

# HIGGS + 2 JET PRODUCTION

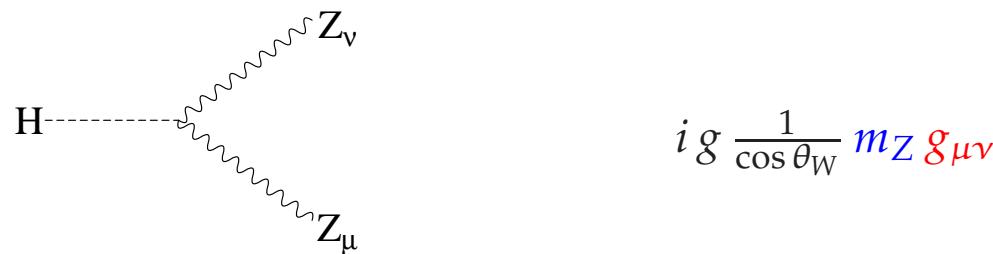
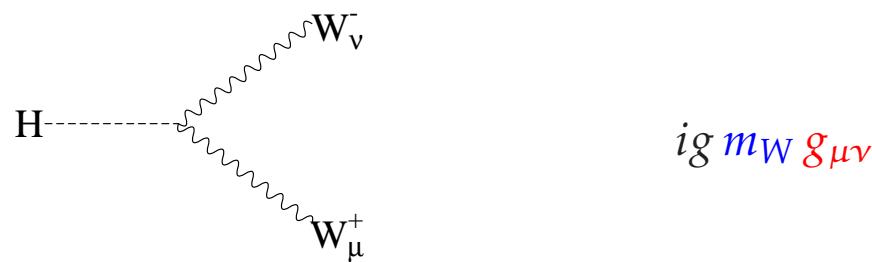
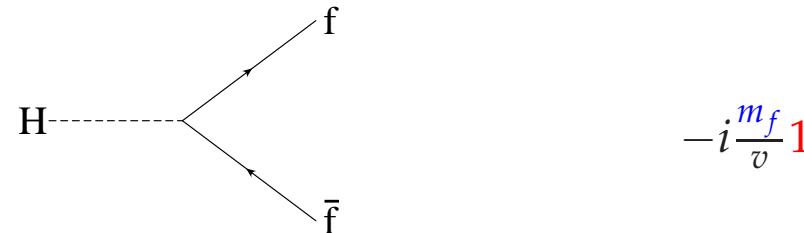
Dieter Zeppenfeld  
Universität Karlsruhe, Germany

Workshop on Higgs Boson Phenomenology, Zürich, January 7–9, 2009

- Introduction
- Probing CP properties
- $H\rightarrow jj$  production via gluon fusion
- $H\rightarrow WW$  study
- $H\rightarrow\tau\tau$  study
- Conclusions



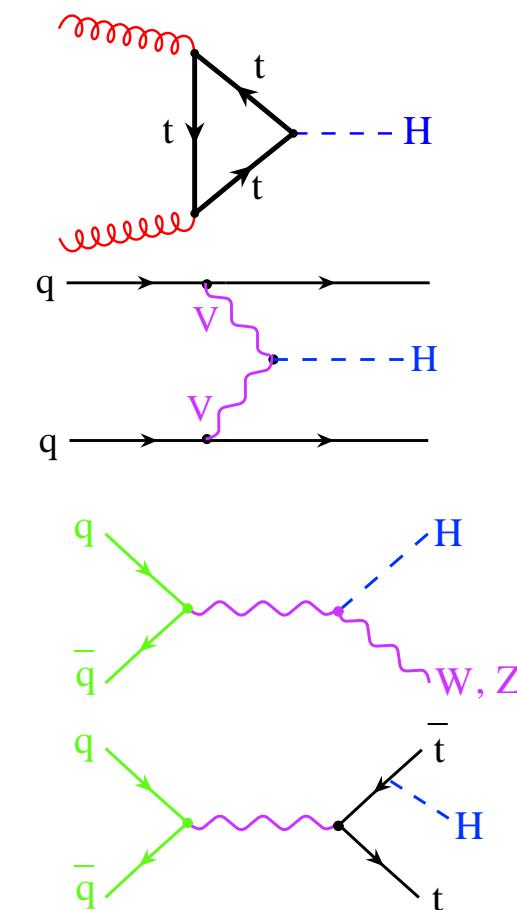
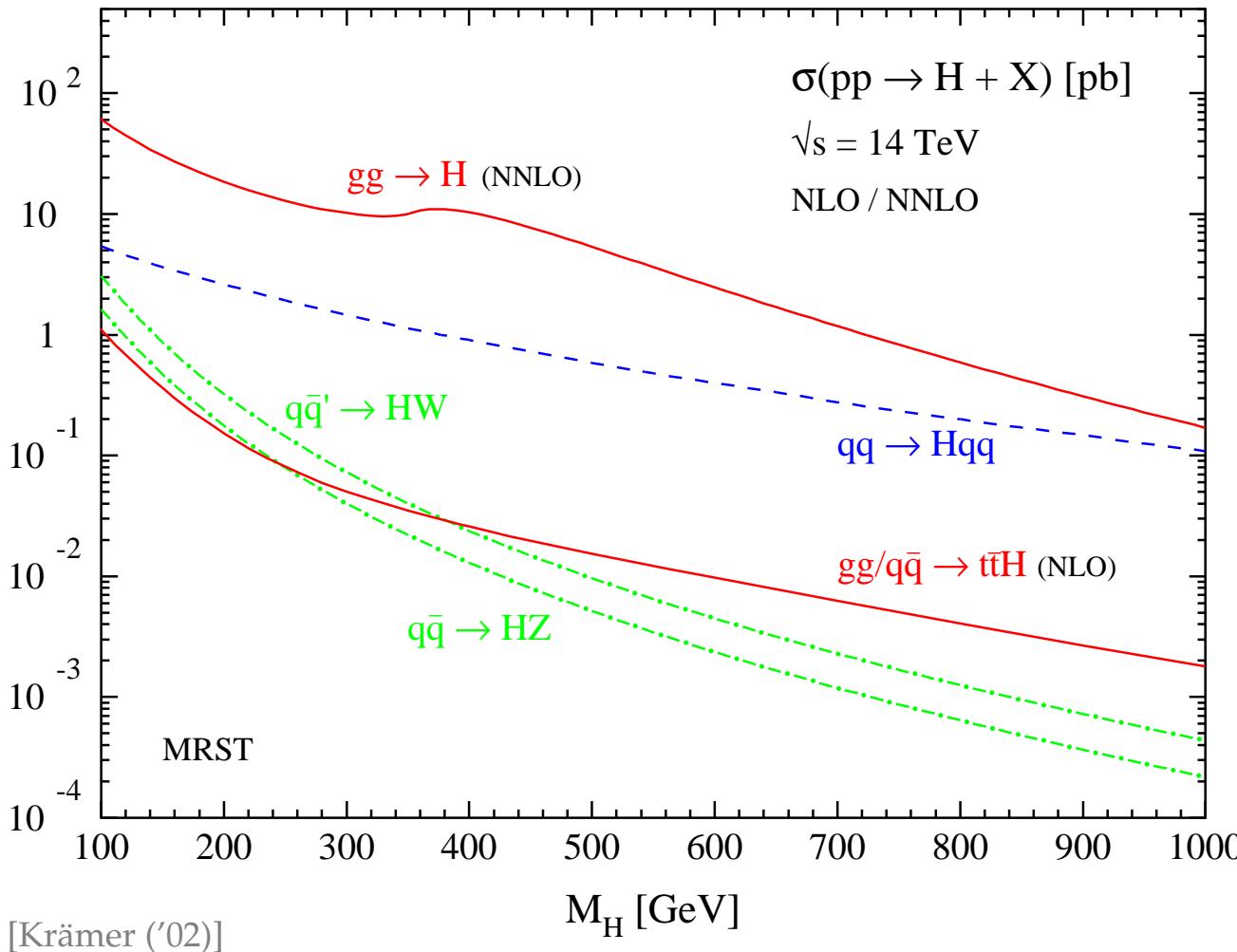
## Feynman rules for SM Higgs couplings



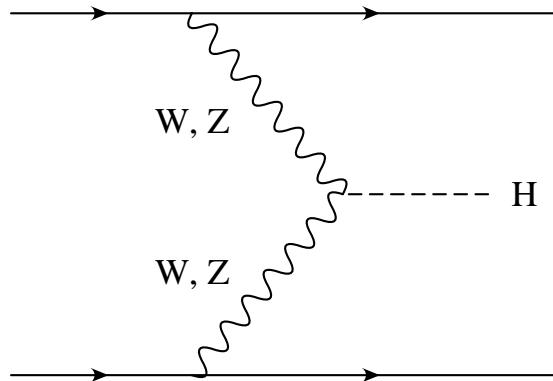
Verify tensor structure of  $HVV$  couplings. Loop induced couplings lead to  $H V_{\mu\nu} V^{\mu\nu}$  effective coupling and different tensor structure:  $g_{\mu\nu} \rightarrow q_1 \cdot q_2 g_{\mu\nu} - q_{1\nu} q_{2\mu}$

Distinguish scalar from pseudoscalar Higgs couplings to fermions.

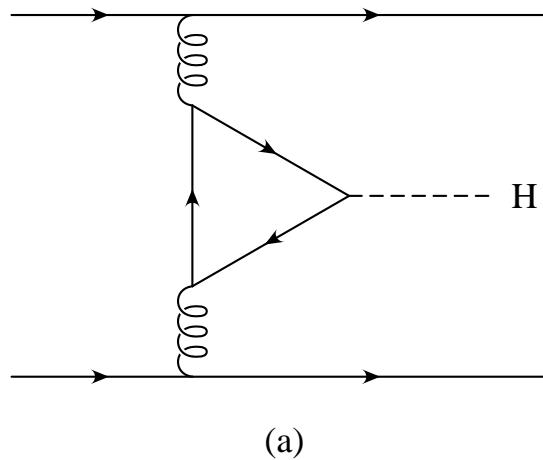
## SM Higgs production processes at the LHC



## How to distinguish VBF and gluon fusion?



vs.



(a)

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

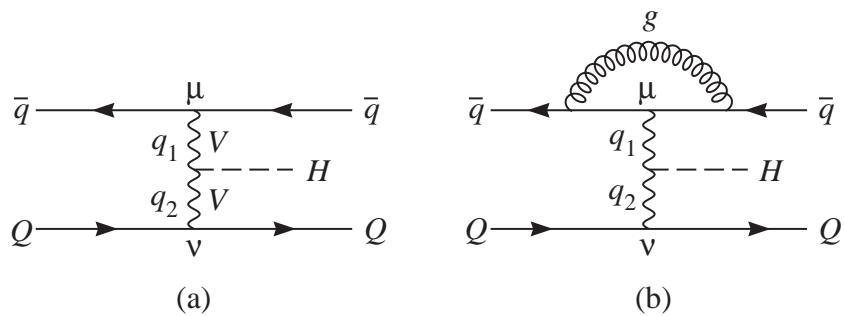
- ⇒ we need to **investigate the phenomenology** of these two processes and understand the differences that can be exploited to **distinguish** between gluon fusion and VBF
- ⇒ derive **cuts** to be applied to **enhance VBF** with respect to gluon fusion.

Measure  $HWW$  and  $HZZ$  coupling

- ⇒ derive **cuts** to be applied to **enhance gluon fusion** with respect to VBF.
- Measure **effective  $Hgg$  coupling** or  **$Htt$  coupling**

## Tensor structure of the $HVV$ coupling

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



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

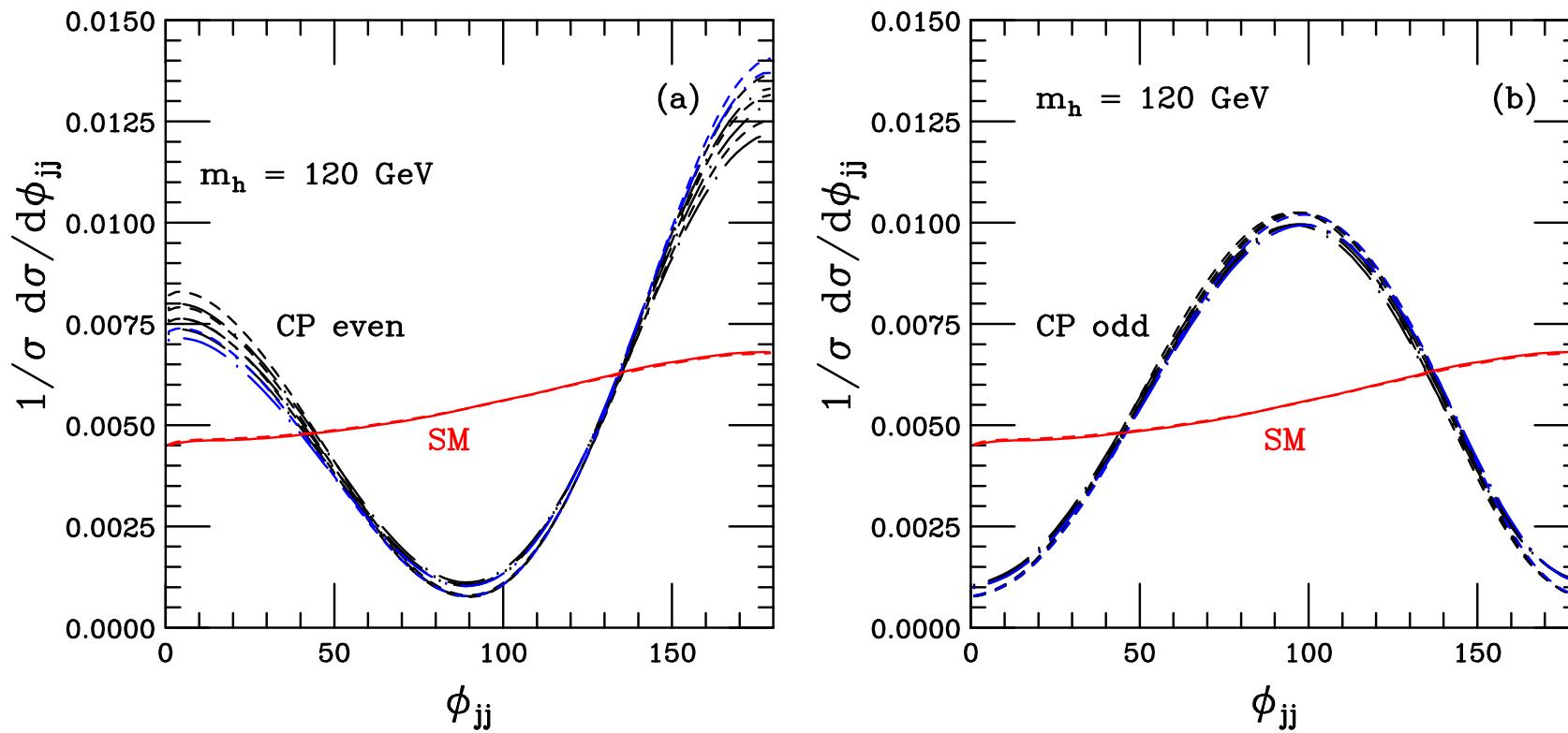
**CP odd**       $\mathcal{L}_{eff} \sim HV_{\mu\nu} \tilde{V}^{\mu\nu} \longrightarrow a_3$

Must distinguish  $a_1, a_2, a_3$  experimentally

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

## Azimuthal angle correlations

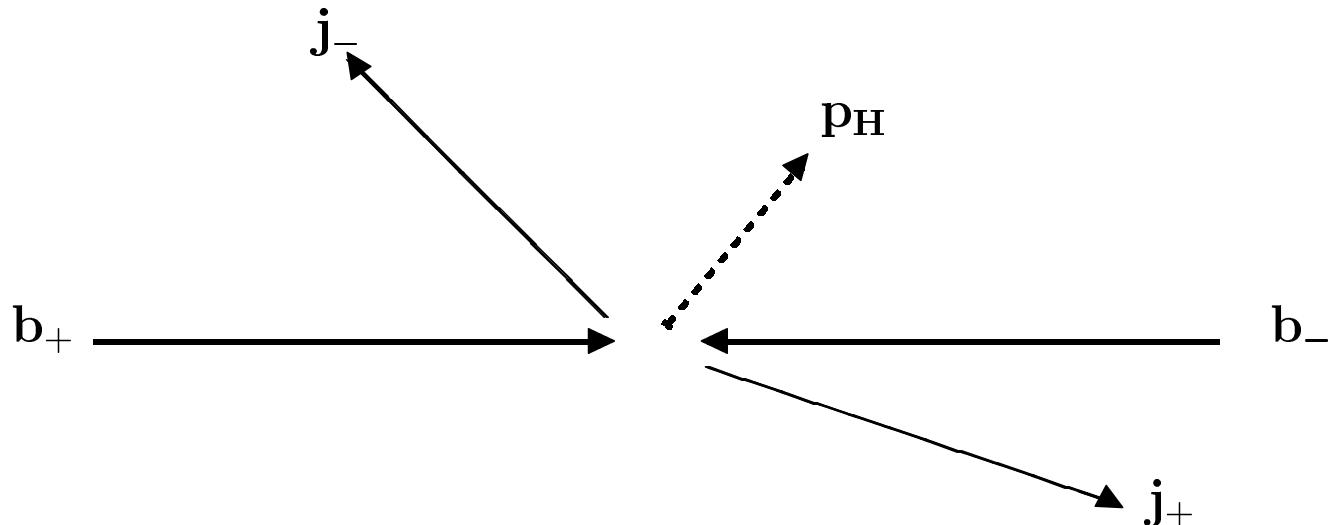
Tell-tale signal for non-SM coupling is azimuthal angle between tagging jets



Dip structure at  $90^\circ$  (CP even) or  $0/180^\circ$  (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:



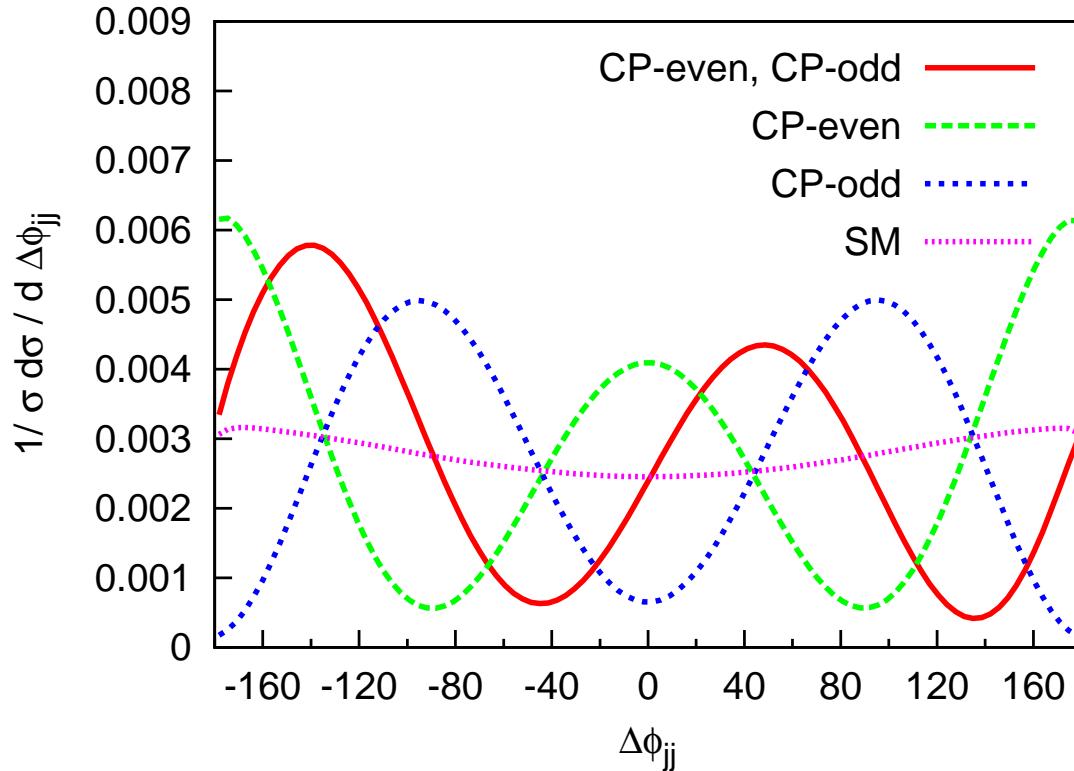
Define azimuthal angle between jet momenta  $j_+$  and  $j_-$  via

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

- $\Delta\phi_{jj}$  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

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

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

## From VBF to gluon fusion

- Loop induced  $HVV$  couplings are almost certainly too small to give observable azimuthal angle modulation at the LHC in VBF. Interest for VBF is in experimentally confirming the structure of the tree level  $HVV$  coupling as coming from  $(D^\mu \Phi)^\dagger (D_\mu \Phi)$
- The  $a_2$  and  $a_3$  terms naturally arise for  $\Phi gg$  couplings from top quark triangles and lead to effective Lagrangians

CP – even :

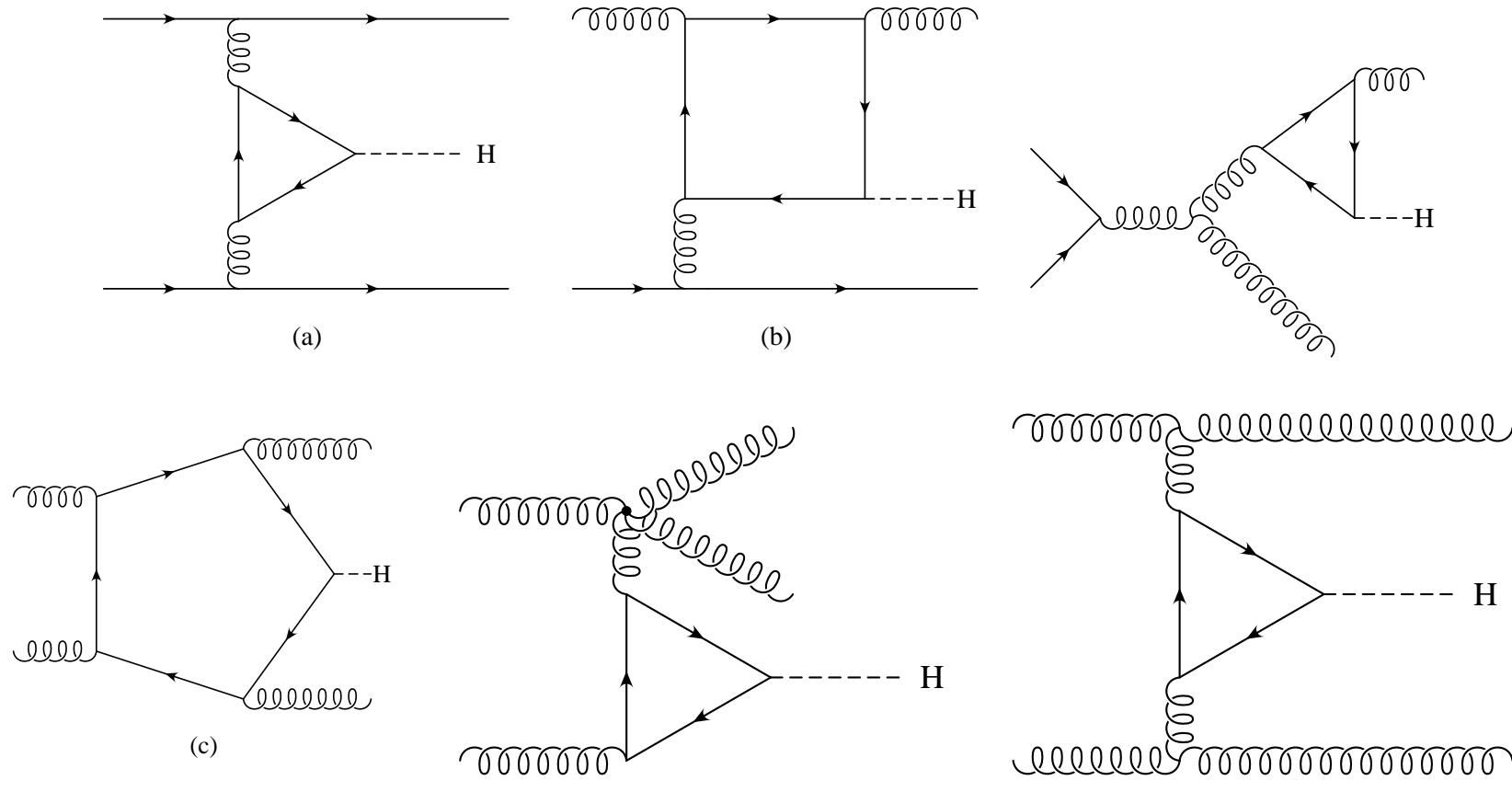
$$i \frac{m_Q}{v} \rightarrow \mathcal{L}_{eff} = \frac{\alpha_s}{12\pi v} H G_{\mu\nu}^a G^{\mu\nu,a}$$

CP – odd :

$$-\frac{m_Q}{v} \gamma_5 \rightarrow \mathcal{L}_{eff} = \frac{\alpha_s}{8\pi v} A G_{\mu\nu}^a \tilde{G}^{\mu\nu,a} = \frac{\alpha_s}{16\pi v} A G_{\mu\nu}^a G_{\alpha\beta}^a \epsilon^{\mu\nu\alpha\beta}$$

- Study gluon fusion induced  $\Phi jj$  events to distinguish CP-even and CP-odd couplings

## Diagrams for gg fusion with finite $m_t$ effects



$q \bar{Q} \rightarrow q \bar{Q} H$

$q g \rightarrow q g H$

$g g \rightarrow g g H$

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

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

- **VBF cuts** to enhance VBF over gluon fusion

In addition to the previous ones, we impose

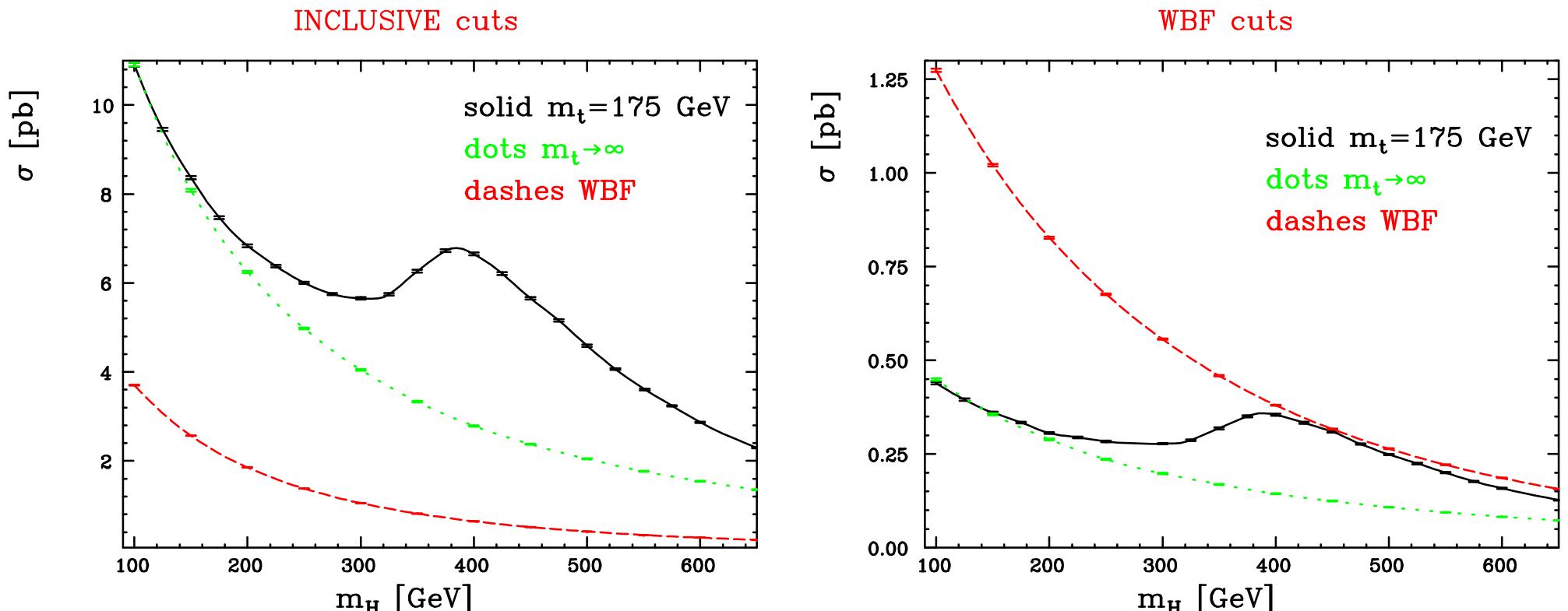
$$|\eta_{j_1} - \eta_{j_2}| > 4.2 \quad \eta_{j_1} \cdot \eta_{j_2} < 0 \quad m_{jj} > 600 \text{ GeV}$$

- 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  $\alpha_s = 0.12$

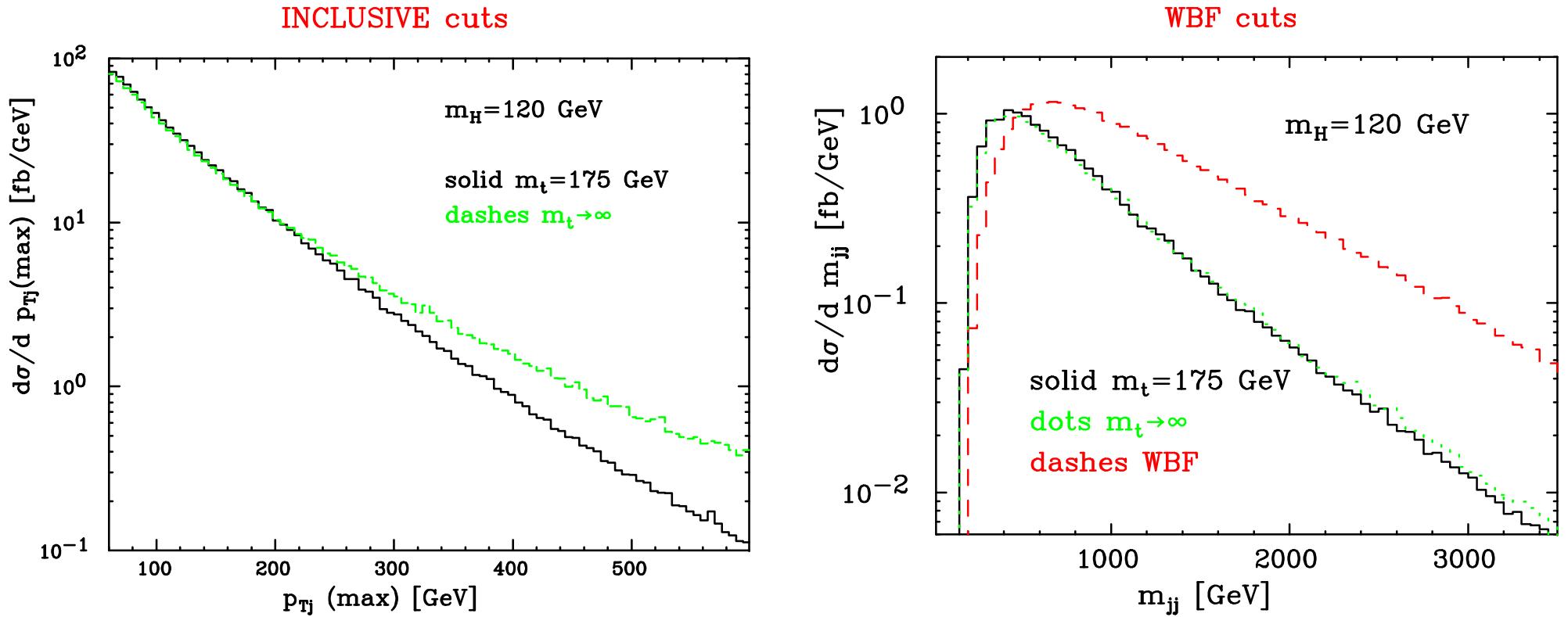
Expect factor  $\approx 1.5$  to 2 scale uncertainty due to  $\sigma \sim \alpha_s^4$

## 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 $m_t \rightarrow \infty$ limit

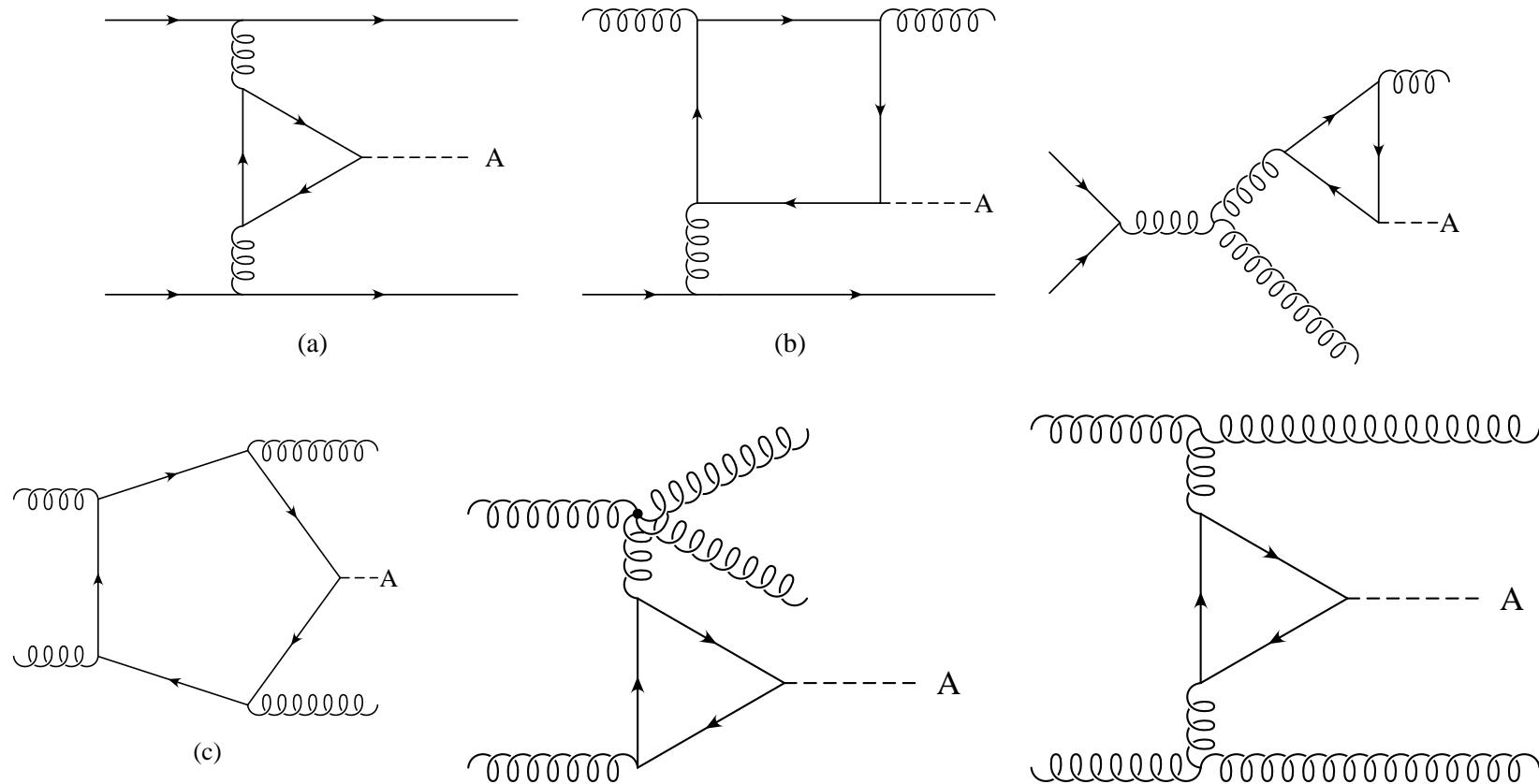


Transverse momentum: Large top mass limit ok provided  $p_{T,j} \lesssim m_t$

Dijet invariant mass: Large top mass limit ok throughout

## New calculation: pseudoscalar Higgs production

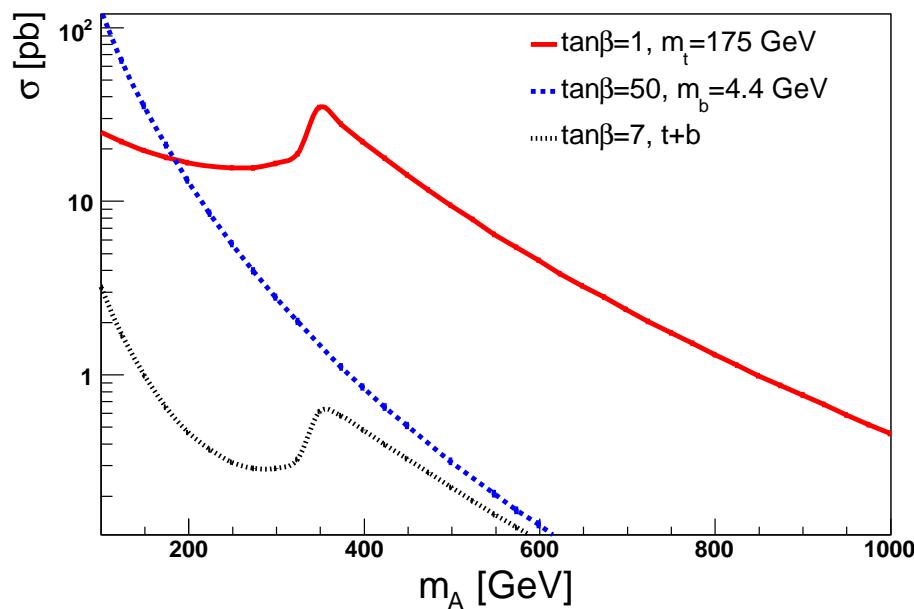
$pp \rightarrow AjjX$  including top and bottom loops + interference [Michael Kubocz, DZ]



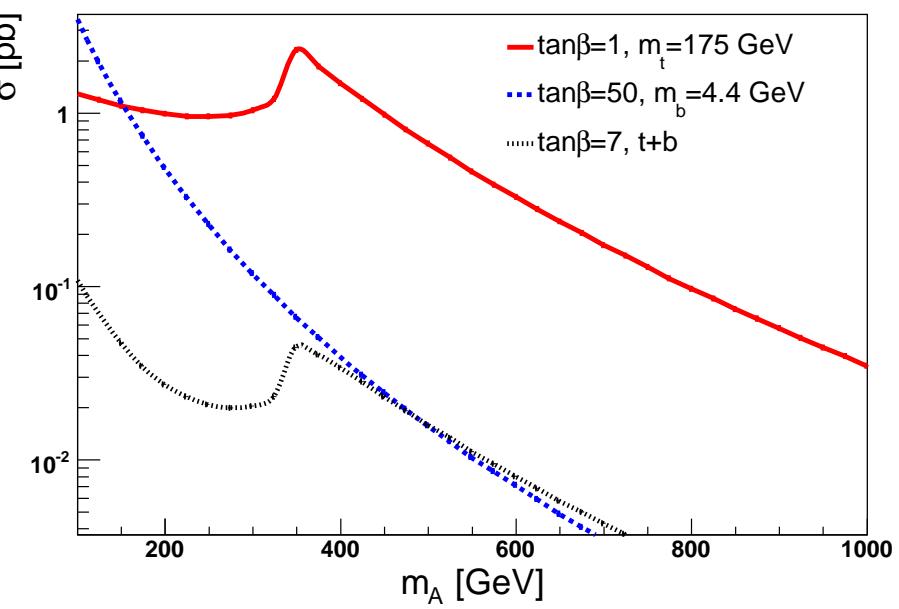
## New elements in the calculation

- $AQQ$  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
- Interference of A and H contributions for  $\tau^+ \tau^- jj$  production

Inclusive cuts



VBF cuts



## Gluon Fusion as a signal channel

Heavy quark loop induces effective  $Hgg$  vertex:

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

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

Azimuthal angle between tagging jets probes difference

- Use gluon fusion induced  $\Phi jj$  signal to probe structure of  $Hgg$  vertex
- Find **cuts** to enhance gluon fusion over VBF and other backgrounds

⇒ Study by **Gunnar Klämke** in  $m_Q \rightarrow \infty$  limit (hep-ph/0703202)

## Gluon fusion signal and backgrounds: $H \rightarrow WW$ case

Signal channel (LO):

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

dominant backgrounds:

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

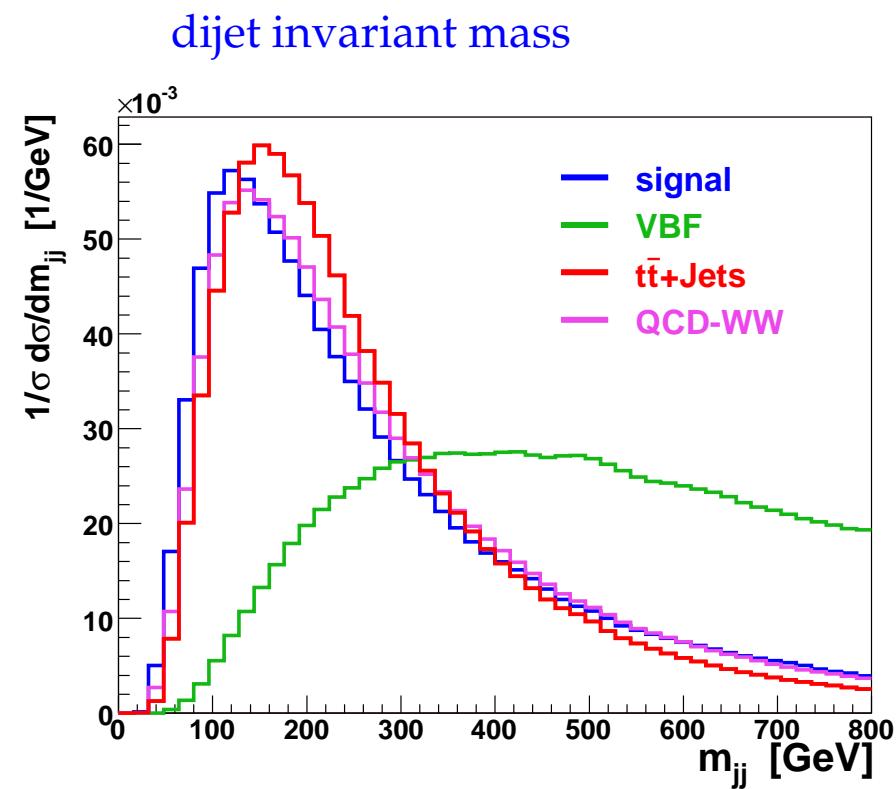
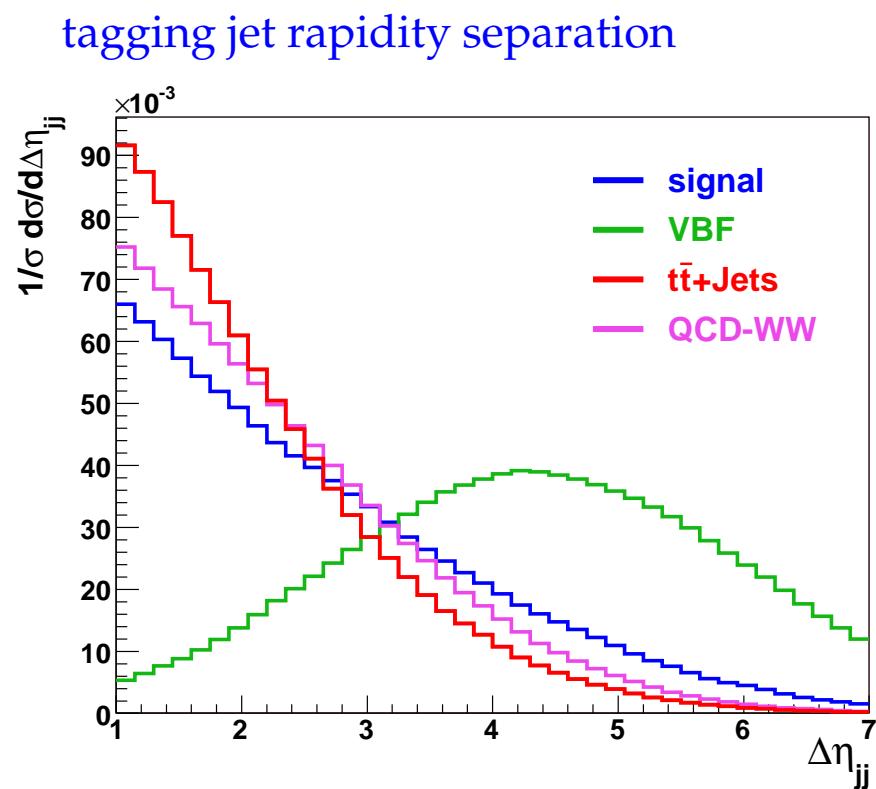
applied inclusive cuts (minimal cuts):

- 2 tagging-jets  
 $p_{Tj} > 30 \text{ GeV}, \quad |\eta_j| < 4.5$
- 2 identified leptons  
 $p_{Tl} > 10 \text{ GeV}, \quad |\eta_l| < 2.5$
- separation of jets and leptons  
 $\Delta\eta_{jj} > 1.0, \quad R_{jl} > 0.7$

process	$\sigma [\text{fb}]$
GF $pp \rightarrow H + jj$	<b>115.2</b>
VBF $pp \rightarrow W^+W^- + jj$	<b>75.2</b>
$pp \rightarrow t\bar{t}$	<b>6832</b>
$pp \rightarrow t\bar{t} + j$	<b>9518</b>
$pp \rightarrow t\bar{t} + jj$	<b>1676</b>
QCD $pp \rightarrow W^+W^- + jj$	<b>363</b>

## Characteristic distributions

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



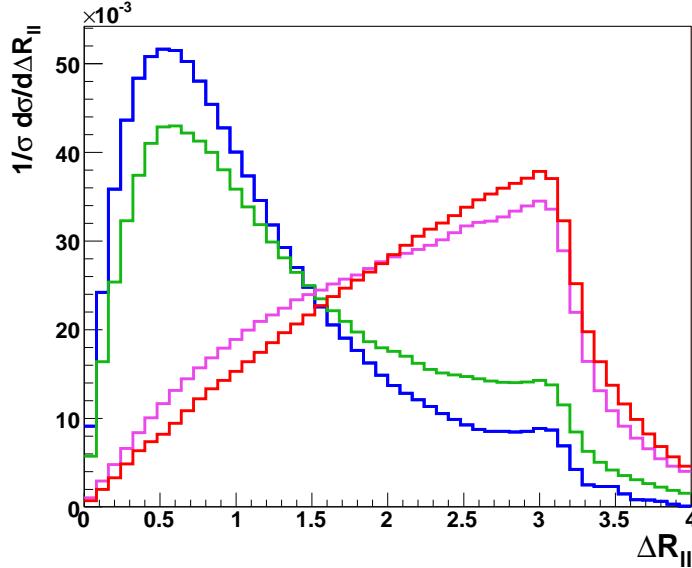
## Selection continued

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

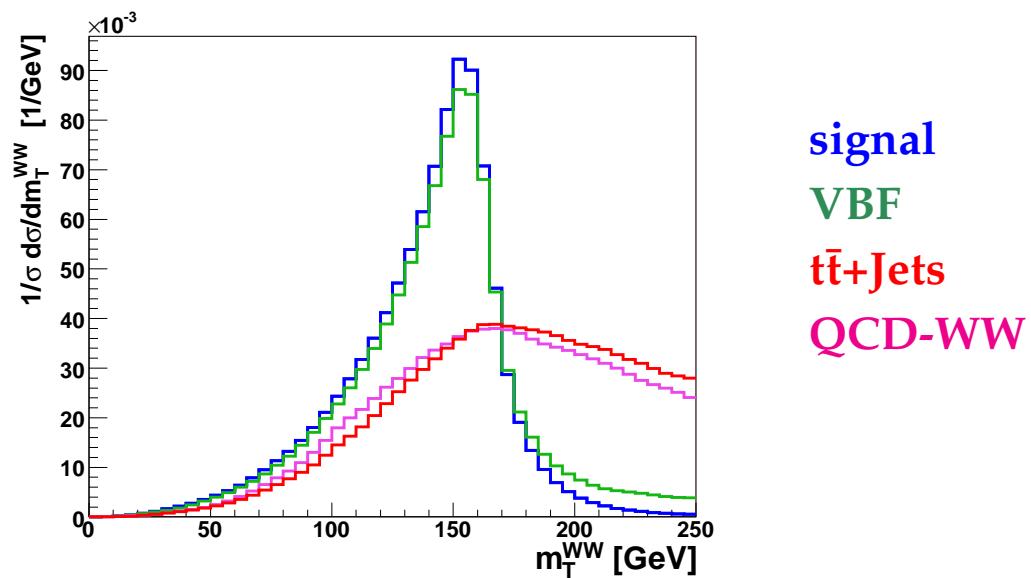
- selection cuts:

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

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



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



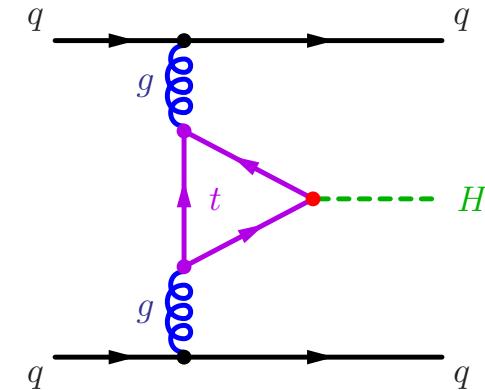
## Results

process	$\sigma$ [fb]	events / $30 \text{ fb}^{-1}$
GF $pp \rightarrow H + jj$	<b>31.5</b>	<b>944</b>
VBF $pp \rightarrow W^+W^- + jj$	<b>16.5</b>	<b>495</b>
$pp \rightarrow t\bar{t}$	<b>23.3</b>	<b>699</b>
$pp \rightarrow t\bar{t} + j$	<b>51.1</b>	<b>1533</b>
$pp \rightarrow t\bar{t} + jj$	<b>11.2</b>	<b>336</b>
QCD $pp \rightarrow W^+W^- + jj$	<b>11.4</b>	<b>342</b>
$\Sigma$ backgrounds	<b>113.5</b>	<b>3405</b>

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

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

- interesting for SM Higgs ( $\approx 120$  GeV) and SUSY scenario with large  $\tan \beta$  ( $m_H \approx m_A \gtrsim 150$  GeV)
- $\times$ -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  $p_T$ : Crucial for  $m_{\tau\tau}$  resolution

$$\Delta p_x = 0.46 \cdot \sqrt{\sum E_{Tj}}$$

## SM Higgs with 120 GeV mass

### inclusive cuts

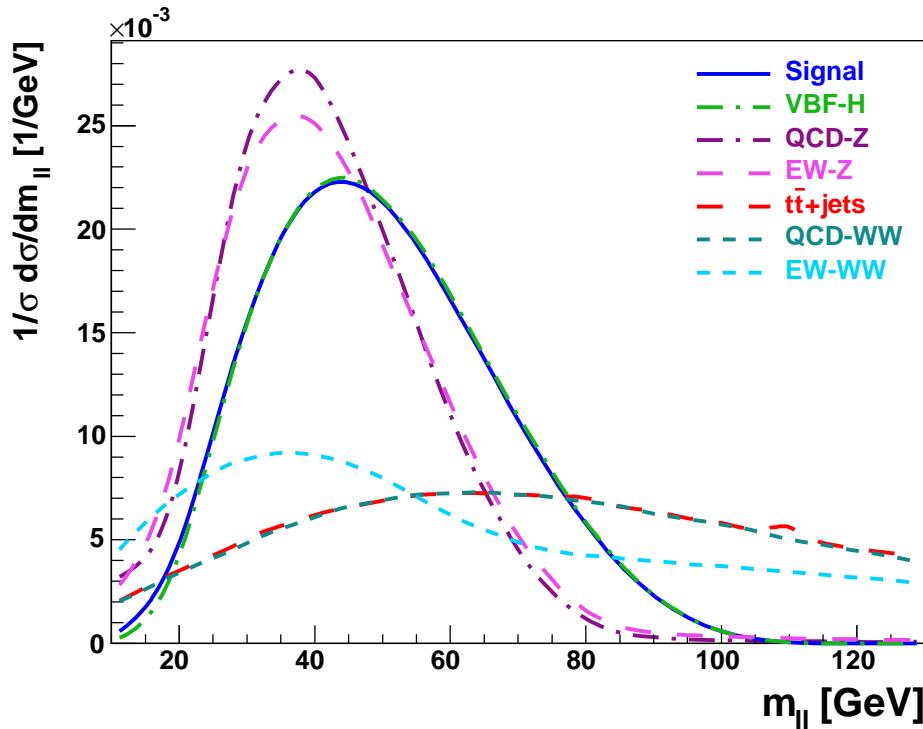
$$p_{T,jets} > 30 \text{ GeV}, \quad p_{T,\ell} > 10 \text{ GeV}, \quad |\eta_j| < 4.5, \quad |\eta_\ell| < 2.5, \quad \Delta\eta_{jj} > 1.0, \quad \Delta R_{j\ell} > 0.7,$$

cross sections for inclusive cuts for signal and background

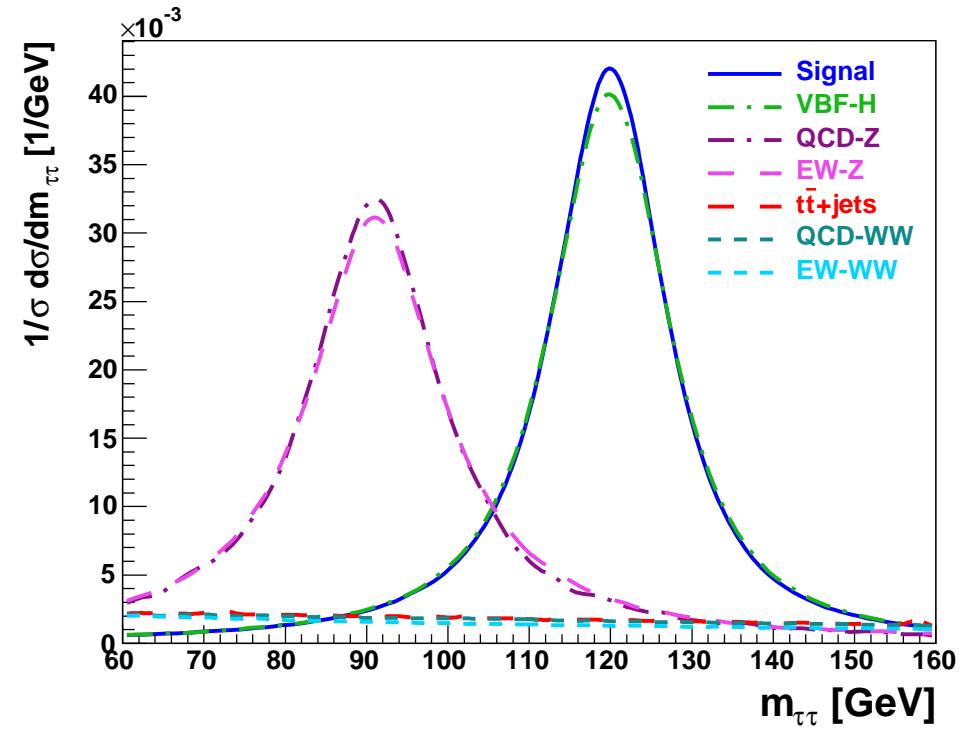
---

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

## Distributions



dilepton invariant mass



reconstructed  $\tau\tau$  invariant mass

## $H \rightarrow \tau\tau \rightarrow \ell^+ \ell^- \nu\bar{\nu}$ rates after selection cuts

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

$$R_{\ell\ell} < 2.4, \quad p_T > 30 \text{ GeV}, \quad m_{\ell\ell} < 80 \text{ GeV}, \quad 110 \text{ GeV} < m_{\tau\tau} < 135 \text{ GeV}, \quad 0 < x_i < 1$$

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

for cp-even higgs:  $S/\sqrt{B} \approx 17$  ( $600 \text{ fb}^{-1}$ )

this corresponds to:  $S/\sqrt{B} \approx 5$  ( $50 \text{ fb}^{-1}$ )

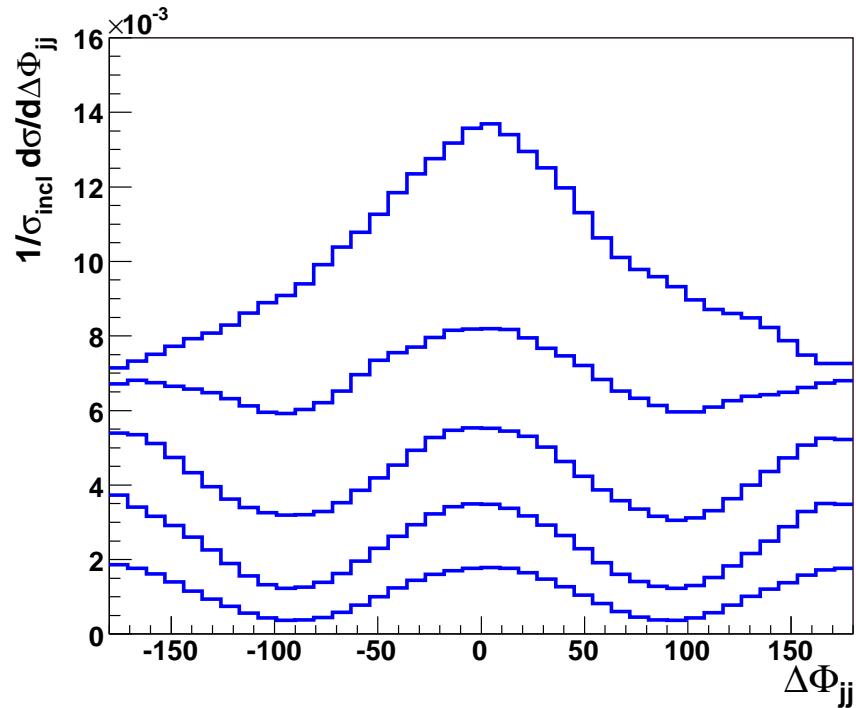
for cp-odd higgs:  $S/\sqrt{B} \approx 40$  ( $600 \text{ fb}^{-1}$ )

this corresponds to:  $S/\sqrt{B} \approx 5$  ( $10 \text{ fb}^{-1}$ )

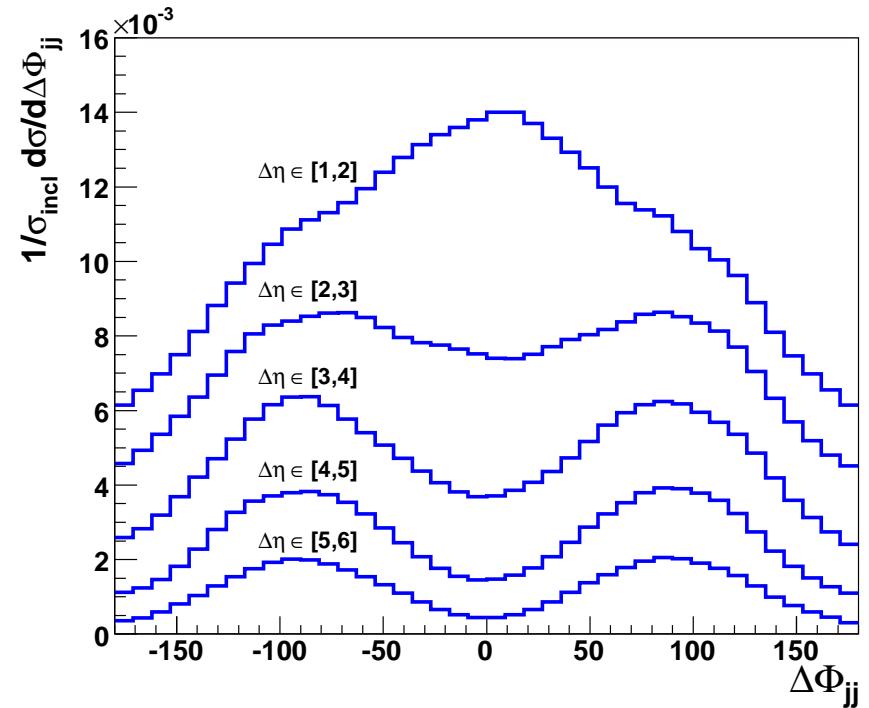
## Sensitivity of gluon fusion to structure of $Hgg$ vertex

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

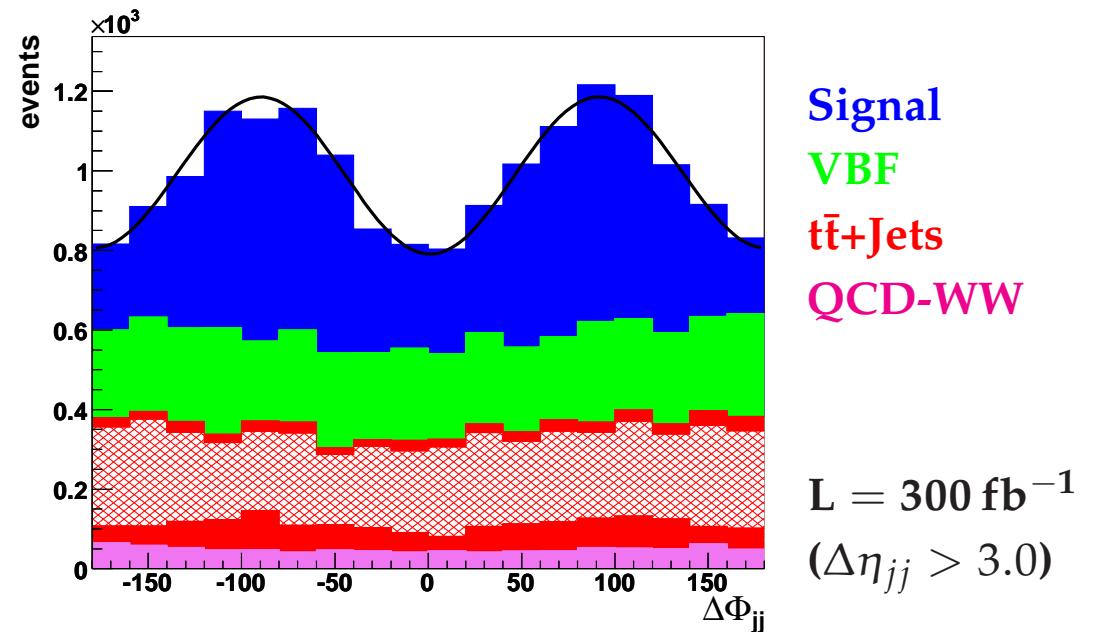
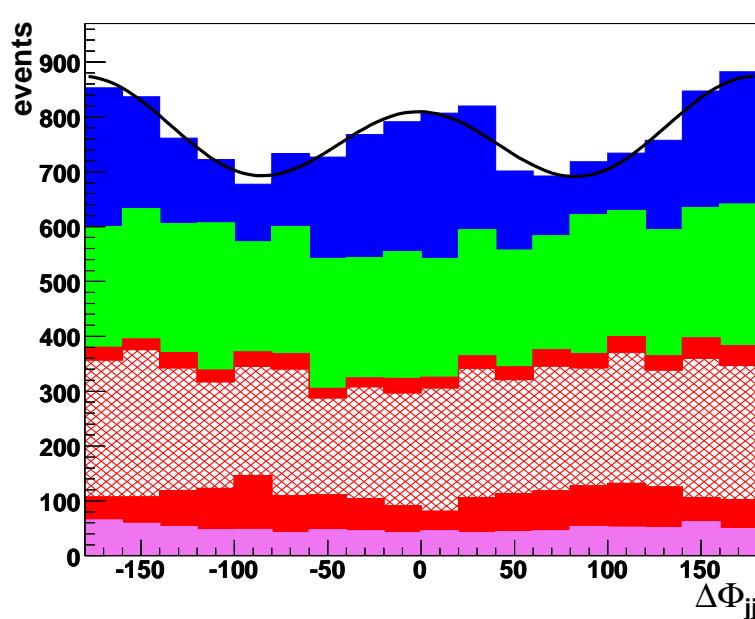


CP-odd coupling



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

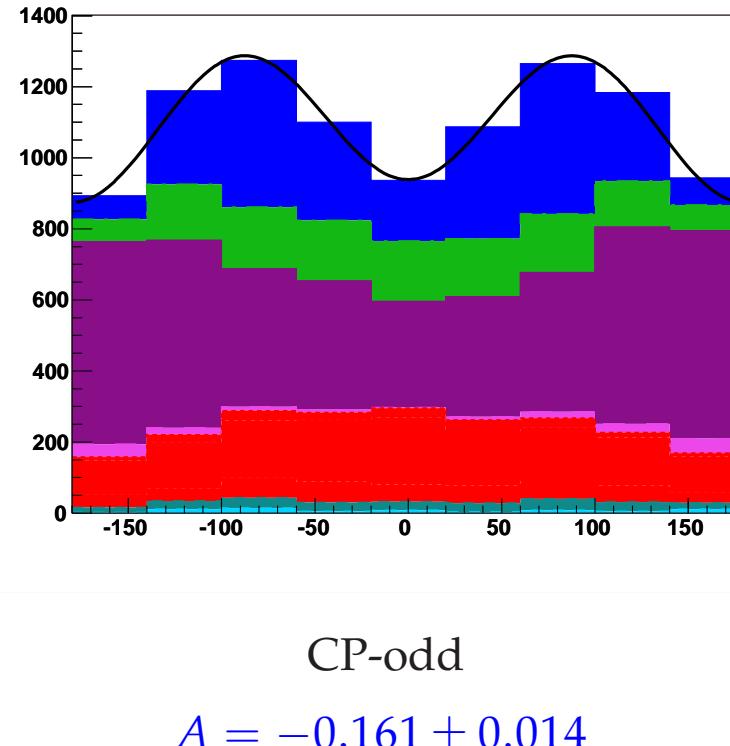
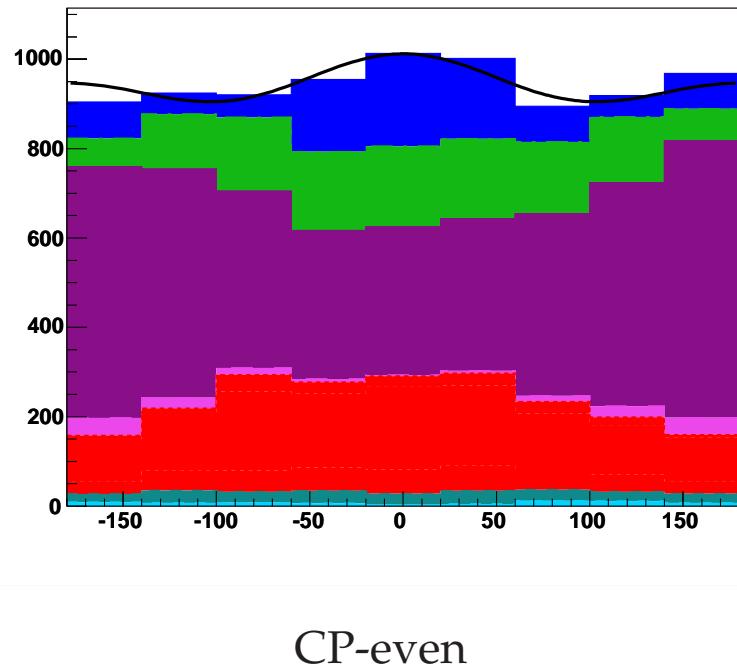
Fit to  $\Phi_{jj}$ -distribution with function  $f(\Delta\Phi) = N(1 + A \cos[2(\Delta\Phi - \Delta\Phi_{max})] - B \cos(\Delta\Phi))$



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  $L = 30 \text{ fb}^{-1}$  each)

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

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



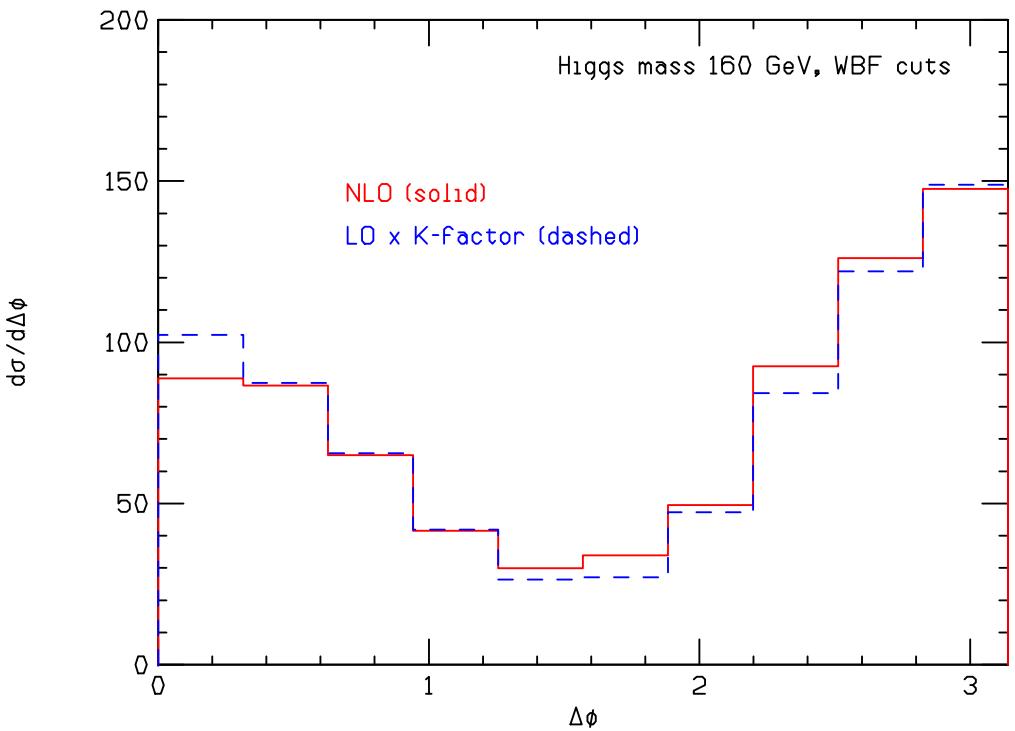
Signal  
VBF-H  
QCD-Z  
EW-Z  
 $t\bar{t}+{\text{Jets}}$

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

fit of the background only :  $-0.043 \pm 0.016$   
 $\Rightarrow$  significance for CP-even vs. CP-odd  $\approx 8$

## Open questions

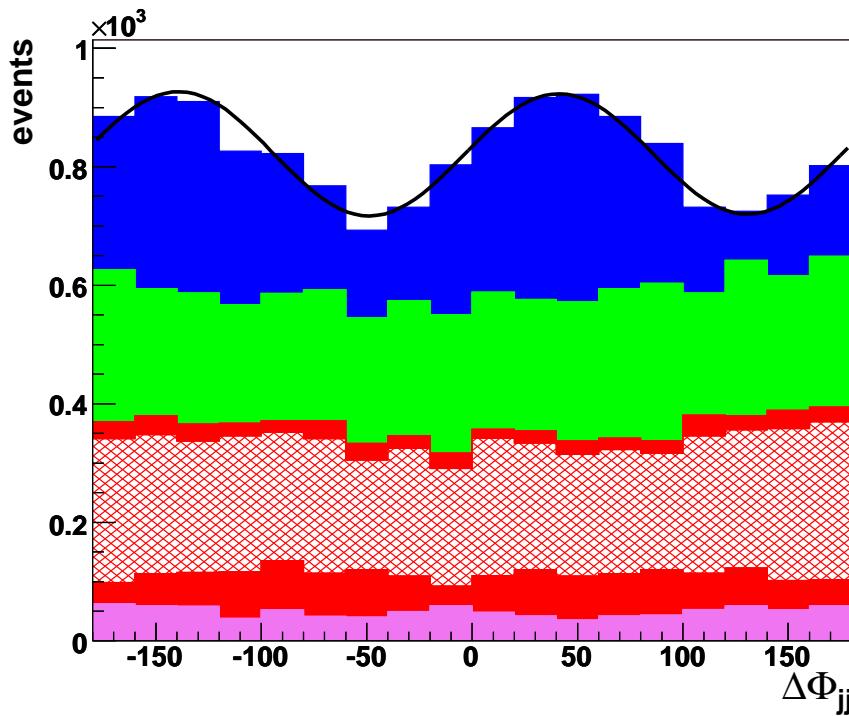
- Analysis has been done with tree level simulation at parton level. How much will more realistic simulation of detector effects change the picture?
- Only the double leptonic decays in the  $H \rightarrow \tau\tau$  channel have been considered. VBF studies suggest that hadronic decays of one tau can at least double the statistics.
- Does additional parton emission lead to a decorrelation of the two jets, i.e. a weakening of the azimuthal angle modulation? Parton shower simulations indicate that this is the case. However, the NLO calculation of Campbell, Ellis, Zanderighi does not support a strong effect



## Conclusions

- Higgs + 2 Jet events at the LHC provide very useful information on Higgs couplings
- 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  $H \rightarrow WW$  the gluon fusion induced signal at the LHC is visible above backgrounds.  $H \rightarrow \tau\tau$  is somewhat more challenging
- CP-violation in the Higgs sector is observable via the shape of the azimuthal angle distribution  $d\sigma/d\Delta\phi_{jj}$

## $\Delta\Phi_{jj}$ -Distribution: CP violating case for $H \rightarrow WW$



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

$$A = 0.153 \pm 0.037$$

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