Elementary Particles II

SM Higgs:
A Very Short Introduction

Higgs Field, Higgs Boson, Production, Decays
First Observation

Reminder - I

Extend Abelian Higgs model to non-Abelian gauge symmetry:

Gauge group = $SU(2)_L \otimes U(1)_Y$

SSB in the Standard Model :

Add a doublet of complex, scalar fields:

$$\phi(x) = \begin{pmatrix} \phi^+(x) \\ \phi^0(x) \end{pmatrix}$$

$$\text{Assuming } y = 1 \rightarrow \begin{cases} Q\left[\phi^+(x)\right] = +1 \\ Q\left[\phi^0(x)\right] = 0 \end{cases}$$

Reminder - II

$SU(2)_L \otimes U(1)_Y$ Gauge transformation of doublet:

$$\phi \rightarrow \phi' = \exp\left\{-i\left[\frac{g}{2}\boldsymbol{\alpha}(x)\cdot\boldsymbol{\tau} + \frac{g'}{2}y\theta(x)I\right]\right\}\phi$$

$SU(2)_L \otimes U(1)_Y$ Covariant derivative:

$$D^\mu = \partial^\mu + i\left[\frac{g}{2}\boldsymbol{\tau}\cdot\mathbf{W}^\mu + \frac{g'}{2}yB^\mu\right]$$

$\rightarrow$ Additional term to EW lagrangian:

$$L_H = D_\mu\phi^\dagger D^\mu\phi - \mu^2\phi^\dagger\phi - \lambda\left(\phi^\dagger\phi\right)^2$$

Take $\mu^2 < 0, \ \ \lambda > 0$:

$$\left|\phi\right|^2_{\min} = -\frac{\mu^2}{2\lambda} = \frac{v^2}{2} \rightarrow v = \sqrt{-\frac{\mu^2}{\lambda}}$$

Pick ground state (= vacuum) as

$$\left\langle\phi\right\rangle_0 = \begin{pmatrix} 0 \\ \frac{v}{\sqrt{2}} \end{pmatrix} \rightarrow \text{SSB of Electroweak gauge symmetry}$$

$v = 246\ GeV$

Reminder - III

Introduce field deviation from vacuum:

$$\phi = \frac{1}{\sqrt{2}}\begin{pmatrix} \sigma_1 + i\sigma_2 \\ v + \eta_1 + i\eta_2 \end{pmatrix} \rightarrow V = -\frac{\mu^4}{4\lambda} + \lambda v^2 \eta_1^2 + \lambda v \eta_1 \left(\sigma_1^2 + \sigma_2^2 + \eta_1^2 + \eta_2^2\right) + \frac{\lambda}{4}\left(\sigma_1^2 + \sigma_2^2 + \eta_1^2 + \eta_2^2\right)^2$$

After properly 'rotating' to Unitary Gauge:

1 massive scalar: $\eta_1, m_{\eta_1} \equiv m_H = \sqrt{2\lambda v^2} \leftarrow$ The Higgs

2 massive, charged vectors: $W^{\pm}, m_W = \frac{g}{2}\sqrt{-\frac{\mu^2}{\lambda}}$

1 massive, neutral vector: $Z^0, m_Z = \frac{\sqrt{\left(g^2 + g'^2\right)}}{2}\sqrt{-\frac{\mu^2}{\lambda}}$

$\rightarrow$ Relating model parameters to independently measured constants $e, G_F, \sin\theta_W$:

$$M_W = \sqrt{\frac{\sqrt{2}g^2}{8G_F}} = \sqrt{\frac{\sqrt{2}e^2}{8G_F \sin^2\theta_W}} \simeq 77.5\ \ GeV, \quad M_Z = \frac{M_W}{\cos\theta_W} \simeq 88.4\ \ GeV$$

$$M_H = \frac{\sqrt{2}\lambda}{G_F} = ???$$

Reminder - IV

Gauge terms of L in the unitary gauge, in terms of the physical fields:

$$L_B + L_H$$

$$= -\frac{1}{4} F_{\mu\nu}(x) F^{\mu\nu}(x) \quad \text{Photon}$$

$$-\frac{1}{2} F^W{}_{\mu\nu}(x) F^{W\dagger\mu\nu}(x) + \frac{1}{2} m_W^2 W_\mu^\dagger W^\mu \quad W^\pm \text{ boson}$$

$$-\frac{1}{4} Z_{\mu\nu}(x) Z^{\mu\nu}(x) + \frac{1}{2} m_Z^2 Z_\mu Z^\mu \quad Z^0 \text{ boson}$$

$$+(\partial_\mu \sigma)(\partial^\mu \sigma) - \frac{1}{2} m_H^2 \sigma^2 \quad H \text{ Higgs boson}$$

$$+L_{BB}^I + L_{HH}^I + L_{HB}^I \quad \text{Gauge-Higgs, Higgs self-, Gauge self-interactions}$$

Reminder - V

Fermion masses: Yukawa (scalar) coupling

Describing interaction between Dirac and scalar fields:

Example: Single lepton family

$$L_{HL} = -g_l \left[\bar{\Psi}_l^L \Phi \psi_l^R + \bar{\psi}_l^R \Phi^\dagger \Psi_l^L \right] - \underbrace{g_{\nu_l}}_{=0 \text{ for massless neutrino}} \left[\bar{\Psi}_l^L \tilde{\Phi} \psi_{\nu_l}^R + \bar{\psi}_{\nu_l}^R \tilde{\Phi}^\dagger \Psi_l^L \right], \quad \tilde{\Phi} = \begin{pmatrix} \phi_b^* \\ -\phi_a^* \end{pmatrix}$$

In the unitary gauge:

$$L_{HL} = -\frac{1}{v} m_l \bar{\psi}_l \psi_l \sigma - \frac{1}{v} m_{\nu_l} \bar{\psi}_{\nu_l} \psi_{\nu_l} \sigma$$

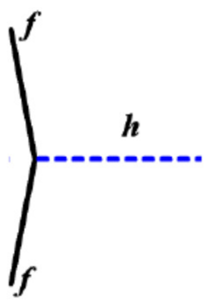
Lepton masses in terms of model parameters:

$$m_l = \frac{v g_l}{\sqrt{2}}, \quad m_{\nu_l} = \frac{v g_{\nu_l}}{\sqrt{2}} (= 0 \text{ in the Minimal Standard Model})$$

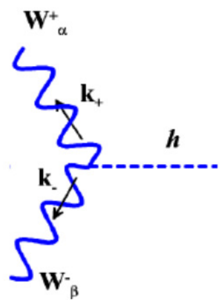
g_l individual constant

Reminder - VI

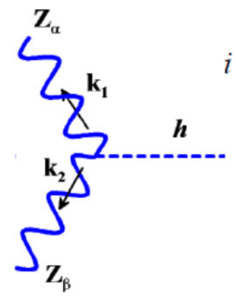
Higgs vertexes:



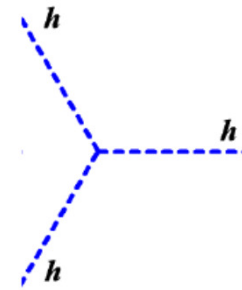
$$-im_f\sqrt{\sqrt{2}G_F}\,\bar{f}f$$



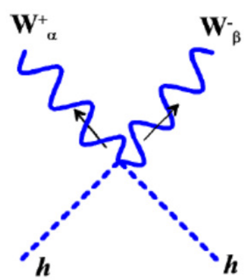
$$2iM_W^2\sqrt{\sqrt{2}G_F}\,g^{\alpha\beta}W_\alpha^{+\dagger}W_\beta^{-\dagger}h$$



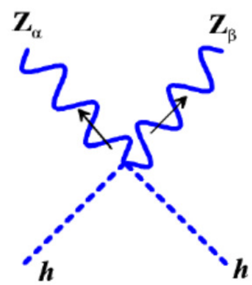
$$2iM_Z^2\sqrt{\sqrt{2}G_F}\,g^{\alpha\beta}Z_\alpha^\dagger Z_\beta^\dagger h$$



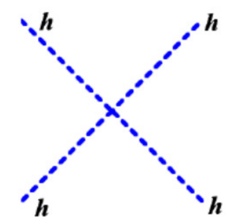
$$-3im_h^2\sqrt{\sqrt{2}G_F}\,hhh$$



$$2iM_W^2\sqrt{2}G_F\,g^{\alpha\beta}hhW_\alpha^{+\dagger}W_\beta^{-\dagger}$$



$$2iM_Z^2\sqrt{2}G_F\,g^{\alpha\beta}hhZ_\alpha^\dagger Z_\beta^\dagger$$



$$-3im_h^2\sqrt{2}G_F\,hhhh$$

Observe: Amplitude ~ mass(fermions), mass^2(bosons)

About the Higgs Field - I

Universal, constant field

Lorentz scalar $\to$ Same value in any frame

Higgs boson: Quantum excitation of the field

Non-standard feature:

Vacuum expectation value $v \neq 0$

Some analogy to a spontaneously magnetized ferromagnet: $\mathbf{M} \neq 0$

Actually, more similar to a superconductor:

Quantum condensate of superconducting electrons (= Cooper pairs : The 'Higgs field' of superconductivity)

State of minimal energy: Density $\neq 0$ $\to$ SSB of QED gauge symmetry

$\to$ Photon becoming massive inside the superconductor

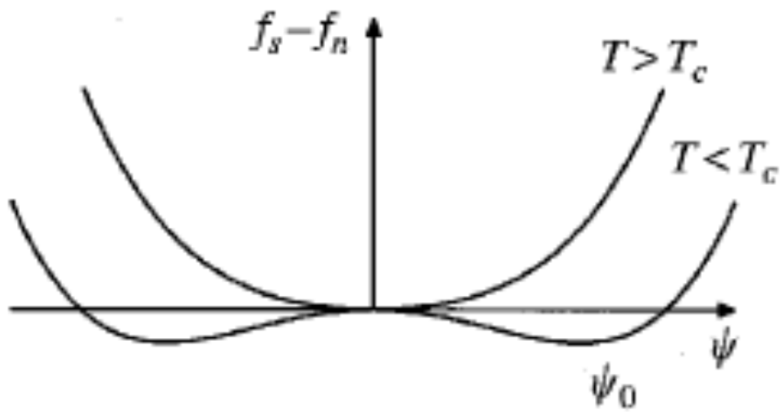
$\to$ Meissner effect, $\mathbf{B} \to 0$ inside

About the Higgs Field - II

Energy difference between normal and s.c. state at two different temperatures

$\Delta E = a(T)|\psi|^2 + \frac{1}{2} b(T)|\psi|^4 + \ldots$ From Landau theory of phase transitions

ψ is the Cooper pair 'wave function' → $|\psi|^2$ ~ density of Cooper pairs



Below T_c, the minimum energy state ('vacuum') occurs for $\psi = \psi_0 \neq 0$, phase undefined
→*U(1) QED* gauge invariance spontaneously broken → Photon becomes massive → $\boldsymbol{B} = 0$ inside

About the Higgs Field - III

ψ 'Higgs field' of superconductivity: $<\psi>\neq 0$ ↔ Permanent supercurrents

Superconductive state:
'Higgs field' = 'Wave function' of Cooper pairs

→Not a fundamental field
→'Composite' field of fundamentals fermions (electrons)

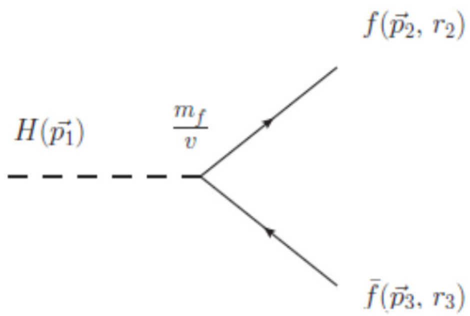
Why there is the composite?

e-*e* effective interaction: Attractive (!) due to *e* – lattice interaction

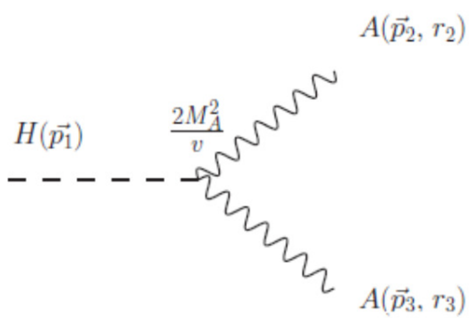
Is the 'real' Higgs field a genuine, fundamental field or a composite?

Good question..No answer (yet):
Take it as a fundamental field

Higgs Decays - I



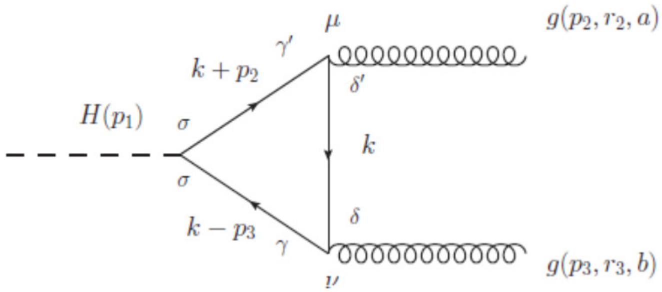
$$\Gamma(H \to f\bar{f}) = N_C \frac{1}{8\pi}\frac{m_f^2}{v^2} M_H (1 - \frac{4m_f^2}{M_H^2})^{3/2}$$

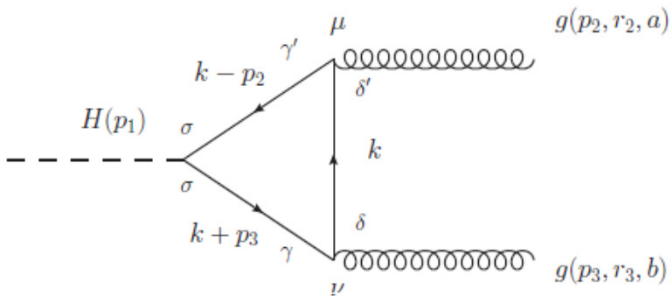


$$\Gamma(H \to WW) = \frac{1}{4\pi}\frac{M_W^4}{M_H v^2}\Big(1 - \frac{4M_W^2}{M_H^2}\Big)^{1/2}\Big(3 + \frac{1}{4}\frac{M_H^4}{M_W^4} - \frac{M_H^2}{M_W^2}\Big)$$

$$\Gamma(H \to ZZ) = \frac{1}{8\pi}\frac{M_Z^4}{M_H v^2}\Big(1 - \frac{4M_Z^2}{M_H^2}\Big)^{1/2}\Big(3 + \frac{1}{4}\frac{M_H^4}{M_Z^4} - \frac{M_H^2}{M_Z^2}\Big)$$

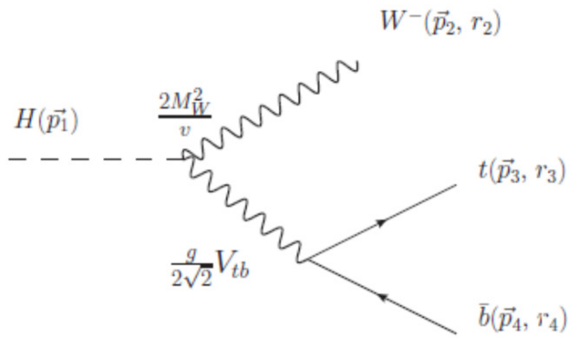
Higgs Decays - II





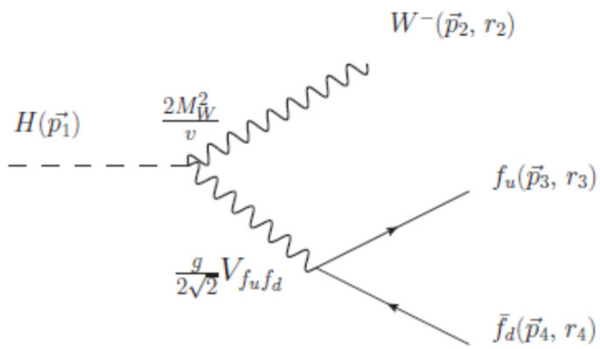
$$\Gamma(H \to gg) = \frac{M_H^3}{8\pi\, v^2} \left(\frac{\alpha_s}{\pi}\right)^2 n^2\, |D(n)|^2$$

Higgs Decays - III



$$\Gamma(H \to W t b) = N_C \frac{g^2}{2v^2}\frac{M_W^4}{M_H}|V_{tb}|^2 \int dQ_3 \frac{G^{\beta\nu}T_{\beta\nu}}{[s_{34} - M_W^2]^2}$$

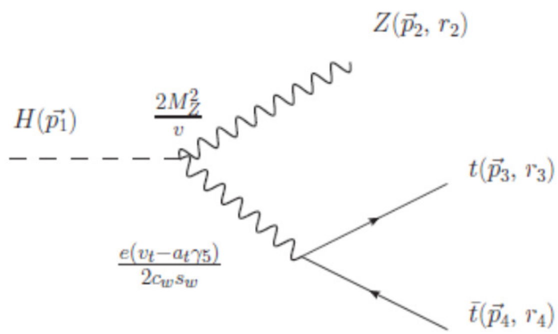
3-body phase space factor



$$\Gamma(H \to W f_u f_d) = \frac{g^2}{v^2}\frac{3M_W^2}{256\pi^3} M_H S(x)$$

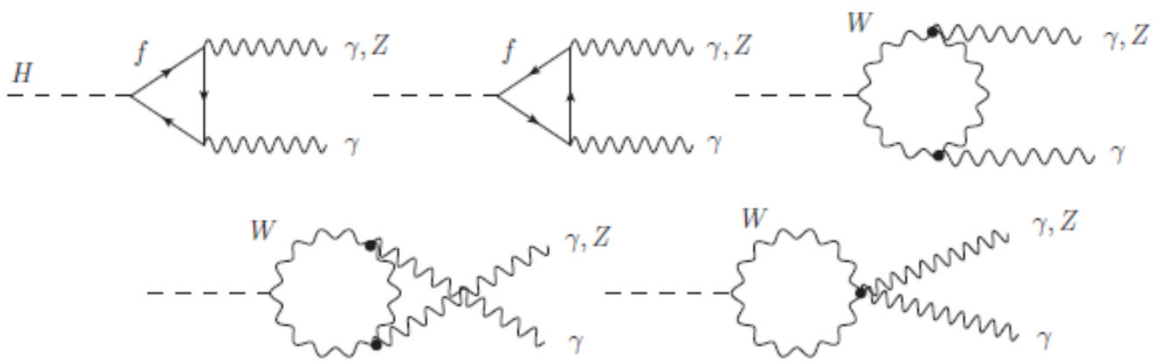
3-body phase space factor

Higgs Decays - IV



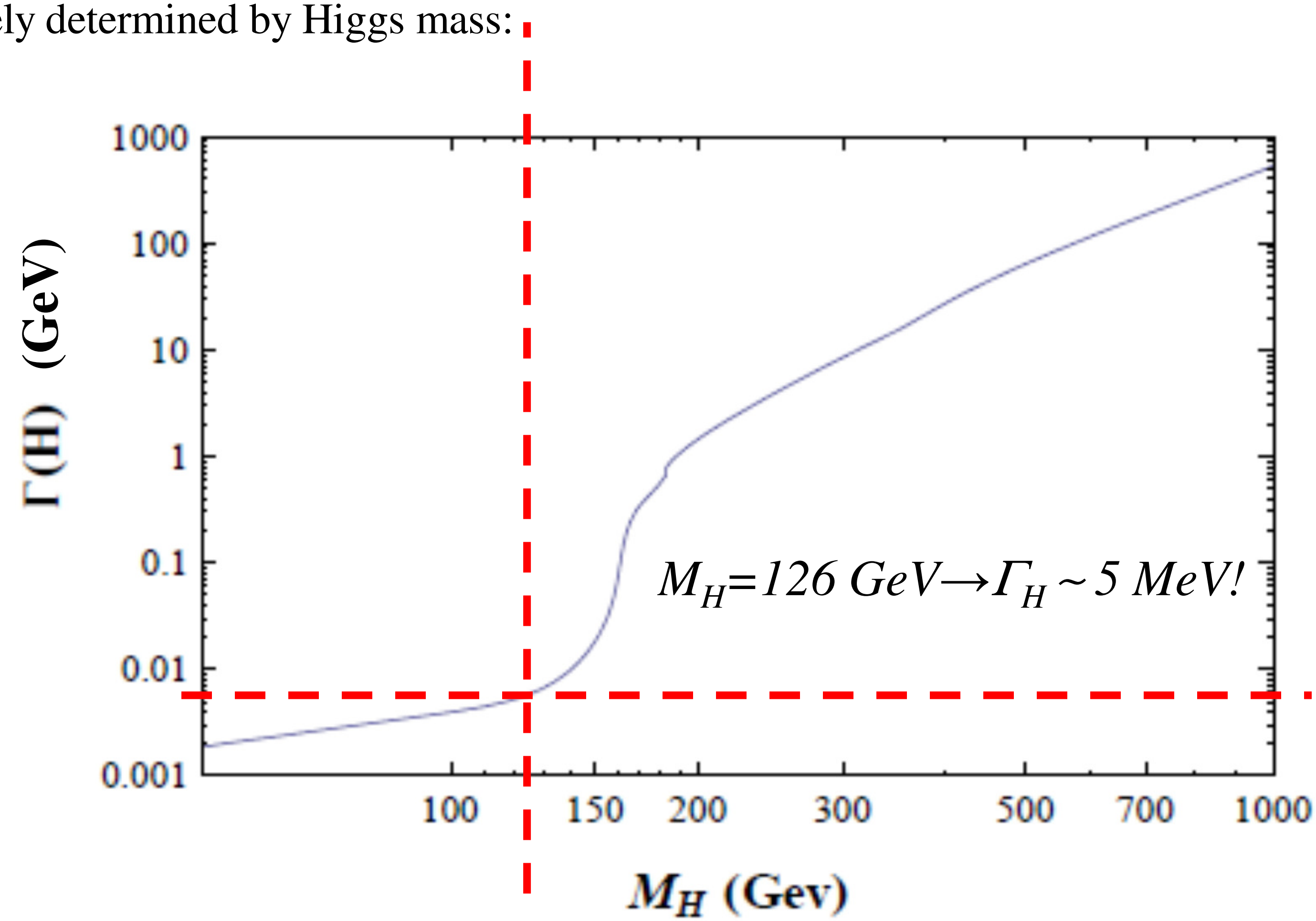
$$\Gamma(H \to Z f \bar{f}) = \frac{g^2}{v^2} \frac{3M_Z^2}{256\,\pi^3} M_H\, S(x) \frac{R(\theta_w)}{\cos^2\theta_w}$$
$$\left(\frac{7}{12} - \frac{10}{9}\sin^2\theta_w + \frac{40}{27}\sin^4\theta_w\right)$$

3-body phase space factor

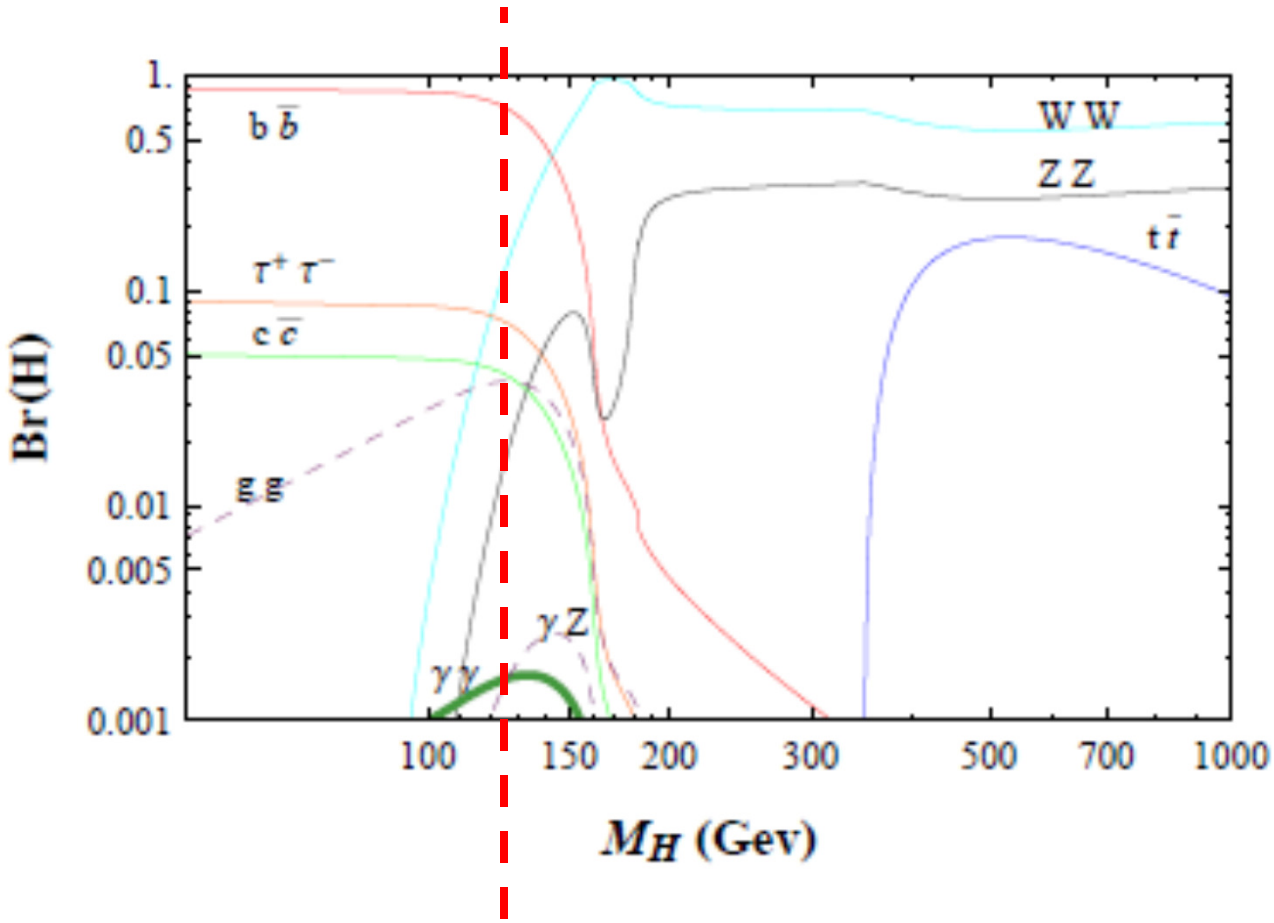


H Width

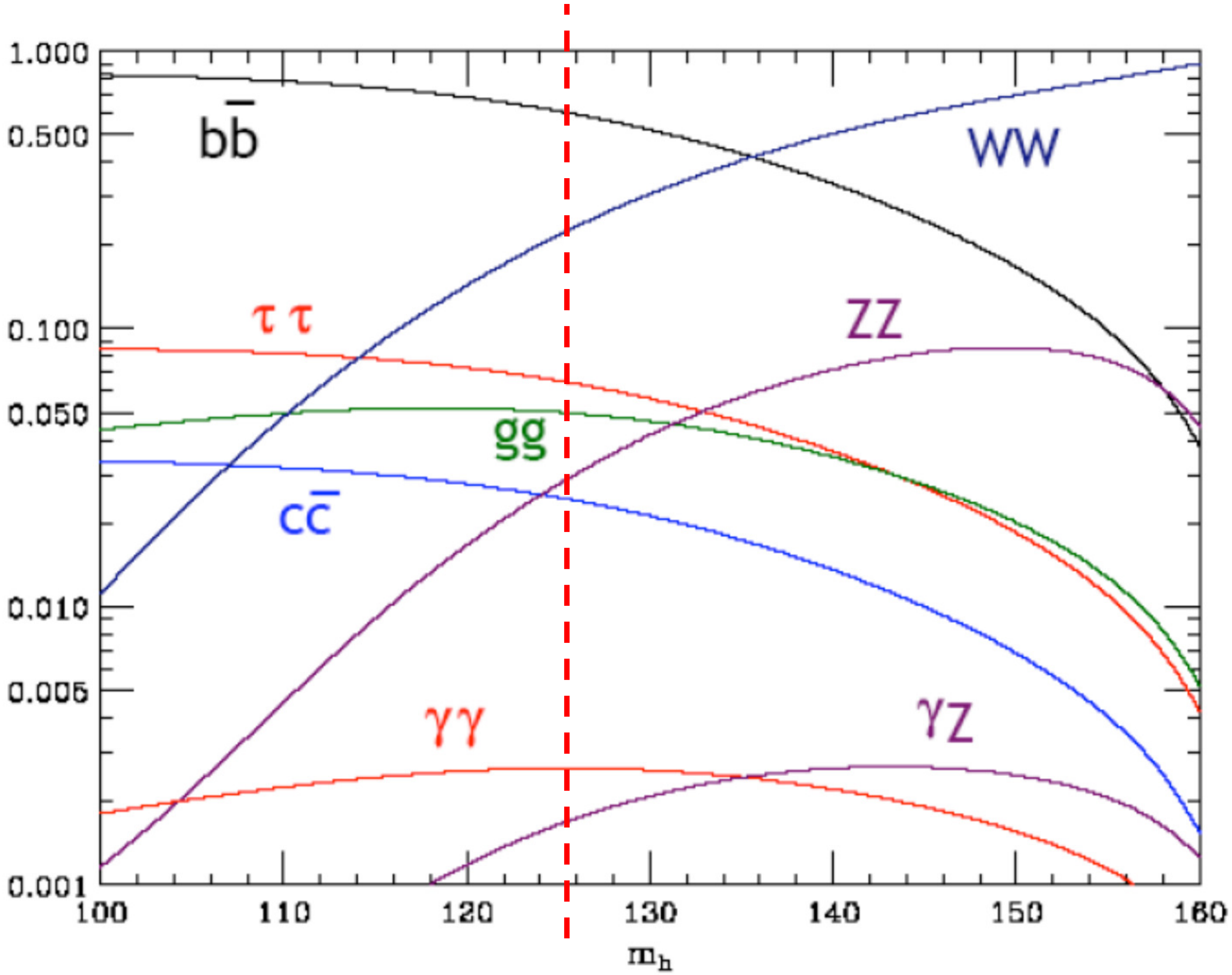
Entirely determined by Higgs mass:



H Branching Ratios -I



H Branching Ratios -II



H Branching Ratios - III

Selecting best decay channels for detection:

Strongly dependent on (unknown) M_H

By taking $M_H < 2M_W$

$b\bar{b}$: Large $BR > 50\ \%$, good signature (secondary vertexes), *lots* of QCD background

$\tau^+\tau^-$: Large $BR \sim 7\ \%$, somewhat harder than $b\bar{b}$ (neutrinos)

$\gamma\gamma$: Tiny $BR \sim 2\ 10^{-3}$, small background, experimentally challenging

gg : Large $BR \sim 5\ \%$, 2 jets, *lots* of QCD background

ZZ^* : Small $BR \sim 3\ \%$, small background in the 4 leptons mode

WW^* : Large $BR \sim 20\ \%$, sizeable QCD background in the 4 jets mode, harder than ZZ^* in leptonic modes (neutrinos)

Detector Guidelines

Go for:

Excellent muon tracking

Excellent e.m. calorimetry

Vertexing

Large acceptance

High momentum/energy resolution

High vertex resolution

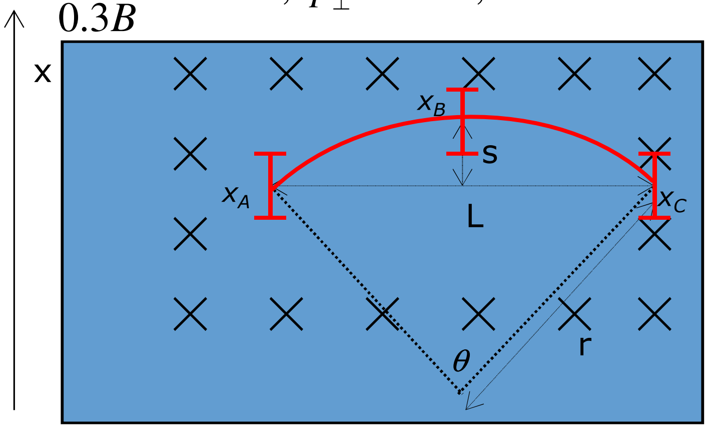
No way of directly measuring H width for $M_H \leq 2M_W$

PDG (2013) best estimate: $M = 125.9\ GeV,\ \ \sigma_M \sim 400\ MeV$

Magnetic Analysis & Accuracy

Motion of a charged particle in a uniform magnetic field: Cylindrical helix coaxial to ***B***

$$r = \frac{p_\perp}{0.3B} \qquad r:\ m,\ p_\perp:\ GeV,\quad B:\ T$$



$$\sin\frac{\theta}{2} = \frac{L}{2r} \underset{L \ll 2r}{\longrightarrow} \frac{\theta}{2} \approx \frac{L}{2r} \to \theta \approx \frac{0.3BL}{p_\perp}$$

$$s = r - r\cos\frac{\theta}{2} \approx r\left[1 - \left(1 - \frac{\theta^2}{4}\right)\right] = r\frac{\theta^2}{8} \approx \frac{0.3BL^2}{8p_\perp}$$

$$\to p_\perp \approx \frac{0.3BL^2}{8s}$$

Take 3 measured points, with single point accuracy σ

Then: $s = x_B - \frac{x_A + x_B}{2} \to \sigma_s^2 = \sigma^2 + \frac{1}{2}\sigma^2 = \frac{3}{2}\sigma^2$

$$\frac{\sigma_{p_\perp}}{p_\perp} = \frac{\sigma_s}{s} = \sqrt{\frac{3}{2}}\frac{\sigma}{s} = \sqrt{\frac{3}{2}}\frac{\sigma 8 p_\perp}{0.3BL^2} = \sqrt{\frac{300 \cdot 64}{18}}\frac{\sigma p_\perp}{BL^2} \approx 32.7\frac{\sigma p_\perp}{BL^2}$$

$N \geq 10$, uniformly spaced points: $\frac{\sigma_{p_\perp}}{p_\perp} \approx 28.3\frac{\sigma p_\perp}{BL^2\sqrt{N+4}}$

$B = 4T, L = 2m, p_\perp = 50GeV:$

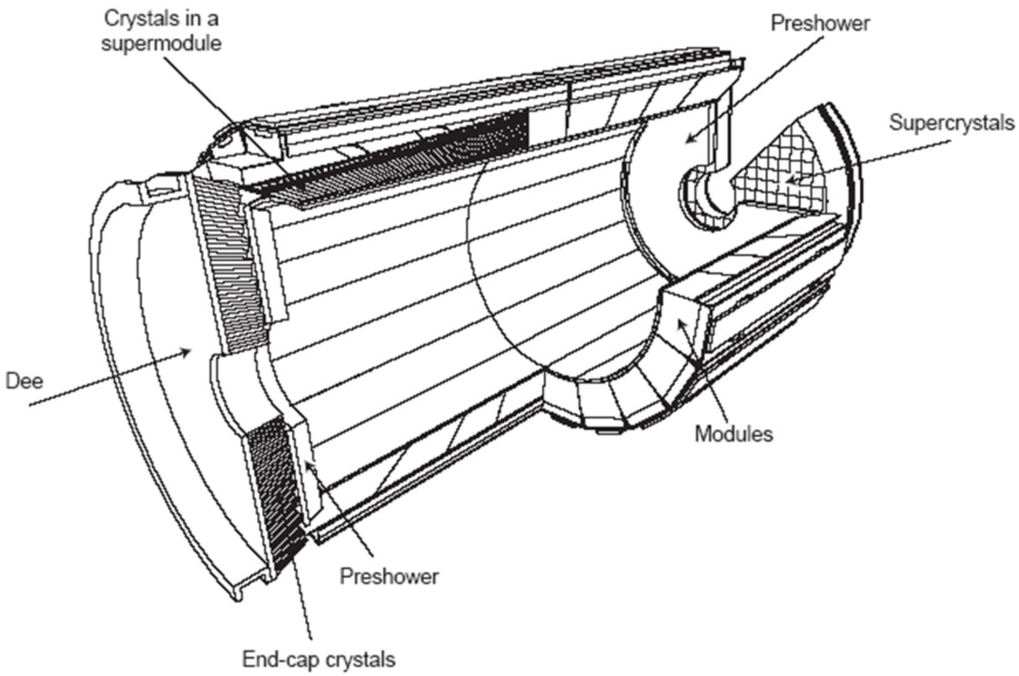
$$\to s \simeq \frac{0.3 \cdot 4 \cdot 4}{400} m \approx \frac{1.2}{100} m \approx 1\ cm$$

$\sigma \sim 100\mu m$

$$\to \left.\frac{\sigma_p}{p}\right|_{p=30GeV} \sim 30\ 10^{-4} = 0.3\% \to \left.\frac{\sigma_M}{M}\right|_{4tracks} \sim 0.6\%$$

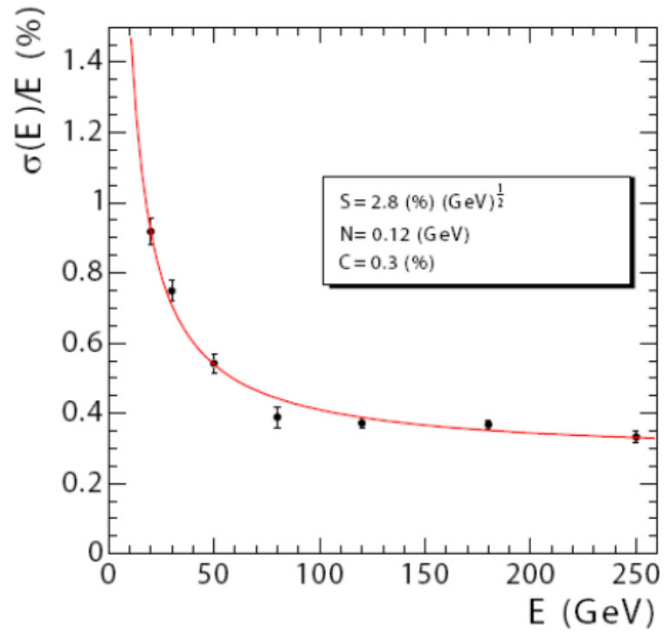
$$\to \frac{\sigma_{\langle M \rangle}}{\langle M \rangle} \sim 0.6‰ \to \sigma_{\langle M \rangle} \geq 80MeV$$

Electromagnetic Calorimetry



$$\left.\frac{\sigma_E}{E}\right|_{E=50GeV} \sim 0.5\% \rightarrow \frac{\sigma_M}{M} \sim .7\%$$

$$\rightarrow \frac{\sigma_{\langle M \rangle}}{\langle M \rangle} \sim 1‰ \quad \rightarrow \quad \sigma_M \geq 130\ MeV$$

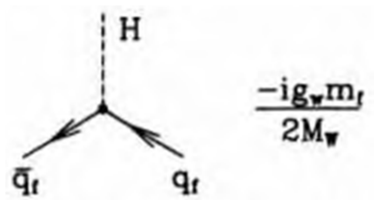


$$(\frac{\sigma}{E})^2 = (\frac{S}{\sqrt{E}})^2 + (\frac{N}{E})^2 + C^2$$

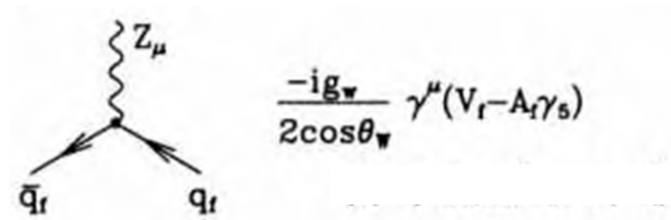
S: Photon statistics, shower containment
N: Electronic noise
C: Intercalibration

Production - I

Start from H coupling to Fermions:



Compare to coupling to Z^0 :



$\rightarrow H$ coupling down by a factor $\sim \dfrac{m_f}{m_W}$ as compared to Z^0

Leptons: Easier to handle

Feasible at $e^- e^+$ colliders ?

Tiny cross section, in view of factor $\dfrac{m_e^2}{M_W^2} \sim 4\ 10^{-11}$

Better chance for a $\mu^- \mu^+$ collider $\dfrac{m_\mu^2}{M_W^2} \sim 1.6\ 10^{-6}$

Major task, several unsolved issues about short muon lifetime vs. intensity

Production - II

Quarks: Best bet is with b

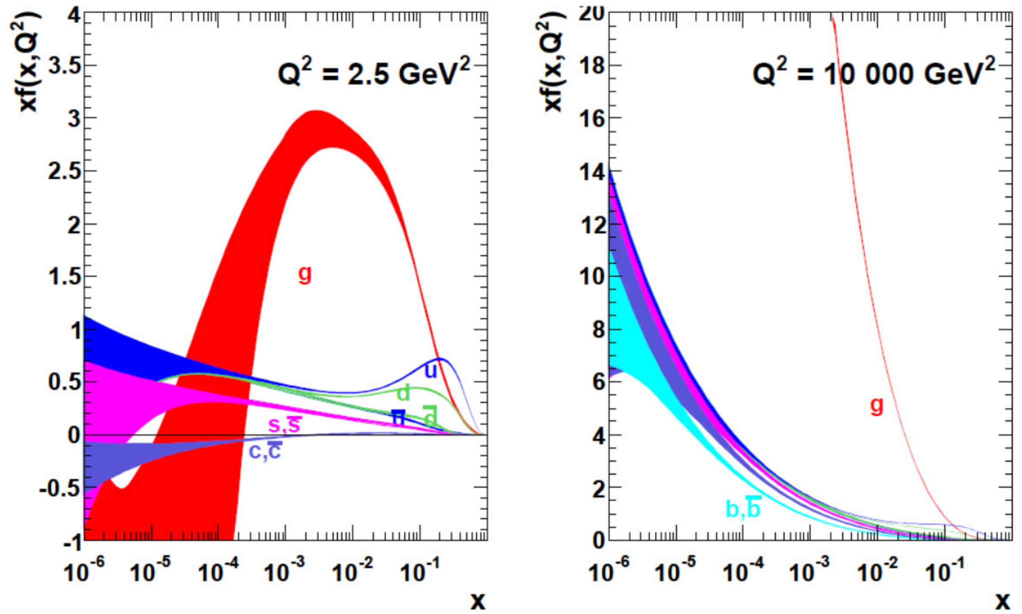
Factor $\frac{m_b^2}{M_W^2} \sim 3\ 10^{-3}$ encouraging

But: No b-quark beams, must rely on $b\bar{b}$ sea inside the nucleon

b-quark partonic density small...

Taking H production at small rapidity $y \sim 0$, with a 7 TeV beam $x \sim 10^{-2}$

$\rightarrow$ Incident flux of sea b-quarks very small



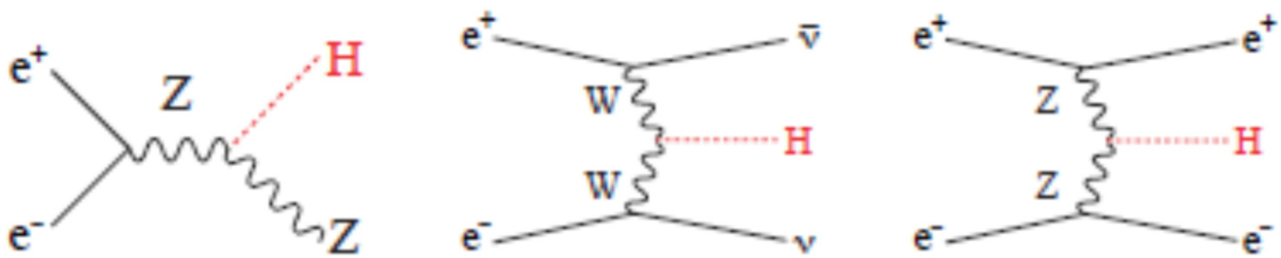
Production - III

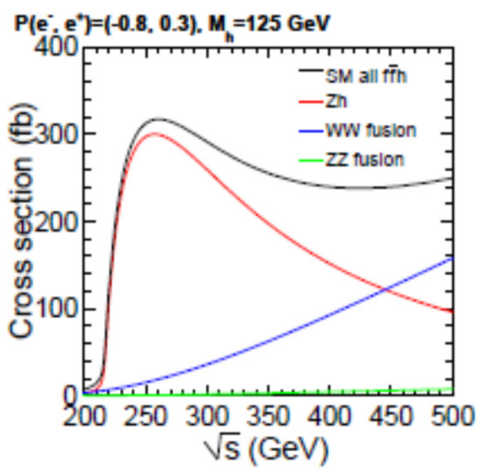
Shift to gauge bosons (Exclude massless photon), Top

More promising: W, Z, t mass very large

e^+e^- colliders

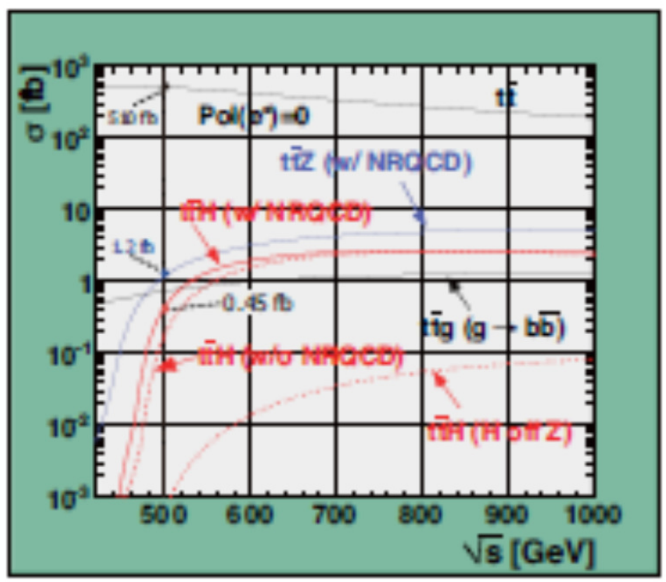
'Higgsstrahlung', 'Gauge boson fusion'



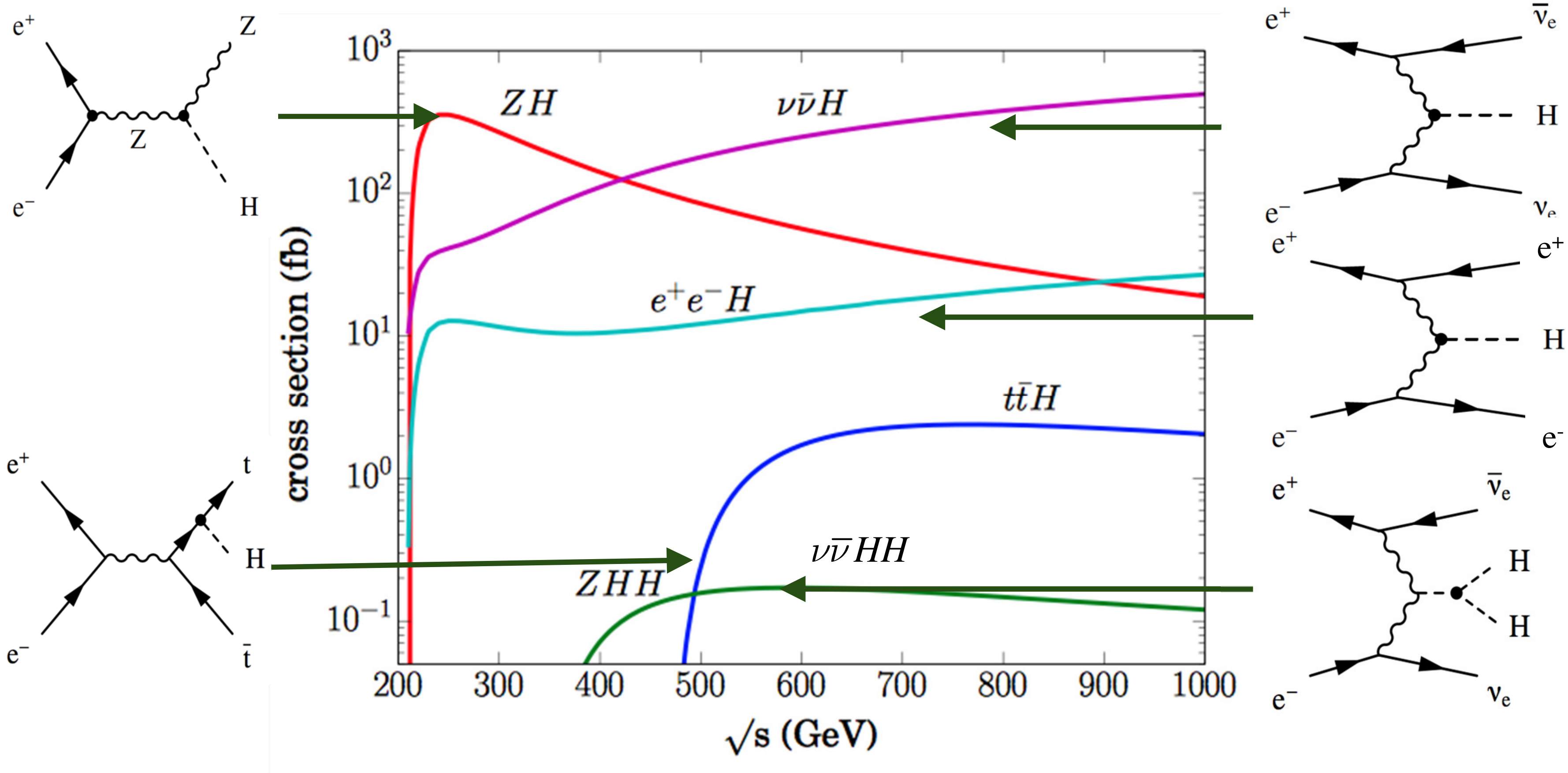


Production - IV

Top

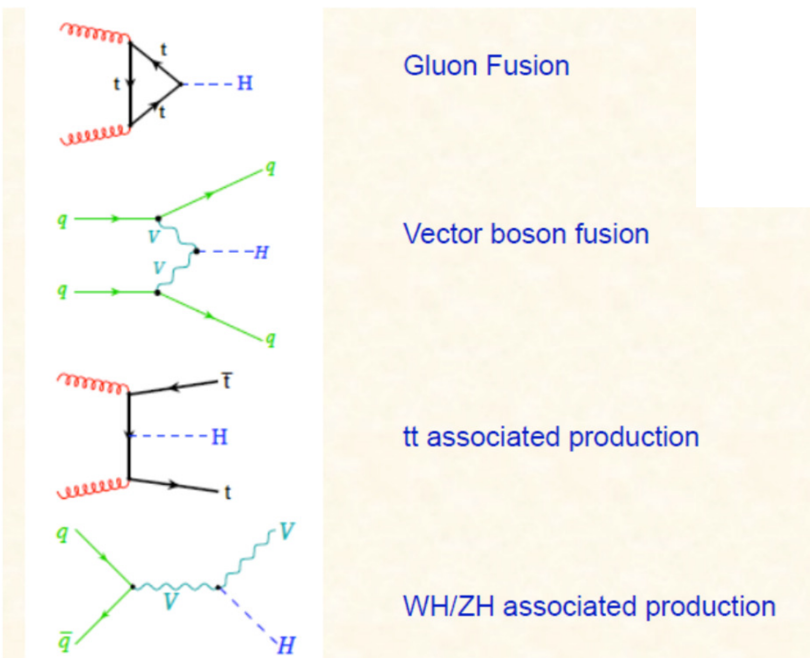


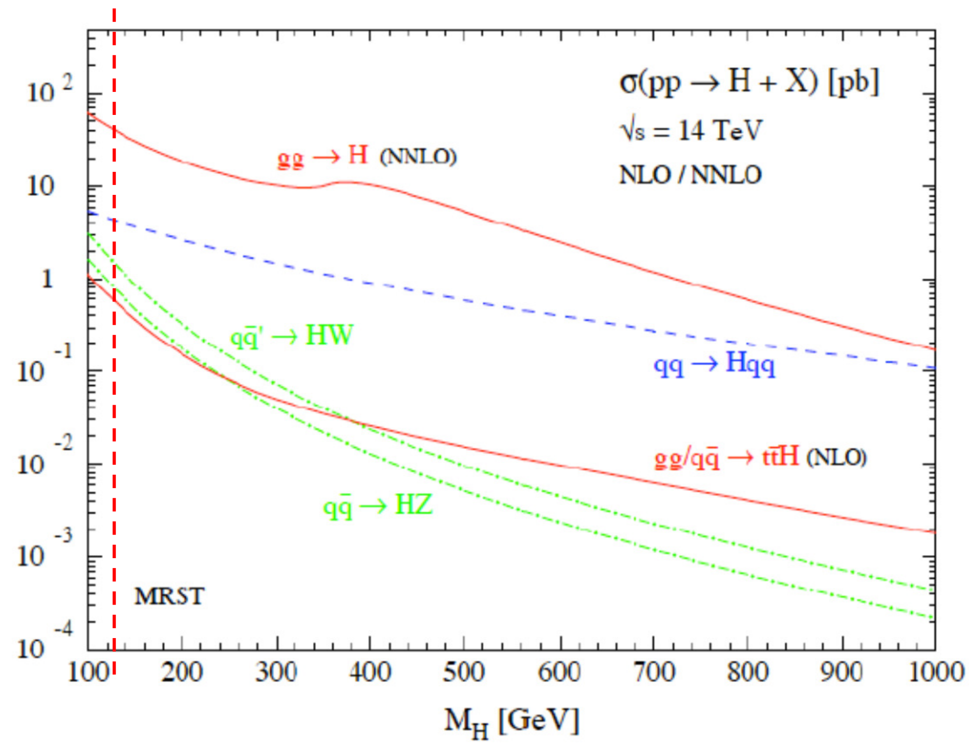
Production - V



Production - VI

$pp, p\overline{p}$ colliders

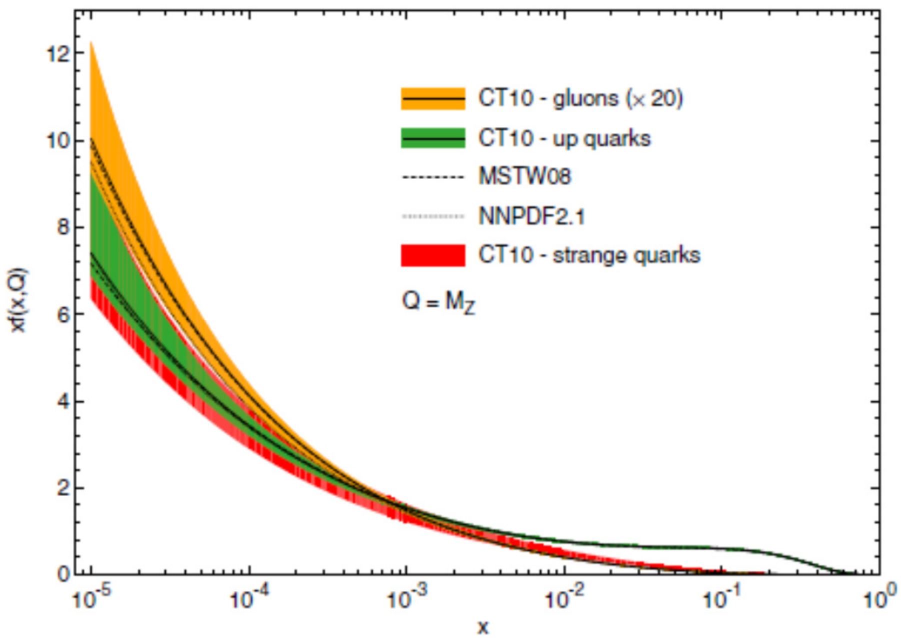


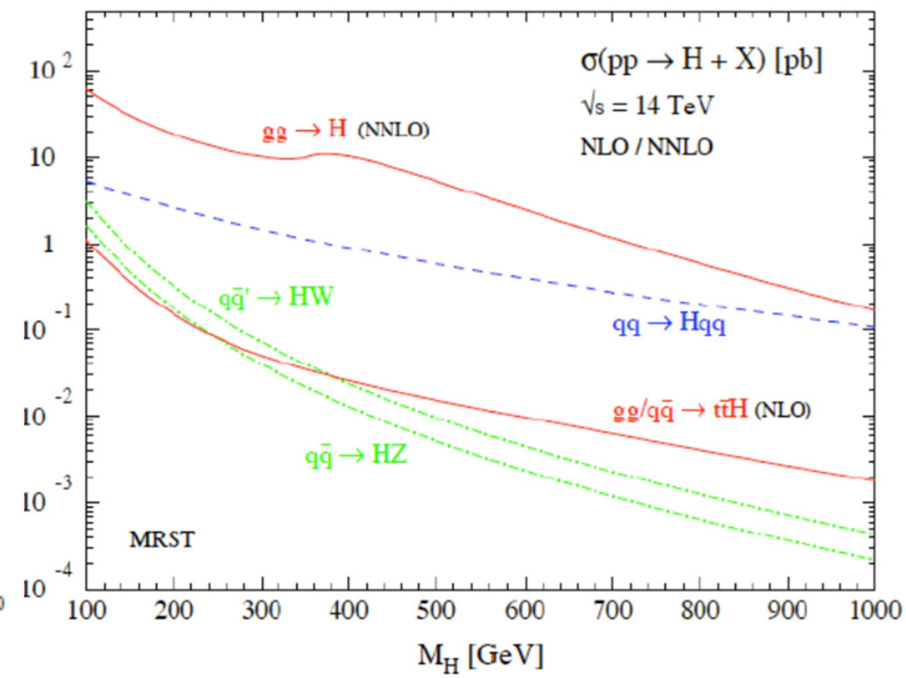


Production - VII

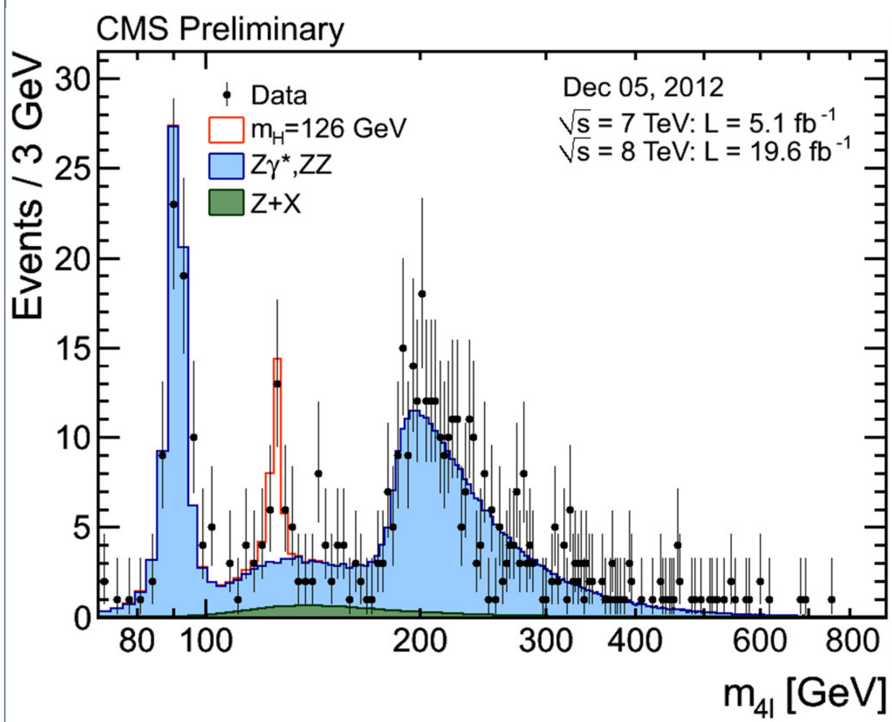
Need to convolute with parton densities…

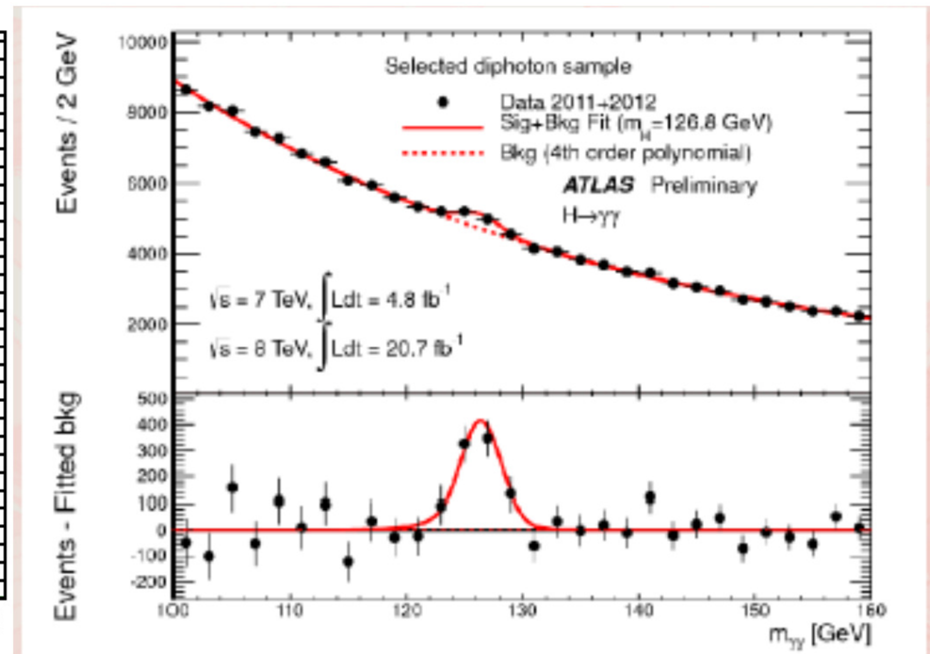
…Results for LHC cross sections





Results





6-7 σ effect = Discovery