HIGGS AT LHC

Electroweak symmetry breaking and Higgs

Lecture 8

DIPARTIMENTO DI FISICA

SAPIENZA
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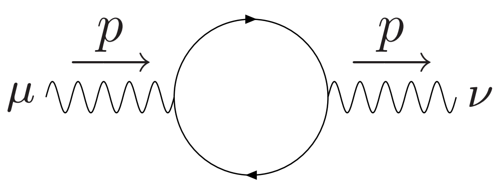
WHO NEEDS HIGGS?

- Gauge invariance of Electroweak theory requires all fermions and W and Z to be massless
- Discovery of W and Z in 1983 proved them to be pretty heavy
- Need a mechanism to dynamically generate mass for all particles and conserve the gauge invariance
- Higgs mechanism and goldstone bosons address this problem
- Experimental evidence needed to validate theory
  - Predict Higgs production processes and decay rates
- Direct search
  - produce Higgs and look for decay products: invariant mass and characteristic kinematics
- Indirect search
  - Calculate contribution of Higgs in corrections to well known SM processes
  - Combined analysis of all precisely measured Z-pole observables and check validity with different Higgs mass assumptions

Generating Mass for W and Z

- Propagator for massless vector bosons at tree level

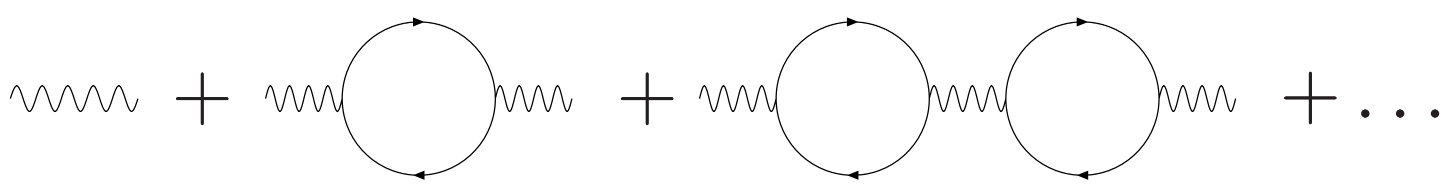


$$i\,\Pi_{\mu\nu}(p) \equiv i(p_\mu p_\nu - p^2 g_{\mu\nu})\Pi(p^2)$$

Gauge invariance

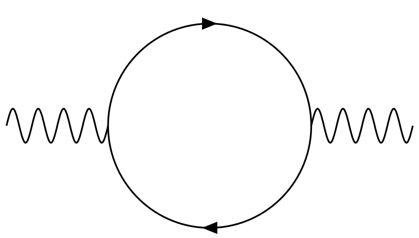
$$p^\mu \Pi_{\mu\nu}(p) = p^\nu \Pi_{\mu\nu}(p) = 0$$

- Renormalized propagator at higher order



$$= \frac{-i(g_{\mu\nu} - \frac{p_\mu p_\nu}{p^2})}{p^2[1+\Pi(p^2)]}$$

- For a massless scalar particle in the loop



$$\Pi(p^2) \underset{p^2 \to 0}{\simeq} \frac{-g^2 v^2}{p^2} \longrightarrow p^2[1+\Pi(p^2)] = p^2 - g^2 v^2$$

- For p=0 we have our vector boson with m = gv !

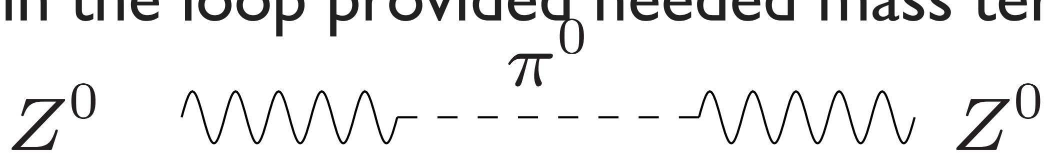
- Do we have already any such scalar?

Generating W and Z Mass with π^0

- W and Z couple to charge and neutral currents

$$\mathcal{L}_{\text{int}} = g_Z j_\mu^Z Z^\mu + g_W (j_\mu^W W^{+\mu} + \text{h.c.})$$

- Charged and neutral pions have very small mass (compared to other hadrons) and are massless in the limit of massless quarks!
- Pions in the loop provided needed mass term



$$\Pi(p^2) = -g_Z^2 f_\pi^2 / p^2$$

- Prediction for W and Z mass

$$m_W = g_W f_\pi \qquad m_Z = g_Z f_\pi$$

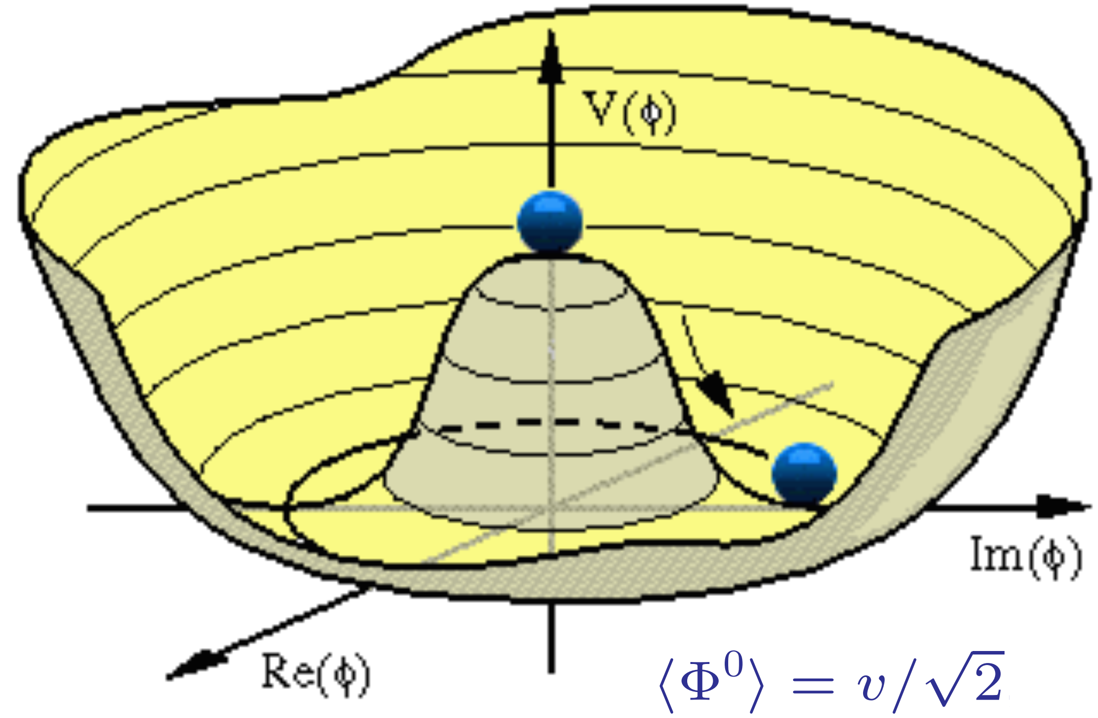
- Pion decay constant measured from decay rate to be $f_\pi = 93$ MeV
- W and Z mass related in SM through $\frac{m_W}{m_Z} = \frac{g_W}{g_Z} \equiv \cos\theta_W \simeq 0.88$
  - Good agreement with measurement
- We know $g_Z \simeq 0.37$ which corresponds to m_Z = 35 MeV!
  - Off by 3 orders of magnitude!
- Need a new scalar for dynamic mass generation

Spontaneous Symmetry Breaking

- New complex SU(2) doublet with four degrees of freedom (massless scalar particles)
- Self-interaction potential

$$V(\Phi) = \frac{\lambda}{4}(\Phi^\dagger\Phi - \tfrac{1}{2}v^2)^2$$

- Non-zero vacuum expectation value (VEV) generates one massive scalar
  - remaining 3 scalar absorbed by W, Z, and photon



$$\langle\Phi^0\rangle = v/\sqrt{2}$$

- We want this scalar to couple to generate correct mass $m_Z = g_Z v \simeq 91$ GeV
- Therefore the VEV must be $v = 246$ GeV

- New massive scalar particle commonly known as Higgs Boson
  - Interactions, decay rates known precisely
  - But its mass not determined and must be measured

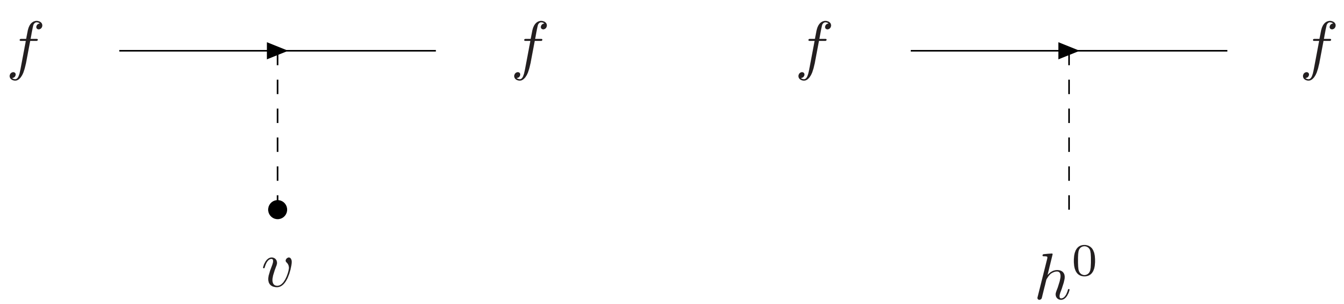
$$m_h = \tfrac{1}{2}\lambda v^2$$

Fermion Massed and CP Violation

- In addition to Z and W, also fermions acquire mass in SM thanks to Yukawa coupling to Higgs boson

$$\mathcal{L}_{\text{Yukawa}} = -h_u(\bar{u}_R u_L \Phi^0 - \bar{u}_R d_L \Phi^+) - h_d(\bar{d}_R d_L \Phi^{0\,*} + \bar{d}_R u_L \Phi^-) + \text{h.c.}$$

fermions	SU(2)	U(1)$_Y$
$(\nu\,,\,e^-)_L$	2	-1
e^-_R	1	-2
$(u\,,\,d)_L$	2	$1/3$
u_R	1	$4/3$
d_R	1	$-2/3$

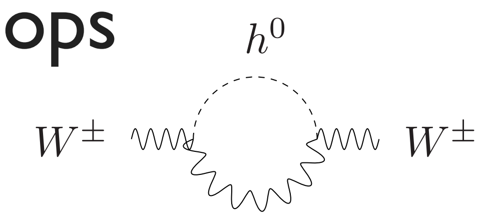


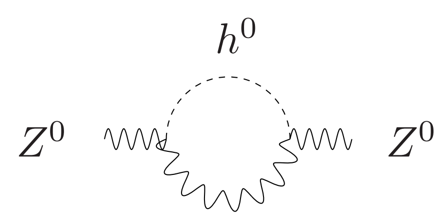
- Coupling proportional to fermion mass $g_{hf\bar{f}} = m_f/v$
  - Will determine Higgs decay branching fractions

- Diagonalization of complex mass matrix cornerstone of Kobayashi-Maskawa mechanism to introduce CP violation in Standard Model
  - Discussed in detail in CP-violation lectures

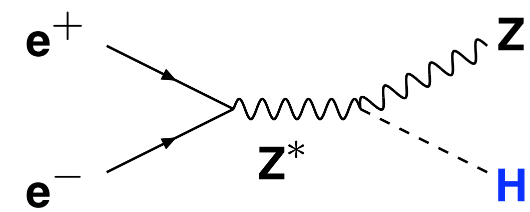
EXPERIMENTAL CONSTRAINTS ON HIGGS MASS

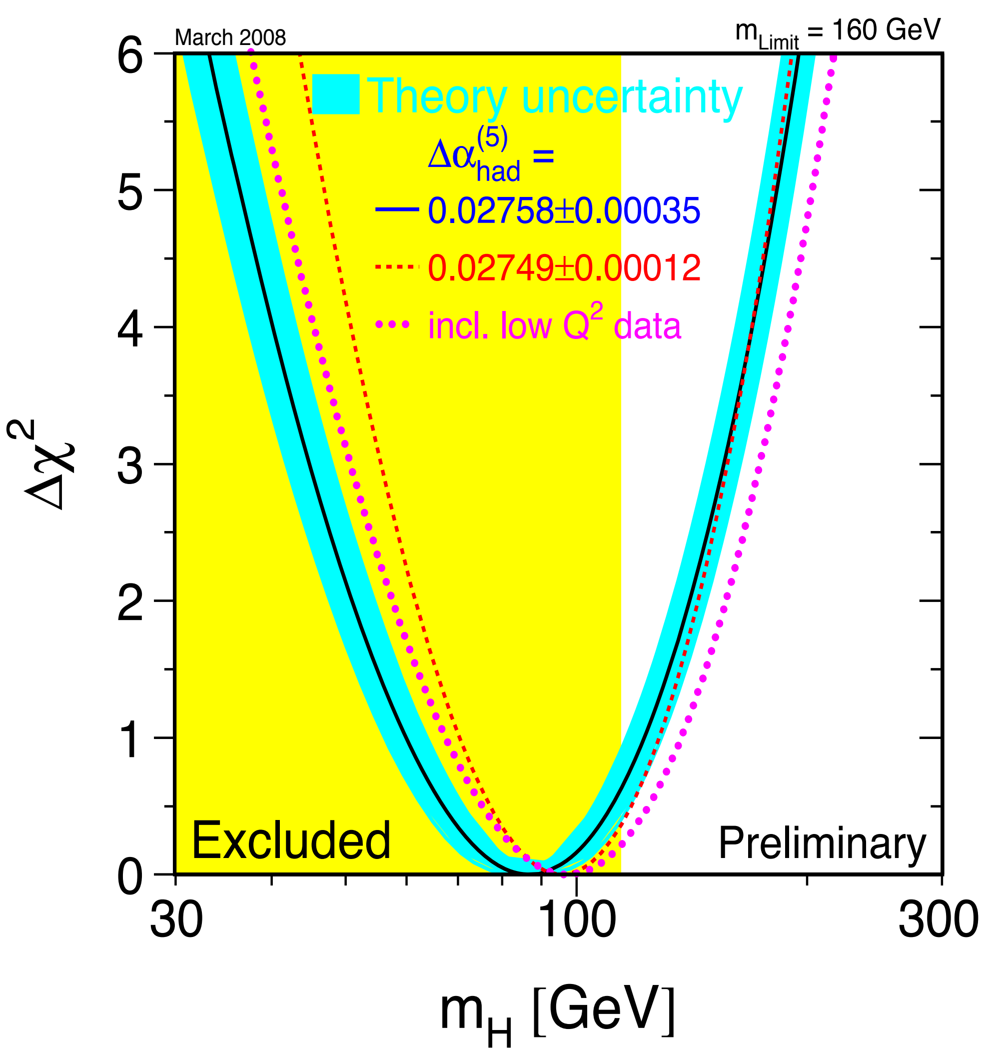
- Indirect search through precision measurement of SM sensitive to radiative corrections to Higgs in loops

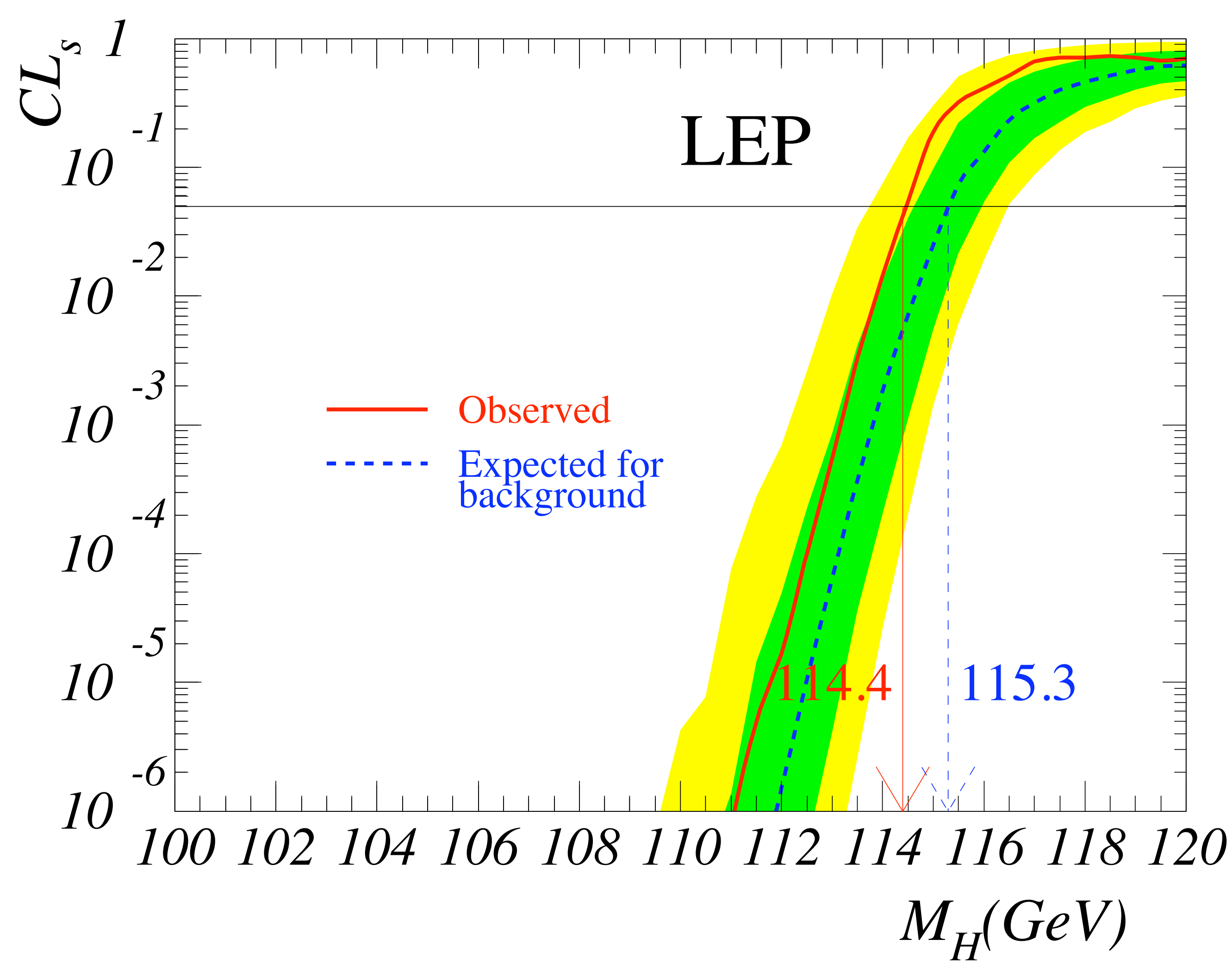




- Direct search at LEP in Higgs-strahlung production channel







Implications of Unitarity on Higgs Mass

- EW equivalence theorem: for $m_W^2 \ll s \ll \Lambda_{\mathrm{EW}}^2$ W behaves like a Goldstone boson
  - Recall: longitudinal W generated by absorbing a massless Goldstone boson

$$W_L^+ W_L^- \to W_L^+ W_L^- \longrightarrow \overset{1}{G^+}\overset{2}{G^-} \to \overset{3}{G^+}\overset{4}{G^-}$$

  - Amplitude of such process can be computed with the Jacob-Wick partial wave expansion

$$\mathcal{M}(\lambda_3\lambda_4\,;\,\lambda_1\lambda_2) = \frac{8\pi\sqrt{s}}{(p_i p_f)^1/2} e^{i(\lambda_i-\lambda_f)\phi} \sum_{J=J_0}^{\infty} (2J+1)\mathcal{M}_\lambda^J(s) d^J_{\lambda_i\lambda_f}(\theta)$$

final helicities

initial helicities

$$J_0 \equiv \max\{\lambda_i\,,\,\lambda_f\} \qquad \lambda_i \equiv \lambda_1 - \lambda_2$$

$$\lambda_f \equiv \lambda_3 - \lambda_4$$

- For longitudinal W $\lambda_{i,f} = 0$ so $J_0 = 0$ with

$$\mathcal{M}^{J=0} = \frac{G_F s}{16\pi\sqrt{2}} \qquad A(W^+W^- \to W^+W^-) \xrightarrow{s \gg M_W^2} \frac{1}{v^2}\left[s + t - \frac{s^2}{s - M_H^2} - \frac{t^2}{t - M_H^2}\right]$$

- Partial wave unitarity implies

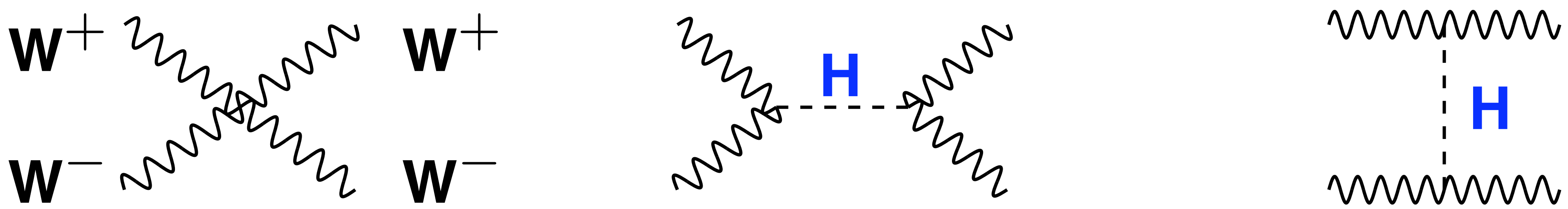
$$|\mathcal{M}^J|^2 \le |\mathrm{Im}\ \mathcal{M}^J| \le 1 \longrightarrow (\mathrm{Re}\ \mathcal{M}^J)^2 \le |\mathrm{Im}\ \mathcal{M}^J|\Big(1 - |\mathrm{Im}\ \mathcal{M}^J|\Big) \le \frac{1}{4}$$

- unitarity would be lost for

$$s_c = \frac{4\pi\sqrt{2}}{G_F} = (1.2\ \mathrm{TeV})^2$$

Upper Bound on Higgs Mass

- WW scattering sensitive to Higgs mass

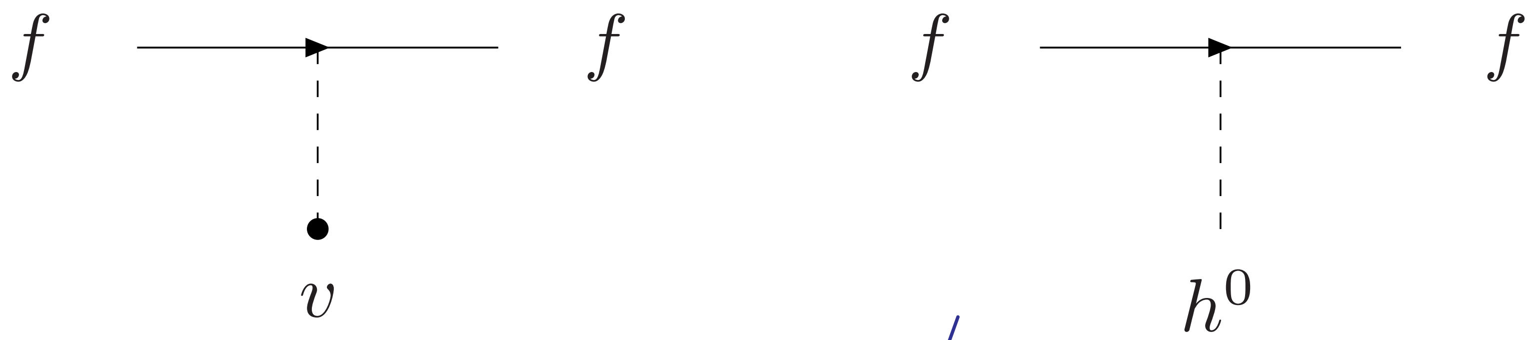


- For $s \gg m_h^2$ $$\mathcal{M}^{J=0} = -\frac{G_F m_h^2}{4\pi\sqrt{2}}$$

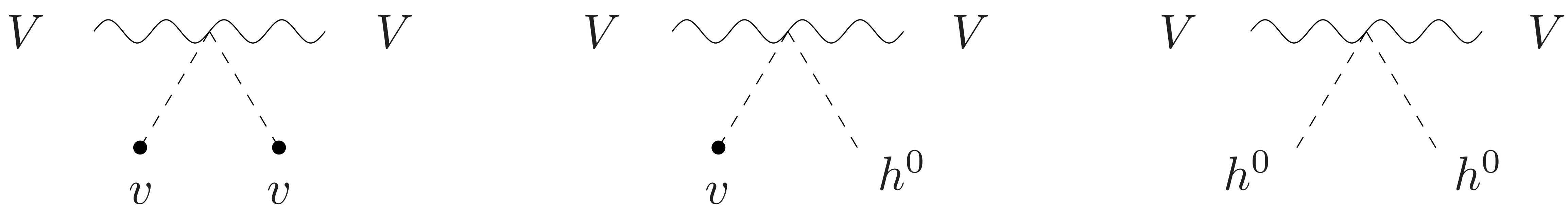
- Unitarity conservation provides upper bound on Higgs mass

$$|\mathrm{Re}\ \mathcal{M}^J| \leq \tfrac{1}{2} \longrightarrow m_h^2 \leq \frac{4\pi\sqrt{2}}{3G_F} \simeq (700\ \mathrm{GeV})^2$$

HIGGS COUPLINGS



$$g_{hf\bar{f}} = m_f / v$$



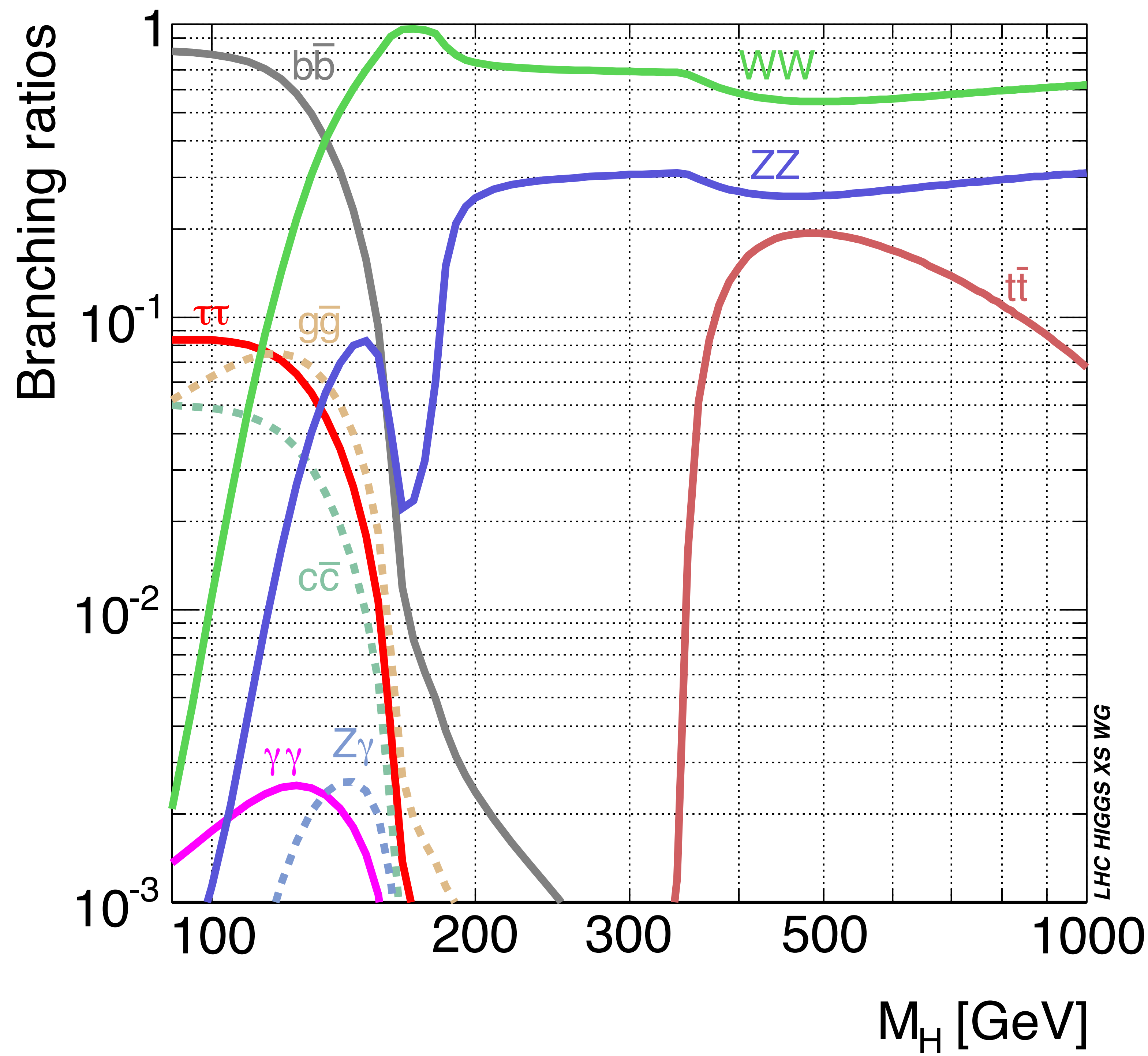
$$g_{hVV} = 2m_V^2 / v \qquad g_{hhVV} = 2m_V^2 / v^2$$

- Higgs coupling enhanced for heavier particles
- Vector bosons always preferred to fermions
  – But must be kinematically allowed
- Fixing mass of Higgs fixes decay rates for all final states

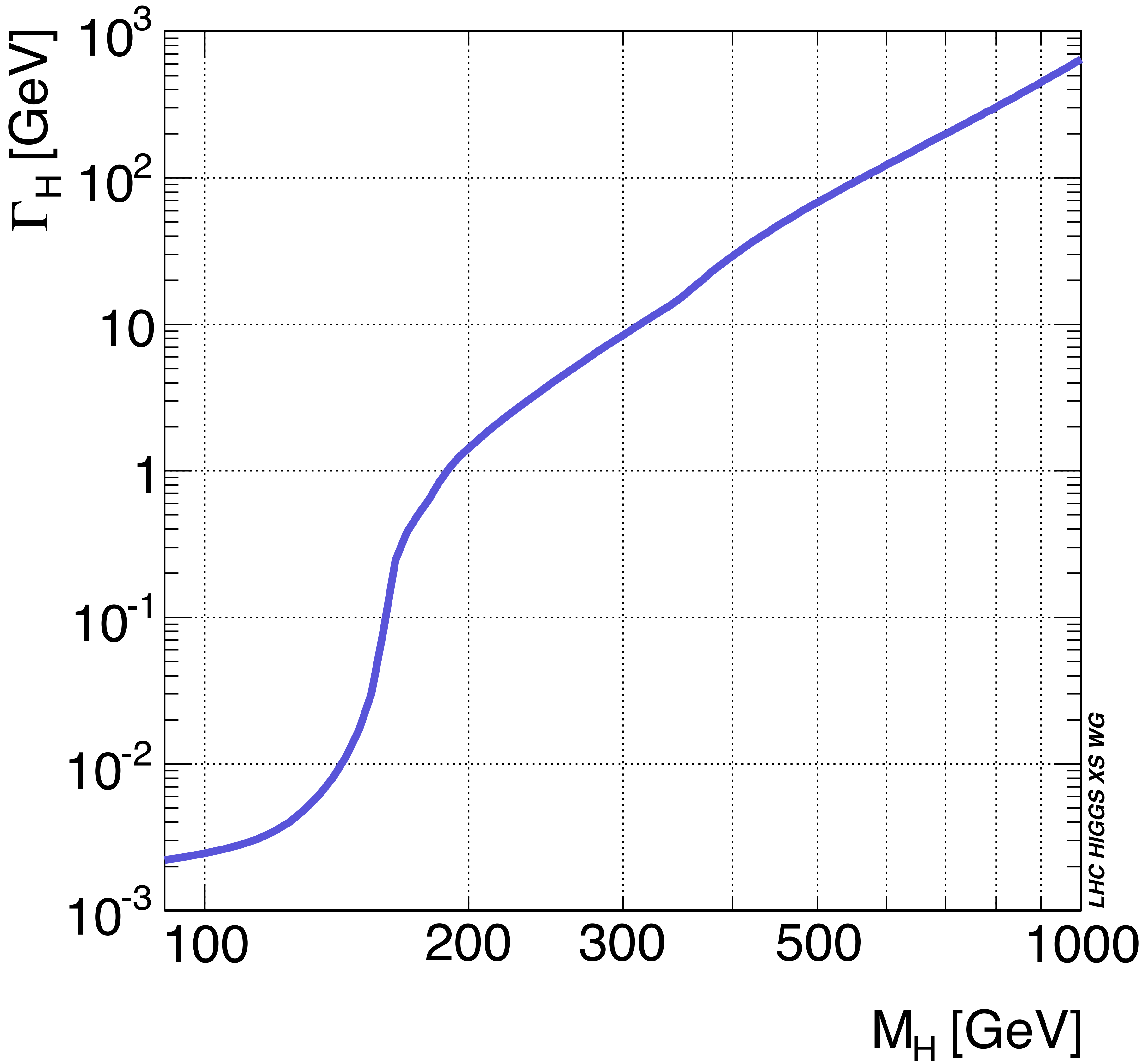
Higgs Branching Fractions

- Low Mass < 140 GeV
  - $H \to b\bar{b}$ **dominant, BR = 60–90%**
  - $H \to \tau^+\tau^-, c\bar{c}, gg$ **BR= a few %**
  - $H \to \gamma\gamma, \gamma Z$**, BR = a few permille**

- High Mass > 140 GeV
  - $H \to WW^*, ZZ^*$ **up to** $\gtrsim 2M_W$
  - $H \to WW, ZZ$ **above (BR** $\to \frac{2}{3}, \frac{1}{3}$**)**
  - $H \to t\bar{t}$ **for high** M_H**; BR** $\lesssim 20\%$.

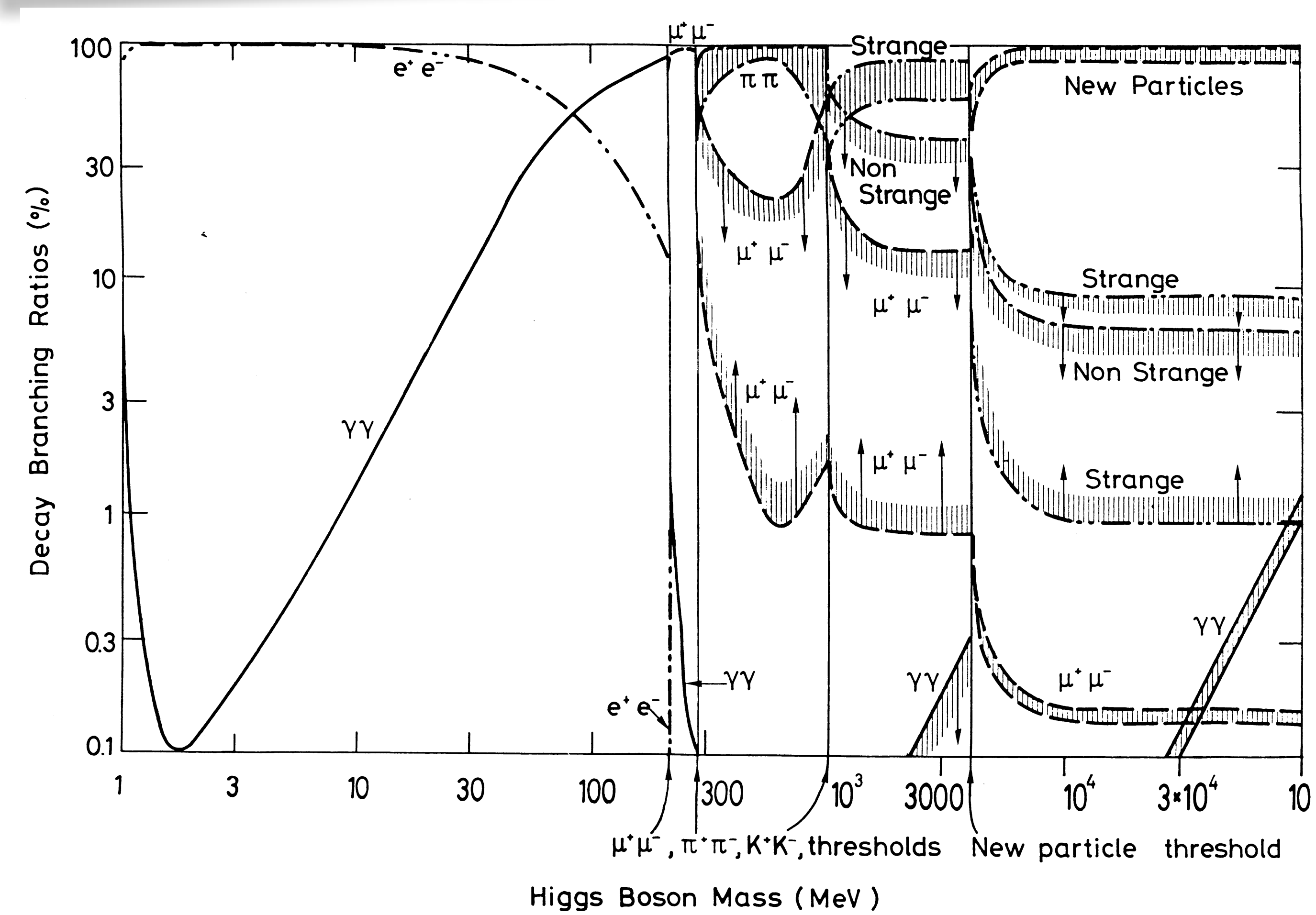


HIGGS WIDTH



Γ_H [GeV]
10^3
10^2
10
1
10^{-1}
10^{-2}
10^{-3}
100
200
300
500
1000
M_H [GeV]
LHC HIGGS XS WG

Phenomenological Profile of Higgs in 1976



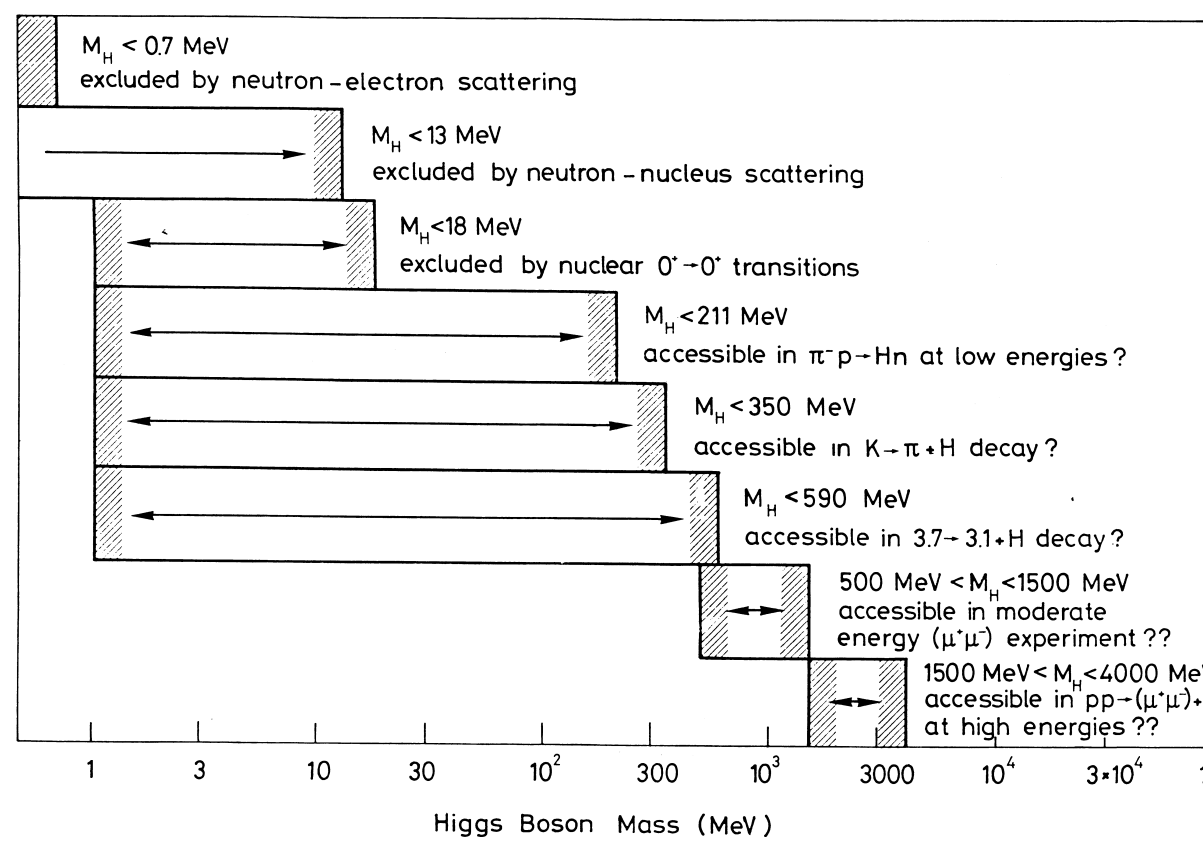
http://cdsweb.cern.ch/record/874049

A PHENOMENOLOGICAL PROFILE OF THE HIGGS BOSON

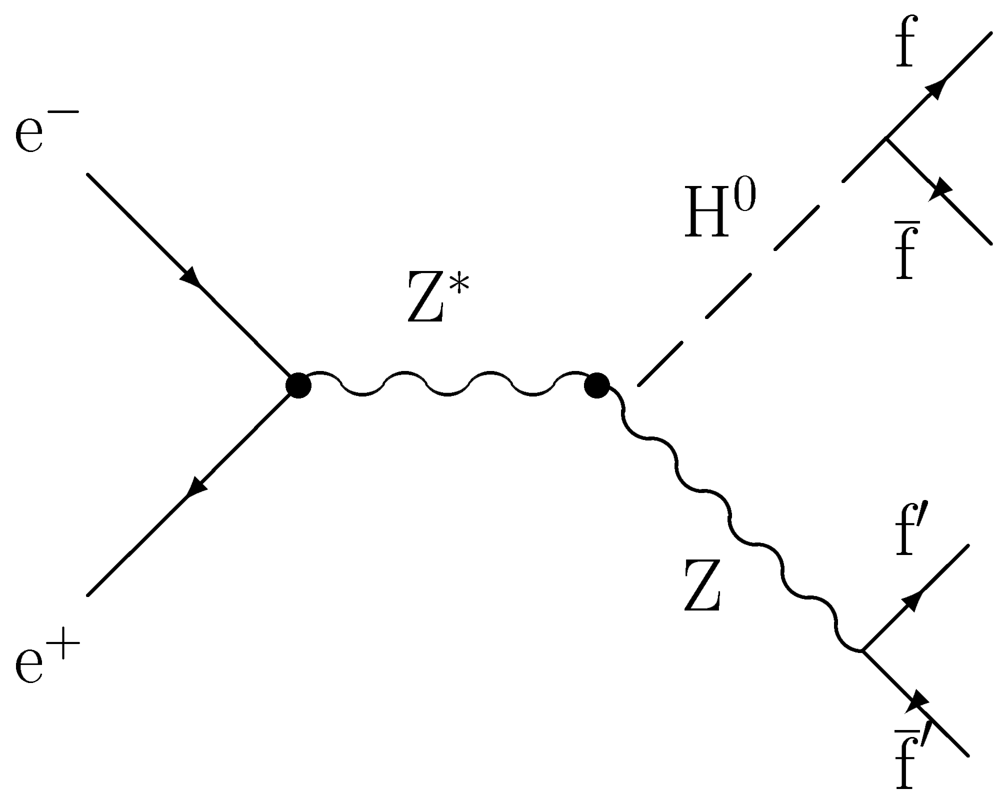
John Ellis, Mary K. Gaillard *) and D.V. Nanopoulos +)

CERN -- Geneva

We should perhaps finish with an apology and a caution. We apologize to experimentalists for having no idea what is the mass of the Higgs boson, unlike the case with charm [3),4)] and for not being sure of its couplings to other particles, except that they are probably all very small. For these reasons we do not want to encourage big experimental searches for the Higgs boson, but we do feel that people performing experiments vulnerable to the Higgs boson should know how it may turn up.



Higgs Production at LEP



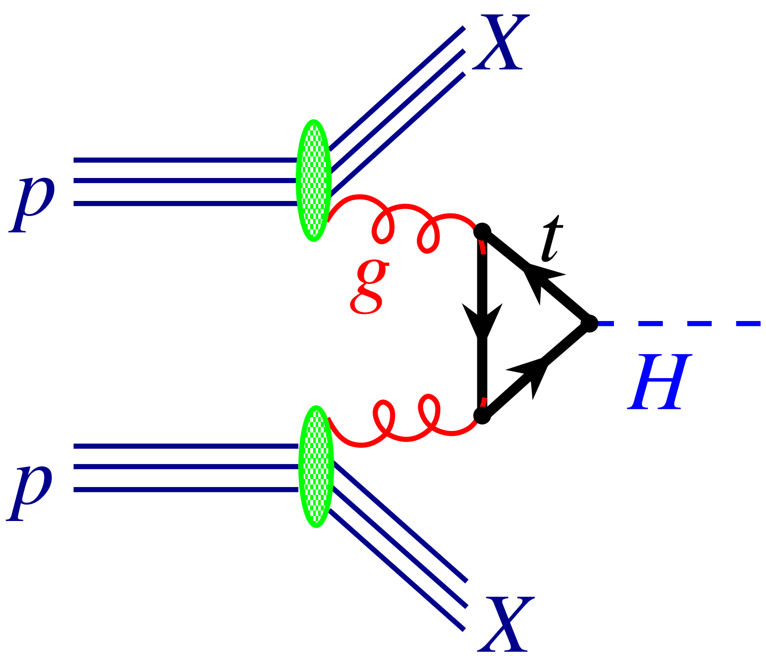
$$H^0 \rightarrow b\bar{b} \text{ dominant (BR} \approx 84\%)$$

$$H^0(\rightarrow b\bar{b})Z(\rightarrow q\bar{q}) \sim 60\%$$

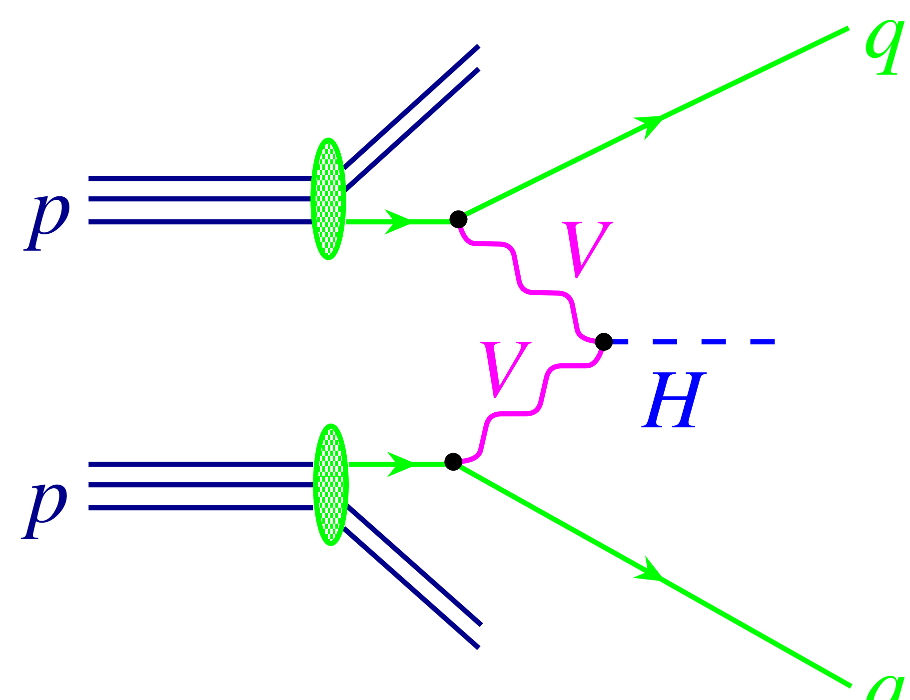
$$H^0(\rightarrow b\bar{b})Z(\rightarrow \nu\bar{\nu}) \sim 17\%$$

$$H^0(\rightarrow b\bar{b})Z(\rightarrow \ell^+\ell^-) \text{ and } H^0(\rightarrow \tau^+\tau^-)Z(\rightarrow q\bar{q}) \sim 14\%$$

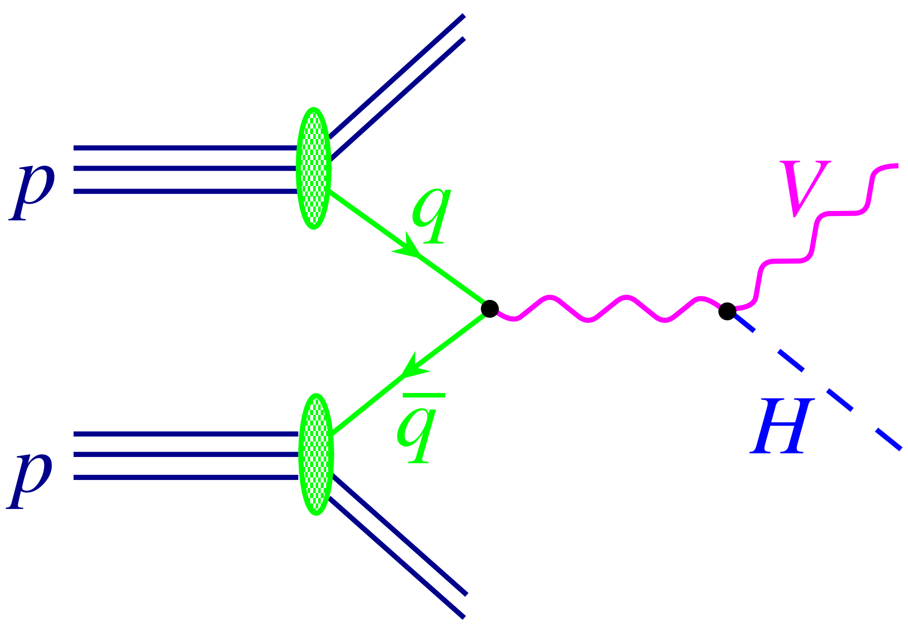
Higgs Production at Hadron Colliders



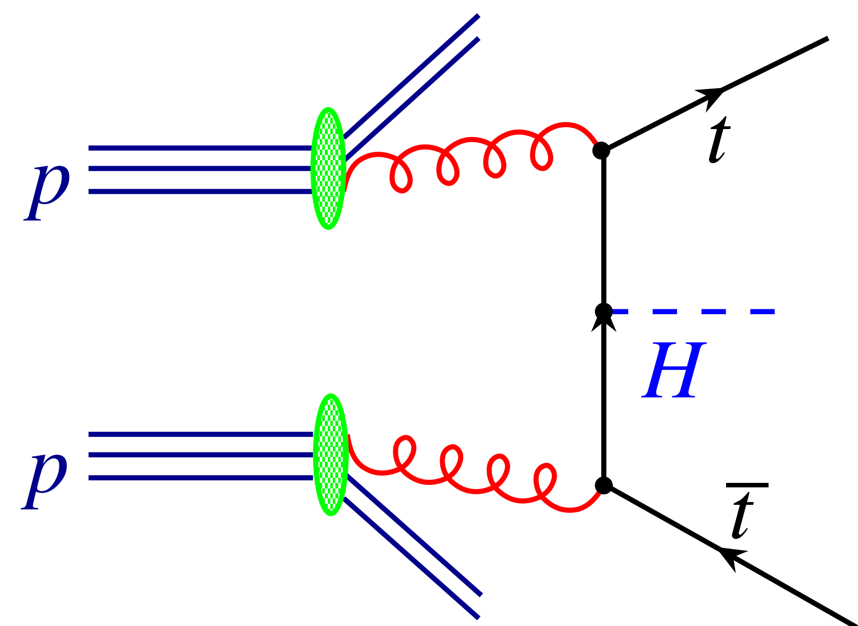
Gluon fusion



Weak-Boson Fusion



Higgs Strahlung



$t\bar{t}H$