Gauge Boson Fusion Processes at the LHC

Dieter Zeppenfeld
Universität Karlsruhe

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- Introduction
- VBF Higgs Production
- QCD corrections to VBF
- Central Jet Veto at NLO
- 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 $\Phi^\dagger \to (0, \frac{v+H}{\sqrt{2}})$

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

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

- 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

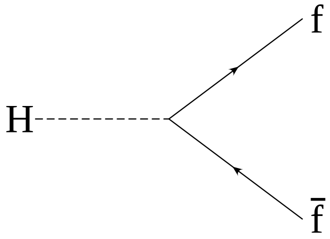
Kinetic energy term of Higgs doublet field:

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

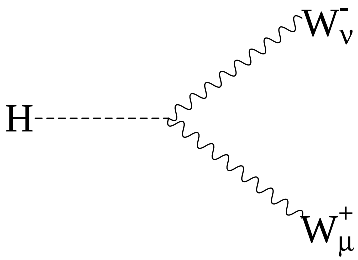
- W, Z mass generation: $m_W^2 = \left(\frac{gv}{2}\right)^2$, $m_Z^2 = \frac{(g^2+g'^2)v^2}{4}$
- WWH and ZZH couplings are generated
- Higgs couples propotional to mass: coupling strength $= 2\, m_V^2/v \sim g^2 v$ within SM

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

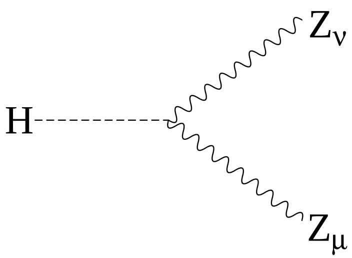
Feynman rules



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



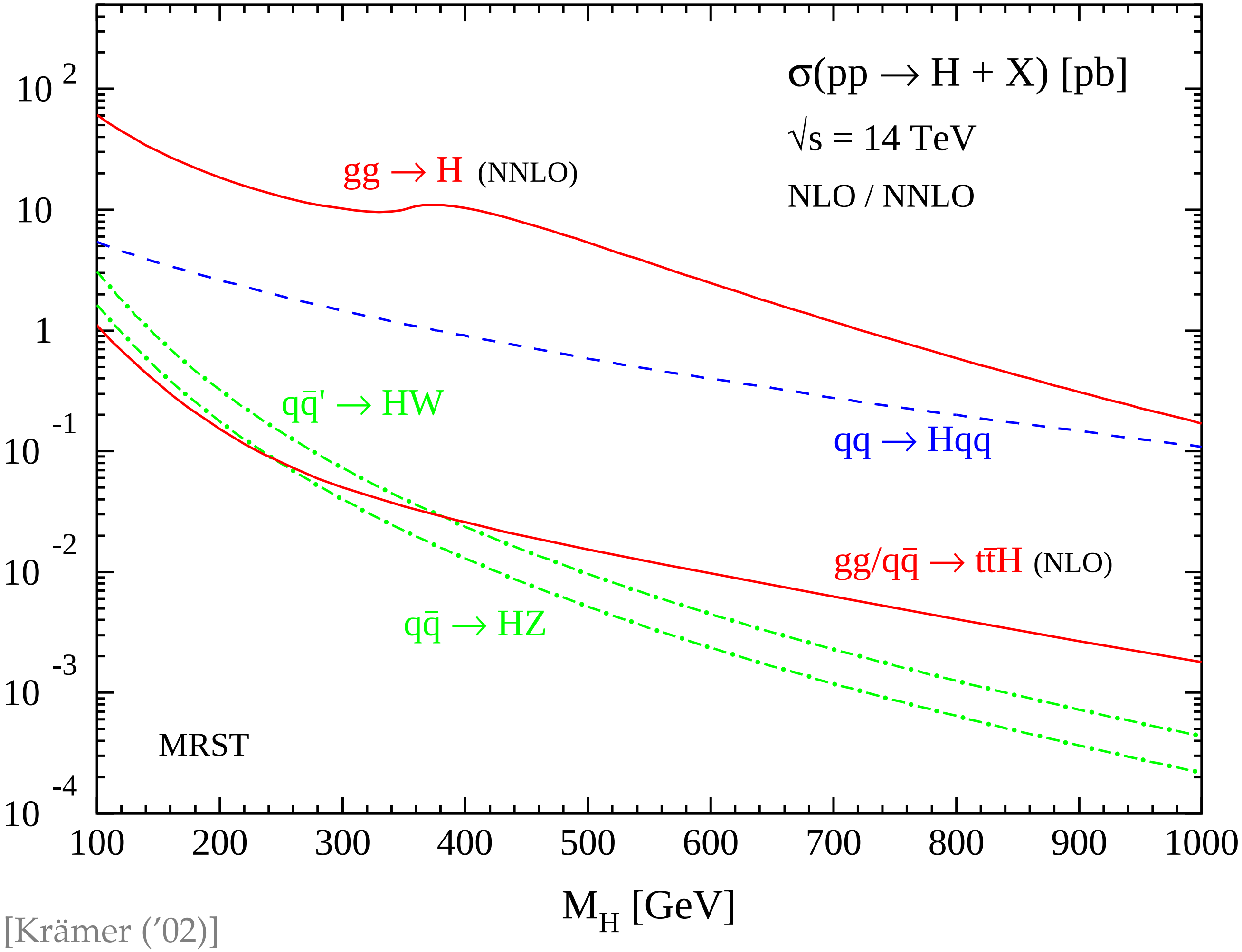
$$ig\, m_W\, g_{\mu\nu}$$

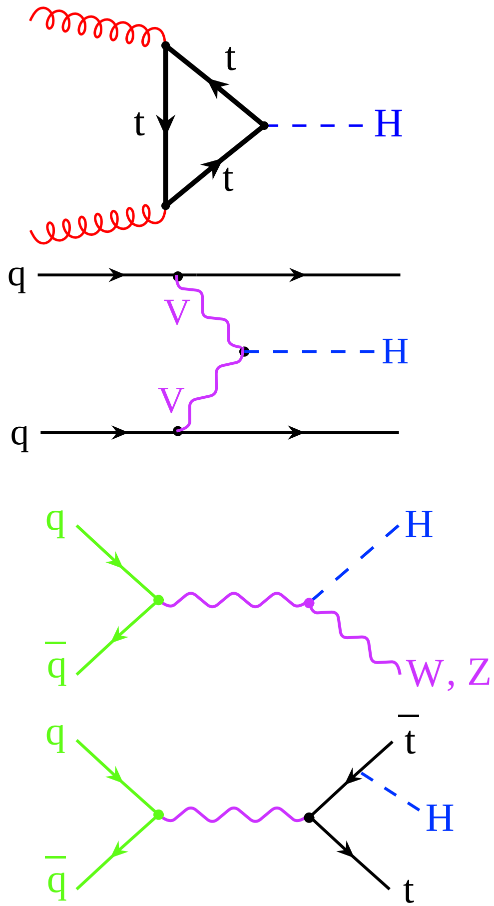


$$i\, g\, \frac{1}{\cos\theta_W}\, m_Z\, g_{\mu\nu}$$

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

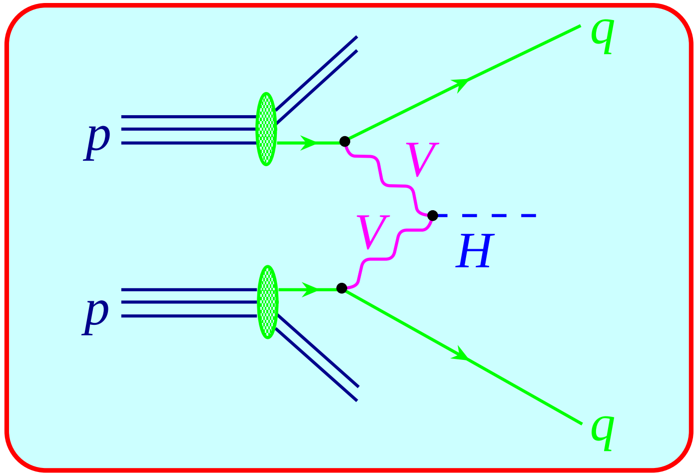
Total cross sections at the LHC

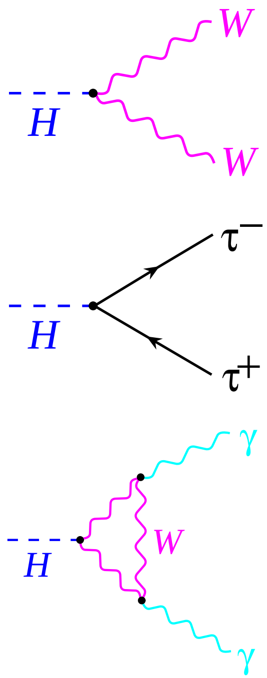




[Krämer ('02)]

Vector Boson Fusion (VBF)





$m_H > 120$ GeV

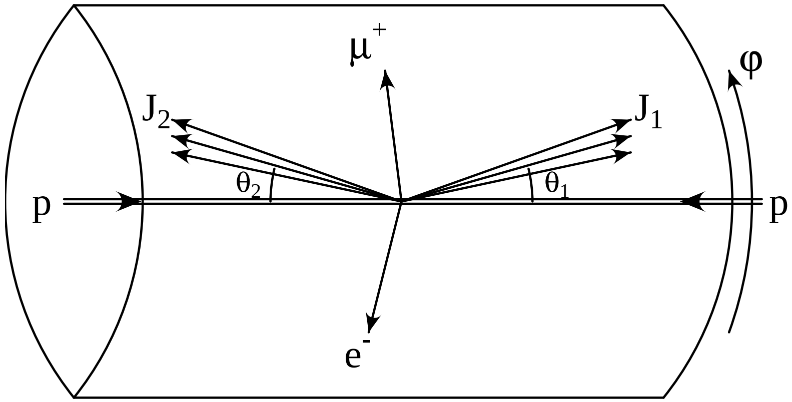
$m_H < 140$ GeV

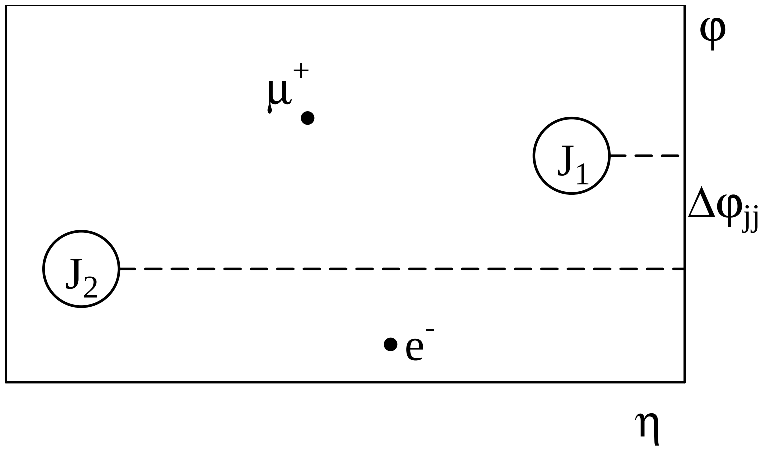
$m_H < 150$ GeV

[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:

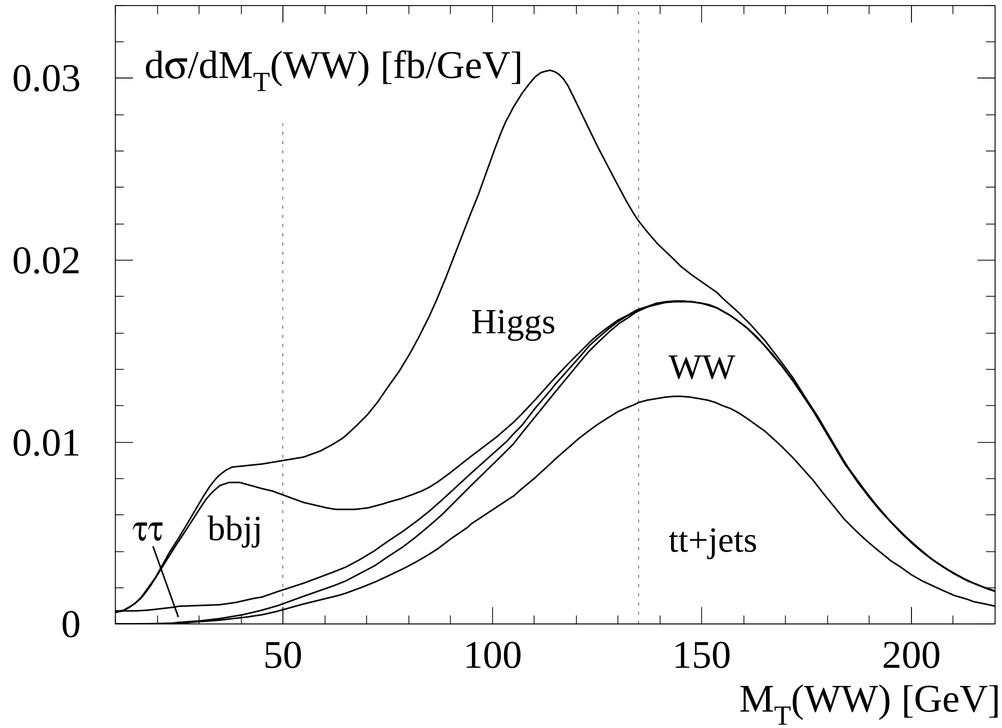
$$E_{T,ll} = \sqrt{\mathbf{p}^2_{T,ll} + m^2_{ll}}$$

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

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

Observe Jacobian peak below $M_T = m_H$

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

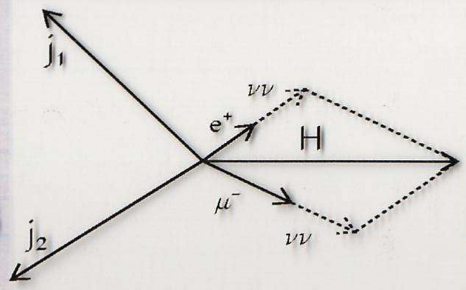


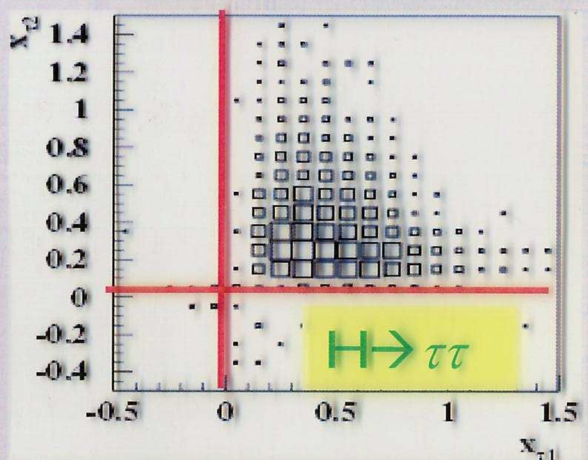
Transverse mass distribution for $m_H = 115$ GeV and $H \to WW^* \to e^\pm \mu^\mp \not{p}_T$

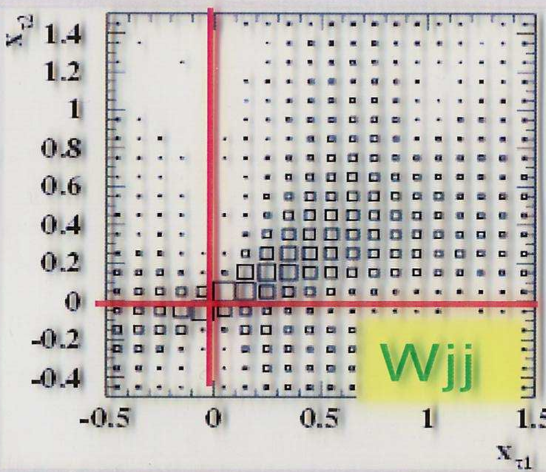
Weak Boson Fusion: $H \to \tau\tau$

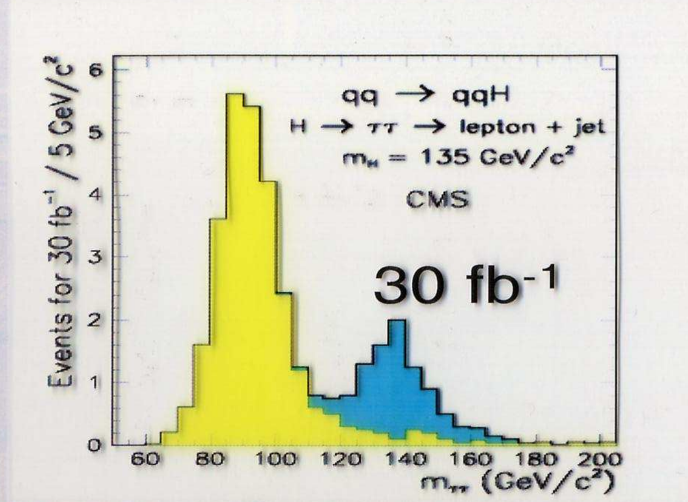
Mass can be reconstructed in collinear approximation

x_τ = momentum fraction carried by tau decay products









$\sigma_M =$ 11 to 12 GeV

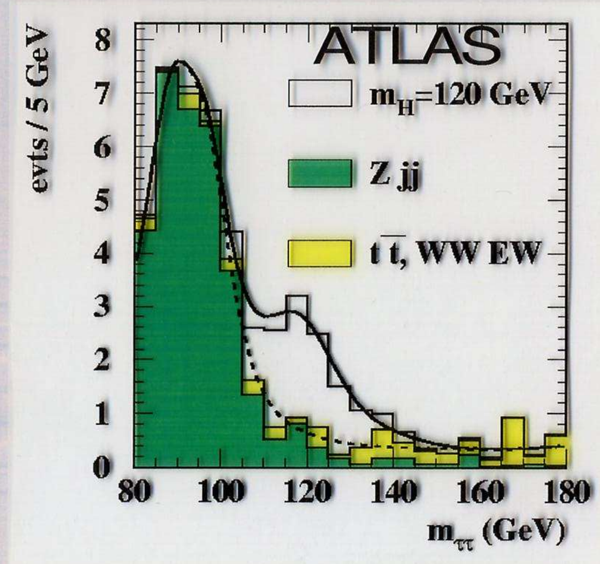
★ significance > 5 for 30 fb^{-1} and

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

★ background estimate: ~10%

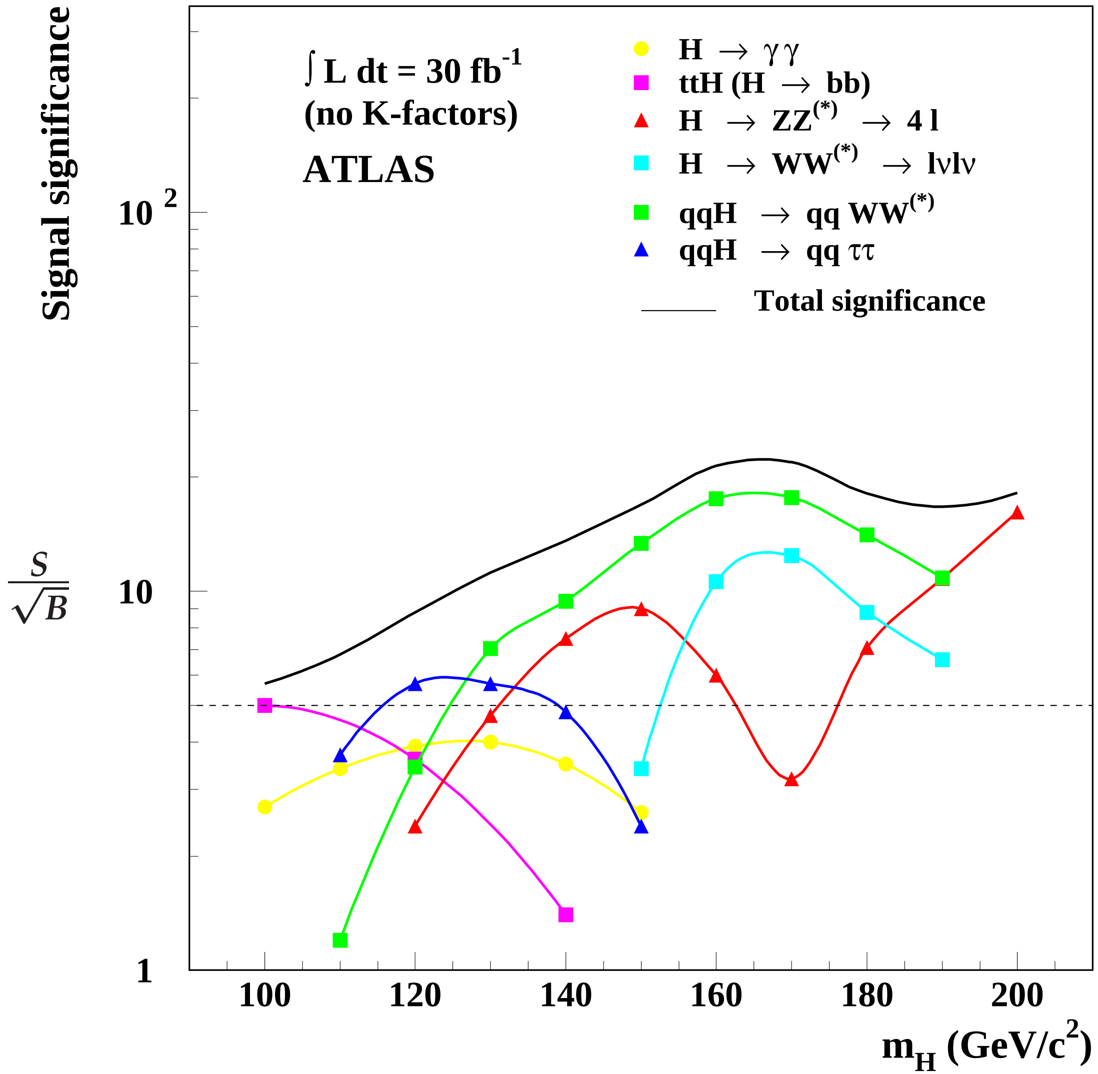
for M_H>125 GeV from side bands

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



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

Higgs discovery potential



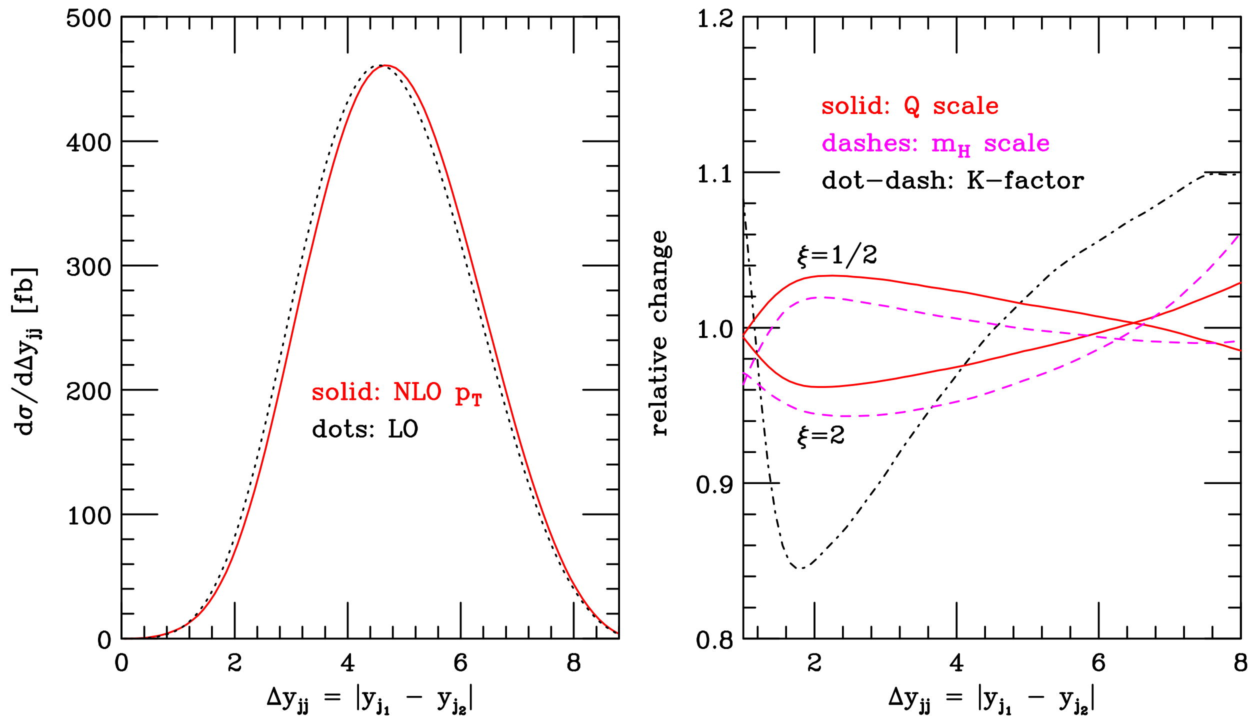
Corrections for Higgs production cross sections

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)

NLO QCD corrections to VBF

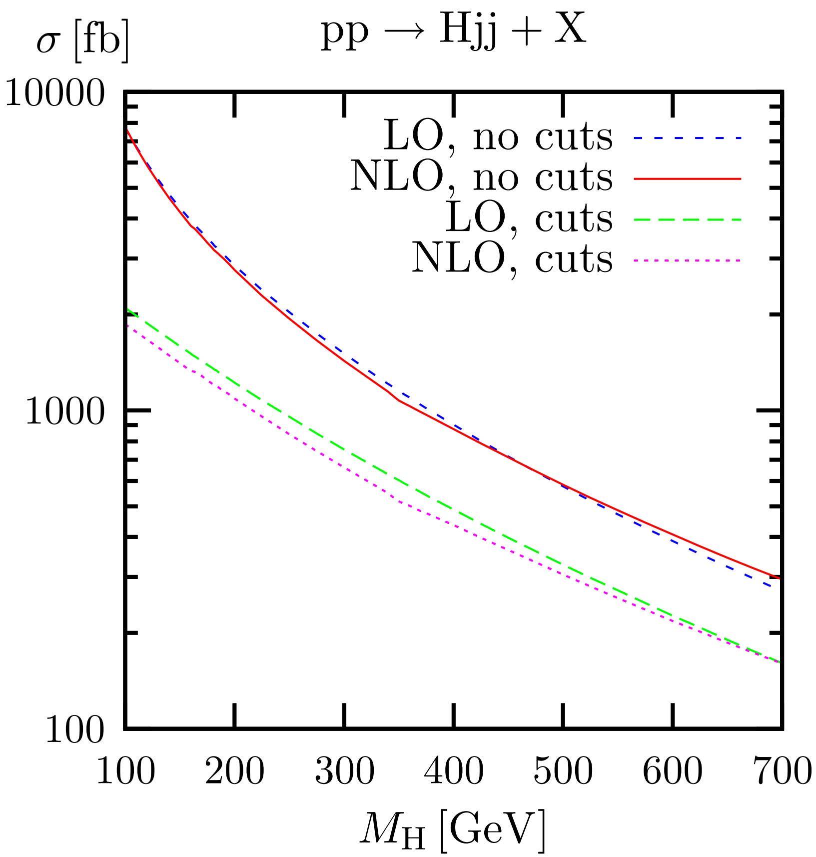
- ✓ Small QCD corrections of order 10%
- ✓ Tiny scale dependence of NLO result
  - - ±5% for distributions
  - - $< 2\%$ for σ_{total}
- ✓ K-factor is phase space dependent
- ✓ QCD corrections under excellent control
- ✗ Need electroweak corrections for 5% uncertainty

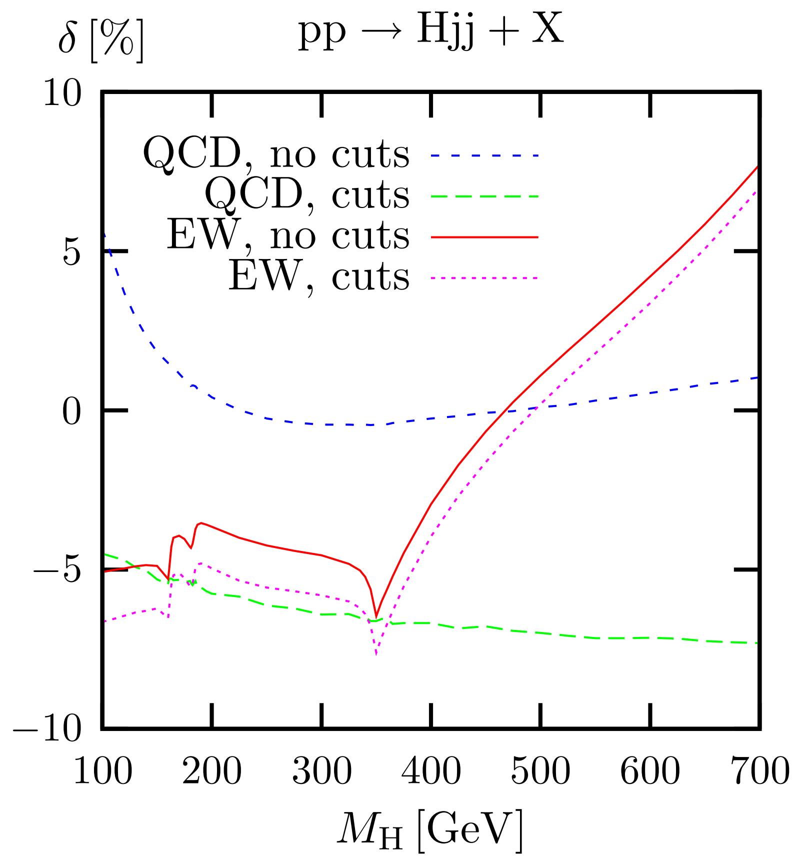


$m_H = 120\,\text{GeV}$, typical VBF cuts

QCD + EW corrections to Hjj production

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





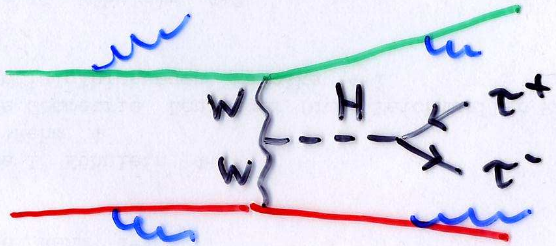
Ciccolini, Denner, Dittmaier, arXiv:0710.4749

Central jet veto

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

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

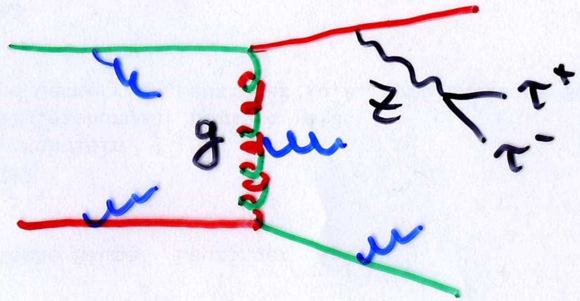
- t-channel color singlet exchange



"synchrotron" radiation between initial and final quark direction

$\Rightarrow$ central jets suppressed

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

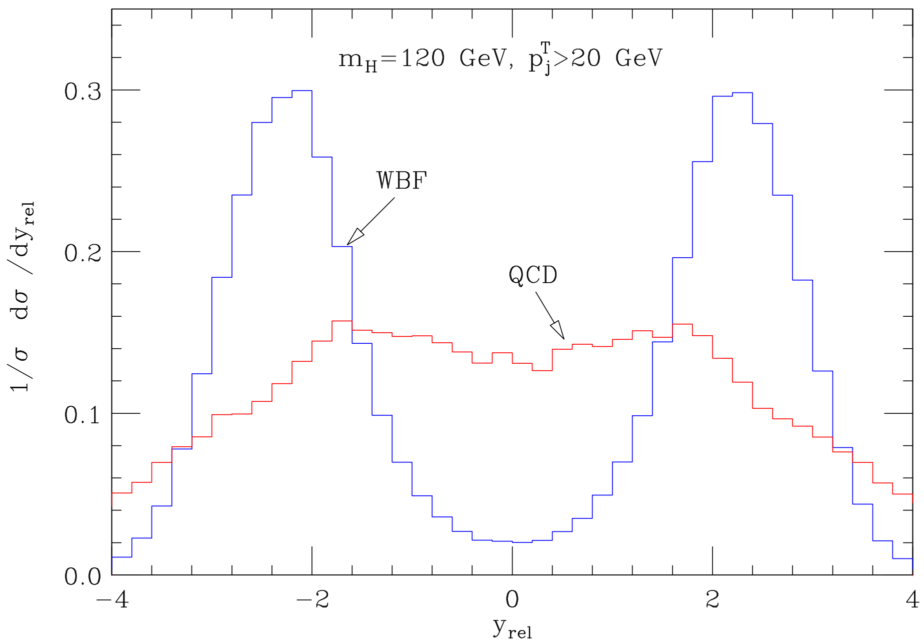


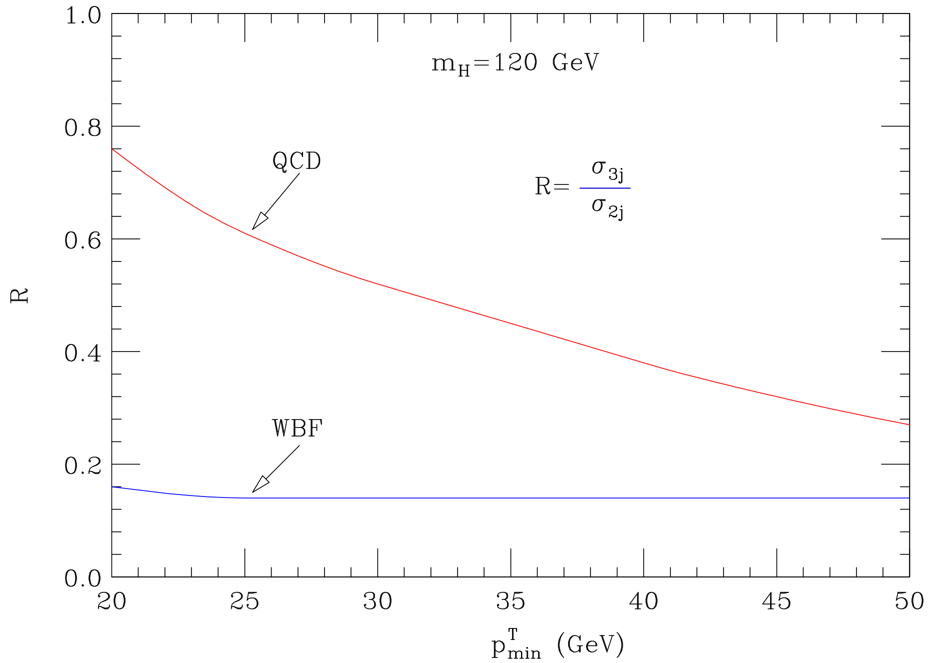
deflection of color charge by ~180° $\Rightarrow$ strong color acceleration

$\Rightarrow$ enhanced central gluon emis.

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

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

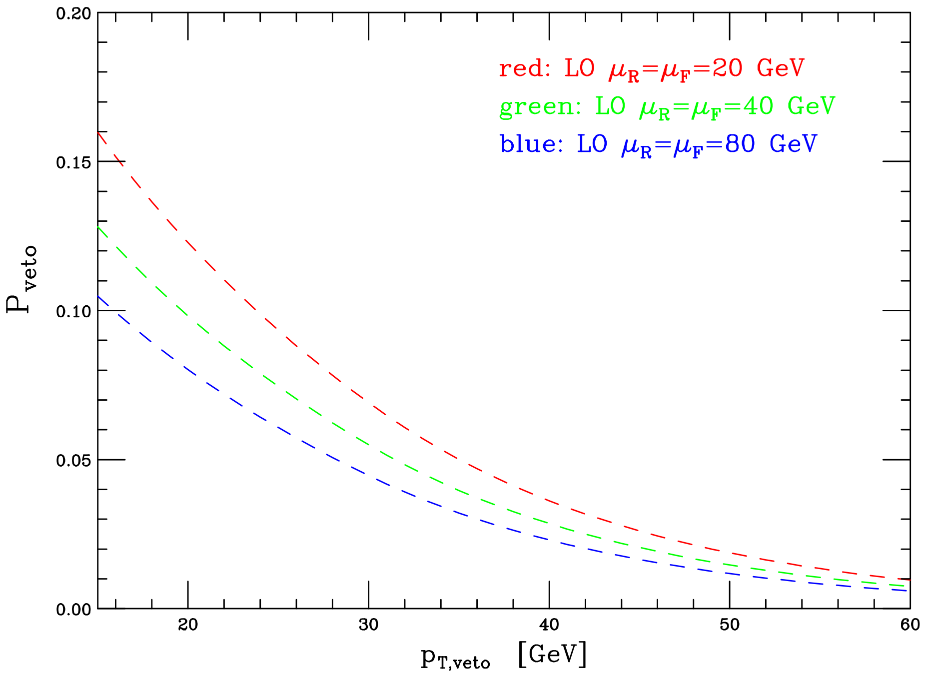




[Del Duca, Frizzo, Maltoni, JHEP 05 (2004) 064]

- 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



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

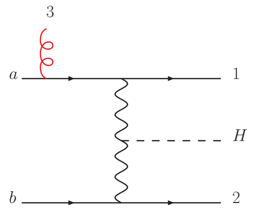
$$P_{\text{veto}} = \frac{1}{\sigma_2^{NLO}} \int_{p_{T,veto}}^{\infty} dp_{Tj}^{veto} \frac{d\sigma_3^{LO}}{dp_{Tj}^{veto}}$$

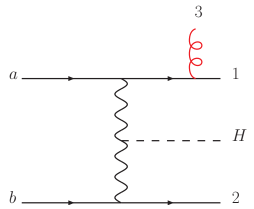
- Scale variation at LO for σ_{3j}: $+33\%$ to -17% for $p_{T,veto} = 15$ GeV
- The uncertainty in P_{veto} feeds into the uncertainty of coupling measurements at the LHC
- In order to constrain couplings more precisely, the NLO QCD corrections to $Hjjj$ are needed: T. Figy, V. Hankele, and DZ, arXiv:0710.5621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

Ingredients of the NLO Calculation

- Born: 3 final state partons + Higgs via VBF

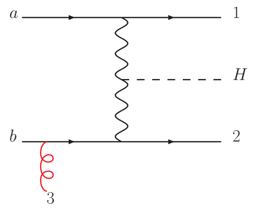
$$\mathcal{M}_B = \delta_{i_2 i_b} t^{a_3}_{i_1 i_a} \Big[\mathcal{M}_{B,1a} :$$

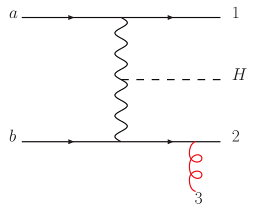




$$\Big]$$

$$+ \delta_{i_1 i_a} t^{a_3}_{i_2 i_b} \Big[\mathcal{M}_{B,2b} :$$

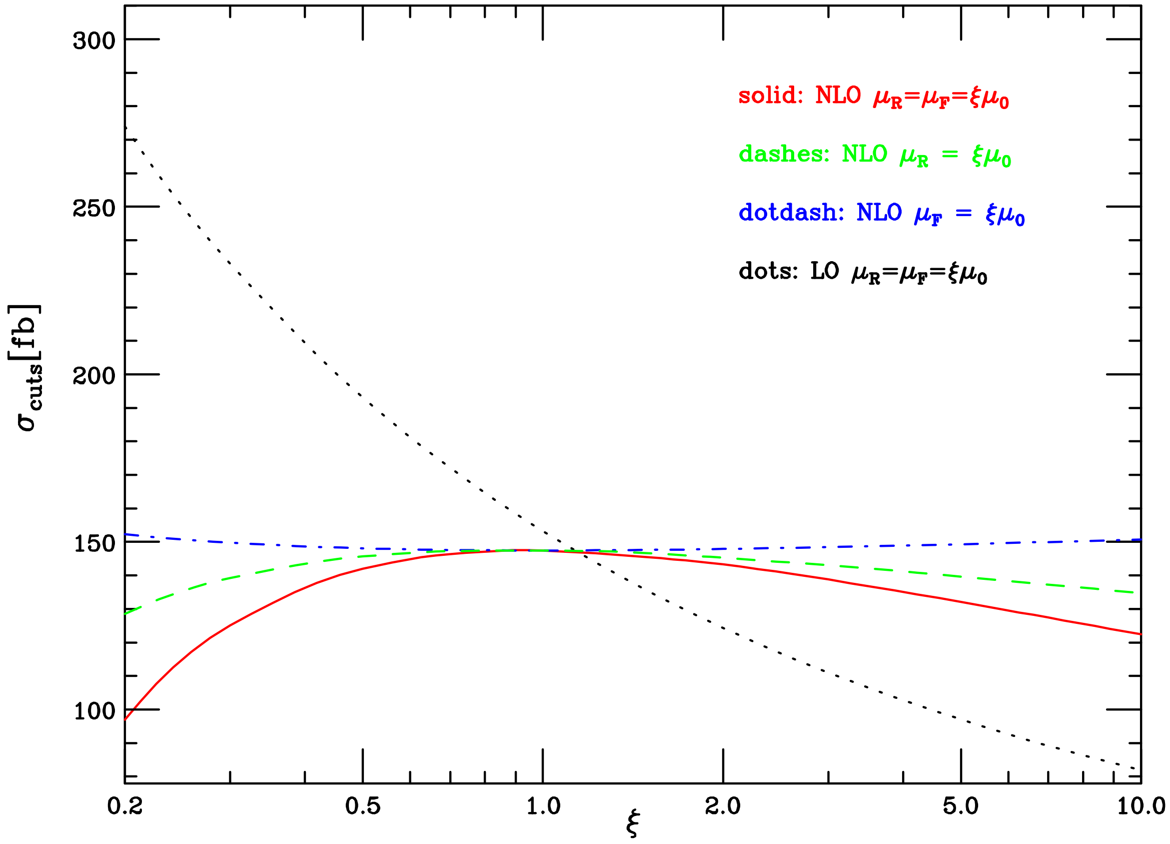




$$\Big]$$

- Catani, Seymour subtraction method
- Real: 4 final state partons + Higgs via VBF
- Virtual: Two classes of gauge invariant subsets
  - Box + Vertex + Propagator
  - Pentagon + Hexagon are small and can be neglected

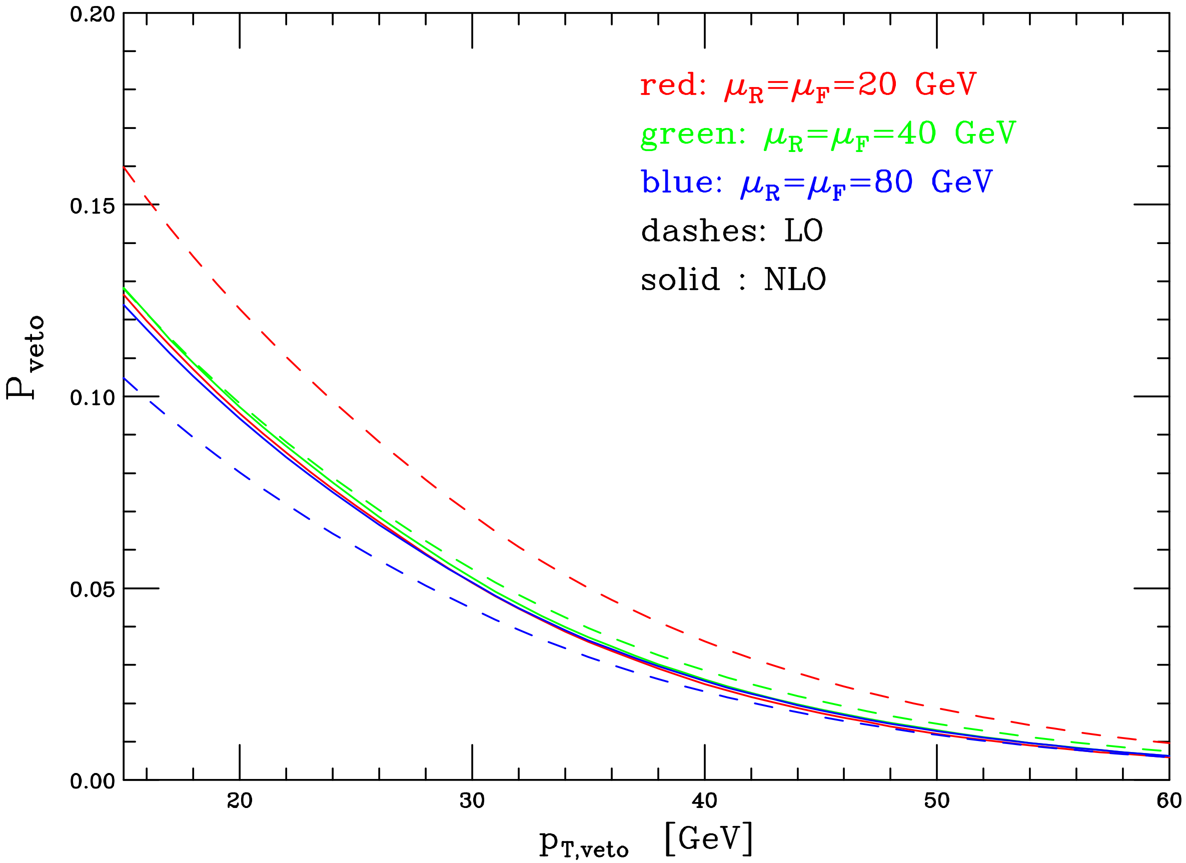
Total $Hjjj$ Cross Section at the LHC: NLO vs LO



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

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

Veto Probability for the VBF Signal



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

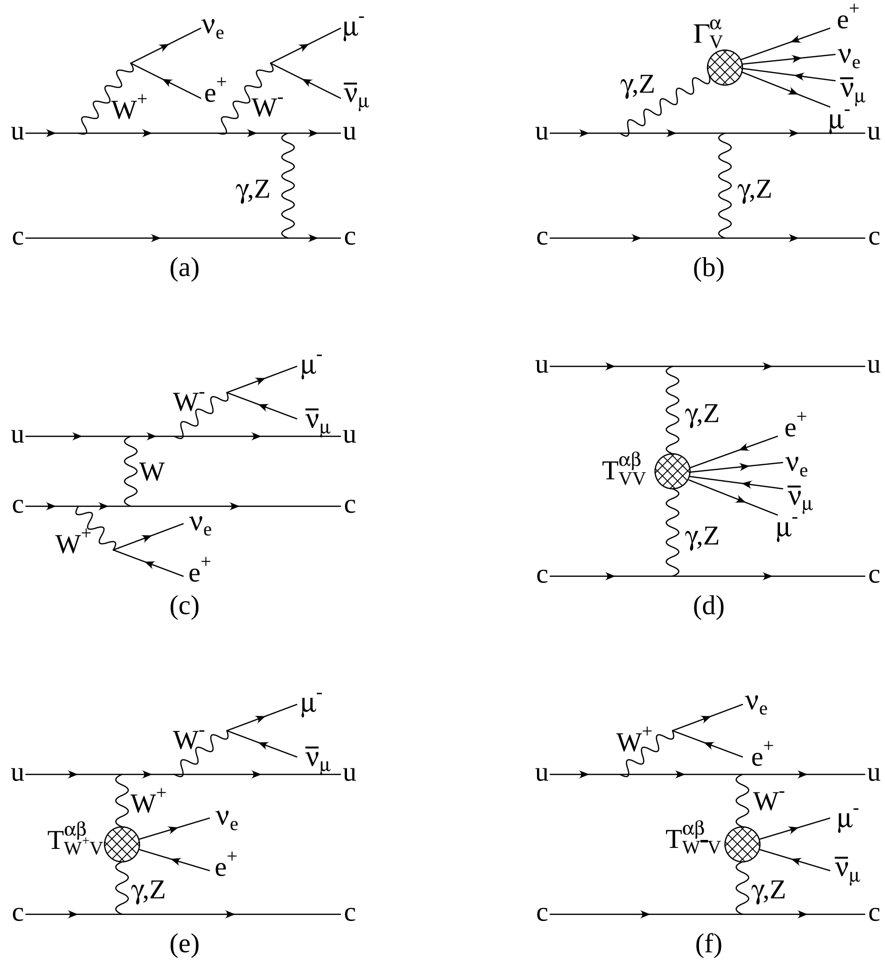
Scale variations, $p_{T,veto} = 15$ GeV:

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

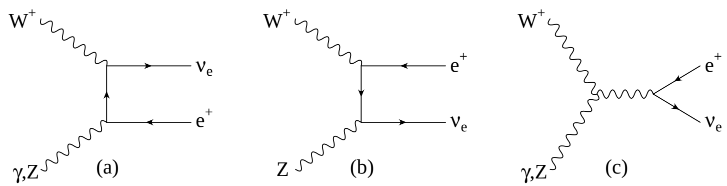
Reliable prediction for perturbative part of veto probability at NLO

Weak boson scattering: $qq \to qqWW$, $qqZZ$, $qqWZ$ at NLO

- example: WW production via VBF with leptonic decays: $pp \to e^+ \nu_e \mu^- \bar{\nu}_\mu + 2j$
- Spin correlations of the final state leptons
- All resonant and non-resonant Feynman diagrams included
- NC $\Longrightarrow$ 181 Feynman diagrams at LO
- CC $\Longrightarrow$ 92 Feynman diagrams at LO



Use modular structure, e.g. leptonic tensor

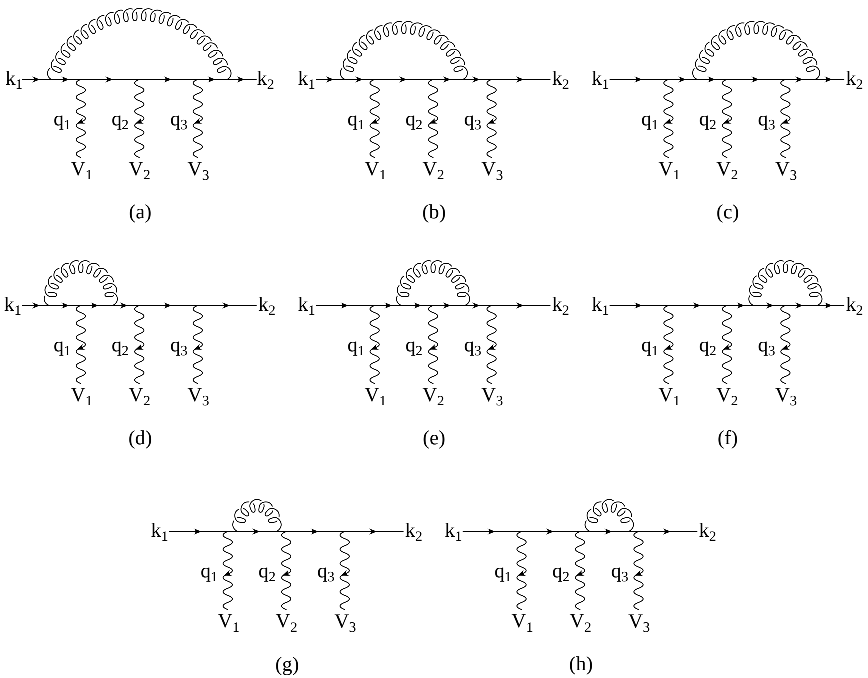


Calculate once, reuse in different processes

Speedup factor ≈ 70 compared to MadGraph for real emission corrections

Most challenging for virtual: pentagon corrections

Virtual corrections involve up to pentagons



The external vector bosons correspond to $V \to l_1 \bar{l}_2$ decay currents or quark currents

The sum of all QCD corrections to a single quark line is simple

$$
\begin{aligned}
\mathcal{M}_V^{(i)} &= \mathcal{M}_B^{(i)} \frac{\alpha_s(\mu_R)}{4\pi} C_F \left(\frac{4\pi\mu_R^2}{Q^2}\right)^\epsilon \Gamma(1+\epsilon) \\
&\qquad \left[-\frac{2}{\epsilon^2} - \frac{3}{\epsilon} + c_{\text{virt}}\right] \\
&\quad + \widetilde{\mathcal{M}}^{(i)}_{V_1V_2V_3,\tau}(q_1,q_2,q_3) + \mathcal{O}(\epsilon)
\end{aligned}
$$

- Divergent pieces sum to Born amplitude: canceled via Catani Seymour algorithm
- Use amplitude techniques to calculate finite remainder of virtual amplitudes

Pentagon tensor reduction with Denner-Dittmaier is stable at 0.1% level

Phenomenology

Study LHC cross sections within typical VBF cuts

- Identify two or more jets with k_T-algorithm ($D = 0.8$)

$$p_{Tj} \geq 20\text{ GeV}, \qquad |y_j| \leq 4.5$$

- Identify two highest p_T jets as tagging jets with wide rapidity separation and large dijet invariant mass

$$\Delta y_{jj} = |y_{j_1} - y_{j_2}| > 4, \qquad M_{jj} > 600\text{ GeV}$$

- Charged decay leptons ($\ell = e,\ \mu$) of W and/or Z must satisfy

$$p_{T\ell} \geq 20\text{ GeV}, \qquad |\eta_\ell| \leq 2.5, \qquad \triangle R_{j\ell} \geq 0.4,$$
$$m_{\ell\ell} \geq 15\text{ GeV}, \qquad \triangle R_{\ell\ell} \geq 0.2$$

and leptons must lie between the tagging jets

$$y_{j,min} < \eta_\ell < y_{j,max}$$

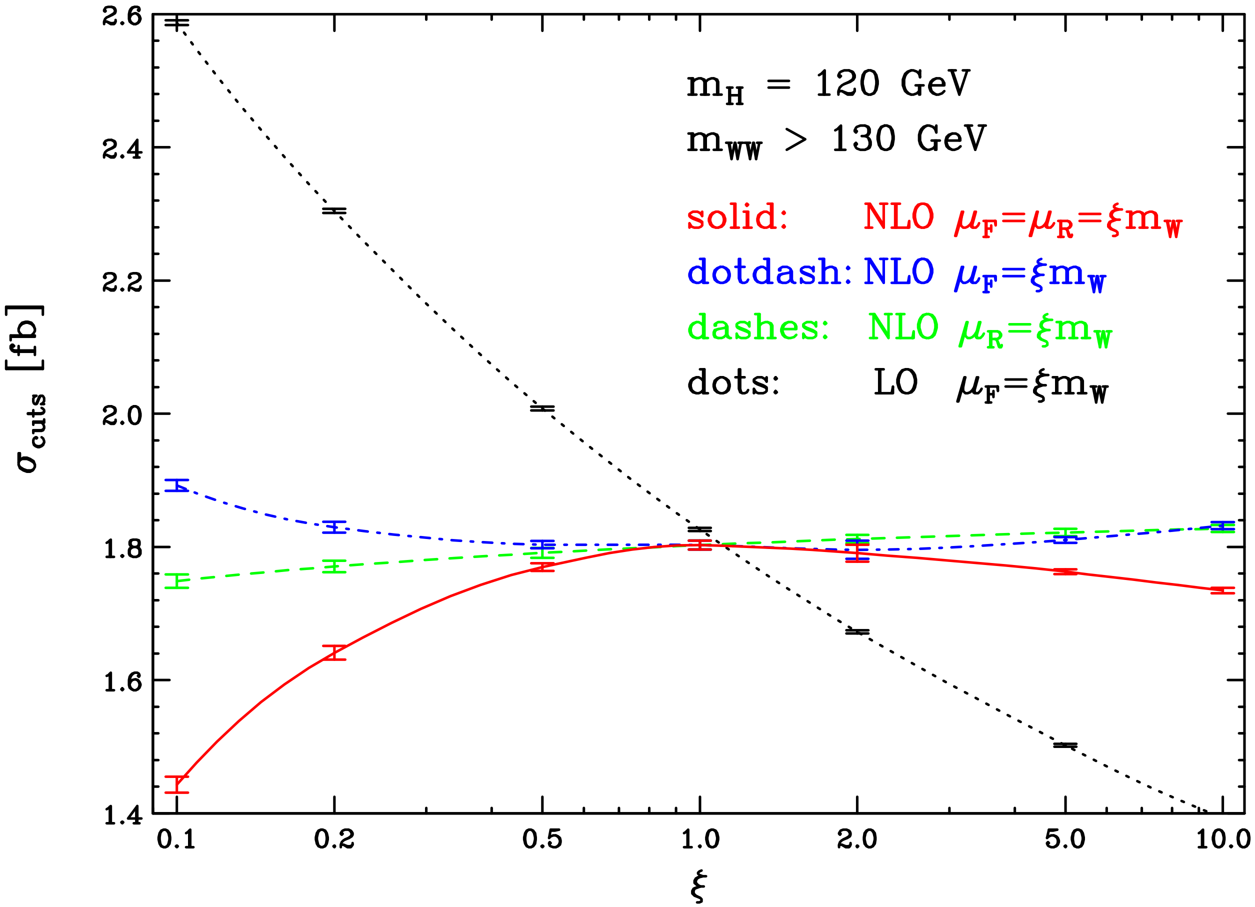
For scale dependence studies we have considered

$\mu = \xi\ m_V$ fixed scale $\qquad$ $\mu = \xi\ Q_i$ weak boson virtuality : $Q_i^2 = 2k_{q_1} \cdot k_{q_2}$

WW production: $pp \to jj e^+ \nu_e \mu^- \bar{\nu}_\mu X$ @ LHC

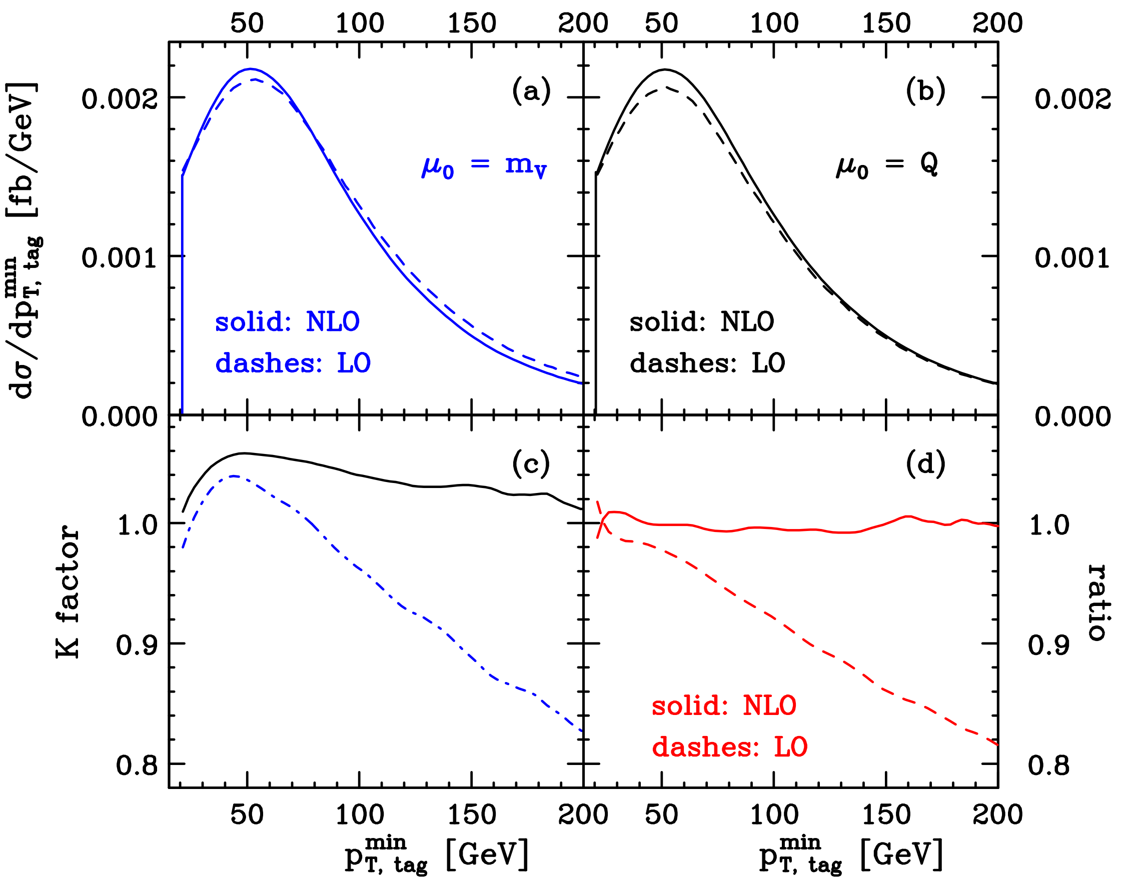
Stabilization of scale dependence at NLO

Jäger, Oleari, DZ hep-ph/0603177



WZ production in VBF, $WZ \to e^+ \nu_e \mu^+ \mu^-$

Transverse momentum distribution of the softer tagging jet

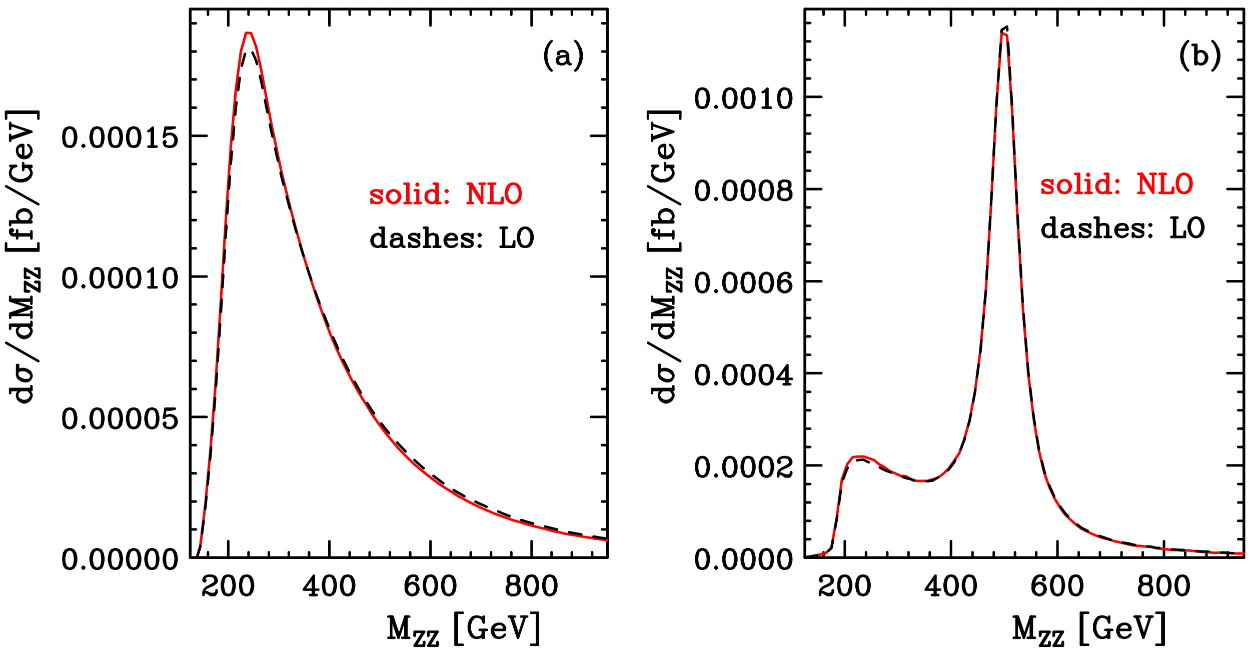


- Shape comparison LO vs. NLO depends on scale
- Scale choice $\mu = Q$ produces approximately constant K-factor
- Ratio of NLO curves for different scales is unity to better than 2%: scale choice matters very little at NLO

Use $\mu_F = Q$ at LO to best approximate the NLO results

ZZ production in VBF, $ZZ \to e^+e^-\mu^+\mu^-$

4-lepton invariant mass distribution without/with Higgs resonance

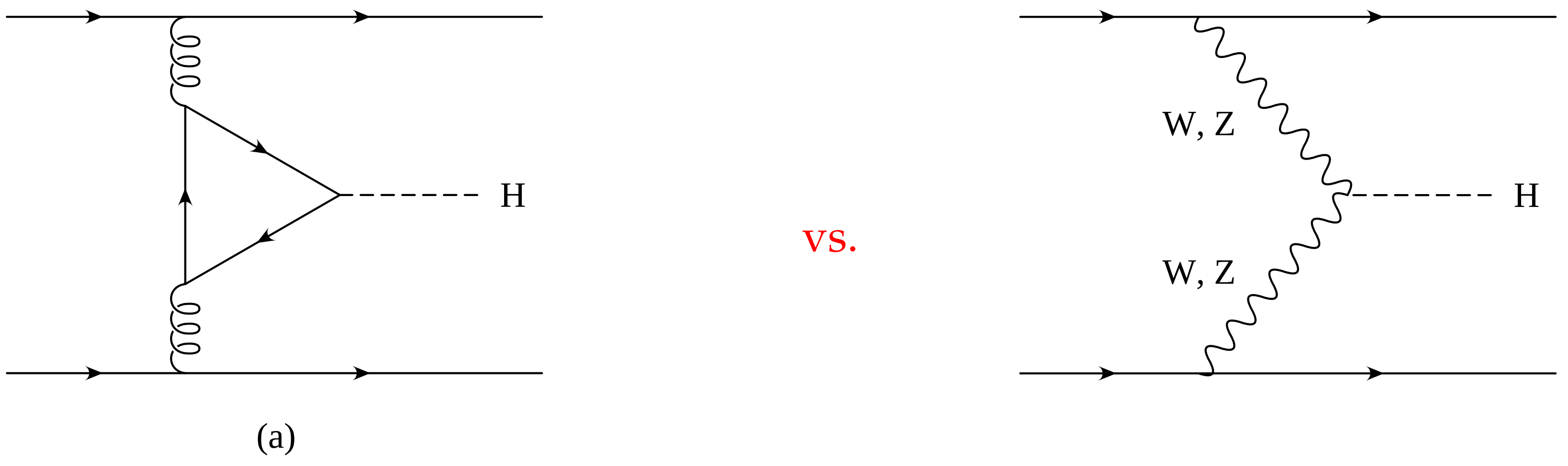


Good agreement of LO and NLO due to low scale choice $\mu = m_Z$. Alternative choice $\mu = m_H$ or $\mu = m_{4\ell}$ leads to smaller LO cross section at high $m_{4\ell}$

NLO QCD correction for VBF now available in VBFNLO: parton level Monte Carlo for Hjj, Wjj, Zjj, W^+W^-jj, $ZZjj$ production by Bozzi, Figy, Hankele, Jäger, Klämke, Oleari, Worek, DZ, ...

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

How to distinguish VBF and gluon fusion?



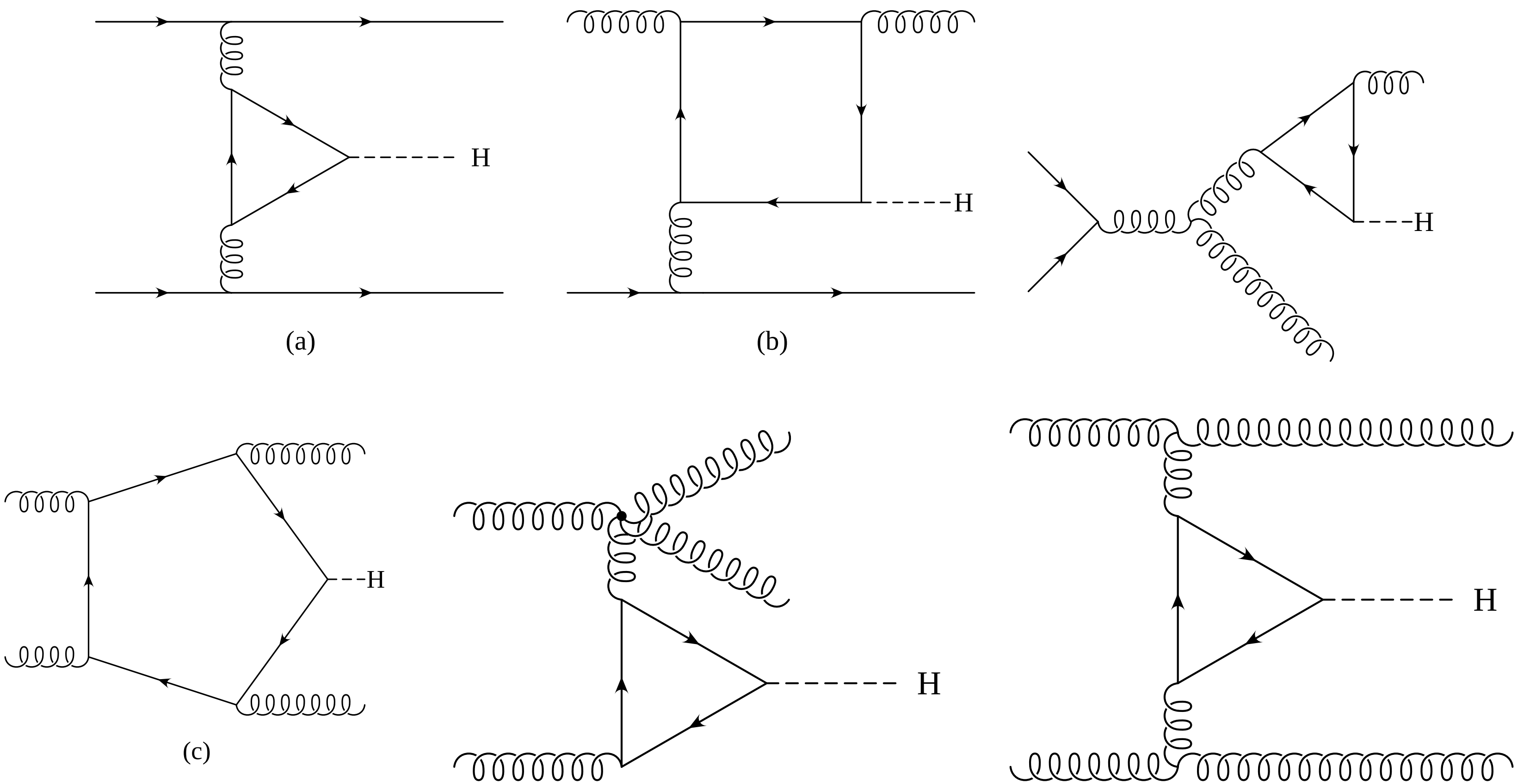
Double real corrections to $gg \to H$ can "fake" VBF

$\Longrightarrow$ 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



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

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

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
- Measure size of coupling (requires NLO corrections for precision [Campbell, Ellis, Zanderighi (2006)])
- Find cuts to enhance gluon fusion over VBF and other backgrounds

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

Gluon fusion signal and backgrounds

Signal channel (LO):

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

dominant backgrounds:

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

applied inclusive cuts (minimal cuts):

- 2 tagging-jets

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

- 2 identified leptons

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

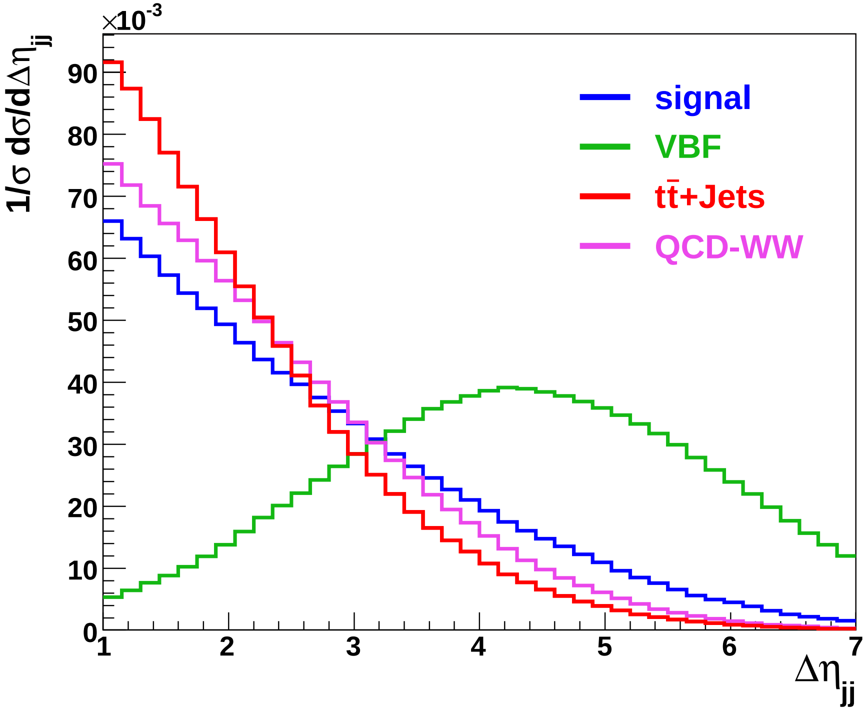
- separation of jets and leptons

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

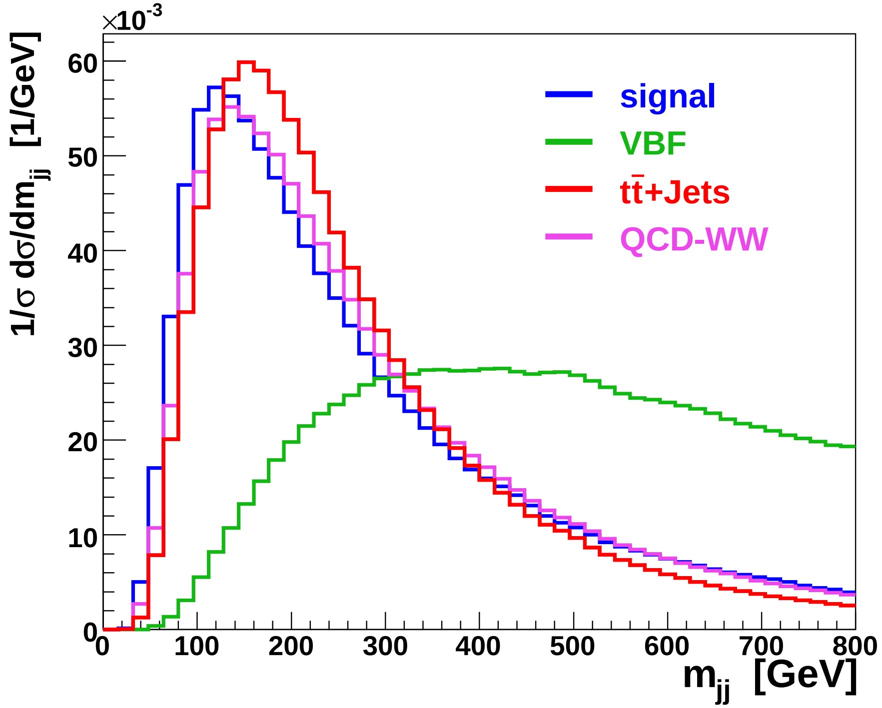
process	σ [fb]
GF $pp \to H + jj$	**115.2**
VBF $pp \to W^+W^- + jj$	**75.2**
$pp \to t\bar{t}$	**6832**
$pp \to t\bar{t} + j$	**9518**
$pp \to t\bar{t} + jj$	**1676**
QCD $pp \to W^+W^- + jj$	**363**

Characteristic distributions

tagging jet rapidity separation



dijet invariant mass



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

Selection continued

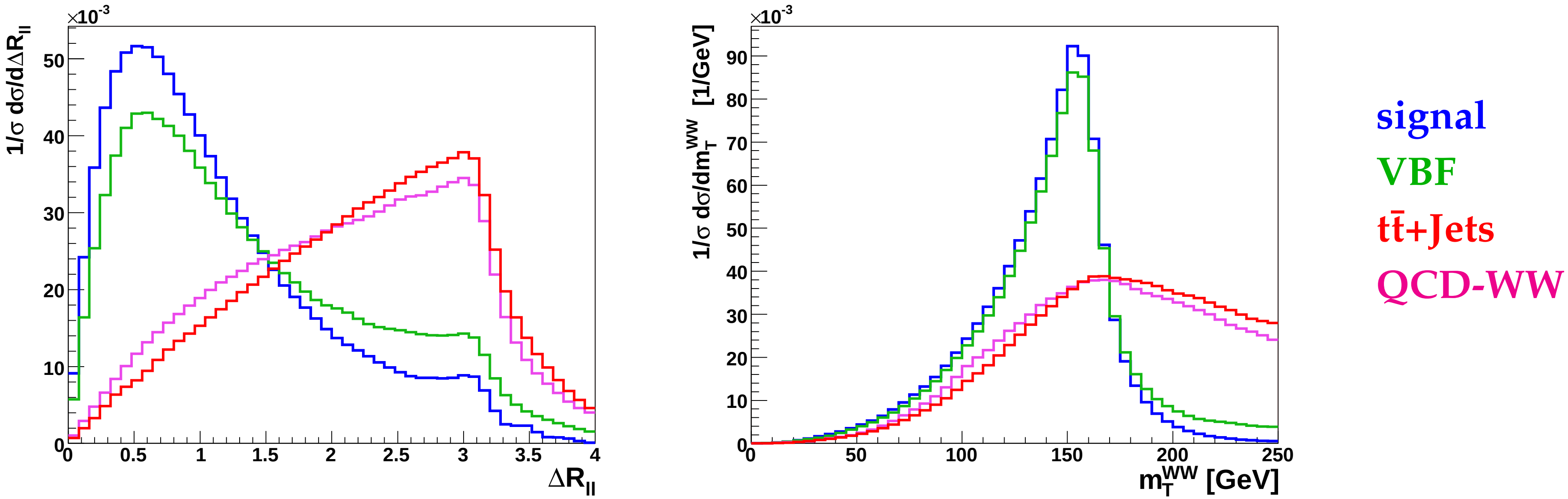
- b-tagging for reduction of top-backgrounds. *(CMS Note 06/014)*
  - (η, p_T) - dependent tagging-efficiencies (60% - 75%) with 10% mistagging - probability

- <u>selection cuts:</u>

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

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

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



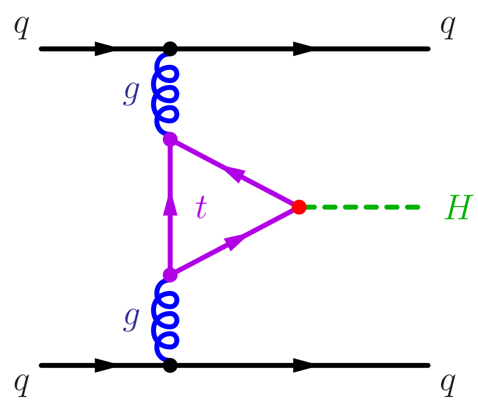
Results

process	σ [fb]	events/ $30\ \mathrm{fb}^{-1}$
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**

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

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

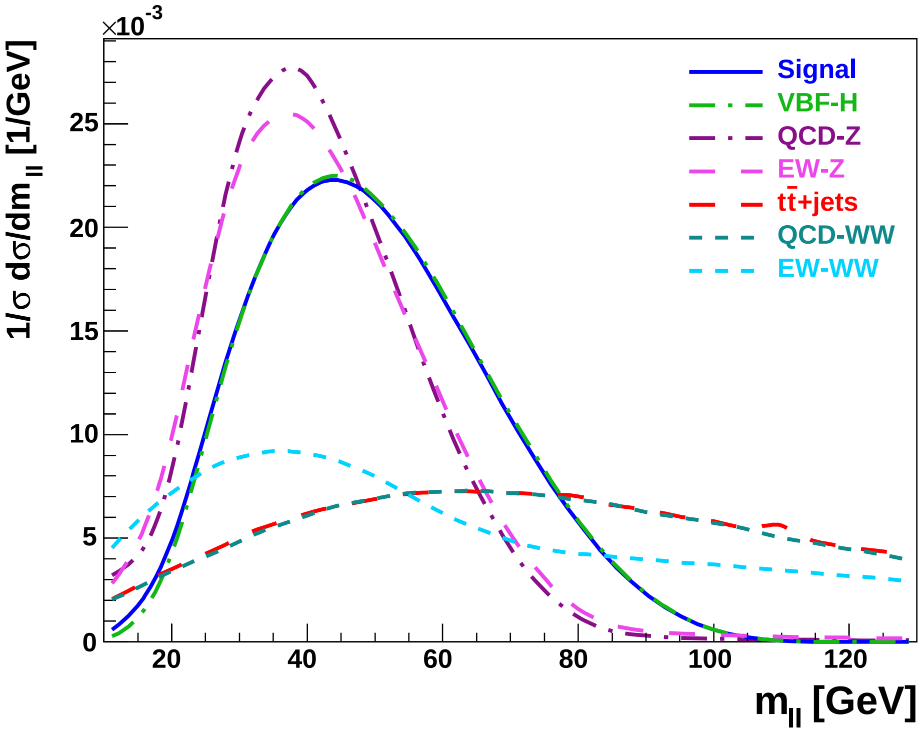
inclusive cuts

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

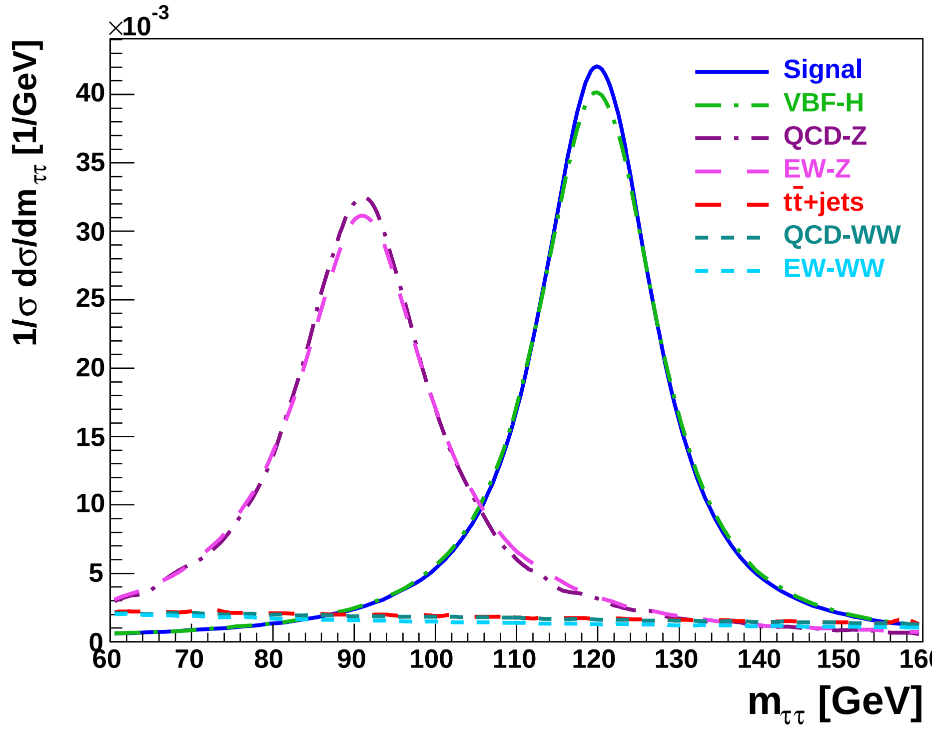
cross sections for inclusive cuts for signal and background

process	σ [fb]	events / 600 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.

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

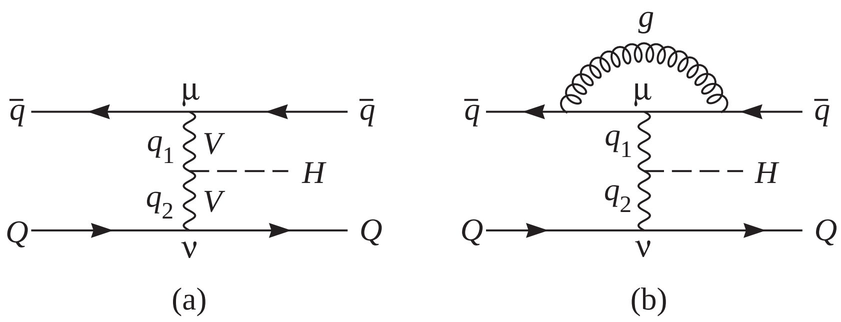
process	σ [fb]	events / 600 fb^{-1}
GF $pp \to H + jj \to \tau\tau jj$	**4.927**	**2956**
GF $pp \to A + jj \to \tau\tau jj$	**11.43**	**6860**
VBF $pp \to H + jj \to \tau\tau jj$	**2.523**	**1514**
QCD $pp \to Z + jj \to \tau\tau jj$	**27.62**	**16573**
VBF $pp \to Z + jj \to \tau\tau jj$	**0.475**	**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})

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

loop induced couplings for neutral scalar

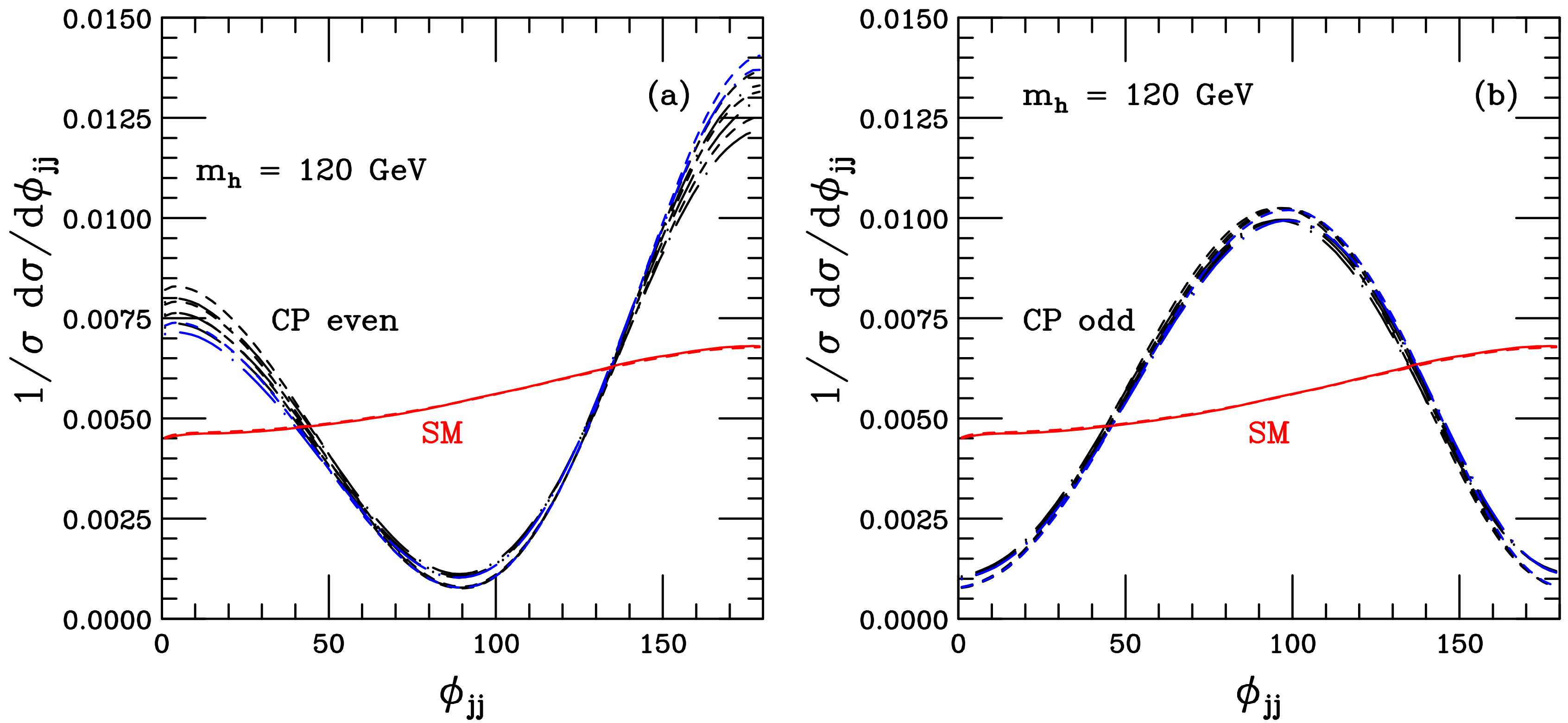
CP even $\quad \mathcal{L}_{eff} \sim H V_{\mu\nu} V^{\mu\nu} \longrightarrow a_2$

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

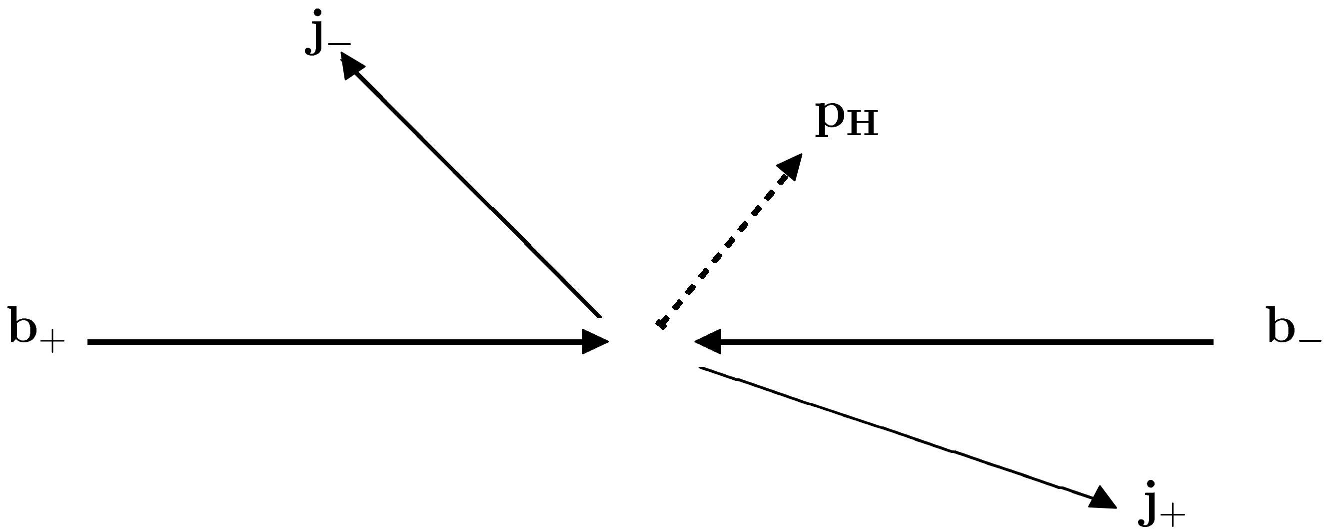
Tell-tale signal for non-SM coupling is azimuthal angle between tagging jets



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:



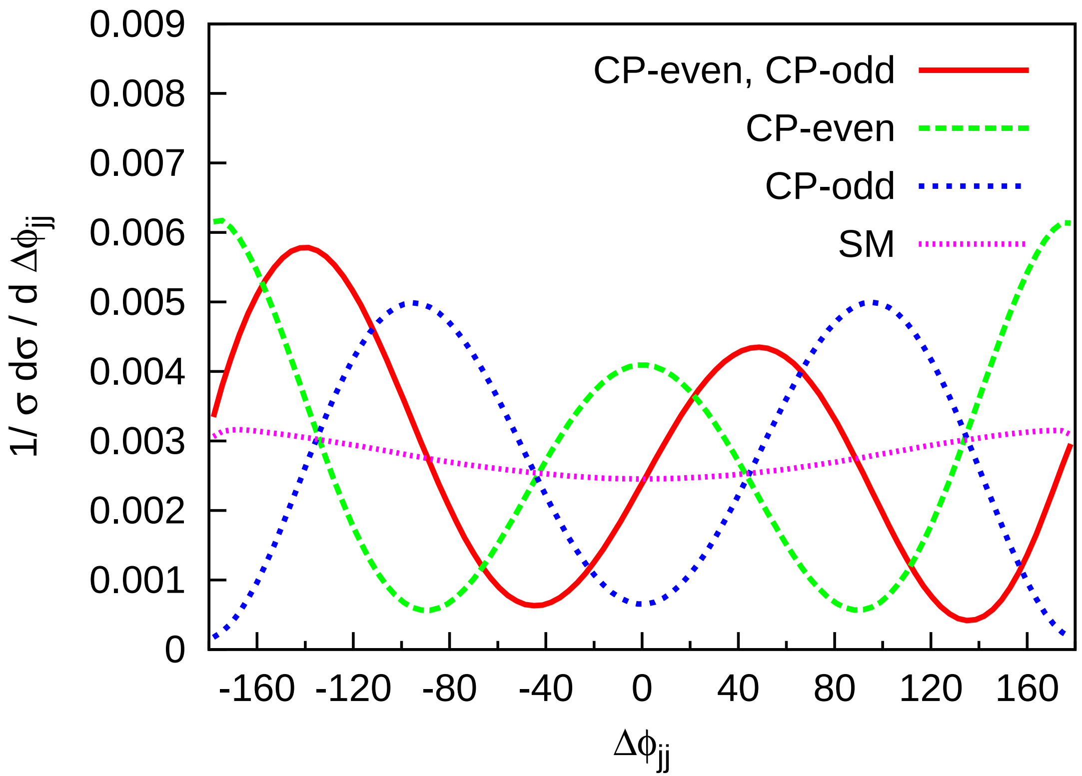
Define azimuthal angle between jet momenta j_+ and j_- via

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

- $\Delta\phi_{jj}$ 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

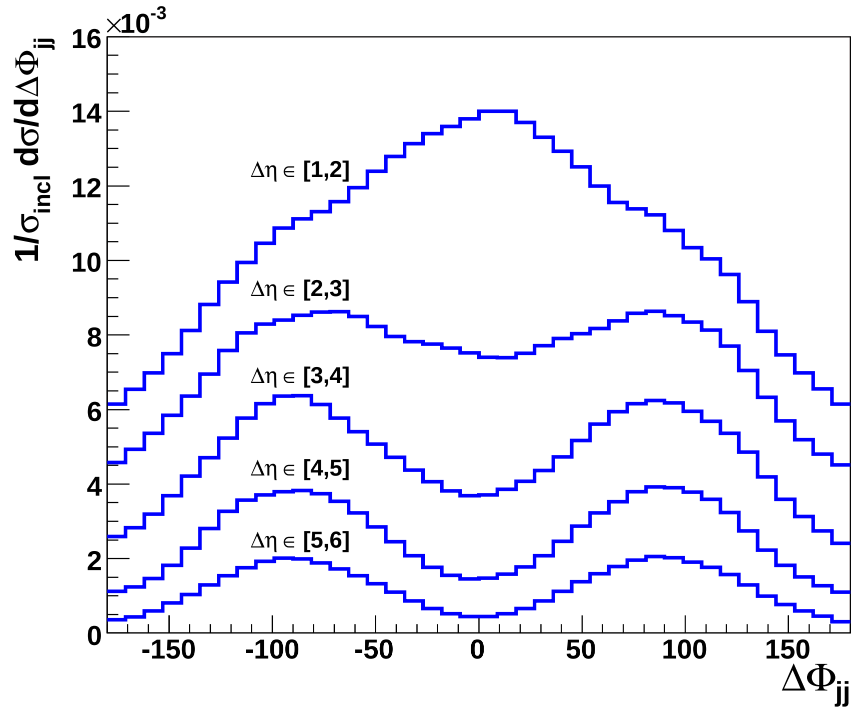
$$a_1 = 0, \qquad a_2 = d\ \cos\alpha, \qquad a_3 = d\ \sin\alpha,$$

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

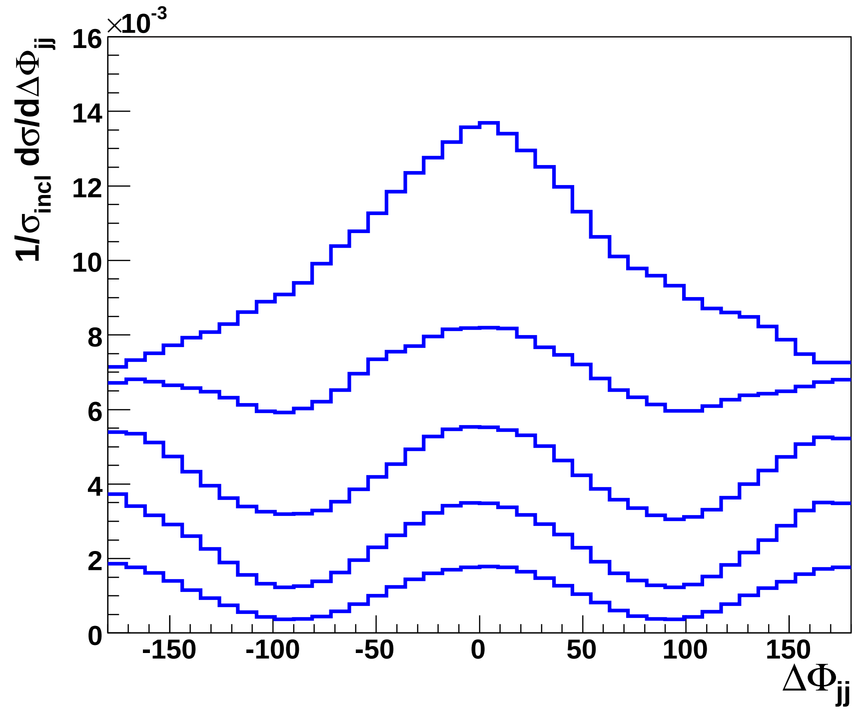
Gluon fusion: structure of Hgg vertex

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

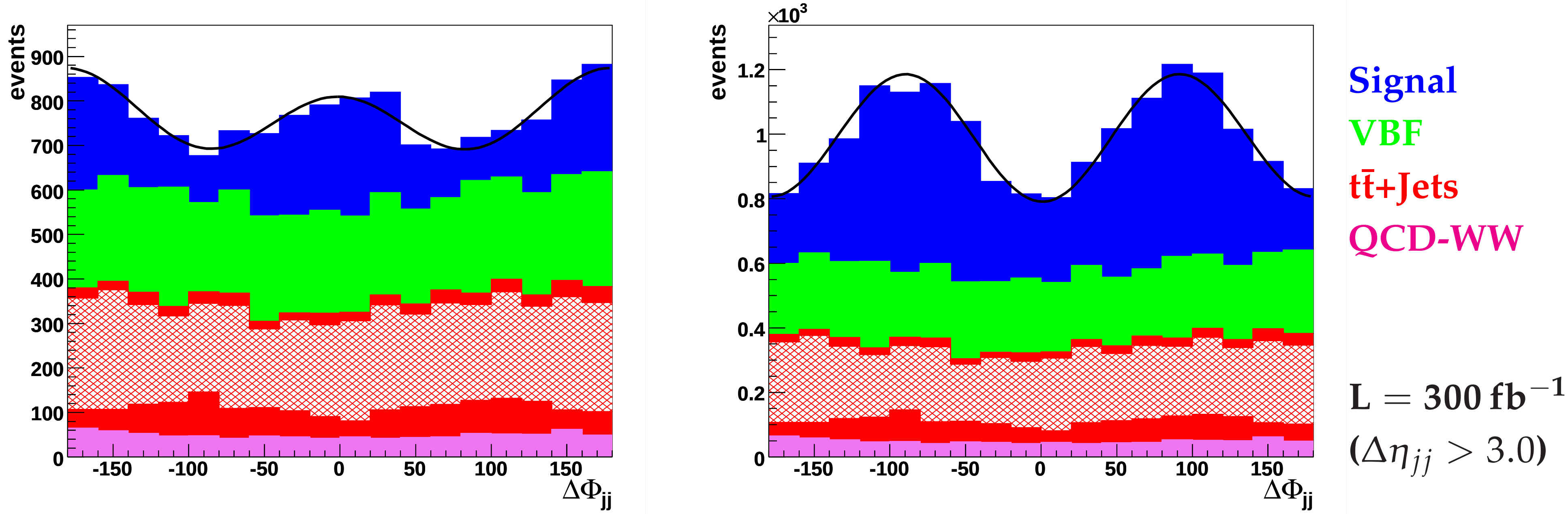


CP-odd coupling



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

$A = 0.100 \pm 0.039$

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

CP-odd

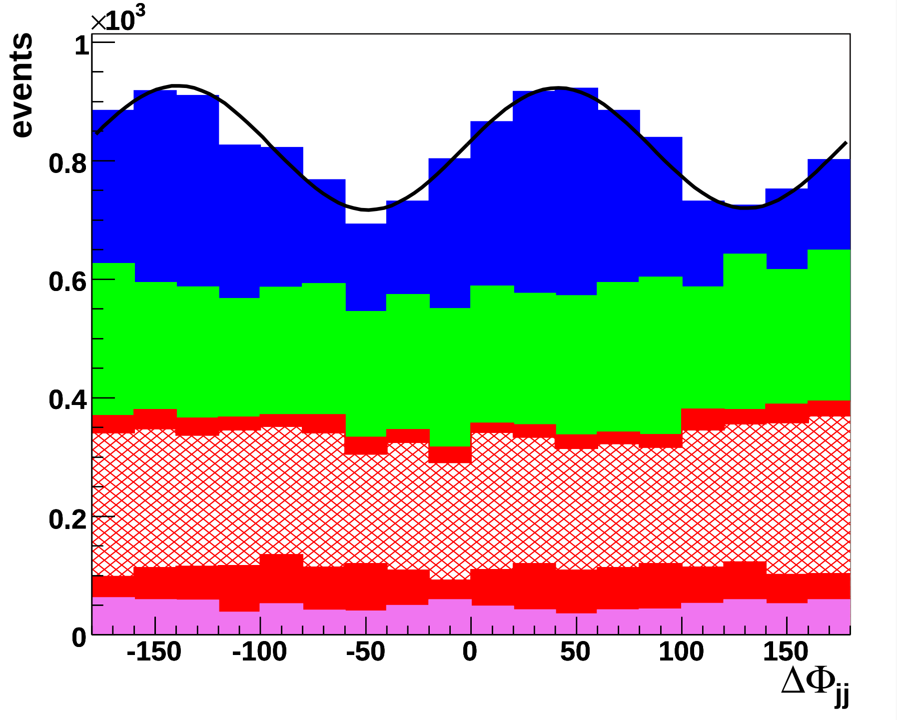
$A = 0.199 \pm 0.034$

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

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

$$A = 0.153 \pm 0.037$$

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

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 $pp \rightarrow Hjj$ 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

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- We are all anxiously waiting for LHC data....

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- Thanks to Giuseppe Bozzi, Christoph Englert, Terrance Figy, Christoph Hackstein, Vera Hankele, Barbara Jäger, Gunnar Klämke, Michael Kubocz, Carlo Oleari, Malgorzata Worek and many others for their work and most enjoyable collaborations on gauge boson fusion.
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