Higgs at the LHC: Theory

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Goals of Higgs Physics

Signatures for intermediate masses

Weak boson fusion

- CP properties
- invisible decay modes

Measurement of couplings

Challenges: better tools

Goals of Higgs Physics

- Find the (pseudo) scalar(s)

  LEP II ?? ($m_H = 115$ 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 $\longleftrightarrow$ $H W_\mu W^\mu$ coupling

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

$H W_{\mu\nu} \tilde{W}^{\mu\nu}$ 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.

Need variety of measurements to pin down couplings

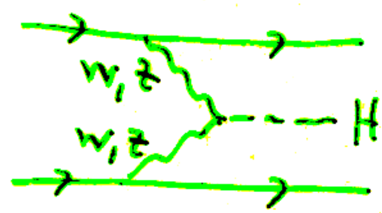
$gg \to H$

$t\bar{t}H$ coupling

$e^+e^- \to ZH$

$q\bar{q} \to WH$

$qq \to qqH$



WWH, ZZH couplings

$H \to \gamma\gamma$

Higgs couples to charged fields

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

$H\bar{\tau}\tau$ coupling

$\Rightarrow$ develop methods to investigate all

Higgs decay width and branching fractions in the SM

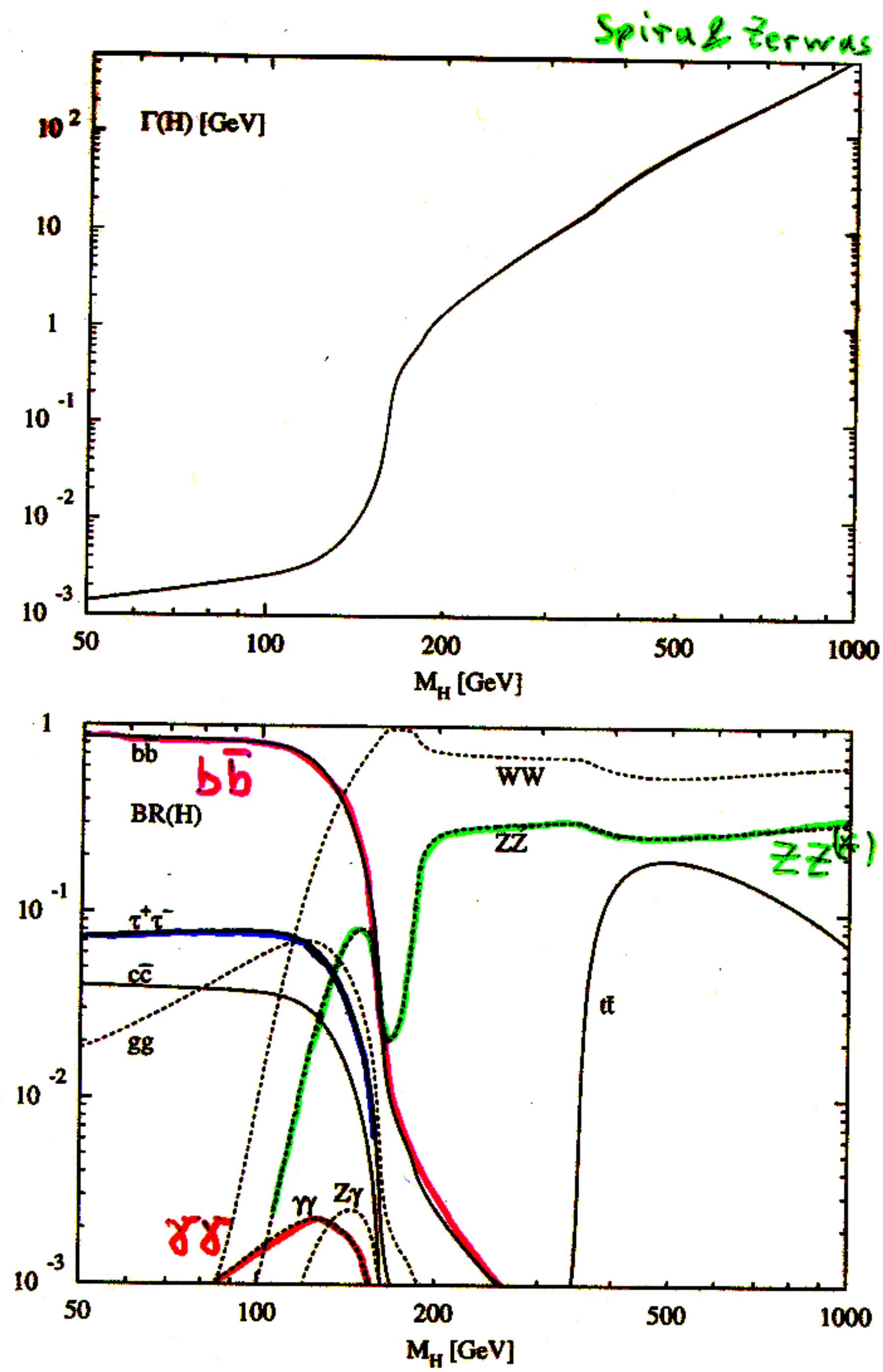
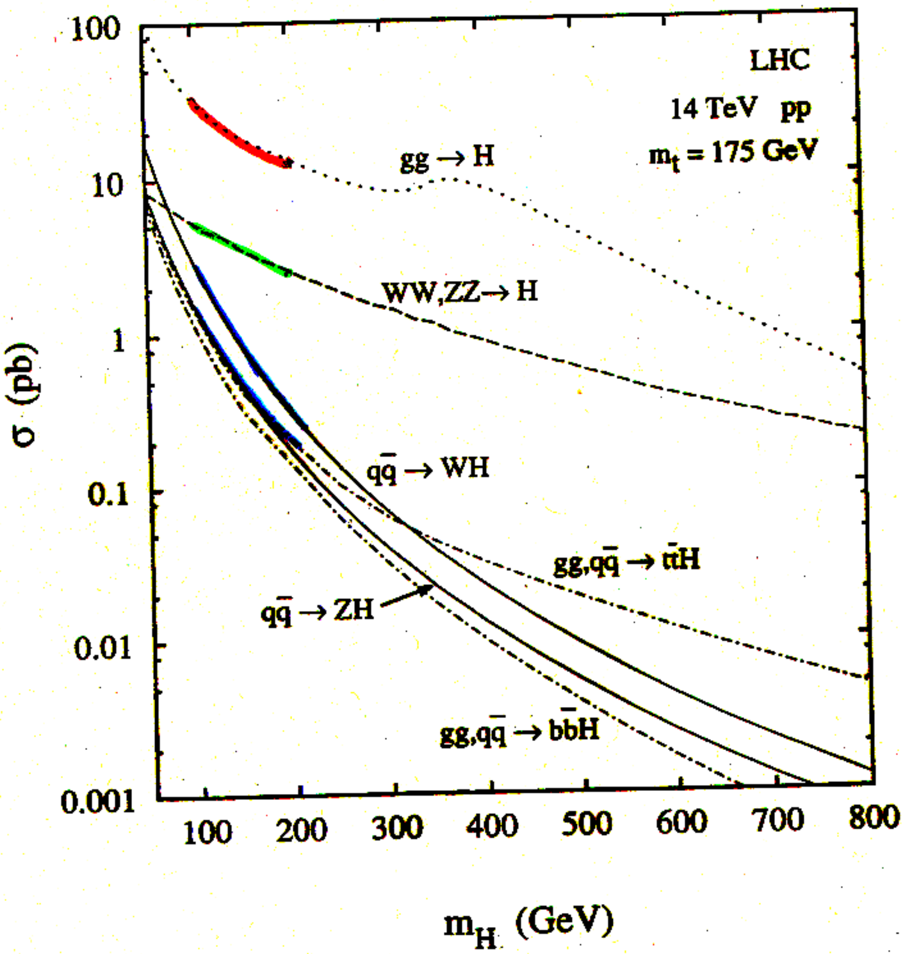


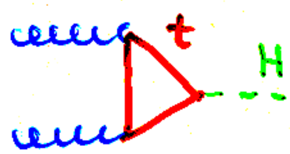
Figure 5: *(a) Total decay width (in GeV) of the SM Higgs boson as a function of its mass. (b) Branching ratios of the dominant decay modes of the SM Higgs particle. All relevant higher-order corrections are taken into account.*

Higgs production at the LHC



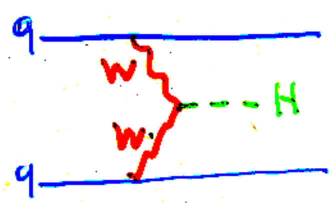
Dominant production processes

gluon fusion



~ 10 – 30 pb

weak boson fusion



~ 3 – 5 pb

WH, $t\bar{t}$H associated production

~ 0.2 – 2 pb

Standard search modes

$m_H \lesssim 150$ GeV

look for narrow $H \to \gamma\gamma$ mass peak

- inclusive $m_{\gamma\gamma}$ spectrum
- in association with $W \to \ell\nu$ from WH, $t\bar{t}H$ production

$m_H \gtrsim 120$ GeV

$$H \to ZZ \to \ell^+\ell^-\ell^+\ell^-$$

$m_H \gtrsim 130$ GeV

$$H \to W^+W^- \to \ell^+\nu\,\ell^-\bar{\nu}$$ (Dittmar, Dreiner)

close hole around $m_H \approx 170$ GeV in $H \to ZZ \to 4\ell$ search

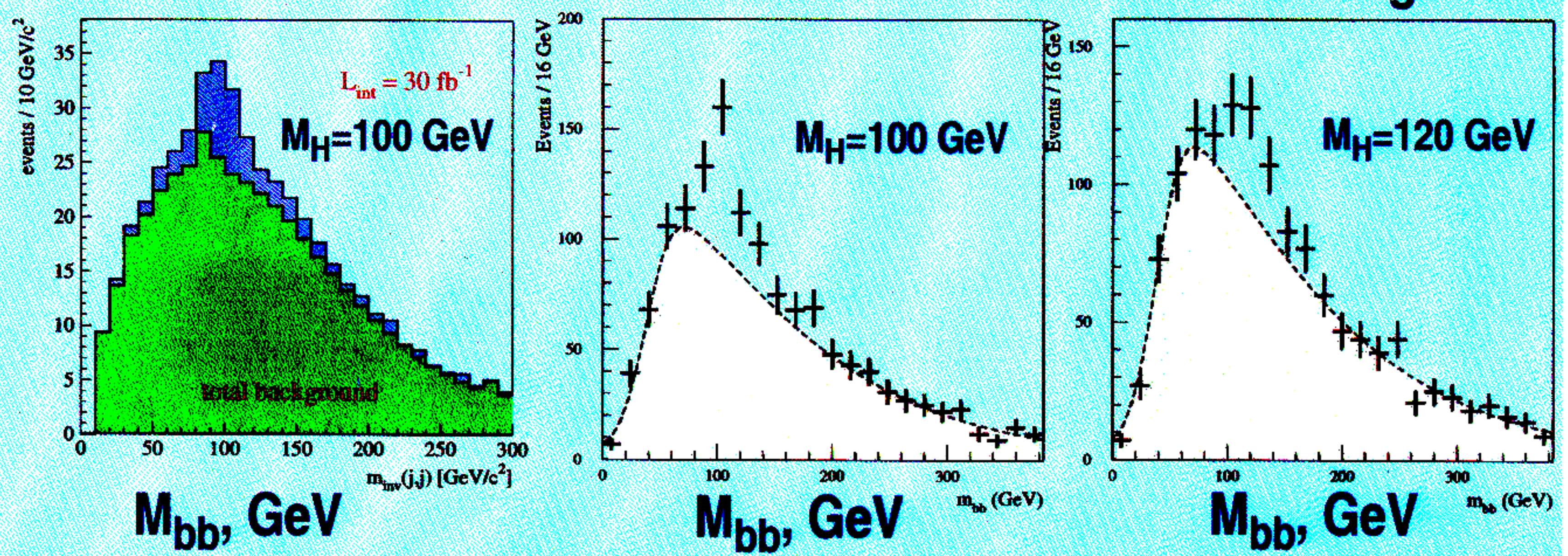
$m_H \lesssim 120$ GeV

$t\bar{t}H$ associated production
$H \to b\bar{b}$ measures Hbb coupling directly

ttH, H->bb in SM. with t-> l ν b, t-> j j b

requires an excellent b-tagging and calorimeter performance

CMS. 30 fb^{-1} low lumi ATLAS. 30 fb^{-1} low lumi + 70 fb^{-1} high lumi



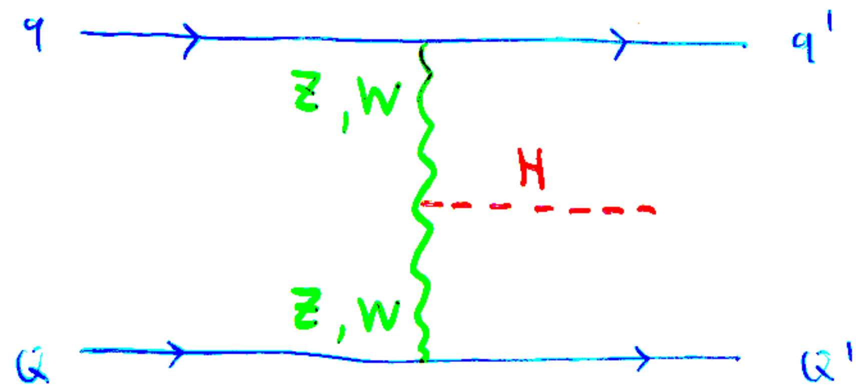
significance > 5 can be achieved for SM Higgs 80 < M_H < 120 GeV with 100 fb^{-1}

very important channel for MSSM parameter space coverage !

Nikitenko, Susy2k

NLO corrections: talks by Reina, Dittmaier

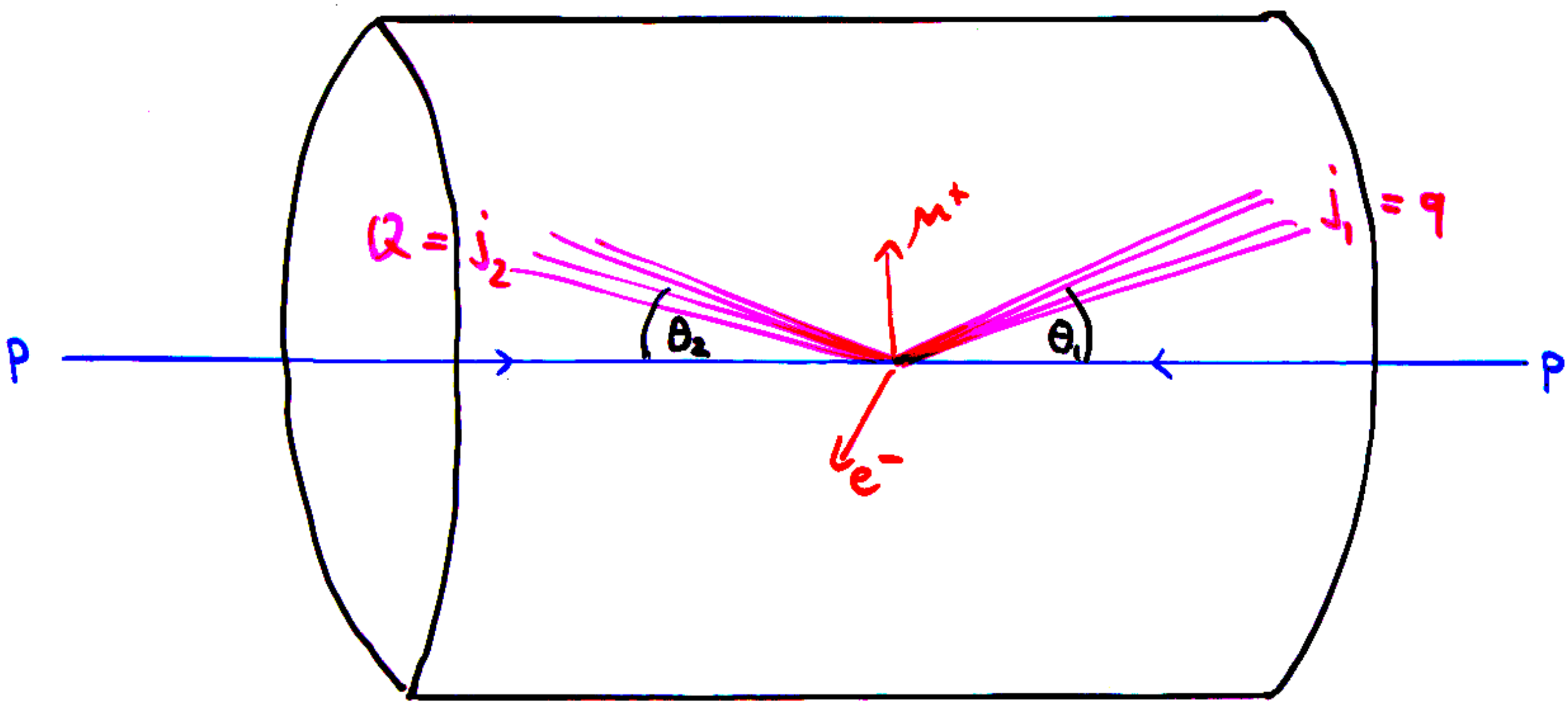
Exploit weak boson fusion (WBF)



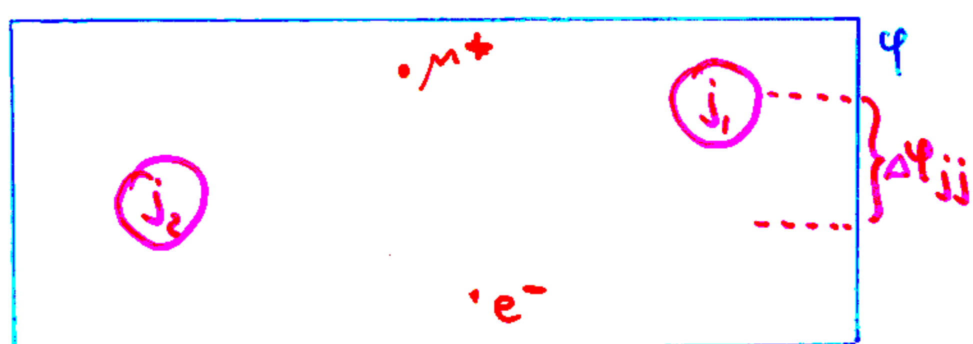
Characteristics:

- 2 forward tagging jets (q', Q')
  $(p_{Tj} > 20$ 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)

Generic picture of WBF event



legoplot:

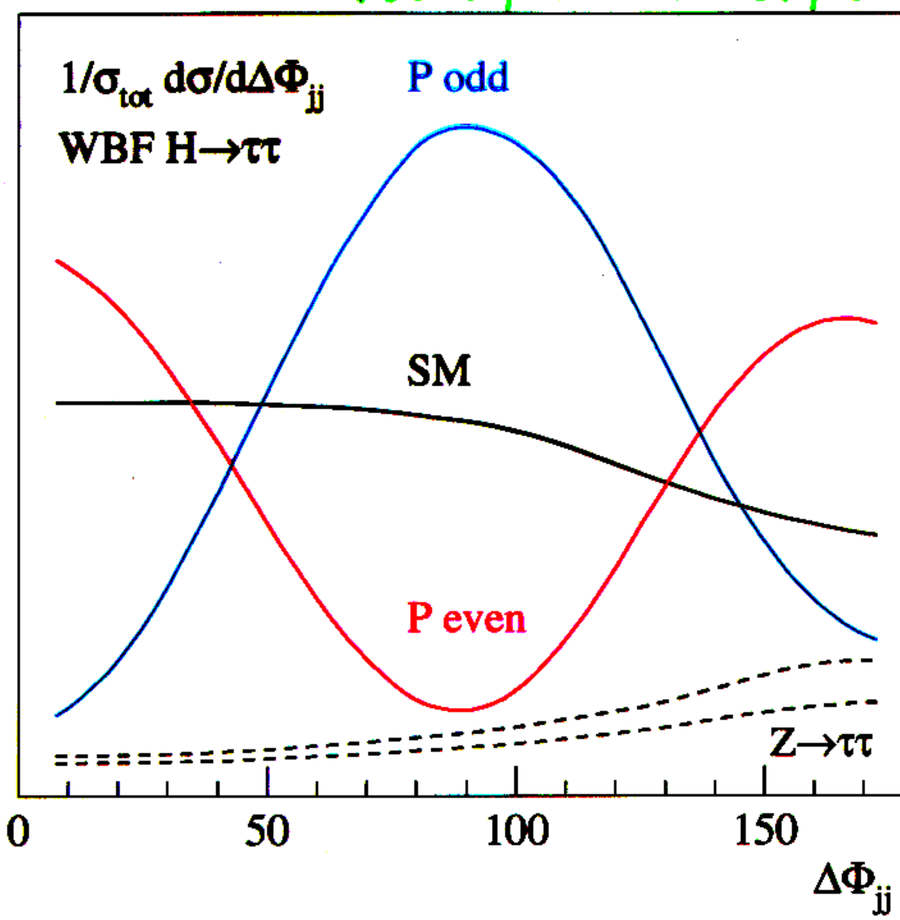


$$\eta = \frac{1}{2}\ln\frac{1+\cos\theta}{1-\cos\theta}$$

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

central jet veto: no extra $p_T > 20$ GeV jets between tag. jets jet-jet azimuthal angle $\Delta\varphi_{jj}$ determines tensor structure of HWW coupling

Plehn, Rainwater, Z



same for

$H \to \gamma\gamma$

$H \to \tau\tau$

$H \to WW$

SM : $H\, W^{+}_{\mu} W^{\mu}$

CP even: $H\, W^{+}_{\mu\nu} W^{\mu\nu}$

CP odd: $H\, W^{+}_{\mu\nu} W_{\rho\sigma}\, \varepsilon^{\mu\nu\rho\sigma}$

⇒ talk by T. Plehn

Parton level analyses available for specific decay channels

[Rainwater et al.]

$H \to \gamma\gamma$ hep-ph/9712271

$H \to WW$ hep-ph/9906218
00 12 351

$H \to \tau\tau$ hep-ph/9808468
9911385

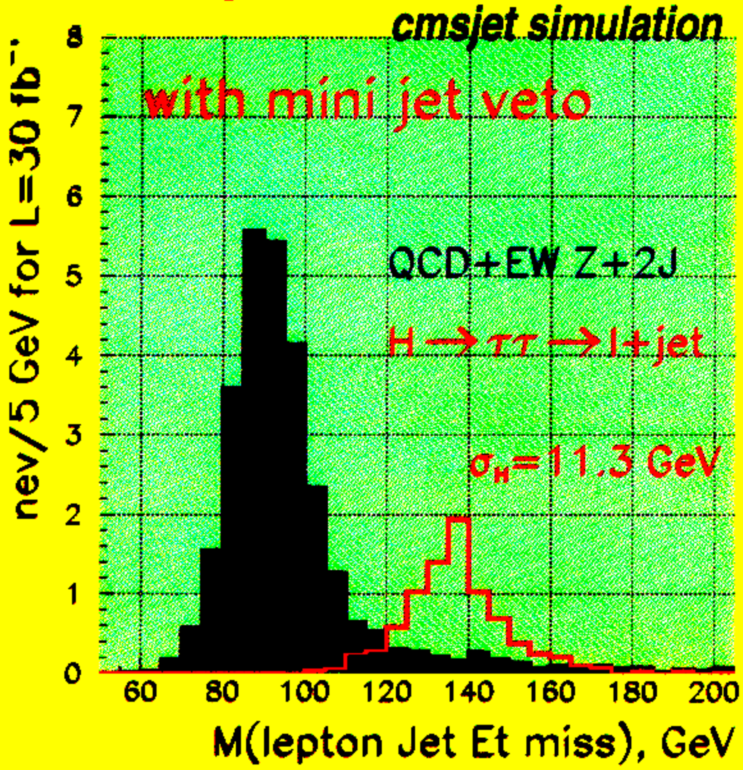
Full detector simulations are on the way

Nikitenko, SUSY2k

S. Ilyin, A. Nikitenko,(D. Zeppenfeld)

SM qq->qqH, H -> 2τ -> *l* + j

Preliminary results for low luminosirty



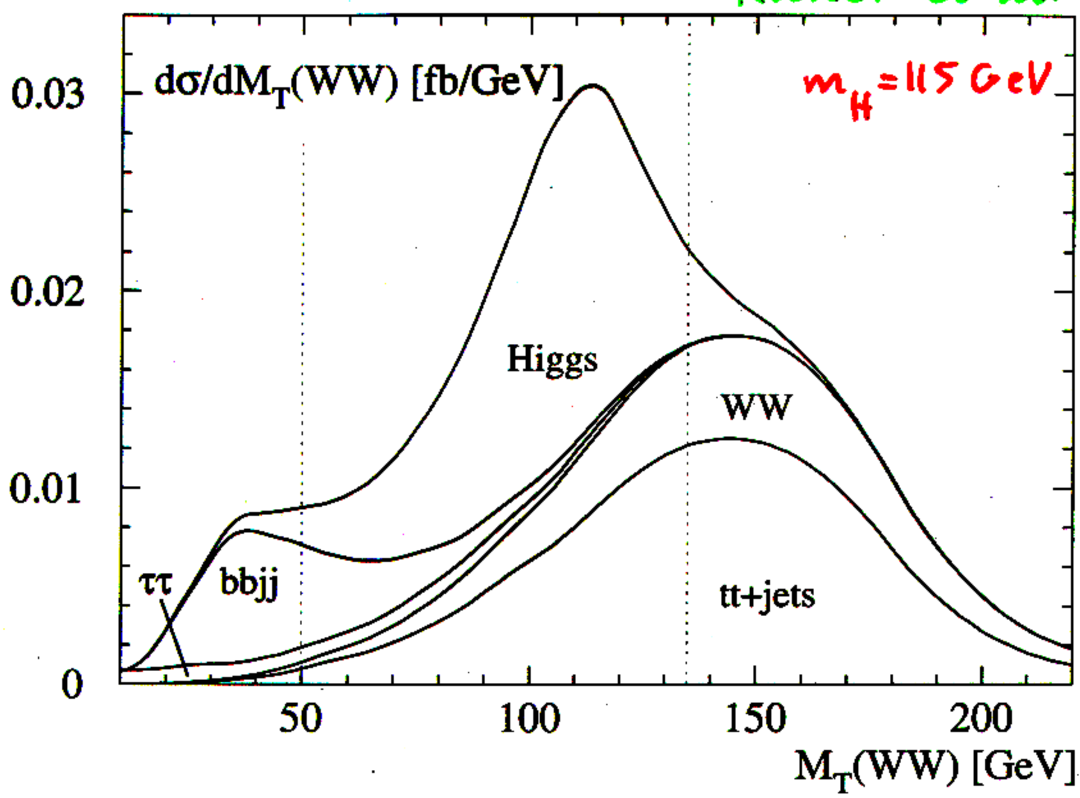
Data for 30 fb^{-1} at low luminosity running

Mass, GeV	115	125	135	145
σ, pb	4.49	4.15	3.81	3.57
Br, %	7.2	6.1	4.5	2.6
S	12.6	9.9	6.7(6.2)	3.6
B	5.5	2.3	1.5(1.1)	1.1

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

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}

What if the Higgs decays invisibly?

[Eboli & D.Z.]

In non-SM scenarios the Higgs boson may decay into invisible final states with large branching fraction

$h \to \chi_1^0 \chi_1^0$ neutralinos

$\to$ scalar gravitons

$\to$ majorons

$\to$ your (invisible) choice

Signal can be observed in WBF

Require:

2 jets $\quad p_{Tj} > 40$ GeV, $|\eta_j| < 5$

$|\eta_{j_1} - \eta_{j_2}| > 4.4$, $M_{jj} > 1.2$ TeV

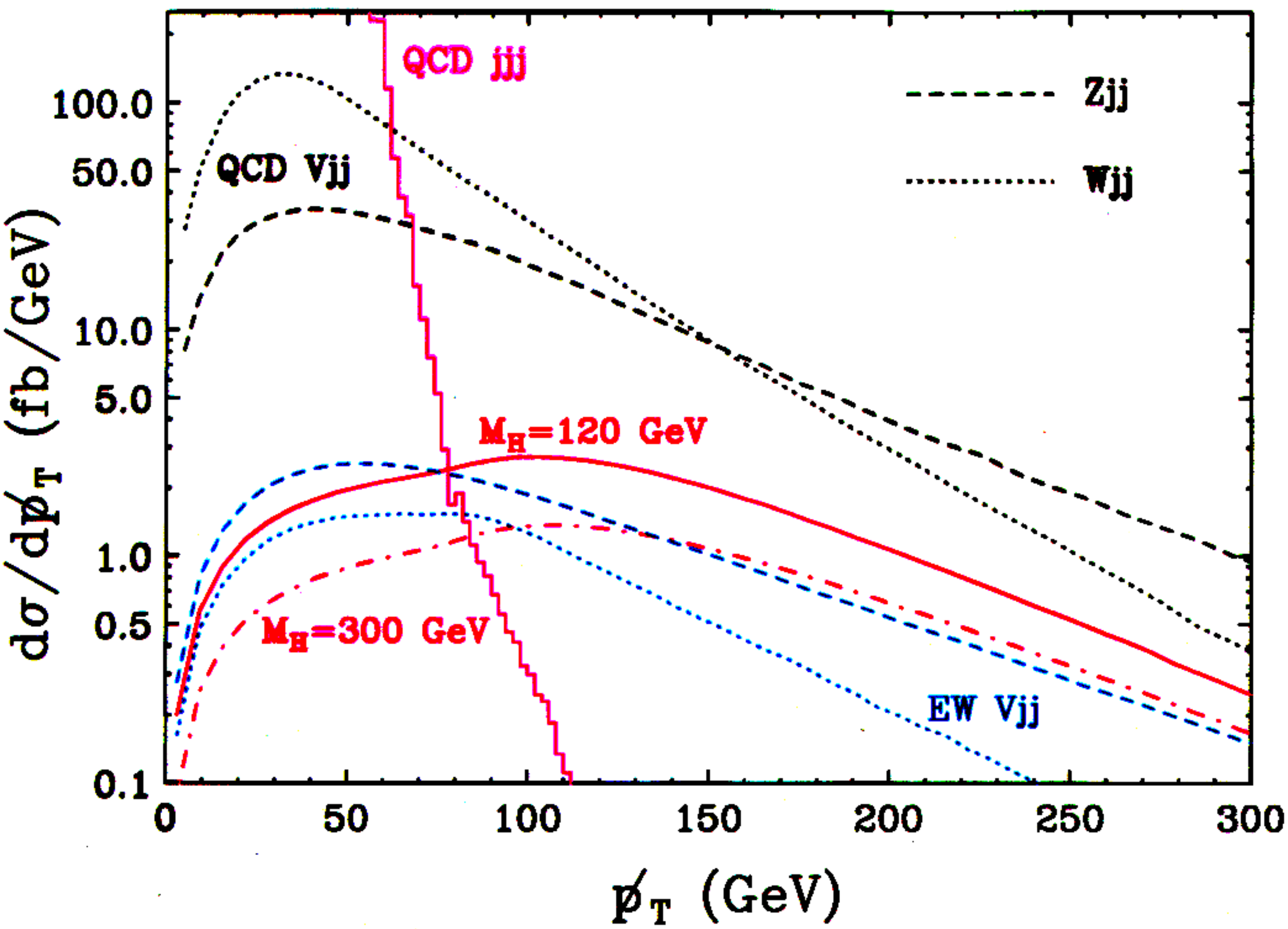
+ large $\not{p}_T$: $\quad \not{p}_T > 100$ GeV main backgrounds

$Z+jj$, $Z \to \nu\bar{\nu}$

$W+jj$, $W \to \ell\nu$ (ℓ is lost)

jjj (mismeasured, 1 jet lost)

$\Delta E/E = 0.5/\sqrt{E} \oplus 2\%$

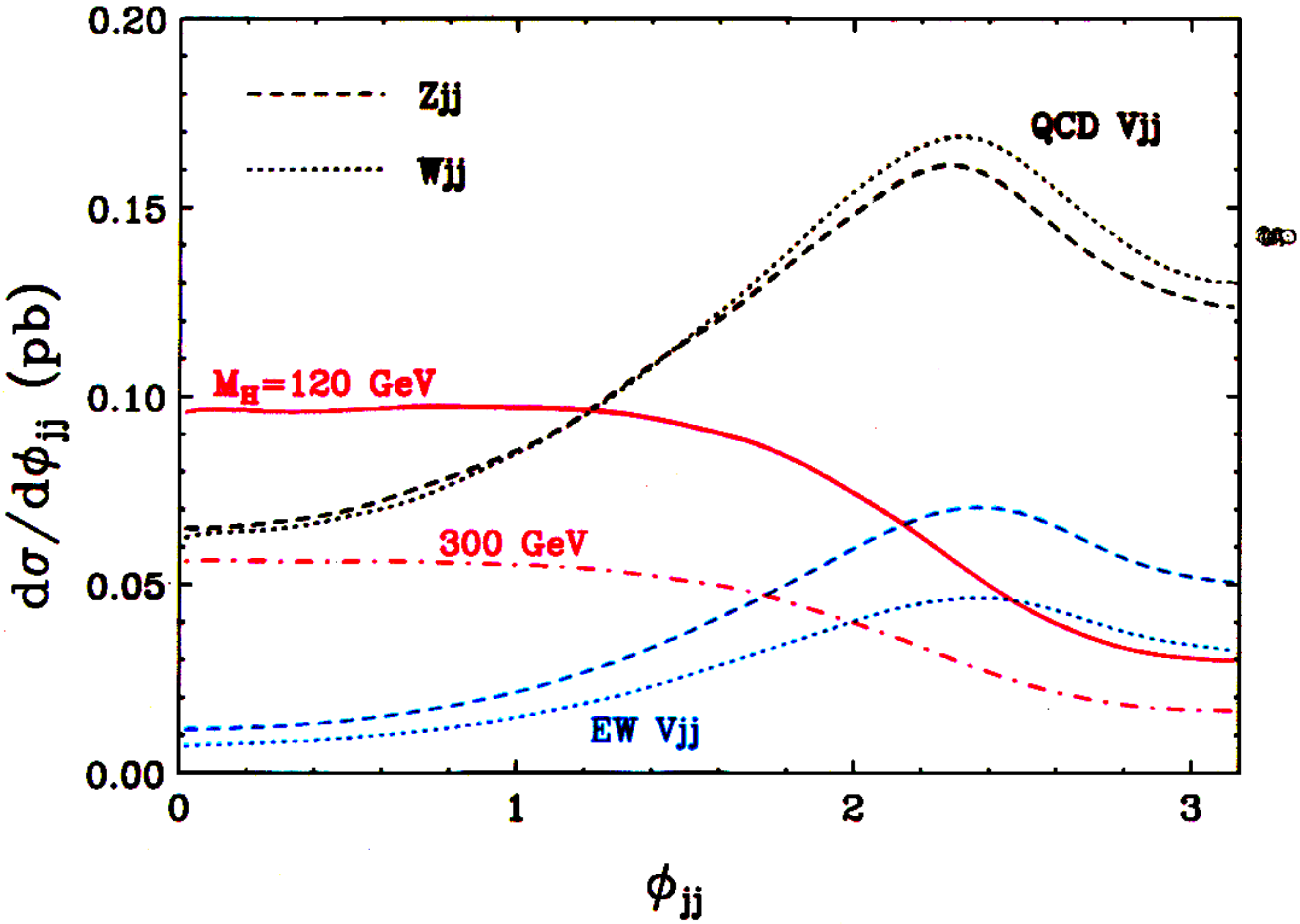


dominant QCD jj(j) background is eliminated by

$|\varphi_{j_1} - \varphi_{j_2}| < 2.6$

$\not{p}_T > 100$ GeV

Characteristic azimuthal angle dist.



presence of H → invisible mode significantly changes ϕ_{jj} distribution between 2 tagging jets

Obtain expected rates for $Z \to \nu\bar{\nu}$ etc. from observed

$Z\,jj$, $Z \to \ell^+\ell^-$

$W\,jj$, $W \to \ell\nu$

events: few $\times 10^3$

Expected error with $10\ \text{fb}^{-1}$: 3 %

	all φ_{jj}	$\varphi_{jj} < 1$
Σ bkgd	920 fb	170 fb
$m_H = 120$	$B \cdot 240$ fb	$B \cdot 97$ fb

$\Downarrow$

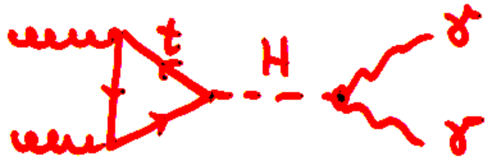
$10\ \text{fb}^{-1}$: $B\sigma(qq \to qqH, H \to \text{invisible}) < 12.5\ \text{fb}$ @ 95% CL

$10\ \text{fb}^{-1}$ of LHC data, and assuming a SM production cross section in WBF

$\Rightarrow$ $B(H \to \text{invisible}) < 13\%$ @ 95% CL

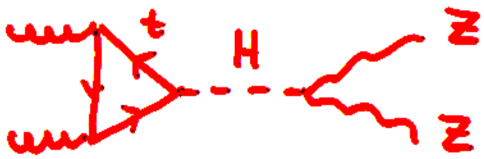
Summary of main SM Higgs channels

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



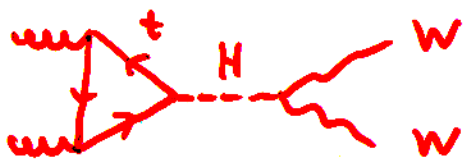
$$\sim \Gamma_g \frac{\Gamma_\gamma}{\Gamma} = Y_\gamma$$

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



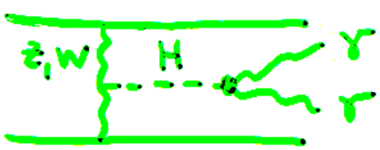
$$\sim \Gamma_g \frac{\Gamma_Z}{\Gamma} = Y_Z$$

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



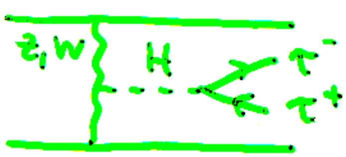
$$\sim \Gamma_g \frac{\Gamma_W}{\Gamma} = Y_W$$

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



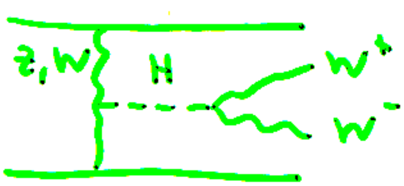
$$\sim \Gamma_W \frac{\Gamma_\gamma}{\Gamma} = X_\gamma$$

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



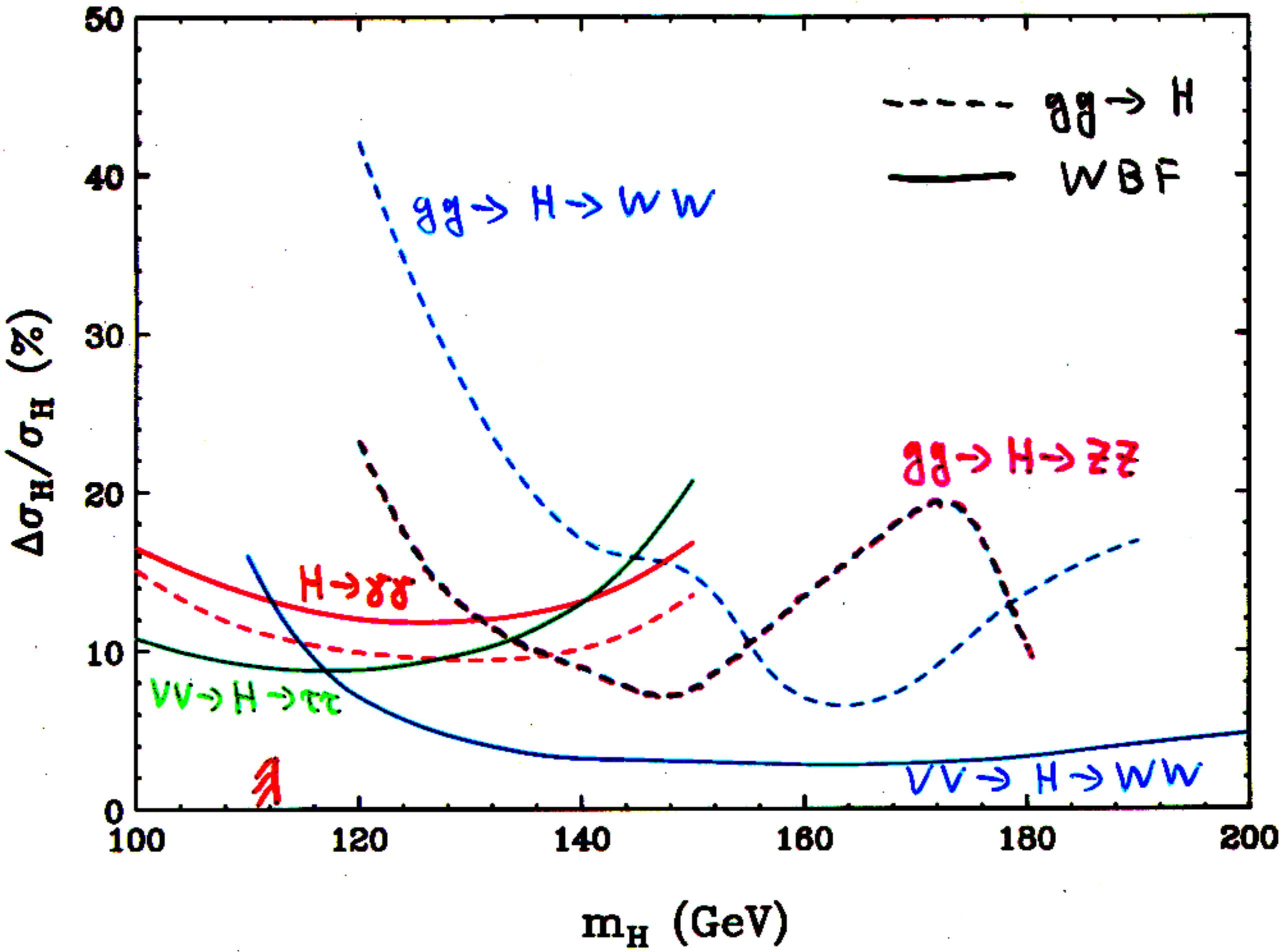
$$\sim \Gamma_W \frac{\Gamma_\tau}{\Gamma} = X_\tau$$

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



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

Statistical errors with 200 fb^{-1}



Systematic errors:

QCD / pdf uncertainties

± 5% for WBF

± 20% for gluon fusion

Luminosity / acceptance uncertainty

± 5%

Largely cancel in cross section ratios

→ Γ_τ/Γ_W, $[\Gamma_g/\Gamma_W]$, Γ_γ/Γ_W, Γ_Z/Γ_W

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

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

$$+ \tilde{X}_\gamma + Y_W$$

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

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

and

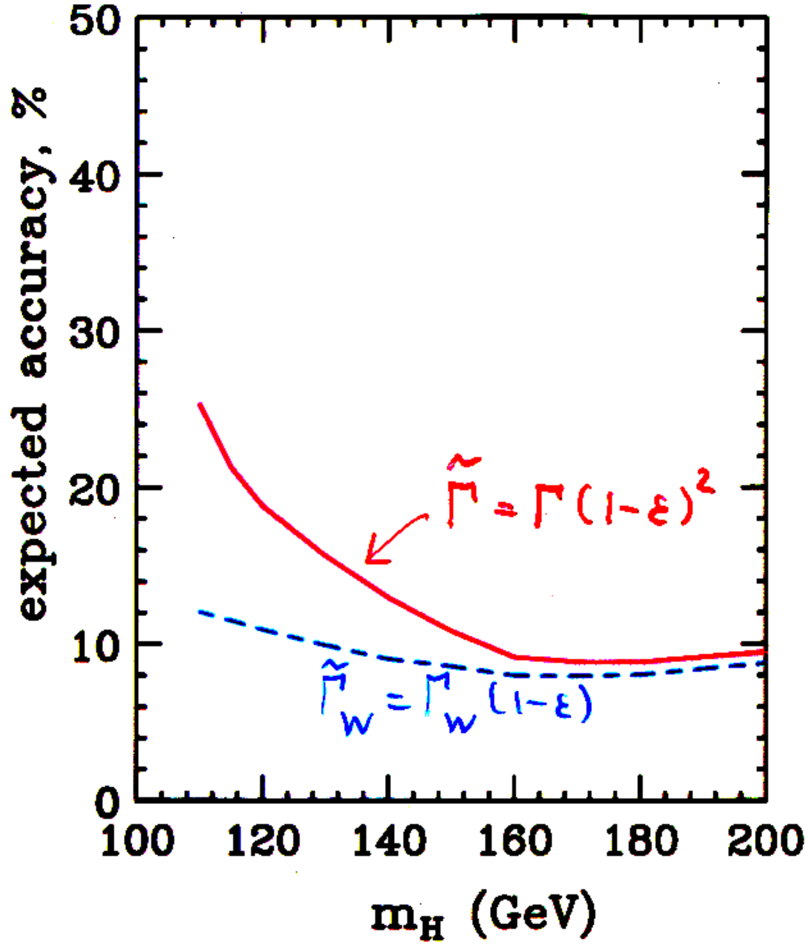
$$\tilde{\Gamma} = \frac{\tilde{\Gamma}_W^2}{X_W} = \frac{\Gamma_W^2(1-\varepsilon)^2}{\Gamma_W \, \Gamma_W/\Gamma} = \Gamma(1-\varepsilon)^2$$

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

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

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

Expected accuracy with 200 fb^{-1} of data

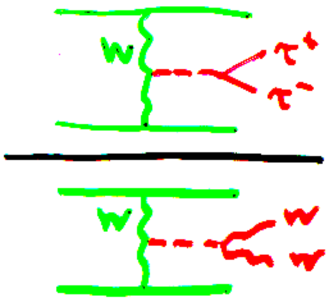


- 5 % measurement of HWW coupling
- 10 – 20 % measurement of Higgs decay width

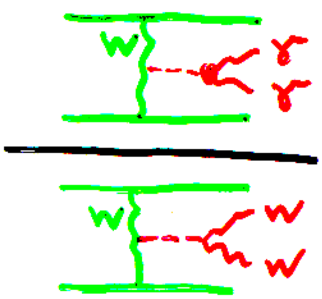
$\Gamma_{total} = \tilde{\Gamma}/(1-\varepsilon)^2$ requires measuring

$$\sigma(qq \to qqH,\ H \to WW) \sim \Gamma_W^2/\Gamma_{total}$$

Combine with cross section ratios



7 - 10 % measurement of $H\tau\tau$ Yukawa coupling



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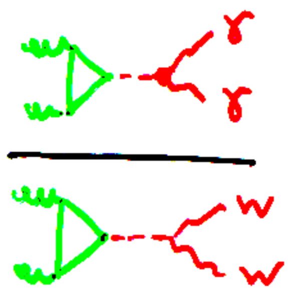
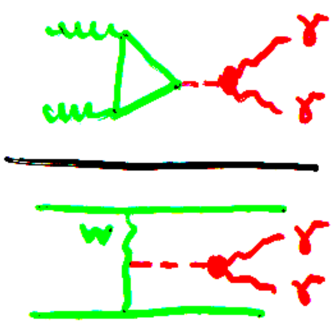


7 - 10 % measurement $H\gamma\gamma$ coupling



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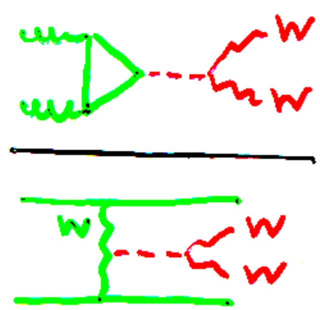


10 - 15 % measurement of Hgg coupling $\Rightarrow Ht\bar{t}$ coupling

+ 5 % measurement of HWW coupling

Pre-LHC challenges

Improve understanding of QCD properties of H signal and backgrounds

- NLO calculations

  $t\bar{t}H$ [talks by Reina, Dittmaier]

  needed for many backgrounds

- better modeling of jet activity in hard scattering events

  → central jet veto efficiencies

  learn from Tevatron

  $t\bar{t} \to b\bar{b}WW$ + jets

  W/Z + n jets

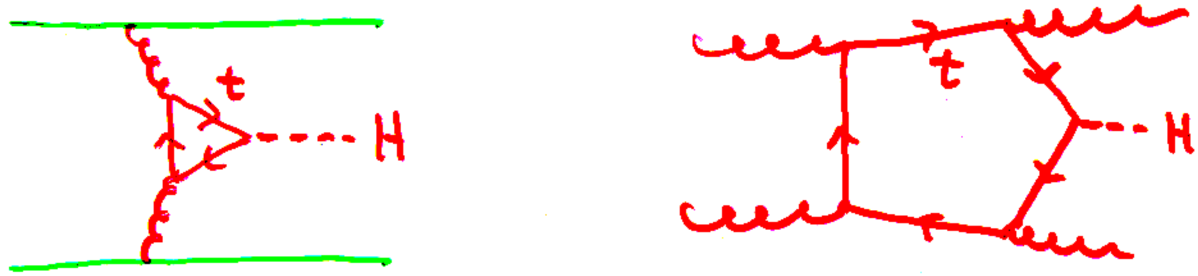
- NNLO calculations

  $gg \to H$ in $m_t \to \infty$ limit

  [talk by Harlander]

- Separation of gluon fusion & WBF

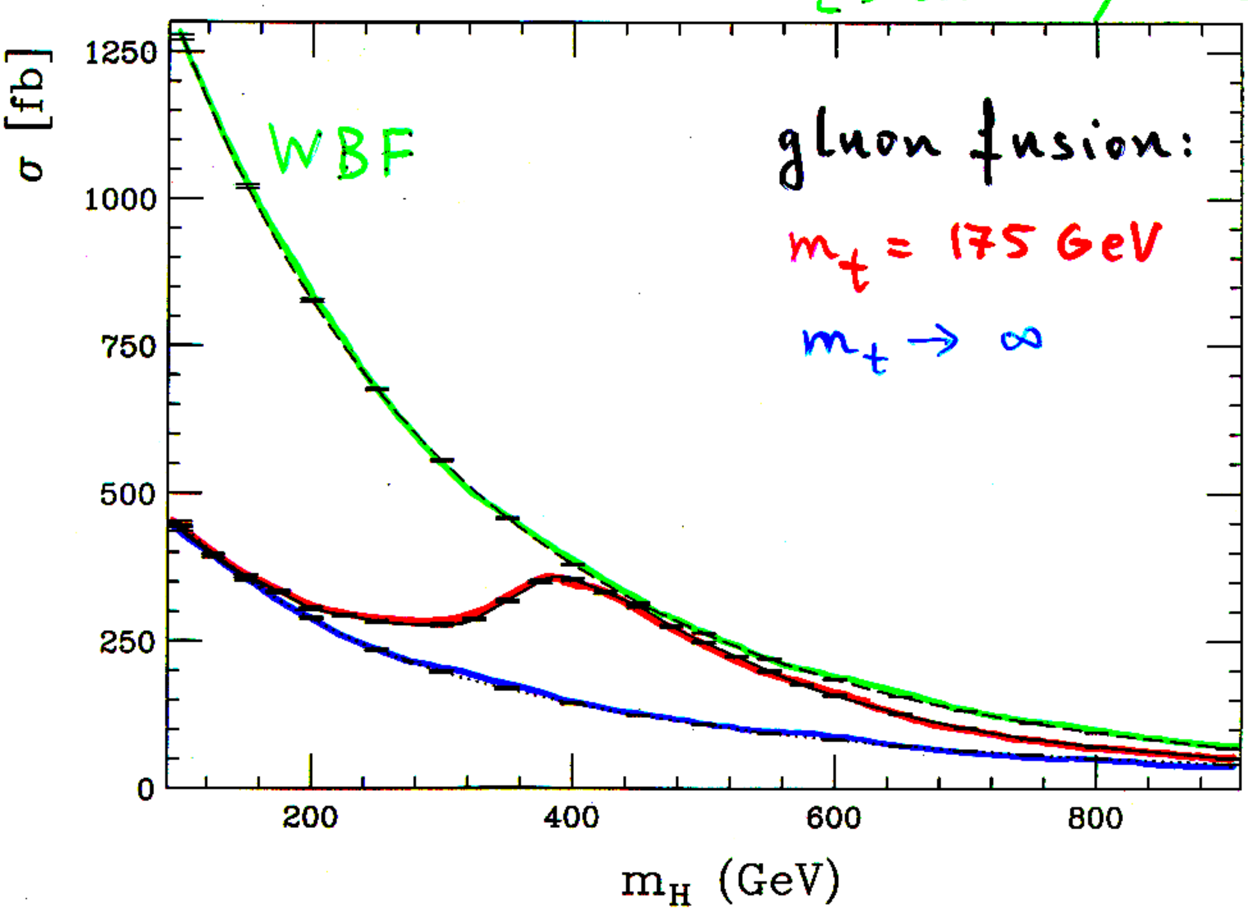
What is background to WBF from



$\sigma(\text{gluon fusion}) \ll \sigma_{WBF}$ for typical cuts

$p_{Tj} > 20$ GeV, $\Delta\eta_{jj} > 4.2$, $m_{jj} > 600$ GeV

[→ talk by Oleari]



Conclusions

LHC has excellent potential for studying dynamics of the Higgs sector.

Much additional QCD work is needed to sharpen tools for measuring Higgs couplings at the LHC.