Improved constraint on Higgs boson self-couplings with quartic and cubic power dependence in the cross section

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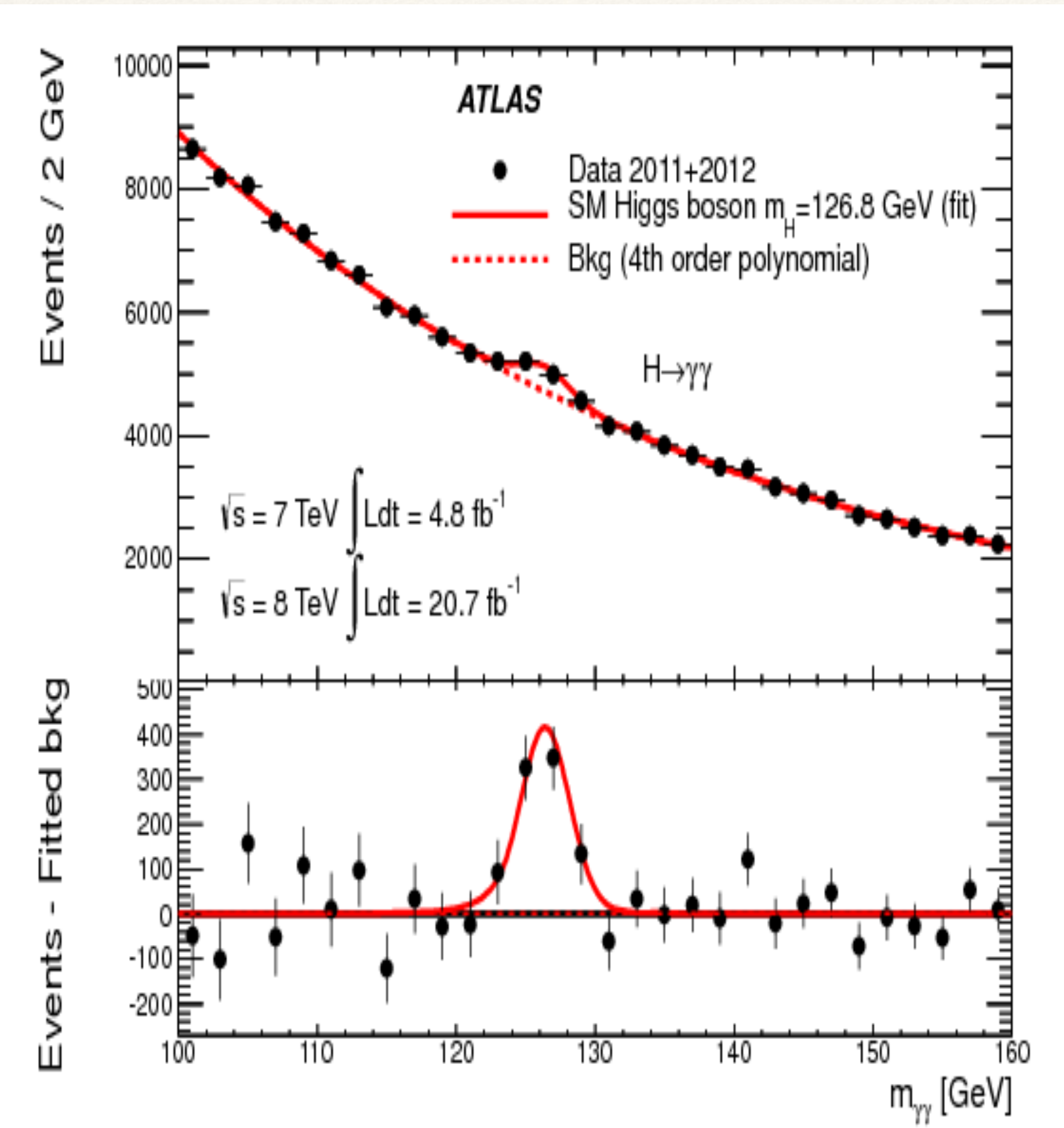
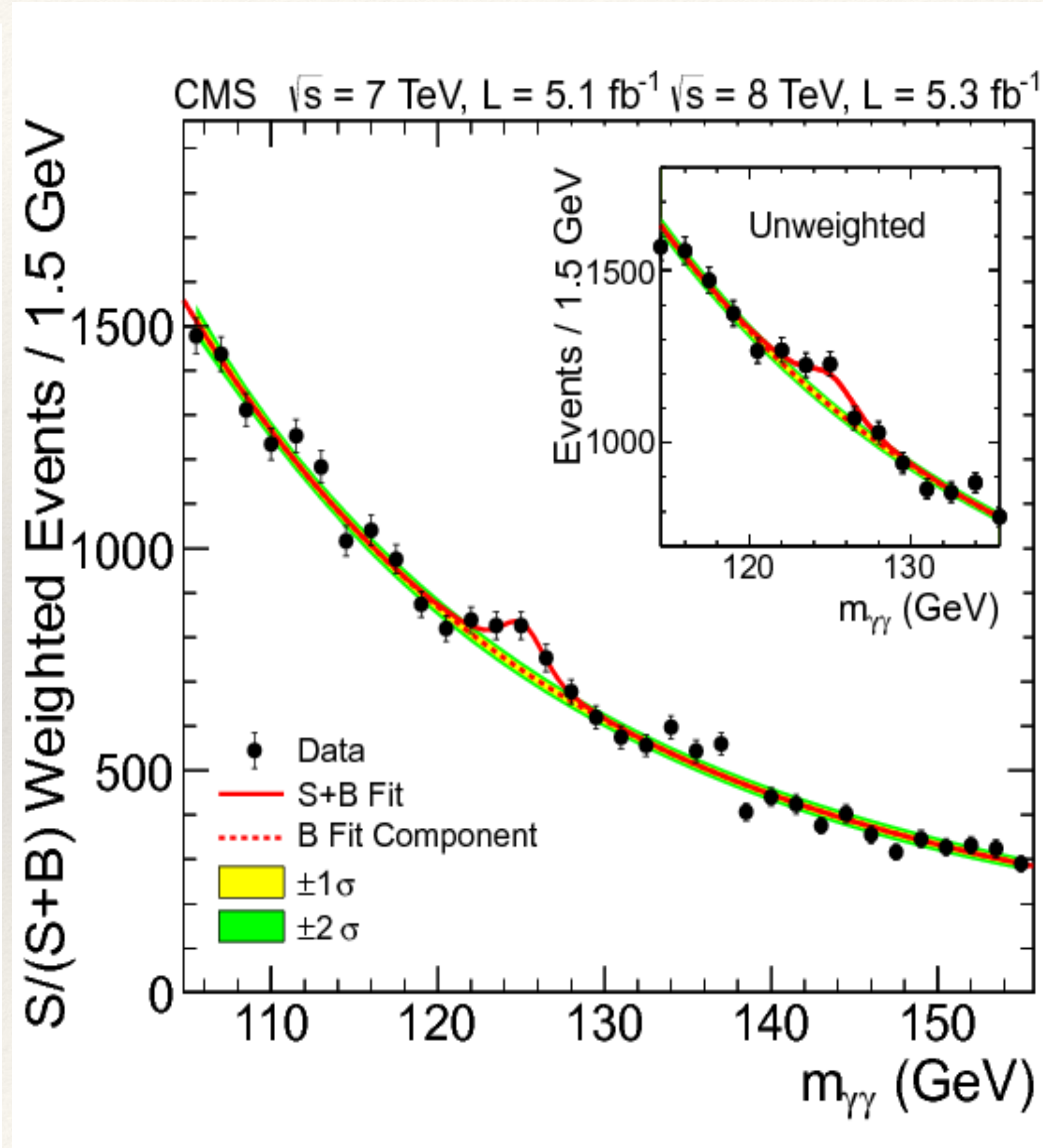
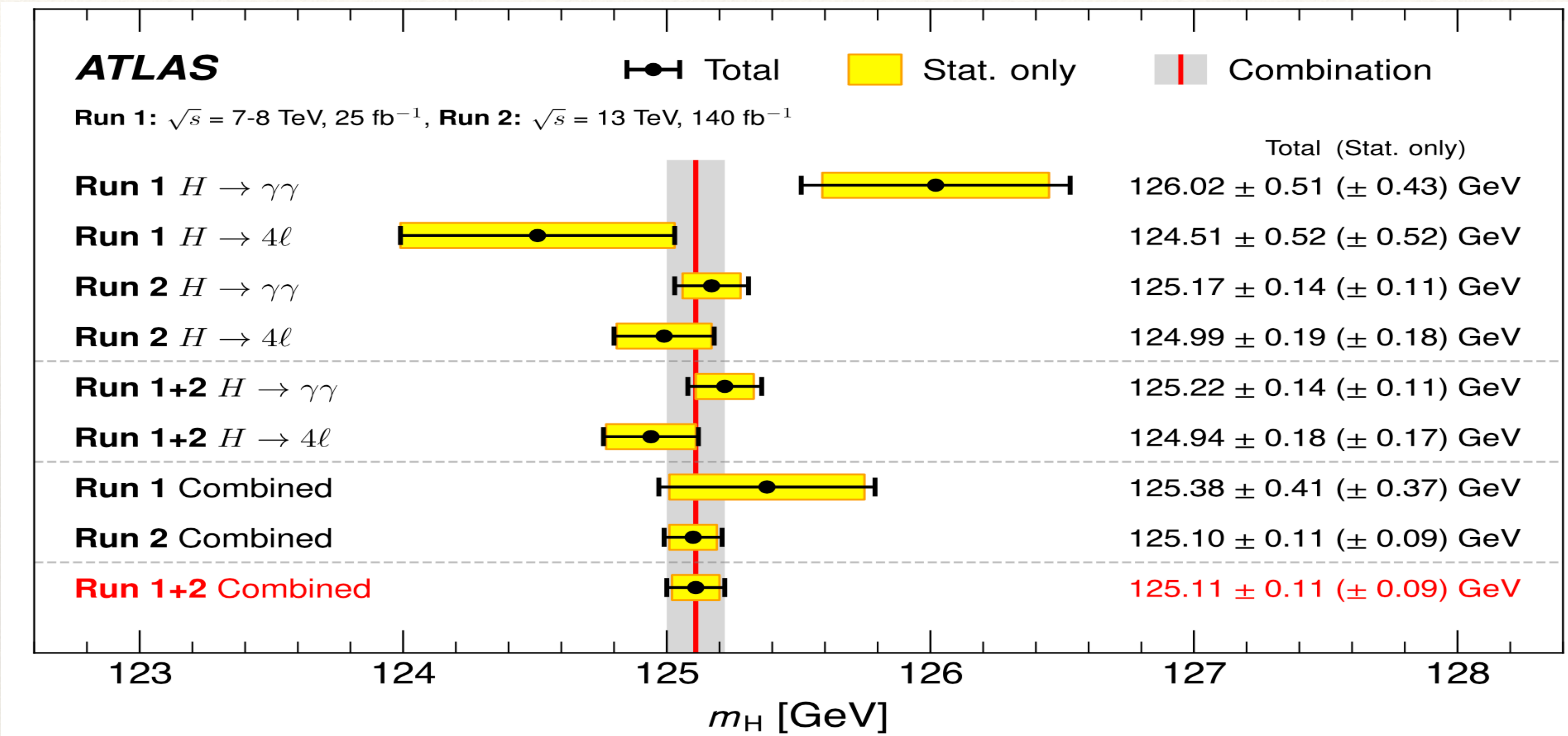
Discovery in 2012

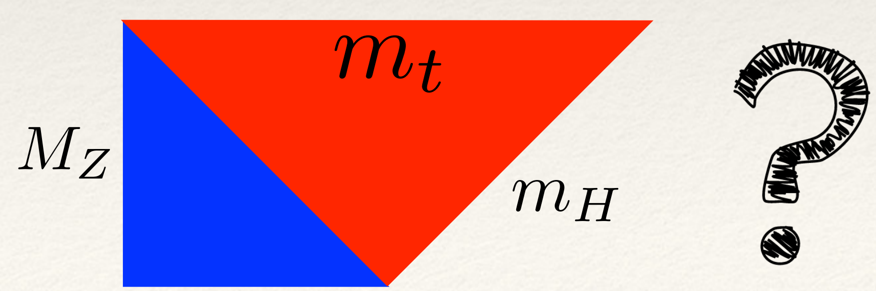


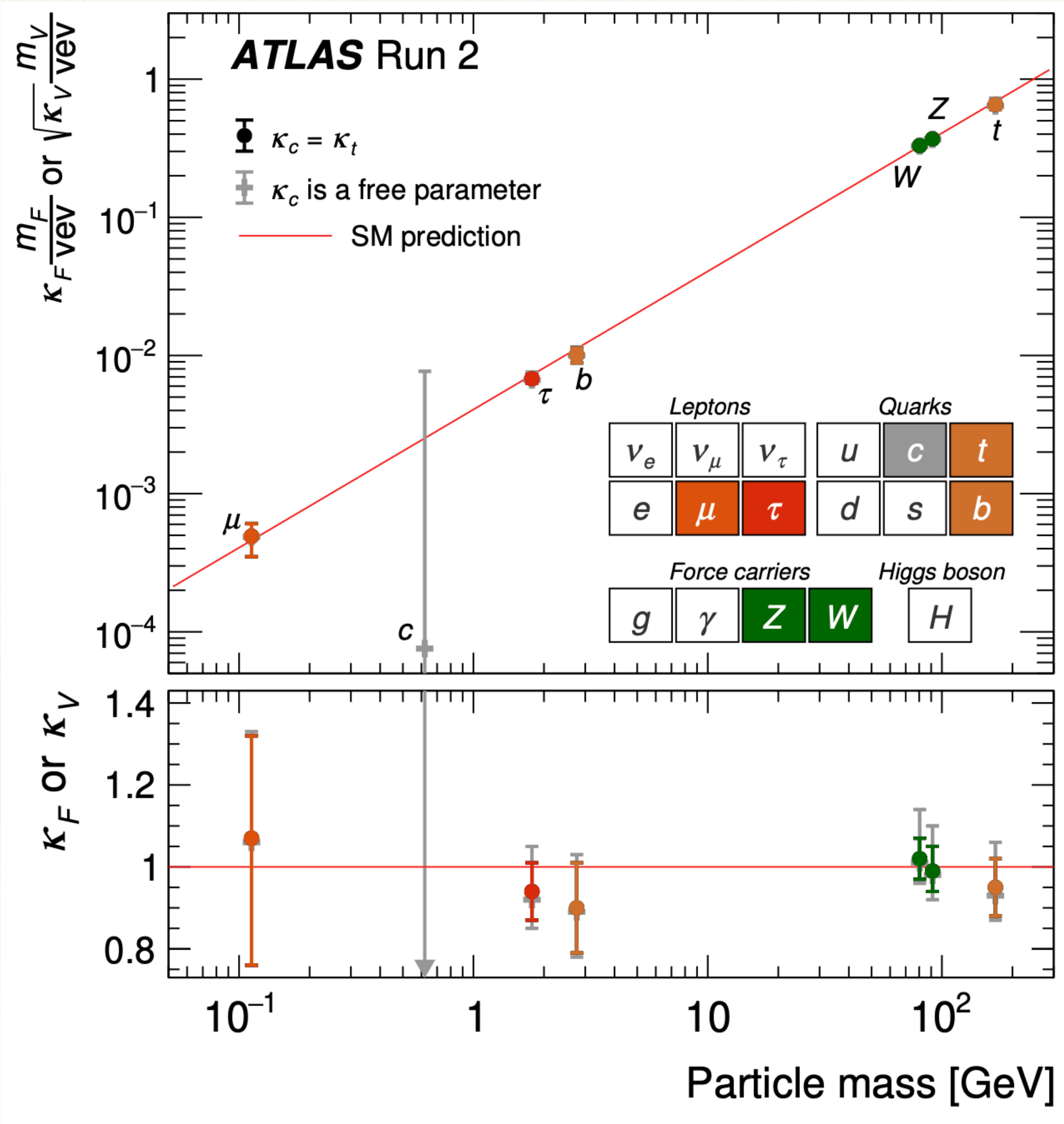


How precise is our understanding?



$$\frac{m_t}{m_H} = \frac{m_H}{M_Z} \approx \sqrt{2} \pm 0.04$$





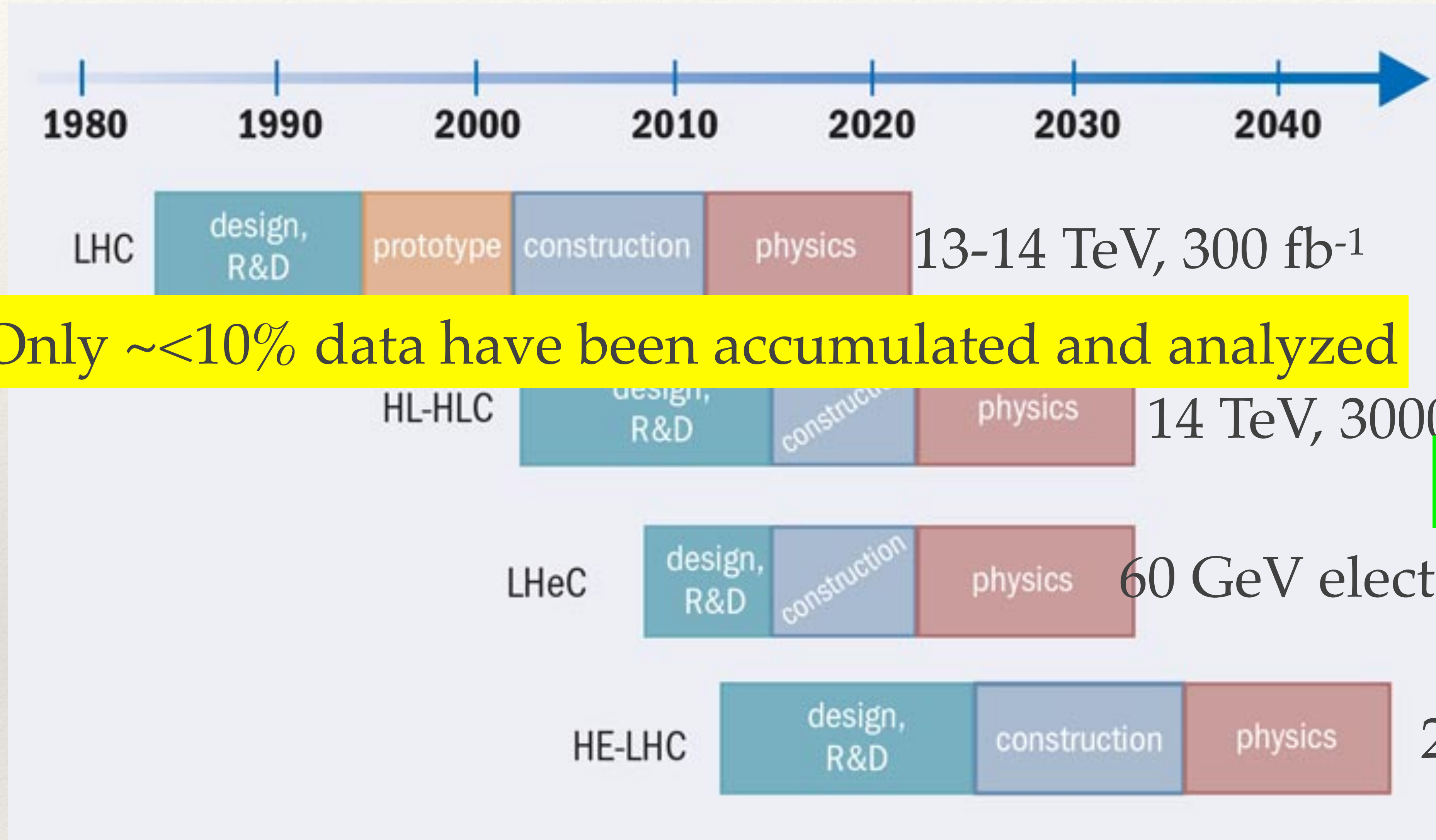
Nature 607(2022)52

So far, the H(125) properties are consistent with the SM expectation!

Its couplings with SM particles are proportional to their masses; Higgs mechanism

existence of a “fifth force” different from gravity

Future plan of LHC



13-14 TeV, 300 fb^{-1}

Only ~<10% data have been accumulated and analyzed

14 TeV, 3000 fb^{-1}

150000000 H

60 GeV electron beam

27 TeV

High precision theoretical calculation is important for measuring SM parameters, and thus for predicting backgrounds for new physics searches. It is also needed to detect new physics that appears as a small deviation.

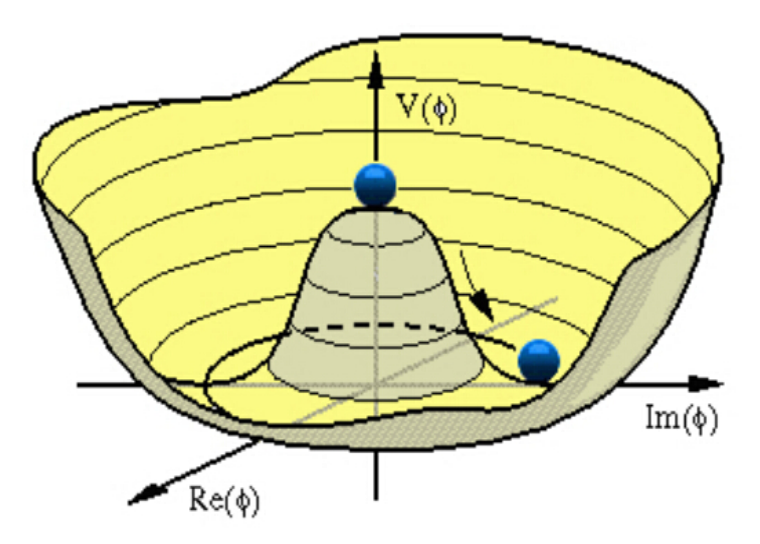
Higgs self-coupling in the SM

$$V(\phi) = -\mu^2\phi^\dagger\phi + \lambda(\phi^\dagger\phi)^2$$

$$\phi = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v+h \end{pmatrix}$$

$$V(h) = \tfrac{1}{2}m_h^2 h^2 + \sqrt{\tfrac{\lambda}{2}}m_H h^3 + \tfrac{1}{4}\lambda h^4$$

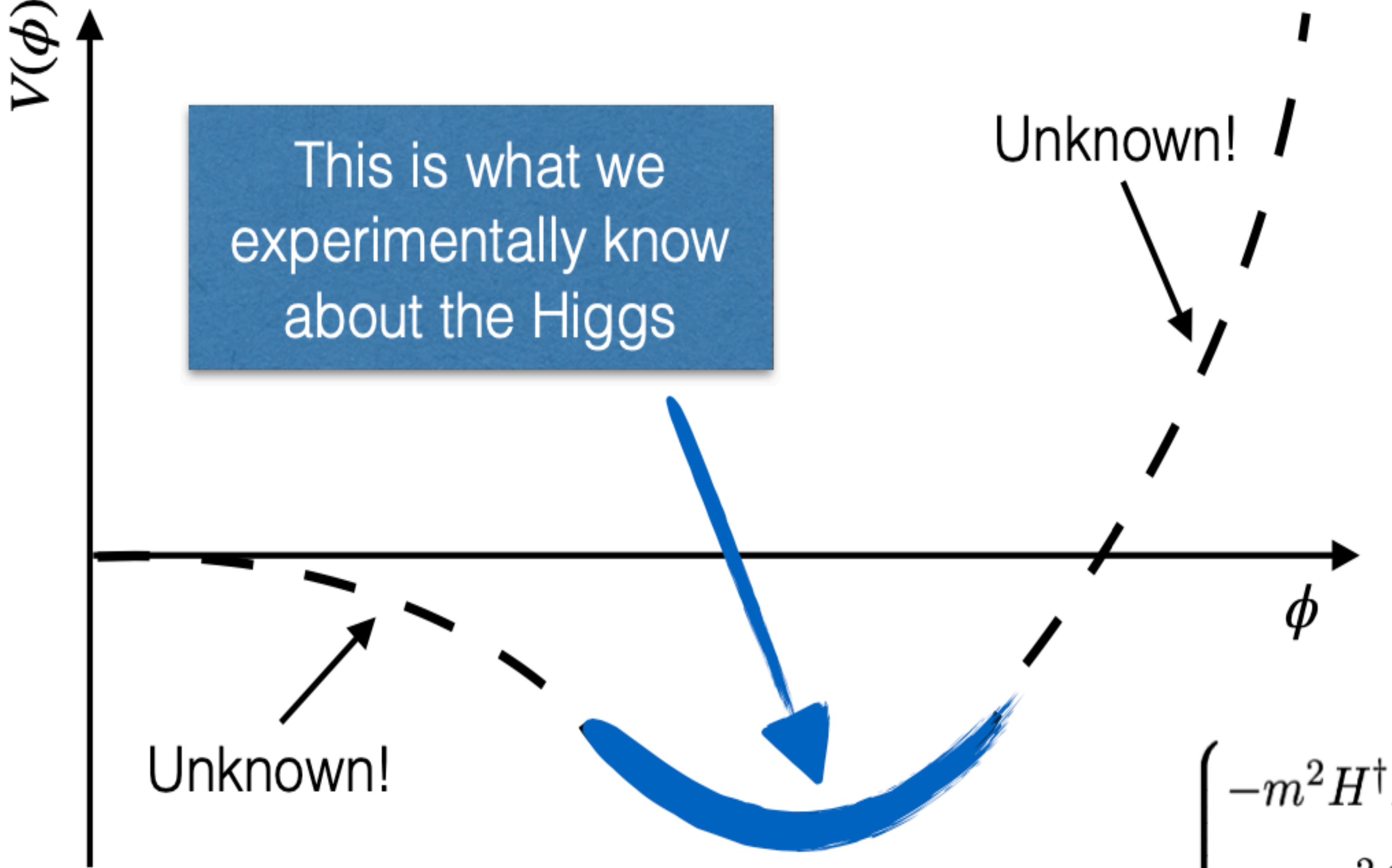
$$\lambda = m_H^2/2v^2$$



In some new physics models, the trilinear Higgs self-coupling may change by O(100)%, while the couplings with gauge bosons and fermions are still in agreement with SM.

S.Kanemura, et al, PLB558,157

We need to measure the trilinear self coupling directly.

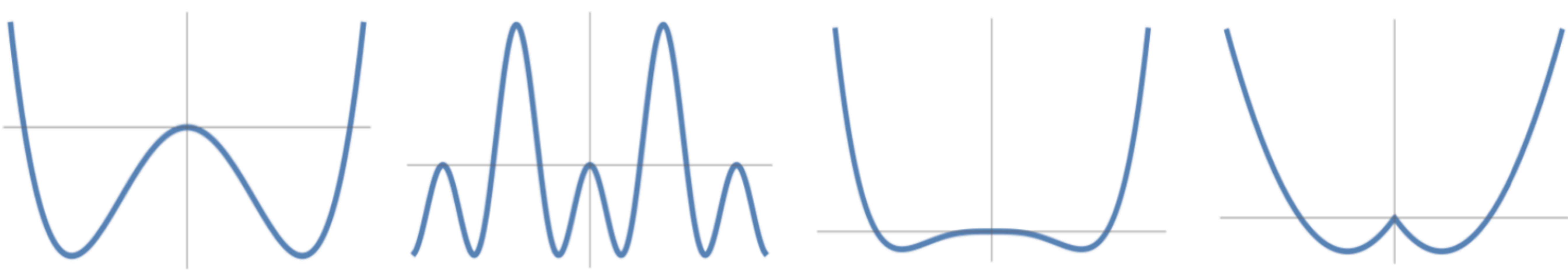


Different potential shapes could explain the same physics we see now!

$$V(H) \simeq \begin{cases} -m^2 H^\dagger H + \lambda (H^\dagger H)^2 + \frac{c_6 \lambda}{\Lambda^2}(H^\dagger H)^3, & \text{Elementary Higgs} \\ -a \sin^2(\sqrt{H^\dagger H}/f) + b \sin^4(\sqrt{H^\dagger H}/f), & \text{Nambu-Goldstone Higgs} \\ \lambda (H^\dagger H)^2 + \epsilon (H^\dagger H)^2 \log \frac{H^\dagger H}{\mu^2}, & \text{Coleman-Weinberg Higgs} \\ -\kappa^3 \sqrt{H^\dagger H} + m^2 H^\dagger H, & \text{Tadpole-induced Higgs} \end{cases}$$

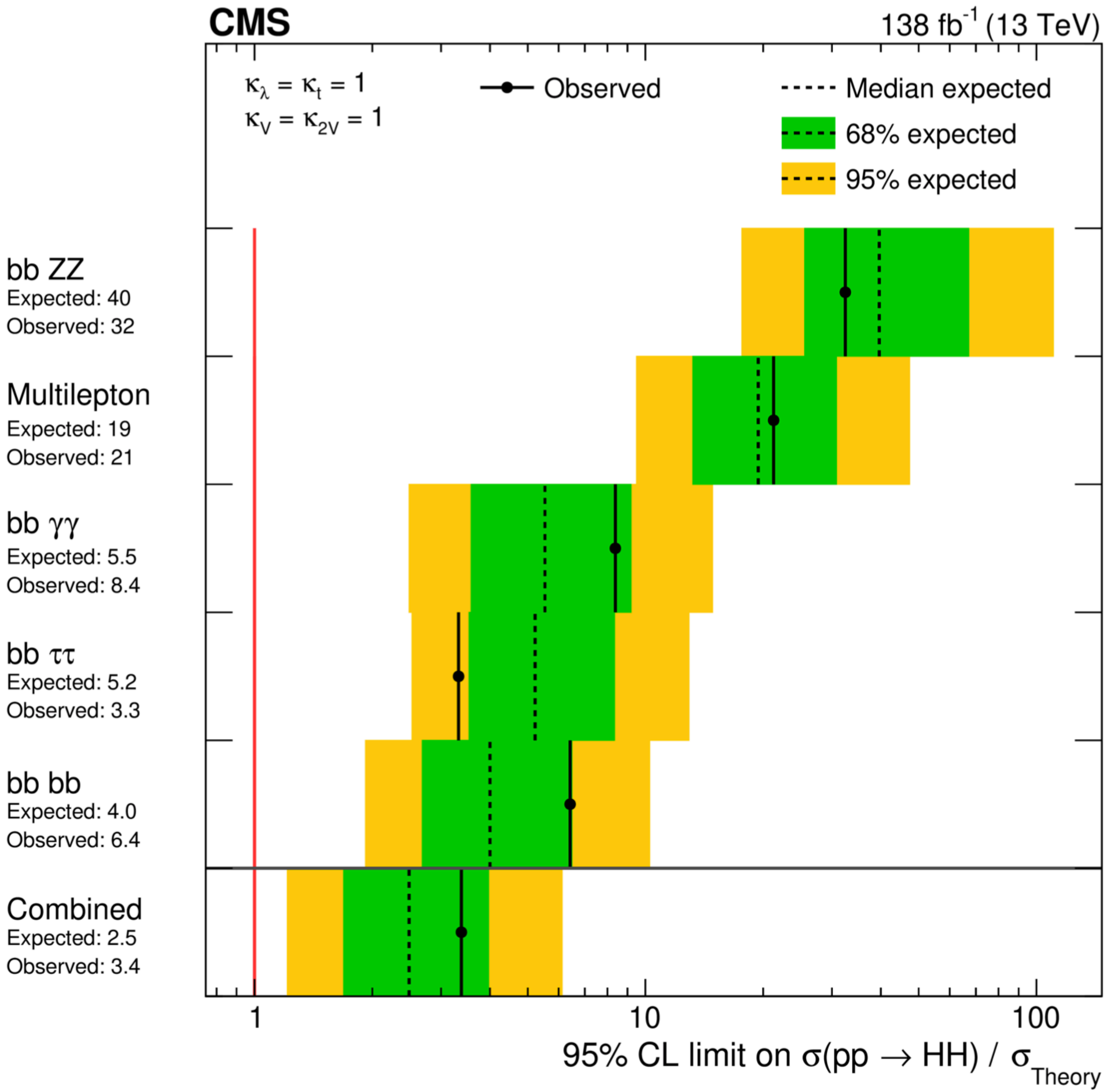
Agrawal, Saha, L.X.Xu, J.-H. Yu, C.-P. Yuan

arxiv:1907.02078



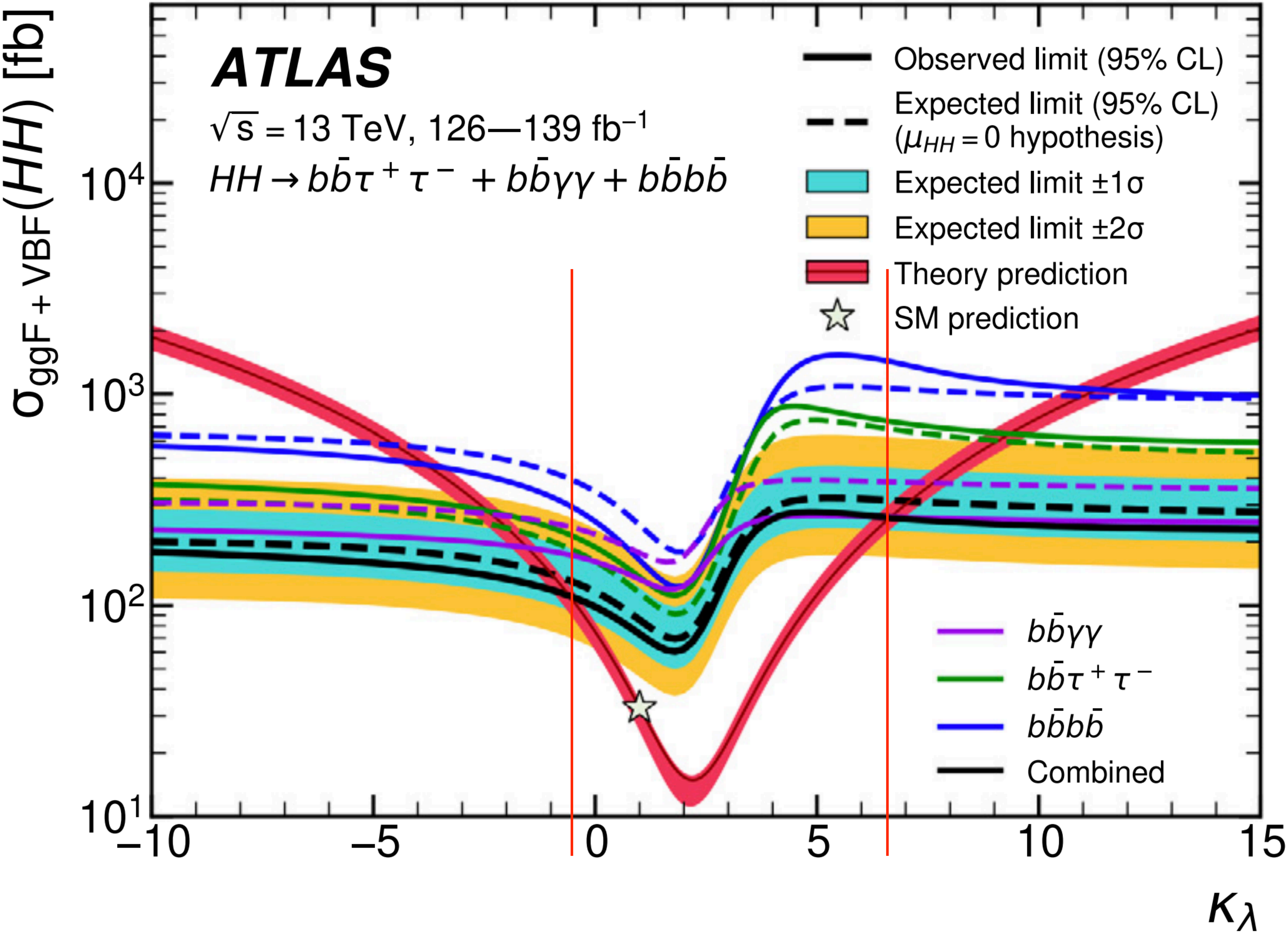
Landau-Ginzburg Higgs **Nambu-Goldstone Higgs** **Coleman-Weinberg Higgs** **Tadpole-Induced Higgs**

From Marco Valente

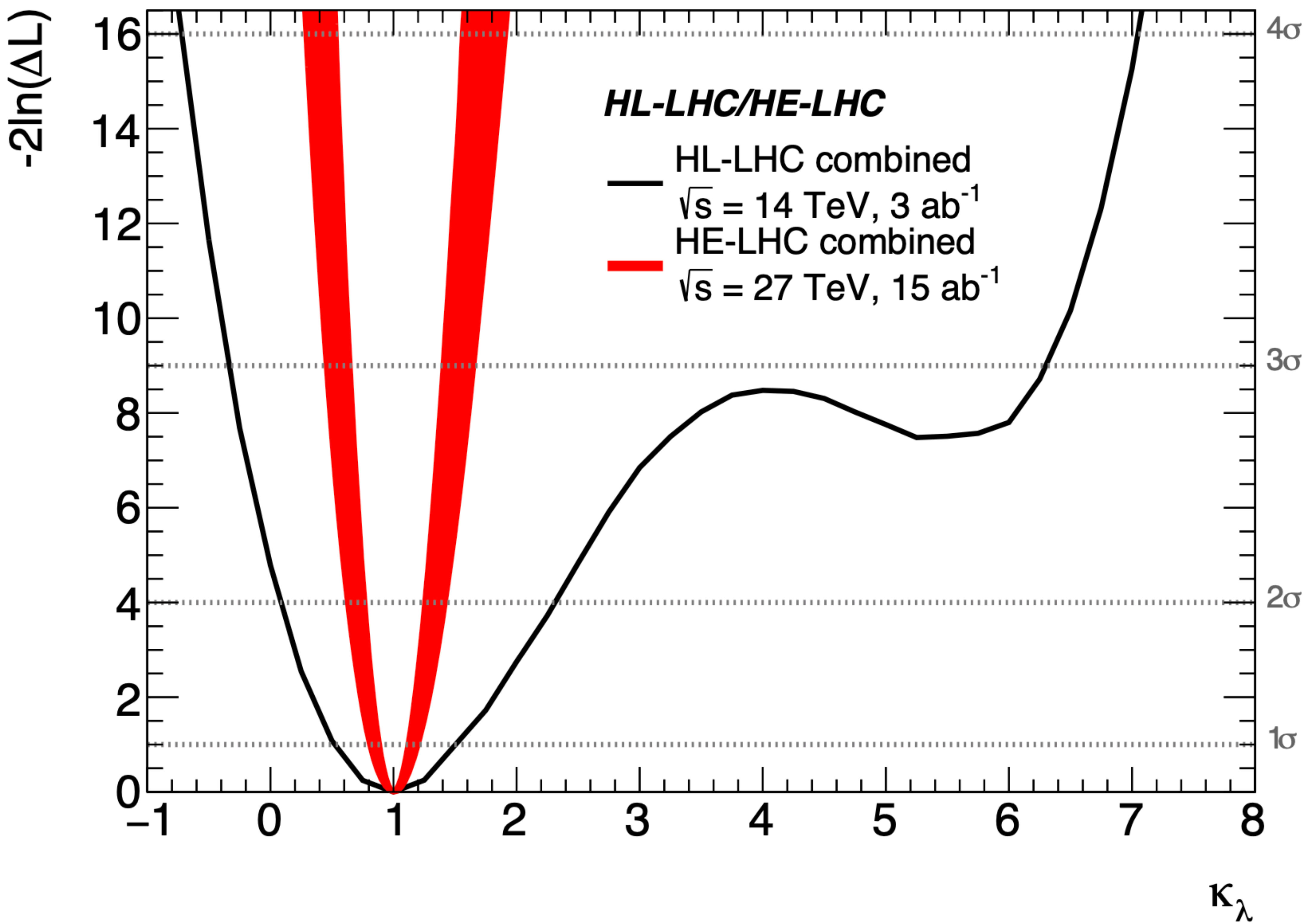


$$-1.2 < \kappa_\lambda < 6.5$$

Nature 607(2022)60



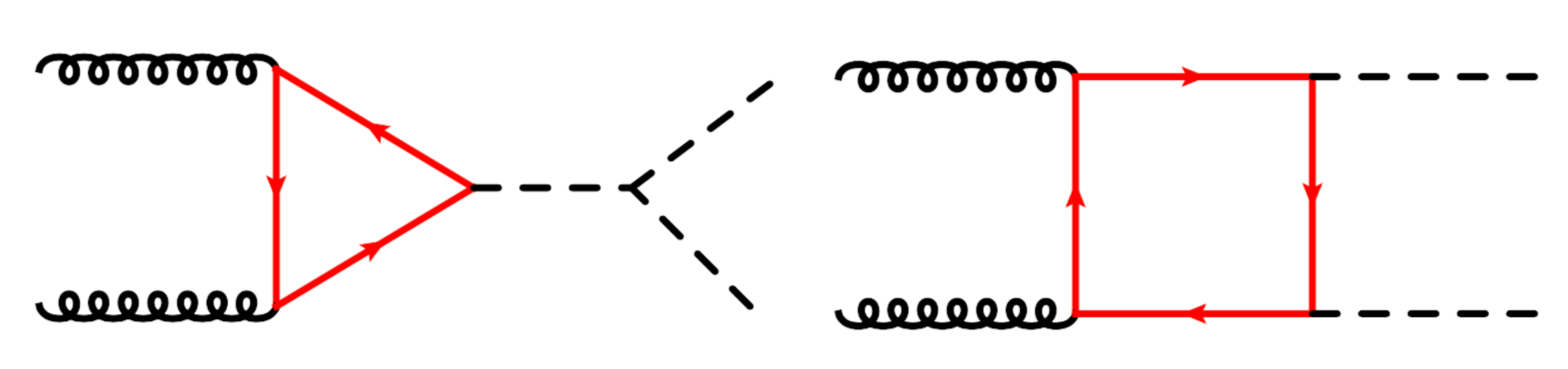
Physics Letters B 843 (2023) 137745



Expected accuracy:
~50% at HL-LHC
~10% at HE-LHC

1902.00134

pp →HH as a function of κ

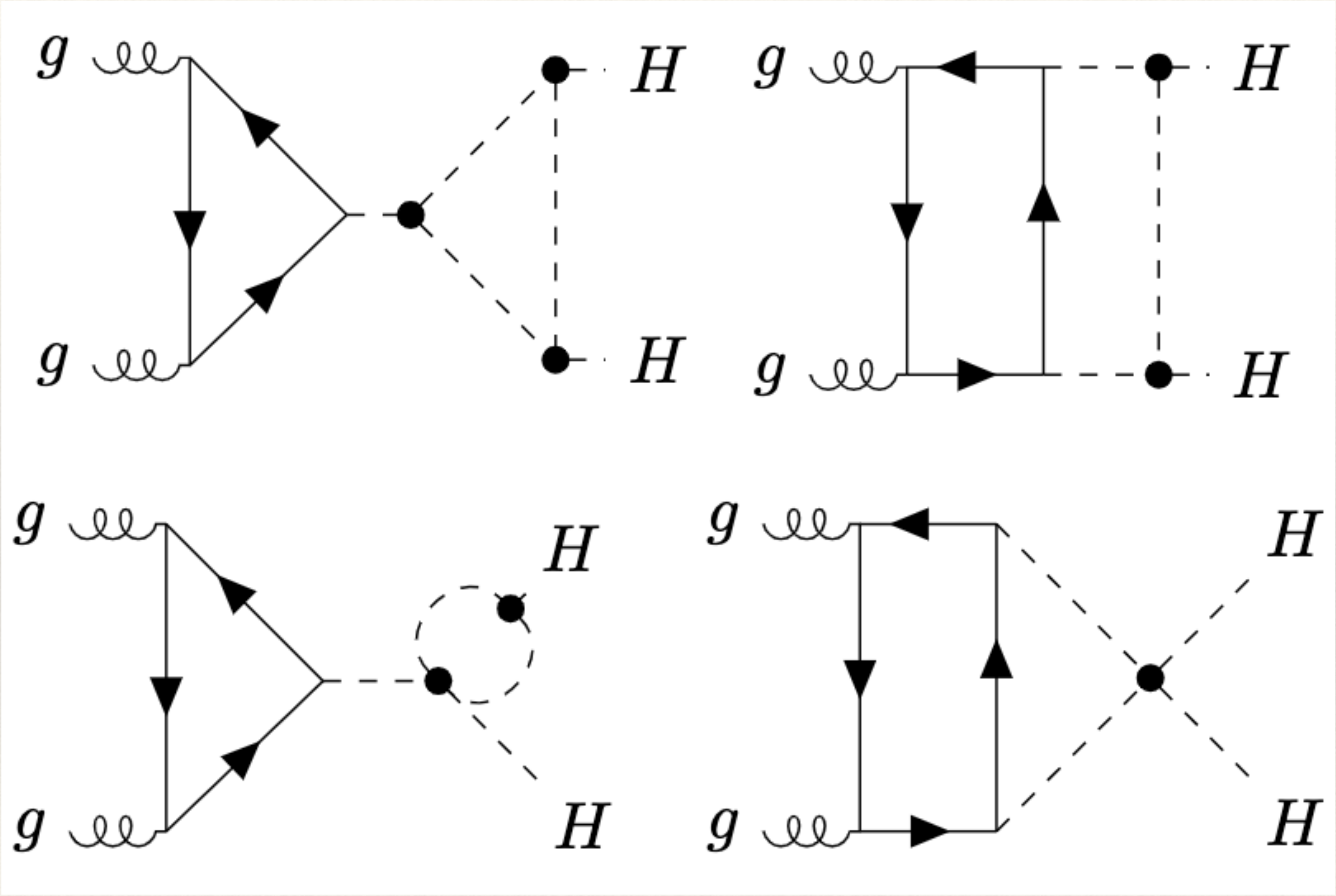


$$\sigma_{HH} = A + B\kappa + C\kappa^2$$

computation	A [fb]	A/A(LO)	B [fb]	B/B(LO)	C [fb]	C/C(LO)
LO m_t fin	35.0		-23.0		4.73	
NLO m_t fin	62.6	1.79	-44.4	1.93	9.64	2.04
NLO m_t fin × NNLO SM FTApprox	70.0	2.00	-49.6	2.16	10.8	2.28
NNLO + NNLL $m_t \to \infty$ × NNLO+NLL SM (partial m_t fin)	71.3	2.04	-47.7	2.08	9.93	2.10

1910.00012

A more realistic function form



$$\sigma_{HH} = A + B\kappa + C\kappa^2 + D\kappa^3 + E\kappa^4$$

Non-trivial task

Input parameters of conventional EW calculations:

e, m_H, m_t, m_W, m_Z

If one takes the Higgs self-coupling λ as an input, the correction would be proportional to λ.

Performing rescaling $\lambda \to \kappa\lambda$ before or after substituting $m_H^2 = 2\lambda v^2$ gives different results.

Renormalization

The renormalized Lagrangian in the κ framework after EW gauge symmetry breaking:

$$\mathscr{L}_{\mathrm{H}}^{\kappa} = \frac{1}{2} Z_\phi (\partial_\mu H)^2 - \left(-\frac{1}{2} Z_{\mu^2} Z_\phi Z_v^2 \mu^2 v^2 + \frac{1}{4} Z_\lambda Z_\phi^2 Z_v^4 \lambda v^4 \right) - (Z_\lambda Z_\phi^2 Z_v^3 \lambda v^3 - Z_{\mu^2} Z_\phi Z_v \mu^2 v) H$$
$$- \left(\frac{3}{2} Z_\lambda Z_\phi^2 Z_v^2 \lambda v^2 - \frac{1}{2} Z_{\mu^2} Z_\phi \mu^2 \right) H^2 - Z_{\kappa_{3\mathrm{H}}} Z_\lambda Z_\phi^2 Z_v \lambda_{3\mathrm{H}} v H^3 - \frac{1}{4} Z_{\kappa_{4\mathrm{H}}} Z_\lambda Z_\phi^2 \lambda_{4\mathrm{H}} H^4 + \cdots$$

The linear term is

$$(\mu^2 v - \lambda v^3) H + [(\delta Z_{\mu^2} + \delta Z_\phi + \delta Z_v) \mu^2 v - (\delta Z_\lambda + 2\delta Z_\phi + 3\delta Z_v) \lambda v^3] H$$

We choose the renormalization scheme in which there is no tadpole contributions.

$\mu^2 = \lambda v^2$ and $(\delta Z_{\mu^2} - \delta Z_\lambda - \delta Z_\phi - 2\delta Z_v)\mu^2 v + T = 0$ with T the one-loop diagrams.

$$T = \frac{3\lambda_{3\mathrm{H}} v}{16\pi^2} m_H^2 \left(\frac{1}{\epsilon} + \ln \frac{\mu_R^2}{m_H^2} + 1 \right)$$

H.T. Li, Z.G. Si, JW, X. Zhang, D. Zhao, 2407.14716

Renormalization

The quadratic term is

$$\frac{1}{2}(\partial_\mu H)^2 - \mu^2 H^2 + \frac{1}{2}\delta Z_\phi (\partial_\mu H)^2 - \left(\frac{3}{2}\delta Z_\lambda + \frac{5}{2}\delta Z_\phi - \frac{1}{2}\delta Z_{\mu^2} + 3\delta Z_v\right)\mu^2 H^2$$
$$\equiv \frac{1}{2}(\partial_\mu H)^2 - \frac{1}{2}m_H^2 H^2 + \frac{1}{2}\delta Z_\phi (\partial_\mu H)^2 - \frac{1}{2}(\delta Z_{m_H^2} + \delta Z_\phi) m_H^2 H^2$$

We choose the on-shell renormalization scheme.

$$\delta Z_{m_H^2} = \frac{3\lambda_{4\mathrm{H}}}{16\pi^2}\left(\frac{1}{\epsilon} + \ln\frac{\mu_R^2}{m_H^2} + 1\right) + \frac{9\lambda_{3\mathrm{H}}^2 v^2}{m_H^2}\frac{1}{8\pi^2}\left(\frac{1}{\epsilon} + \ln\frac{\mu_R^2}{m_H^2} + 2 - \frac{\pi}{\sqrt{3}}\right)$$
$$\delta Z_\phi = \frac{9\lambda_{3\mathrm{H}}^2 v^2}{8\pi^2}\frac{\sqrt{3} - 2\pi/3}{\sqrt{3}m_H^2}$$

We also have to introduce the renormalization factor for the coupling modifier.

$$\delta Z_{\kappa_{3\mathrm{H}}} = -\frac{3}{16\pi^2}\frac{1}{\epsilon}\left(-2\lambda_{4\mathrm{H}} - \lambda_{3\mathrm{H}} + 6\lambda_{3\mathrm{H}}^2\frac{v^2}{m_H^2}\right)$$

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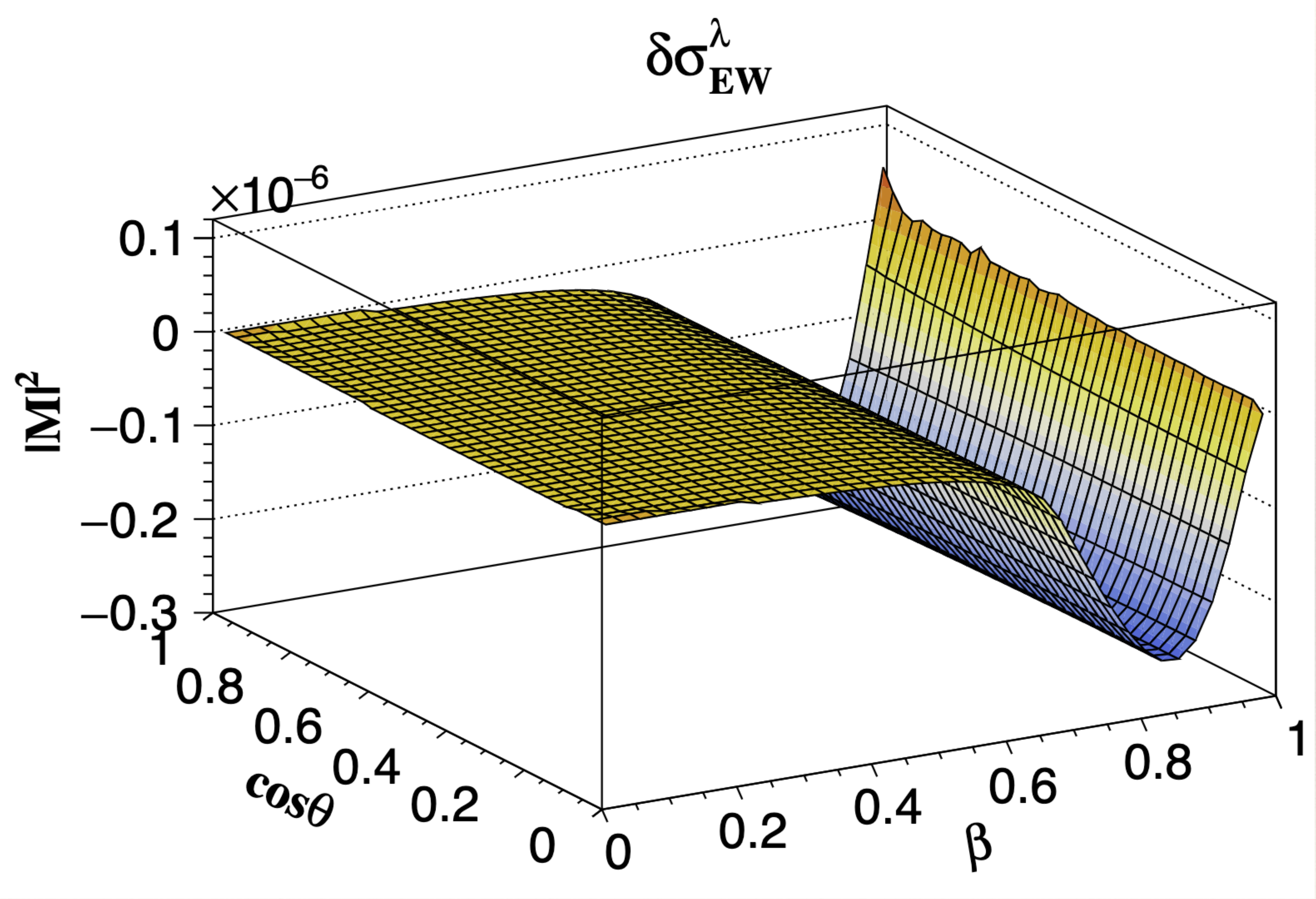
Renormalization

The result of one-particle reducible diagrams and counter-terms:

$$\mathcal{M}^{\text{LO}}_{gg\to H^*\to HH} \times \Bigg\{ \frac{3}{16\pi^2}\frac{1}{\epsilon}\left(-2\lambda_{4\text{H}} - \lambda_{3\text{H}} + 6\lambda_{3\text{H}}^2 \frac{v^2}{m_H^2}\right) + \delta Z_{\kappa_{3\text{H}}}$$
$$+ \frac{3}{16\pi^2}\ln\frac{\mu_R^2}{m_H^2}\left[-2\lambda_{4\text{H}} - \lambda_{3\text{H}} + 6\lambda_{3\text{H}}^2\frac{v^2}{m_H^2}\right]$$
$$- \frac{9\lambda_{3\text{H}}^2}{8\pi^2}\frac{v^2}{s-m_H^2}\left[\beta\left(\ln\left(\frac{1-\beta}{1+\beta}\right) + i\pi\right) + \frac{s}{m_H^2}\left(1 - \frac{2\pi}{3\sqrt{3}}\right) + \frac{5\pi}{3\sqrt{3}} - 1\right]$$
$$+ \frac{3\lambda_{3\text{H}}^2}{16\pi^2}\frac{v^2}{m_H^2}(21 - 4\sqrt{3}\pi) - \frac{9\lambda_{3\text{H}}^2 v^2}{4\pi^2}C_0[m_H^2, m_H^2, s, m_H^2, m_H^2, m_H^2]$$
$$- \frac{3\lambda_{4\text{H}}}{16\pi^2}\left[\beta\left(\ln\left(\frac{1-\beta}{1+\beta}\right) + i\pi\right) + 5 - \frac{2\pi}{\sqrt{3}}\right] - \frac{3\lambda_{3\text{H}}}{16\pi^2}\Bigg\},$$

Squared matrix elements



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Updated function form

The λ dependent correction is

$$\delta\sigma^{\kappa_\lambda}_{\rm ggF,EW} = (0.075\kappa^4_{\lambda_{3H}} - 0.158\kappa^3_{\lambda_{3H}} - 0.006\kappa^2_{\lambda_{3H}}\kappa_{\lambda_{4H}} - 0.058\kappa^2_{\lambda_{3H}} + 0.070\kappa_{\lambda_{3H}}\kappa_{\lambda_{4H}} - 0.149\kappa_{\lambda_{4H}})\ \ {\rm fb}$$

$$\delta\sigma^{\kappa_\lambda}_{\rm VBF,EW} = (0.0215\kappa^4_{\lambda_{3H}} - 0.0324\kappa^3_{\lambda_{3H}} - 0.0019\kappa^2_{\lambda_{3H}}\kappa_{\lambda_{4H}} - 0.0043\kappa^2_{\lambda_{3H}} + 0.0151\kappa_{\lambda_{3H}}\kappa_{\lambda_{4H}} - 0.0211\kappa_{\lambda_{4H}})\ \ {\rm fb}$$

$\kappa_{\lambda_{3H}}$	$\kappa_{\lambda_{4H}}$	ggF			VBF		
		$\sigma^{\kappa_\lambda}_{\rm LO}$	$\sigma^{\kappa_\lambda}_{\rm NNLO-FT}$	$\delta\sigma^{\kappa_\lambda}_{\rm EW}$	$\sigma^{\kappa_\lambda}_{\rm LO}$	$\sigma^{\kappa_\lambda}_{\rm NNNLO}$	$\delta\sigma^{\kappa_\lambda}_{\rm EW}$
1	1	16.7	31.2	-0.225	1.71	1.69	-2.30×10^{-2}
3	1	8.59	18.4	1.28	3.59	3.53	8.35×10^{-1}
6	1	67.3	161	60.6	25.1	24.6	20.7
1	3	16.7	31.2	-0.393	1.71	1.69	-3.89×10^{-2}
1	6	16.7	31.2	-0.646	1.71	1.69	-6.27×10^{-2}
3	3	8.59	18.4	1.30	3.59	3.53	8.50×10^{-1}
6	6	67.3	161	61.0	25.1	24.6	20.7

The QCD corrections are significant in ggF, but not sensitive to κ_{3H}.

The EW corrections are 91% (82%) in ggF (VBF) for $\kappa_{3H} = 6$.

The dependence on λ_{4H} is weak.

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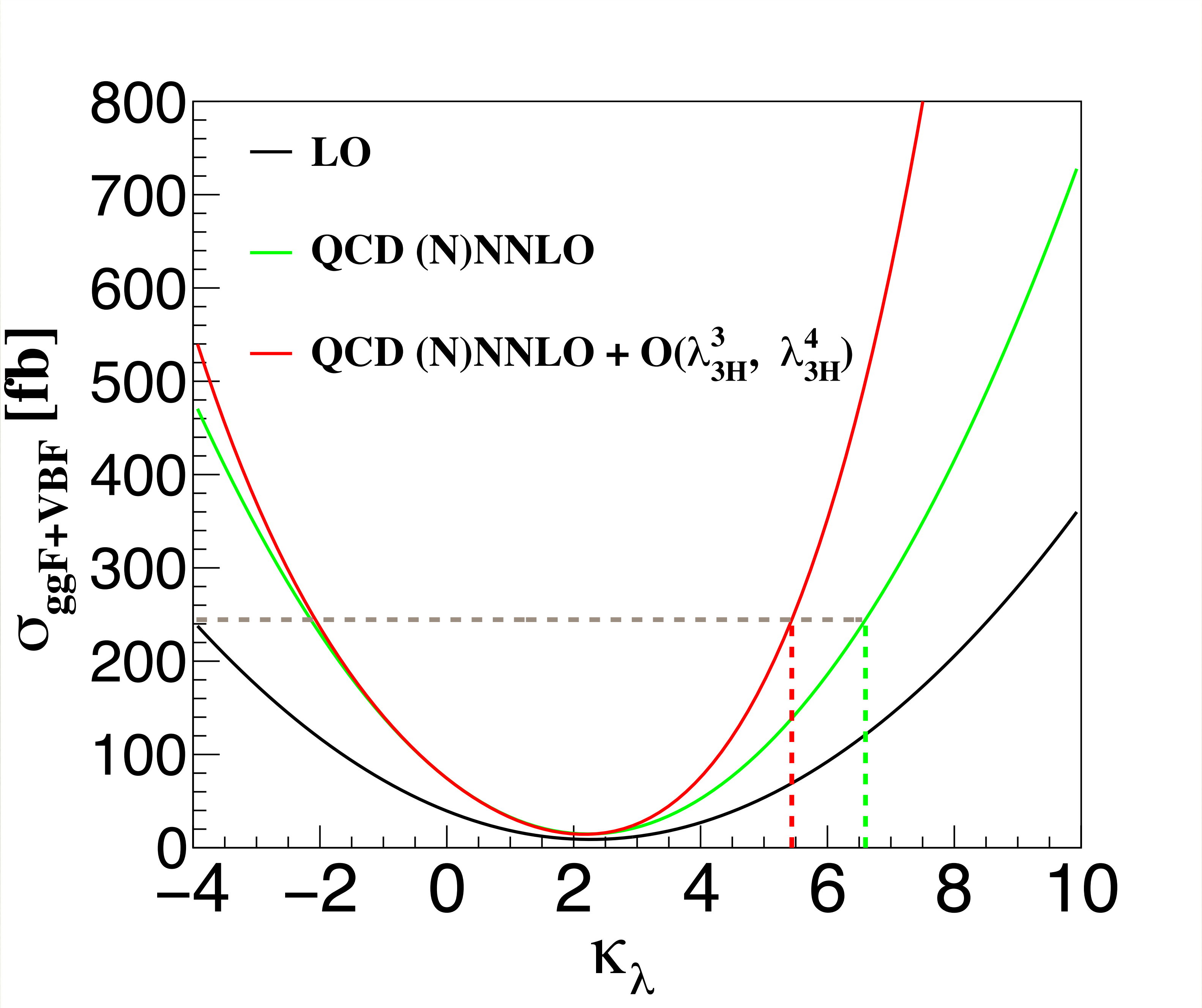
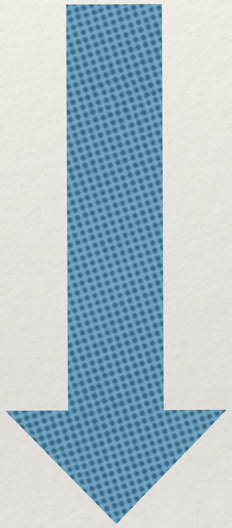
More stringent constraint



ATLAS (CMS) limit

6.6 (6.49)



5.4 (5.37)

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Summary

The SM is a master piece in human history. It has been tested by a lot of experiments at very high precision level.

However, the Higgs sector still needs more precise comparison between theories and experiments.

Higher-order quantum corrections provide more precise estimate of the dependence on Higgs self-couplings.

Thanks a lot for your attention!