Issues at the LHC: Higgs Physics

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Sangam@HRI, February 15 - 19, 2016

- Higgs review: SM
- Supersymmetric extension
- Higgs boson decay
- Higgs boson signals at LHC
- Higgs coupling measurement

The Standard Model of particle physics

Interactions are described by gauge theory with gauge group

$$SU(3) \quad \times \quad SU(2) \times U(1)$$

Strong interactions: **QCD**

$SU(3)$ 8 massless gluons

Electroweak interactions:

$SU(2) \times U(1)$ γ massless

$W^{\pm}, Z$ massive

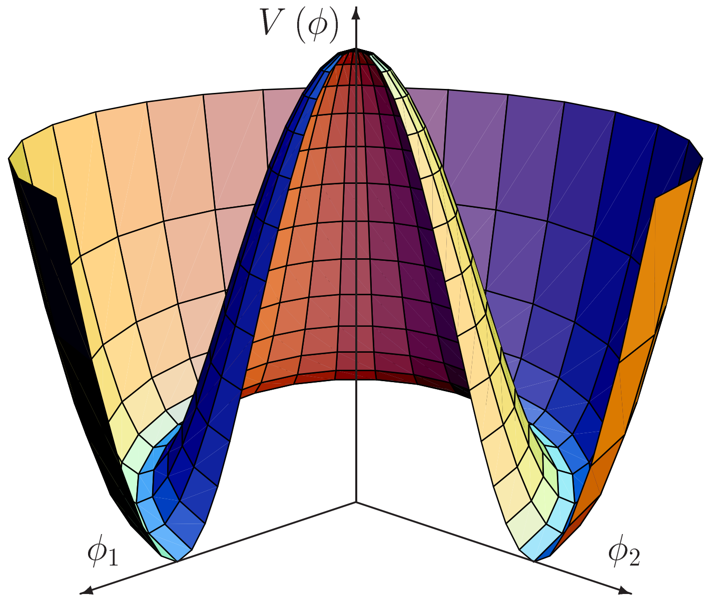
W and Z masses and fermion masses violate $SU(2) \times U(1)$ gauge symmetry.

Spontaneous symmetry breaking

Experimentally, the weak bosons are massive. The Standard Model gives mass to gauge bosons and fermions via the Higgs mechanism:

Postulate existence of a complex scalar doublet

$$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} = \begin{pmatrix} 0 \\ \frac{v+H}{\sqrt{2}} \end{pmatrix} + \text{Goldstone terms},$$



$$\mathcal{L}_{\text{Higgs}} = (D_\mu\Phi)^\dagger (D^\mu\Phi) - V\left(\Phi^\dagger\Phi\right)$$

$$D^\mu = \partial^\mu - igW_i^\mu \frac{\sigma^i}{2} - ig' \frac{Y_\Phi}{2} B^\mu$$

$$V\left(\Phi^\dagger\Phi\right) = \lambda \left(\Phi^\dagger\Phi - \frac{v^2}{2}\right)^2$$

$V\left(\Phi^\dagger\Phi\right)$ is $SU(2)_L \times U(1)_Y$ symmetric.

Consequences for the scalar field H

The scalar potential

$$V\left(\Phi^\dagger\Phi\right) = \lambda\left(\Phi^\dagger\Phi - \frac{v^2}{2}\right)^2$$

expanded around the vacuum state

$$\Phi(x) = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v + H(x) \end{pmatrix}$$

becomes

$$V = \frac{\lambda}{4}\left(2vH + H^2\right)^2 = \frac{1}{2}(2\lambda v^2)H^2 + \lambda v H^3 + \frac{\lambda}{4}H^4$$

Consequences:

- the scalar field H gets a mass which is given by the quartic coupling λ

$$m_H^2 = 2\lambda v^2 \qquad \Longrightarrow \qquad \lambda \approx 0.13 \qquad \text{since} \quad m_H \approx 125\,\text{GeV} \quad \text{and} \quad v = 246.22\,\text{GeV}$$

- there is a term of cubic and quartic self-coupling.
- The coupling $\lambda \approx 0.13$ is small, i.e. perturbation theory is warranted.

Higgs kinetic terms and coupling to W, Z

$$D^\mu\Phi = \left(\partial^\mu - igW_i^\mu\frac{\sigma^i}{2} - ig'\frac{1}{2}B^\mu\right)\frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v+H(x)\end{pmatrix}$$

$$= \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ \partial^\mu H\end{pmatrix} - \frac{i}{2\sqrt{2}}\left[g\begin{pmatrix} W_3^\mu & W_1^\mu - iW_2^\mu \\ W_1^\mu + iW_2^\mu & -W_3^\mu\end{pmatrix} + g'B^\mu\right]\begin{pmatrix} 0 \\ v+H\end{pmatrix}$$

$$= \frac{1}{\sqrt{2}}\left[\begin{pmatrix} 0 \\ \partial^\mu H\end{pmatrix} - \frac{i}{2}(v+H)\begin{pmatrix} g\left(W_1^\mu - iW_2^\mu\right) \\ -gW_3^\mu + g'B^\mu\end{pmatrix}\right]$$

$$= \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ \partial^\mu H\end{pmatrix} - \frac{i}{2}\left(1+\frac{H}{v}\right)\begin{pmatrix} gv\ \ W^{\mu+} \\ -\sqrt{(g^2+g'^2)/2}\ \ v\ \ Z^\mu\end{pmatrix}$$

$$(D^\mu\Phi)^\dagger D_\mu\Phi = \frac{1}{2}\partial^\mu H\partial_\mu H + \left[\left(\frac{gv}{2}\right)^2 W^{\mu+}W_\mu^- + \frac{1}{2}\frac{\left(g^2+g'^2\right)v^2}{4}Z^\mu Z_\mu\right]\left(1+\frac{H}{v}\right)^2$$

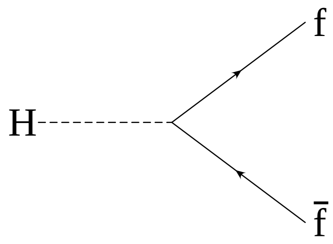
Fermion masses and couplings to the Higgs boson

Fermion masses arise from Yukawa couplings via $\Phi^\dagger \rightarrow (0, \frac{v+H}{\sqrt{2}})$

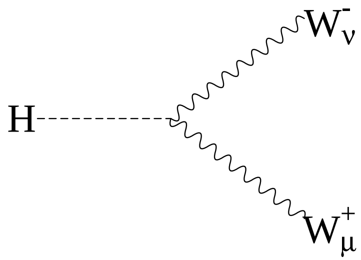
$$
\begin{aligned}
\mathcal{L}_{\text{Yukawa}} &= -\Gamma_d \bar{Q}_L \Phi d_R - \Gamma_d^* \bar{d}_R \Phi^\dagger Q_L + \ldots \\
&= -\Gamma_d \, (\bar{u}_L, \bar{d}_L) \begin{pmatrix} 0 \\ \frac{v+H}{\sqrt{2}} \end{pmatrix} d_R + \ldots \\
&= -\Gamma_d \, \frac{v+H}{\sqrt{2}} \, \bar{d}_L \, d_R + \ldots \\
&= -\sum_f m_f \, \bar{f} f \left(1 + \frac{H}{v}\right)
\end{aligned}
$$

- Test SM prediction: $\bar{f} f H$ Higgs coupling strength $= m_f / v$

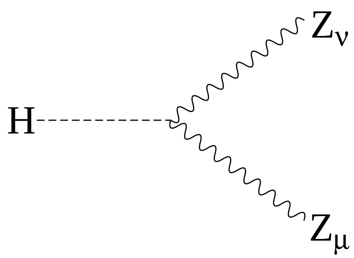
Feynman rules for Higgs couplings



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



$$ig\, m_W\, g_{\mu\nu}$$



$$i\, g\, \frac{1}{\cos\theta_W}\, m_Z\, g_{\mu\nu}$$

Within the Standard Model, the Higgs couplings are completely constrained since the masses of all SM particles[a] have been measured.

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[a]except neutrinos

The MSSM Higgs sector

The SM uses the conjugate field $\Phi_c = i\sigma_2\Phi^*$ to generate down quark and lepton masses. In supersymmetric models this must be an independent field

$$\begin{aligned}\mathcal{L}_{\text{Yukawa}} &= -\Gamma_d \bar{Q}_L \Phi_1 d_R - \Gamma_e \bar{L}_L \Phi_1 e_R + \text{h.c.} \\ &\quad -\Gamma_u \bar{Q}_L \Phi_2 u_R + \text{h.c.}\end{aligned}$$

Two complex Higgs doublet fields Φ_1 and Φ_2 receive mass and VEVs v_1, v_2 from generalized Higgs potential. Mass eigenstates constructed out of these 8 real fields are

Neutral sector:

2 CP even Higgs bosons: h and H

1 CP odd Higgs boson: A

1 Goldstone boson: χ_0

Charged sector:

charged Higgs bosons: $H^\pm$

charged Goldstone boson: $\chi^\pm$

Higgs mixing and MSSM parameters

The Higgs potential leads to general mixing of the 2 doublet fields

$$\Phi_1 = \frac{1}{\sqrt{2}} \begin{pmatrix} \sqrt{2}[H^+ \sin\beta - \chi^+ \cos\beta] \\ v_1 + [H \cos\alpha - h \sin\alpha] + i[A \sin\beta + \chi_0 \cos\beta] \end{pmatrix} \to \frac{1}{\sqrt{2}} \begin{pmatrix} \sqrt{2}H^+ \sin\beta \\ v_1 + \varphi_1 + iA \sin\beta \end{pmatrix}$$

$$\Phi_2 = \frac{1}{\sqrt{2}} \begin{pmatrix} v_2 + [H \sin\alpha + h \cos\alpha] + i[A \cos\beta - \chi_0 \sin\beta] \\ \sqrt{2}[H^- \cos\beta + \chi^- \sin\beta] \end{pmatrix} \to \frac{1}{\sqrt{2}} \begin{pmatrix} v_2 + \varphi_2 + iA \cos\beta \\ \sqrt{2}H^- \cos\beta \end{pmatrix}$$

The angle β is determined by the VEVs:

$$v_1 = v \cos\beta\,, \qquad v_2 = v \sin\beta\,, \qquad \Longrightarrow \qquad \frac{v_2}{v_1} = \tan\beta$$

The mixing angle α between the 2 CP even scalars and the masses are determined by

$$\tan\beta\,, \qquad m_A\,, \qquad v = \sqrt{v_1^2 + v_2^2} = 246\ \text{GeV}$$

Tree level relations

Higgs potential in the MSSM produces distinct mass relations at tree level

$$m_h^2, m_H^2 = \frac{1}{2}\left[m_A^2 + m_Z^2 \pm \sqrt{\left(m_A^2 + m_Z^2\right)^2 - 4m_A^2 m_Z^2 \cos^2 2\beta}\right]$$

$$m_{H^\pm} = \sqrt{m_A^2 + m_W^2} > m_W$$

Mixing angle α is also fixed by masses and $\tan\beta$

$$\cos(\beta-\alpha) = \frac{m_h^2(m_Z^2 - m_h^2)}{m_A^2(m_H^2 - m_h^2)}$$

Behaviour for $m_A \gg m_Z$:

$$m_H^\pm \approx m_A \approx m_H\,,$$

$$\cos(\beta-\alpha) \approx \frac{m_Z^4 \sin^2 4\beta}{4m_A^4} \rightarrow 0 \quad \text{for} \quad m_A \rightarrow \infty \qquad \text{(decoupling limit)}$$

Coupling to gauge bosons

$$\begin{aligned} \mathcal{L} &= (D^\mu\Phi_1)^\dagger D_\mu\Phi_1 + (D^\mu\Phi_2)^\dagger D_\mu\Phi_2 \\ &= \frac{1}{2}|\partial_\mu\varphi_1|^2 + \frac{1}{2}|\partial_\mu\varphi_2|^2 + \left(\frac{g_Z^2}{8} Z_\mu Z^\mu + \frac{g^2}{4} W_\mu^+ W^{-\mu}\right)\left[(v_1+\varphi_1)^2 + (v_2+\varphi_2)^2\right] + \ldots \end{aligned}$$

The $v_1^2 + v_2^2 = v^2$ term gives same masses to W, Z as in the SM

$$m_W^2 = \frac{g^2 v^2}{4} \qquad m_Z^2 = \frac{(g^2 + g'^2)\, v^2}{4} = \frac{m_W^2}{\cos^2\theta_W}$$

The couplings to the gauge bosons arise from

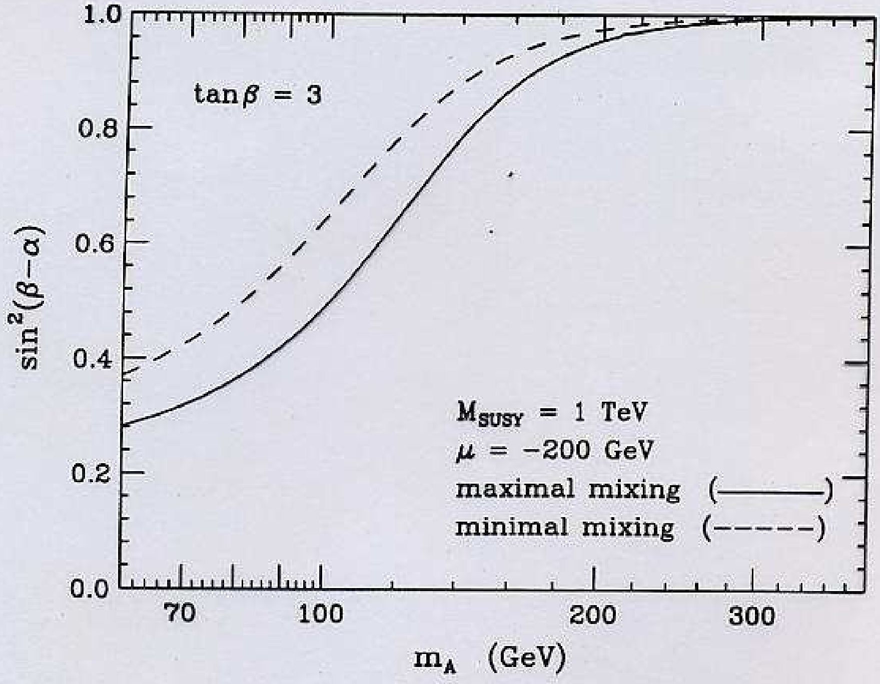
$$\begin{aligned} 2v_1\varphi_1 + 2v_2\varphi_2 &= 2v\cos\beta[H\ \cos\alpha - h\ \sin\alpha] + 2v\sin\beta[H\ \sin\alpha + h\ \cos\alpha] \\ &= 2v\ [\ H\cos(\beta-\alpha) + h\sin(\beta-\alpha)\ ] \end{aligned}$$

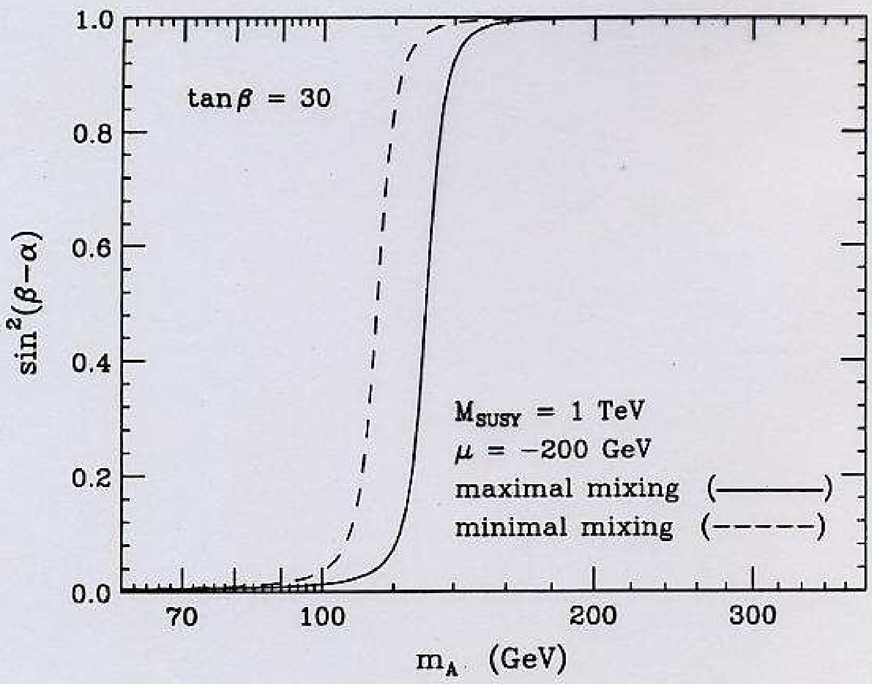
$\Longrightarrow$ extra coupling factors for hVV and HVV couplings as compared to SM

$$hVV \sim \sin(\beta-\alpha) \qquad HVV \sim \cos(\beta-\alpha)$$

Note: $\cos(\beta-\alpha) \to 0$ for $m_A \to \infty \Longrightarrow$ H decouples from WW and ZZ, h has SM coupling radiative corrections included

run II report





Coupling to fermions

$$\mathcal{L}_{\text{Yuk.}} = -\Gamma_b \bar{b}_L \Phi_1^0 b_R - \Gamma_t \bar{t}_L \Phi_2^0 u_R + \text{h.c.}$$
$$= -\Gamma_b \bar{b}_L \frac{v_1 + H\cos\alpha - h\sin\alpha + iA\ \sin\beta}{\sqrt{2}} b_R - \Gamma_t \bar{t}_L \frac{v_2 + H\sin\alpha + h\cos\alpha + iA\ \cos\beta}{\sqrt{2}} t_R + \text{h.c.}$$

The v_1, v_2 terms are the fermion masses

$$m_b = \frac{\Gamma_b v_1}{\sqrt{2}} \qquad m_t = \frac{\Gamma_t v_2}{\sqrt{2}} \qquad \Longrightarrow \qquad \frac{\Gamma_b}{\sqrt{2}} = \frac{m_b}{v\cos\beta} \qquad \frac{\Gamma_t}{\sqrt{2}} = \frac{m_t}{v\sin\beta}$$

Expressed in terms of masses the Yukawa Lagrangian is

$$\mathcal{L}_{\text{Yuk.}} = -\frac{m_b}{v}\bar{b}\left(v + H\frac{\cos\alpha}{\cos\beta} - h\frac{\sin\alpha}{\cos\beta} - i\gamma_5 A\ \tan\beta\right) b - \frac{m_t}{v}\bar{t}\left(v + H\frac{\sin\alpha}{\sin\beta} + h\frac{\cos\alpha}{\sin\beta} - i\gamma_5 A\ \cot\beta\right) t$$

$\Longrightarrow$ coupling factors compared to SM hff coupling $-i\ m_f/v$

Decoupling limit for fermions

Consider limit $\sin(\beta-\alpha)\to 1, \quad \cos(\beta-\alpha)\to 0$

- $hbb, h\tau\tau$:

$$-\frac{\sin\alpha}{\cos\beta} = \sin(\beta-\alpha) - \tan\beta\,\cos(\beta-\alpha) \to 1$$

- htt:

$$\frac{\cos\alpha}{\sin\beta} = \sin(\beta-\alpha) + \frac{\cos(\beta-\alpha)}{\tan\beta} \to 1$$

- $Hbb, H\tau\tau$:

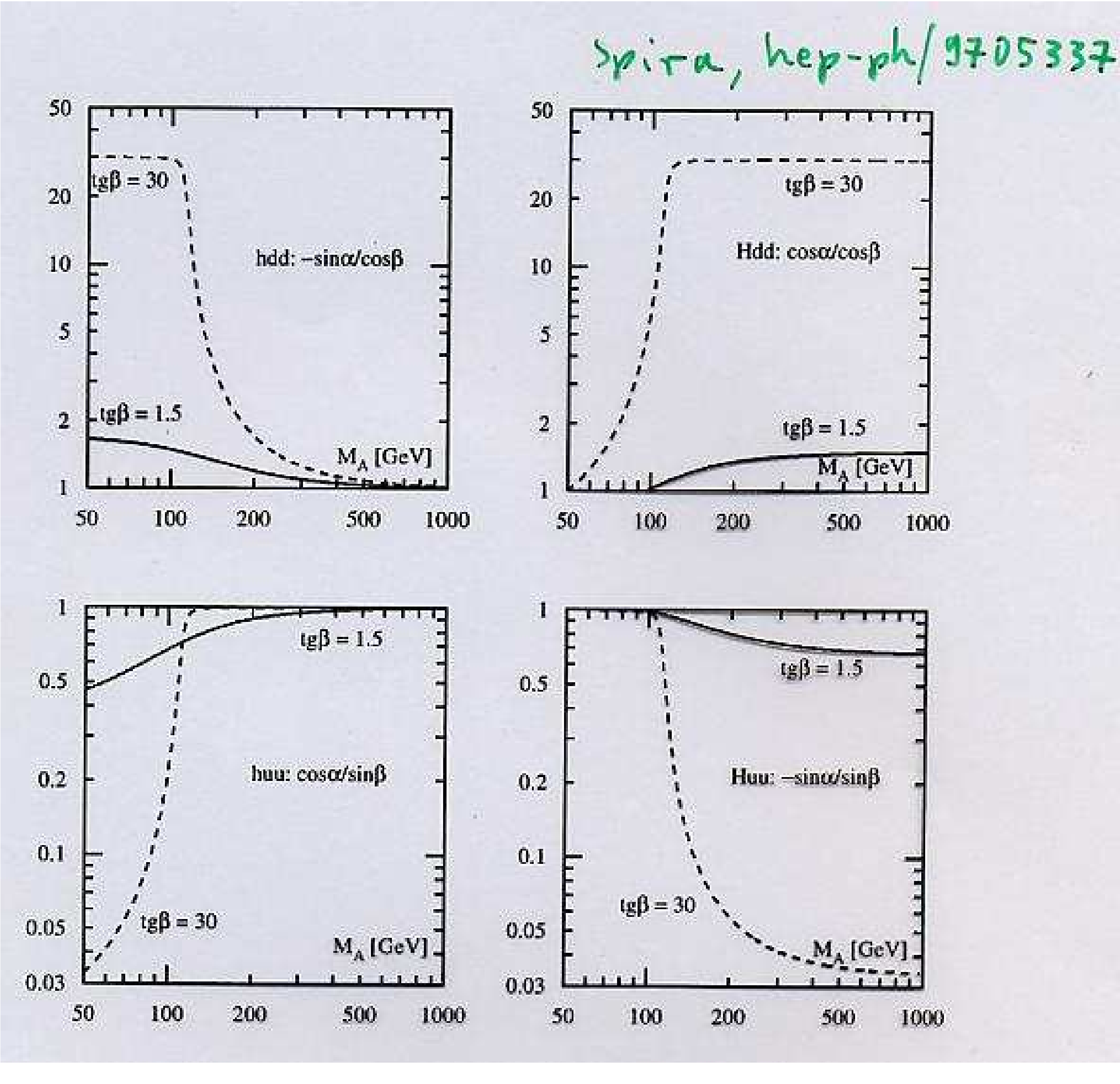
$$\frac{\cos\alpha}{\cos\beta} = \cos(\beta-\alpha) + \tan\beta\,\sin(\beta-\alpha) \to \tan\beta$$

- Htt:

$$\frac{\sin\alpha}{\sin\beta} = \cos(\beta-\alpha) - \frac{\sin(\beta-\alpha)}{\tan\beta} \to \frac{-1}{\tan\beta}$$

In the large m_A regime

- light h couplings to fermions approach SM values
- $H\bar{b}b$ (and $A\bar{b}b$, $H/A\tau\tau$) couplings are enhanced $\sim \tan\beta$ $\Longrightarrow$ potentially large cross sections at LHC



Spira, hep-ph/9705337
hdd: −sinα/cosβ
tgβ = 30
tgβ = 1.5
Hdd: cosα/cosβ
huu: cosα/sinβ
Huu: −sinα/sinβ
M_A [GeV]

Higgs phenonomenology

Importance of decoupling limit in MSSM (large m_A) $\Longrightarrow$ Concentrate on SM case

Higgs couples to fermions and gauge bosons proportional to their mass $\Longrightarrow$
Heavy SM particles are involved in both production and decay processes

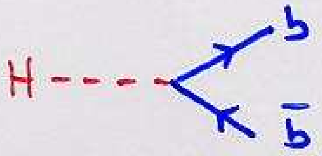
$$W, Z, t, b, \tau$$

Consider

- Higgs decay: partial widths, total width and decay branching fractions
- Production cross sections at LHC
- Signatures and backgrounds
- Measurement of Higgs couplings

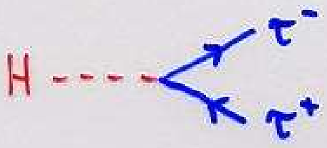
Main Higgs decay channels

$H \to b\bar{b}$



$m_H \lesssim 150$ GeV

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



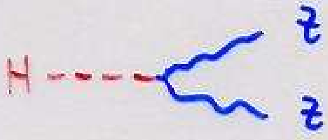
$m_H \lesssim 140$ GeV

and into gauge bosons

$H \to W^+W^-$

$m_H \gtrsim 120$ GeV

$H \to ZZ$

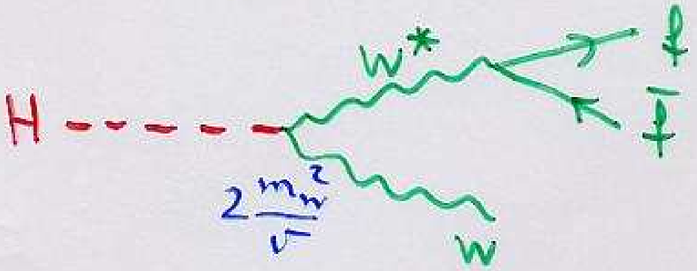


$m_H \gtrsim 120/180$ Ge

$H \to \gamma\gamma$

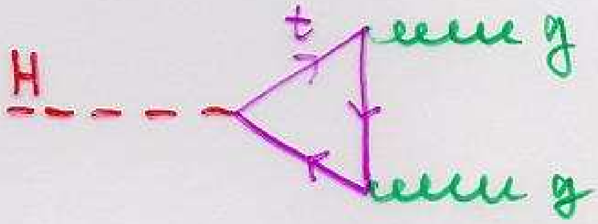
$m_H \lesssim 150$ Ge

For $m_H \gtrsim 110$ GeV : $H \to WW^*$

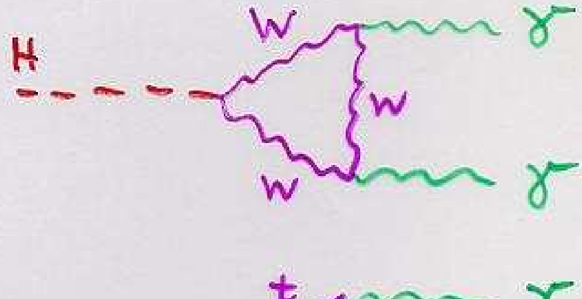


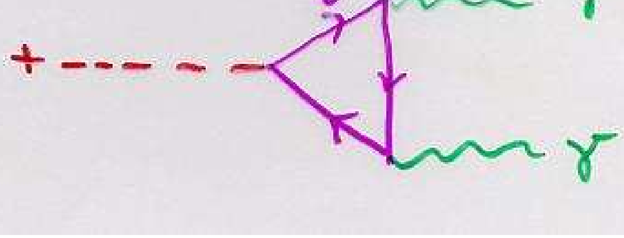
Loop decays

$H \to gg$



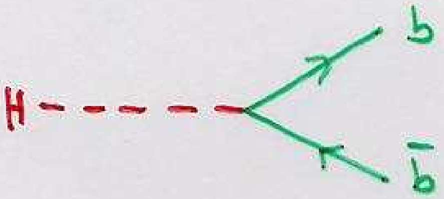
$H \to \gamma\gamma$





Higgs decays

For $m_H \lesssim 135$ GeV, $H \to b\bar{b}$ dominate



$-i\,\frac{m_b}{v}$

$$\Gamma(H \to b\bar{b}) = 3\,\frac{m_H}{8\pi}\left(\frac{\overline{m}_b(m_H)}{v}\right)^2 \beta^3 \left(1 + \frac{17}{3}\frac{\alpha_s}{\pi} + \ldots\right.$$

QCD radiative corrections are important

- Use running b mass $\overline{m}_b(m_H)$

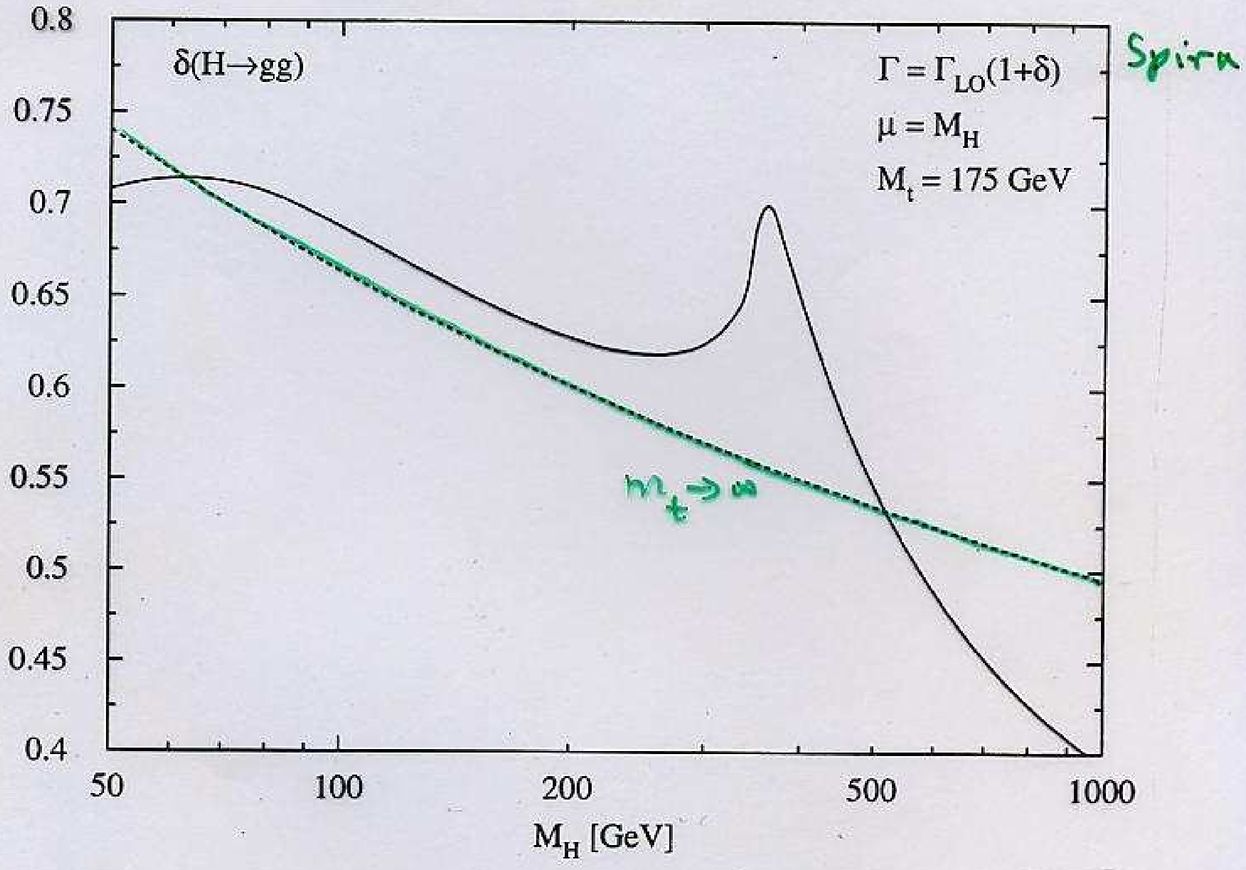
  $\overline{m}_b(m_H = 100\text{ GeV}) \simeq 2.9\text{ GeV} \simeq 0.69\,\overline{m}_b(m_b$

- include 2 loop QCD corrections

f	m_f	$m_f(100\text{ GeV})$	
b	4.7 GeV	2.42 GeV	
c	1.2 GeV	0.62 GeV	$\Gamma(H \to c\bar{c})$
τ	1.8 GeV	1.8 GeV	$< \Gamma(H \to \tau\tau$

NLO QCD corrections to $\Gamma(H \to gg)$

$$\Gamma(H \to gg, q\bar{q}g) = \Gamma_{LO}(H \to gg)(1+\delta)$$



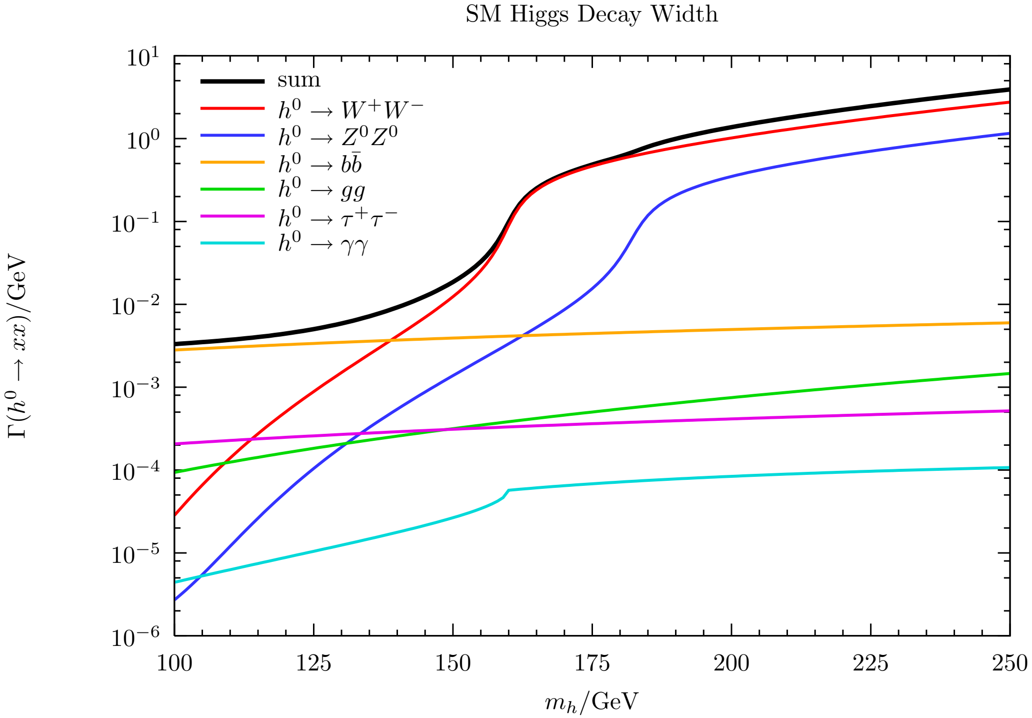
Radiative corrections for various decay modes implemented in HDECAY

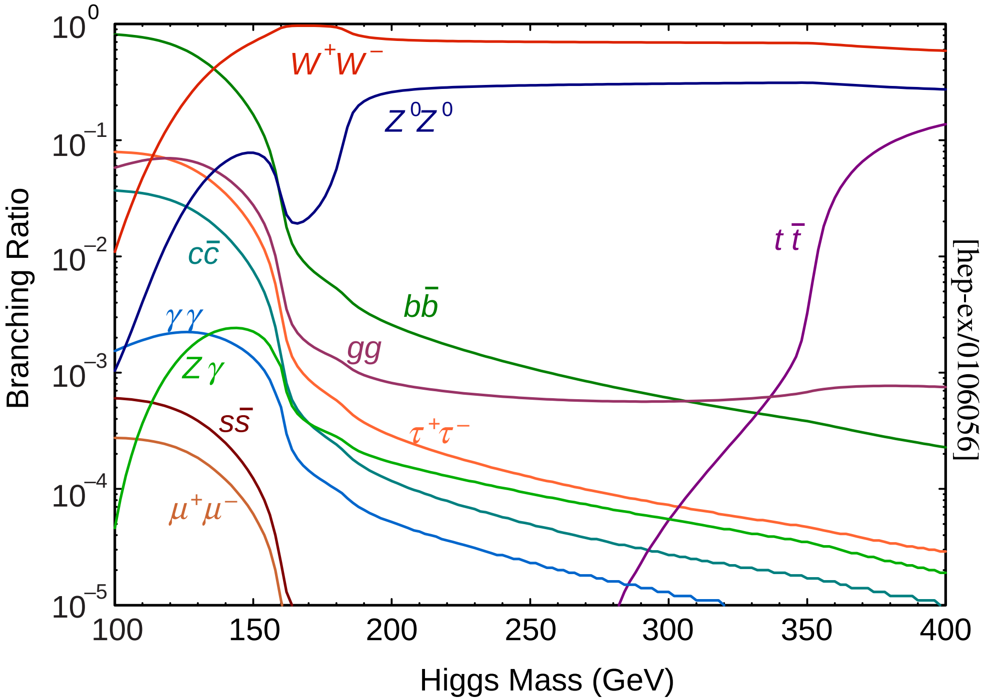
Djouadi, Kalinowski, Spira, hep-ph/9704448

Continuously updated for SM & MSSM

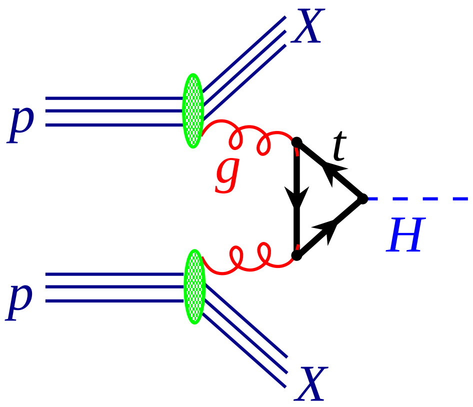
Decay of the SM Higgs

Higgs decay width and branching fractions within the SM

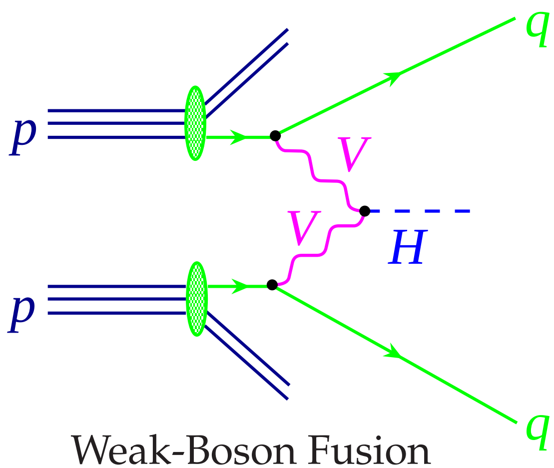




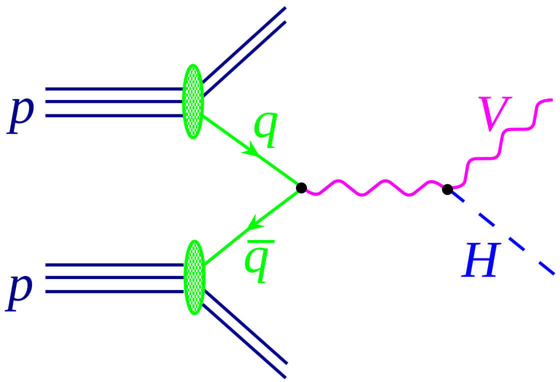
Higgs Production Channels at Hadron Colliders



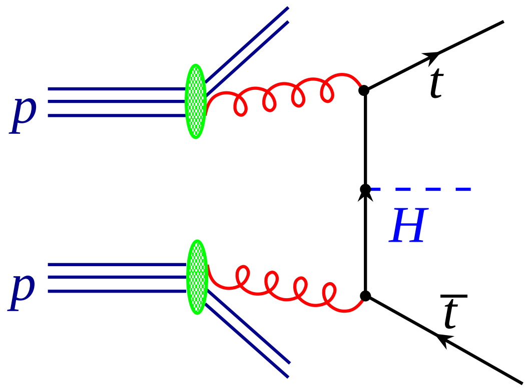
Gluon fusion



Weak-Boson Fusion

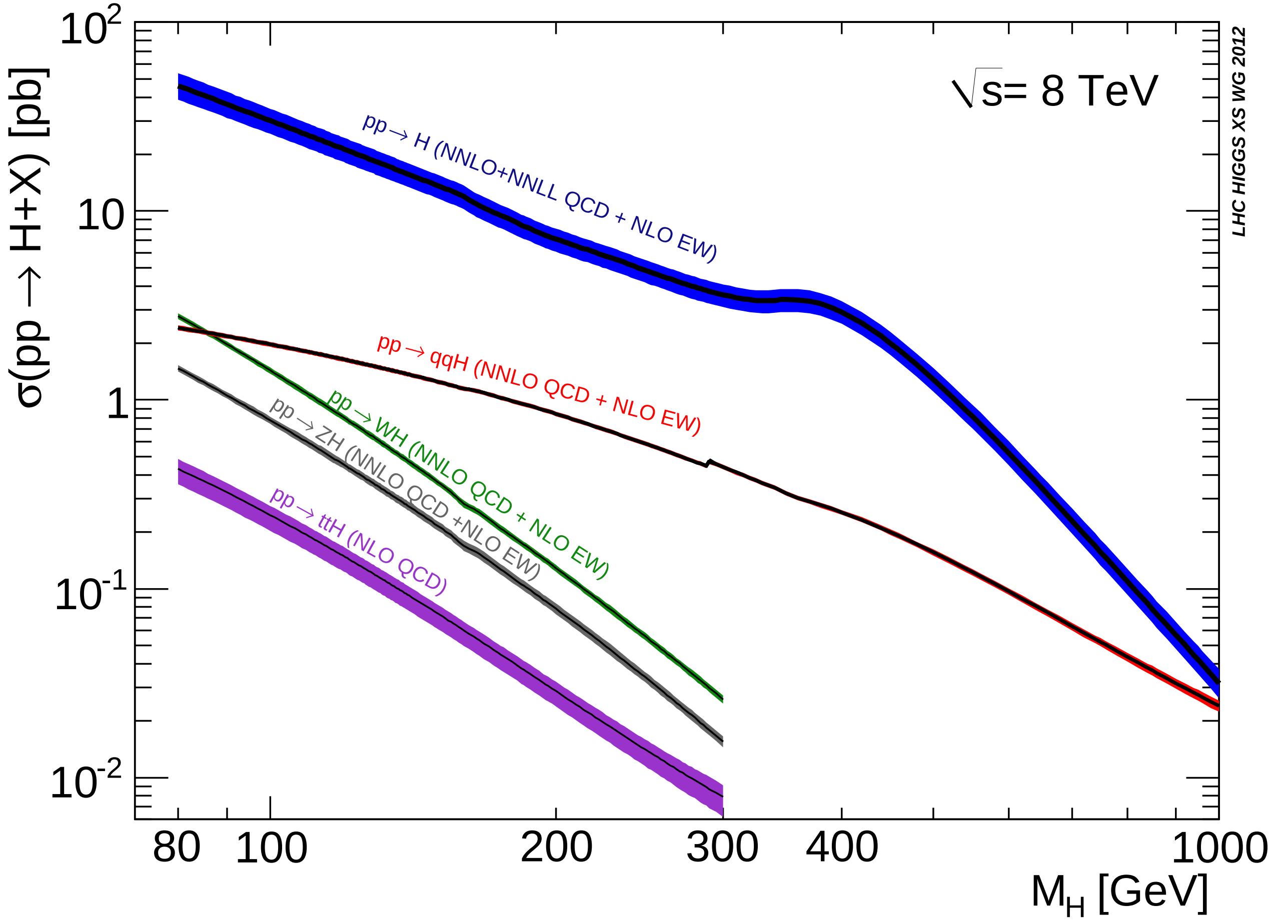


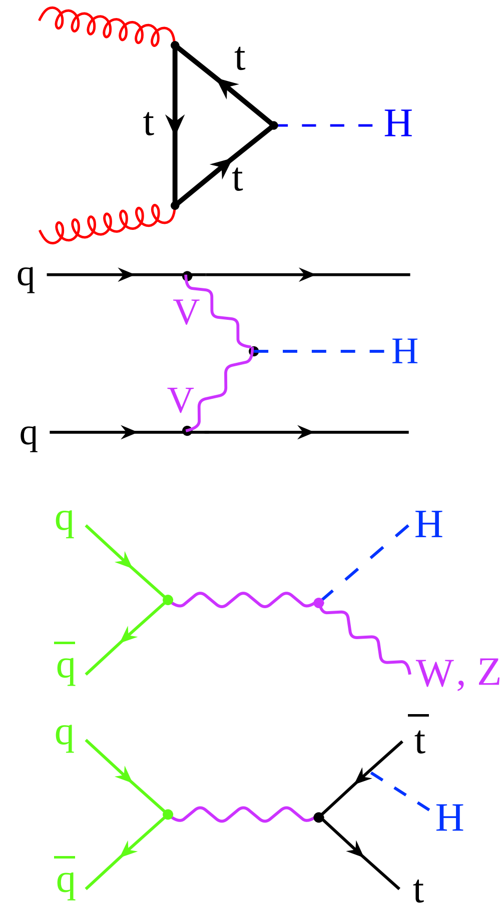
Higgs Strahlung



$t\bar{t}H$

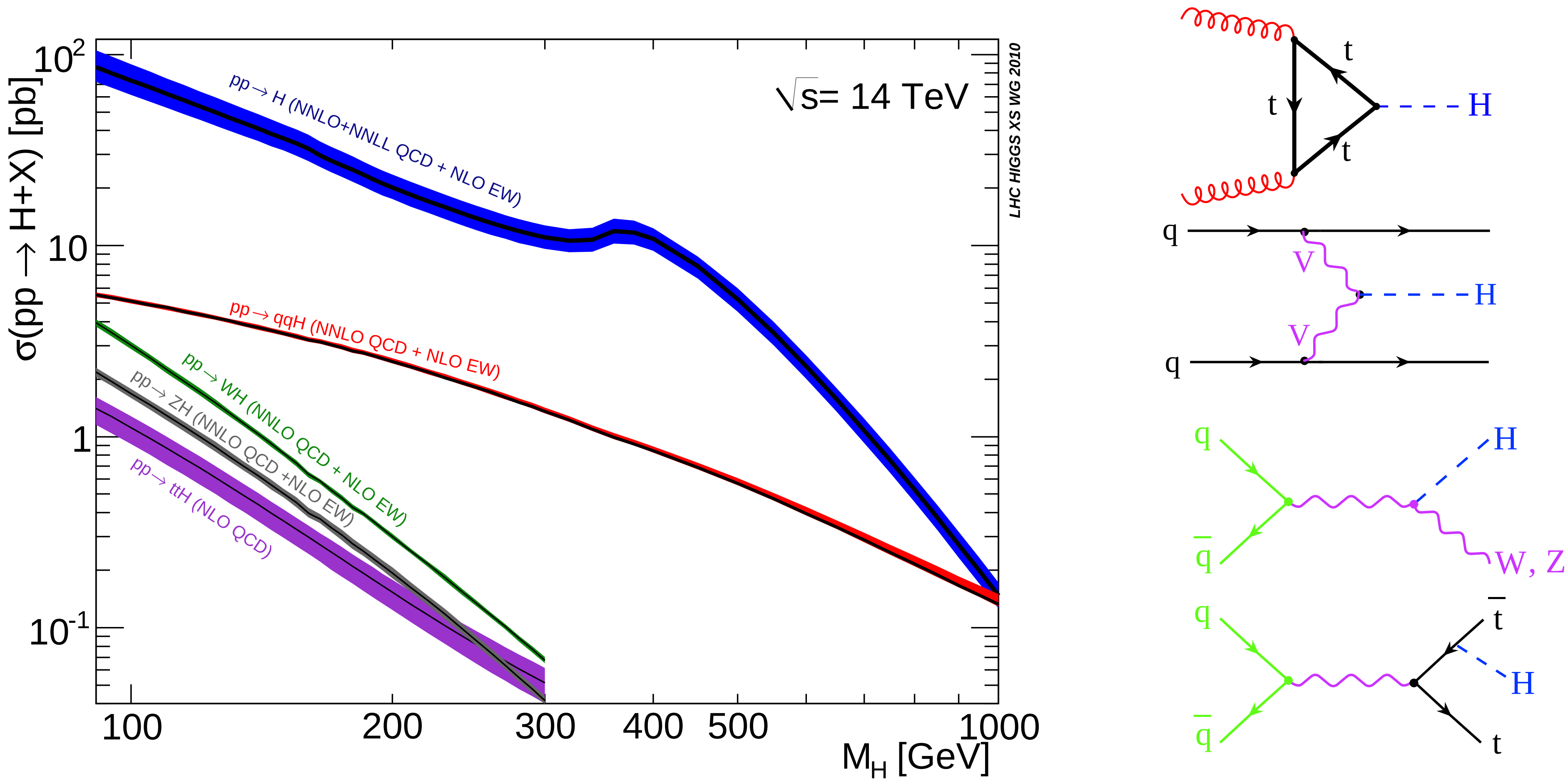
Total cross sections at the LHC





Gluon fusion cross section for $m_h = 125$ GeV at 8 TeV: $\sigma(gg \to h) = 21.4$ pb at N^{3}LO

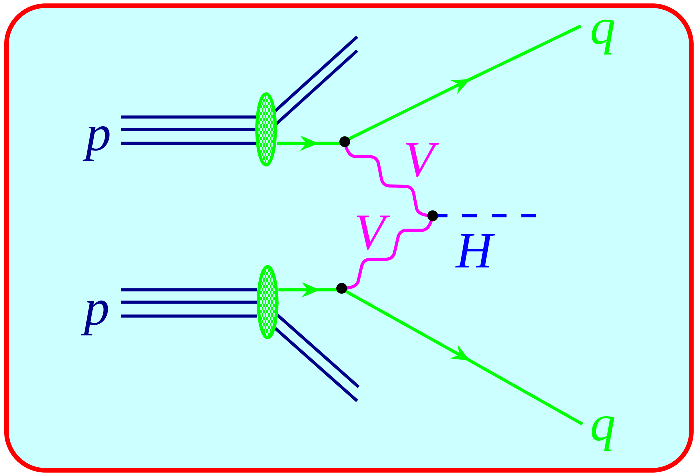
Total cross sections at the LHC

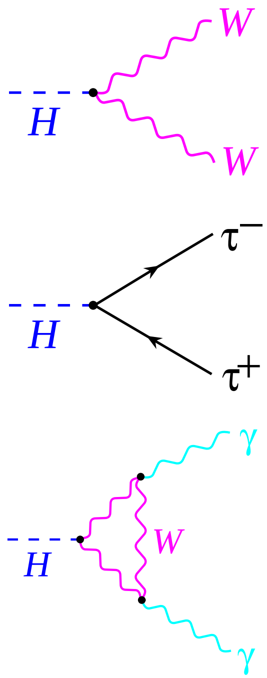


Gluon fusion cross section for $m_h = 125$ GeV at 13 TeV: $\sigma(gg \to h) = 48.6$ pb at N^{3}LO

Gluon fusion cross section for $m_h = 125$ GeV at 14 TeV: $\sigma(gg \to h) = 54.7$ pb at N^{3}LO

Vector Boson Fusion





$m_H > 120$ GeV

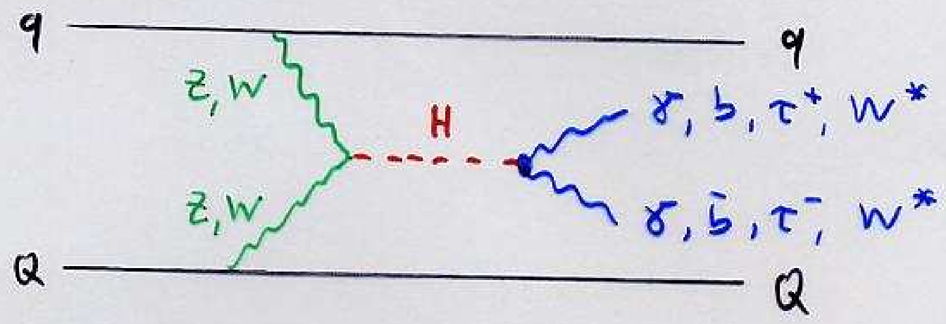
$m_H < 140$ GeV

$m_H < 150$ GeV

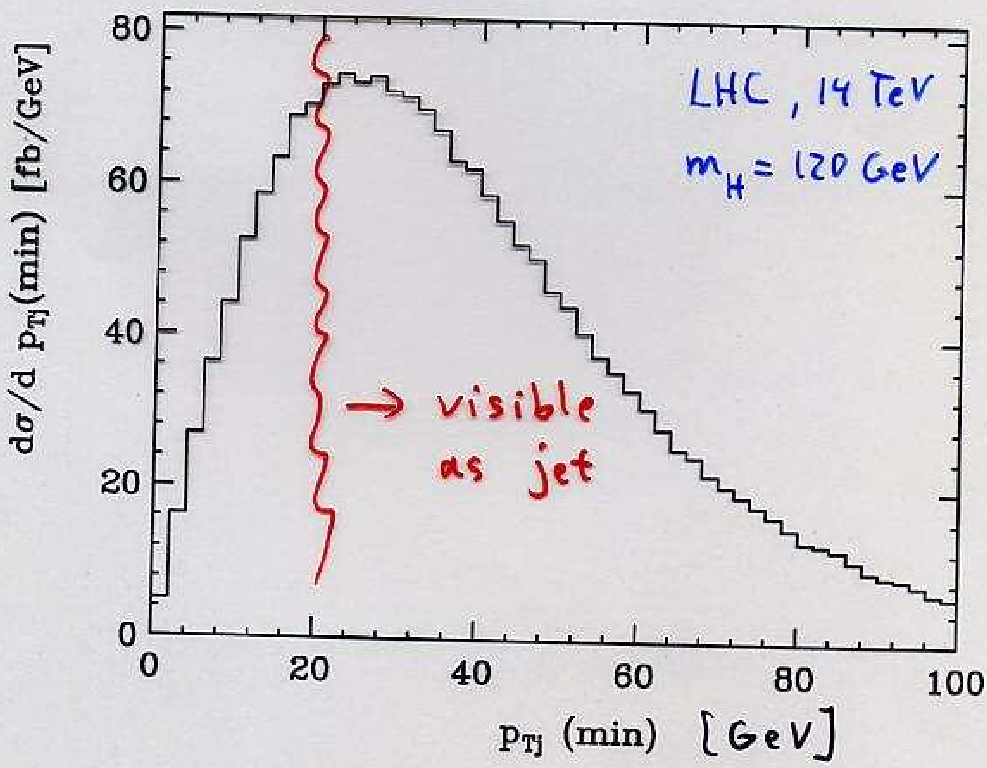
[Eboli, Hagiwara, Kauer, Plehn, Rainwater, D.Z. . . .]

Most measurements can be performed at the LHC with statistical accuracies on the measured cross sections times decay branching ratios, $\sigma \times$ BR, of order 10% (sometimes even better).

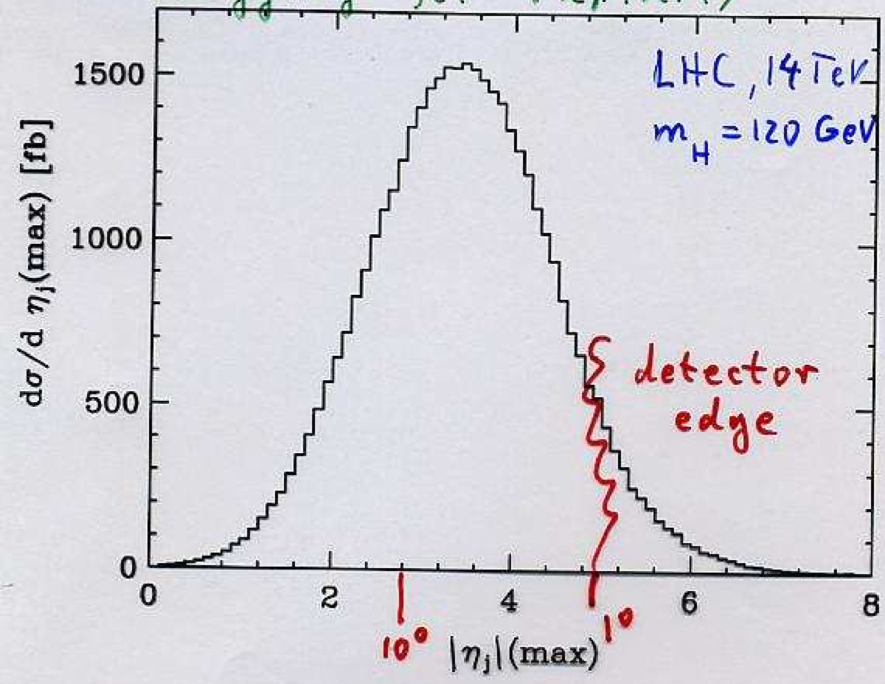
Characteristics of weak boson fusion



• scattered quarks lead to 2 forward tagging jets [Cahn, Kleiss, Stirlin



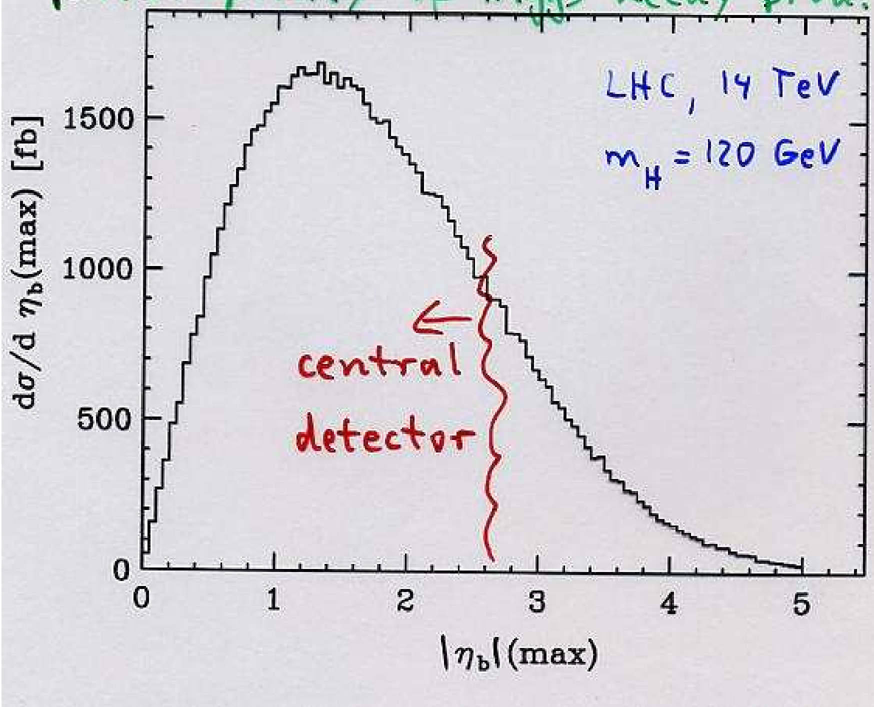
tagging jet rapidity



tagging je
forward bu
well inside
detector

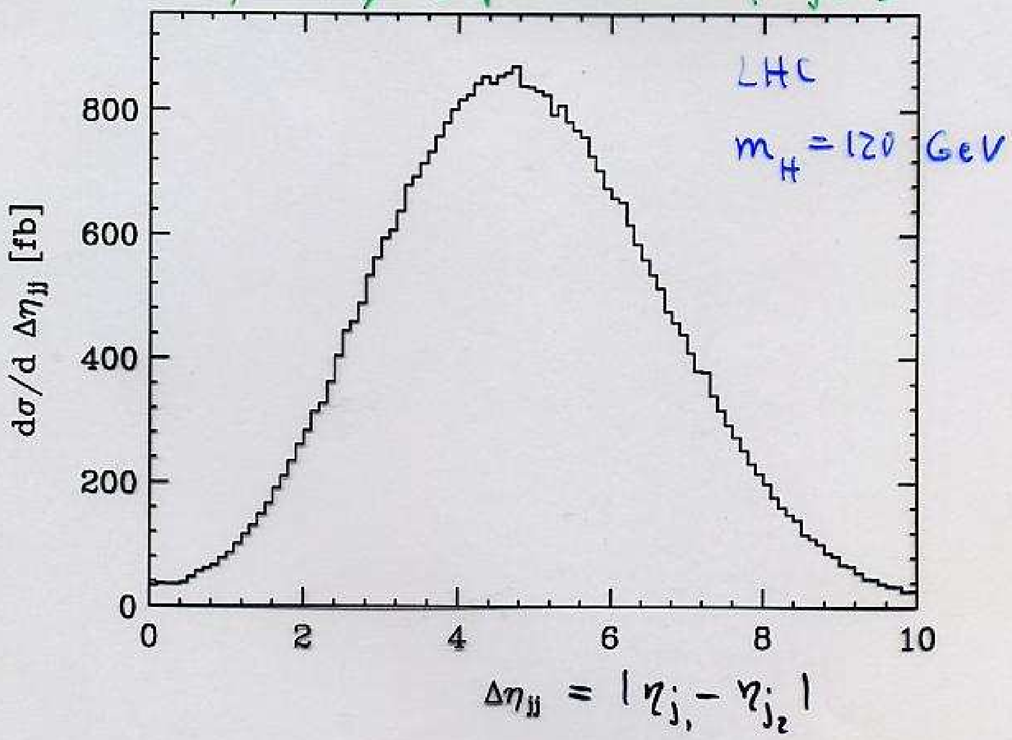
$\eta = \frac{1}{2} \ln \frac{1+\cos}{1-\cos}$

pseudorapidity of Higgs decay prod.



Higgs deca
products
are quite
central

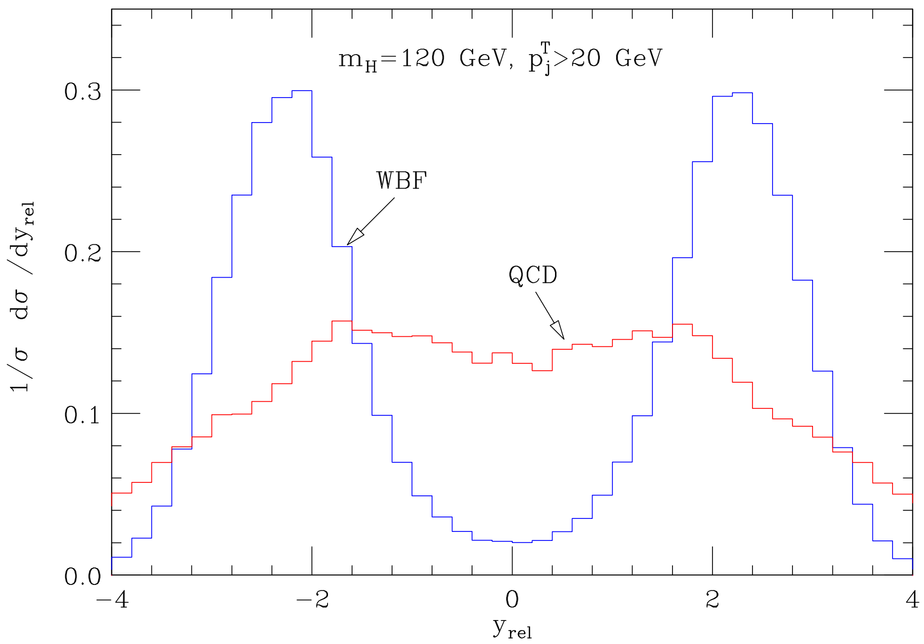
rapidity separation of jets

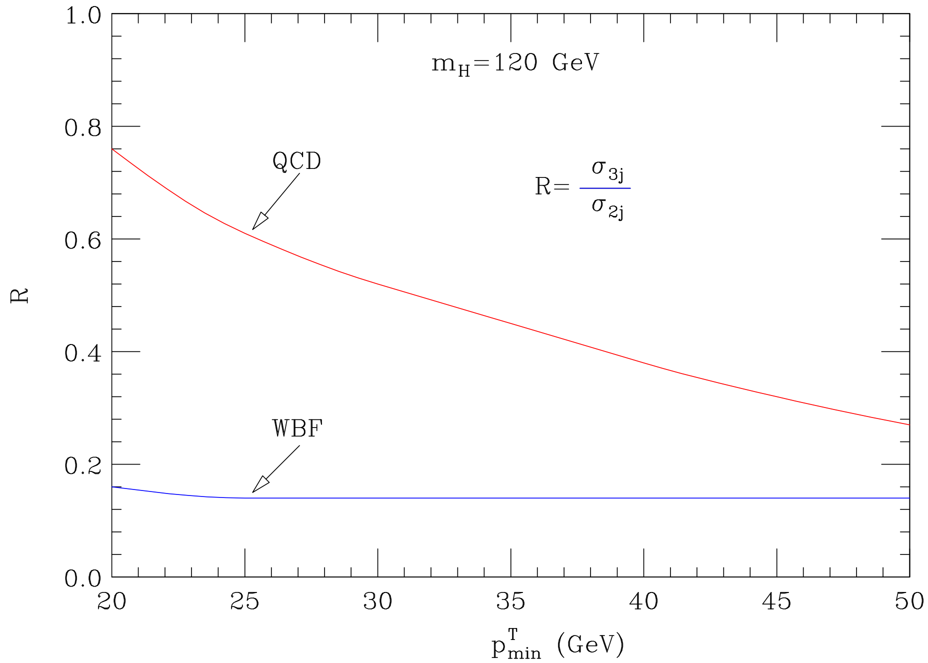


Tagging jets are typically far apart. Higgs decay products usually between 2 tagging jets

Central jet veto

Central Jet Veto: $Hjjj$ from VBF vs. gluon fusion

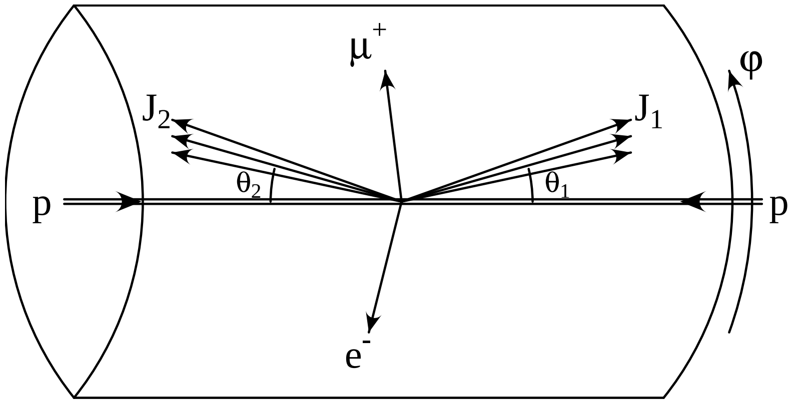


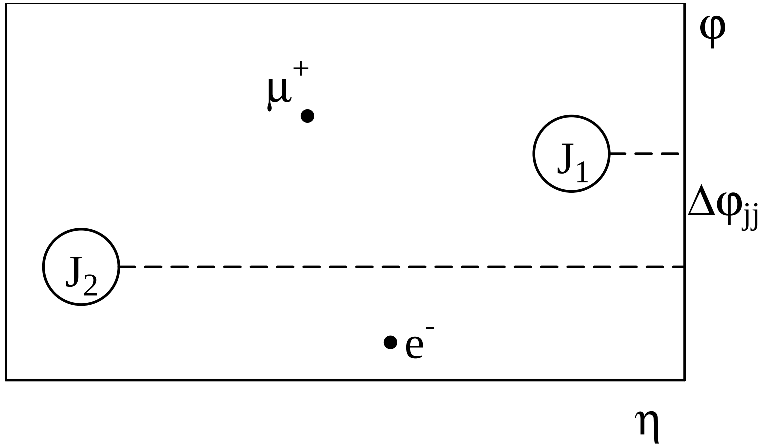


[Del Duca, Frizzo, Maltoni, JHEP 05 (2004) 064]

- Angular distribution of third (softest) jet follows classically expected radiation pattern
- QCD events have higher effective scale and thus produce harder radiation than VBF (larger three jet to two jet ratio for QCD events)
- Central jet veto can be used to distinguish Higgs production via GF from VBF

VBF signature





Characteristics:

- energetic jets in the forward and backward directions ($p_T > 20$ GeV)
- large rapidity separation and large invariant mass of the two tagging jets
- Higgs decay products between tagging jets
- Little gluon radiation in the central-rapidity region, due to colorless W/Z exchange (central jet veto: no extra jets with $p_T > 20$ GeV and $|\eta| < 2.5$)