# HIGGS + 2 JET PRODUCTION AT THE LHC

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- LHC goals
- Vector boson fusion
- Measurement of Higgs couplings
- Hjj production via gluon fusion
- $H \rightarrow WW$ study
- $H \rightarrow \tau\tau$ study
- Probing CP properties
- Summary

# 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 $\Phi^\dagger \to (0, \frac{v+H}{\sqrt{2}})$

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

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

- 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

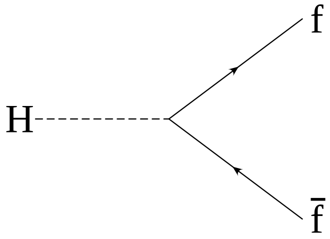
Kinetic energy term of Higgs doublet field:

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

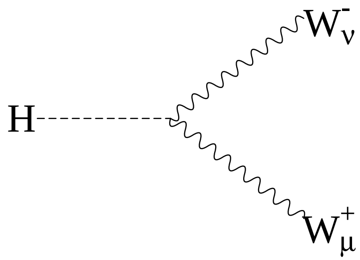
- $W, Z$ mass generation: $m_W^2 = \left(\frac{gv}{2}\right)^2$, $m_Z^2 = \frac{(g^2+g'^2)v^2}{4}$
- $WWH$ and $ZZH$ couplings are generated
- Higgs couples propotional to mass: coupling strength $= 2\,m_V^2/v \sim g^2 v$ within SM

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

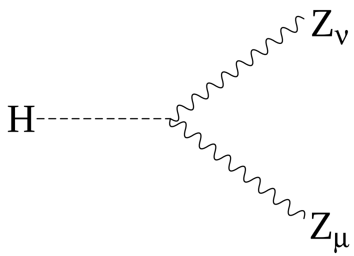
# Feynman rules




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



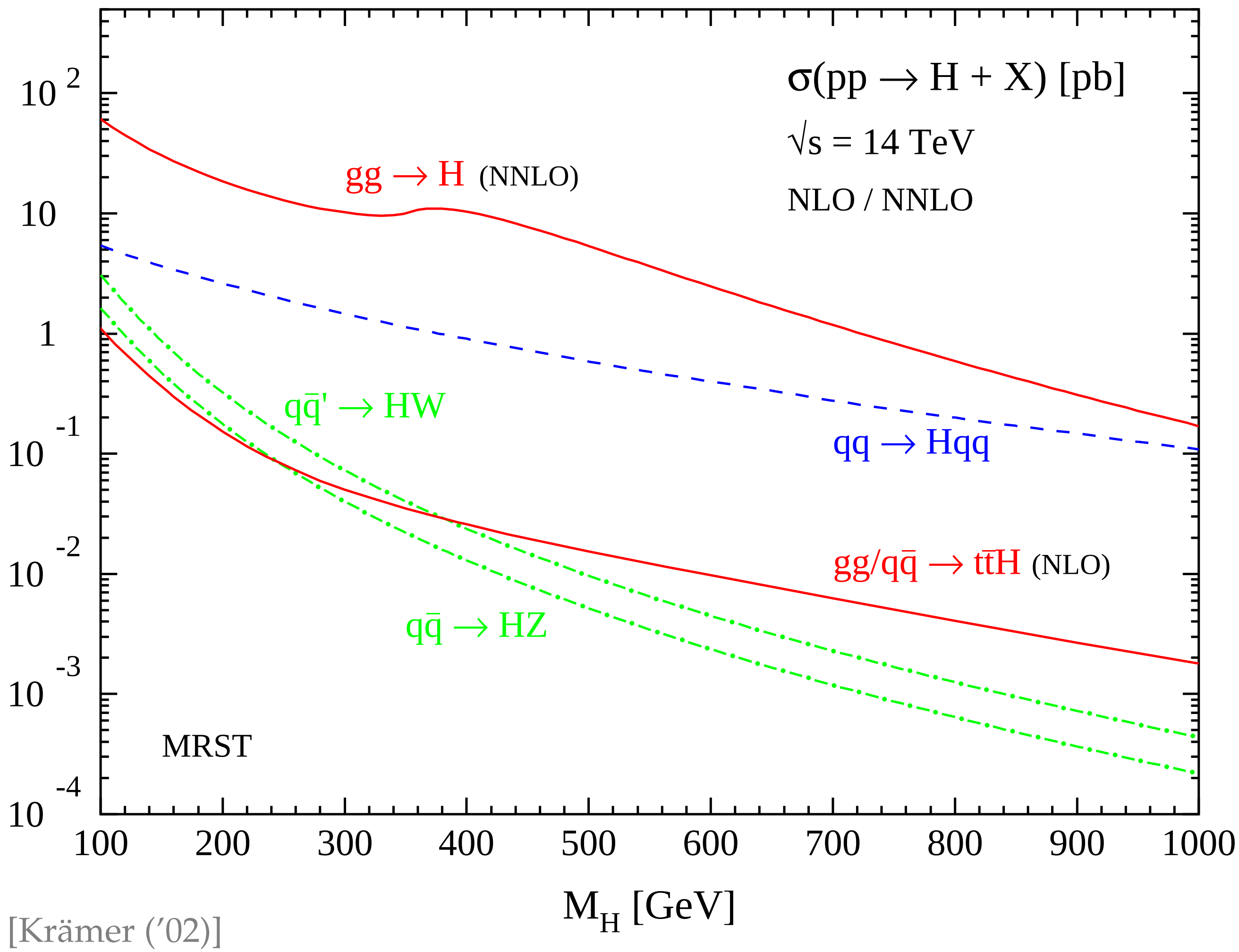

$i g\, m_W\, g_{\mu\nu}$

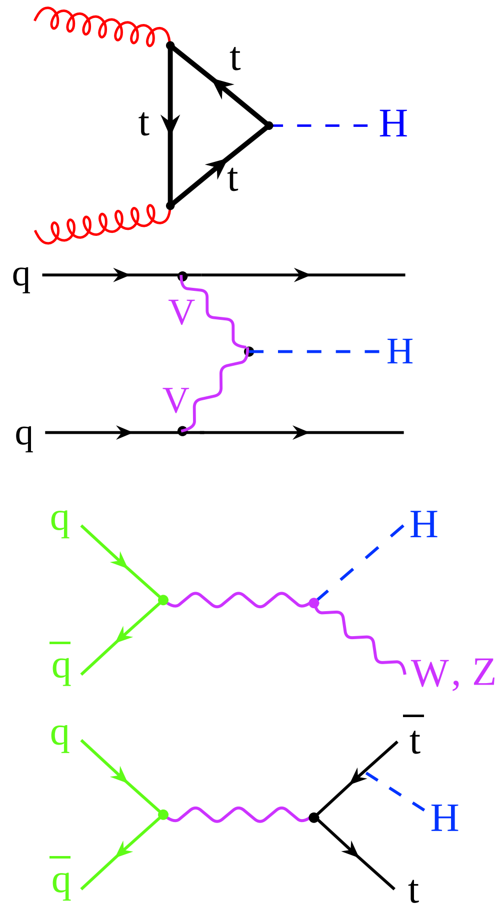



$i\, g\, \frac{1}{\cos\theta_W}\, m_Z\, g_{\mu\nu}$

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

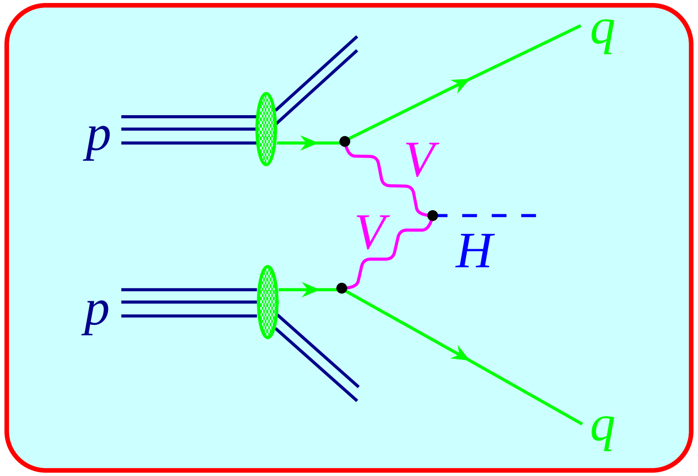
# Total cross sections at the LHC

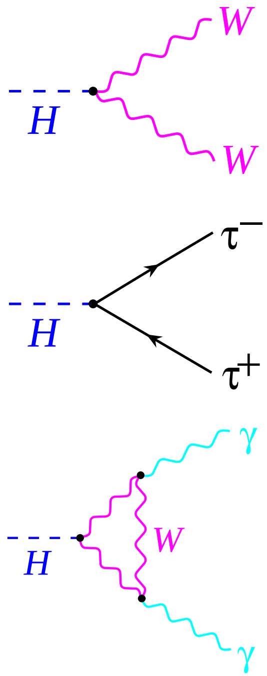



[Krämer ('02)]

# Vector Boson Fusion (VBF)




$m_H > 120$ GeV

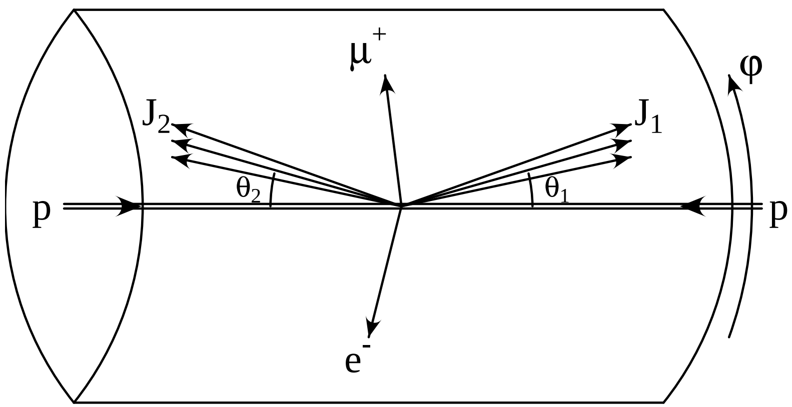
$m_H < 140$ GeV

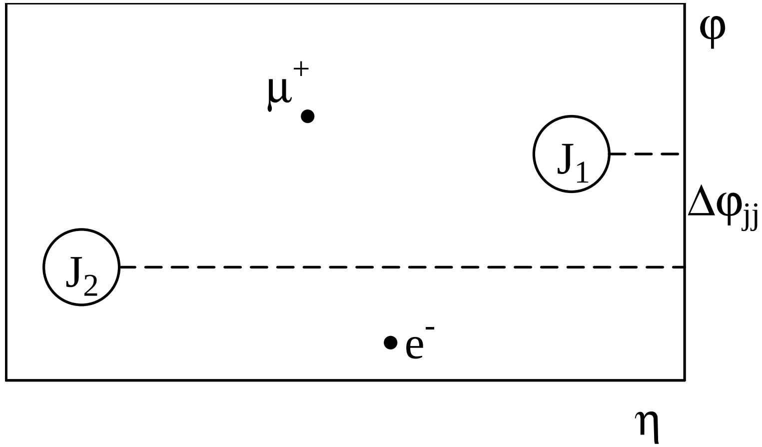
$m_H < 150$ GeV

[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 between tagging jets)

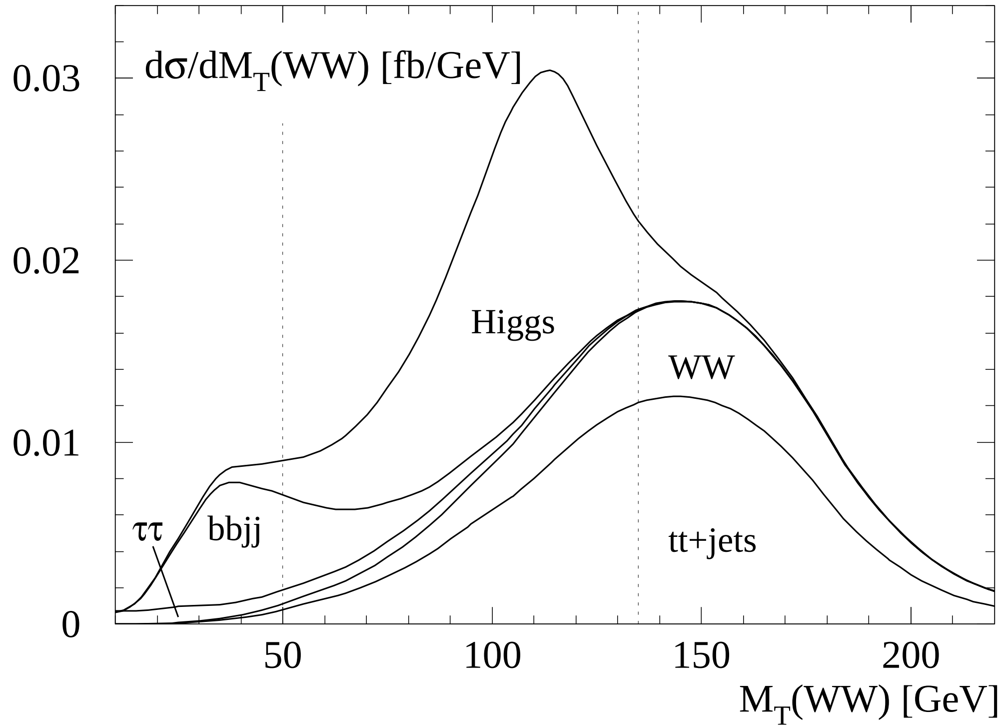
## Example: Parton level analysis of $H \to WW$

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 $H \to WW^* \to e^\pm \mu^\mp \not{p}_T$

# tau reconstruction

in collinear approximation, the decay lepton has the same direction as the $\tau$, i.e. $p^\mu_{\ell,i} = x_i \cdot p^\mu_{\tau,i}$
$\Rightarrow$ the energy fractions $x_1$, $x_2$ of the decay leptons can be reconstructed by solving the equation:

$$\not{\vec{p}}_T = \left(\frac{1}{x_1} - 1\right) \vec{p}_{1,T} + \left(\frac{1}{x_2} - 1\right) \vec{p}_{2,T}$$

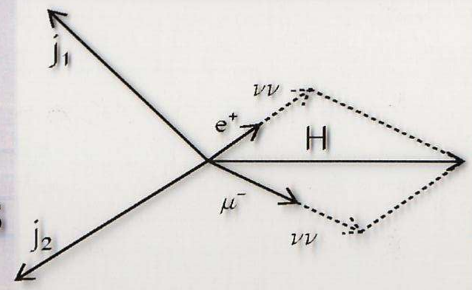
the invariant tau pair mass is then given by

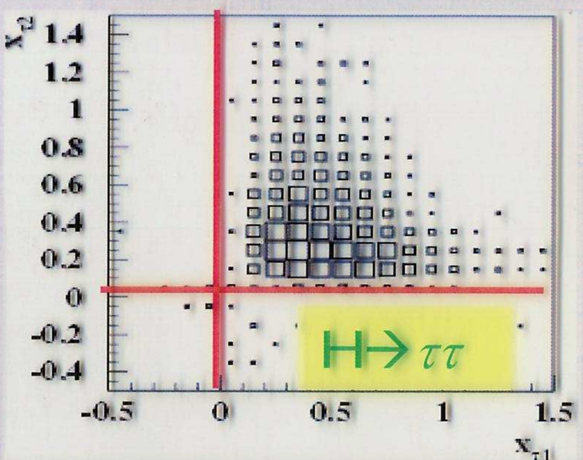
$$m^2_{\tau\tau} = \frac{2 p_{\ell,1} \cdot p_{\ell,2}}{x_1 x_2} = \frac{m^2_{\ell\ell}}{x_1 x_2}$$

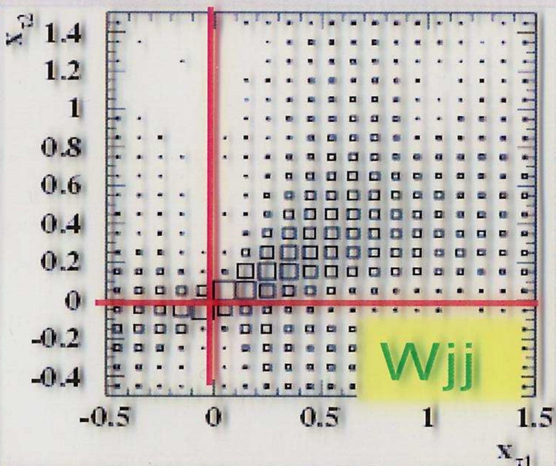
# Weak Boson Fusion: $H \rightarrow \tau\tau$

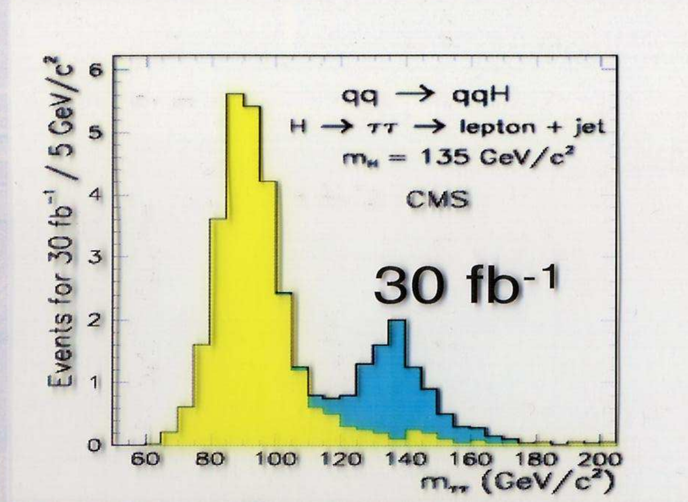
Mass can be reconstructed in collinear approximation

$x_\tau$ = momentum fraction carried by tau decay products




$\sigma_M =$ 11 to 12 GeV

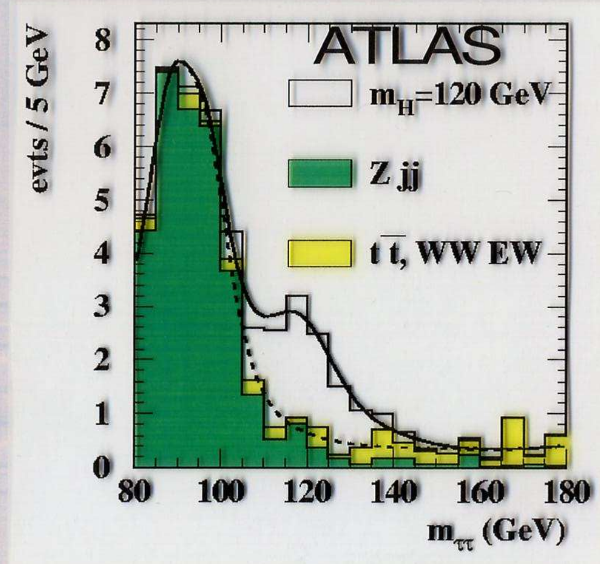
★significance > 5 for 30 $fb^{-1}$ and

$M_H$=110 to 140 GeV ($\tau\tau \rightarrow e\mu$, $\tau\tau \rightarrow ll$, $\tau\tau \rightarrow l$ had)

★background estimate: ~10%

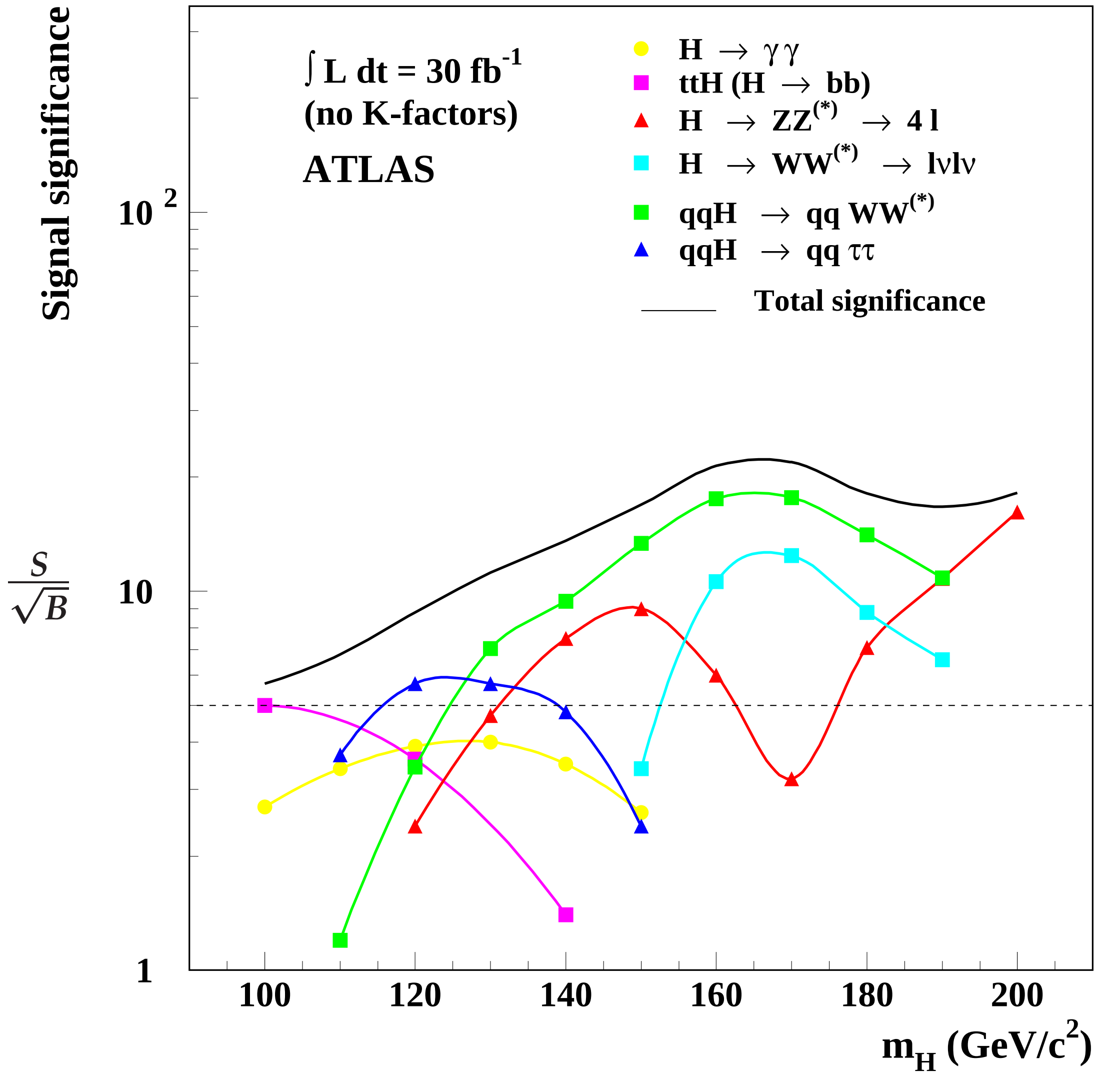
for $M_H$>125 GeV from side bands

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

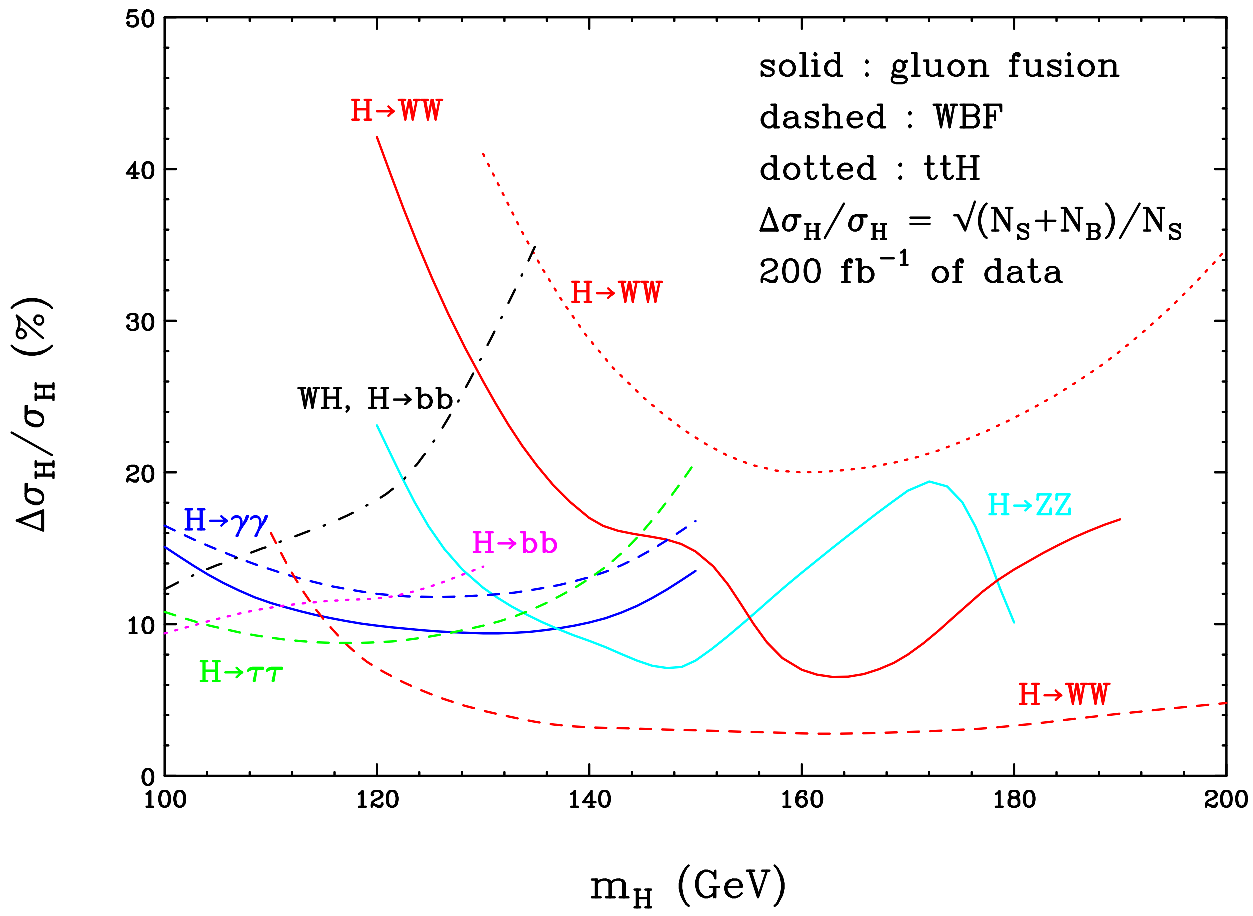



$H \rightarrow \tau\tau \rightarrow e\mu$ 30 $fb^{-1}$

# Higgs discovery potential



# 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:

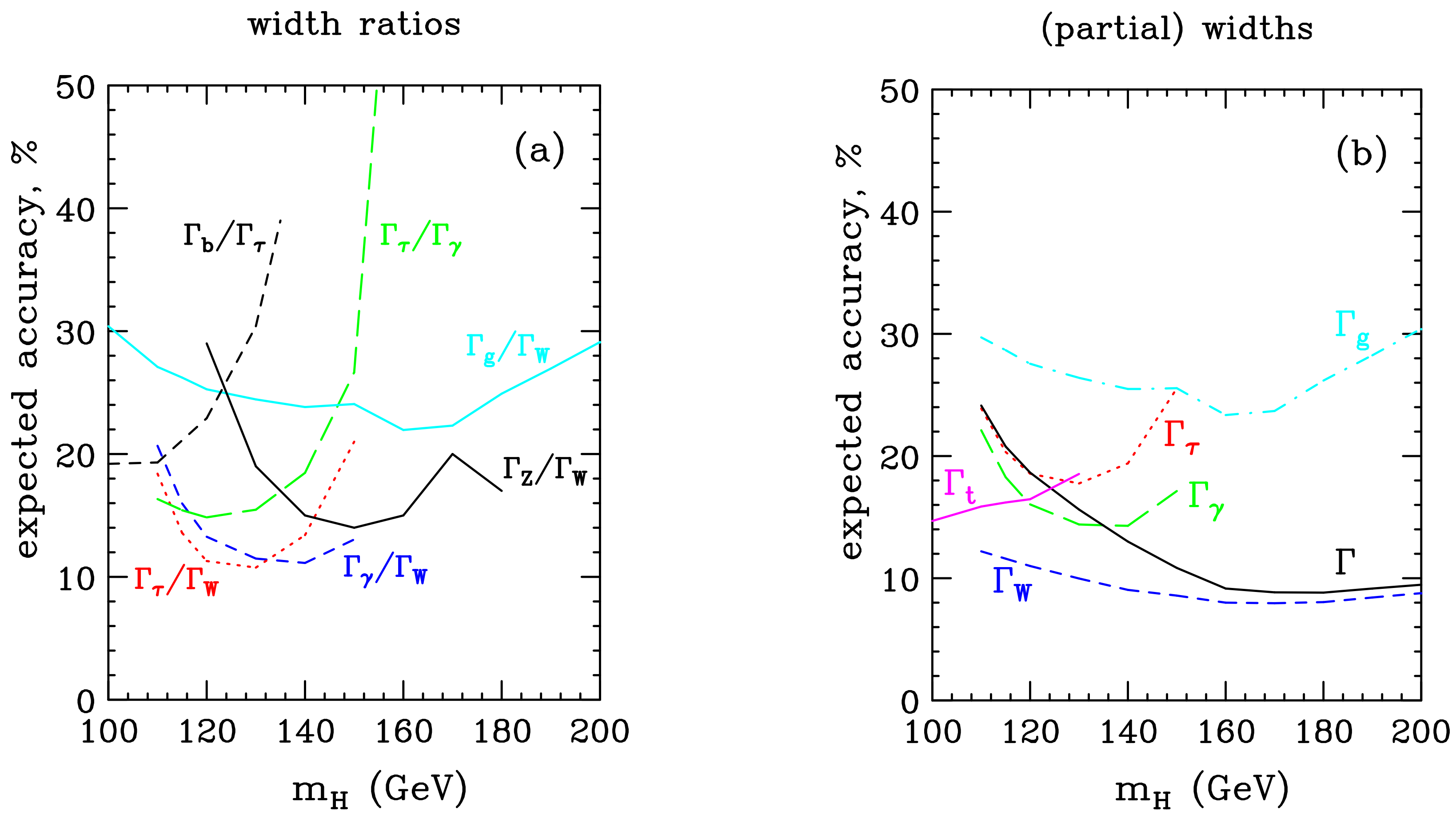
$$f^2\Gamma > \sum_{obs.} f\Gamma_x \qquad \Longrightarrow \qquad f > \sum_{obs.}\frac{\Gamma_x}{\Gamma} = \sum_{obs.} BR(H\to xx)(=\mathcal{O}(1))$$

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

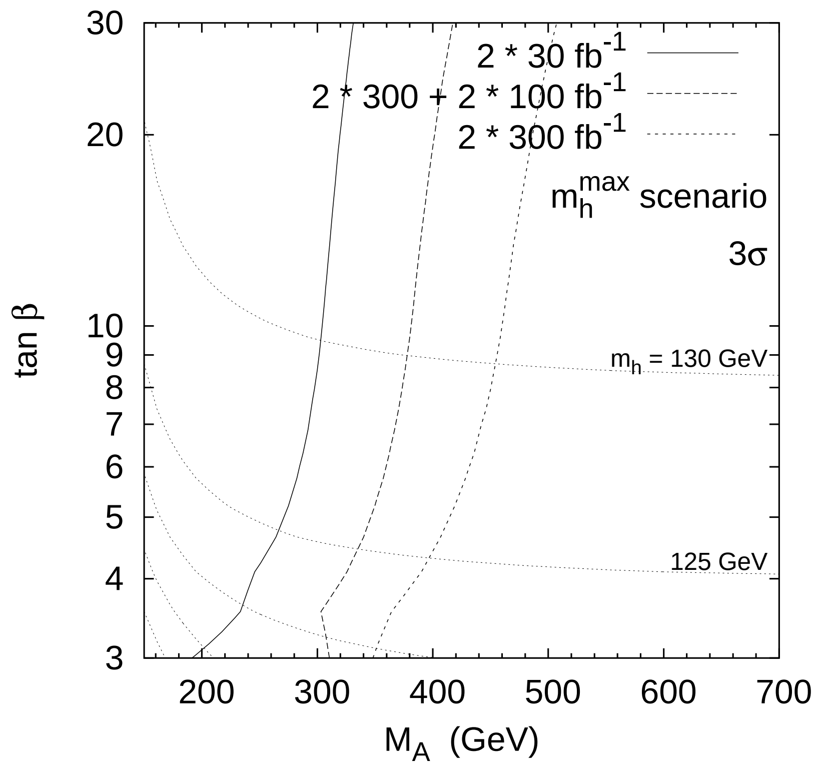
Consider modest $m_A$:

- 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 $h$

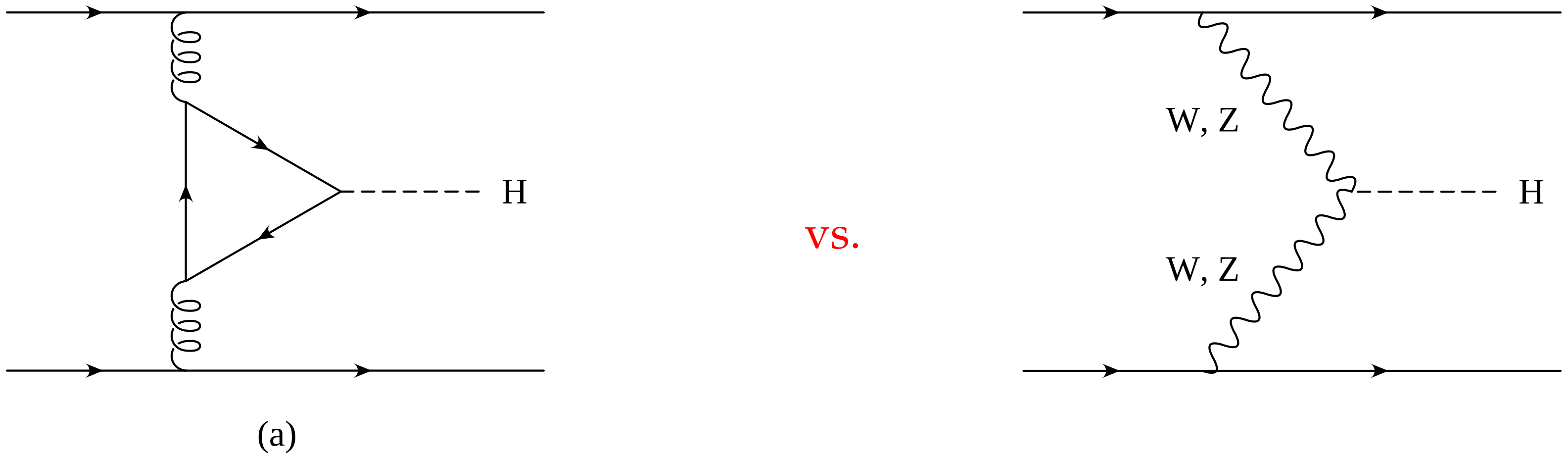
$\Longrightarrow$

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

$3\sigma$-effects or more at small $m_A$



# How to distinguish VBF and gluon fusion?



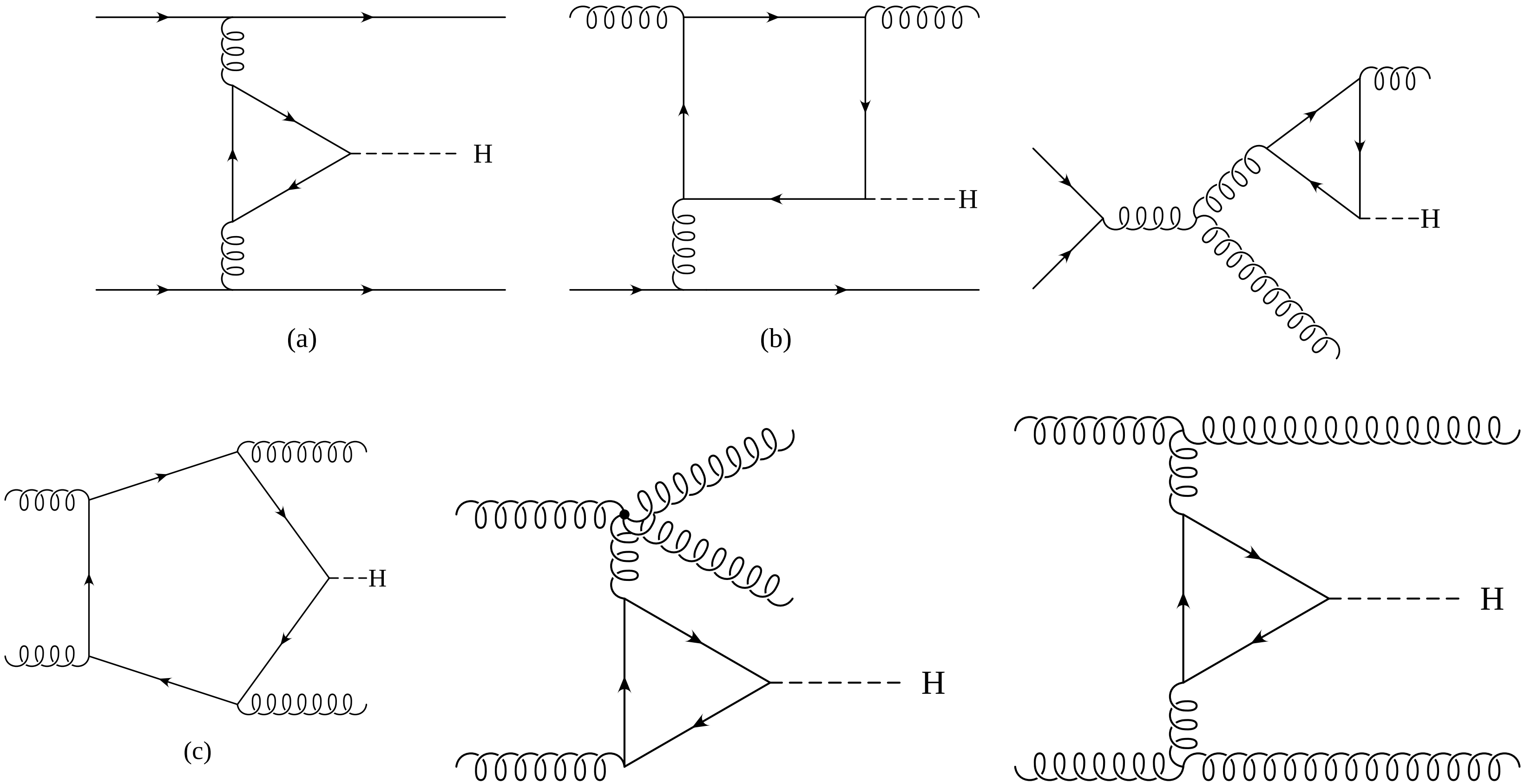

Double real corrections to $gg \to H$ can "fake" VBF

$\Longrightarrow$ 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




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

plus crossed processes. In total 61 independent diagrams. [DelDuca, Kilgore, Oleari, Schmidt, DZ (2001)]

# Applied cuts for LHC predictions

The cross section diverges in collinear and soft regions

- INCLUSIVE cuts to define $H + 2$ jets

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

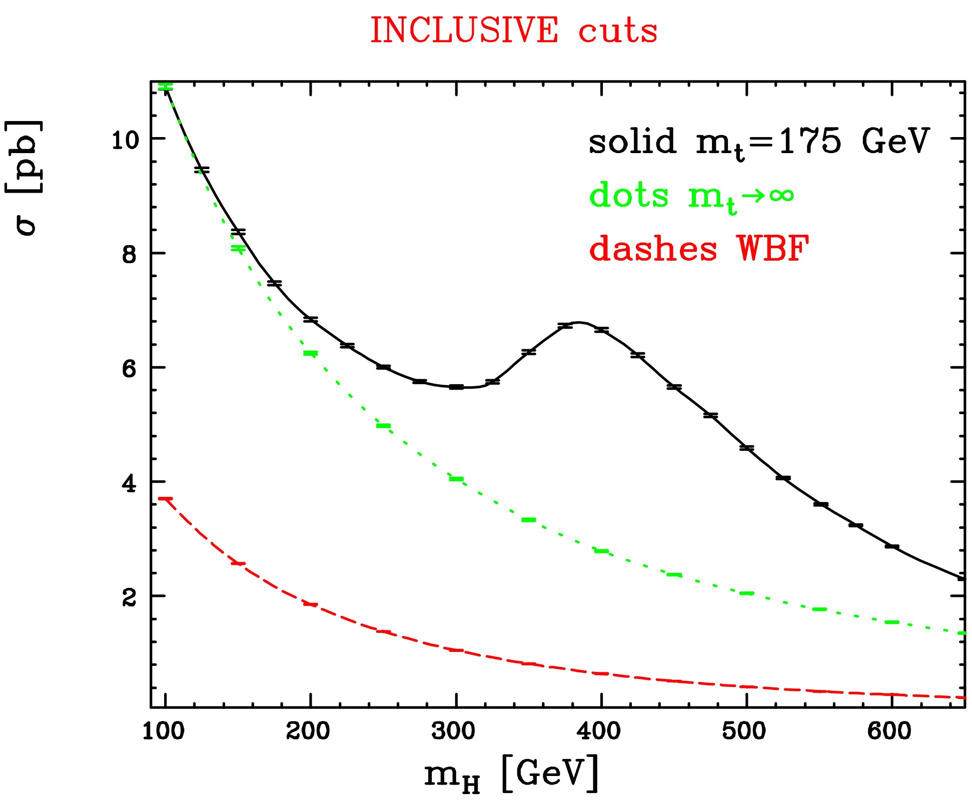
- VBF cuts to enhance VBF over gluon fusion
  In addition to the previous ones, we impose

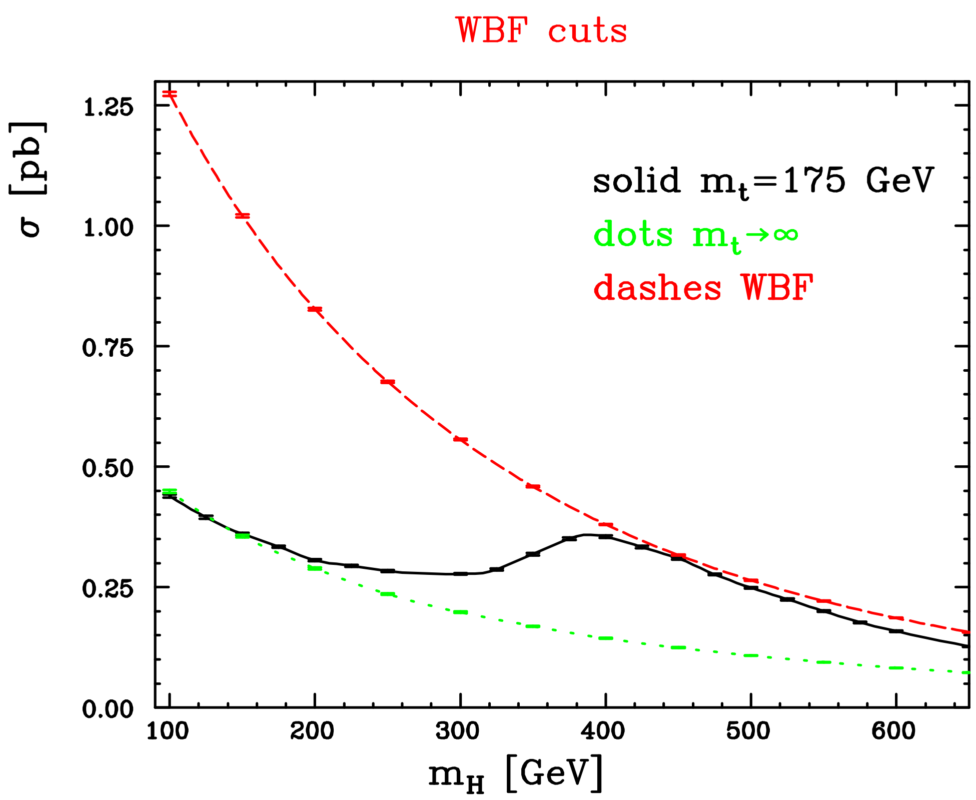
$$|\eta_{j_1} - \eta_{j_2}| > 4.2 \qquad \eta_{j_1} \cdot \eta_{j_2} < 0 \qquad m_{jj} > 600 \text{ GeV}$$

  - 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 $\approx 1.5$ to 2 scale uncertainty due to $\sigma \sim \alpha_s^4$

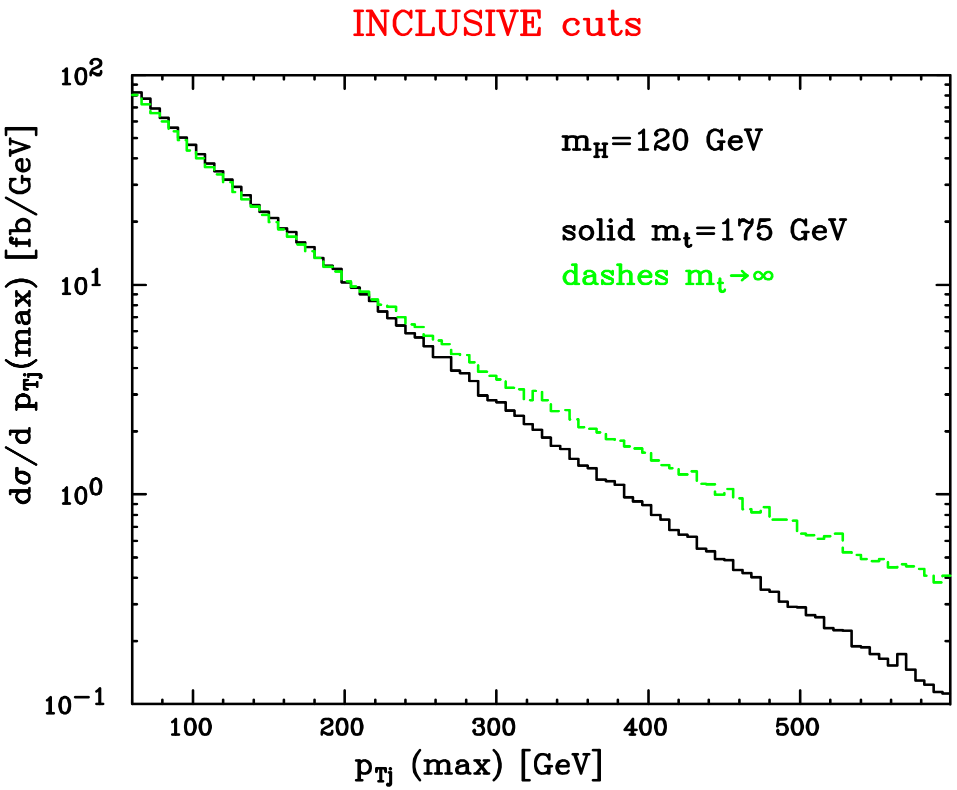
## Total cross section with cuts as function of $m_H$

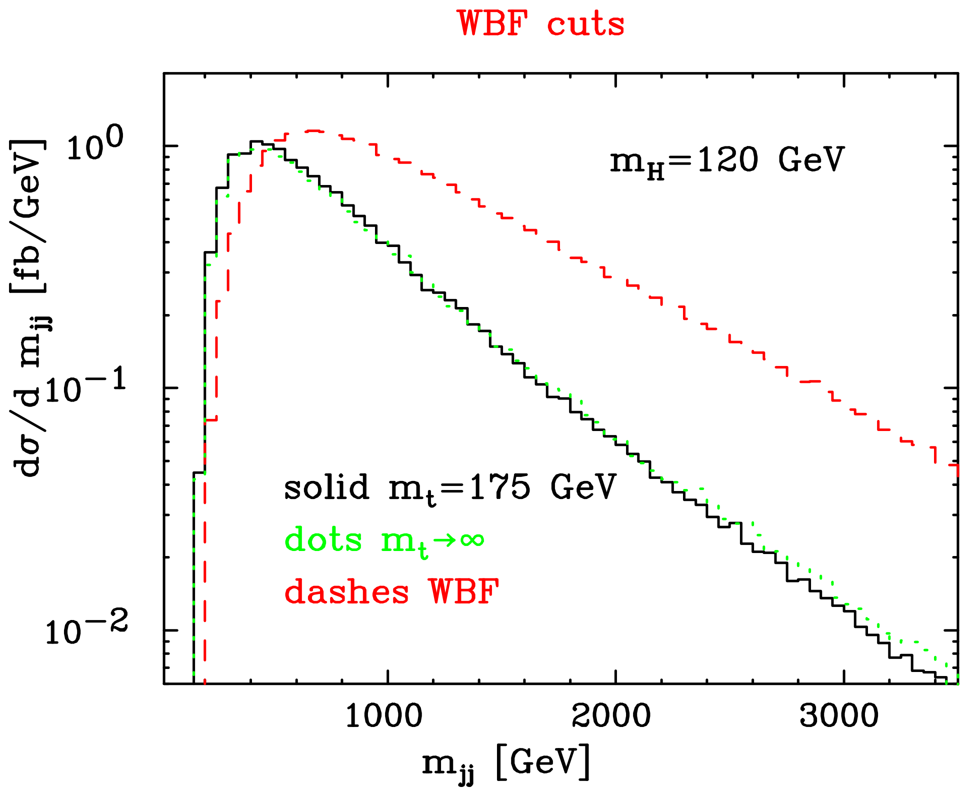



Large top mass limit ok for total cross section provided $m_H \lesssim m_t$

# Distributions and $m_t \to \infty$ limit



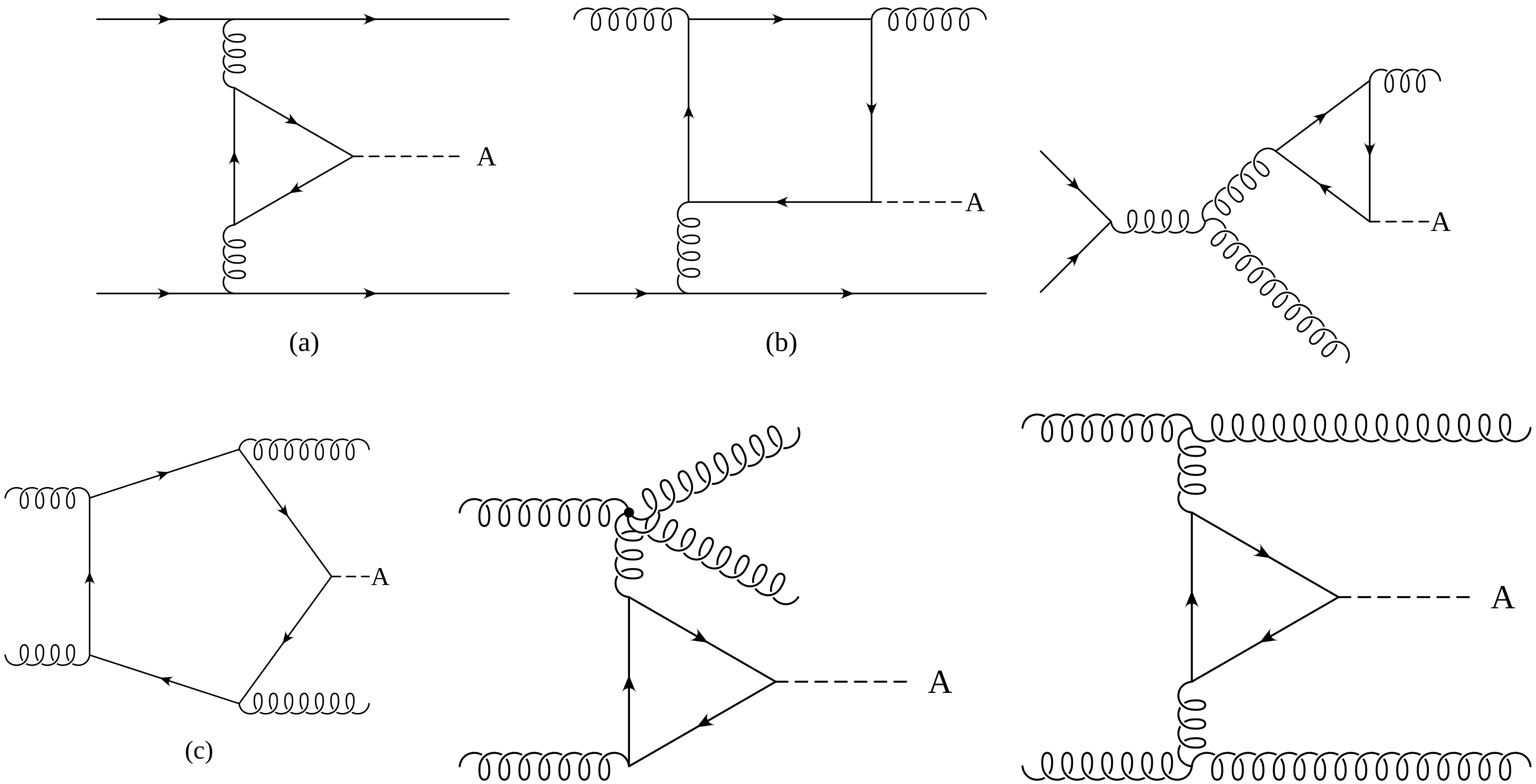




Transverse momentum: Large top mass limit ok provided $p_{T,j} \lesssim m_t$

Dijet invariant mass: Large top mass limit ok throughout

# New calculation: pseudoscalar Higgs production

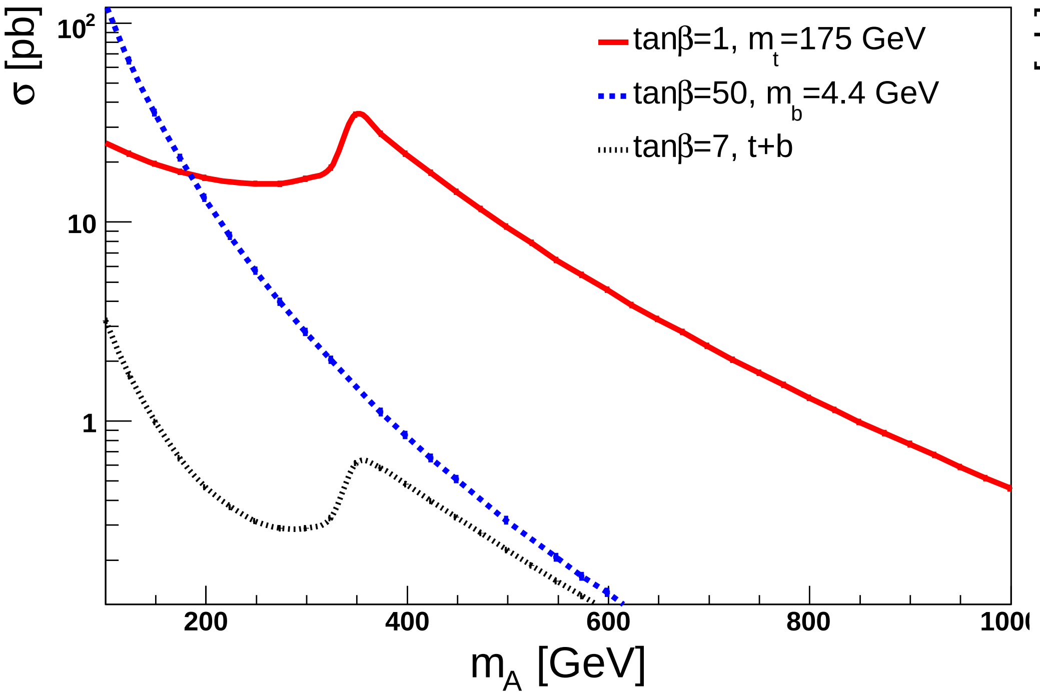
$pp \to AjjX$ including top and bottom loops + interference [Michael Kubocz, diploma thesis]



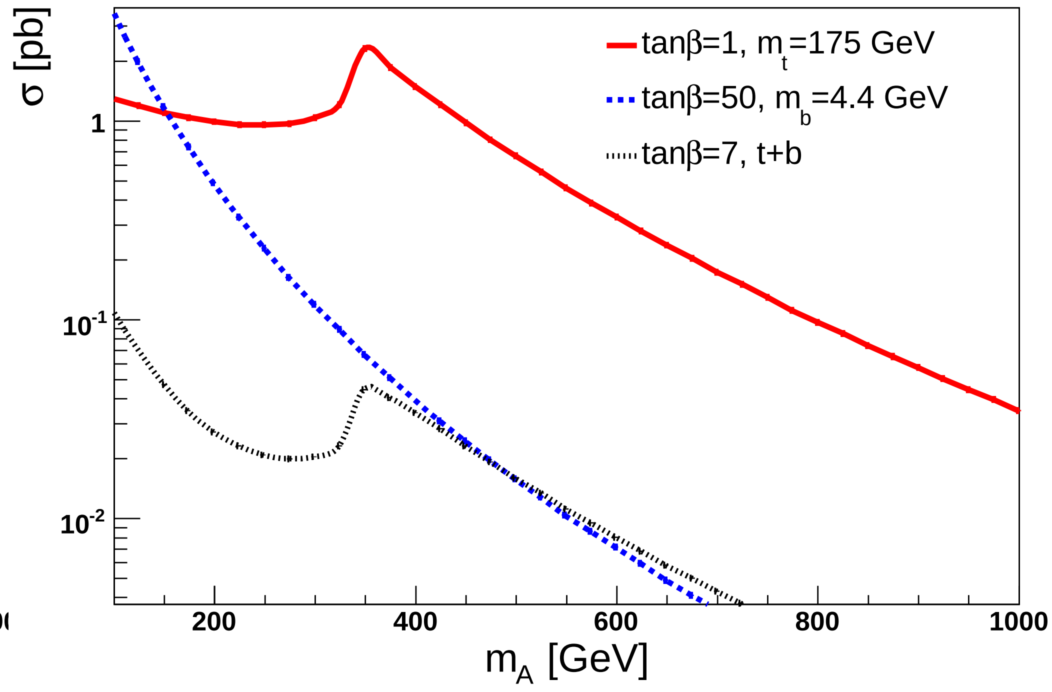
## New elements in the calculation

- $AQQ$ 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



# Gluon Fusion as a signal channel

Heavy quark loop induces effective $Hgg$ vertex:

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

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

Azimuthal angle between tagging jets probes difference

- Use gluon fusion induced $\Phi jj$ signal to probe structure of $Hgg$ vertex
- Measure size of coupling (requires NLO corrections for precision)
- Find cuts to enhance gluon fusion over VBF and other backgrounds

$\Longrightarrow$ Study by Gunnar Klämke in $m_Q \to \infty$ limit (hep-ph/0703202)

# 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

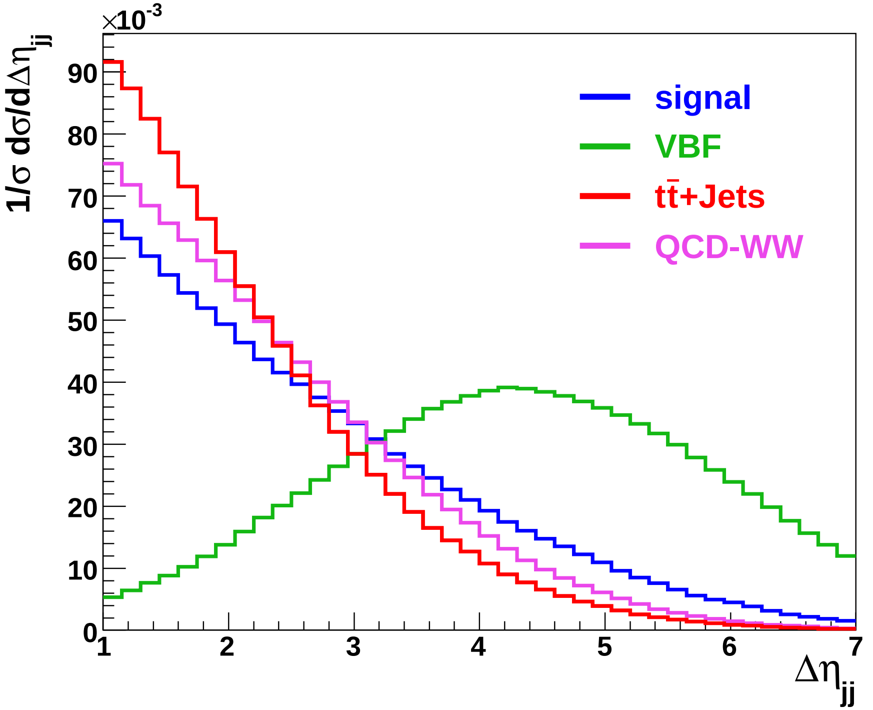
$$\Delta\eta_{jj} > 1.0, \qquad R_{jl} > 0.7$$

| process | $\sigma$ [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** |

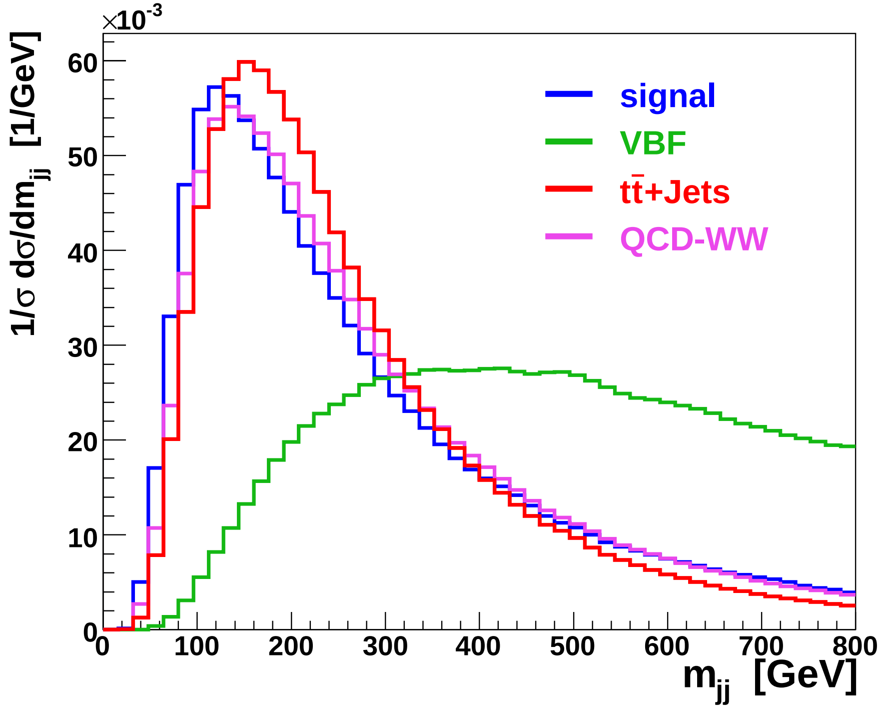
# Characteristic distributions

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

tagging jet rapidity separation




dijet invariant mass



# Selection continued

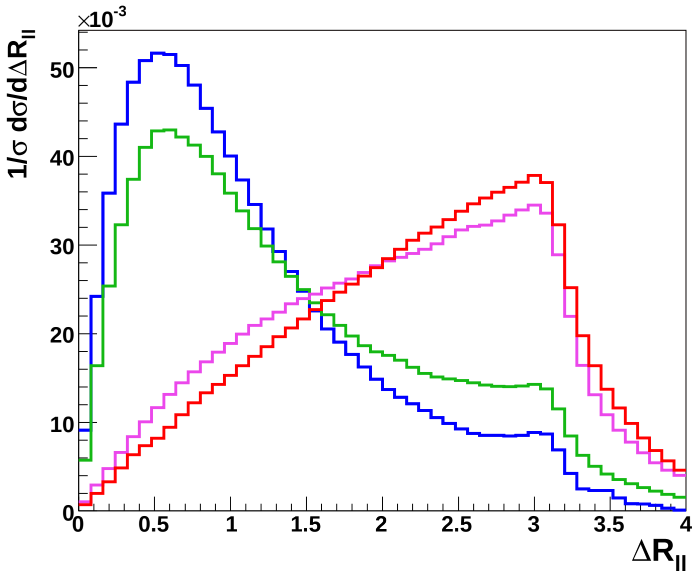
- b-tagging for reduction of top-backgrounds. *(CMS Note 06/014)*
  - $(\eta,\, p_T)$ - dependent tagging-efficiencies (60% - 75%) with 10% mistagging - probability

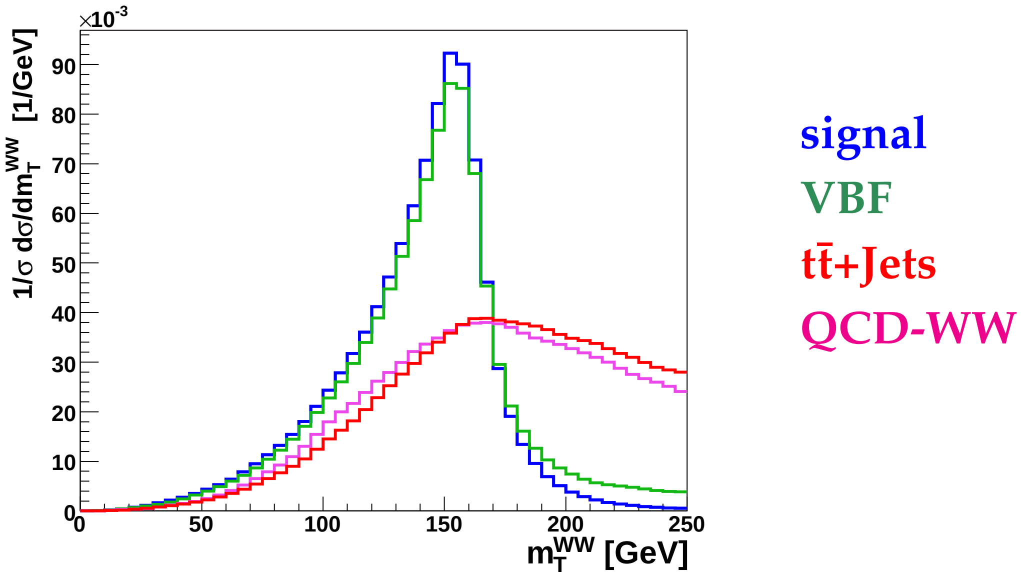
- <u>selection cuts:</u>

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

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

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



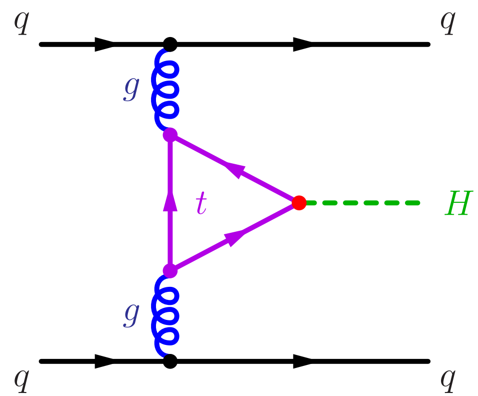
# Results

| process | $\sigma$ [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** |
| $\Sigma$ backgrounds | **113.5** | **3405** |

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

## Higgs + 2 Jets in Gluon Fusion, $H \to \tau\tau \to \ell^+\ell^-\nu\bar{\nu}$

- this channel has not been studied so far
- interesting for SM Higgs ($\approx$ 120 GeV) and SUSY scenario with large $\tan\beta$ ($m_H \approx m_A \gtrsim 150$ GeV)
- x-section times branching ratio of $\approx$ 50 fb looks promising (SM)
- has potential for study of Higgs CP-properties




Studied so far (by Gunnar Klämke):

- Study of signal and SM backgrounds for $m_H = 120$ GeV case (simple cut based analysis)
- same for one MSSM scenario $m_A = 200$ GeV, $\tan\beta = 50$

  Questions:

- How many signal and background events are there after cuts (what's the statistical significance)
- What are the prospects of CP-measurements via jet-jet azimuthal angle correlation

# finite detector resolution

The detector has a finite resolution. The measured jet energy and missing transverse energy have large uncertainties. Parameterization (from CMS NOTE 2006/035, CMS NOTE 2006/036):

Jets :

$$\frac{\Delta E_j}{E_j} = \left( \frac{a}{E_{Tj}} \oplus \frac{b}{\sqrt{E_{Tj}}} \oplus c \right)$$

| | a | b | c |
|---|---|---|---|
| $\eta_j < 1.4$ | 5.6 | 1.25 | 0.033 |
| $1.4 < \eta_j < 3$ | 4.8 | 0.89 | 0.043 |
| $\eta_j > 3$ | 3.8 | 0 | 0.085 |

Leptons :

$$\frac{\Delta E_\ell}{E_\ell} = 2\%$$

Missing $p_T$:

$$\Delta \not{p}_x = 0.46 \cdot \sqrt{\sum E_{Tj}}$$

# SM Higgs with 120 GeV mass

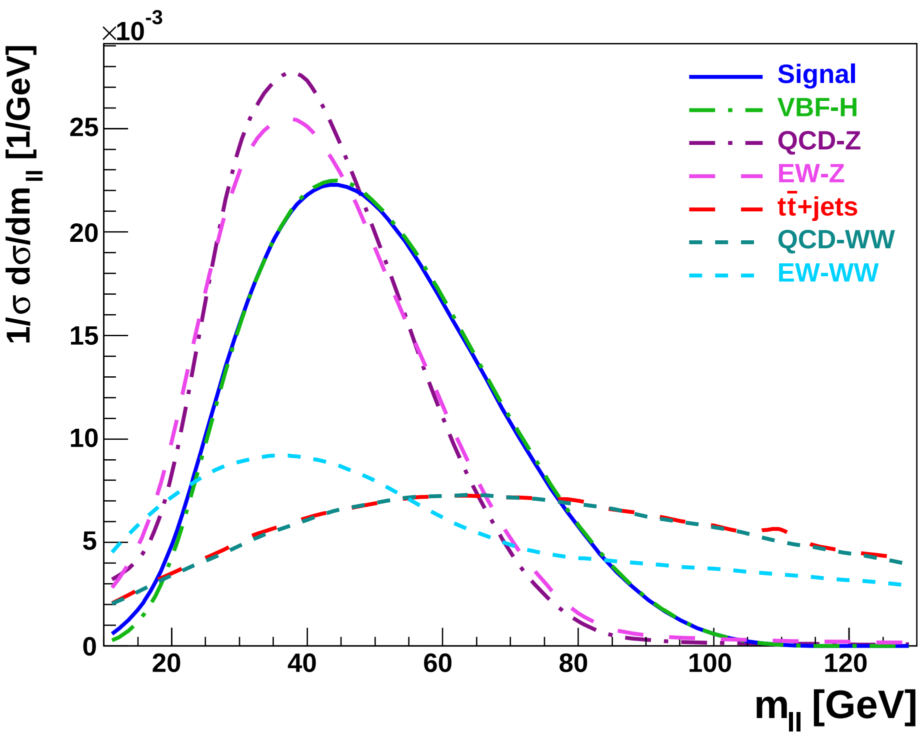
inclusive cuts

$$p_{T,jets} > 30\,\text{GeV}\,, \quad p_{T,\ell} > 10\,\text{GeV}\,, \quad |\eta_j| < 4.5\,, \quad |\eta_\ell| < 2.5\,, \quad \Delta\eta_{jj} > 1.0\,, \quad \Delta R_{j\ell} > 0.7\,,$$

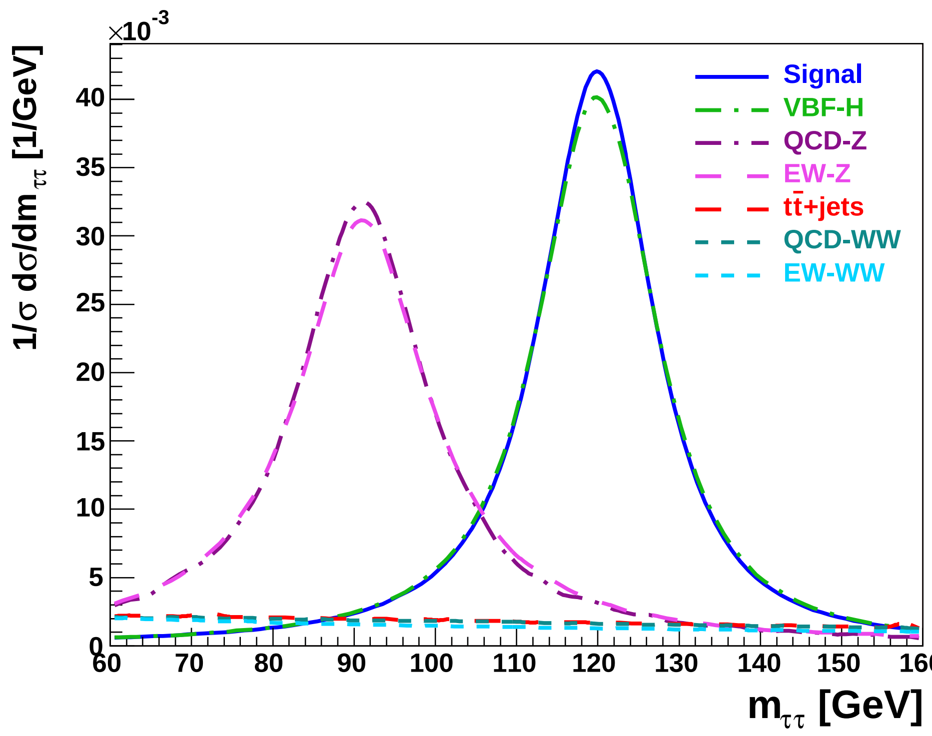
cross sections for inclusive cuts for signal and background

| process | $\sigma$ [fb] | events / 600 $\text{fb}^{-1}$ |
|---|---|---|
| GF $pp \to H + jj \to \tau\tau jj$ | **11.283** | **6770** |
| GF $pp \to A + jj \to \tau\tau jj$ | **25.00** | **15002** |
| VBF $pp \to H + jj \to \tau\tau jj$ | **5.527** | **3316** |
| QCD $pp \to Z + jj \to \tau\tau jj$ | **1652.8** | **991700** |
| VBF $pp \to Z + jj \to \tau\tau jj$ | **15.70** | **9418** |
| $pp \to t\bar{t}$ | **6490** | **3893900** |
| $pp \to t\bar{t} + j$ | **9268** | **5560890** |
| $pp \to t\bar{t} + jj$ | **1629** | **977263** |
| QCD $pp \to W^+W^- + jj$ | **334.2** | **200540** |
| VBF $pp \to W^+W^- + jj$ | **24.78** | **14871** |

# Distributions




dilepton invariant mass




reconstructed $\tau\tau$ invariant mass

# selection cuts

a b-veto was applied to reduce the top backgrounds.

$$R_{\ell\ell} < 2.4\,, \quad \not{p}_T > 30\,\mathrm{GeV}\,, \quad m_{\ell\ell} < 80\,\mathrm{GeV}\,, \quad 110\,\mathrm{GeV} < m_{\tau\tau} < 135\,\mathrm{GeV}\,, \quad 0 < x_i < 1$$

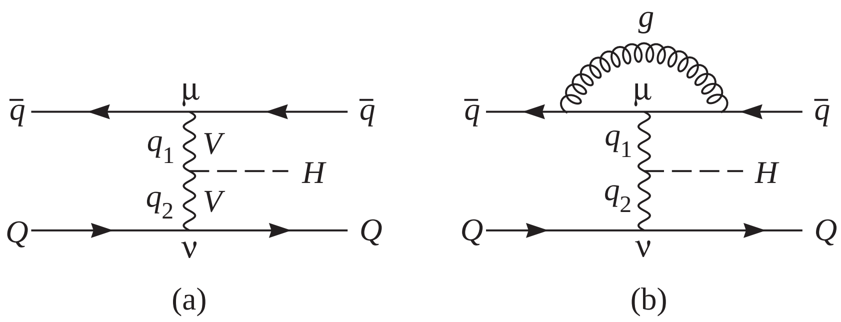
| process | $\sigma$ [fb] | events / 600 $\mathrm{fb}^{-1}$ |
|---|---|---|
| GF $pp \to H + jj \to \tau\tau jj$ | **4.927** | **2956** |
| GF $pp \to A + jj \to \tau\tau jj$ | **11.43** | **6860** |
| VBF $pp \to H + jj \to \tau\tau jj$ | **2.523** | **1514** |
| QCD $pp \to Z + jj \to \tau\tau jj$ | **27.62** | **16573** |
| VBF $pp \to Z + jj \to \tau\tau jj$ | **0.475** | **285** |
| $pp \to t\bar{t}$ | **3.86** | **2316** |
| $pp \to t\bar{t} + j$ | **8.84** | **5306** |
| $pp \to t\bar{t} + jj$ | **3.8** | **2283** |
| QCD $pp \to W^+W^- + jj$ | **1.48** | **887** |
| VBF $pp \to W^+W^- + jj$ | **0.147** | **88** |
| $\sum$ backgrounds | **48.84** | **29300** |

**for cp-even higgs:** $S/\sqrt{B} \approx 17\,(\,600\,\mathrm{fb}^{-1})$
this corresponds to: $S/\sqrt{B} \approx 5\,(\,50\,\mathrm{fb}^{-1})$

**for cp-odd higgs:** $S/\sqrt{B} \approx 40\,(\,600\,\mathrm{fb}^{-1})$
this corresponds to: $S/\sqrt{B} \approx 5\,(\,10\,\mathrm{fb}^{-1})$

# 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 $\quad \mathcal{L}_I \sim H V_\mu V^\mu \longrightarrow a_1$

loop induced couplings for neutral scalar

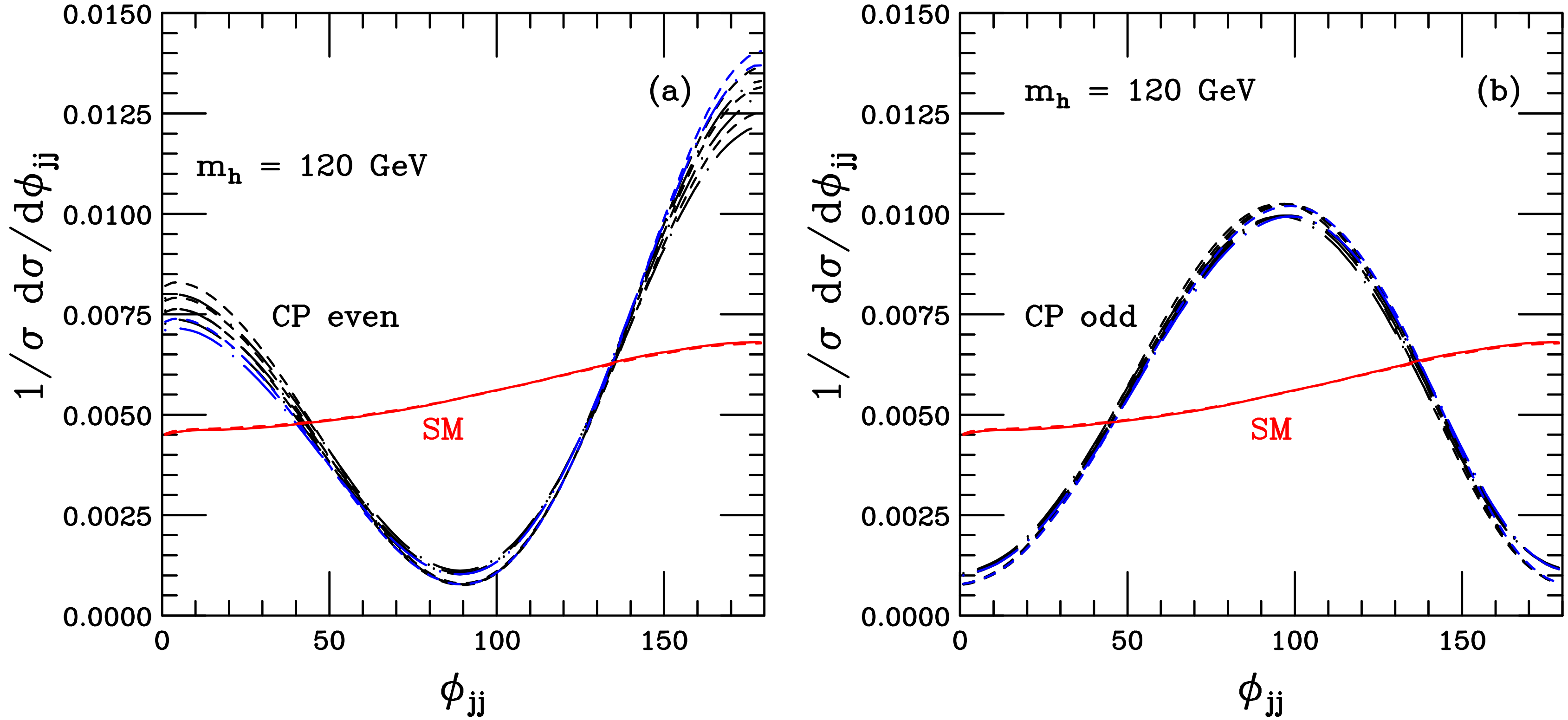
CP even $\quad \mathcal{L}_{eff} \sim H V_{\mu\nu} V^{\mu\nu} \longrightarrow a_2$

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

Must distinguish $a_1$, $a_2$, $a_3$ experimentally

# Azimuthal angle correlations

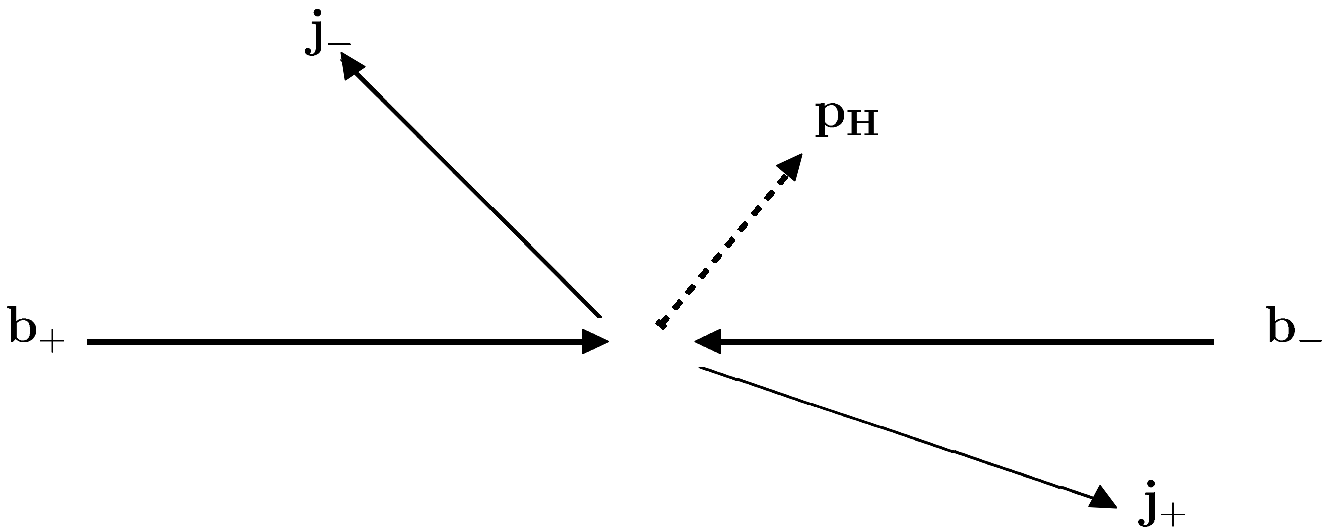
Tell-tale signal for non-SM coupling is azimuthal angle between tagging jets




Dip structure at 90° (CP even) or 0/180° (CP odd) only depends on tensor structure of $HVV$ vertex. Very little dependence on form factor, LO vs. NLO, Higgs mass etc.

## Azimuthal angle distribution and Higgs CP properties

Kinematics of $Hjj$ event:



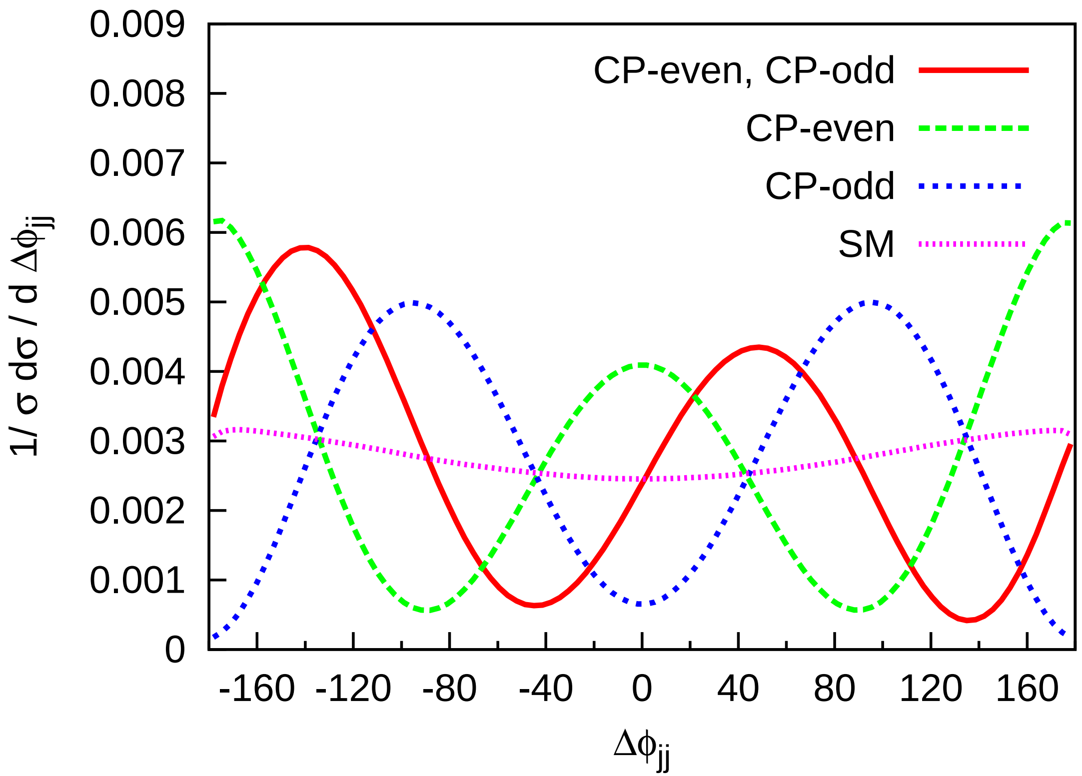

Define azimuthal angle between jet momenta $j_+$ and $j_-$ via

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

- $\Delta\phi_{jj}$ 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

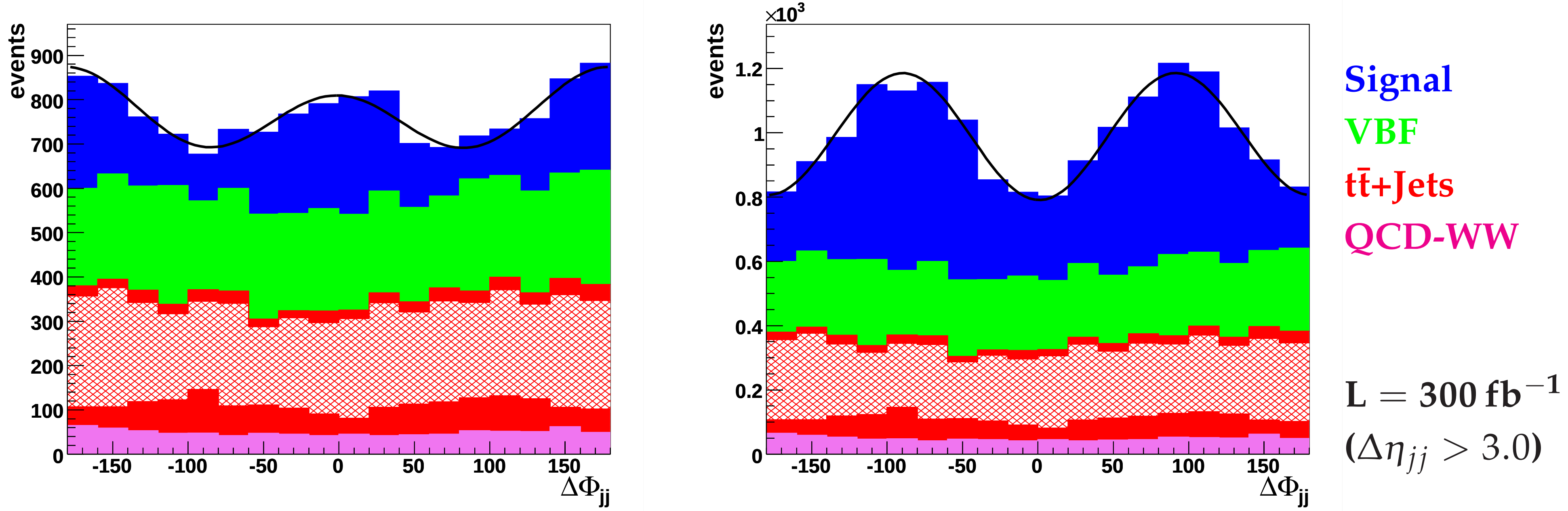
Position of minimum of $\Delta\phi_{jj}$ distribution measures relative size of CP-even and CP-odd couplings. For

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

$\Longrightarrow$ Minimum at $-\alpha$ and $\pi - \alpha$

# $\Delta\Phi_{jj}$-Distribution in gluon fusion: WW case

Fit to $\Phi_{jj}$-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

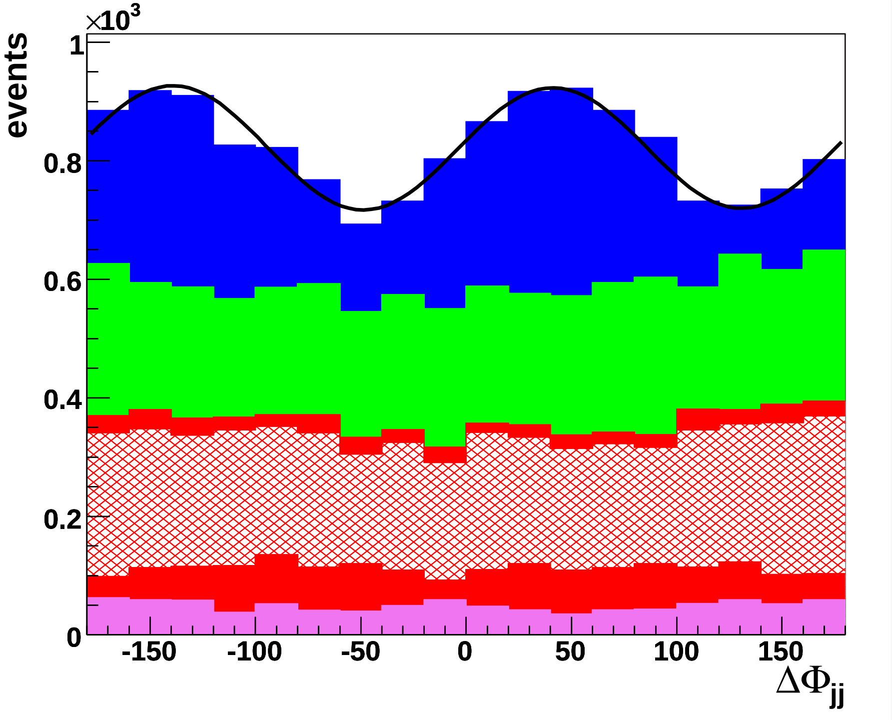
$A = 0.199 \pm 0.034$

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

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)

# $\Delta\Phi_{jj}$-Distribution: CP violating case



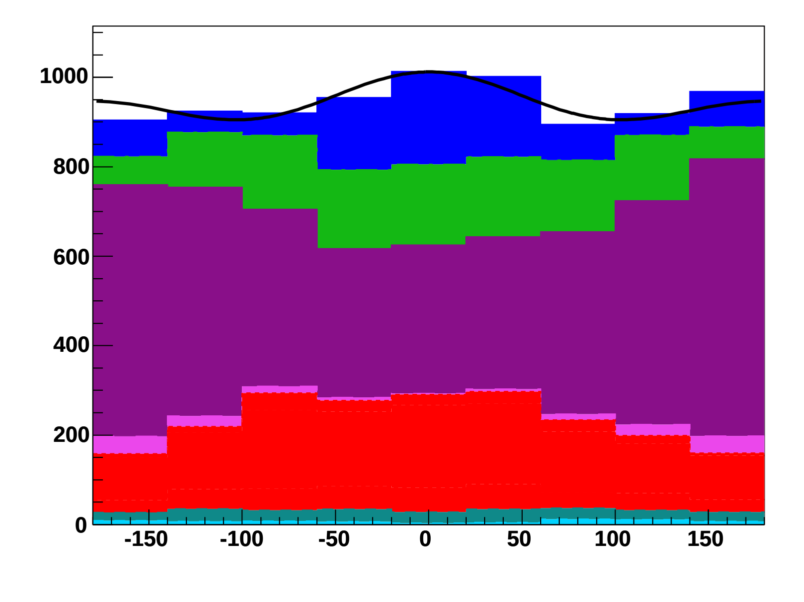

CP-mixture: equal CP-even and CP-odd contributions

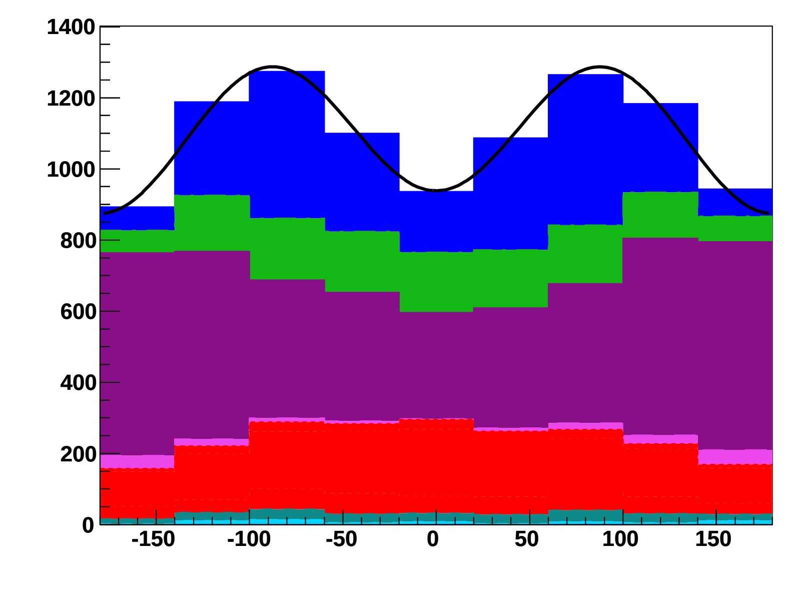
$$A = 0.153 \pm 0.037$$

$$\Delta\Phi_{max} = 45.6 \pm 7.3$$

# $H \to \tau\tau$ case: $\Delta\Phi_{jj}$-distribution with backgrounds

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




**Signal**
**VBF-H**
**QCD-Z**
**EW-Z**
**$t\bar{t}$+Jets**

**L = 600 fb$^{-1}$**
**($\Delta\eta_{jj} > 3.0$)**

CP-even

$A = 0.004 \pm 0.015$

CP-odd

$A = -0.161 \pm 0.014$

fit of the background only : $-0.043 \pm 0.016$

$\Rightarrow$ significance for CP-even vs. CP-odd $\approx 8$

# Summary

- Higgs + 2 Jet events at the LHC provide very useful information on Higgs couplings
- Order 200 $\text{fb}^{-1}$ of LHC data allow to probe Higgs couplings at the 10% level
- Beside VBF, gluon fusion is a second copious source of $\Phi jj$ events at the LHC
- Full one-loop calculations are available for quark-loop induced $Hjj$ and $Ajj$ production, including CP-even CP-odd interference and finite quark mass effects
- For $m_H = 160$ GeV and dominant decay $H \to WW$ the gluon fusion induced signal at the LHC is visible above backgrounds. $H \to \tau\tau$ is somewhat more challenging
- CP-violation in the Higgs sector is observable via the shape of the azimuthal angle distribution $d\sigma/d\Delta\phi_{jj}$