Higgs signals at the LHC

- Production and decay channels

- The main search modes

  $gg \to H \to \gamma\gamma,\ ZZ,\ WW$

  $gg \to t\bar{t}H$

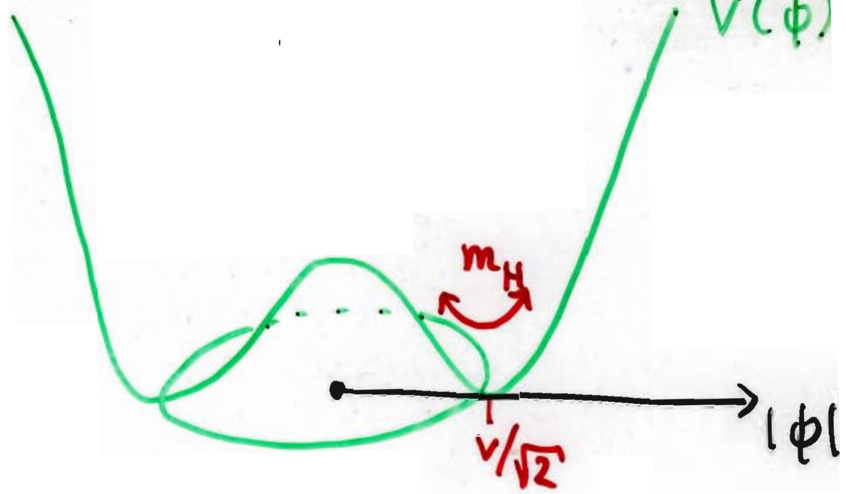
  weak boson fusion

- Measurement of couplings

Higgs mechanism

$$\phi = \begin{pmatrix} \varphi_1 \\ \varphi_2 \end{pmatrix}$$

$$\rightarrow \begin{pmatrix} 0 \\ \frac{v + H}{\sqrt{2}} \end{pmatrix}$$



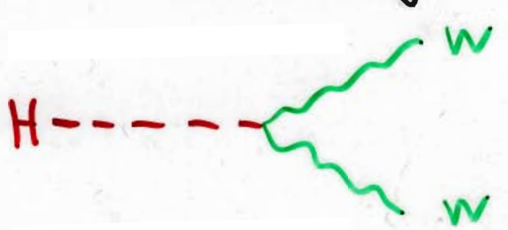
W & Z mass generation $D_\mu = \partial_\mu - i g W_\mu - \ldots$

$$(D_\mu \phi)^\dagger (D^\mu \phi) \rightarrow \frac{g^2}{4} (v + H)^2 \, W_\mu^+ W^{-\mu} + \ldots$$

W mass : v^2 term

$$m_W = \frac{g v}{2}$$

HWW coupling : $2vH$ term



$$\frac{g^2 v}{2} \, g^{\mu\nu}$$

Tree level HWW coupling is proof of spontaneous symmetry breaking by ϕ

Generation of fermion masses

Yukawa couplings

$$\mathcal{L}_Y = \lambda \bar{Q}_L \phi b_R + h.c.$$

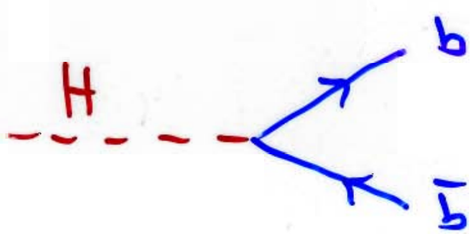
$$\to \lambda (\bar{t}_L, \bar{b}_L) \begin{pmatrix} 0 \\ \frac{v+H}{\sqrt{2}} \end{pmatrix} b_R + h.c.$$

$$= \left(1 + \frac{H}{v}\right) \frac{\lambda v}{\sqrt{2}} \bar{b}_L b_R + h.c.$$

$\Rightarrow$ mass for bottom quark (d, s)

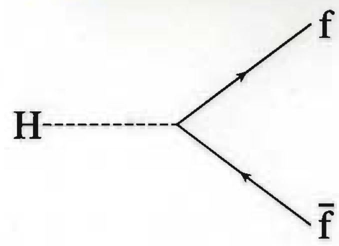
$$m_b = \frac{\lambda v}{\sqrt{2}}$$

and Hbb coupling

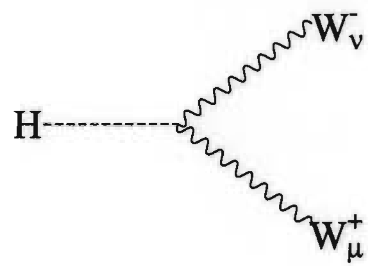


$$-i \frac{\lambda}{\sqrt{2}} = -i \frac{m_b}{v}$$

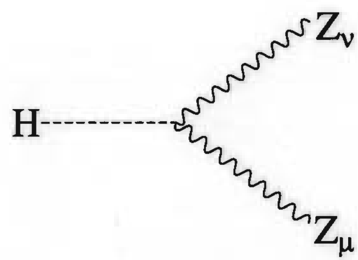
Feynman rules



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



$$i g\, m_W\, g_{\mu\nu}$$



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

Within the Standard Model, the Higgs couplings are almost completely constrained. The only free parameter (not yet measured) is the Higgs mass

$$m_H^2 = 2\lambda v^2$$

Variations : 2 Higgs doublets (SUSY)

top quark mass (and m_c, m_u)

$$\lambda_t \bar{Q}_L \phi_1 t_R \rightarrow \lambda_t \bar{Q}_L \begin{pmatrix} \frac{v_1 + H_1}{\sqrt{2}} \\ \varphi_1^- \end{pmatrix} t_R$$

bottom quark mass (and m_τ, m_s etc.)

$$\lambda_b \bar{Q}_L \phi_2 b_R \rightarrow \lambda_b \bar{Q}_L \begin{pmatrix} \varphi_2^+ \\ \frac{v_2 + H_2}{\sqrt{2}} \end{pmatrix} b_R$$

decouples mass generation for top vs. b, τ

$$m_W = \frac{g}{2}\sqrt{v_1^2 + v_2^2} = \frac{gv}{2}$$

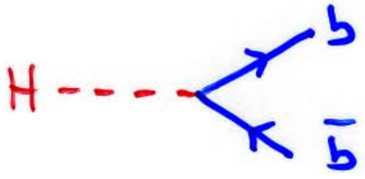
$$\frac{v_1}{v_2} = \tan\beta$$

Yukawa couplings

$$\lambda_\tau \sim \frac{m_\tau}{v_2} = \frac{m_\tau}{v\cos\beta} \qquad \lambda_t \sim \frac{m_t}{v\sin\beta}$$

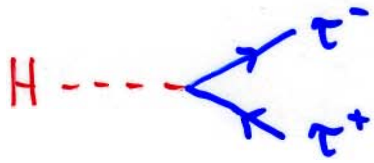
Main Higgs decay channels

$H \to b\bar{b}$



$m_H \lesssim 150$ GeV

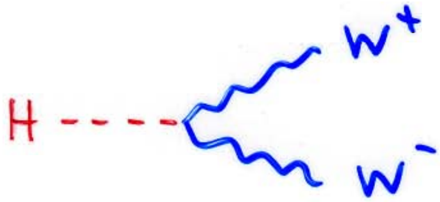
$H \to \tau^+\tau^-$



$m_H \lesssim 140$ GeV

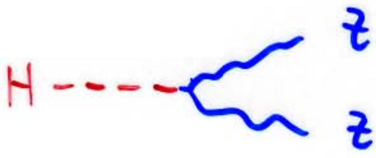
and into gauge bosons

$H \to W^+W^-$



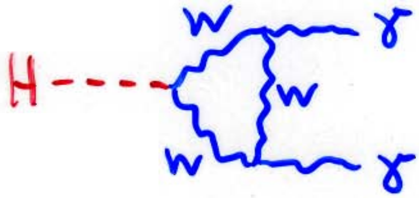
$m_H \gtrsim 120$ GeV

$H \to ZZ$



$m_H \gtrsim 120/180$ GeV

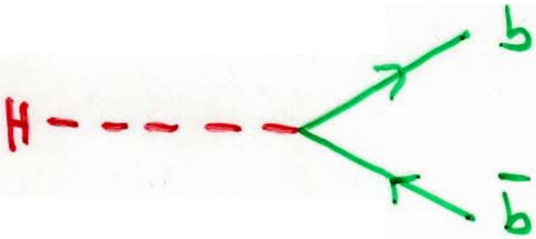
$H \to \gamma\gamma$



$m_H \lesssim 150$ GeV

Higgs decays

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



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

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

QCD radiative corrections are important

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

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

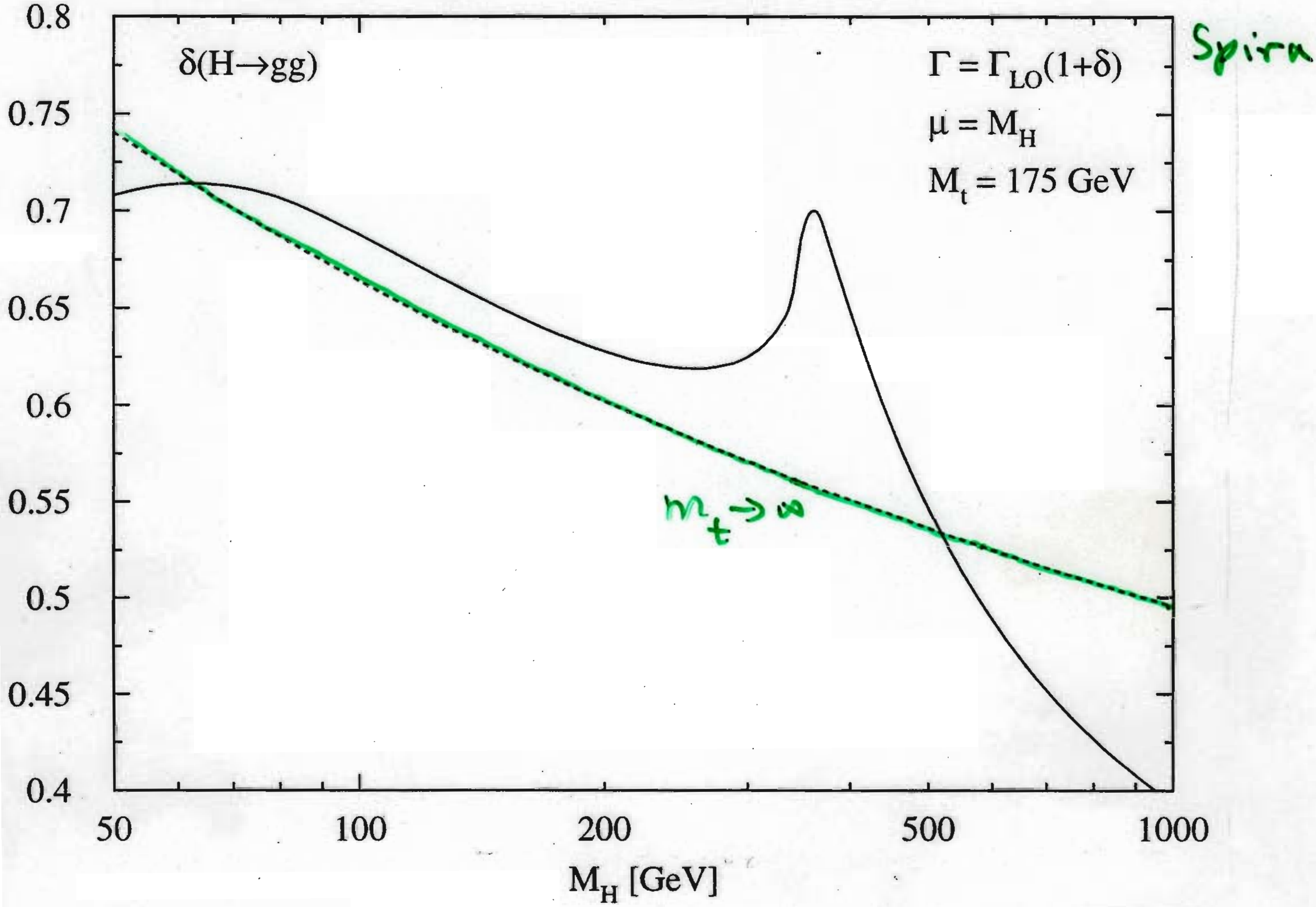
- include 2 loop QCD corrections

f	m_f	$m_f(100\,\text{GeV})$
b	4.7 GeV	2.92 GeV
c	1.2 GeV	0.62 GeV
τ	1.8 GeV	1.8 GeV

$\}$ $\Gamma(H \to c\bar{c}) < \Gamma(H \to \tau\bar{\tau})$

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

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

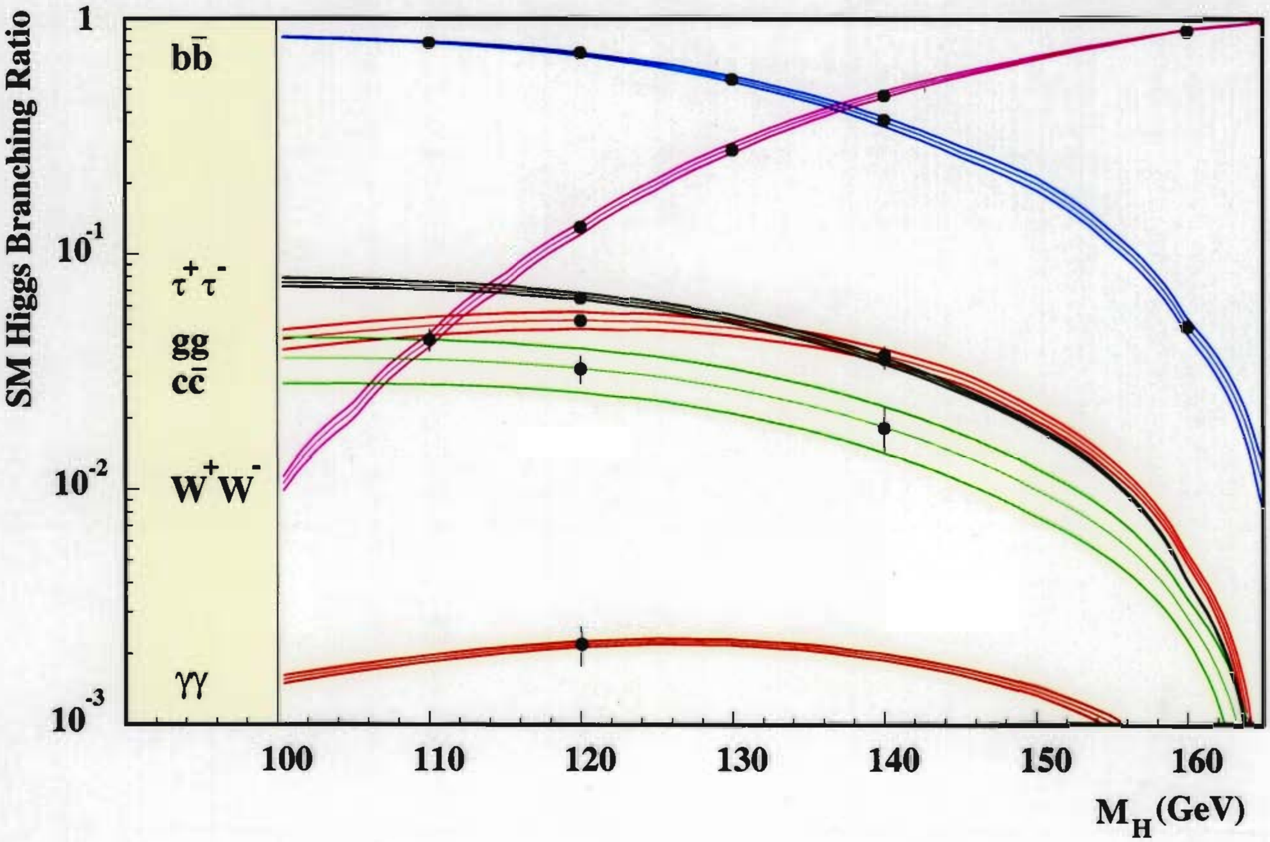


Radiative corrections for various decay modes implemented in HDECAY

Djouadi, Kalinowski, Spira, hep-ph/9704448

Continuously updated for SM & MSSM

Present theoretical accuracy



Example: $M_H = 120$ GeV

Decay mode:	$b\bar{b}$	WW^*	$\tau^+\tau^-$	$c\bar{c}$	gg	$\gamma\gamma$
Theory	1.4%	2.3%	2.3%	23%	5.7%	2.3%

Mainly due to: pole masses m_c and m_b, and $\alpha_s(\mu)$.

From HDECAY when (Carena et al., hep-ph/0106116):

$$\alpha_s(M_Z) = 0.1185 \pm 0.0020$$
$$m_c(m_c) = 1.23 \pm 0.09 \text{ GeV}$$
$$m_b(m_b) = 4.17 \pm 0.05 \text{ GeV}$$

Higgs decay width and branching fractions in the SM

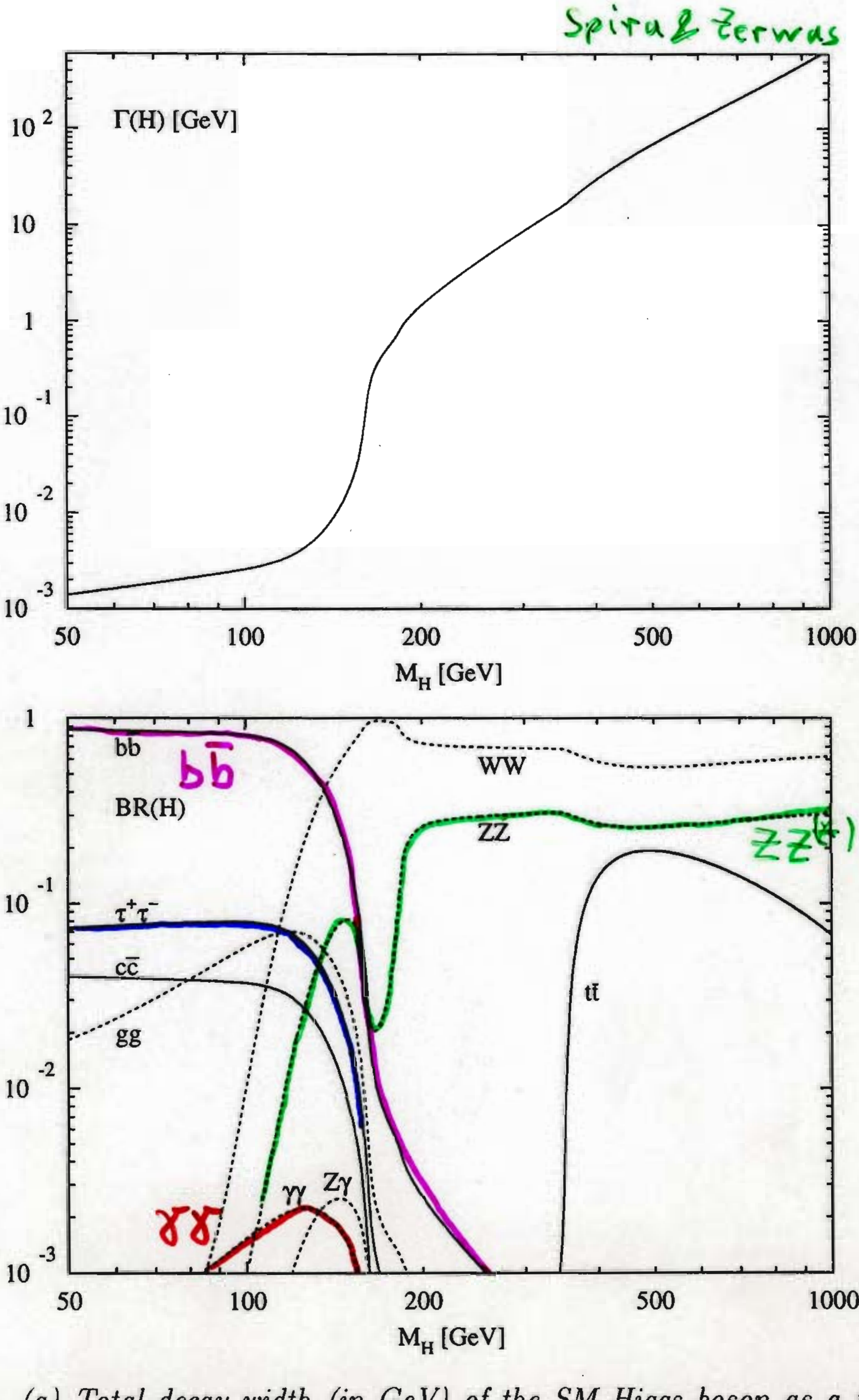
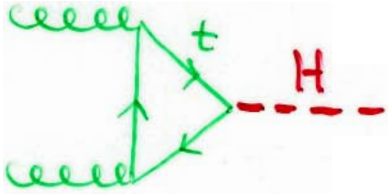


Figure 5: *(a) Total decay width (in GeV) of the SM Higgs boson as a function of its mass. (b) Branching ratios of the dominant decay modes of the SM Higgs particle. All relevant higher-order corrections are taken into account.*

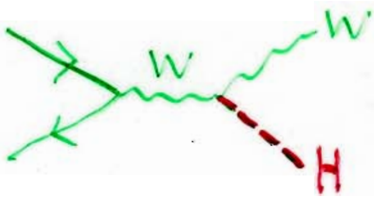
Principal production modes at hadron colliders

gluon fusion



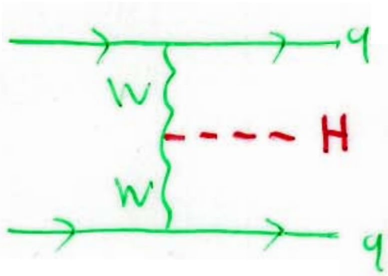
Tevatron LHC

WH/ZH production



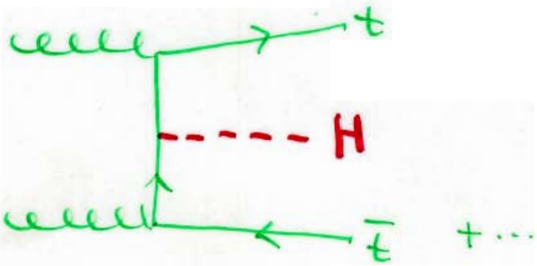
Tevatron

weak boson fusion



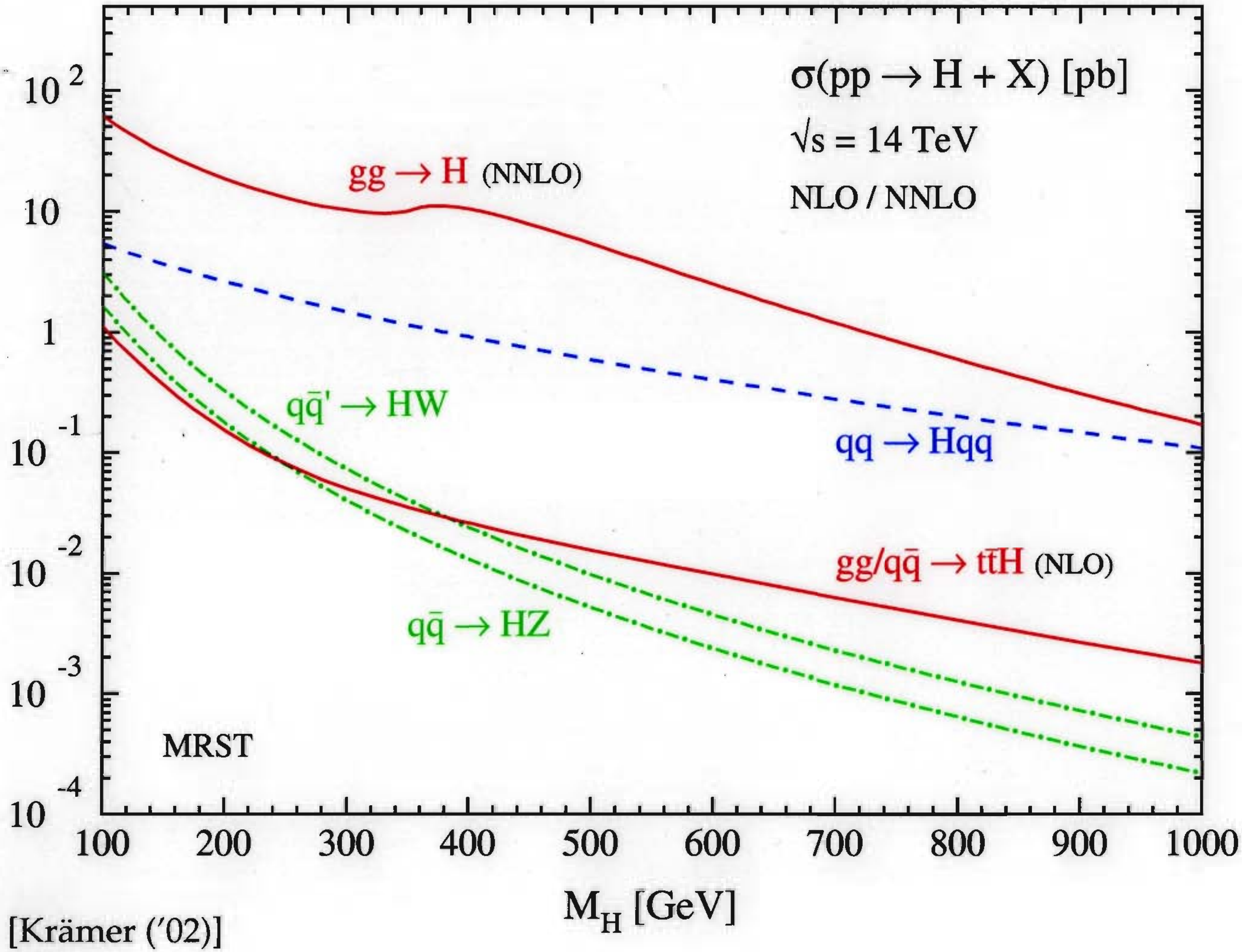
LHC

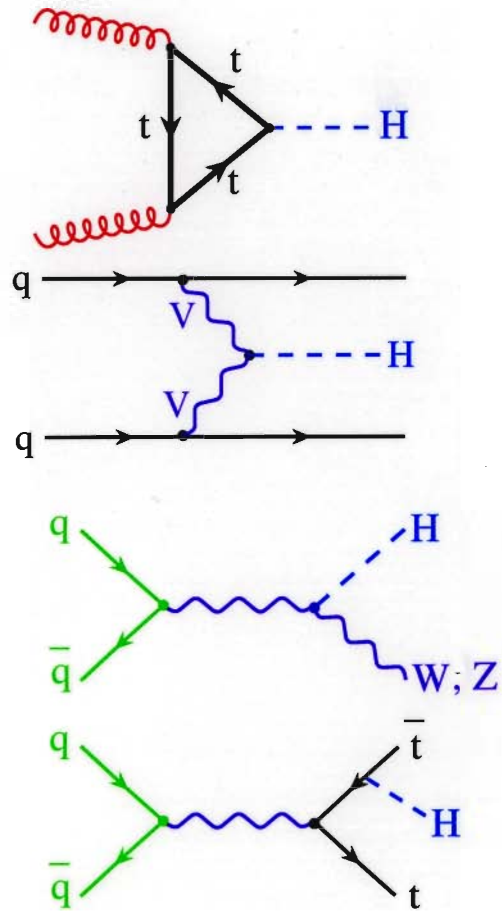
$t\bar{t}H$ production



LHC

Total cross sections at the LHC





[Krämer ('02)]

(12)

Traditional search channels are dominated by gluon fusion

- inclusive search for

  $H \to \gamma\gamma$ $\qquad$ ($m_H \lesssim 150$ GeV)

  invariant mass peak

- search for

  $H \to ZZ^* \to e^+e^-e^+e^-$

  for $m_H \gtrsim 130$ GeV , $m_H \not\approx 160$ GeV

- inclusive search for

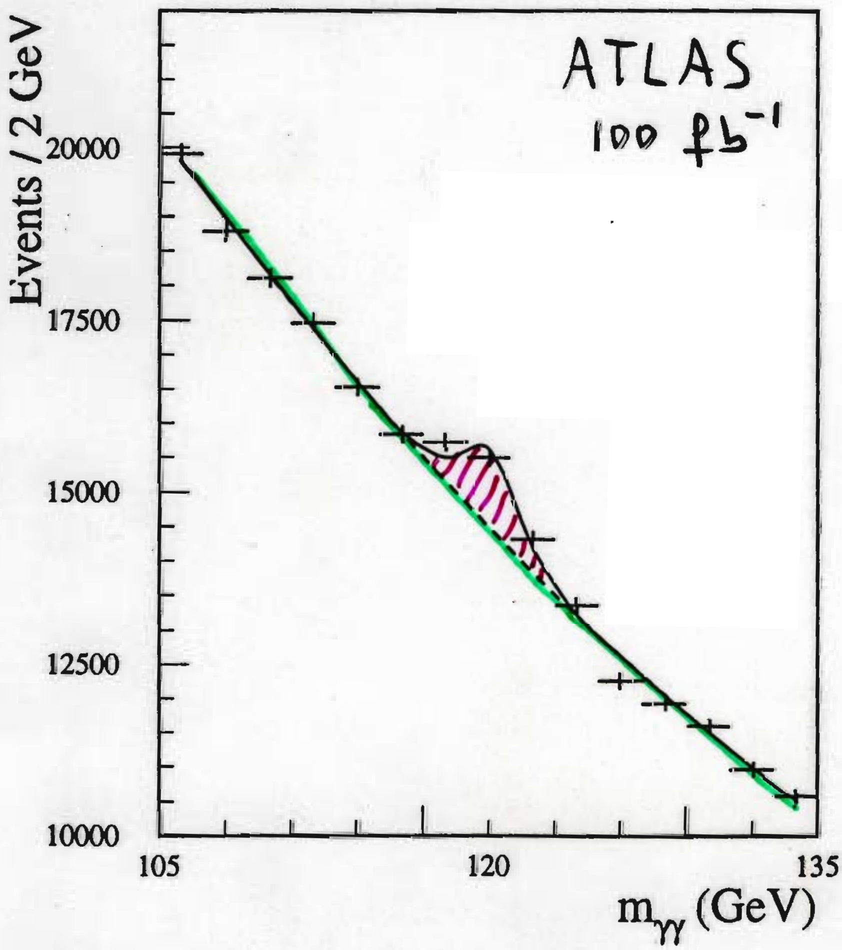
  $H \to W^+W^- \to \ell^+\nu\, \ell^-\bar{\nu}$

  for $140 \text{ GeV} \lesssim m_H \lesssim 200$ GeV

$H \to \gamma\gamma$

CMS and ATLAS will have excellent photon energy resolution (order 1%)

- Look for narrow $\gamma\gamma$ invariant mass peak
- Large backgrounds from
  - $q\bar{q} \to \gamma\gamma$
  - $gg \to \gamma\gamma$
  - isolated bremsstr.



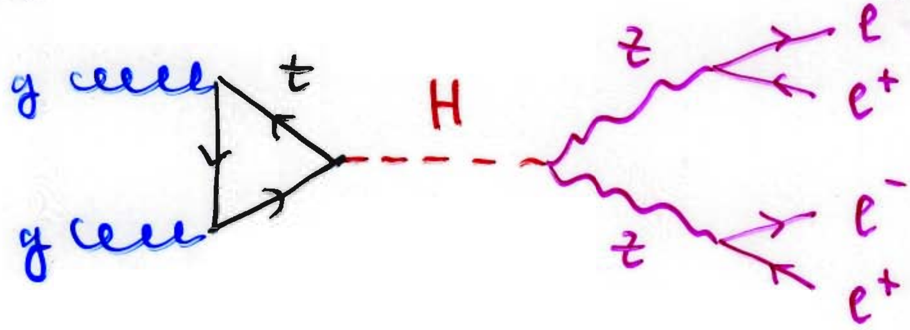
Expected spectrum for 100 fb^{-1} of data with the ATLAS detector

Resolution of CMS is somewhat better

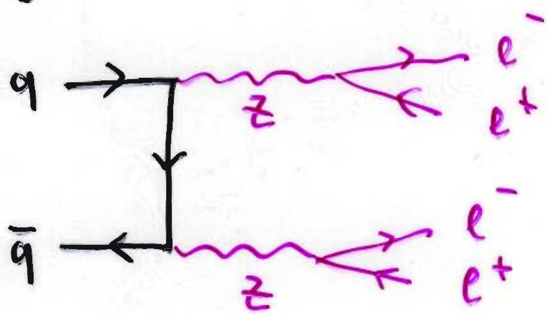
100 fb^{-1} expected after ~ 4 years

The gold plated mode: $H \to ZZ \to 4\ell$

Signal:



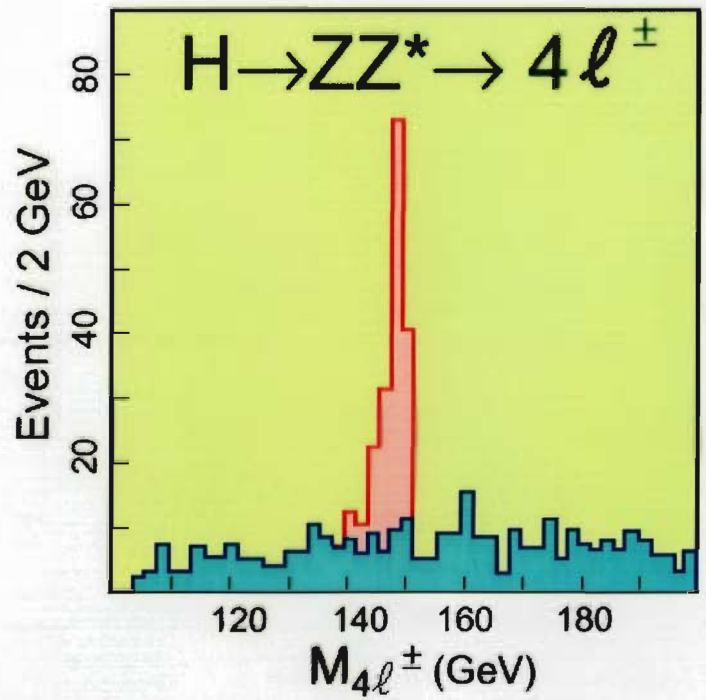
background: mainly ZZ

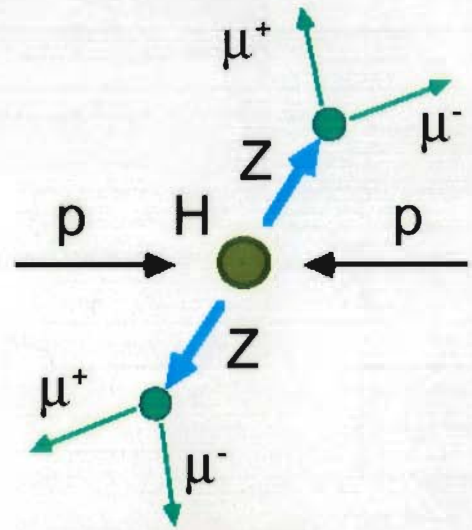


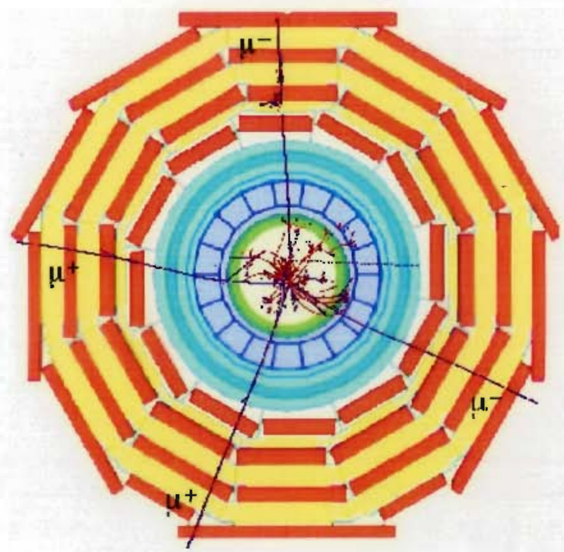
This is the most important search mode for $2m_Z < m_H \lesssim 600$ GeV

Intermediate Mass Higgs

- $H \rightarrow ZZ \rightarrow \ell^+\ell^- \ell^+\ell^-$ (ℓ = e, μ)
  - Very clean
    - Resolution: better than 1 GeV
    - Valid for the mass range $130 < M_H < 500\ GeV/c^2$







For larger m_H, mass reach can be extended by looking for

$$H \to ZZ \to \nu\bar{\nu}\,\ell^+\ell^- \qquad (\ell = e, \mu)$$

$$B(H \to \nu\bar{\nu}\ell\ell) = 6\,B(H \to \ell\ell\ell\ell) \approx 6 * 0.15\,\%$$

$\Rightarrow$ search possible up to $m_H = 0.8 - 1\,\text{TeV}$

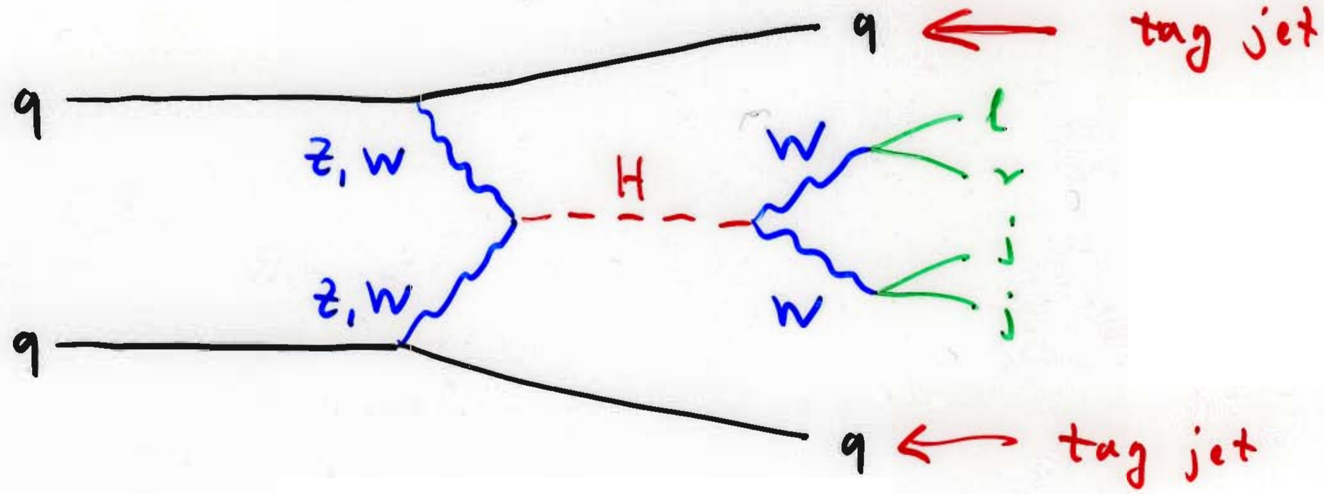
More challenging experimentally but higher rate

$$H \to WW \to \ell\nu jj$$

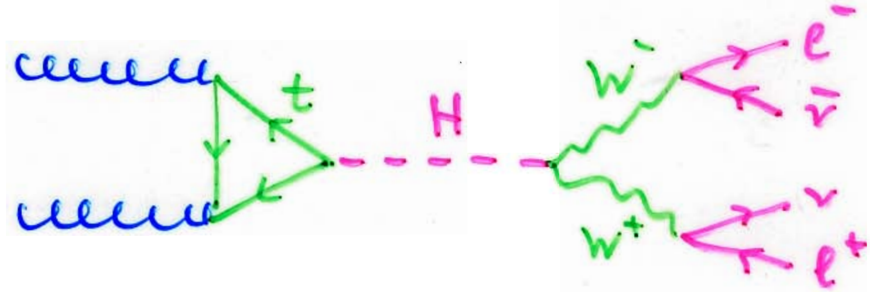
$$B(H \to \ell\nu jj) \approx 20\,\%$$

This mode is good for studying weak boson scattering in general. Make use of

- forward jet tagging of q-jets in

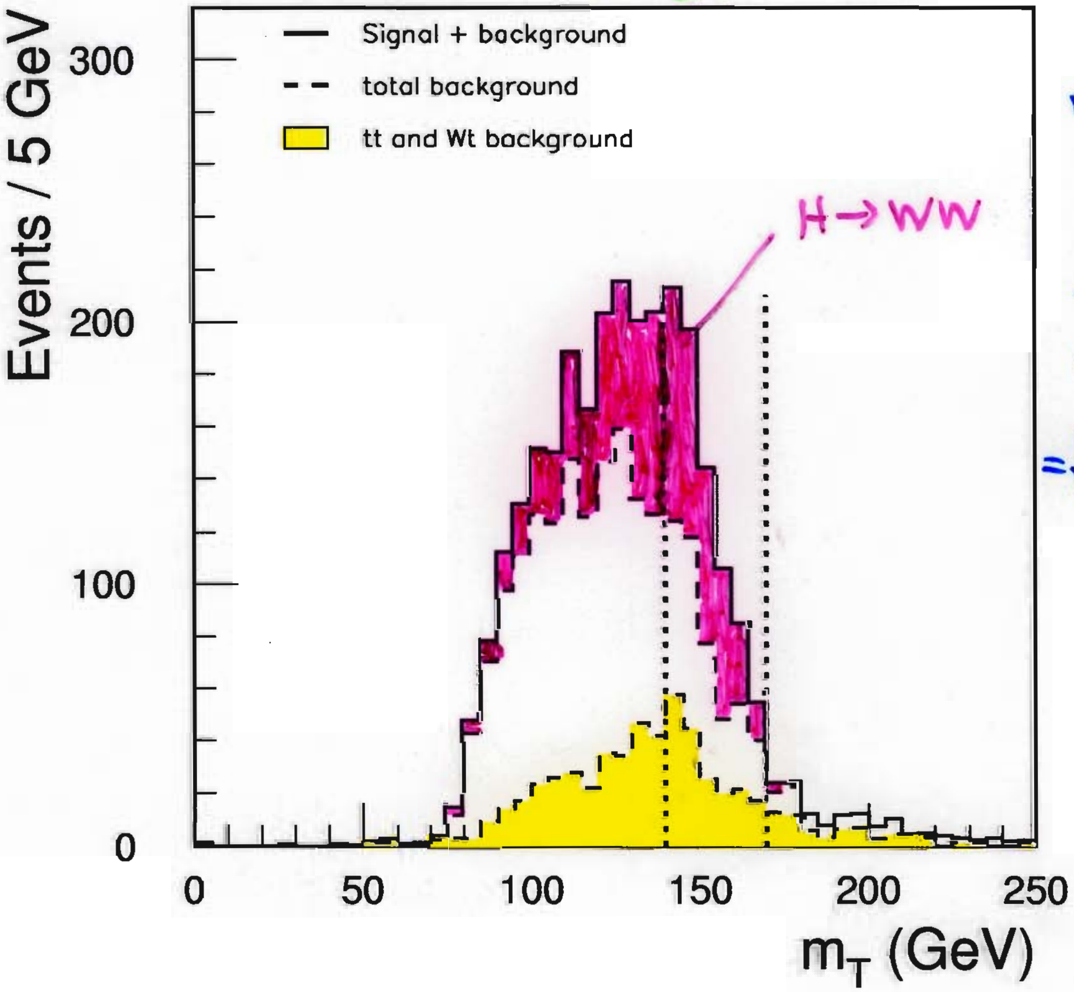


$H \to WW \to e^+e^-\nu\bar{\nu}$ (inclusive search)



Exploit e^+e^- angular correlations [Dittmar Dreiner]

ATLAS TDR



$m_H = 170$ GeV

transverse mass m_T

$= \sqrt{2 p_T^{\ell\ell} \not{E}_T (1-\cos\phi)}$

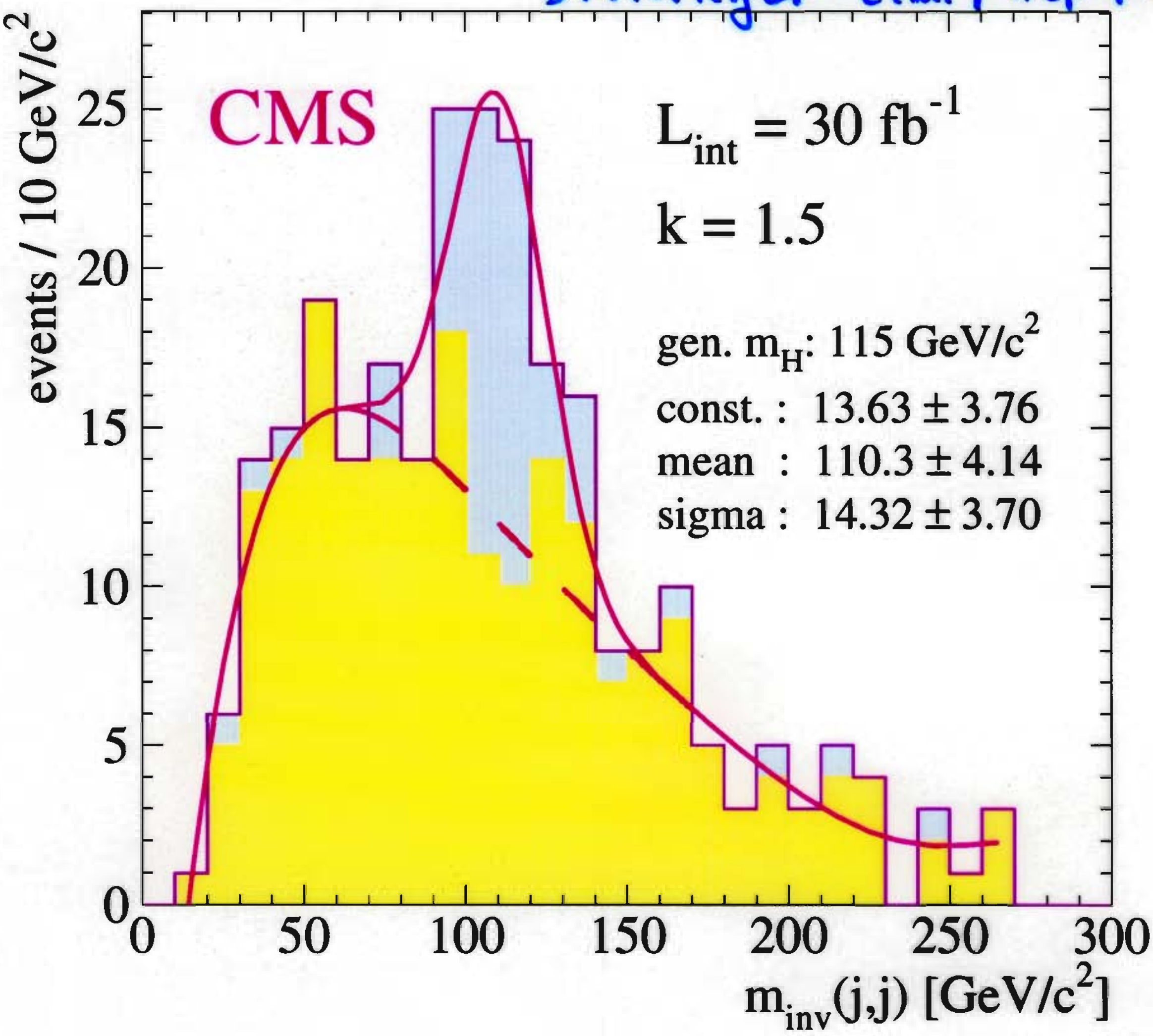
Background and signal have similar shape

$\Rightarrow$ must know bkgd normalization precisely

Important for $m_H \lesssim$ 120-130 GeV

$gg \to t\bar{t}H, \ H \to b\bar{b}$

Drollinger et al., hep-ph/0111312

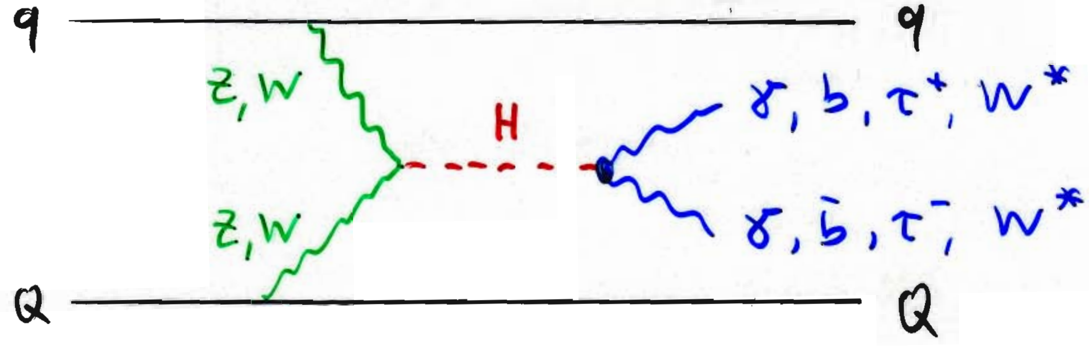


Y_t = $t\bar{t}H$ Yukawa coupling

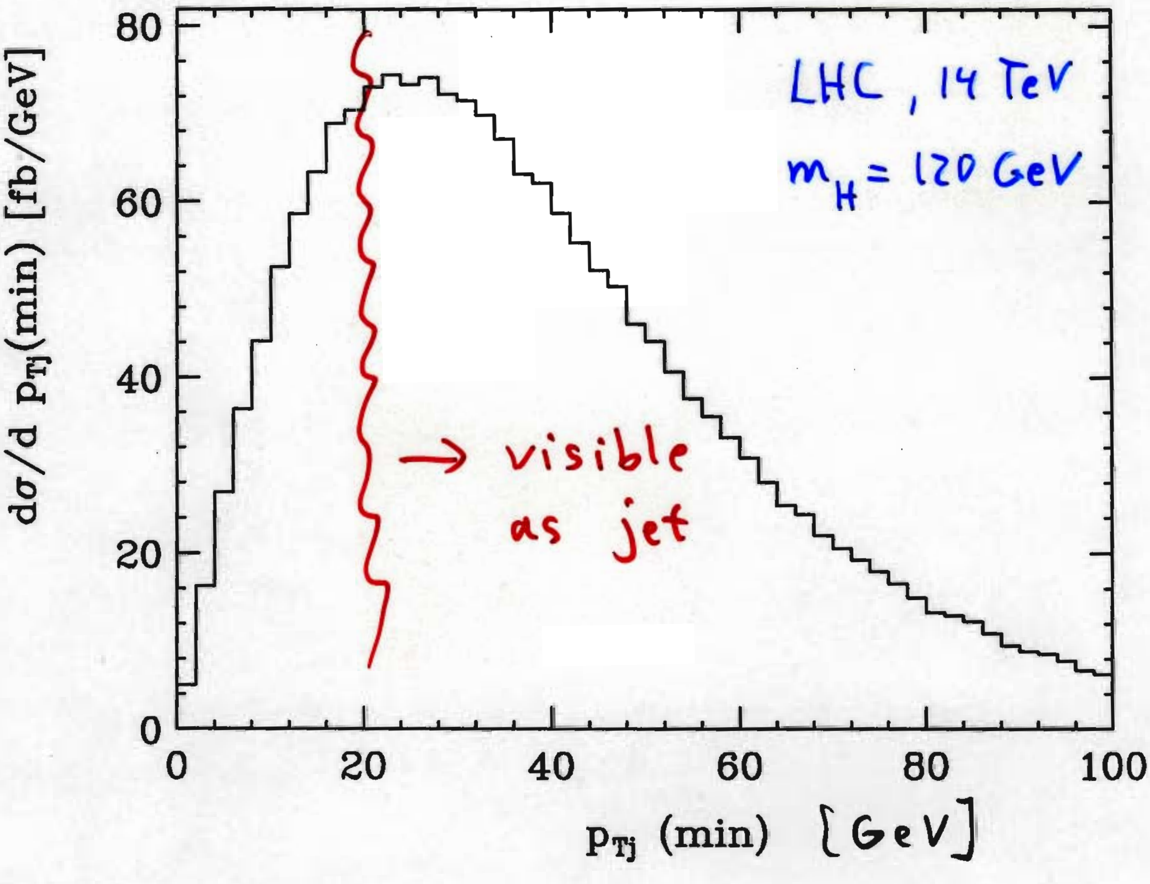
⇒ measure

$$Y_t^2 \, B(H \to b\bar{b})$$

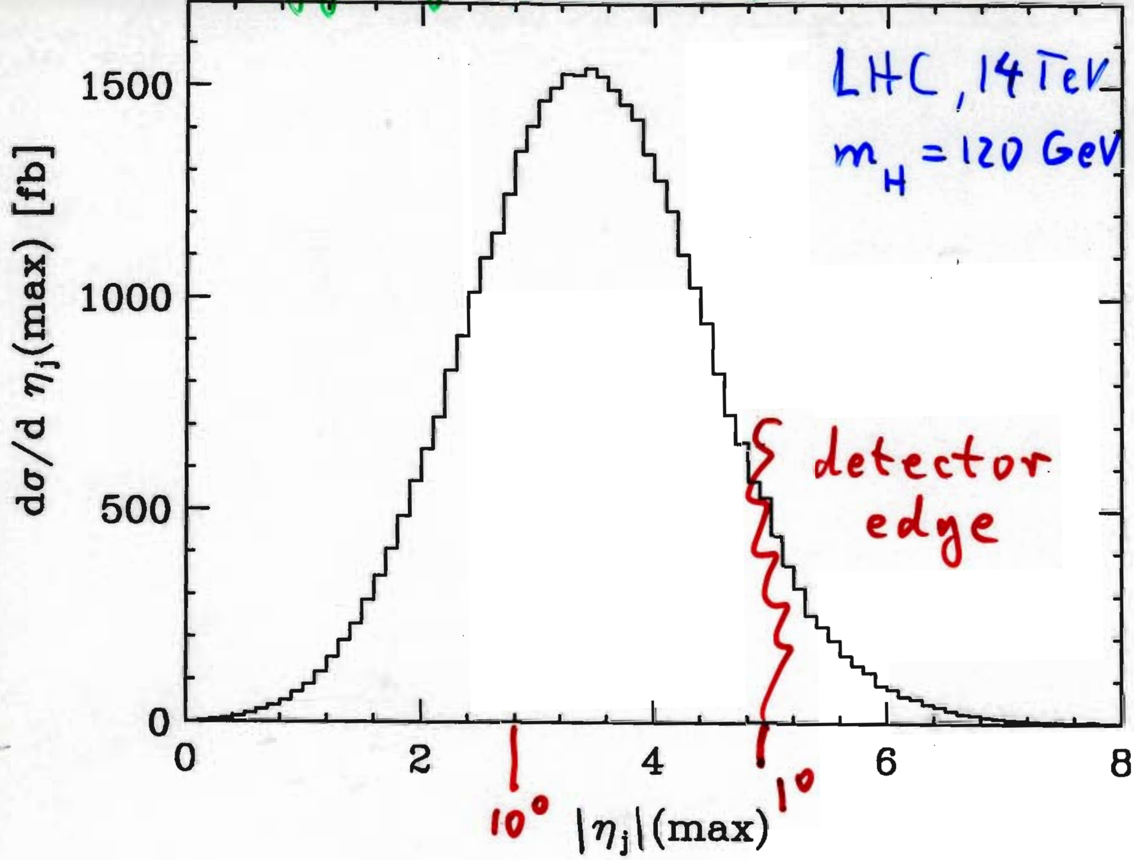
Characteristics of weak boson fusion



- scattered quarks lead to 2 forward tagging jets [Cahn, Kleiss, Stirling]



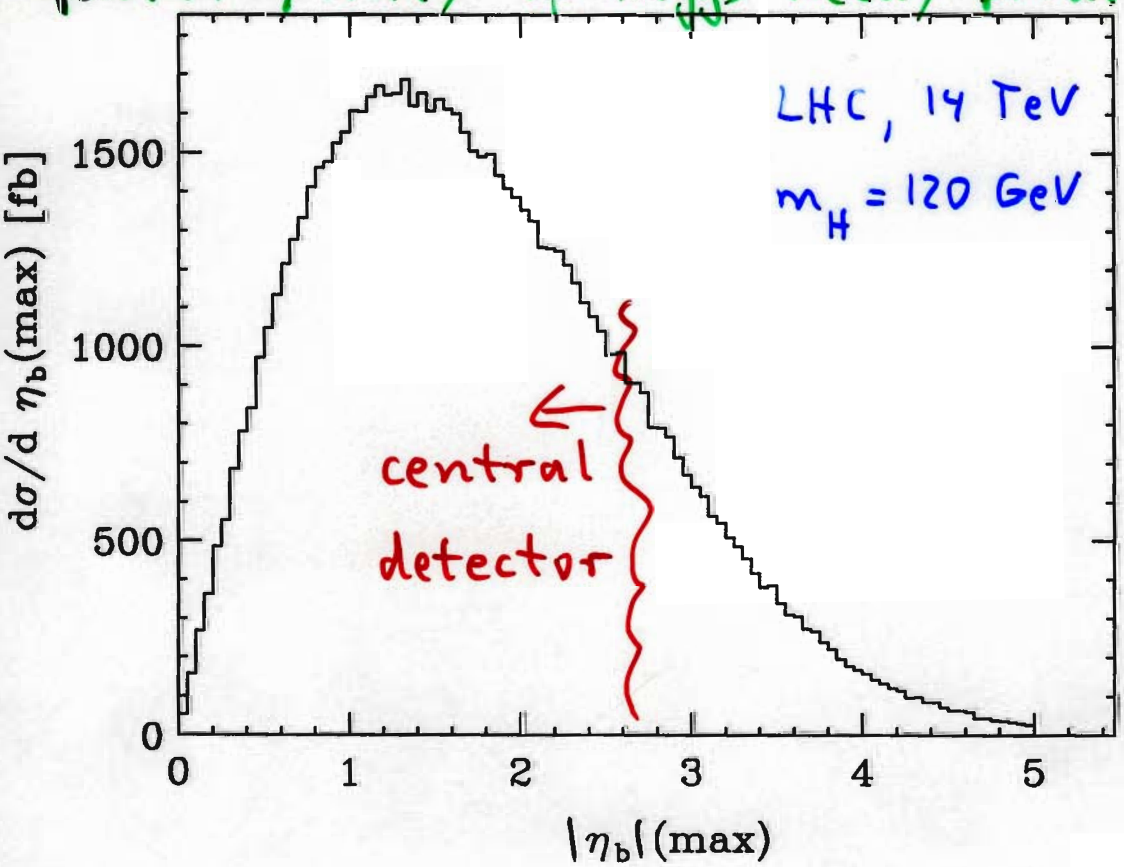
tagging jet rapidity



tagging jets forward but well inside detector

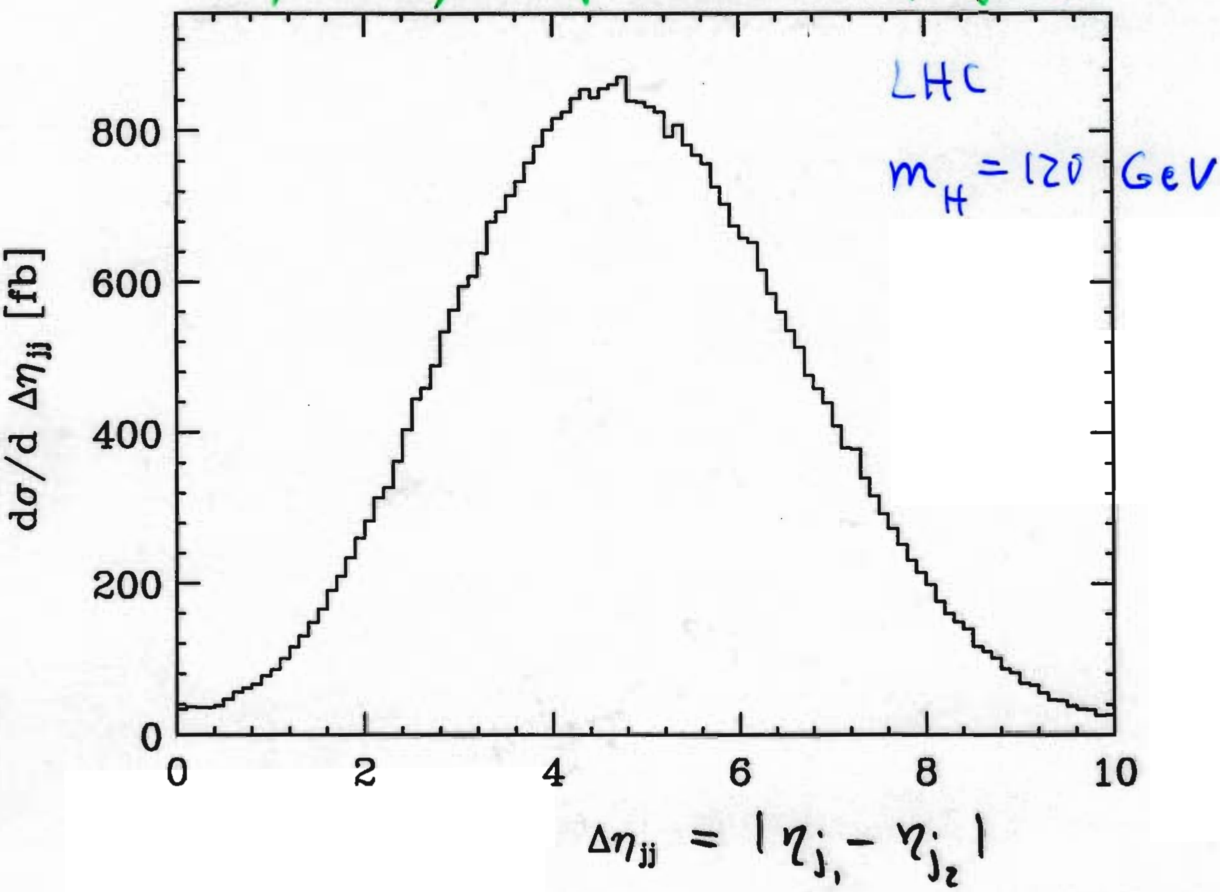
$$\eta = \frac{1}{2} \ln \frac{1+\cos\theta}{1-\cos\theta}$$

pseudorapidity of Higgs decay prod.



Higgs decay products are quite central

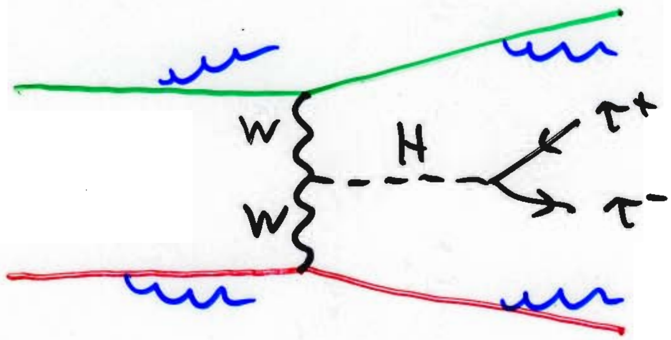
rapidity separation of jets



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

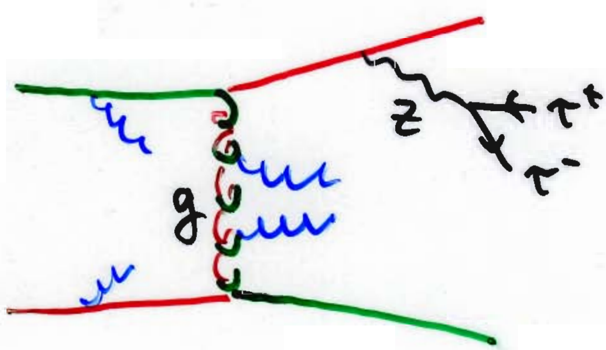
Gluon emission in WBF events

Color singlet exchange in t-channel
⟺ "synchrotron" radiation between
initial and final quark direction



⇒ central jets suppressed

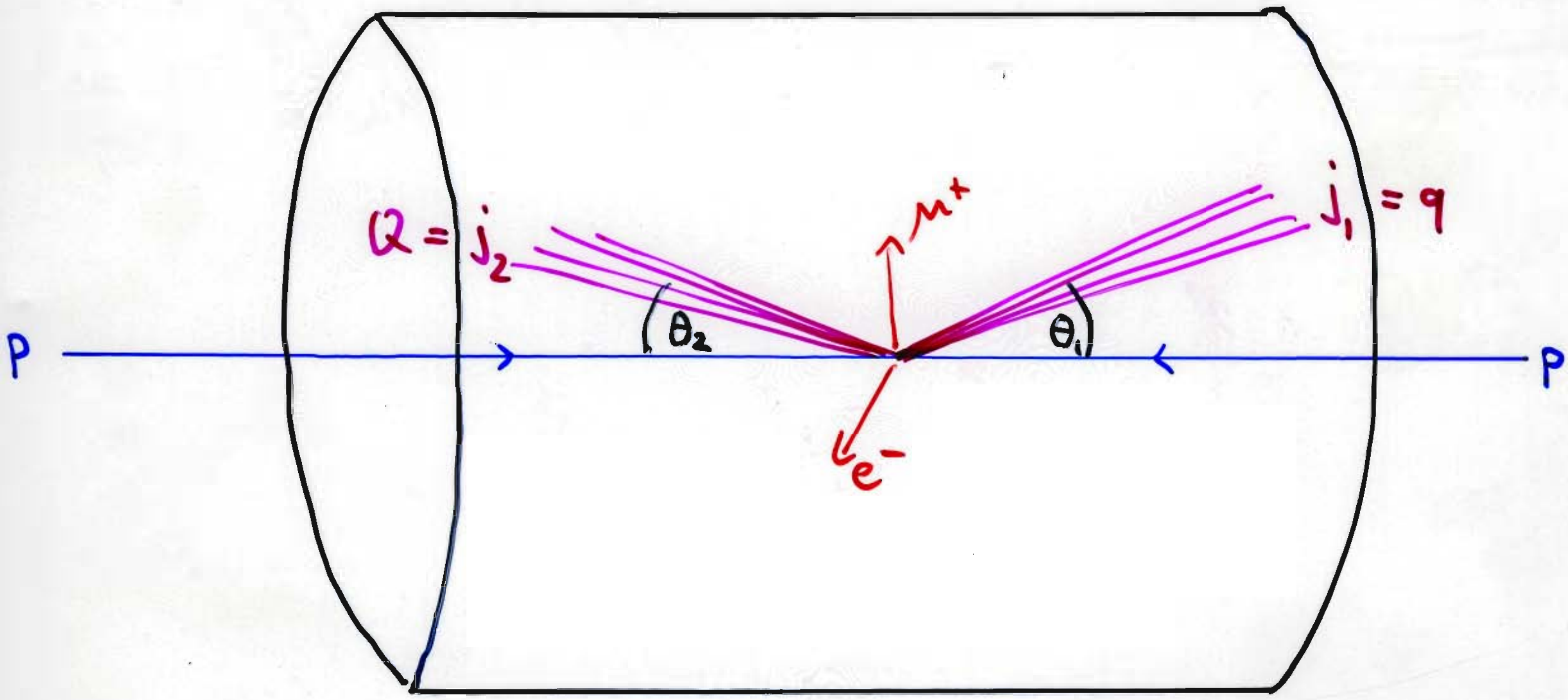
Major backgrounds: t-channel color exch



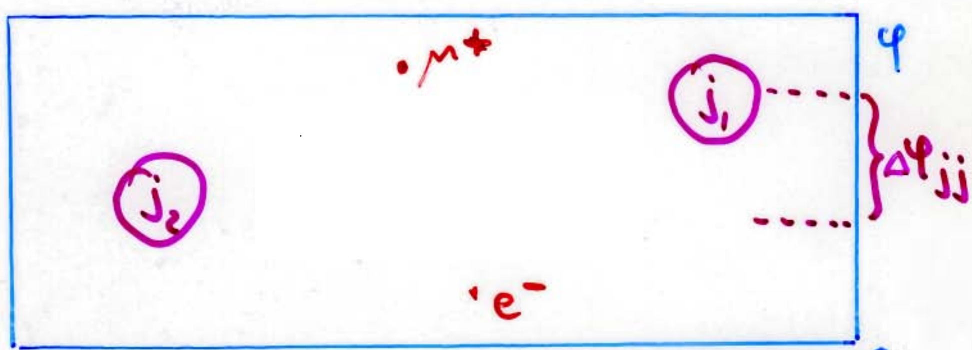
deflection of color charge by ~ 180°

⇒ central gluon emission

Generic picture of WBF event



Legoplot:



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

tagging jets $|\eta_{j_1} - \eta_{j_2}| > 4.2$

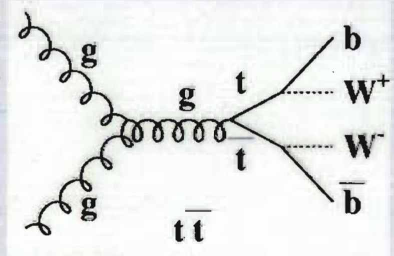
central jet veto: no extra $p_T > 20$ GeV jets between tag. jets

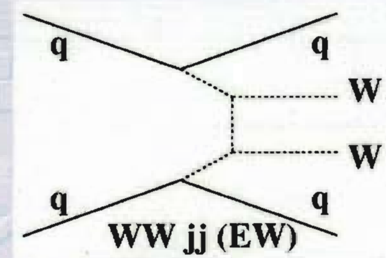
Weak Boson Fusion: H→WW

Cross section: 500 to 2000 fb for M_H = 120 to 190 GeV

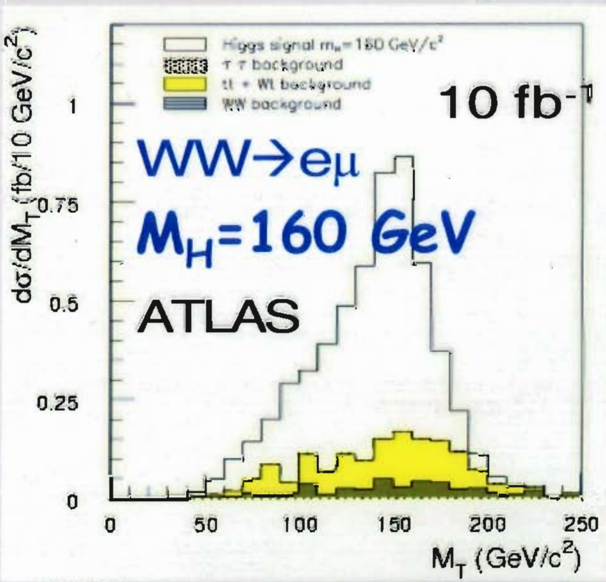
Dominant backgrounds

tt   WWjj,
W + 4 jets

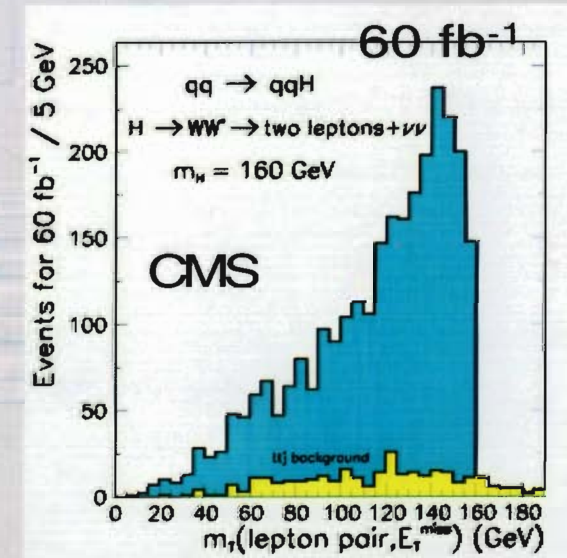




Selection: tag jets with rapididty gap, central jet veto, b-jet veto, m_{jj}, lepton angles (Spin 0←→1), transverse mass (llE$_T^{miss}$)



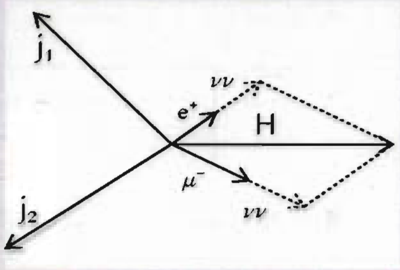
significance > 5
for 10 fb^{-1} and
M_H=135 to 190 GeV
(WW→llνν and lνjj,
incl. ΔBG = 10%)

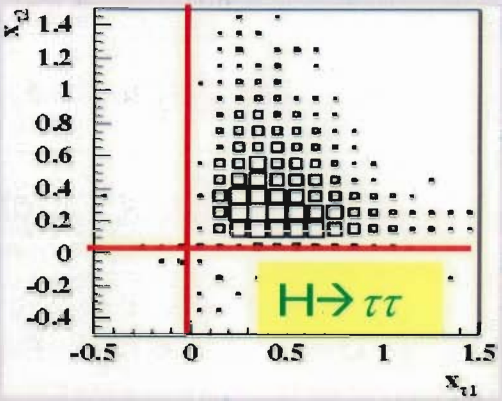


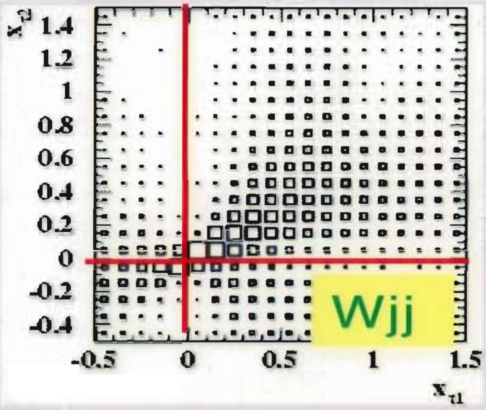
Weak Boson Fusion: $H \rightarrow \tau\tau$

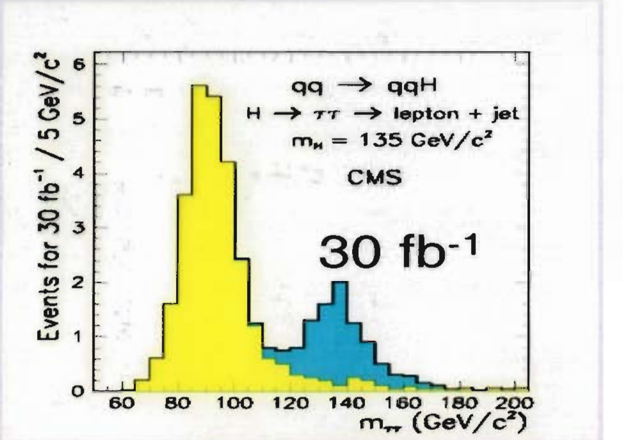
Mass can be reconstructed
in collinear approximation

x_τ = momentum fraction
carried by tau decay products

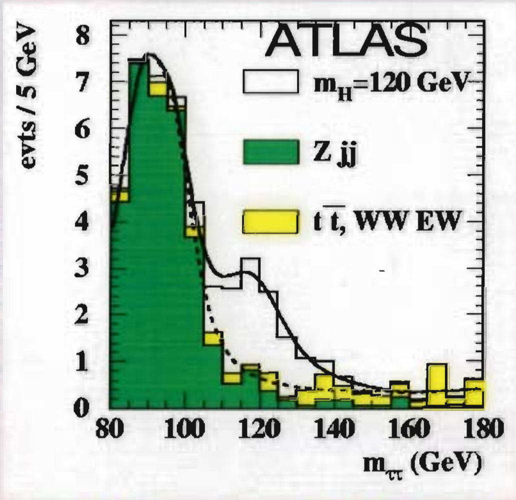








σ_M = 11 to 12 GeV



$H \rightarrow \tau\tau \rightarrow e\mu$ 30 fb^{-1}

★significance > 5 for 30 fb^{-1} and
M_H=110 to 140 GeV ($\tau\tau \rightarrow e\mu$, $\tau\tau \rightarrow ll$, $\tau\tau \rightarrow l$ had)

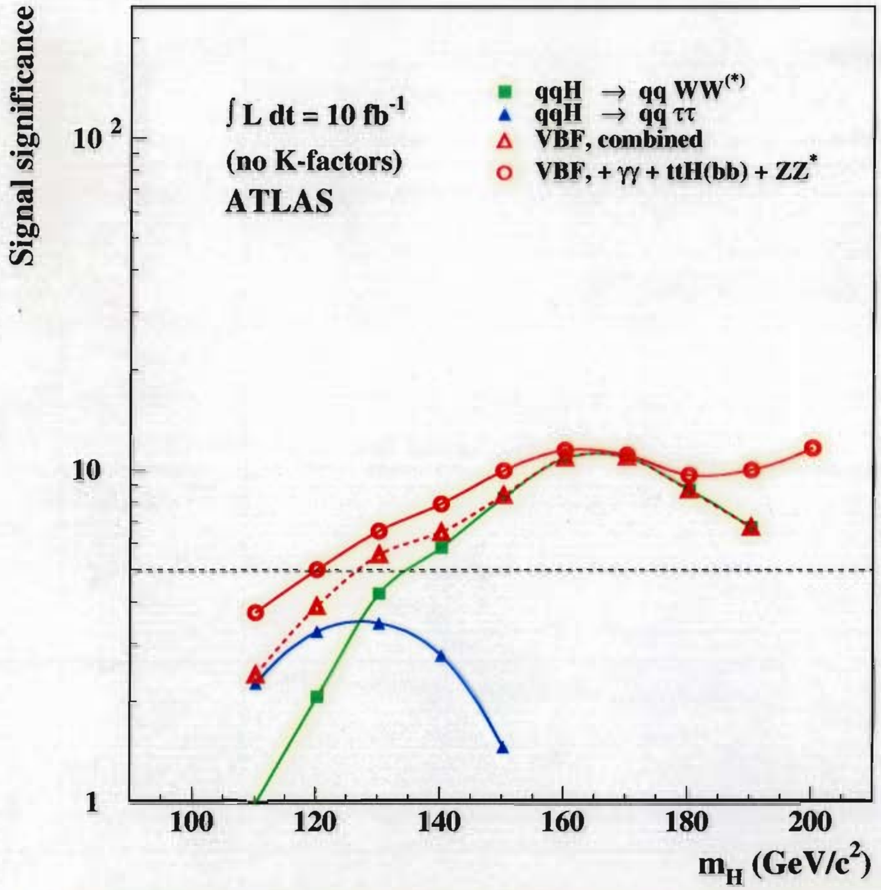
★background estimate: ~10%

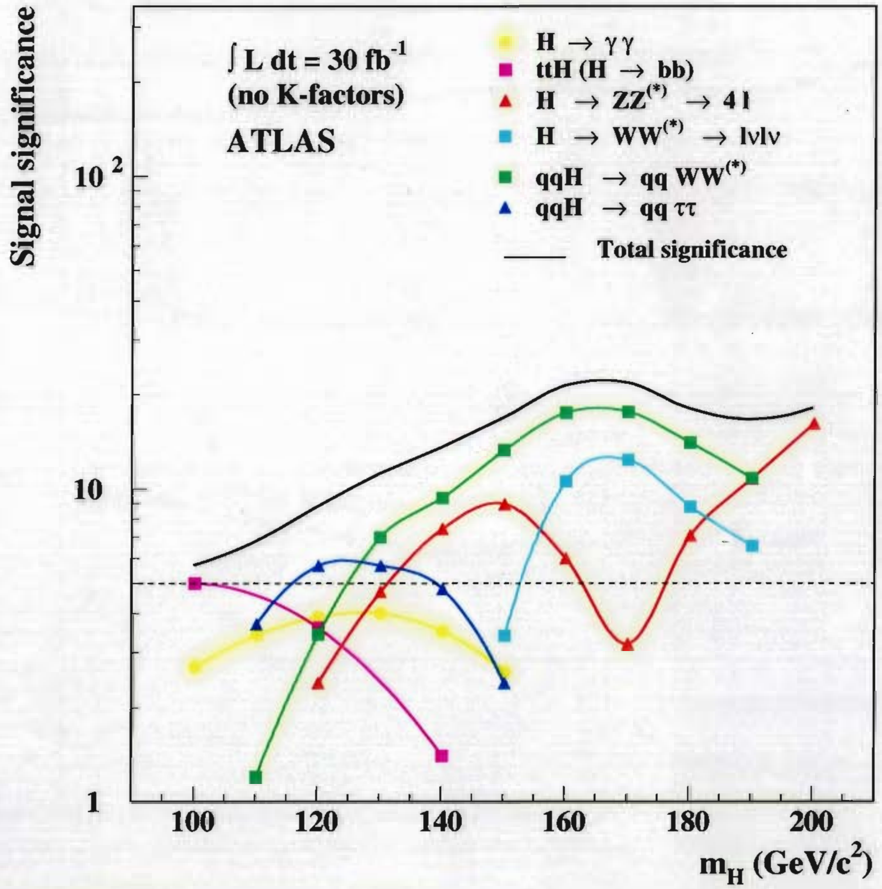
for M_H>125 GeV from side bands

for M_H>125 GeV from normalisation of $Z \rightarrow \tau\tau$ peak

Results from VBF Cut Analyses

J.Asai et al. SN-ATLAS-2003-024





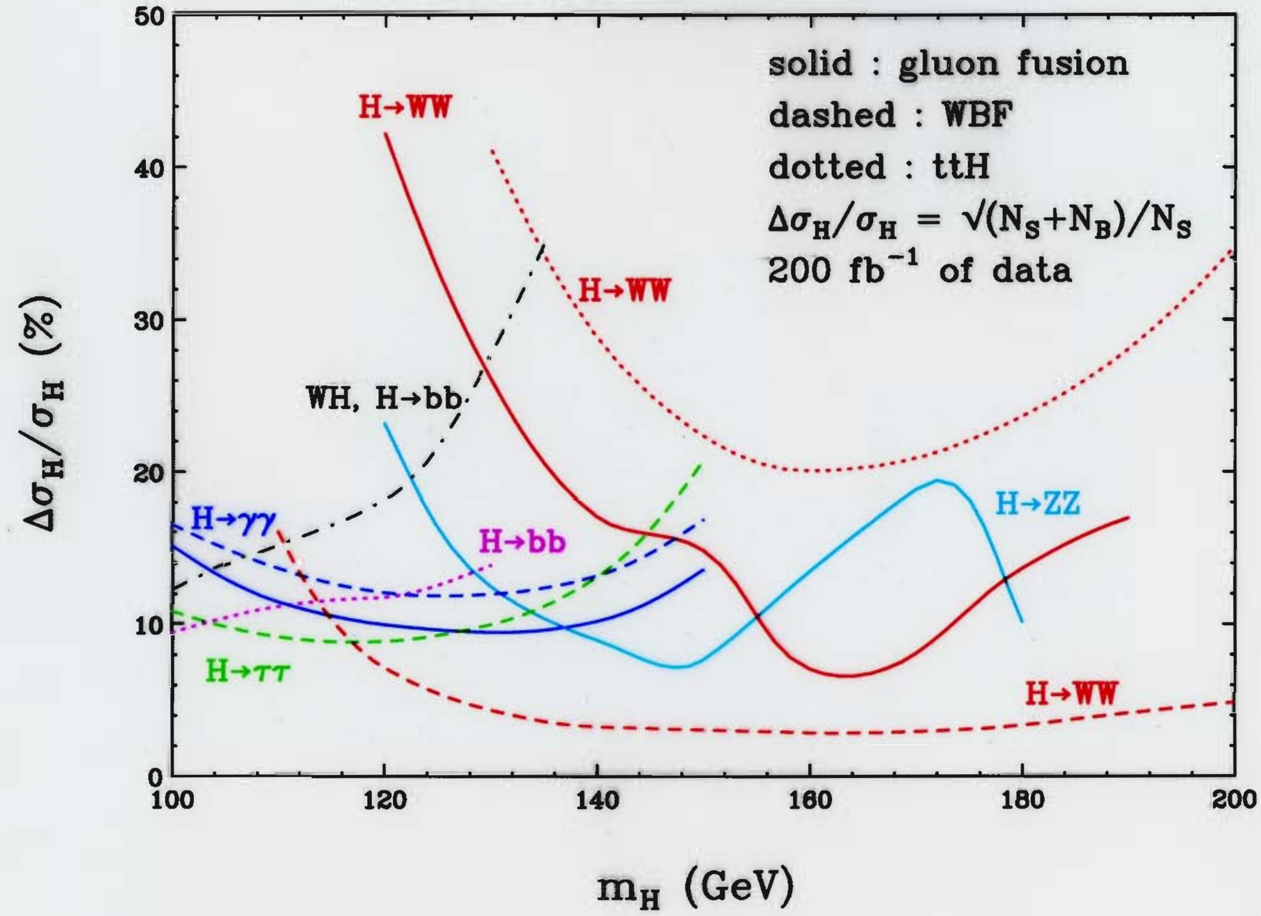
Measurement of Higgs couplings

Understanding dynamics of EW symmetry breaking requires knowledge of Higgs couplings to gauge bosons and fermions.

What can be learnt from LHC after a few years of running?

Assume 100 fb^{-1} of data collected by both, CMS and ATLAS ...

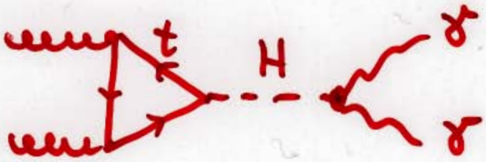
Statistical and systematic errors at LHC



- QCD/PDF uncertainties
  - ±5% for WBF
  - ±20% for gluon fusion
- luminosity/acceptance uncertainties
  - ±5%

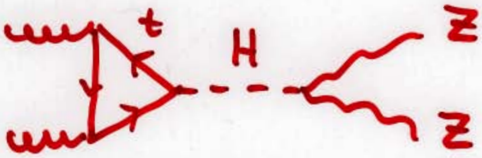
Summary of main SM Higgs channels

$gg \to H \to \gamma\gamma$ $\qquad m_H \lesssim 150$ GeV



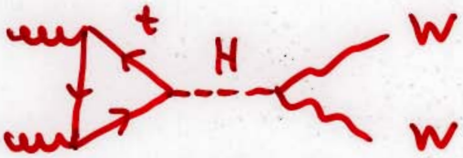
$\sim \Gamma_g \frac{\Gamma_\gamma}{\Gamma} = Y_\gamma$

$gg \to H \to ZZ \to 4\ell^\pm$ $\qquad m_H \gtrsim 120$ GeV



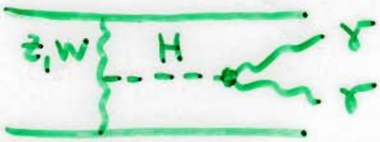
$\sim \Gamma_g \frac{\Gamma_Z}{\Gamma} = Y_Z$

$gg \to H \to WW \to \ell^\pm \ell'^\mp \not{p}_T$ $\qquad m_H \gtrsim 130$ GeV



$\sim \Gamma_g \frac{\Gamma_W}{\Gamma} = Y_W$

$qq \to qqH,\ H \to \gamma\gamma$ $\qquad m_H \lesssim 150$ GeV

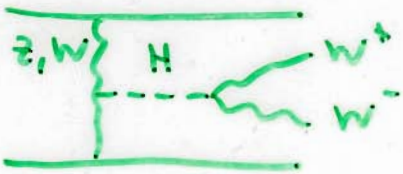


$\sim \Gamma_W \frac{\Gamma_\gamma}{\Gamma} = X_\gamma$

$qq \to qqH,\ H \to \tau\tau$ $\qquad 100\ \text{GeV} \leq m_H < 150\ \text{GeV}$

$\sim \Gamma_W \frac{\Gamma_\tau}{\Gamma} = X_\tau$

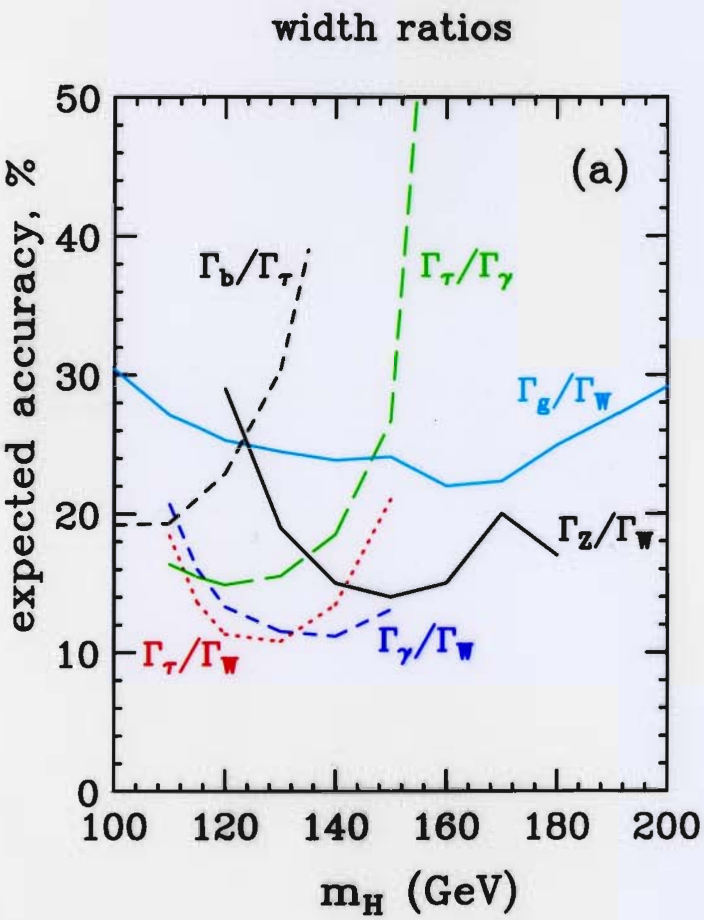
$qq \to qqH,\ H \to WW \to \ell^\pm \ell'^\mp \not{p}_T$ $\qquad m_H \gtrsim 115$ GeV

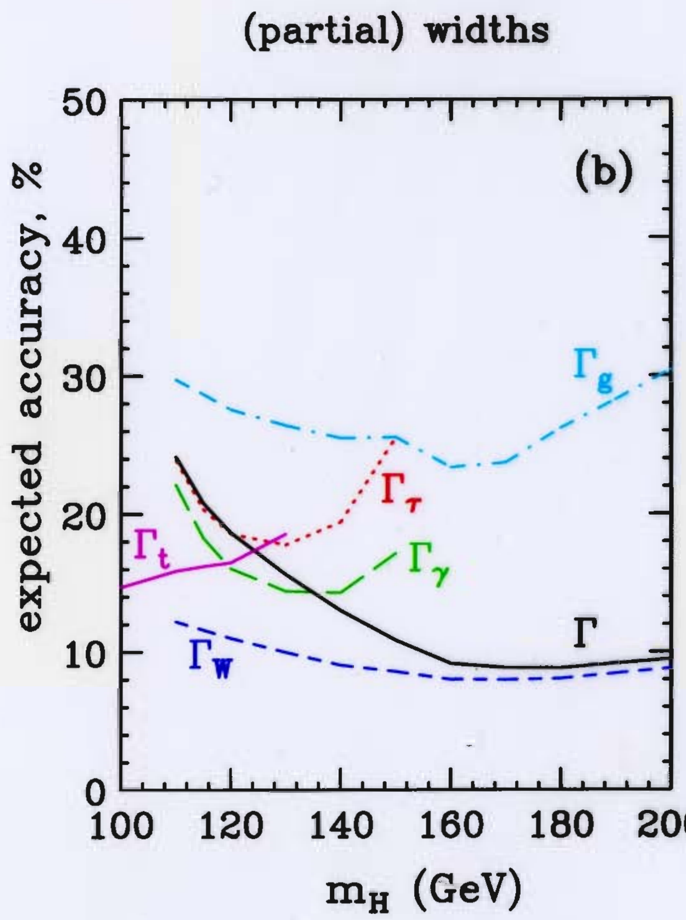


$\sim \frac{\Gamma_W^2}{\Gamma} = X_W$

Fit LHC data within constrained models

- $\frac{g_{H\tau\tau}}{g_{Hbb}}$ = SM value
- $\frac{g_{HWW}}{g_{HZZ}}$ = SM value
- no exotic channels





With 200 fb^{-1} measure partial width with 10–30% errors, couplings with 5–15% errors