INTRODUCTION TO ELECTROWEAK THEORY AND HIGGS PHYSICS

Dieter Zeppenfeld
Universität Karlsruhe, Germany

Second CERN-Fermilab Hadron Collider Physics Summer School, June 6-15, 2007

Wednesday:

- Theoretical introduction

Yesterday:

- Constraints on the Higgs
- Supersymmetric extension

Today:

- Higgs boson decay
- Higgs boson signals at LHC

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

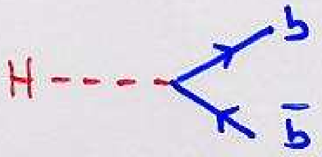
$$W, Z, t, b, \tau$$

Consider

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

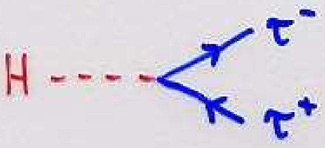
Main Higgs decay channels

$H \to b\bar{b}$



$m_H \lesssim 150$ GeV

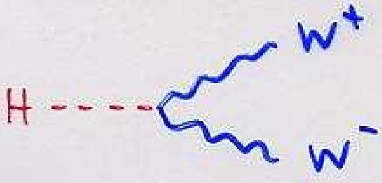
$H \to \tau^+\tau^-$



$m_H \lesssim 140$ GeV

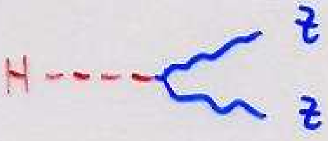
and into gauge bosons

$H \to W^+W^-$



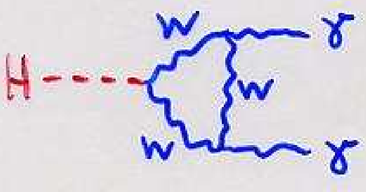
$m_H \gtrsim 120$ GeV

$H \to ZZ$



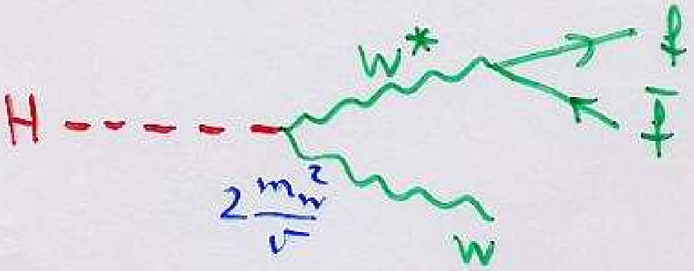
$m_H \gtrsim 120/180$ Ge

$H \to \gamma\gamma$



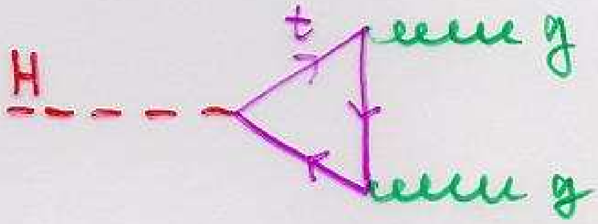
$m_H \leq 150$ Ge

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

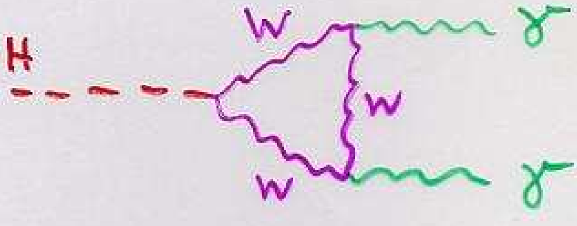


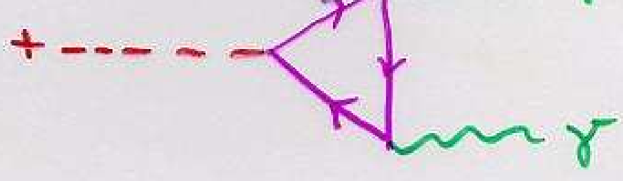
Loop decays

$H \to gg$



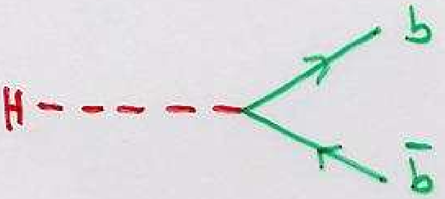
$H \to \gamma\gamma$





Higgs decays

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



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

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

QCD radiative corrections are important

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

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

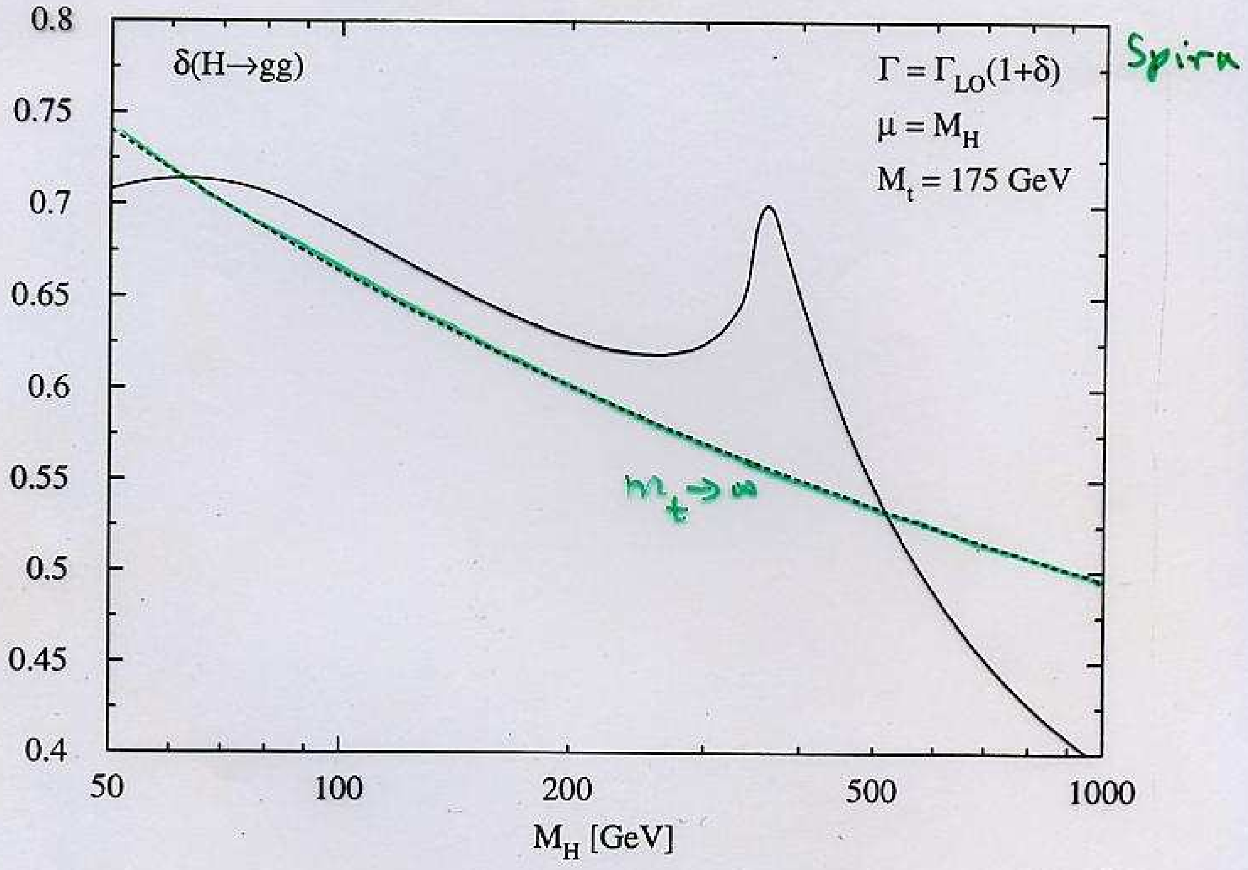
- include 2 loop QCD corrections

f	m_f	$m_f(100\text{ GeV})$
b	4.7 GeV	2.42 GeV
c	1.2 GeV	0.62 GeV
τ	1.8 GeV	1.8 GeV

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

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

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

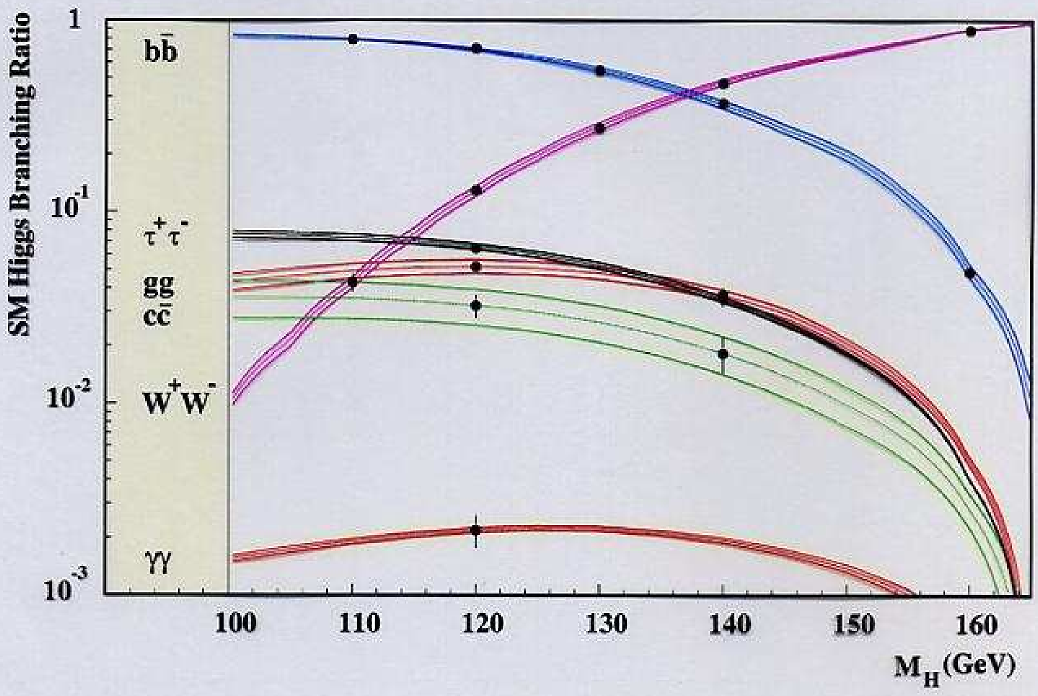


Radiative corrections for various decay modes implemented in HDECAY

Djouadi, Kalinowski, Spira, hep-ph/9704448

Continuously updated for SM & MSSM

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%

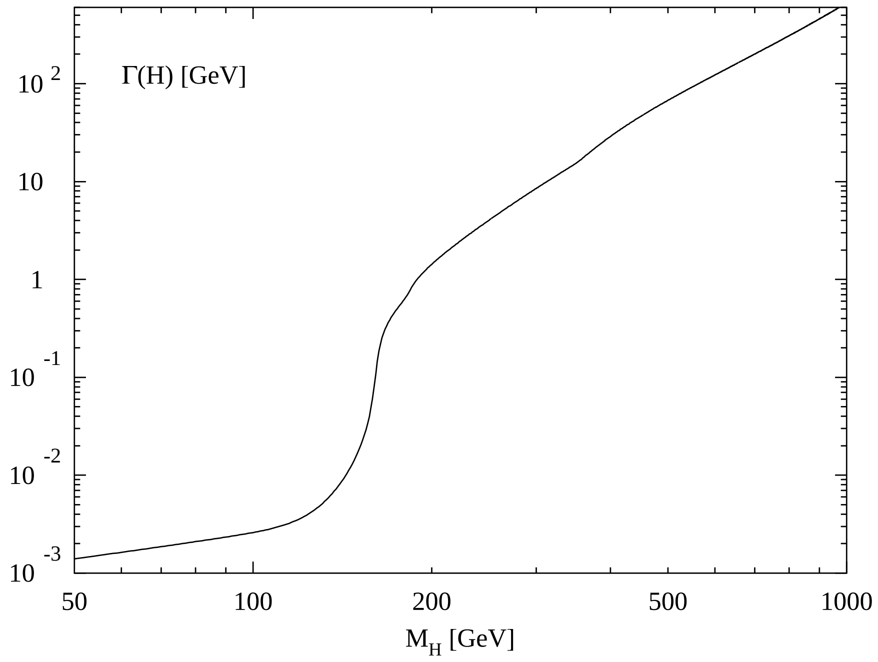
Mainly due to: pole masses m_c and m_b, and $\alpha_s(\mu)$.

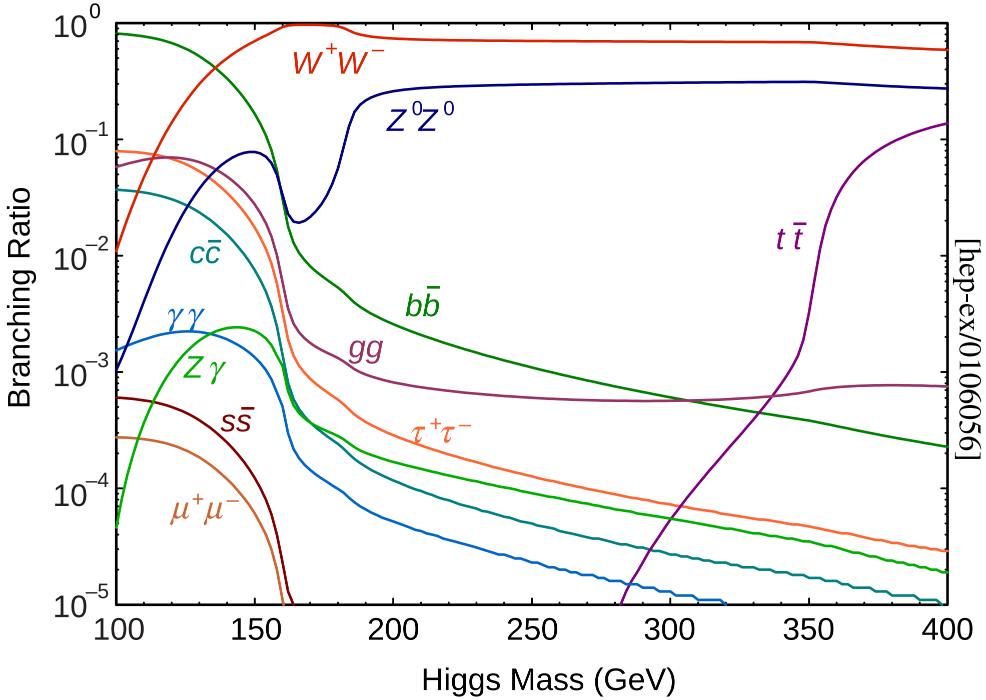
From HDECAY when (Carena et al., hep-ph/0106116

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

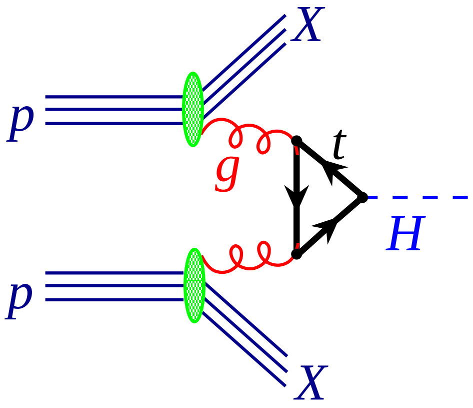
Decay of the SM Higgs

Higgs decay width and branching fractions within the SM

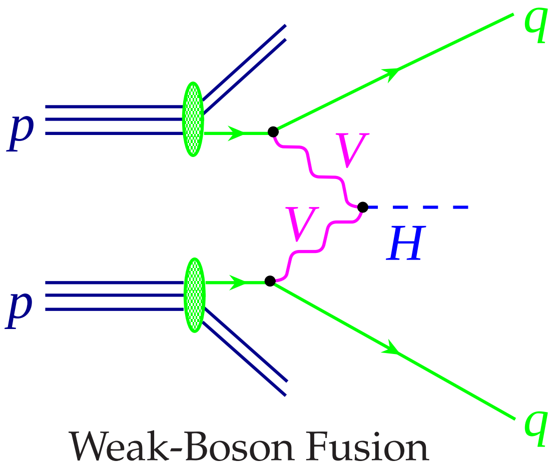




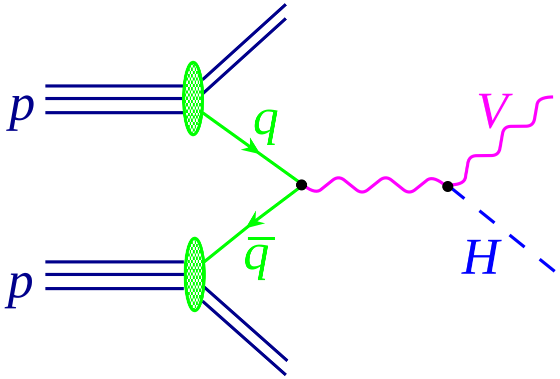
Higgs Production Modes at Hadron Colliders



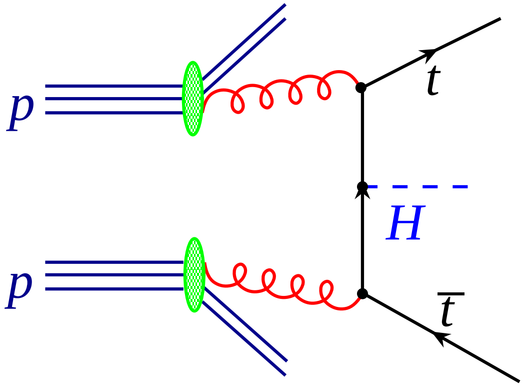
Gluon fusion



Weak-Boson Fusion

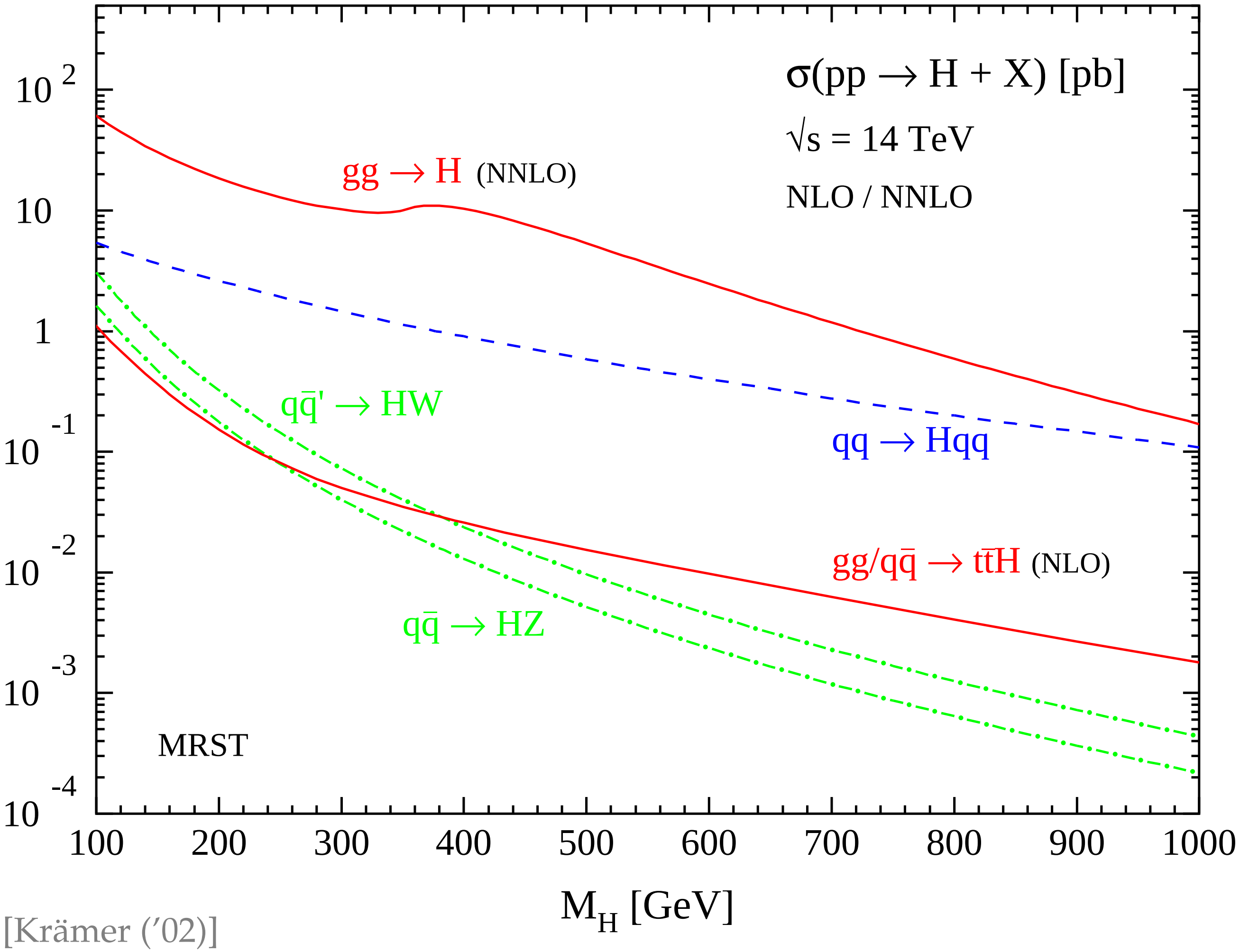


Higgs Strahlung

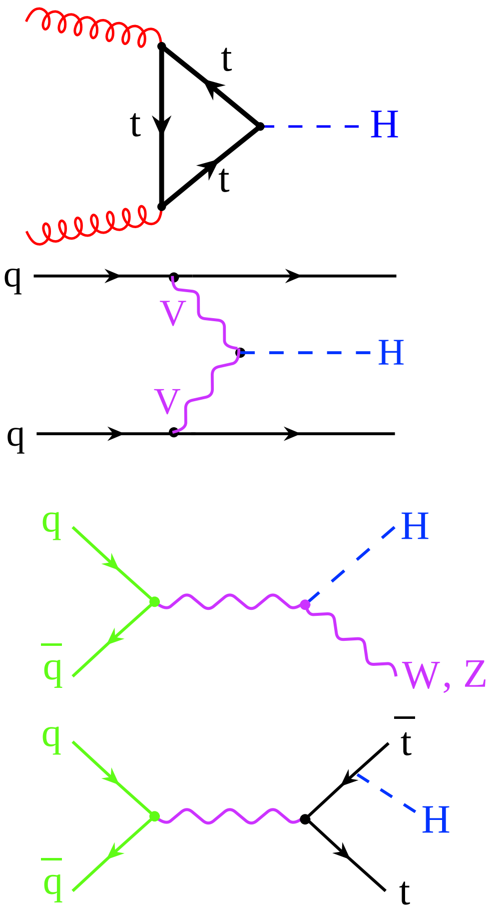


$t\bar{t}H$

Total SM Higgs cross sections at the LHC



[Krämer ('02)]



Inclusive search channels

- inclusive search for

$$H \to \gamma\gamma$$

  invariant-mass peak, for $m_H < 150$ GeV

- inclusive search for

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

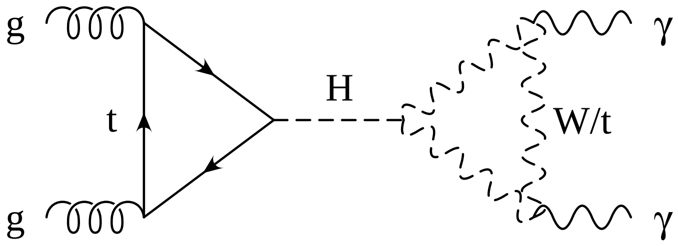
  for $m_H \geq 130$ GeV and $m_H \neq 2m_W$.

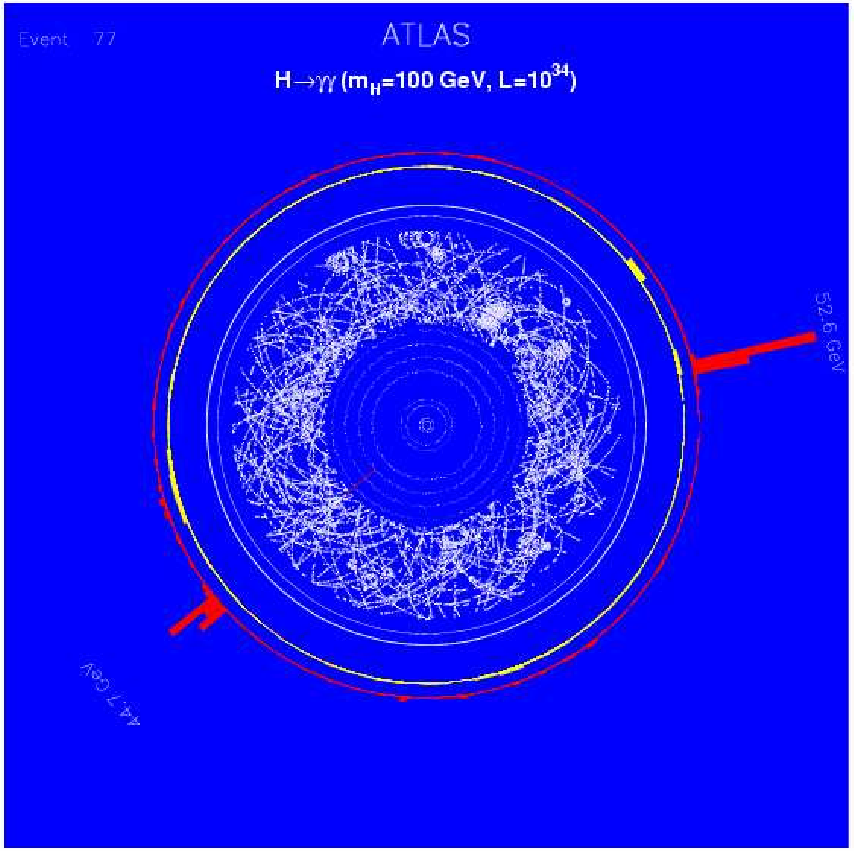
- inclusive search for

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

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

$H \longrightarrow \gamma\gamma$



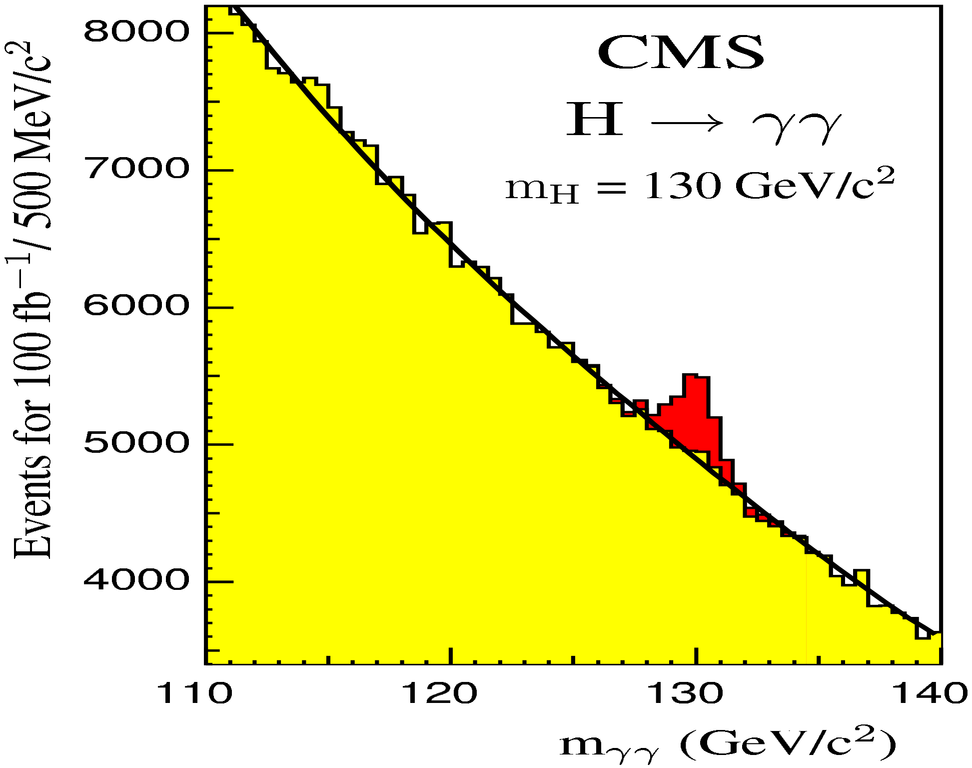


- ✗ $\text{BR}(H \rightarrow \gamma\gamma) \approx 10^{-3}$
- ✗ large backgrounds from $q\bar{q} \rightarrow \gamma\gamma$ and $gg \rightarrow \gamma\gamma$
- ✓ but CMS and ATLAS will have excellent photon-energy resolution (order of 1%)

Look for two isolated photons.

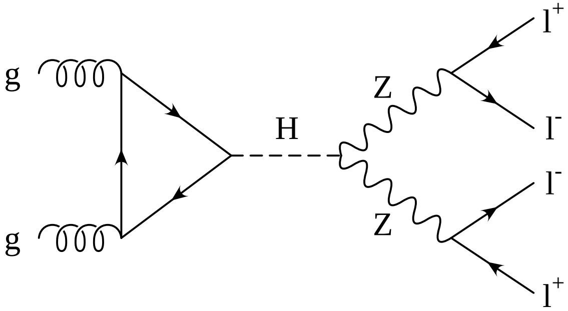
$H \to \gamma\gamma$

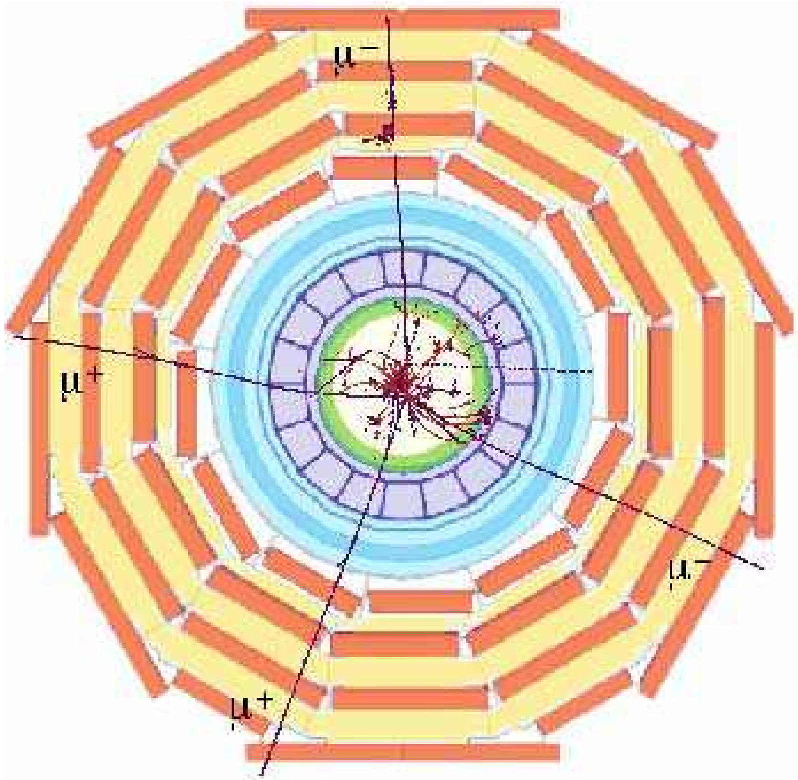
- ✓ Look for a narrow $\gamma\gamma$ invariant mass peak
- ✓ extrapolate background into the signal region from sidebands.



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

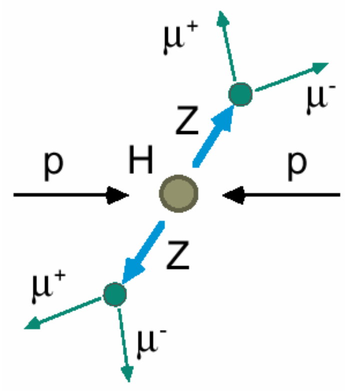
The gold-plated mode

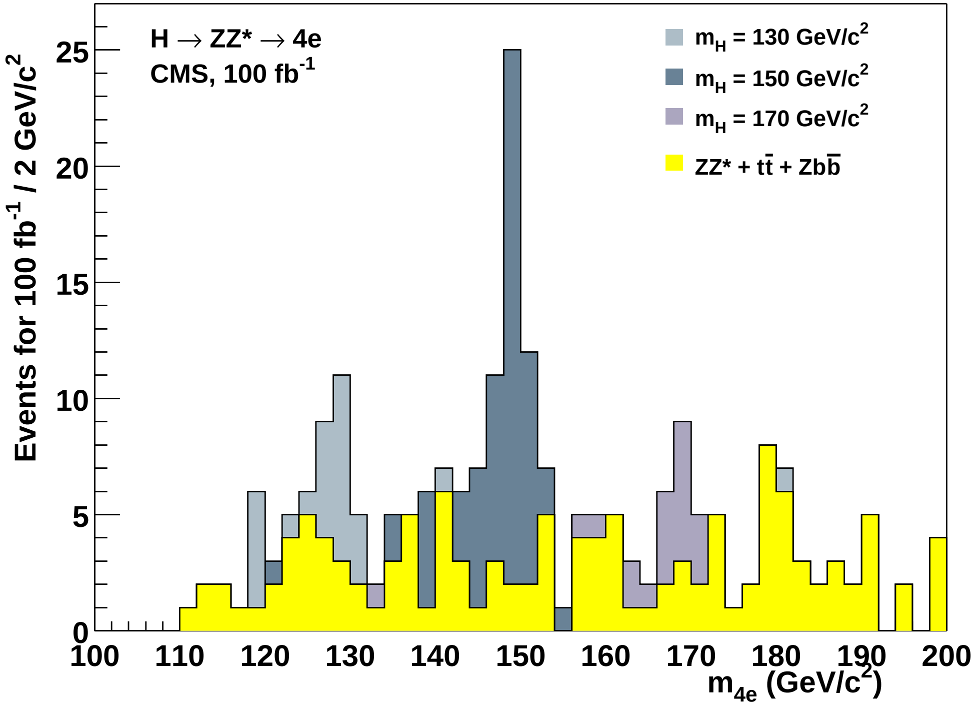




- ✓ This is the most important and clean search mode for $2m_Z < m_H < 600$ GeV.
- ✓ continuum, limited, irreducible background from $q\bar{q} \to ZZ$
- ✗ small BR$(H \to \ell^+\ell^-\ell^+\ell^-) \approx 0.15\%$ (even smaller when $m_H < 2m_Z$)

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



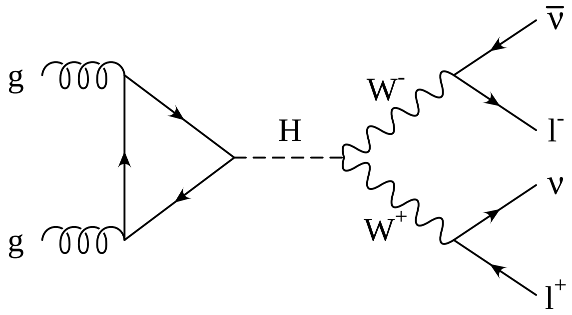


- ✓ invariant mass of the charged leptons fully reconstructed

For $m_H \approx 0.6$–1 TeV, use the "silver-plated" mode $H \to ZZ \to \nu\bar{\nu}\ell^+\ell^-$

- ✓ $\mathrm{BR}(H \to \nu\bar{\nu}\ell^+\ell^-) = 6\ \mathrm{BR}(H \to \ell^+\ell^-\ell^+\ell^-)$
- ✓ the large E_T missing allows a measurement of the transverse mass

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

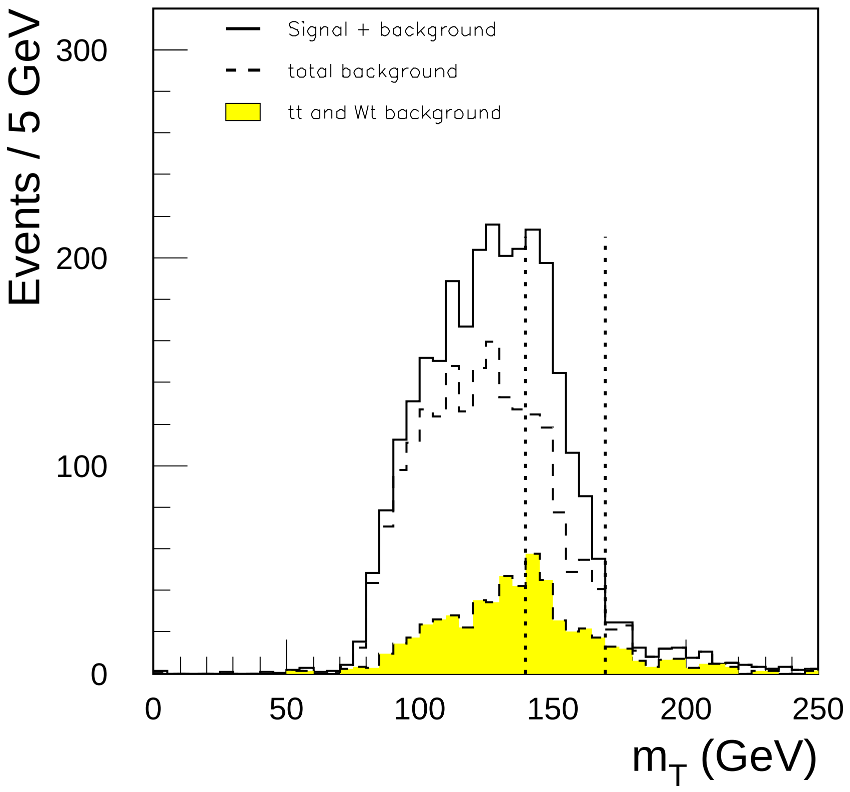


- ✓ Exploit $\ell^+\ell^-$ angular correlations
- ✓ measure the transverse mass with a Jacobian peak at m_H

$$m_T = \sqrt{2\, p_T^{\ell\ell}\, \not{E}_T\, (1 - \cos(\Delta\Phi))}$$

- ✗ background and signal have similar shape $\Longrightarrow$ must know the background normalization precisely

ATLAS TDR



$m_H = 170\,\mathrm{GeV}$

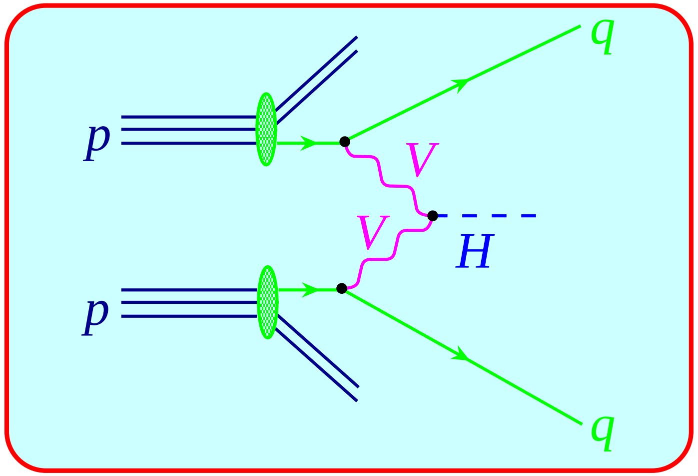
integrated luminosity = 20 fb^{-1}

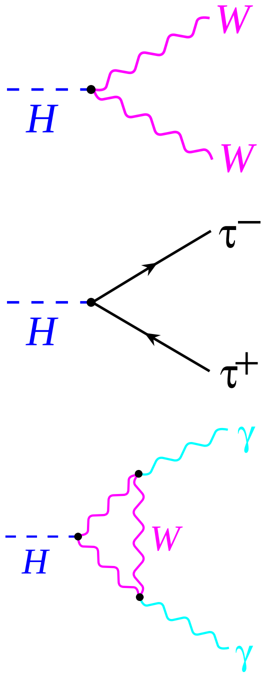
Associated production search channels

- $pp \to t\bar{t}H \to t\bar{t}b\bar{b}$
  for $m_H < 120$–130 GeV
- $q\bar{q} \to WH\ ,\ ZH$
  with Higgs decay $H \to b\bar{b}$

The leptons from W or Z decay produced in association with the Higgs boson serve to trigger the event.

Vector Boson Fusion





$m_H > 120$ GeV

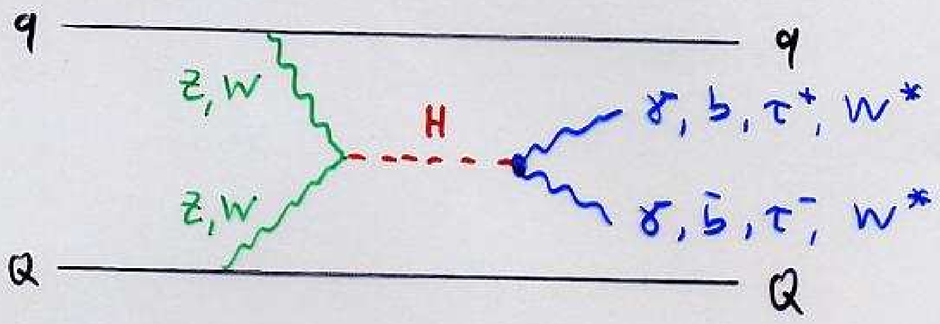
$m_H < 140$ GeV

$m_H < 150$ GeV

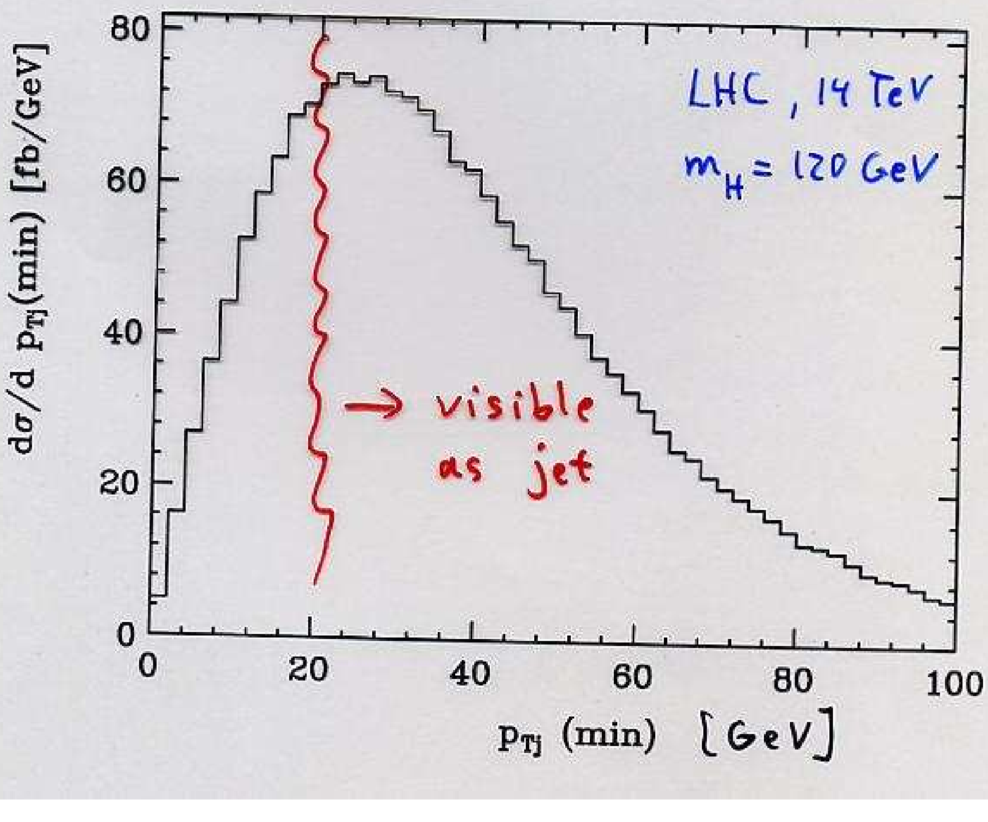
[Eboli, Hagiwara, Kauer, Plehn, Rainwater, D.Z. . . .]

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).

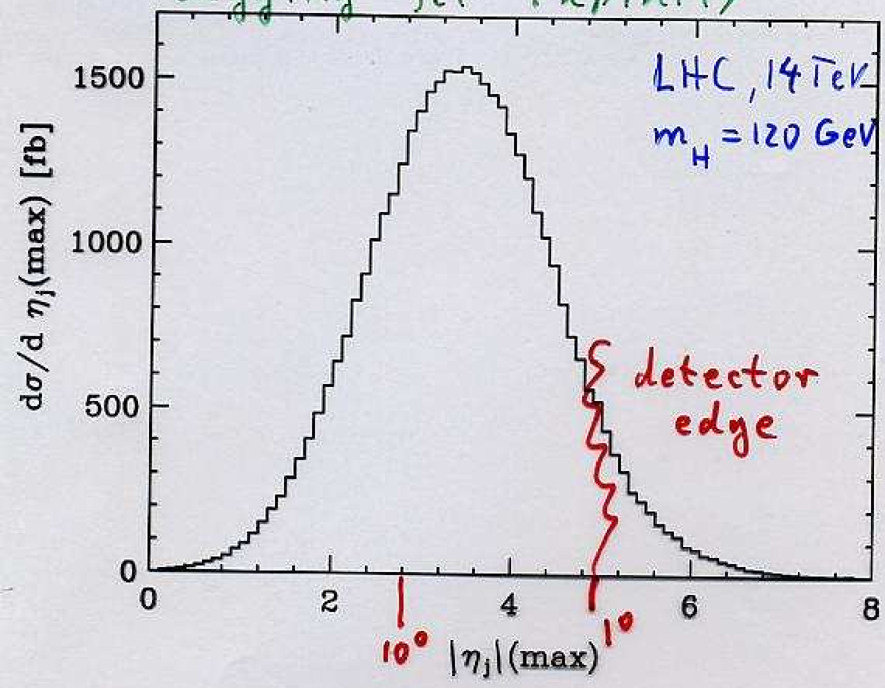
Characteristics of weak boson fusio



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



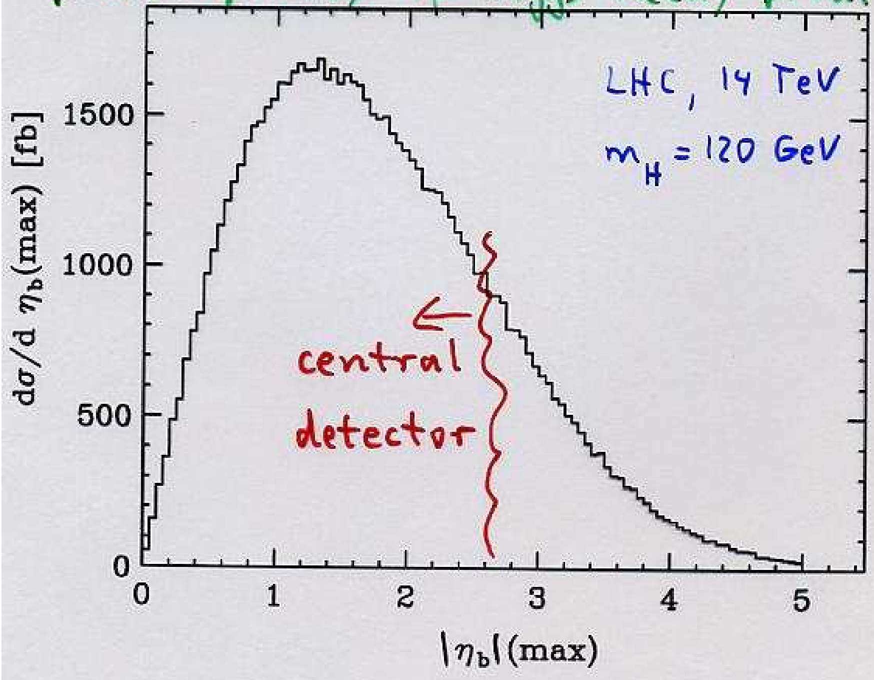
tagging jet rapidity



tagging je
forward bu
well inside
detector

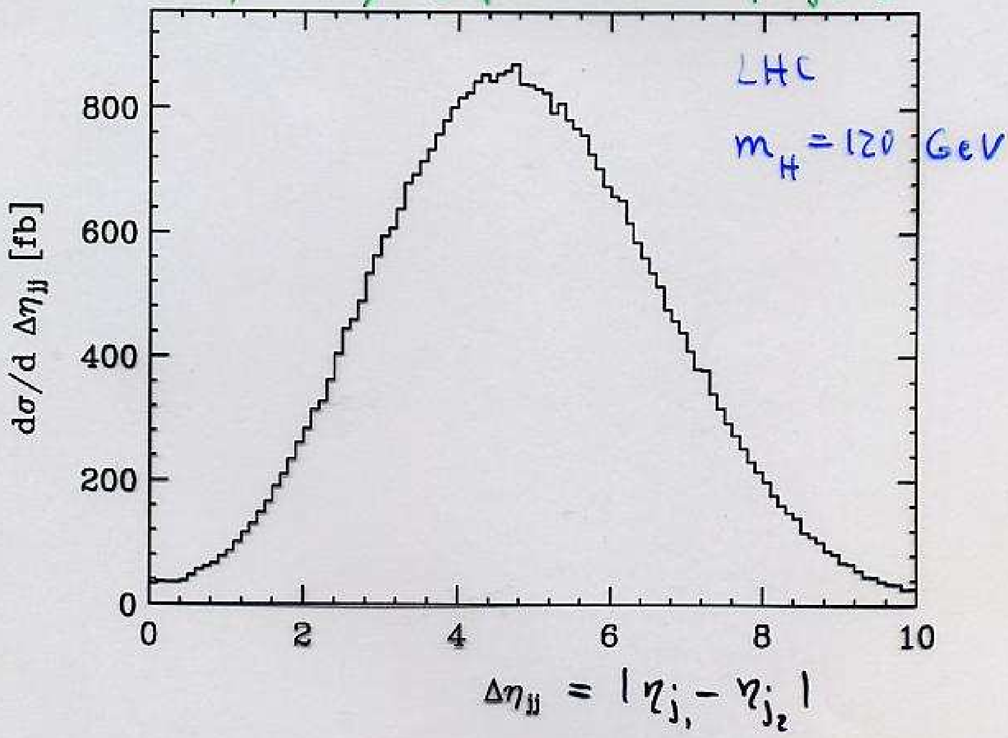
$\eta = \frac{1}{2} \ln \frac{1+\cos}{1-\cos}$

pseudorapidity of Higgs decay prod.



Higgs deca
products
are quite
central

rapidity separation of jets



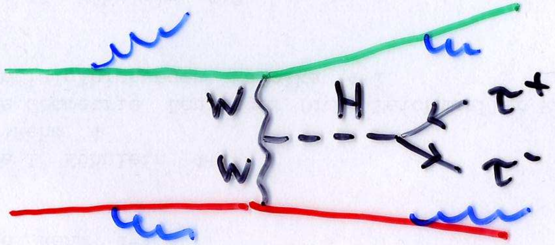
Tagging jets are typically far apart. Higgs decay products usually between 2 tagging jets

Central jet veto

- $t\bar{t}$ + jets background for $qq \to qqH$, $H \to W^+W^-$

  $\Rightarrow$ veto b-jets from $t \to bW$

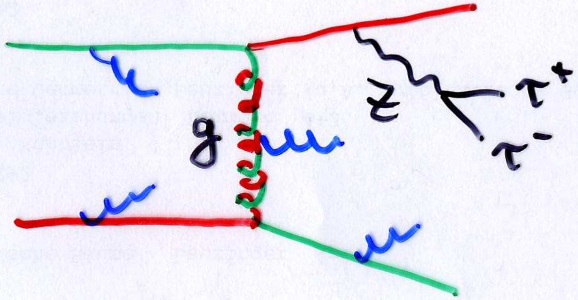
- t-channel color singlet exchange



"synchrotron" radiation between initial and final quark direction

$\Rightarrow$ central jets suppressed

- Major QCD backgrounnds: t-channel color octet exch.

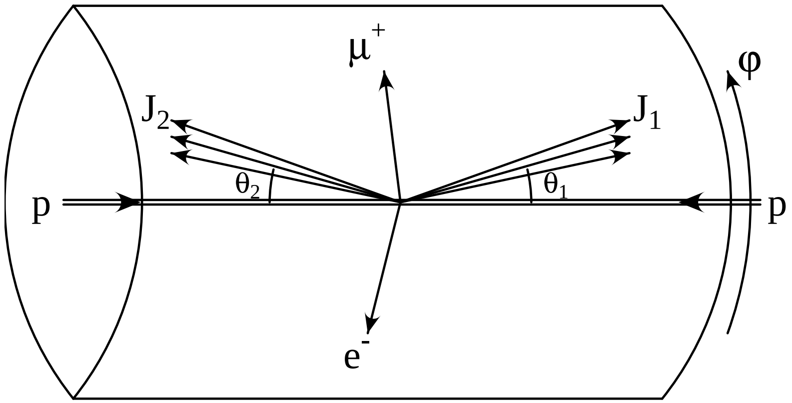


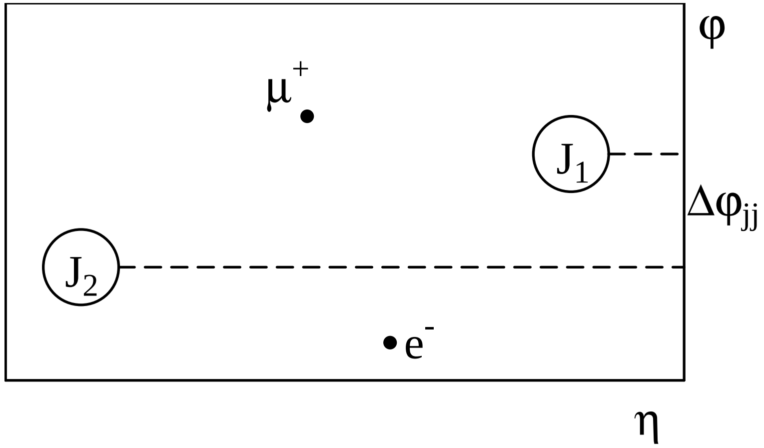
deflection of color charge by ~180° $\Rightarrow$ strong color acceleration

$\Rightarrow$ enhanced central gluon emis.

$\Rightarrow$ central jet veto suppresses QCD backgrounnds to weak boson fusion

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 $|\eta| < 2.5$)

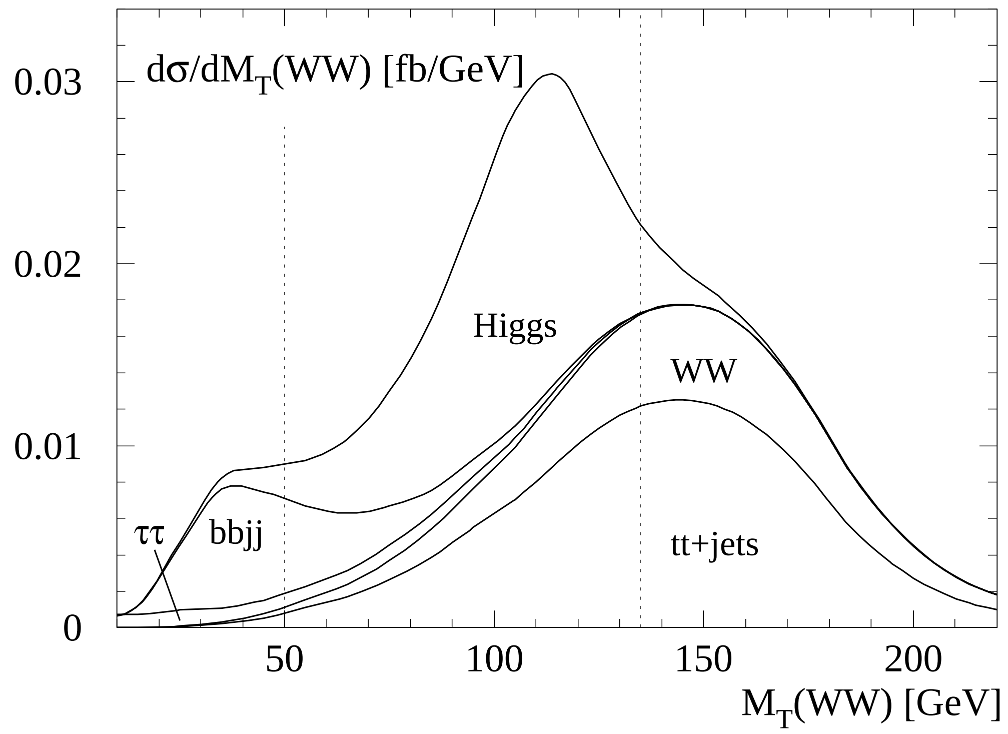
Example: Parton level analysis of $H \to WW$

Near threshold: W and W^* almost at rest in Higgs rest frame $\Longrightarrow$ use $m_{ll} \approx m_{\nu\nu}$ for improved transverse mass calculation:

$$\begin{aligned} E_{T,ll} &= \sqrt{\mathbf{p}_{T,ll}^2 + m_{ll}^2} \\ \not{E}_T &= \sqrt{\not{\mathbf{p}}_T^2 + m_{\nu\nu}^2} \approx \sqrt{\not{\mathbf{p}}_T^2 + m_{ll}^2} \\ M_T &= \sqrt{(\not{E}_T + E_{T,ll})^2 - (\mathbf{p}_{T,ll} + \not{\mathbf{p}}_T)^2} \end{aligned}$$

Observe Jacobian peak below $M_T = m_H$

Kauer, Plehn, Rainwater, D.Z. hep-ph/0012351

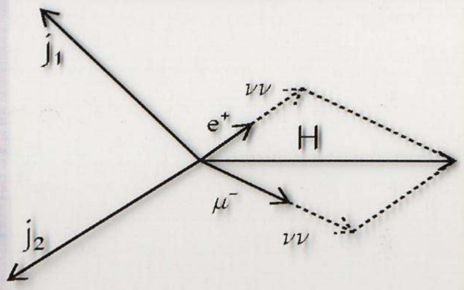


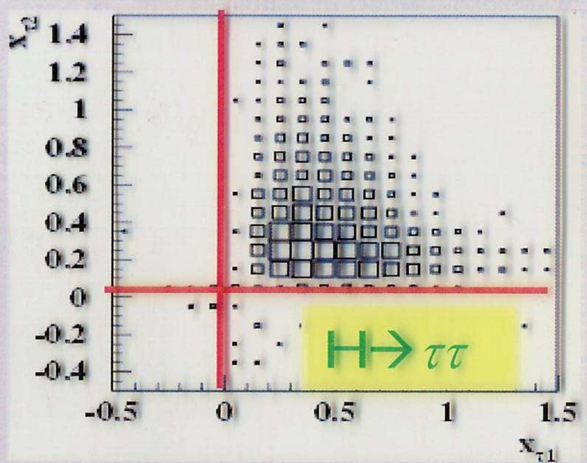
Transverse mass distribution for $m_H =$ 115 GeV and $H \to WW^* \to e^{\pm}\mu^{\mp}\not{p}_T$

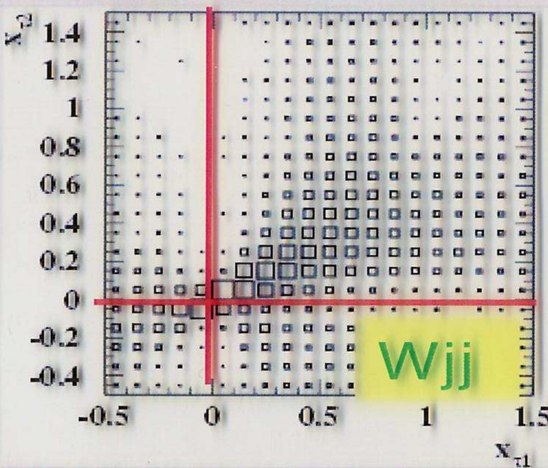
Weak Boson Fusion: H→$\tau\tau$

Mass can be reconstructed in collinear approximation

x_τ = momentum fraction carried by tau decay products







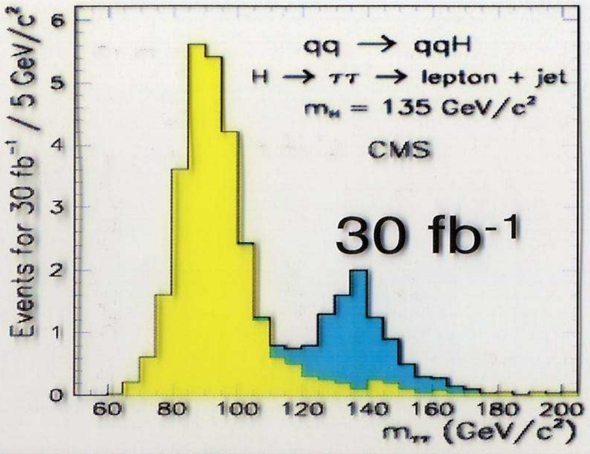
★significance > 5 for 30 fb^{-1} and

M_H=110 to 140 GeV ($\tau\tau$→eμ, $\tau\tau$→ ll , $\tau\tau$→l had)

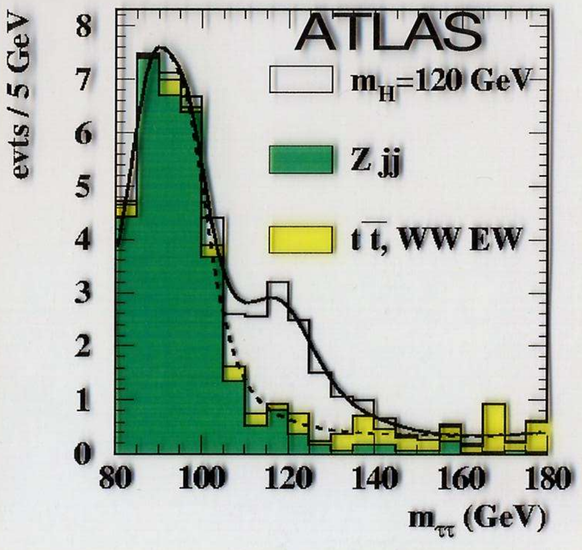
★background estimate: ~10%

for M_H>125 GeV from side bands

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

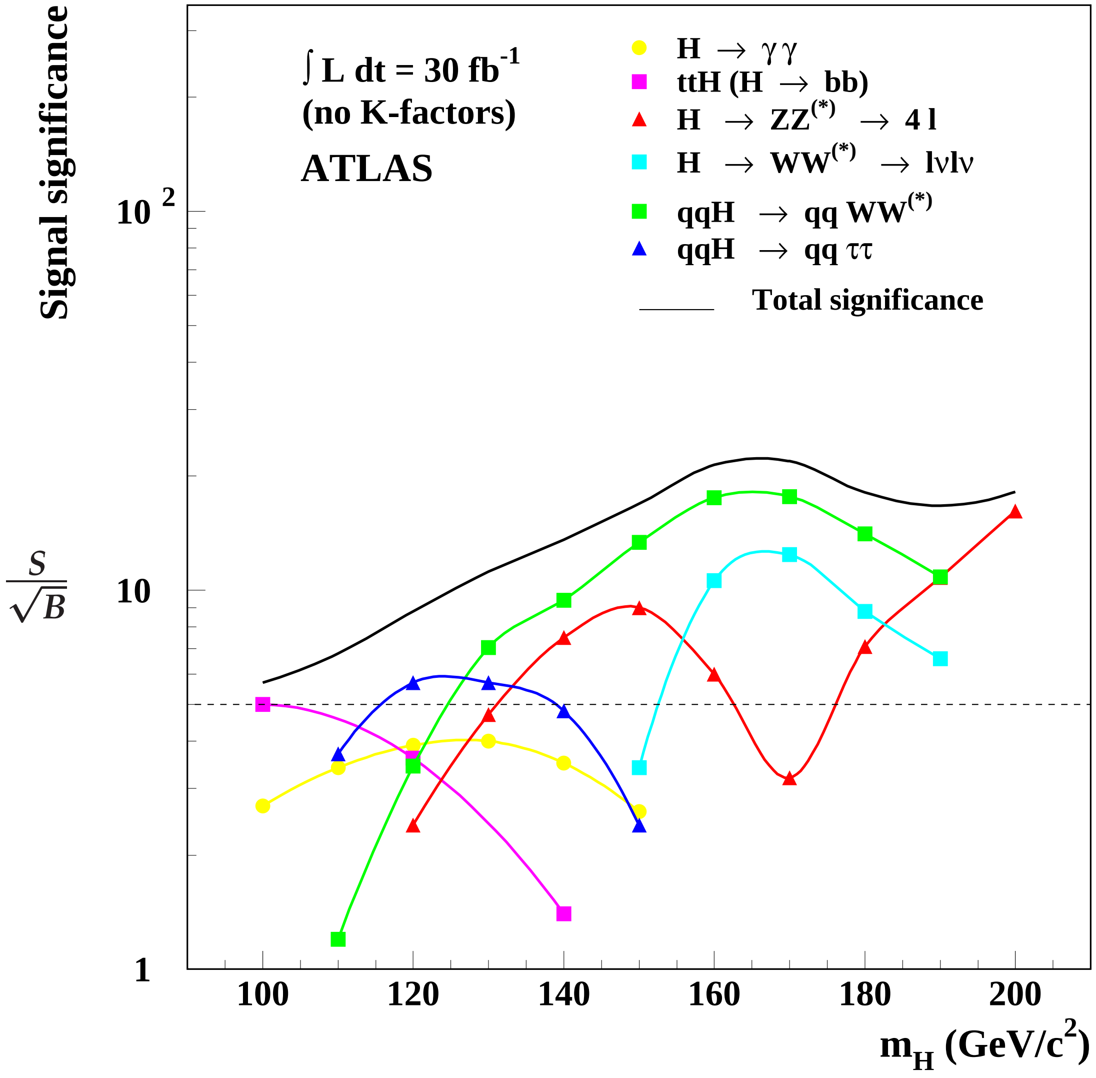


σ_{M} = 11 to 12 GeV



H→$\tau\tau$→eμ 30 fb^{-1}

Higgs discovery potential



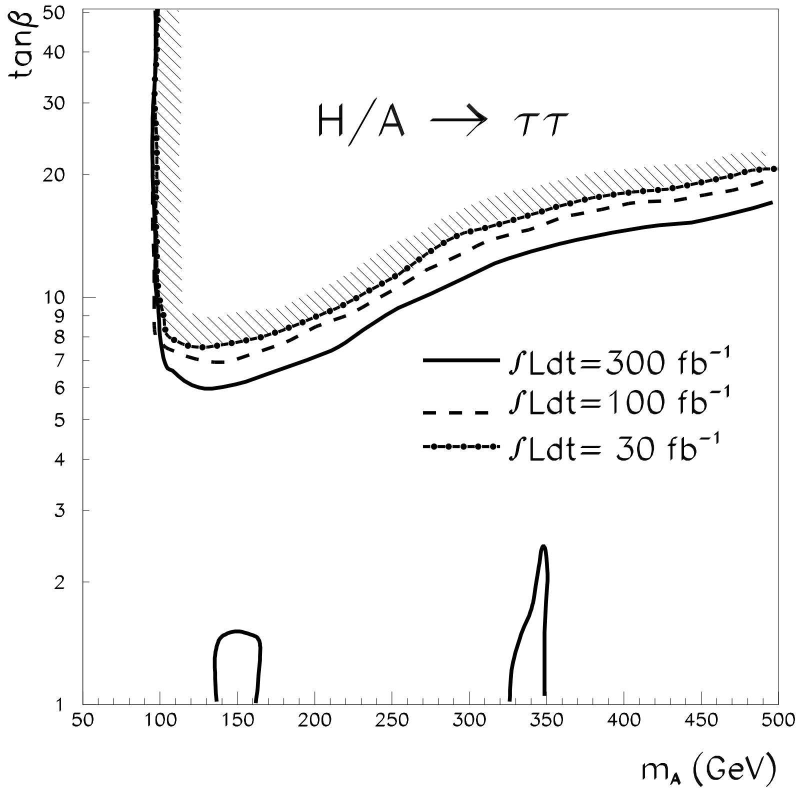
Reach for H/A discovery within MSSM

Enhancement of
Hbb and *Abb* coupling
by factor $\tan\beta$
compared to SM Higgs

⟹ large production cross section for $pp \to \bar{b}bH/A$

⟹ decay dominated by $H/A \to \bar{b}b,\ \tau^+\tau^-$

ATLAS TDR



5σ discovery contours

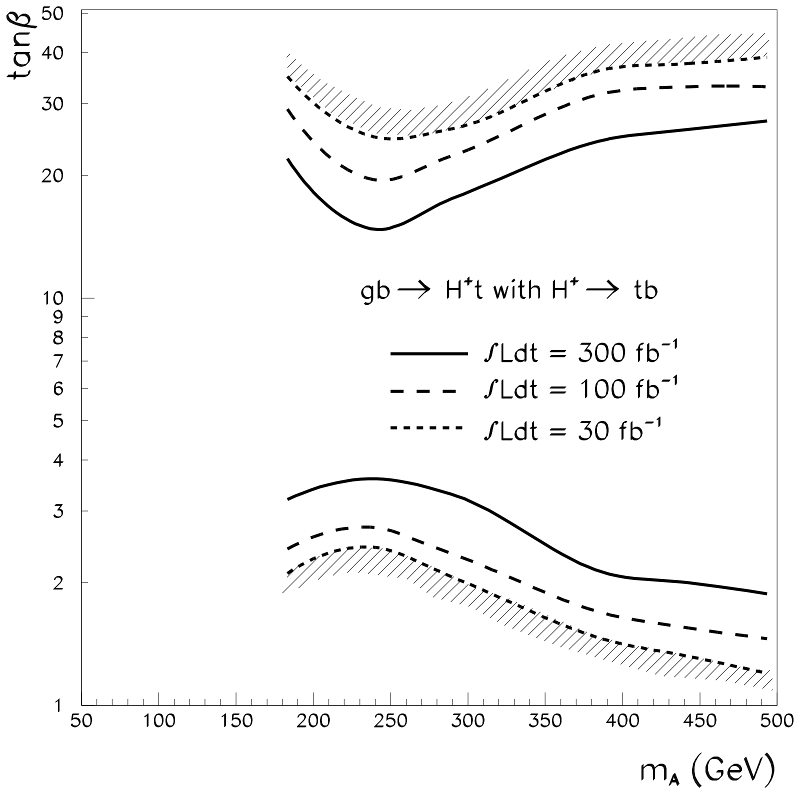
Reach for $H^\pm$ discovery within MSSM

- For $m_{H^\pm} > m_t + m_b$ expect $H^\pm \to tb$ decay
- Dominant production process

  $$gg \to H^\pm tb$$

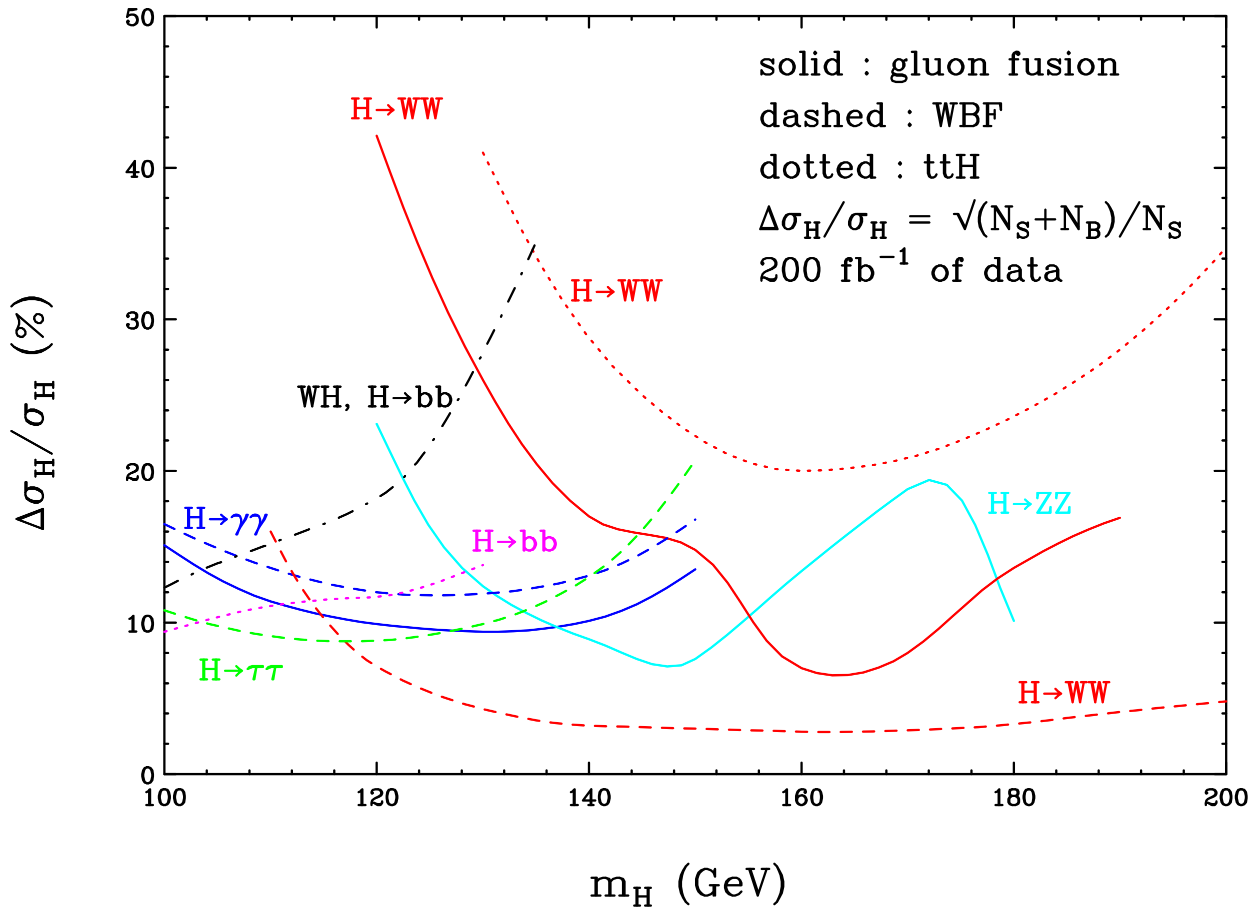
  b-quark has low p_T: $gb \to H^\pm t$ is dominant subprocess
- Main background from $\bar{t}t(+\text{jets})$ production

ATLAS TDR



5σ discovery contours

Statistical and systematic errors at LHC for SM Higgs rate



Assumed errors in fits to couplings:

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

Measuring Higgs couplings at LHC

LHC rates for partonic process $pp \to H \to xx$ given by $\sigma(pp \to H) \cdot BR(H \to xx)$

$$\sigma(H) \times \mathrm{BR}(H \to xx) = \frac{\sigma(H)^{\mathrm{SM}}}{\Gamma_p^{\mathrm{SM}}} \cdot \frac{\Gamma_p \Gamma_x}{\Gamma} \;,$$

Measure products $\Gamma_p \Gamma_x / \Gamma$ for combination of processes ($\Gamma_p = \Gamma(H \to pp)$)

Problem: rescaling fit results by common factor f

$$\Gamma_i \to f \cdot \Gamma_i \,, \qquad \Gamma \to f^2 \Gamma = \sum_{obs} f \Gamma_i + \Gamma_{rest}$$

leaves observable rate invariant $\Longrightarrow$ no model independent results at LHC

Loose bounds on scaling factor:

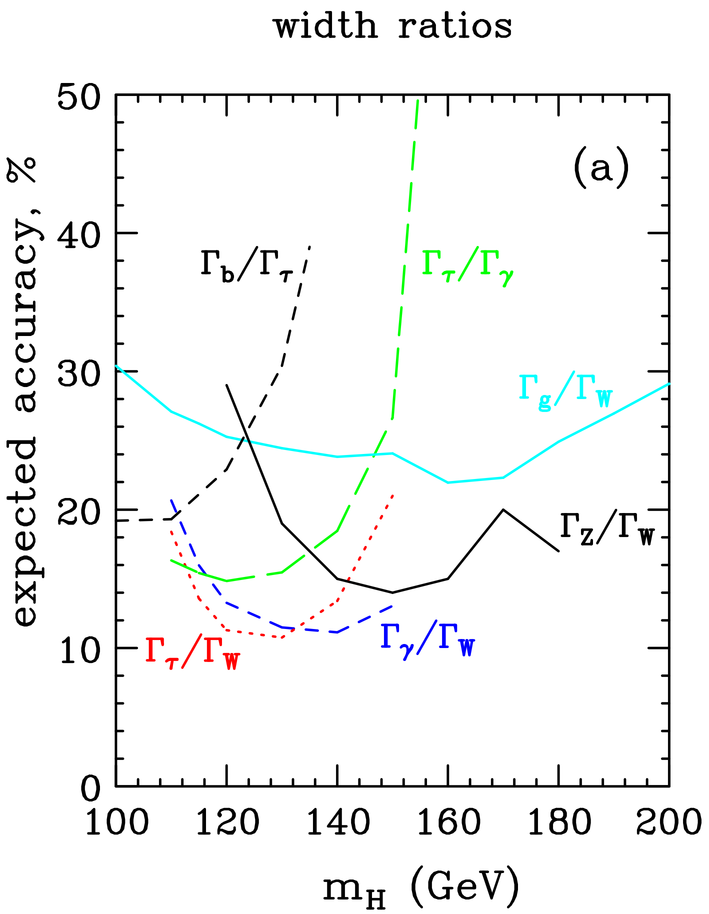
$$f^2 \Gamma > \sum_{obs.} f \Gamma_x \qquad \Longrightarrow \qquad f > \sum_{obs.} \frac{\Gamma_x}{\Gamma} = \sum_{obs.} BR(H \to xx) (= \mathcal{O}(1))$$

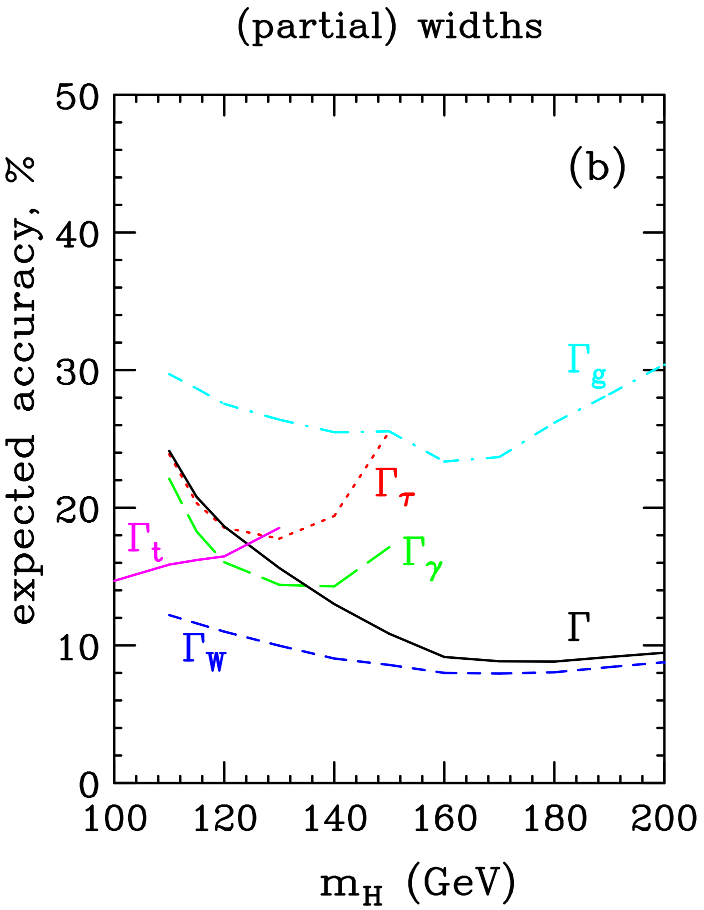
Total width below experimental resolution of Higgs mass peak ($\Delta m = 1 \ldots 20$ GeV)

$$f^2 \Gamma < \Delta m \qquad \Longrightarrow \qquad f < \sqrt{\frac{\Delta m}{\Gamma}} < \mathcal{O}(10 - 40)$$

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

Distinguishing the MSSM Higgs sector from the SM

Alternative: compare data to predictions of specific models

Example: m_H^{max} scenario of LEP analyses

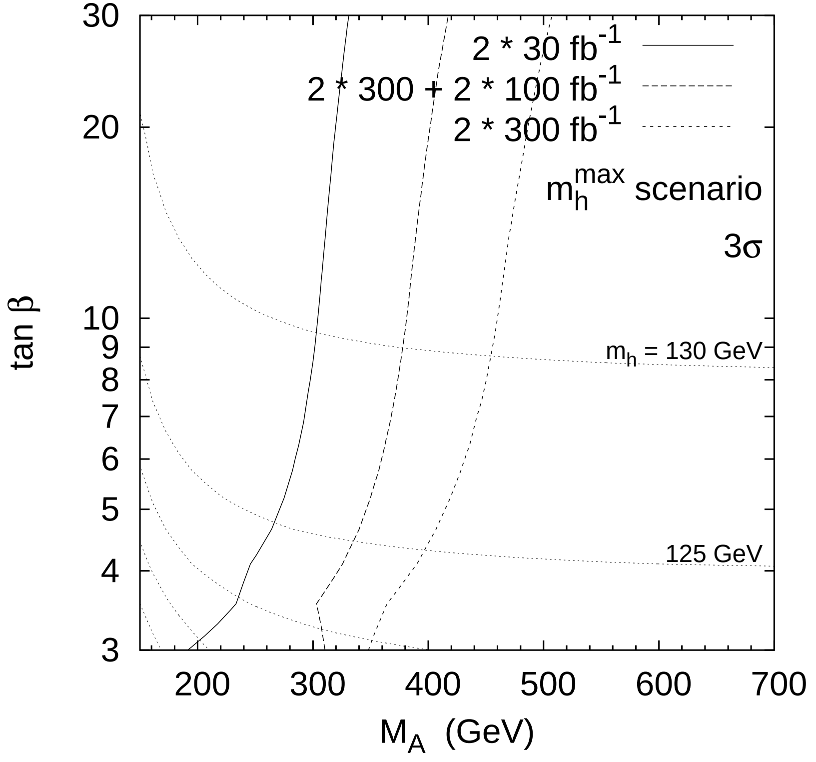
Consider modest m_A:

- decoupling almost complete for hWW and $h\gamma\gamma$ (effective) vertices
- enhanced hbb and $h\tau\tau$ couplings compared to SM increases total width of h

$\Longrightarrow$

- $\approx$ SM rates for $h \to \tau\tau$ in VBF
- suppressed $h \to \gamma\gamma$ and $h \to WW$ rates in VBF

3σ-effects or more at small m_A



QCD corrections for Higgs production

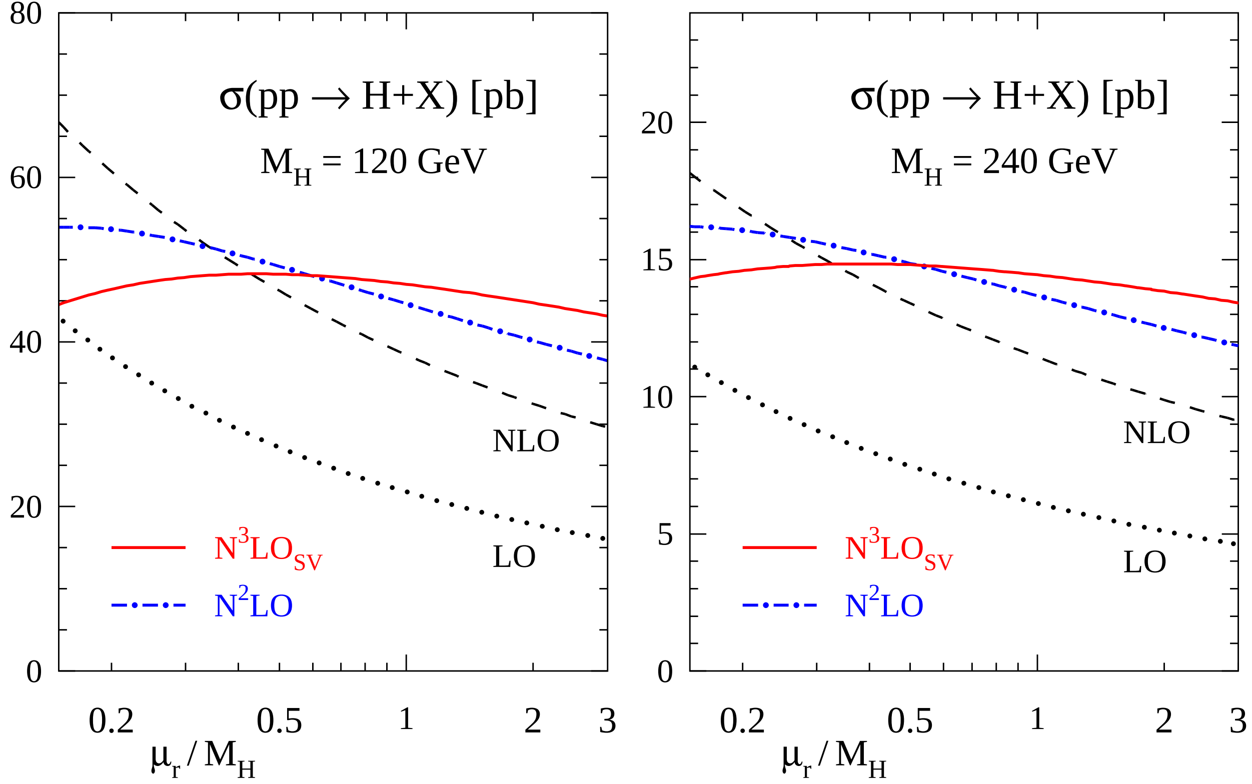
Measurement of partial widths at 10–20% level or couplings at 5–10% level requires predictions of SM production cross sections at 10% level or better

$\Longrightarrow$ need QCD corrections to production cross sections. Much progress in recent years

- $gg \to H$ (all but NLO in $m_t \to \infty$ limit)
  - NLO for finite m_t: Graudenz, Spira, Zerwas (1993)
  - NNLO: Harlander, Kilgore (2001); Anastasiou, Melnikov (2002); Ravindran, Smith, van Neerven (2003)
  - NNLL: Catani, de Florian, Grazzini, Nason (2003)
  - N^3LO in soft approximation: Moch, Vogt (2005)
- Hjj by gluon fusion at NLO: Campbell, Ellis, Zanderighi (2006)
- weak boson fusion
  - total cross section at NLO: Han, Willenbrock (1991)
  - distributions at NLO: Figy, Oleari, D.Z (2003); Campbell, Ellis, Berger (2004)
- $\bar{t}tH$ associated production at NLO: Beenakker et al.; Dawson, Orr, Reina, Wackeroth (2002)
- $\bar{b}bH$ associated production at NLO: Dittmaier, Krämer, Spira; Dawson et al. (2003)

QCD corrections to $gg \to H$

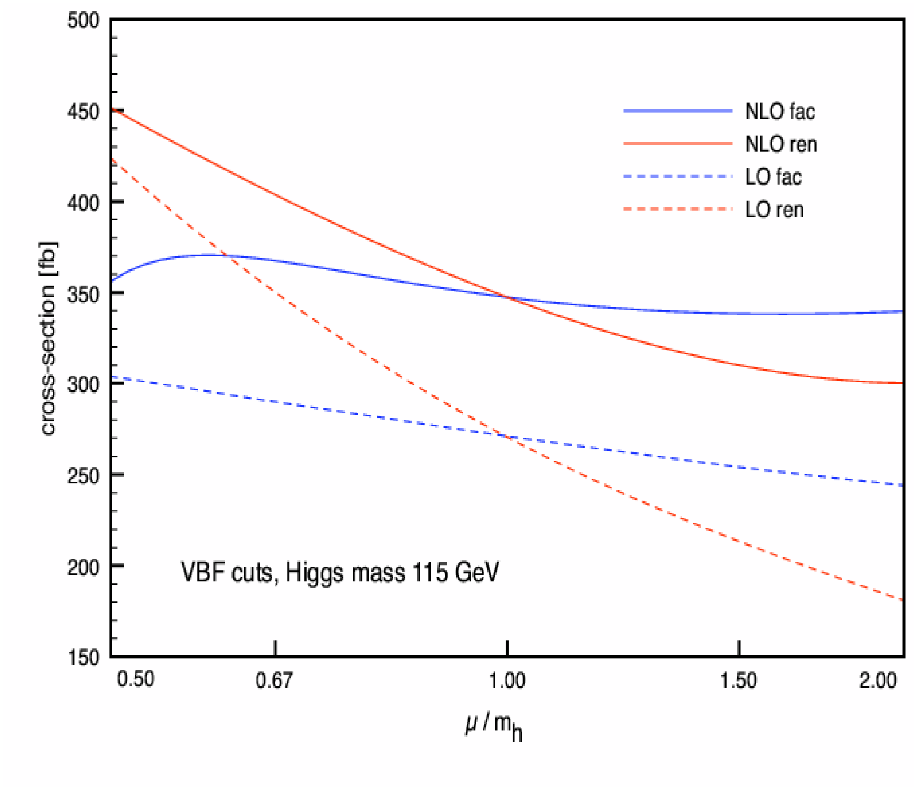
Moch & Vogt, hep-ph/0508265

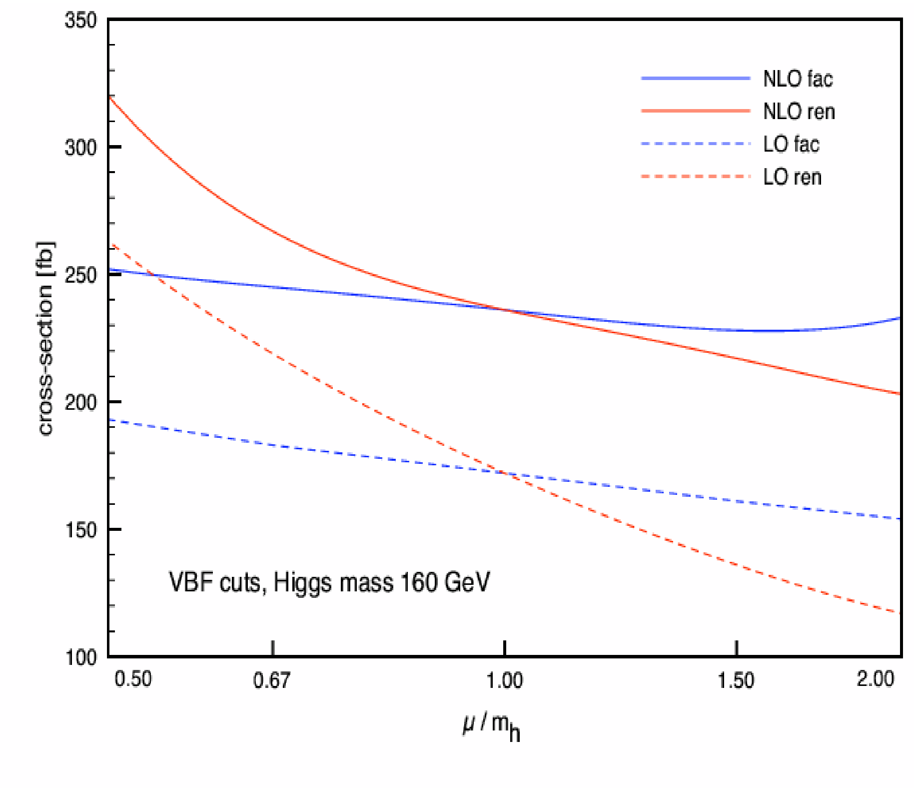


- ✓ Huge improvement in recent years
- ✓ Remaining scale uncertainty below 10%
- ✓ Uncertainty from gluon pdf $\approx 4 - 7\%$
- ✗ What is K-factor for cross section with cuts? Most problematic: central jet veto against $\bar{t}t$ background for $H \to WW$ search

Hjj cross section for gluon fusion

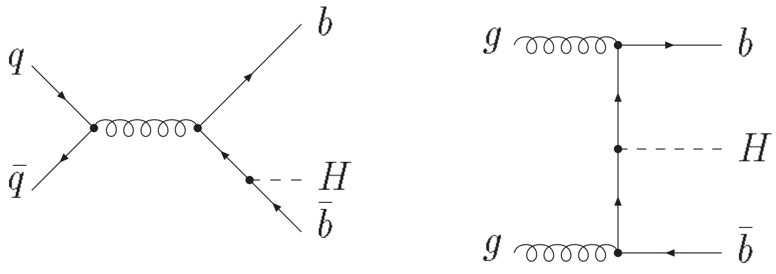
Calculation of Hjj cross section at NLO in $m_t \to \infty$ limit by Campbell, Ellis, Zanderighi, hep-ph/0608194





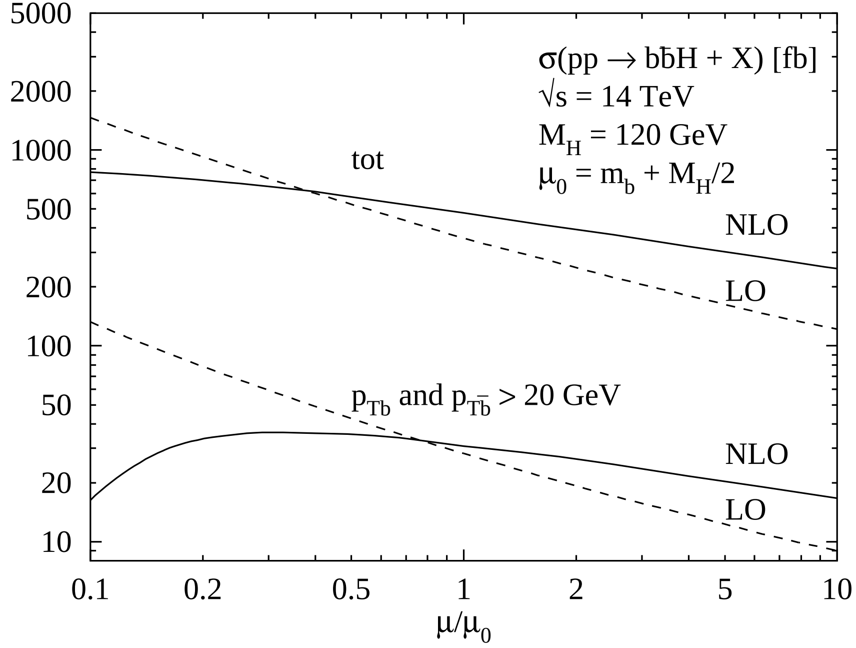
- Modest increase of cross section at 1-loop: K-factor of order 1.2 - 1.4
- Reduced scale dependence at NLO: remaining scale uncertainty $\approx \pm 20\%$

NLO QCD corrrections to $b\bar{b}H$ production



- Discovery channel for H/A in the MSSM at sizeable tan β
- NLO corrections known for $\bar{b}bH$ final state
- b-quarks at low p_T: effective process is $\bar{b}b \to H$: cross section known at NLNO Harlander, Kilgore (2003)

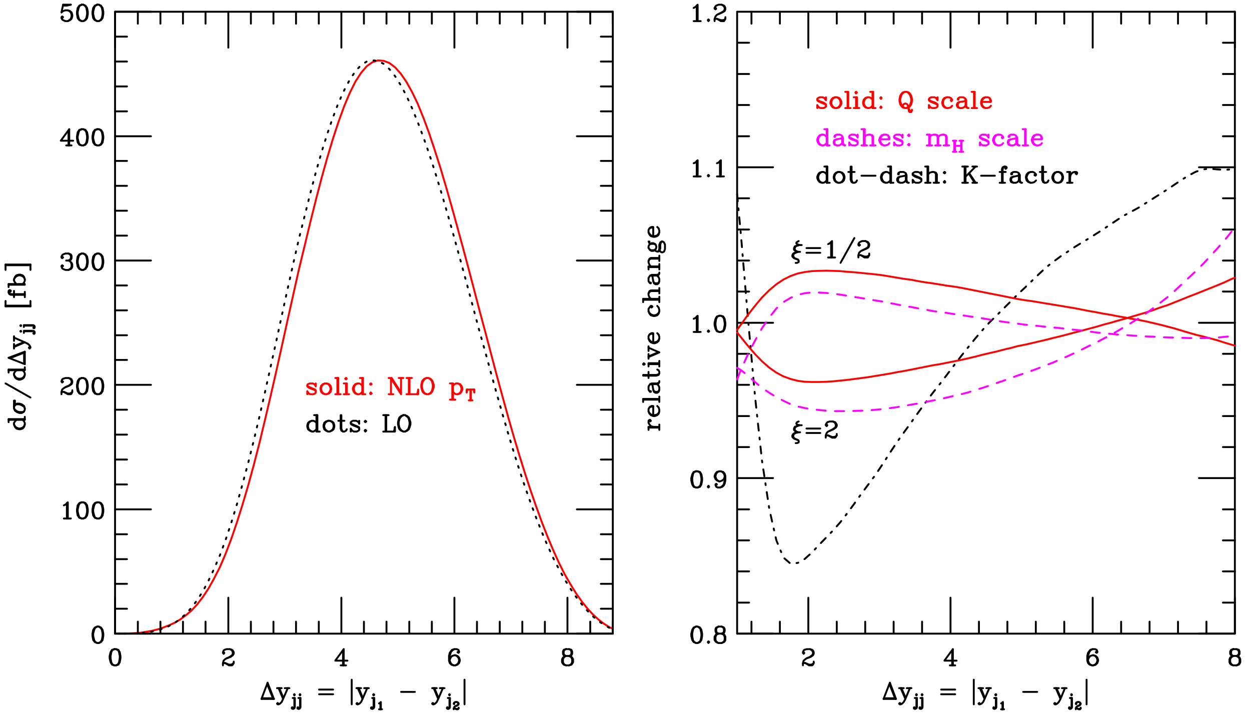
Dittmaier, Krämer, Spira hep-ph/0309204



scale dependence of inclusive vs. double b-tagged cross section

NLO QCD corrections to VBF

- ✓ Small QCD corrections of order 10%
- ✓ Tiny scale dependence of NLO result
  - $\pm 5\%$ for distributions
  - $< 2\%$ for σ_{total}
- ✓ K-factor is phase space dependent
- ✓ QCD corrections under excellent control
- ✗ Need electroweak corrections for 5% uncertainty



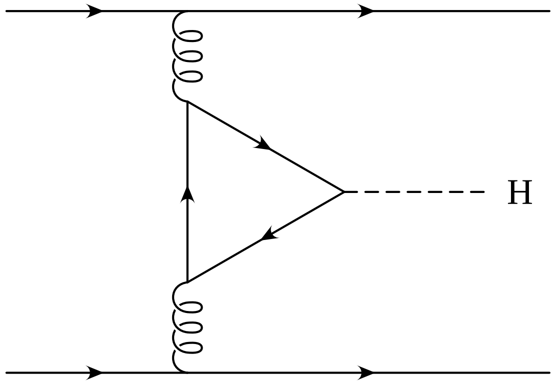
$m_H = 120$ GeV, typical VBF cuts

NLO QCD correction for VBF now available in VBFNLO: Figy, Hankele, Jäger, Klämke, Oleari, DZ, ...

parton level Monte Carlo for Hjj, Wjj, Zjj, W^+W^-jj, $ZZjj$ production

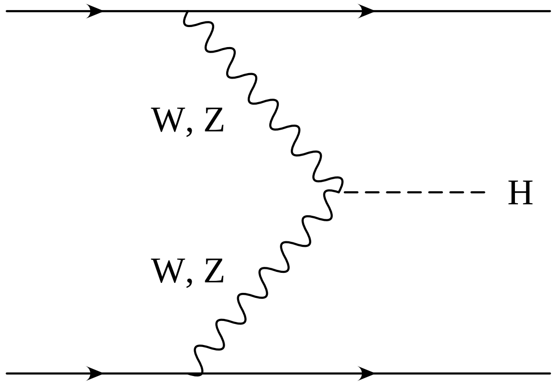
http://www-itp.physik.uni-karlsruhe.de/∼vbfnloweb/

How to distinguish gluon fusion and VBF?



(a)

vs.



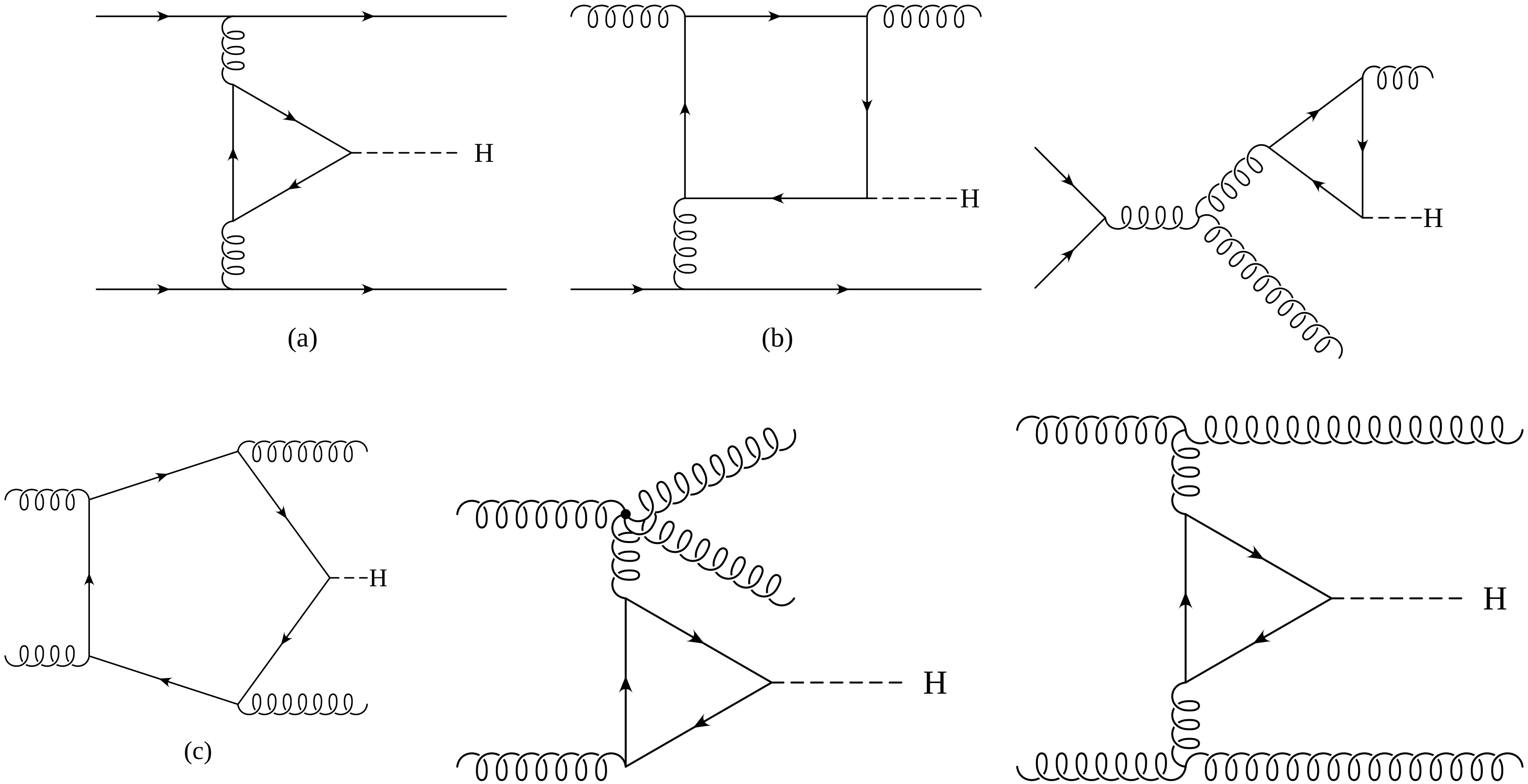
Double real corrections to $gg \to H$ can “fake” VBF

$\Longrightarrow$ we need to investigate the phenomenology of these two processes and understand the differences that can be exploited to distinguish between gluon fusion and VBF

$\Longrightarrow$ derive cuts to be applied to enhance VBF with respect to gluon fusion.
Measure HWW and HZZ coupling

$\Longrightarrow$ derive cuts to be applied to enhance gluon fusion with respect to VBF.
Measure effective Hgg coupling or Htt coupling

Diagrams for gg fusion with finite m_t effects



$q\,Q \to q\,Q\,H/A$ $\quad$ $q\,g \to q\,g\,H/A$ $\quad$ $g\,g \to g\,g\,H/A$

plus crossed processes. [DelDuca, Kilgore, Oleari, Schmidt, DZ (2001); Kubocz, DZ (2006)]

Gluon Fusion as a signal channel

Heavy quark loop induces effective Hgg vertex:

$$\text{CP}-\text{even}: \qquad i\frac{m_Q}{v} \quad \longrightarrow \quad \mathcal{L}_{eff} = \frac{\alpha_s}{12\pi v} H\, G^a_{\mu\nu} G^{\mu\nu,a}$$

$$\text{CP}-\text{odd}: \qquad -\frac{m_Q}{v}\gamma_5 \quad \longrightarrow \quad \mathcal{L}_{eff} = \frac{\alpha_s}{8\pi v} A\, G^a_{\mu\nu} \tilde{G}^{\mu\nu,a} = \frac{\alpha_s}{16\pi v} A\, G^a_{\mu\nu} G^a_{\alpha\beta} \varepsilon^{\mu\nu\alpha\beta}$$

Azimuthal angle between tagging jets probes difference

- Use gluon fusion induced Φjj signal to probe structure of Hgg vertex
- Measure size of coupling (requires NLO corrections for precision [Campbell, Ellis, Zanderighi (2006)])
- Find cuts to enhance gluon fusion over VBF and other backgrounds

$\Longrightarrow$ Study in $m_Q \rightarrow \infty$ limit [Klämke, DZ (2007)]

Gluon fusion signal and backgrounds

Signal channel (LO):

- $pp \to Hjj$ in gluon fusion with $H \to W^+W^- \to l^+l^-\nu\bar{\nu}$, $(l = e,\ \mu)$
- $m_H = 160\,\mathrm{GeV}$

dominant backgrounds:

- W^+W^--production via VBF (including Higgs-channel): $pp \to W^+W^-jj$
- top-pair production: $pp \to t\bar{t},\ t\bar{t}j,\ t\bar{t}jj$ *(N. Kauer)*
- QCD induced W^+W^--production: $pp \to W^+W^-jj$

applied inclusive cuts (minimal cuts):

- 2 tagging-jets

$$p_{Tj} > 30\,\mathrm{GeV}, \qquad |\eta_j| < 4.5$$

- 2 identified leptons

$$p_{Tl} > 10\,\mathrm{GeV}, \qquad |\eta_l| < 2.5$$

- separation of jets and leptons

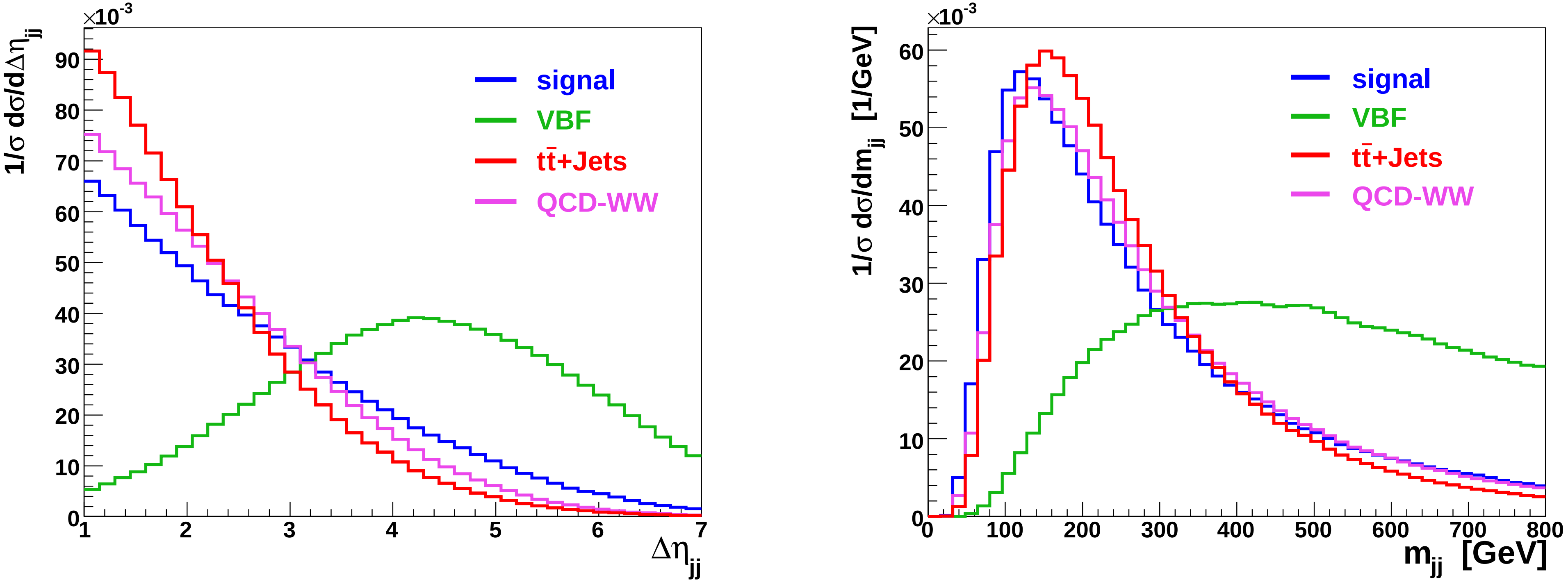
$$\Delta\eta_{jj} > 1.0, \qquad R_{jl} > 0.7$$

process	σ [fb]
GF $pp \to H + jj$	**115.2**
VBF $pp \to W^+W^- + jj$	**75.2**
$pp \to t\bar{t}$	**6832**
$pp \to t\bar{t} + j$	**9518**
$pp \to t\bar{t} + jj$	**1676**
QCD $pp \to W^+W^- + jj$	**363**

Characteristic distributions

tagging jet rapidity separation

dijet invariant mass



Separation of VBF Hjj signal from QCD background is much easier than separation of gluon fusion Hjj signal

Selection continued

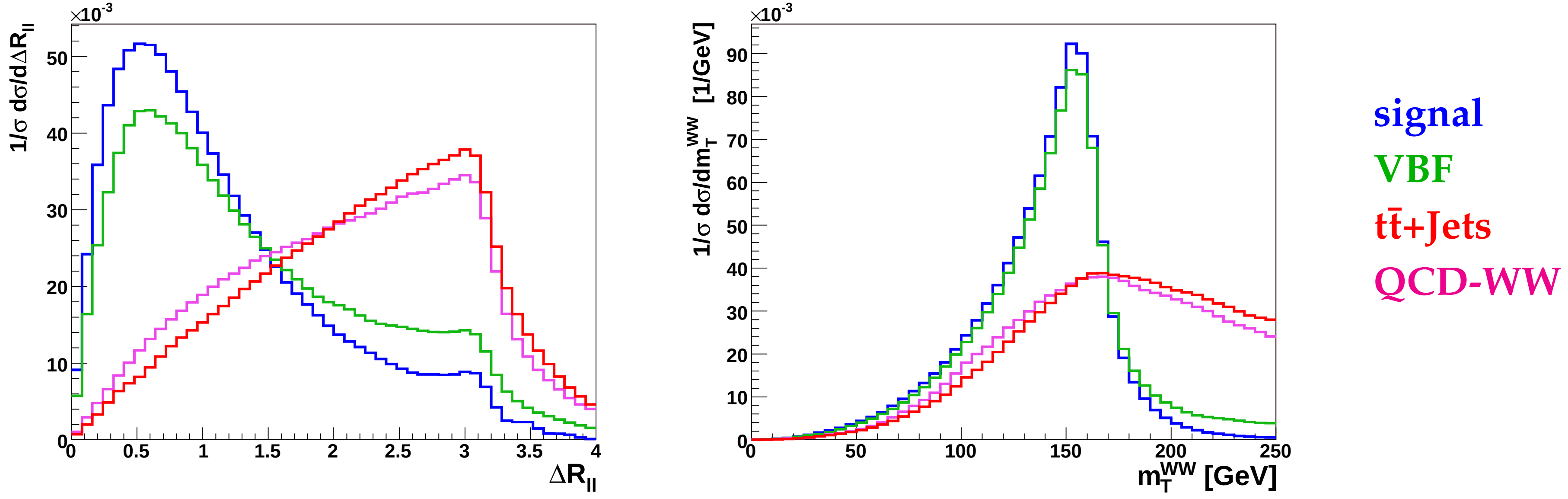
- b-tagging for reduction of top-backgrounds. *(CMS Note 06/014)*
  - $(\eta,\, p_T)$ - dependent tagging-efficiencies (60% - 75%) with 10% mistagging - probability

- selection cuts:

$R_{ll} < 1.1,\qquad M_{ll} < 75\,\mathrm{GeV},\qquad M_{ll} < 0.44 \cdot M_T^{WW},\qquad p_{Tl} > 30\,\mathrm{GeV},$

$M_T^{WW} < 170\,\mathrm{GeV},\qquad \not{p}_T > 30\,\mathrm{GeV}$

$$M_T^{WW} = \sqrt{(\not{E}_T + E_{T_{ll}})^2 - (\vec{p}_{T_{ll}} + \vec{\not{p}}_T)^2}$$



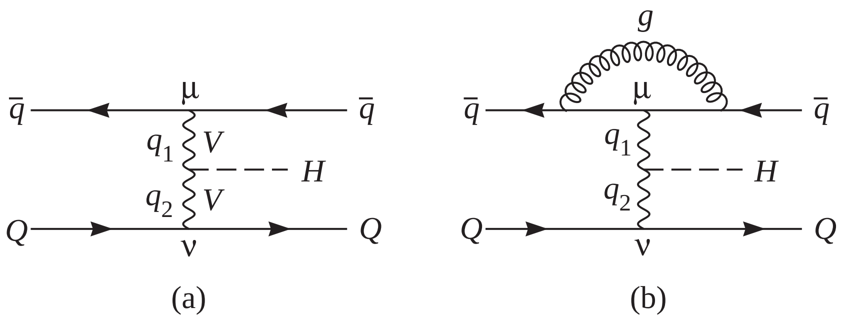
Results

process	σ [fb]	events/ 30 fb^{-1}
GF $pp \to H + jj$	**31.5**	**944**
VBF $pp \to W^+W^- + jj$	**16.5**	**495**
$pp \to t\bar{t}$	**23.3**	**699**
$pp \to t\bar{t} + j$	**51.1**	**1533**
$pp \to t\bar{t} + jj$	**11.2**	**336**
QCD $pp \to W^+W^- + jj$	**11.4**	**342**
Σ backgrounds	**113.5**	**3405**

$$\Rightarrow \mathbf{S}/\sqrt{\mathbf{B}} \approx \mathbf{16.2} \text{ for } 30\ \text{fb}^{-1}$$

Tensor structure of the HVV coupling

Most general HVV vertex $T^{\mu\nu}(q_1,q_2)$



$$
\begin{aligned}
T^{\mu\nu} \;=\; & a_1\, g^{\mu\nu} \;+ \\
& a_2\, \left(q_1\cdot q_2\, g^{\mu\nu} - q_1^{\nu} q_2^{\mu}\right) + \\
& a_3\, \varepsilon^{\mu\nu\rho\sigma}\; q_{1\rho} q_{2\sigma}
\end{aligned}
$$

The $a_i = a_i(q_1,q_2)$ are scalar form factors

Physical interpretation of terms:

SM Higgs $\qquad \mathcal{L}_I \sim H V_\mu V^\mu \longrightarrow \; a_1$

loop induced couplings for neutral scalar

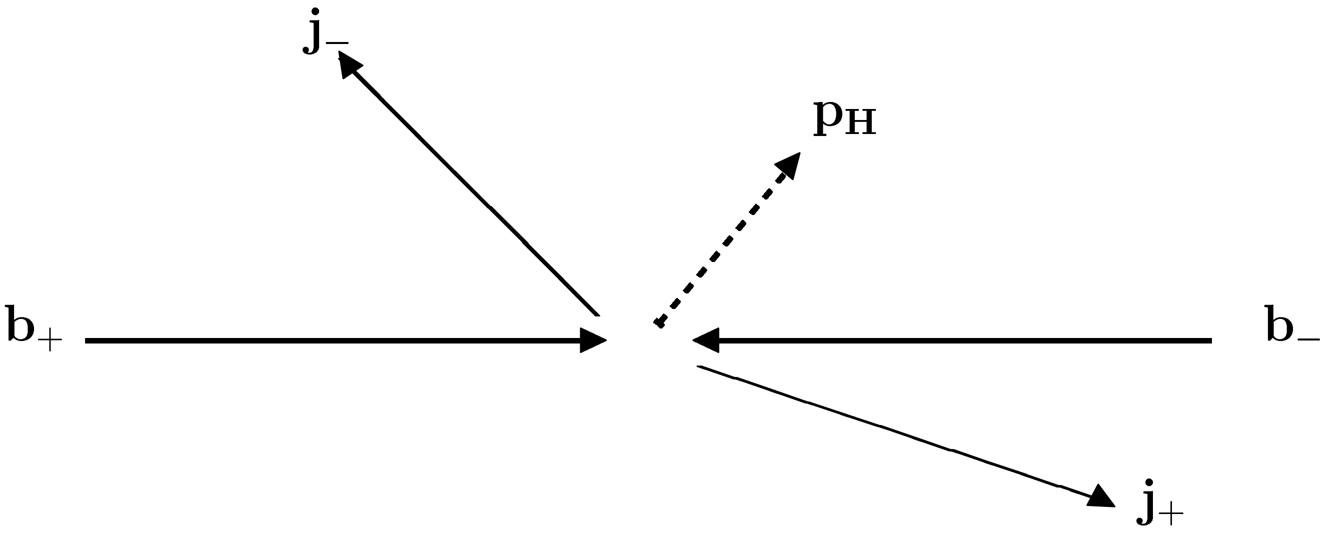
CP even $\qquad \mathcal{L}_{eff} \sim H V_{\mu\nu} V^{\mu\nu} \longrightarrow \; a_2$

CP odd $\qquad \mathcal{L}_{eff} \sim H V_{\mu\nu} \tilde{V}^{\mu\nu} \longrightarrow \; a_3$

Must distinguish a_1, a_2, a_3 experimentally

Azimuthal angle distribution and Higgs CP properties

Kinematics of Hjj event:



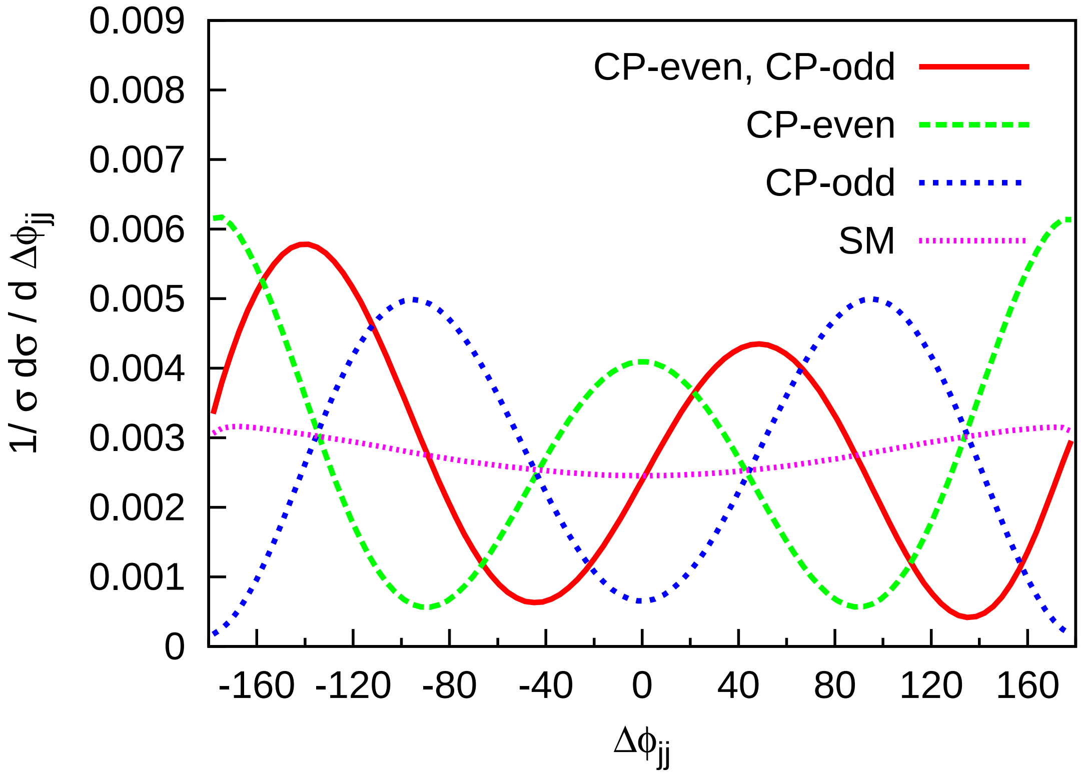
Define azimuthal angle between jet momenta j_+ and j_- via

$$\varepsilon_{\mu\nu\rho\sigma} b_+^\mu j_+^\nu b_-^\rho j_-^\sigma = 2 p_{T,+} p_{T,-} \sin(\phi_+ - \phi_-) = 2\ p_{T,+} p_{T,-}\ \sin \Delta\phi_{jj}$$

- $\Delta\phi_{jj}$ is a parity odd observable
- $\Delta\phi_{jj}$ is invariant under interchange of beam directions $(b_+, j_+) \leftrightarrow (b_-, j_-)$

Work with Vera Hankele, Gunnar Klämke and Terrance Figy: hep-ph/0609075

Signals for CP violation in the Higgs Sector



mixed CP case:

$a_2 = a_3, a_1 = 0$

pure CP-even case:

a_2 only

pure CP odd case:

a_3 only

Position of minimum of $\Delta\phi_{jj}$ distribution measures relative size of CP-even and CP-odd couplings. For

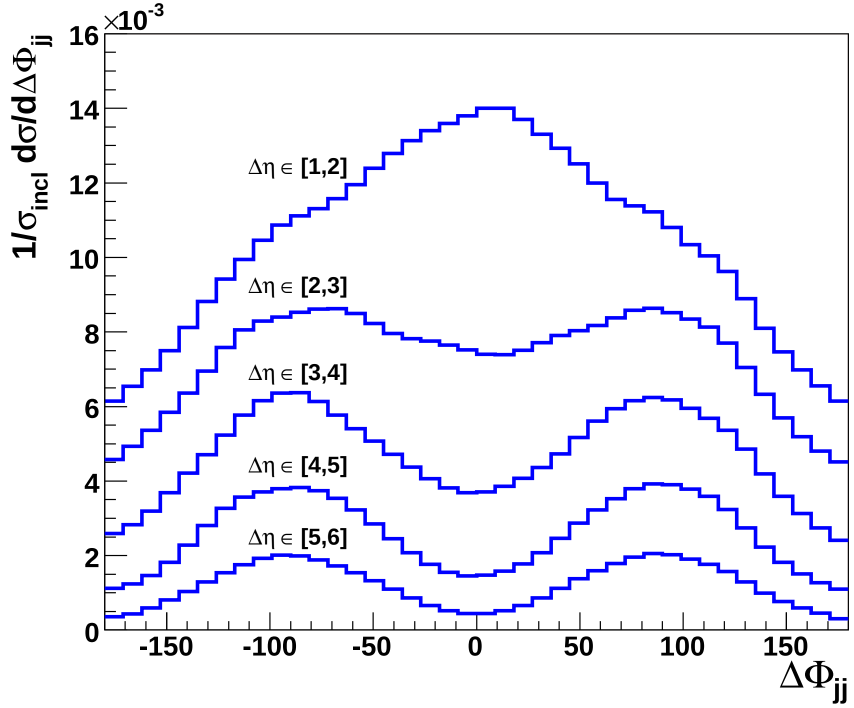
$$a_1 = 0, \qquad a_2 = d\ \cos\alpha, \qquad a_3 = d\ \sin\alpha,$$

$\Longrightarrow$ Maxima at α and $\alpha \pm \pi$

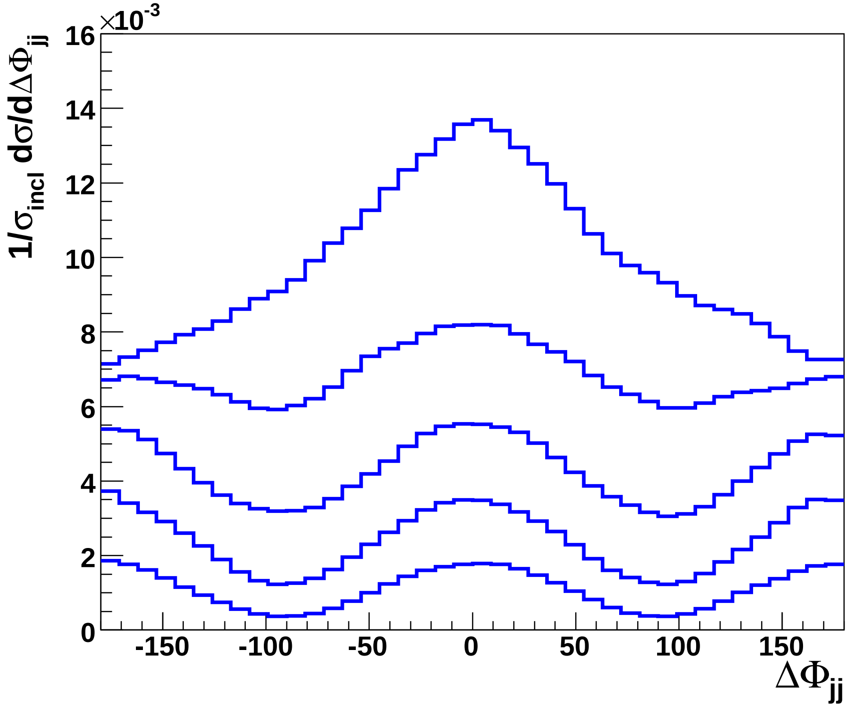
Gluon fusion: structure of Hgg vertex

Sensitivity of the $\Delta\phi_{jj}$ distribution to the structure of the effective Hgg coupling increases with the rapidity separation of the two tagging jets

CP-even coupling

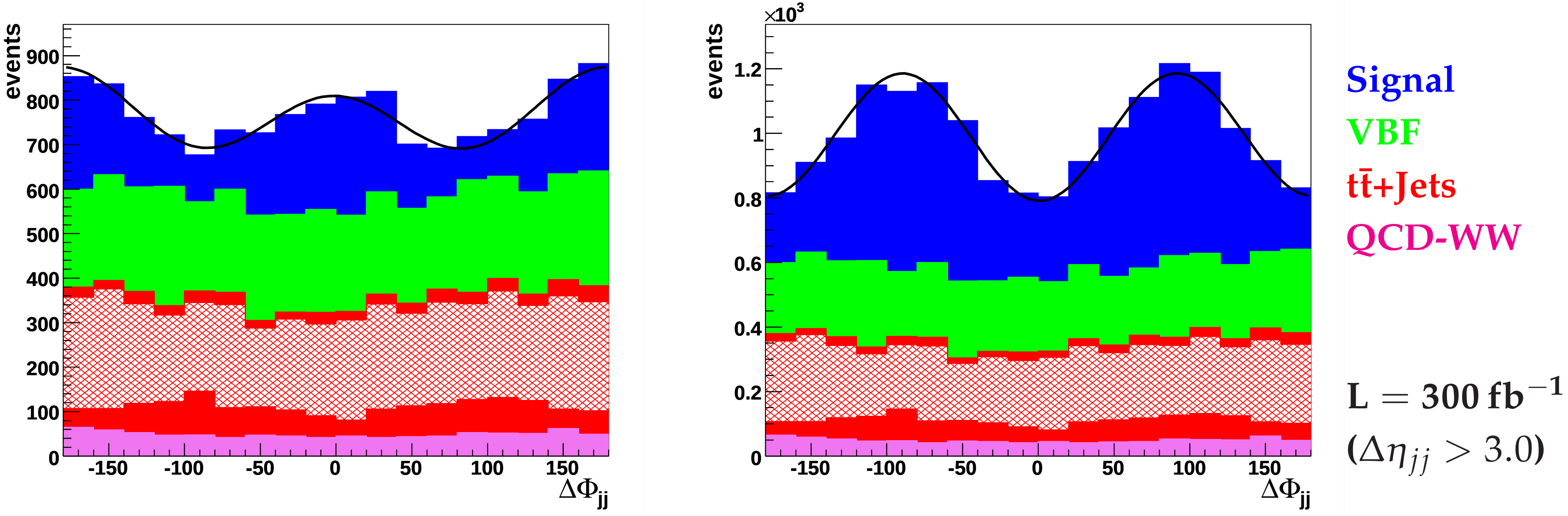


CP-odd coupling



$\Delta\Phi_{jj}$-Distribution in gluon fusion: $\Delta\eta_{jj} > 3$

Fit to Φ_{jj}-distribution with function $f(\Delta\Phi) = N(1 + A\cos[2(\Delta\Phi - \Delta\Phi_{max})] - B\cos(\Delta\Phi))$



CP-even

$A = 0.100 \pm 0.039$

$\Delta\Phi_{max} = 5.8 \pm 15.3$

CP-odd

$A = 0.199 \pm 0.034$

$\Delta\Phi_{max} = 93.7 \pm 5.1$

fit of the background only : $A = 0.069 \pm 0.044$ and $\Delta\Phi_{max} = 64 \pm 25$

(mean values of 10 independent fits of data for $L = 30\, fb^{-1}$ each)

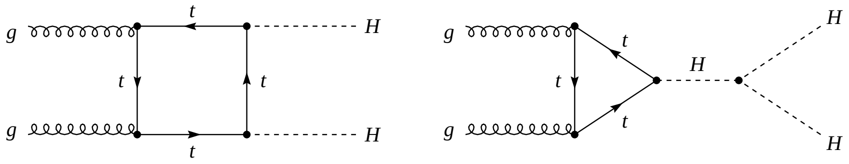
Probing the Higgs potential

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

$\Longrightarrow$ Higgs mass: $m_H^2 = 2\lambda v^2$

HHH coupling: $6\lambda v = 3m_H^2/v$

Probe this relation in $gg \rightarrow HH$

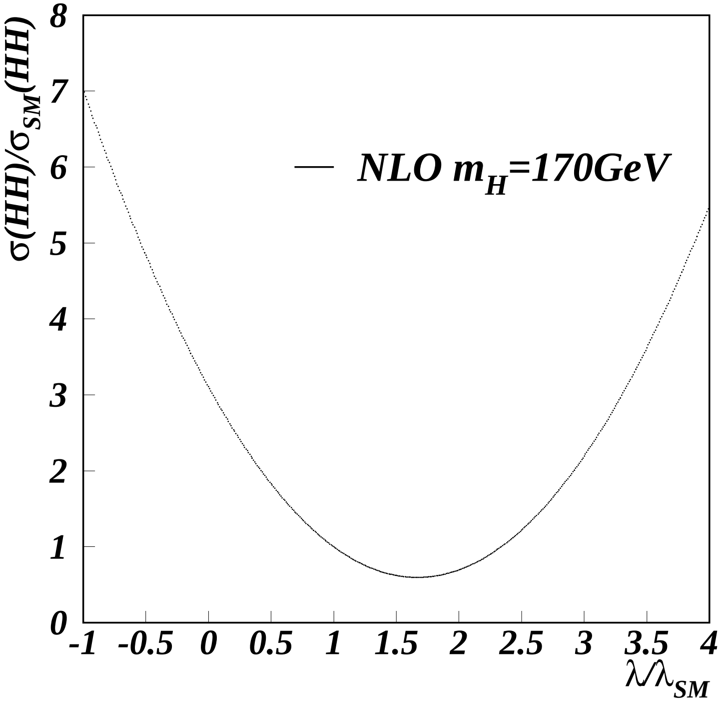


Most sensitive decay channel:

$$\begin{aligned} HH &\rightarrow W^+W^-W^+W^- \\ &\rightarrow l^\pm l'^\pm + 4j + \not{p}_T \end{aligned}$$

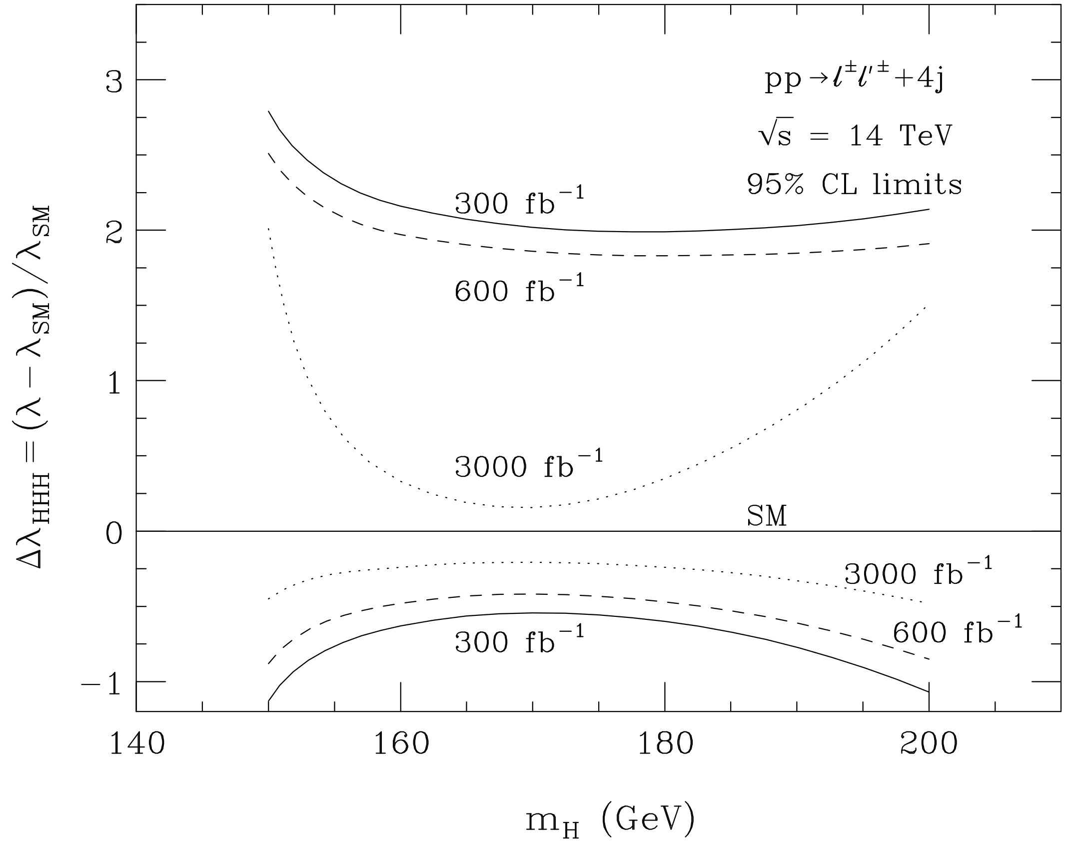
$\sigma(gg \rightarrow HH) \approx 20 - 30$ fb at 14 TeV

Gianotti et al., hep-ph/0204087



LHC sensitivity to HHH coupling

Baur, Plehn, Rainwater: hep-ph/0211224

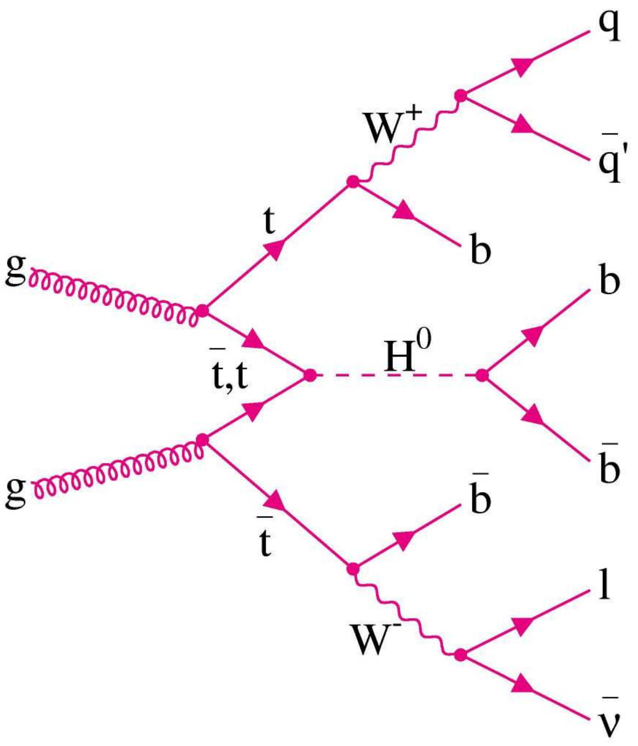


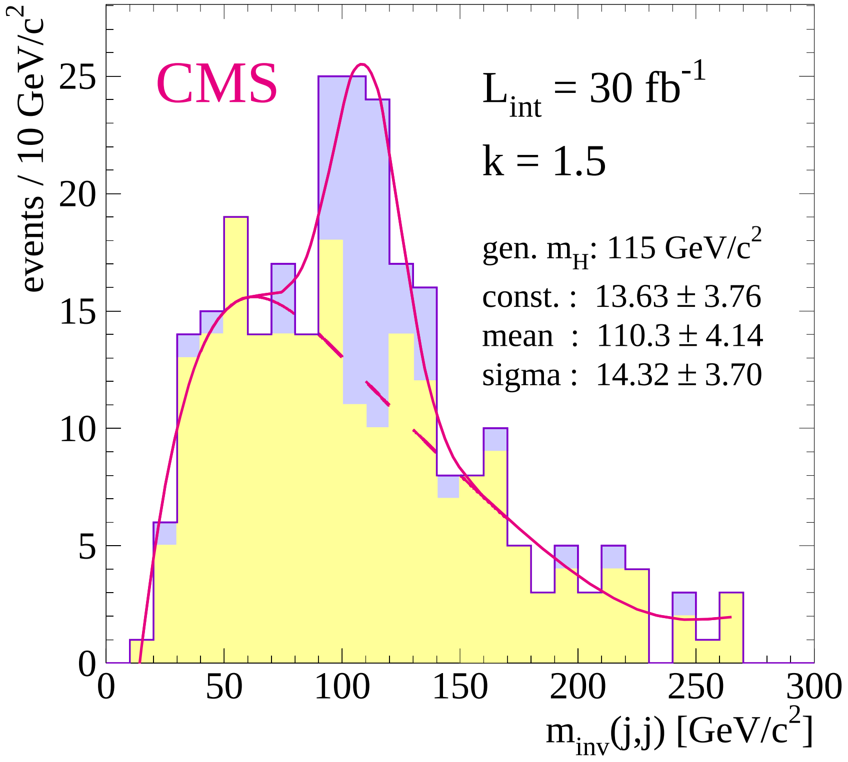
- Need very high luminosity for serious measurement of self coupling
- SLHC sensitivity: up to ±20%

Conclusions

- Spontaneous breaking of $SU(2) \times U(1)$ symmetry is largely untested experimentally ⟹ most important task for the LHC
- LHC will observe a SM-like Higgs boson in multiple channels, with $5 \ldots 20\%$ statistical errors
  ⟹ great source of information on Higgs couplings
- Absence of HVV and AVV couplings for the heavy H/A of the MSSM make their observation more challenging
  ⟹ Need large $\tan\beta$ rate enhancement for their discovery
- NLO QCD corrections and improved simulation tools are important for precise measurements with full LHC data.
- An exciting new era of particle physics starts in 2008.

$t\bar{t}H \longrightarrow t\bar{t}b\bar{b}$





- ✓ $h_t = t\bar{t}H$ Yukawa coupling $\Longrightarrow$ measure $h_t^2\ \mathrm{BR}(H \rightarrow b\bar{b})$
- ✗ must know the background normalization precisely

Applied cuts for LHC predictions

The cross section diverges in collinear and soft regions

- INCLUSIVE cuts to define $H + 2$ jets

$$p_{Tj} > 20 \text{ GeV} \qquad |\eta_j| < 5 \qquad R_{jj} = \sqrt{(\eta_{j_1} - \eta_{j_2})^2 + (\phi_{j_1} - \phi_{j_2})^2} > 0.6$$

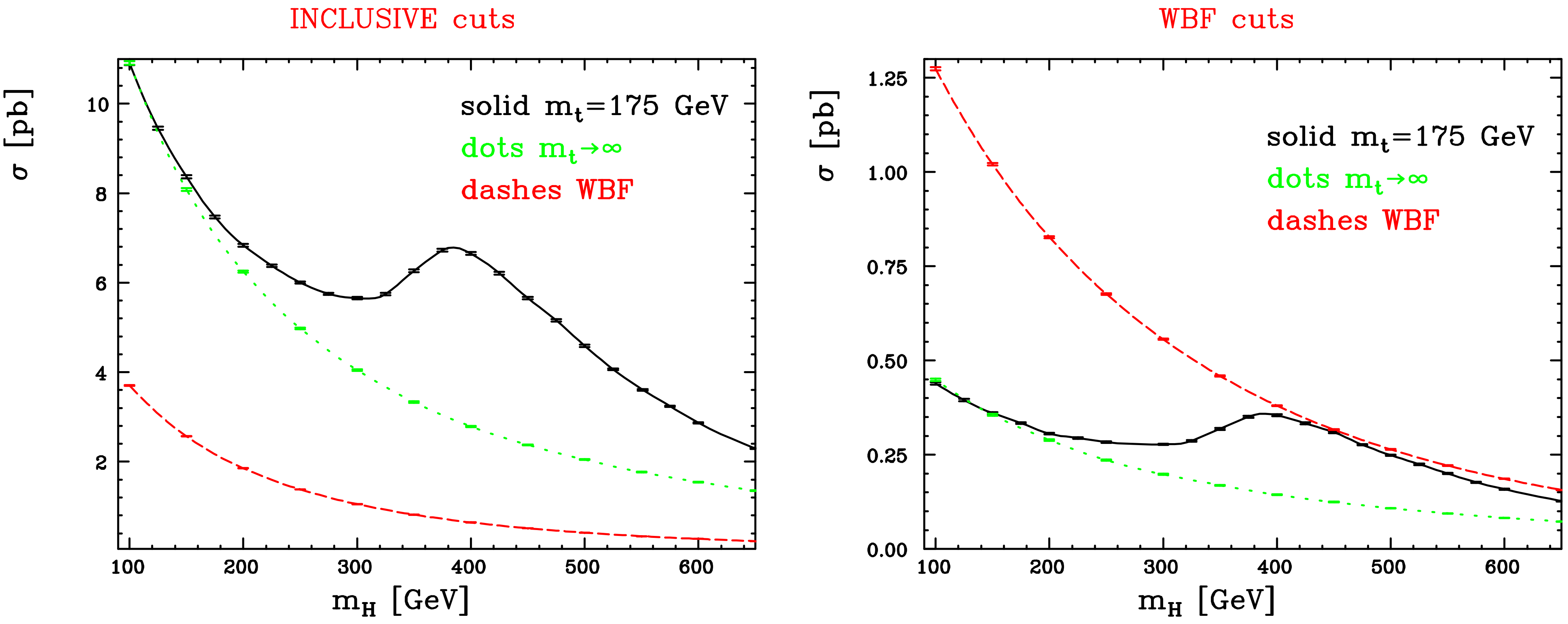
- WBF cuts to enhance WBF over gluon fusion
  In addition to the previous ones, we impose

$$|\eta_{j_1} - \eta_{j_2}| > 4.2 \qquad \eta_{j_1} \cdot \eta_{j_2} < 0 \qquad m_{jj} > 600 \text{ GeV}$$

  - the two tagging jets must be well separated in rapidity
  - they must reside in opposite detector hemispheres
  - they must possess a large dijet invariant mass.

LHC cross sections below calculated with CTEQ6L1 pdfs and fixed $\alpha_s = 0.12$
Expect factor $\approx$ 1.5 to 2 scale uncertainty due to $\sigma \sim \alpha_s^4$

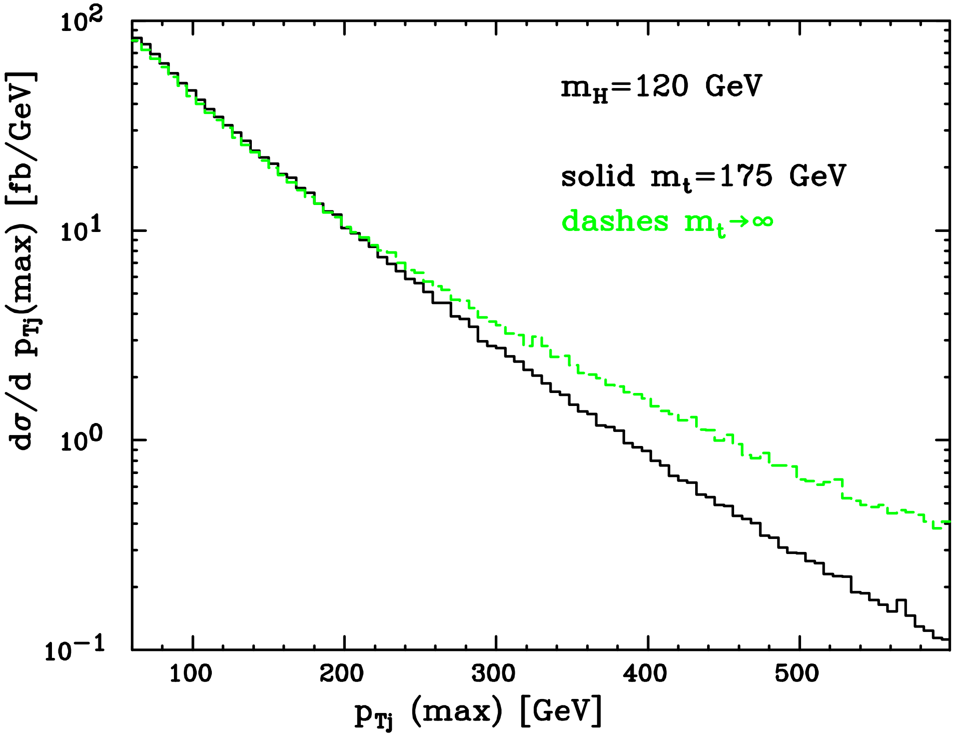
Total cross section with cuts as function of m_H



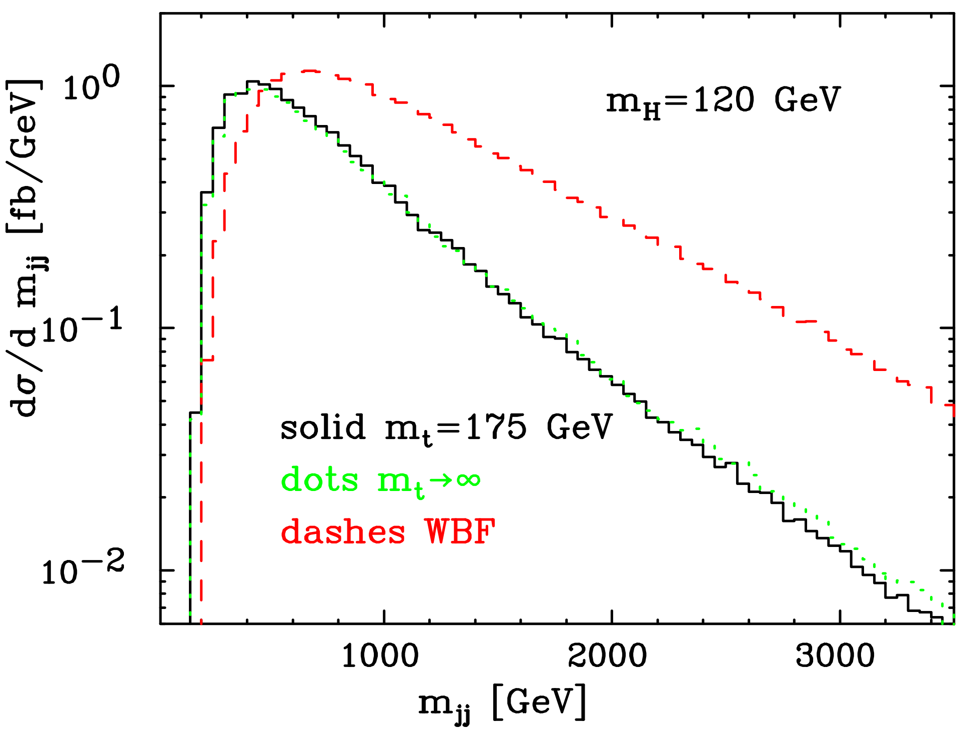
Large top mass limit ok for total cross section provided $m_H \lesssim m_t$

Distributions and $m_t \to \infty$ limit

INCLUSIVE cuts



WBF cuts



Transverse momentum: Large top mass limit ok provided $p_{T,j} \lesssim m_t$

Dijet invariant mass: Large top mass limit ok throughout