Probing the Higgs Sector at LHC

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Introduction

Extraction of Higgs couplings

- search channels
- LHC accuracy

Verifying the HWW vertex structure

H+2jets: gluon vs. weak boson fusion

Goals of Higgs Physics

- Find the (pseudo) scalar(s)

  LEP II ?? ($m_H = 115\,\text{GeV}$?)

  Tevatron ?

  LHC

- Identify H as agent for spontaneous $SU(2) \times U(1)$ breaking

$$(D_\mu \phi)^\dagger (D^\mu \phi) \rightarrow \frac{1}{2}(v + H)^2\, W_\mu W^\mu$$

W, Z mass $\leftrightarrow$ $H W_\mu^\dagger W^\mu$ coupling

loop induced: $\frac{1}{\Lambda_e} H W_{\mu\nu}^\dagger W^{\mu\nu}$ CP even

$\frac{1}{\Lambda_o} H W_{\mu\nu}^\dagger \tilde{W}^{\mu\nu}$ CP odd

- Probe fermion mass generation

$\lambda \bar{L} \phi \tau_R \rightarrow \frac{m_\tau}{v}(v+H)\,\bar{\tau}_L \tau_R$

measure relation between

fermion mass $\Leftrightarrow$ $Hf\bar{f}$ coupling

$\Rightarrow$ measure Higgs' Yukawa coupl.

$H\tau\tau$

Hbb

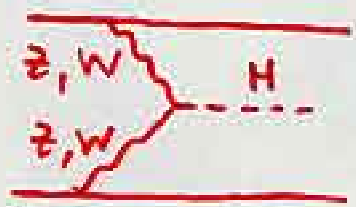
Htt etc.

Main SM Higgs production processes @ LHC

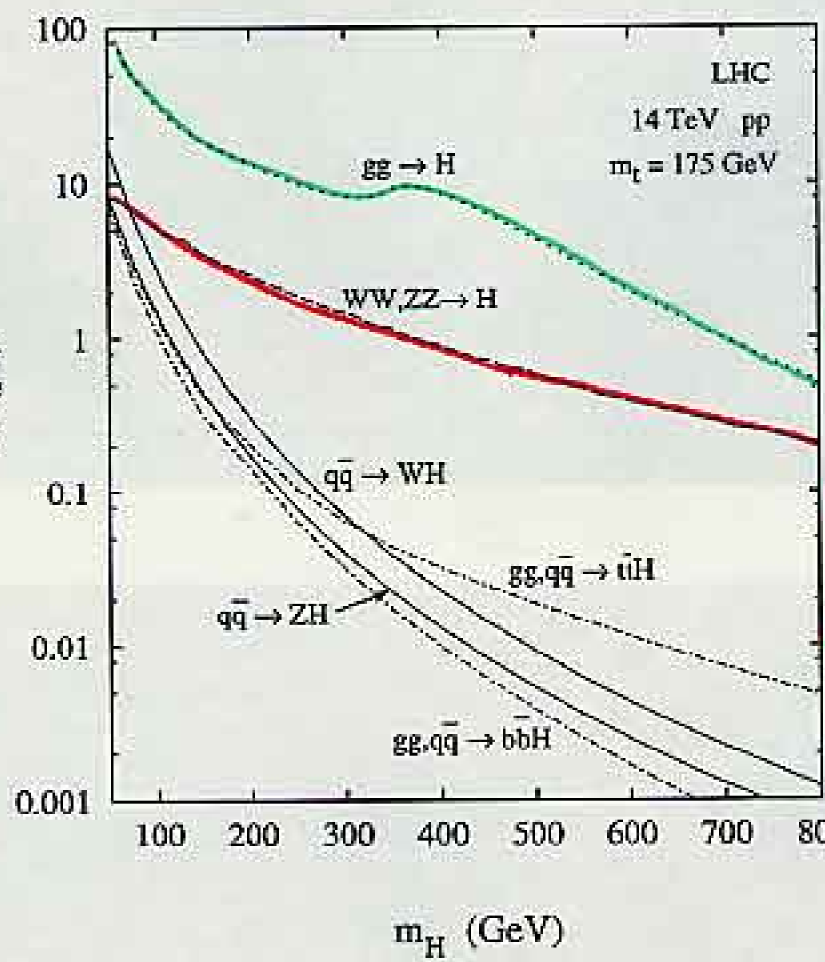
gluon fusion

$\sigma_{gg \to H} \sim 10 - 30\ pb$

weak boson fusion



$\sigma_{qq \to qqH} \sim \frac{1}{5}\ \sigma_{gg \to H}$



10^4

1000

100

10 events/year @ $10\ fb^{-1}/y$

Weak boson fusion is the most copious of the associated Higgs production channels

24

Traditional search channels are dominated by gluon fusion

- inclusive search for

  $H \to \gamma\gamma$ $\quad (m_H \lesssim 150$ 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

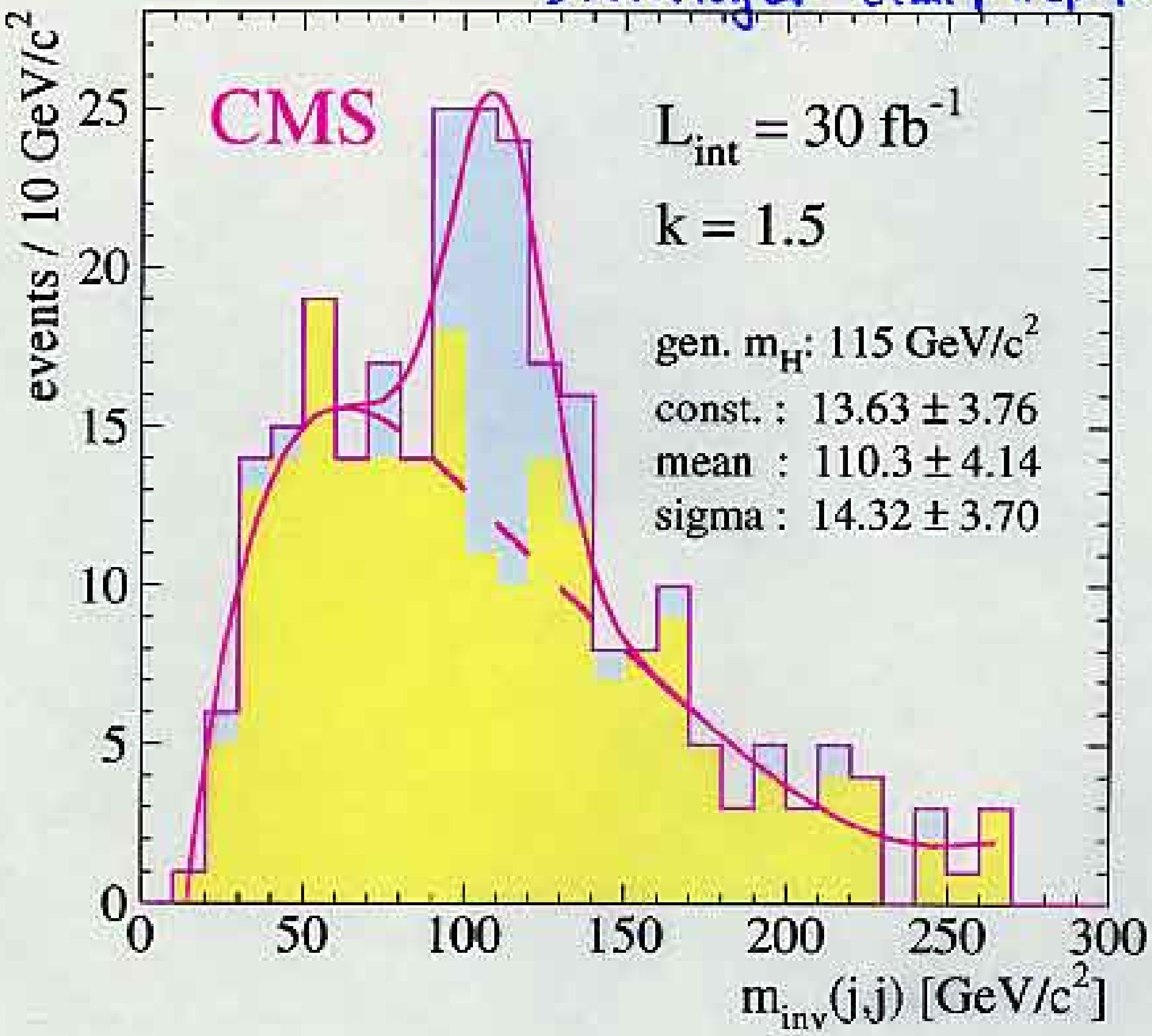
  $H \to W^+W^- \to \ell^+\nu\,\ell^-\bar{\nu}$

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

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

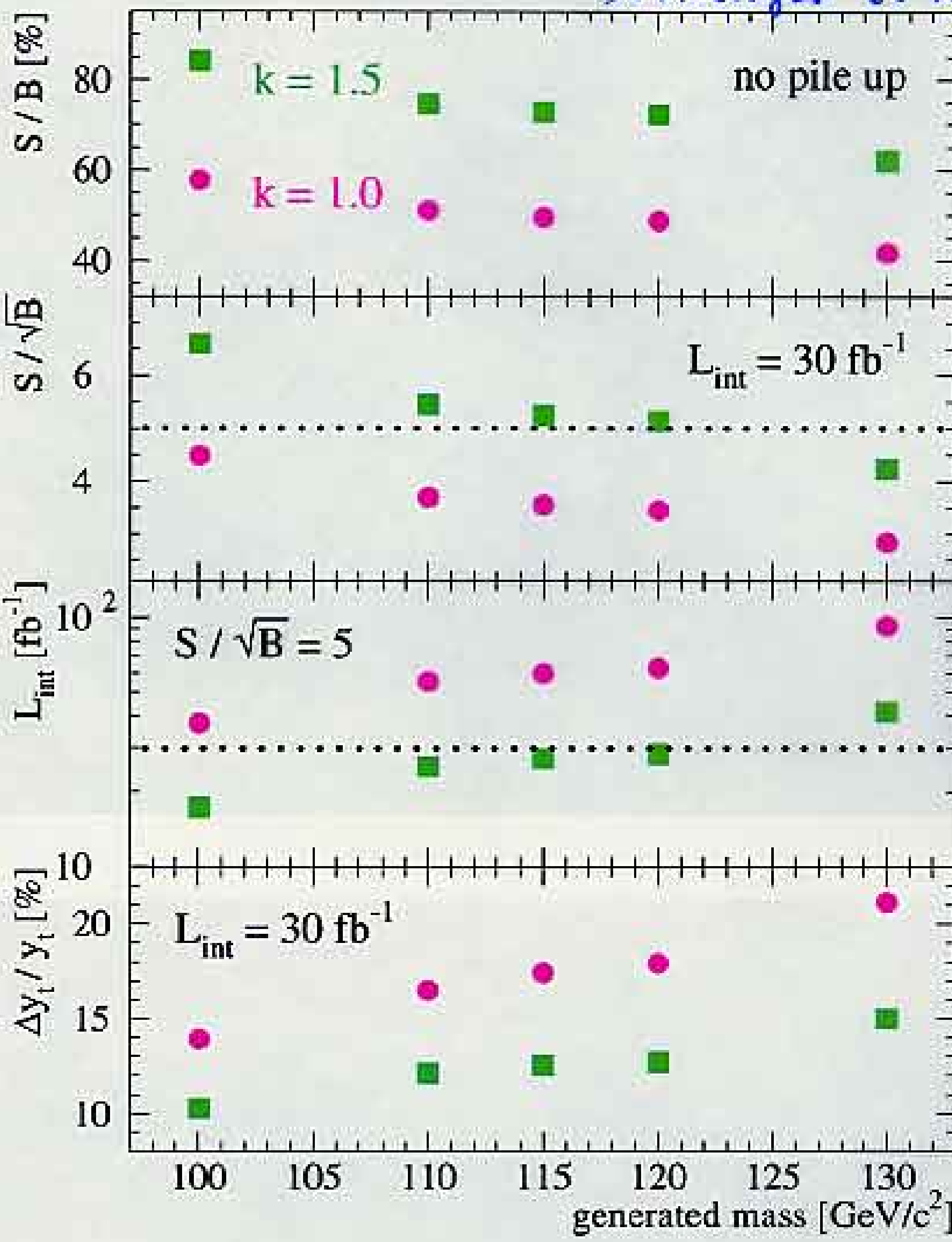
⇒ measure

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

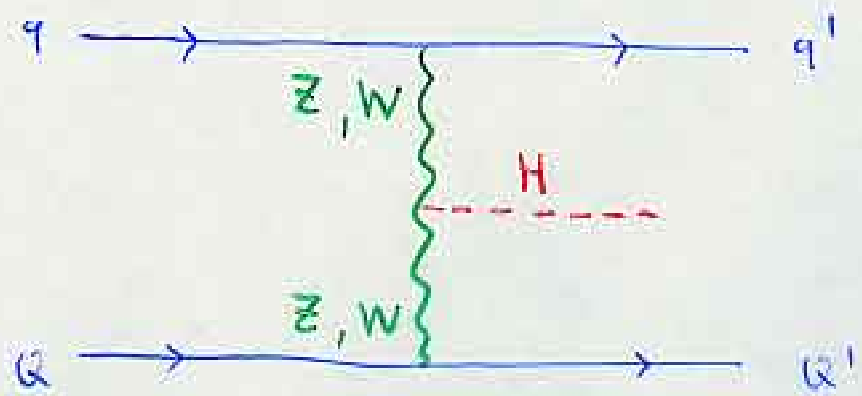
Expected CMS performance:

K ≈ 1.2 [Beenakker et al.]
at NLO QCD

Drollinger et al



Exploit weak boson fusion (WBF)



Characteristics:

- 2 forward tagging jets (q', Q')
  $(p_{Tj} > 20\ \text{GeV},\ |\eta| < 5)$

- Observe Higgs decay products between tagging jets

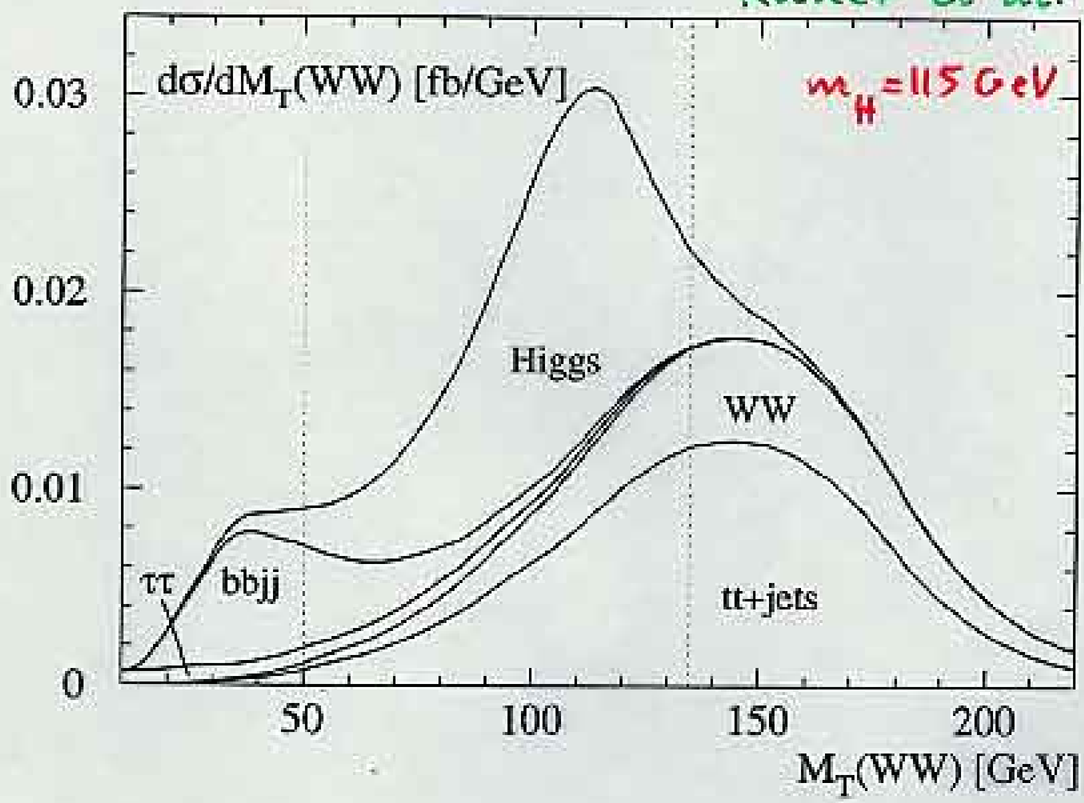
- Little gluon radiation due to W, Z exchange (no color exchange)
  (central jet veto, $p_T > 20$ GeV)

- small NLO corrections $(K \approx 1.1)$

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

Higgs Jacobian peak in $\ell\ell + \not{p}_T$ transverse mass distribution

Kauer et al.



$\not{p}_T < 20$ allowed for $p_{TH} < 50$

Required luminosity for a 5σ $H \to WW$ signal

m_H	115	120	125	130	GeV
$\int \mathcal{L}\,dt$	35	15	8	4	fb^{-1}

Summary of main SM Higgs channels

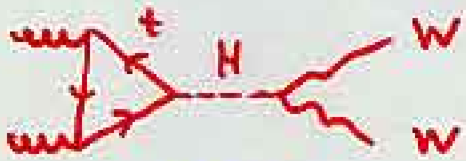
$gg \to H \to \gamma\gamma$ $\qquad m_H \lesssim 150\,\text{GeV}$

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

$gg \to H \to ZZ \to 4\ell^\pm$ $\qquad m_H \gtrsim 120\,\text{GeV}$

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

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



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

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

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

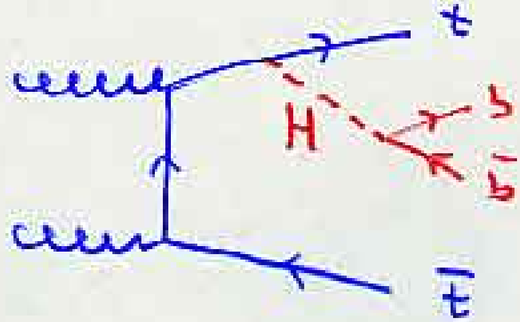
$qq \to qqH,\ H \to \tau\tau$ $\qquad 100\,\text{GeV} \leq m_H < 150\,\text{GeV}$

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

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

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

Big improvements recently for



Drollinger et al.

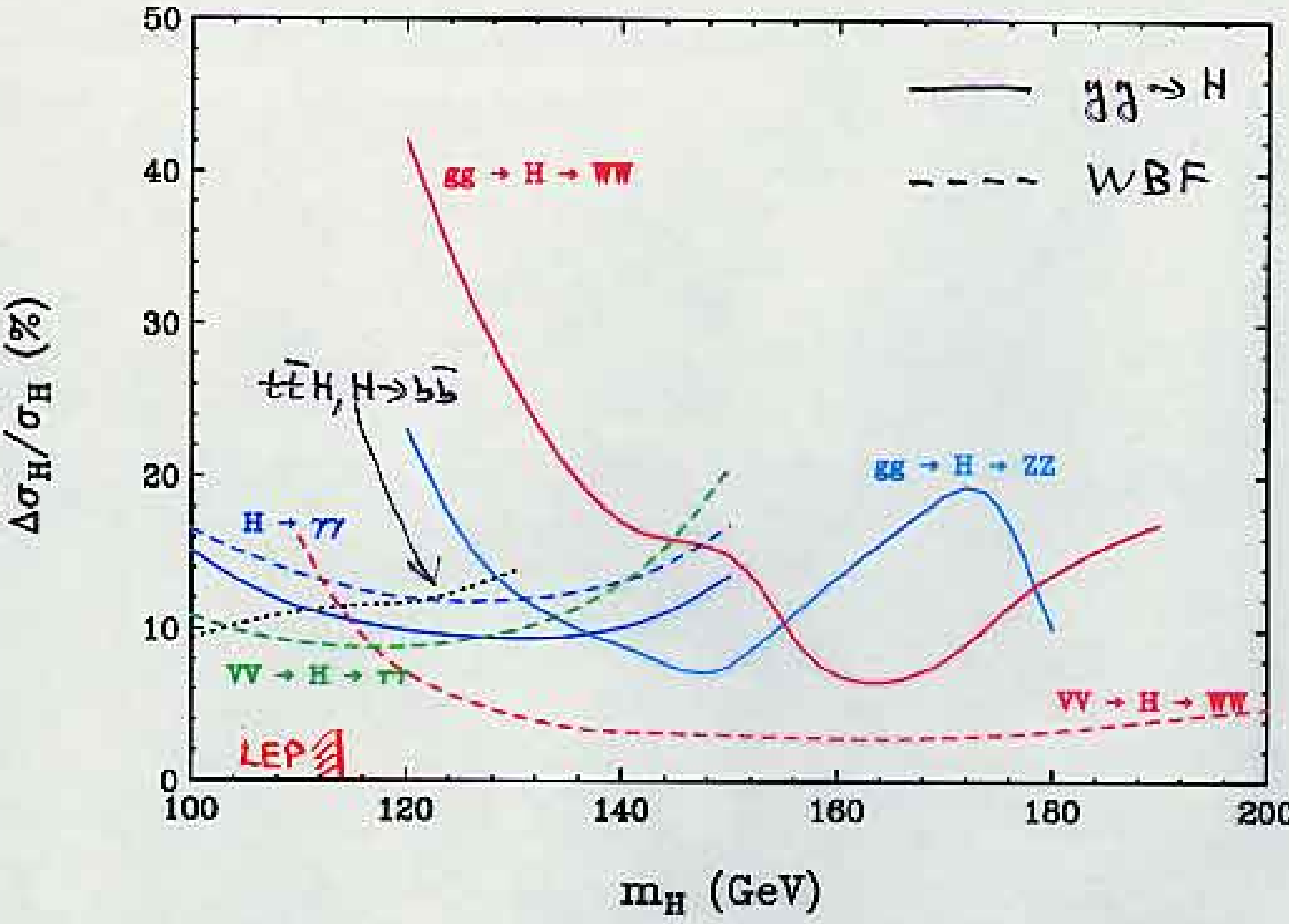
Green et al.

determines

$$\Gamma_t \frac{\Gamma_b}{\Gamma}$$

for $m_H \lesssim 130$ GeV

Statistical errors with 200 fb^{-1}:



Systematic errors:

QCD/pdf uncertainties

±5% for WBF

±20% for gluon fusion

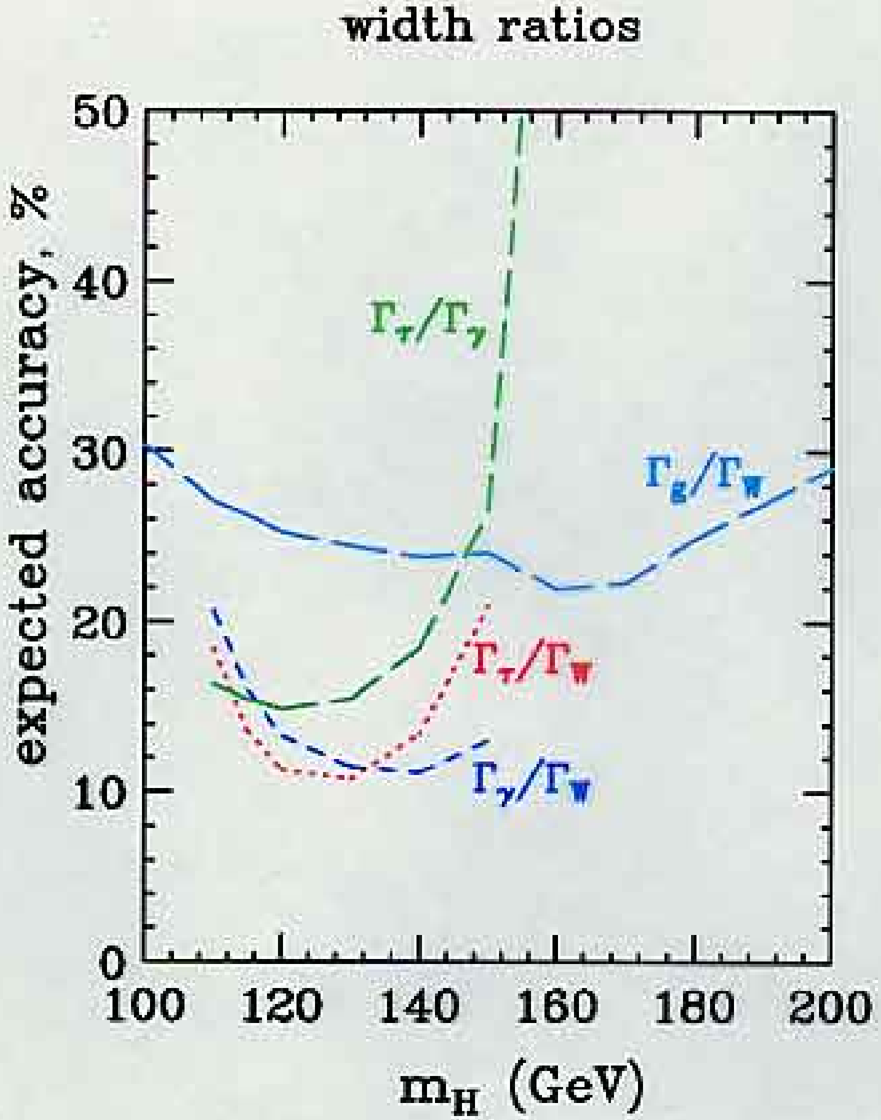
Luminosity/acceptance error

±5%

Largely cancel in cross section ratios

$\to \frac{\Gamma_\tau}{\Gamma_W}, \frac{\Gamma_\gamma}{\Gamma_W}, \frac{\Gamma_Z}{\Gamma_W}, \frac{\Gamma_g}{\Gamma_W}, \frac{\Gamma_t \Gamma_b}{\Gamma_g \Gamma_\gamma}$

$2 \times 100\ fb^{-1}$ of LHC data :



Extraction of width ratios is model-independent ⇒ measure coupling ratios at 5-10 % level

3 Assumptions

- HWW and HZZ couplings related by SU(2), as in SM, i.e.

$$\frac{\Gamma_Z}{\Gamma_W} = \frac{\Gamma_Z^{SM}}{\Gamma_W^{SM}}$$

- $I = -\frac{1}{2}$ third generation fermions have same origin of mass, i.e.

$$y = \frac{\Gamma(H \to b\bar{b})}{\Gamma(H \to \tau\tau)} = 3\, C_{QCD}^{SM} \frac{m_b^2(m_H)}{m_\tau^2(m_H)}$$

- No large unexpected decay modes

$$\varepsilon = 1 - B(H \to \tau\tau, b\bar{b}, WW, ZZ, gg, \gamma\gamma) \ll 1$$

SM: $\varepsilon \approx B(H \to c\bar{c}) \lesssim 3.5\%$

Combine LHC measurements

$$\tilde{\Gamma}_W = X_\tau\left(1 + \frac{B(H\to b\bar{b})}{B(H\to\tau\tau)}\bigg|_{SM}\right) + X_W\left(1 + \frac{B(H\to ZZ)}{B(H\to WW)}\bigg|_{SM}\right)$$

$$+ X_\gamma + Y_W$$

$$= \frac{\Gamma_W}{\Gamma}\left(\Gamma_\tau + \Gamma_b + \Gamma_W + \Gamma_Z + \Gamma_\gamma + \Gamma_g\right)$$

$$= \Gamma_W(1-\varepsilon) \approx \Gamma_W$$

and

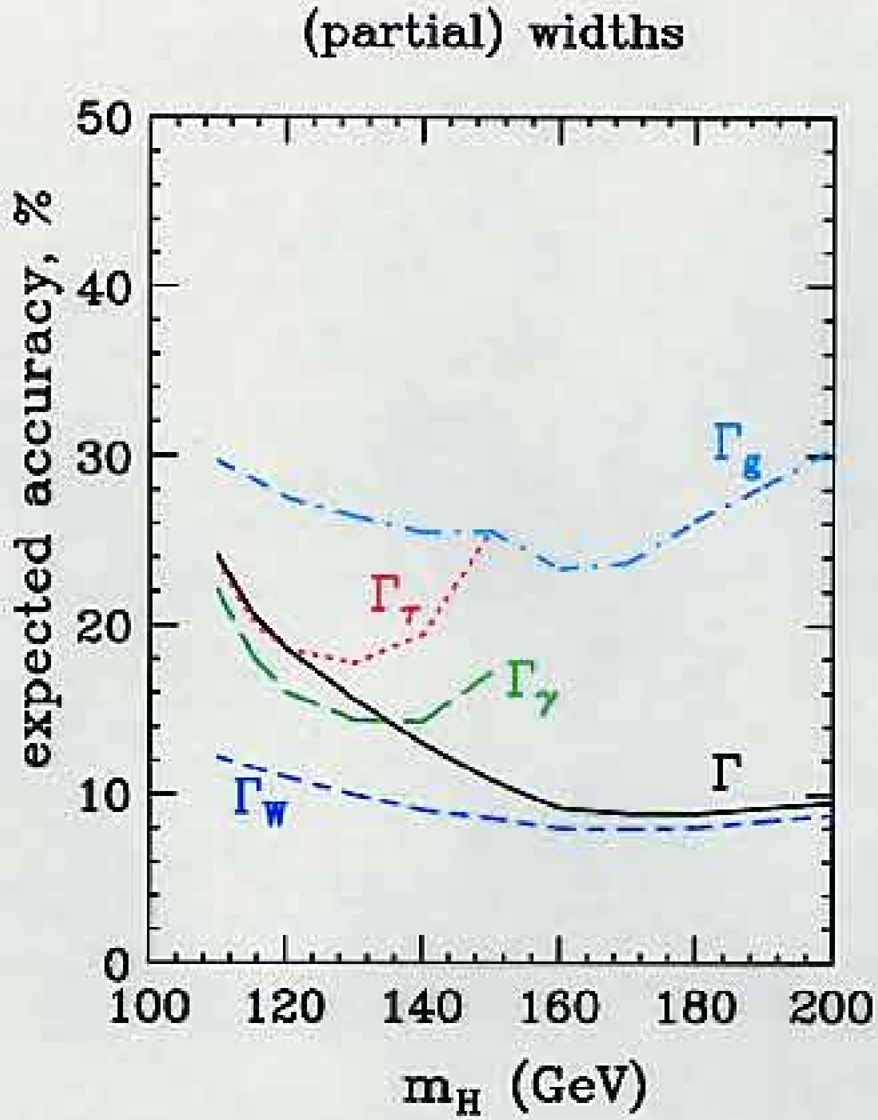
$$\tilde{\Gamma} = \frac{\tilde{\Gamma}_W^2}{X_W} = \frac{\Gamma_W^2(1-\varepsilon)^2}{\Gamma_W \, \Gamma_W/\Gamma} = \Gamma(1-\varepsilon)^2$$

$\Rightarrow$ modulo $B(H\to c\bar{c})$ correction, extract

$\Gamma_W = \Gamma(H\to WW)$ partial width

$\Gamma = \Gamma(H\to X)$ total width

$2 \times 100\ fb^{-1}$ of LHC data:



⇒ Extract (partial) widths at 10-25%.

→ couplings at 5-15% level

- $t\bar{t}H$, $H \to b\bar{b}$ gives consistency check on b-τ universality for $m_H \lesssim$ 130-140 GeV

How to identify H as remnant of SU(2) x U(1) breaking

$$\phi \to \begin{pmatrix} \chi^+ \\ \frac{v + H + i\chi^0}{\sqrt{2}} \end{pmatrix}$$

A tree level HWW or HZZ coupling is the smoking gun : requires v.e.v.

$$(D_\mu \phi)^\dagger (D^\mu \phi) \to \frac{g^2}{2} \frac{(v+H)^2}{2} W_\mu^\dagger W^\mu$$

$$\left(\frac{gv}{2}\right)^2 W_\mu^\dagger W^\mu \leftrightarrow \text{W mass}$$

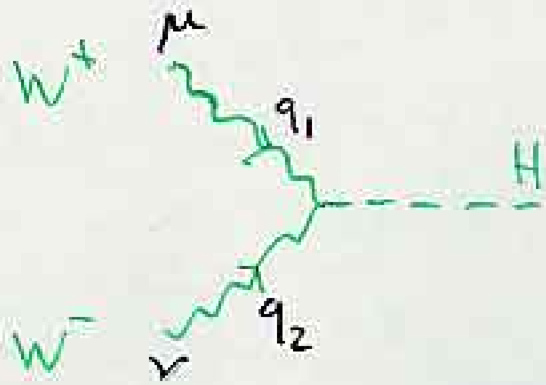
$$\frac{g^2 v}{2} H W_\mu^\dagger W^\mu \leftrightarrow \text{HWW coupling}$$

Gauge interactions of non-vev scalar

$$\sim \phi^\dagger \phi W \ , \quad \phi^\dagger \phi W W$$

are bilinear in ϕ

Most general HWW coupling



$$T^{\mu\nu}(q_1, q_2)$$

q_1^μ and q_2^ν terms vanish when contracted with conserved charged current $\Rightarrow$

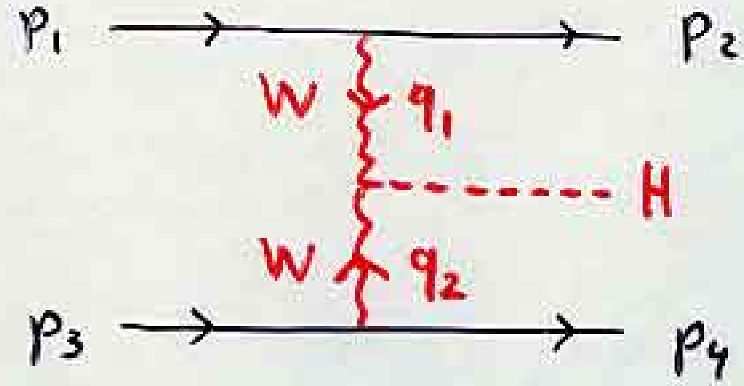
$$T^{\mu\nu} = a_1 g^{\mu\nu} + a_2 q_1^\nu q_2^\mu + a_3 \varepsilon^{\mu\nu\rho\sigma} q_{1\rho} q_{2\sigma}$$

- SM: $\frac{g^2 v}{2} H W_\mu^\dagger W^\mu \rightarrow g m_W g^{\mu\nu}$

Loop effects

- CP even: $\frac{1}{\Lambda} H W_{\mu\nu}^\dagger W^{\mu\nu} \rightarrow \frac{2}{\Lambda}\left(q_1 \cdot q_2 g^{\mu\nu} - q_1^\nu q_2^\mu\right)$
- CP odd: $\frac{1}{\Lambda} H W_{\mu\nu}^\dagger \tilde{W}^{\mu\nu} \rightarrow \frac{2}{\Lambda} \varepsilon^{\mu\nu\rho\sigma} q_{1\rho} q_{2\sigma}$

Effective HWW coupling affects WBF



For CP-odd coupling

$$|\mathcal{M}_{CP\text{-odd}}|^2 \sim |\varepsilon^{\mu\nu\alpha\beta} p_{1\mu} p_{2\nu} p_{3\alpha} p_{4\beta}|^2$$

~ vanishes for planar events

⇒ cross section zero for 0, 180° azimuthal angle between jets

$\varphi_{jj} = \varphi_{j_1} - \varphi_{j_2}$ distribution of quark jets is characteristic for 3 couplings

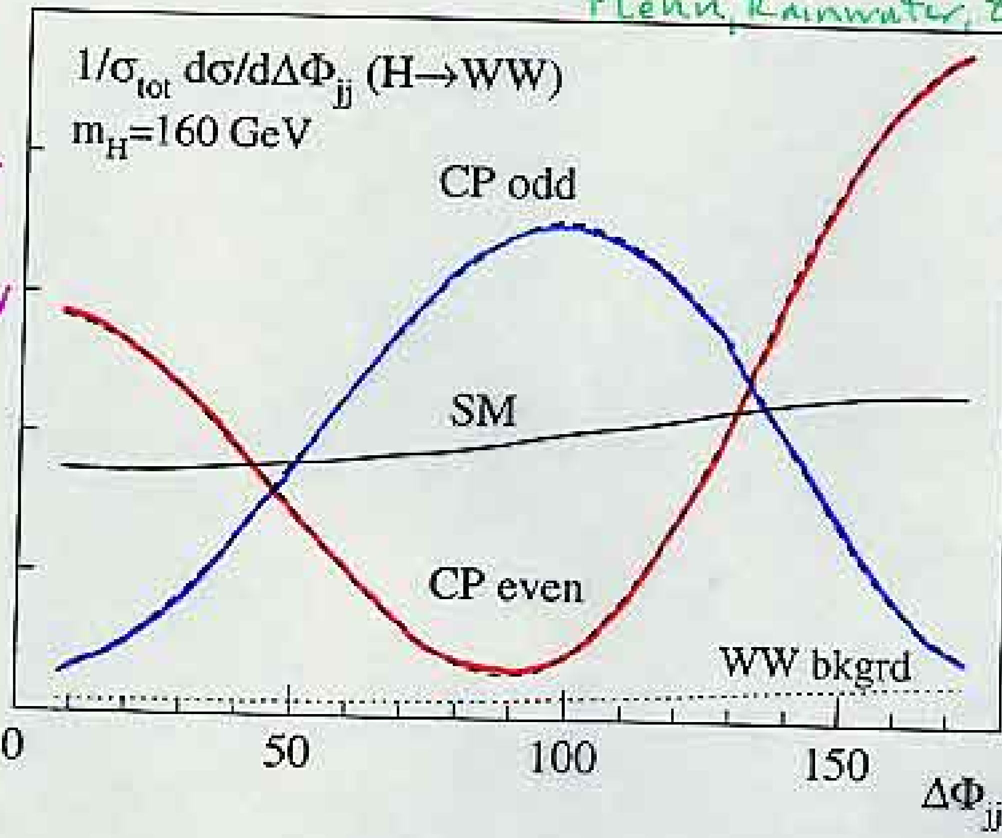
Assume $\sigma(qq \to qqH)$ as in SM

$\Rightarrow \Lambda_5 \approx 500$ GeV

Plehn, Rainwater, Z.

$H \to W^+W^-$

$m_H = 160$ GeV



CP odd: $H W_{\mu\nu} \tilde{W}^{\mu\nu}$

CP even: $H W_{\mu\nu} W^{\mu\nu}$

SM: $H W_\mu W^\mu$

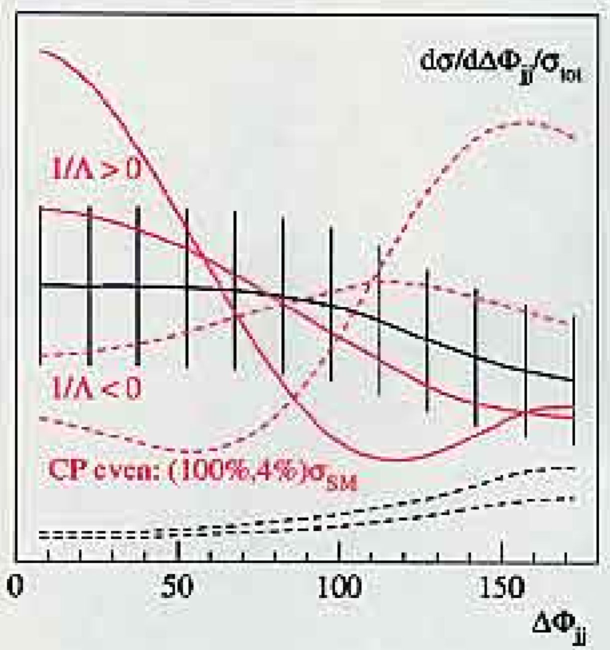
Azimuthal angle distribution

$$\Delta\varphi_{jj} = \varphi_{j_1} - \varphi_{j_2} \mod \pi$$

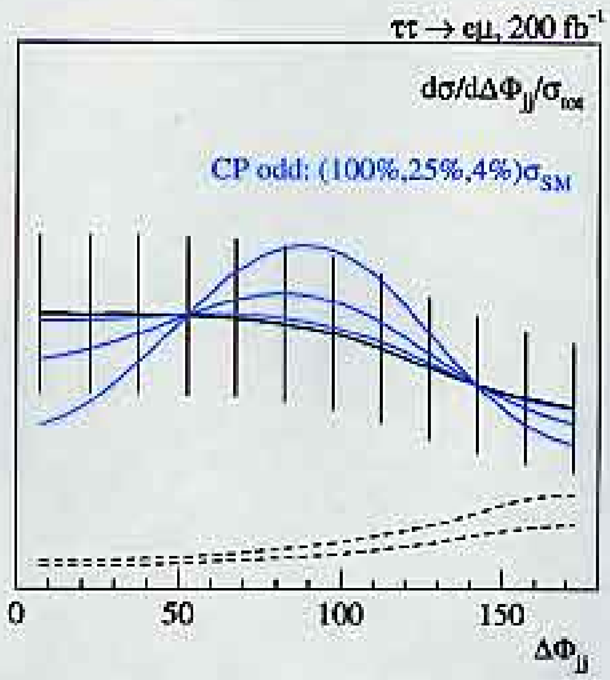
is little affected by typical acceptance cuts for H search in WBF.

Interference of SM coupling with "loop" induced

CP even



CP odd



Error bars:

$h \to e\mu \not{p}_T$ only, 200 fb^{-1}

may gain factor 2

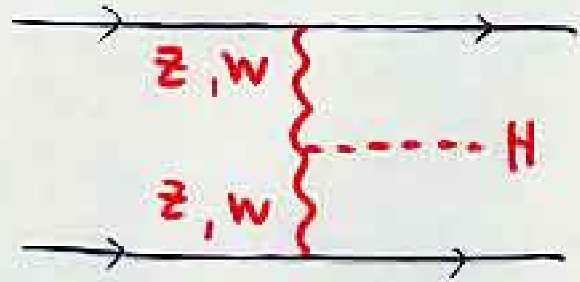
by combining WBF channels

- $h \to WW \to e e' \nu \bar{\nu}$
- $h \to \gamma\gamma$
- $h \to \tau\tau$

σ_5/σ_{SM}	Λ_5	Λ_6
1	0.5 TeV	0.3 TeV
10^{-1}	1.6 TeV	0.6 TeV
10^{-2}	5.0 TeV	1.1 TeV
10^{-3}	16.4 TeV	2.0 TeV

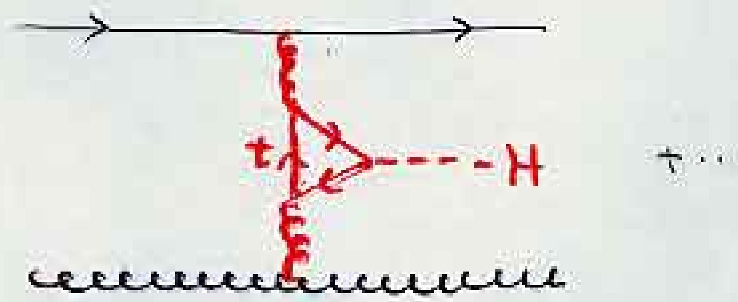
Sources of H+2 jet events

weak boson fusion



vs.

gluon fusion



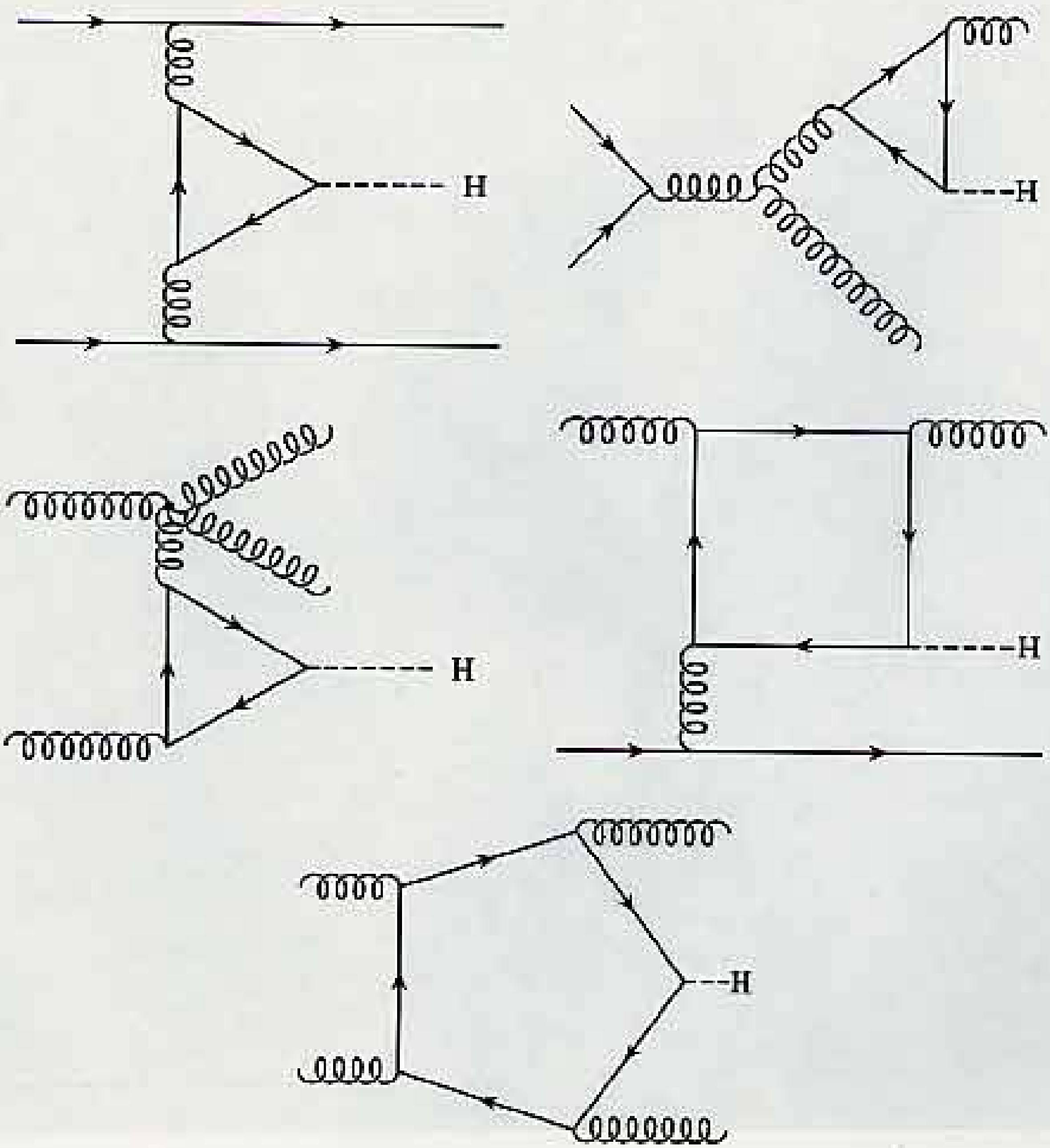
Separation of Hgg vs. HWW couplings:

- determine relative rates
- characteristic distributions

New: full H+2j calculation at finite m_t

Del Duca, Kilgore, Oleari, Schmidt, Z.

Diagrams



$$
\begin{aligned}
qQ &\to qQH \qquad\qquad Q = q, q' \\
qg &\to qgH \\
gg &\to ggH
\end{aligned}
$$

plus crossed processes.

Consider H+2j cross sections in two phase space regions:

A) Minimal cuts

$$p_{Tj} > 20 \text{ GeV}, \quad |\eta_j| < 5$$

$$R_{jj} = \sqrt{(\Delta\eta)^2 + (\Delta\varphi)^2} > 0.6$$

B) WBF cuts = typical selection for weak boson fusion Higgs search

Require in addition

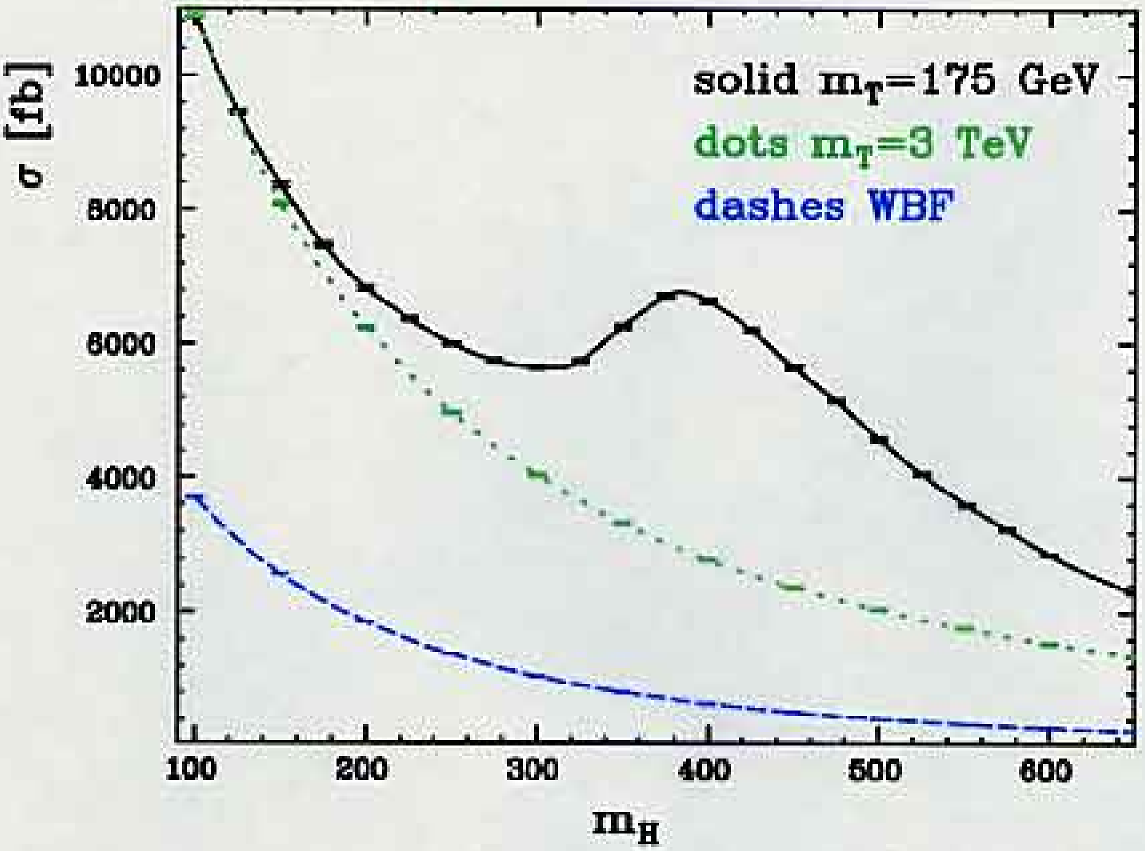
$$\Delta\eta_{jj} = |\eta_{j_1} - \eta_{j_2}| > 4.2$$

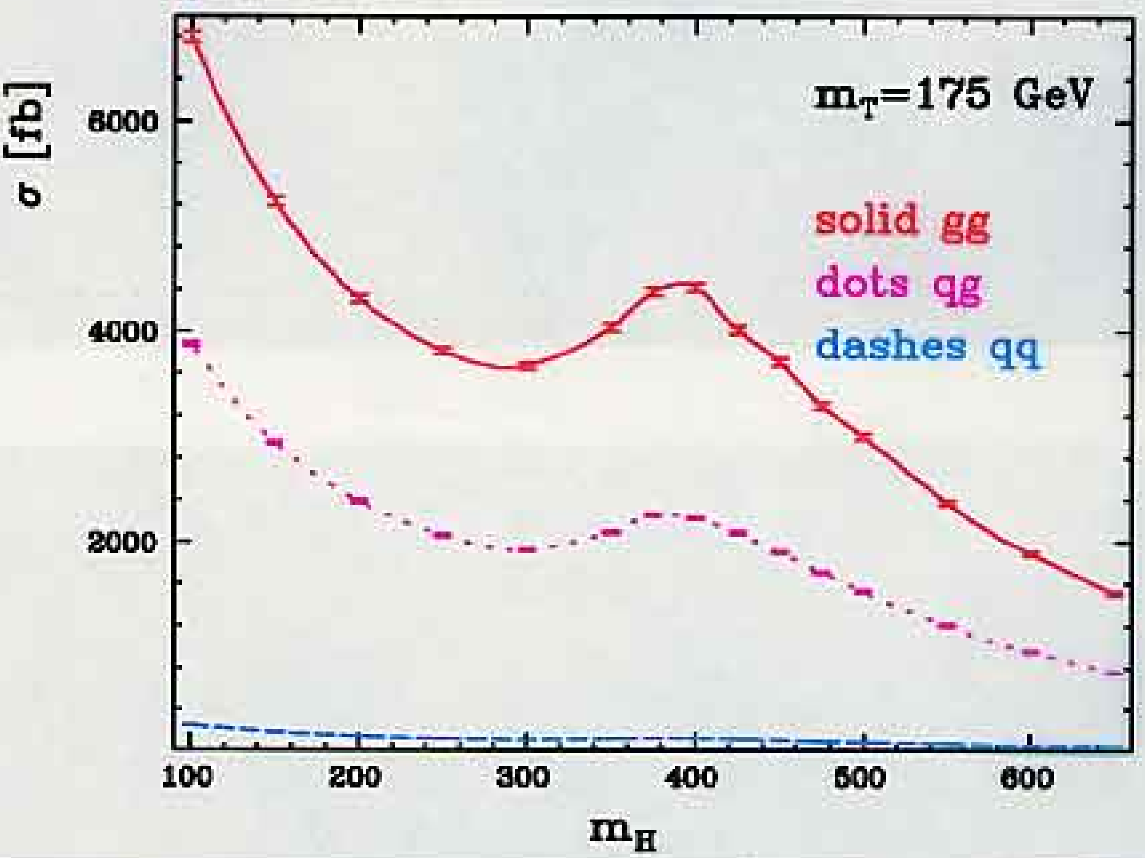
$$\eta_{j_1} \cdot \eta_{j_2} < 0 \quad \text{(opposite hemispheres)}$$

$$m_{jj} > 600 \text{ GeV}$$

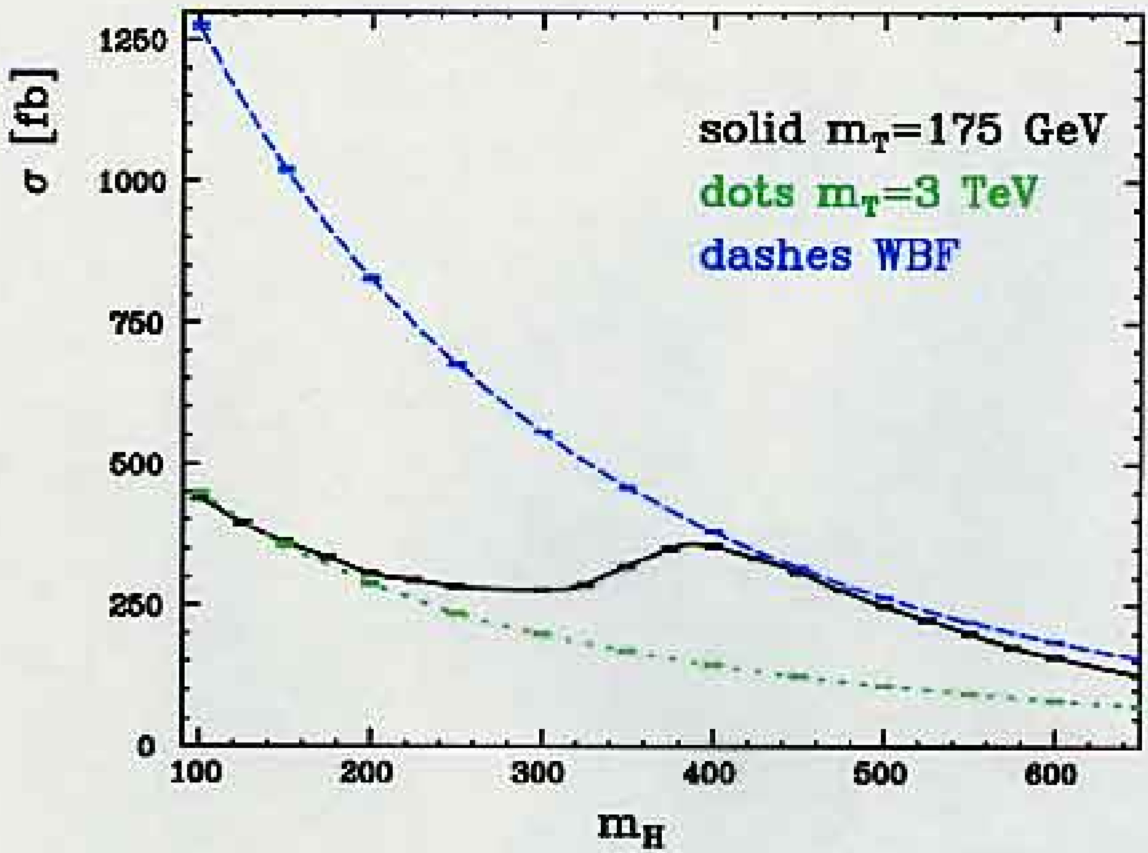
Total cross section: minimal cuts

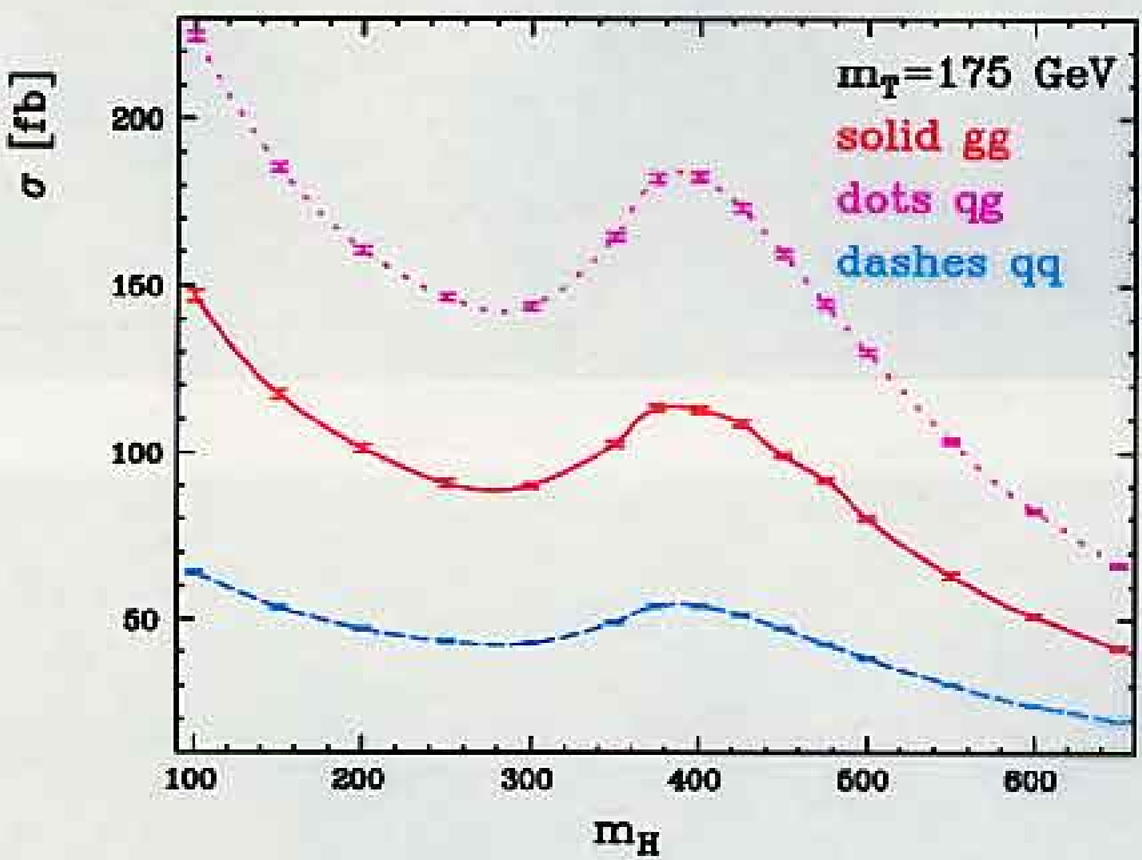
$\sqrt{s} = 14$ TeV



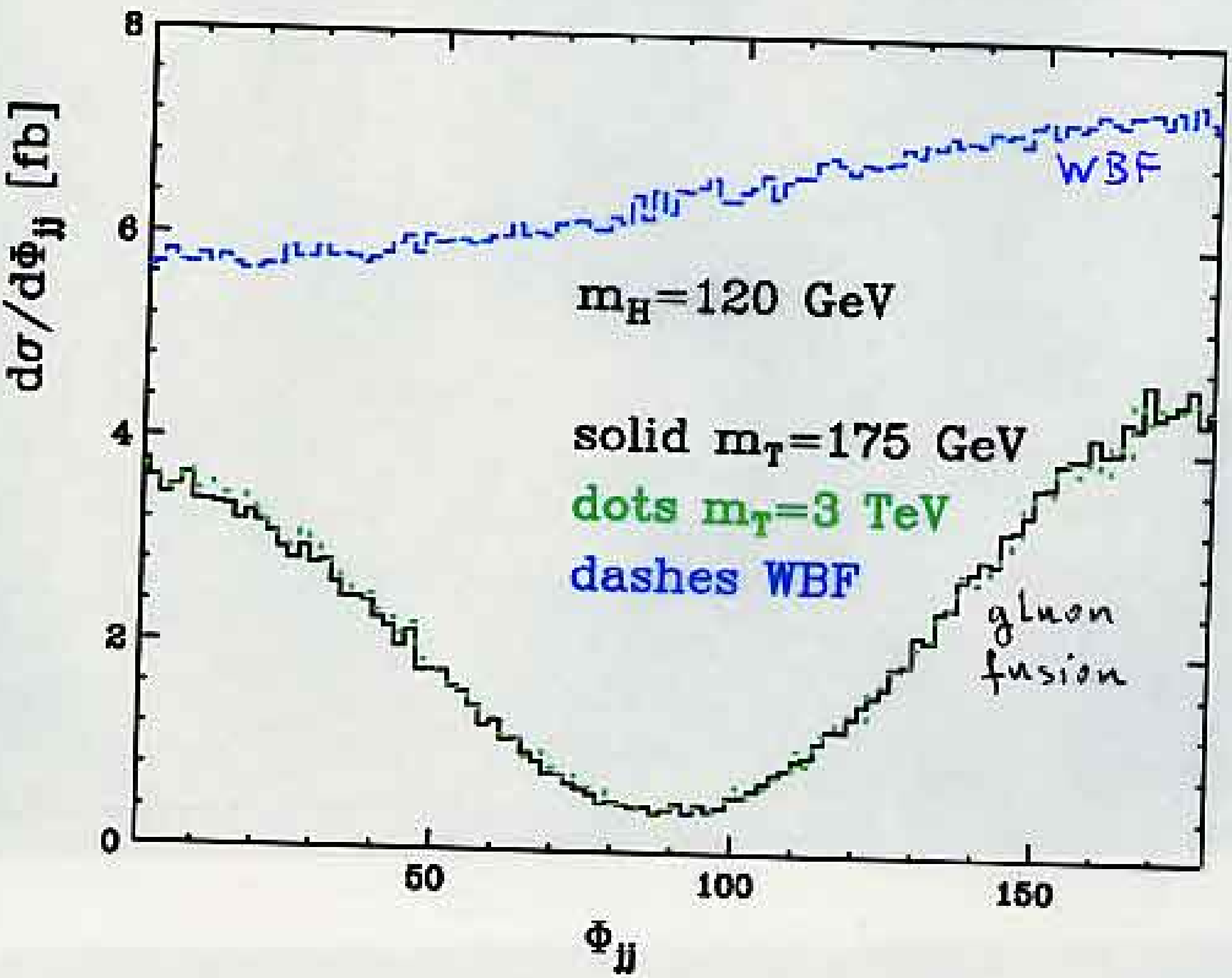


Total cross section: WBF cuts





Azimuthal angle between jets ϕ_{jj}: WBF cuts



Observation of "flat" ϕ_{jj} distribution identifies SM HWW vertex vs.

- loop induced HWW coupling
- loop induced Hgg coupling !!

Conclusions

LHC has great potential to probe the Higgs sector in multiple channels

Rate measurements at ~10% level allow to extract HWW, $H\tau\tau$, Hgg, Htt... couplings at 5-15% level, with $2\times 100\,fb^{-1}$

The tensor structure of the SM HWW coupling can be positively identified in weak boson fusion:

LHC can prove that it has found remnant of $SU(2)\times U(1)$ breaking.