TOPICS ON HIGGS PHYSICS

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Outline

1. Introduction to gauge symmetry
2. Higgs mechanism
3. Higgs production and decay
4. Higgs and new physics (naturalness, SUSY, DM)

1. Introduction to gauge symmetry

The discovery of the Dirac equation (1928) led to a reformulation for the theory of electronic and magnetic phenomenon, creating quantum electrodynamics (QED)—the first gauge theory of fundamental interactions.

$$S_{\text{QED}} = \int d^4x \left[i\overline{\psi}(x)\gamma^\mu D_\mu \psi(x) - m\overline{\psi}(x)\psi(x) - \frac{1}{4}\, F^{\mu\nu}(x)\, F_{\mu\nu}(x) \right]$$

with $D_\mu = \partial_\mu + ieQ_e A_\mu$, $Q_e = -1$. This has local gauge invariance under

$$\psi(x) \to \psi'(x) = e^{-ieQ_e\alpha}\, \psi(x), \qquad A_\mu(x) \to A'_\mu(x) = A_\mu(x) + \partial_\mu \alpha(x)$$

which is equivalent to the conservation of the Noether current

$$\partial_\mu J^\mu(x) = 0, \qquad J_\mu(x) = e\overline{\psi}(x)\gamma_\mu \psi(x)$$

1. Introduction to gauge symmetry

1899, Rutherford discovered alpha and beta radiation.

1901, Becquerel identified beta rays as high-energy electrons. These electrons have energies around an MeV, much larger than the binding energies of a few tens of keV at most. They cannot come from the atomic orbital electrons.

In 1932, Chadwick discovered the neutron. Heisenberg postulated the existence of the strong nuclear force. In 1935, Yukawa proposed a field theory.

$$\mathscr{L} = i\bar{N}\gamma^\mu\partial_\mu N - m\bar{N}N + \frac{1}{2}(\partial_\mu\phi)^2 - \frac{\mu^2}{2}\phi^2 - ig\bar{N}\gamma^5\sigma_i N\phi_i$$

The nucleon has a mass around GeV. So does the electron, if it is inside the nuclei.

The beta rays must be produced at the instant of interaction, which is not strong.

1. Introduction to gauge symmetry

1930, Pauli postulated an massless, neutral particle to ensure energy-momentum conservation in beta decays.

1934, Fermi put the ingredients together with the famous Fermi interaction.

$$S_\beta = \int d^4x G_W J_h^\mu(x) J_\mu^l(x), \quad J_h^\mu(x) = \bar{\psi}_p(x)\gamma^\mu\psi_n(x),\ J_\mu^l(x) = \bar{\psi}_e(x)\gamma_\mu\psi_\nu(x)$$

This is inspired by the QED process $e^+e^- \to \mu^+\mu^-$. The main difference is that the coupling is a constant, energy-independent. This theory agrees with the experimental results of the energy distribution of the beta particles, confirming Pauli's idea that the neutrino is massless.

1936, Gamow and Teller added an axial vector-axial vector current in order to explain many other cases of beta decay. Soon it was realized that this new interaction is universal, i.e., the same constant G_W was required.

1. Introduction to gauge symmetry

However, the Fermi theory breaks down at higher energies since the weak cross-section grows without limit, rendering the S-matrix non-unitary.

$$\sigma \sim \frac{G_W^2}{12\pi} E_{cm}^2$$

Solution needed: A new theoretical framework that preserves low-energy predictions while ensuring good high-energy behavior.

1949, intermediate vector boson (IVB) hypothesis by Lee, Rosenbluth, Yang.

$$\left(\frac{g^2}{E_{cm}^2 - M_W^2} \right)^2 \rightarrow (g^2/M_W^2)^2 \ when \ E_{cm} \ll M_W$$

Gives Fermi's constant

$$\left(\frac{g^2}{E_{cm}^2 - M_W^2} \right)^2 \rightarrow (g^2/E_{cm}^2)^2 \ when \ E_{cm} \gg M_W$$

Ensures perturbative unitarity

1. Introduction to gauge symmetry

However, quantization of a massive gauge boson shows that the propagator contains $g_{\mu\nu} - p_\mu p_\nu / M_W^2$. The first term has a good high-energy behavior. But the second momentum dependent term leads to bad behavior. The unitarity problem comes back.

Schwinger's Solution (1957): the weak interaction satisfies $p_\mu J^\mu = 0$. These are conserved currents, requiring an underlying gauge symmetry. Two gauge bosons are needed, $W^\pm$. He also proposed that the photon and $W^\pm$ form a triplet in an non-abelian theory, as Yang and Mills had shown in 1954. If this is true, he obtained a unified theory of electroweak interactions.

1. Introduction to gauge symmetry

The coupling between gauge bosons and electrons and neutrinos are

$$\mathscr{L}_W = \frac{g_2}{\sqrt{2}}\,\bar{e}(x)\gamma^\mu \nu_e(x) W_\mu^-(x) + \frac{g_2}{\sqrt{2}}\,\bar{\nu}_e(x)\gamma^\mu e(x) W_\mu^+(x) - \frac{g_2}{2}\,\bar{e}(x)\gamma^\mu e(x) W_\mu^0(x) + \frac{g_2}{2}\,\bar{\nu}_e(x)\gamma^\mu \nu_e(x) W_\mu^0(x)$$

To make the photon-neutrino coupling vanish while keeping electron-photon coupling requires a more sophisticated approach.

1961, Glashow extended his model by adding an extra $U(1)$ symmetry. The neutral coupling becomes

$$\mathscr{L}_{W,B}^0 = \frac{g_2}{2}\,\bar{\nu}_e(x)\gamma^\mu \nu_e(x) W_\mu^0(x) - \frac{g_2}{2}\,\bar{e}(x)\gamma^\mu e(x) W_\mu^0(x) - \frac{g_1}{2}\,\bar{\nu}_e(x)\gamma^\mu \nu_e(x) B_\mu^0(x) - \frac{g_1}{2}\,\bar{e}(x)\gamma^\mu e(x) B_\mu^0(x)$$

The two neutral gauge bosons are mixed states.

$$W_\mu^0 = Z_\mu(x)\cos\theta - A_\mu(x)\sin\theta, \quad B_\mu^0 = Z_\mu(x)\sin\theta + A_\mu(x)\cos\theta$$

1. Introduction to gauge symmetry

The new coupling between gauge bosons and electrons and neutrinos are

$$\mathscr{L}^0_{W,B} = \frac{1}{2}\left(g_2 \sin\theta - g_1 \cos\theta\right)\ \bar{\nu}_e(x)\gamma^\mu \nu_e(x)\ A_\mu(x) - \frac{1}{2}\left(g_2 \sin\theta + g_1 \cos\theta\right)\ \bar{e}(x)\gamma^\mu e(x)\ A_\mu(x)\ldots$$

Define $\tan\theta = g_1/g_2$, then there is no photon-neutrino coupling and $e = g_2 \sin\theta$.

Problem 1: If we replace the lepton doublet by a nucleon doublet, we would obtain

$$\mathscr{L}^0_{W,B} = \frac{1}{2}\left(g_2 \cos\theta - g_1 \sin\theta\right)\ \bar{p}(x)\gamma^\mu p(x)\ A_\mu(x) - \frac{1}{2}\left(g_2 \sin\theta + g_1 \cos\theta\right)\ \bar{n}(x)\gamma^\mu n(x)\ A_\mu(x) + \ldots$$

No photon-proton coupling but the neutron couples to a photon.

Problem 2: Why is the photon massless while $W^\pm$ are massive although they form a triplet?

1. Introduction to gauge symmetry

Gauge theory requires massless gauge bosons for consistency, but the weak interaction is mediated by massive W and Z bosons. How can we reconcile these seemingly contradictory requirements?

One approach is to add mass terms directly to the Lagrangian

$$\mathscr{L} = M_W^2 W_\mu^+ W^{-\mu} + \cdots$$

But such terms explicitly break gauge invariance and lead to non-renormalizable theories with bad high-energy behavior.

2. Higgs mechanism

How does one postulate a symmetry and also introduce terms that break it? This is not difficult to envisage for small breaking, but the W and Z masses are large—of order 100 GeV.

A similar problem plagued strong interaction theory. The nucleon mass (938 MeV) is large and cannot be attributed to explicit symmetry breaking of the global SU(2)×SU(2) symmetry.

Solution: Spontaneous symmetry breaking, discovered in condensed matter physics!

Key Insight from Superconductivity: In superconductors, the photon effectively acquires a mass below the critical temperature through spontaneous symmetry breaking of the gauge symmetry. This phenomenon—now called the Higgs mechanism—would prove to be the solution.

2. Higgs mechanism

In 1950, Landau and Ginzburg developed a theory of superconductivity where a dynamical variable (the order parameter) is close to a ground state that does not obey the symmetry of the Lagrangian. Below the critical temperature:

- The photon effectively acquires a mass
- The medium becomes a perfect conductor
- The medium becomes a perfect diamagnet (Meissner effect)

In 1957, Bardeen, Cooper, and Schrieffer provided the microscopic basis: the order parameter is the density of a Bose-Einstein condensate of paired electrons (Cooper pairs), forming quasi-bosons. The BCS ground state breaks the gauge symmetry of electromagnetism, which would otherwise preclude a photon mass.

2. Higgs mechanism

In 1960, Nambu and Jona-Lasinio constructed a theory based on BCS, with a nucleonic condensate $\langle \bar{\mathrm{N}}\mathrm{N} \rangle$ that breaks chiral $SU(2)_L \times SU(2)_R$ down to $SU(2)_V$ of isospin. And Gell-Mann and Levy created the simple sigma model.

$$\Phi(x) = \mathbb{I}\ \sigma(x) + i\ \overrightarrow{\mathbb{T}} \cdot \overrightarrow{\pi}(x)$$

The potential energy term of the form

$$V(\Phi) = -\mu^2 \Phi^\dagger \Phi + \lambda(\Phi^\dagger \Phi)^4$$

This potential breaks the SU(2) symmetry spontaneously and permits the nucleons to have large masses.

In 1962, Goldstone, Salam, and Weinberg proved: Whenever a continuous global (or local) symmetry is spontaneously broken, there will be massless bosons—now called Goldstone bosons.

2. Higgs mechanism

Problem for Electroweak Theory: A sigma model analogue for electroweak interactions would:

✓ Make vector bosons massive (except photon)

✗ Produce three massless scalars with interactions of the same strength

Such bosons would have shown up long before in cosmic rays or nuclear reactions!

Anderson's Clue (1963): In superconductors, the Goldstone degree of freedom actually reappears as a longitudinal mode of the photon, not as an independent massless boson. The two massless bosons "cancel," leaving a massive vector boson.

2. Higgs mechanism

The Higgs Mechanism (1964): Three groups arrived independently at the relativistic formulation:

- Englert and Brout (Brussels)
- Higgs (Edinburgh)
- Guralnik, Hagen, and Kibble (London)

The Anderson-Brout-Englert-Guralnik-Hagen-Kibble mechanism—or Higgs mechanism for short.

Three Miracles:

1. Gauge Bosons Acquires Mass
2. Real Scalar Mode Acquires Mass
3. Goldstone Mode Disappears

BROKEN SYMMETRIES AND THE MASSES OF GAUGE BOSONS

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In a recent note[1] it was shown that the Goldstone theorem,[2] that Lorentz-covariant field theories in which spontaneous breakdown of symmetry under an internal Lie group occurs contain zero-mass particles, fails if and only if the conserved currents associated with the internal group are coupled to gauge fields. The purpose of the present note is to report that, as a consequence of this coupling, the spin-one quanta of some of the gauge fields acquire mass; the longitudinal degrees of freedom of these particles (which would be absent if their mass were zero) go over into the Goldstone bosons when the coupling tends to zero. This phenomenon is just the relativistic analog of the plasmon phenomenon to which Anderson[3] has drawn attention: that the scalar zero-mass excitations of a superconducting neutral Fermi gas become longitudinal plasmon modes of finite mass when the gas is charged.

The simplest theory which exhibits this behavior is a gauge-invariant version of a model used by Goldstone[2] himself: Two real[4] scalar fields φ_1, φ_2 and a real vector field A_μ interact through the Lagrangian density

$$L = -\tfrac{1}{2}(\nabla\varphi_1)^2 - \tfrac{1}{2}(\nabla\varphi_2)^2 - V(\varphi_1^{\ 2} + \varphi_2^{\ 2}) - \tfrac{1}{4}F_{\mu\nu}F^{\mu\nu}, \qquad (1)$$

where

$$\nabla_\mu\varphi_1 = \partial_\mu\varphi_1 - eA_\mu\varphi_2,$$

$$\nabla_\mu\varphi_2 = \partial_\mu\varphi_2 + eA_\mu\varphi_1,$$

$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu,$$

e is a dimensionless coupling constant, and the metric is taken as $-+++$. L is invariant under simultaneous gauge transformations of the first kind on $\varphi_1 \pm i\varphi_2$ and of the second kind on A_μ. Let us suppose that $V'(\varphi_0^{\ 2}) = 0$, $V''(\varphi_0^{\ 2}) > 0$; then spontaneous breakdown of U(1) symmetry occurs. Consider the equations [derived from (1) by treating $\Delta\varphi_1$, $\Delta\varphi_2$, and A_μ as small quantities] governing the propagation of small oscillations about the "vacuum" solution $\varphi_1(x) = 0$, $\varphi_2(x) = \varphi_0$:

$$\partial^\mu\{\partial_\mu(\Delta\varphi_1) - e\varphi_0 A_\mu\} = 0, \qquad (2a)$$

$$\{\partial^2 - 4\varphi_0^{\ 2}V''(\varphi_0^{\ 2})\}(\Delta\varphi_2) = 0, \qquad (2b)$$

$$\partial_\nu F^{\mu\nu} = e\varphi_0\{\partial^\mu(\Delta\varphi_1) - e\varphi_0 A_\mu\}. \qquad (2c)$$

Equation (2b) describes waves whose quanta have (bare) mass $2\varphi_0\{V''(\varphi_0^{\ 2})\}^{1/2}$; Eqs. (2a) and (2c) may be transformed, by the introduction of new variables

$$B_\mu = A_\mu - (e\varphi_0)^{-1}\partial_\mu(\Delta\varphi_1),$$

$$G_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu = F_{\mu\nu}, \qquad (3)$$

into the form

$$\partial_\mu B^\mu = 0, \quad \partial_\nu G^{\mu\nu} + e^2\varphi_0^{\ 2}B^\mu = 0. \qquad (4)$$

Equation (4) describes vector waves whose quanta have (bare) mass $e\varphi_0$. In the absence of the gauge field coupling ($e = 0$) the situation is quite different: Equations (2a) and (2c) describe zero-mass scalar and vector bosons, respectively. In passing, we note that the right-hand side of (2c) is just the linear approximation to the conserved current: It is linear in the vector potential, gauge invariance being maintained by the presence of the gradient term.[5]

When one considers theoretical models in which spontaneous breakdown of symmetry under a semisimple group occurs, one encounters a variety of possible situations corresponding to the various distinct irreducible representations to which the scalar fields may belong; the gauge field always belongs to the adjoint representation.[6] The model of the most immediate interest is that in which the scalar fields form an octet under SU(3): Here one finds the possibility of two nonvanishing vacuum expectation values, which may be chosen to be the two $Y = 0$, $I_3 = 0$ members of the octet.[7] There are two massive scalar bosons with just these quantum numbers; the remaining six components of the scalar octet combine with the corresponding components of the gauge-field octet to describe

massive vector bosons. There are two $I = \frac{1}{2}$ vector doublets, degenerate in mass between $Y = \pm 1$ but with an electromagnetic mass splitting between $I_3 = \pm\frac{1}{2}$, and the $I_3 = \pm 1$ components of a $Y = 0$, $I = 1$ triplet whose mass is entirely electromagnetic. The two $Y = 0$, $I = 0$ gauge fields remain massless: This is associated with the residual unbroken symmetry under the Abelian group generated by Y and I_3. It may be expected that when a further mechanism (presumably related to the weak interactions) is introduced in order to break Y conservation, one of these gauge fields will acquire mass, leaving the photon as the only massless vector particle. A detailed discussion of these questions will be presented elsewhere.

It is worth noting that an essential feature of the type of theory which has been described in this note is the prediction of incomplete multiplets of scalar and vector bosons.[8] It is to be expected that this feature will appear also in theories in which the symmetry-breaking scalar fields are not elementary dynamic variables but bilinear combinations of Fermi fields.[9]

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[1] P. W. Higgs, to be published.

[2] J. Goldstone, Nuovo Cimento 19, 154 (1961); J. Goldstone, A. Salam, and S. Weinberg, Phys. Rev. 127, 965 (1962).

[3] P. W. Anderson, Phys. Rev. 130, 439 (1963).

[4] In the present note the model is discussed mainly in classical terms; nothing is proved about the quantized theory. It should be understood, therefore, that the conclusions which are presented concerning the masses of particles are conjectures based on the quantization of linearized classical field equations. However, essentially the same conclusions have been reached independently by F. Englert and R. Brout, Phys. Rev. Letters 13, 321 (1964): These authors discuss the same model quantum mechanically in lowest order perturbation theory about the self-consistent vacuum.

[5] In the theory of superconductivity such a term arises from collective excitations of the Fermi gas.

[6] See, for example, S. L. Glashow and M. Gell-Mann, Ann. Phys. (N.Y.) 15, 437 (1961).

[7] These are just the parameters which, if the scalar octet interacts with baryons and mesons, lead to the Gell-Mann–Okubo and electromagnetic mass splittings: See S. Coleman and S. L. Glashow, Phys. Rev. 134, B671 (1964).

[8] Tentative proposals that incomplete SU(3) octets of scalar particles exist have been made by a number of people. Such a rôle, as an isolated $Y = \pm 1$, $I = \frac{1}{2}$ state, was proposed for the κ meson (725 MeV) by Y. Nambu and J. J. Sakurai, Phys. Rev. Letters 11, 42 (1963). More recently the possibility that the σ meson (385 MeV) may be the $Y = I = 0$ member of an incomplete octet has been considered by L. M. Brown, Phys. Rev. Letters 13, 42 (1964).

[9] In the theory of superconductivity the scalar fields are associated with fermion pairs; the doubly charged excitation responsible for the quantization of magnetic flux is then the surviving member of a U(1) doublet.

SPLITTING OF THE 70-PLET OF SU(6)

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1. In a previous note,[1] hereafter called I, we proposed an expression for the mass operator responsible for lifting the degeneracies of spin-unitary spin supermultiplets [Eq. (31)-I]. The purpose of the present note is to apply this expression to the 70-dimensional representation of SU(6).

The importance of the 70-dimensional representation has already been underlined by Pais.[2] Since

$$\underline{35}\otimes\underline{56} = \underline{56}\oplus\underline{70}\oplus\underline{700}\oplus\underline{1134}, \qquad (1)$$

it follows that $\underline{70}$ is the natural candidate for accommodating the higher meson-baryon resonances. Furthermore, since the SU(3)⊗SU(2) content is

$$\underline{70} = (\underline{1},\underline{2}) + (\underline{8},\underline{2}) + (\underline{10},\underline{2}) + (\underline{8},\underline{4}), \qquad (2)$$

we may assume that partial occupancy of the $\underline{70}$ representation has already been established through the so-called γ octet[2] $(\frac{3}{2})^-$. Recent experiments appear to indicate that some $(\frac{1}{2})^-$ states may also be at hand.[3] With six masses at one's disposal, our formulas can predict the masses of all the other occupants of $\underline{70}$ and also provide a consistency check on the input. Our discussion of the $\underline{70}$ representation thus appears to be of immediate physical interest.

2. Higgs mechanism

Glashow-Salam-Weinberg Model:

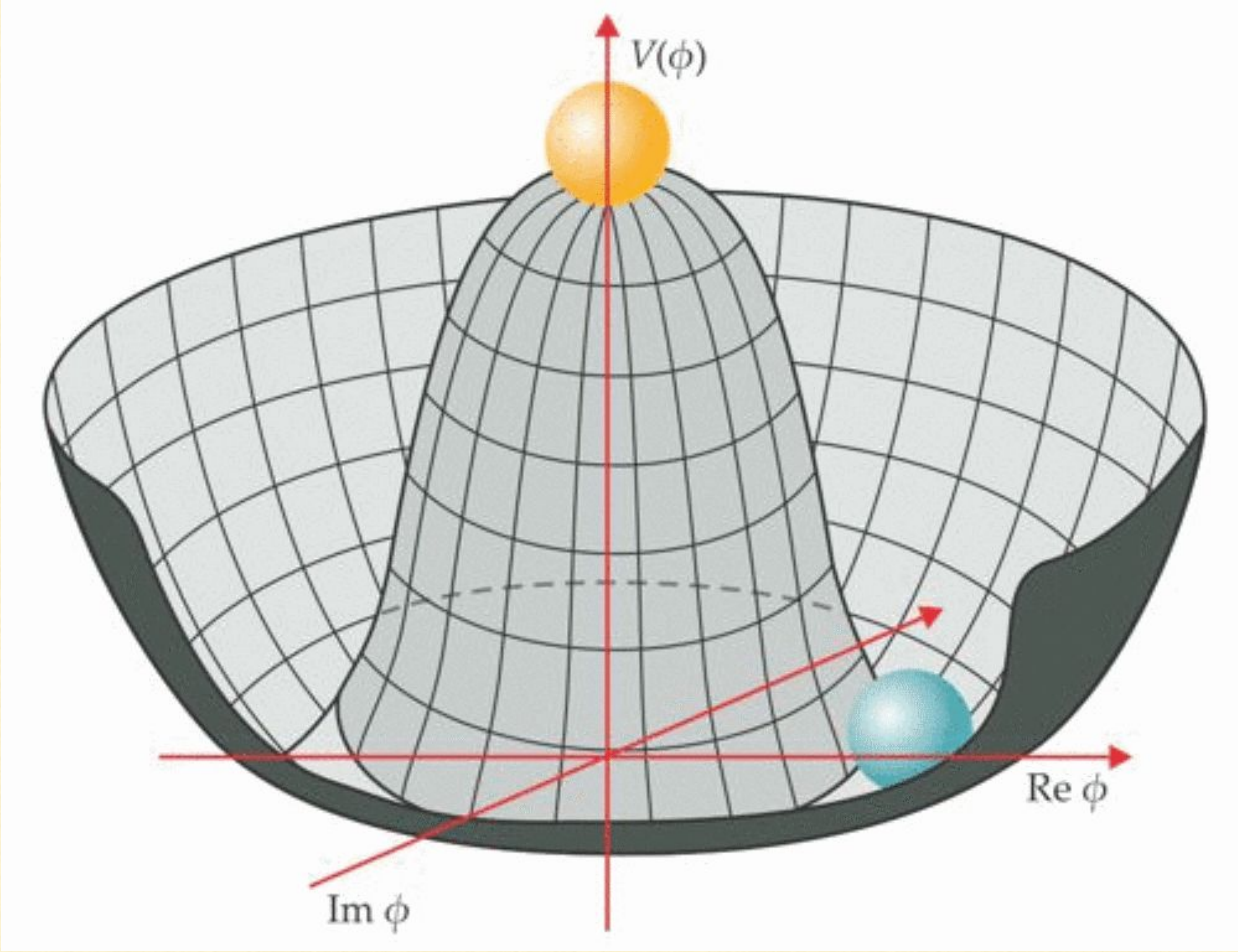
The Higgs field: $\Phi(x) = \begin{pmatrix} 0 \\ \eta(x) \end{pmatrix} \ e^{i \, \overrightarrow{\mathbb{T}} \cdot \overrightarrow{G}(x)} \rightarrow \begin{pmatrix} 0 \\ \eta(x) \end{pmatrix}$

And potential: $V(\Phi) = -\mu^2 \Phi^\dagger \Phi + \lambda(\Phi^\dagger \Phi)^4$

Define $\eta(x) = v/\sqrt{2} + h(x)/\sqrt{2}$ with $v = \mu/\sqrt{\lambda}$, The potential becomes

$$\mathscr{L}_V = -\mu^2 h^2 - \lambda v h^3 - \frac{1}{4}\lambda h^4 = -\frac{1}{2}m_h^2 h^2 - \sqrt{\lambda/2}m_h h^3 - \frac{1}{4}\lambda h^4$$

The Higgs boson mass $m_h = \sqrt{2}\mu = \sqrt{2\lambda}v$. The trilinear self-coupling is $\lambda_3 = \sqrt{\lambda/2}m_h$ and the quartic self-coupling is $\lambda_4 = \lambda/4$.



$V(\phi)$
Re ϕ
Im ϕ

2. Higgs mechanism

The covariant derivative of the Higgs field:

$$D_\mu \Phi(x) = (\partial_\mu - ig\mathbb{W}^\mu - \frac{1}{2}g'\mathbb{I}B_\mu)\Phi(x)$$

And potential: $V(\Phi) = -\mu^2\Phi^\dagger\Phi + \lambda(\Phi^\dagger\Phi)^4$

Define $\eta(x) = v/\sqrt{2} + H(x)/\sqrt{2}$ with $v = \mu/\sqrt{\lambda}$, gauge bosons obtain mass

$$\mathscr{L}_{V,m} = \begin{pmatrix} 0 & v/\sqrt{2} \end{pmatrix} \left(g\,\mathbb{W}^\mu + \frac{g'}{2}\mathbb{I}\,B^\mu \right) \left(g\,\mathbb{W}_\mu + \frac{g'}{2}\mathbb{I}\,B_\mu \right) \begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix}$$

$$= \frac{g^2v^2}{8}\left(W_1^\mu - iW_2^\mu\right)\left(W_{1\mu} + iW_{2\mu}\right) + \frac{v^2}{8}\begin{pmatrix} W_3^\mu & B^\mu \end{pmatrix} \begin{pmatrix} g^2 & -gg' \\ -gg' & g'^2 \end{pmatrix} \begin{pmatrix} W_{3\mu} \\ B_\mu \end{pmatrix}$$

2. Higgs mechanism

Define the complex fields: $W_\mu^\pm = \frac{1}{\sqrt{2}}(W_{1\mu} \mp iW_{2\mu})$

and $Z_\mu = \frac{gW_{3\mu} - g'B_\mu}{\sqrt{g^2 + g'^2}}$, $A_\mu = \frac{g'W_{3\mu} + gB_\mu}{\sqrt{g^2 + g'^2}}$, then the mass terms become

$\mathscr{L}_{V,m} = \frac{g^2v^2}{4}W^{+\mu}W_\mu^- + \frac{v^2}{8}(g^2 + g'^2)Z^\mu Z_\mu$. So,
$M_W = gv/2, M_Z = \sqrt{g^2 + g'^2}v/2, M_\gamma = 0.$

The mixing angle is determined by $M_W = M_Z g/\sqrt{g^2 + g'^2} = M_Z \cos\theta_W$.

The electron charge $e = gg'/\sqrt{g^2 + g'^2} = g\sin\theta_W$.

2. Higgs mechanism

Now $\tan\theta_W = g'/g$, which is precisely Glashow's relation, but now it emerges from spontaneous symmetry breaking, not fine-tuning! The massless gauge boson (the photon) does not couple to the neutrino.

The charged current interaction:

$$\mathscr{L}_{cc} = \frac{g}{2\sqrt{2}} \left[\overline{\nu}_e(x)\gamma^\mu \left(1-\gamma_5\right) e(x) W_\mu^+(x) + \mathrm{H.c.}\right]$$

In the low energy limit, $\dfrac{G_F}{\sqrt{2}} = \dfrac{g^2}{8M_W^2}$.

2. Higgs mechanism

The electromagnetic interaction: take $D_\mu = \partial_\mu - ig\mathbb{W} - ig'Y/2B_\mu$, then

$$\mathcal{L}_{em} = \frac{1}{2} g \sin\theta_W \left(1 + Y_L\right) \ \overline{\nu_{eL}}\gamma^\mu \nu_{eL} A_\mu + \frac{1}{2} g \sin\theta_W \left(-1 + Y_L\right) \ \overline{e_L}\gamma^\mu e_L A_\mu + \frac{1}{2} g \sin\theta_W Y_e \ \overline{e_R}\gamma^\mu e_R A_\mu$$

We have $Y_L = -1, \quad Y_e = -2, \quad g\sin\theta_W = e$.

The neutral current interaction:

$$\mathcal{L}_{nc} = \frac{g}{4\cos\theta_W} \overline{\nu_e}\gamma^\mu \left(1 - \gamma_5\right) \nu_e Z_\mu - \frac{g}{4\cos\theta_W} \bar{e}\gamma^\mu \left(1 - 4\sin^2\theta_W - \gamma_5\right) e Z_\mu$$

The neutral current was observed in 1973 at CERN. This discovery was the first crucial experimental evidence for the existence of the Z boson, which would eventually be directly observed at CERN in 1983.

Problems with the Glashow-Weinberg-Salam

1. We cannot write the interaction for a nucleon doublet. Otherwise, we have neutron-photon coupling.

2. The fermions are not allowed to have a mass term $m_e(\bar{e}_L e_R + \bar{e}_R e_L)$. e_L has weak isospin $T_3 = -1/2, Y_L = -1$ while e_R has $T_3 = 0, Y_e = -2$.

3. The axial vector current is not conserved due to the chiral anomaly. The anomaly is proportional to $tr[\gamma^5 t^a \{t^b, t^c\}]$. For a $U(1)$ and two $SU(2)_L$ bosons, $tr[\tau^a \tau^b Y] = \delta^{ab} \sum_{fL} Y_{fL}$. For a theory containing only particles ν_{eL}, e_L, e_R, there is anomaly because $-1 - 1 - 2 = -4$

The first and third problems were solved after the introduction of quarks.

Problems with the Glashow-Weinberg-Salam

The second problem is solved by writing down the Yukawa coupling:

$$\mathscr{L}_m = -y_e \bar{L}_L \Phi e_R + H.c.$$

After symmetry-breaking, we have the mass term

$$\mathscr{L}_m = -y_e \frac{v}{\sqrt{2}} \bar{e}_L e_R + H.c. = -m_e(\bar{e}_L e_R + H.c.)$$

And the Yukawa coupling of the fermions:

$$\mathscr{L}_m = -\frac{m_e}{v} \bar{e}_L h e_R + H.c.$$

2. Higgs mechanism

The Higgs mass is a free parameter in the Glashow-Weinberg-Salam model. The constraint can be derived from the W boson scattering.

$$W^+ + W^- \to W^+ + W^-$$

In the high energy limit, due to the Goldstone equivalence theorem, the dominant contribution is from the longitudinal mode. The amplitude has the form

$$\mathscr{M}_L(s,t) \approx -\frac{2M_H^2}{v^2} - \frac{M_H^4}{v^2}\left(\frac{1}{s-M_H^2} + \frac{1}{t-M_H^2}\right) \approx -\frac{2M_H^2}{v^2}$$

2. Higgs mechanism

The S-wave ($J = 0$) partial wave amplitude is

$$a_0 = \frac{1}{32\pi}\int_{-1}^{1} d\cos\theta \mathscr{M}(s, \cos\theta) = \frac{1}{32\pi}\cdot 2 \cdot \left(-\frac{2M_H^2}{v^2}\right) = -\frac{M_H^2}{8\pi v^2}$$

The unitarity of the S-matrix requires $|a_0| \leq 1$. Thus,

$$M_H \leq \sqrt{8\pi} v \approx 1200\,\text{GeV}$$

Vacuum stability

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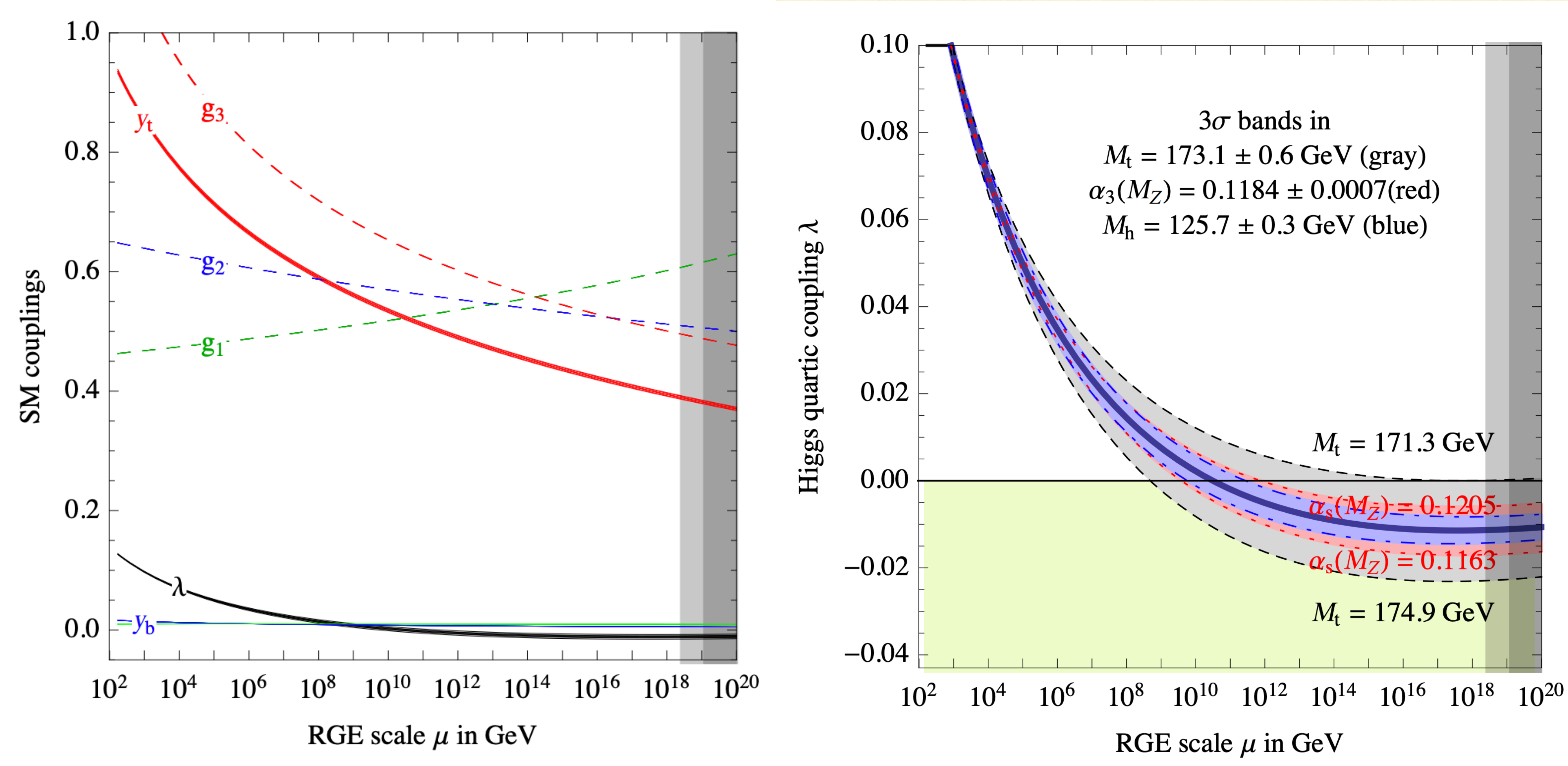
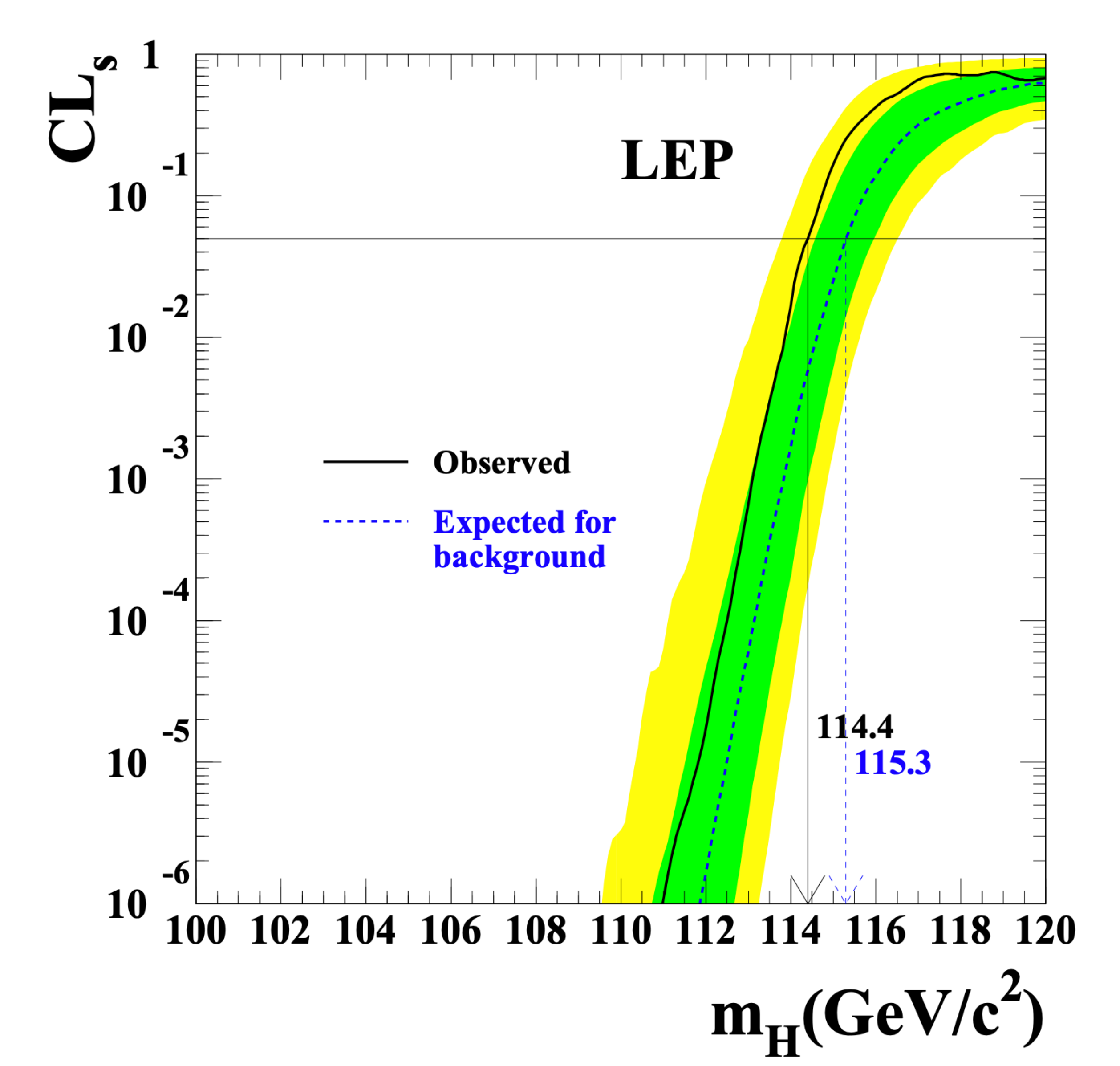


3. Higgs production and decay

Direct search at the large electron–positron (LEP) collider (189-209 GeV)



Production modes:

$e^+e^- \to ZH$

$e^+e^- \to e^+e^-H, \nu\bar{\nu}H$

Decay modes:

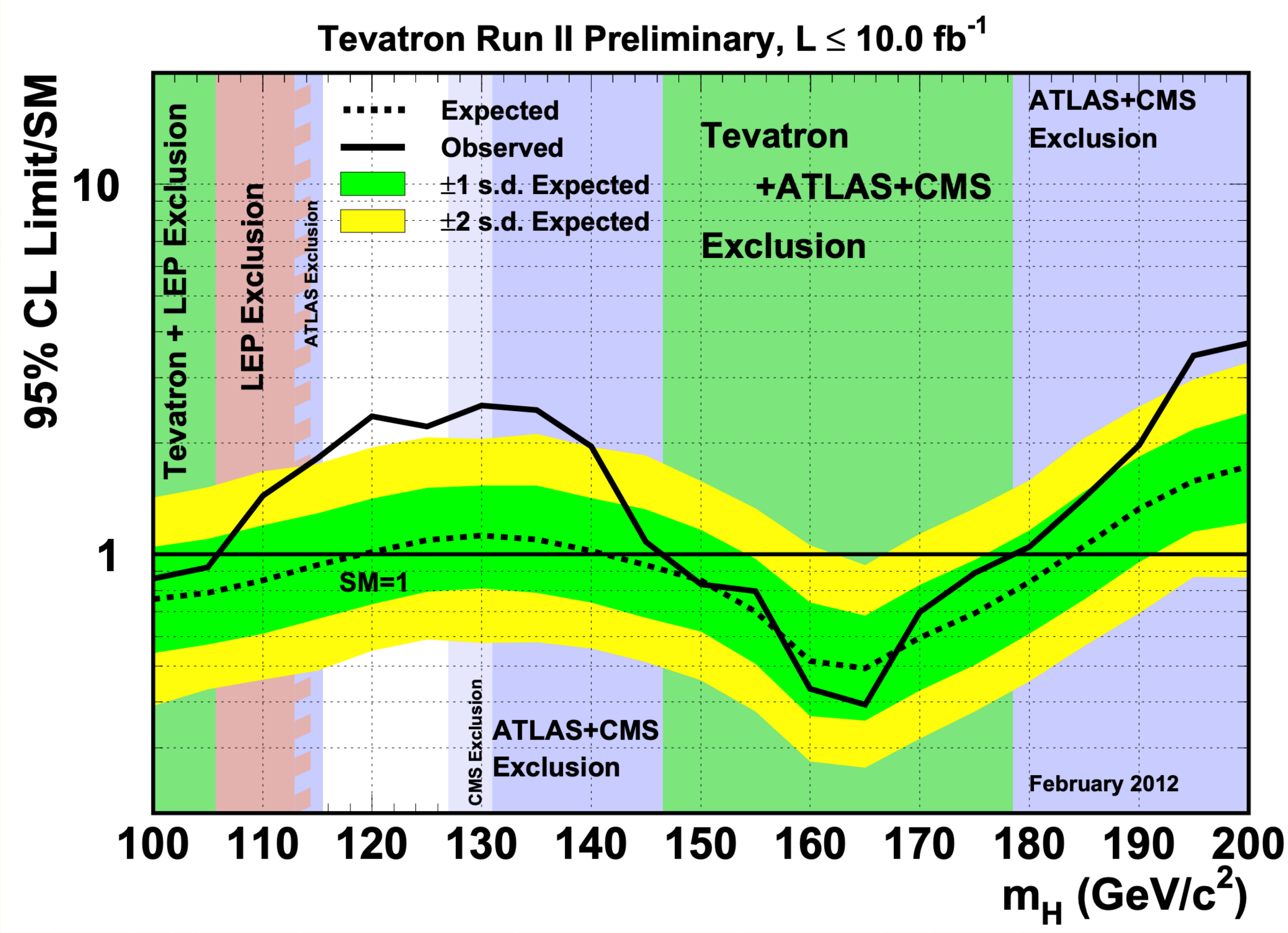
$H \to b\bar{b}$

$H \to \tau^+\tau^-$

hep-ex/0306033

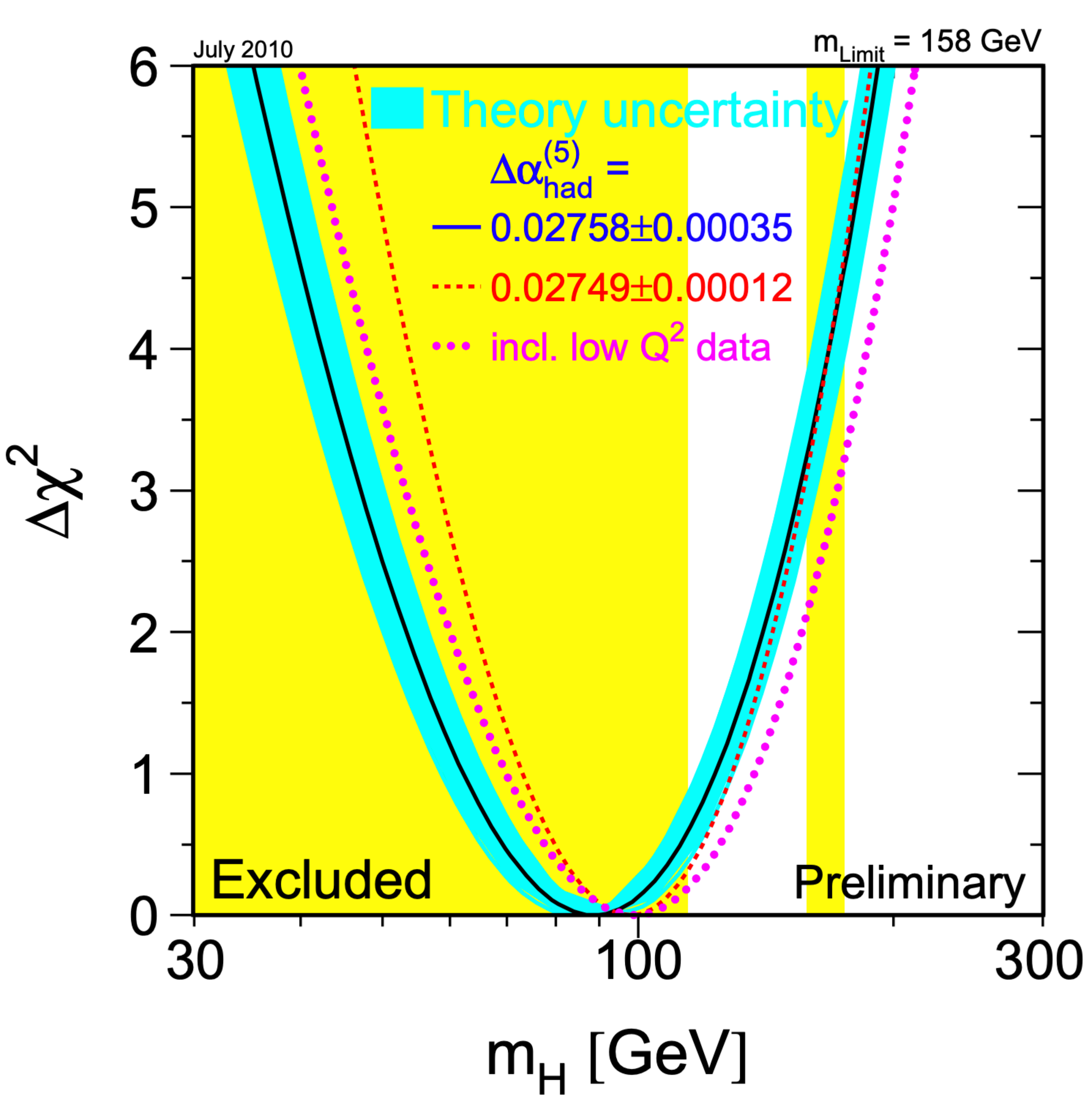
3. Higgs production and decay

Direct search at the Fermilab TeVatron (1.96 TeV)



1203.3774

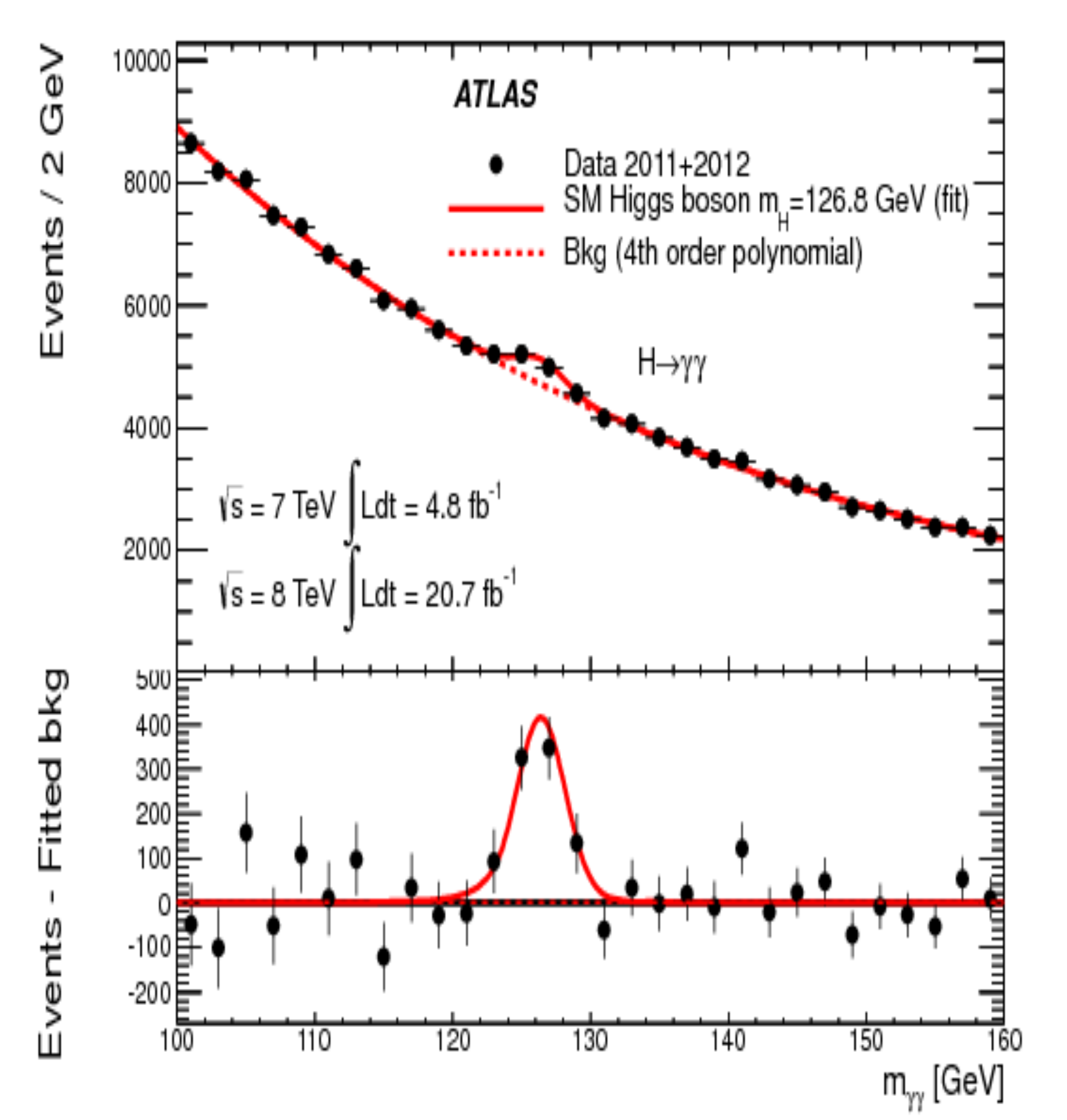
3. Higgs production and decay

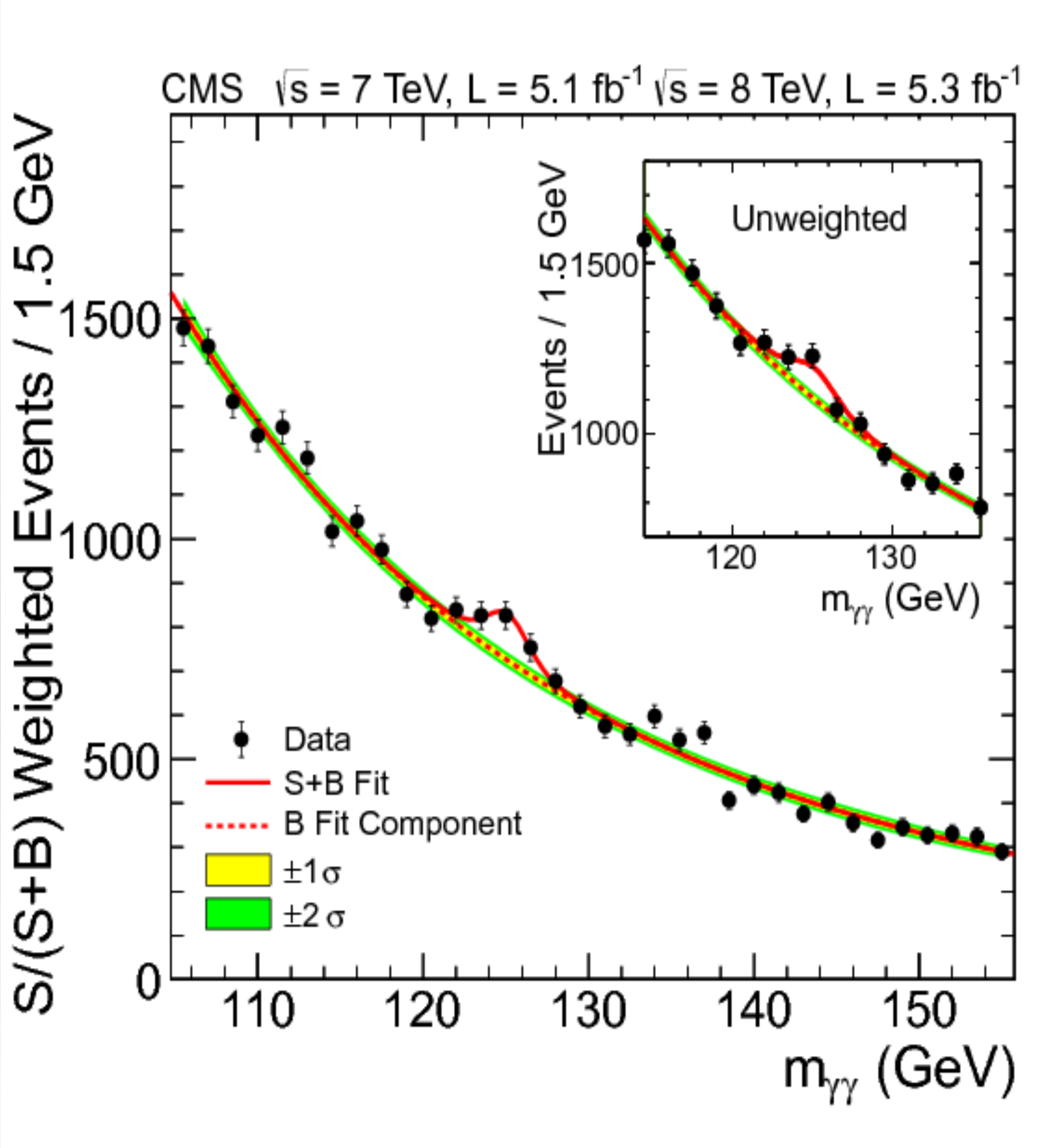


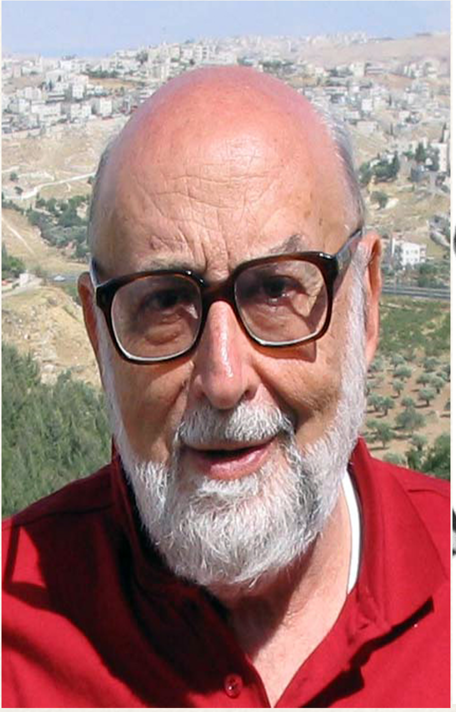
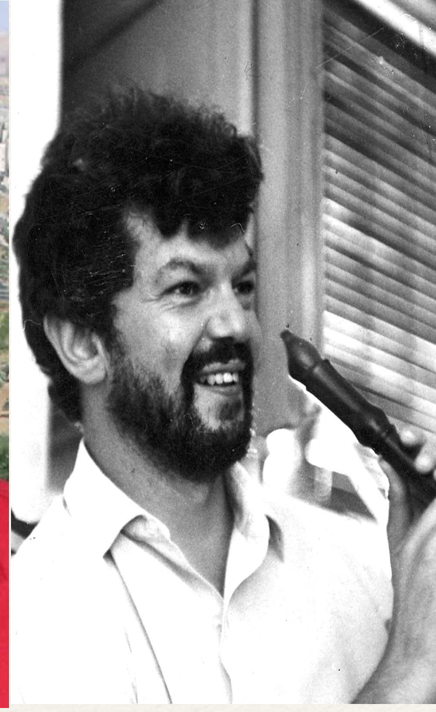
Electroweak precision data

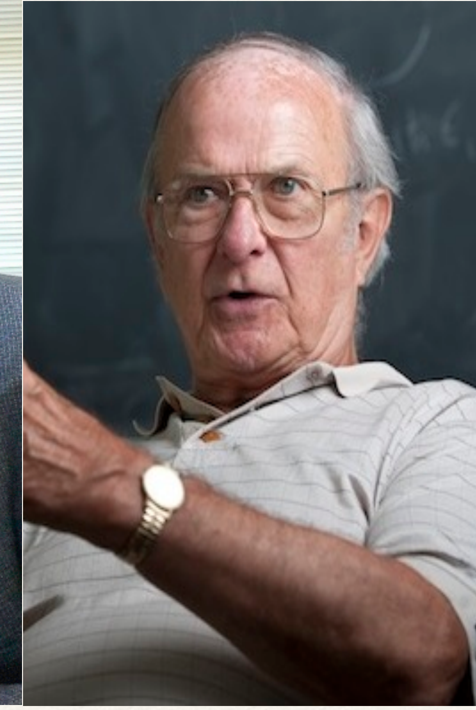
CERN-PH-EP-2010-095

Discovery in 2012





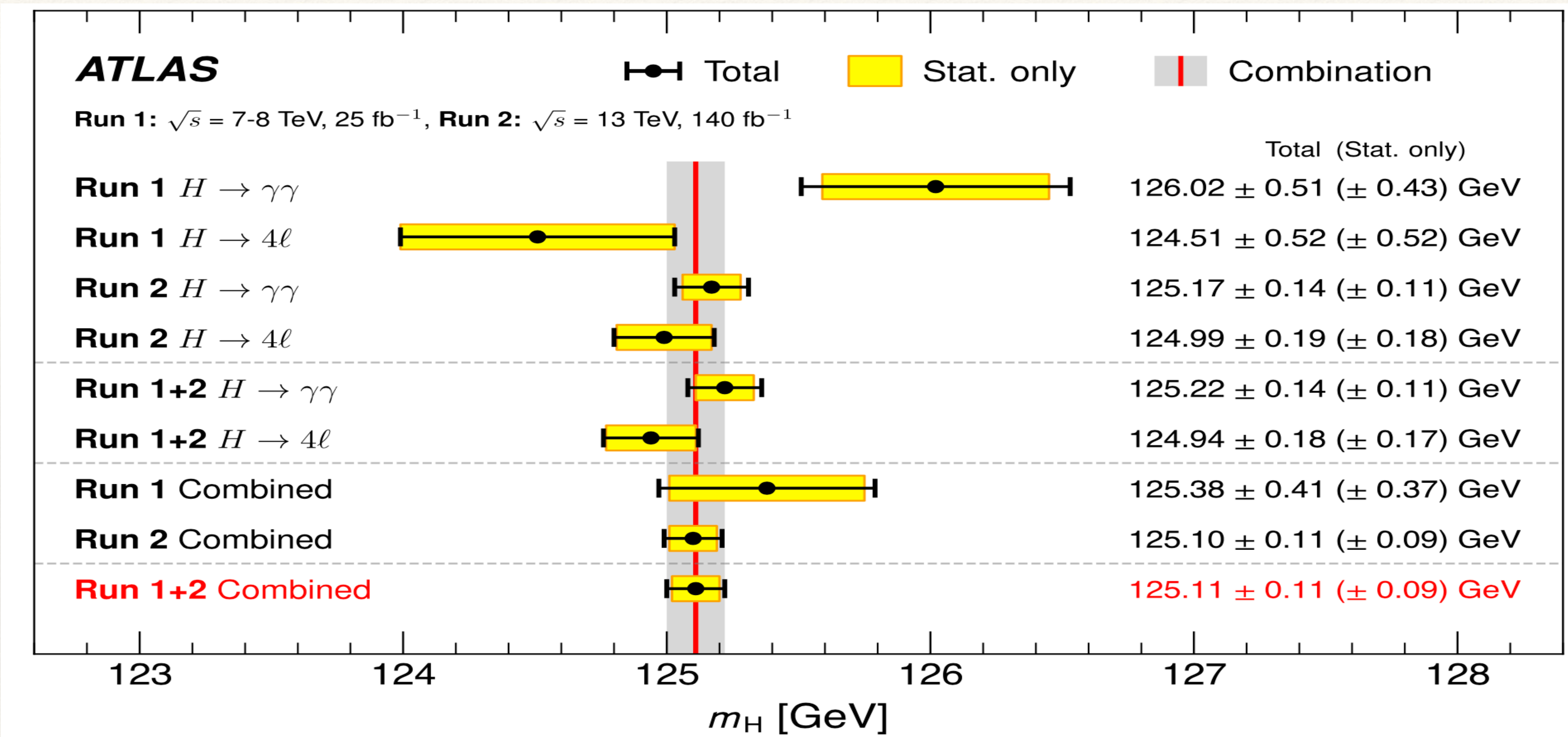




François Englert and Peter Higgs were awarded the 2013 Nobel Prize in Physics "for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles."

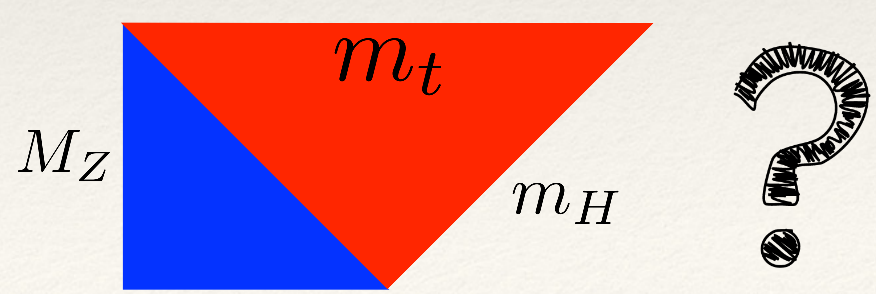
Robert Brout, Englert's co-author, had died in 2011.
Peter Higgs died in 2024.

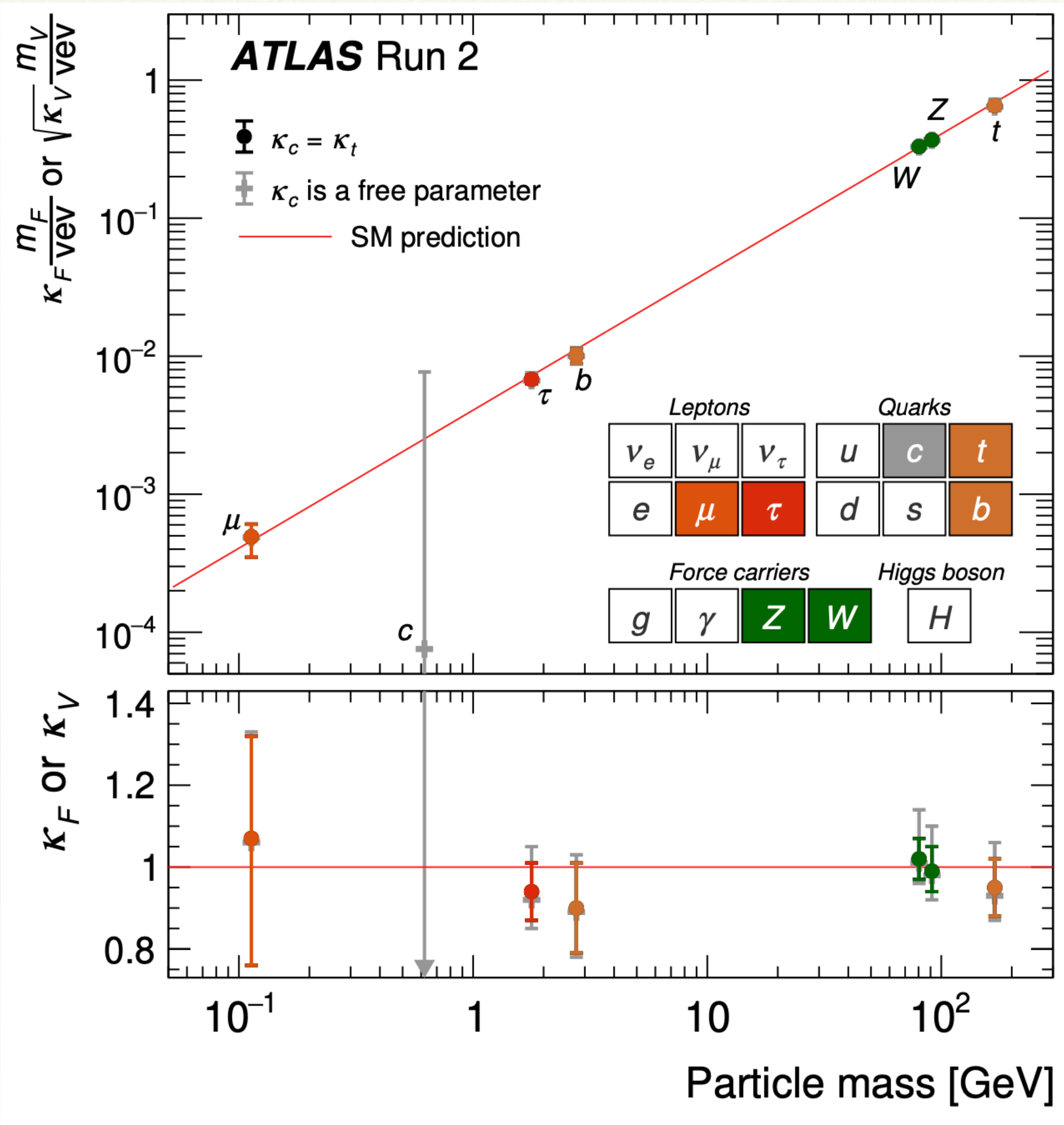
With the Higgs discovery, the Standard Model was complete. All particles predicted by the theory had been observed, and their properties measured with remarkable precision.

How precise is our understanding?



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





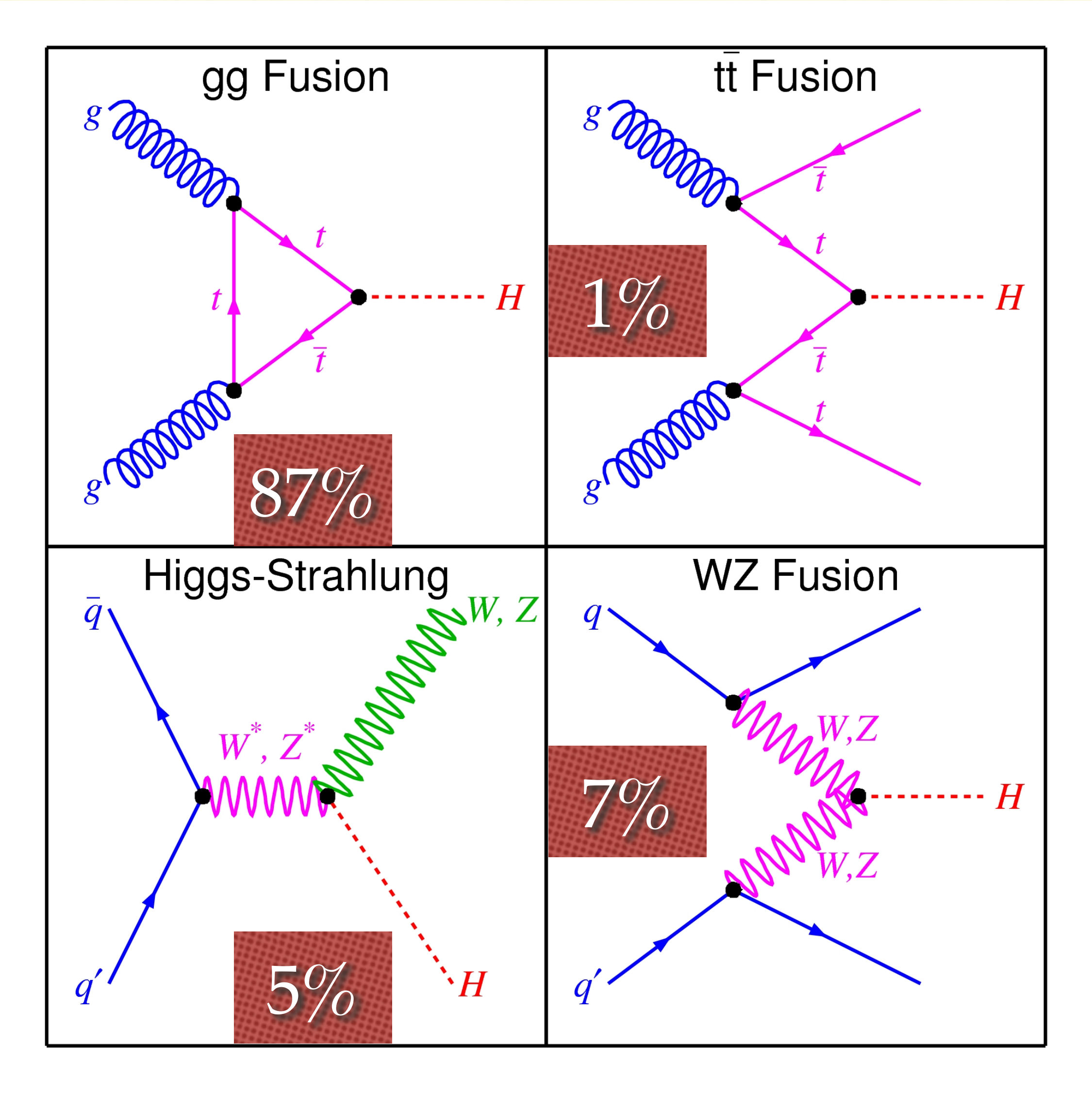
So far, the H(125) properties are consistent with the SM expectation!

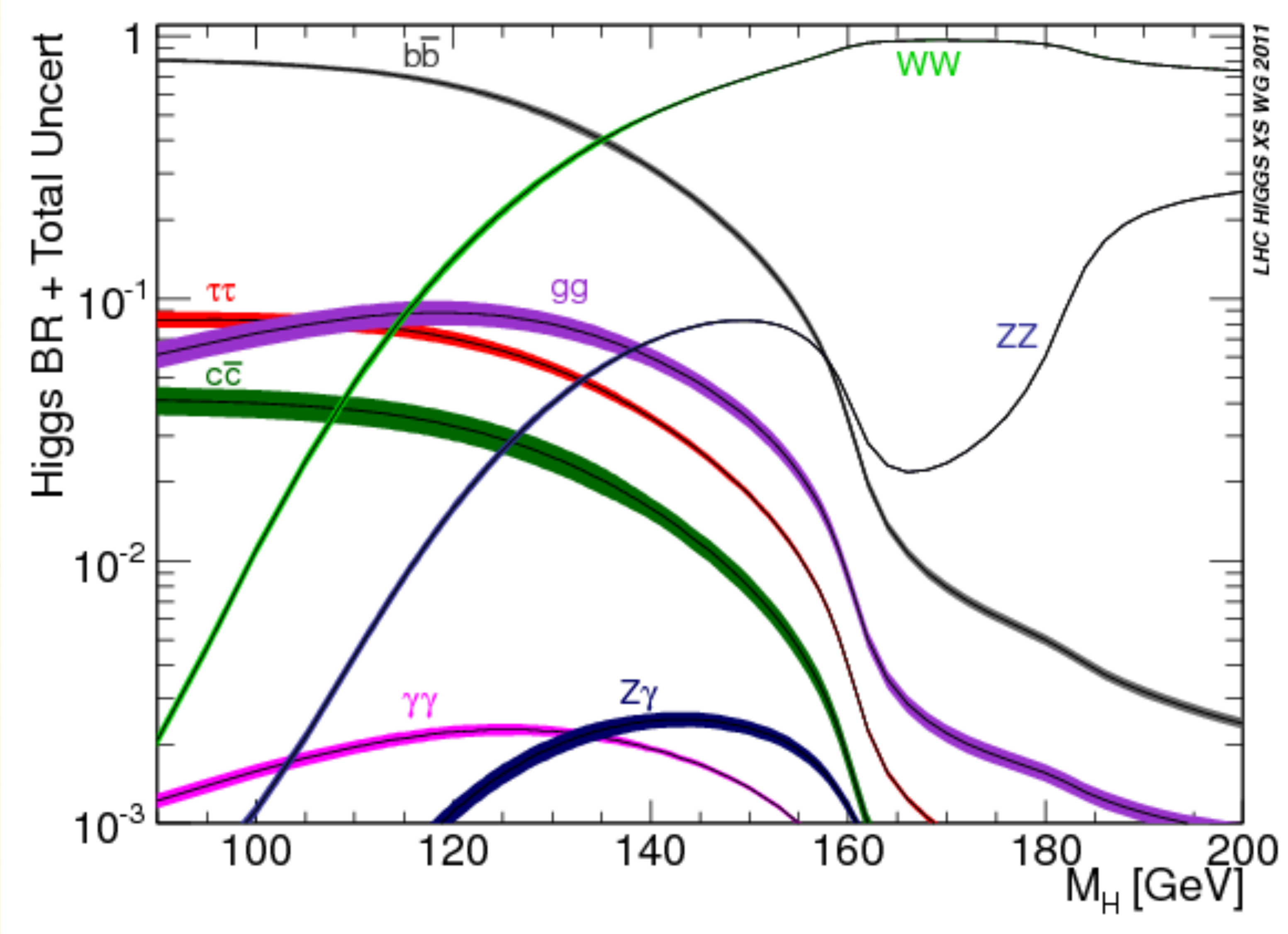
Its couplings with SM particles are proportional to their masses; Higgs mechanism

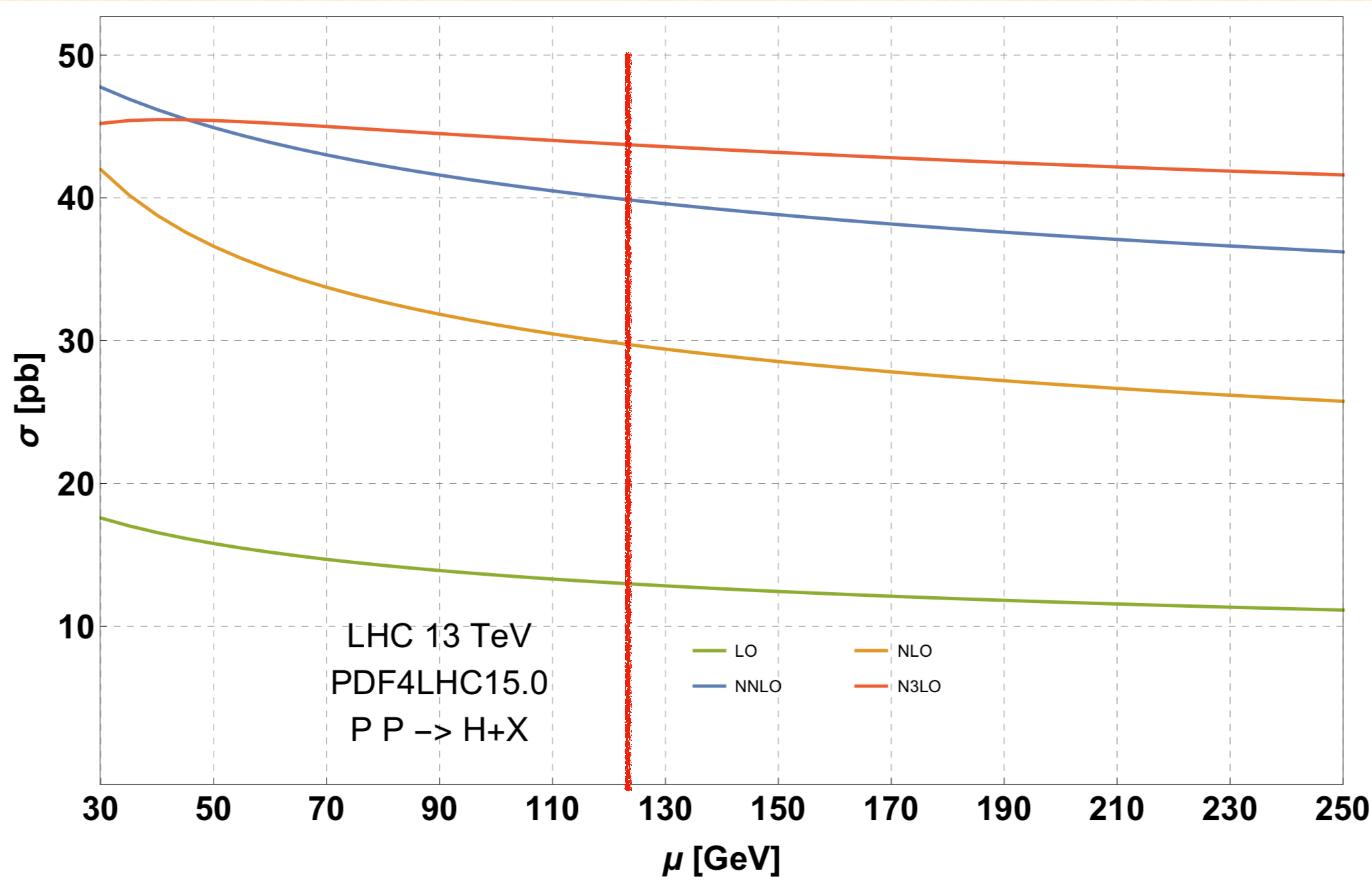
existence of a “fifth force” different from gravity

Nature 607(2022)52

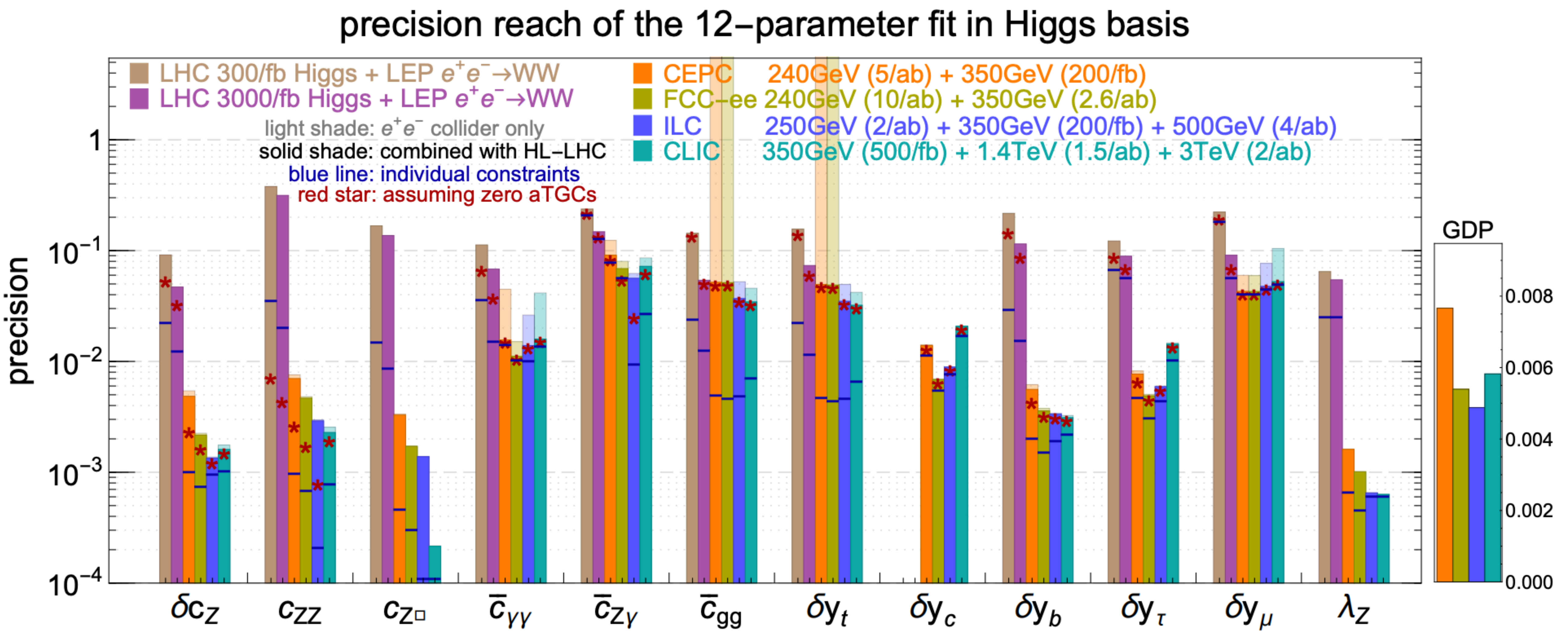
Higgs boson production and decay at the LHC







arXiv:1802.00833



- Assuming the following run plans (no official plan for CEPC 350 GeV run)
  - CEPC 240 GeV(5/ab) + 350 GeV(200/fb)
  - FCC-ee 240 GeV(10/ab) + 350 GeV(2.6/ab)
  - ILC 250 GeV(2/ab) + 350 GeV(200/fb) + 500 GeV(4/ab)
  - CLIC 350 GeV(500/fb) + 1.4 TeV(1.5/ab) + 3 TeV(2/ab)

From Jiayin Gu

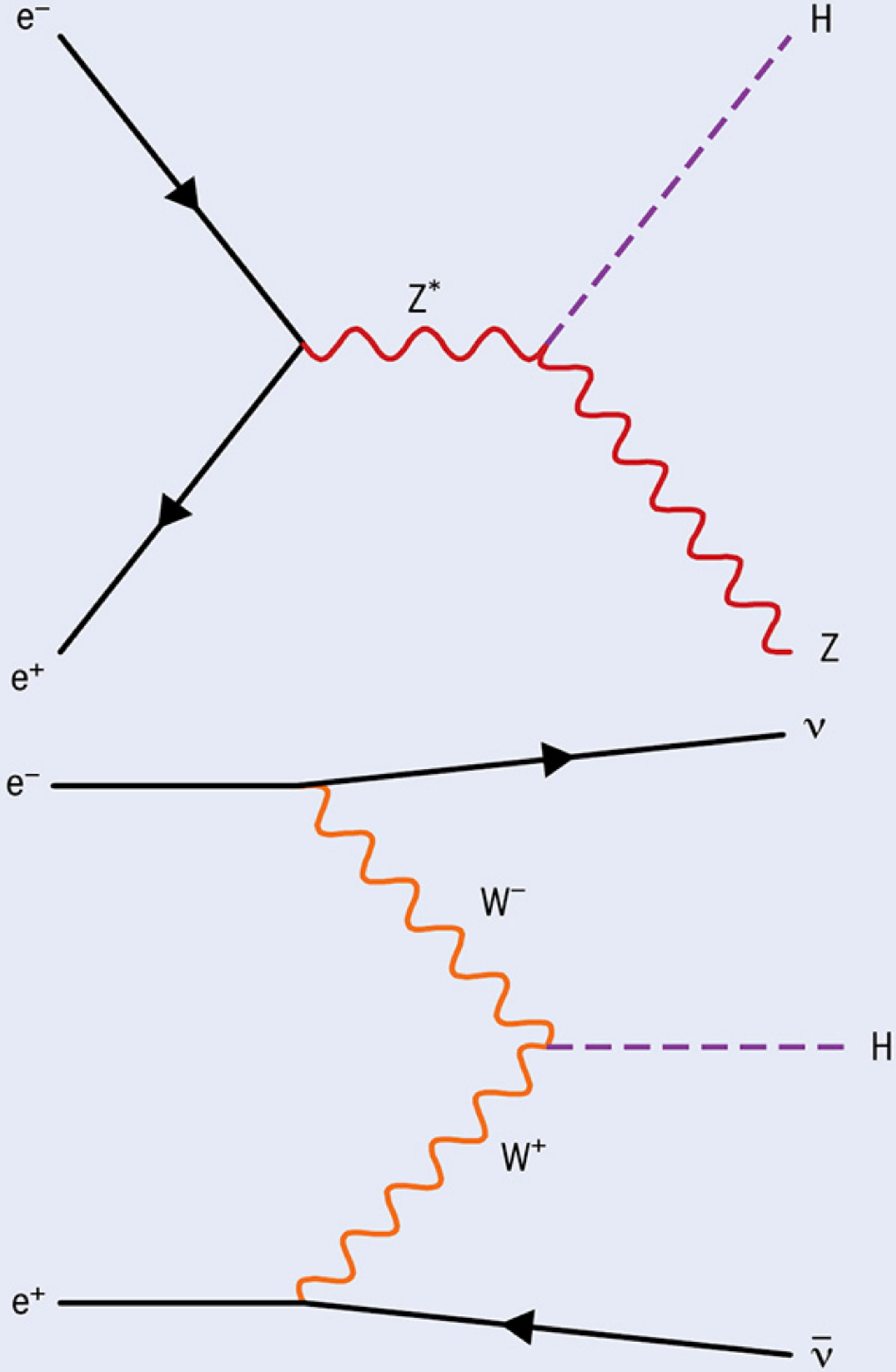
$\sqrt{s}$	240 GeV		365 GeV	
channel	**ZH**	**WW → H**	**ZH**	**WW → H**
ZH → any	±0.31		±0.52	
γH → any	±150			
H → bb	±0.21	±1.9	±0.38	±0.66
H → cc	±1.6	±19	±2.9	±3.4
H → ss	±120	±990	±350	±280
H → gg	±0.80	±5.5	±2.1	±2.6
H → $\tau\tau$	±0.58		±1.2	±5.6 (*)
H → $\mu\mu$	±11		±25	
H → WW*	±0.80		±1.8 (*)	±2.1 (*)
H → ZZ*	±2.5		±8.3 (*)	±4.6 (*)
H → $\gamma\gamma$	±3.6		±13	±15
H → Zγ	±11.8		±22	±23
H → $\nu\nu\nu\nu$	±25		±77	
H → inv.	$< 5.5 \times 10^{-4}$		$< 1.6 \times 10^{-3}$	
H → dd	$< 1.2 \times 10^{-3}$			
H → uu	$< 1.2 \times 10^{-3}$			
H → bs	$< 3.1 \times 10^{-4}$			
H → bu	$< 2.2 \times 10^{-4}$			
H → sd	$< 2.0 \times 10^{-4}$			
H → cu	$< 6.5 \times 10^{-4}$			

DM?

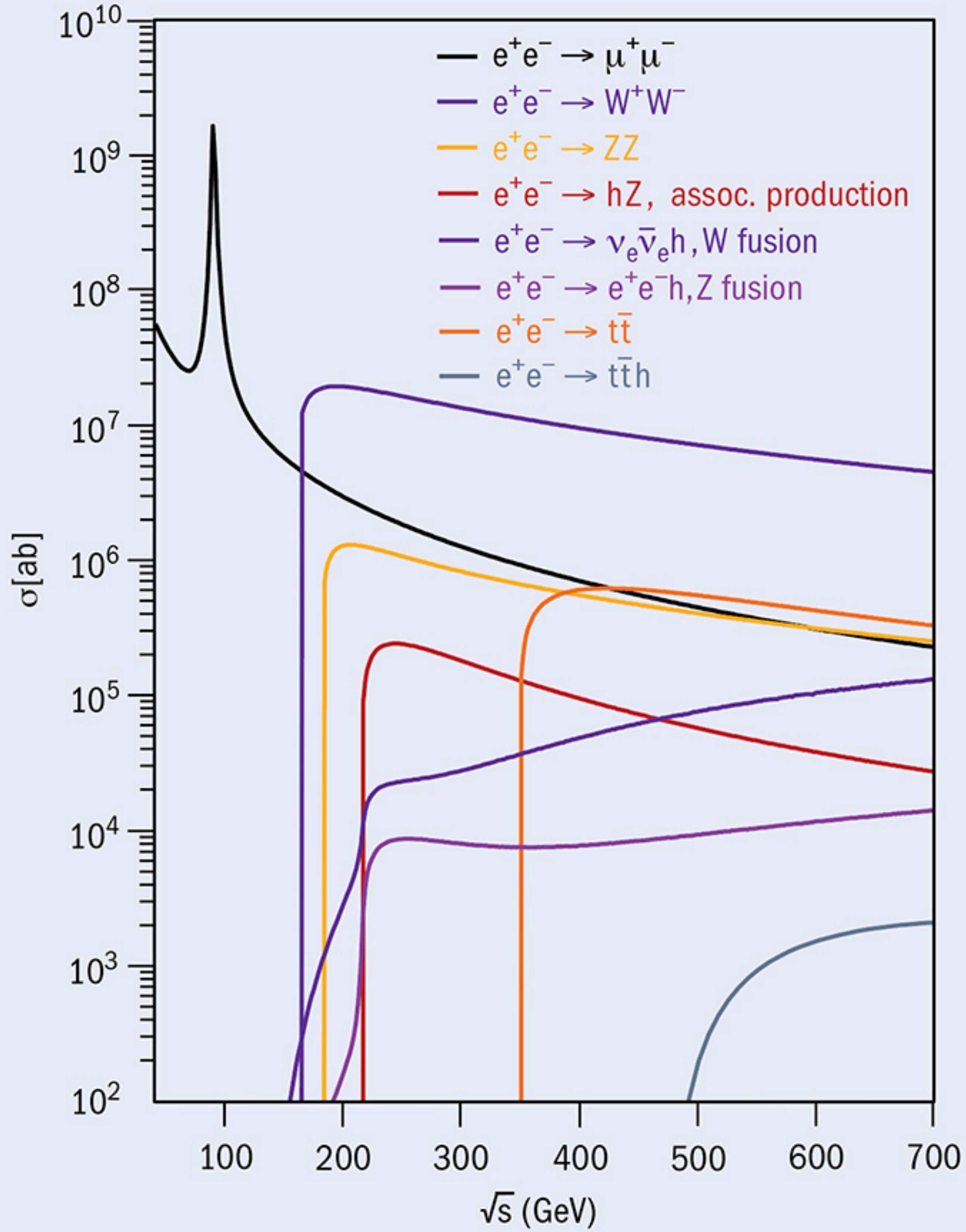
NP?

HEWT summary

(*) analyses ongoing, results scaled from FCC CDR



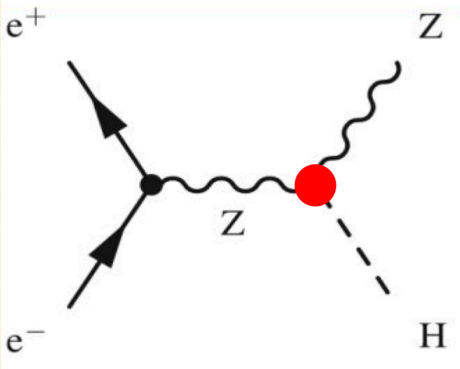
e⁻
H
Z*
e⁺
Z
e⁻
ν
W⁻
H
W⁺
e⁺
ν̄



$e^+e^- \to \mu^+\mu^-$
$e^+e^- \to W^+W^-$
$e^+e^- \to ZZ$
$e^+e^- \to hZ$, assoc. production
$e^+e^- \to \nu_e\bar{\nu}_e h$, W fusion
$e^+e^- \to e^+e^-h$, Z fusion
$e^+e^- \to t\bar{t}$
$e^+e^- \to t\bar{t}h$
σ[ab]
$\sqrt{s}$ (GeV)
10^{10}
10^9
10^8
10^7
10^6
10^5
10^4
10^3
10^2
100
200
300
400
500
600
700

Higgs boson production and decay at electron colliders

Measurements of Higgs total width, and all Higgs couplings at the LHC are model-dependent.



Measurements are model independent at e^+e^- colliders.

$$\sigma(ZH) \times B(H \to XX) \propto g^2_{HZZ} \times \frac{g^2_{HXX}}{\Gamma_H}$$

$$\Gamma_H \propto \frac{\sigma(ZH)^2}{\sigma(ZH, H \to ZZ)}$$, and it is expected that $\delta\Gamma_H = 0.78\,\%$

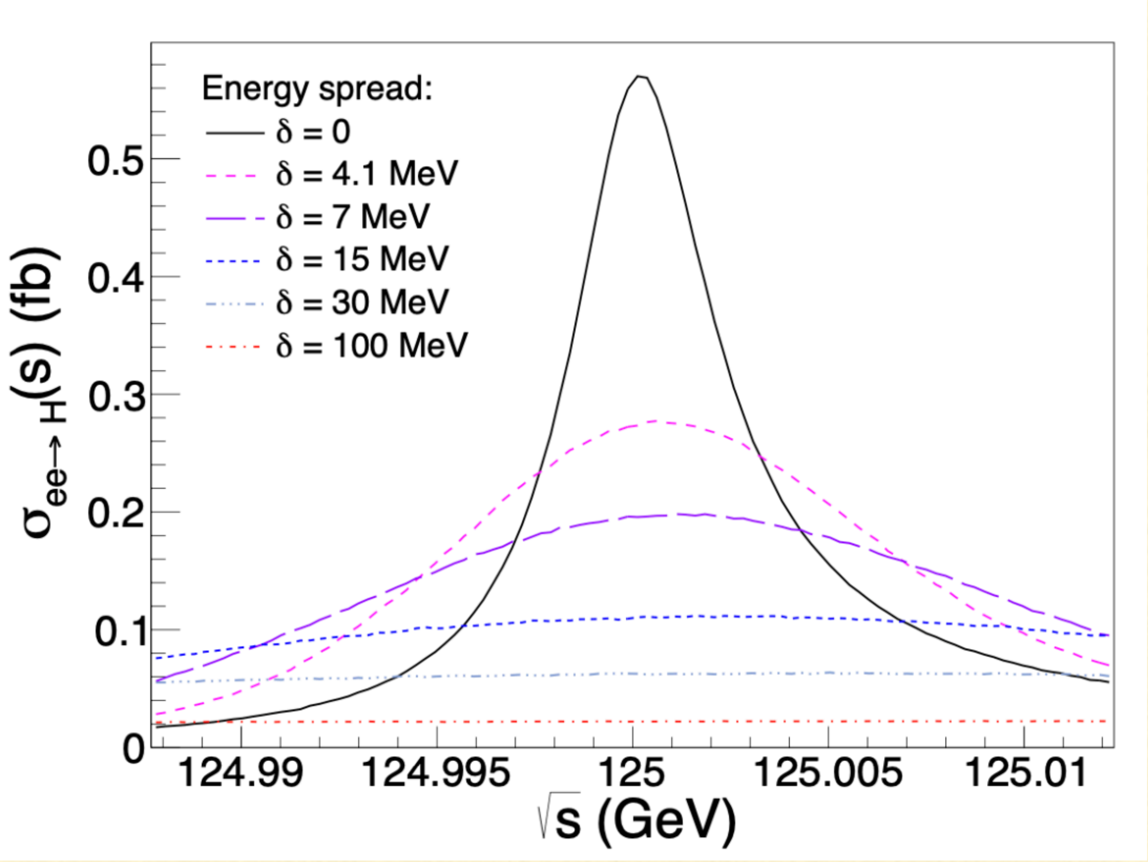
With Γ_H determined, each $B(H \to XX)$ measurement can be used to determine g_{HXX} couping.

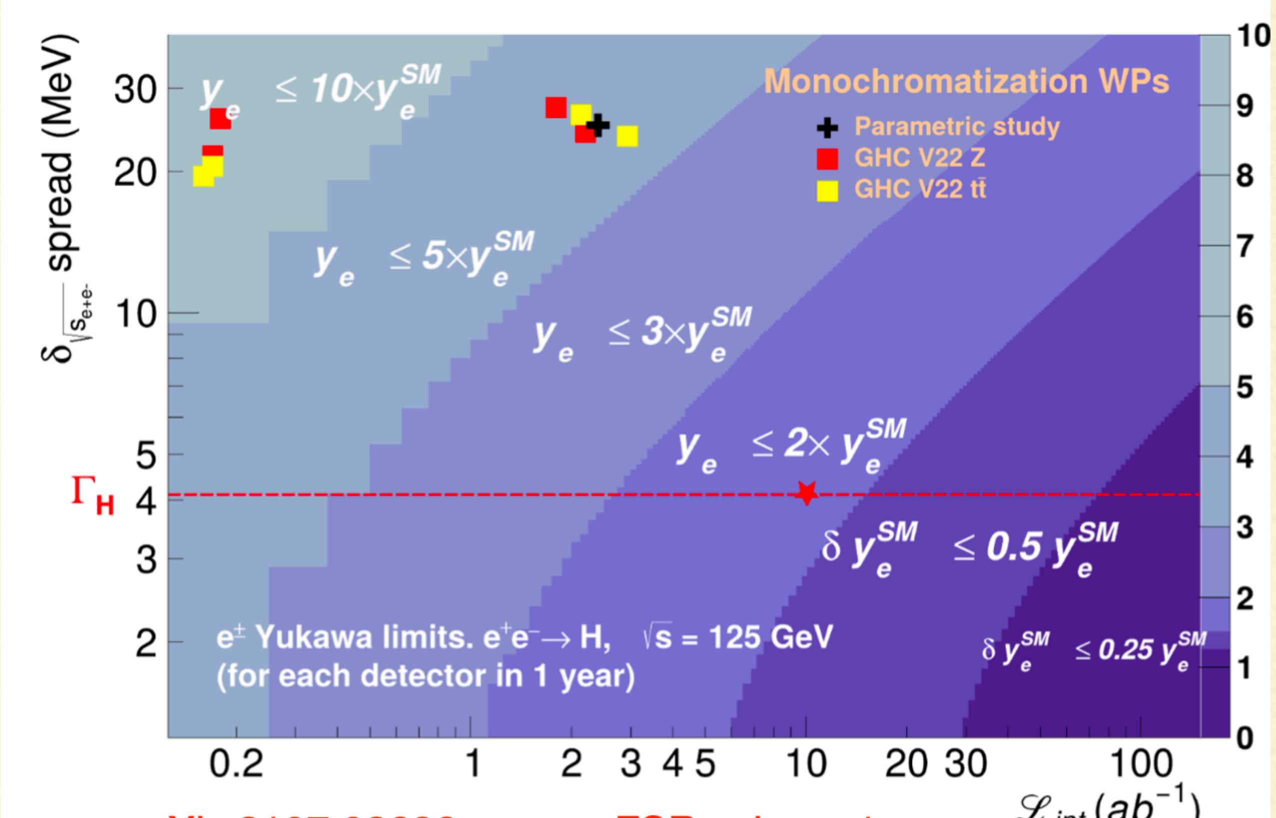
Higgs boson production and decay at electron colliders

Resonant Higgs production at 125 GeV provides the possibility to probe the electron Yukawa coupling, $B(H \to ee) \sim \mathcal{O}(10^{-9})$

No $Z \to gg$

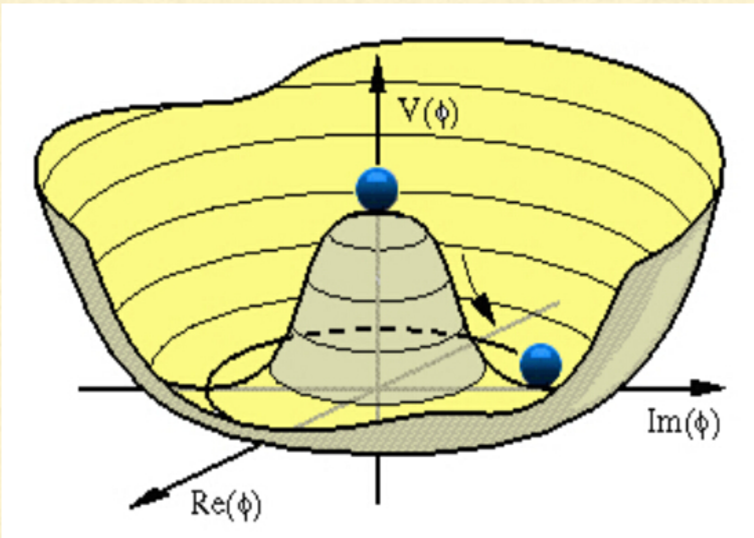
1.64 fb	→	0.57 fb(ISR)	→	0.28 fb	vs. $\sigma(ee \to Z) \sim \mathcal{O}(10^5)$ fb



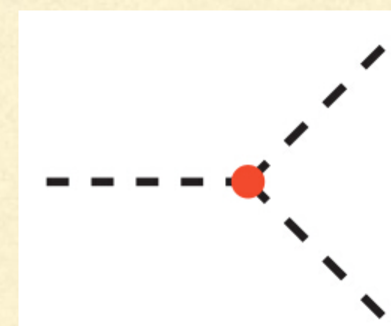


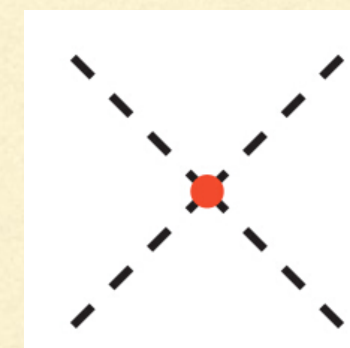
arXiv 2107.02686 FSR volume 1

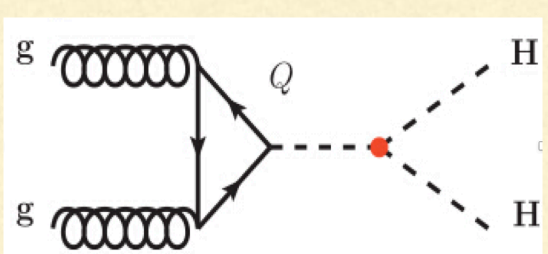
$$V(\phi) = -m^2|\phi|^2 + \lambda|\phi|^4$$

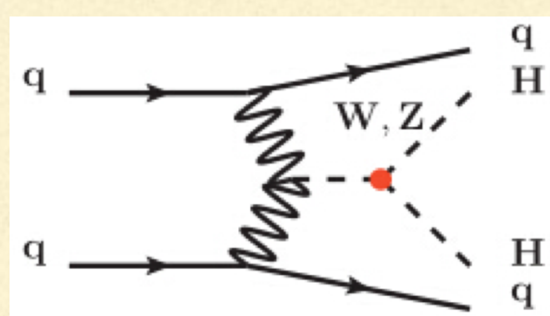


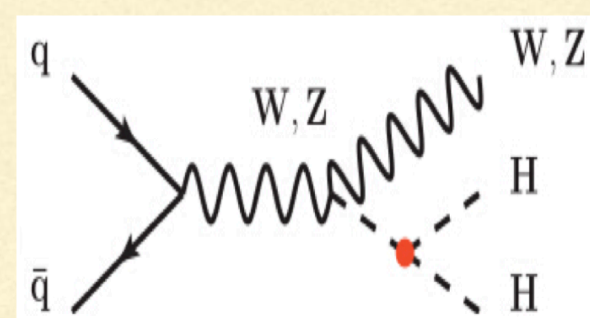
$$\phi = \begin{pmatrix} 0 \\ \frac{v + H(x)}{\sqrt{2}} \end{pmatrix} \Rightarrow V(H) = \frac{1}{2}M_H^2 H^2 + \frac{1}{2}\frac{\mathbf{M_H^2}}{\mathbf{v}}\mathbf{H^3} + \frac{1}{8}\frac{M_H^2}{v^2}H^4$$

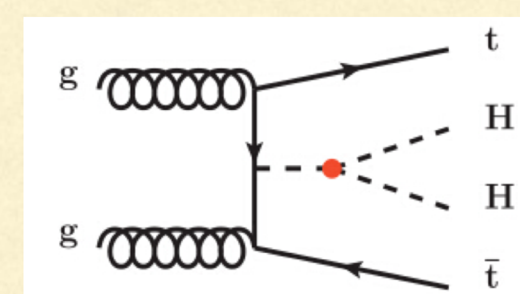


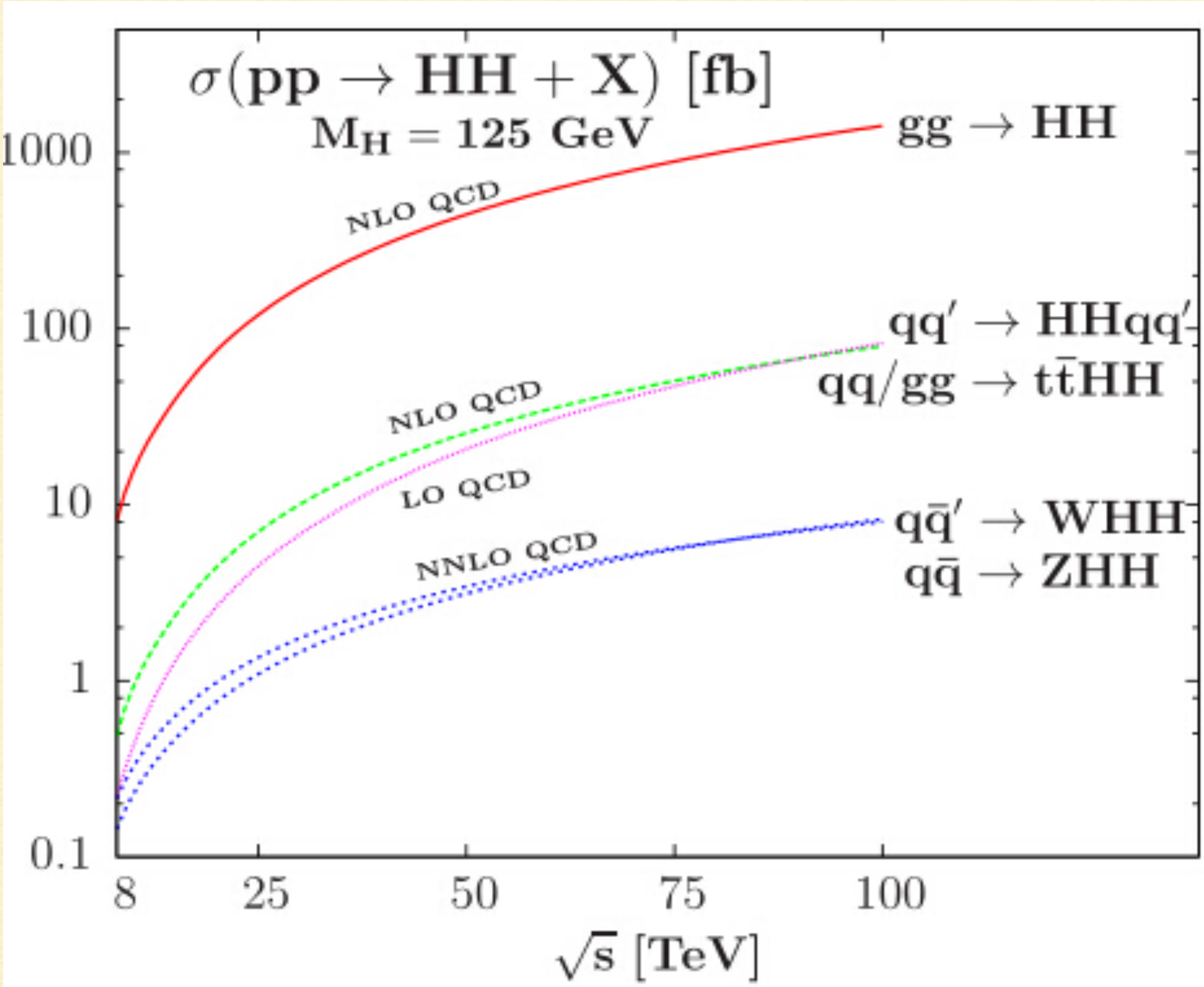




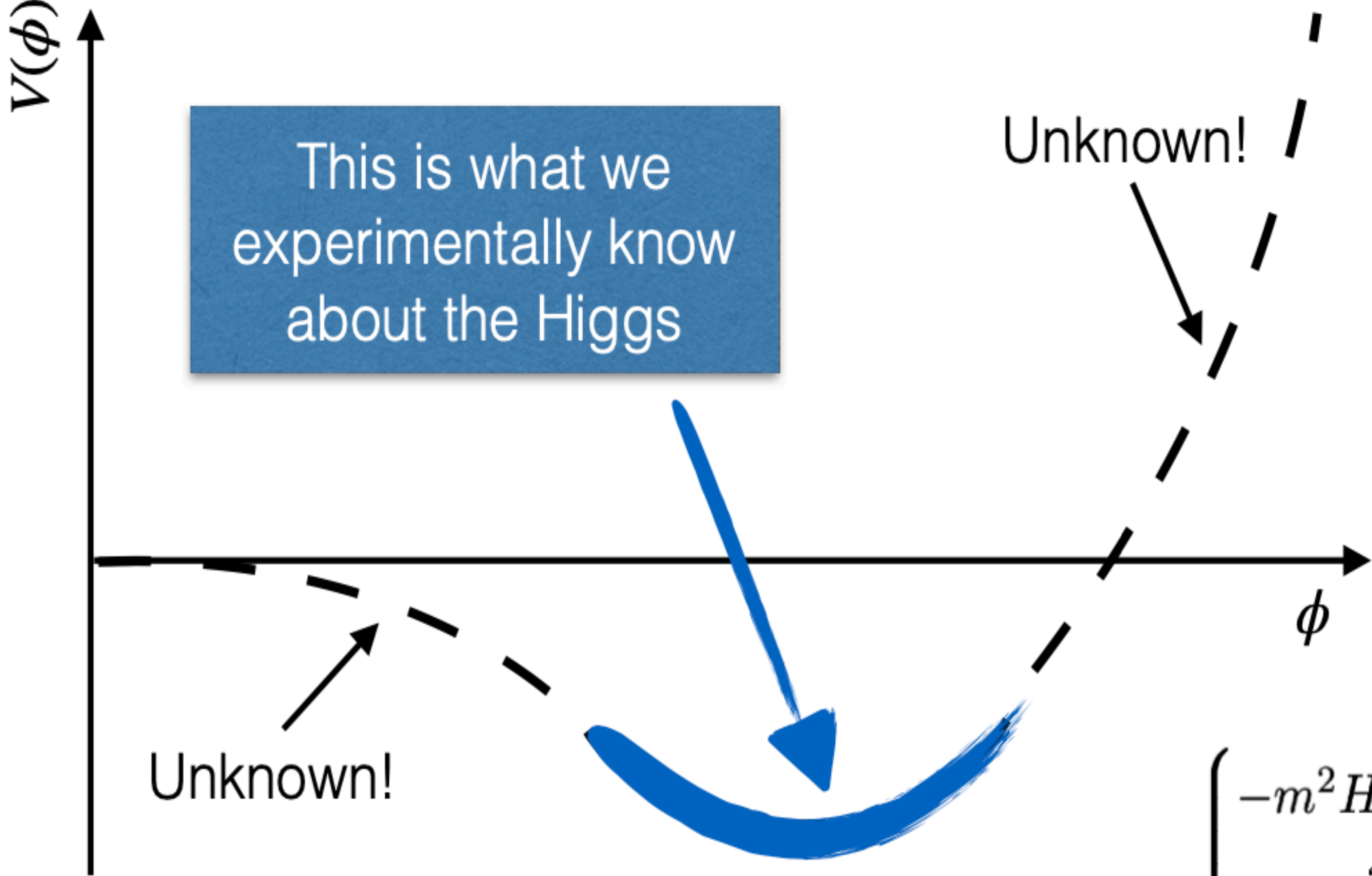








σ(pp → HH + X) [fb]
M_H = 125 GeV
gg → HH
NLO QCD
qq′ → HHqq′
qq/gg → tt̄HH
NLO QCD
LO QCD
qq̄′ → WHH
qq̄ → ZHH
NNLO QCD
1000
100
10
1
0.1
8
25
50
75
100
√s [TeV]

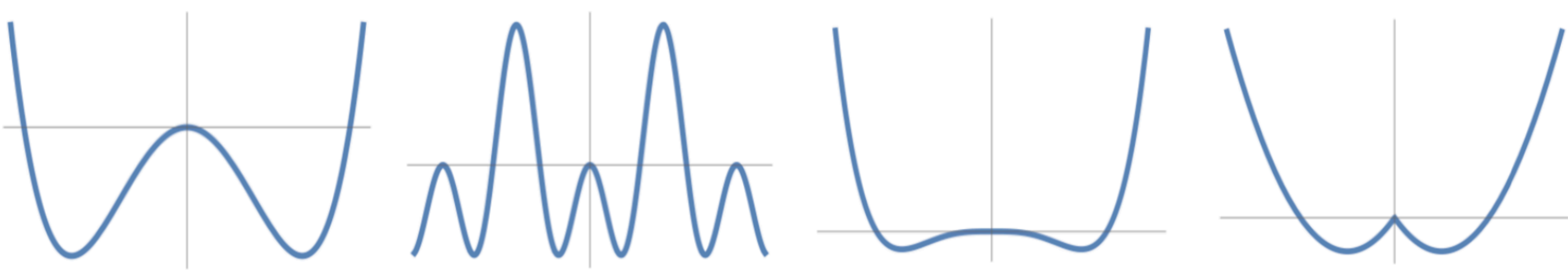


Different potential shapes could explain the same physics we see now!

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

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

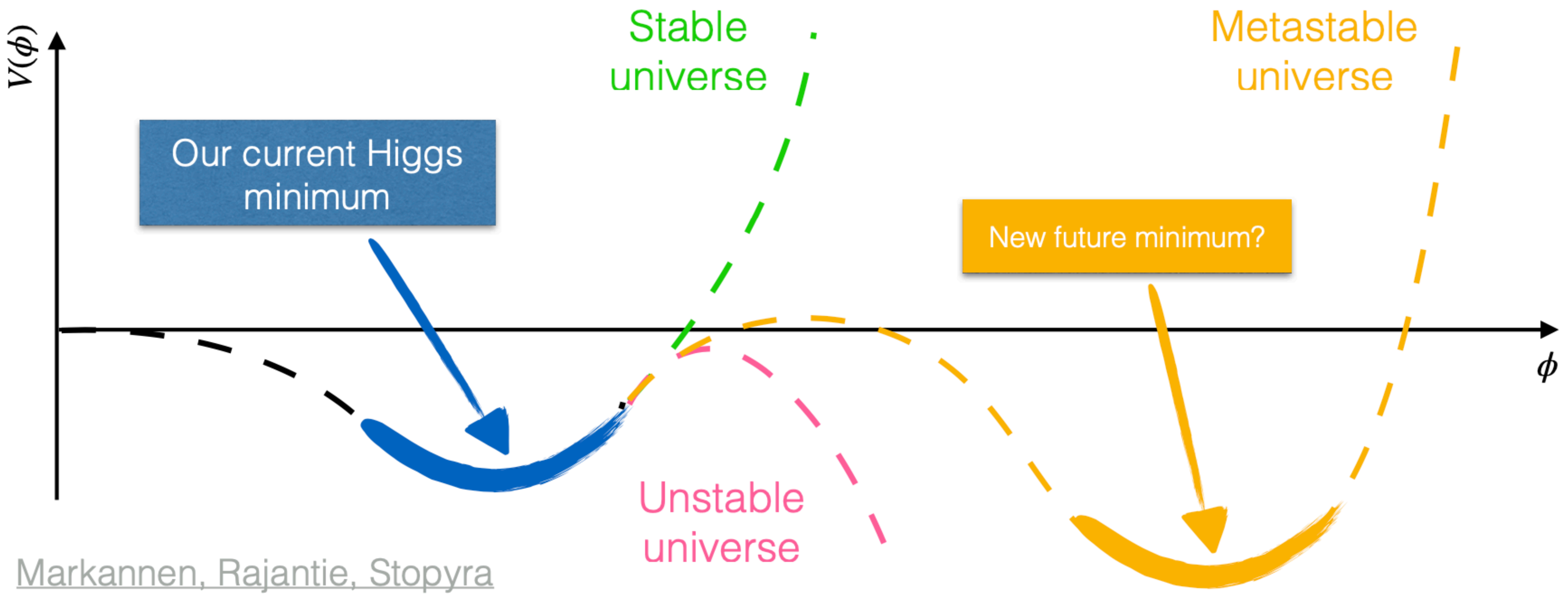
arxiv:1907.02078



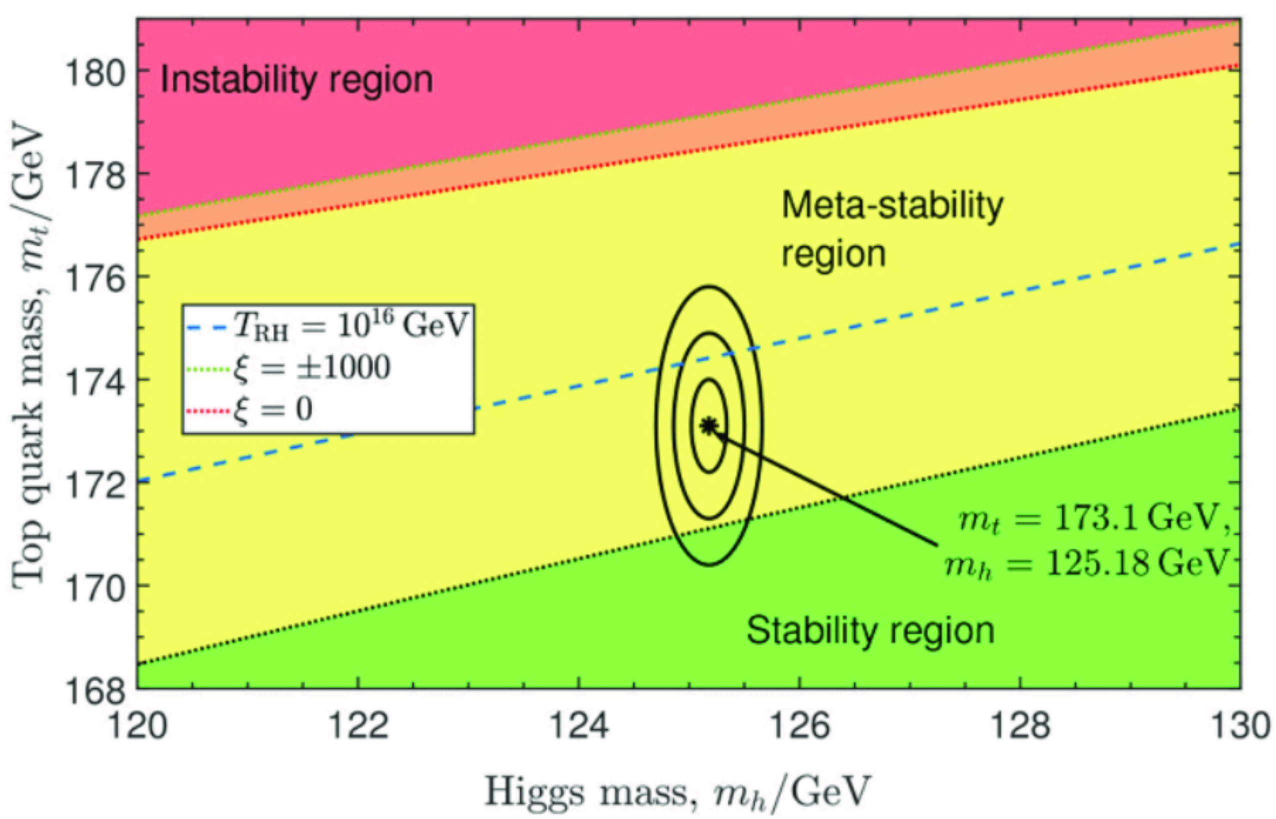
Landau-Ginzburg Higgs **Nambu-Goldstone Higgs** **Coleman-Weinberg Higgs** **Tadpole-Induced Higgs**

From Marco Valente

- Fermions (in particular tops) **contribute to the Higgs potential** with a negative sign.



Markannen, Rajantie, Stopyra



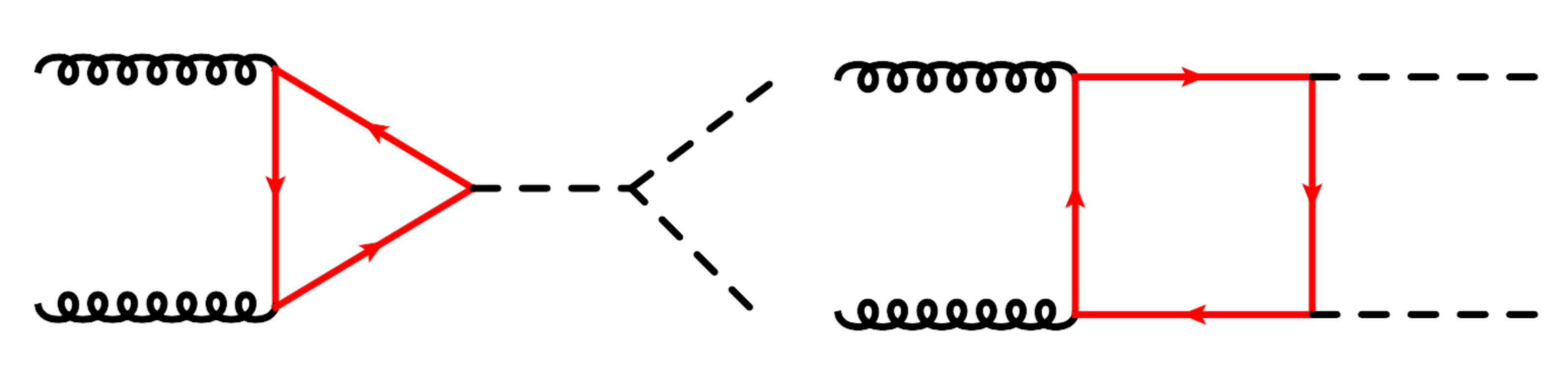
Current measurements suggest that we live in a **metastable** universe!

However, universe **decay expected in a larger time the current universe age** 😎

But it will eventually decay 😢

From Marco Valente

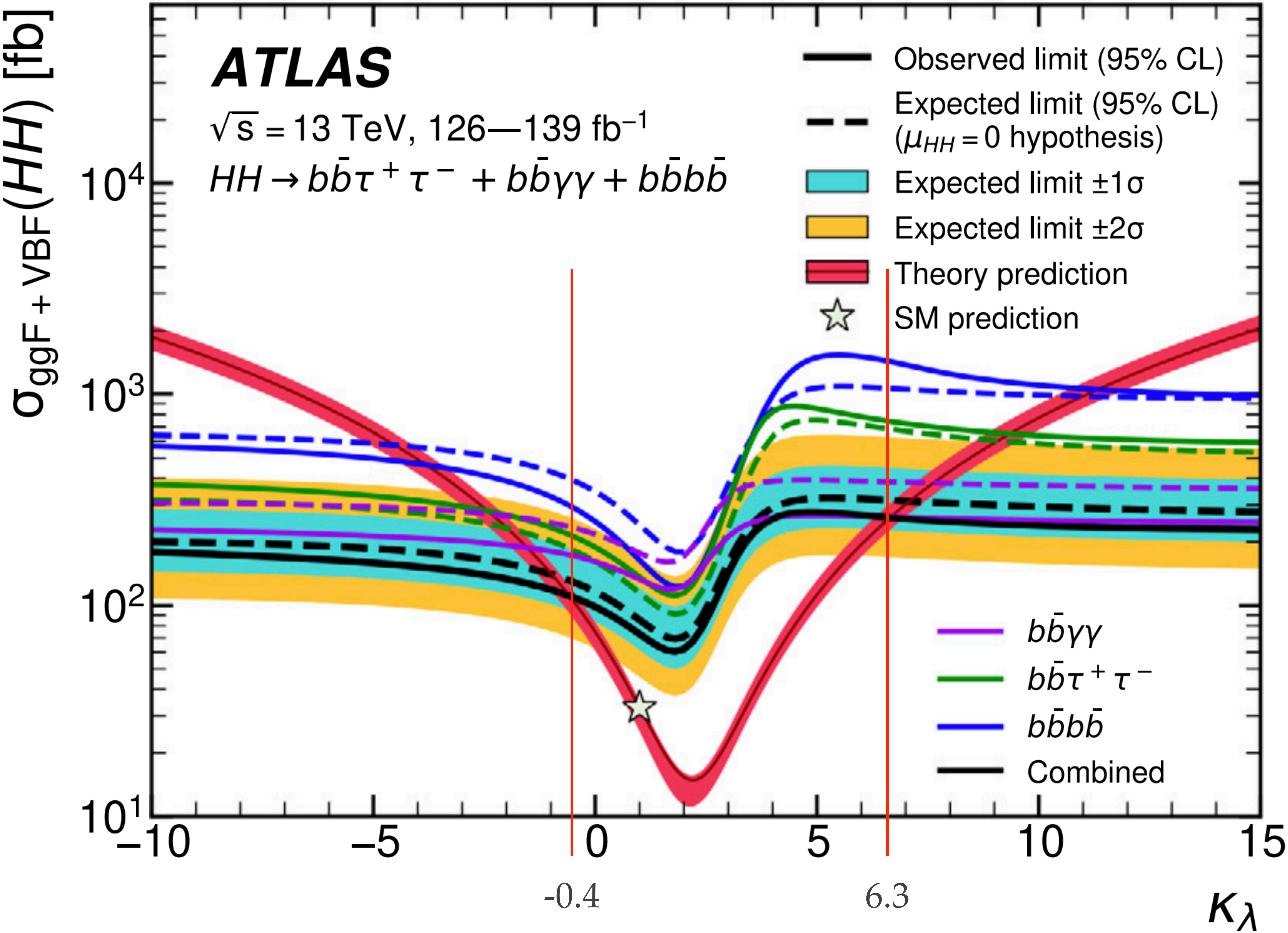
gg →HH as a function of κ

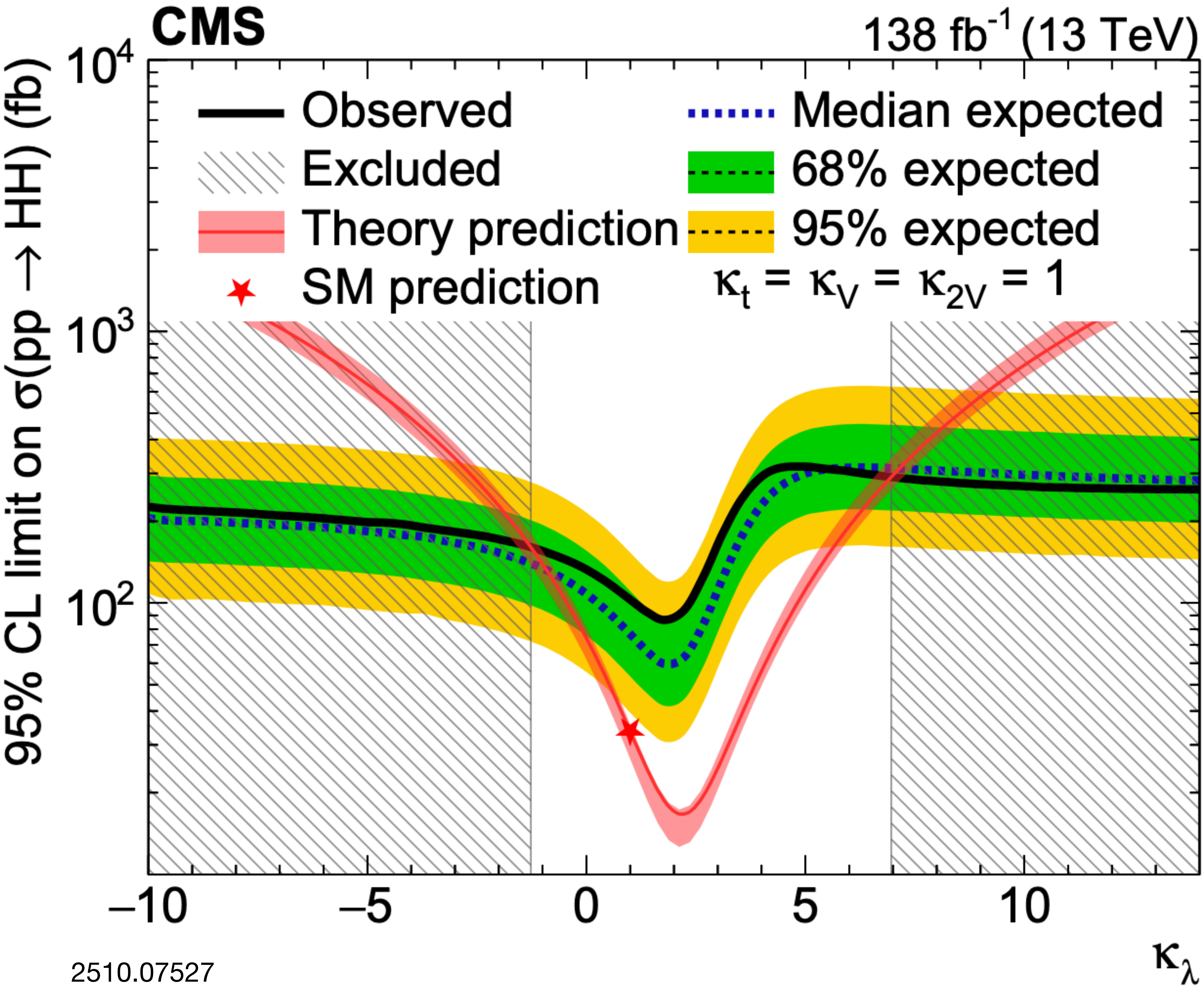


$$\sigma_{HH} = A + B\kappa + C\kappa^2$$

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

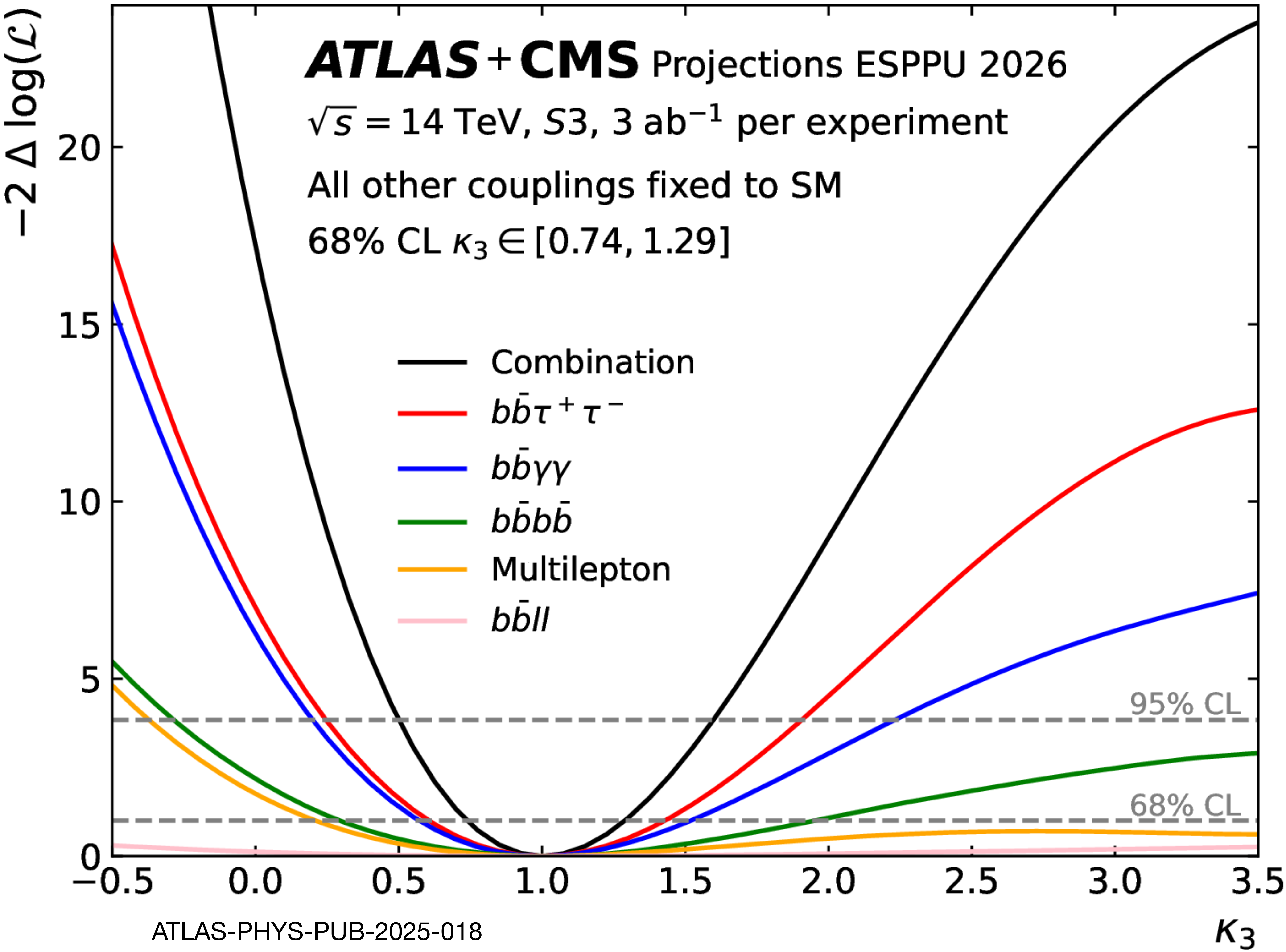
1910.00012


ATLAS
√s = 13 TeV, 126—139 fb⁻¹
HH → bb̄τ⁺τ⁻ + bb̄γγ + bb̄bb̄
Observed limit (95% CL)
Expected limit (95% CL)
(μ_HH = 0 hypothesis)
Expected limit ±1σ
Expected limit ±2σ
Theory prediction
SM prediction
bb̄γγ
bb̄τ⁺τ⁻
bb̄bb̄
Combined
σ_ggF + VBF(HH) [fb]
10⁴
10³
10²
10¹
−10
−5
0
5
10
15
-0.4
6.3
κ_λ



CMS
138 fb^{-1} (13 TeV)
95% CL limit on σ(pp → HH) (fb)
Observed
Excluded
Theory prediction
SM prediction
Median expected
68% expected
95% expected
$\kappa_t = \kappa_V = \kappa_{2V} = 1$
10^4
10^3
10^2
–10
–5
0
5
10
κ_λ

2510.07527



ATLAS-PHYS-PUB-2025-018

The meaning of κ

$$(\sigma \cdot \mathrm{BR})\,(gg \to H \to \gamma\gamma) \quad = \quad \sigma_{\mathrm{SM}}(gg \to H) \cdot \mathrm{BR}_{\mathrm{SM}}(H \to \gamma\gamma) \cdot \frac{\kappa_g^2 \cdot \kappa_\gamma^2}{\kappa_H^2}$$

Handbook of LHC Higgs Cross Sections,1307.1347

It can be considered as a rescaling factor of the corresponding parameter in the Lagrangian.

It is a ratio of two parameters in two Lagrangians ($\mathscr{L}_{NP}$ and $\mathscr{L}_{SM}$).

$$\kappa_{3H} = \frac{\lambda_{3H}}{\lambda_{SM}} \qquad \kappa_{4H} = \frac{\lambda_{4H}}{\lambda_{SM}}$$

How to rescale the single parameter in $\mathscr{L}_{SM}$?

HEFT

- To describe the new physics beyond the SM, we often take a consistent effective field theory framework.
- HEFT: Higgs field as a singlet, non-linear, no explicit constraints on couplings

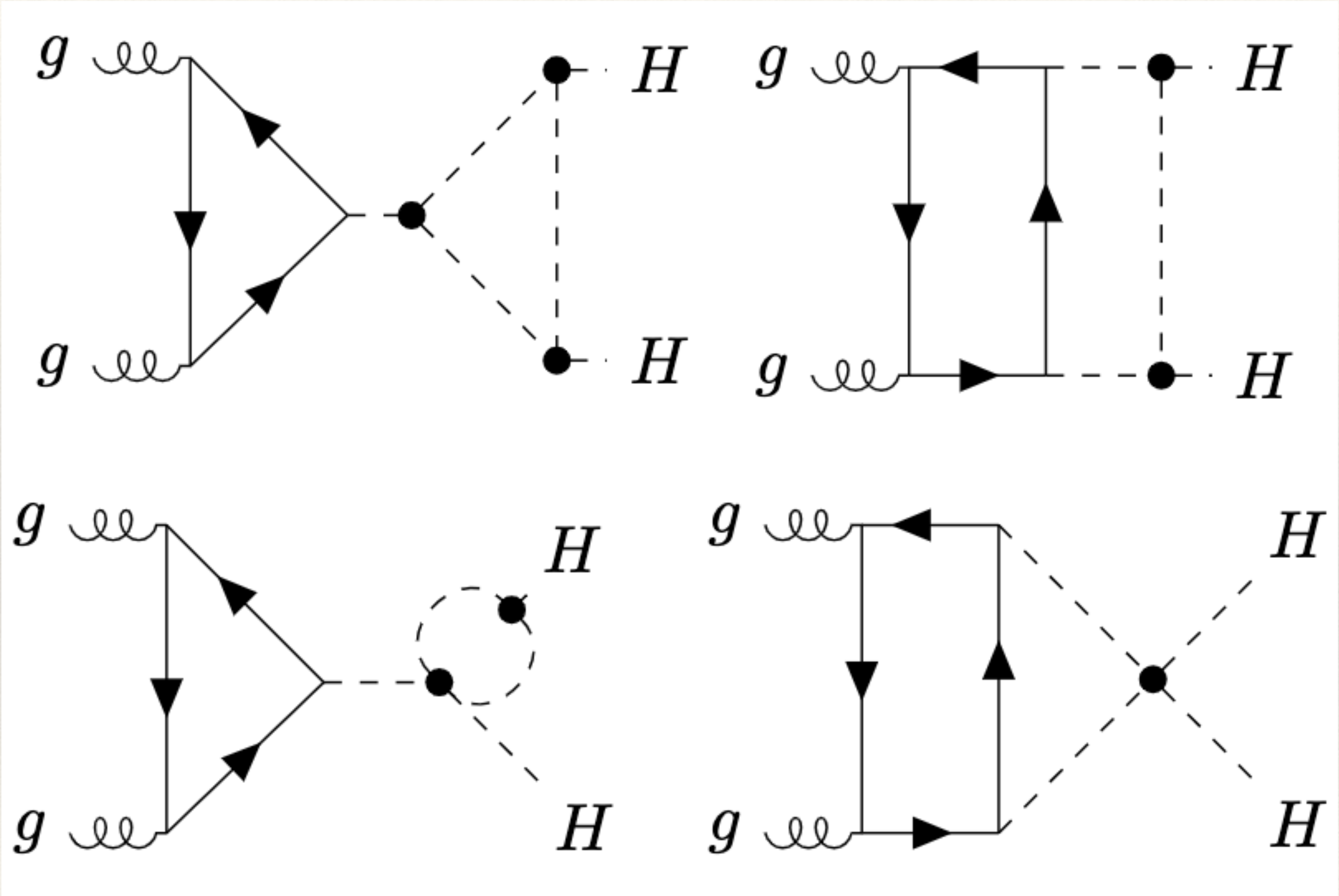
$$\mathcal{L}_{\text{HEFT}} = \mathcal{L}_2 + \mathcal{L}_4$$

$$\mathcal{L}_2 = \frac{v^2}{4}\left(1 + 2a\frac{H}{v} + b\left(\frac{H}{v}\right)^2 + \cdots\right)\text{Tr}[D_\mu U^\dagger D^\mu U] + \frac{1}{2}\partial_\mu H \partial^\mu H - V(H) - \frac{1}{2g^2}\text{Tr}[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}] - \frac{1}{2g'^2}\text{Tr}[\hat{B}_{\mu\nu}\hat{B}^{\mu\nu}] + \mathcal{L}_{GF} + \mathcal{L}_{FP}.$$

$$U(\pi^a) = e^{i\pi^a \tau^a / v}$$

$$V(H) = (-\mu^2 + \lambda v^2) v H + \frac{1}{2}(-\mu^2 + 3\lambda v^2) H^2 + \kappa_3 \lambda v H^3 + \kappa_4 \frac{\lambda}{4} H^4.$$

A more realistic function form



$$\sigma_{HH} = A + B\kappa_3 + C\kappa_3^2 + D\kappa_3^3 + E\kappa_3^4 + F\kappa_3^2\kappa_4 + G\kappa_3\kappa_4 + H\kappa_4 + \cdots$$

Renormalization

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

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

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.

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

$$\delta Z_\phi = \frac{9\lambda_{3\mathrm{H}}^2 v^2}{8\pi^2}\frac{\sqrt{3} - 2\pi/3}{\sqrt{3}m_H^2}$$

Since we focus on the corrections induced by the Higgs self-couplings, we can simply take $\delta Z_v + \delta Z_\phi/2 = 0$

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

Renormalization

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

$\overline{\text{MS}}$ scheme

$$\mathcal{M}^{\text{LO}}_{gg\to H^*\to HH} \times \left\{ \frac{3}{16\pi^2}\frac{1}{\epsilon}\left(-2\lambda_{4\text{H}} - \lambda_{3\text{H}} + 6\lambda_{3\text{H}}^2\frac{v^2}{m_H^2}\right) + \delta Z_{\kappa_{3\text{H}}} \right.$$
$$+ \frac{3}{16\pi^2}\ln\frac{\mu_R^2}{m_H^2}\left[-2\lambda_{4\text{H}} - \lambda_{3\text{H}} + 6\lambda_{3\text{H}}^2\frac{v^2}{m_H^2}\right]$$
$$- \frac{9\lambda_{3\text{H}}^2}{8\pi^2}\frac{v^2}{s-m_H^2}\left[\beta\left(\ln\left(\frac{1-\beta}{1+\beta}\right)+i\pi\right) + \frac{s}{m_H^2}\left(1-\frac{2\pi}{3\sqrt{3}}\right) + \frac{5\pi}{3\sqrt{3}} - 1\right]$$
$$+ \frac{3\lambda_{3\text{H}}^2}{8\pi^2}\frac{v^2}{m_H^2}\left(12 - \frac{7\pi}{\sqrt{3}}\right) - \frac{9\lambda_{3\text{H}}^2 v^2}{4\pi^2}C_0[m_H^2, m_H^2, s, m_H^2, m_H^2, m_H^2]$$
$$\left. - \frac{3\lambda_{4\text{H}}}{16\pi^2}\left[\beta\left(\ln\left(\frac{1-\beta}{1+\beta}\right)+i\pi\right) + 5 - \frac{2\pi}{\sqrt{3}}\right] - \frac{3\lambda_{3\text{H}}}{16\pi^2}\right\},$$

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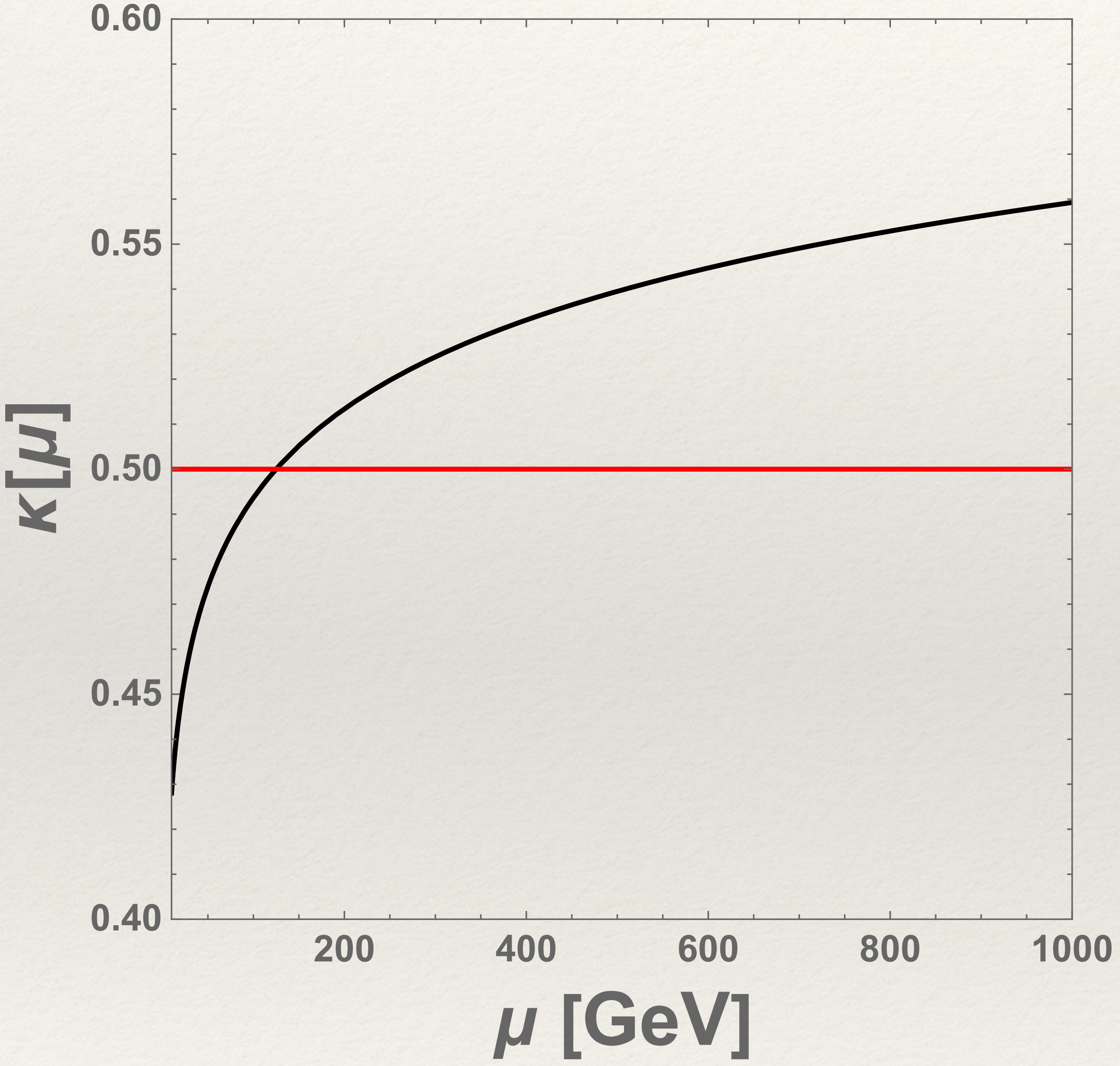
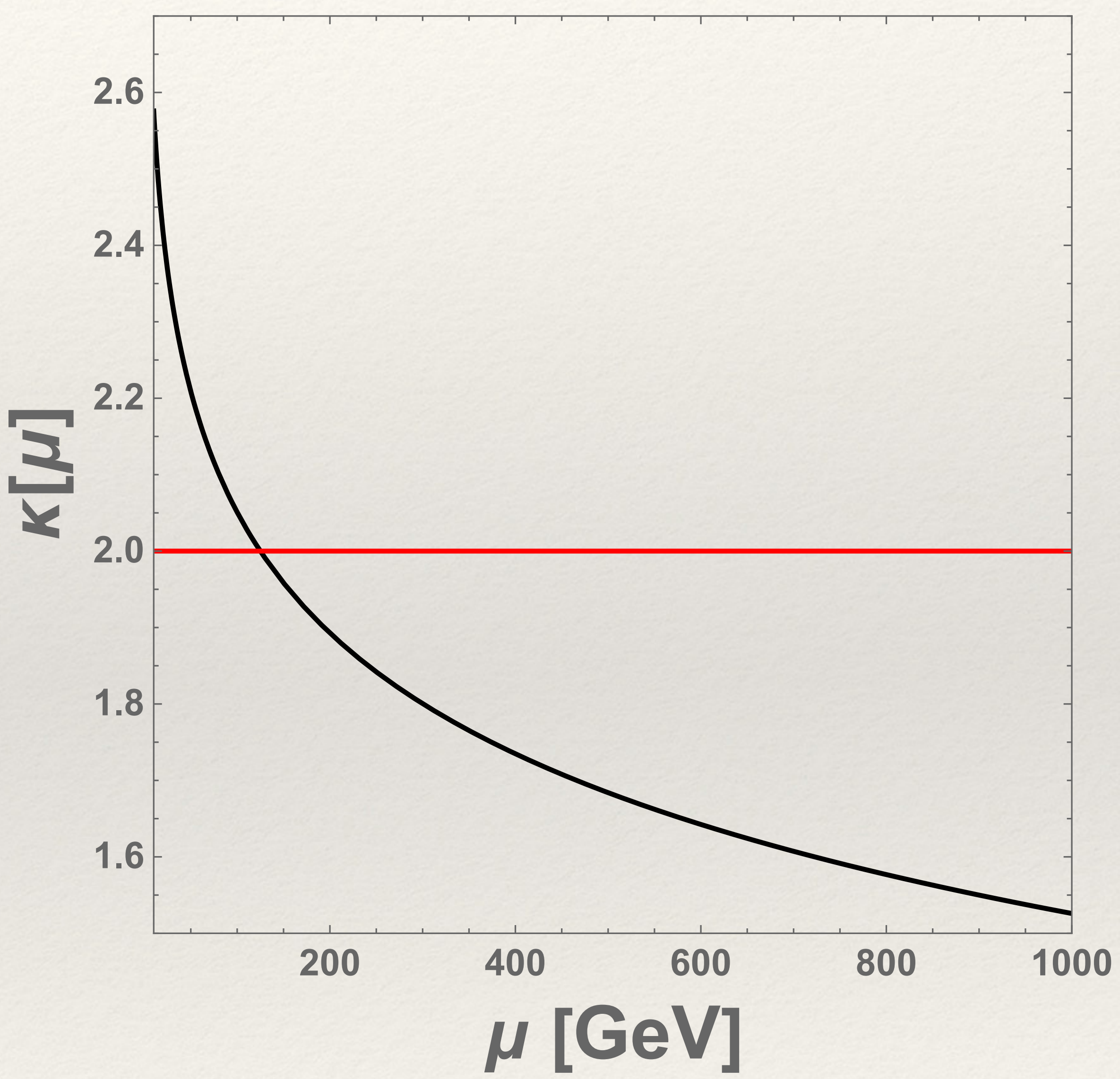
Running of $\kappa(\mu)$

$\kappa(\mu = 125 \text{ GeV}) = 0.5$



$\kappa(\mu = 125 \text{ GeV}) = 2$



Updated function forms

The λ dependent correction is

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

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

$\kappa_{\lambda_{3H}}$	$\kappa_{\lambda_{4H}}$	ggF			VBF		
		$\sigma^{\kappa_\lambda}_{\mathrm{LO}}$	$\sigma^{\kappa_\lambda}_{\mathrm{NNLO-FT}}$	$\delta\sigma^{\kappa_\lambda}_{\mathrm{EW}}$	$\sigma^{\kappa_\lambda}_{\mathrm{LO}}$	$\sigma^{\kappa_\lambda}_{\mathrm{NNNLO}}$	$\delta\sigma^{\kappa_\lambda}_{\mathrm{EW}}$
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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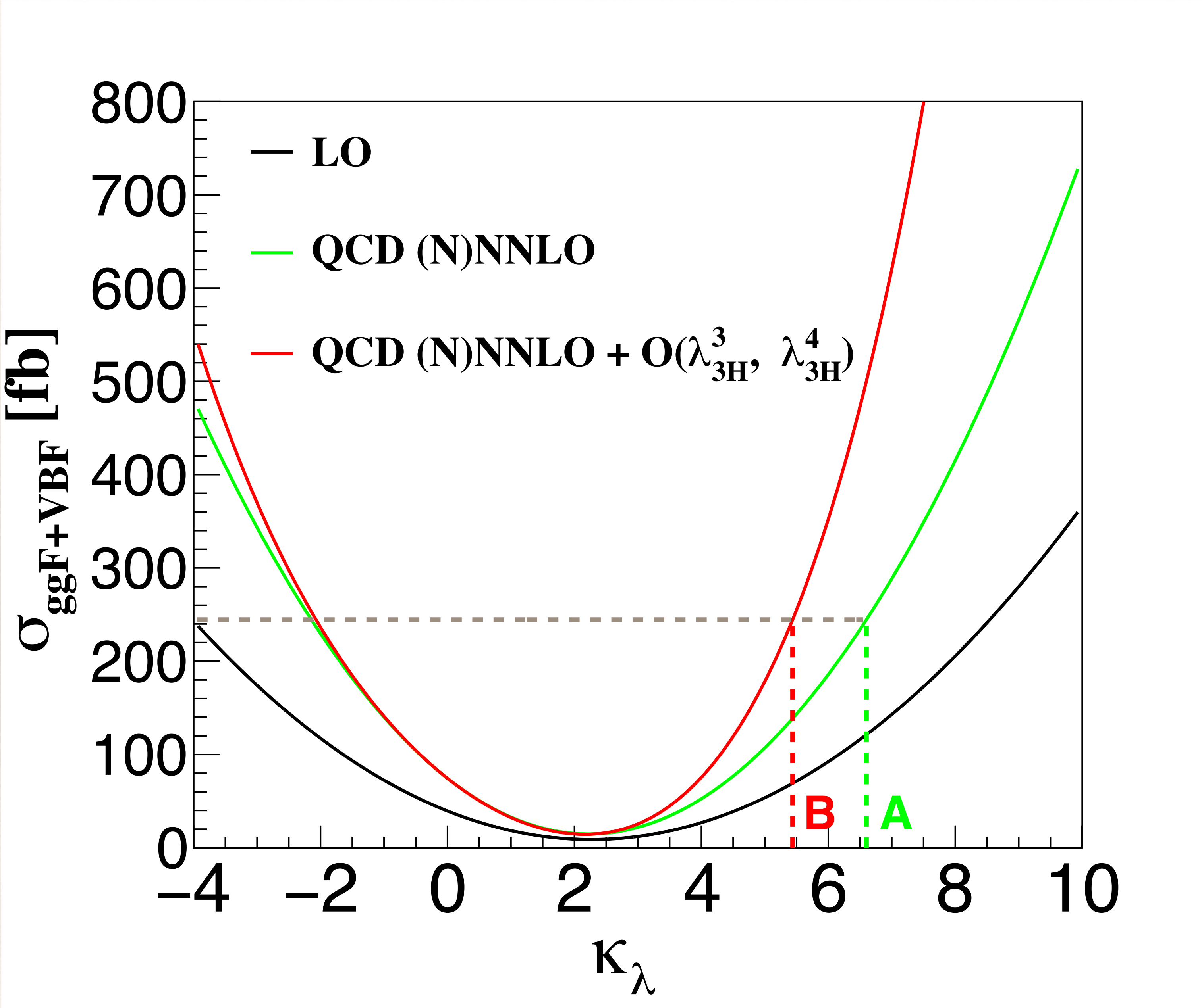
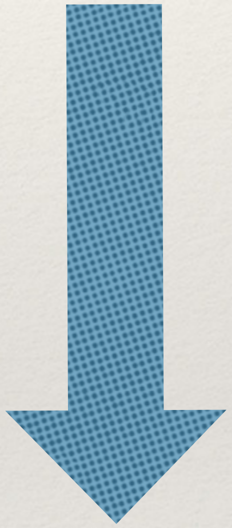
More stringent constraint



ATLAS (CMS) limit

6.6 (6.49)



5.4 (5.37)

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4. Higgs and new physics: Hierarchy problem

Electroweak scale: $v \approx 246$ GeV

Planck scale: $M_{\mathrm{Pl}} \approx 1.22 \times 10^{19}$ GeV

The mass of the Higgs boson is determined by its potential, but is sensitive to the quantum loop corrections.

$\Delta m_H^2 \sim -\frac{y_t^2}{16\pi^2}\Lambda^2$, Λ is a cut-off, where new physics would appear.

If $\Lambda \sim M_{\mathrm{Pl}}$, then Δm_H^2 is 10^{34} times larger than $m_H^2 \sim (100$ GeV$)^2$.

To obtain the physical Higgs mass, there must be fine tuning of the bare mass, which seems unnatural.

Naturalness: 一个物理参数不应依赖于不同能标的贡献之间的极端抵消；若存在大尺度分离，应有对称性或动力学机制来保护低能参数。

4. Higgs and new physics: Hierarchy problem

Is this just a taste or a real problem?

One may adopt the dimensional regularization so that no quadratic divergences exist (logarithmic divergences still exist).

$$\delta m_H^2 = -\frac{9y_t^2}{4\pi^2}m_t^2\left[\frac{1}{\epsilon} + \log\left(\frac{\mu^2}{m_t^2}\right) + \frac{1}{3}\right]$$

The correction is sensitive to the new physics scale (denoted by m_t).

This dependence is the same, irrespective of the new particle's spin.

The core of the problem: the mass of a scalar should be at the same order as the heaviest particle which it can couple with.

4. Higgs and new physics: Hierarchy problem

Solutions to the hierarchy problem:

1. Supersymmetry (SUSY): fermion-boson symmetry. If this symmetry is unbroken, the corrections are cancelled. If it is broken at the TeV scale, the corrections are at the TeV scale. However, no signal of SUSY particles at the LHC was found.
2. Composite Higgs: Higgs boson is not elementary, but a composite particle, like the pion in QCD. Its mass is dominated by a new strong interaction, which is not sensitive to high scale physics. However, EW precision measurements, FCNC flavor physics, and new particle searches at the LHC impose stringent constraints.
3. Extra Dimensions: Randall-Sundrum model: Gravity can propagate in extra curved space and thus the Planck scale is not far from TeV scale. No missing energy and new resonances (Kaluz-Klein modes) have been observed.

4. Higgs and new physics: Spontaneous symmetry breaking

Higgs potential: $V(\Phi) = -\mu^2\Phi^\dagger\Phi + \lambda(\Phi^\dagger\Phi)^4$

Can we explain this structure?

In the early state of the Universe, the temperature is high. The potential is given by

$$V(\Phi, T) = C(T^2 - T_c)^2\Phi^2 + \frac{\lambda(T)}{4}\Phi^4$$

where C and T_c are positive constants.

At zero temperature, the potential has a negative mass squared term. The state $\Phi = 0$ is unstable. The favored state corresponds to the minimum at $\Phi = \pm\sqrt{\frac{2C}{\lambda}}T_c$.

4. Higgs and new physics: Spontaneous symmetry breaking

The curvature of the potential is now T-dependent,

$$m^2(\Phi, T) = 3\lambda\Phi + 2C(T^2 - T_c^2)$$

The minimal state corresponds to $dV(\Phi, T)/d\Phi = 0$, given by

$$\Phi(T) = 0, \quad \Phi(T) = \sqrt{\frac{2C(T_c^2 - T^2)}{\lambda(T)}}\theta(T_c - T)$$

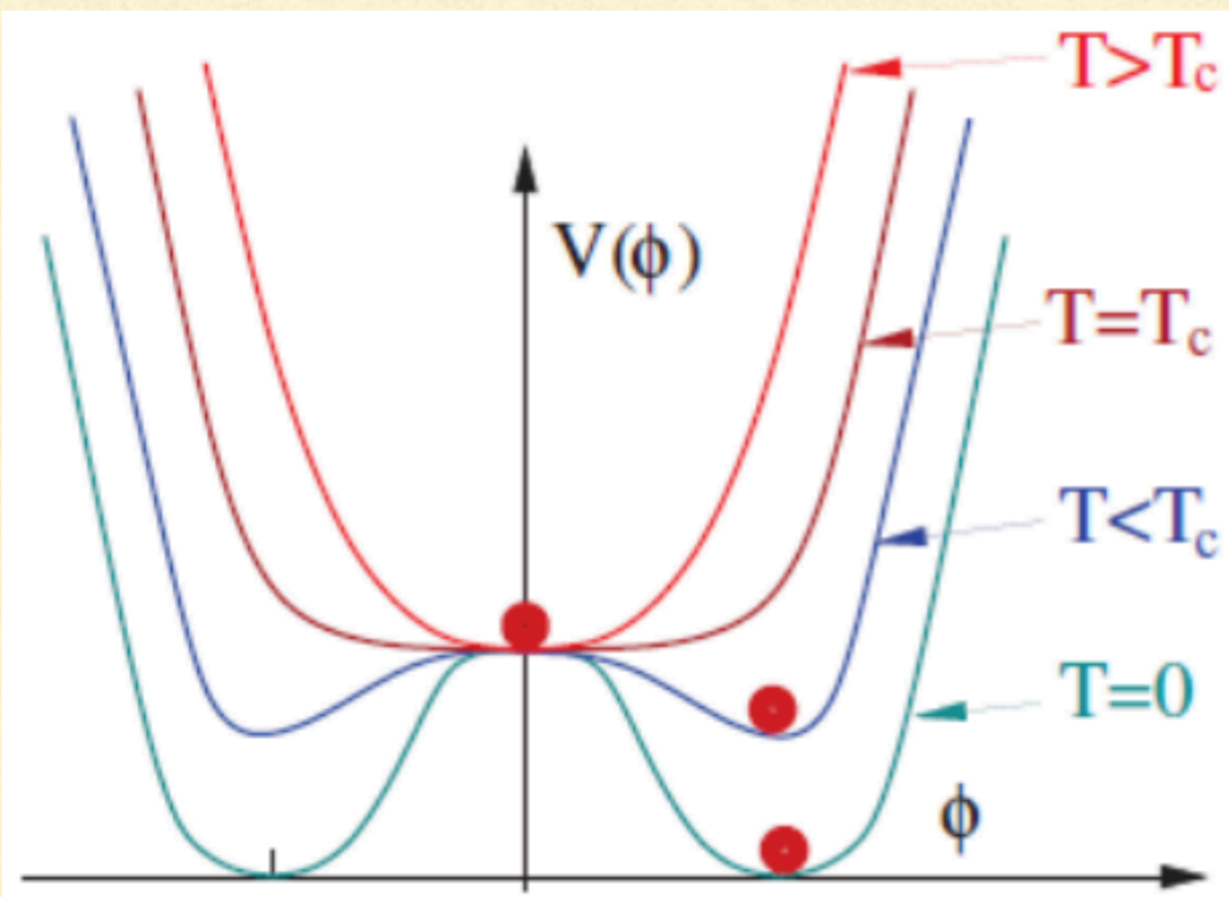
At $T > T_c$, $m^2(0,T) > 0$, and thus the origin is a only minimum.

At $T = T_c$, $m^2(0,T) = 0$, the potential becomes $V(\Phi, T_c) = \frac{\lambda(T_c)}{4}\Phi^4$

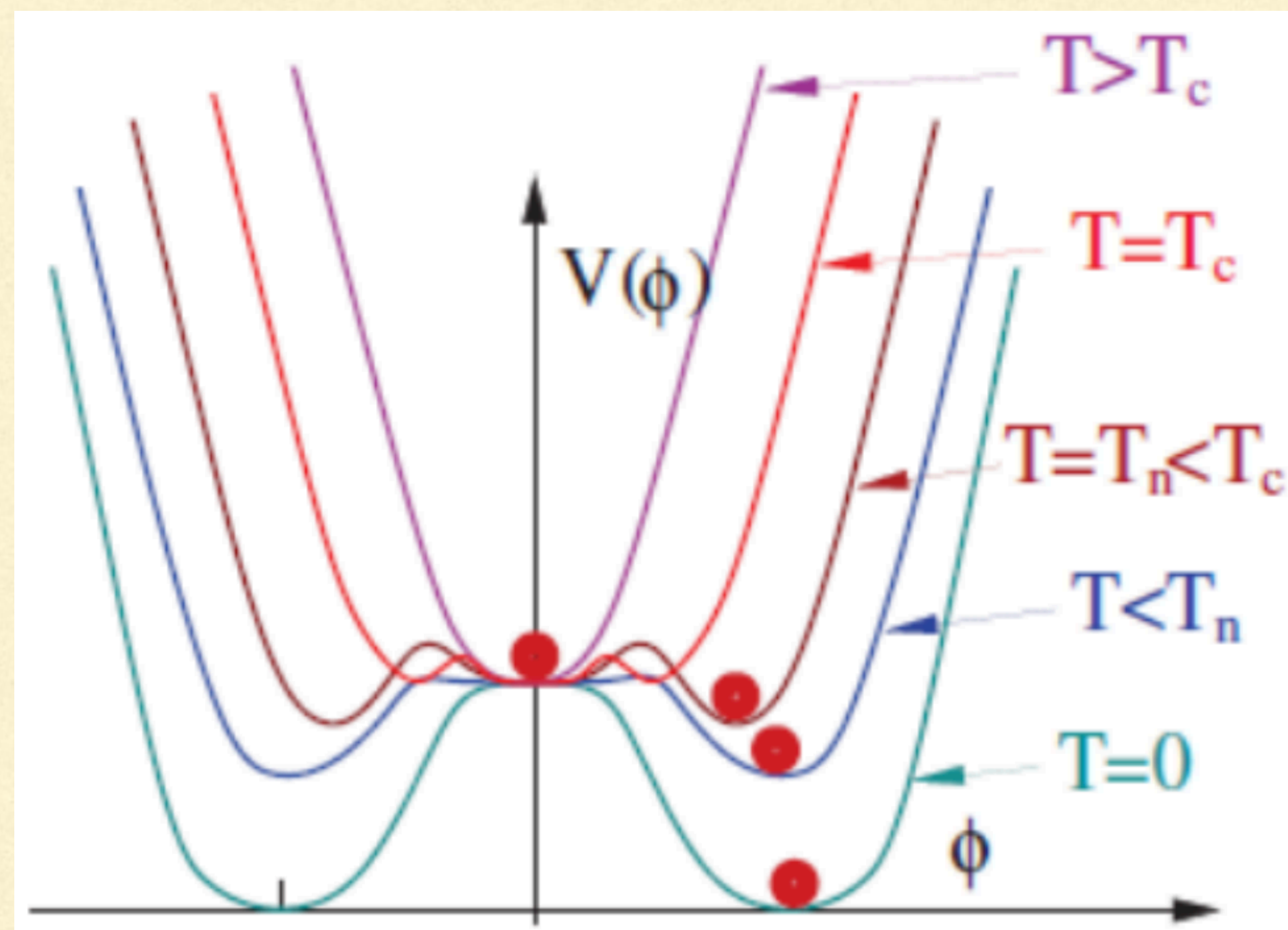
At $T < T_c$, $m^2(0,T) < 0$, the origin becomes a maximum. The minimum is at $\Phi = \sqrt{\frac{2C(T_c^2 - T^2)}{\lambda}}$.

4. Higgs and new physics: Spontaneous symmetry breaking

There is no barrier between the symmetric and broken phases. The phase transition may be achieved by a thermal fluctuation for a field located at the origin. This phase transition is called of second order.



Second order PT



First order PT

4. Higgs and new physics: Spontaneous symmetry breaking

Sakharov conditions for baryogenesis:

1. Baryon number violation. Nonperturbative physics.
2. C and CP violation. CKM matrix
3. Out of equilibrium. First order phase transition.

The Standard Model fails to explain the observed baryon asymmetry.

- New scalar states: 2HDM, MSSM, xSM
- Modified Higgs potential: dim-6 operators
- Additional CP violation: Complex couplings
- Testable at colliders and GW observatories


Higgs boson
The Room of Particle Physics