Karlsruhe Institute of Technology

Particle Physics 1
Lecture 20: Higgs

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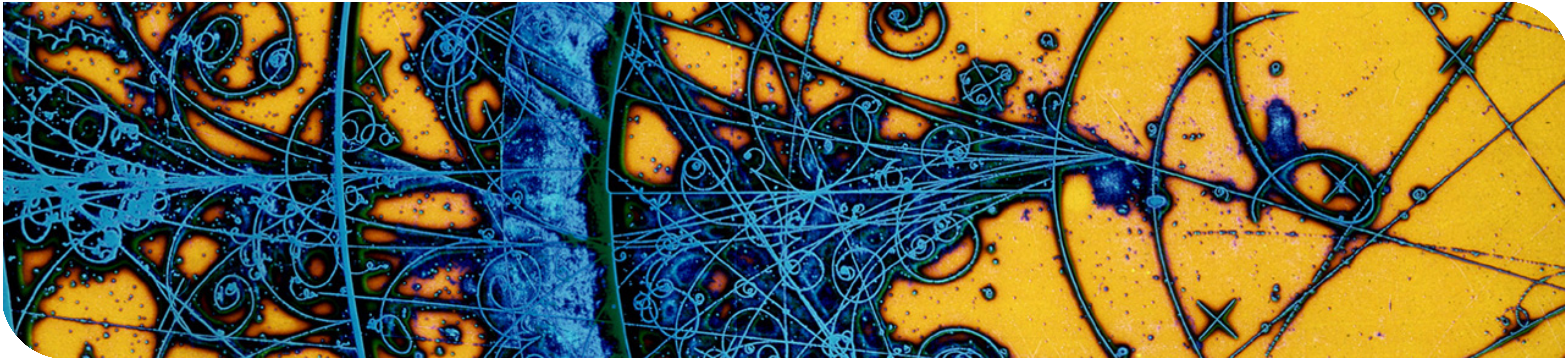
Winterterm 2023/2024



Credit: CERN

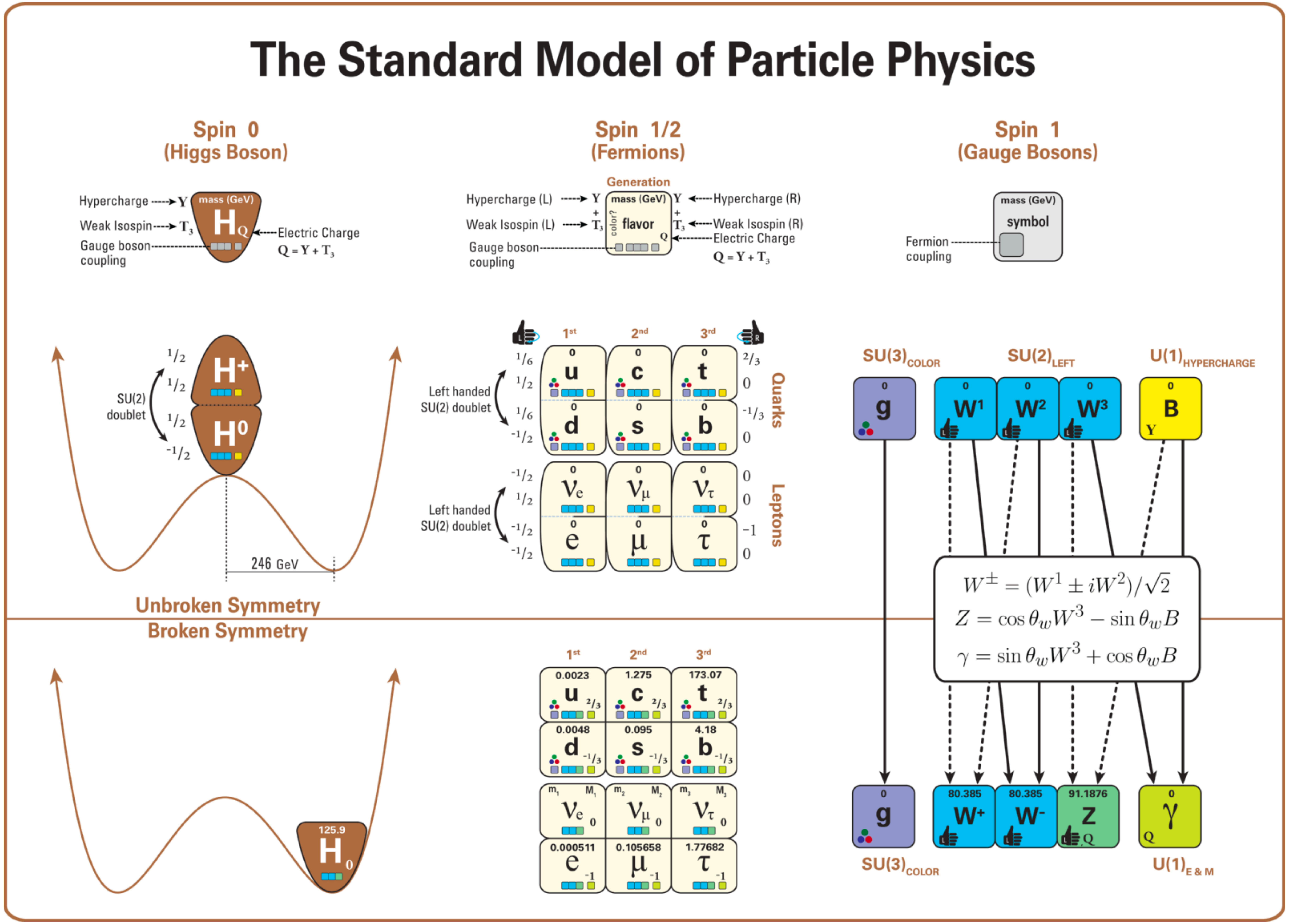
Questions from past lectures

Learning goals

- Understand vacuum stability
- Understand experimental steps towards the Higgs discovery
- Get an overview of state-of-the art Higgs parameters

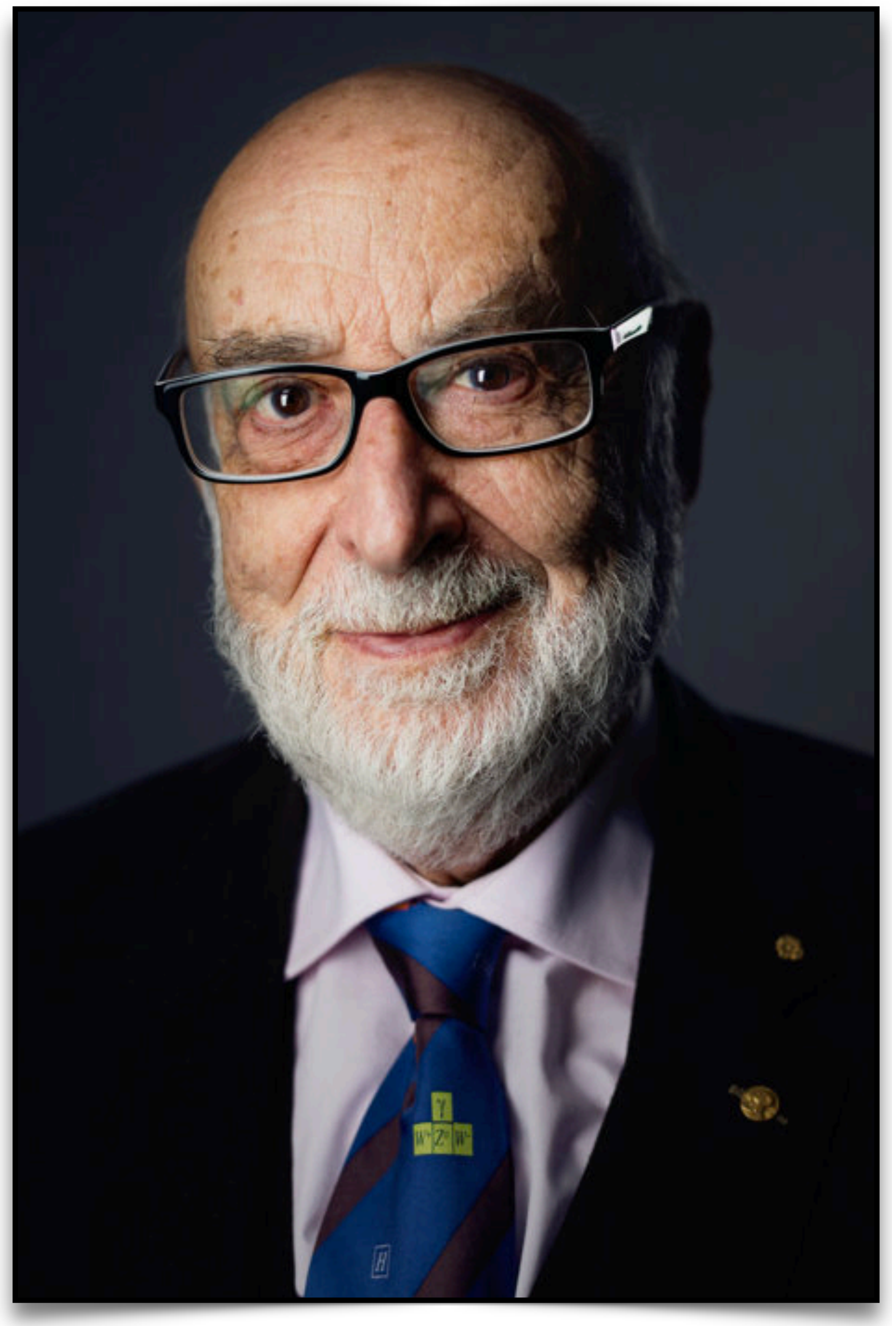
Reminder: Higgs mechanism

- Elektroweak theory (Glashow, Salam, Weinberg):
  - Gauge theory: postulate local symmetry under gauge group $SU(2)_L \times U(1)_Y$
    → four massless gauge bosons and their interactions
  - Contradiction to experimental results: electromagnetic $U(1)$ symmetry conserved (→ massless photons), but three massive gauge bosons $W^\pm$, Z
  - Conflict resolved via electroweak symmetry breaking (EWSB)
- EWSB in the standard model: spontaneous symmetry breaking (SSB) via “Brout–Englert–Higgs mechanism”
  - SSB: ground state (“vacuum”) does not show symmetries of Lagrangian



Source: Latham Boyle, CC4.0

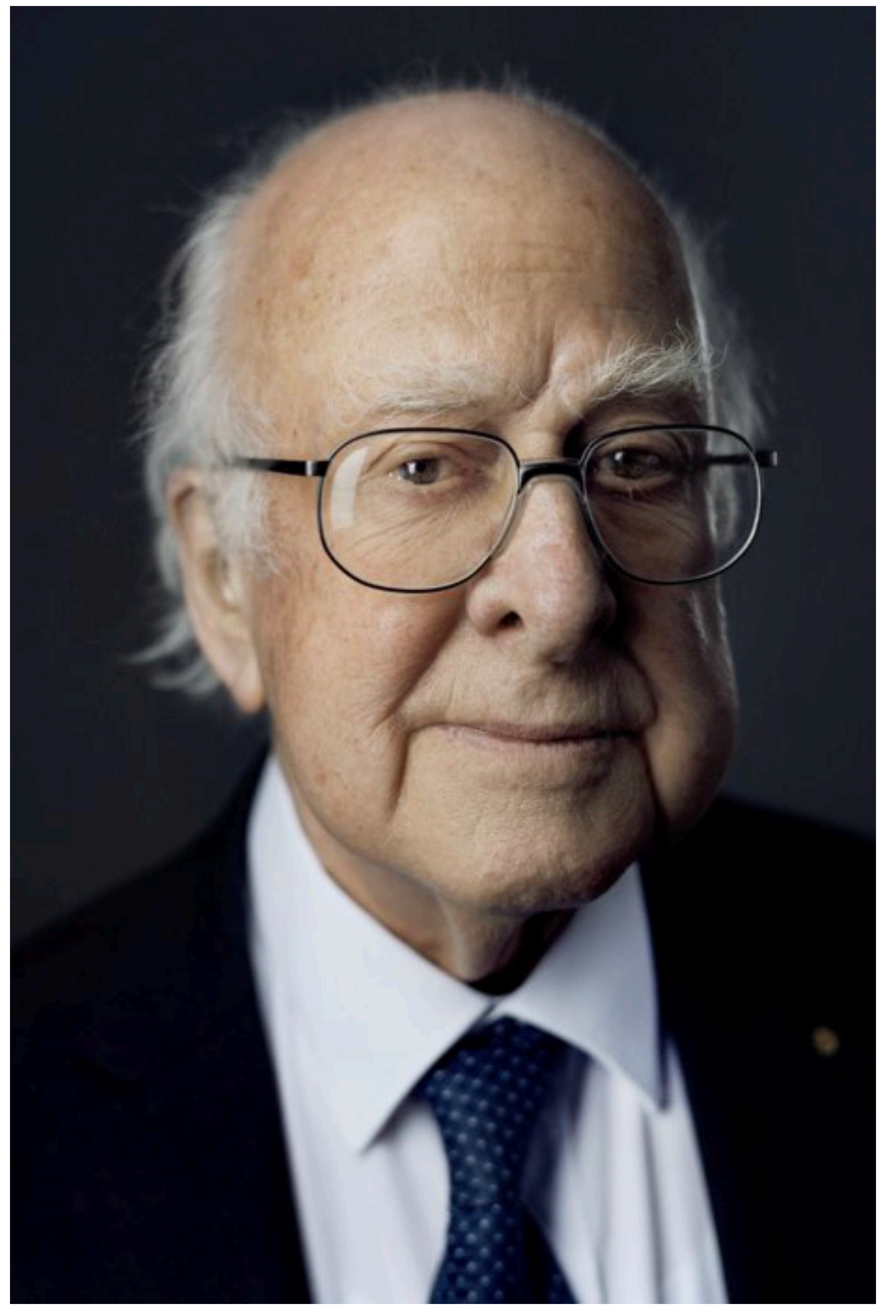
Nobel Prize 2013



Source: https://www.nobelprize.org/prizes/physics/2013/englert/facts/

Francois Englert

Born: 6 November 1932, Etterbeek, Belgium



Source: https://www.nobelprize.org/prizes/physics/2013/higgs/facts/

Peter Higgs

Born: 29 May 1929, Newcastle upon Tyne, United Kingdom

“for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider”

Reminder: Higgs mechanism

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    → four massless gauge bosons and their interactions
  - Contradiction to experimental results: electromagnetic $U(1)$ symmetry conserved (→ massless photons), but three massive gauge bosons $W^{\pm}$, Z
  - Contradiction to experimental results: fermions are massive
  - Conflict resolved via electroweak symmetry breaking (EWSB)
- EWSB in the standard model: spontaneous symmetry breaking (SSB) via “Brout–Englert–Higgs mechanism”
  - SSB: ground state (“vacuum”) does not show symmetries of Lagrangian

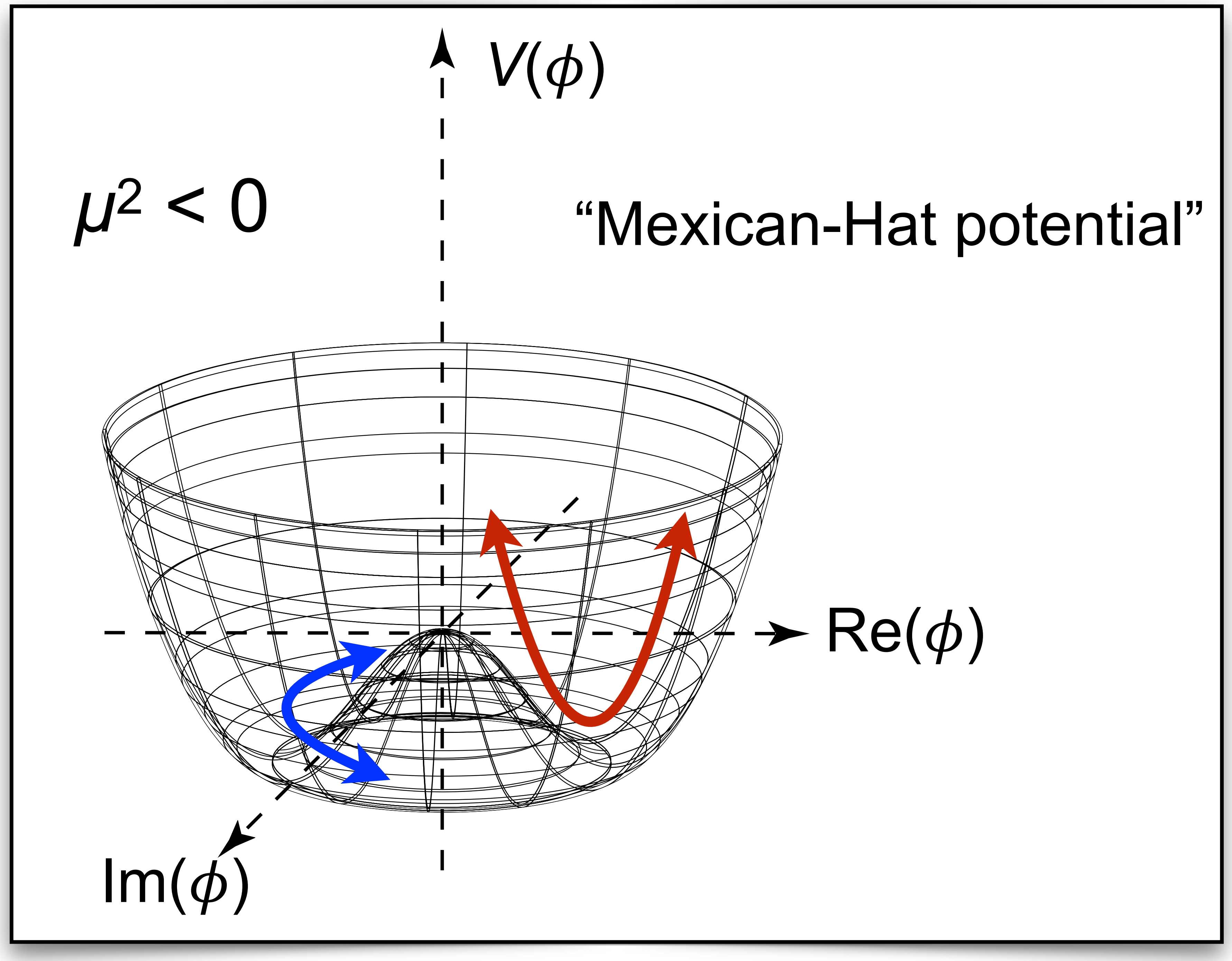
Reminder: Higgs mechanism

- EWSB in the standard model:
  - Add new complex scalar field to Lagrangian:

$$\mathcal{L}_\phi = (D^\mu \phi)^\dagger (D_\mu \phi) - V(\phi) = |D_\mu \phi|^2 - V(\phi)$$

  - Potential invariant under gauge transformations:

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



- Expansion around new ground after EWSB:

$$\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} = \begin{pmatrix} \phi_1 + i\phi_2 \\ \phi_3 + i\phi_4 \end{pmatrix} \rightarrow \phi_{vac} = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + H(x) \end{pmatrix}$$

  - v is the vacuum expectation value (VEV) of the higgs field
  - H(x) is the physical higgs boson (neutral scalar particle, $J^P = 0^+$)

Reminder: Boson and fermion masses

- Gauge boson masses from coupling to Higgs field:

$$\mathcal{L}_\phi = \frac{1}{2}(\partial^\mu H)(\partial_\mu H) + \frac{1}{4}g^2(v+H)^2 W^{+,\mu}W^-_\mu + \frac{1}{2}(g^2+g'^2)(v+H)^2 Z^\mu Z_\mu - V(\phi)$$

  - $\rightarrow \quad \frac{1}{4}g^2v^2W^{+,\mu}W^-_\mu + \frac{1}{2}(g^2+g'^2)v^2Z^\mu Z_\mu \;=\; m_W^2 W^{+,\mu}W^-_\mu + \frac{1}{2}m_Z^2 Z^\mu Z_\mu$

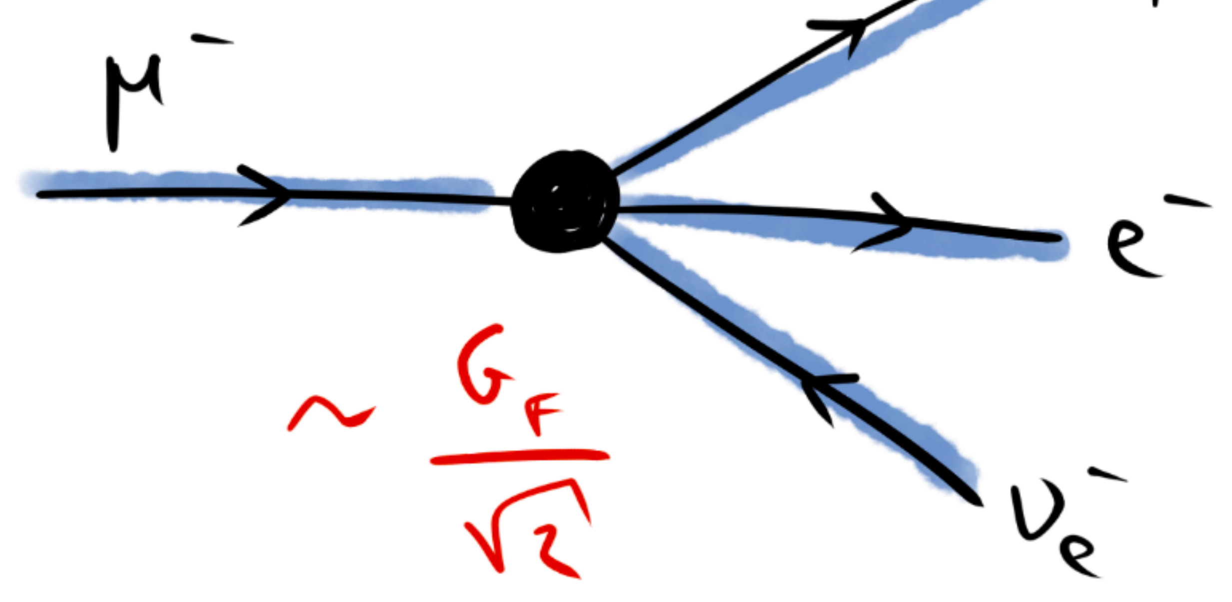
- Fermion masses from Yukawa coupling with $m_d = c_d \frac{v}{\sqrt{2}}$:

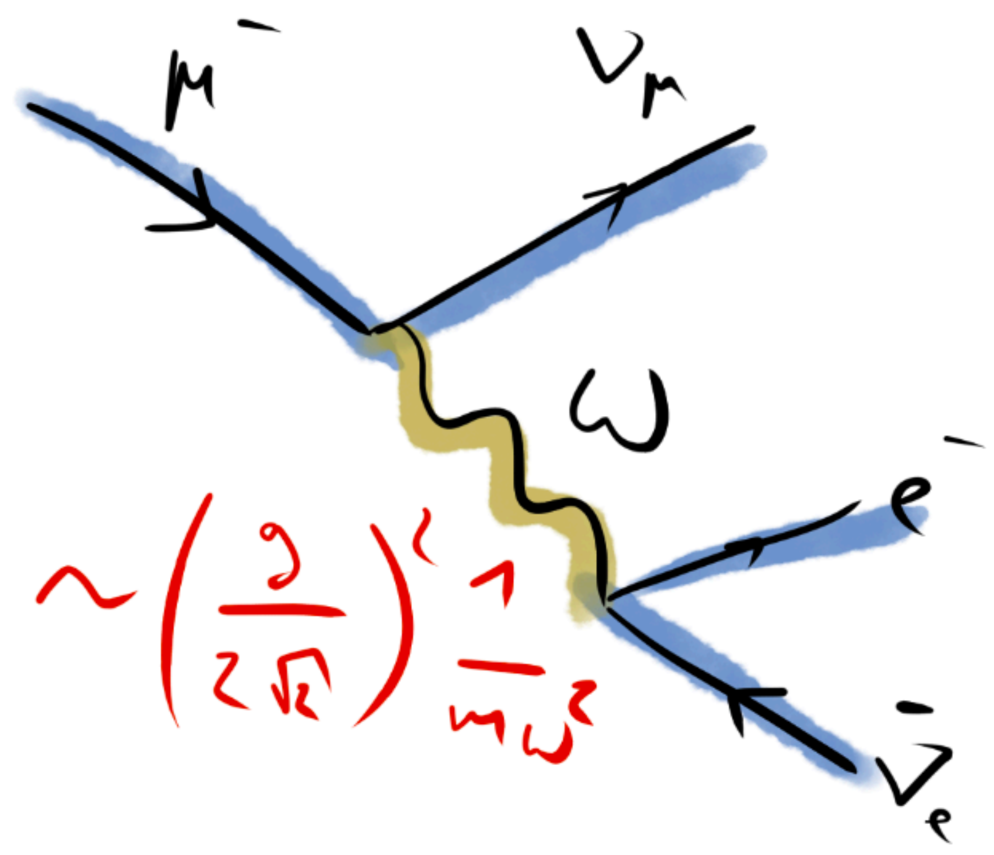
$$\begin{aligned}\mathcal{L} &= -c_d\frac{1}{\sqrt{2}}(\bar{d}_L(v+H)d_R + \bar{d}_R(v+H)d_L) \\ &= -c_d\frac{v}{\sqrt{2}}(\bar{d}_L d_R + \bar{d}_R d_L) - c_d\frac{1}{\sqrt{2}}H(\bar{d}_L d_R + \bar{d}_R d_L)\end{aligned}$$

  - Conceptually similar, but more complicated for quark masses (CKM matrix…)

Vacuum expectation value (vev)

- Experimentally from charged-current processes at low energies:
  - $m_W^2 = \frac{g^2 v^2}{4} \rightarrow v^2 = \frac{1}{\sqrt{2} G_F} \approx (246\text{GeV})^2$
- Compare "contact interaction" with W-boson exchange
  - most precise measurement from muon lifetime $\propto \frac{1}{G_F^2}$ up to correction of m_μ / m_W





How many free parameters does the standard model have?

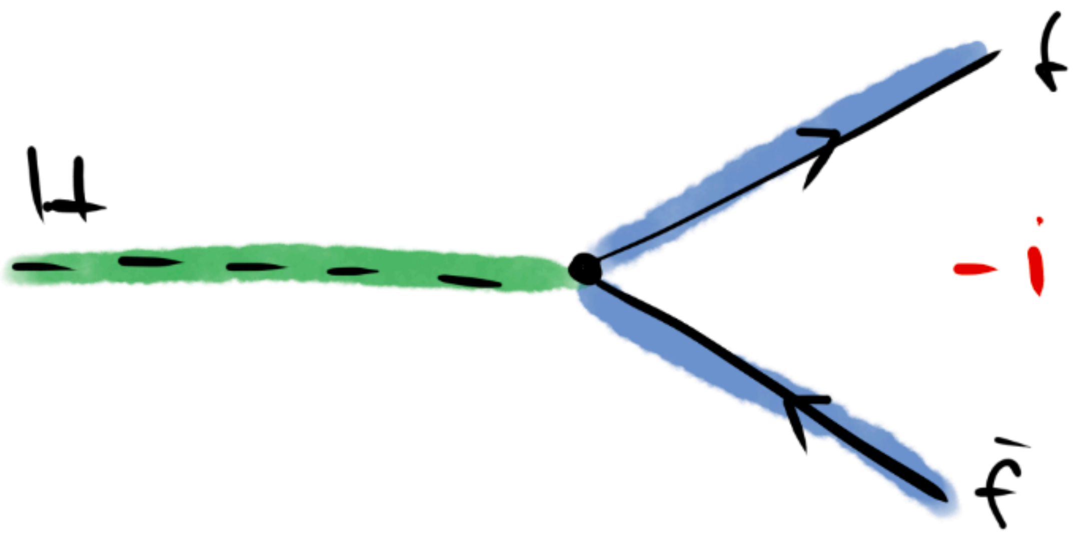
- Covered in TP1 so far:
  - 3 couplings constants (g, g', g_s) or ($\alpha_{QED}(0)$, $\alpha_S(m_Z)$, G_F) and running of couplings
  - m_Z
  - 3 rotation angles and one CP violating phase (CKM matrix)
  - CP violating phase θ in QCD (strongly limited by not observing a neutron EDM)
  - W mass
  - Quark masses (top is special since it decays before hadronization)
- Missing so far:
  - **Higgs mass**
  - Neutrino masses
  - Neutrino 3 rotation angles and one CP violating phase (PMNS matrix)

Other predictions of the Standard Model

- Shape of the Higgs potential and running Higgs self-coupling λ, remember: $v = \sqrt{-\mu^2/\lambda}$ with $m_H = \sqrt{-2\mu^2}$
- Higgs coupling to all fermions, bosons, and itself (if all masses are known)
- Spin and parity of the Higgs boson

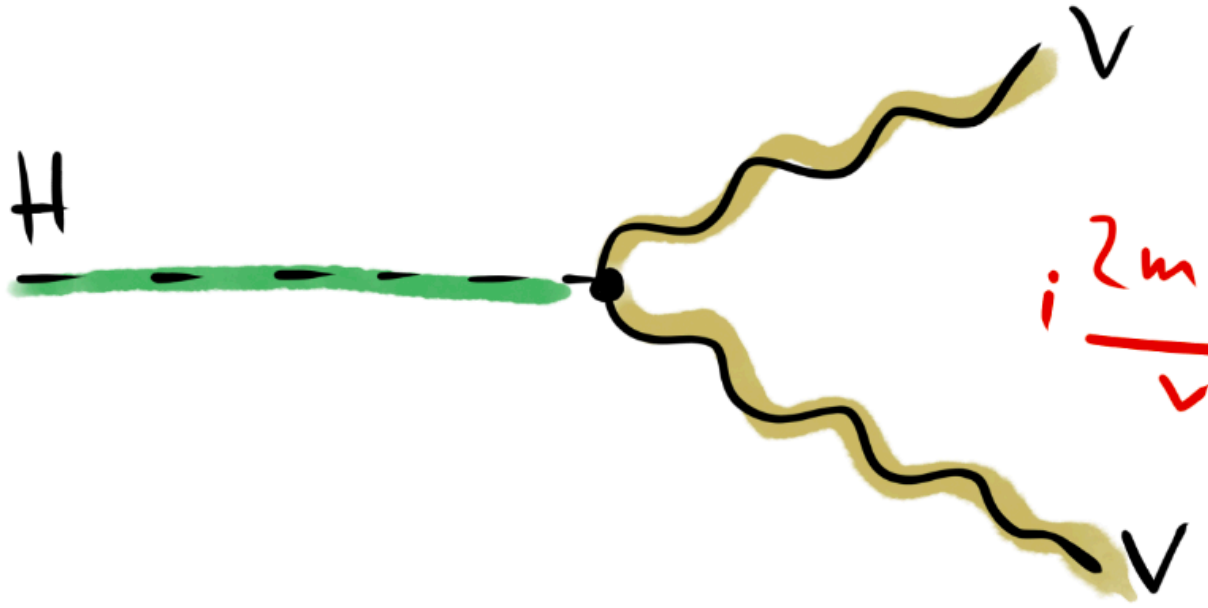
Higgs boson couplings

Fermions

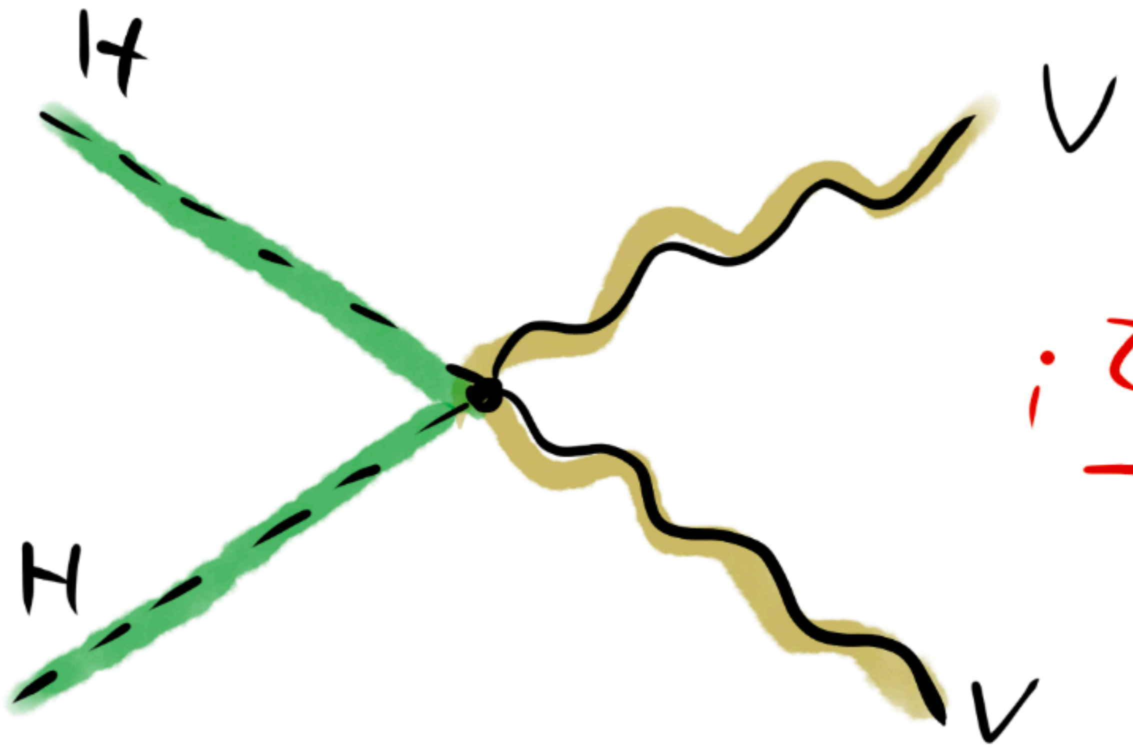


$-i\frac{m_f}{v}$

W and Z bosons
(V=W±, Z)

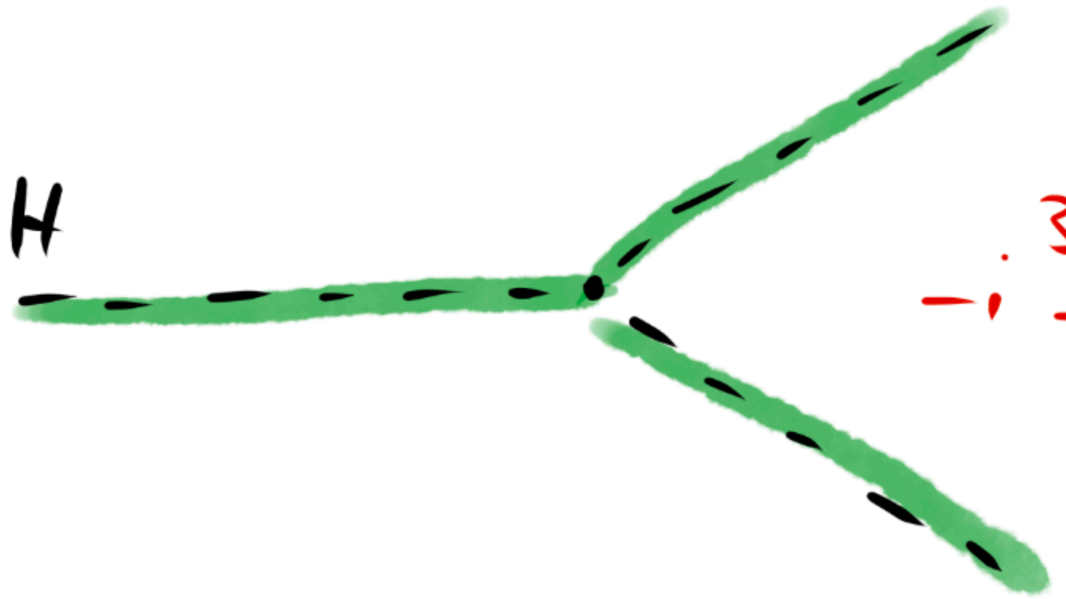


$i\frac{2m_V^2}{v}g^{\mu\nu}$

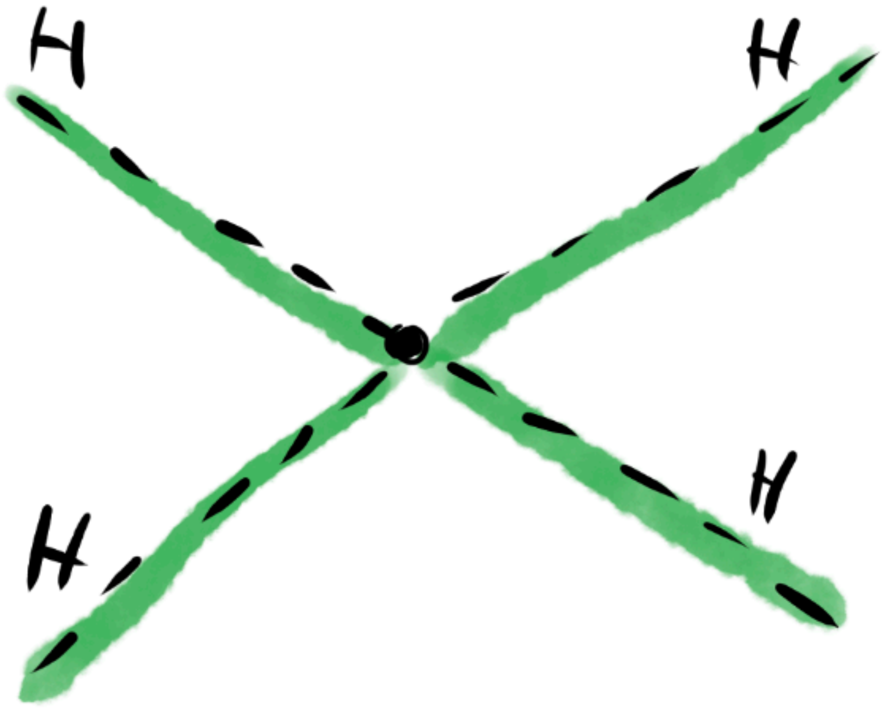


$i\frac{2m_V^2}{v^2}g^{\mu\nu}$

Higgs-boson
self couplings



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



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

PINGO: Higgs coupling

- Which of the elementary particles listed below can the Higgs boson not couple to directly?
  - Strange quarks (second generation)
  - Top quarks (third generation)
  - Electrons
  - Gluons
  - Neutrinos
  - Anti-Neutrinos
  - Photons

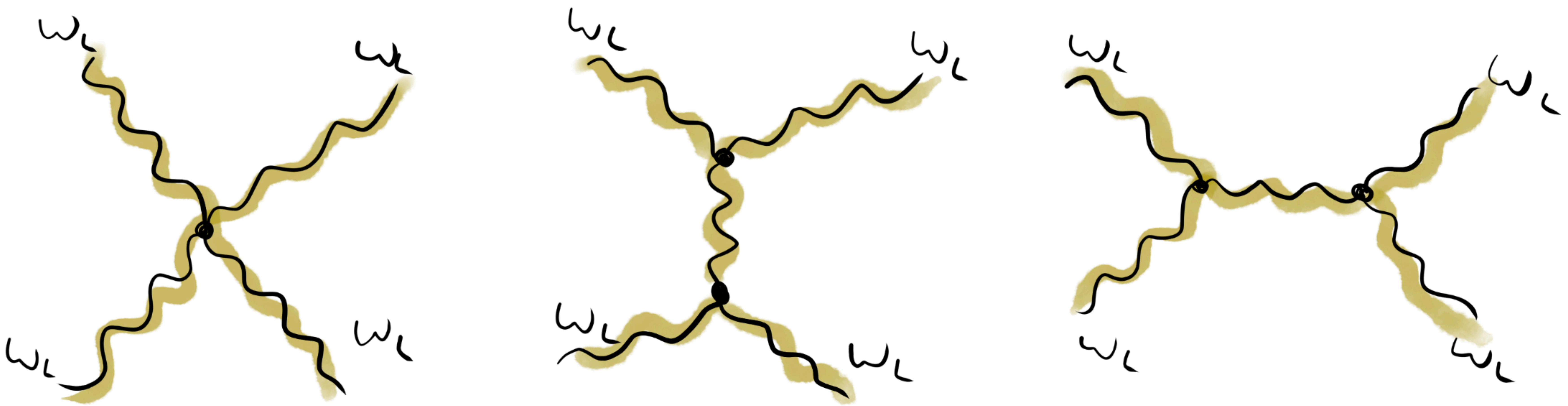
PINGO: Higgs coupling

- Which of the elementary particles listed below can the Higgs boson not couple to directly?
  - Strange quarks *
  - Top quarks
  - Electrons *
  - **Gluons (The Higgs field doesn't carry color charge and the gluons don't carry weak hypercharge)**
  - Neutrinos *
  - Anti-Neutrinos *
  - **Photons (The Higgs field doesn't carry electric charge and the photons don't carry weak hypercharge)**

* not measured yet!

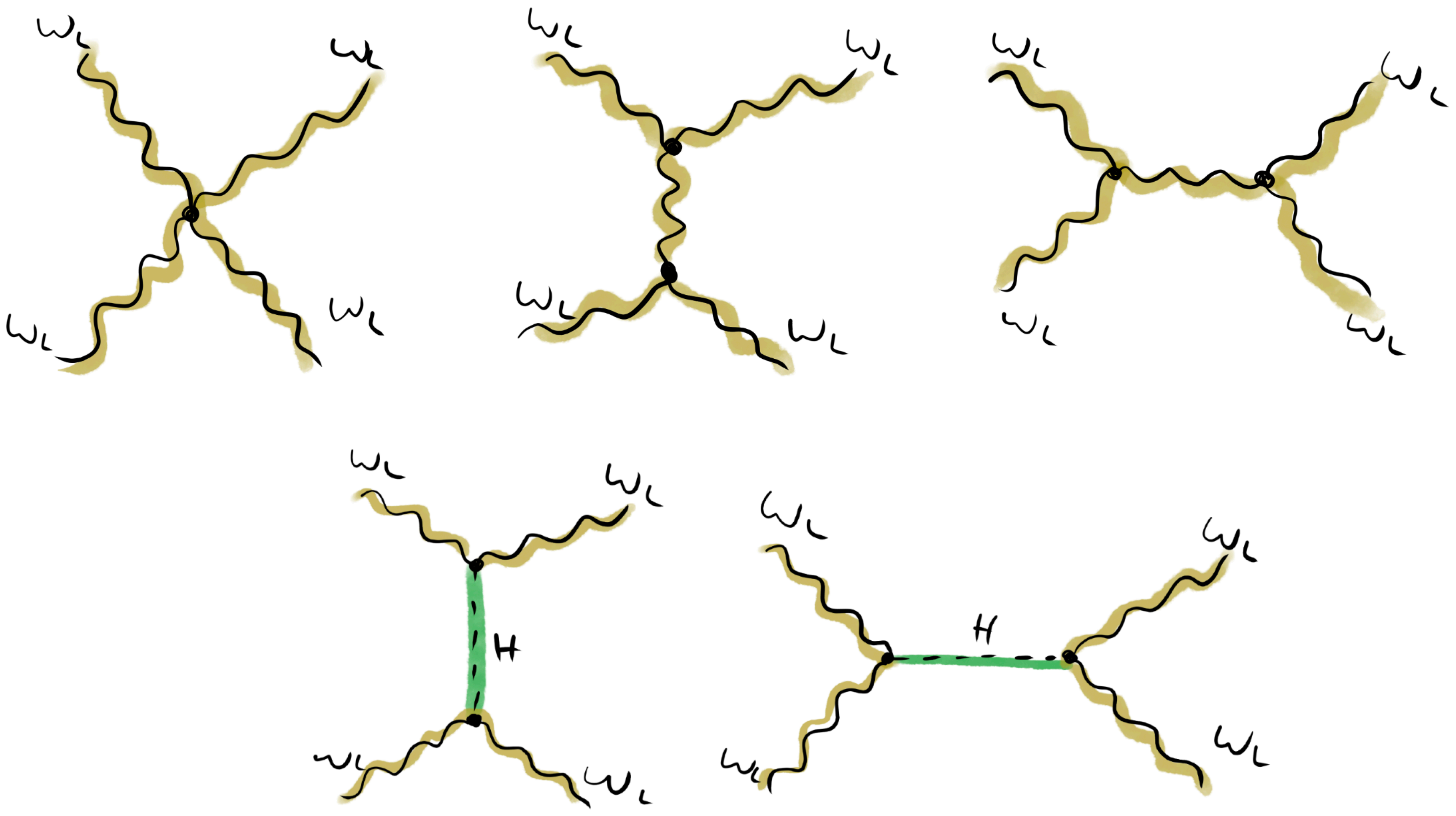
Alternatives to the Higgs mechanism?

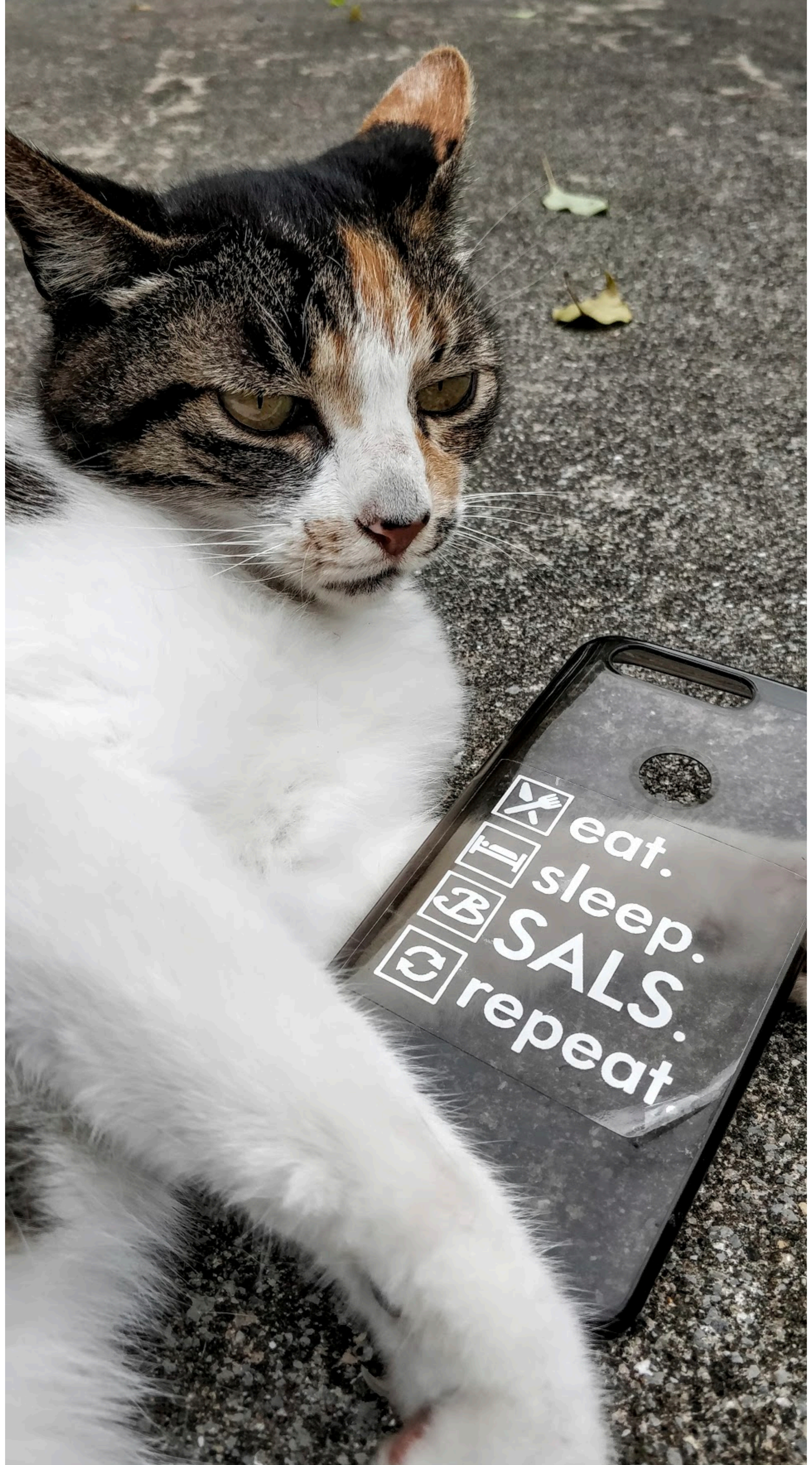
- Scattering of longitudinally polarized W-bosons violates unitarity bound ($\sigma \to \infty$) for $\sqrt{S} \to \infty$



Alternatives to the Higgs mechanism?

- Unitarity bound not violated if additional boson with $m \lesssim 850$ GeV exists:

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SALS.
repeat

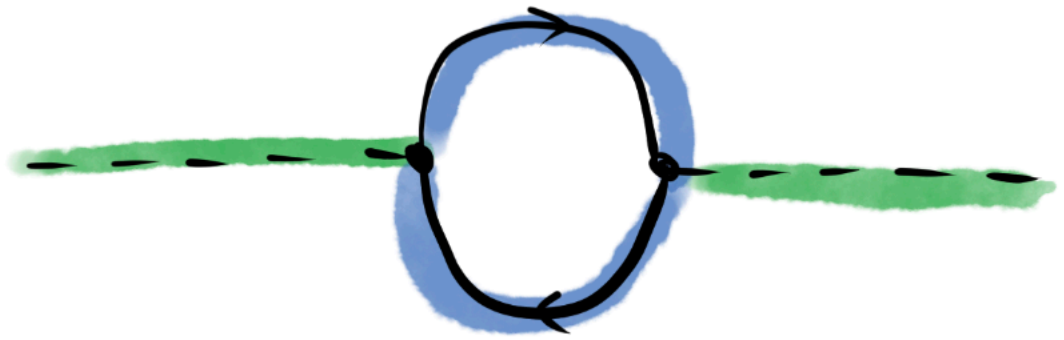

eat.
sleep.
SALS.
repeat

Higgs self-coupling

- The SM is (very likely) an effective theory, valid up to a certain energy Λ
  - Above Λ the SM is not valid anymore (like Newton mechanics → General Relativity)
- Largest possible range of validity of SM: up to Planck scale Λ_{Pl}
  - Planck scale = scale at which reduced Compton wavelength of a particle is 2× the Schwarzschild radius and gravity becomes relevant for particle physics

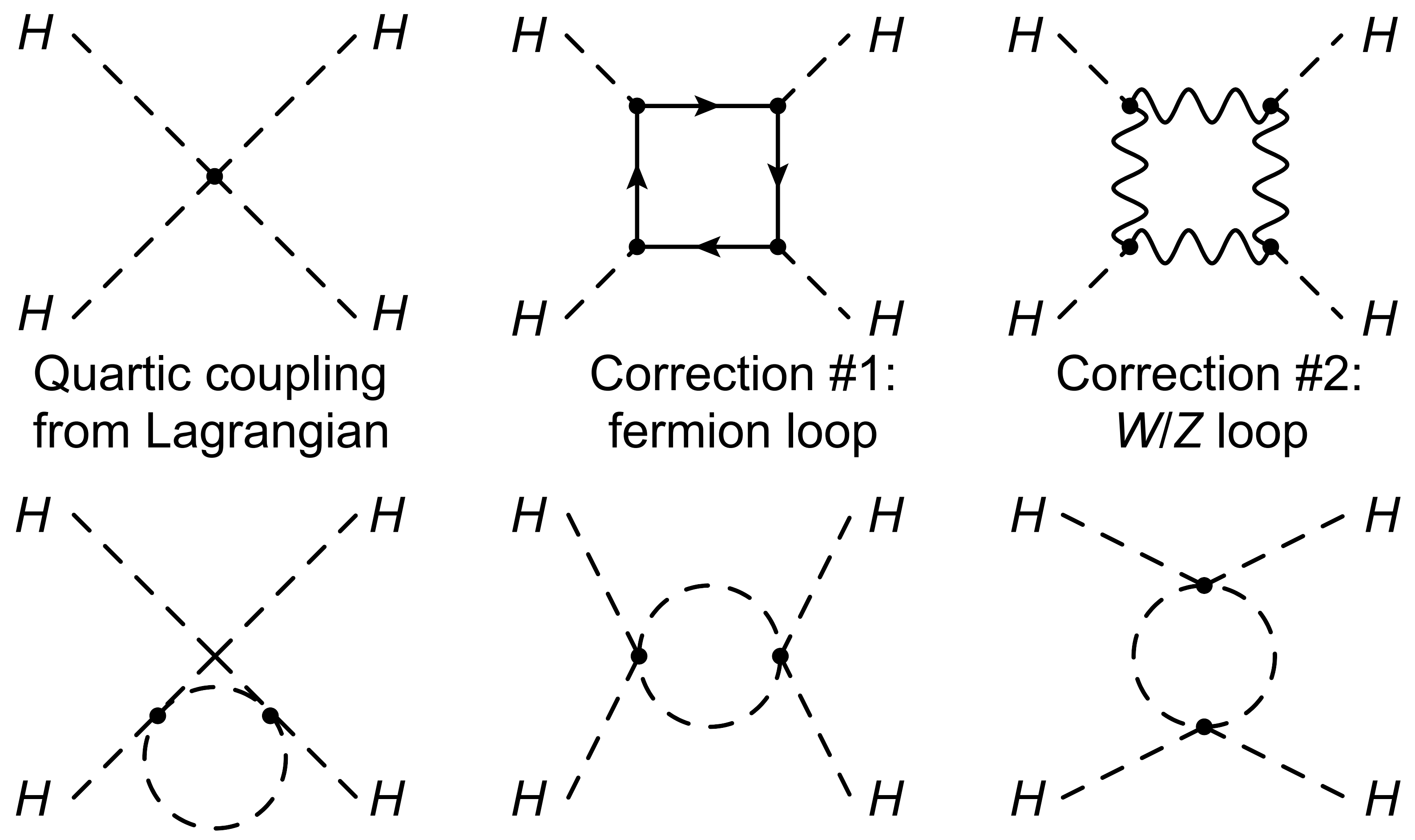
$$\frac{\lambda_c}{2\pi} = 2R_S \rightarrow \frac{\hbar}{mc} = \frac{Gm}{c^2} \rightarrow \Lambda_{\mathrm{Pl}} = \sqrt{\frac{\hbar c}{G}} = 1.22 \times 10^{19}\,\mathrm{GeV}$$

- Relevant for Higgs physics since the Higgs mass receives energy dependent loop corrections



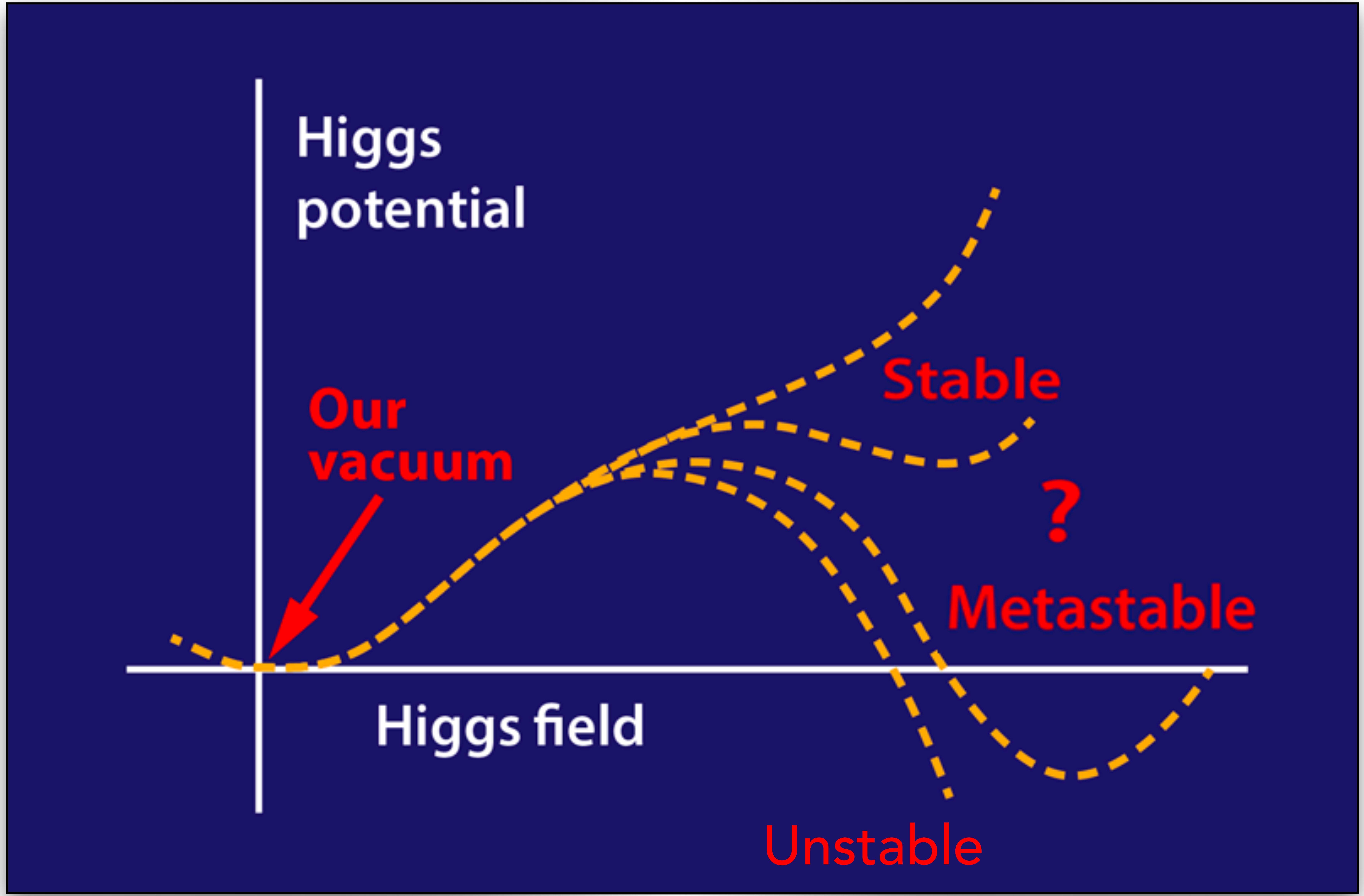
Higgs self-coupling

- Contributions to running of Higgs self-coupling constant λ (RGE formalism similar to running of strong coupling α_s):



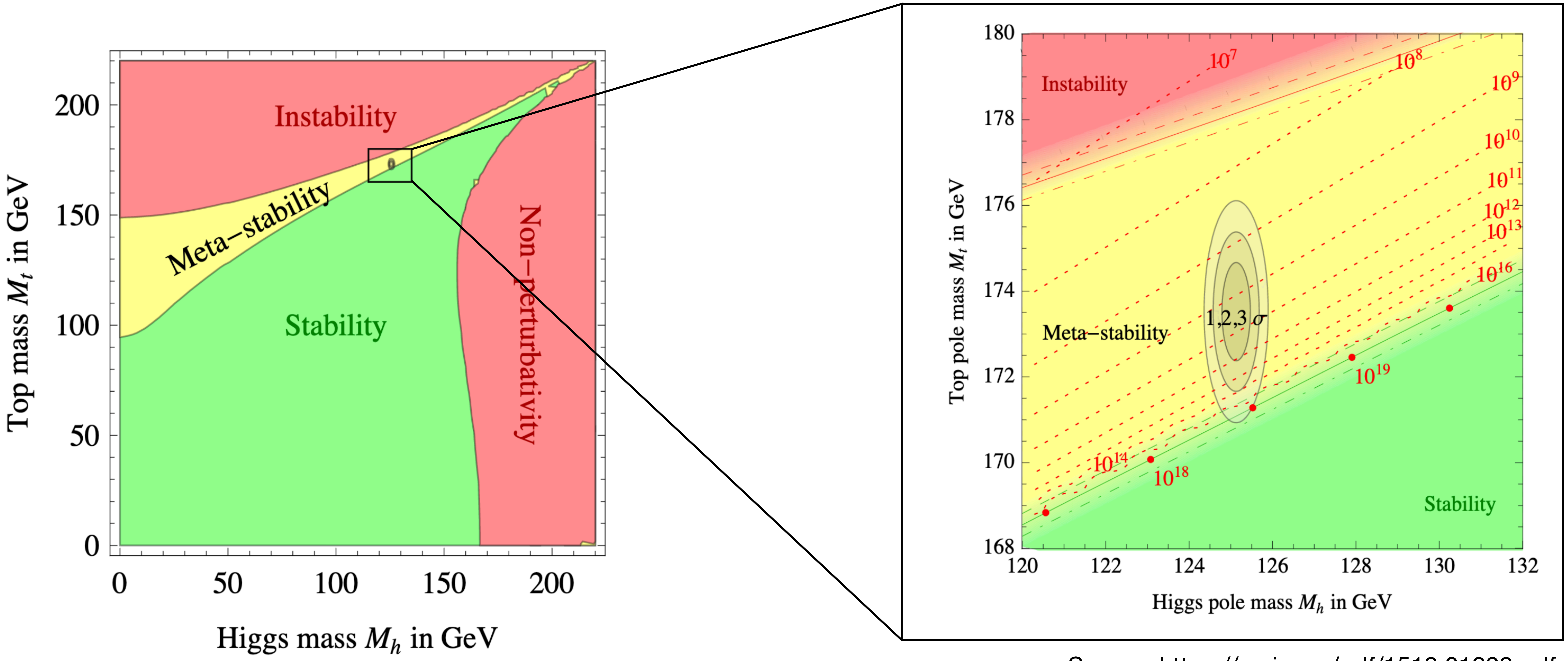
- Question: which values can $\lambda(\Lambda)$ assume, so that the Higgs-mechanism remains valid up to maximum energy scale Λ?
  - Perturbativity: $\lambda(\Lambda) \geq \pi$ (or 2π) → coupling too strong at energy scale Λ
  - Stability: $\lambda(\Lambda) < 0$ (negative coupling) → Higgs potential turns around

Stability



Source: https://physics.aps.org/articles/v8/108

Stability (NNLO)

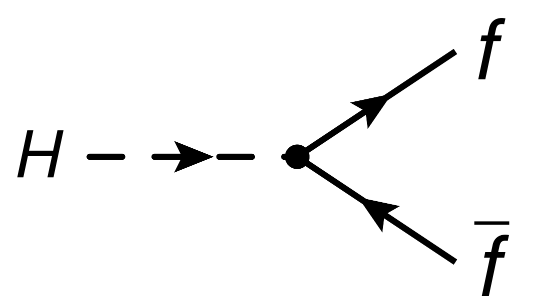


Source: https://arxiv.org/pdf/1512.01222.pdf

Higgs boson partial decay width

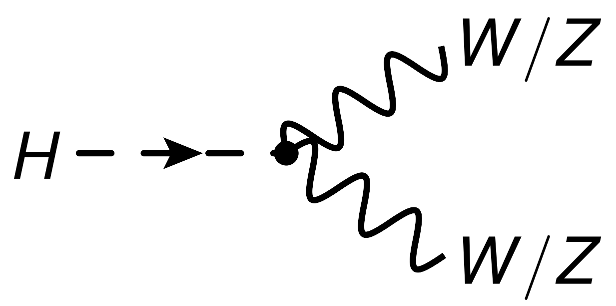
- Decays to fermions or boson pairs (at leading order):

$$\Gamma(H \to f\bar{f}) = N_C \frac{G_F}{4\sqrt{2}\pi} m_f^2(m_H)\, m_H\, \beta_f^3$$



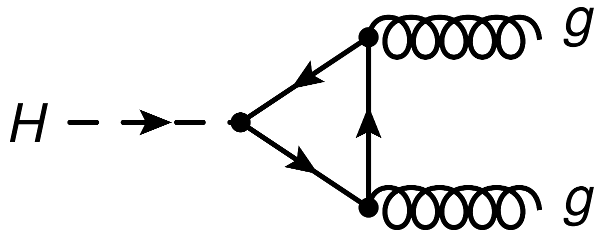
$$\Gamma(H \to ZZ) = \frac{G_F}{16\sqrt{2}\pi} m_H^3 (1 - 4x + 12x^2)\, \beta_Z$$

$$\Gamma(H \to WW) = 2\frac{G_F}{16\sqrt{2}\pi} m_H^3 (1 - 4x + 12x^2)\, \beta_W$$

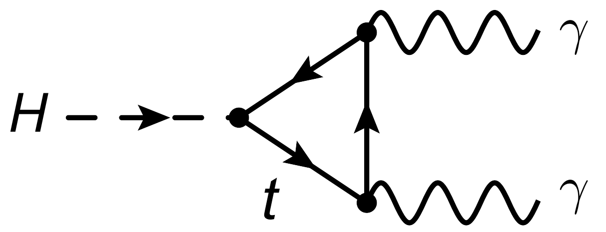


$$\text{with} \quad x_{f,W,Z} = \frac{m_{f,W,Z}^2}{m_H^2}, \qquad \beta_{f,W,Z} = \sqrt{1 - 4x}$$

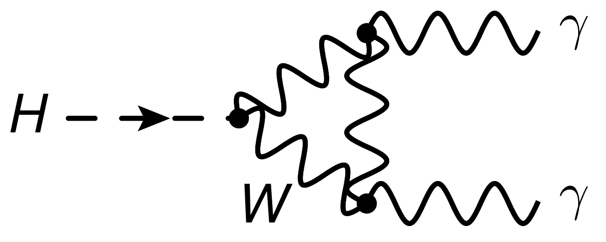
- Decays into massless gluons or photons ($m_H \ll 2m_{W/t}$)



$$\Gamma(H \to gg) = \frac{G_F\, \alpha_S^2(m_H^2)}{36\sqrt{2}\pi^3} m_H^3 \left[1 + C(m_h^2/m_t^2)\frac{\alpha_S}{\pi}\right]$$



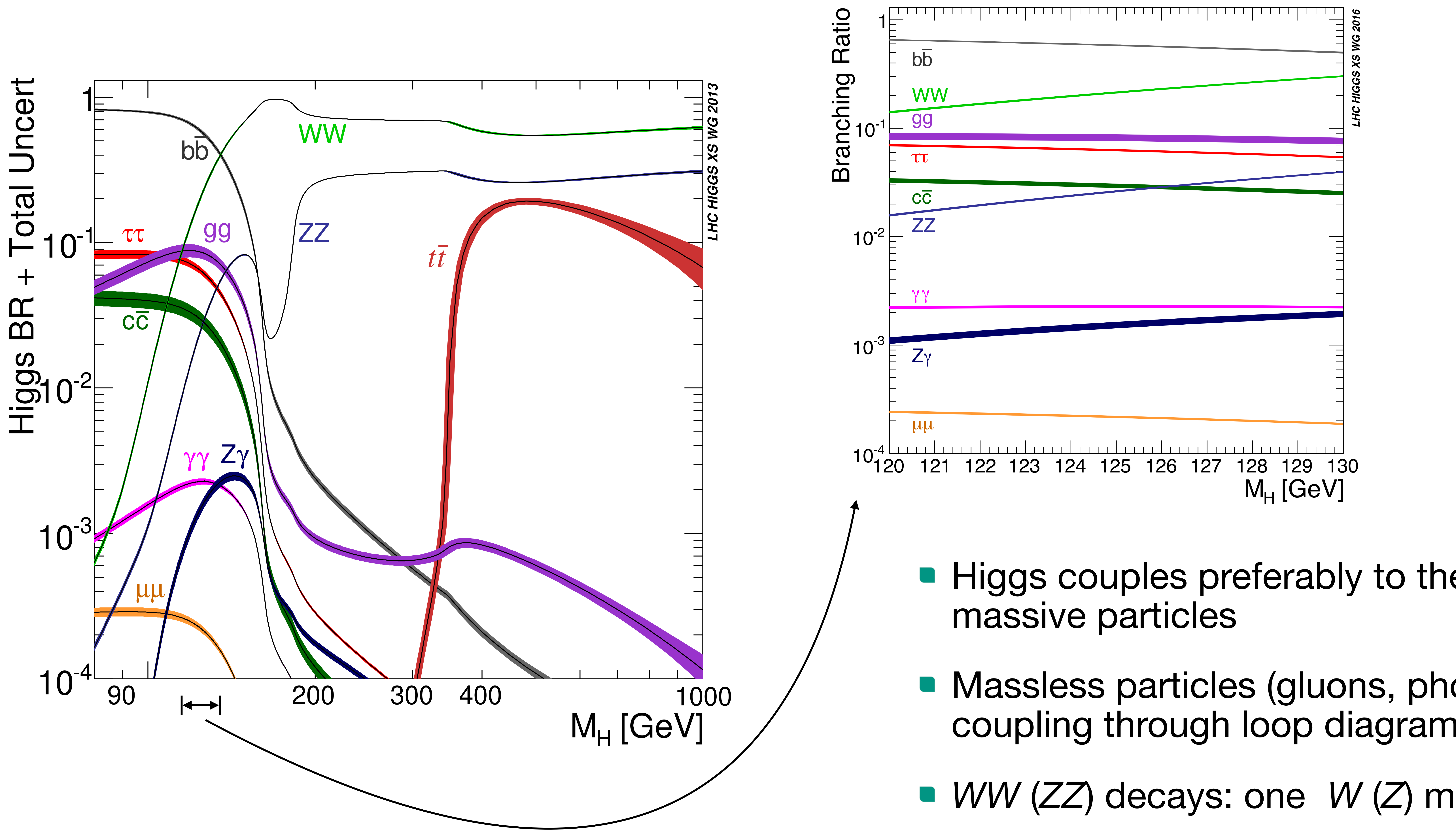
$$\Gamma(H \to \gamma\gamma) = \frac{G_F\, \alpha^2}{128\sqrt{2}\pi^3} m_H^3 \left[\frac{4}{3} N_C Q_t^2 - 7\right]^2$$



top

W (about 4 times larger, opposite sign)

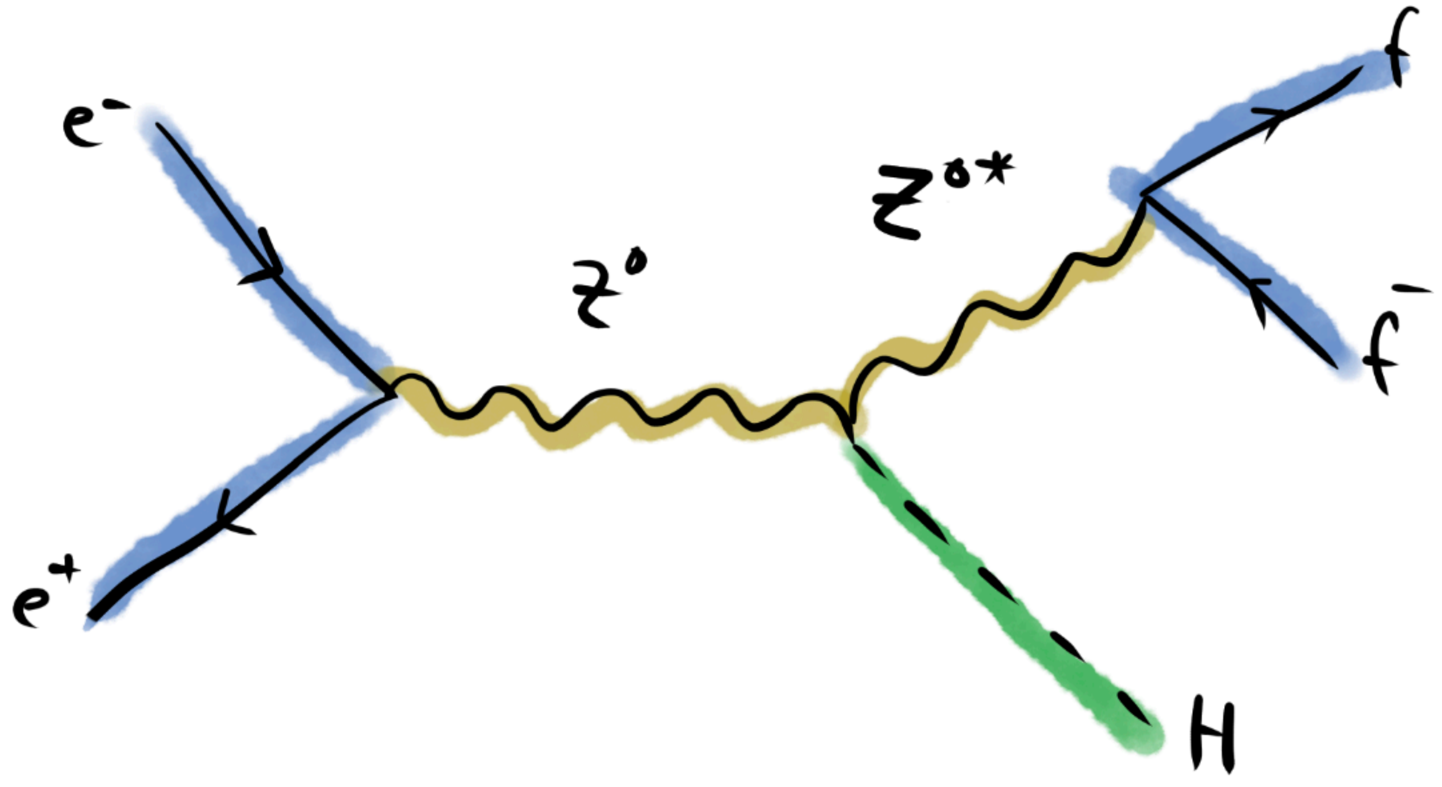
Higgs boson branching fractions

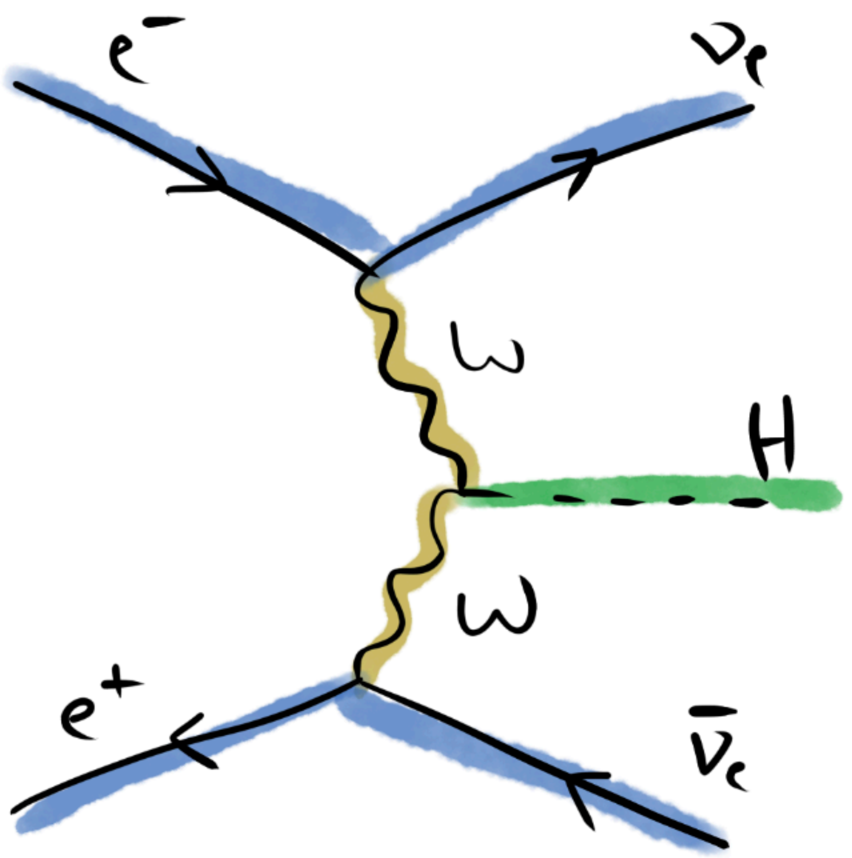


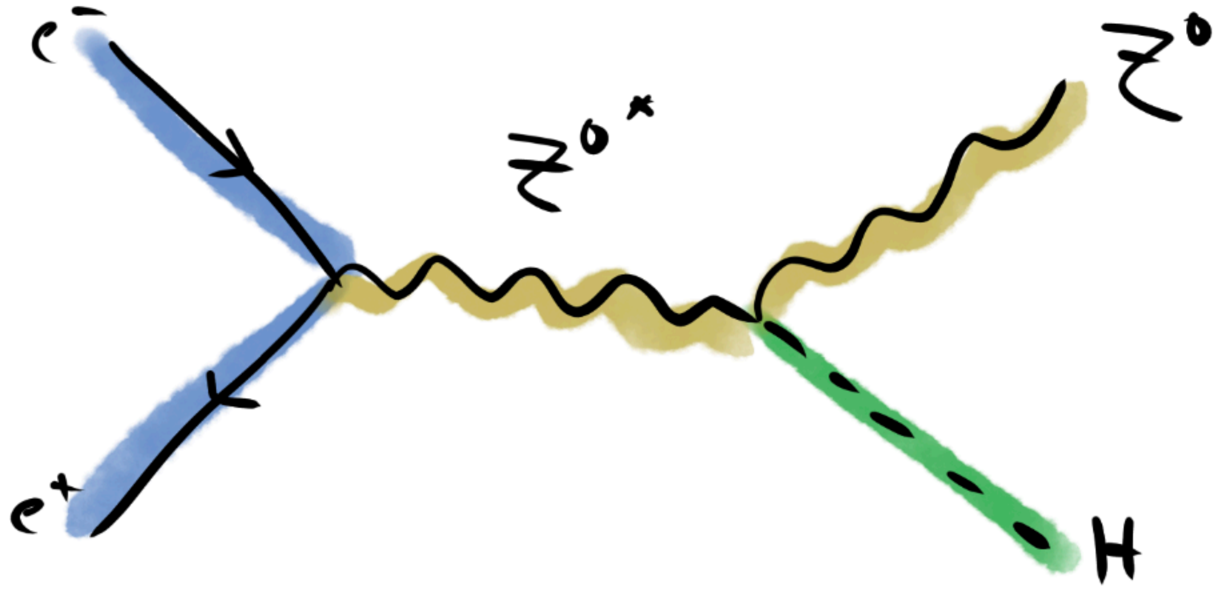
- Higgs couples preferably to the most massive particles
- Massless particles (gluons, photons): coupling through loop diagrams
- *WW* (*ZZ*) decays: one *W* (*Z*) may be virtual

Higgs search at LEP and LEP2

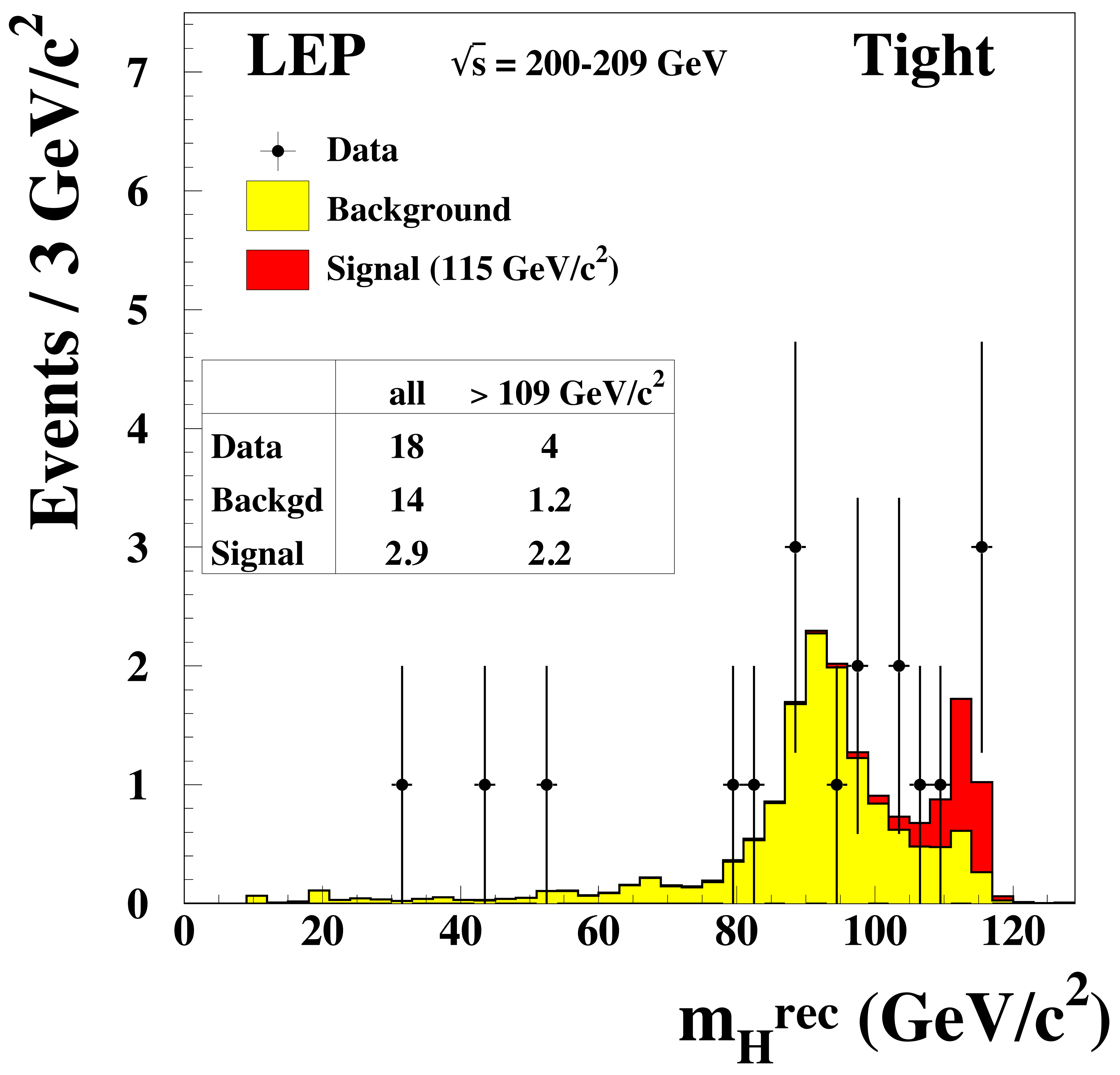
- LEP: center of mass energy around 91.2 GeV
  - Dominant production: $Z \to H + f\bar{f}$
  - Background small if Z can be reconstructed
  - Lower limit on Higgs mass: $m_H \gtrsim 65$ GeV
- LEP2: center of mass energy up to 206 GeV
  - Dominant production: $Z \to H + Z$ (Higgs-Strahlung)
  - Lower limit on Higgs mass: $m_H \gtrsim 115$ GeV

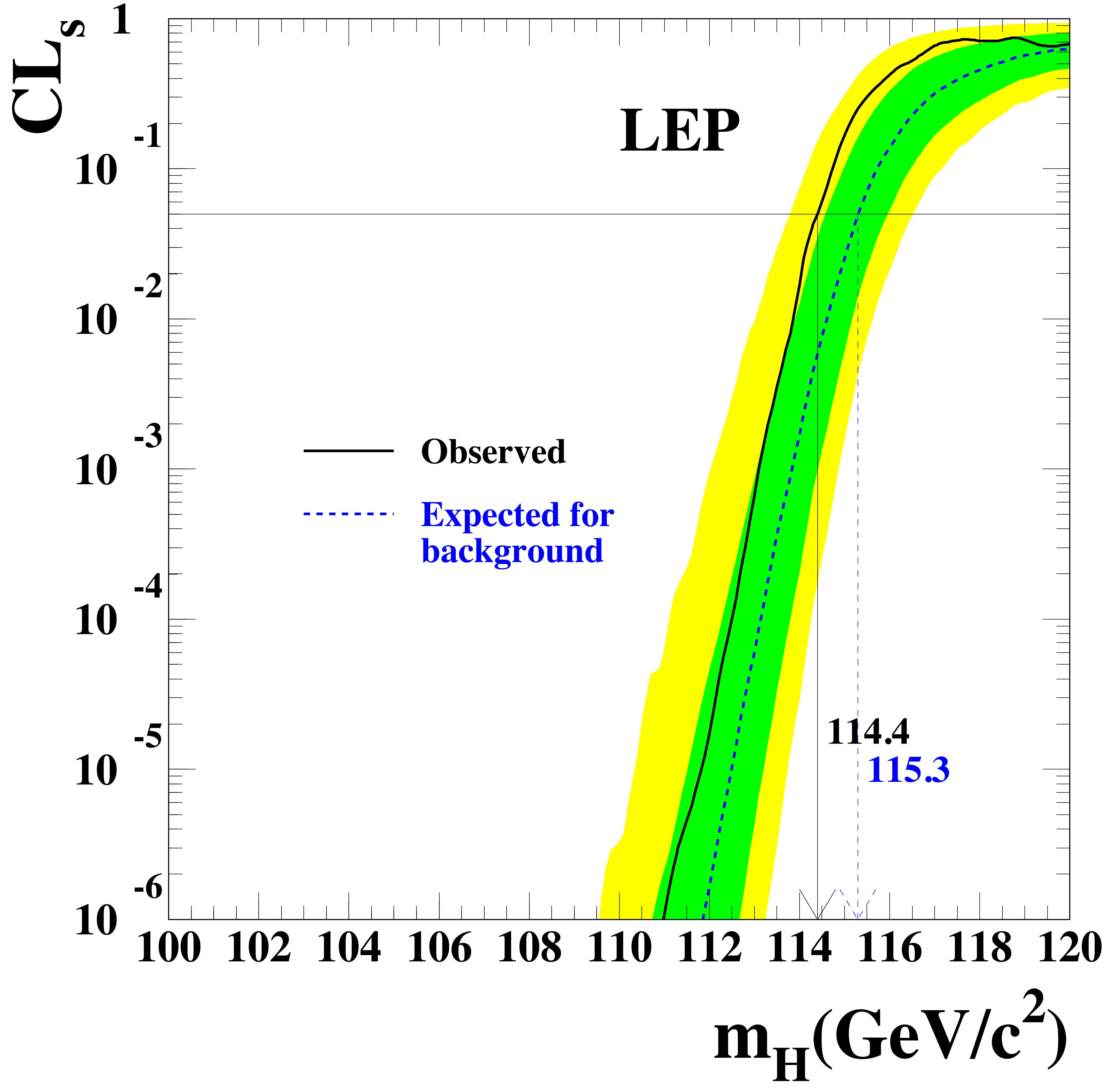






Higgs search at LEP2, final results



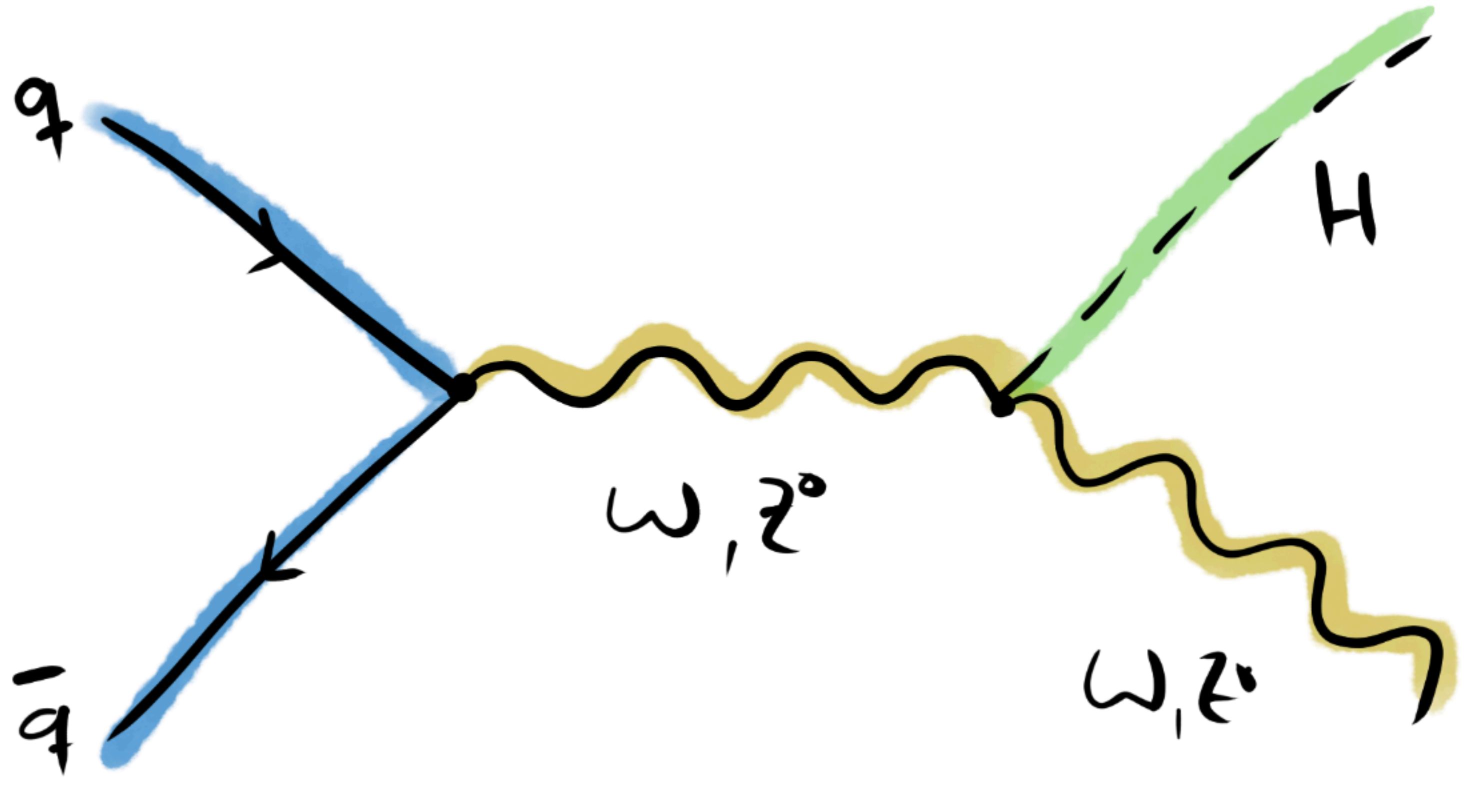


Source: https://arxiv.org/abs/hep-ex/0306033

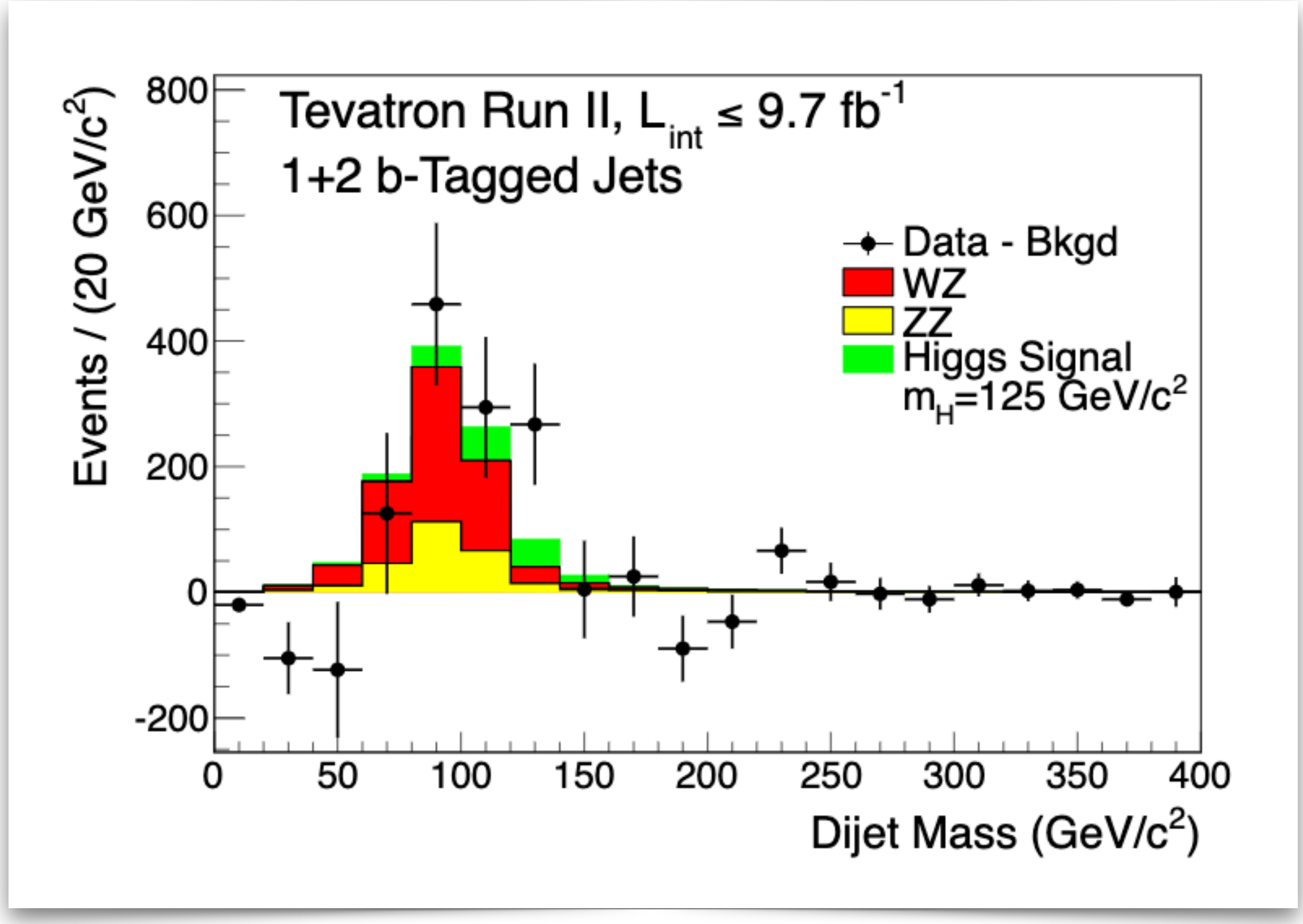
Higgs search at Tevatron

- $p\bar{p}$ collider: coverage of large mass range, but also very large background (often: uncertainty on background larger than expected signal)
- Good sensitivity primarily in associated *WH* and *ZH* production
- Relevant Higgs-boson decay channels at the Tevatron:
  - $H \to \mathrm{bb}$: identified using B-tagging, but large background from QCD jets
  - $H \to \tau\tau$: large backgrounds (QCD, $Z \to \tau\tau$)
  - $H \to WW$: very sensitive around *WW* threshold, $m_H = 2m_W \approx 160$ GeV
  - $H \to \gamma\gamma$: very clean but small branching fraction

Credit: Fermilab



Higgs search at Tevatron



- Combined analysis of full dataset at both detectors:

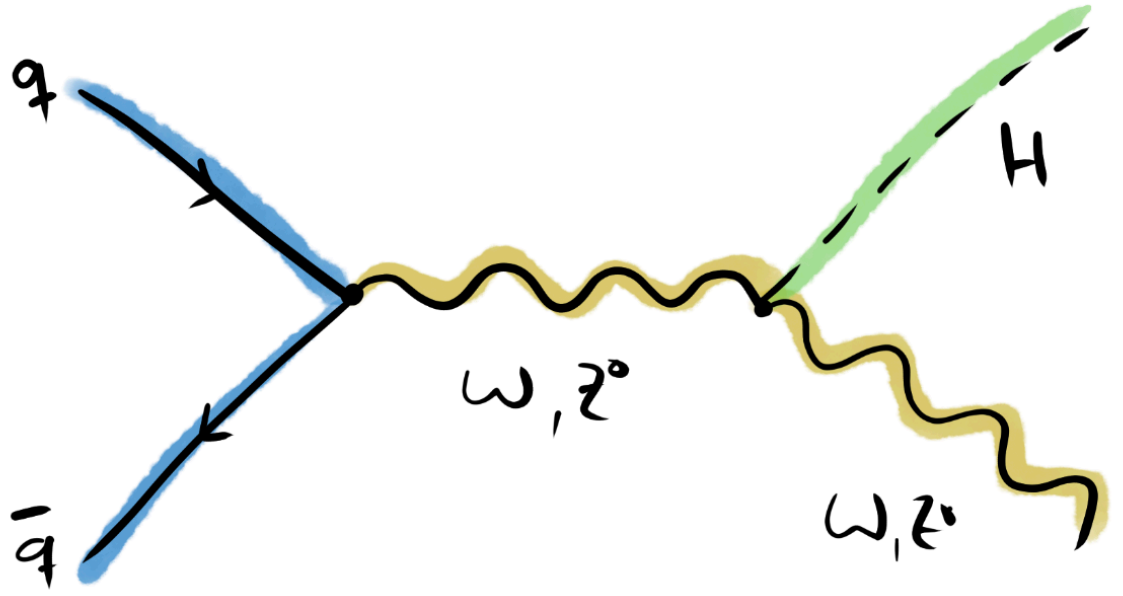
  3.1σ significance ("evidence) of a particle with mass m=135 GeV
- Published one day before the Higgs discovery at the LHC

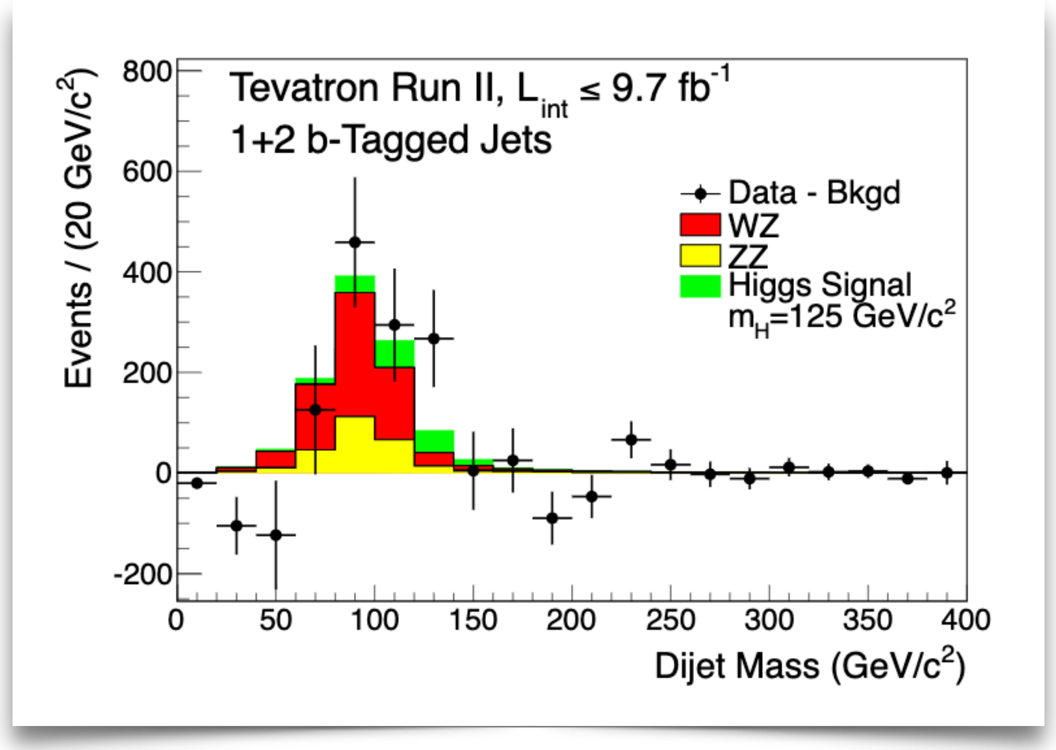
Source: https://arxiv.org/pdf/1207.6436.pdf

PINGO: Higgs coupling

- The SM 125-GeV Higgs boson has a total decay width of around 4 MeV (!). Why is the Tevatron excess observed in a much wider mass range of 30 GeV?

  - In associated *WH* production, the exclusion limits are “smeared” due to the limited mass resolution of bb pairs.
  - The resolution for leptons in $H \to 4\ell$ at the Tevatron is much worse than at the LHC.
  - The resolution for photons in $H \to \gamma\gamma$ at the Tevatron is much worse than at the LHC.
  - In associated *WH* production followed by leptonic *W* decays, the neutrino reconstruction deteriorates the mass resolution.





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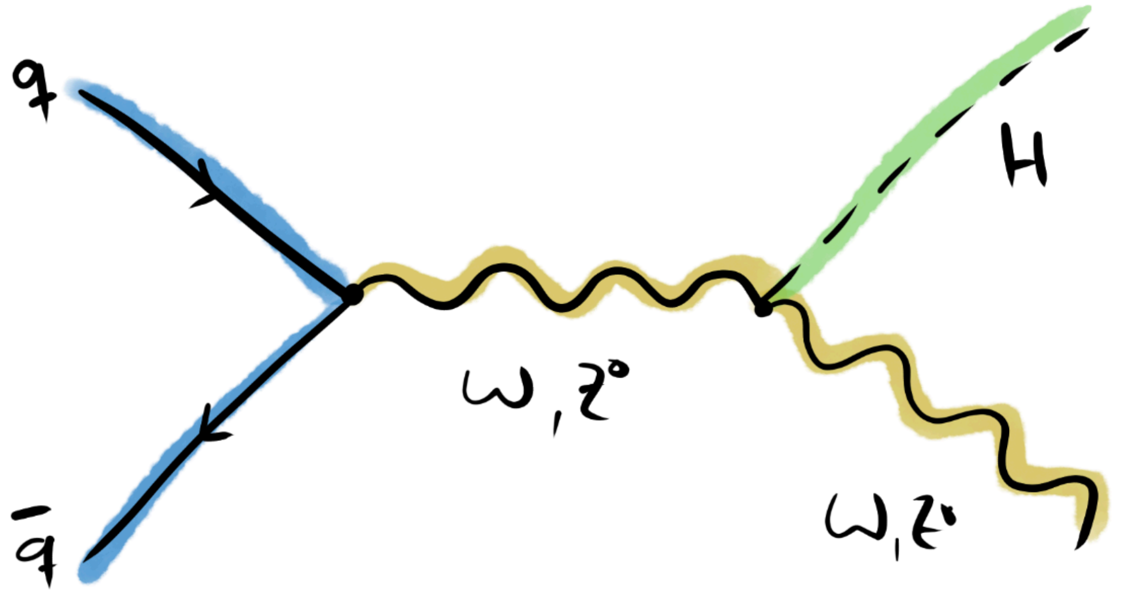
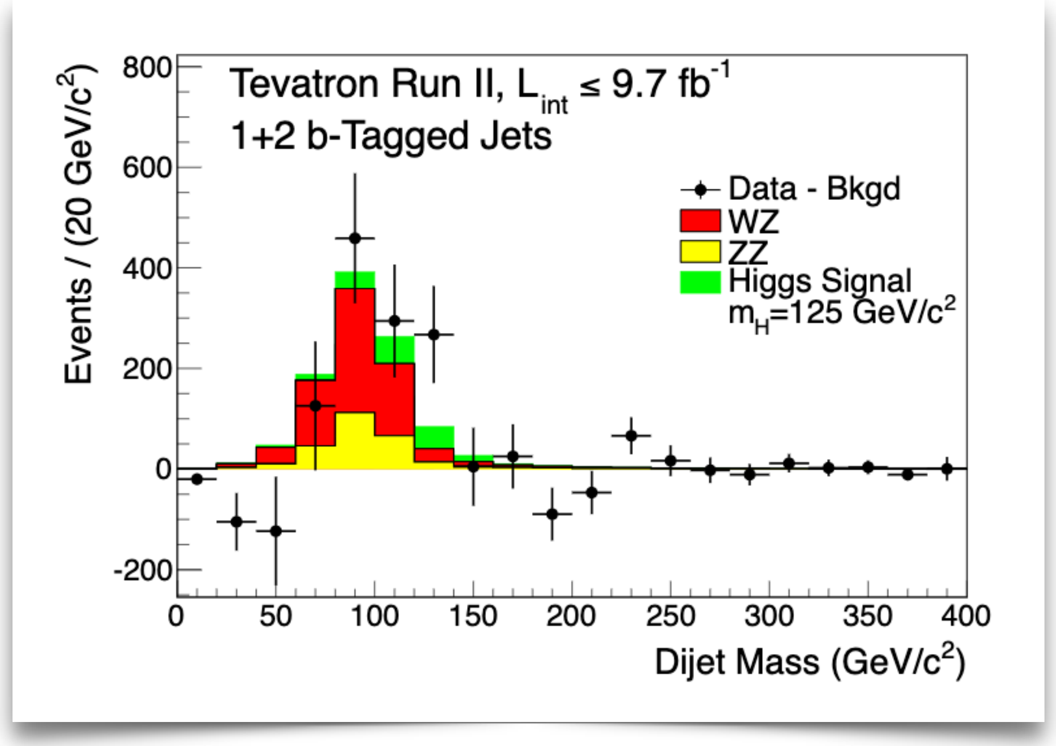
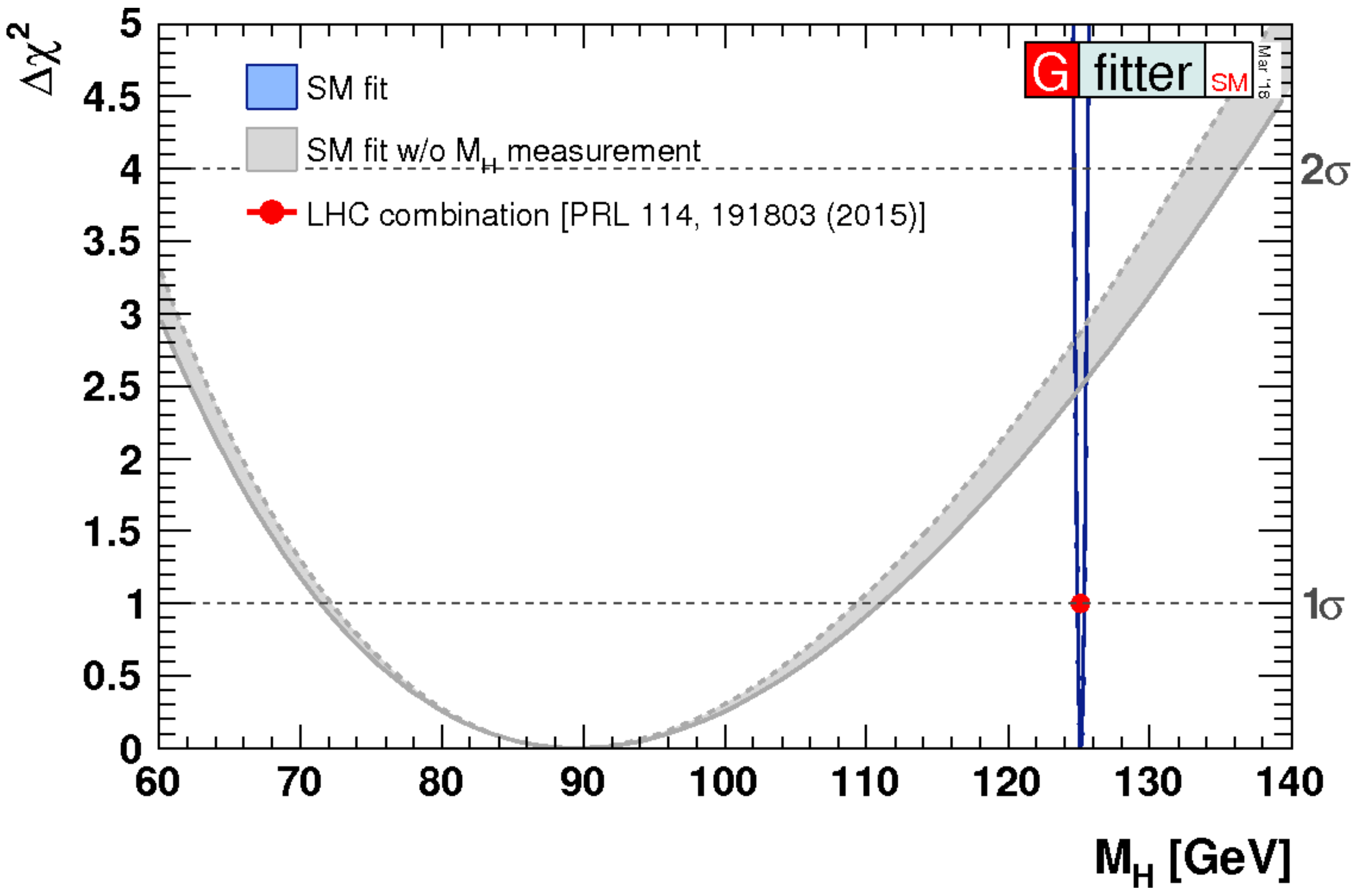
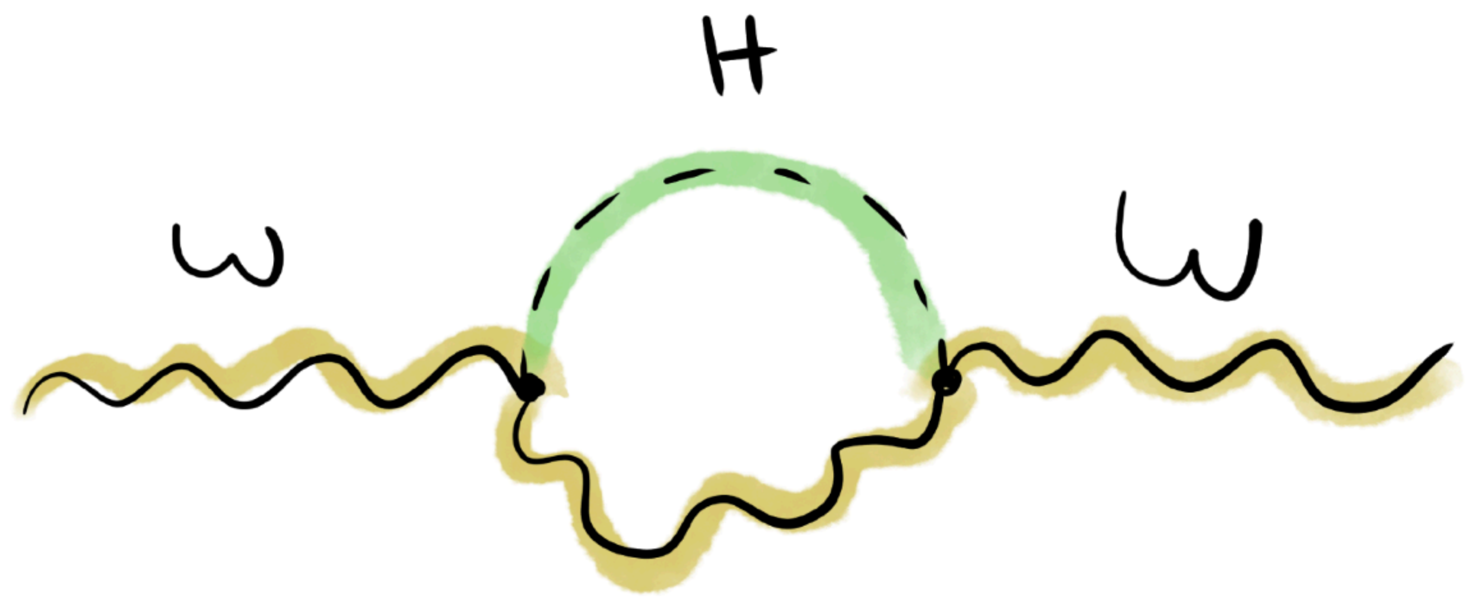
  - **In associated *WH* production followed by leptonic *W* decays, the neutrino reconstruction deteriorates the mass resolution.**





Indirect Higgs Searches



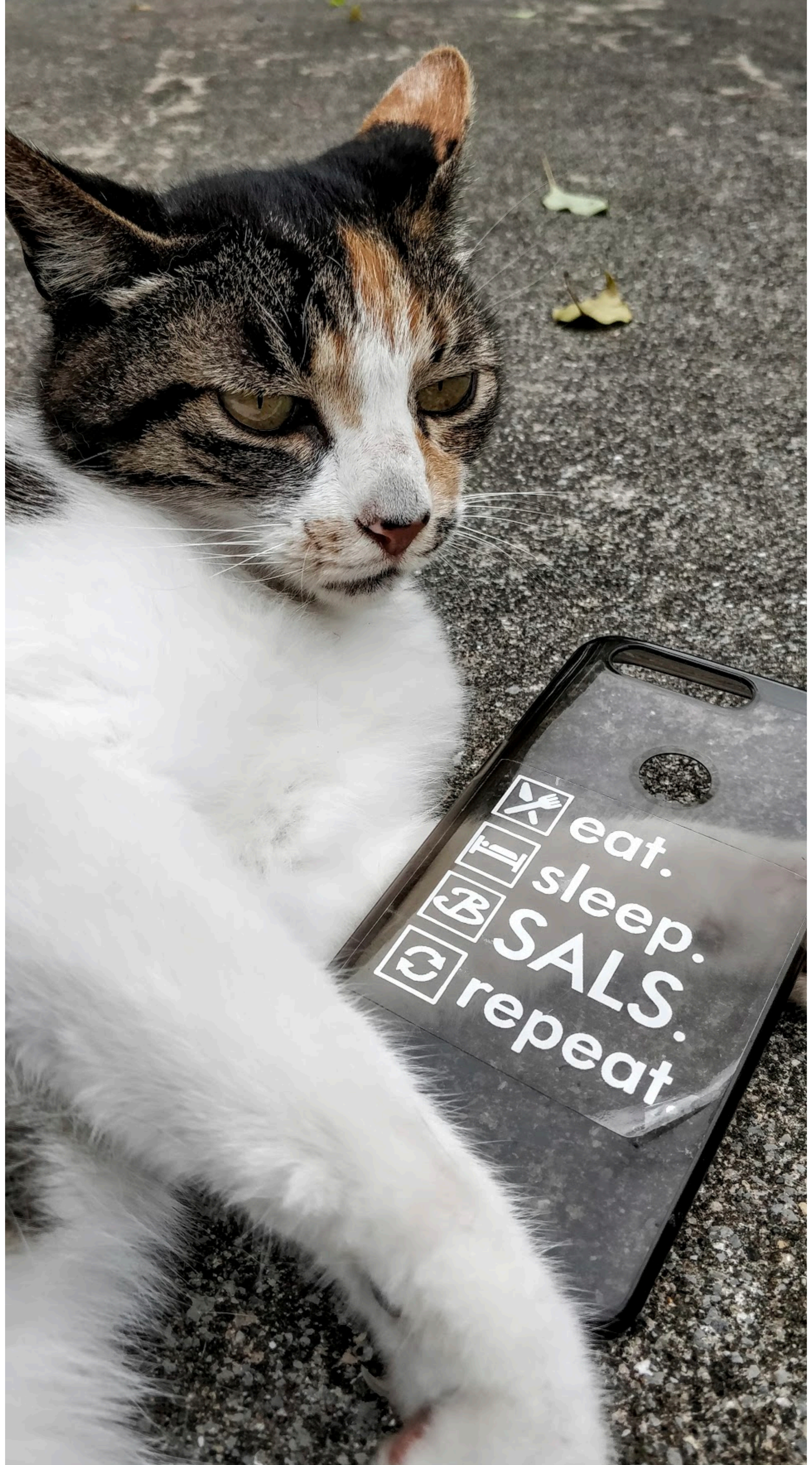


- Higgs boson leads to corrections of SM observables like the Z or W-boson mass
- Best fit before LHC:

$$m_h = 94^{+29}_{-24}\ \text{GeV}$$

$$m_h < 161\ \text{GeV (95\% C.L.)}$$

Source: http://project-gfitter.web.cern.ch/project-gfitter/Figures/Standard_Model/2018_03_20_HiggsScan_logo_large.gif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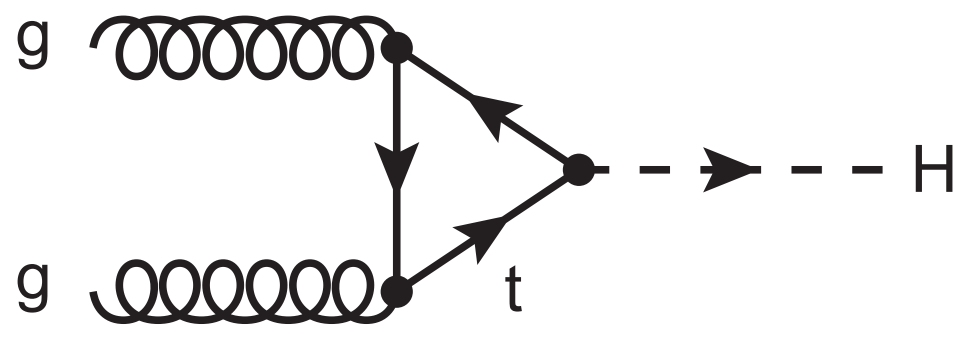
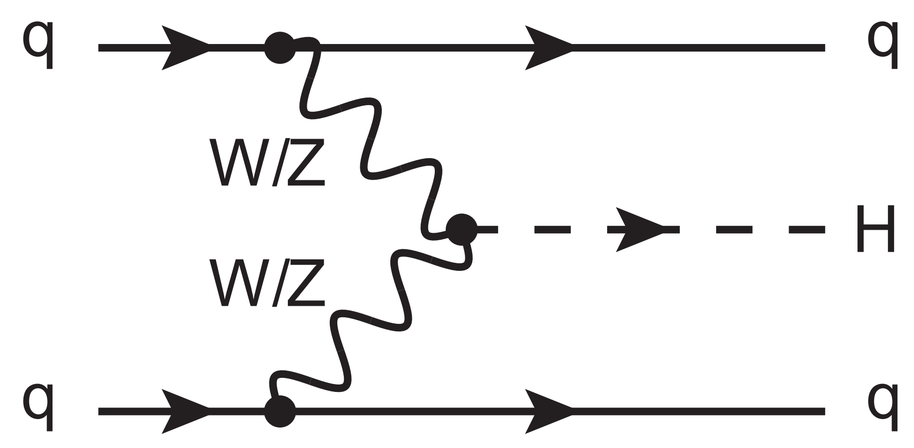
Higgs search at the LHC

Gluon-Gluon Fusion

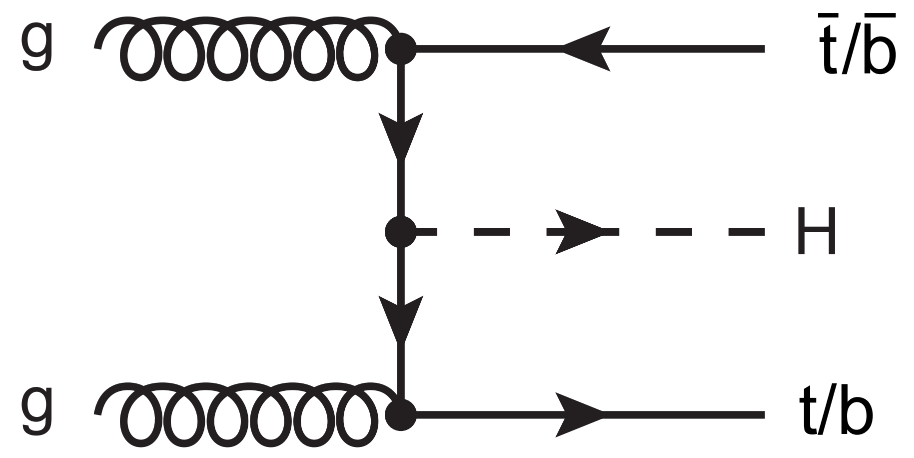


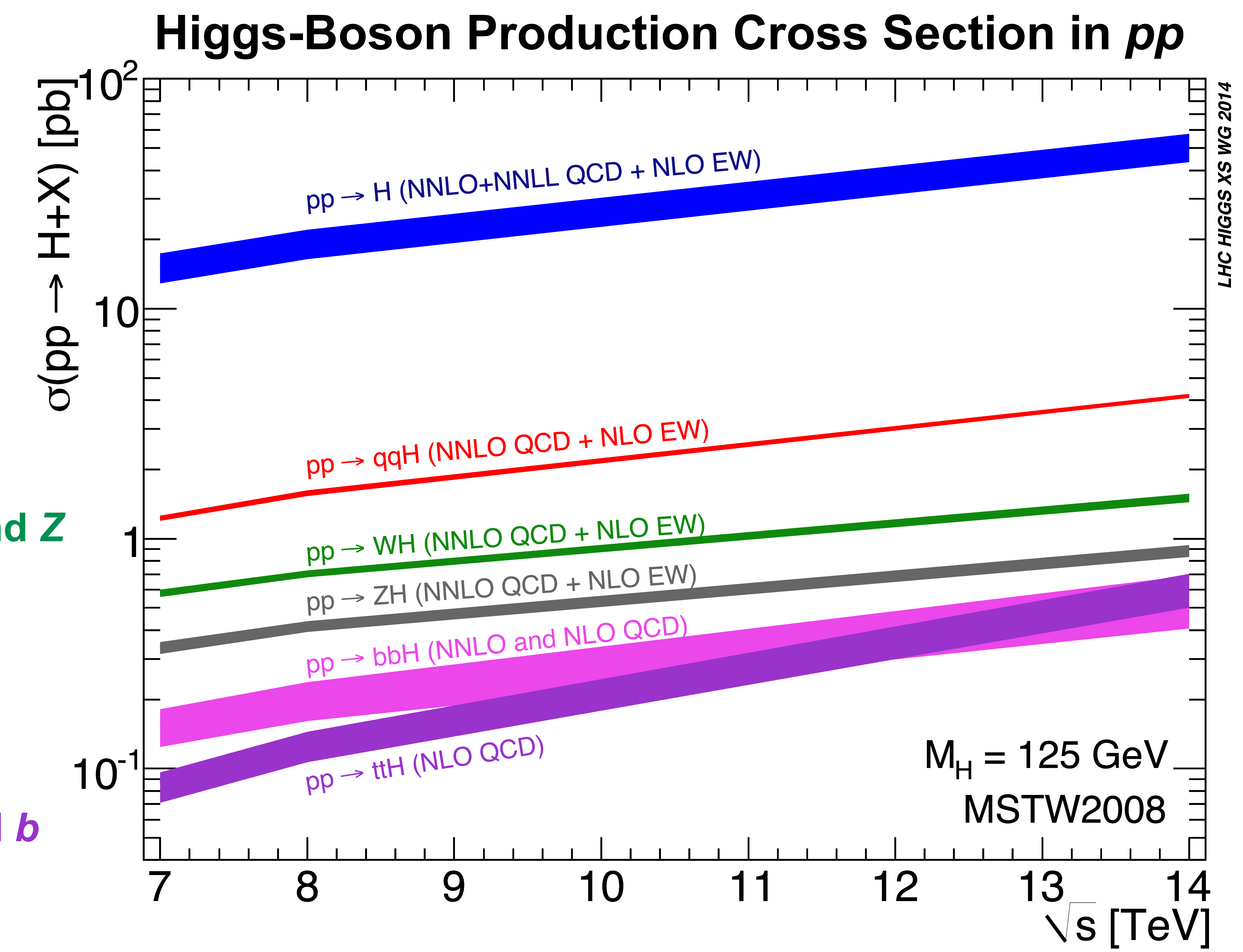
Vector Boson Fusion (VBF)



Associated Production with *W* and *Z*

Associated Production with *t* and *b*





https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHXSWGCrossSectionsFigures

Higgs discovery at the LHC

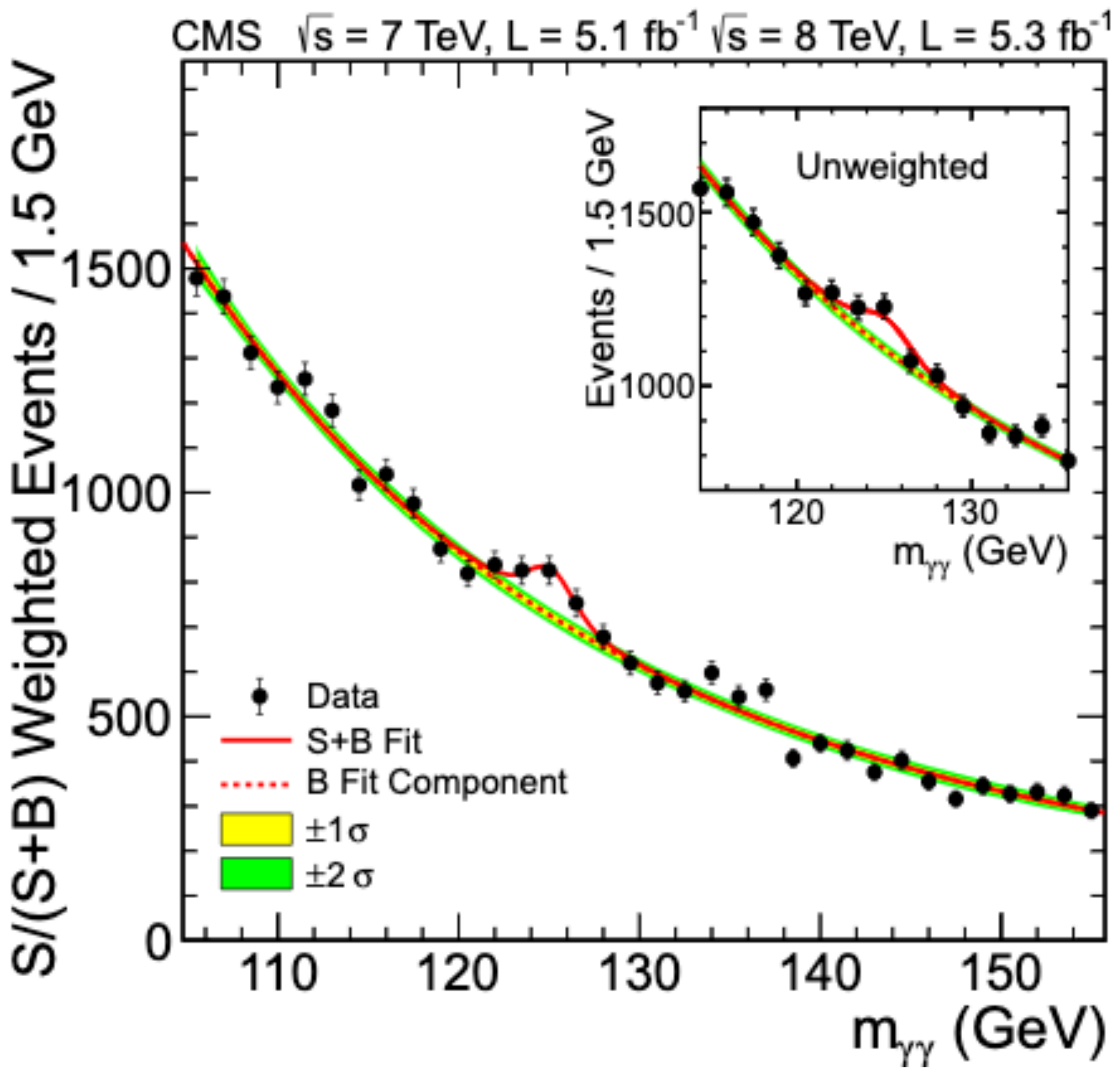
Production	Decay	Remarks
$gg \to H$	$H \to ZZ(*) \to 4\ell$	excellent mass resolution
$gg \to H$ $qq \to qqH$	$H \to \gamma\gamma$	small branching fraction, but excellent mass resolution
$gg \to H$ $qq \to qqH$	$H \to WW(*) \to \ell\nu\,\ell\nu$	large production cross section
$gg \to H$ $qq \to qqH$	$H \to \tau\tau$	decay into fermions with large branching fraction
$\mathrm{q\bar{q}} \to VH$	$H \to \mathrm{b\bar{b}}$	only separable from background in associated production
$gg \to \mathrm{t\bar{t}}H$	$H \to \mathrm{b\bar{b}}$, $\gamma\gamma$, leptons	direct measurement of top-quark Yukawa coupling

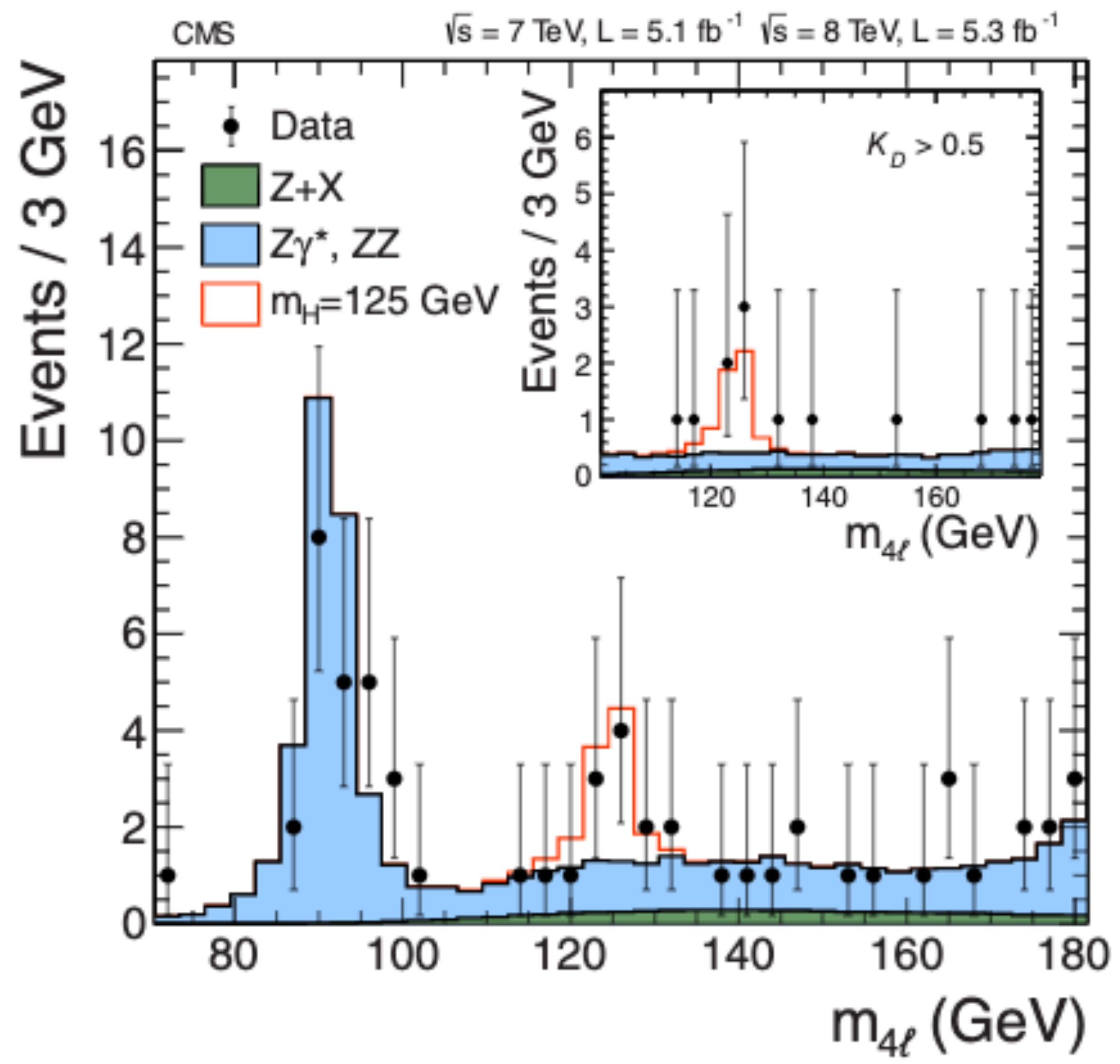
Credit: U. Husemann

Higgs discovery at the LHC

Credit: CERN

Higgs discovery 2012

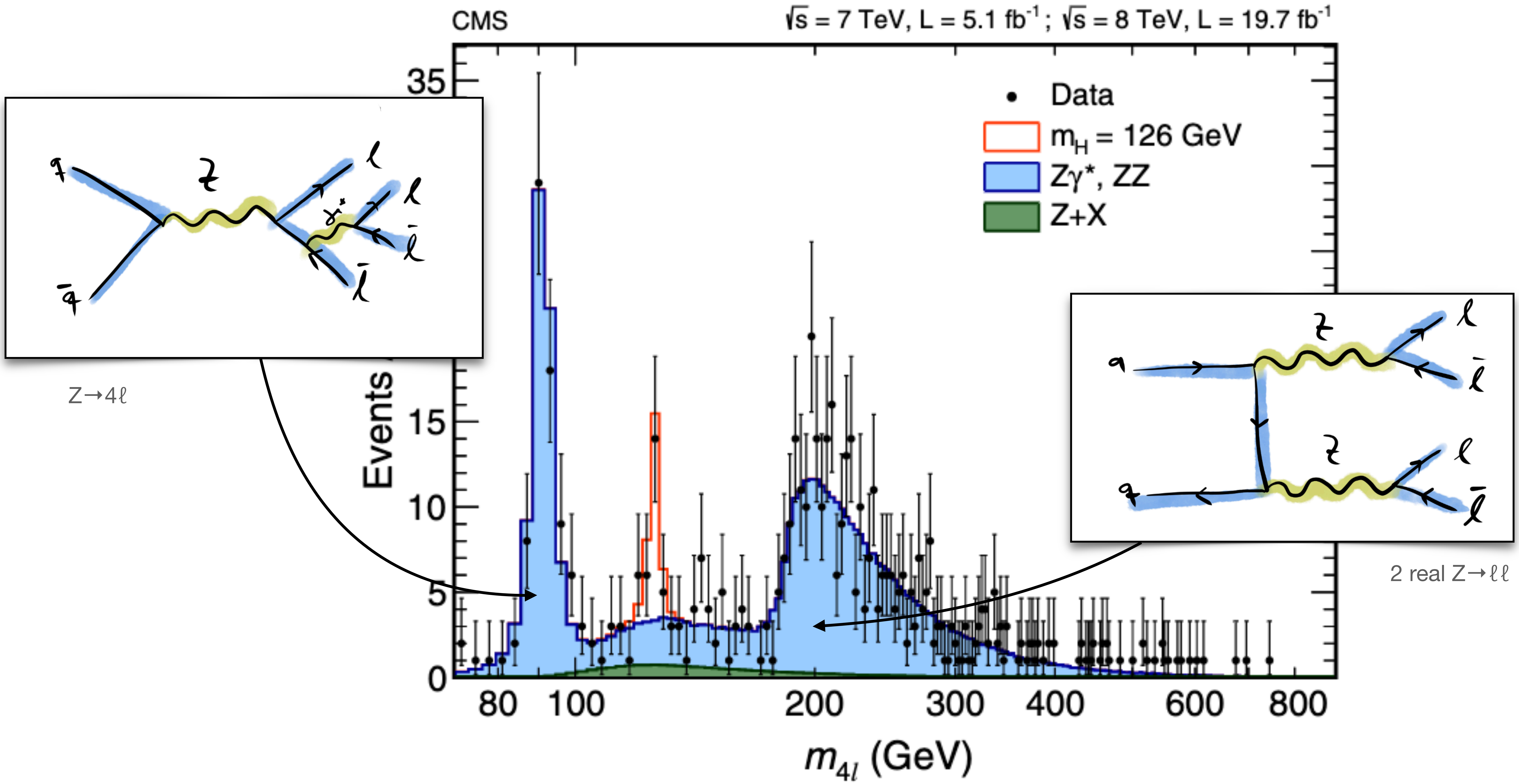




- Allowed Higgs boson mass region “known” to a few ten GeV before 2012
  - Width of the Higgs boson in the SM much smaller than experimental resolution → need the best experimental resolution: $H \to \gamma\gamma$ and $H \to 4\ell$
  - $H \to \gamma\gamma$: “Bump” in diphoton mass spectrum (background from random combinations), needs good ECAL
  - $H \to 4\ell$: One ℓ pair compatible with Z-mass, the other Z is off-shell (“Z*”), ℓ=e or μ: eeee, μμμμ, eeμμ
- Production mode: Vector-Boson fusion
- “Discovery” ($\sigma > 5\sigma$) at CMS and ATLAS by combining all channels

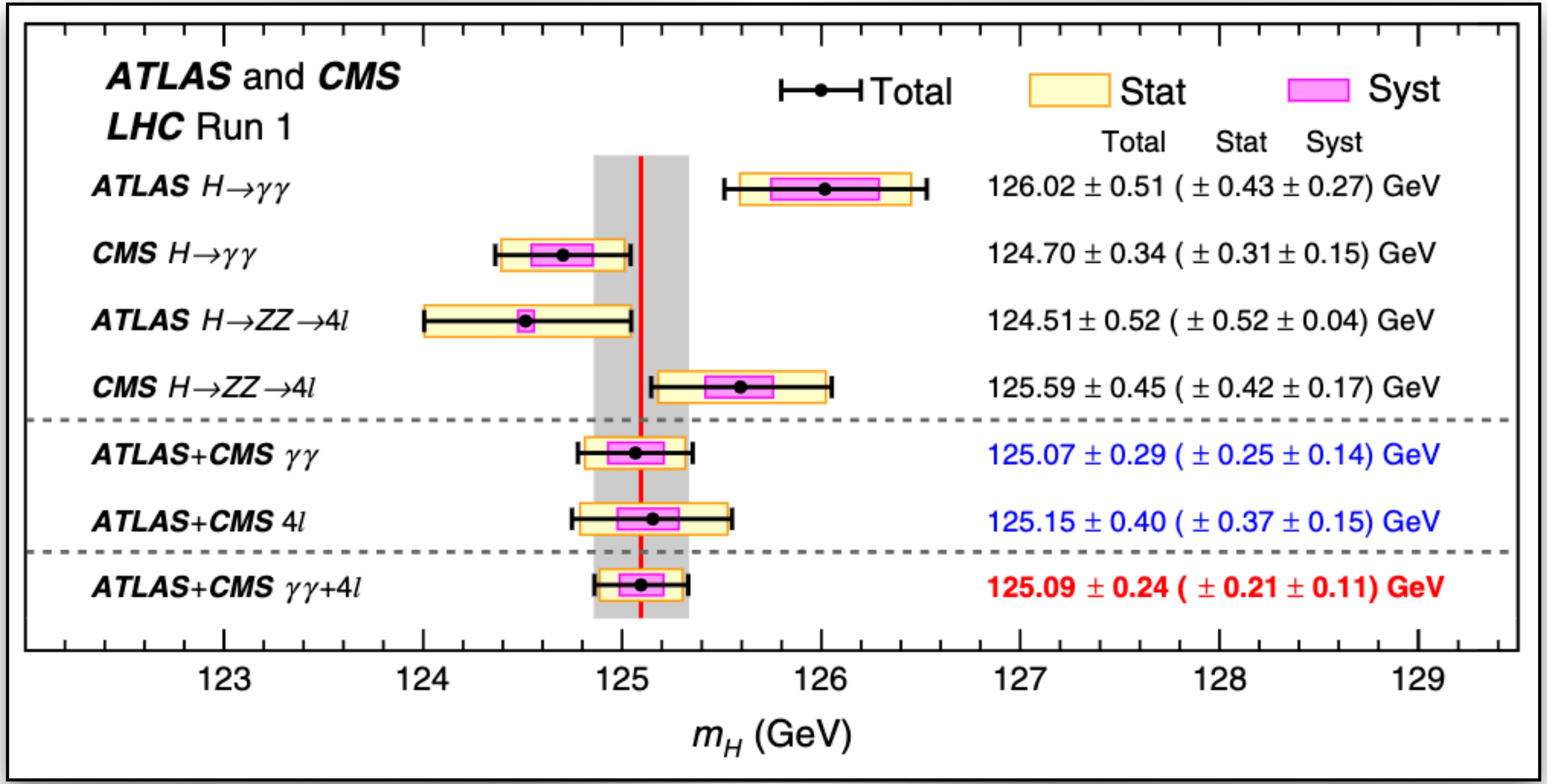
Source: https://arxiv.org/abs/1207.7235

Higgs → 4ℓ (2015)



Source: https://journals.aps.org/prd/pdf/10.1103/PhysRevD.89.092007

Higgs boson mass



as of 2022: $m_H = (125.10 \pm 0.14)$ **GeV**

Source: https://journals.aps.org/prl/pdf/10.1103/PhysRevLett.114.191803
and https://pdg.lbl.gov/2022/reviews/rpp2022-rev-higgs-boson.pdf

Higgs boson production and decay modes

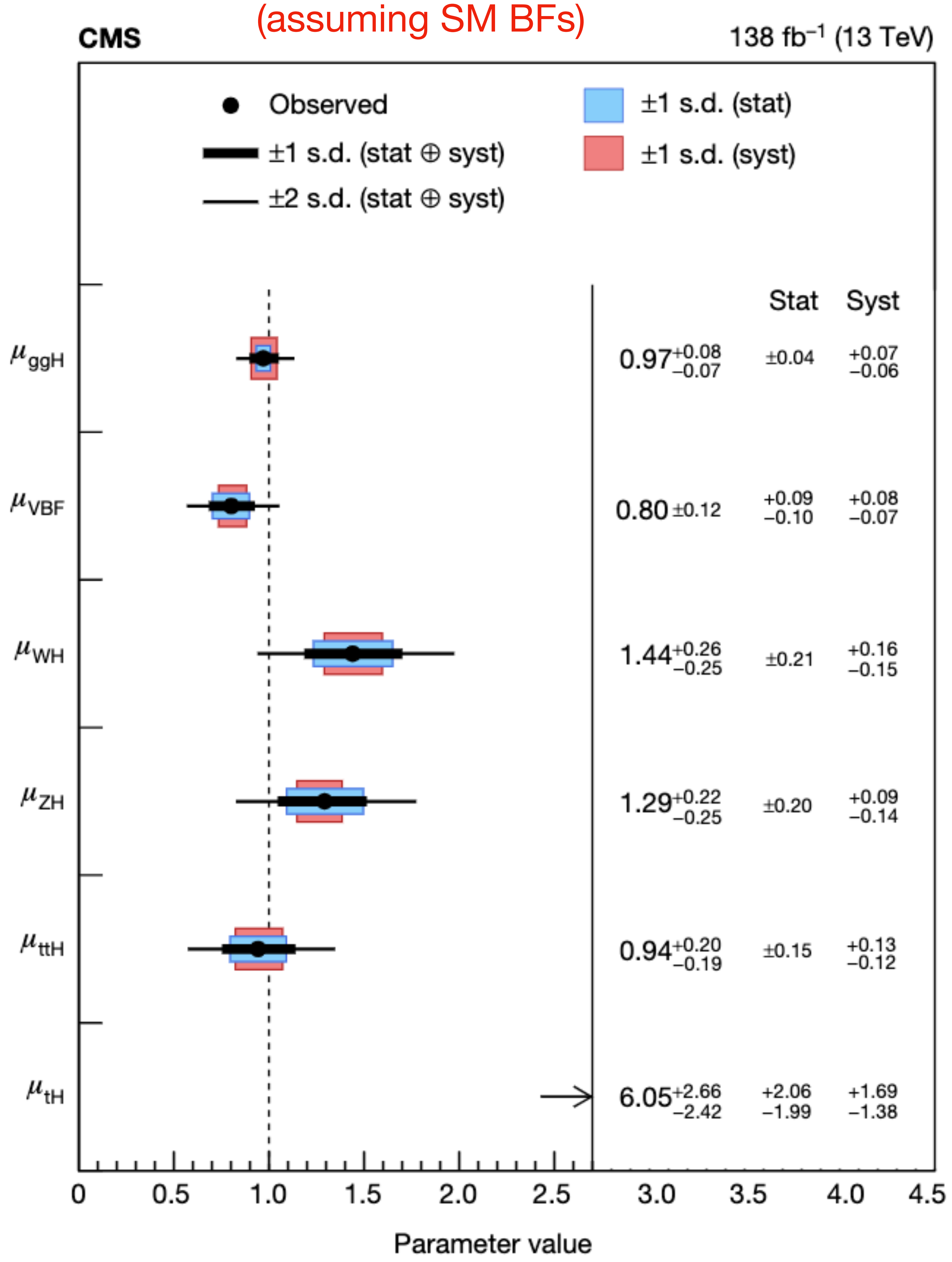
- All parameters of the SM known:
  All couplings of the Higgs to all fermions, bosons, and itself can be calculated and compared to measurements

- Assumptions:
  - There is only one Higgs boson (and not several, overlapping, or interfering Higgs bosons)
  - The width of the Higgs boson is very small ("zero width approximation") → production and decay factorize: $(\sigma \times \mathrm{BF})(i \to H \to f) = \dfrac{\sigma_i \Gamma_f}{\Gamma_H}$ (initial state i, final state f)
  - Any new physics (not in the SM) does change cross sections and branching factions, but not kinematics

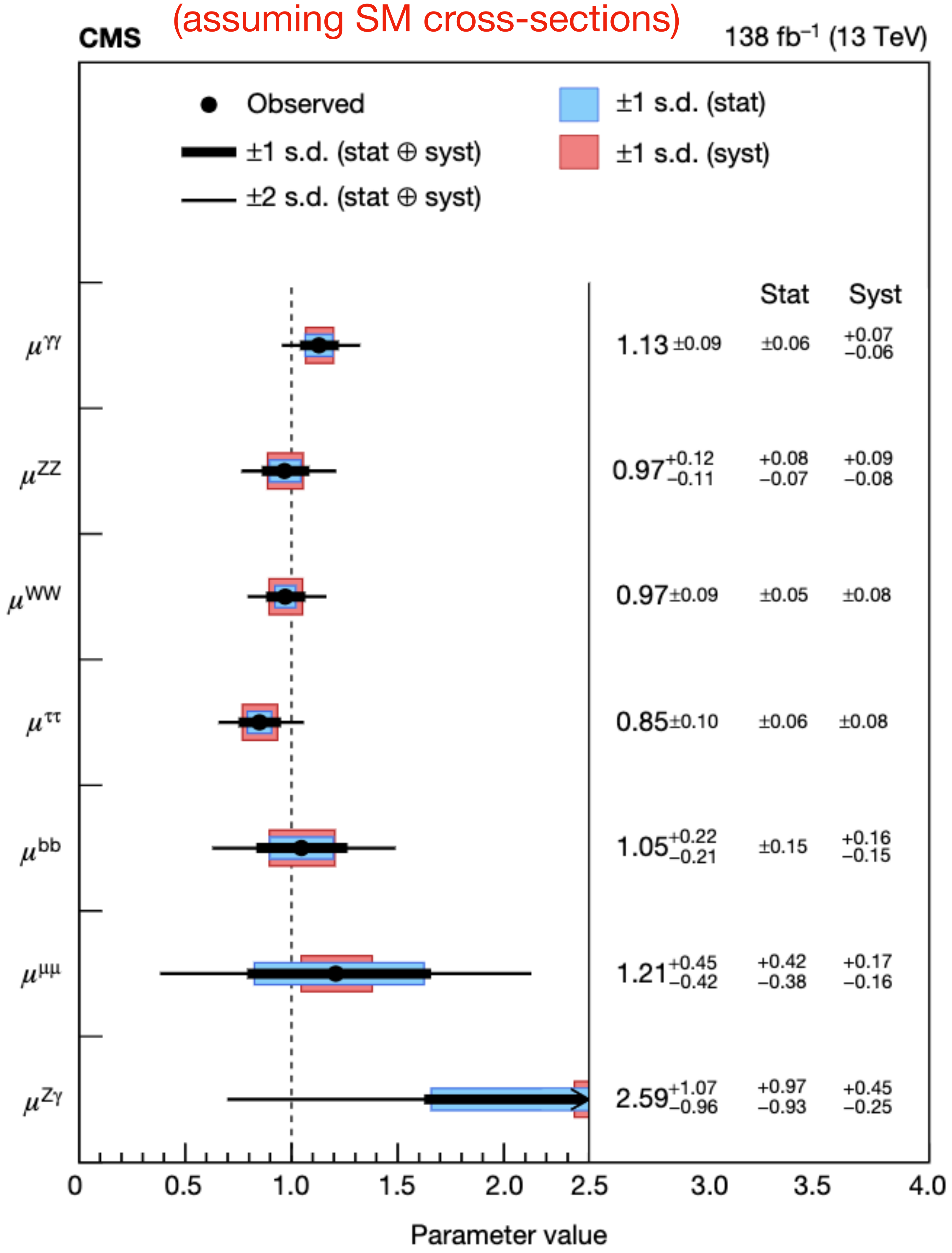
μ framework for signal strengths (CMS 2022)

$$\mu = \frac{\sigma(pp \to H+X)}{\sigma(pp \to H+X)^{\mathrm{SM}}} \frac{\mathrm{BF}(H \to Y)}{\mathrm{BF}(H \to Y)^{\mathrm{SM}}}$$

production modes
(assuming SM BFs)



decay modes
(assuming SM cross-sections)



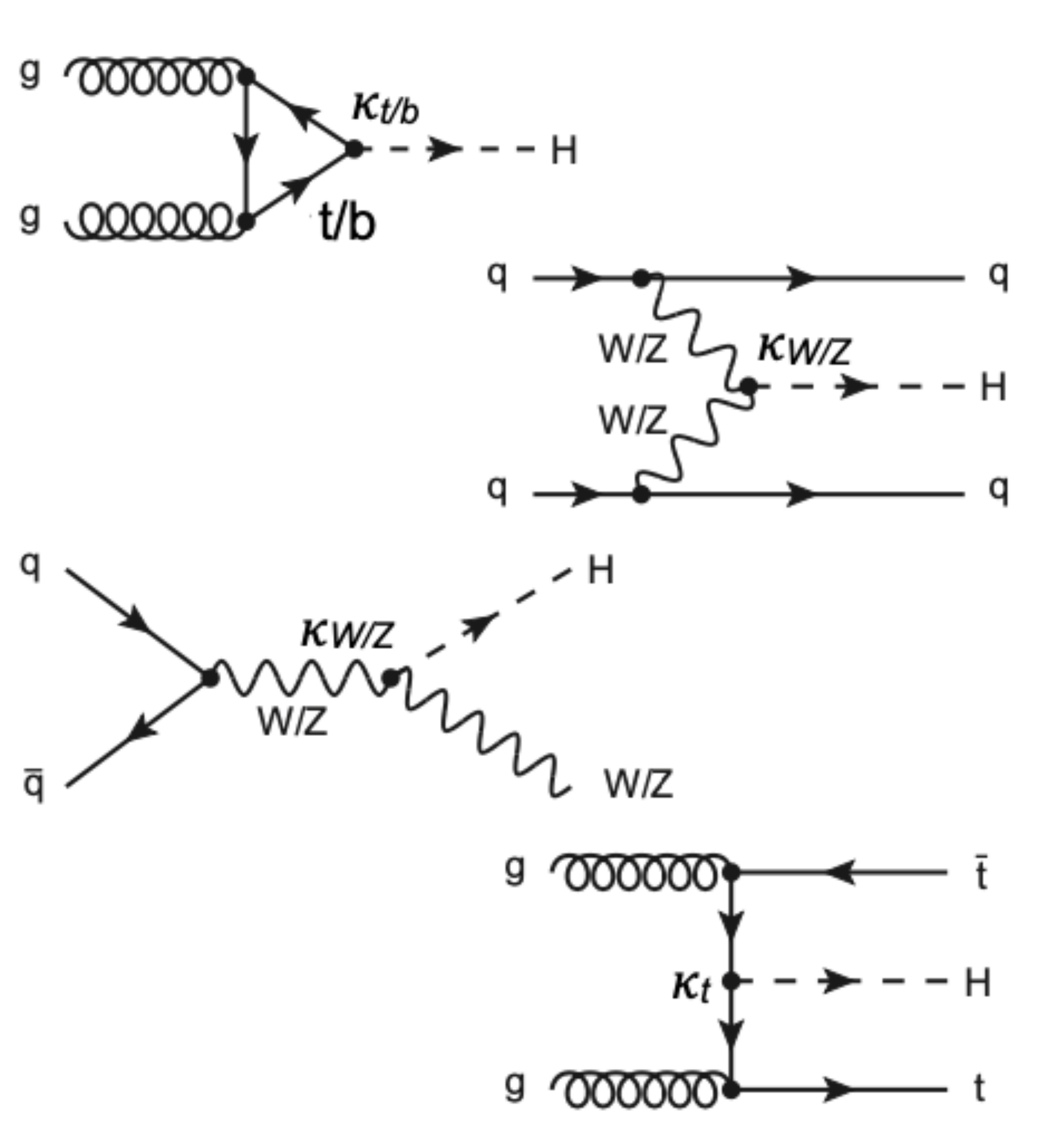
Source: https://www.nature.com/articles/s41586-022-04892-x

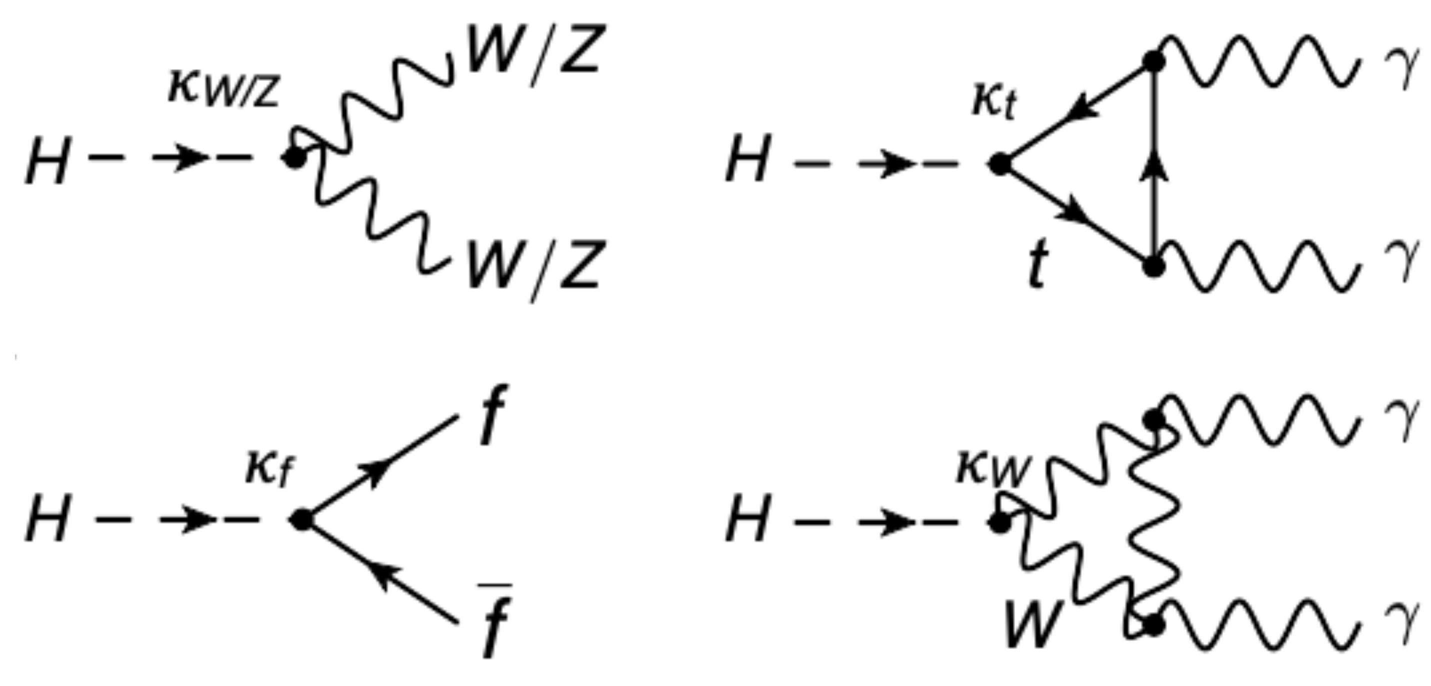
Kappa framework for coupling modifiers

$$(\sigma \times \mathrm{BF})(i \to H \to f) = (\sigma \times \mathrm{BF})(i \to H \to f)\frac{\kappa_i^2 \kappa_f^2}{\kappa_H^2}$$

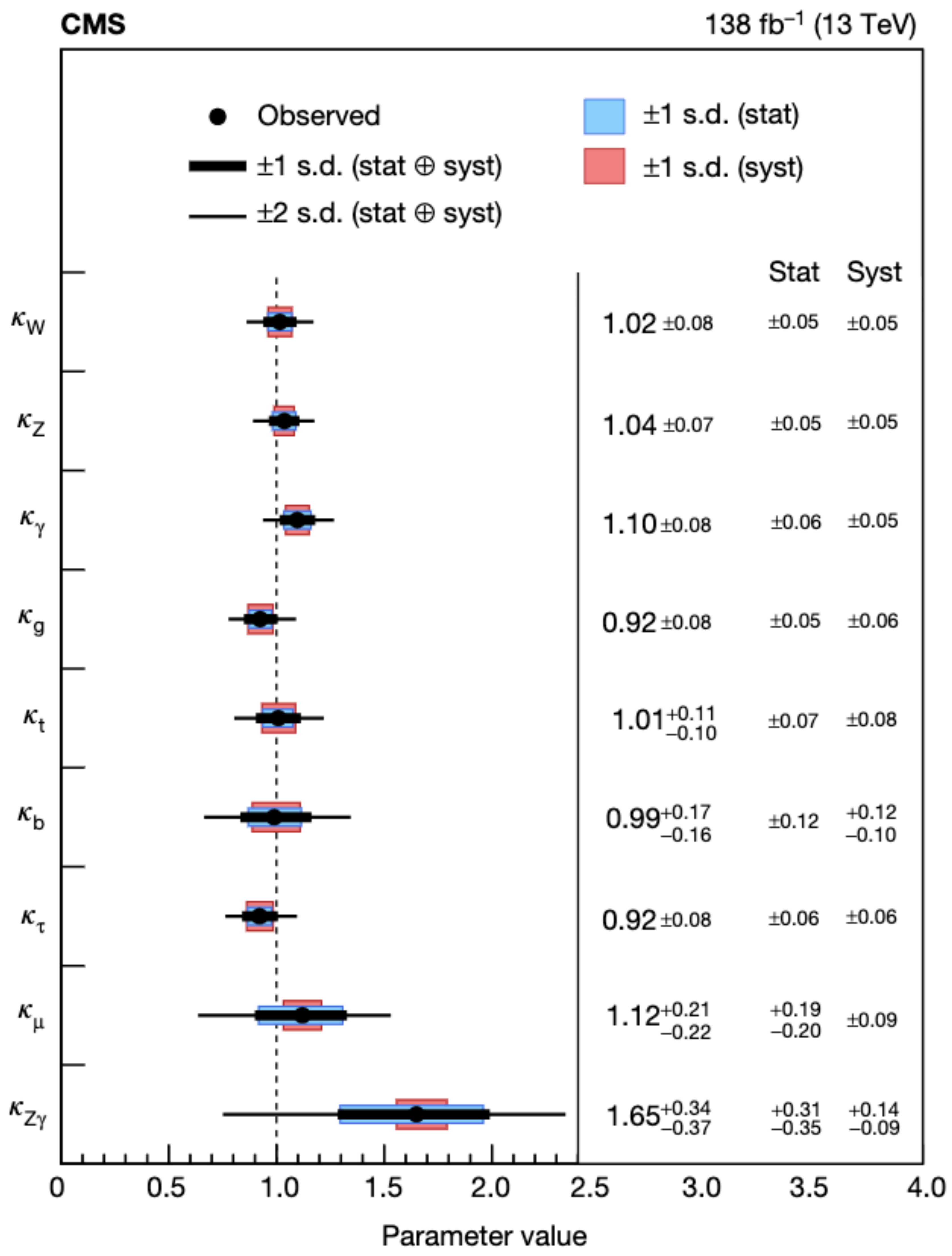
Production process	σ proportional to
$gg \to H$	$1.06\kappa_t^2 + 0.01\kappa_b^2 - 0.07\kappa_t\kappa_b$
Vector-boson fusion	$0.74\kappa_W^2 + 0.26\kappa_Z^2$
WH	κ_W^2
$q\bar{q} \to ZH$	κ_Z^2
$gg \to ZH$	$2.27\kappa_Z^2 + 0.37\kappa_t^2 - 1.64\kappa_Z\kappa_t$
$t\bar{t}H$	κ_t^2
$b\bar{b}H$	κ_b^2

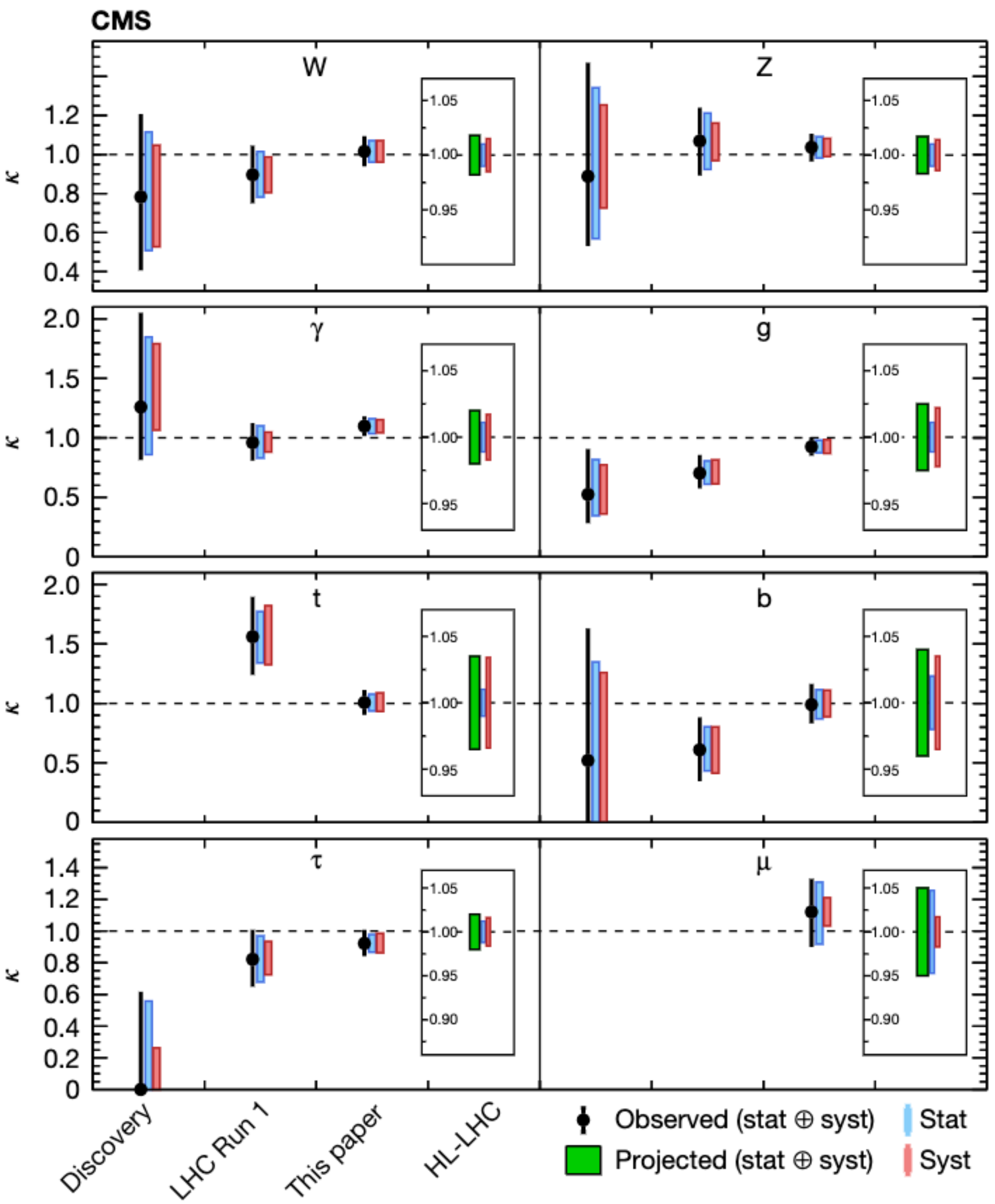
Decay channel	Γ proportional to
$H \to ZZ$	κ_Z^2
$H \to WW$	κ_W^2
$H \to \gamma\gamma$	$1.59\kappa_W^2 + 0.07\kappa_t^2 - 0.66\kappa_W\kappa_t$
$H \to b\bar{b}$	κ_b^2
$H \to \tau\tau$	κ_τ^2





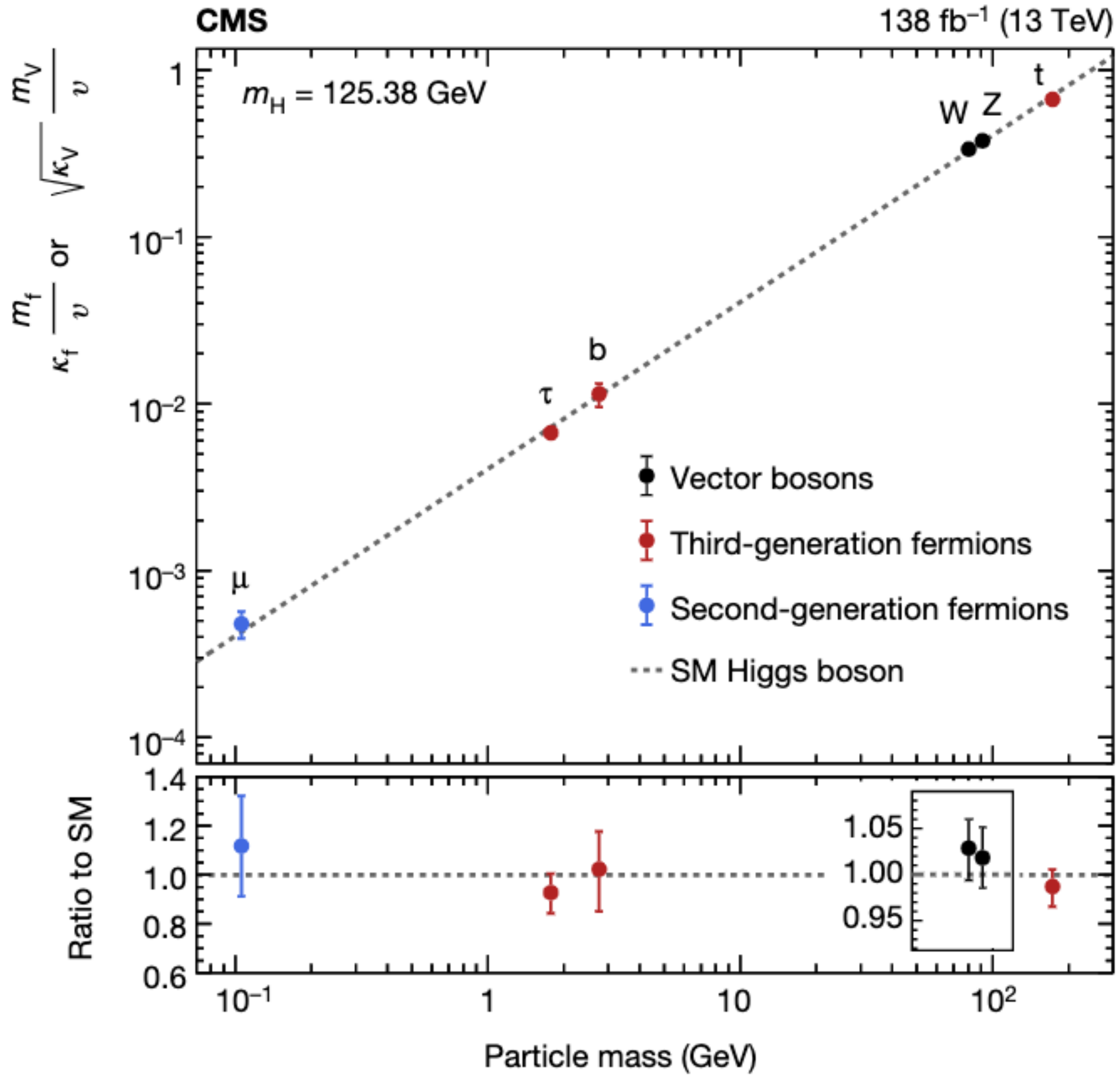
Kappa framework (CMS 2022)





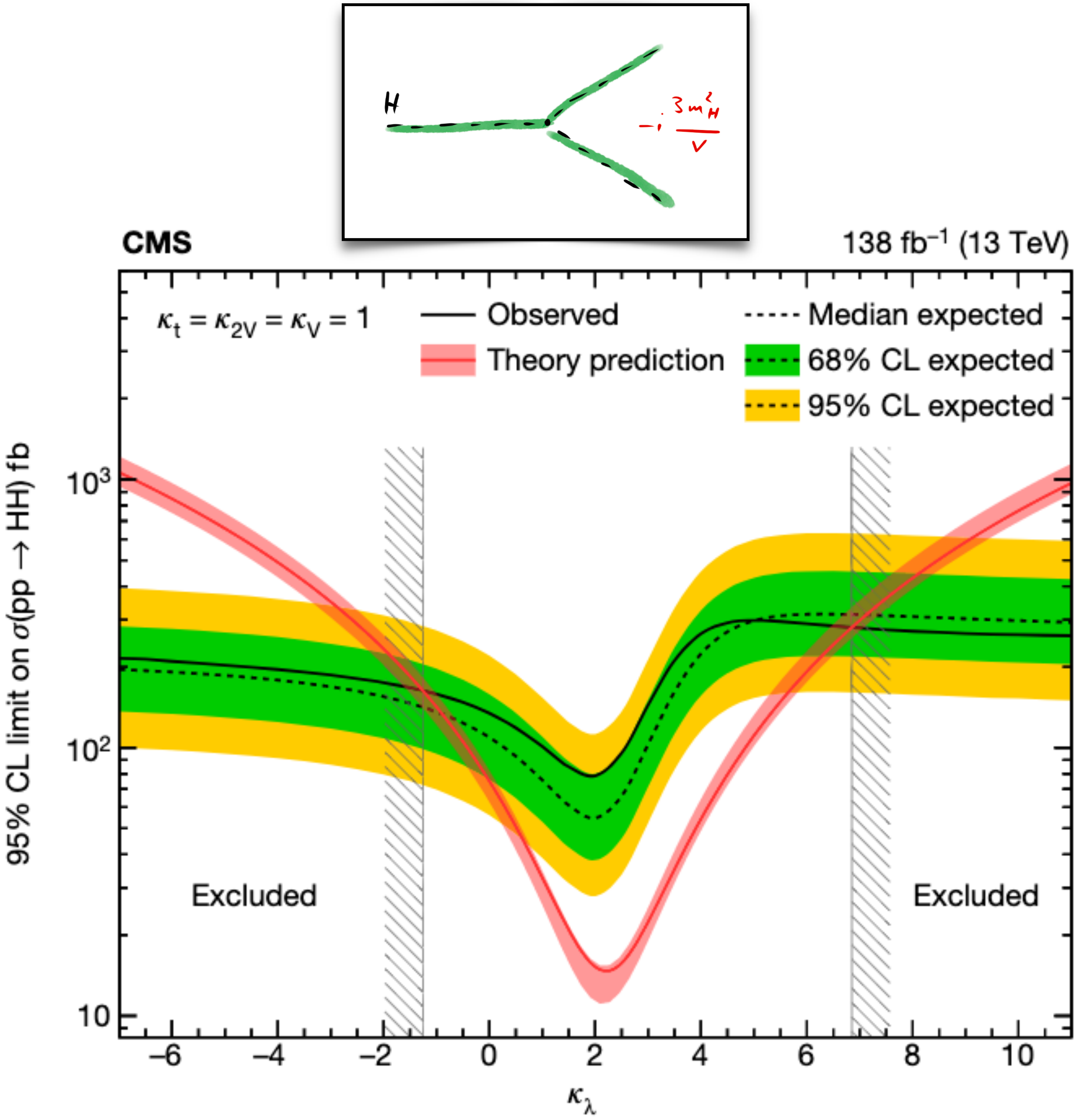
Source: https://www.nature.com/articles/s41586-022-04892-x

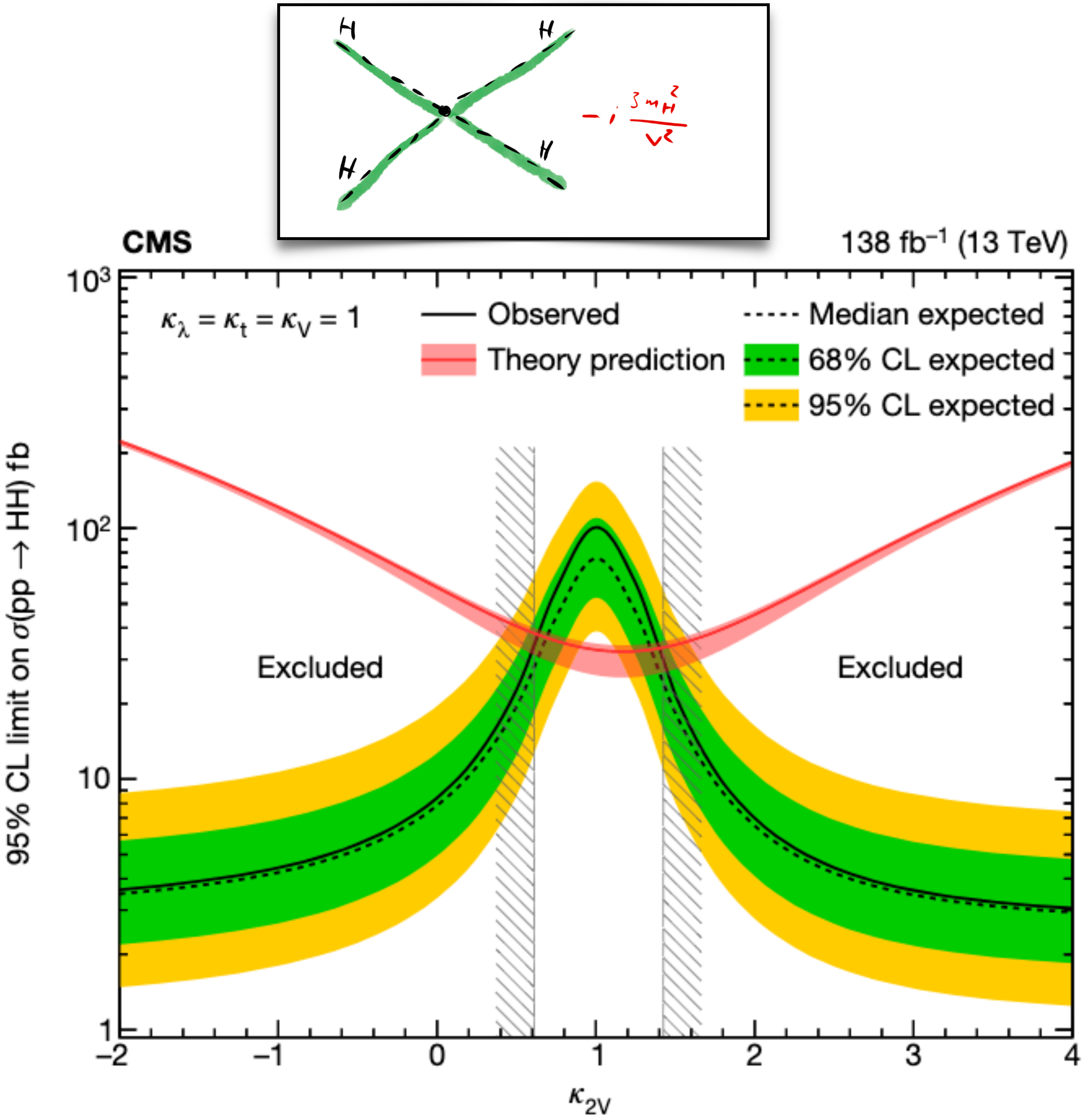
Coupling modifiers (CMS 2022)



Source: https://www.nature.com/articles/s41586-022-04892-x

Higgs self-interactions and quartic couplings (CMS 2022)

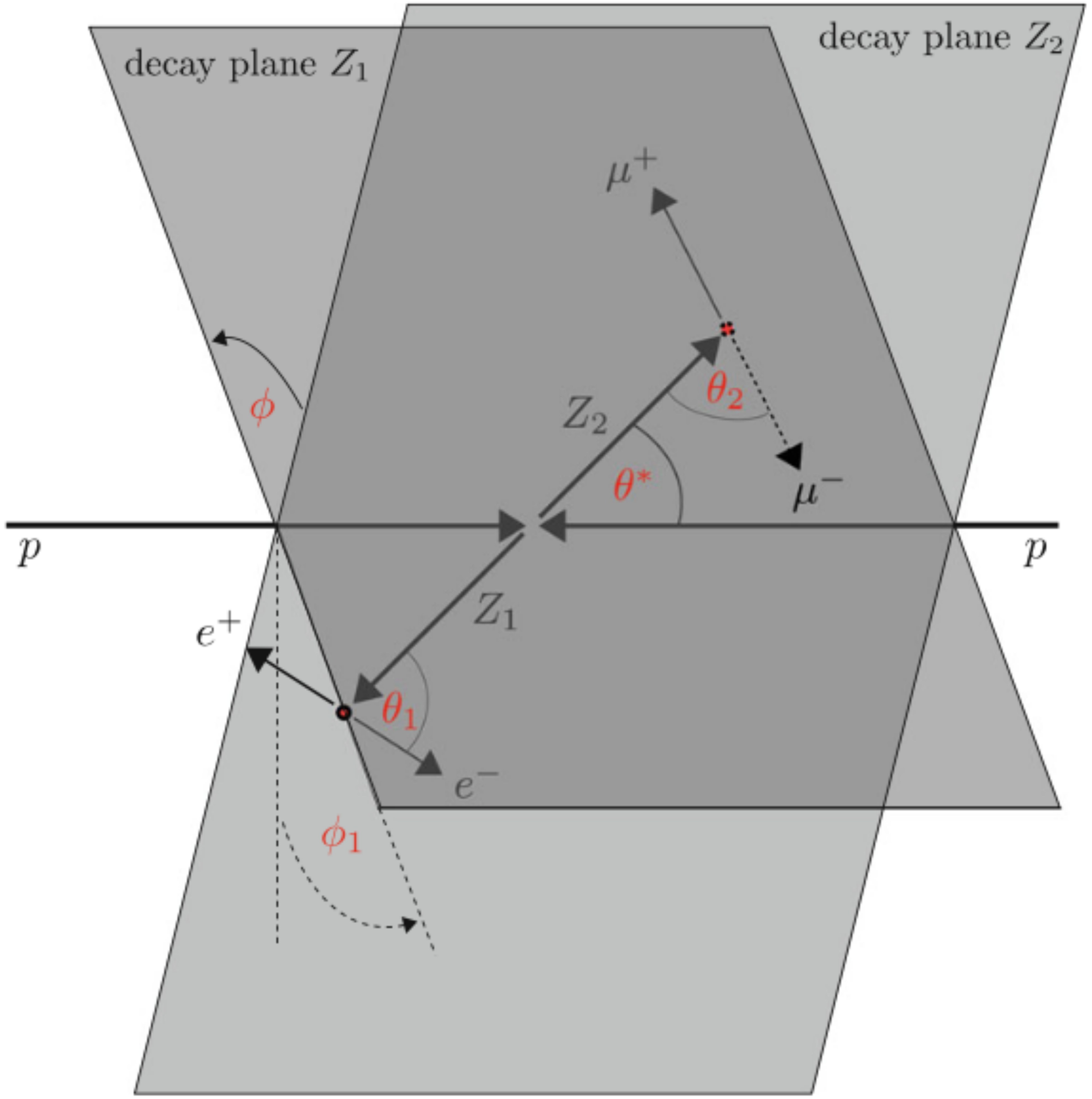




Source: https://www.nature.com/articles/s41586-022-04892-x

Spin and parity

- Standard model Higgs is a scalar with $J^P = 0^+$
- Landau-Yang theorem [1, 2]: massive spin-1 particle cannot decay into two massless spin-1 particles → spin 1 excluded due to observation of H → γγ
- Spin and parity from angular analysis of H→ZZ→4ℓ comparing null hypothesis ($J^P = 0^+$) with many other hypotheses



Credit: R. Wolf

more info:
[1] Lew Dawidowitsch Landau: On the angular momentum of a system of two photons, Doklady Akademii Nauk Ser. Fiz. Band 60, Nr. 2, 1948, 207 – 209 (englisch)
[2] Chen Ning Yang: Selection Rules for the Dematerialization of a Particle into Two Photons. In: Physical Review. Band 77, Nr. 2, 1950, 242 – 245 (englisch)

What questions do you have?