Gauge Boson Fusion Processes at the LHC

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- Introduction
- VBF Higgs Production
- Central Jet Veto at NLO
- H coupling measurements
- QCD corrections to VBF
- 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

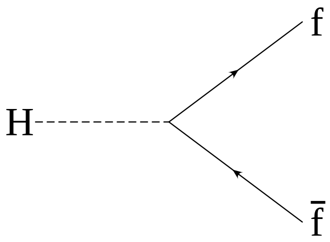
Kinetic energy term of Higgs doublet field:

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

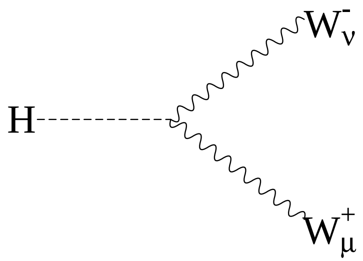
- W, Z mass generation: $m_W^2 = \left(\frac{gv}{2}\right)^2,\ m_Z^2 = \frac{(g^2+g'^2)v^2}{4}$
- WWH and ZZH couplings are generated
- Higgs couples propotional to mass: coupling strength $= 2\,m_V^2/v \sim g^2 v$ within SM

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

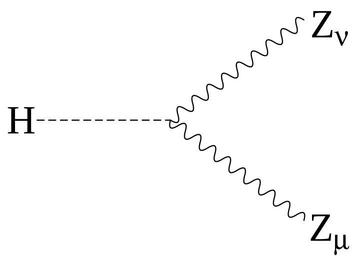
Feynman rules



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



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



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

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

SM Higgs mass fit to EW precision data

$$m_H = 87^{+36}_{-27}\ \text{GeV}$$

Including theory uncertainty

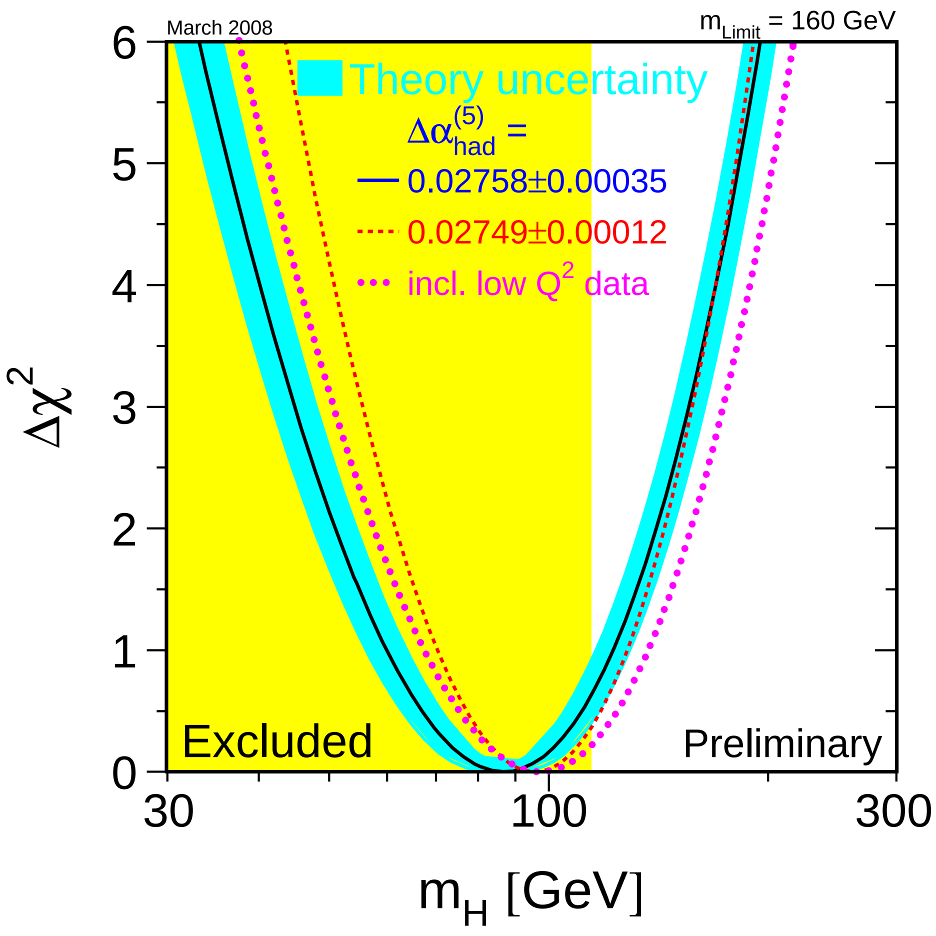
$$m_H < 160\ \text{GeV} \quad (95\%\ \text{CL})$$

Does not include
Direct search limit from LEP

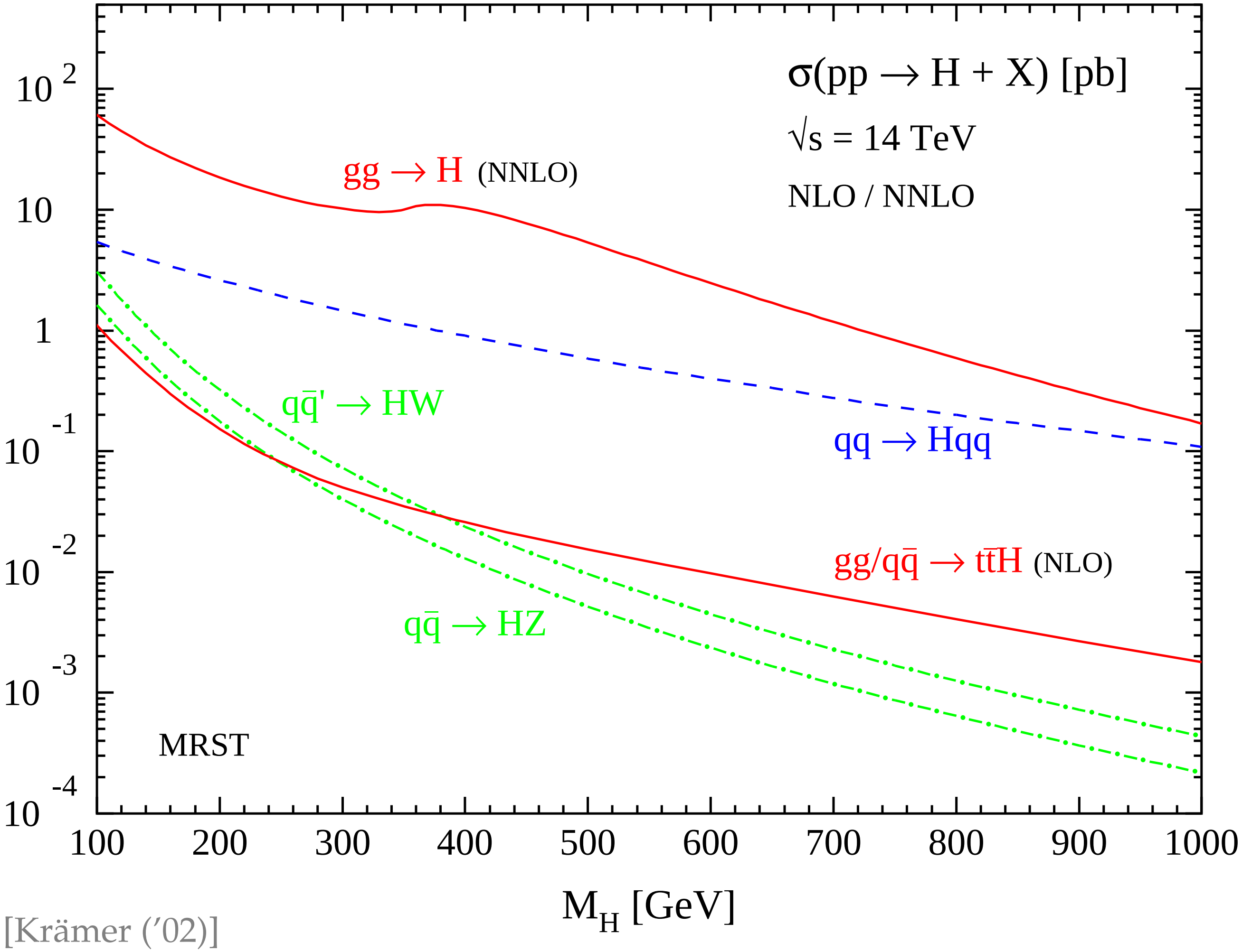
$$m_H > 114\ \text{GeV} \quad (95\%\ \text{CL})$$

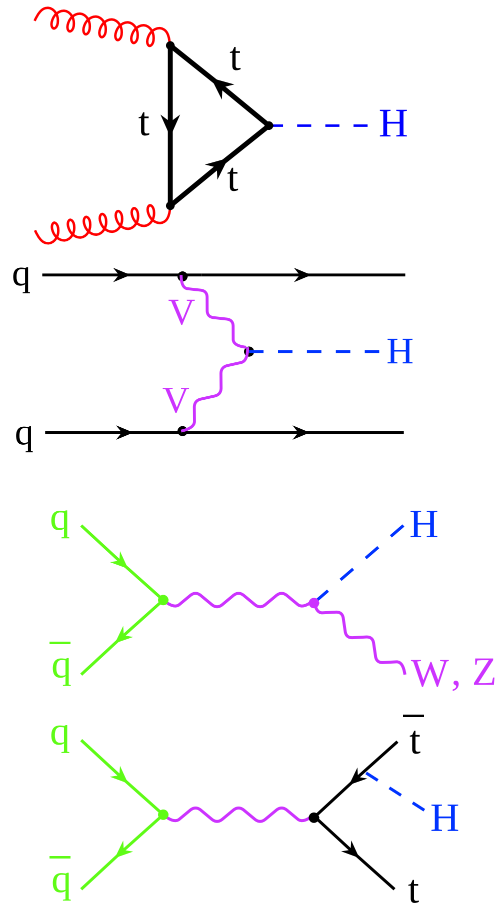
Renormalize probability for
$m_H > 114$ GeV to 100%:

$$m_H < 190\ \text{GeV} \quad (95\%\ \text{CL})$$



Total cross sections at the LHC





[Krämer ('02)]

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 $m_H \neq 2m_W$.

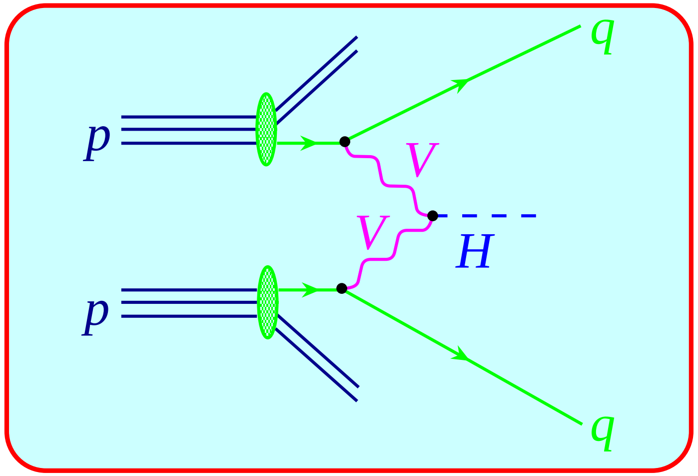
- inclusive search for

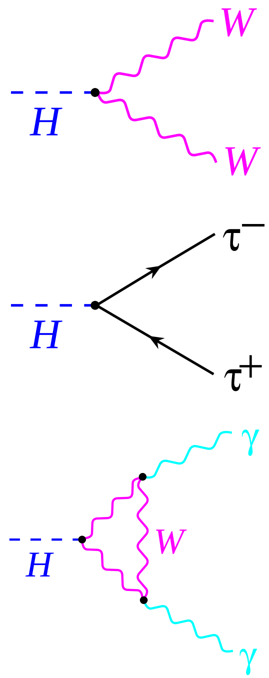
$$H \to W^+W^- \to \ell^+\bar{\nu}\ell^-\nu$$

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

Inclusive production is dominated by gluon fusion
$\Longrightarrow$ probe Higgs Yukawa coupling to top quark

Vector Boson Fusion





$m_H > 120$ GeV

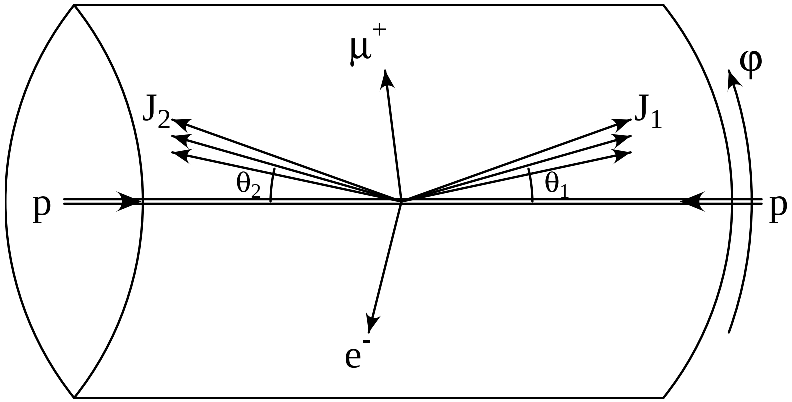
$m_H < 140$ GeV

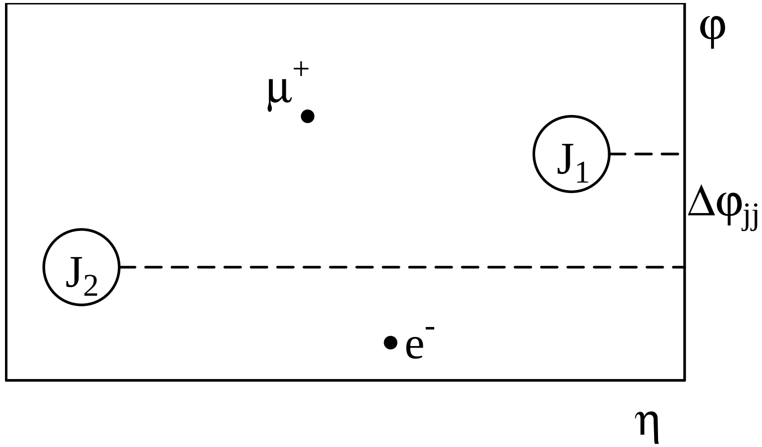
$m_H < 150$ GeV

[Eboli, Hagiwara, Kauer, Plehn, Rainwater, D.Z. . . .]

Most measurements can be performed at the LHC with statistical accuracies on the measured cross sections times decay branching ratios, $\sigma \times$ BR, of order 10% (sometimes even better).

VBF signature



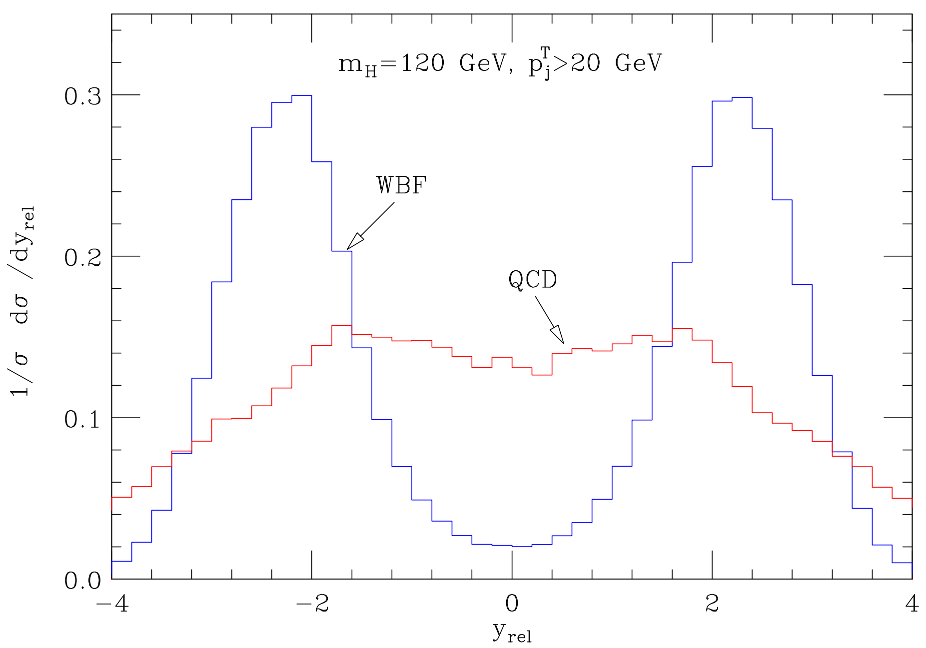


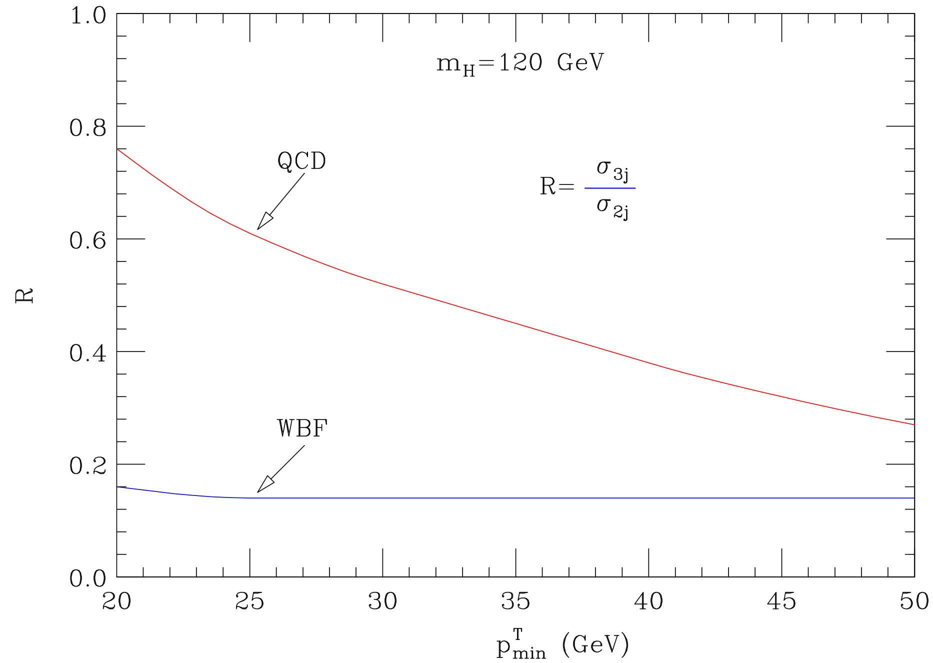
$$\eta = \frac{1}{2} \log \frac{1 + \cos\theta}{1 - \cos\theta}$$

Characteristics:

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

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

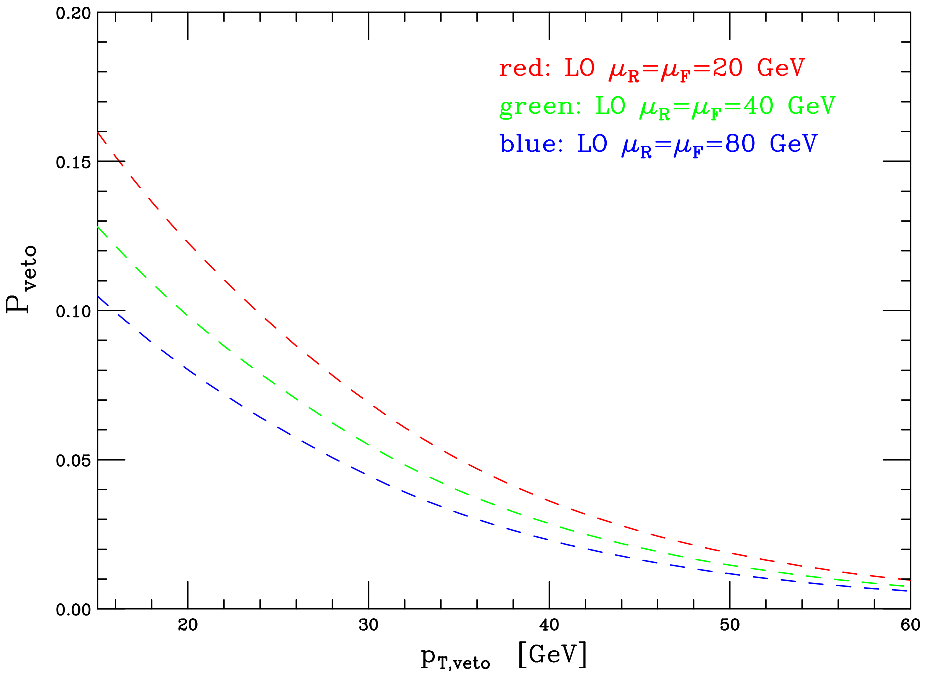




[Del Duca, Frizzo, Maltoni, JHEP 05 (2004) 064]

- A distinguishing feature of VBF is that at LO no color is exchanged in the t-channel.
- The central-jet veto is based on the different radiation pattern expected for VBF versus its major backgrounds [hep-ph/9412276, hep-ph/0012351]
- Central jet veto can be used to distinguish Higgs production via GF from VBF

VBF Higgs signal and CJV



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

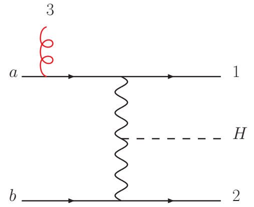
$$P_{\text{veto}} = \frac{1}{\sigma_2^{NLO}} \int_{p_{T,veto}}^{\infty} dp_{Tj}^{veto} \frac{d\sigma_3^{LO}}{dp_{Tj}^{veto}}$$

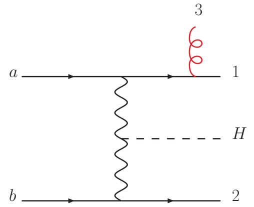
- Scale variation at LO for σ_{3j}: $+33\%$ to -17% for $p_{T,veto} = 15$ GeV
- The uncertainty in P_{veto} feeds into the uncertainty of coupling measurements at the LHC
- In order to constrain couplings more precisely, the NLO QCD corrections to $Hjjj$ are needed: T. Figy, V. Hankele, and DZ, arXiv:0710.5621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

Ingredients of the NLO Calculation

- Born: 3 final state partons + Higgs via VBF

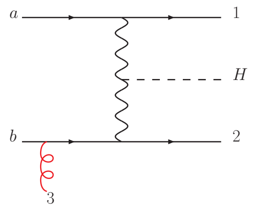
$$\mathcal{M}_B = \delta_{i_2 i_b} t^{a_3}_{i_1 i_a} \Big[\mathcal{M}_{B,1a} :$$

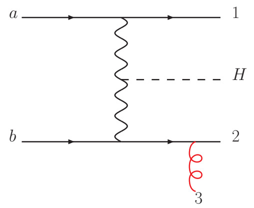




$$\Big]$$

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

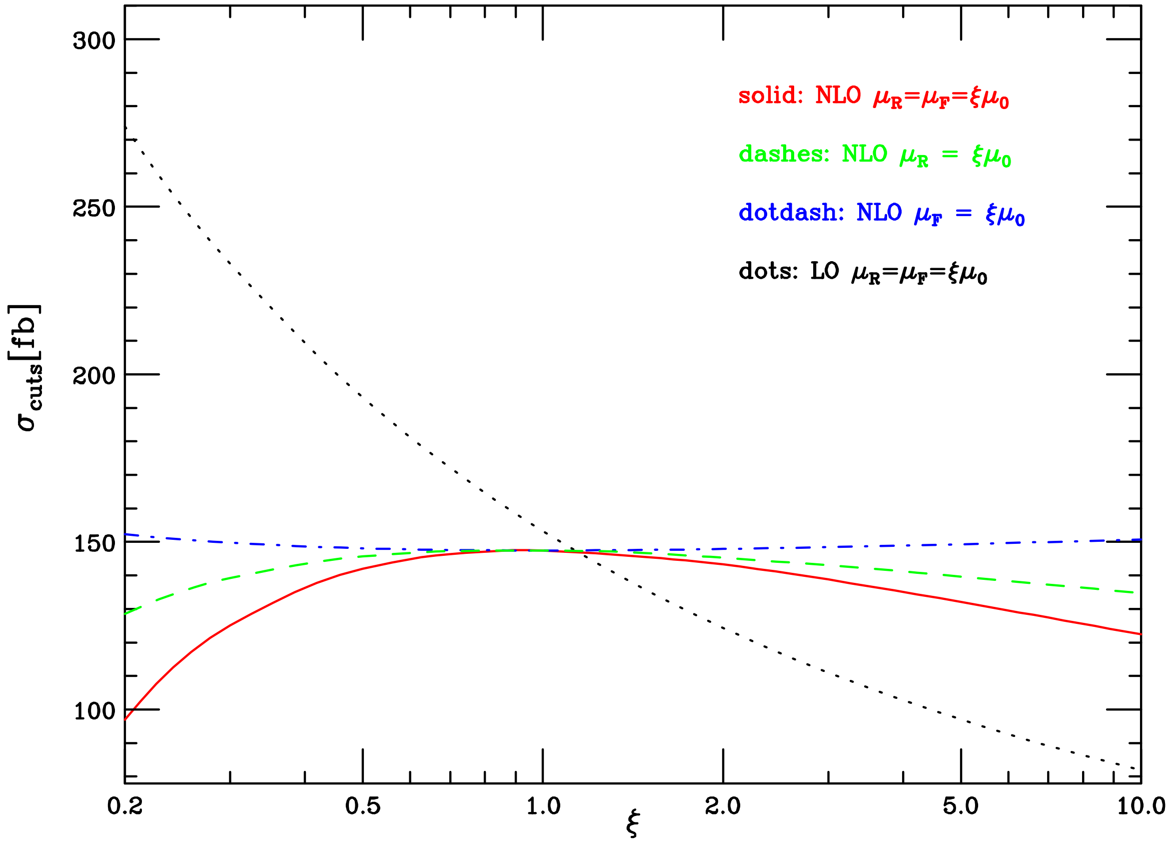




$$\Big]$$

- 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

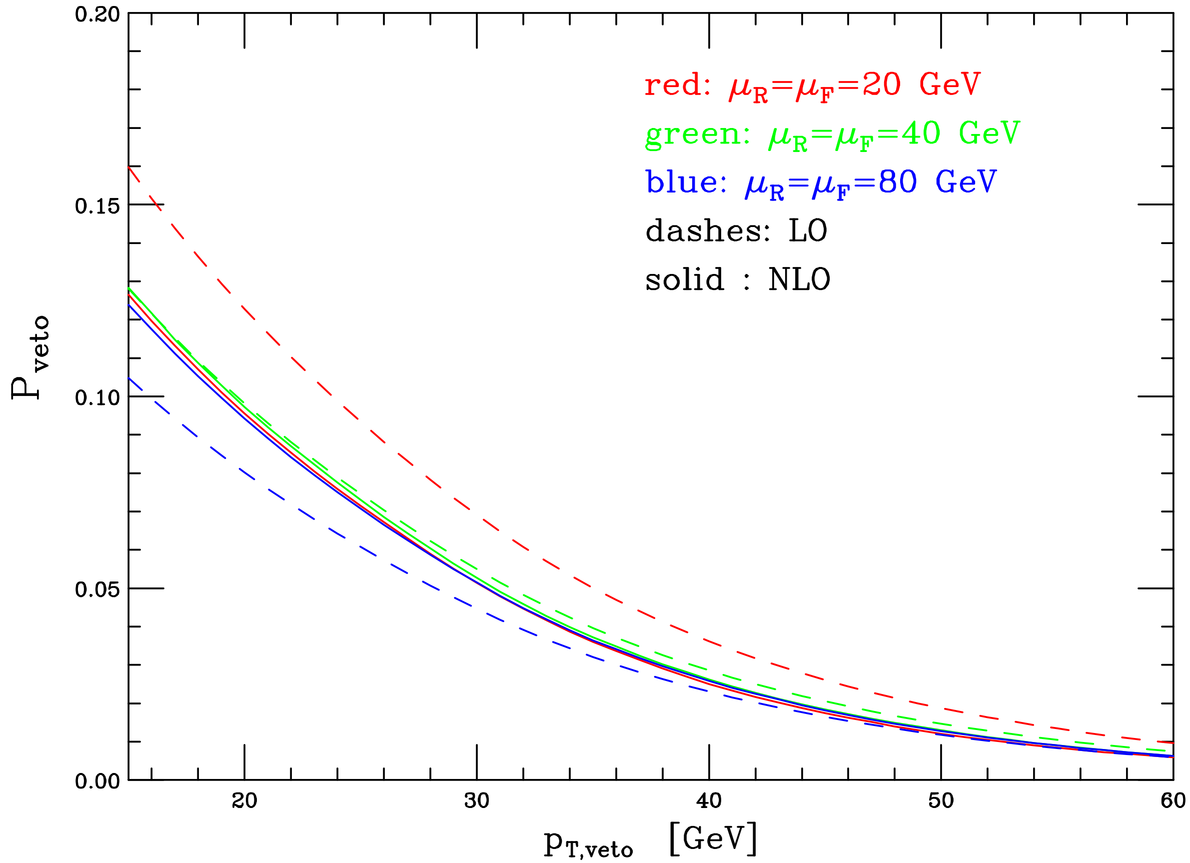


$\mu_0 = 40$ GeV

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

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

Veto Probability for the VBF Signal



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

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

VBF example: parton level analysis of $H \to WW$

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

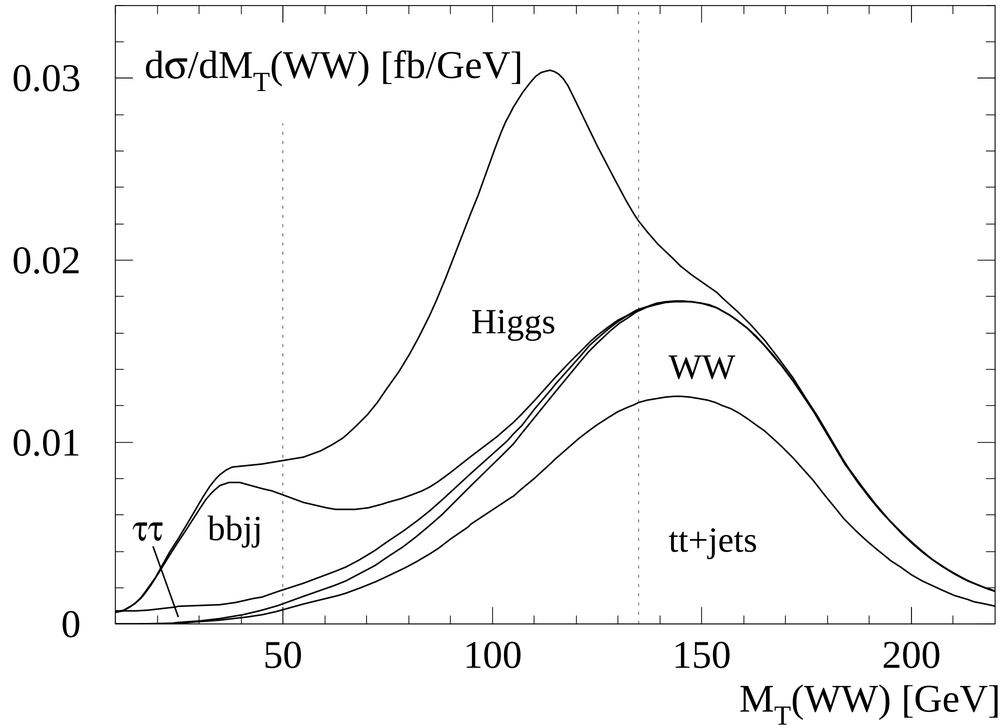
Near threshold: W and W^* almost at rest in Higgs rest frame $\Longrightarrow$ use $m_{ll} \approx m_{\nu\nu}$ for improved transverse mass calculation:

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

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

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

Observe Jacobian peak below $M_T = m_H$

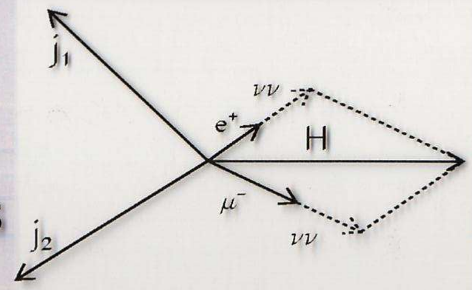


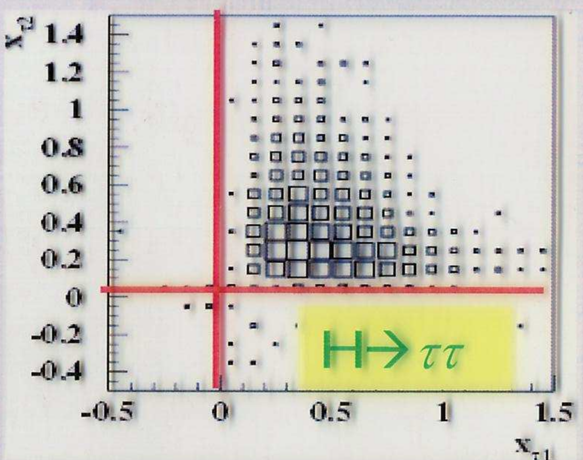
Transverse mass distribution for $m_H = 115$ GeV and $H \to WW^* \to e^{\pm}\mu^{\mp}\not{p}_T$

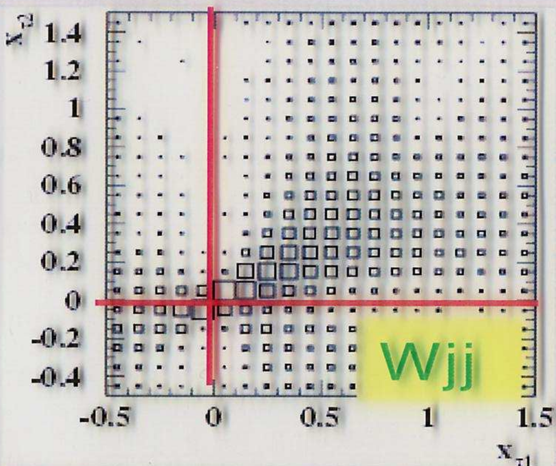
Weak Boson Fusion: H→ττ

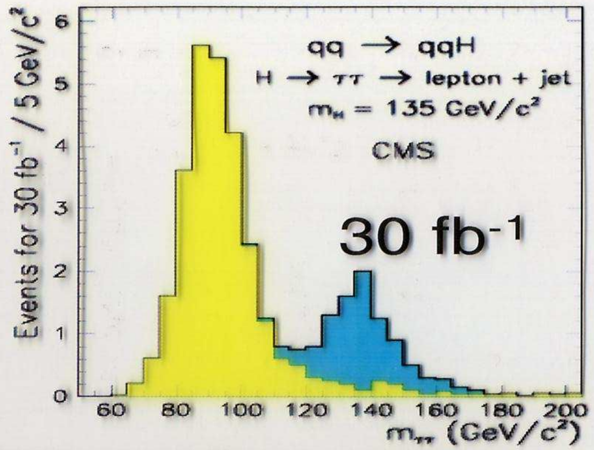
Mass can be reconstructed in collinear approximation

x_τ = momentum fraction carried by tau decay products

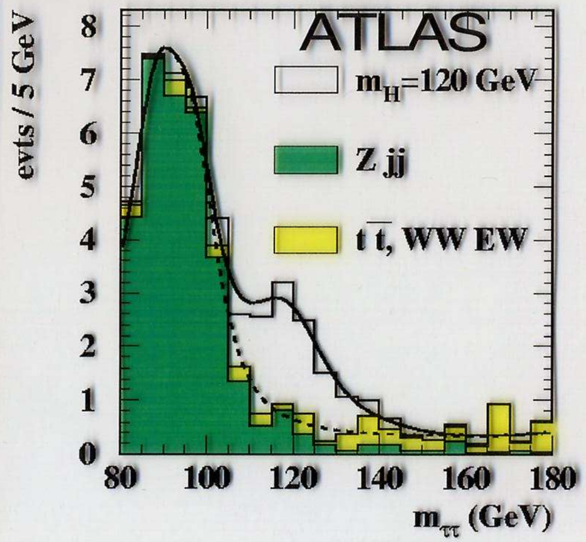








σ_M = 11 to 12 GeV



H→ττ→eμ 30 fb^{-1}

★ significance > 5 for 30 fb^{-1} and

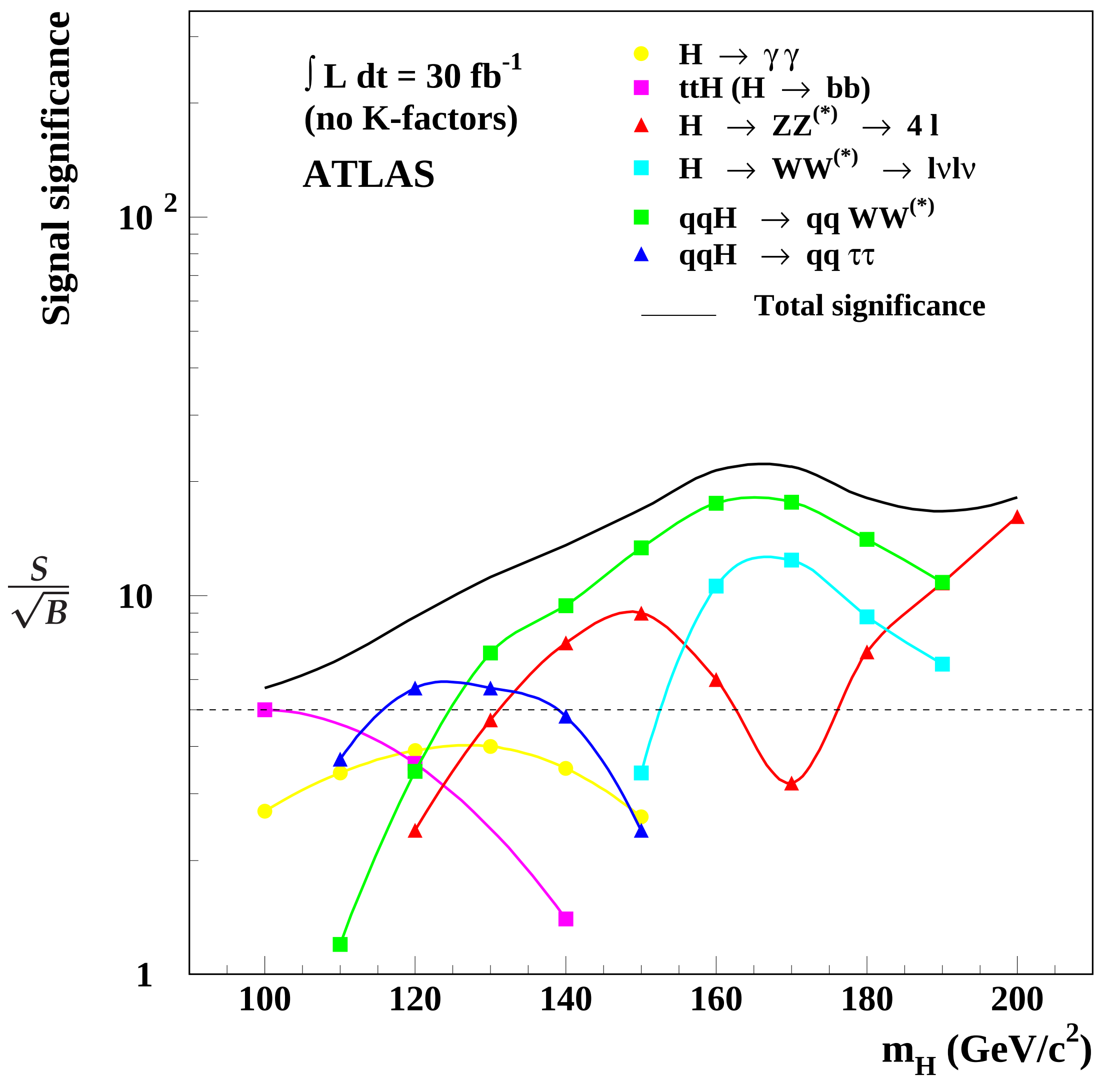
M_H=110 to 140 GeV (ττ→eμ, ττ→ ll , ττ→l had)

★ background estimate: ~10%

for M_H>125 GeV from side bands

for M_H>125 GeV from normalisation of Z→ττ peak

Higgs discovery potential



Measuring Higgs couplings at LHC

LHC rates for partonic process $pp \to H \to xx$ given by $\sigma(pp \to H) \cdot BR(H \to xx)$

$$\sigma(H) \times \mathrm{BR}(H \to xx) = \frac{\sigma(H)^{\mathrm{SM}}}{\Gamma_p^{\mathrm{SM}}} \cdot \frac{\Gamma_p \Gamma_x}{\Gamma} \, ,$$

Measure products $\Gamma_p \Gamma_x / \Gamma$ for combination of processes ($\Gamma_p = \Gamma(H \to pp)$)

Problem: rescaling fit results by common factor f

$$\Gamma_i \to f \cdot \Gamma_i \, , \qquad \Gamma \to f^2 \Gamma = \sum_{obs} f \Gamma_i + \Gamma_{rest}$$

leaves observable rate invariant $\Longrightarrow$ no model independent results at LHC

Loose bounds on scaling factor:

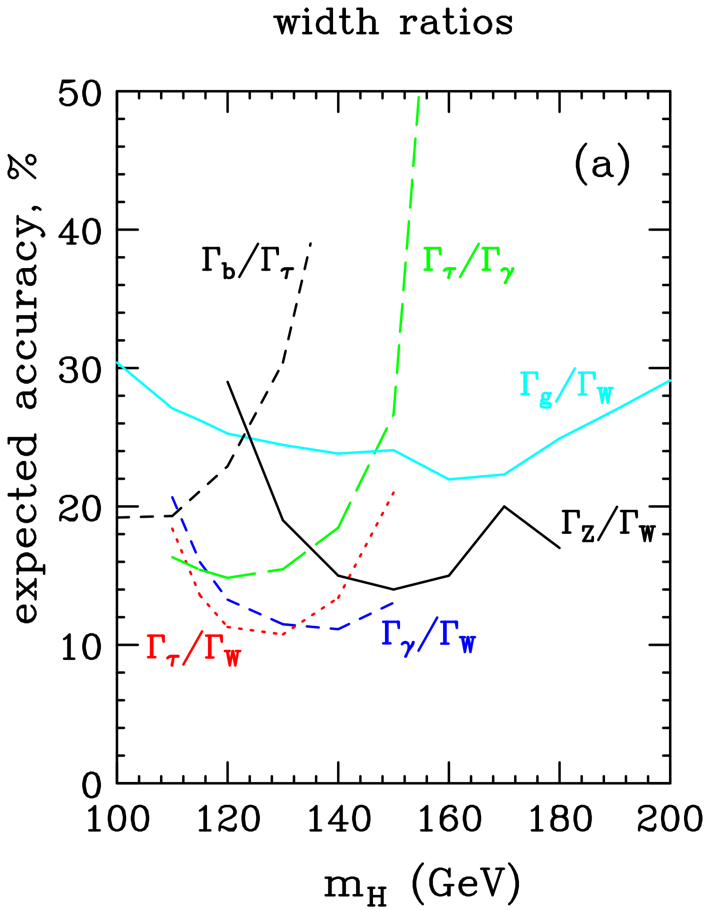
$$f^2 \Gamma > \sum_{obs.} f \Gamma_x \qquad \Longrightarrow \qquad f > \sum_{obs.} \frac{\Gamma_x}{\Gamma} = \sum_{obs.} BR(H \to xx) (= \mathcal{O}(1))$$

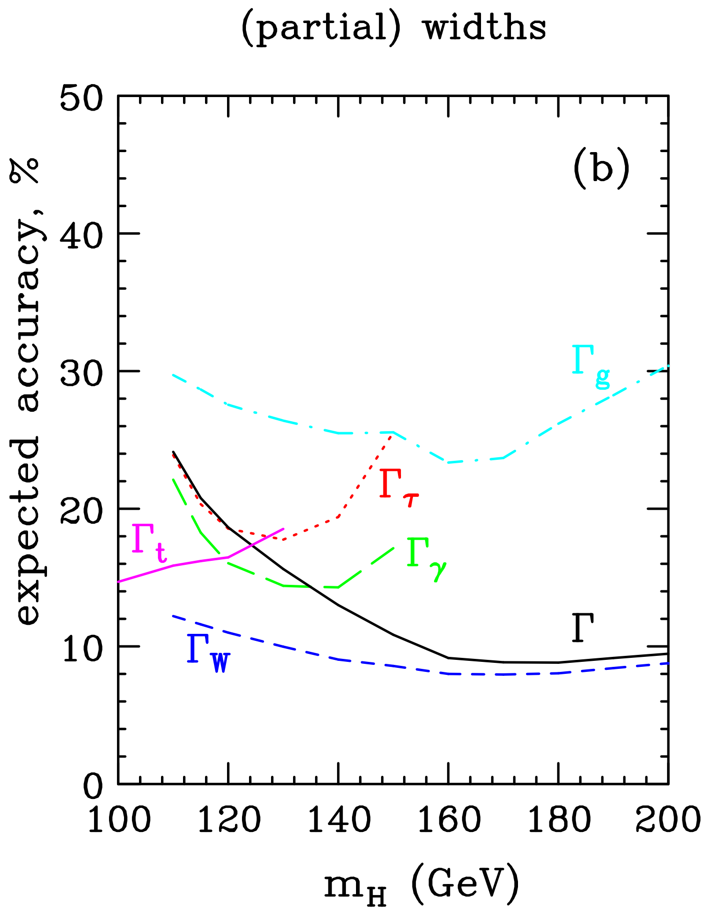
Total width below experimental resolution of Higgs mass peak ($\Delta m = 1 \ldots 20$ GeV)

$$f^2 \Gamma < \Delta m \qquad \Longrightarrow \qquad f < \sqrt{\frac{\Delta m}{\Gamma}} < \mathcal{O}(10 - 40)$$

Fit LHC data within constrained models

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





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

Distinguishing the MSSM Higgs sector from the SM

Alternative: compare data to predictions of specific models

Example: m_H^{max} scenario of LEP analyses

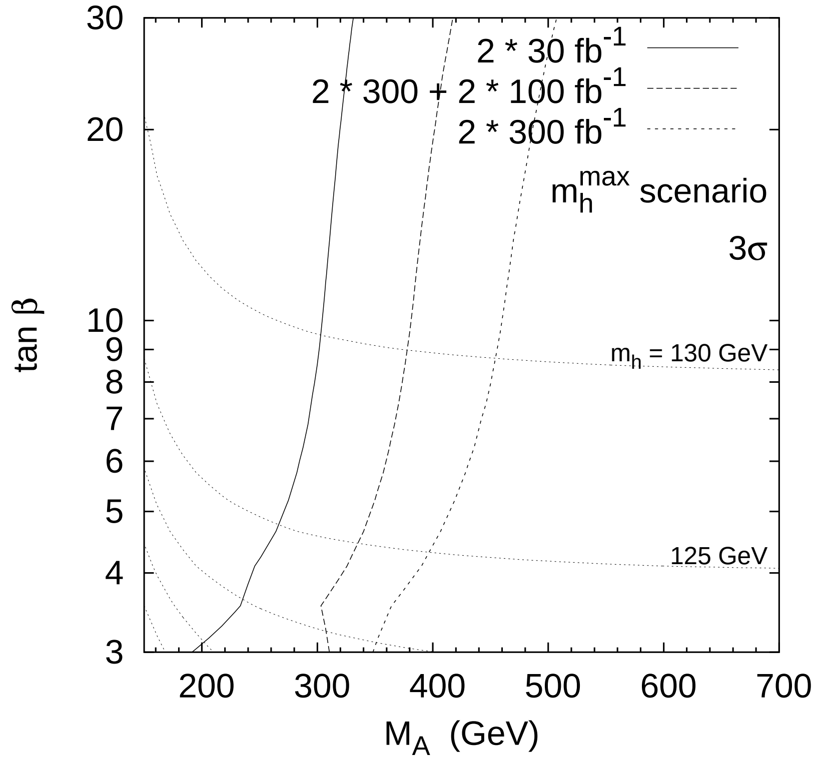
Consider modest m_A:

- decoupling almost complete for hWW and $h\gamma\gamma$ (effective) vertices
- enhanced hbb and $h\tau\tau$ couplings compared to SM increases total width of h

$\Longrightarrow$

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

3σ-effects or more at small m_A



Corrections for Higgs production cross sections

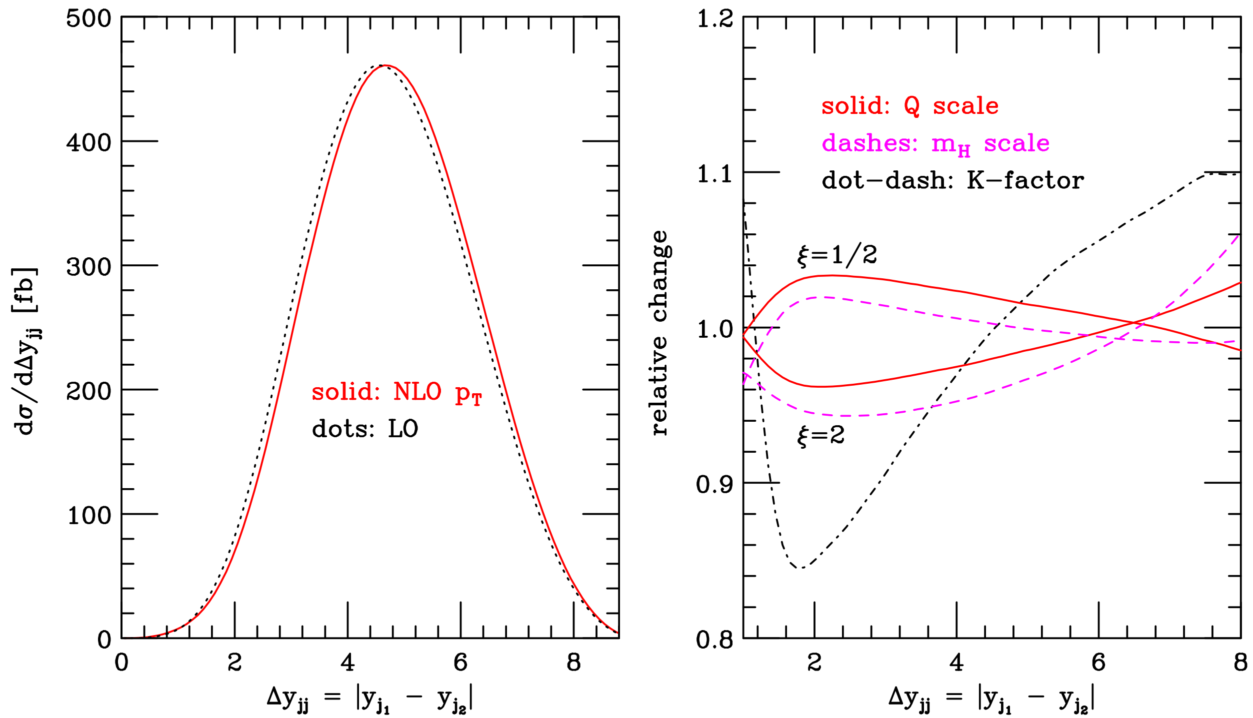
Measurement of partial widths at 10–20% level or couplings at 5–10% level requires predictions of SM production cross sections at 10% level or better

$\Longrightarrow$ 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

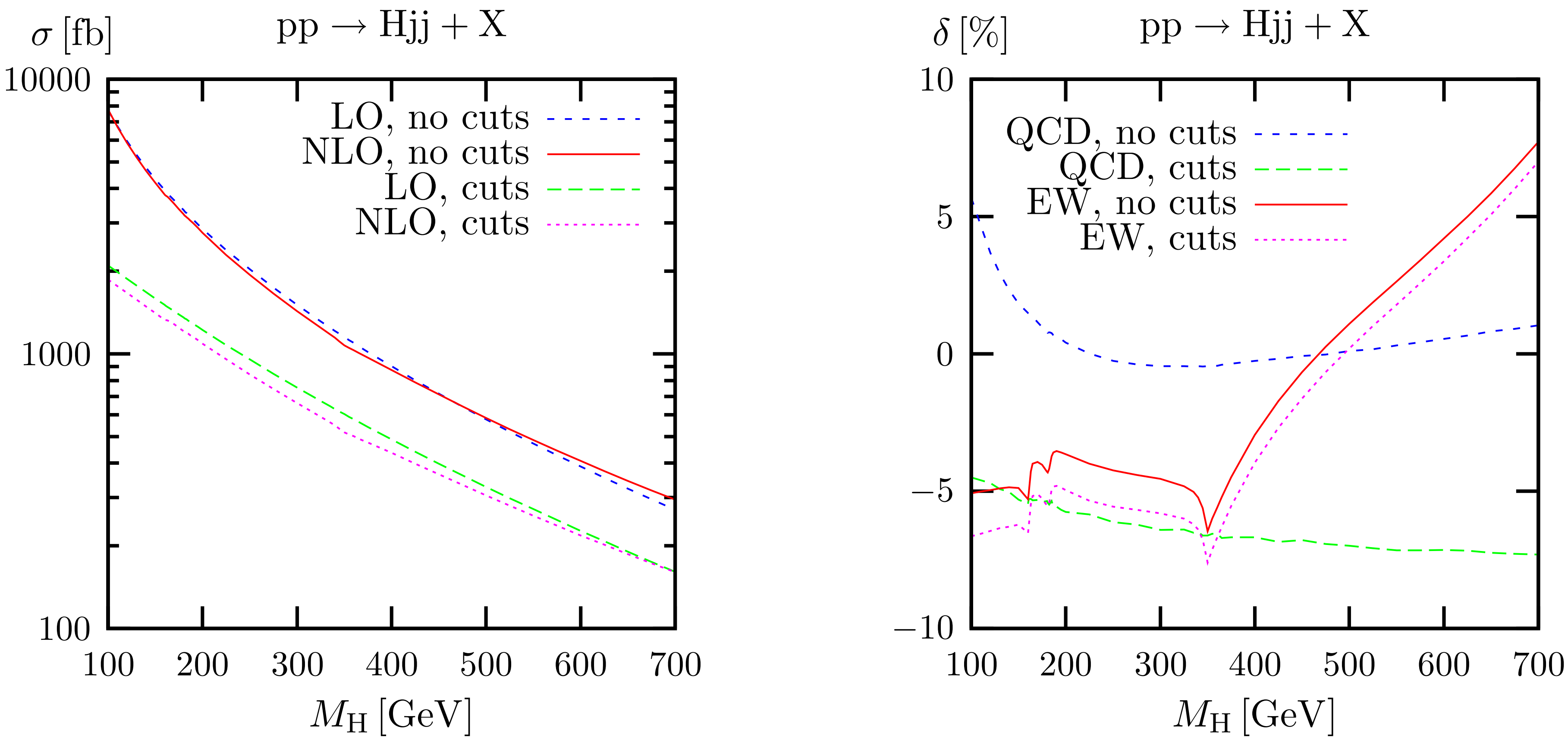
- ✓ Small QCD corrections of order 10%
- ✓ Tiny scale dependence of NLO result
  - $\pm 5\%$ for distributions
  - $< 2\%$ for σ_{total}
- ✓ K-factor is phase space dependent
- ✓ QCD corrections under excellent control
- ✗ Need electroweak corrections for 5% uncertainty



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

QCD + EW corrections to Hjj production

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

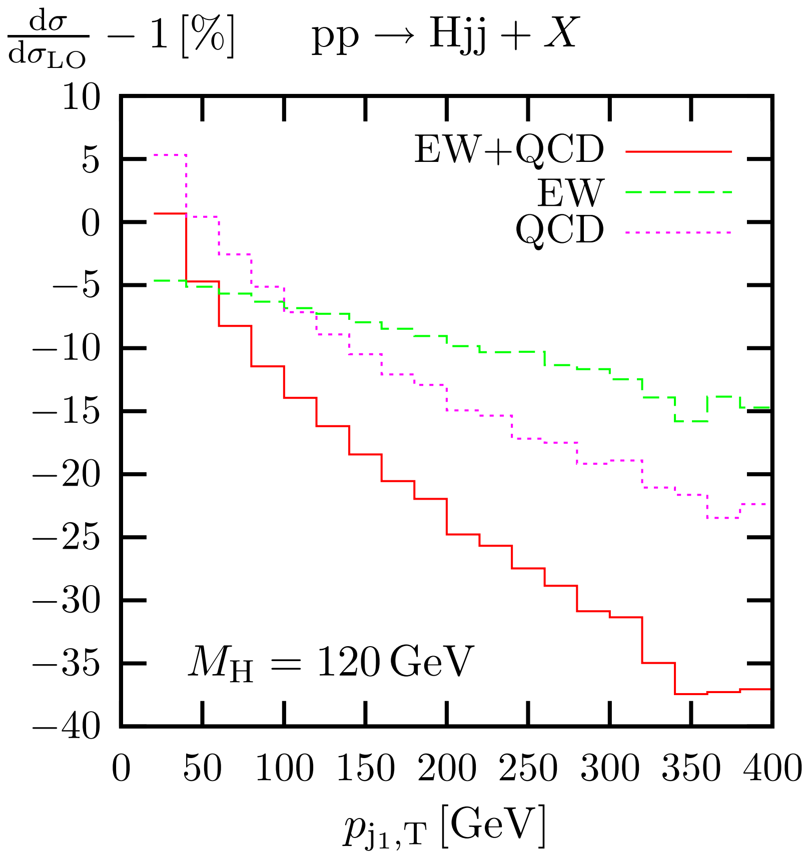


Ciccolini, Denner, Dittmaier, arXiv:0710.4749

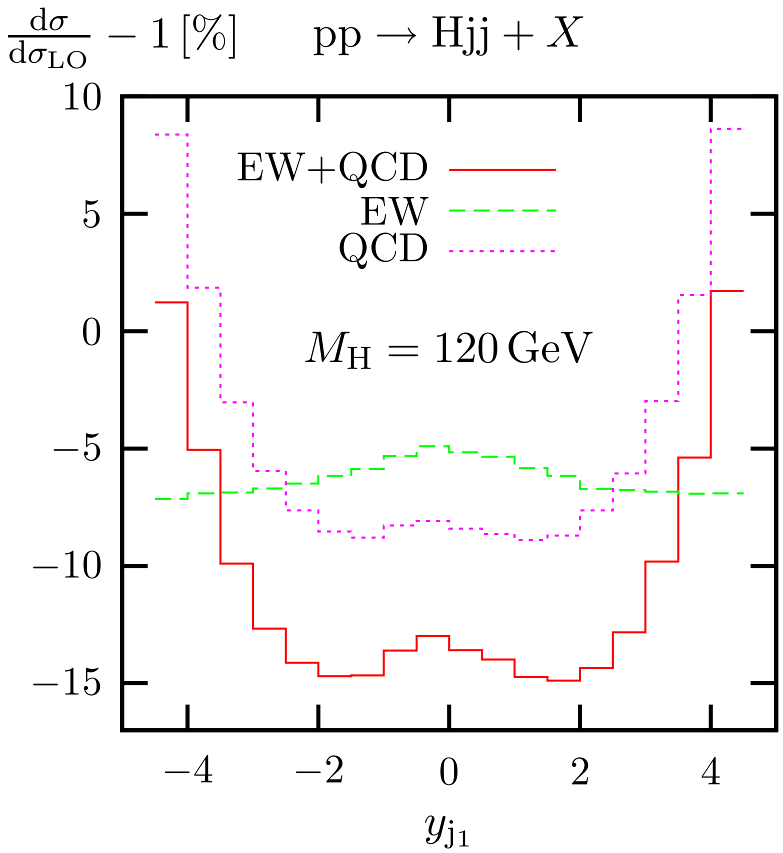
Relative size of 1-loop corrections

Consider distributions of hardest jet in the event:

p_T distribution



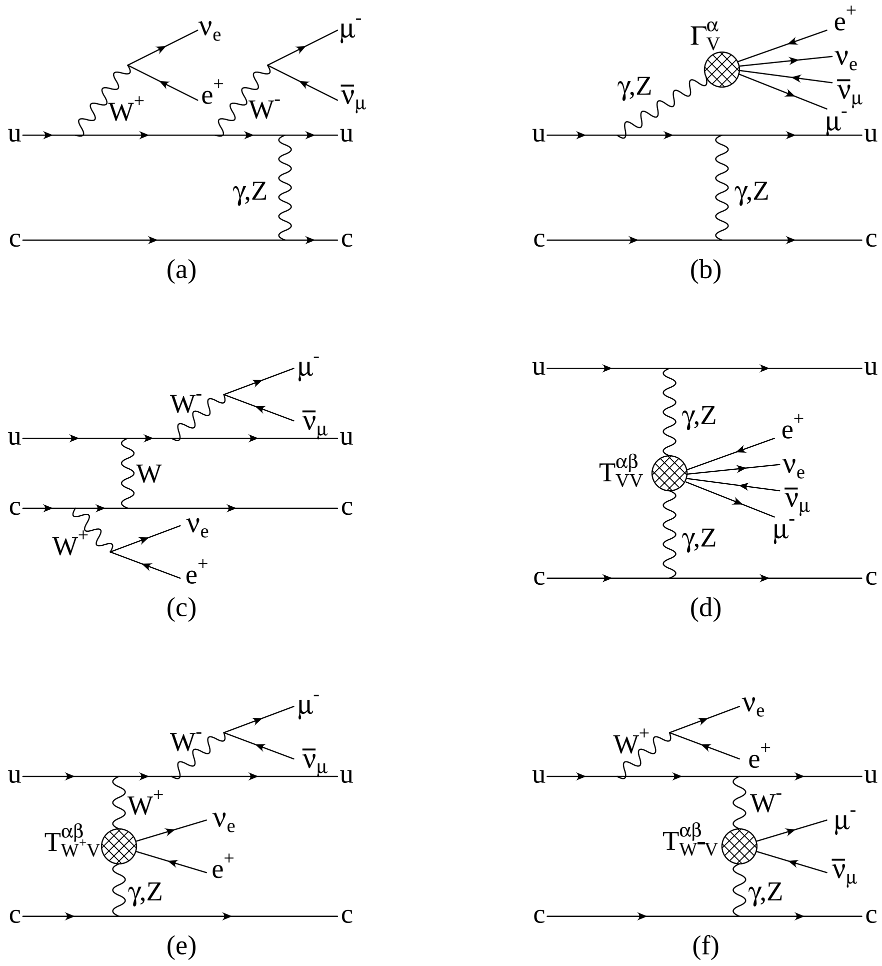
rapidity distribution



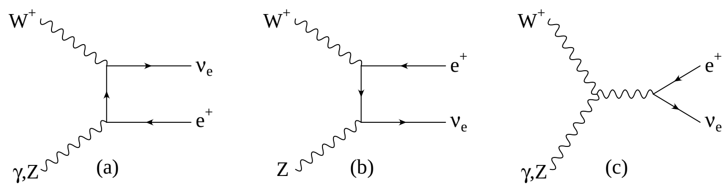
strong shape changes by QCD corrections, EW corrections affect mostly normalization

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

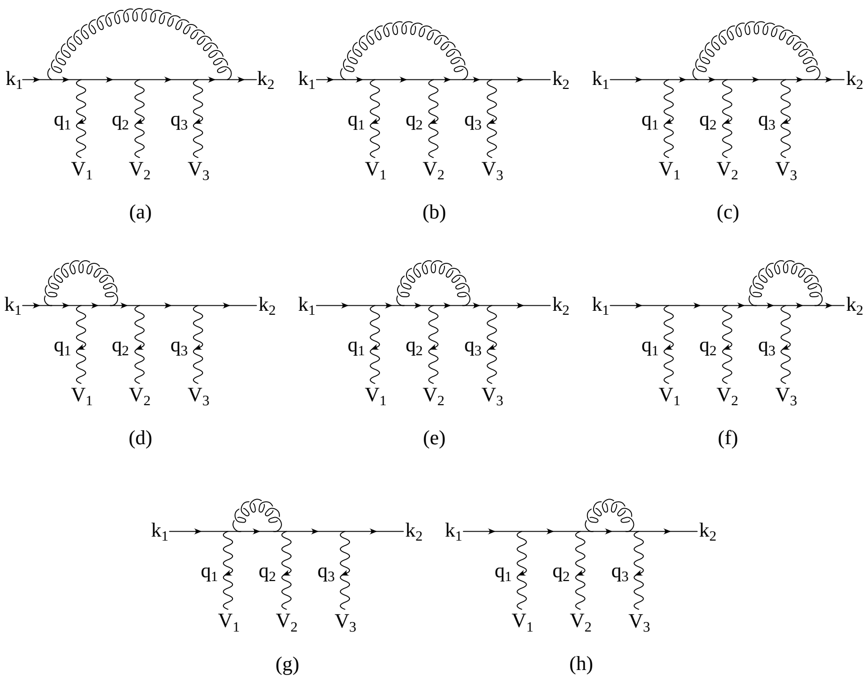


Calculate once, reuse in different processes

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

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

- 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

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

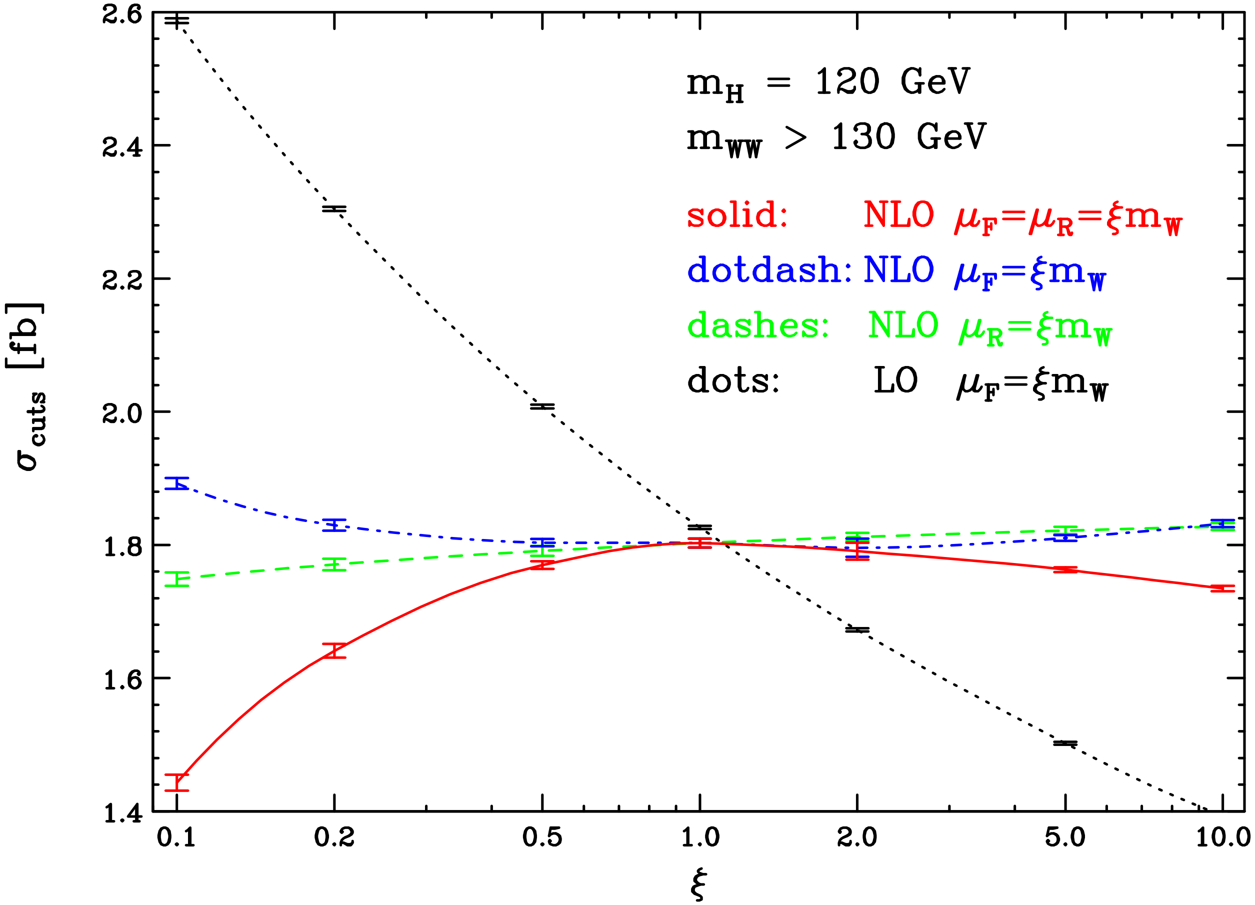
For scale dependence studies we have considered

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

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

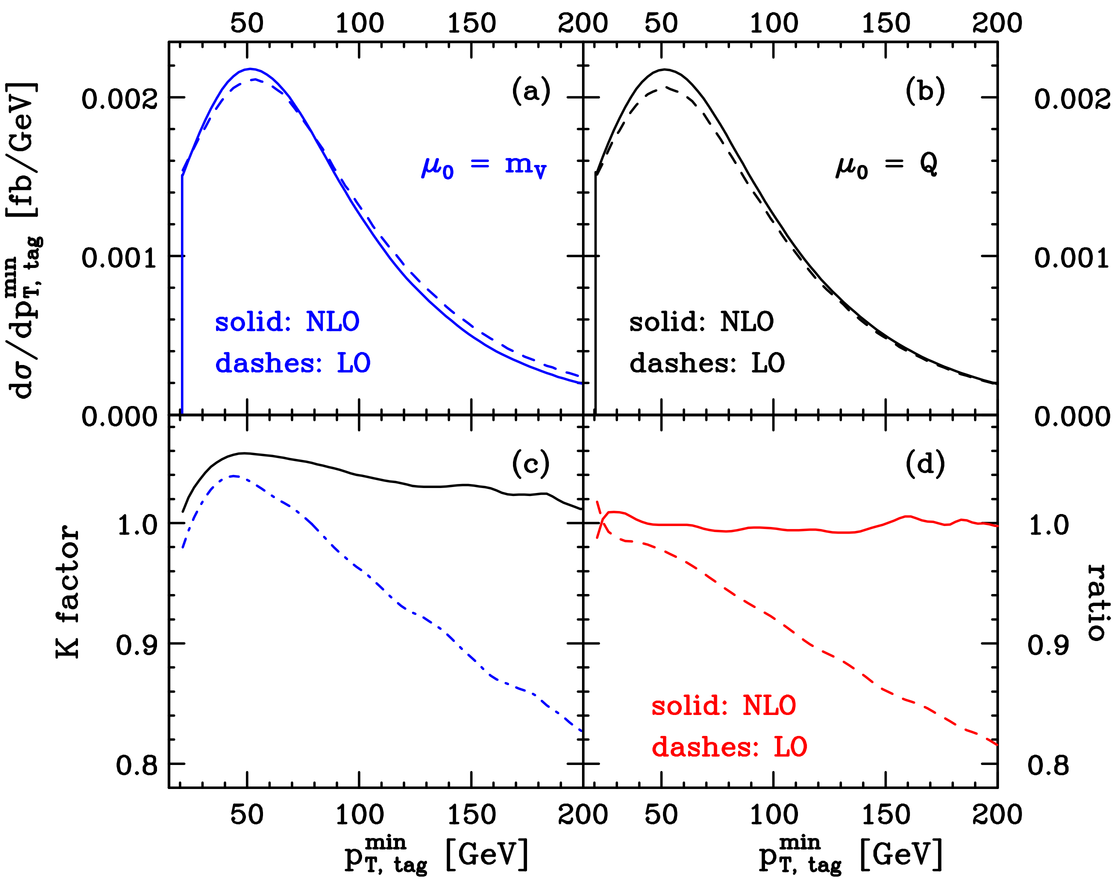
Stabilization of scale dependence at NLO

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

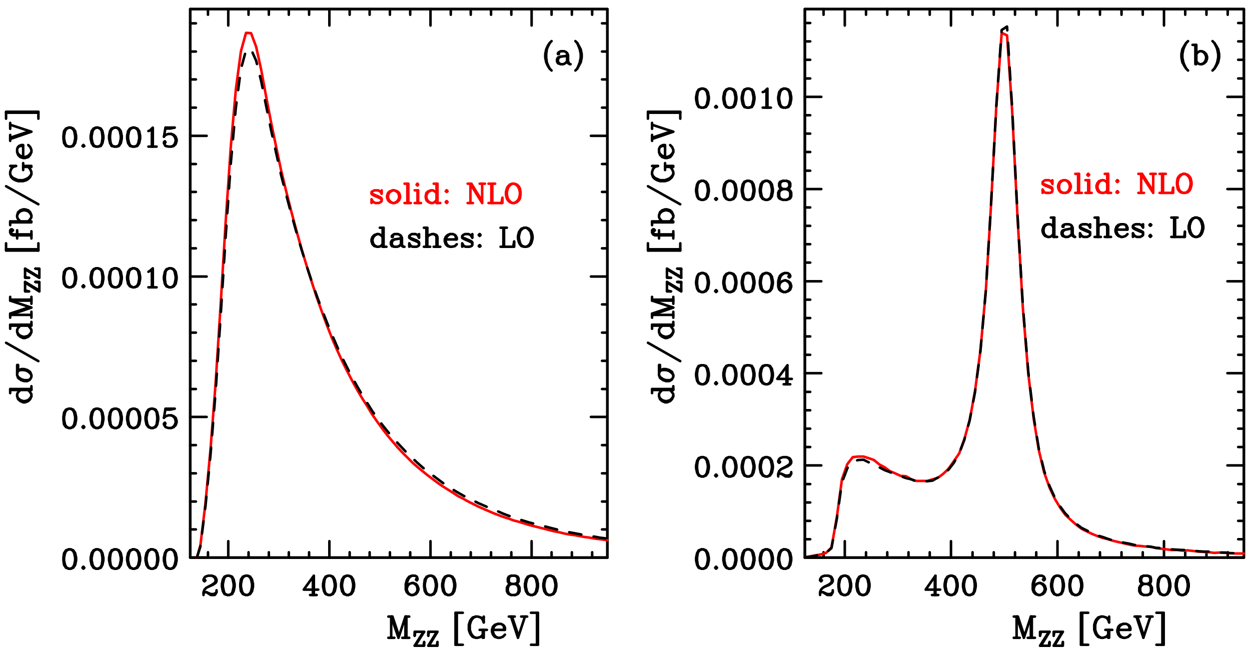


- Shape comparison LO vs. NLO depends on scale
- Scale choice $\mu = Q$ produces approximately constant K-factor
- Ratio of NLO curves for different scales is unity to better than 2%: scale choice matters very little at NLO

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

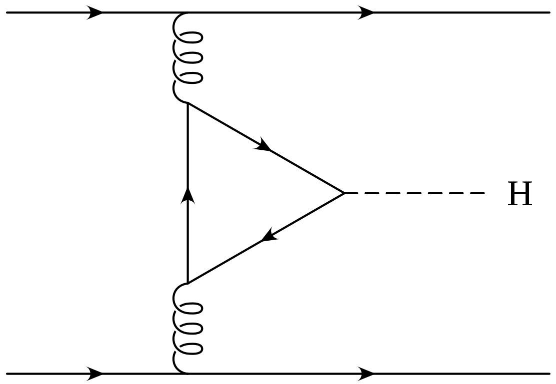


Good agreement of LO and NLO due to low scale choice $\mu = m_Z$. Alternative choice $\mu = m_H$ or $\mu = m_{4\ell}$ leads to smaller LO cross section at high $m_{4\ell}$

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, ...

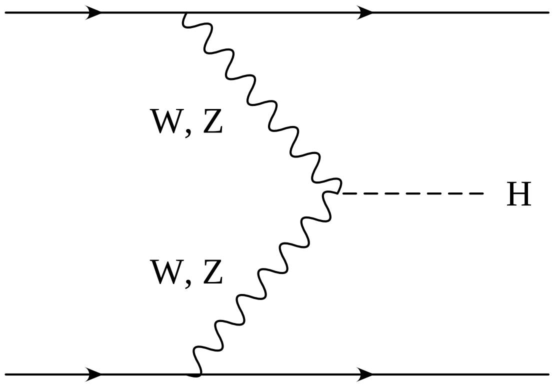
Available at http://www-itp.physik.uni-karlsruhe.de/∼vbfnloweb/

How to distinguish gluon fusion and VBF?



(a)

vs.



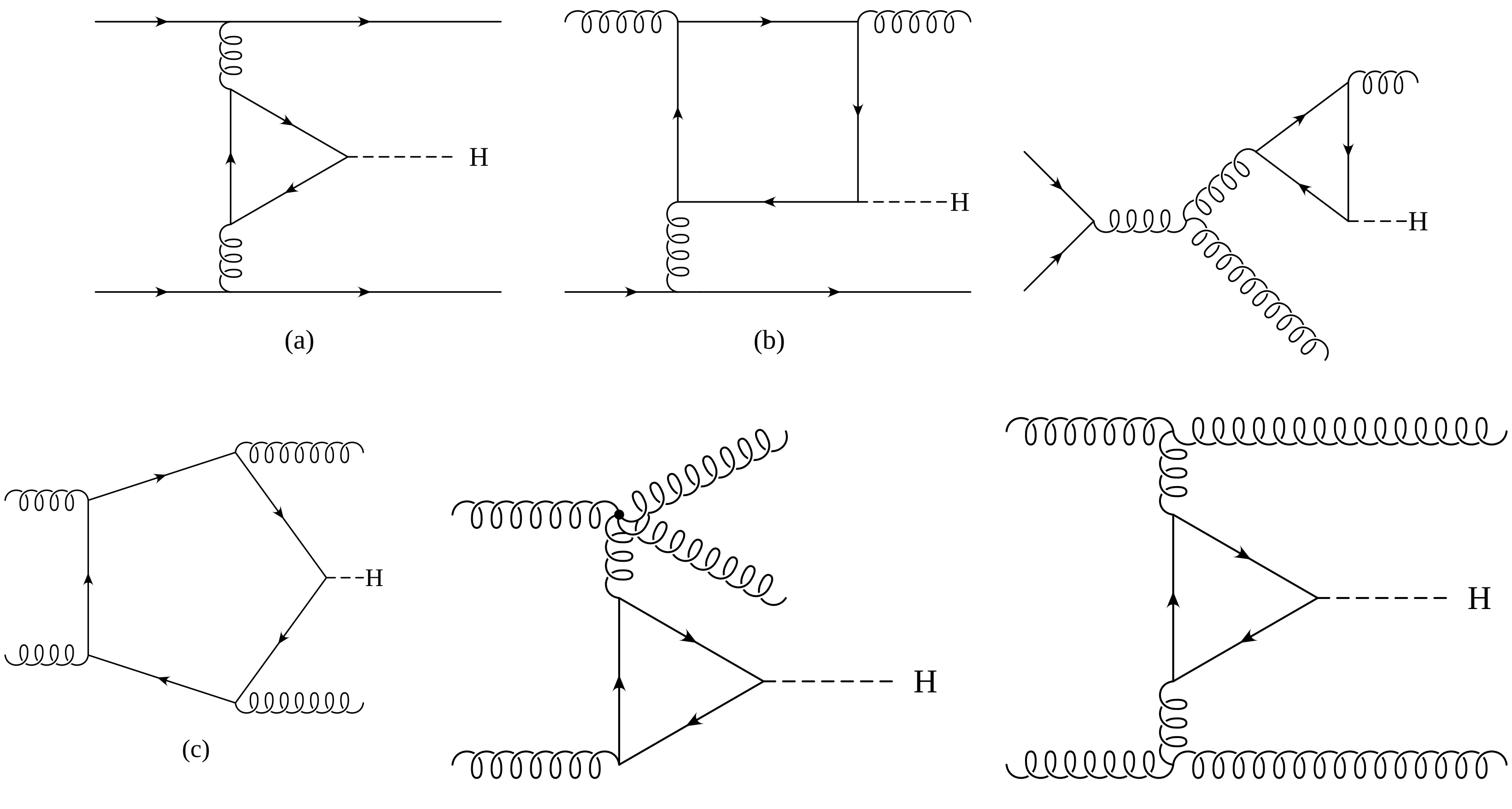
Double real corrections to $gg \to H$ can "fake" VBF

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

$\Longrightarrow$ derive cuts to be applied to enhance VBF with respect to gluon fusion.
Measure HWW and HZZ coupling

$\Longrightarrow$ derive cuts to be applied to enhance gluon fusion with respect to VBF.
Measure effective Hgg coupling or Htt coupling

Diagrams for gg fusion with finite m_t effects



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

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

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 $H \to W^+W^- \to l^+l^-\nu\bar{\nu}$, $(l = e, \mu)$
- $m_H = 160\,\text{GeV}$

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

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

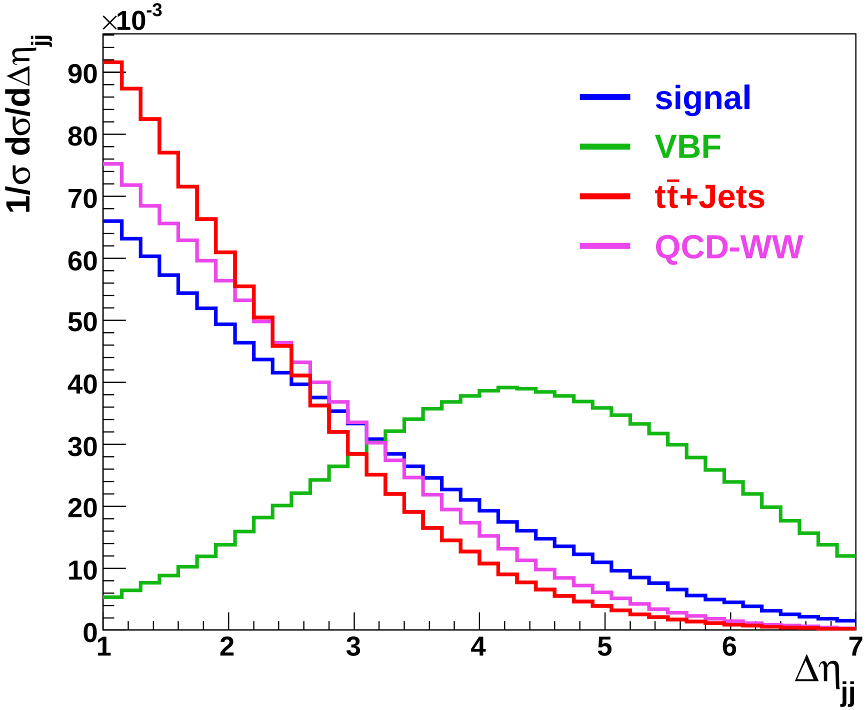
- separation of jets and leptons

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

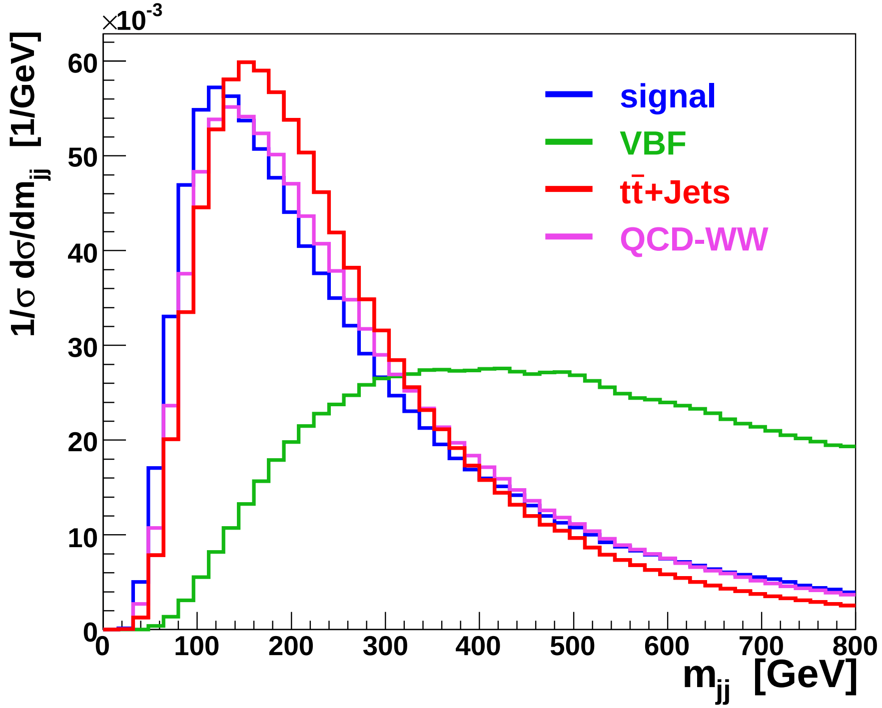
process	σ [fb]
GF $pp \to H + jj$	**115.2**
VBF $pp \to W^+W^- + jj$	**75.2**
$pp \to t\bar{t}$	**6832**
$pp \to t\bar{t} + j$	**9518**
$pp \to t\bar{t} + jj$	**1676**
QCD $pp \to W^+W^- + jj$	**363**

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

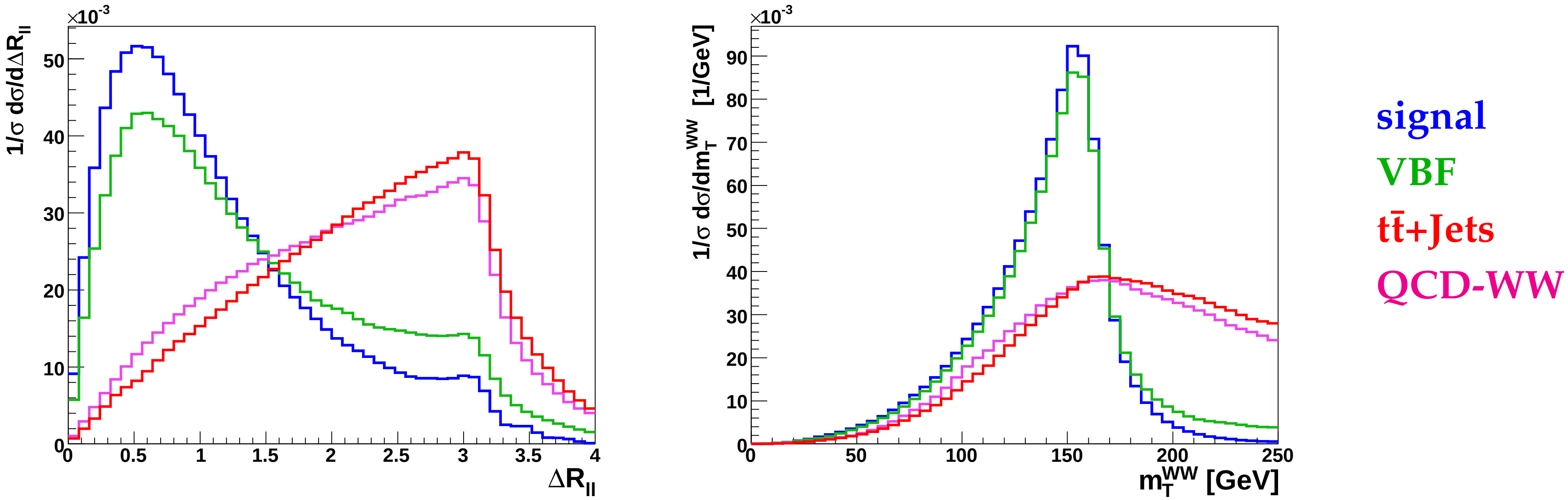
- b-tagging for reduction of top-backgrounds. *(CMS Note 06/014)*
  - (η, p_T) - dependent tagging-efficiencies (60% - 75%) with 10% mistagging - probability

- selection cuts:

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

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

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



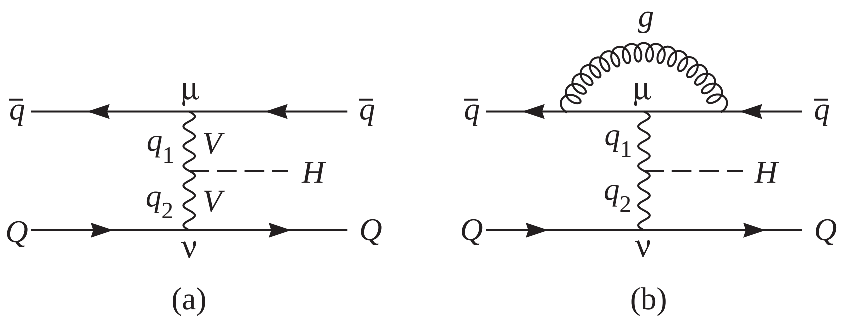
Results

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**

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

Tensor structure of the HVV coupling

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



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

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

Physical interpretation of terms:

SM Higgs $\qquad \mathcal{L}_I \sim H V_\mu V^\mu \longrightarrow \; a_1$

loop induced couplings for neutral scalar

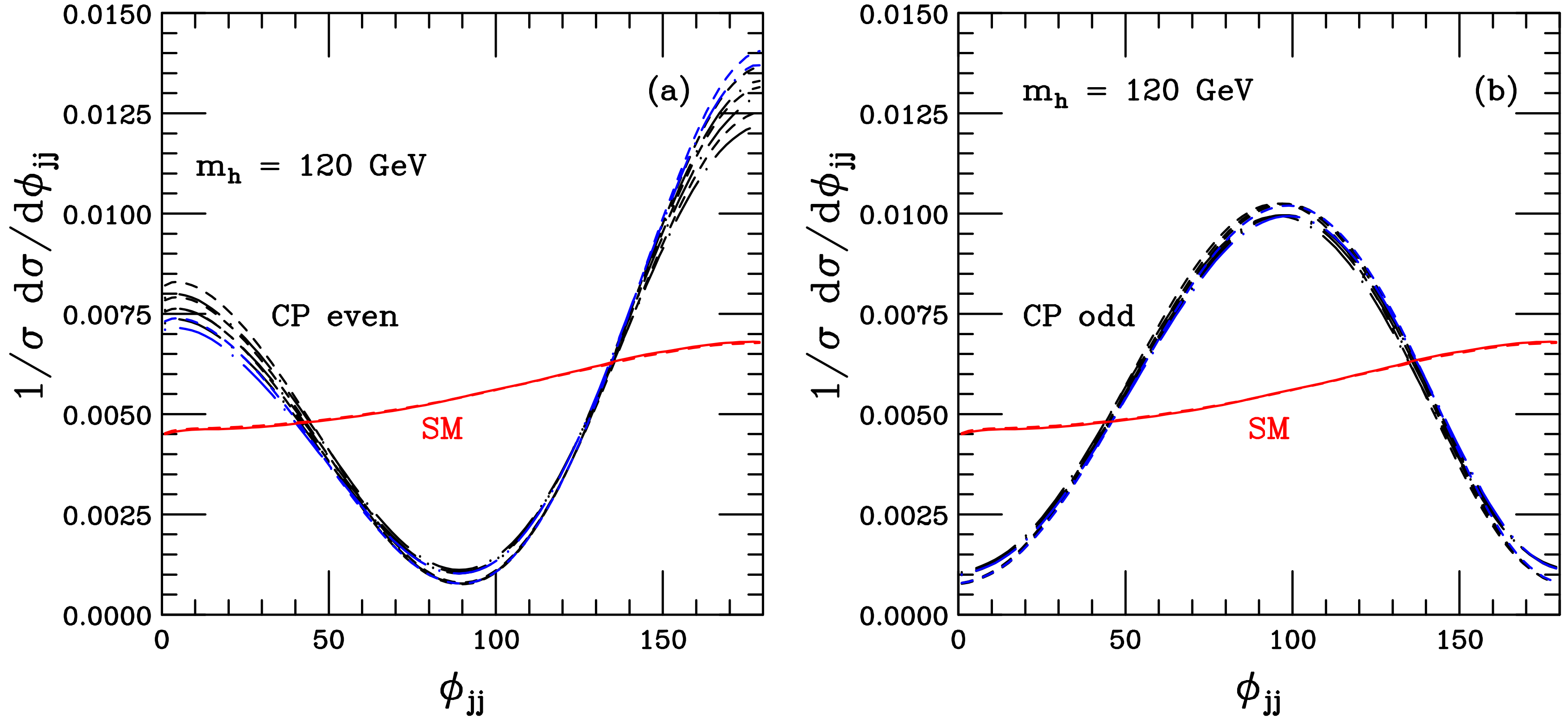
CP even $\qquad \mathcal{L}_{eff} \sim H V_{\mu\nu} V^{\mu\nu} \longrightarrow \; a_2$

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

Must distinguish a_1, a_2, a_3 experimentally

Azimuthal angle correlations

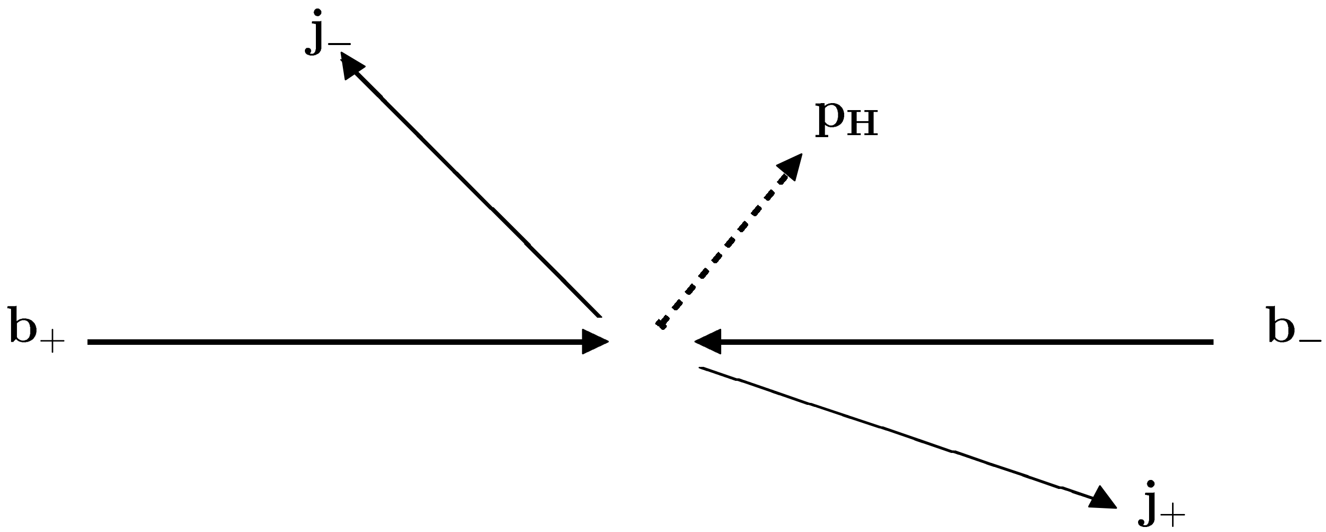
Tell-tale signal for non-SM coupling is azimuthal angle between tagging jets



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:



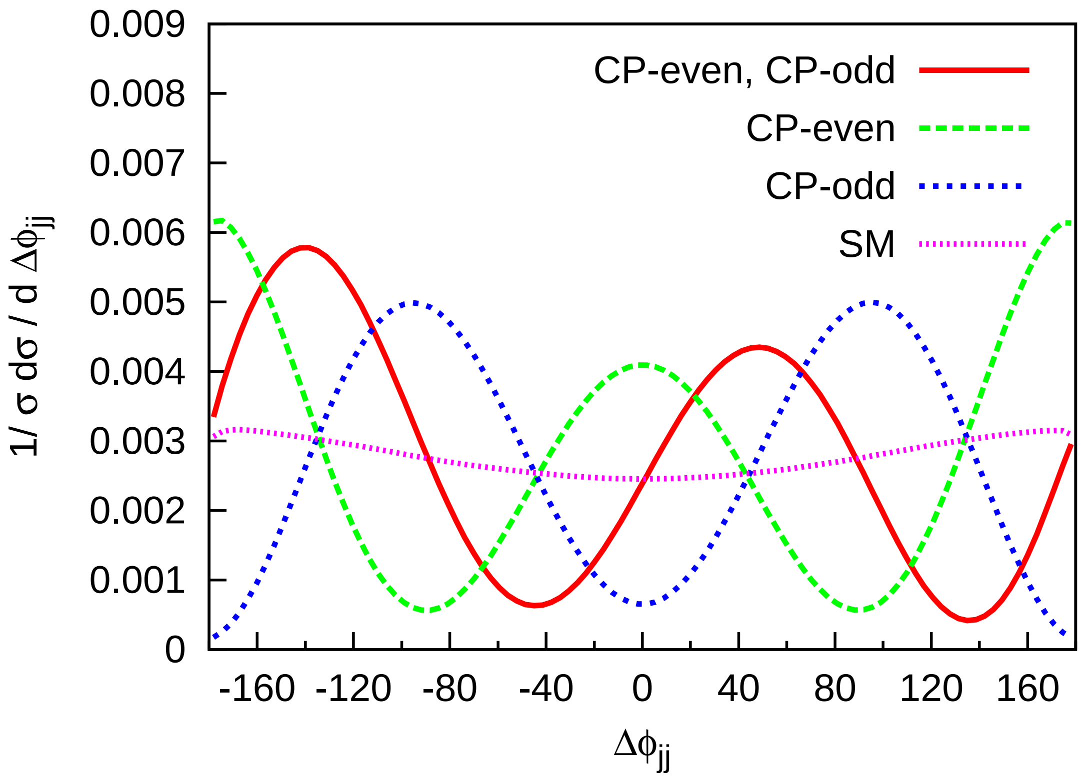
Define azimuthal angle between jet momenta j_+ and j_- via

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

- $\Delta\phi_{jj}$ 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

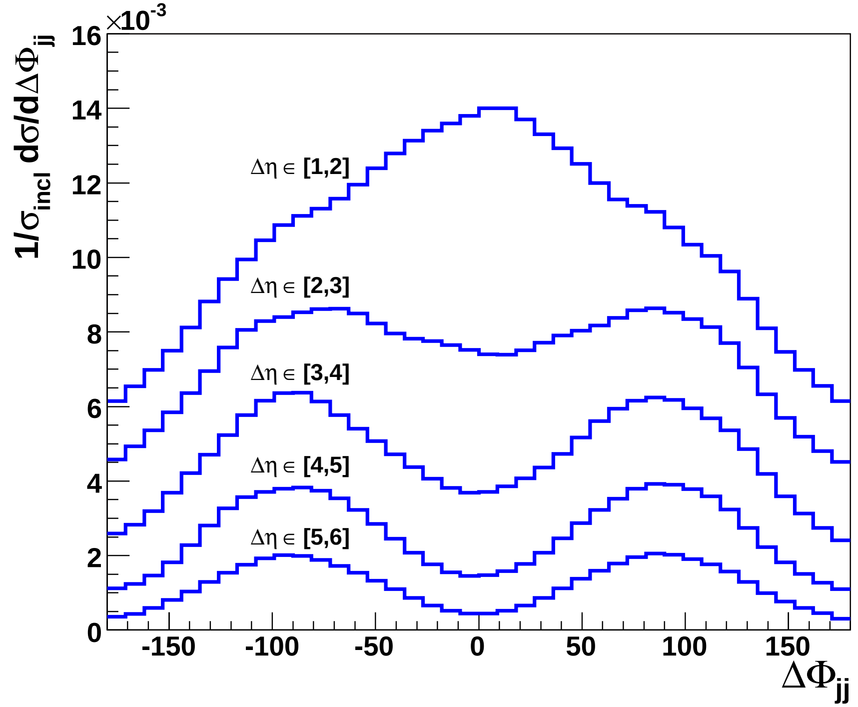
$$a_1 = 0, \qquad a_2 = d\ \cos\alpha, \qquad a_3 = d\ \sin\alpha,$$

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

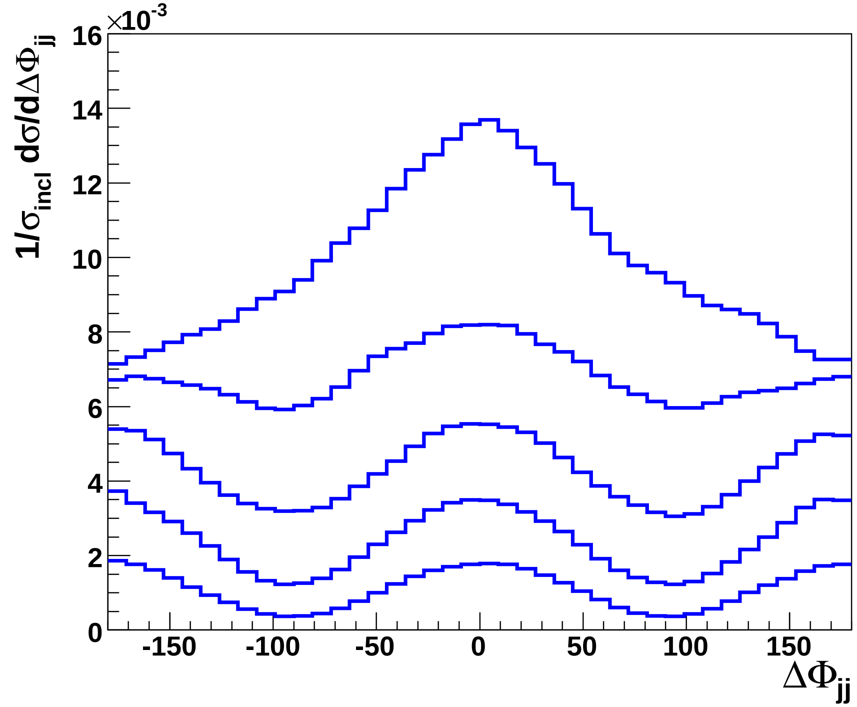
Gluon fusion: structure of Hgg vertex

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

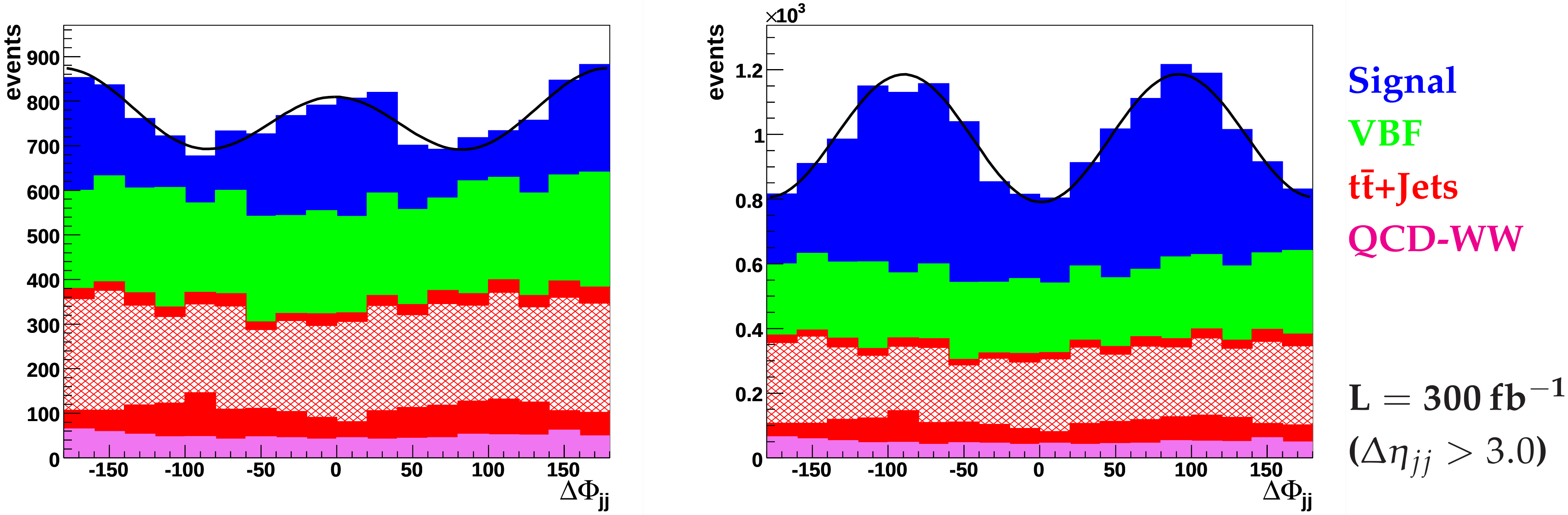


CP-odd coupling



$\Delta\Phi_{jj}$-Distribution in gluon fusion: $\Delta\eta_{jj} > 3$

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

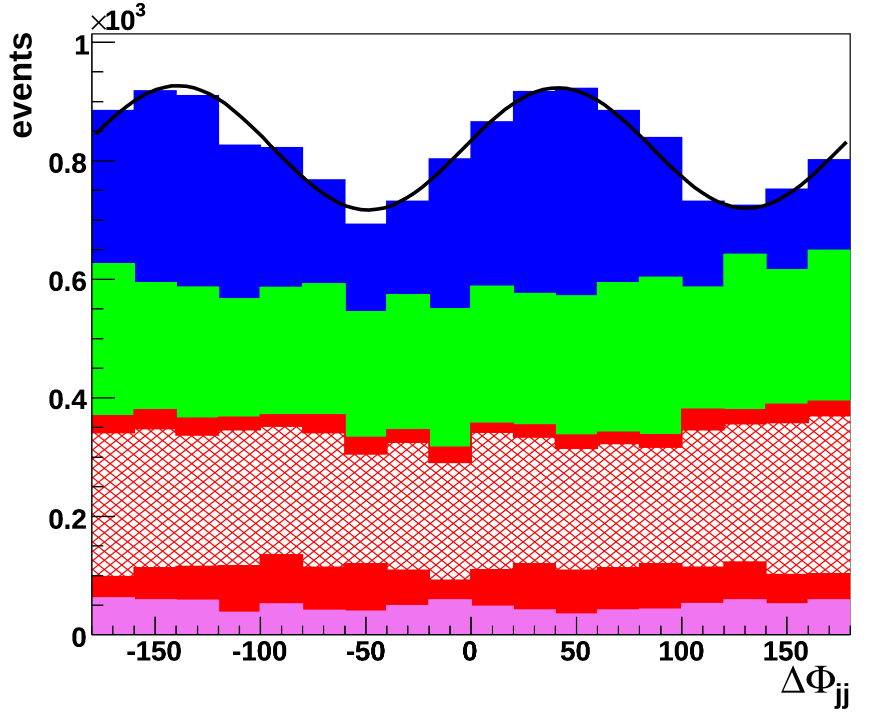


CP-even
$A = 0.100 \pm 0.039$
$\Delta\Phi_{max} = 5.8 \pm 15.3$

CP-odd
$A = 0.199 \pm 0.034$
$\Delta\Phi_{max} = 93.7 \pm 5.1$

fit of the background only : $A = 0.069 \pm 0.044$ and $\Delta\Phi_{max} = 64 \pm 25$
(mean values of 10 independent fits of data for $L = 30\ fb^{-1}$ each)

$\Delta\Phi_{jj}$-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 . . . 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

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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.
- Thank you to BMBF and DFG for generous support