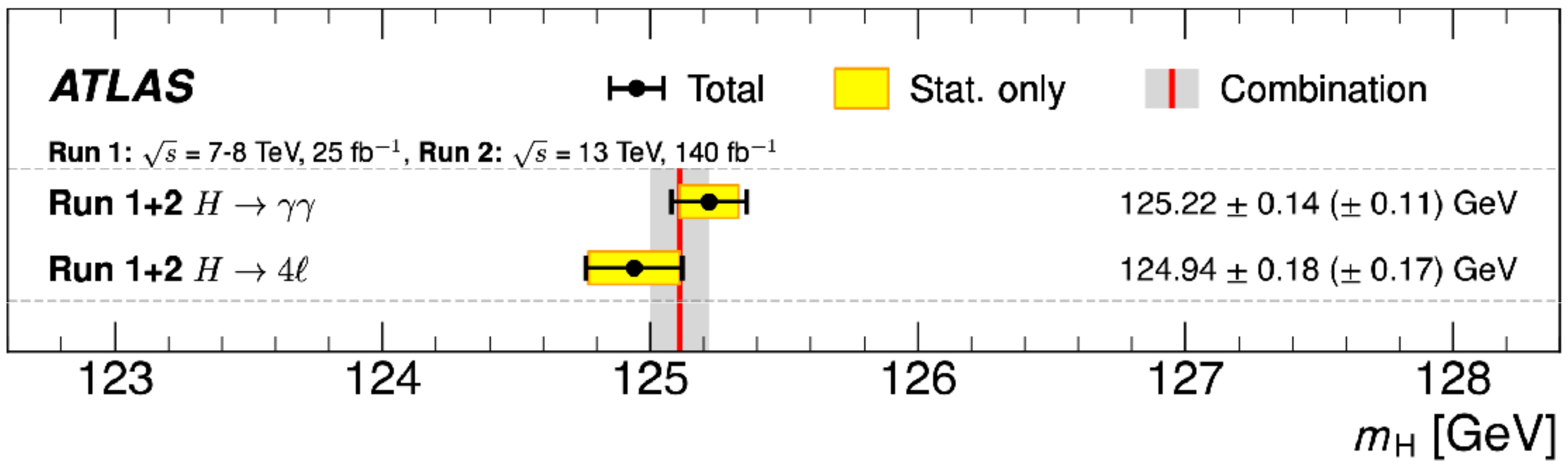
Requiring that the signal cross section remains what it is, one can relate the mass shift to the width of the Higgs boson.

$$\delta m_h = \frac{2I\delta}{\sigma_0} \sim \frac{A_B}{A_s}\Gamma_H \qquad \sigma_0 \sim \frac{A_s^2}{\Gamma_H} \qquad I \sim A_B A_S$$

$$\sigma_0 \sim \text{const} \qquad \Rightarrow \qquad A_s \sim \sqrt{\Gamma_H}$$

$$\delta m_H \sim 100\ \text{MeV} \times \sqrt{\frac{\Gamma_H}{\Gamma_H^{\text{SM}}}}$$

Dixon and Siu



Taking the current mass differences in diphoton and four-lepton channels at the face value, we estimate $\Gamma_H < \mathcal{O}(20)\Gamma_{\text{SM}}$

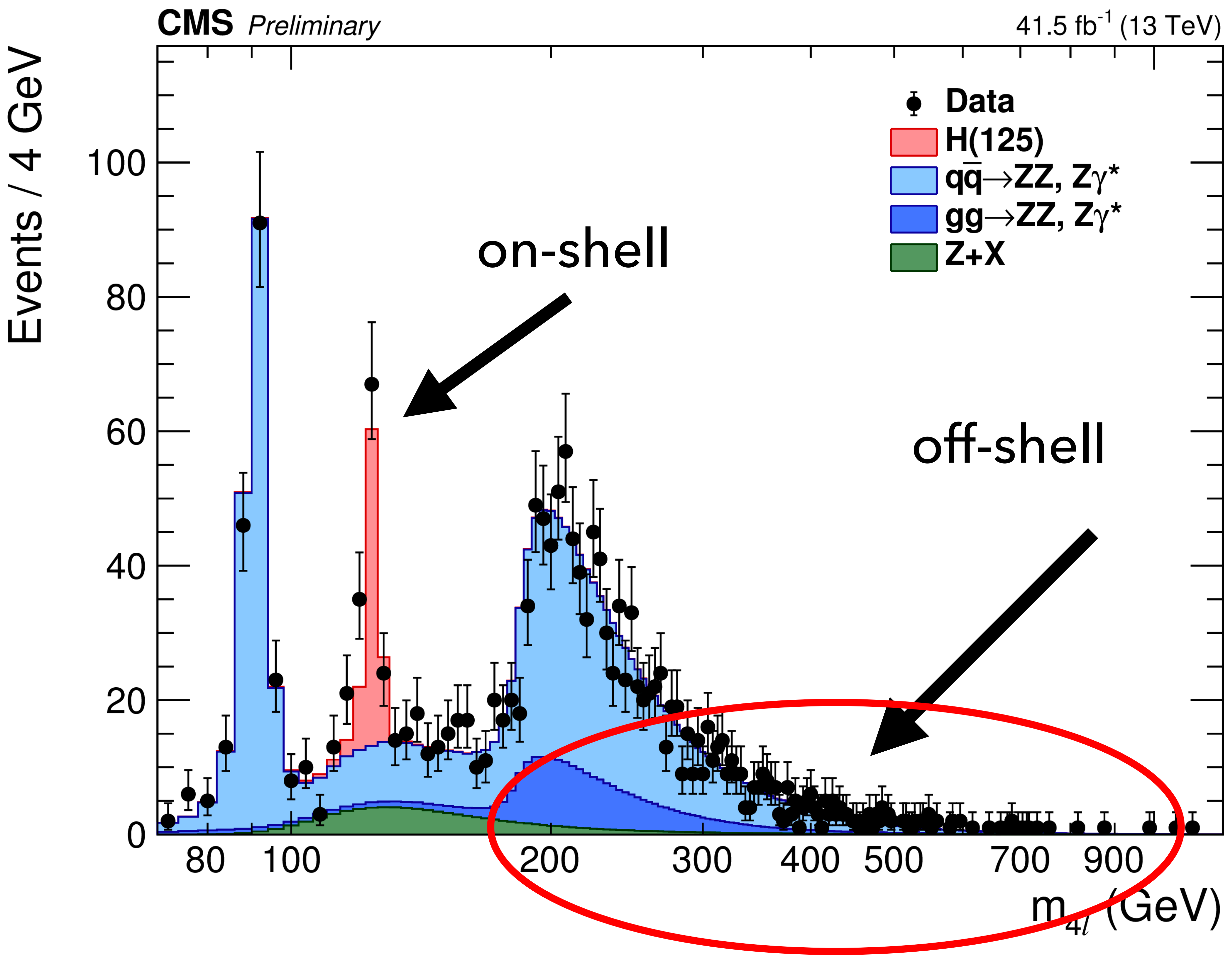
The measurement of the Higgs width uses off-shell production and interference — Quantum Mechanics at its best!

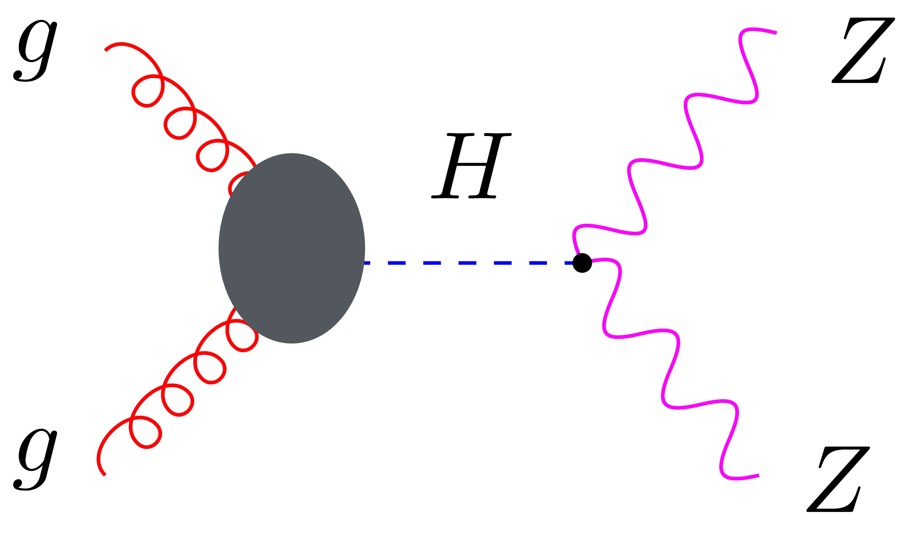
Large off-shell contribution

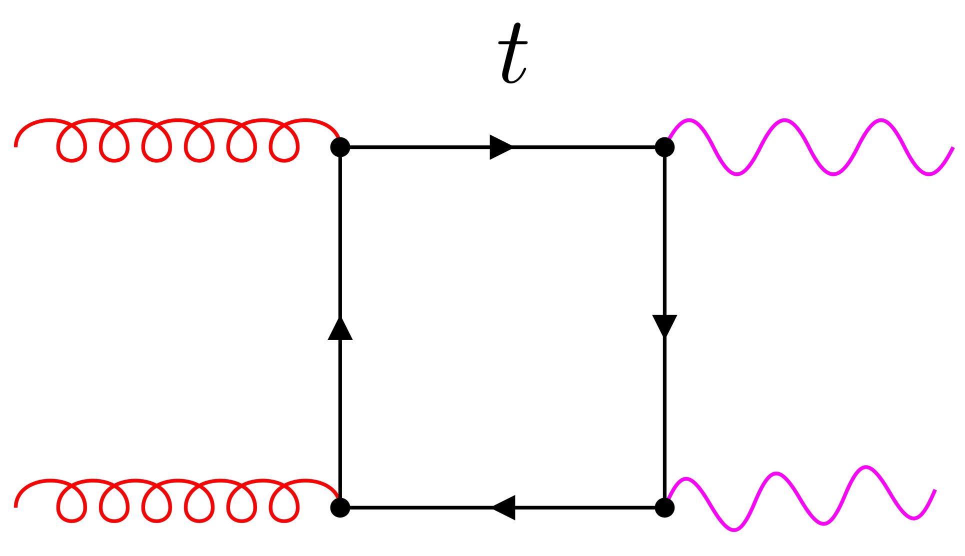
$$\sigma_{\text{on}} \sim \frac{g_G^2 g_Z^2}{m_H \Gamma_H} \qquad \sigma_{\text{off}} \sim \frac{g_G^2 g_Z^2}{m_H^2} \quad \Rightarrow \; \Gamma_H \sim \frac{\sigma_{\text{off}}}{\sigma_{\text{on}}} m_H$$

Small off-shell contribution; interference

$$\Delta\sigma_{\text{off}} \sim \frac{g_G g_Z}{m_H^2} \Rightarrow \Gamma_H \sim \frac{[\Delta\sigma_{\text{eff}}]^2 m_H^4}{m_H \sigma_{\text{on}}}$$







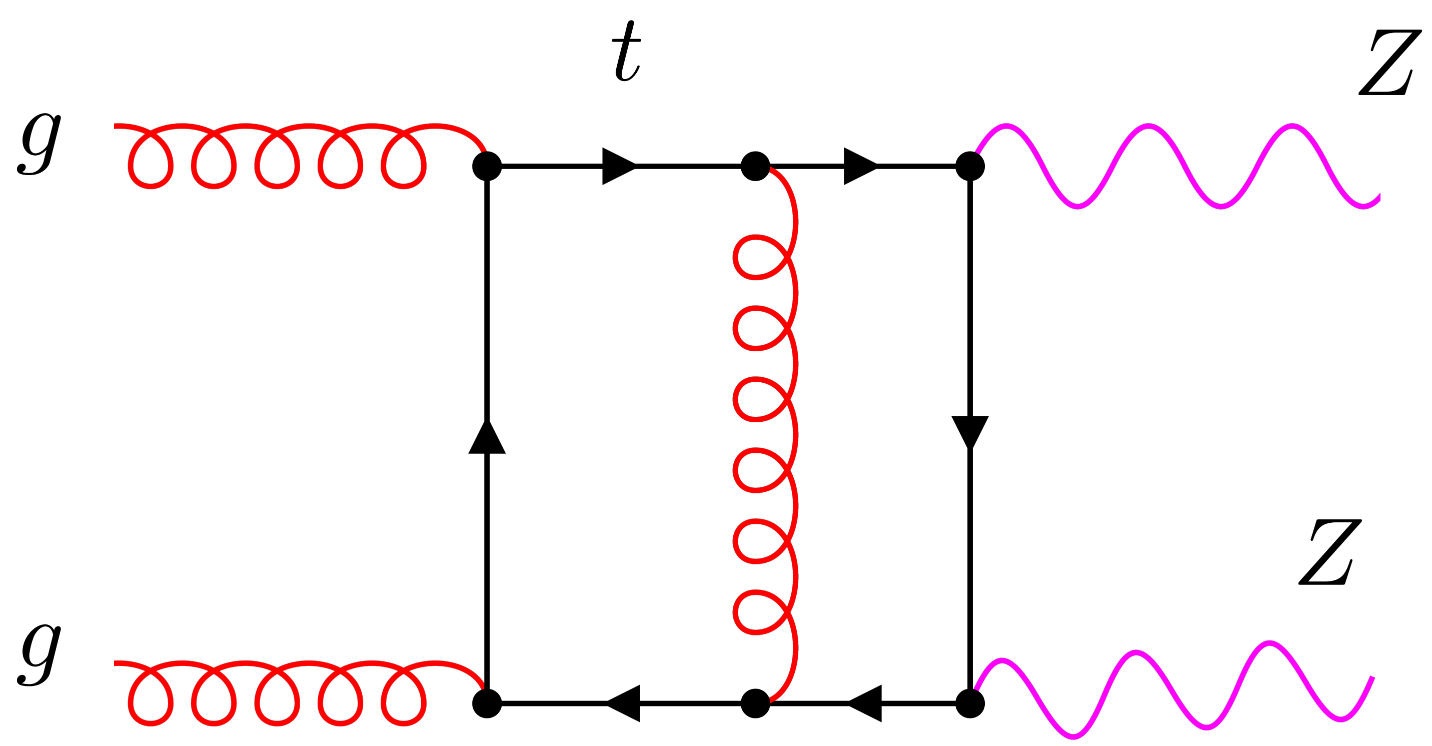
$\Gamma_H = 3.2^{+2.4}_{-1.7}$ MeV [ATLAS] $\qquad \Gamma_H = 4.5^{+3.3}_{-2.5}$ MeV [CMS]

$\Gamma_H = 4$ MeV [SM] $\qquad \Gamma_H < 1100$ MeV [Direct]

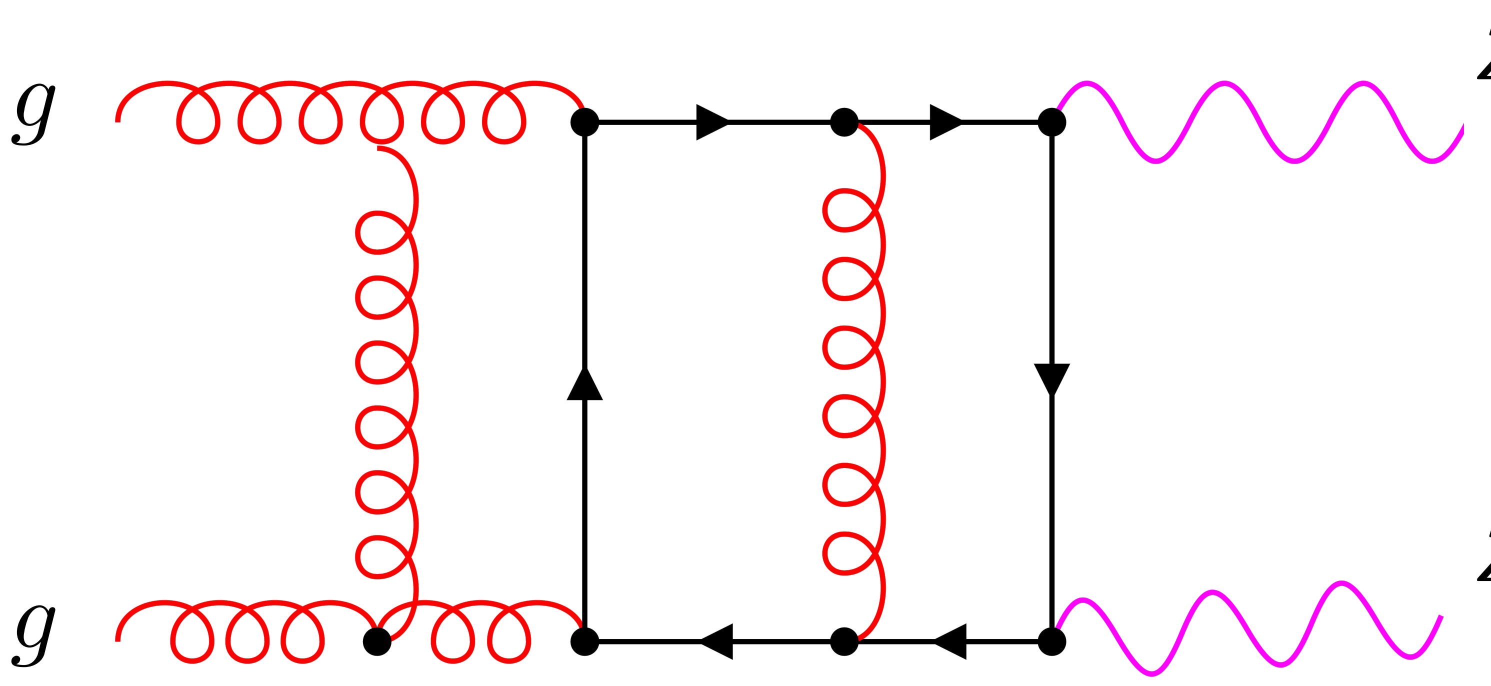
There are estimates that the HL-LHC should be able to extract the Higgs width with O(25) percent precision!

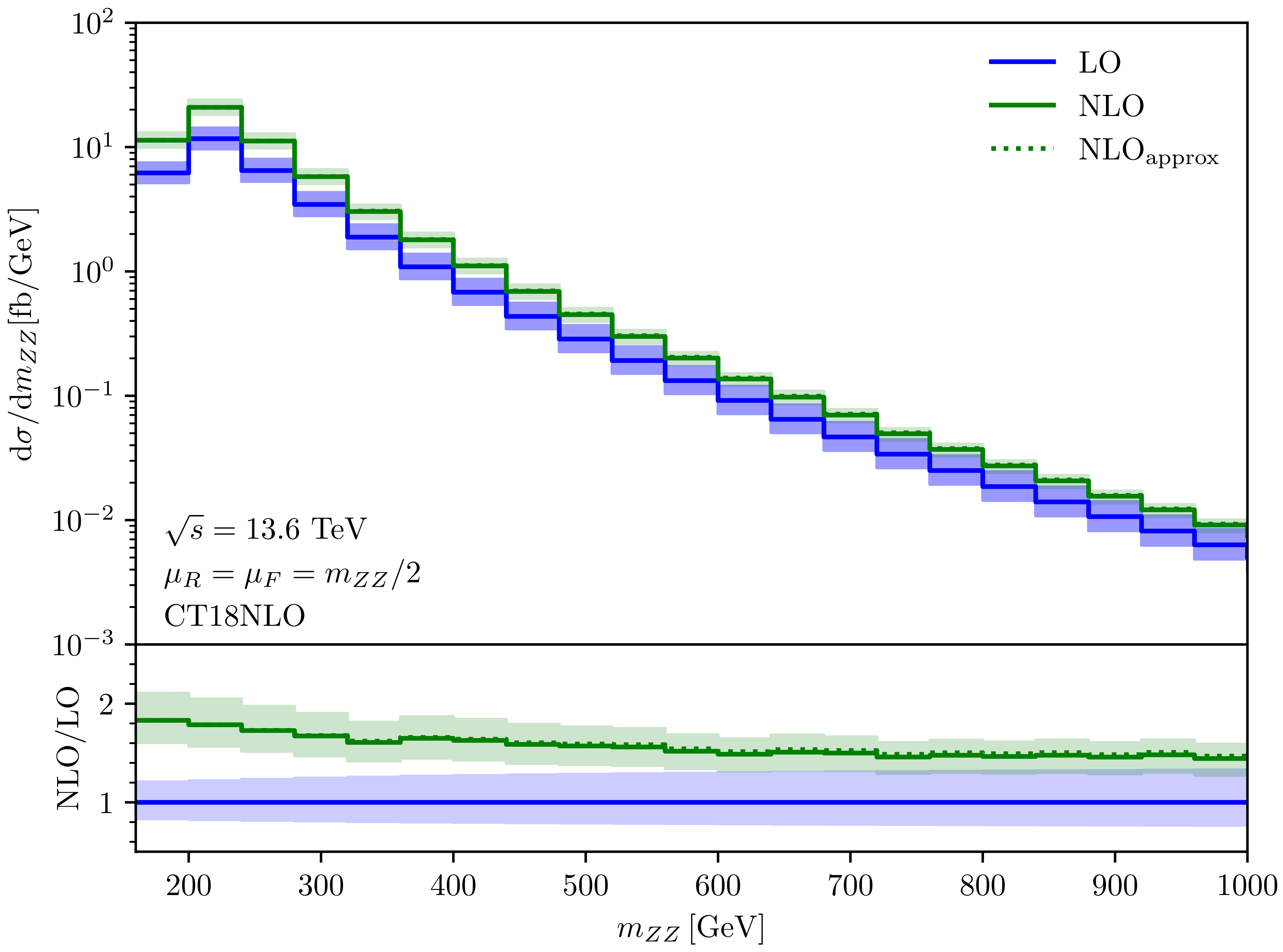
$\Gamma_H = 4 \pm 1$ MeV [HL-LHC goal]

To reach O(25) percent precision on the extracted width, significant theoretical progress is required. Just to for the calibration — note that the NLO (top quark loop) background computation was completed only recently because (two and more) massive loops is a problem. However, one will have to go one order higher (N3LO) and include electroweak effects. This is a hard problem but it is well defined, and it isn't a science fiction on the scale of a few years.



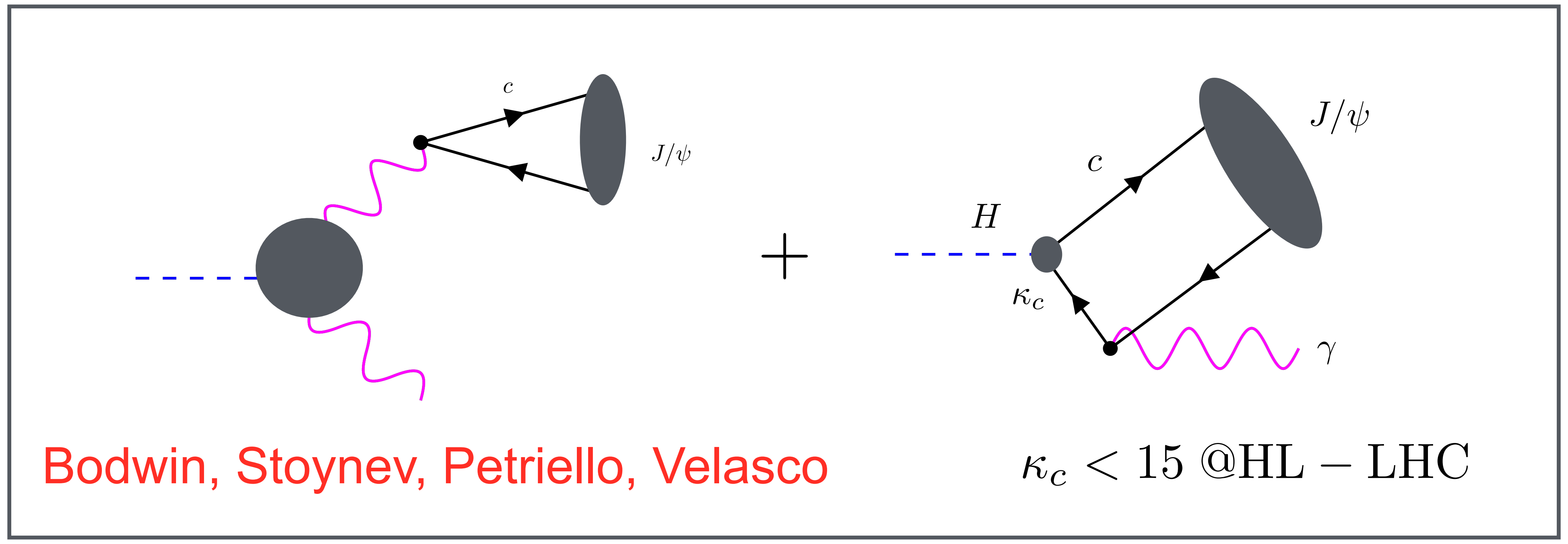
Agarwal, Jones, Kerner, von Manteuffel (2024)

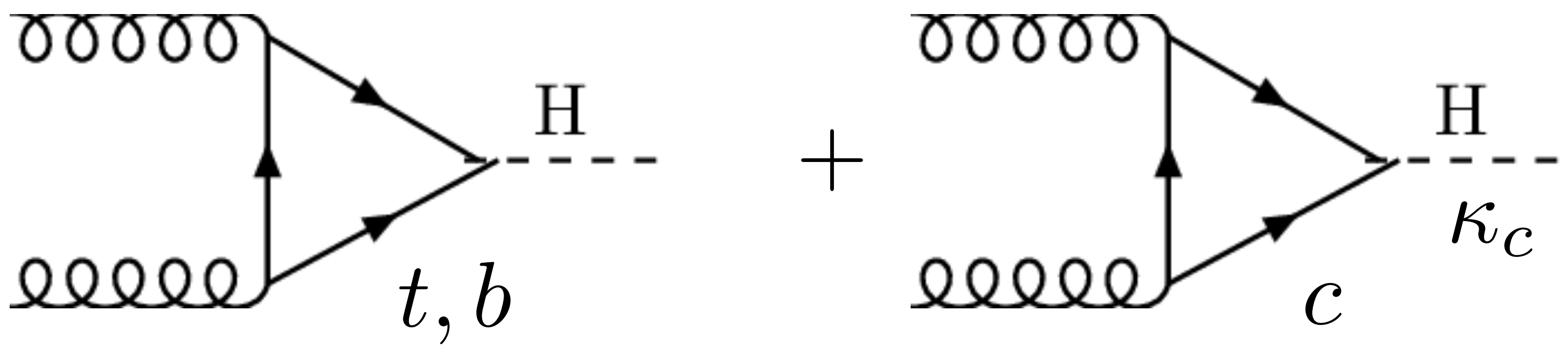




Agarwal, Jones, Kerner, von Manteuffel (2024)

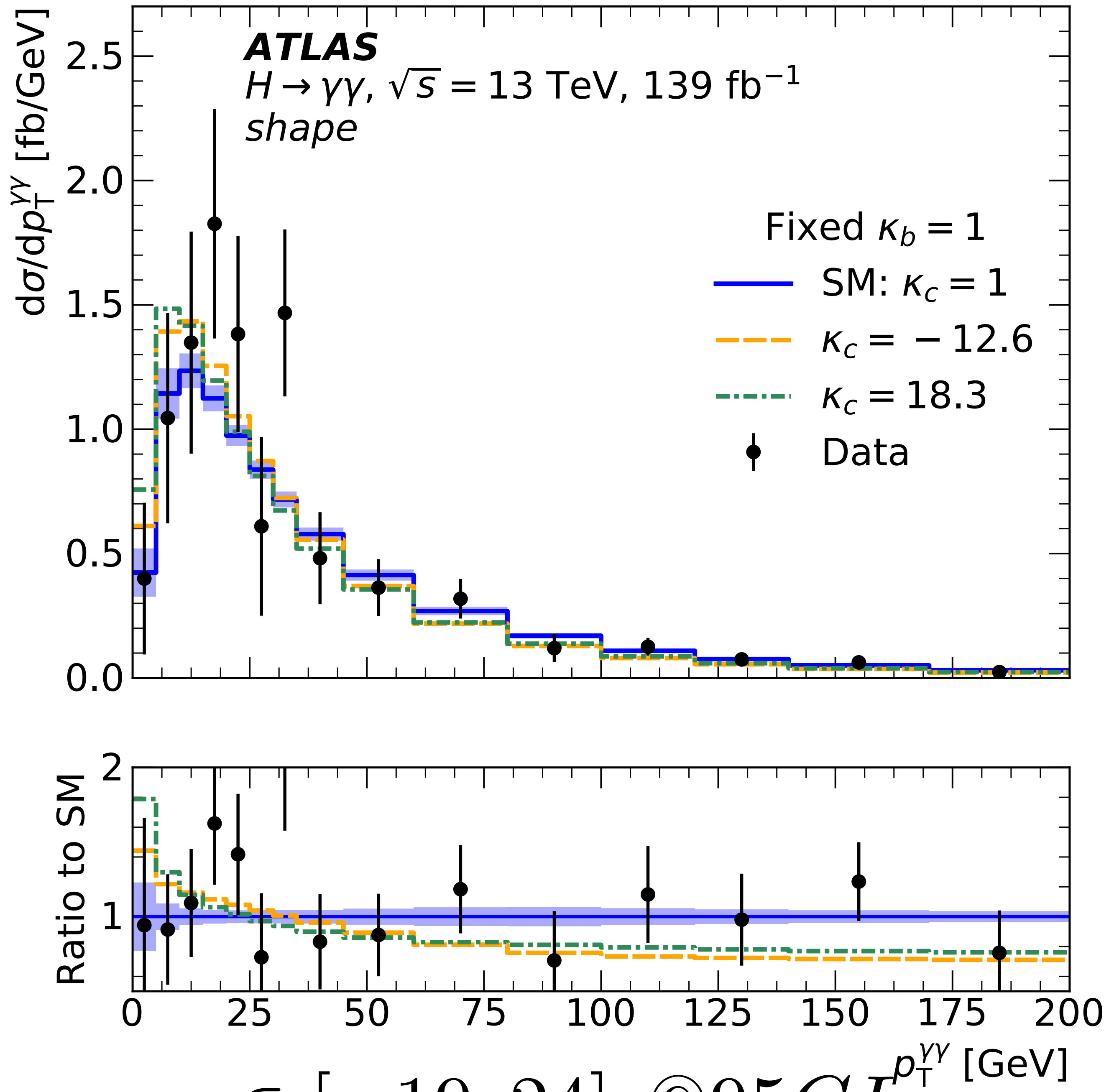
Another famous interference example is the story of the charm Yukawa measurement. It started as an interference of two ways to produce a J/psi and a photon in Higgs decays but evolved towards different ways to produce a Higgs in collisions of gluons.



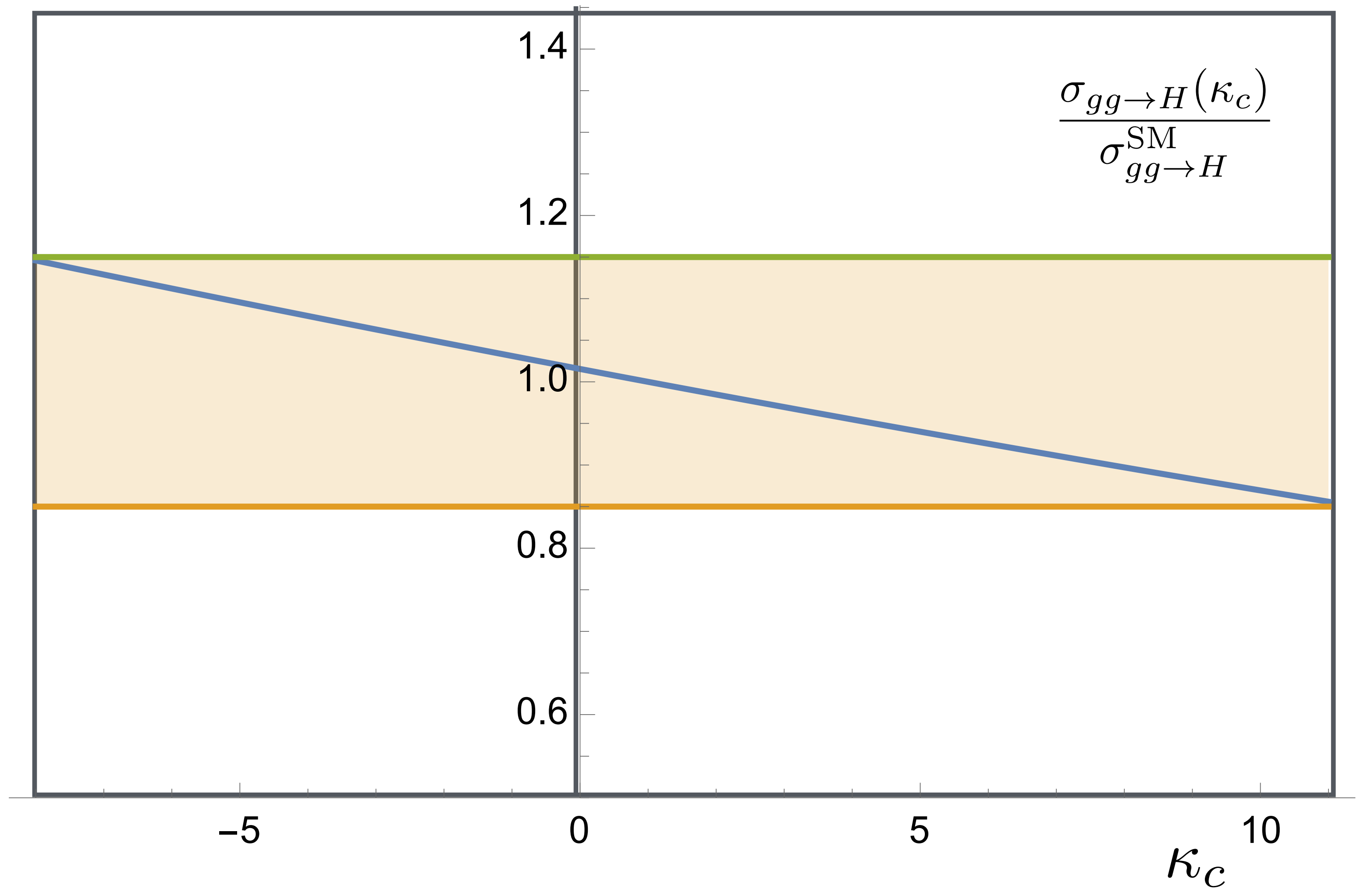


More details about this and other rare decays are in the talk by David d'Enterria

$$\frac{|\mathcal{A}_t + \mathcal{A}_c|^2}{|\mathcal{A}_t|^2} \approx 1 - \kappa_c \frac{3m_c^2}{m_t^2} \ln^2 \frac{m_H^2}{m_c^2} \approx 1 - 2\kappa_c \times 10^{-2}$$



$\kappa_c \in [-19, 24]$ @95CL



$\kappa_c \in [-8, 11]$ assuming a 5 percent (1 sigma) uncertainty on the ggH cross section

Interestingly, measuring the Higgs width to 25 percent at the LHC can also help to constrain the charm Higgs Yukawa coupling.

$$\Gamma_c < \Gamma_H - \Gamma_b - \Gamma_V$$

Imagine that from the couplings constraints, the width measurement and the SM calculations, we have

$$\frac{\Gamma_b}{\Gamma_H} = \left.\frac{\Gamma_b}{\Gamma_H}\right|_{\mathrm{SM}} \approx 0.58 \qquad \frac{\Gamma_V}{\Gamma_H} = \left.\frac{\Gamma_V}{\Gamma_H}\right|_{\mathrm{SM}} \approx 0.31 \qquad \Gamma_c = 3 \ \times 10^{-2}\Gamma_{\mathrm{SM}}\ \kappa_c^2$$

With the current constraint on the width, one gets a similar constraint on the charm Yukawa coupling that what is expected to be achieved at the HL-LHC $(\kappa_c < 3)$.

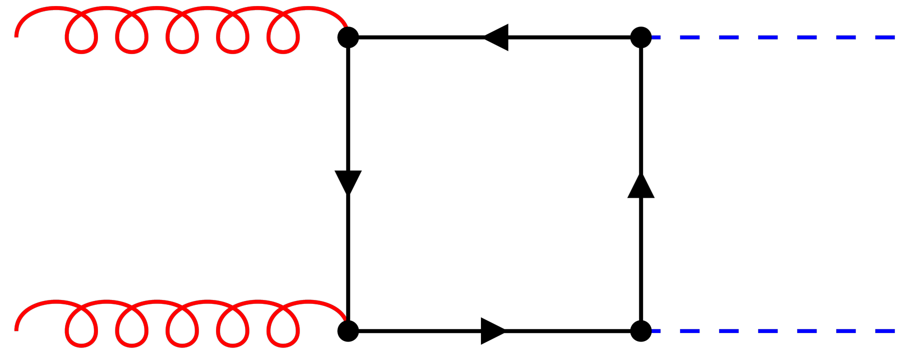
$$\Gamma_H = 4.5^{+3.3}_{-2.5}\ \mathrm{MeV} \qquad \Gamma_H < 3\Gamma_{\mathrm{SM}} \quad \Leftrightarrow \quad \kappa_c^2 < 11 \ \Rightarrow \kappa_c < 3.3$$

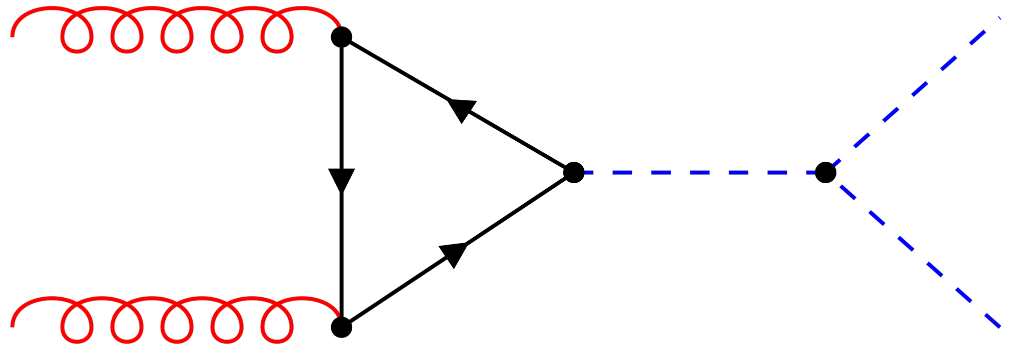
If the HL width measurement constraint is reached, the limit on charm Yukawa becomes even stronger

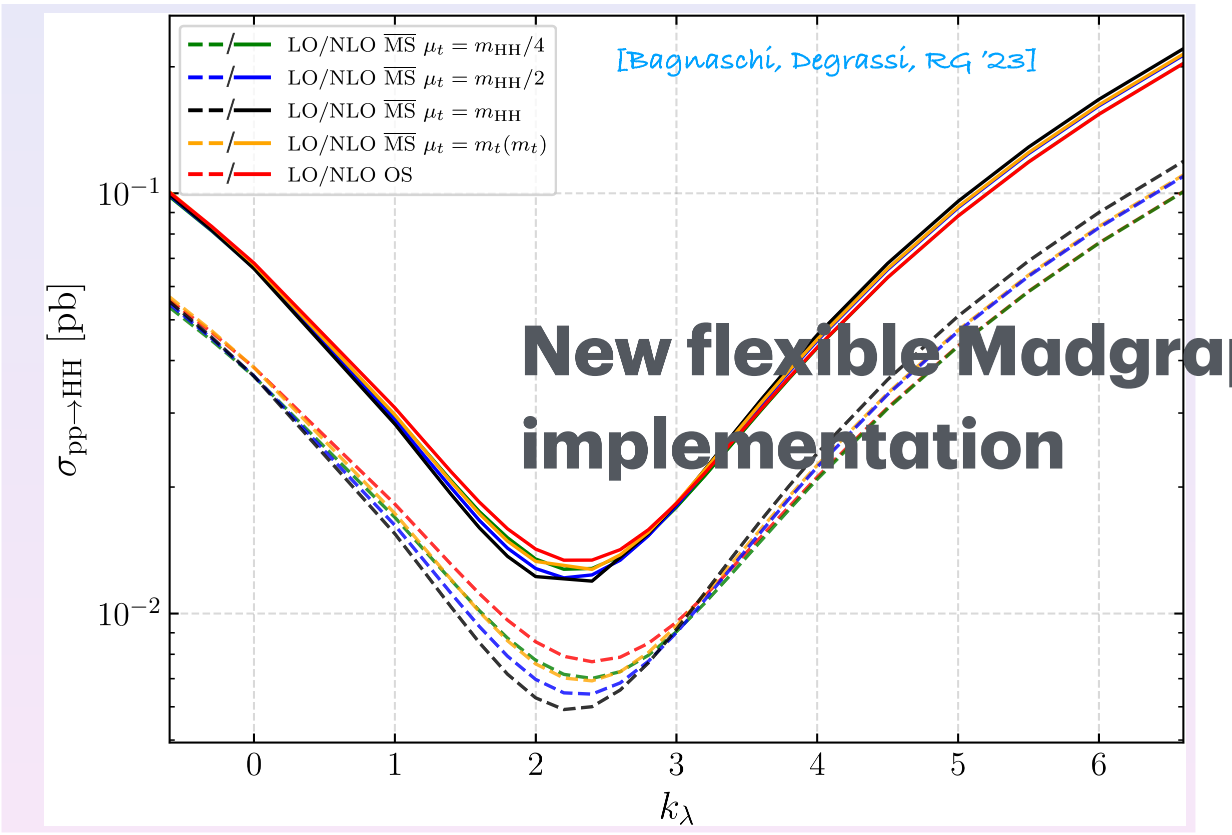
$$\kappa_c < 2.7$$

An important question about the symmetry breaking caused by the Higgs field is whether its self-interaction is as predicted by the Standard Model (which we said looks very simplistic). At the LHC this question can be studied in the process where two Higgs bosons are produced.

Talk by Ramona Groeber

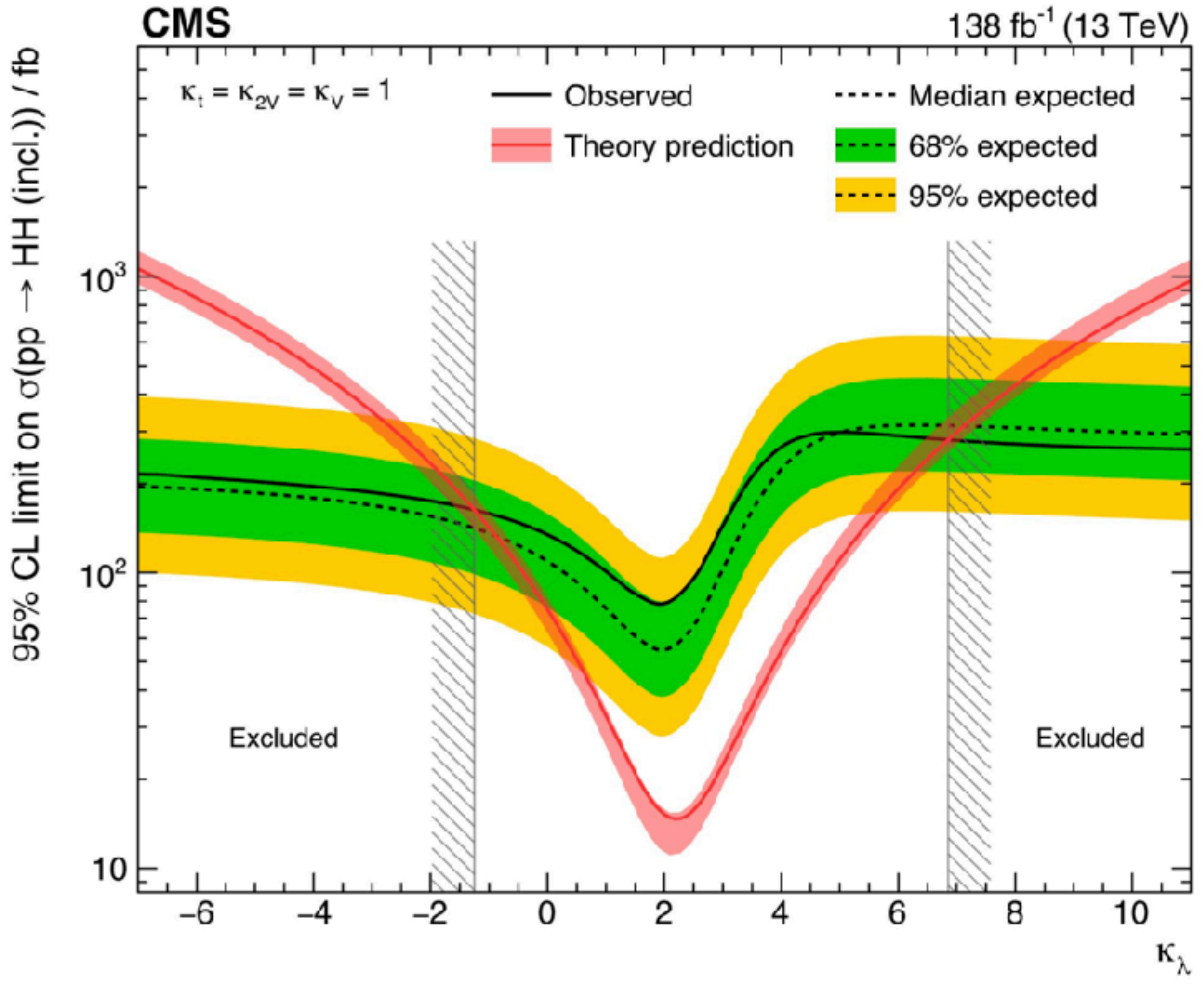




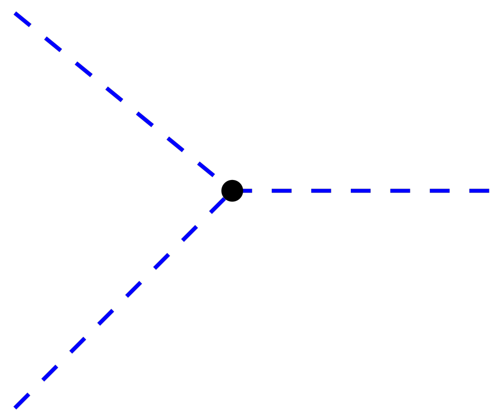


New flexible Madgraph implementation

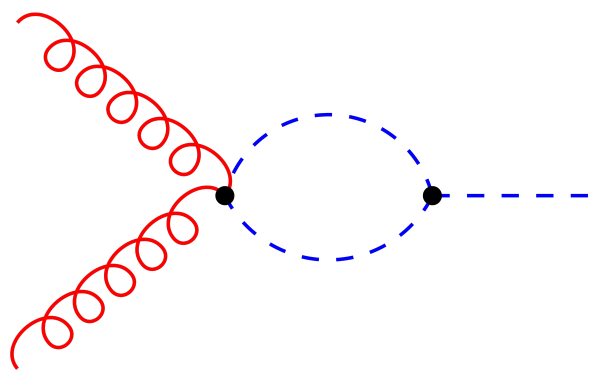
These two amplitudes interfere destructively, so that they exactly cancel at the threshold, in the infinite top quark limit. As the result, limits on Higgs tri-linear coupling are asymmetric; it easier to exclude negative ones.



$$\mathcal{L} = \frac{\alpha_s}{12\pi} G^a_{\mu\nu} G^{a,\mu\nu} \ln\left(1 + \frac{h(x)}{v}\right)$$



$$-3i\frac{m_H^2}{v}\kappa_\lambda$$

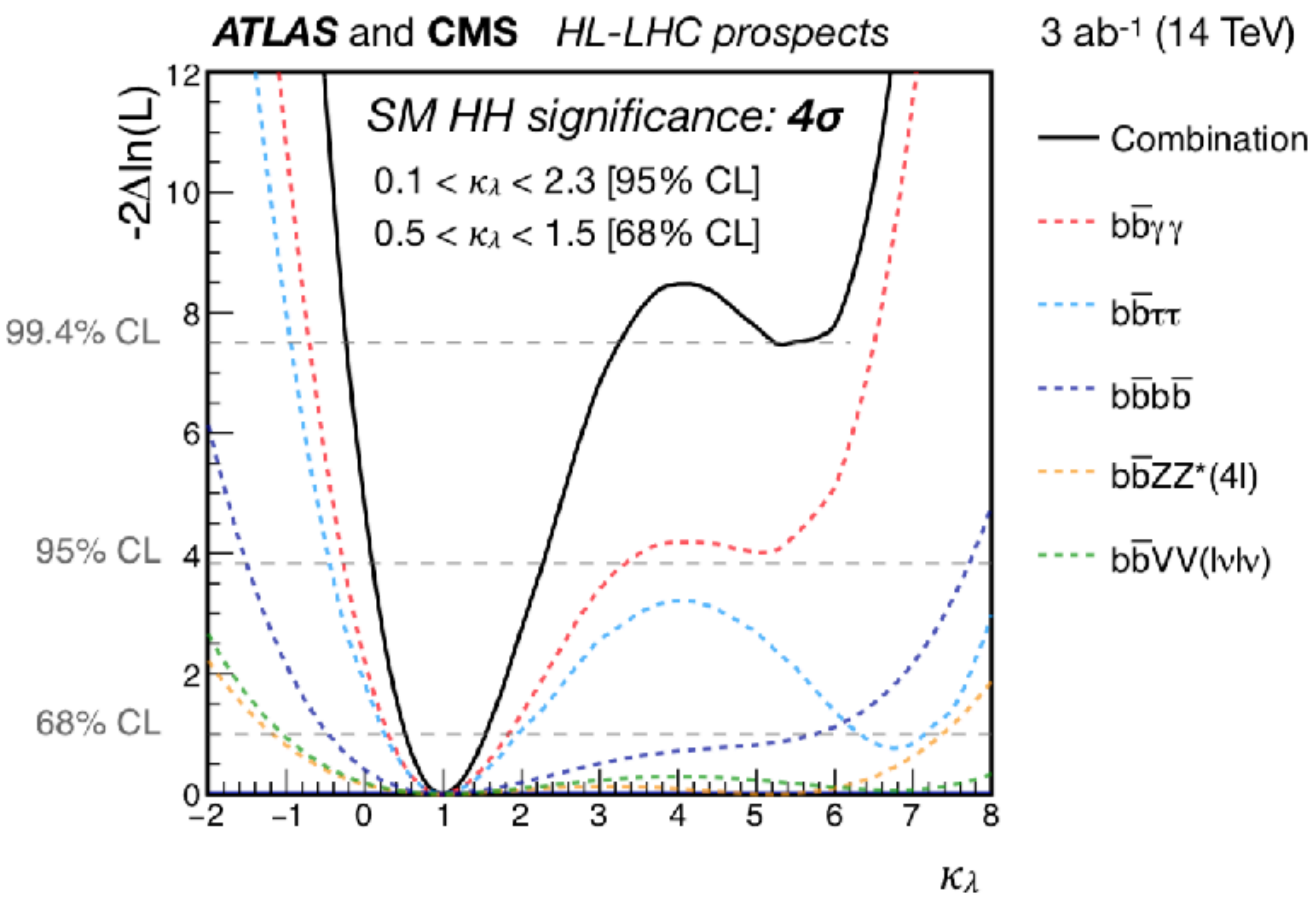


$$\mathcal{M}_{gg\to H} = \mathcal{M}^{(0)}_{gg\to H}\left(1 + \kappa_\lambda c_1 \frac{3m_H^2}{(4\pi)^2 v}\right) \approx \mathcal{M}^{(0)}_{gg\to H}\left(1 + 5\kappa_\lambda c_1 \times 10^{-3}\right)$$

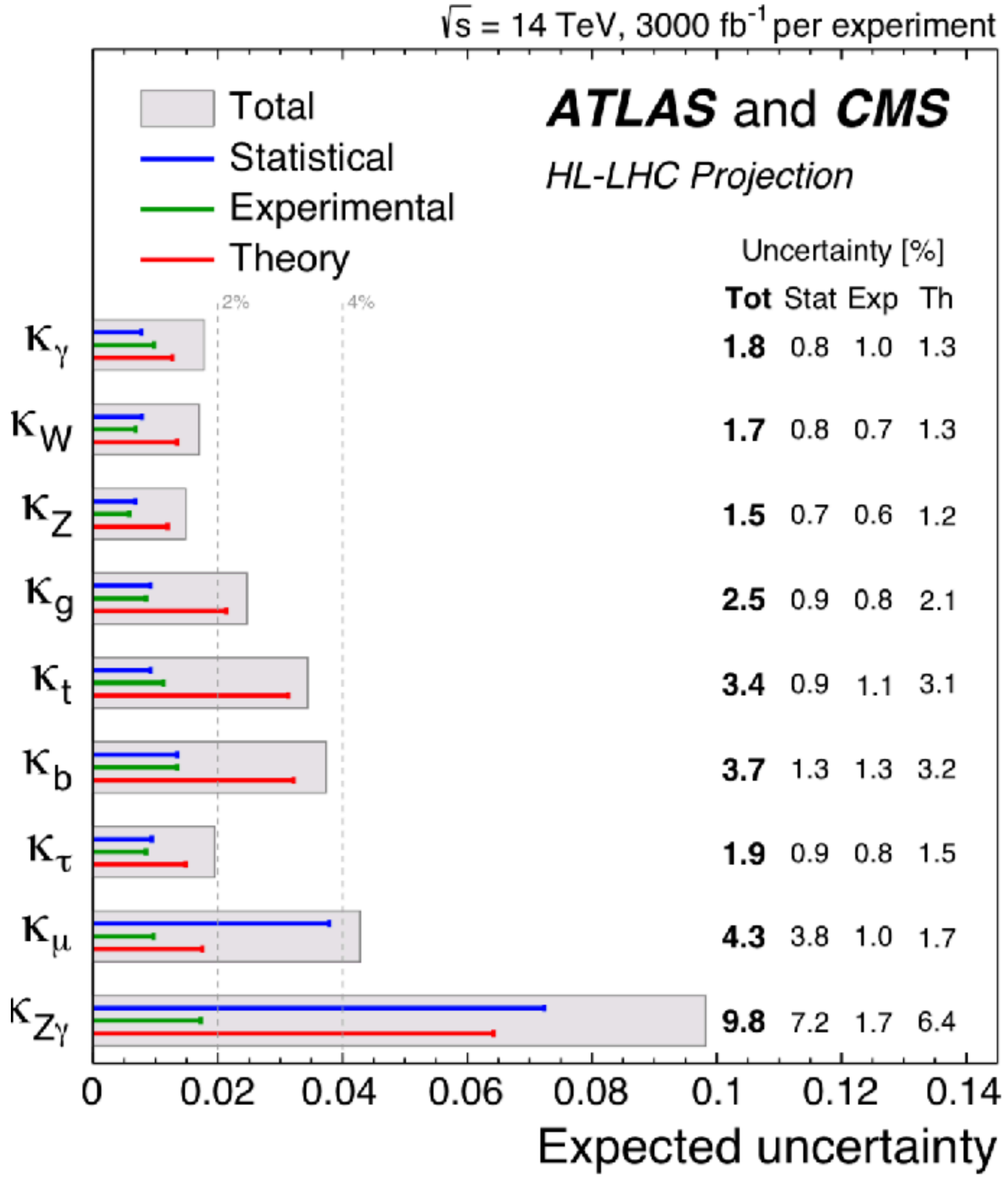
CMS $-1.24 < \kappa_\lambda < 6.49$

Expected interval similar

At the HL-LHC the Higgs self-coupling will be measured to about 50 percent and many other couplings to a few percent. **Or, much more dramatic things can happen — see talk by Yevgeny Kats.**



Is it possible to have models where Higgs self-coupling is very different from the SM but all other couplings are close to it?

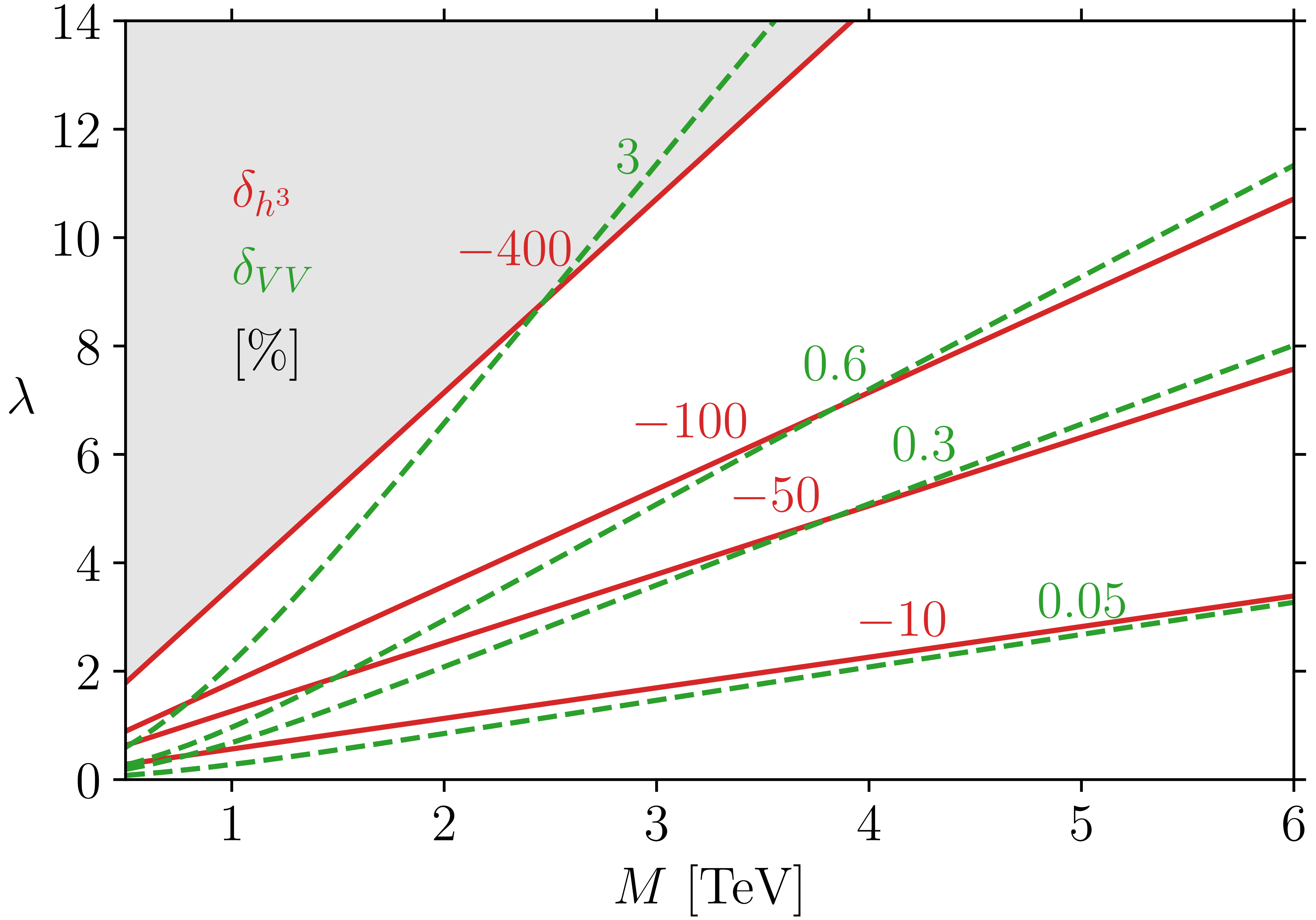


TH Uncertainties dominant (assumed to be 1/2 of Run 2)

What should one do with this precision?

It is possible to have extensions of the SM where BSM effects in the Higgs trilinear couplings are much larger than in the other ones. Hence, even if couplings of H to vector bosons etc. are strongly constrained, it is still worth investigating if Higgs trilinear coupling is properly described by the SM.

Custodial quadruplet model

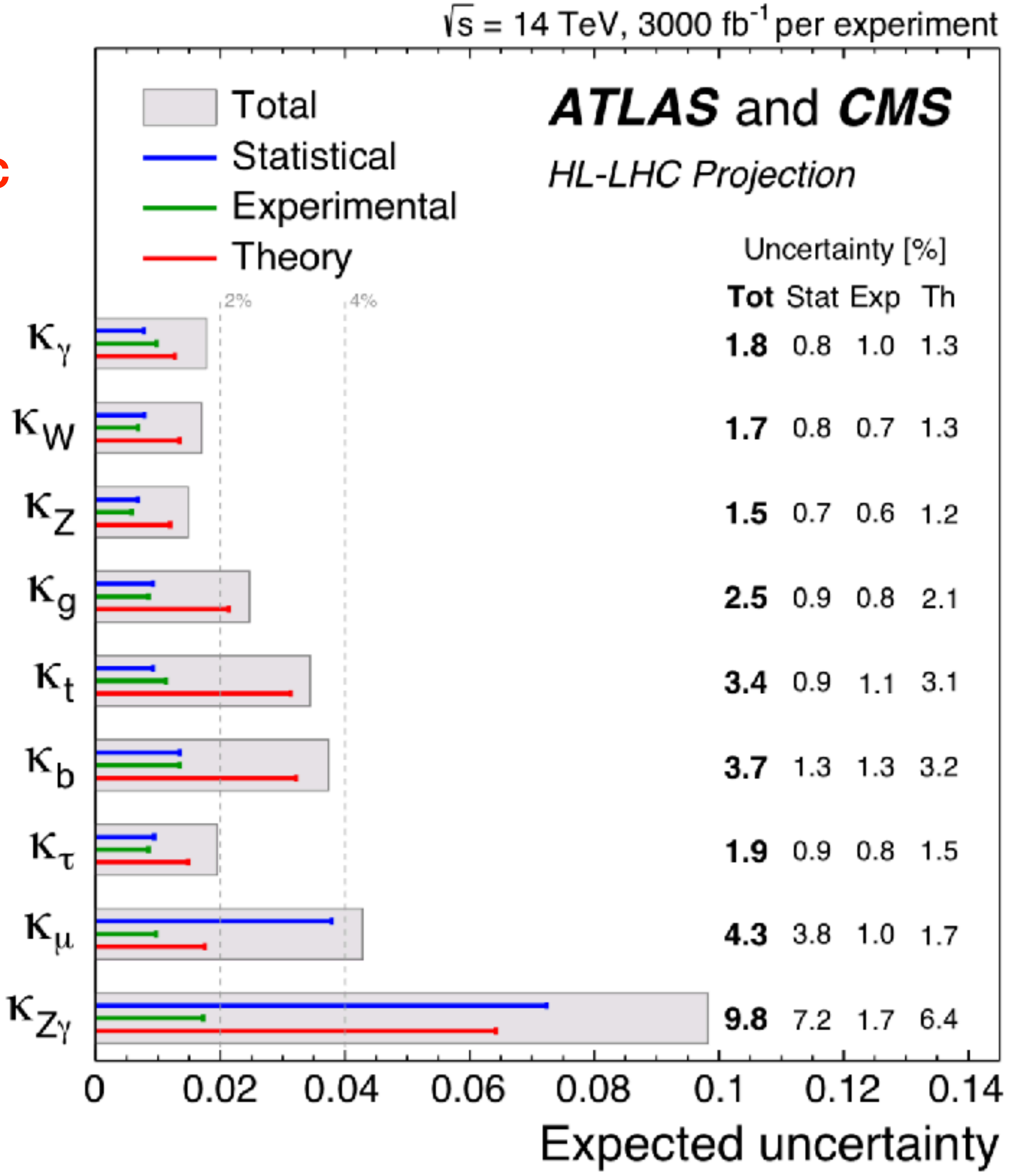


Durieux, McCullough, Salvioni

$$-\frac{\delta_{VV}}{\delta_{h^3}} = 3\left(\frac{m_h}{4\pi v}\right)^2 + \left(\frac{m_h}{M}\right)^2 \approx \frac{1}{200} + \frac{1}{580}\left(\frac{3\text{ TeV}}{M}\right)^2$$

What is the right framework to extract maximal informations from the planned studies of the HIggs boson?

	ATLAS - CMS Run 1 combination	ATLAS Run 2	CMS Run 2	Current precision	HL-LHC
κ_γ	13%	1.04 ± 0.06	1.10 ± 0.08	6%	1.8%
κ_W	11%	1.05 ± 0.06	1.02 ± 0.08	6%	1.7%
κ_Z	11%	0.99 ± 0.06	1.04 ± 0.07	6%	1.5%
κ_g	14%	0.95 ± 0.07	0.92 ± 0.08	7%	2.5%
κ_t	30%	0.94 ± 0.11	1.01 ± 0.11	11%	3.4%
κ_b	26%	0.89 ± 0.11	0.99 ± 0.16	11%	3.7%
κ_τ	15%	0.93 ± 0.07	0.92 ± 0.08	8%	1.9%
κ_μ	-	$1.06^{+0.25}_{-0.30}$	1.12 ± 0.21	20%	4.3%
$\kappa_{Z\gamma}$	-	$1.38^{0.31}_{-0.36}$	1.65 ± 0.34	30%	9.8%
B_{inv}		$< 11\,\%$	$< 16\,\%$	11%	2.5%
		Nature 607, 52-59 (2022)	Nature 607, 60-68 (2022)		



TH Uncertainties dominant (assumed to be 1/2 of Run 2)

Lectures by Marumi Kado at Maria Laach Summer School, 2024.

A common answer these days is to use effective field theory parametrization of the BSM physics.

The central idea of EFTs is that unknown physics at high energy scales is parametrized by an infinite number of local operators in the low-energy Lagrangian; the only requirement that we impose on this Lagrangian is that it is invariant under symmetries of our choosing (e.g. the SM gauge group).

Talks by Tevong You and John Gargalionis

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \sum_\lambda \frac{c_\lambda}{\Lambda^{n_\lambda}} \mathcal{O}^{\lambda,n}$$

EFTs give up on the renormalizability of the SM. This is a direct consequence of saying that the SM is incomplete theory, there is nothing modern or not-so-modern in this step. I suppose that at the end of the day the fundamental theory that we are after has to be either finite or renormalizable or it cannot be reconstructed.

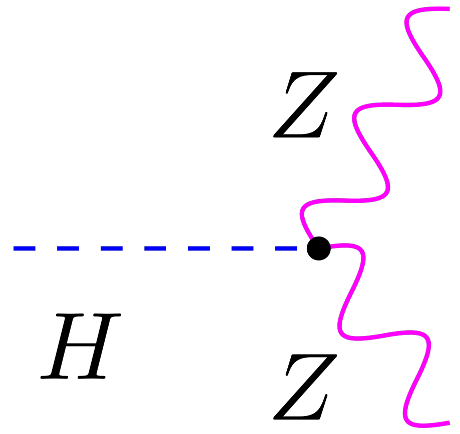
Interest in EFTs stems from the fact that current and even future LHC precision in Higgs physics allows us to probe "reasonable" deviations from the SM using this framework..

For an on-shell perspective on EFTs, see a talk by Lance Dixon

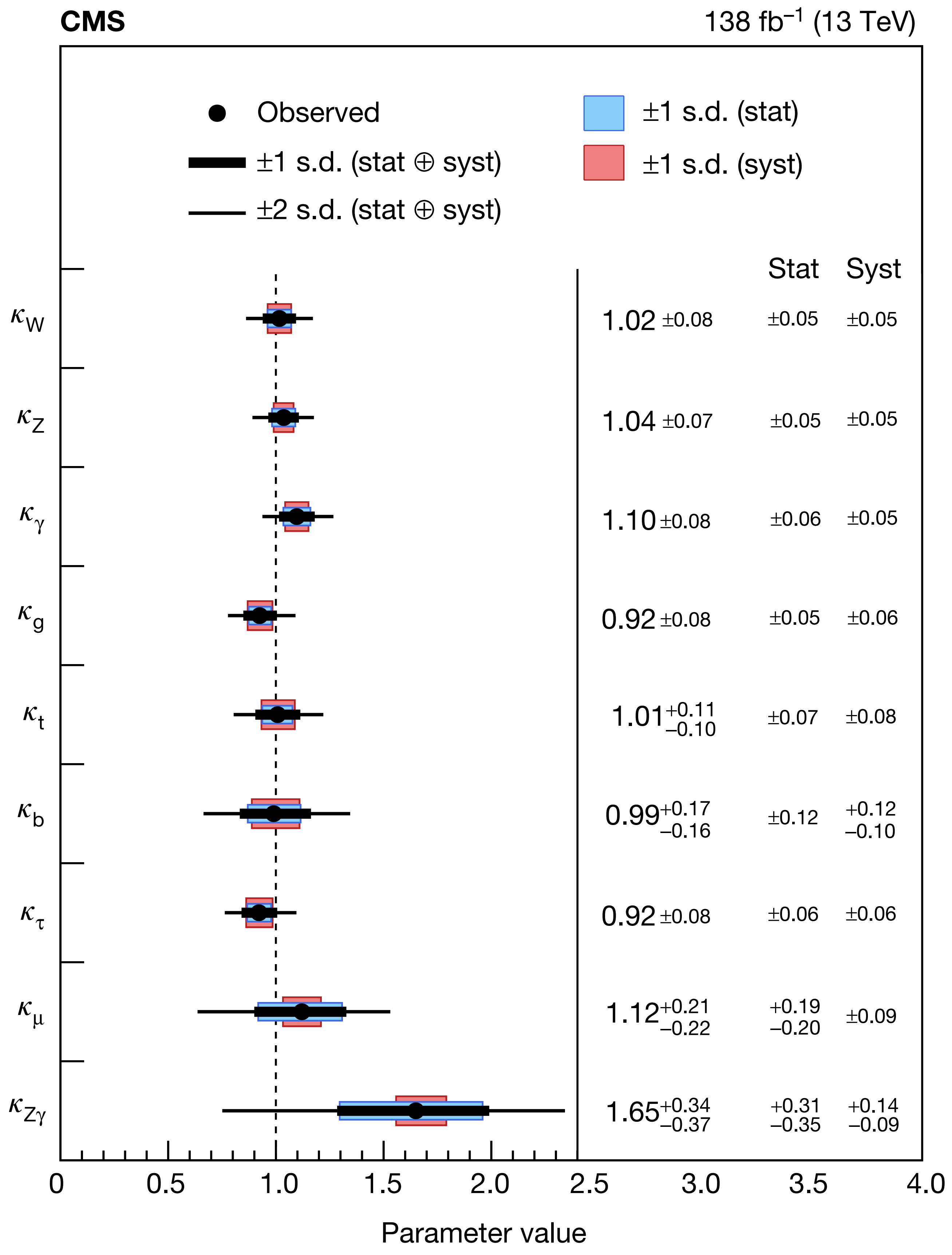
Precision measurements can be used to constrain possible BSM contributions and the scale of New Physics. To see how this works let us add one operator to the Standard Model (not motivated but easy to understand what is going on.)

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{c_H}{2\Lambda^2}\left[\partial_\mu \Phi^+ \Phi\right]\ \left[\partial^\mu \Phi^+ \Phi\right] \qquad \Phi = \begin{pmatrix} 0 \\ \frac{v+h}{\sqrt{2}} \end{pmatrix}$$

$$\frac{c_H}{2\Lambda^2}\left[\partial_\mu \Phi^+ \Phi\right]\ \left[\partial^\mu \Phi^+ \Phi\right] \Rightarrow \frac{c_H v^2}{2\Lambda^2}\,\partial_\mu h\,\partial^\mu h \qquad h \to \left(1 + \frac{c_H v^2}{\Lambda^2}\right)^{-1/2} h$$



$$\frac{i g m_Z}{\cos\theta_W}\left(1 - \frac{c_H v^2}{2\Lambda^2}\right) g_{\mu\nu} \qquad \kappa_Z = 1 - \frac{c_H v^2}{2\Lambda^2}$$

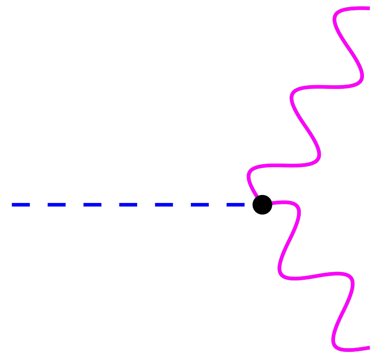


$$M_{\rm new} \sim g_* \Lambda \Rightarrow \begin{cases} M_{\rm new} \sim 0.3\ \text{TeV}, & g_* \sim 0.3\ \text{QED} \\ M_{\rm new} \sim 1\ \text{TeV}, & g_* \sim 1\ \text{QCD} \end{cases}$$

The precision improvement at the HL -LHC will lead to

$$M_{\rm new} \sim 1.5\ \text{TeV}$$

However, we can add another operator and it will also modify the HZZ interaction strength.

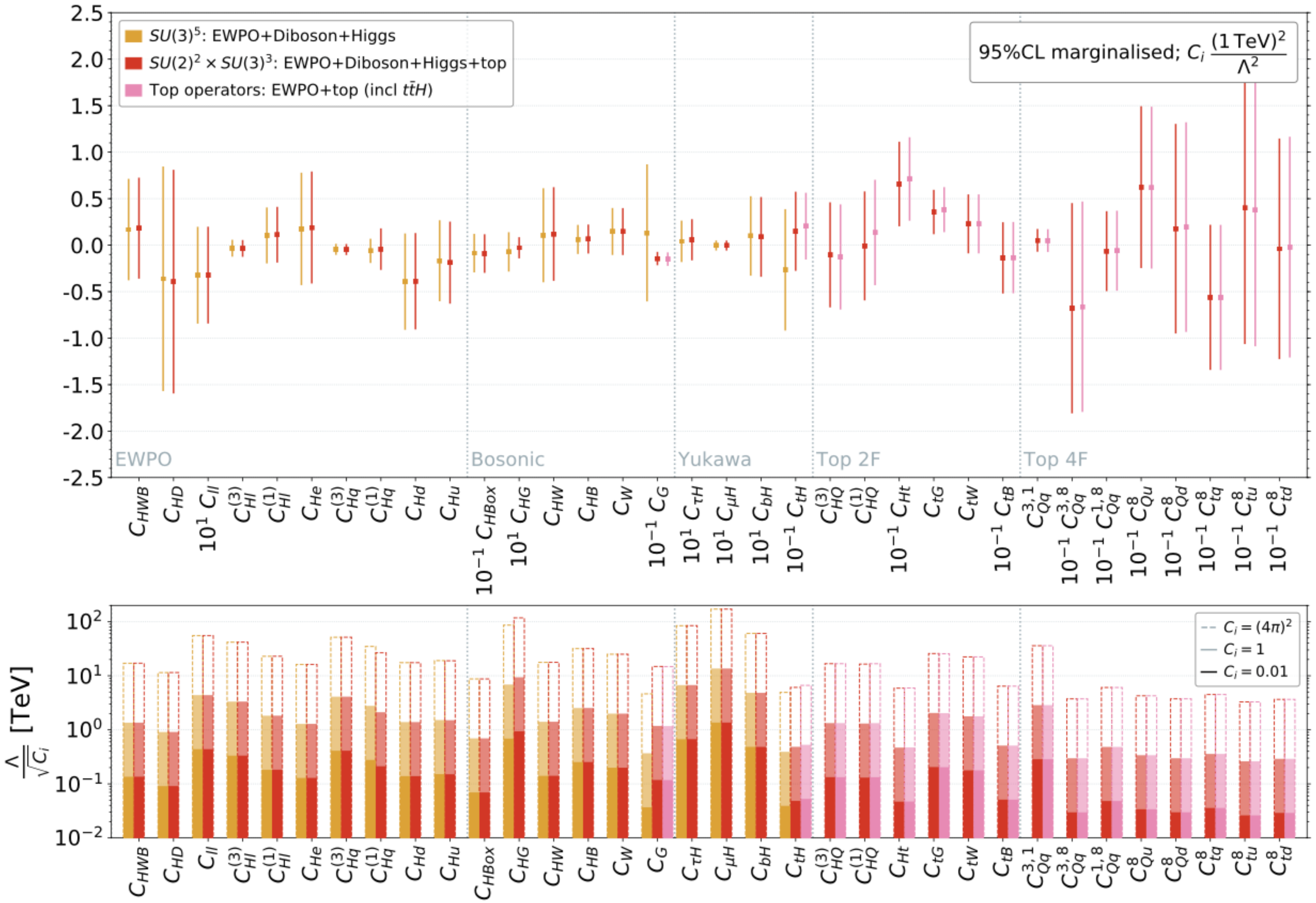


$$\frac{\phi^+\phi}{\Lambda^2}\, W^a_{\mu\nu} W^{a,\mu\nu} \to \frac{v}{\Lambda^2}\left(k_1 k_2 g_{\mu\nu} - k_1^\nu k_2^\mu\right)$$

The two operators can be disentangled by considering Higgs boson decay to ZZ and the associated production. The art of EFT studies is to find ways to do this for as many operators as possible in a consistent way.

Given that one has to deal with O(50) operators at once, this becomes a very complex endeavour that cannot be solved without global fits. However, even the results of global fits at this point do not look very enlightening.

Experimental constraints on SMEFT from LEP electroweak observables and LHC measurements:



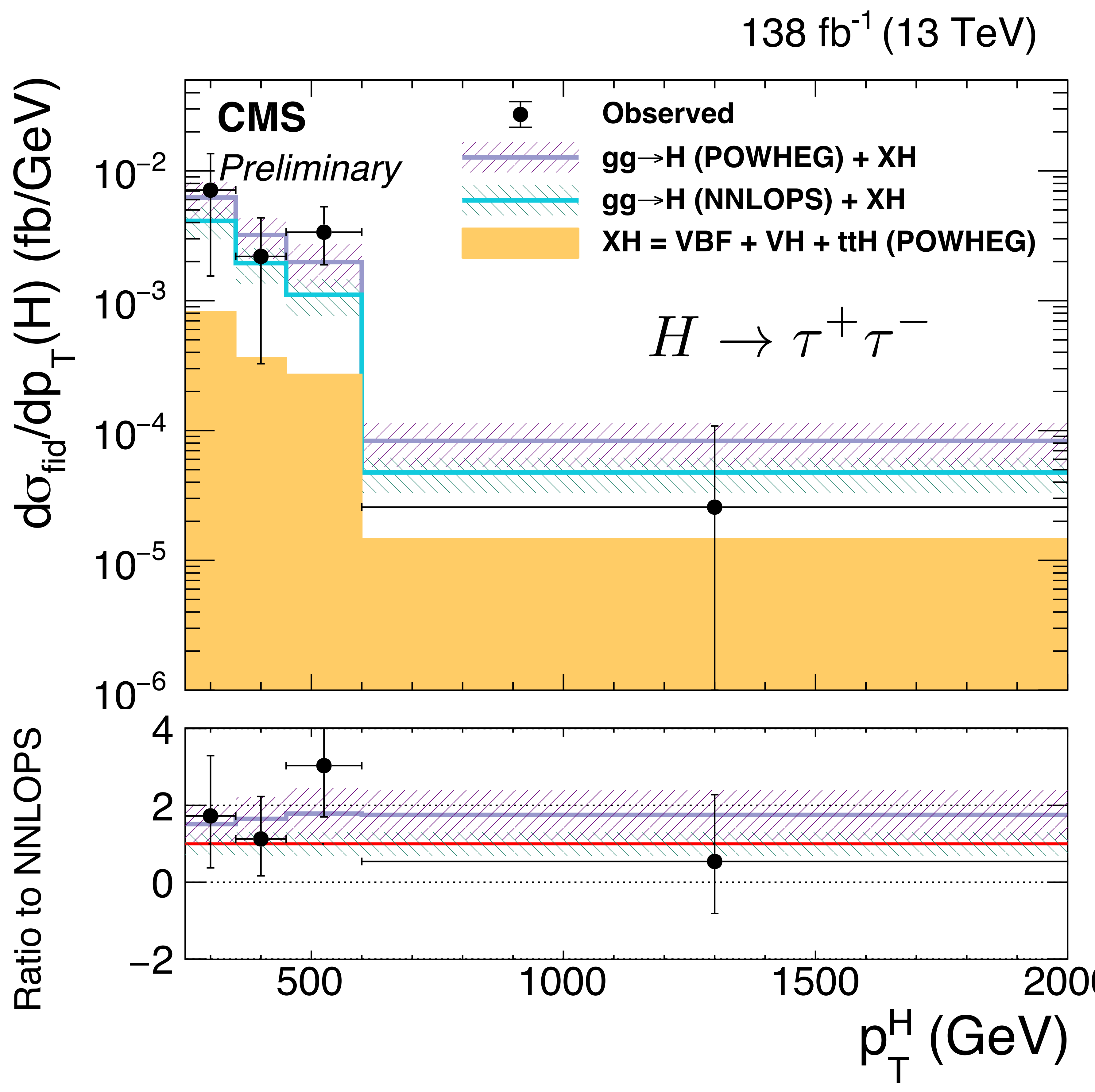
2012.02779 Ellis, Madigan, Mimasu, Sanz, TY

See also other recent global fits, e.g.
2311.00020 Allwicher, Cornella, Isidori, Stefanek
2311.04963 Bartocci, Biekotter, Hurth
2404.12809 SMEFiT collaboration

Marginalised (all operators allowed to vary simultaneously) 95% CL bounds.

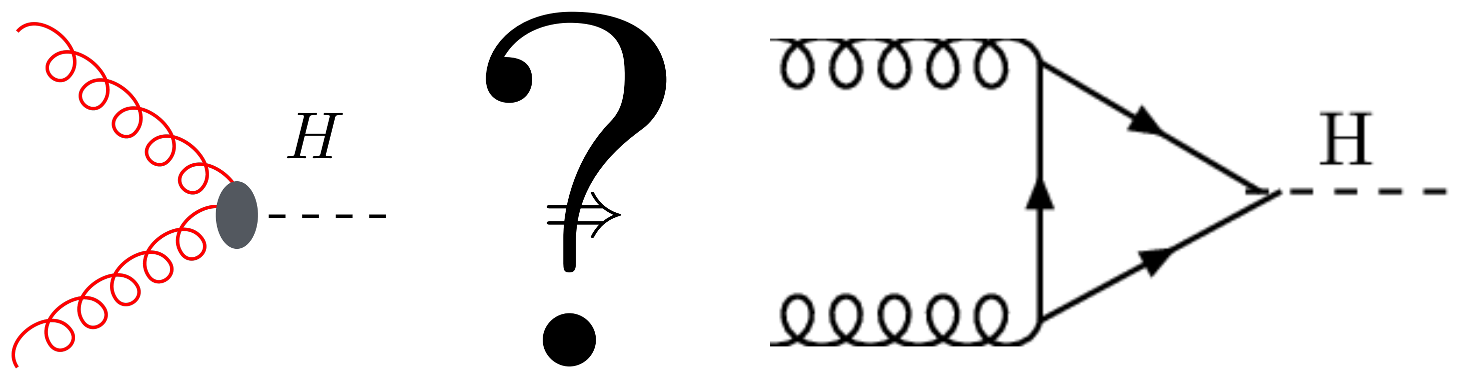
Slide from Tevong You's talk

Measurements of Higgs production at high transverse momentum are very interesting from the BSM/EFT viewpoint. Such measurements are still statistically limited but we do not see very large deviations which tells us that the Higgs is indeed produced through a top quark loop, without substantial ultra-short-range component.



$$p_{\perp,H} > 250 \text{ GeV}$$

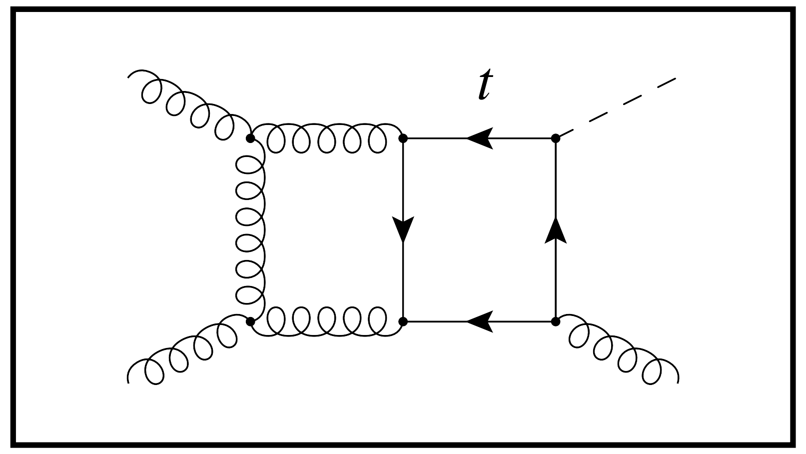
$$\mathrm{d}\sigma_{\text{fid}} = 1.96^{+0.86}_{-0.69} \text{ fb} \quad \mathrm{d}\sigma_{\text{fid,SM}} = 1.2 \pm 0.2 \text{ fb}$$



Talk by S. Jones

HJ production known to NLO including m_t

Kudashkin, (Lindert), Melnikov, Wever 17, (18); SPJ, Kerner, Luisoni 18, 21; Neumann 18; Bonciani, Del Duca, Frellesvig, Hidding, Hirschi, Moriello, Salvatori, Somogyi, Tramontano 22;



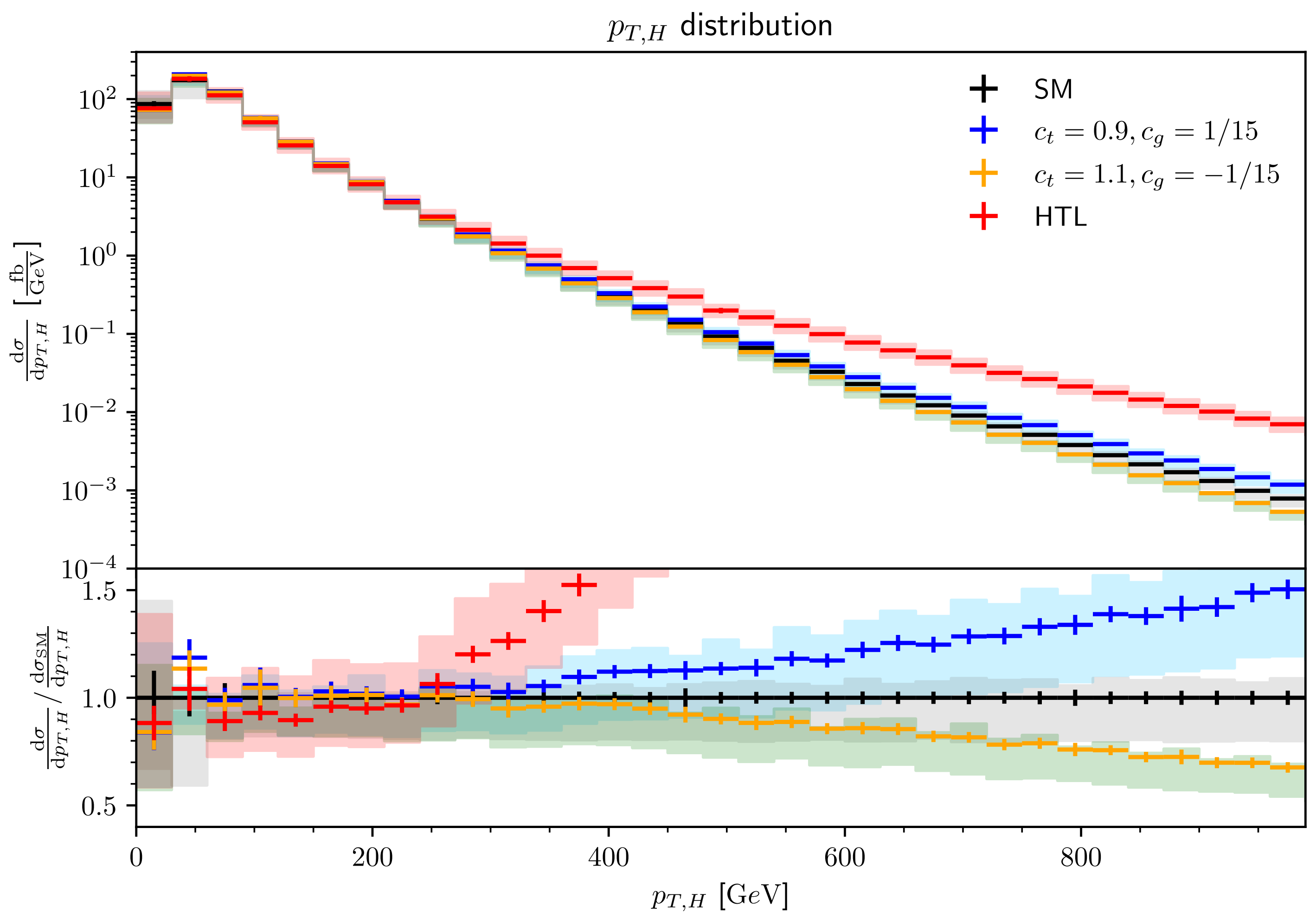
Recent study of impact of anomalous top-Yukawa (c_t) and Higgs-gluon contact interactions (c_g) in HEFT

$$\mathscr{L} \supset c_t m_t \frac{H}{v} \bar{t}t + \frac{\alpha_s}{8\pi} c_g \frac{H}{v} G^a_{\mu\nu} G^{a,\mu\nu}$$

Found scenarios where BSM effects only exceed scale uncertainty for boosted Higgs $p_T > 600$ GeV

NLO K-factor ~1.7 in SM, varies by $\mathscr{O}(30\%)$ as (c_t, c_g) changed

Use of HTL can hide new physics

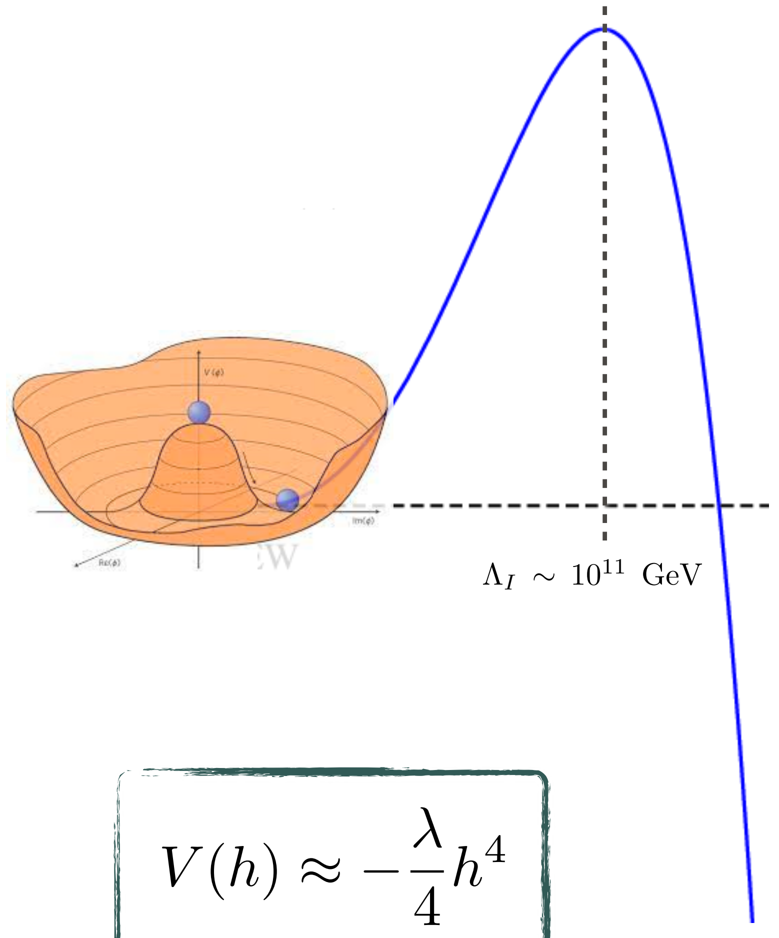


Campillo Aveleira, Heinrich, Kerner, Kunz 24

Although EFT arguments and the current, as well as expected, precision of the coupling measurements still allows for BSM physics in the TeV range which will be accessible at the LHC through new generation of precision measurement, it is probably important to think about the SM narrative if these expectations do not bear out.

SM Lagrangian extended to high-field values shows signs of a strange behaviour because values of low-energy parameters put the SM on the boarder of stable and meta-stable phases.

THE STANDARD MODEL HIGGS POTENTIAL EXTENDED TO HIGHER ENERGIES:

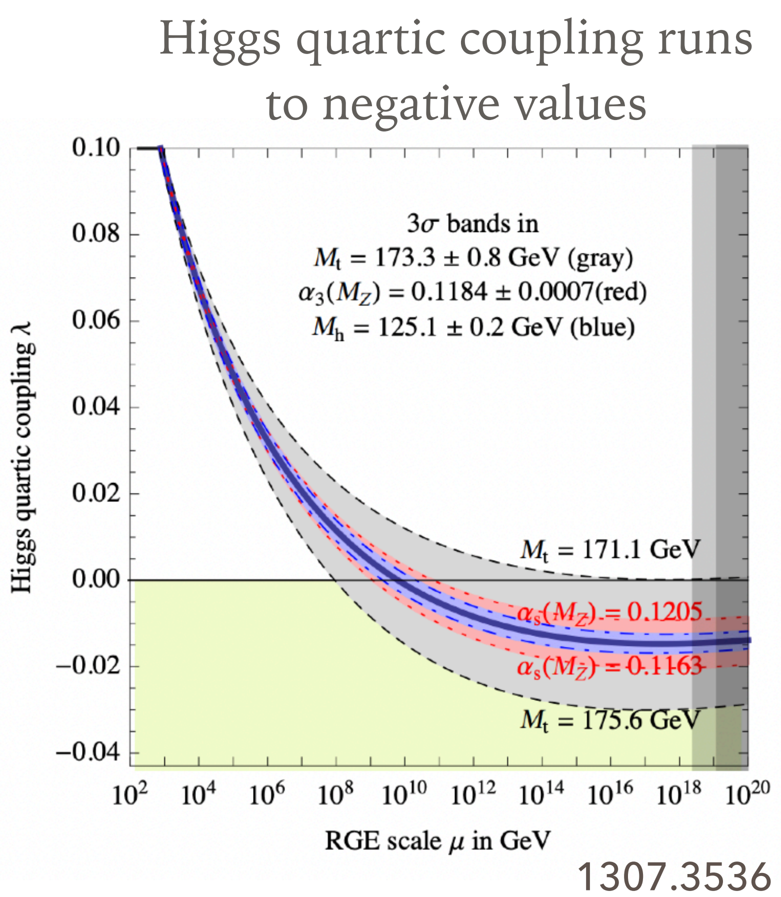


$$V(h) \approx -\frac{\lambda}{4}h^4$$

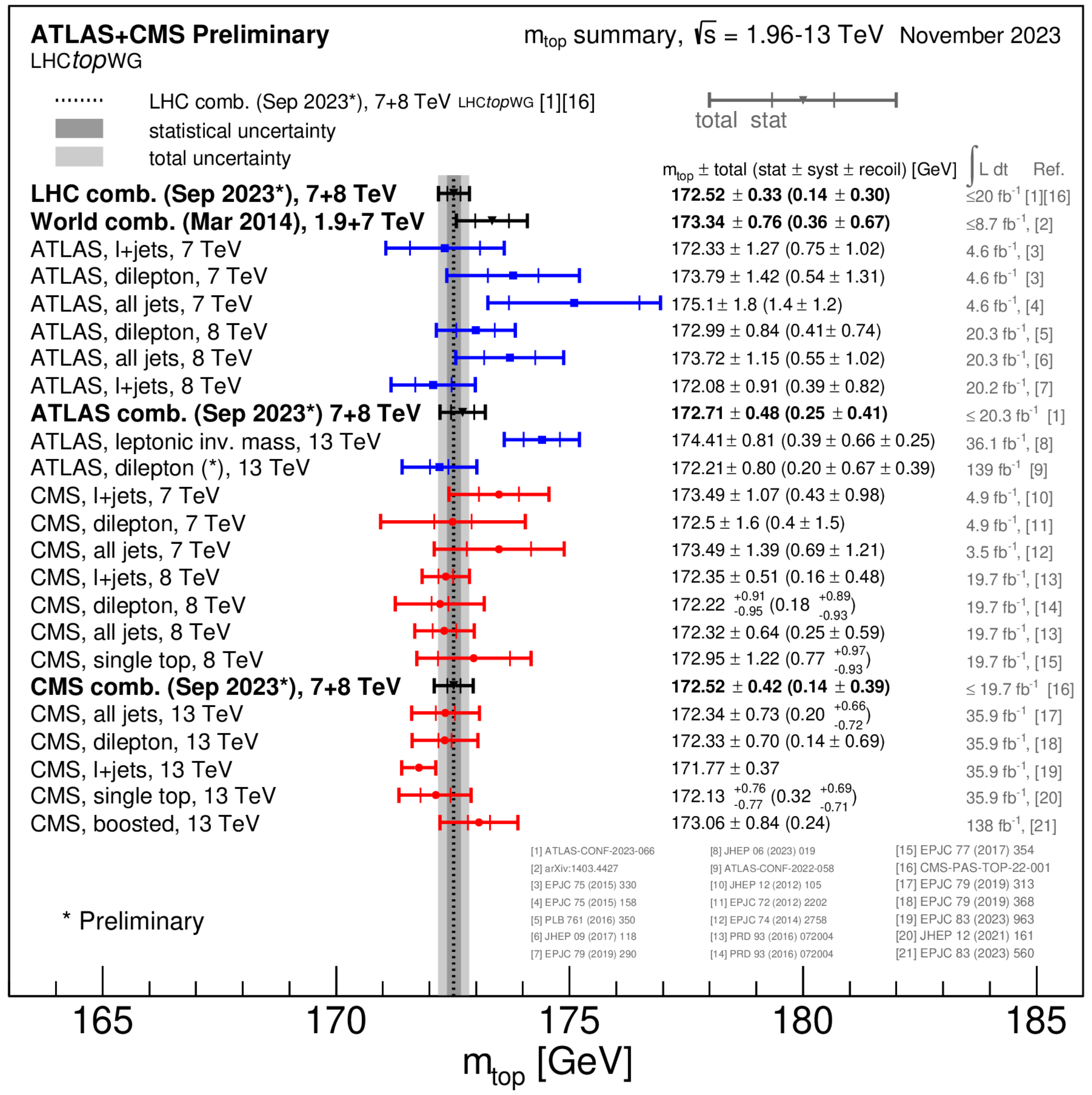
$\lambda \approx 0.01$

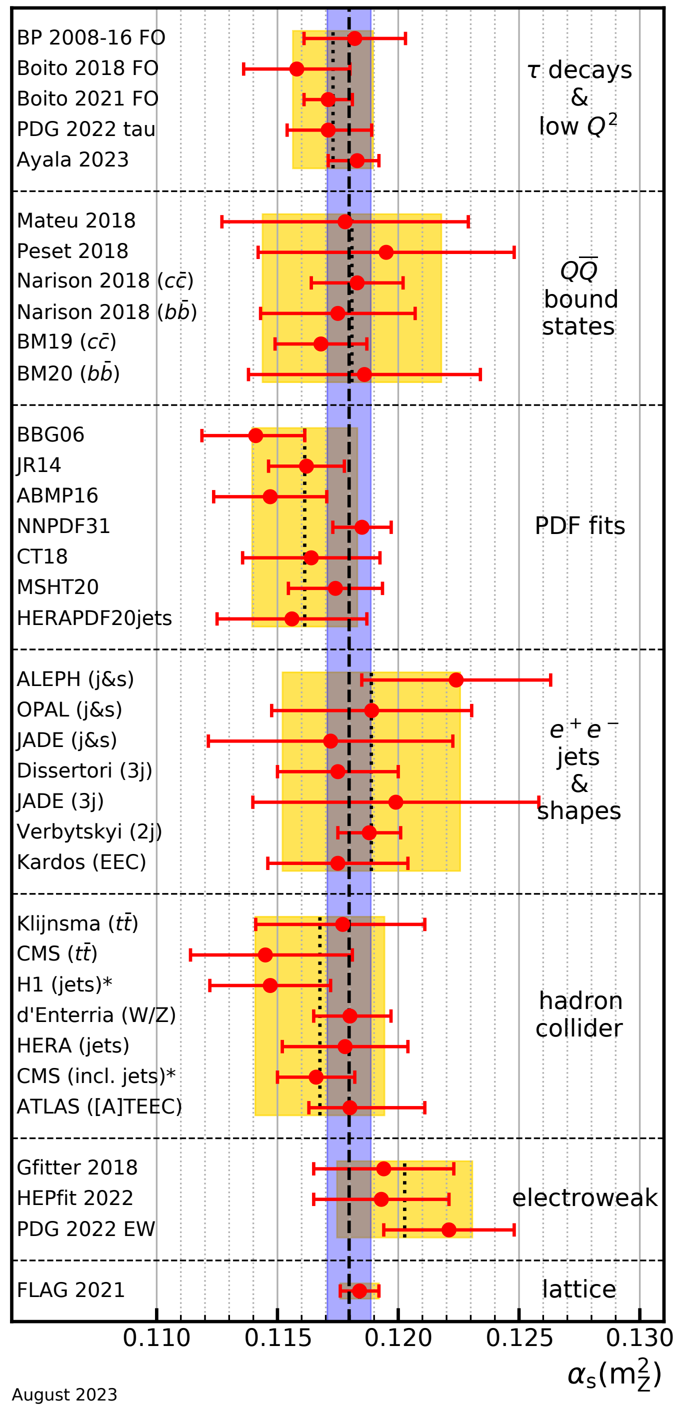
at high scales

A deeper true minimum somewhere



1307.3536 [hep-ph]





Slide from B. Shakya's talk

$$m_t = 172.52 \pm 0.33 \text{ GeV}$$

$$\alpha_s(M_z) = 0.118 \pm 0.001$$

Masses of the Higgs boson, the top quark and the strong coupling constant are extremely important for reaching a definite conclusion about the ultimate fate of the Universe. What this would imply is an open question.

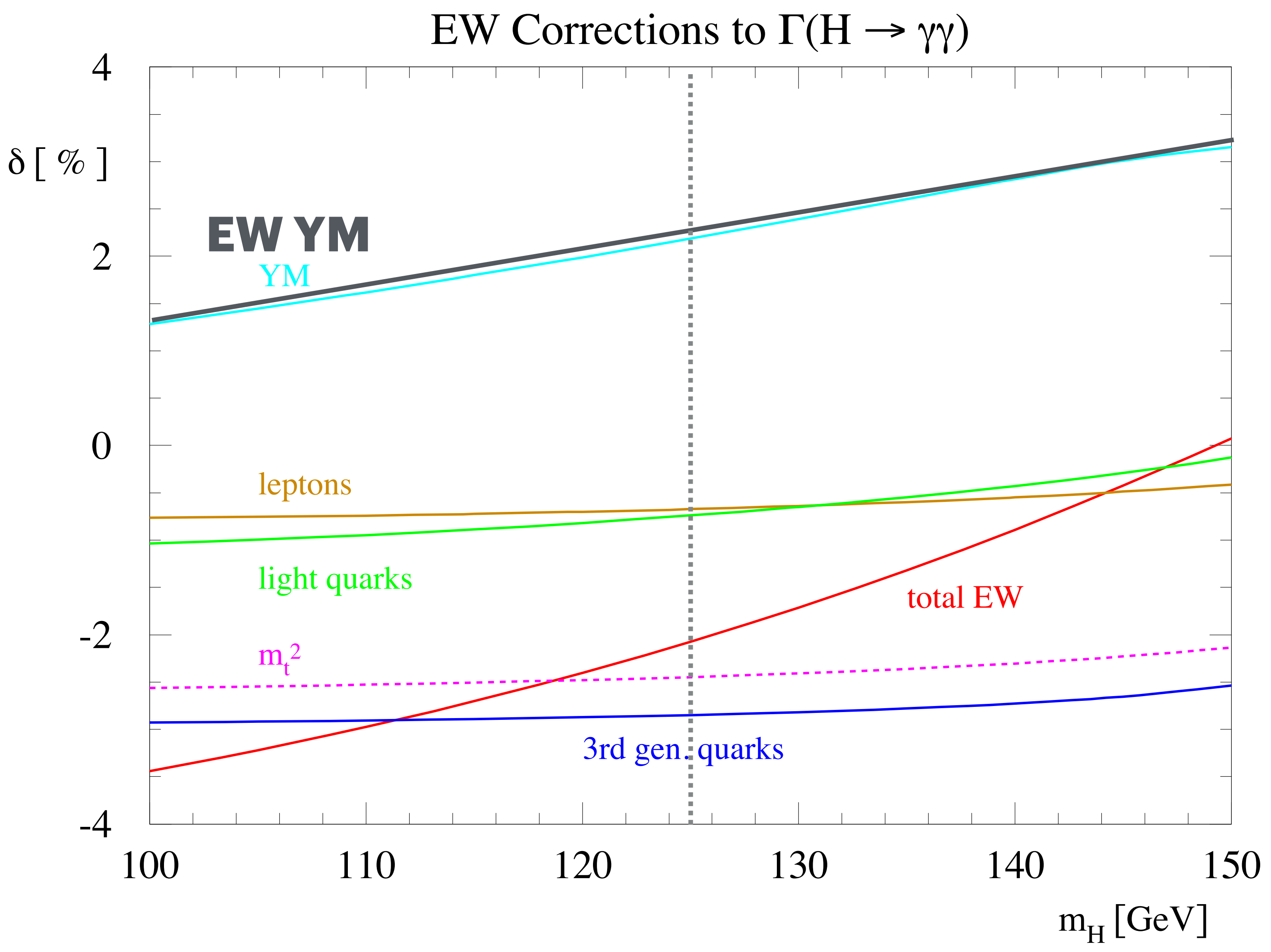
There is an old idea that one can reduce theoretical uncertainties by considering ratios of cross sections and other observables. Ratios may be attractive if common uncertainties in cross section/observables cancel out. The usual problem with ratios is to what extent the good things keep happening in fiducial regions. However, computations for fiducial, realistic cross sections have come a long way, so probably one should take advantage of this.

In the ggH process, the theory uncertainty (strong coupling constant and PDFs) and un-calculated higher-orders is probably 4 percent; they fully cancel in the ratio below:

$$\frac{\sigma(gg \to H \to \gamma\gamma)}{\sigma(gg \to H \to ZZ^* \to 4l)} = \frac{\Gamma(H \to \gamma\gamma)}{\Gamma(H \to ZZ^* \to 4l)}$$

These widths are affected by QCD and EW radiative corrections. QCD corrections are tiny and are known to very high orders. It would be interesting to "observe" (highly-nontrivial) electroweak corrections to be in agreement with the SM.

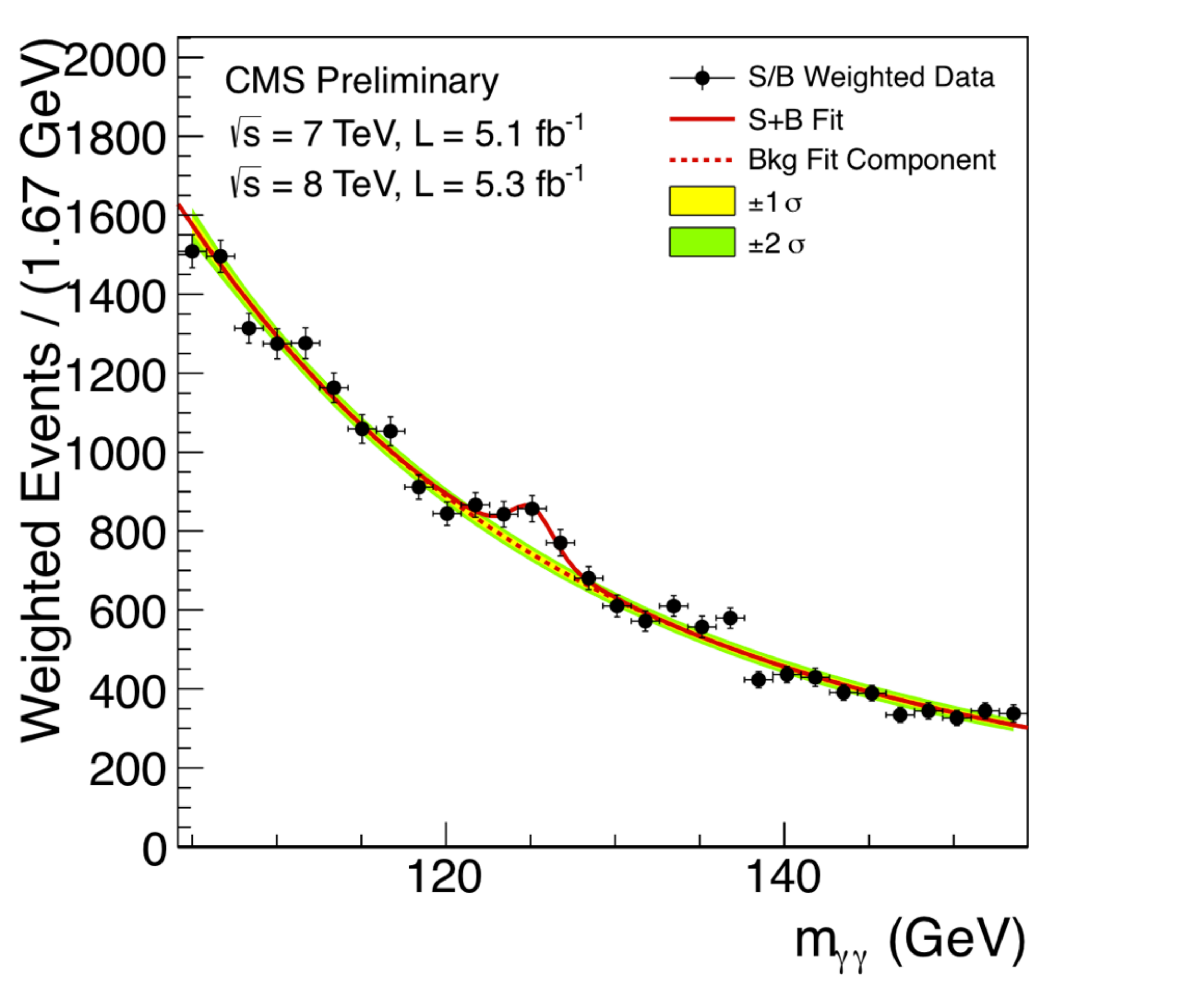
$$\frac{\Gamma(H \to \gamma\gamma)}{\Gamma(H \to ZZ^* \to 4l)} \approx R_{\rm LO}\,(1 + 0.02_{\rm QCD} - 0.04_{\rm EW})$$

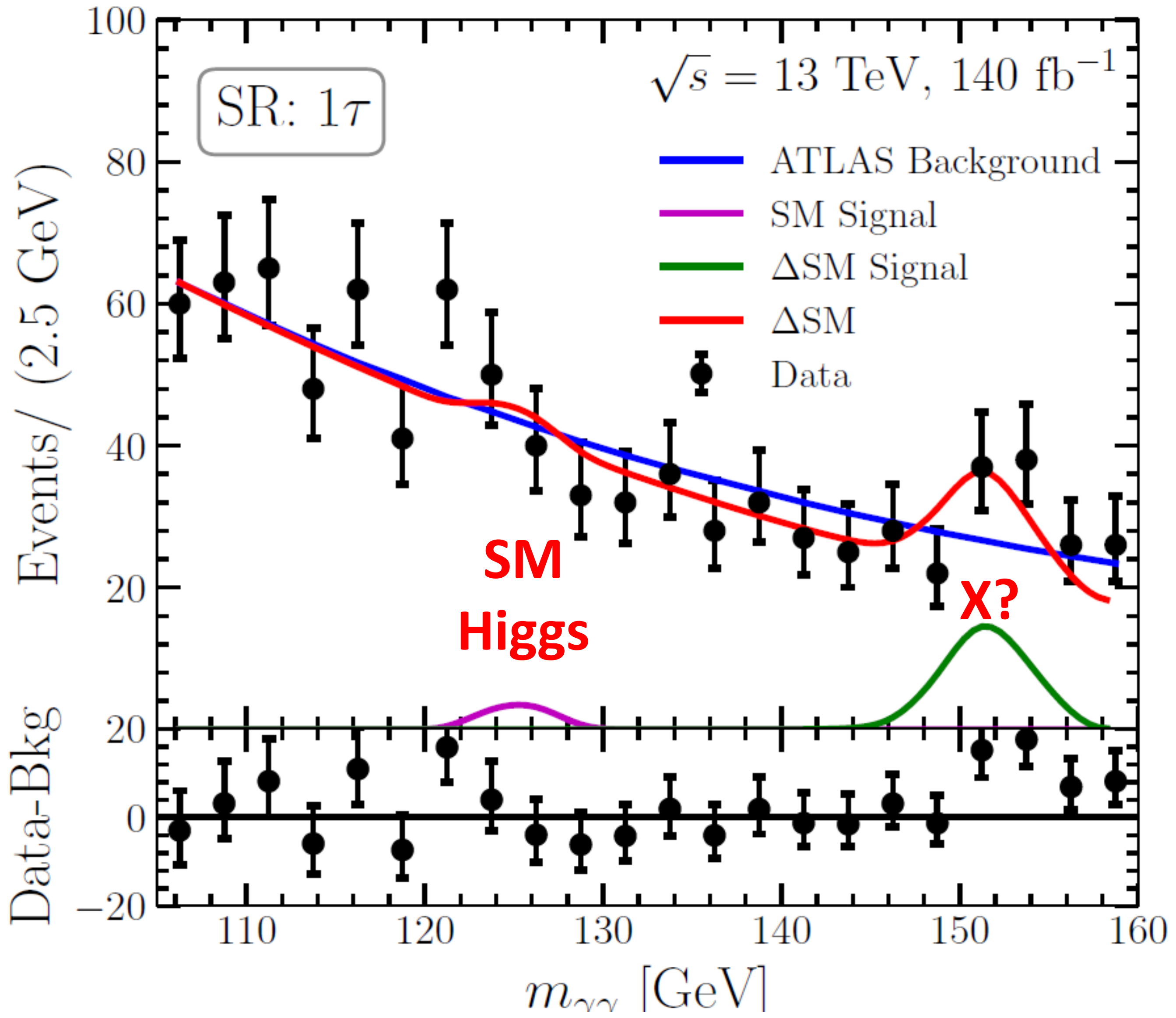


Degrassi, Maltoni

POI	Scenario	$\Delta_{\rm tot}/\sigma_{\rm SM}$	$\Delta_{\rm stat}/\sigma_{\rm SM}$	$\Delta_{\rm exp}/\sigma_{\rm SM}$	$\Delta_{\rm sig}/\sigma_{\rm SM}$	$\Delta_{\rm bkg}/\sigma_{\rm SM}$
$\sigma^{ZZ}_{\rm ggF}$	HL-LHC S1	$^{+0.044}_{-0.044}$	$^{+0.016}_{-0.016}$	$^{+0.031}_{-0.034}$	$^{+0.019}_{-0.017}$	$^{+0.018}_{-0.016}$
	HL-LHC S2	$^{+0.034}_{-0.034}$	$^{+0.016}_{-0.016}$	$^{+0.027}_{-0.027}$	$^{+0.010}_{-0.009}$	$^{+0.010}_{-0.009}$
$B_{\gamma\gamma}/B_{ZZ}$	HL-LHC S1	$^{+0.061}_{-0.057}$	$^{+0.020}_{-0.019}$	$^{+0.053}_{-0.049}$	$^{+0.018}_{-0.017}$	$^{+0.016}_{-0.014}$
	HL-LHC S2	$^{+0.045}_{-0.042}$	$^{+0.020}_{-0.019}$	$^{+0.037}_{-0.035}$	$^{+0.011}_{-0.011}$	$^{+0.010}_{-0.009}$
B_{WW}/B_{ZZ}	HL-LHC S1	$^{+0.065}_{-0.061}$	$^{+0.019}_{-0.018}$	$^{+0.042}_{-0.038}$	$^{+0.036}_{-0.034}$	$^{+0.028}_{-0.027}$
	HL-LHC S2	$^{+0.049}_{-0.047}$	$^{+0.019}_{-0.018}$	$^{+0.036}_{-0.034}$	$^{+0.020}_{-0.018}$	$^{+0.019}_{-0.018}$
$B_{\tau\tau}/B_{ZZ}$	HL-LHC S1	$^{+0.066}_{-0.062}$	$^{+0.024}_{-0.024}$	$^{+0.043}_{-0.038}$	$^{+0.033}_{-0.033}$	$^{+0.029}_{-0.026}$
	HL-LHC S2	$^{+0.053}_{-0.050}$	$^{+0.024}_{-0.024}$	$^{+0.037}_{-0.035}$	$^{+0.023}_{-0.022}$	$^{+0.019}_{-0.017}$
B_{bb}/B_{ZZ}	HL-LHC S1	$^{+0.118}_{-0.105}$	$^{+0.038}_{-0.037}$	$^{+0.053}_{-0.048}$	$^{+0.058}_{-0.052}$	$^{+0.080}_{-0.069}$
	HL-LHC S2	$^{+0.092}_{-0.084}$	$^{+0.038}_{-0.037}$	$^{+0.046}_{-0.043}$	$^{+0.036}_{-0.032}$	$^{+0.061}_{-0.054}$

ATLAS HL projections on branchings





Crivellin, Ashanujjaman, Banik, Coloretti, Maharathy, Mellado, arXiv:2404.14492