HIGGS PHYSICS AT THE LHC

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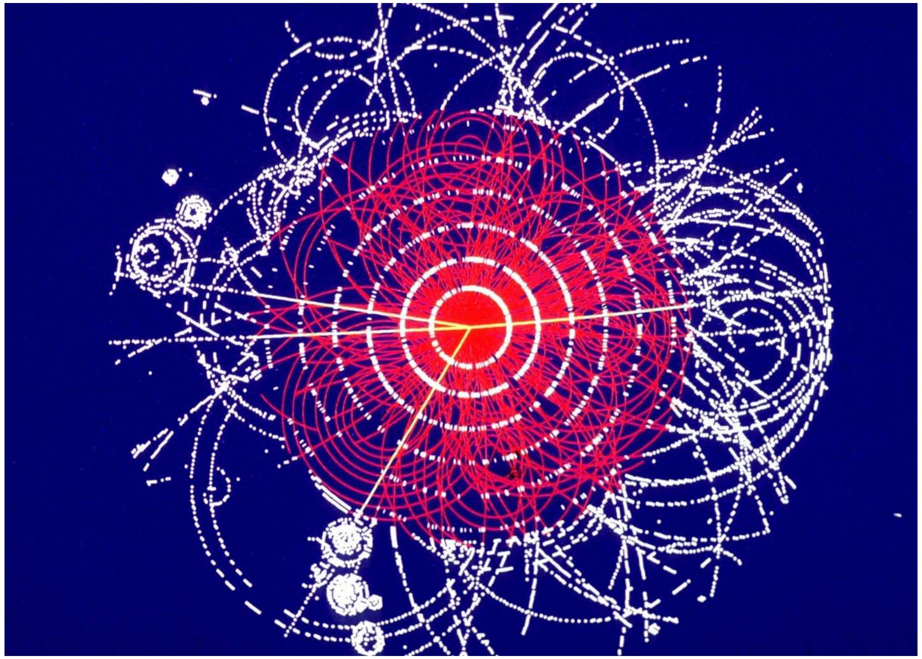
- Goals of Higgs Physics
- SM Channels at the LHC
- Coupling measurements
- QCD Corrections
- Hjj events: VBF vs gluon fusion
- Signs of CP violation
- Conclusions



Goals of Higgs Physics

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

- Discover the Higgs boson
- Measure its couplings and probe
  mass generation for gauge bosons and fermions

Fermion masses arise from Yukawa couplings via $\quad \Phi^\dagger \rightarrow (0, \frac{v+H}{\sqrt{2}})$

$$\mathcal{L}_{\text{Yukawa}} = -\Gamma_d^{ij} \bar{Q}_L'^i \Phi d_R'^j - \Gamma_d^{ij*} \bar{d}_R'^i \Phi^\dagger Q_L'^j + \ldots \qquad = -\Gamma_d^{ij} \frac{v+H}{\sqrt{2}} \bar{d}_L'^i d_R'^j + \ldots$$

$$= -\sum_f m_f \bar{f} f \left(1 + \frac{H}{v}\right)$$

- Test SM prediction: $\bar{f} f H$ Higgs coupling strength $= m_f/v$
- Observation of $H f \bar{f}$ Yukawa coupling is no proof that v.e.v exists

Higgs coupling to gauge bosons

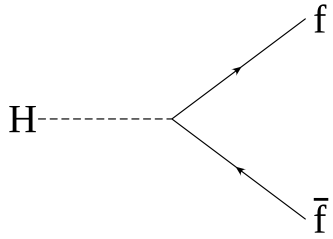
Kinetic energy term of Higgs doublet field:

$$(D^\mu\Phi)^\dagger (D_\mu\Phi) = \frac{1}{2}\partial^\mu H \partial_\mu H + \left[\left(\frac{gv}{2}\right)^2 W^{\mu+}W^-_\mu + \frac{1}{2}\frac{(g^2+g'^2)\,v^2}{4} Z^\mu Z_\mu\right]\left(1+\frac{H}{v}\right)^2$$

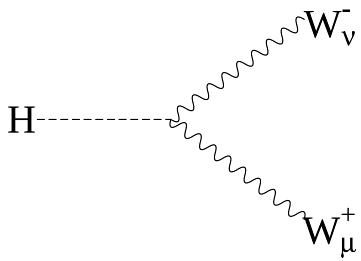
- W, Z mass generation: $m_W^2 = \left(\frac{gv}{2}\right)^2$, $m_Z^2 = \frac{(g^2+g'^2)v^2}{4}$
- WWH and ZZH couplings are generated
- Higgs couples propotional to mass: coupling strength $= 2\, m_V^2/v \sim g^2\, v$ within SM

Measurement of WWH and ZZH couplings is essential for identification of H as agent of symmetry breaking: Without a v.e.v. such a trilinear coupling is impossible at tree level

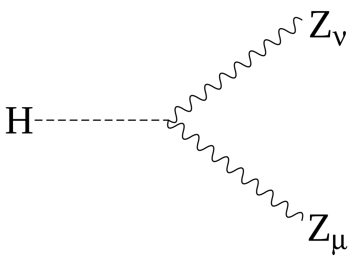
Feynman rules



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



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



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

Verify tensor structure of HVV couplings. Loop induced couplings lead to $HV_{\mu\nu}V^{\mu\nu}$ effective coupling and different tensor structure: $g_{\mu\nu} \quad\longrightarrow\quad q_1 \cdot q_2\, g_{\mu\nu} - q_{1\nu}q_{2\mu}$

The MSSM Higgs sector

The SM uses the conjugate field $\Phi_c = i\sigma_2\Phi^*$ to generate down quark and lepton masses. In supersymmetric models this must be an independent field

$$\begin{aligned}\mathcal{L}_{\text{Yukawa}} &= -\Gamma_d \bar{Q}_L \Phi_1 d_R - \Gamma_e \bar{L}_L \Phi_1 e_R + \text{h.c.} \\ &\quad -\Gamma_u \bar{Q}_L \Phi_2 u_R + \text{h.c.}\end{aligned}$$

Two complex Higgs doublet fields Φ_1 and Φ_2 receive mass and v.e.v.s v_1, v_2 from generalized Higgs potential. Mass eigenstates constructed out of these 8 real fields are

Neutral sector:
2 CP even Higgs bosons: h and H
1 CP odd Higgs boson: A
1 Goldstone boson: χ_0

Charged sector:
charged Higgs bosons: $H^\pm$
charged Goldstone boson: $\chi^\pm$

Goldstone bosons absorbed as longitudinal degrees of freedom of Z, $W^\pm$

Couplings of the MSSM neutral Higgses: h, H, A

Fermions

Two doublet fields Φ_1,Φ_2 mix, two v.e.v's $v_1 = v\cos\beta$, $v_2 = v\sin\beta$:

$$\mathcal{L}_{\text{Yuk.}} = -\Gamma_b \bar{b}_L \Phi_1^0 b_R - \Gamma_t \bar{t}_L \Phi_2^0 u_R + \text{h.c.}$$

$$= -\Gamma_b \bar{b}_L \frac{v_1 + H\cos\alpha - h\sin\alpha + iA\sin\beta}{\sqrt{2}} b_R - \Gamma_t \bar{t}_L \frac{v_2 + H\sin\alpha + h\cos\alpha + iA\cos\beta}{\sqrt{2}} t_R + \ldots$$

Expressed in terms of masses the Yukawa Lagrangian is

$$\mathcal{L}_{\text{Yuk.}} = -\frac{m_b}{v}\bar{b}\left(v + H\frac{\cos\alpha}{\cos\beta} - h\frac{\sin\alpha}{\cos\beta} - i\gamma_5 A\tan\beta\right) b - \frac{m_t}{v}\bar{t}\left(v + H\frac{\sin\alpha}{\sin\beta} + h\frac{\cos\alpha}{\sin\beta} - i\gamma_5 A\cot\beta\right) t$$

$\Longrightarrow$ coupling factors compared to SM hff coupling $-i\, m_f/v$

Gauge Bosons

extra coupling factors for hVV and HVV couplings as compared to SM

$$hVV \sim \sin(\beta-\alpha) \qquad\qquad HVV \sim \cos(\beta-\alpha)$$

SM Higgs mass fit to EW precision data

$$m_H = 76^{+33}_{-24}\ \text{GeV}$$

Including theory uncertainty

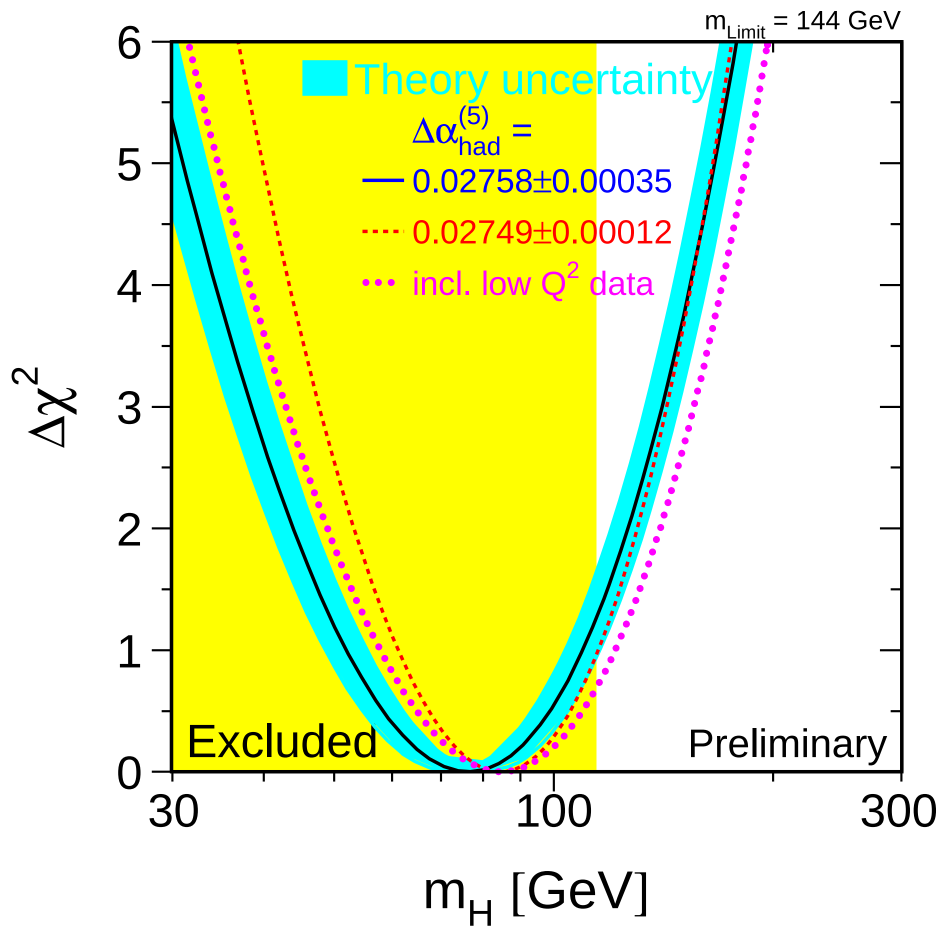
$$m_H < 144\ \text{GeV} \quad (95\%\ \text{CL})$$

Does not include
Direct search limit from LEP

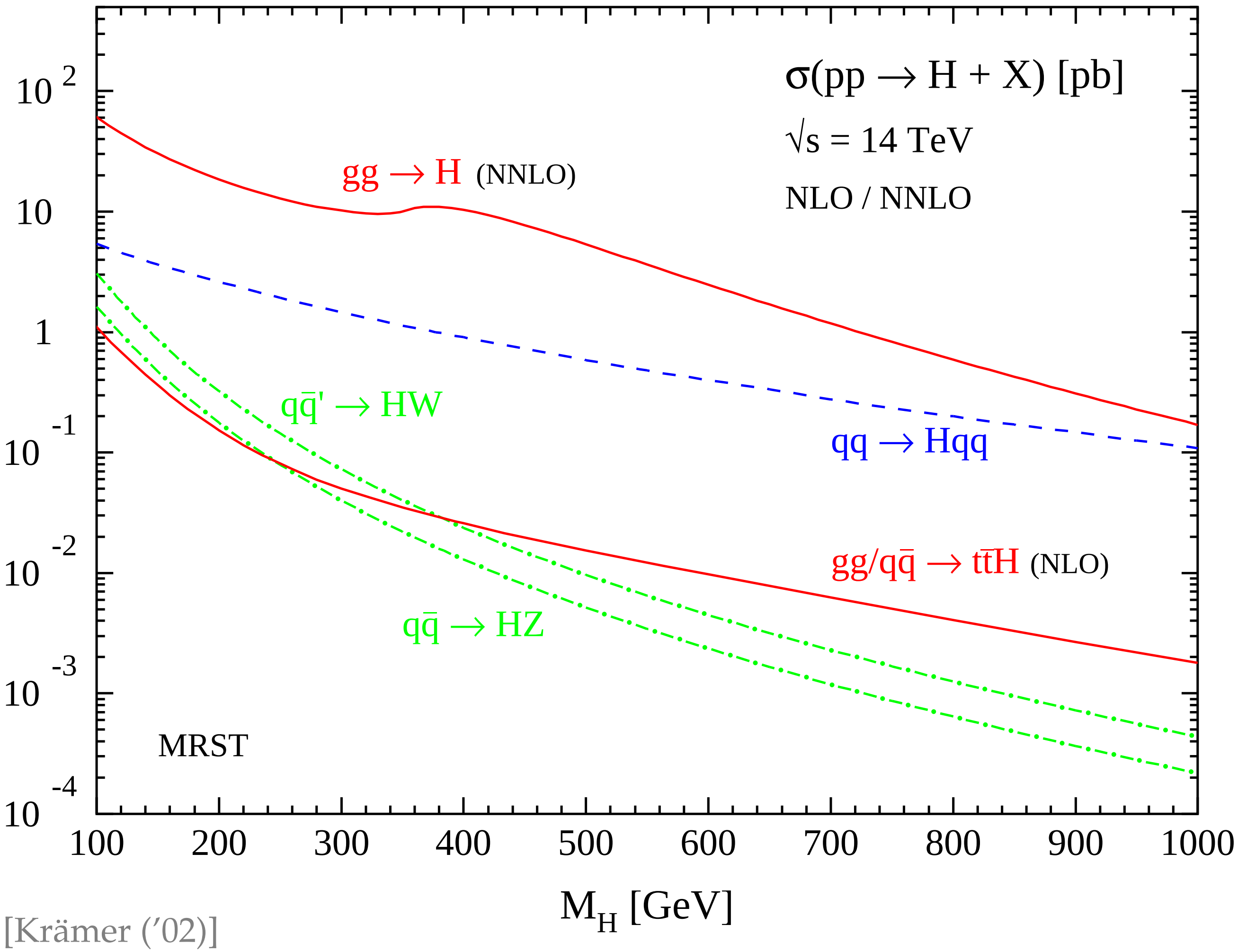
$$m_H > 114\ \text{GeV} \quad (95\%\ \text{CL})$$

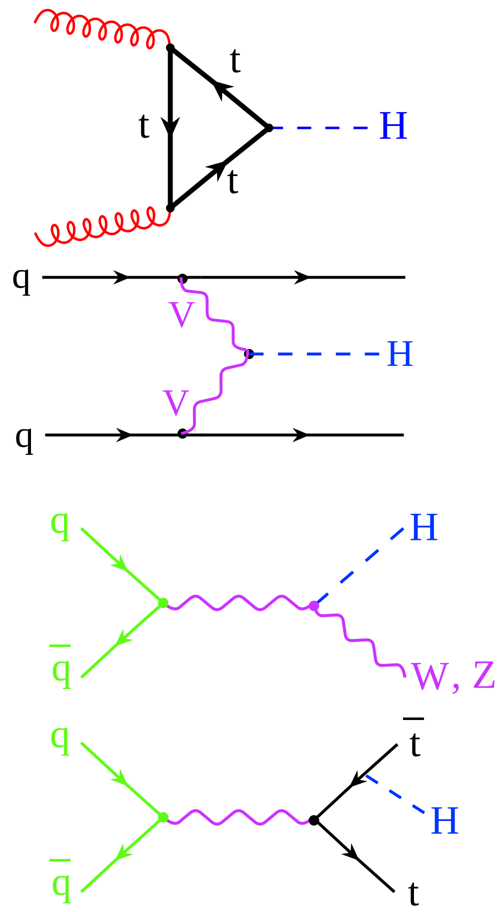
Renormalize probability for
$m_H > 114$ GeV to 100%:

$$m_H < 182\ \text{GeV} \quad (95\%\ \text{CL})$$



Total SM Higgs cross sections at the LHC

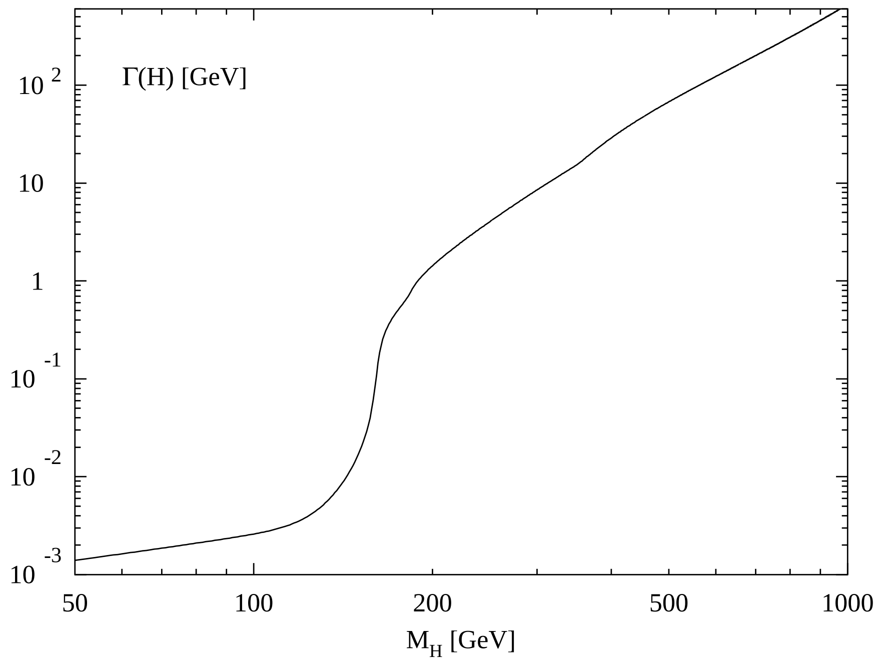


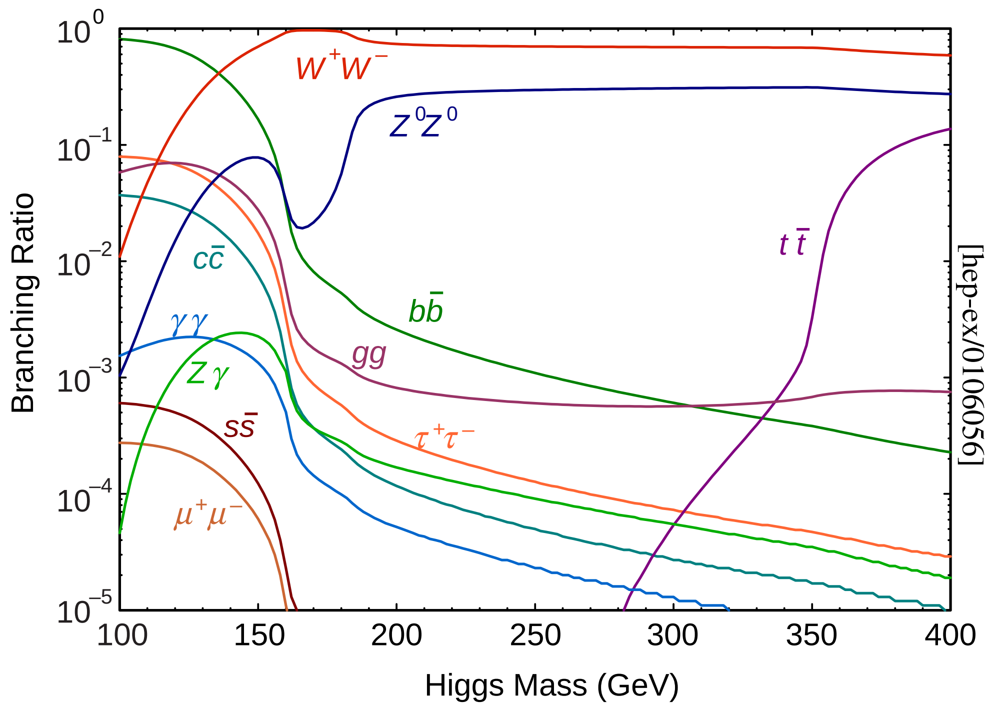


[Krämer ('02)]

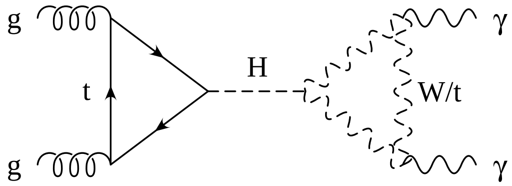
Decay of the SM Higgs

Higgs decay width and branching fractions within the SM

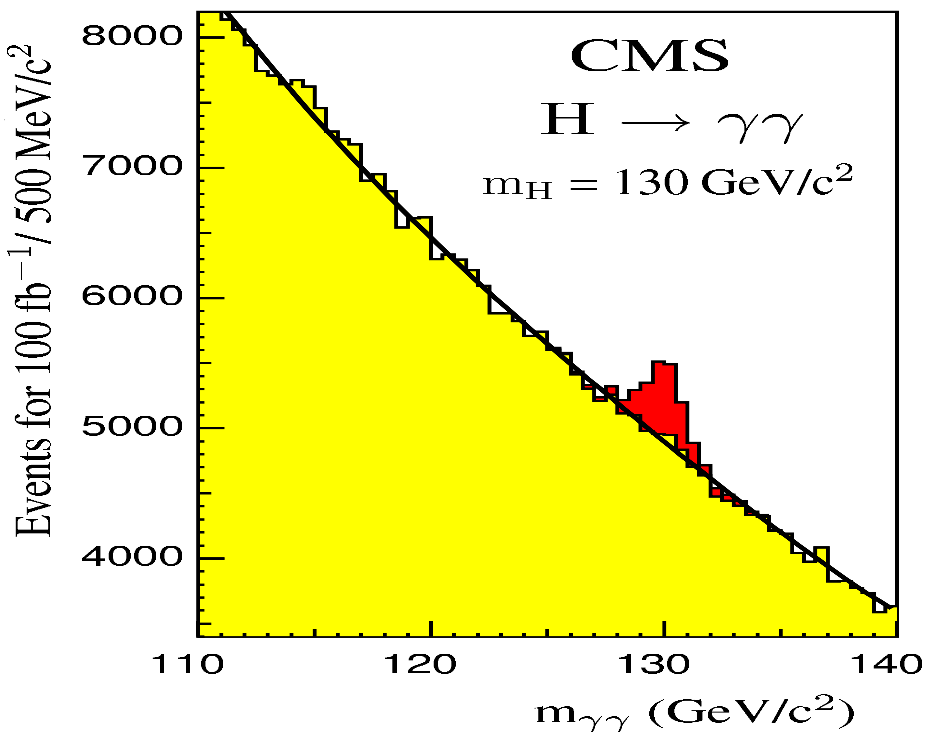




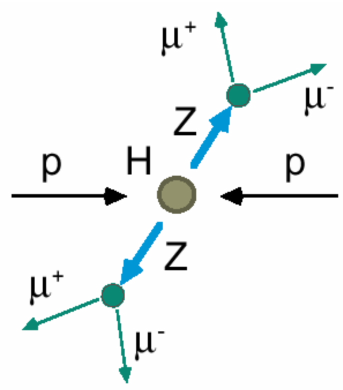
$H \longrightarrow \gamma\gamma$

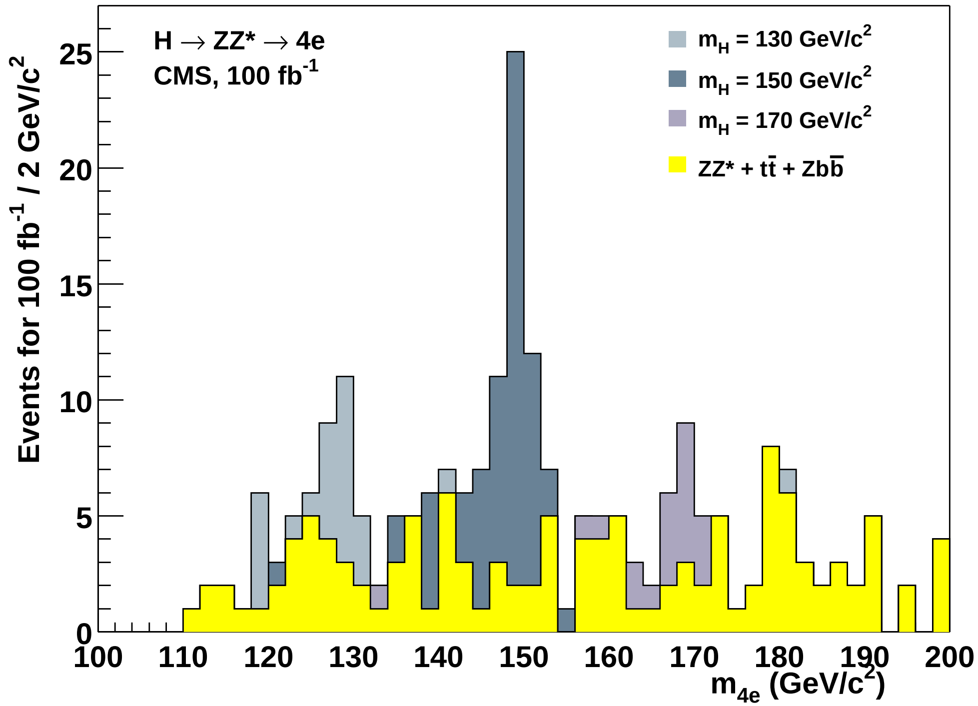


- ✗ $\mathrm{BR}(H \to \gamma\gamma) \approx 10^{-3}$
- ✗ large backgrounds from $q\bar{q} \to \gamma\gamma$ and $gg \to \gamma\gamma$
- ✓ but CMS and ATLAS will have excellent photon-energy resolution (order of 1%)
- ✓ Look for a narrow $\gamma\gamma$ invariant mass peak
- ✓ extrapolate background into the signal region from sidebands.



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





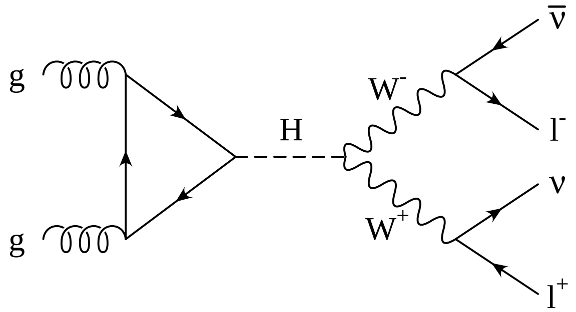
✓ invariant mass of the charged leptons fully reconstructed

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

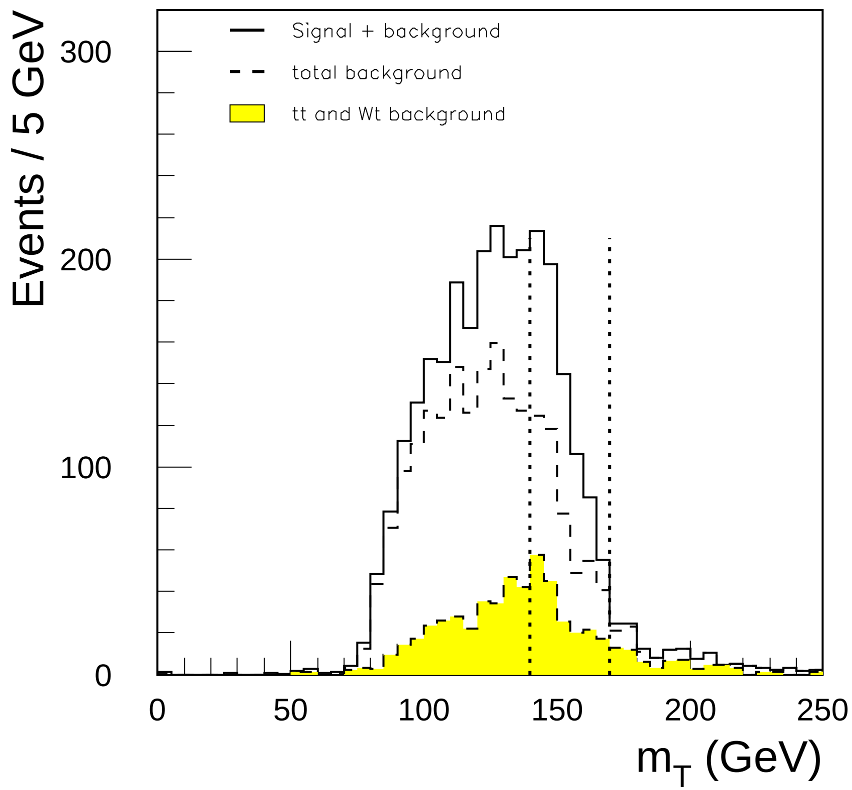
✓ $\mathrm{BR}(H \to \nu\bar{\nu}\ell^+\ell^-) = 6\ \mathrm{BR}(H \to \ell^+\ell^-\ell^+\ell^-)$

✓ the large missing E_T allows a measurement of the transverse mass

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



ATLAS TDR



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

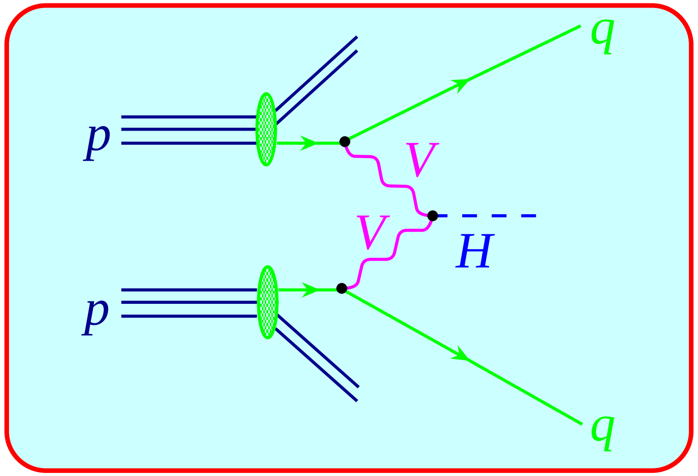
integrated luminosity = 20 fb^{-1}

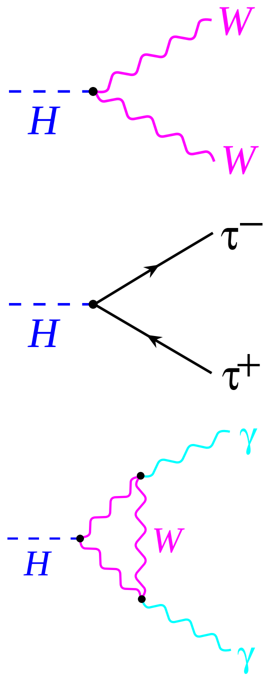
- ✓ Exploit $\ell^+\ell^-$ angular correlations
- ✓ measure the transverse mass with a Jacobian peak at m_H

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

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

Weak Boson Fusion





$m_H > 120$ GeV

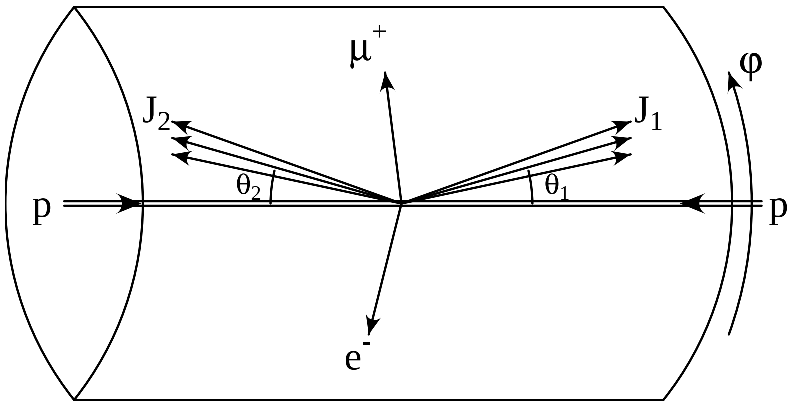
$m_H < 140$ GeV

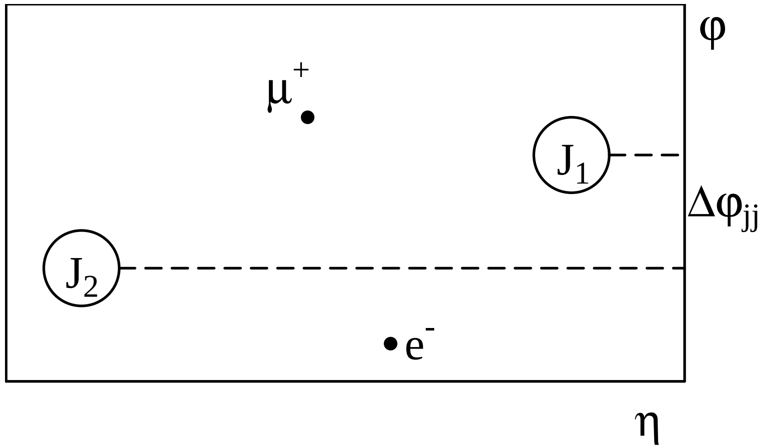
$m_H < 150$ GeV

[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).

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 $H \rightarrow WW$

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:

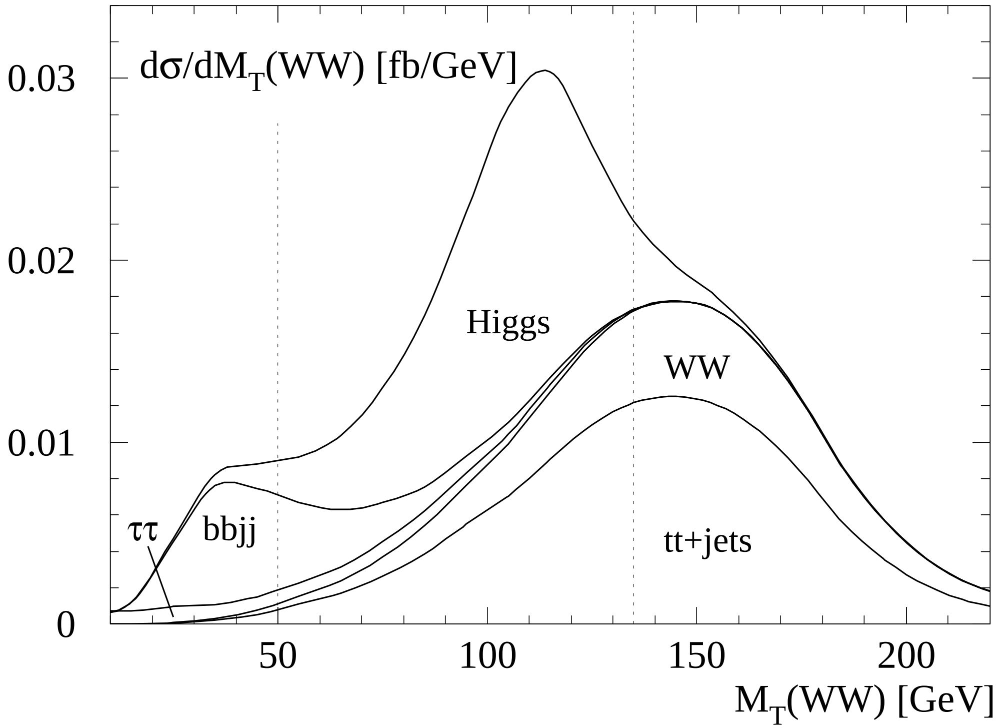
$$E_{T,ll} = \sqrt{\mathbf{p}_{T,ll}^2 + m_{ll}^2}$$

$$\not{E}_T = \sqrt{\not{\mathbf{p}}_T^2 + m_{\nu\nu}^2} \approx \sqrt{\not{\mathbf{p}}_T^2 + m_{ll}^2}$$

$$M_T = \sqrt{(\not{E}_T + E_{T,ll})^2 - (\mathbf{p}_{T,ll} + \not{\mathbf{p}}_T)^2}$$

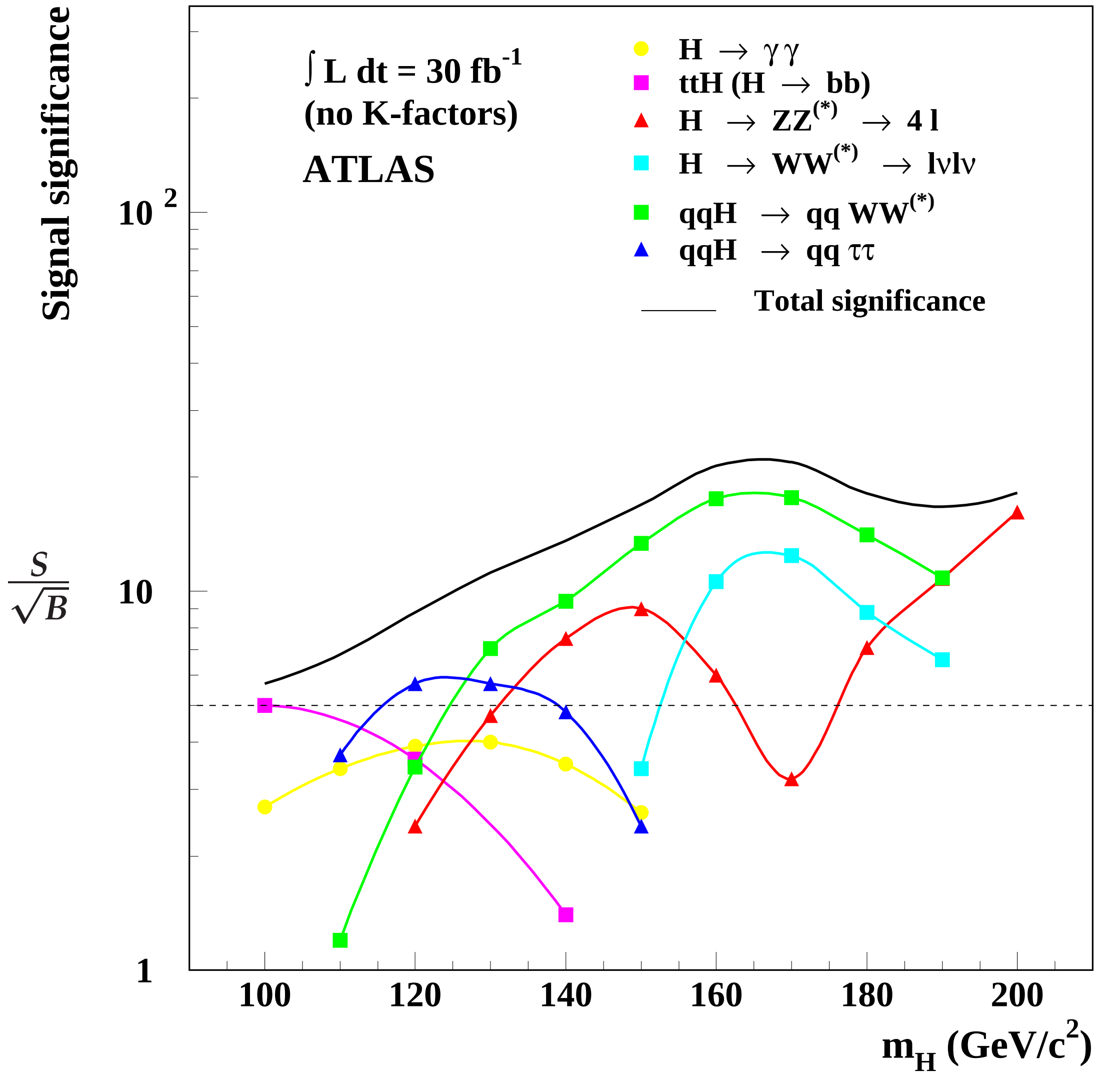
Observe Jacobian peak below $M_T = m_H$

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



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

Higgs discovery potential



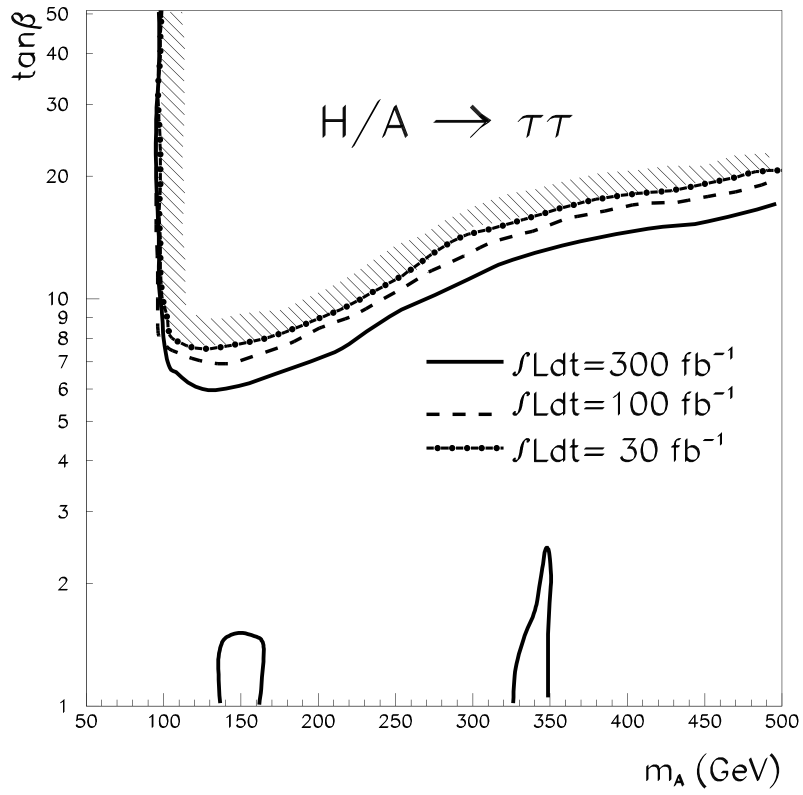
Reach for H/A discovery within MSSM

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

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

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

ATLAS TDR



5σ discovery contours

Reach for $H^{\pm}$ discovery within MSSM

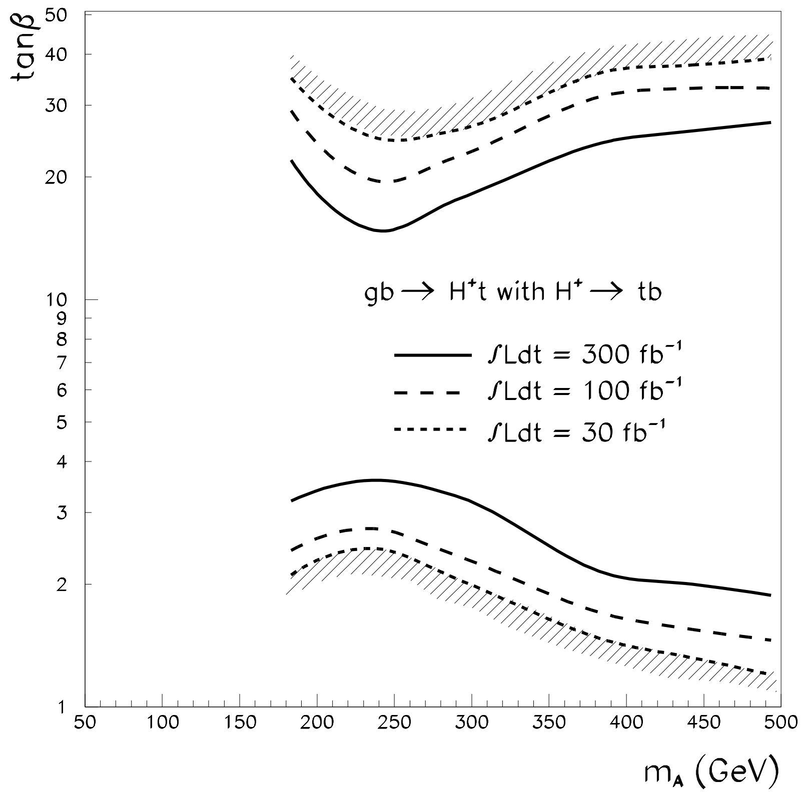
- For $m_{H^{\pm}} > m_t + m_b$ expect $H^{\pm} \to tb$ decay
- Dominant production process

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

b-quark has low p_T: $gb \to H^{\pm} t$ is dominant subprocess

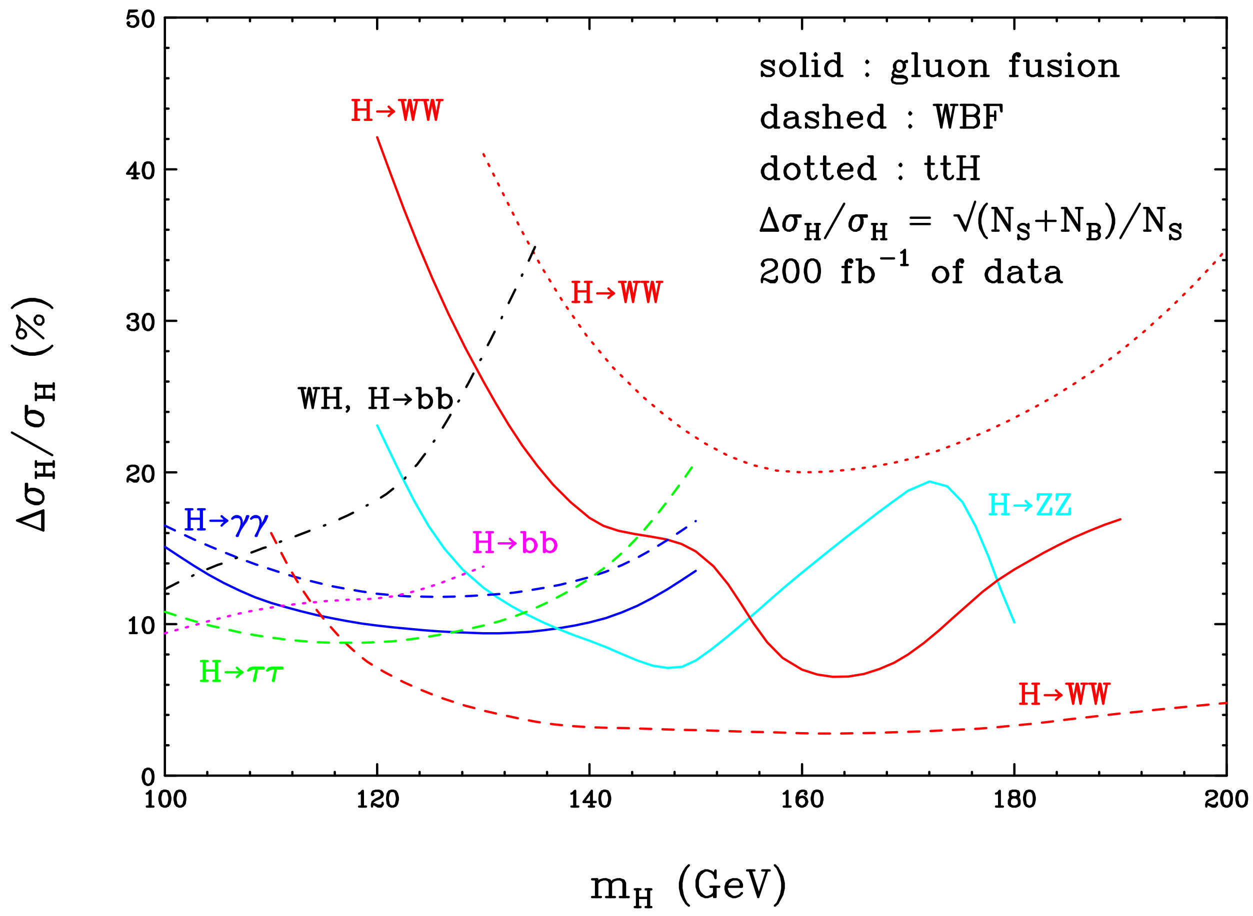
- Main background from $\bar{t}t$(+jets) production

ATLAS TDR



5σ discovery contours

Statistical and systematic errors at LHC



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:

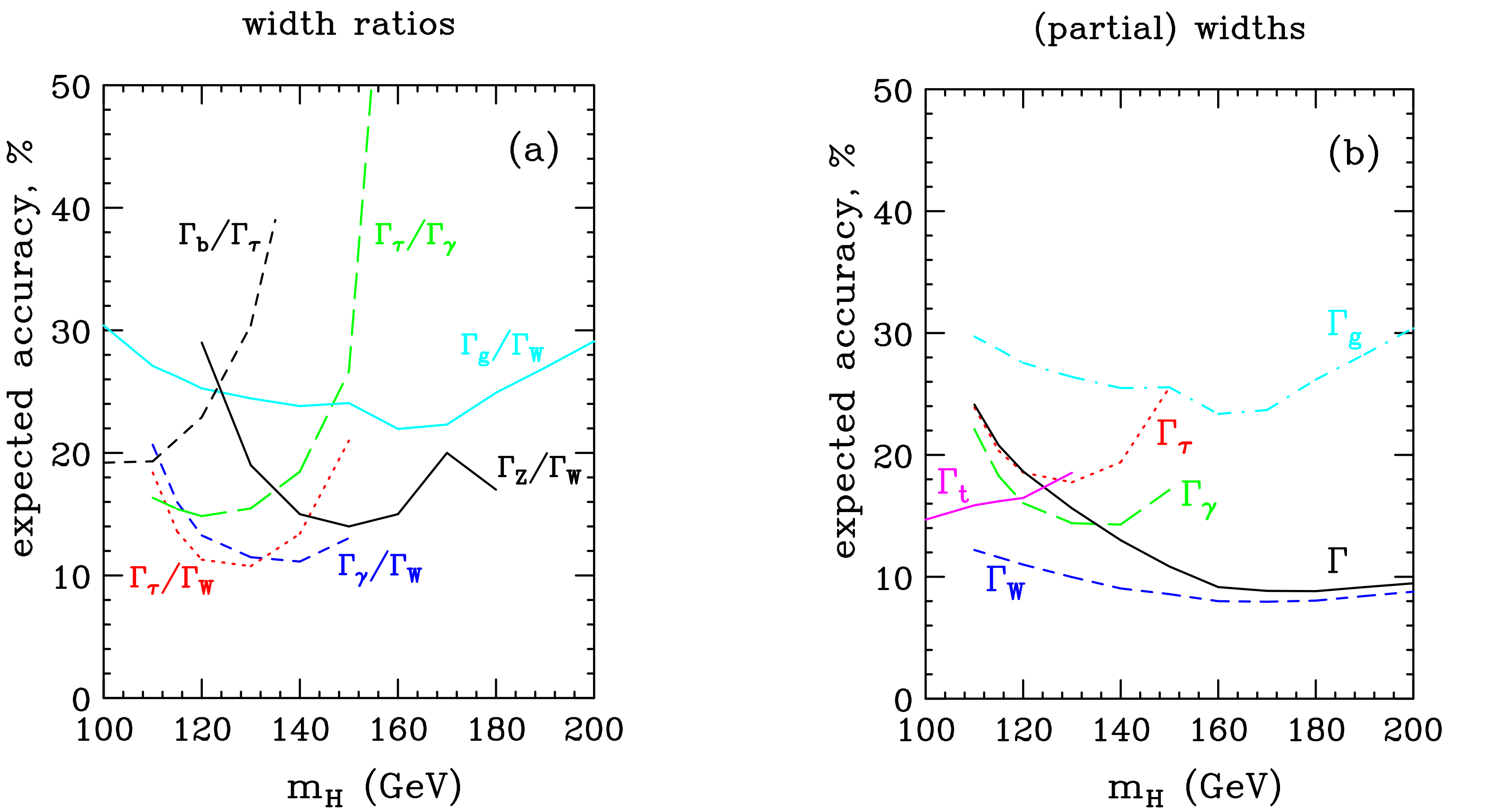
$$f^2 \Gamma > \sum_{obs.} f \Gamma_x \qquad \Longrightarrow \qquad f > \sum_{obs.} \frac{\Gamma_x}{\Gamma} = \sum_{obs.} BR(H \to xx) (= \mathcal{O}(1))$$

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

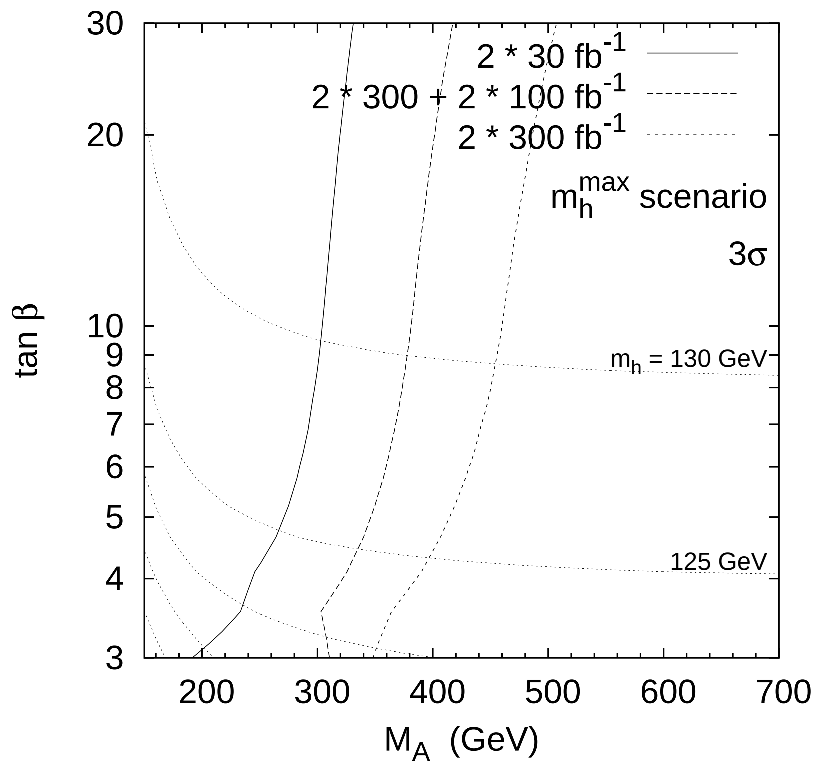
Consider modest m_A:

- 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

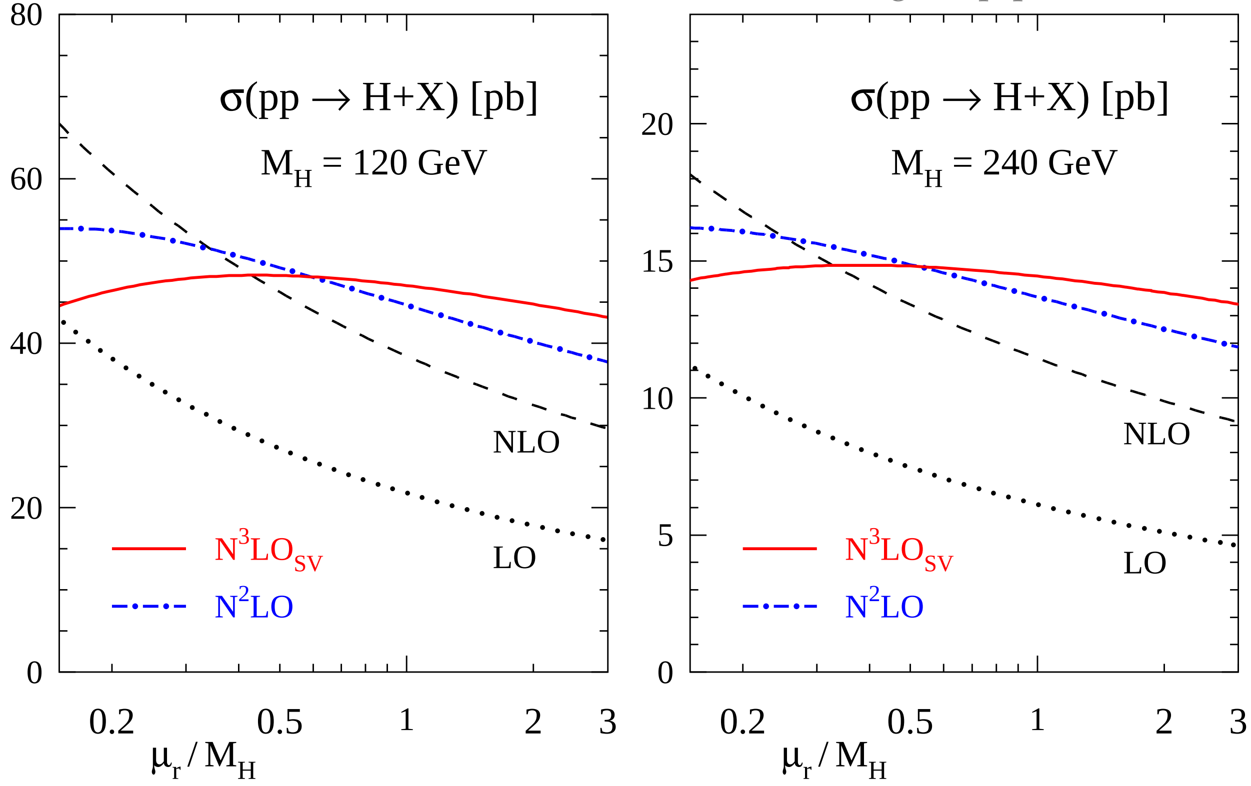
Measurement of partial widths at 10–20% level or couplings at 5–10% level requires predictions of SM production cross sections at 10% level or better

$\Longrightarrow$ 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 $gg \to H$

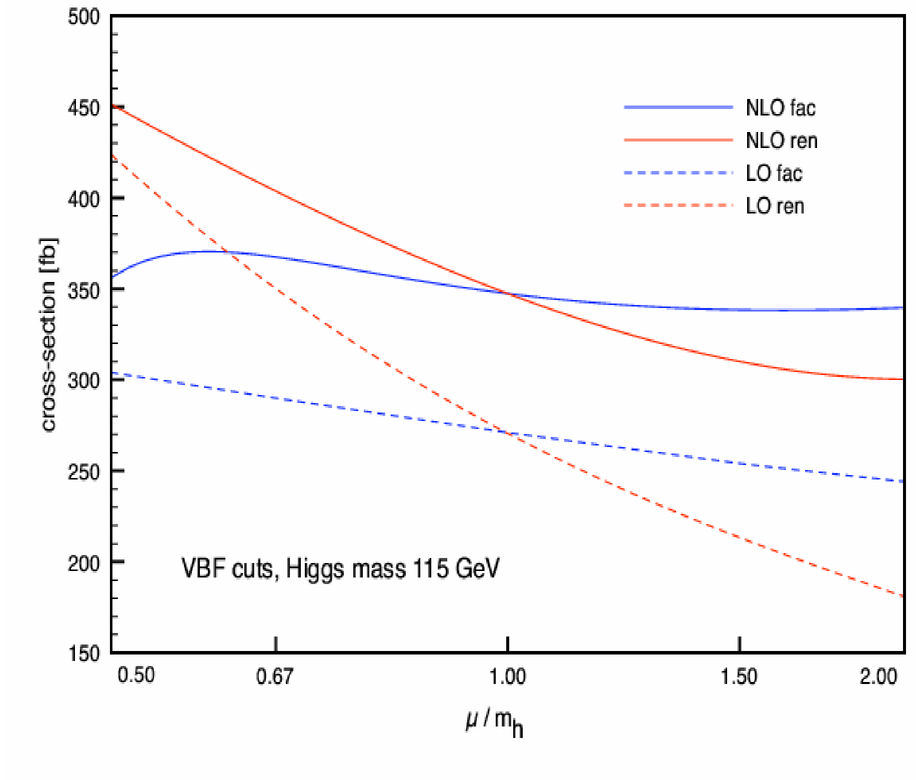
Moch & Vogt, hep-ph/0508265

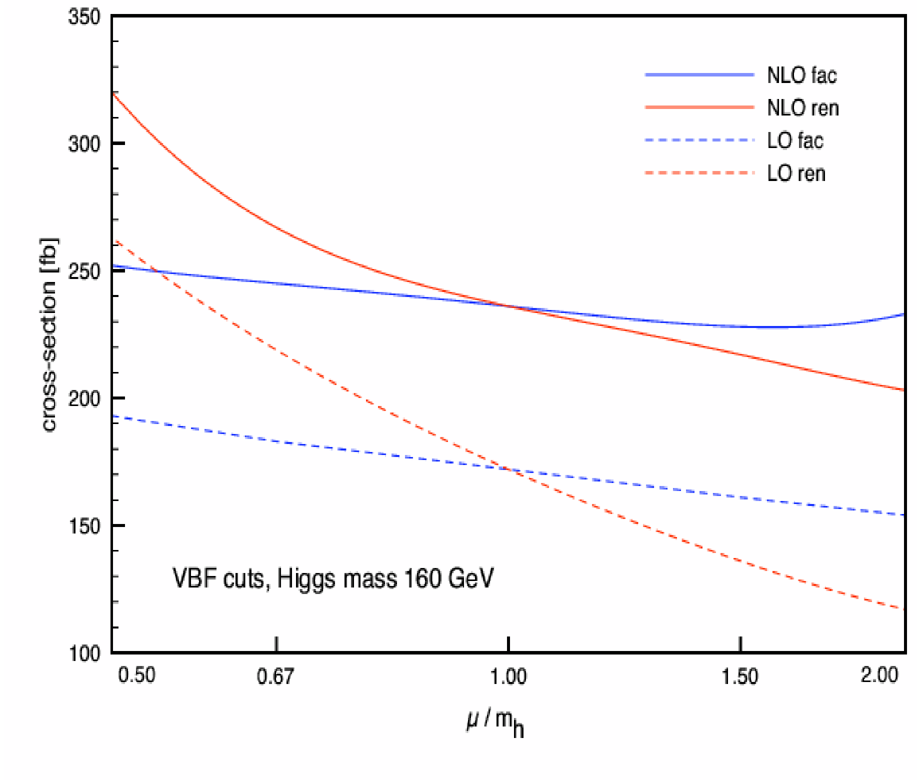


- ✓ Huge improvement in recent years
- ✓ Remaining scale uncertainty below 10%
- ✓ Uncertainty from gluon pdf $\approx 4-7\%$
- ✗ What is K-factor for cross section with cuts? Most problematic: central jet veto against $\bar{t}t$ background for $H \to WW$ search

Hjj cross section for gluon fusion

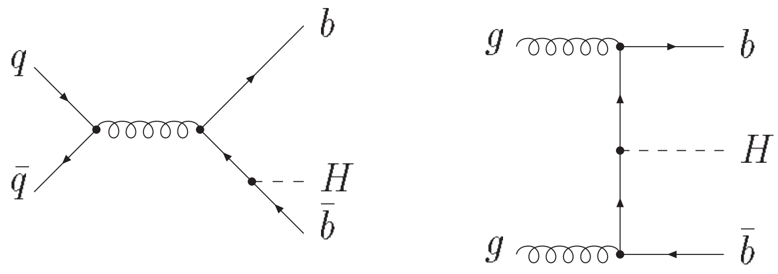
Calculation of Hjj cross section at NLO in $m_t \to \infty$ limit by Campbell, Ellis, Zanderighi, hep-ph/0608194





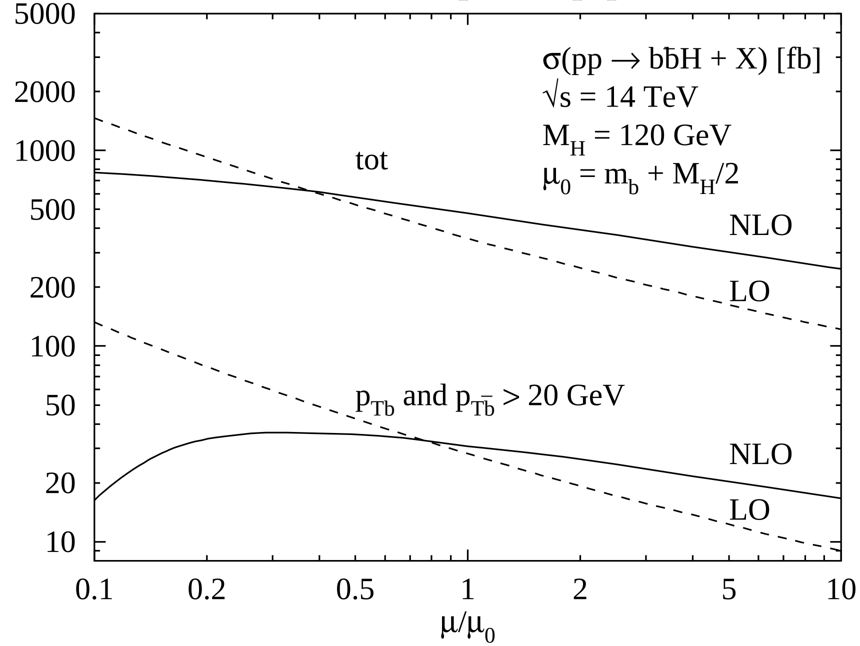
- Modest increase of cross section at 1-loop: K-factor of order 1.2 - 1.4
- Reduced scale dependence at NLO: remaining scale uncertainty $\approx \pm 20\%$

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 $\bar{b}b \rightarrow H$: cross section known at NNLO Harlander, Kilgore (2003)

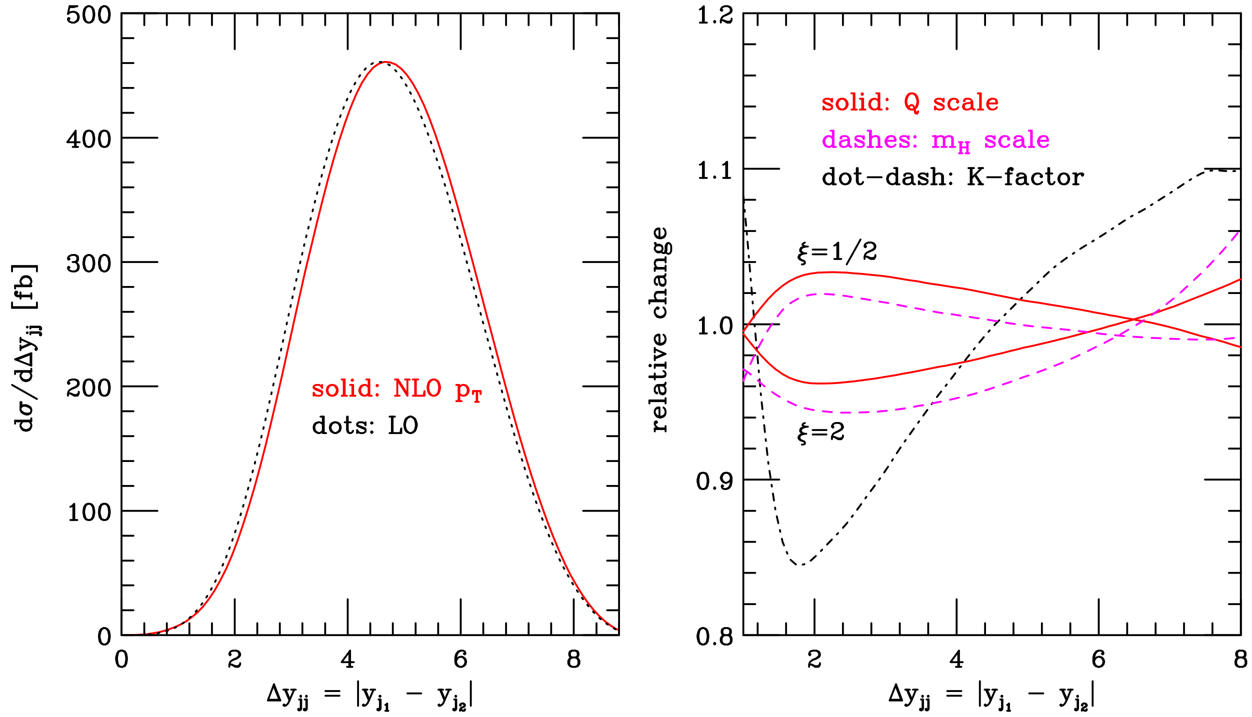
Dittmaier, Krämer, Spira hep-ph/0309204



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



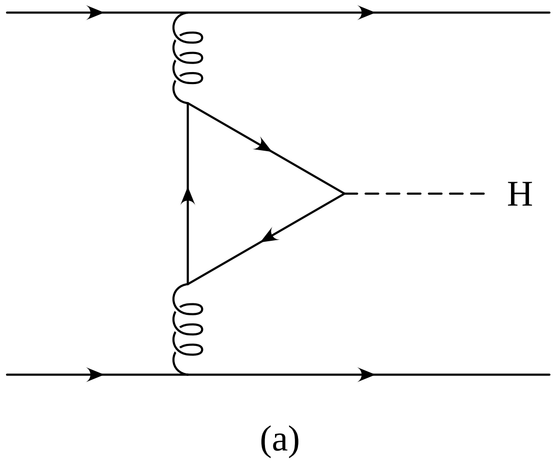
$m_H = 120\,\text{GeV}$, typical VBF cuts

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

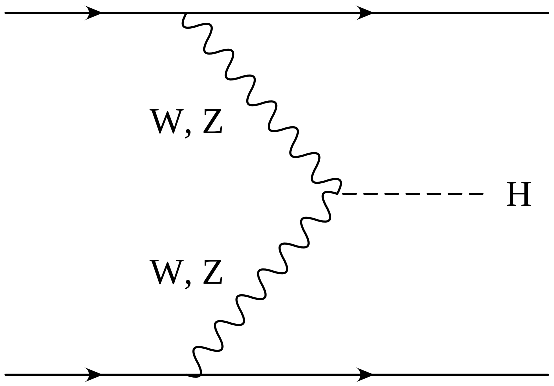
parton level Monte Carlo for Hjj, Wjj, Zjj, W^+W^-jj, $ZZjj$ production

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

How to distinguish gluon fusion and VBF?



vs.



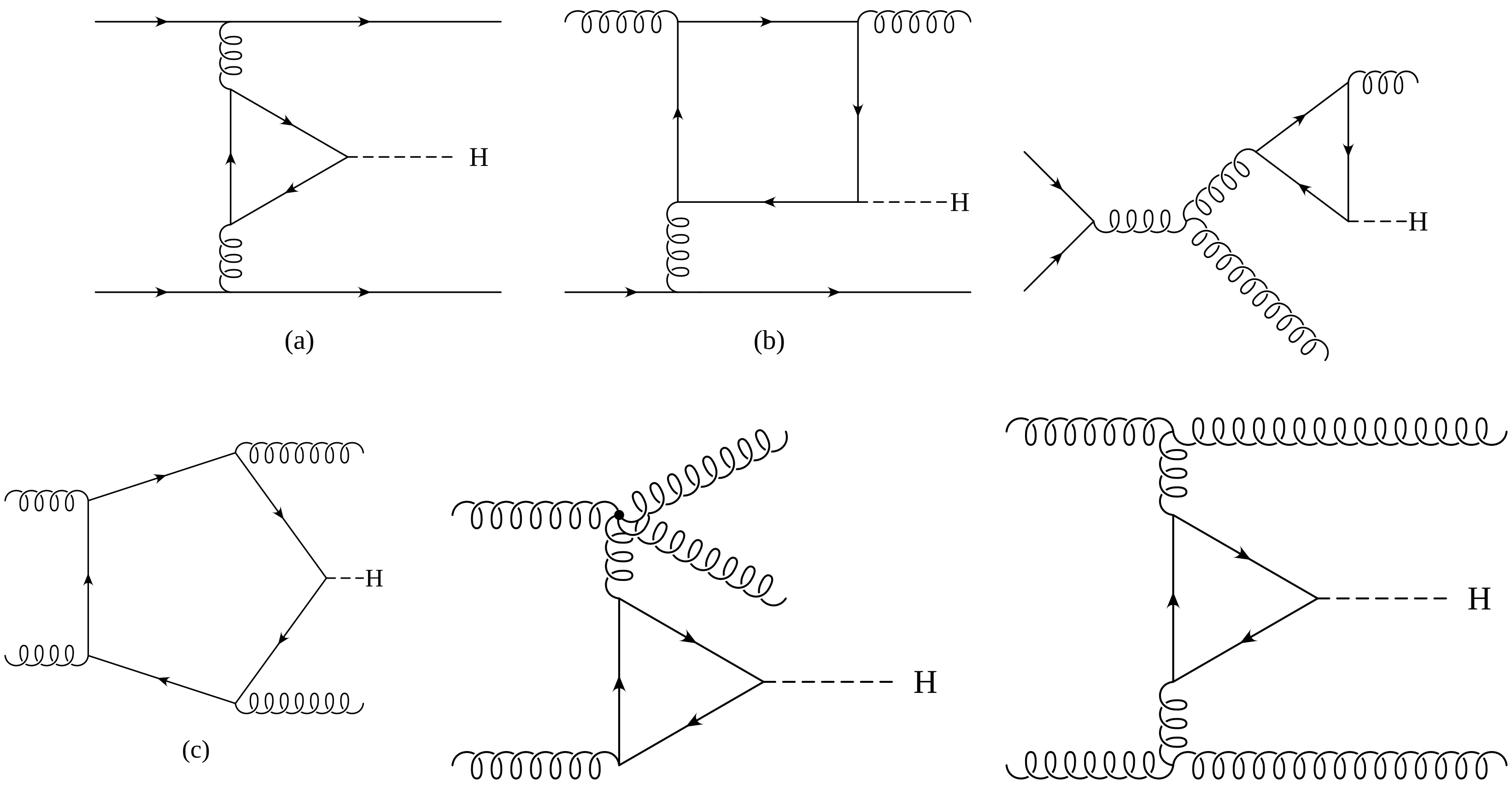
Double real corrections to $gg \to H$ can "fake" VBF

$\Longrightarrow$ 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



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

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

Applied cuts for LHC predictions

The cross section diverges in collinear and soft regions

- INCLUSIVE cuts to define $H/A + 2$ jets

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

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

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

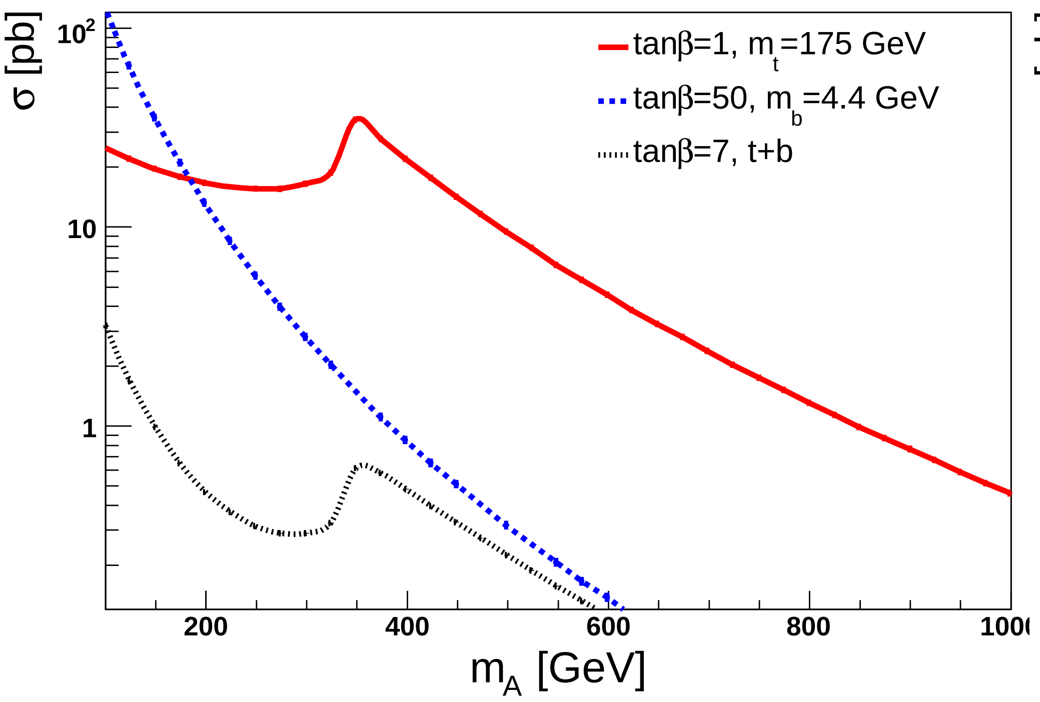
  - the two tagging jets must be well separated in rapidity
  - they must reside in opposite detector hemispheres
  - they must possess a large dijet invariant mass.

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

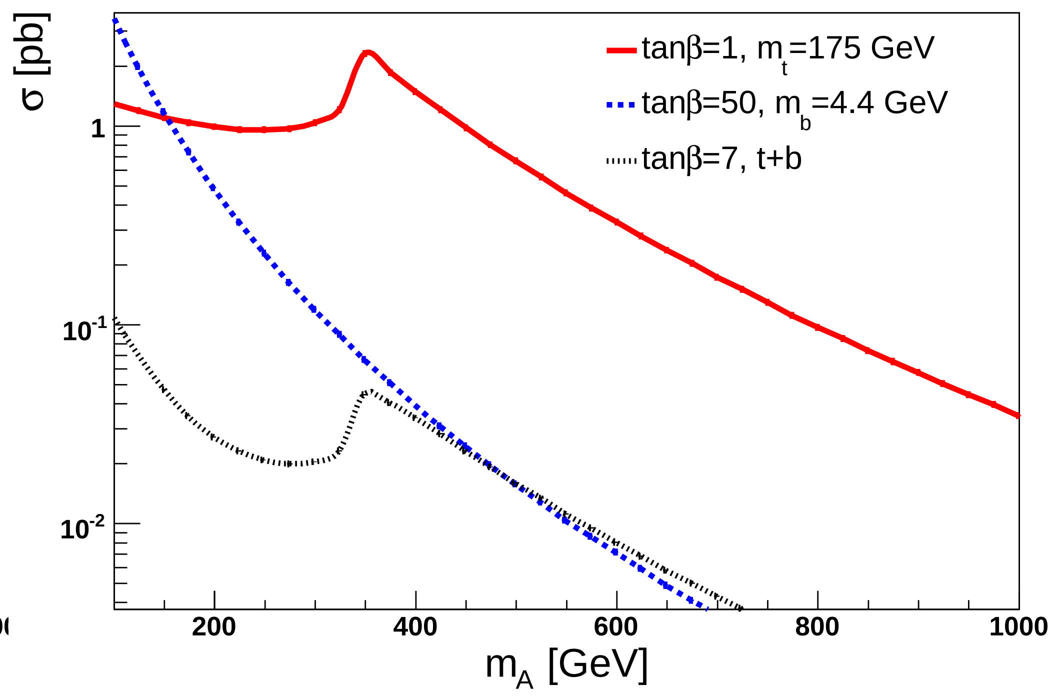
New elements in the calculation

- AQQ vertices given by $-\frac{m_b}{v}\gamma_5 \tan\beta$ and $-\frac{m_t}{v}\gamma_5 \frac{1}{\tan\beta}$
- Interference of top and bottom loops
- Can simulate CP violation in the Higgs sector: $a + ib\gamma_5$ coupling to top and bottom

Inclusive cuts

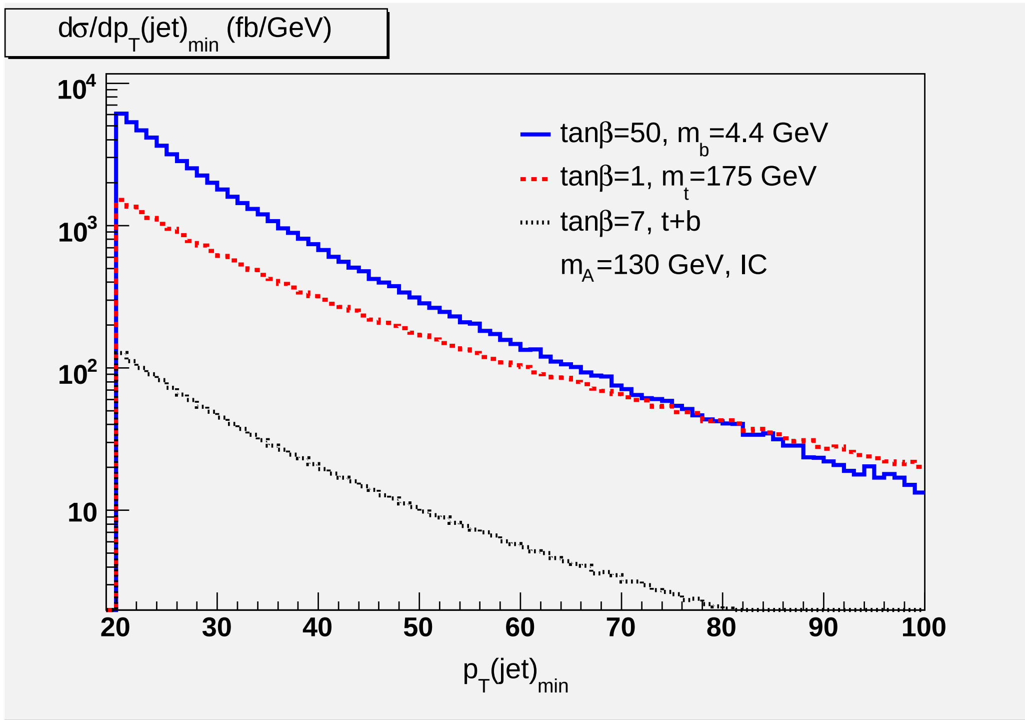


VBF cuts

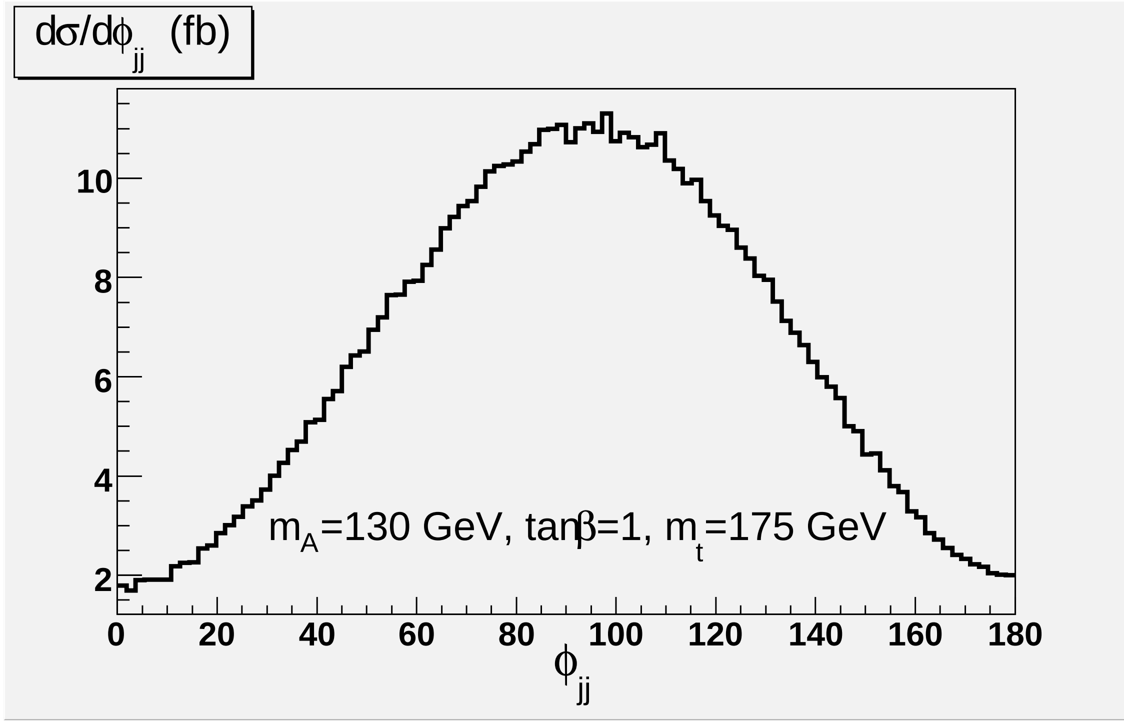


Distributions for Ajj production

p_T of soft jet



Azimuthal angle between jets



- lower scale of bottom quark loops induces steeper p_T falloff since $p_{T,j} > m_b$
- Dips in Φ_{jj} distribution at 0 and 180 degrees are characteristic for effective $AG_{\mu\nu}\tilde{G}^{\mu\nu}$ interaction

Gluon Fusion as a signal channel

Heavy quark loop induces effective Hgg vertex:

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

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

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

⟹ Study in $m_Q \to \infty$ limit [Klämke, DZ (2007)]

Gluon fusion signal and backgrounds

Signal channel (LO):

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

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

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

- 2 identified leptons

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

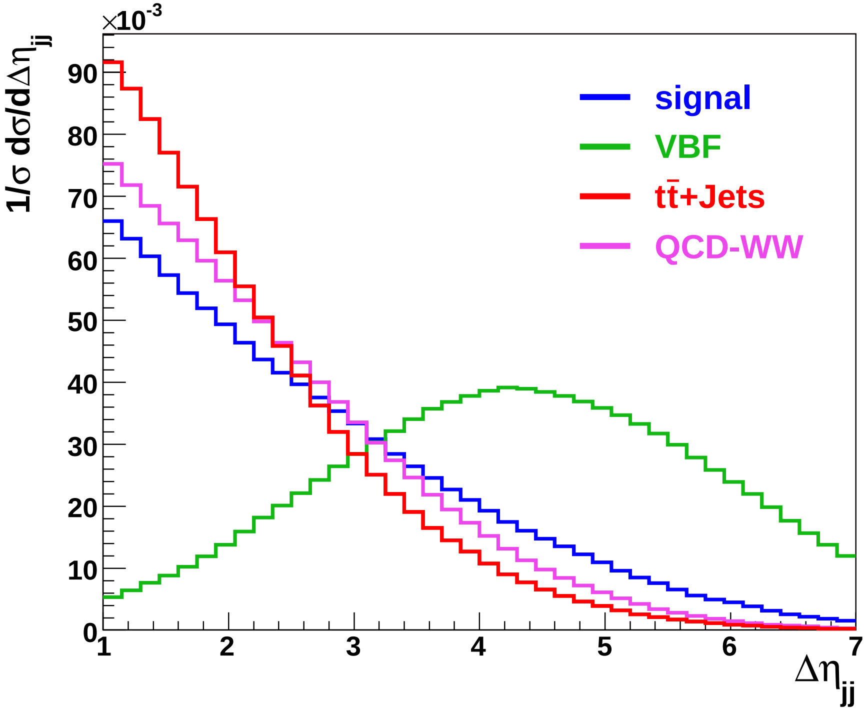
- separation of jets and leptons

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

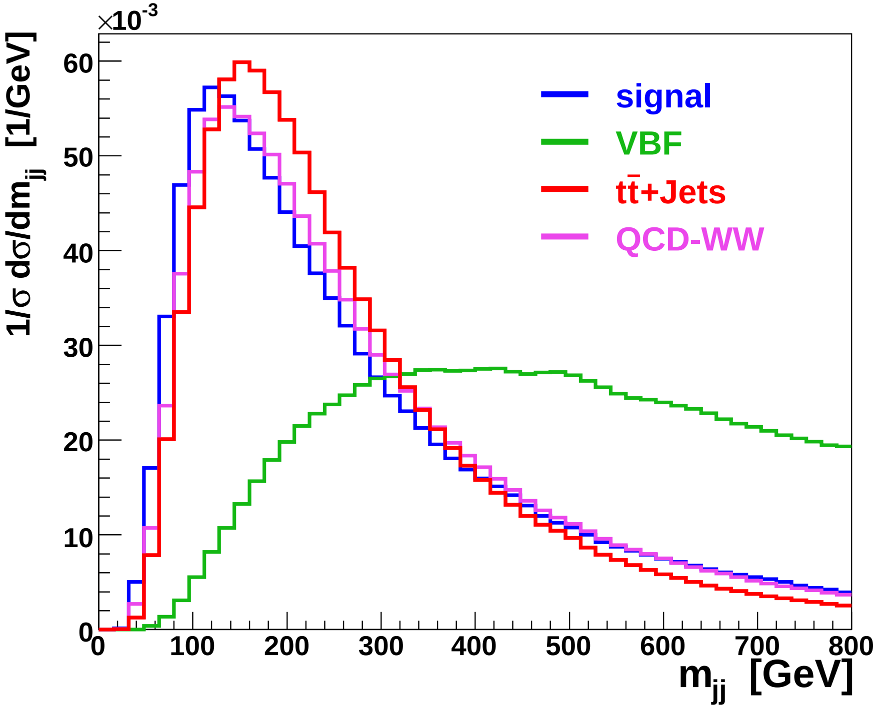
process	σ [fb]
GF $pp \to H + jj$	**115.2**
VBF $pp \to W^+W^- + jj$	**75.2**
$pp \to t\bar{t}$	**6832**
$pp \to t\bar{t} + j$	**9518**
$pp \to t\bar{t} + jj$	**1676**
QCD $pp \to W^+W^- + jj$	**363**

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

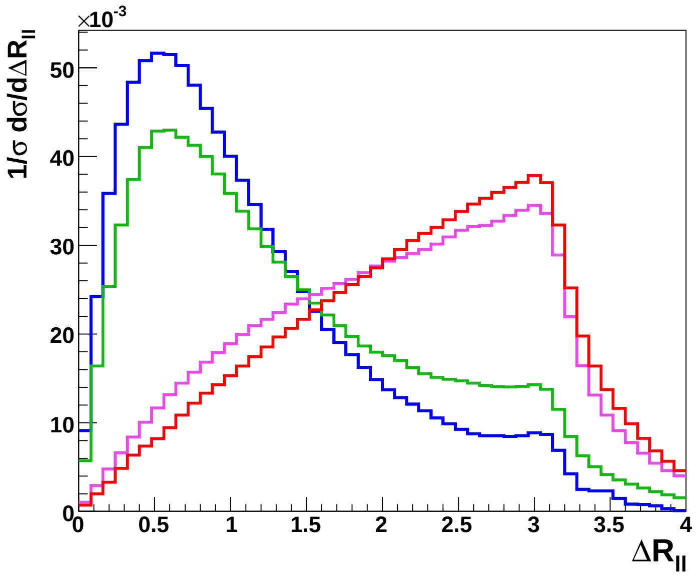
- b-tagging for reduction of top-backgrounds. *(CMS Note 06/014)*
  - (η, p_T) - dependent tagging-efficiencies (60% - 75%) with 10% mistagging - probability

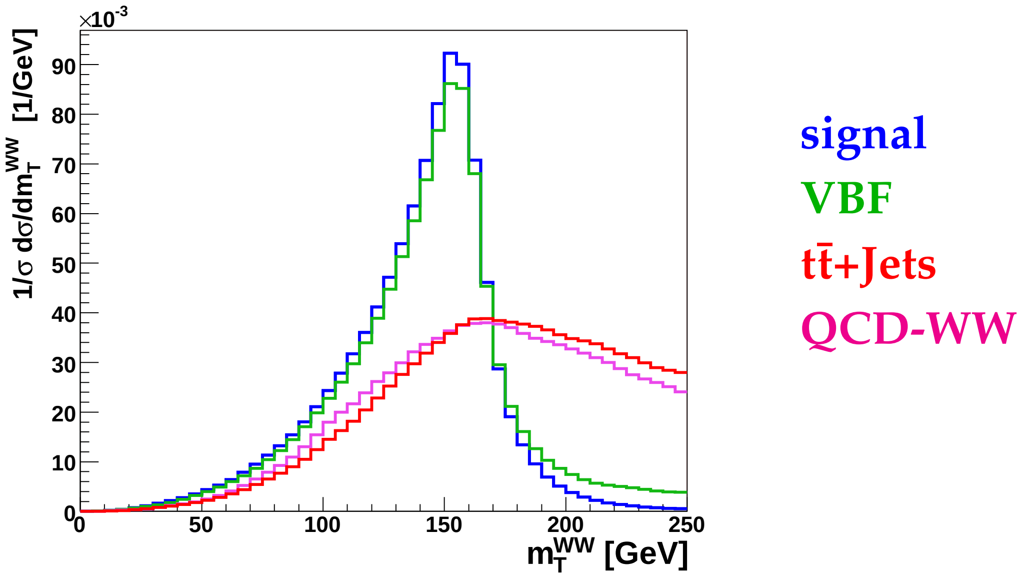
- selection cuts:

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

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

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



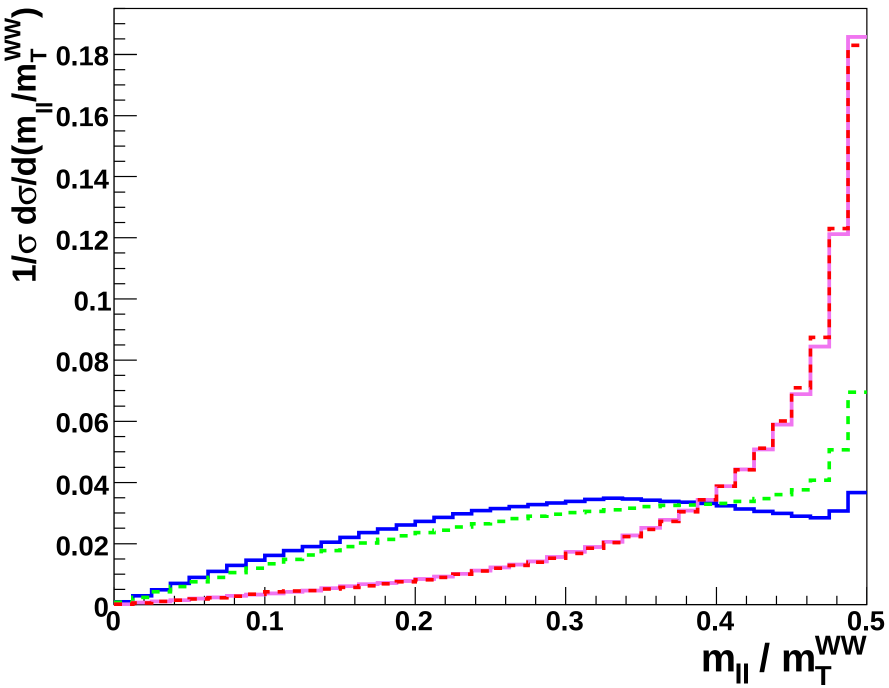


Characteristic distributions: contn'd

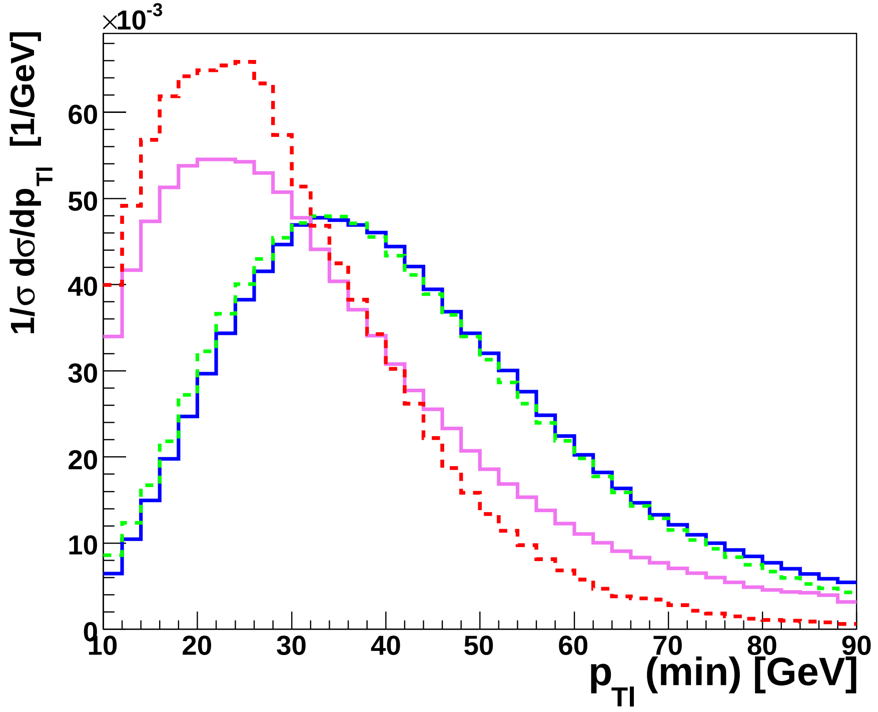
Distributions for the Higgs decay product provide for best handle on background suppression

They do not distinguish between VBF Hjj signal and gluon fusion Hjj signal

m_{ll} to transverse mass ratio



minimal lepton p_T after m_{ll} and R_{ll} cut



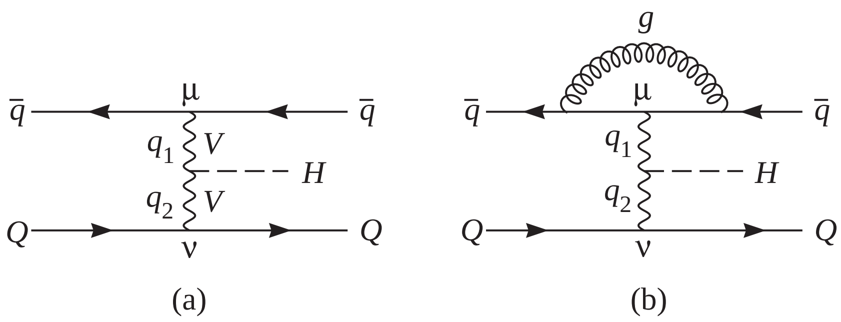
Results

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



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

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

Physical interpretation of terms:

SM Higgs $\mathcal{L}_I \sim HV_\mu V^\mu \longrightarrow a_1$

loop induced couplings for neutral scalar

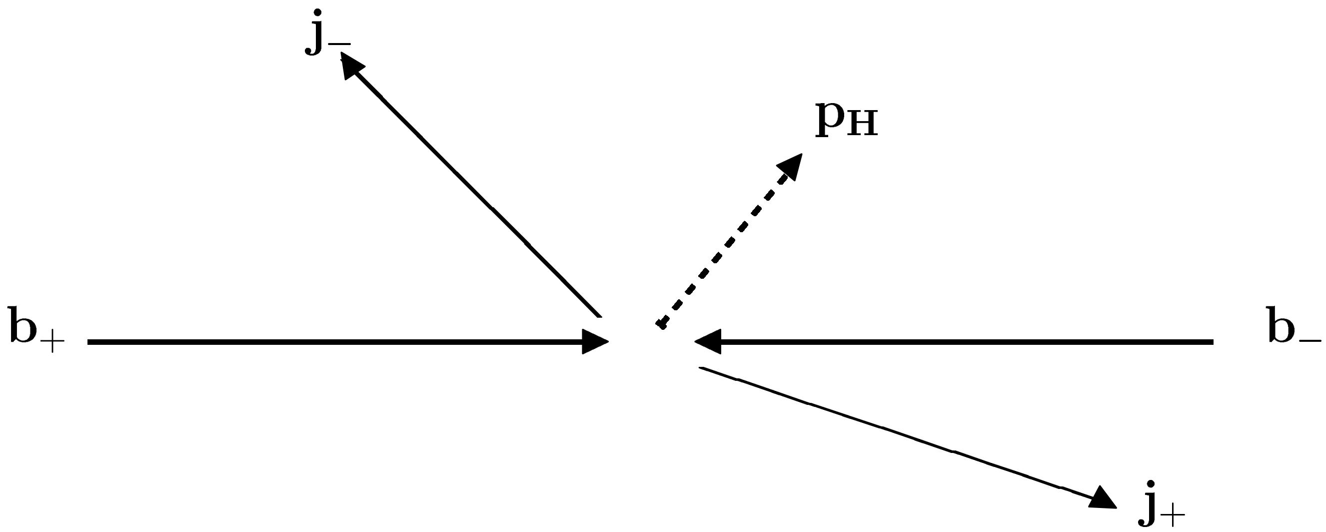
CP even $\mathcal{L}_{eff} \sim HV_{\mu\nu}V^{\mu\nu} \longrightarrow a_2$

CP odd $\mathcal{L}_{eff} \sim HV_{\mu\nu}\tilde{V}^{\mu\nu} \longrightarrow a_3$

Must distinguish a_1, a_2, a_3 experimentally

Azimuthal angle distribution and Higgs CP properties

Kinematics of Hjj event:



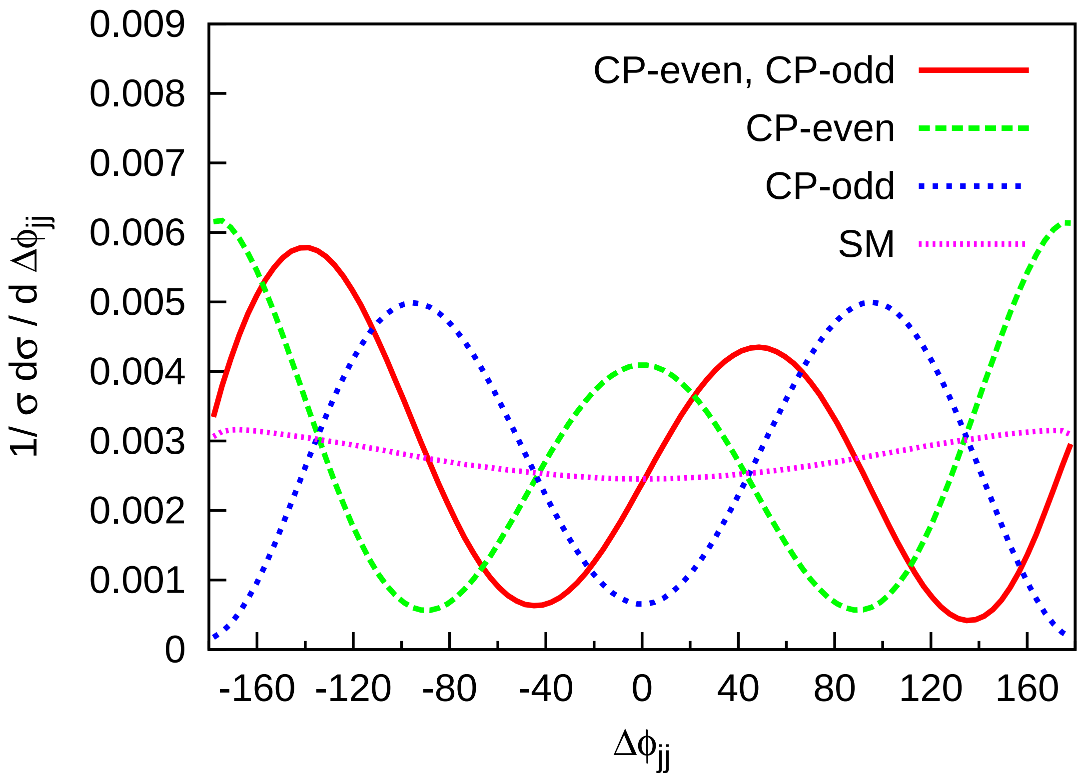
Define azimuthal angle between jet momenta j_+ and j_- via

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

- $\Delta\phi_{jj}$ 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

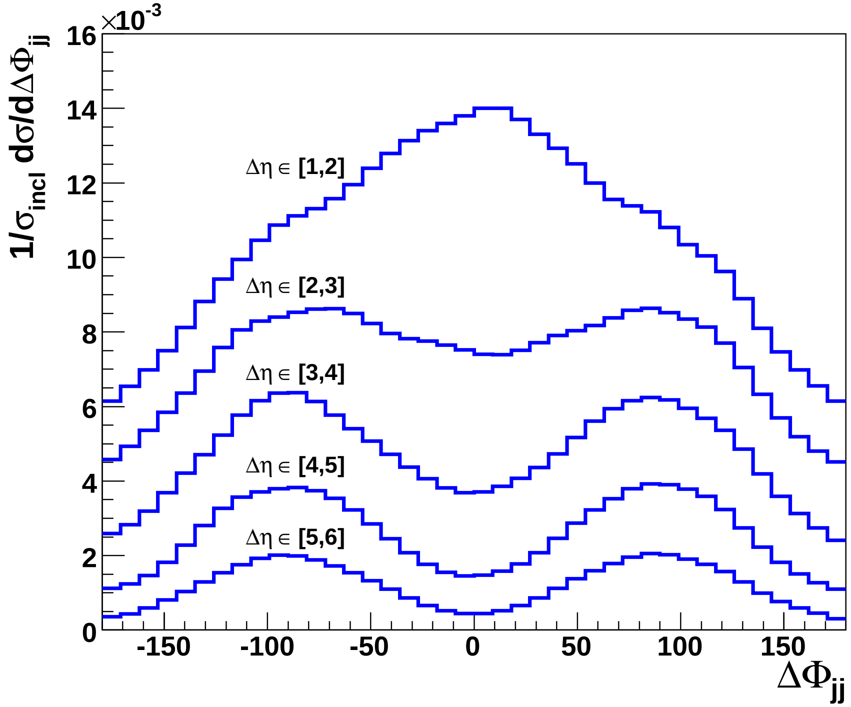
$$a_1 = 0, \qquad a_2 = d\ \cos\alpha, \qquad a_3 = d\ \sin\alpha,$$

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

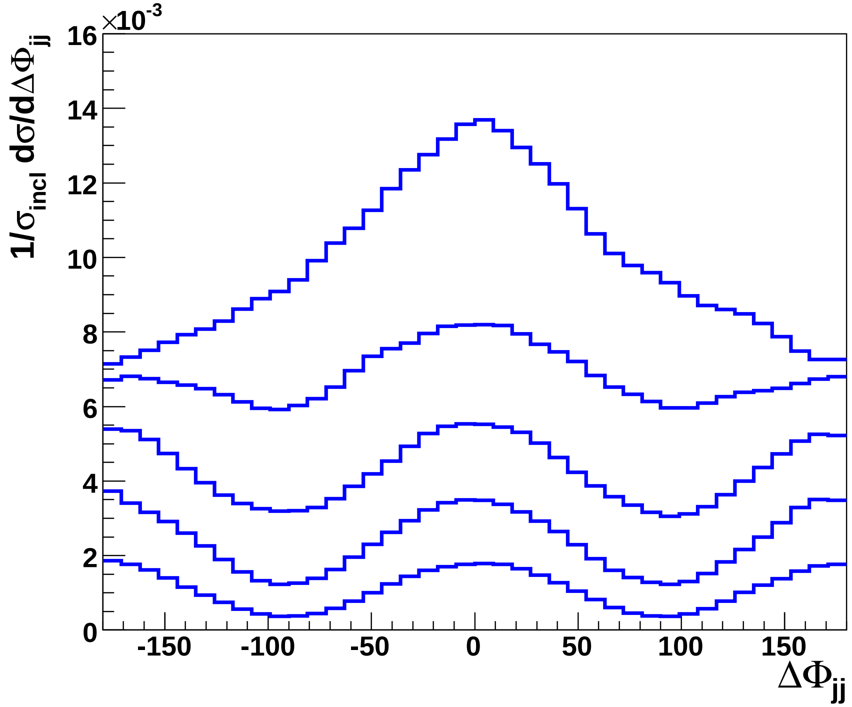
Gluon fusion: structure of Hgg vertex

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

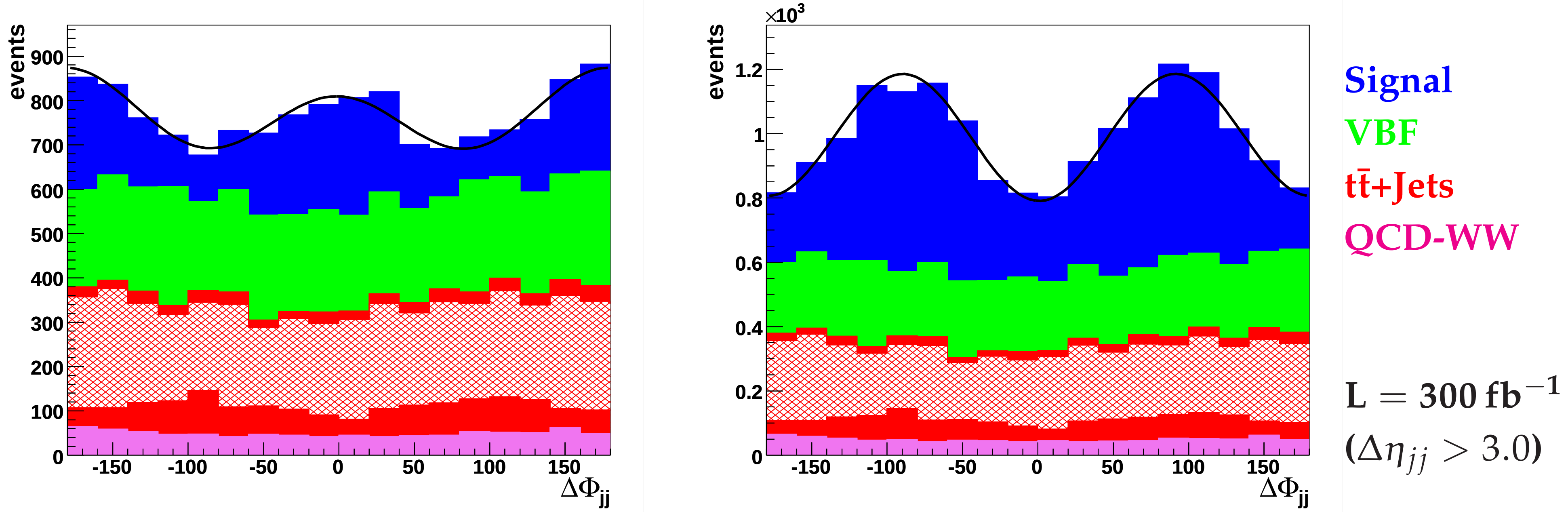


CP-odd coupling



$\Delta\Phi_{jj}$-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)

Conclusions

- LHC will observe a SM-like Higgs boson in multiple channels, with $5 \ldots 20\%$ statistical errors
  $\Longrightarrow$ great source of information on Higgs couplings
- NLO QCD corrections and improved simulation tools are important for precise measurements with full LHC data.
- Absence of HVV and AVV couplings for the heavy H/A of the MSSM make their observation more challenging
  $\Longrightarrow$ Need large $\tan\beta$ rate enhancement for their discovery
- Higgs boson CP properties and structure of the HVV and Hgg vertices from jet-angular correlations in VBF and gluon fusion
- An exciting new era of particle physics starts in 2008.