HIGGS BOSON PHYSICS AT THE LHC

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Les Houches 2009, Physics at TeV Colliders

- Introduction
- Search channels at the LHC
- Higgs coupling measurements
- QCD and EW corrections
- Hjj events: VBF vs gluon fusion
- Higgs CP measurements
- 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 $\Phi^\dagger \rightarrow (0, \frac{v+H}{\sqrt{2}})$

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

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

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

Higgs coupling to gauge bosons

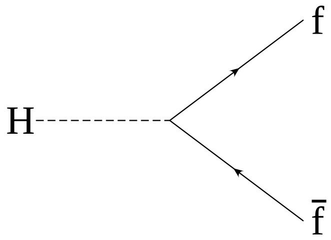
Kinetic energy term of Higgs doublet field:

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

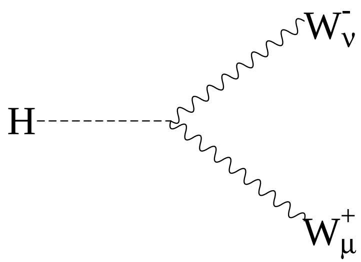
- W, Z mass generation: $m_W^2 = \left(\frac{gv}{2}\right)^2$, $m_Z^2 = \frac{(g^2+g'^2)v^2}{4}$
- WWH and ZZH couplings are generated
- Higgs couples propotional to mass: coupling strength $= 2\, m_V^2 / v \sim g^2 v$ within SM

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

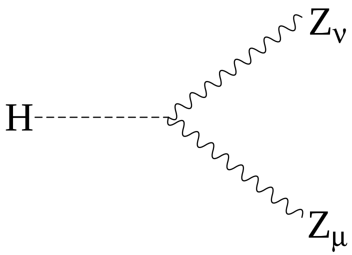
Feynman rules for SM Higgs couplings



$$-i\frac{m_f}{v}\,1$$



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



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

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

Distinguish scalar from pseudoscalar Higgs couplings to fermions.

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 Higgses

Fermions

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

$$\begin{aligned}\mathcal{L}_{\text{Yuk.}} &= -\Gamma_b \bar{b}_L \Phi_1^0 b_R - \Gamma_t \bar{t}_L \Phi_2^0 u_R + \text{h.c.} \\ &= -\Gamma_b \bar{b}_L \frac{v_1 + H\cos\alpha - h\sin\alpha + iA\sin\beta}{\sqrt{2}} b_R - \Gamma_t \bar{t}_L \frac{v_2 + H\sin\alpha + h\cos\alpha + iA\cos\beta}{\sqrt{2}} t_R + \ldots\end{aligned}$$

Expressed in terms of masses the Yukawa Lagrangian is

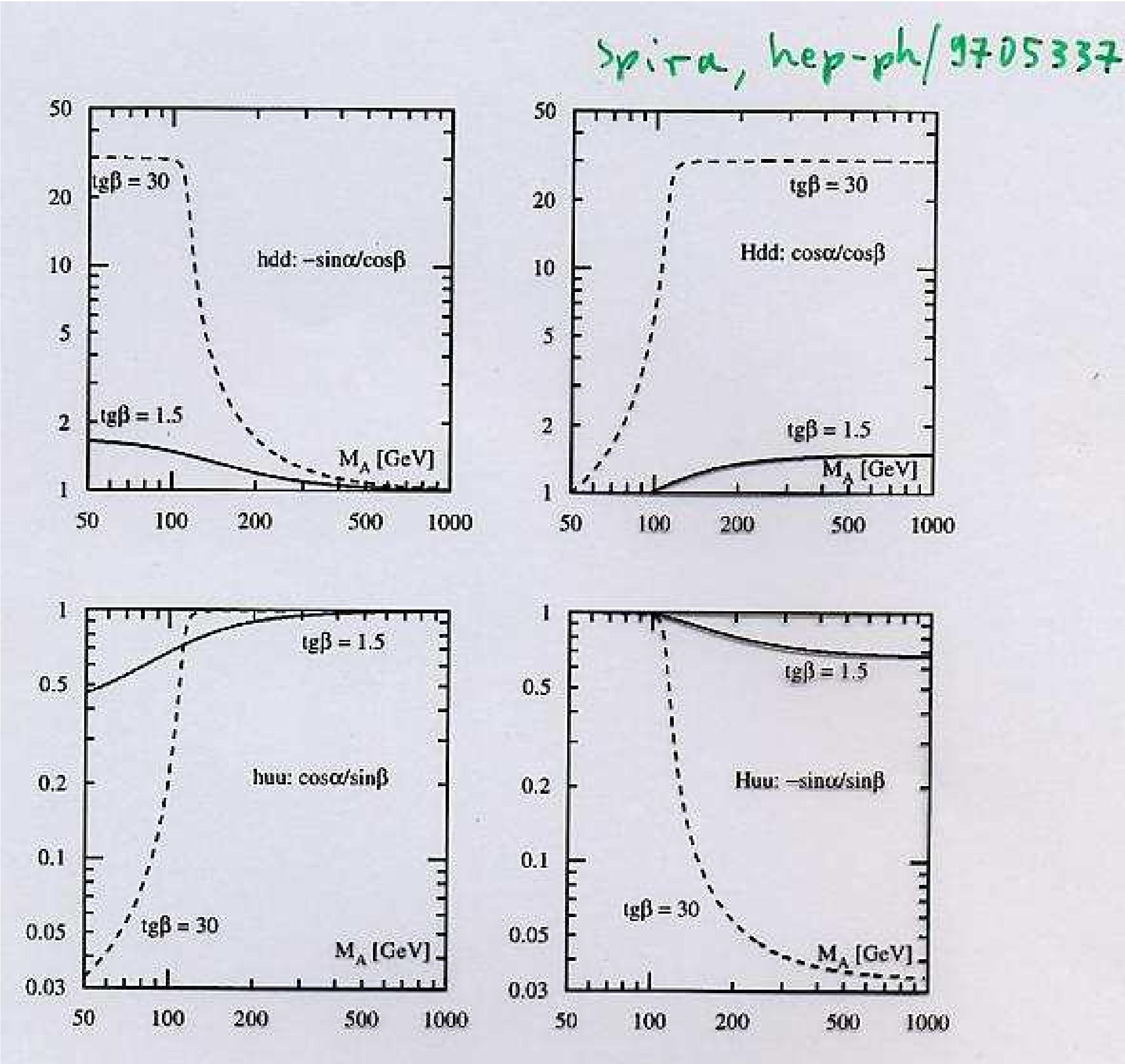
$$\mathcal{L}_{\text{Yuk.}} = -\frac{m_b}{v}\bar{b}\left(v + H\frac{\cos\alpha}{\cos\beta} - h\frac{\sin\alpha}{\cos\beta} - i\gamma_5 A\tan\beta\right) b - \frac{m_t}{v}\bar{t}\left(v + H\frac{\sin\alpha}{\sin\beta} + h\frac{\cos\alpha}{\sin\beta} - i\gamma_5 A\cot\beta\right) t$$

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

Gauge Bosons

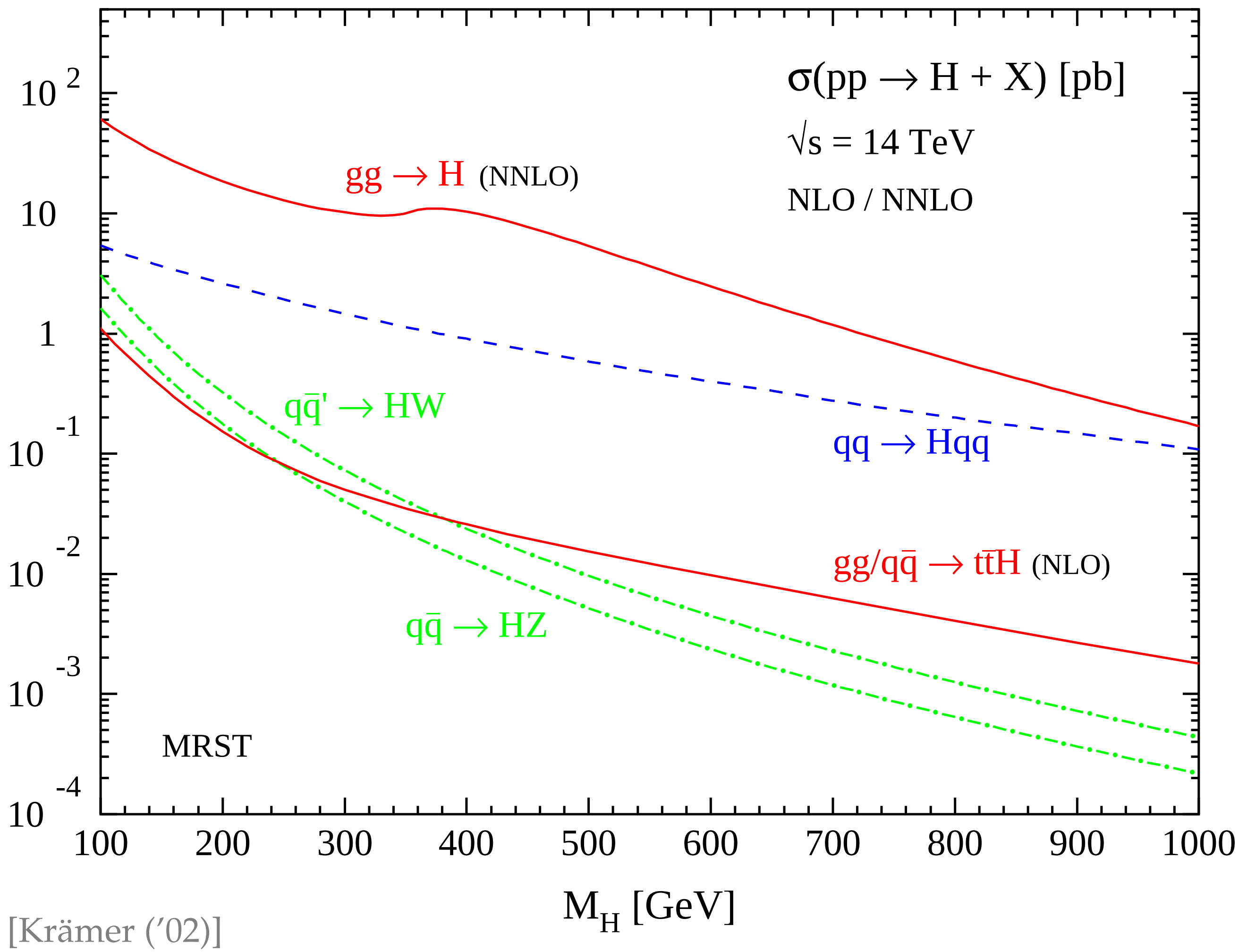
extra coupling factors for hVV and HVV couplings as compared to SM

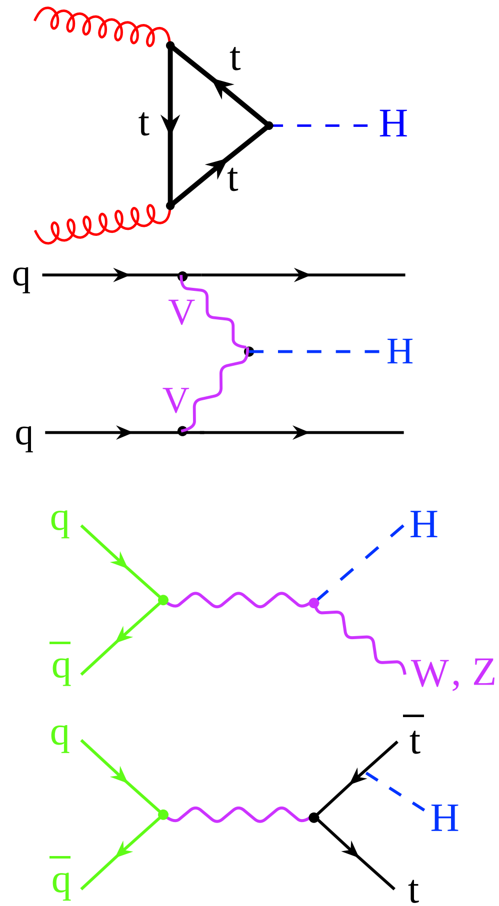
$$hVV \sim \sin(\beta - \alpha) \qquad\qquad HVV \sim \cos(\beta - \alpha)$$



Spira, hep-ph/9705337
hdd: −sinα/cosβ
tgβ = 30
tgβ = 1.5
M_A [GeV]
Hdd: cosα/cosβ
tgβ = 30
tgβ = 1.5
M_A [GeV]
huu: cosα/sinβ
tgβ = 1.5
tgβ = 30
M_A [GeV]
Huu: −sinα/sinβ
tgβ = 1.5
tgβ = 30
M_A [GeV]

Total cross sections at the LHC

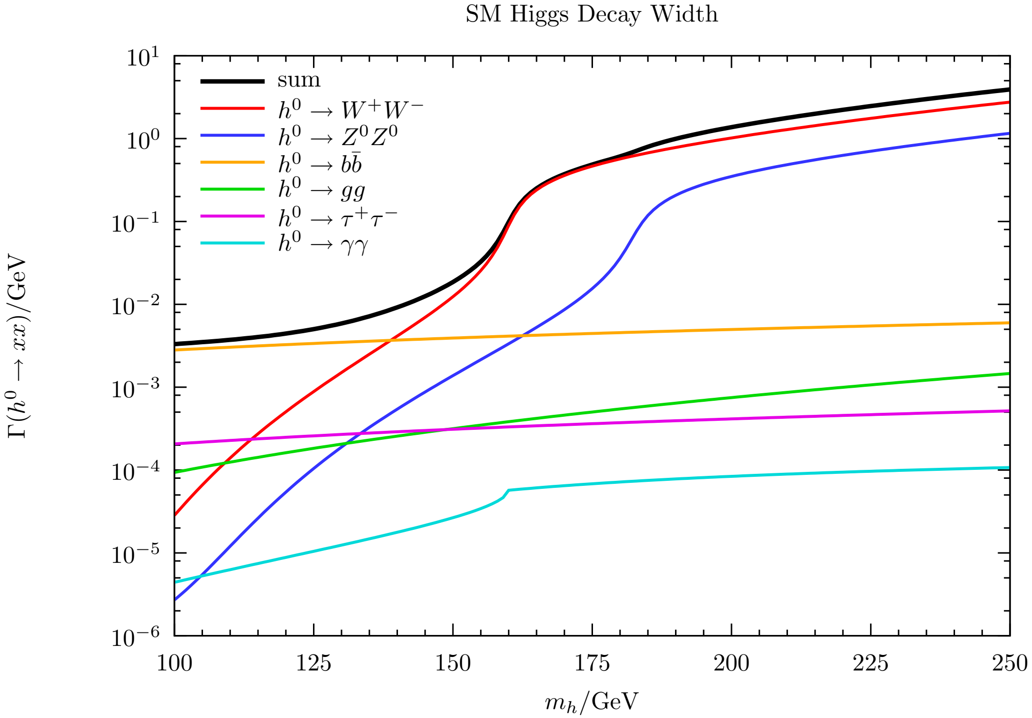


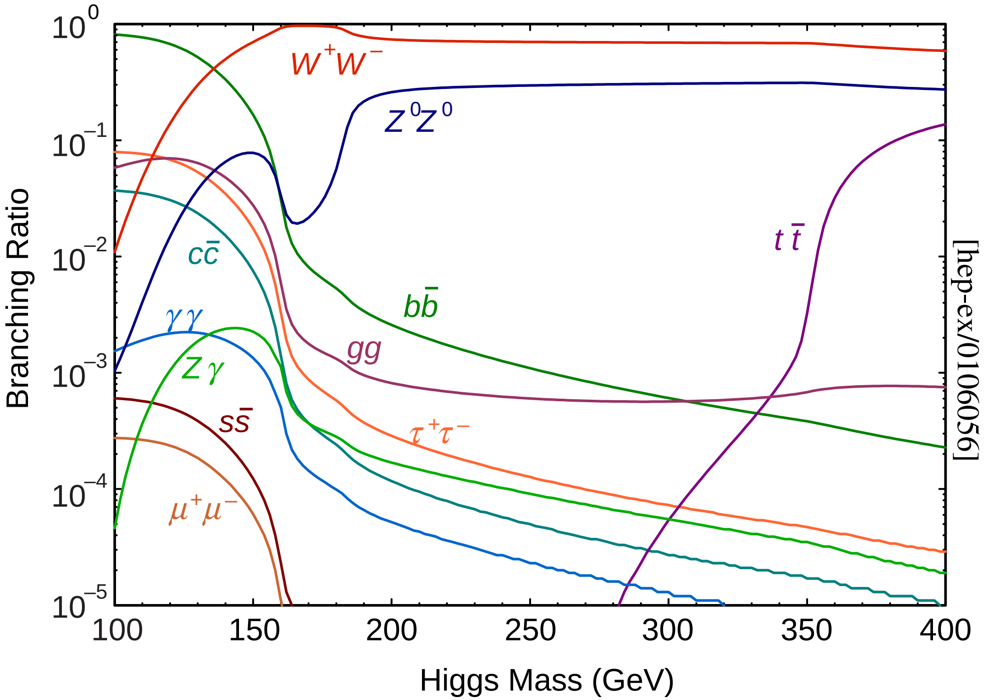


[Krämer ('02)]

Decay of the SM Higgs

Higgs decay width and branching fractions within the SM





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 $m_H \neq 2m_W$.

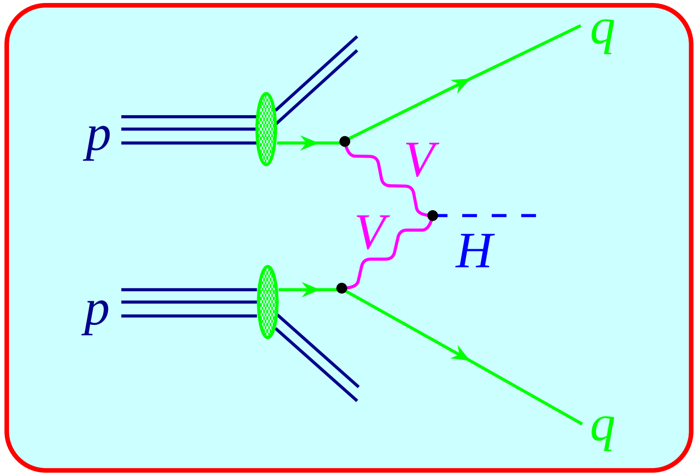
- inclusive search for

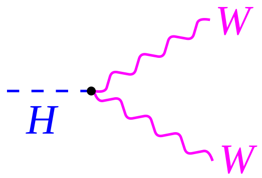
$$H \to W^+W^- \to \ell^+\bar{\nu}\ell^-\nu$$

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

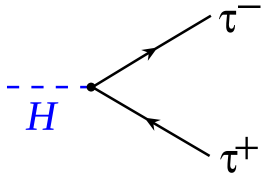
Inclusive searches dominated by gluon fusion production
probe ttH coupling (or ggH effective vertex)

Vector Boson Fusion (VBF)

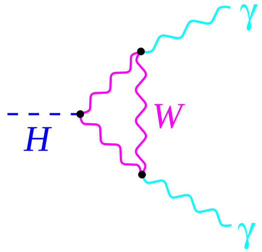




$m_H > 120$ GeV



$m_H < 140$ GeV

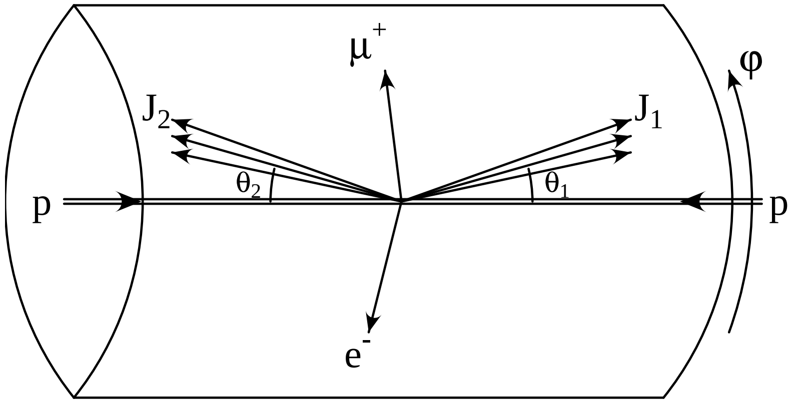


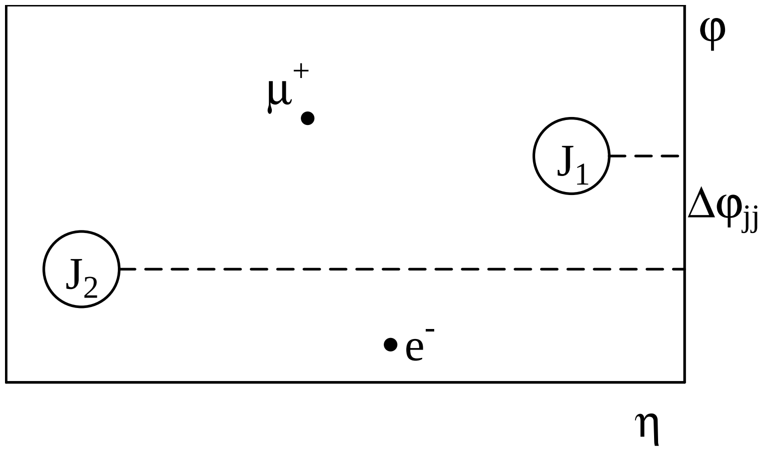
$m_H < 150$ GeV

[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:

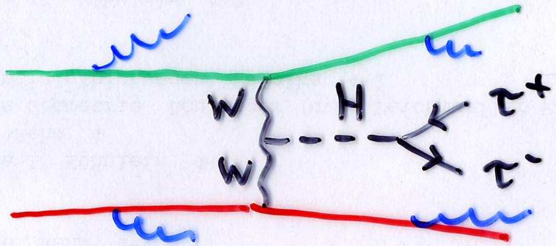
- energetic jets in the forward and backward directions ($p_T > 20$ GeV)
- large rapidity separation and large invariant mass of the two tagging jets
- Higgs decay products between tagging jets
- Little gluon radiation in the central-rapidity region, due to colorless W/Z exchange (central jet veto: no extra jets between tagging jets)

Central jet veto

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

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

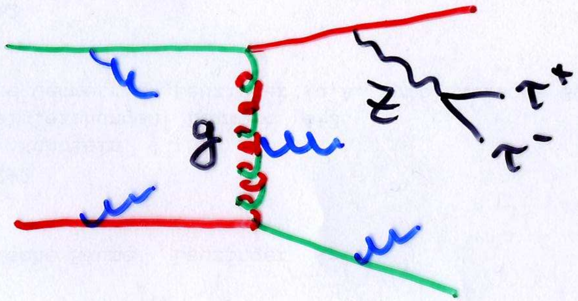
- t-channel color singlet exchange



"synchrotron" radiation between initial and final quark direction

$\Rightarrow$ central jets suppressed

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

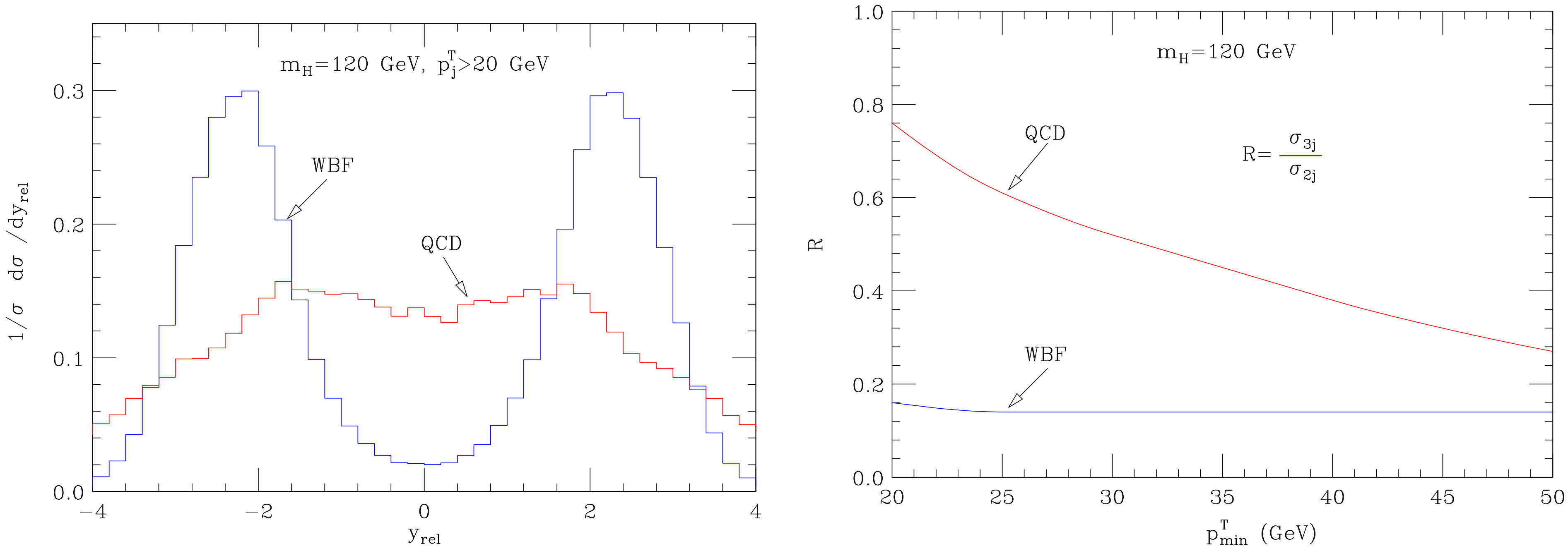


deflection of color charge by ~180° $\Rightarrow$ strong color acceleration

$\Rightarrow$ enhanced central gluon emis.

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

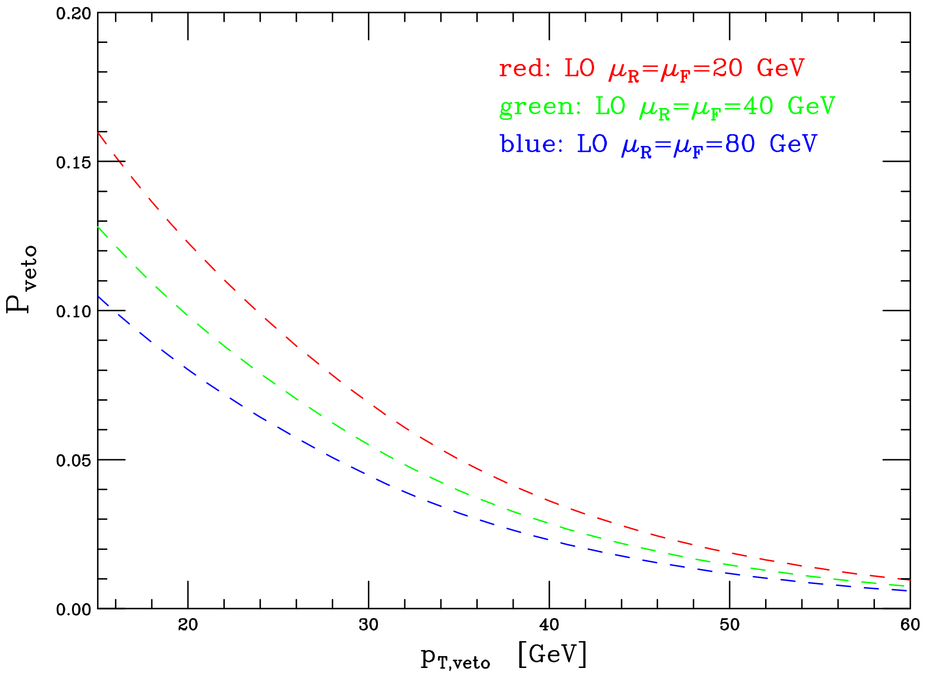
Central Jet Veto: $Hjjj$ from VBF vs. gluon fusion



[Del Duca, Frizzo, Maltoni, JHEP 05 (2004) 064]

- Angular distribution of third (softest) jet follows classically expected radiation pattern
- QCD events have higher effective scale and thus produce harder radiation than VBF (larger three jet to two jet ratio for QCD events)
- Central jet veto can be used to distinguish Higgs production via GF from VBF

VBF Higgs signal and CJV

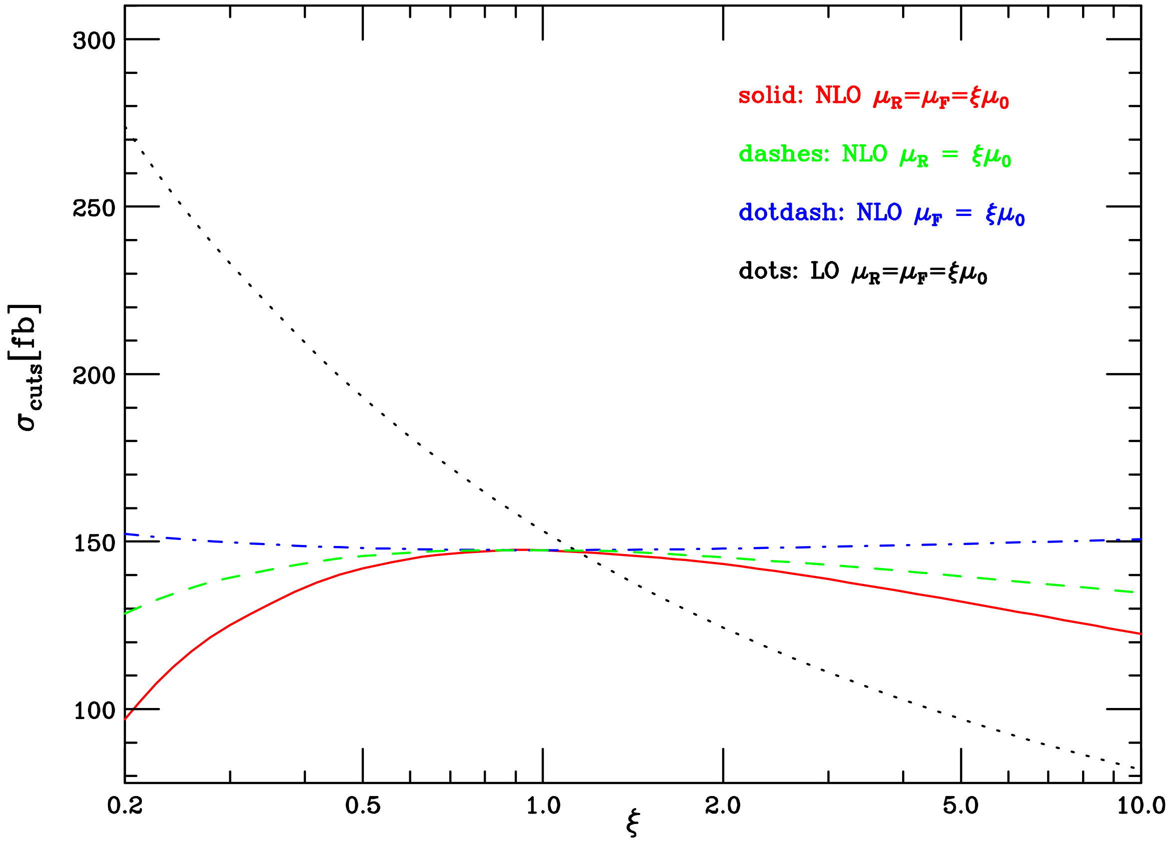


$$p_{Tj}^{veto} > p_{T,veto}, \quad \eta_j^{veto} \in (\eta_j^{\text{tag 1}}, \eta_j^{\text{tag 2}})$$

$$P_{\text{veto}} = \frac{1}{\sigma_2^{NLO}} \int_{p_{T,veto}}^{\infty} dp_{Tj}^{veto} \frac{d\sigma_3^{LO}}{dp_{Tj}^{veto}}$$

- Scale variation at LO for σ_{3j}: $+33\%$ to -17% for $p_{T,veto} = 15$ GeV
- The uncertainty in P_{veto} feeds into the uncertainty of coupling measurements at the LHC
- In order to constrain couplings more precisely, the NLO QCD corrections to $Hjjj$ are needed: T. Figy, V. Hankele, and DZ, arXiv:0710.5621 (JHEP)

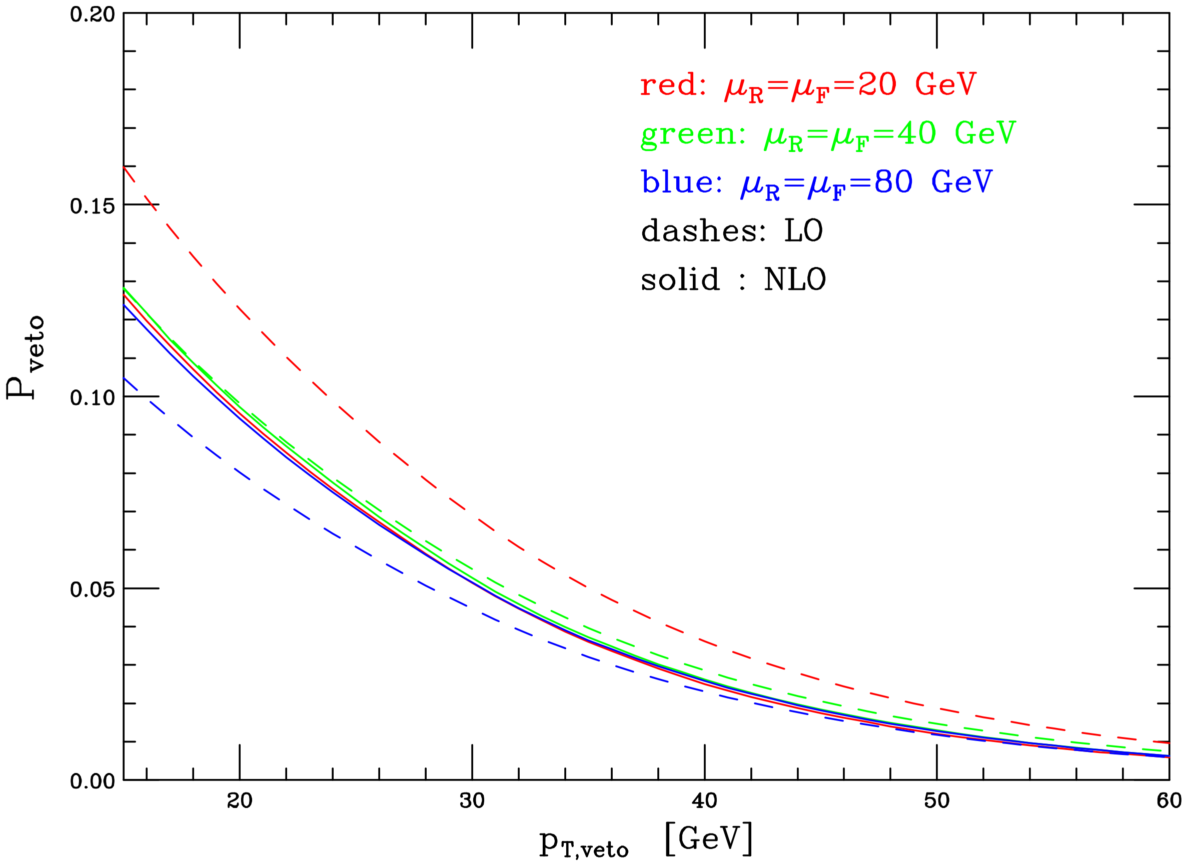
$Hjjj$ Cross Section within VBF cuts: NLO vs LO



$\mu_0 = 40$ GeV
$\xi = 2^{\mp 1}$ scale variations:

- LO: $+26\%$ to -19%
- NLO: less than 5%

Veto Probability for the VBF Signal



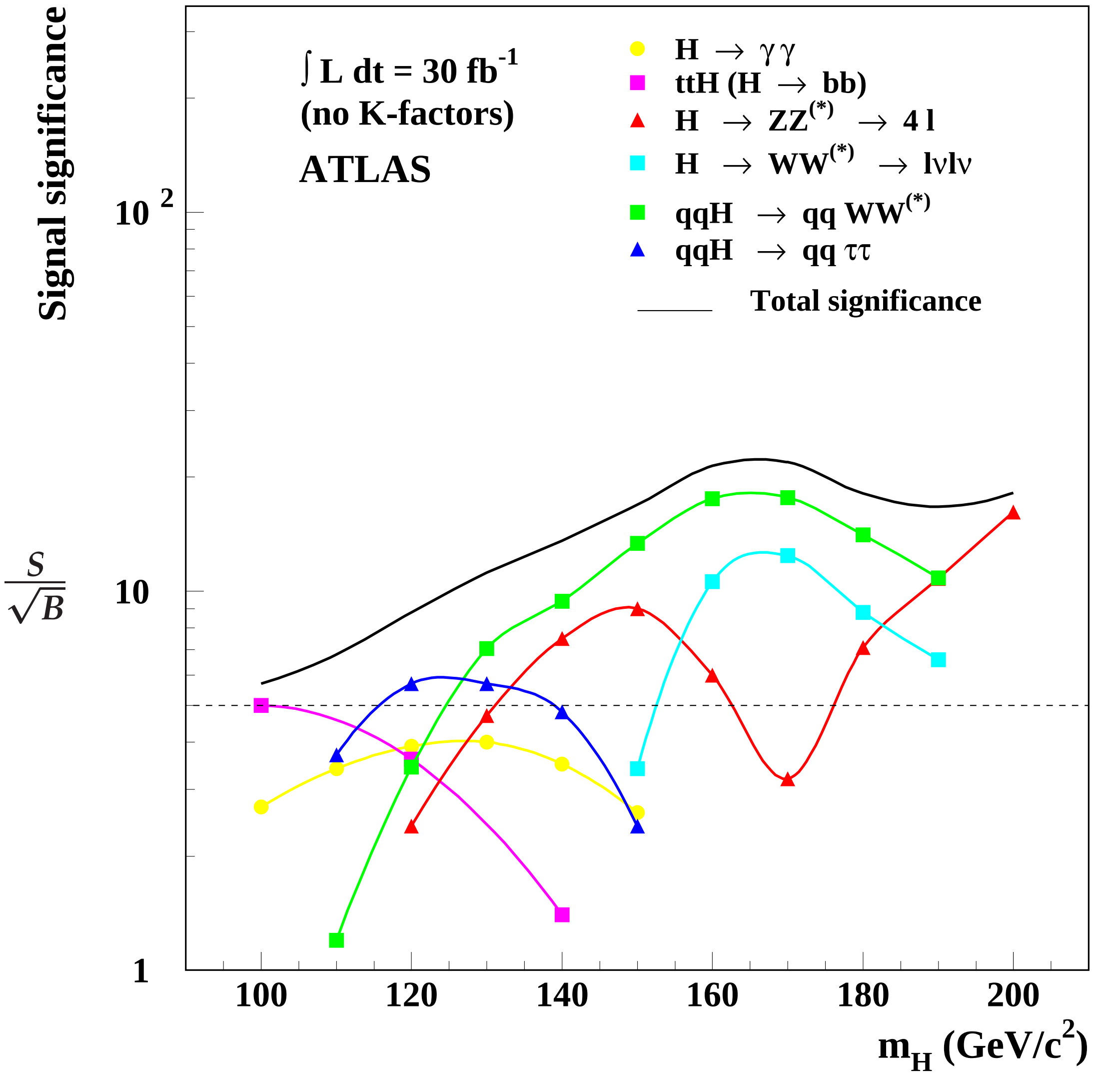
$$P_{\text{veto}} = \frac{1}{\sigma_2^{NLO}} \int_{p_{T,veto}}^{\infty} dp_{Tj}^{veto} \frac{d\sigma_3}{dp_{Tj}^{veto}}$$

Scale variations, $p_{T,veto} = 15$ GeV:

- LO: $+33\%$ to -17%
- NLO: -1.4% to -3.4%

Reliable prediction for perturbative part of veto probability at NLO

Higgs discovery potential



Associated production search channels

- $pp \to t\bar{t}H \to t\bar{t}b\bar{b}$
  for $m_H < 120$–130 GeV

- $q\bar{q} \to WH\ ,\ ZH$ New and improved: Butterworth, Davison, Rubin, Salam, arXiv:0802.2470
  trigger on leptonic decay of W or Z, look for $H \to b\bar{b}$

New idea for WH and ZH associated production: concentrate on high $p_T(H) \gtrsim 200$ GeV:

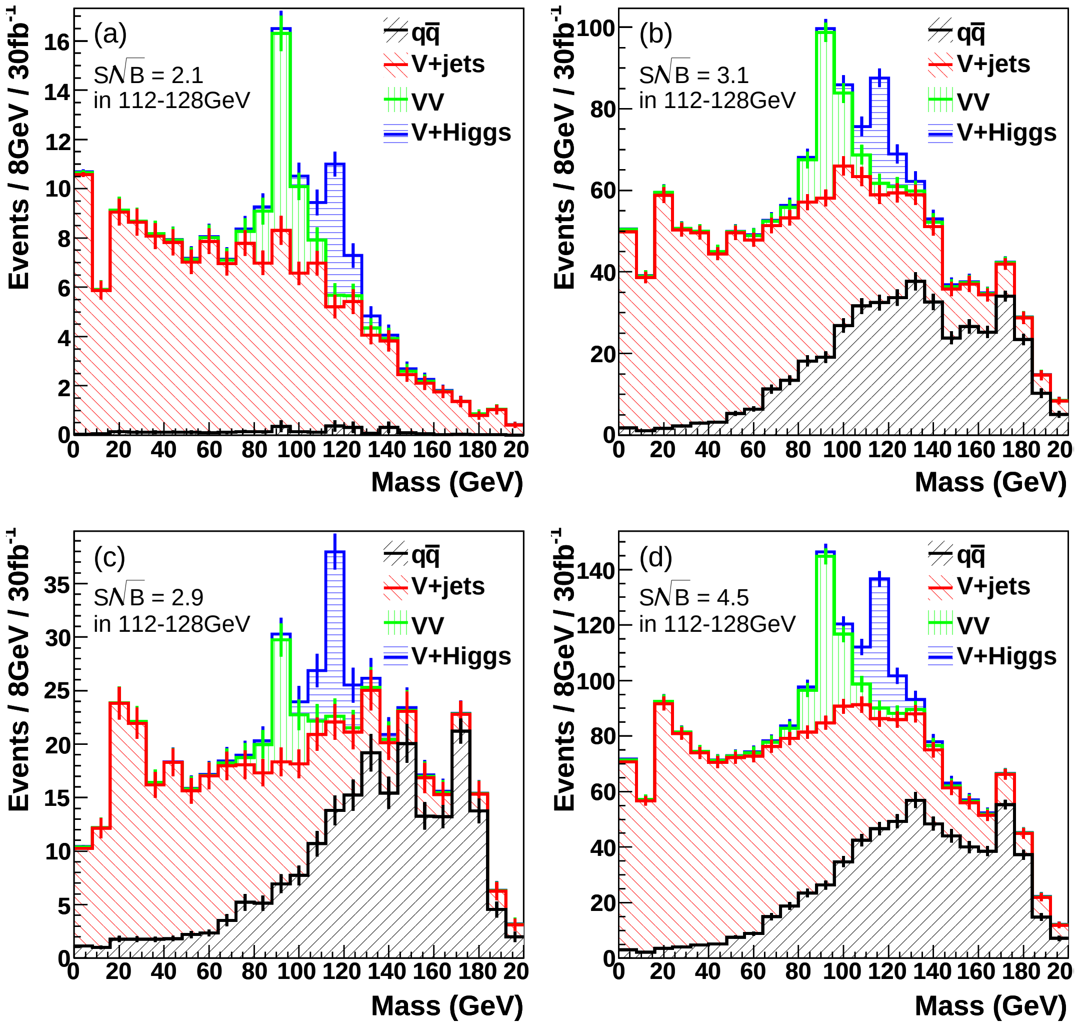
- $\Longrightarrow$ fat Higgs jet with $b\bar{b}(g)$ subjet structure
- small separation of b-quark jets from $H \to bb$ decay $\Longrightarrow$ better $b\bar{b}(g)$ invariant mass resolution
- lower background fraction than at low $p_T(H)$

Expected signal in HZ and HW at $p_T(H) > 200$ GeV

Example: $m_H = 120$ GeV, $\int Ldt = 30\ \text{fb}^{-1}$

- Need excellent b tagging and non-b rejection efficiencies (assumed: 60% and 2% respectively)
- Search in
  (a) HZ with $Z \rightarrow ll$
  (b) HZ with $Z \rightarrow \nu\nu$ and
  (c) $WH \rightarrow l\nu b\bar{b}$ samples
- Promising signal with $30\ \text{fb}^{-1}$ when combining all 3 channels

Detailed studies with full detector simulation on the way



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:

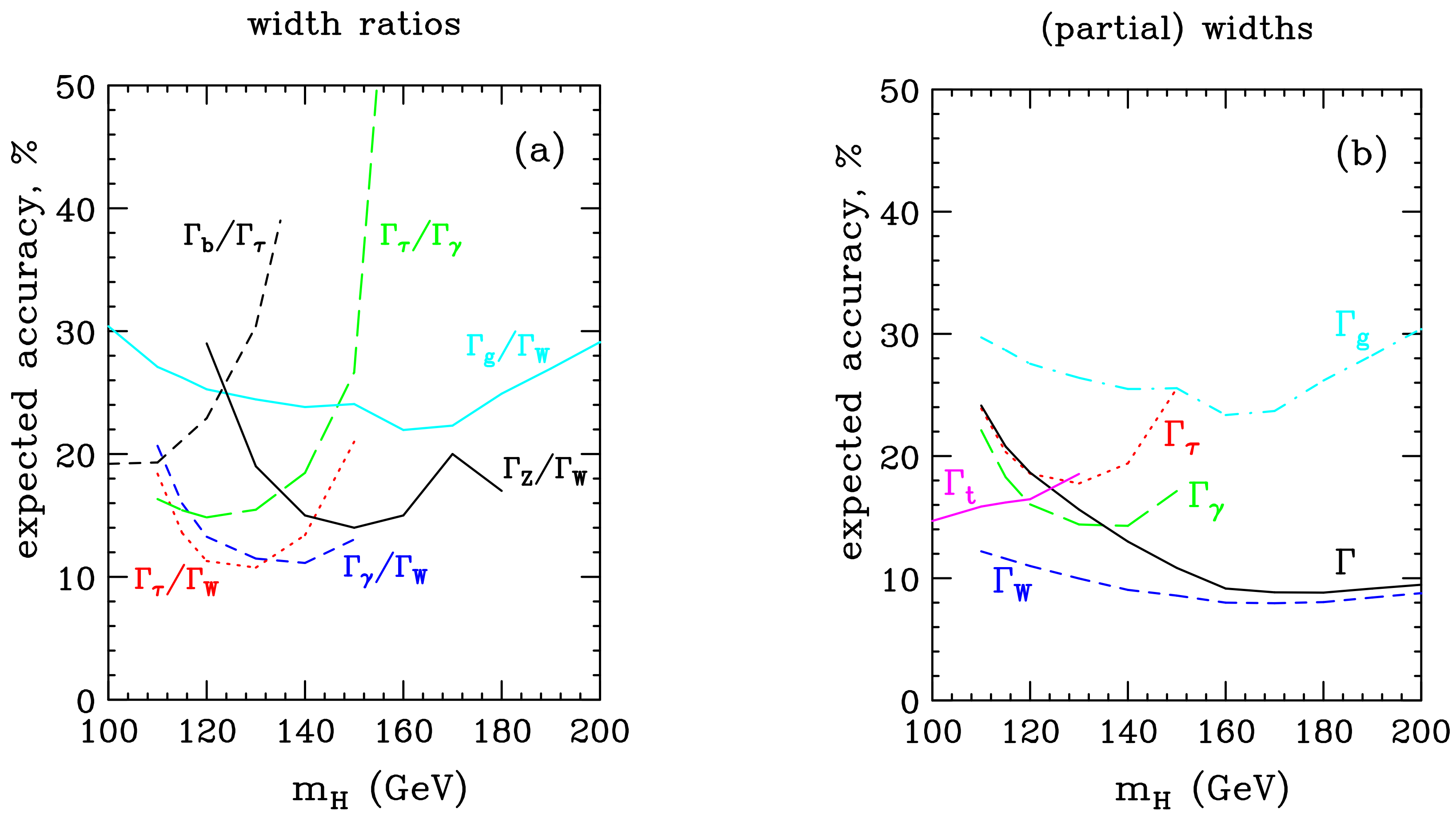
$$f^2 \Gamma > \sum_{obs.} f \Gamma_x \qquad \Longrightarrow \qquad f > \sum_{obs.} \frac{\Gamma_x}{\Gamma} = \sum_{obs.} BR(H \to xx) (= \mathcal{O}(1))$$

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

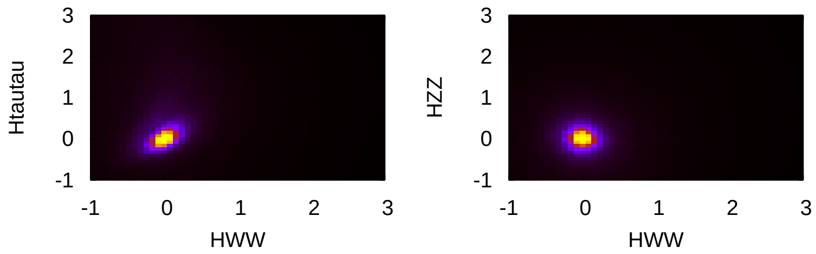
- $\frac{g_{H\tau\tau}}{g_{Hbb}} = \text{SM value}$
- $\frac{g_{HWW}}{g_{HZZ}} = \text{SM value}$
- no exotic channels



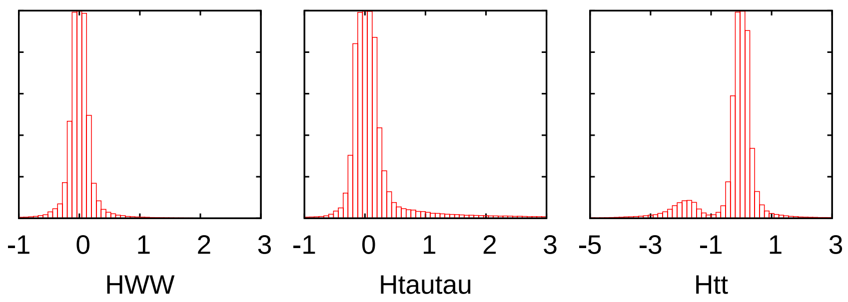
With 200 fb^{-1} measure partial width with 10–30% errors, couplings with 5–15% errors

New analysis: Lafaye et al., arXiv:0904:3866

Correlations $m_H = 120$ GeV and 300 fb^{-1}



$1/\Delta\chi^2$



- theoretical and experimental errors including correlations. Study relative errors

$$g_{Hxx} = g_{Hxx}^{SM}(1 + \Delta_{Hxx})$$

- sophisticated statistical analysis in SFitter framework
- Results for $m_H = 120$ GeV and 30 fb^{-1}

	RMS	σ_{symm}	σ_{neg}	σ_{pos}
Δ_{WWH}	± 0.31	± 0.23	-0.21	$+0.26$
Δ_{ZZH}	± 0.49	± 0.36	-0.40	$+0.35$
$\Delta_{t\bar{t}H}$	± 0.58	± 0.41	-0.37	$+0.45$
$\Delta_{b\bar{b}H}$	± 0.53	± 0.45	-0.33	$+0.56$
$\Delta_{\tau\bar{\tau}H}$	± 0.47	± 0.33	-0.21	$+0.46$

Corrections for Higgs production cross sections

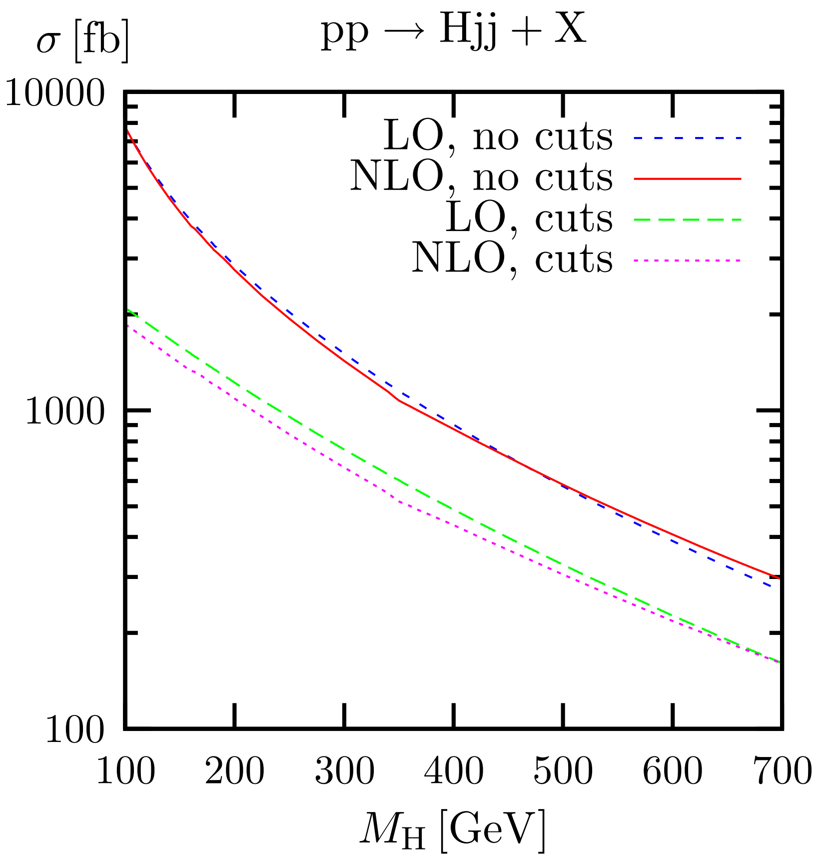
Measurement of partial widths at 10–20% level or couplings at 5–10% level requires predictions of SM production cross sections at 10% level or better

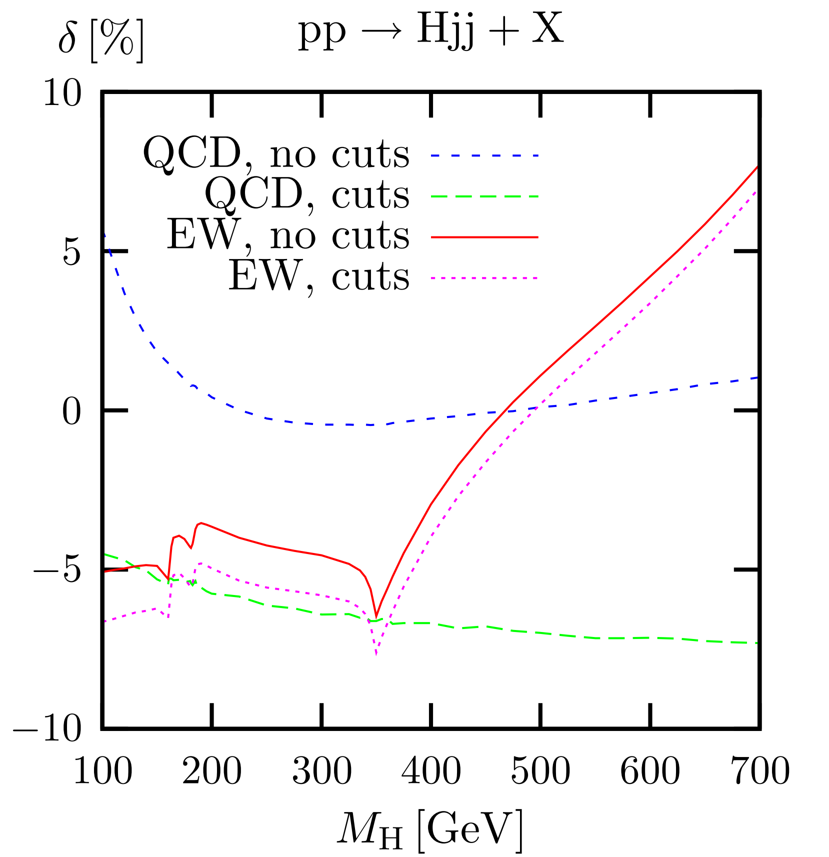
$\Longrightarrow$ need QCD corrections to production cross sections. Much progress in recent years

- $gg \to H$ (all but NLO in $m_t \to \infty$ limit)
  - NNLO: Harlander, Kilgore (2001); Anastasiou, Melnikov (2002); Ravindran, Smith, van Neerven (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)
  - 1-loop EW corrections: Ciccolini, Denner, Dittmaier (2007)
  - approx. NLO QCD to $Hjjj$: Figy, Hankele, D.Z (2007)
- $\bar{t}tH$ 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 + EW corrections to Hjj production

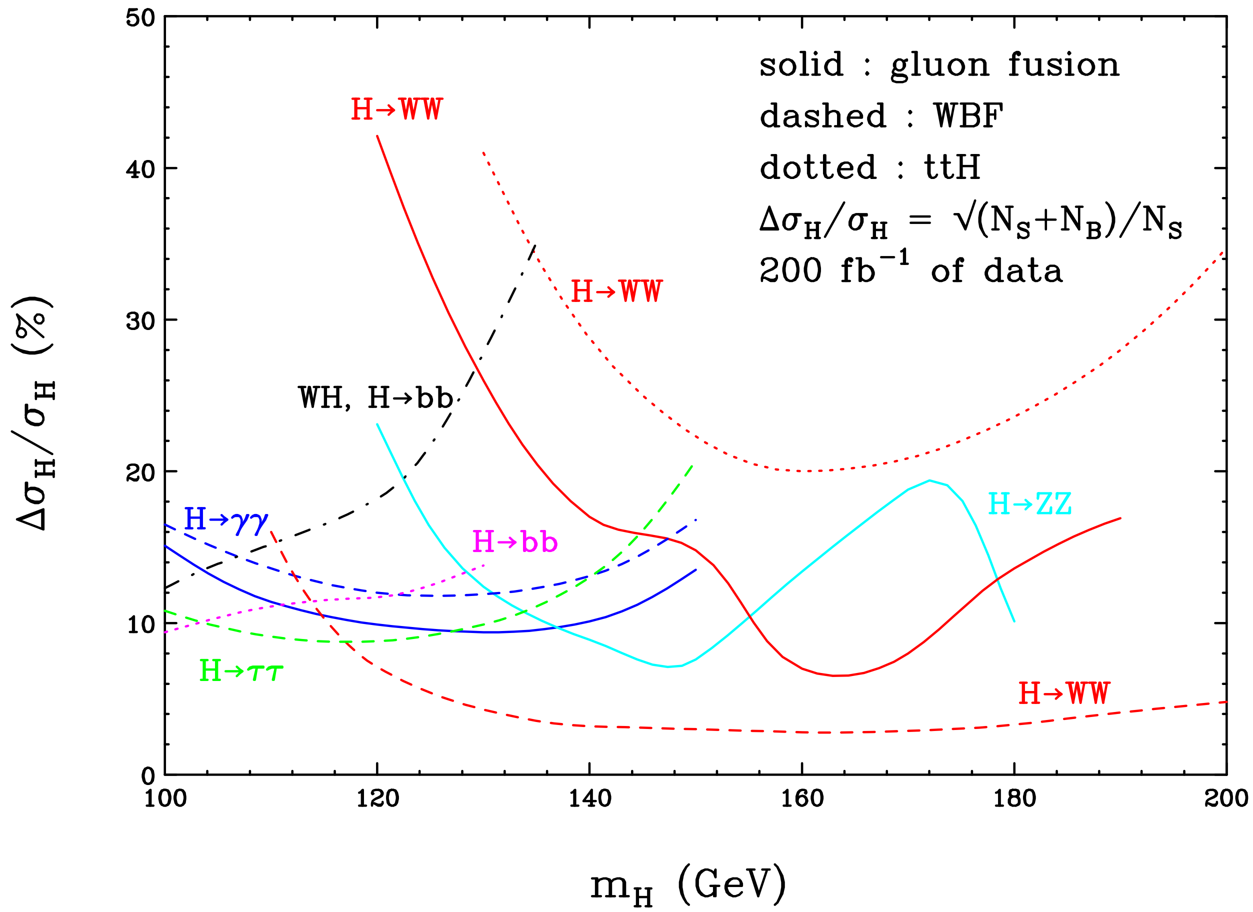
Cross sections without and with VBF cuts: $p_T(j) > 20$ GeV $\quad |y_{j_1} - y_{j_2}| > 4, \;\; y_{j_1} \cdot y_{j_2} < 0$





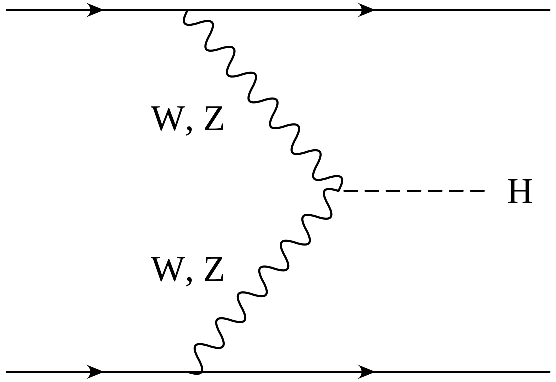
Ciccolini, Denner, Dittmaier, arXiv:0710.4749

Statistical and systematic errors at LHC: snapshot from 2003 for expected SM Higgs rate

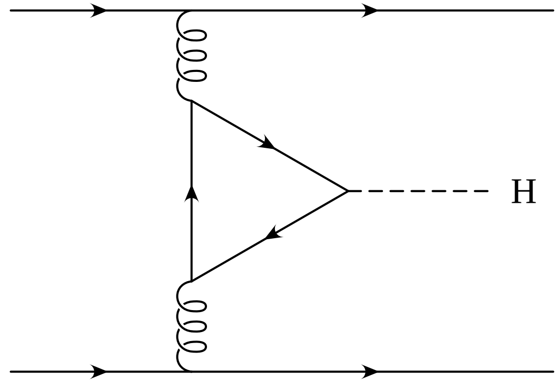


- expected experimental errors on rates
  - ±10 – 20% is typical
  - perhaps ±5% achievable for VBF if measurable at high lumi
- QCD/PDF uncertainties
  - ±5% for VBF
  - ±10% for gluon fusion

How to distinguish VBF and gluon fusion?



vs.



(a)

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

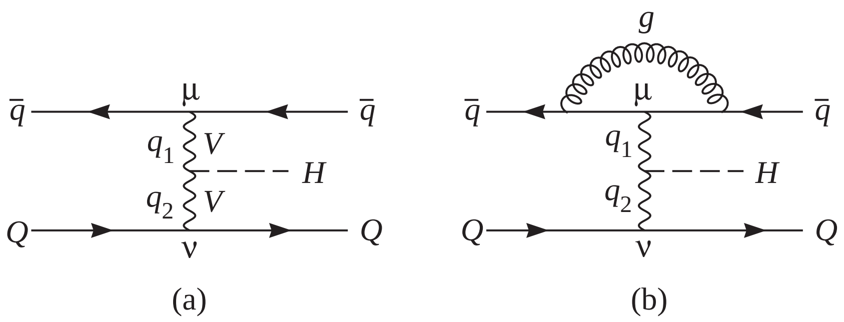
$\Longrightarrow$ we need to investigate the phenomenology of these two processes and understand the differences that can be exploited to distinguish between gluon fusion and VBF

$\Longrightarrow$ 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

Tensor structure of the HVV coupling

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



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

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

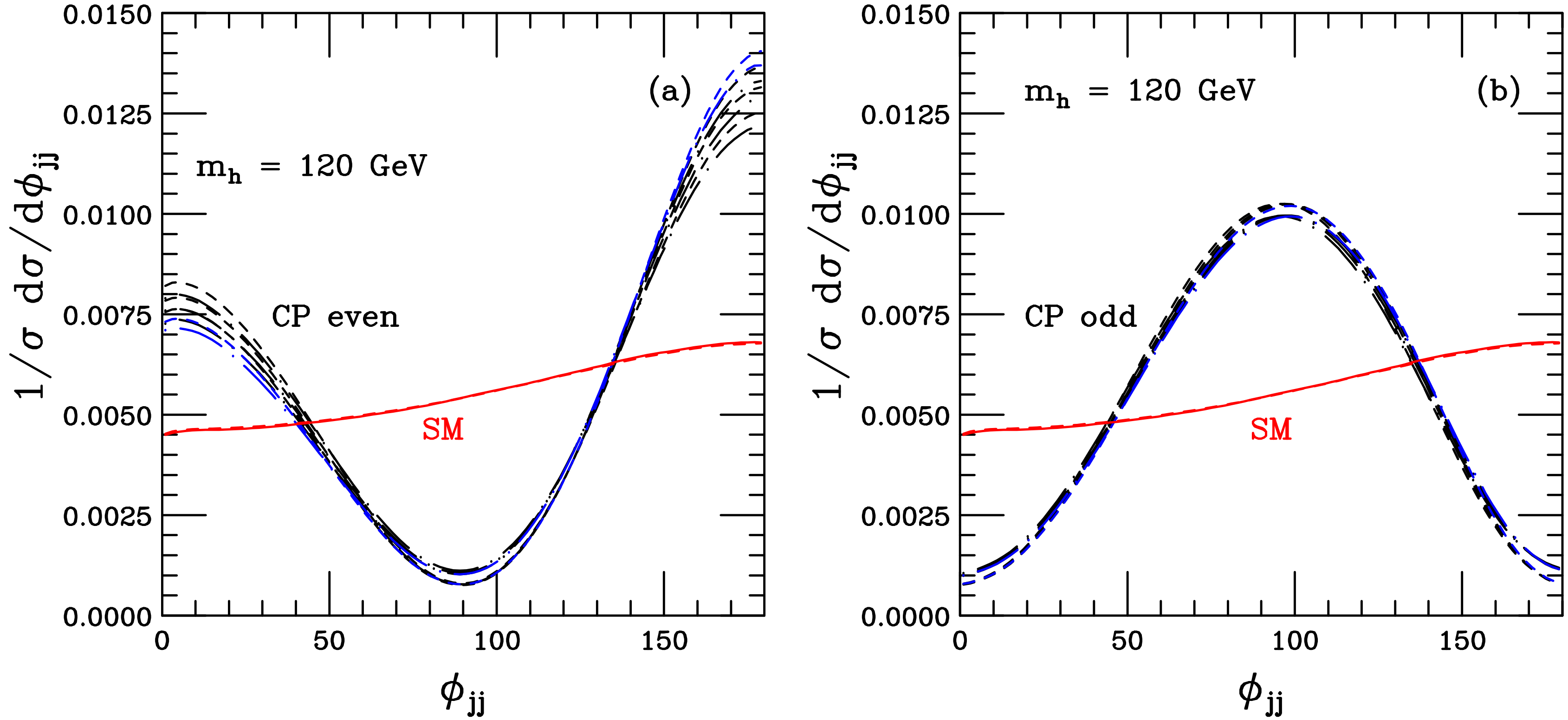
CP even $\quad \mathcal{L}_{eff} \sim H V_{\mu\nu} V^{\mu\nu} \longrightarrow a_2$

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

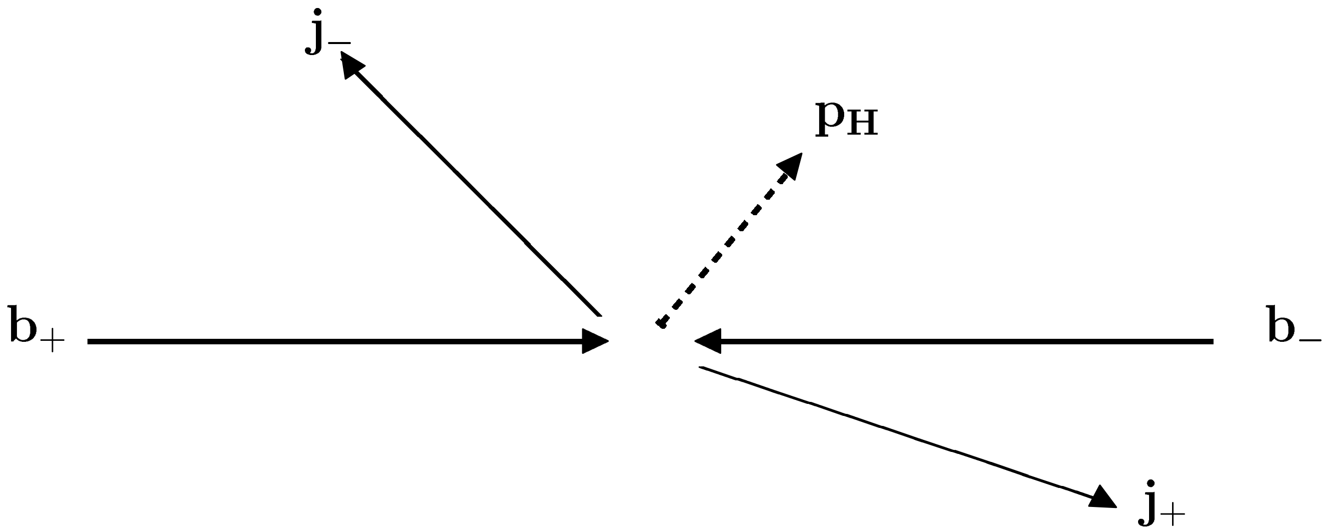
Tell-tale signal for non-SM coupling is azimuthal angle between tagging jets



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:

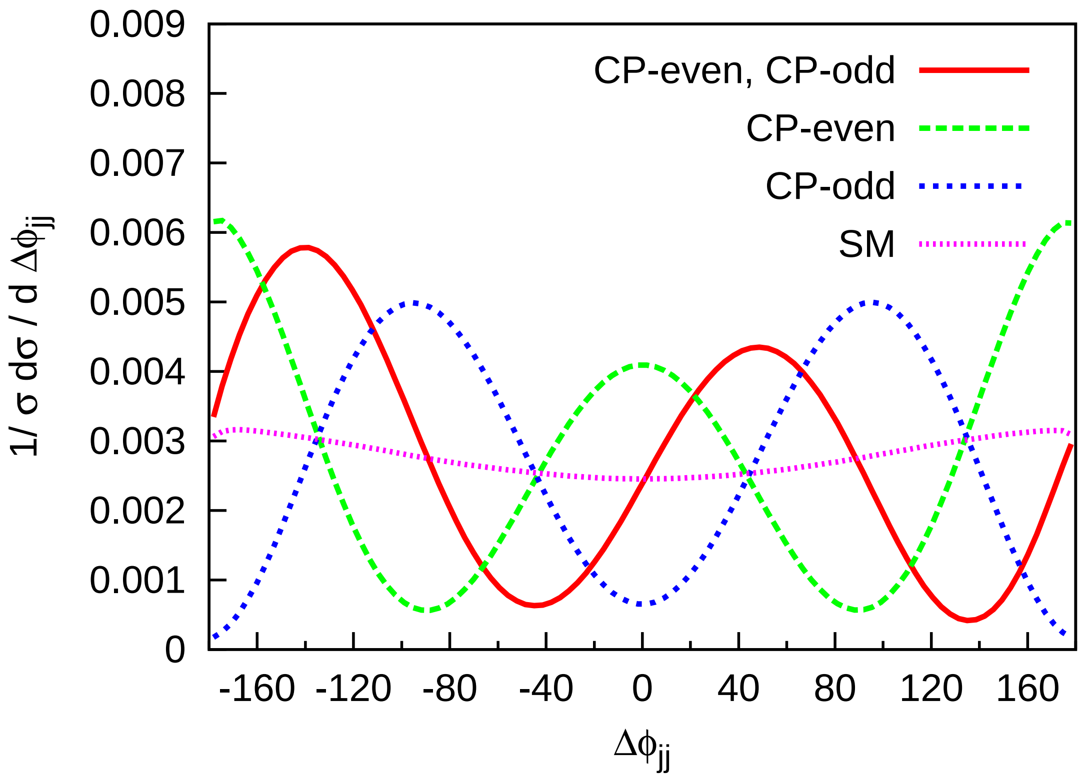


Define azimuthal angle between jet momenta j_+ and j_- via

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

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

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 $\pi - \alpha$

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 Φgg couplings from top quark triangles and lead to effective Lagrangians

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

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

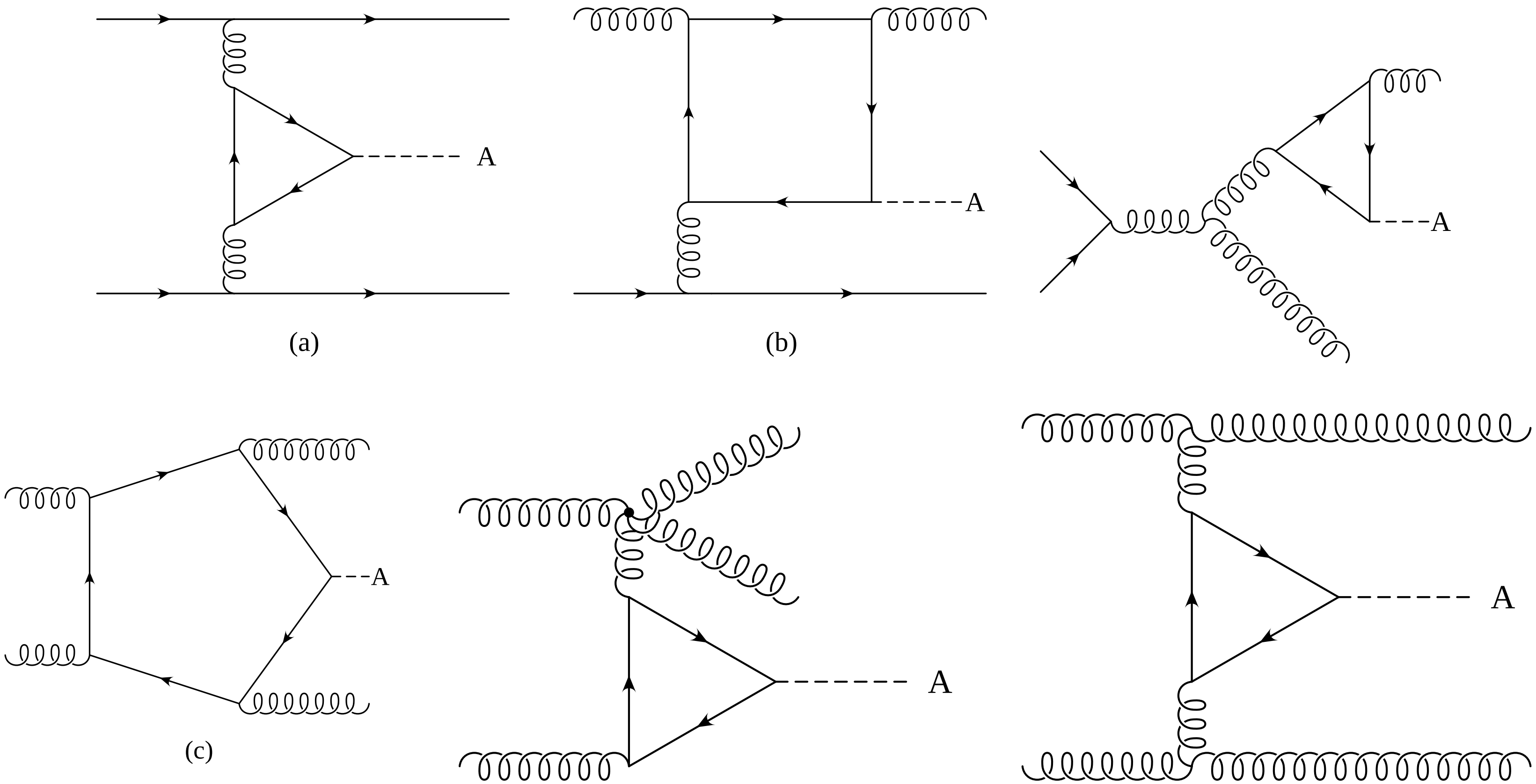
- Study gluon fusion induced Φjj events to distinguish CP-even and CP-odd couplings

Effective Lagrangian and full top and bottom loops implemented in VBFNLO:
parton level Monte Carlo for Hjj, Wjj, Zjj, W^+W^-jj, $ZZjj$, VVV production by Bozzi, Figy, Hankele, Jäger, Klämke, Kubocz, Oleari, Worek, DZ, ...

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

Feynman graphs for (pseudo)scalar Higgs production

$pp \to \Phi jjX$ including top and bottom loops + interference



Gluon Fusion as a signal channel

Heavy quark loop induces effective Hgg vertex:

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

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

Azimuthal angle between tagging jets probes difference

- Use gluon fusion induced Φjj signal to probe structure of Hgg vertex
- Find cuts to enhance gluon fusion over VBF and other backgrounds

$\Longrightarrow$ Study by Gunnar Klämke in $m_Q \rightarrow \infty$ 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

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

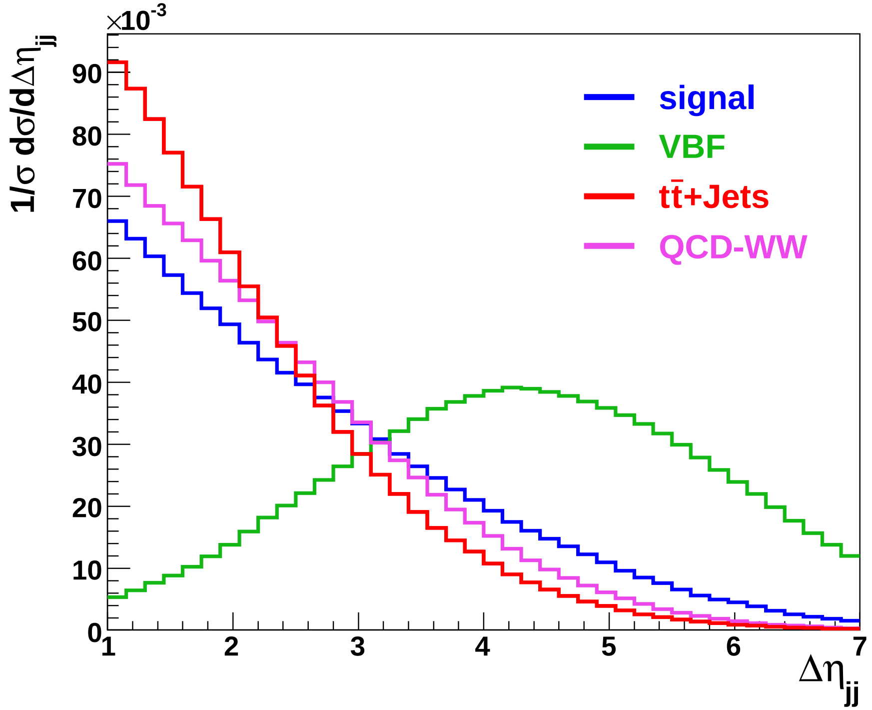
- separation of jets and leptons

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

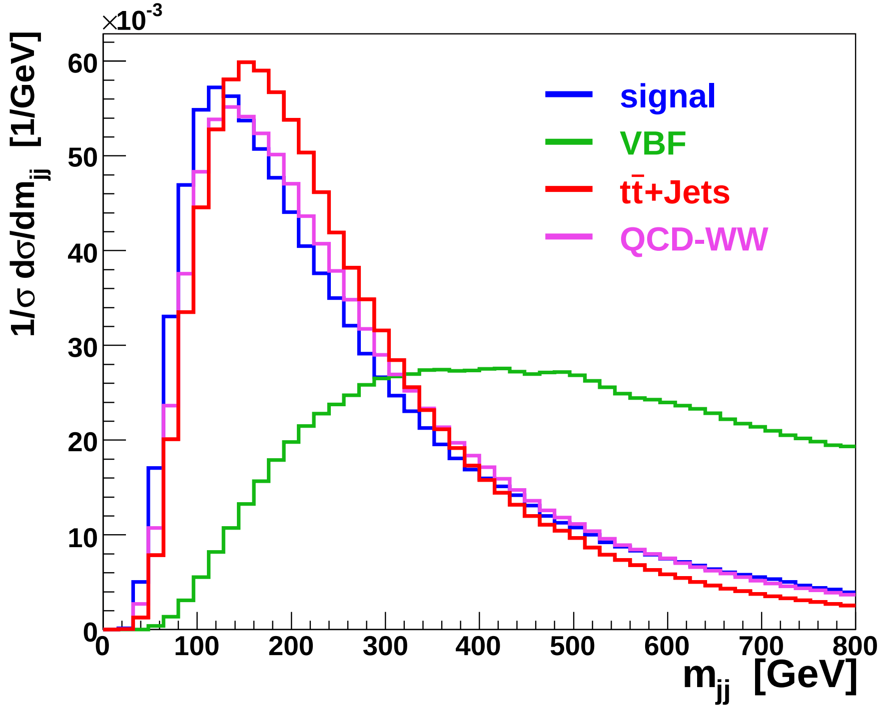
process	σ [fb]
GF $pp \to H + jj$	**115.2**
VBF $pp \to W^+W^- + jj$	**75.2**
$pp \to t\bar{t}$	**6832**
$pp \to t\bar{t} + j$	**9518**
$pp \to t\bar{t} + jj$	**1676**
QCD $pp \to W^+W^- + jj$	**363**

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

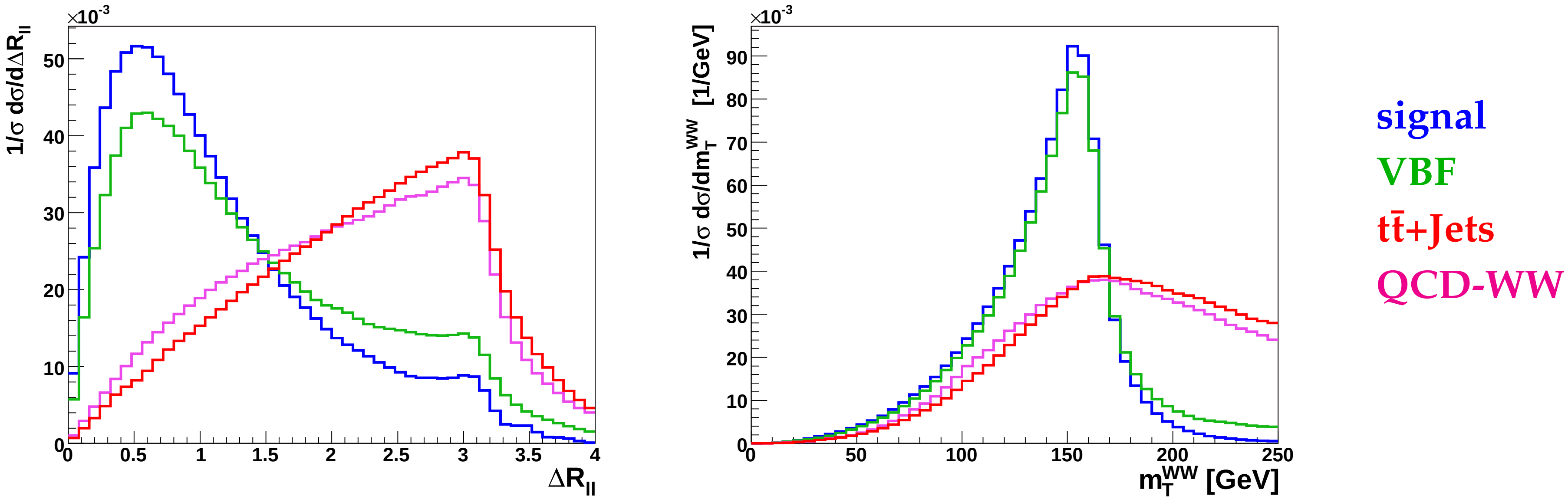
Selection continued

- 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:

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

$M_T^{WW} < 170\,\mathrm{GeV}, \quad \not{p}_T > 30\,\mathrm{GeV} \qquad M_T^{WW} = \sqrt{(\not{E}_T + E_{T_{ll}})^2 - (\vec{p}_{T_{ll}} + \vec{\not{p}}_T)^2}$



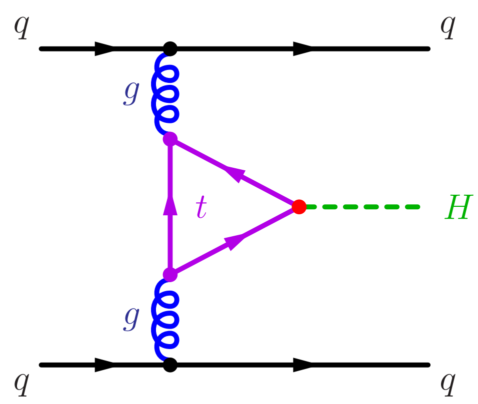
Results

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**

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

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

SM case with $m_H = 120$ GeV

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

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

process	σ [fb]	events / 600 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**

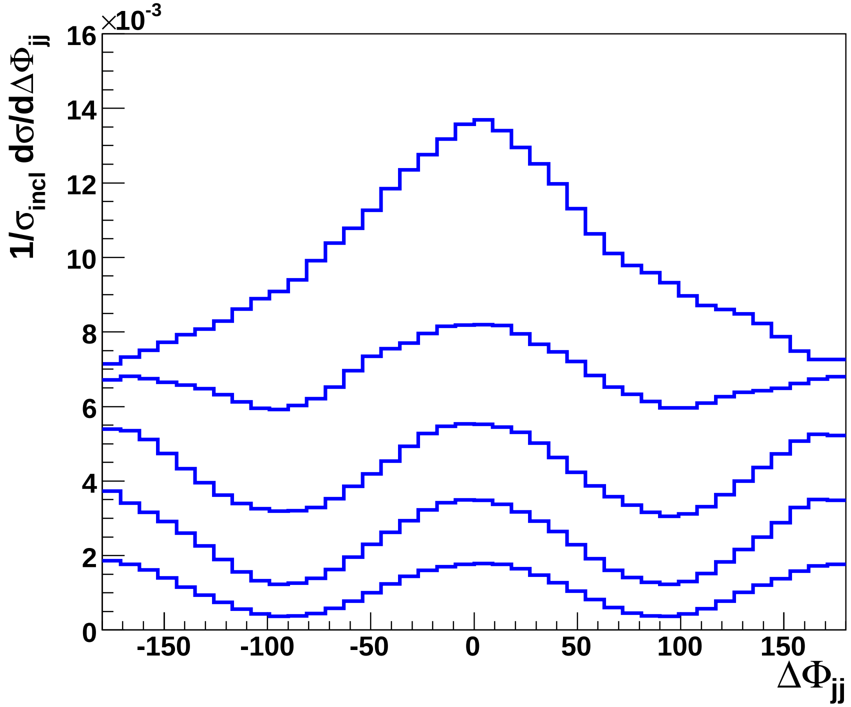
for cp-even higgs: $S/\sqrt{B} \approx 17$ (600 fb^{-1})
this corresponds to: $S/\sqrt{B} \approx 5$ (50 fb^{-1})

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

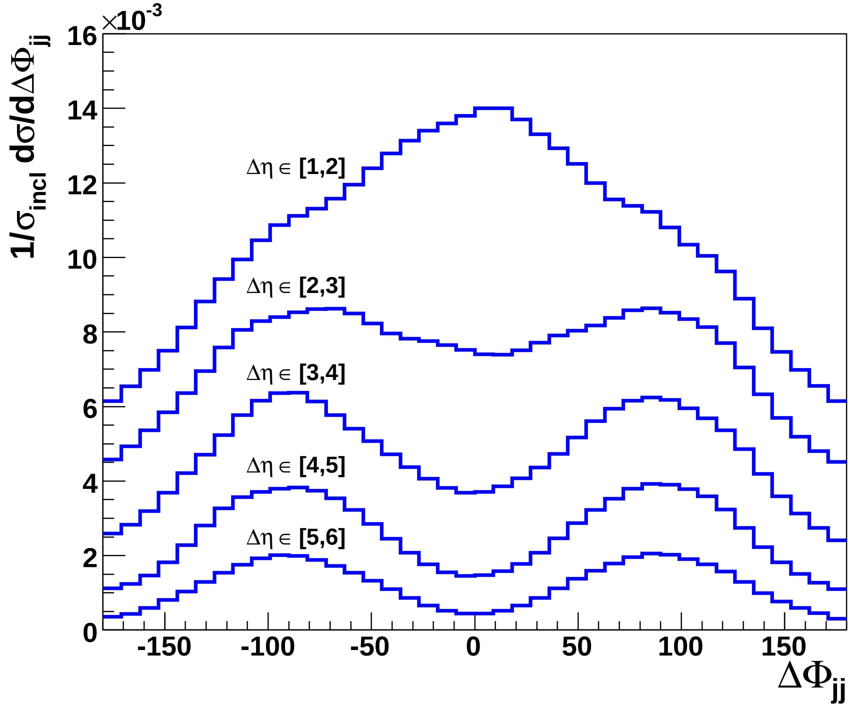
Sensitivity of gluon fusion to structure of Hgg vertex

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

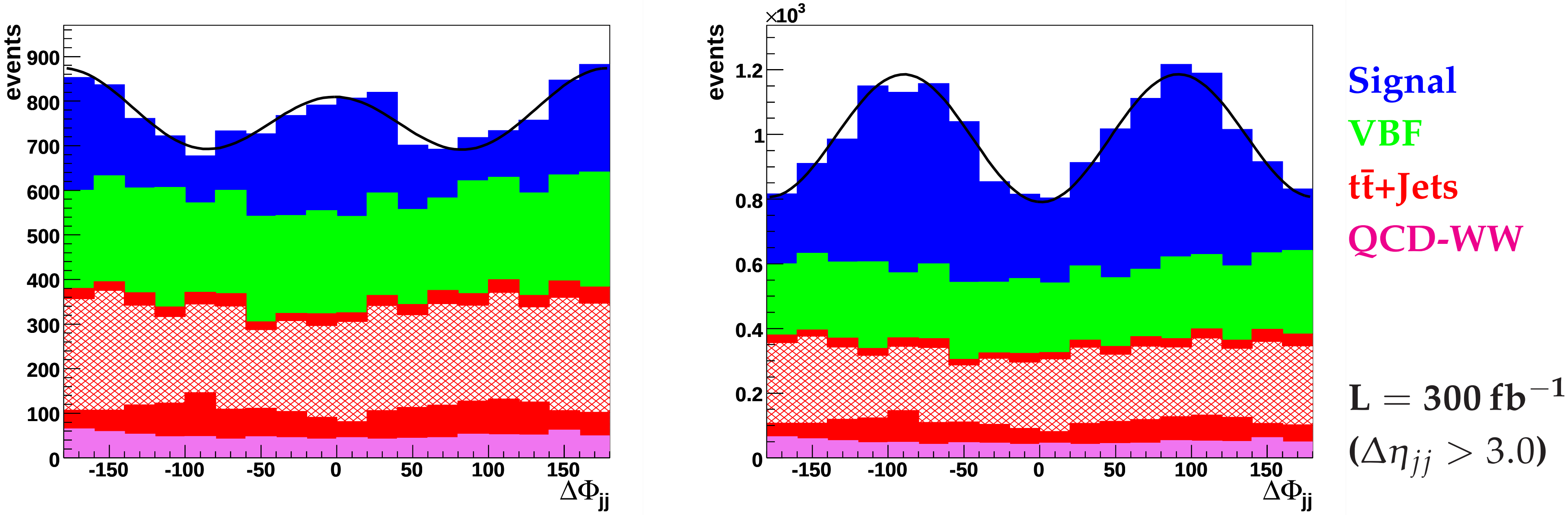


CP-odd coupling



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

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

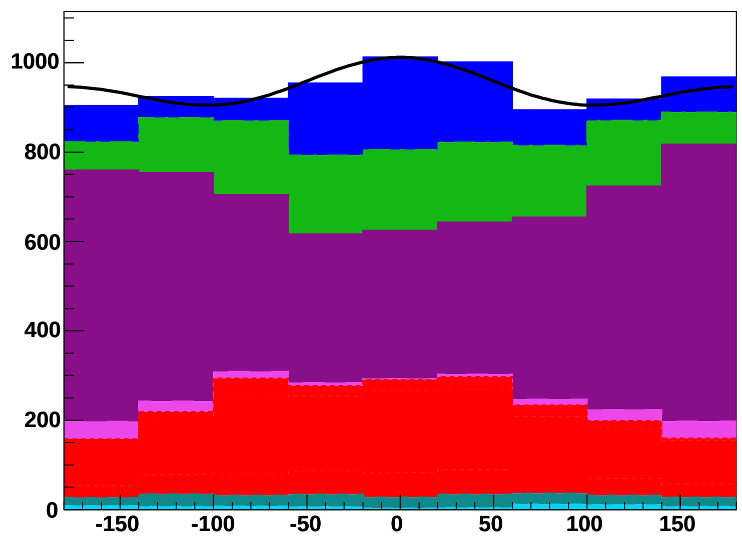


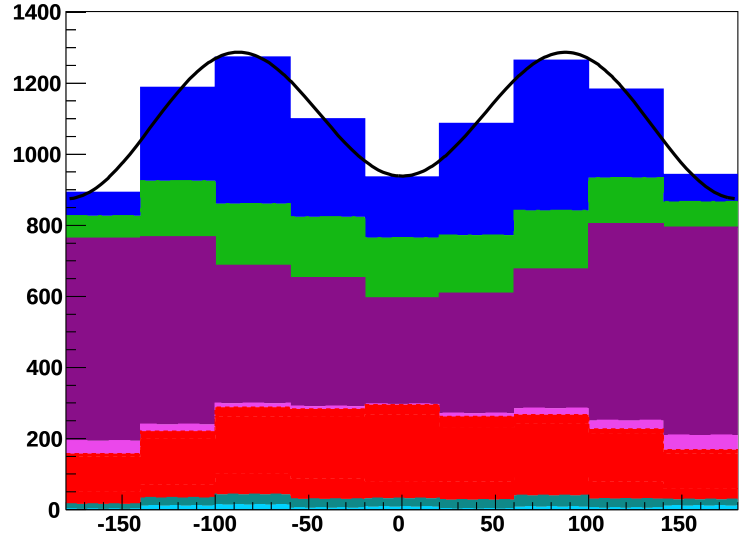
CP-even	CP-odd
$A = 0.100 \pm 0.039$	$A = 0.199 \pm 0.034$
$\Delta\Phi_{max} = 5.8 \pm 15.3$	$\Delta\Phi_{max} = 93.7 \pm 5.1$

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)

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

Fit to Φ_{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 $= 600\,\text{fb}^{-1}$
($\Delta\eta_{jj} > 3.0$)

CP-even

$A = 0.004 \pm 0.015$

CP-odd

$A = -0.161 \pm 0.014$

fit of the background only : -0.043 ± 0.016

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

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
- Gauge boson fusion processes provide important facets of this information, both on absolute values of couplings but also on their tensor structure.
- Loop corrections on signal processes provide SM predictions with 10% accuracy or better.
- Beside weak boson fusion also the gluon fusion process $pp \to Hjj$ is an interesting analysis channel which deserves more work.
- Higgs boson CP properties and structure of the HVV and Hgg vertices from jet-angular correlations in VBF and gluon fusion