Higgs coupling measurements at LHC:
challenges for QCD

D. Zeppenfeld
UW-Madison

Intro: LHC goals in Higgs physics

Overview of channels

Accuracy of coupling extraction

Requirements for signal and background predictions

Introduction

Higgs search ≡ search for dynamics of $SU(2) \times U(1)$ breaking

→ discover Higgs boson

→ measure Higgs couplings

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.

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

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

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

Gauge interactions of non-vev scalar

$$\sim \phi^+ \phi W \,, \quad \phi^+ \phi WW$$

are bilinear in ϕ

- Probe fermion mass generation

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

measure relation between

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

$\Rightarrow$ measure Higgs' Yukawa coupl.

$H\tau\tau$

Hbb

Htt etc.

measure couplings to gauge bosons

HWW

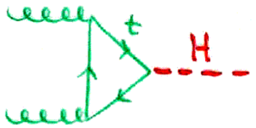
HZZ

$H\gamma\gamma$

Hgg

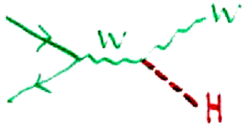
Principal production modes at hadron colliders

gluon fusion



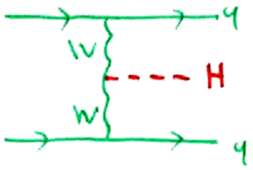
Tevatron LHC

WH/ZH production



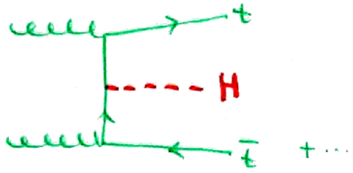
Tevatron

weak boson fusion



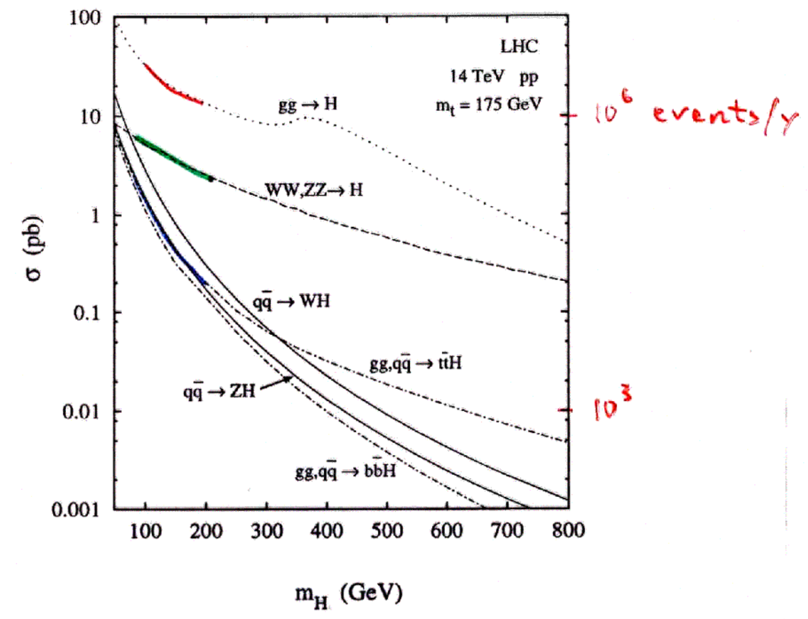
LHC

tt̄H production



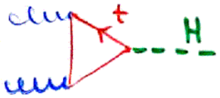
LHC

LHC cross sections



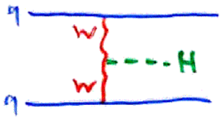
Dominant production processes

gluon fusion



10-30 pb

weak boson fusion



3-5 pb

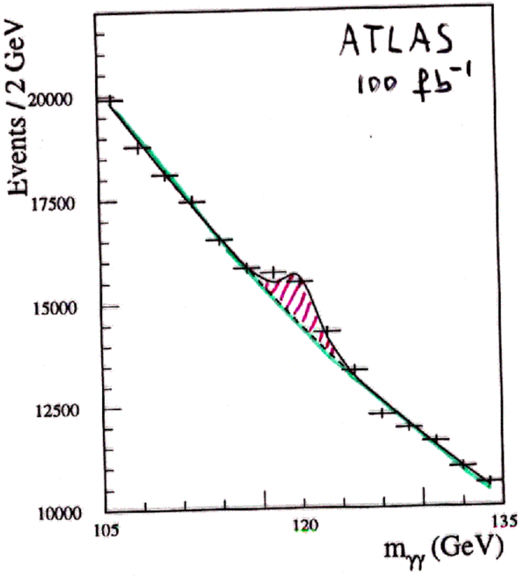
tt̄H production 0.2-2 pb

$H \to \gamma\gamma$

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

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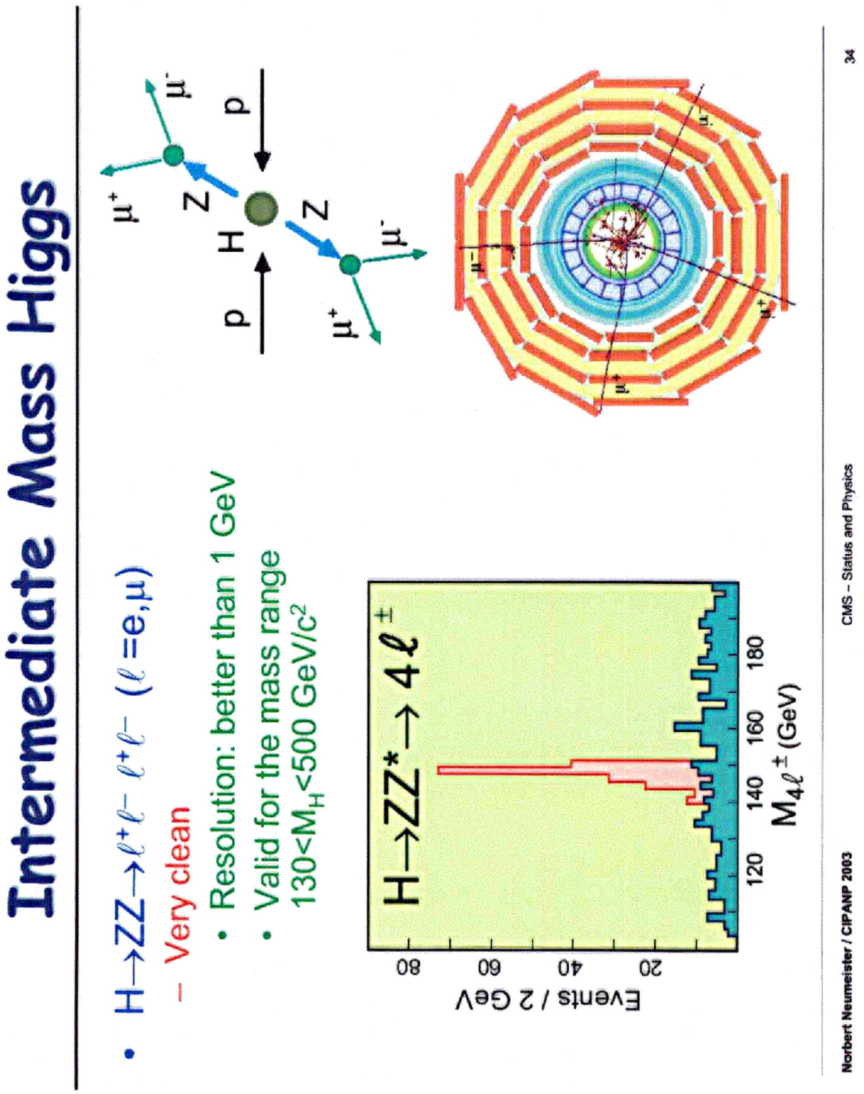

Intermediate Mass Higgs

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

Norbert Neumeister / CIPANP 2003

CMS – Status and Physics

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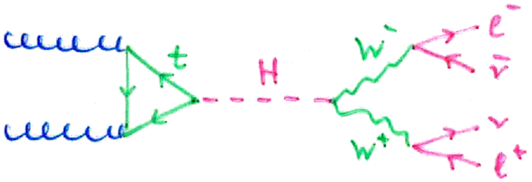
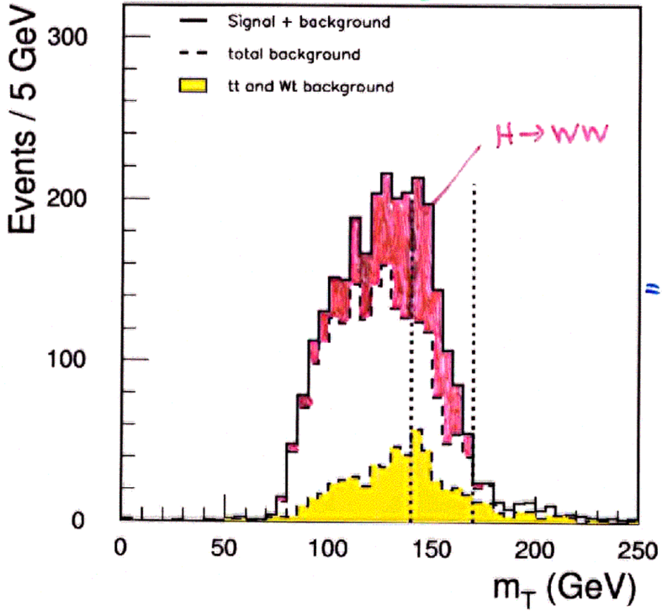
$H \to WW \to \ell^+\ell^-\nu\bar\nu$ (inclusive search)



Exploit $\ell^+\ell^-$ angular correlations [Dittmar Dreiner]

ATLAS TDR



$m_H = 170$ GeV

transverse mass m_T

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

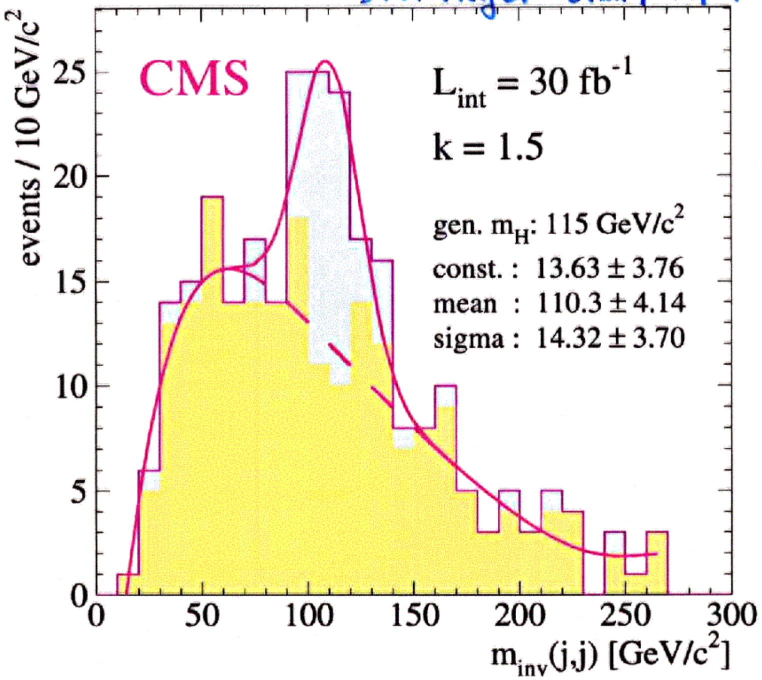
Background and signal have similar shape

⇒ 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



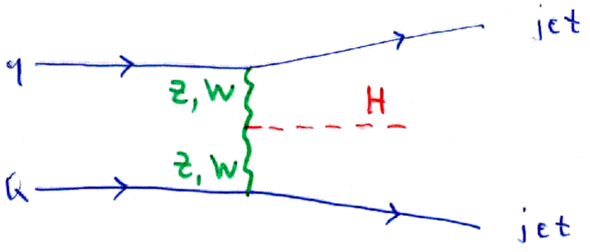
Y_t = $t\bar tH$ Yukawa coupling

⇒ measure

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

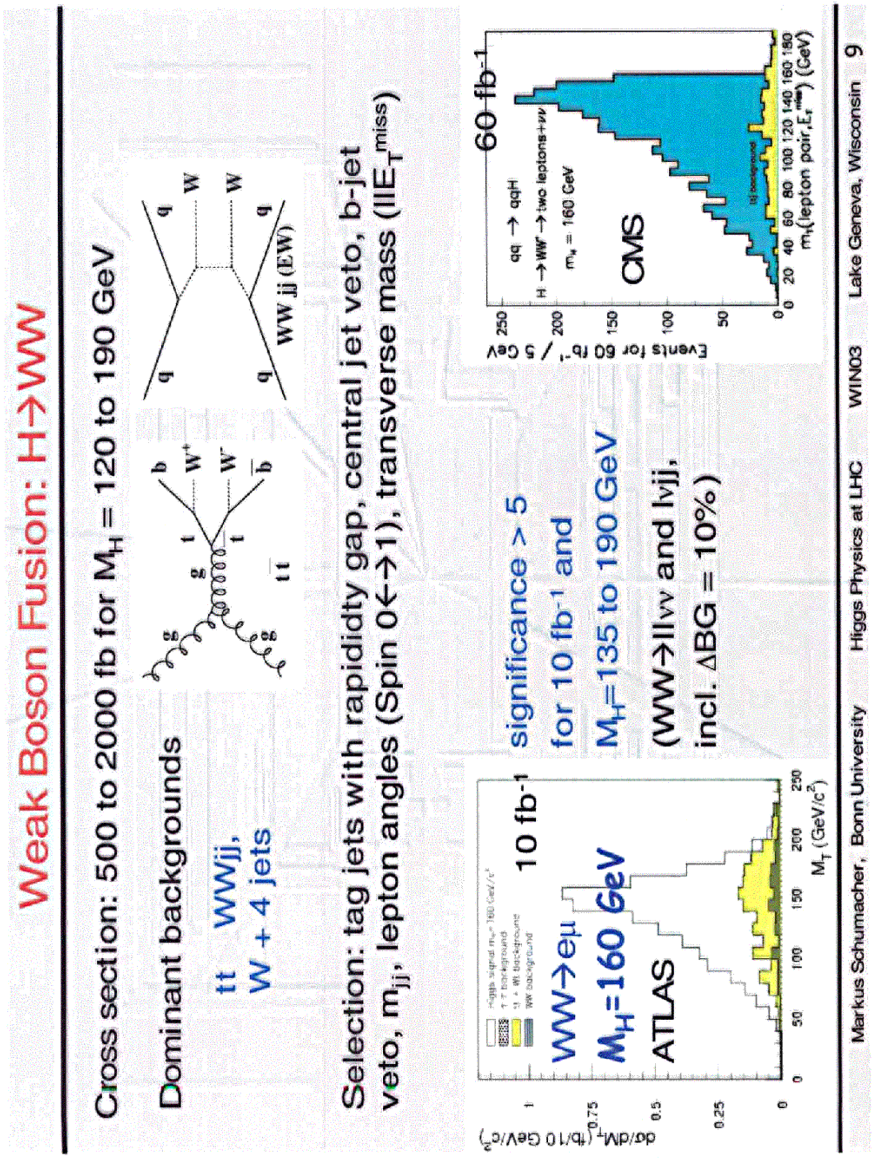
Weak boson fusion (WBF) has emerged as a powerful tool for

- Higgs search } at LHC
- Higgs analysis }



- sizable rate (~$\frac{1}{5}$ of gluon fusion)
- 2 forward tagging jets for efficient background rejection
- color singlet exchange: no central jets
- well known SM cross section: small NLO correction of order 10%.

WBF is crucial for Higgs coupling measurements: Hττ & HWW/HZZ



Weak Boson Fusion: H→WW

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

Dominant backgrounds

$t\bar{t}$

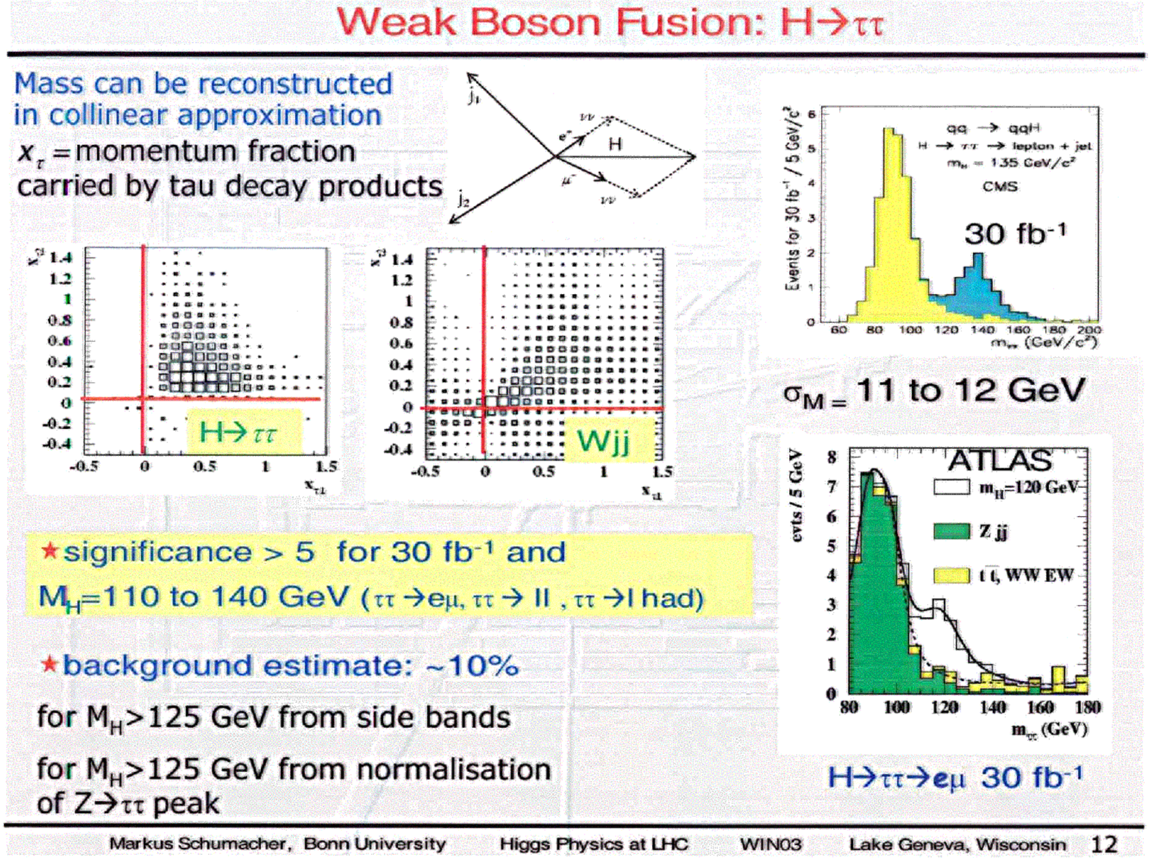
WWjj,

W + 4 jets

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

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

Markus Schumacher, Bonn University Higgs Physics at LHC WIN03 Lake Geneva, Wisconsin 9



Weak Boson Fusion: H→ττ

Mass can be reconstructed in collinear approximation

x_τ = momentum fraction carried by tau decay products

σ_M = 11 to 12 GeV

★significance > 5 for 30 fb^{-1} and M_H=110 to 140 GeV (ττ →eμ, ττ → ll , ττ →l had)

★background estimate: ~10%

for M_H>125 GeV from side bands

for M_H>125 GeV from normalisation of Z→ττ peak

H→ττ→eμ 30 fb^{-1}

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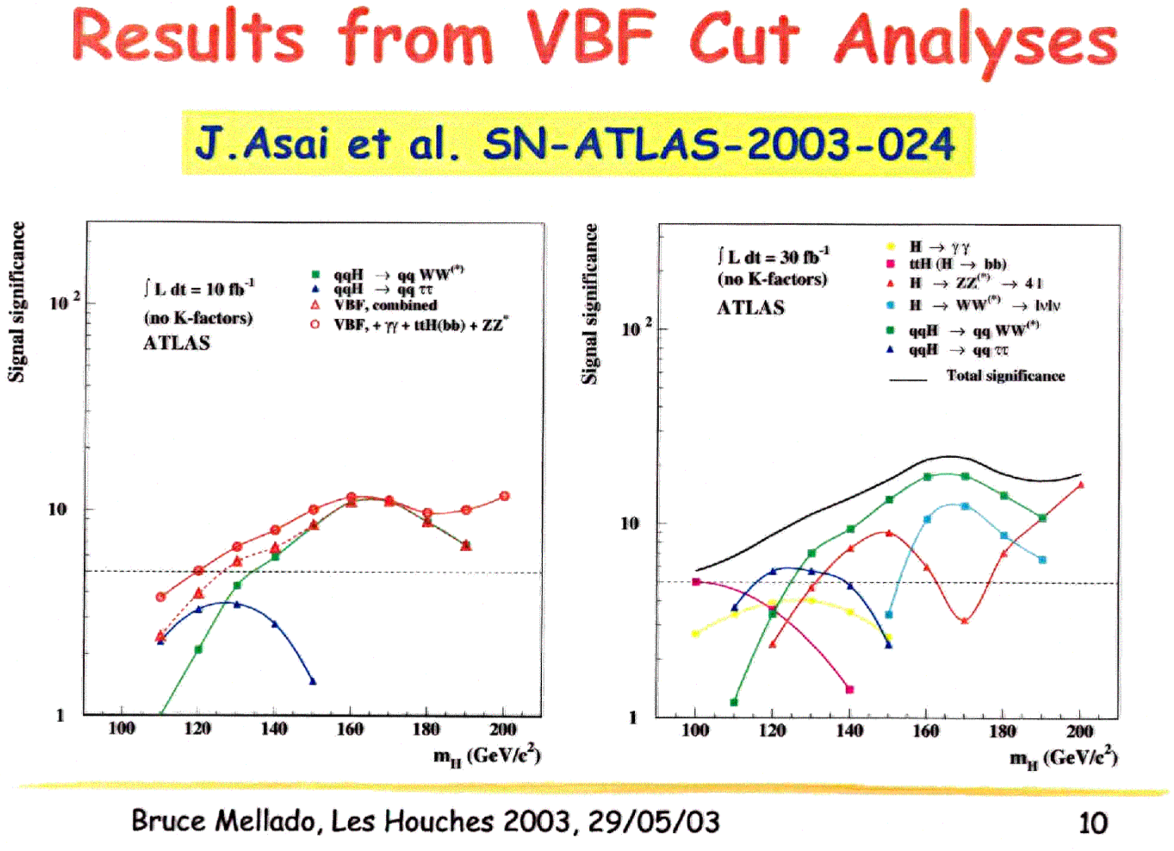

Results from VBF Cut Analyses

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

Bruce Mellado, Les Houches 2003, 29/05/03 10

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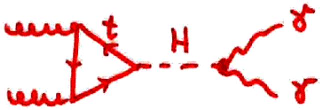
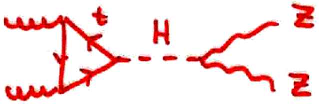
Summary of main SM Higgs channels

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



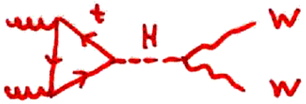
$\sim \Gamma_g \frac{\Gamma_\gamma}{\Gamma} = Y_\gamma$

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



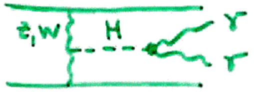
$\sim \Gamma_g \frac{\Gamma_Z}{\Gamma} = Y_Z$

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



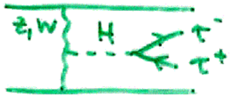
$\sim \Gamma_g \frac{\Gamma_W}{\Gamma} = Y_W$

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



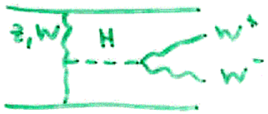
$\sim \Gamma_W \frac{\Gamma_\gamma}{\Gamma} = X_\gamma$

$qq \to qqH,\ H \to \tau\tau$ 100 GeV $\le m_H <$ 150 GeV



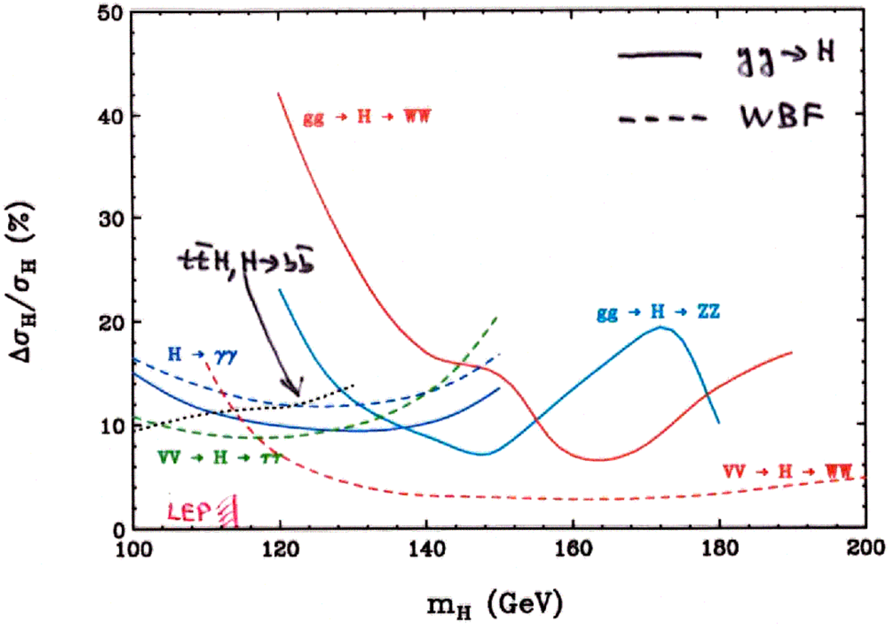
$\sim \Gamma_W \frac{\Gamma_\tau}{\Gamma} = X_\tau$

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

± 5%

Largely cancel in cross section ratios

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

Generic problem for model-independent analysis at LHC:

$$\text{observed} \equiv \hat{\Gamma} = \frac{\Gamma_p \Gamma_d}{\Gamma} = \frac{x\Gamma_p \; x\Gamma_d}{x^2 \Gamma}$$

limits on rescaling factor x

a) total width = sum of partial widths

$$x^2\Gamma = \sum_i x\Gamma_i \geq \underbrace{\sum}_{i\in\{p,d \mid \text{obser.}\}} x\Gamma_i$$

$$\Rightarrow x \geq \sum_{i\in\text{obser.}} \frac{\Gamma_i}{\Gamma} \quad = \text{order } 1$$

observation of production puts lower bound on $x\Gamma_p$.

b) total width < experimental resolution (or is measured directly!)

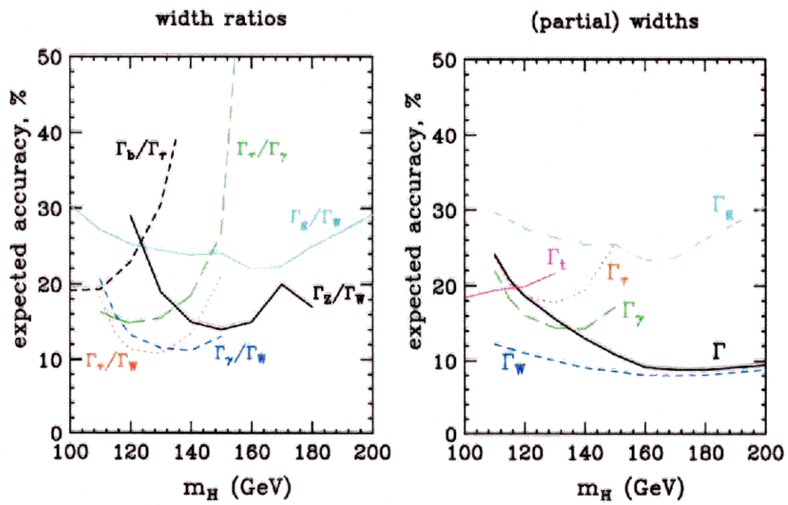
see $H \to \gamma\gamma$ or $H \to 4\ell$

$$\Rightarrow \quad x \lesssim \sqrt{\frac{1\,\text{GeV}}{\Gamma}}$$

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

Assume 100 fb^{-1} of data in each of two detectors



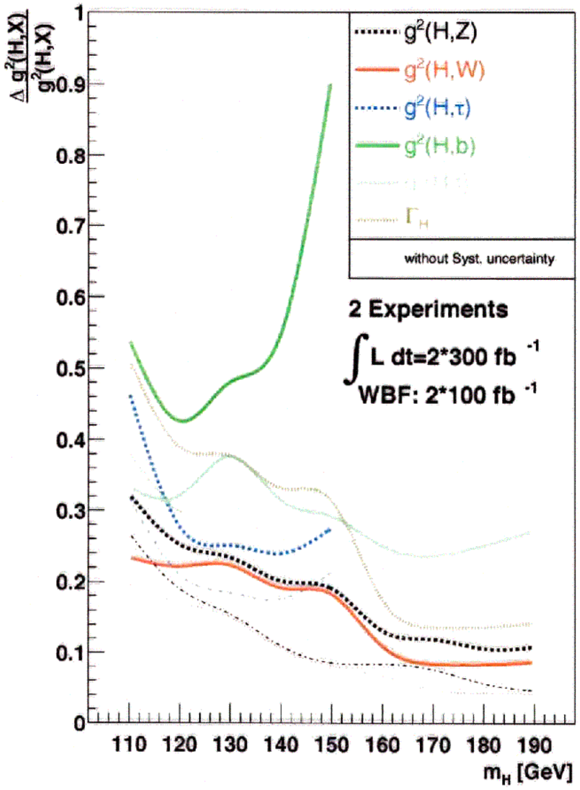
Coupling ratios may differ from SM values in generic models

Example: Large bottom squark corrections to the *hbb* vertex in SUSY models

Assume Higgs doublets/singlets only

$\Longrightarrow g^2_{HWW} = (g^2_{HWW})^{SM} \sin^2(\alpha - \beta) < (g^2_{HWW})^{SM}$

Perform global fit to couplings for expected LHC data



Les Houches
2003

fit allows new particles in $H \to \gamma\gamma$, $H \to gg$ loops and open exotic channels

QCD requirements

Signal: would like to have theory errors on production cross section at 5-10% level

$\sigma(gg \to H)$	±10-20% @NNLL	→ Harlander → Grazzini
$\sigma(WBF)$	±4% @NLO	
$\sigma(t\bar{t}H)$	±10-15% @NLO	→ Reina

QCD corrections are available for all relevant production processes

- Would like to have NLO MC for $t\bar{t}H$ including $t \to bW$ in narrow width approx.
- interface with parton shower MC
- separation of Hjj events:
  "$gg \to Hgg$" vs. WBF

Backgrounds

(1) Narrow resonances: $H \to \gamma\gamma$, $H \to ZZ \to 4\ell$

obtain background experimentally
from sideband analysis

(2) $H \to \tau\tau$ in WBF

dominant backgrounds: $(Z \to \tau\tau) + 2$ jets
NLO MC's are available
Measure bkgd in $Z \to \mu^+\mu^-$ events

(3) $H \to b\bar{b}$ in $t\bar{t}H$ production

dominant background: $t\bar{t}b\bar{b}$

need background shape at 10% level

→ sideband analysis with LO MC

NLO calculation ???

(4) $H \to WW \to e^+\nu\, e^-\bar{\nu}$

dominant background: $t\bar{t} \to W^+W^-b\bar{b}$

(a) inclusive search (Grazzini)

$\sigma(t\bar{t}) < \sigma(tbW)$ after severe jet veto

LO: Kauer

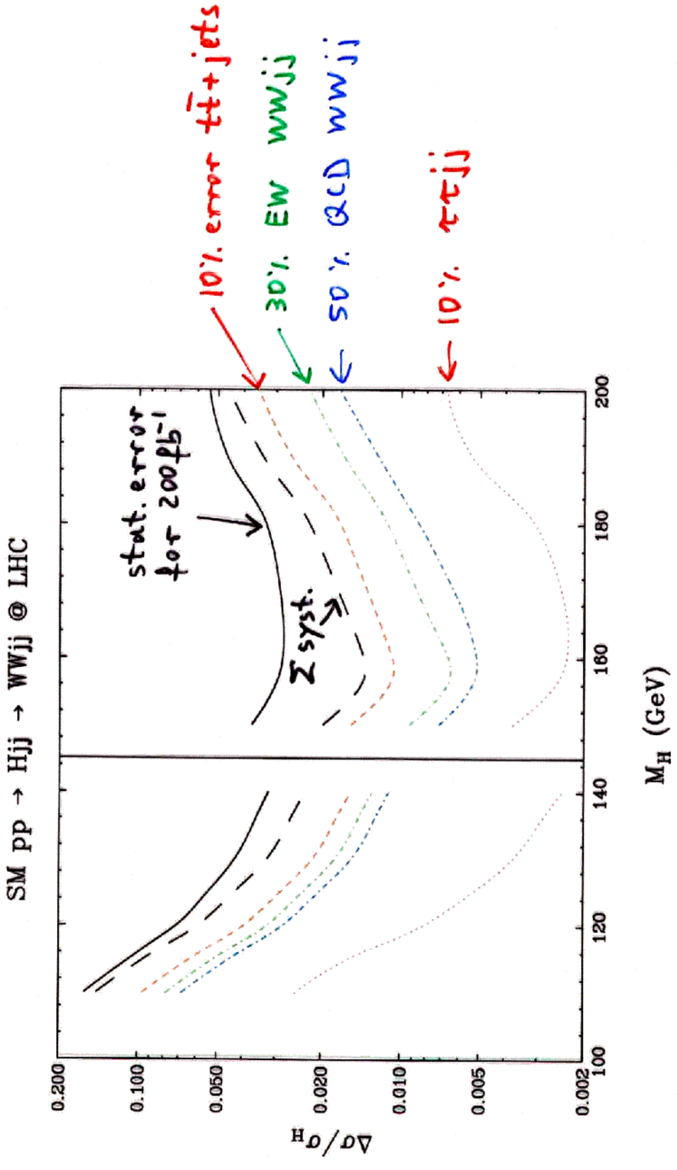
5% normalization uncertainty probably
requires NLO calculation including
off-shell effects

(b) WBF: $H+jj \to WWjj$

need $t\bar{t}j$ @ NLO

off-shell effects give ~15% correction
at LO

Contributions to Higgs measurement errors for σ_{WBF}



Other areas where improvement is needed

- Use of central jet veto for
  - WBF
  - $t\bar{t} \to WWb\bar{b}$ suppression
- disentangling WBF and $gg \to Hgg$

Conclusion:

Higgs discovery is "easy"

Higgs measurements are the true challenge