LHC PHENOMENOLOGY

Dieter Zeppenfeld
Karlsruhe Institute of Technology (KIT)

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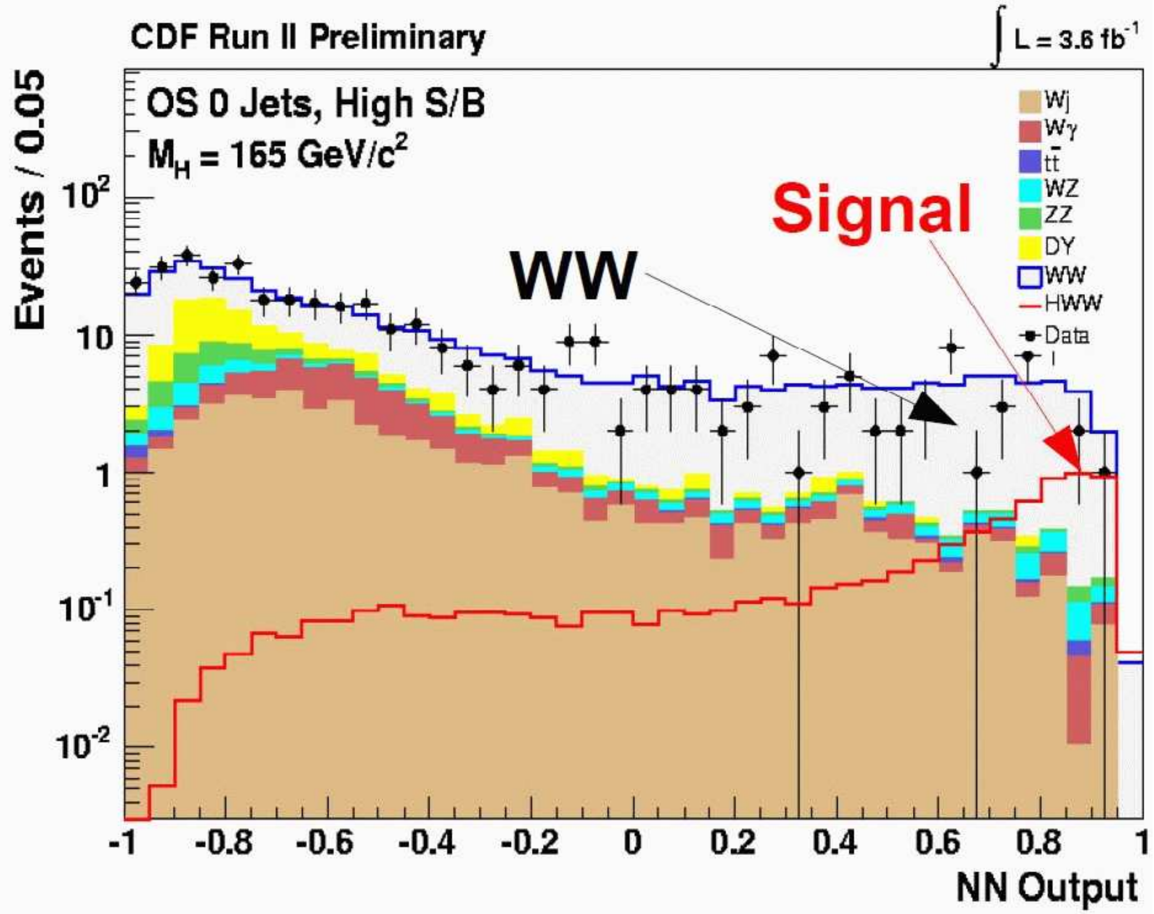
- Introduction
- 1-loop QCD corrections
  - VVV and WWj production at NLO
  - $t\bar{t}b\bar{b}$ and $Wjjj$ production
- Higgs physics
  - survey of search channels
  - coupling measurements
  - Higgs CP properties
- Conclusions

A Tevatron challenge

Search for the Higgs boson in $H \to W^+W^- \to l^+l^-\nu\bar{\nu}$



Challenge:

- Identify signal in presence of large background
- For $S/B = 1/5$, a 10% theory error of the background prediction precludes signal discovery at better than 2σ
- Must predict shapes of background distribution with high certainty

Need NLO QCD corrections for complex final states

Relevant multi-leg processes: 2005 Les Houches wish-list

process ($V \in \{Z, W, \gamma\}$)	relevant for
1. $pp \to V\,V$ jet	$t\bar{t}H$, new physics
2. $pp \to t\bar{t}\,b\bar{b}$	$t\bar{t}H$
3. $pp \to t\bar{t} + 2$ jets	$t\bar{t}H$
4. $pp \to V\,V\,b\bar{b}$	VBF→$H \to VV$, $t\bar{t}H$, new physics
5. $pp \to V\,V + 2$ jets	VBF→$H \to VV$
6. $pp \to V + 3$ jets	various new physics signatures
7. $pp \to V\,V\,V$	SUSY trilepton

Goal set in 2005: Determine NLO QCD corrections for all processes on the wish-list

Example: W^+W^-Z production

- Background for multilepton signals from chargino and neutralino decay
- Signal for measurement of quartic electroweak vector boson couplings; W', Z' vector resonances...
- Calculated by: Hankele, D.Z., arXiv:0712.3544; Binoth, Ossola, Papadopoulos, Pittau, arXiv:0804:0350

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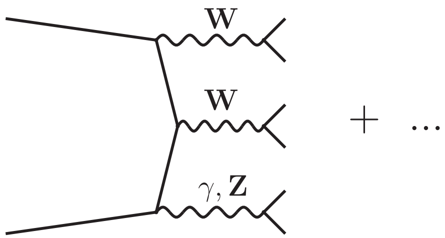

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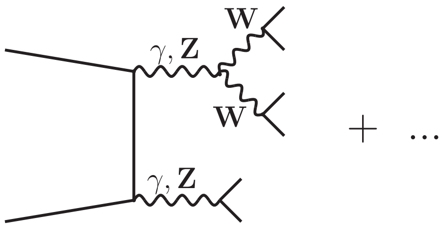

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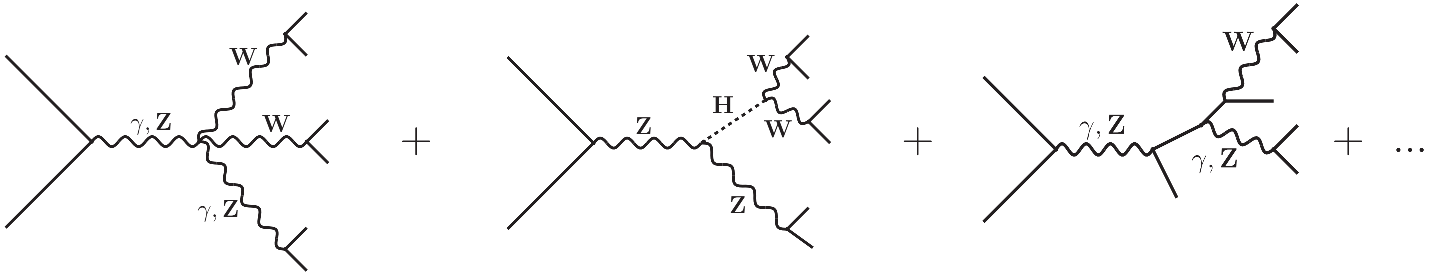


- Loop corrections up to pentagons are infrared divergent: calculate in $D = 4 - 2\epsilon$ dimensions
- Canceled by real emission contributions: attach external gluon in all possible ways

Catani Seymour Dipole Subtraction

Generic structure of NLO corrections for a 2→m process: $\sigma = \sigma^{Born} + \Delta\sigma^{NLO}$

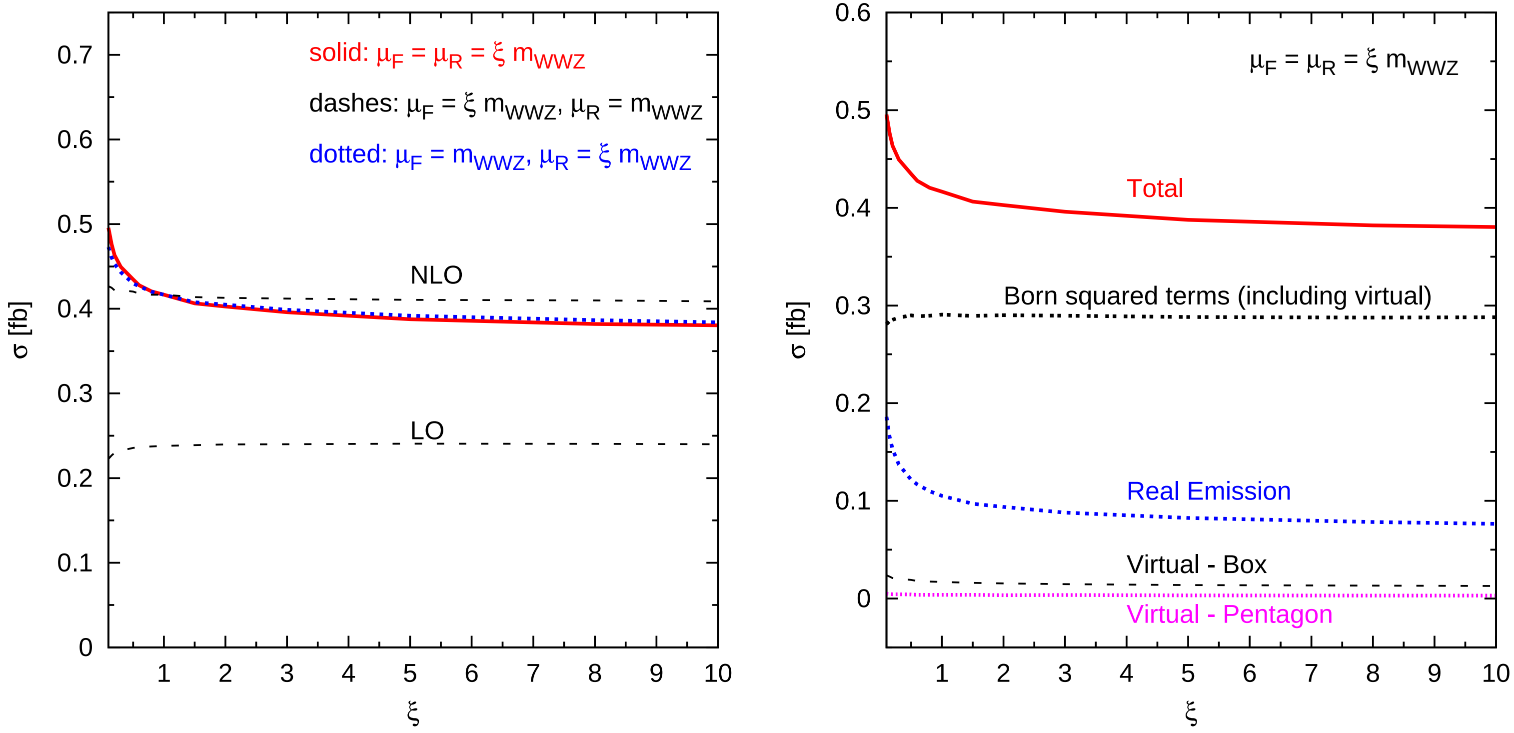
$$\Delta\sigma^{NLO} = \int d\sigma^{NLO} = \int_{m+1} d\sigma^R + \int_m d\sigma^V + \int_m d\sigma^C$$

- $\int_{m+1} d\sigma^R$ and $\int_m d\sigma^V$ are separately IR divergent in 4 dimensions
  $\Longrightarrow$ Use dimensional regularization/dimensional reduction
- Introduce local counter-term $d\sigma^A$ with the same singular behavior as $d\sigma^R$.

$$\Delta\sigma^{NLO} = \underbrace{\int_{m+1}\left[\left(d\sigma^R\right)_{\epsilon=0} - \left(d\sigma^A\right)_{\epsilon=0}\right]}_{\text{Can be integrated numerically in 4 dimensions.}} + \underbrace{\int_m \left[d\sigma^V + \int_1 d\sigma^A\right]_{\epsilon=0}}_{\text{Cancel poles analytically.}} + \underbrace{\int_m d\sigma^C}_{\text{Additional finite collinear term.}}$$

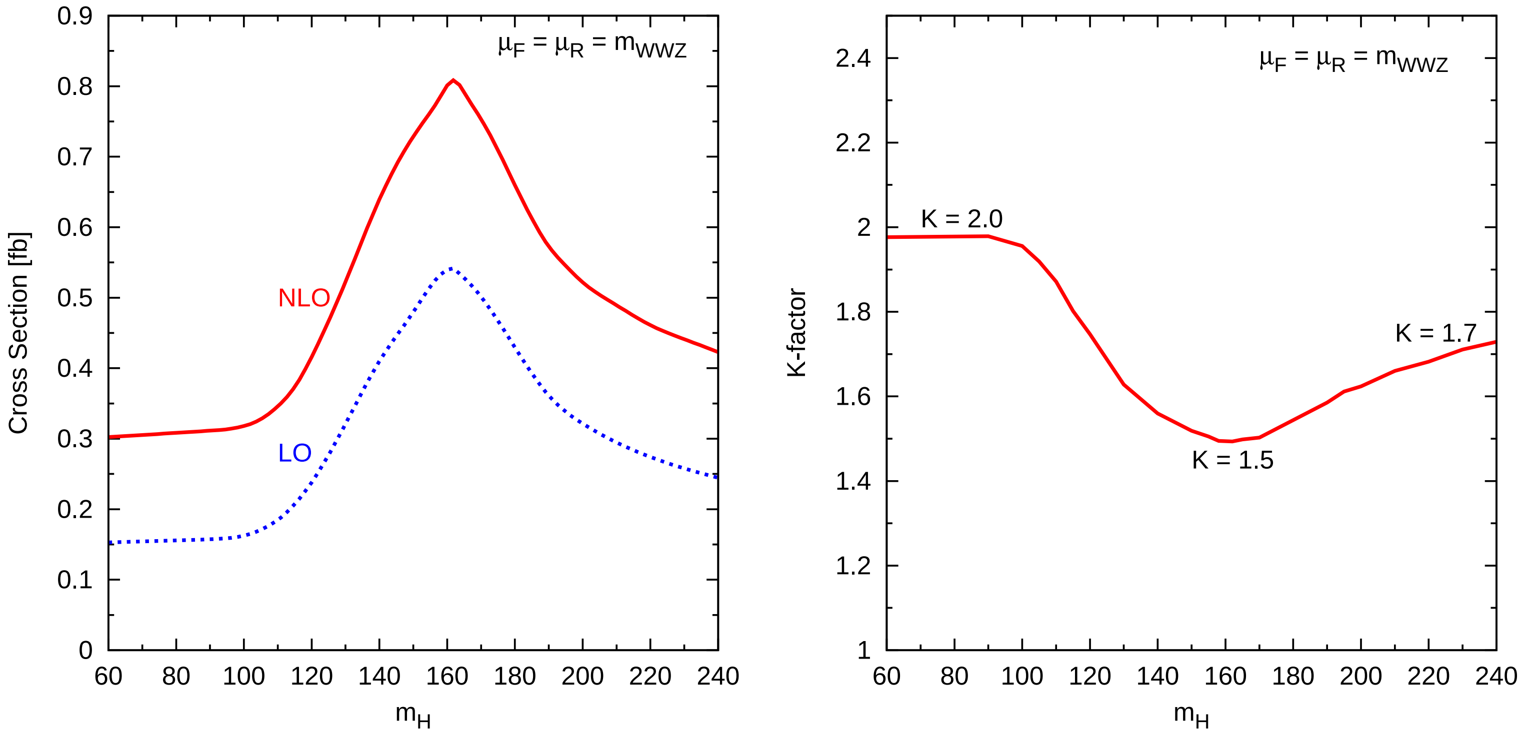
Scale dependence for m_{WWZ} as reference scale

Cross section including leptonic decay to e or μ and cuts: $p_{Tl} > 10$ GeV, $|\eta_l| < 2.5$, $m_{ll} > 15$ GeV



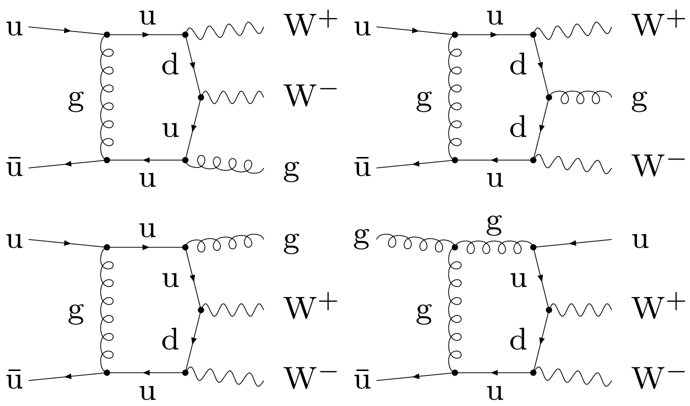
- Enhancement of cross section by NLO correction: factor $K = \frac{\sigma^{NLO}}{\sigma^{LO}} \approx 1.8$
- Scale dependence larger at NLO but still in 10% range

Higgs mass dependence of WWZ cross section

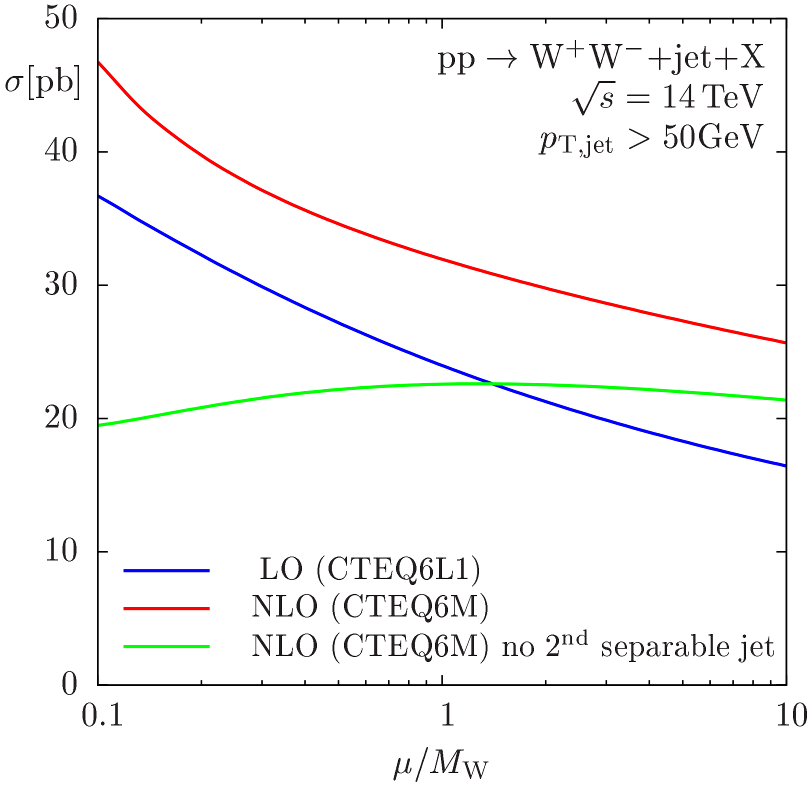


- K-factor is reduced when pure vertex graphs dominate.
- Compare K-factor for $pp \rightarrow ZH$ production, which is about K = 1.3

W^+W^- jet production



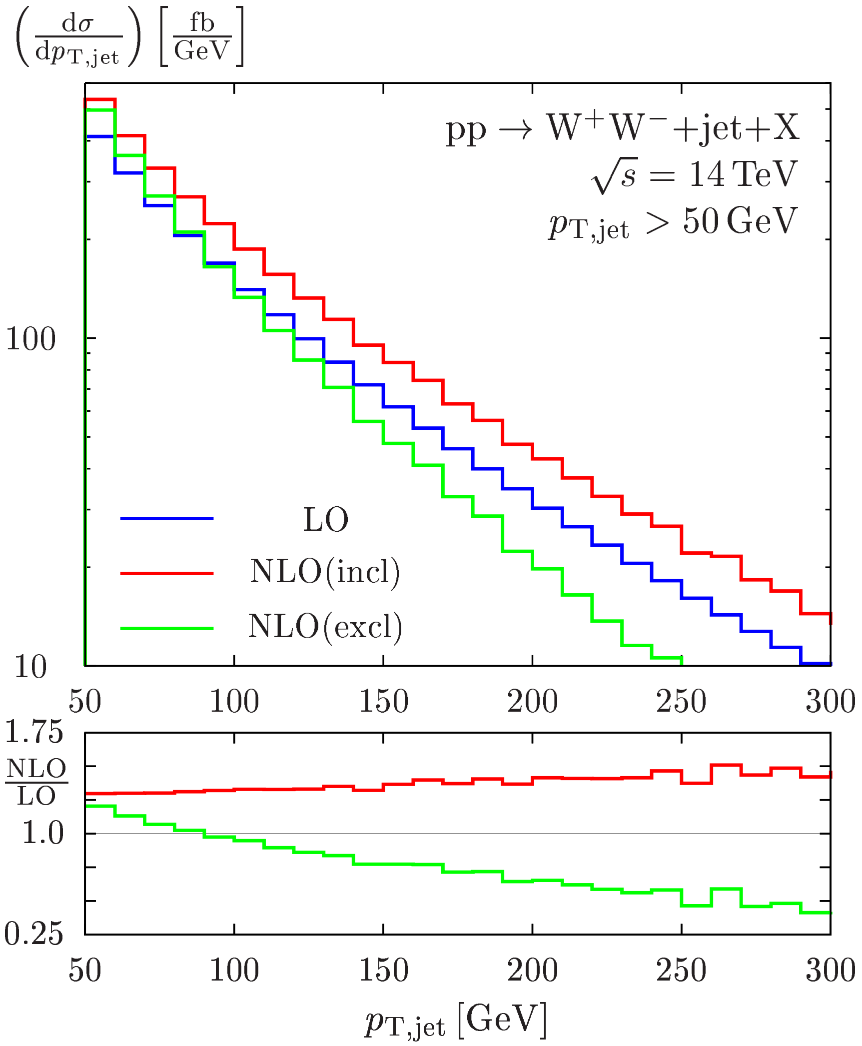
- Loops up to pentagons
- Larger number of subtraction terms in Catani-Seymour algorithm: 10 (instead of 2) combinations for soft/collinear parton with emitter and spectator parton
- Scale dependence reduced for exclusive 1-jet final state (veto on second jet)



Calculations published by two groups: Dittmaier, Kallweit, Uwer, arXiv:0710.1577

Campbell, Ellis, Zanderighi, arXiv:0710.1832

NLO effect on jet transverse momentum



- Approximately constant K-factor for 1-jet inclusive distribution
- A jet veto dramatically reduces cross section at NLO at high p_T
- A large fraction of high p_T WWj events has two or more jets

New frontier: 2⟶4 processes

- Effective 2⟶3 processes (like $pp \to Hjj$, $pp \to VVjj$ in VBF, $pp \to WWW$, $pp \to WWj$, $pp \to t\bar{t}H$, $pp \to t\bar{t}j$ etc.) lead to virtual contributions with up to pentagon diagrams.
- Many 2⟶3 processes at the LHC are now available with NLO QCD corrections
- Going to 2⟶4 processes requires the calculation of hexagon virtual diagrams
- Techniques are in place but calculations become much more complex
- Two brand new results available for LHC phenomenology

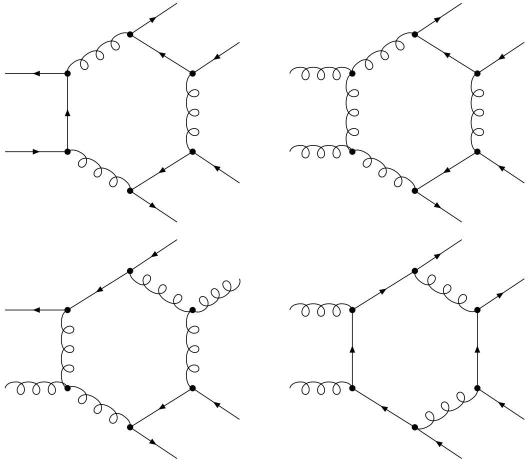
  $t\bar{t}b\bar{b}$ production: Bredenstein, Denner, Dittmaier, Pozzorini, axXiv:0905.0110

  $W+3$ jet production: (in leading color approximation)

  C. F. Berger et al. (Blackhat and Sherpa), arXiv:0902.2760; Ellis, Melnikov, Zanderighi, arXiv:0906.1445

$t\bar{t}b\bar{b}$ production at NLO

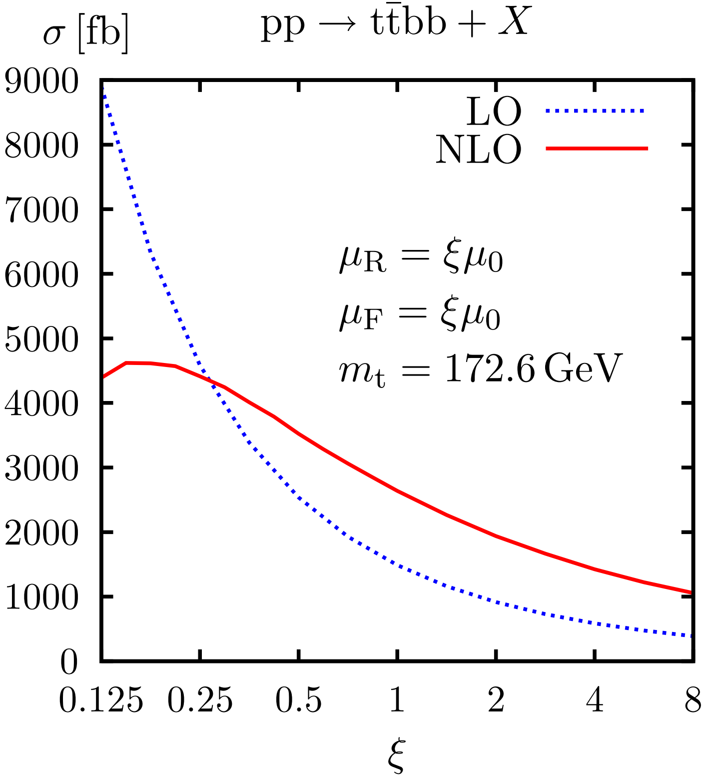
LO contributions from subprocesses
$q\bar{q}\rightarrow t\bar{t}b\bar{b}$ and $gg\rightarrow t\bar{t}b\bar{b}$
lead to virtual graphs with up to hexagons



- Virtual graph calculation based on traditional evaluation of Feynman graphs
- Decomposition of tensor integrals to a few scalar integrals and numerical stability require special care

Bredenstein et al., axXiv:0905.0110

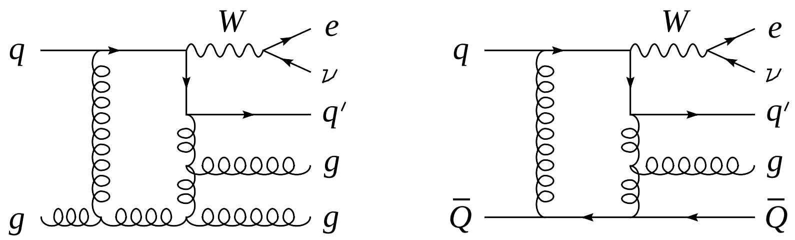
Cuts:
2 b jets with $p_T > 20$ GeV and $|y| < 2.5$



- Scale dependence substantially reduced at NLO for $\mu_R = \mu_F = \xi m_t$

$Wjjj$ production

- Many contributing Feynman graphs and subprocesses already at tree level
- Virtual contributions contain up to hexagons:



- Simplifications so far: neglect $1/N_c^2$ and n_f/N_c (fermion loop) suppressed virtual contributions

- Unitarity based methods for virtual diagrams

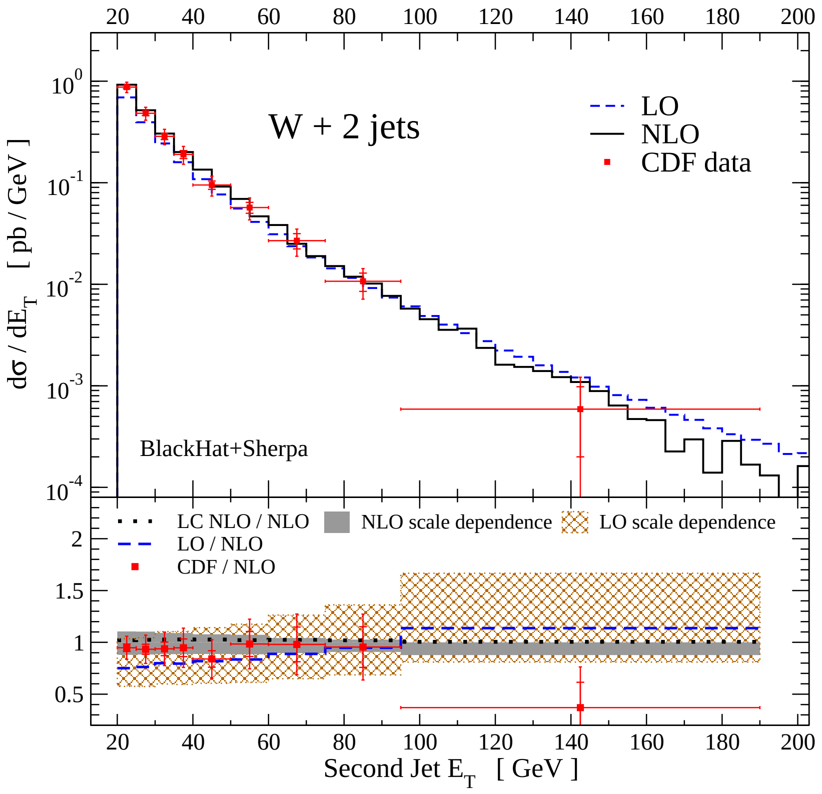
$$\mathcal{A}_{1-\text{loop}} = \sum_{k=2,3,4} C_k I_k + \mathcal{R} \Rightarrow$$

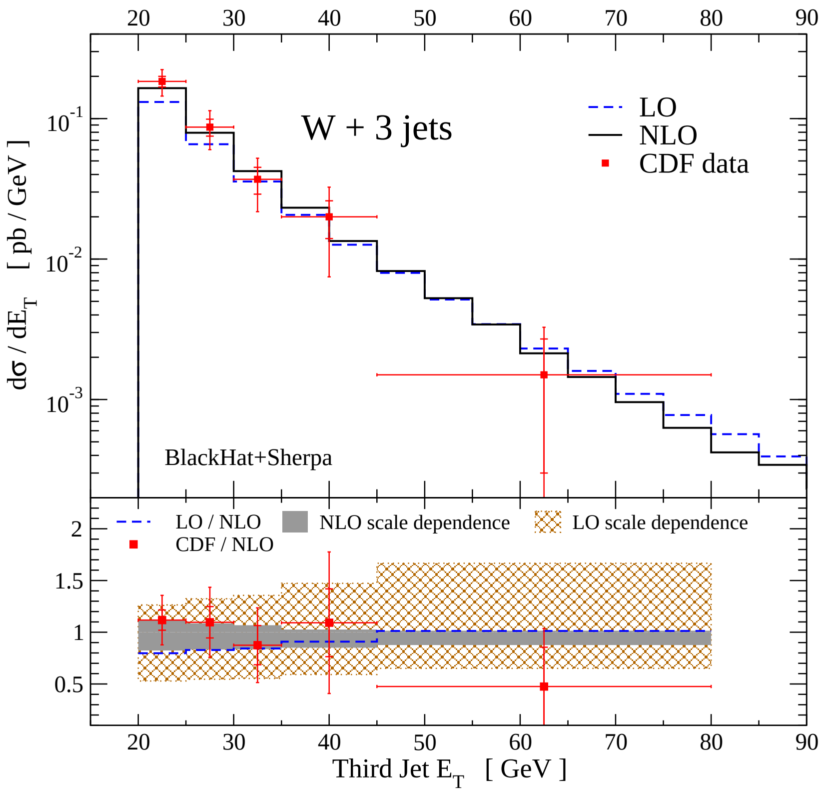
$$\text{Im}\,\mathcal{A}_{1-\text{loop}} = \sum_{k=2,3,4} C_k\,\text{Im}(I_k)$$

  Match imaginary part to tree amplitudes by cut method ⇒ determine coefficients C_k of scalar loop integrals I_k (k legs)

- Recursive methods for evaluation of amplitudes. Bypass Feynman diagrammatic expansion. Efficiency proven at tree level.

Comparison of $W+n$ jet predictions with Tevatron data





- Substantially reduced scale dependence at NLO QCD ($\mu_F = \mu_R = \xi\sqrt{m_W^2 + p_{TW}^2}$)
- Excellent agreement with Tevatron data $\Longrightarrow$ ready for application at LHC

Partially completed 2005 Les Houches wish-list

process ($V \in \{Z, W, \gamma\}$)	status of calculations
1. $pp \to V\, V$ jet	$V = W$: Dittmaier et al.; Campbell et al. (2007)
2. $pp \to t\bar{t}\, b\bar{b}$	Bredenstein, Denner, Dittmaier, Pozzorini (2008/9)
3. $pp \to t\bar{t} + 2$ jets	in progress
4. $pp \to V\, V\, b\bar{b}$	in progress
5. $pp \to V\, V + 2$ jets	VBF: Jäger et al. (2005-2009)
6.$pp \to V + 3$ jets	$V = W$: Berger et al., Ellis et al. (2008/9)
7.$pp \to V\, V\, V$	$V = W, Z$: Hankele et al., Binoth et al. (2007/8)

Summary of NLO calculations

- Impressive progress over the last few years:
  – processes with up to pentagons have become routine. Still much interesting phenomenology to be uncovered
  – first full calculations for 2→4 processes involving hexagons
- Catani Seymour subtraction algorithm has emerged as a preferred tool for cancellation of infrared divergences. Becomes cumbersome, however, for multileg processes: rapid increase in number of subtraction terms
- Some automization of calculations already available, e.g.
  – Blackhat, CutTools, and Golem for virtual contributions
  – MadGraph, HELAC, Amegic++ etc. for Born and real emission graphs
  – MadDipole for automatic generation of subtraction terms

Many applications at the LHC, e.g. in **HIGGS PHYSICS**

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: $\bar{f} f H$ 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

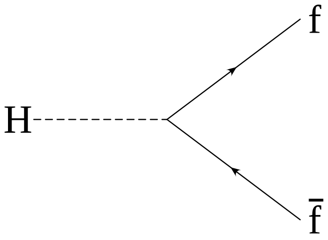
Kinetic energy term of Higgs doublet field:

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

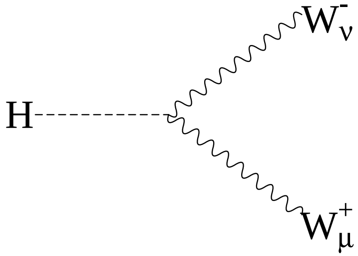
- W, Z mass generation: $m_W^2 = \left(\frac{gv}{2}\right)^2$, $m_Z^2 = \frac{(g^2+g'^2)v^2}{4}$
- WWH and ZZH couplings are generated
- Higgs couples propotional to mass: coupling strength $= 2\,m_V^2/v \sim g^2 v$ within SM

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

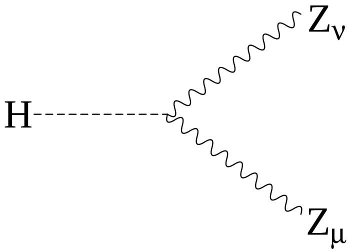
Feynman rules for SM Higgs couplings



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



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

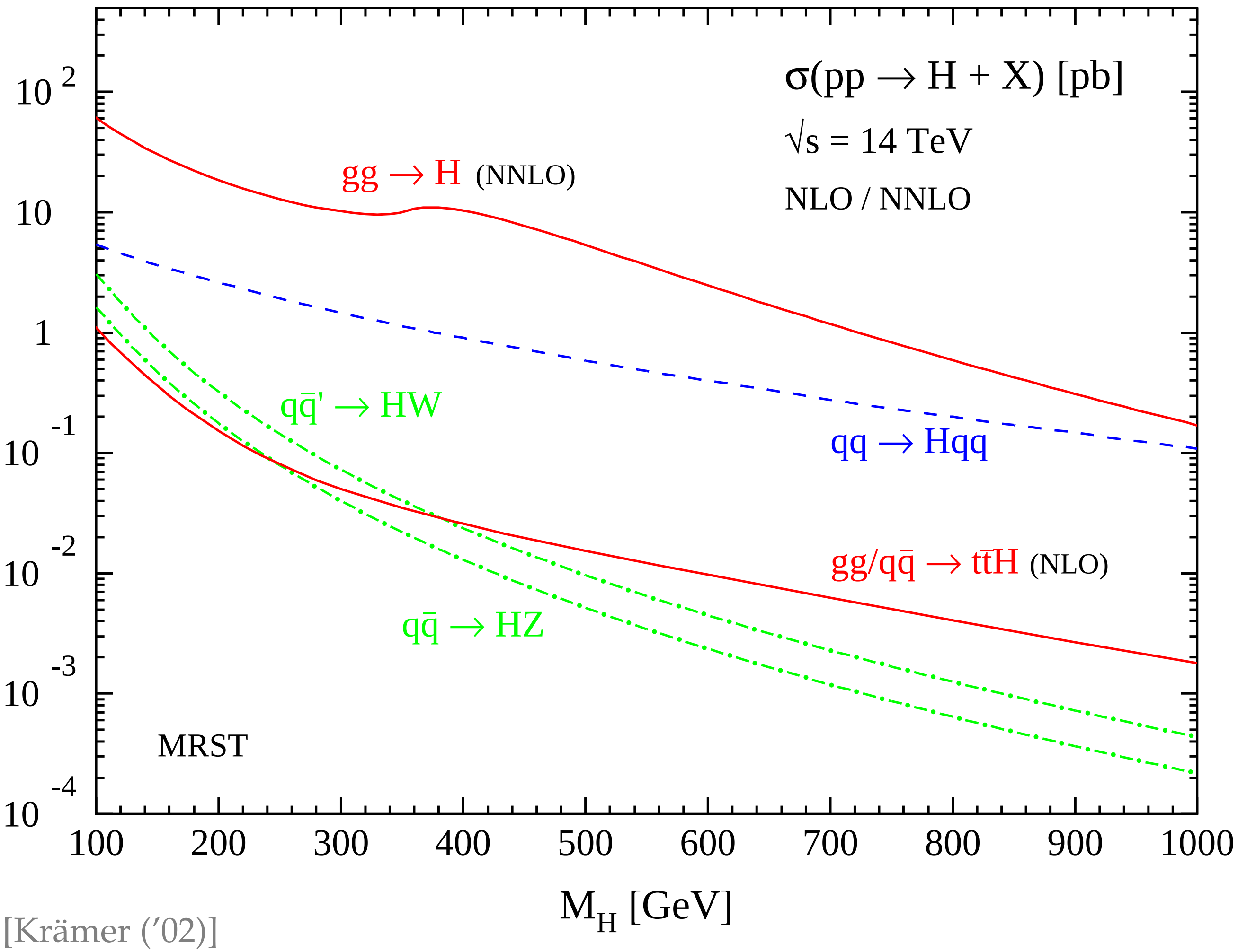


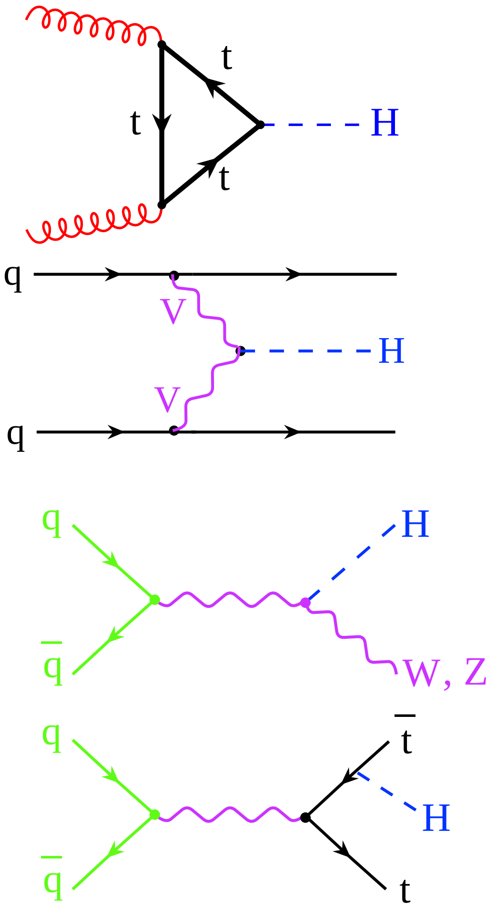
$$i\, g\, \frac{1}{\cos\theta_W}\, m_Z\, g_{\mu\nu}$$

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

Distinguish scalar from pseudoscalar Higgs couplings to fermions.

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 $m_H \neq 2m_W$.

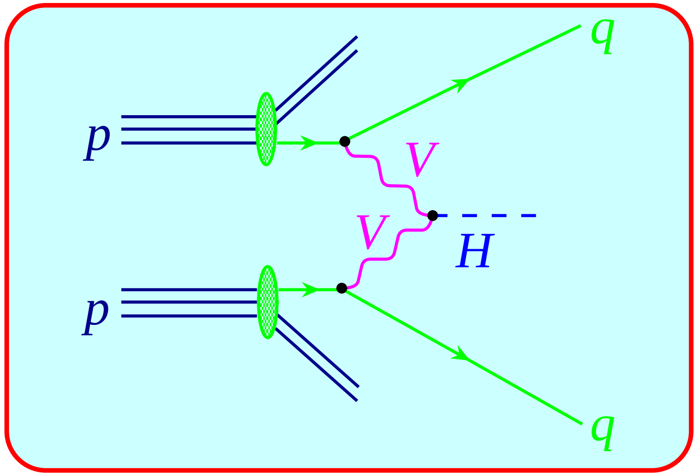
- inclusive search for

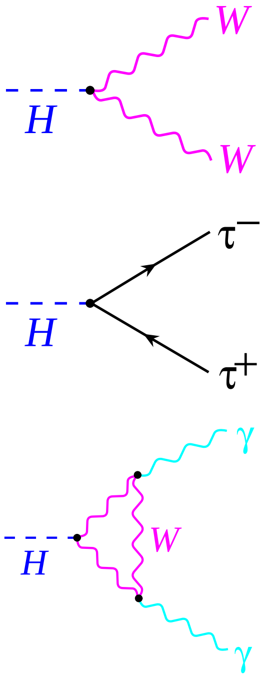
$$H \to W^+W^- \to \ell^+\bar{\nu}\ell^-\nu$$

  for 140 GeV $\leq m_H \leq$ 200 GeV

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

Vector Boson Fusion (VBF)





$m_H > 120$ GeV

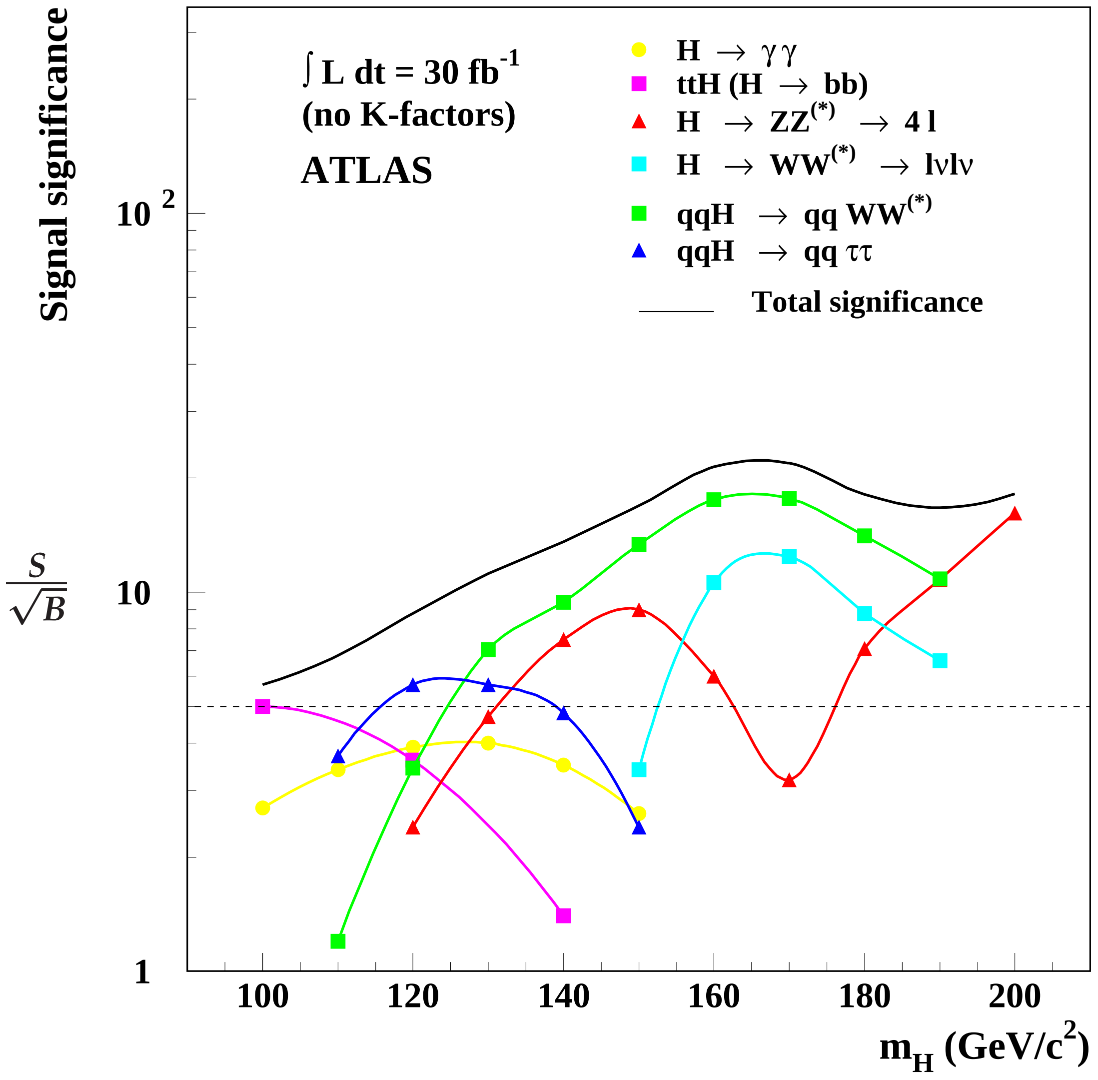
$m_H < 140$ GeV

$m_H < 150$ 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).

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:

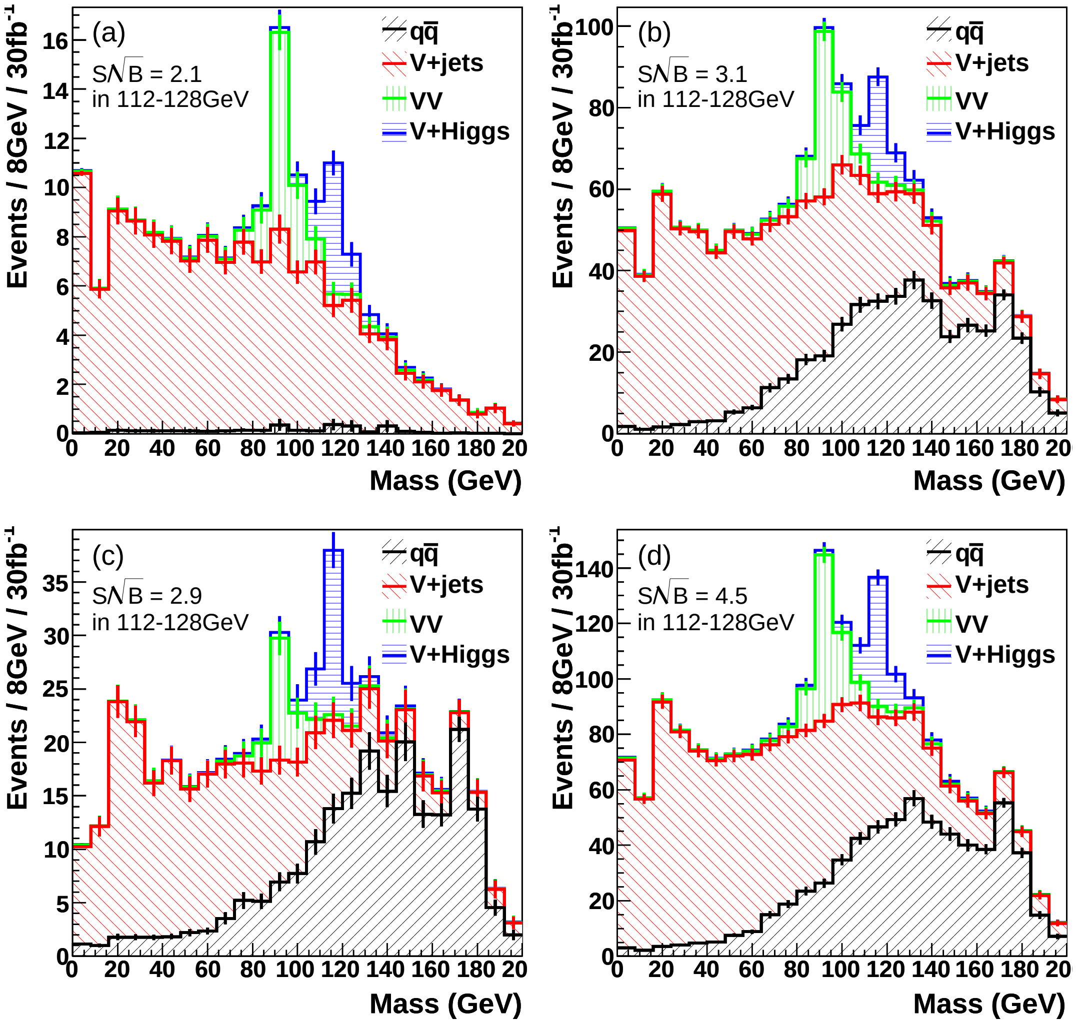
- $\Longrightarrow$ fat Higgs jet with $b\bar{b}(g)$ subjet structure
- small separation of b-quark jets from $H \to bb$ decay $\Longrightarrow$ better $b\bar{b}(g)$ invariant mass resolution
- lower background fraction than at low $p_T(H)$

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 (d)

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. However:

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

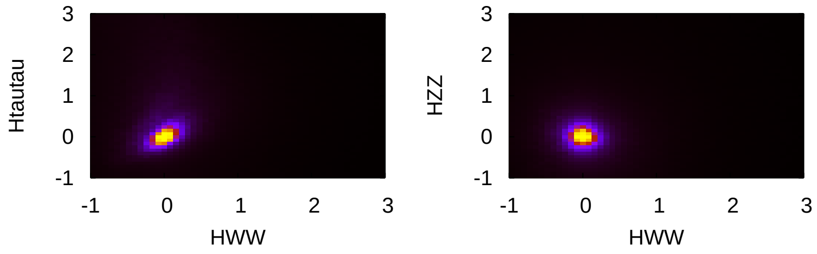
Important input: observation of $H\to bb$ with expected $BR(H\to bb)$ in 50 to 80% range

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

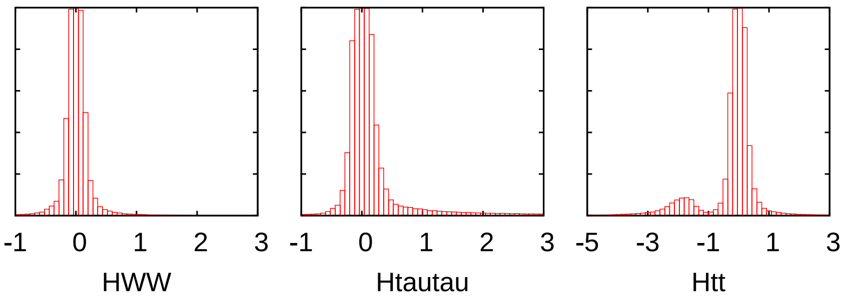
$$f^2\Gamma < \Delta m \qquad\Longrightarrow\qquad f < \sqrt{\frac{\Delta m}{\Gamma}} < \mathcal{O}(10-40)$$

New analysis: Lafaye, Plehn, Rauch, Zerwas, Dührssen: 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	$+0.46$

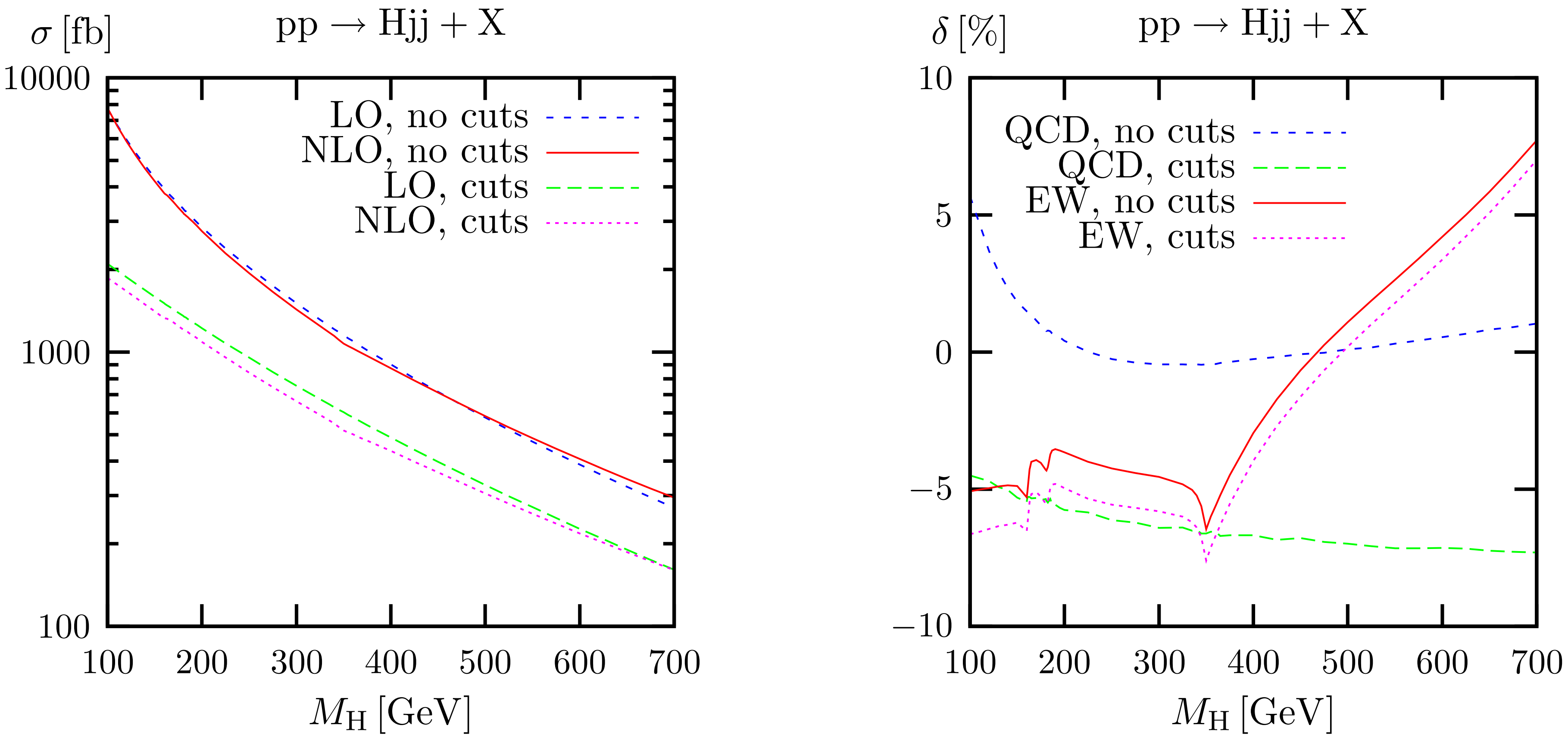
Corrections for Higgs production cross sections

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 this decade

- $gg \to H$ (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 via VBF

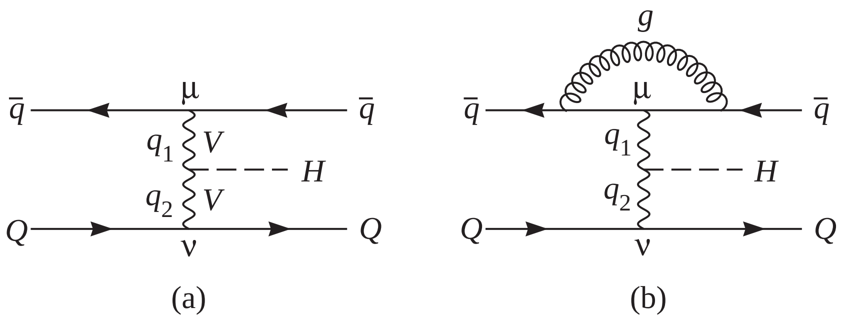
Cross sections without and with VBF cuts: $p_T(j) > 20$ GeV $\quad |y_{j_1} - y_{j_2}| > 4, \quad y_{j_1} \cdot y_{j_2} < 0$



Ciccolini, Denner, Dittmaier, arXiv:0710.4749

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

loop induced couplings for neutral scalar

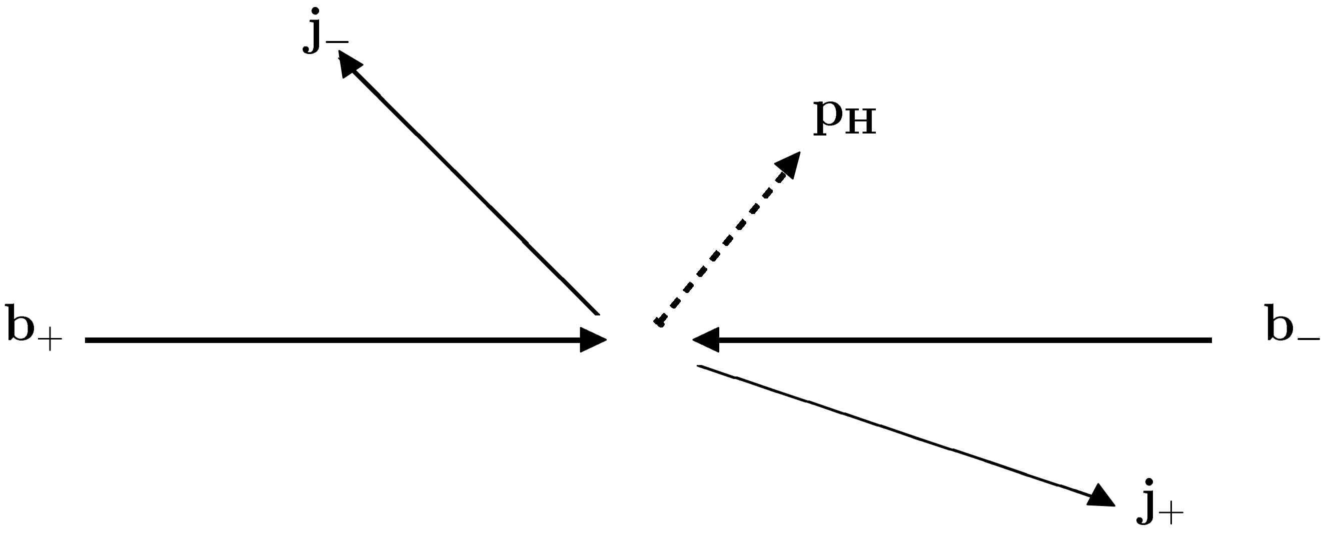
CP even $\quad \mathcal{L}_{eff} \sim H V_{\mu\nu} V^{\mu\nu} \longrightarrow a_2$

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 distribution and Higgs CP properties

Kinematics of Hjj event:

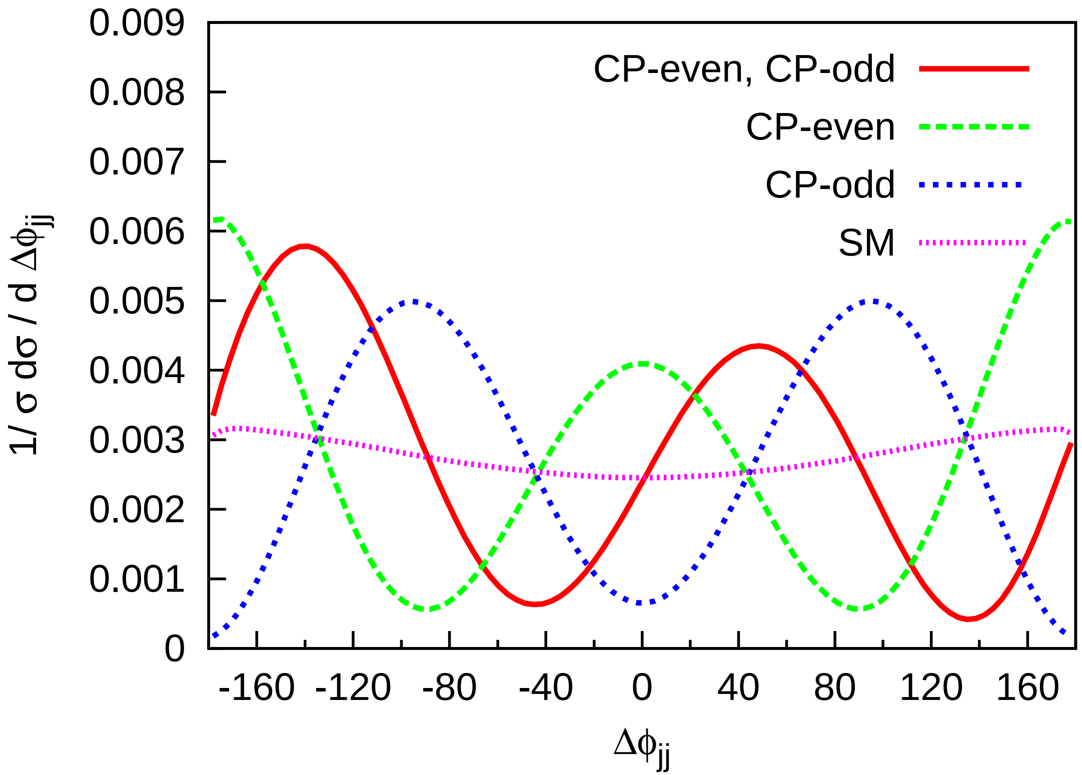


Define azimuthal angle between jet momenta j_+ and j_- via

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

- $\Delta\phi_{jj}$ 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

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

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

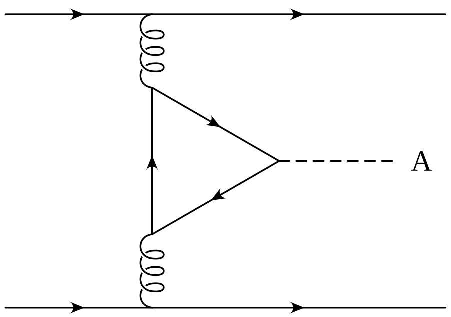
- Study gluon fusion induced Φjj events to distinguish CP-even and CP-odd couplings

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, ...

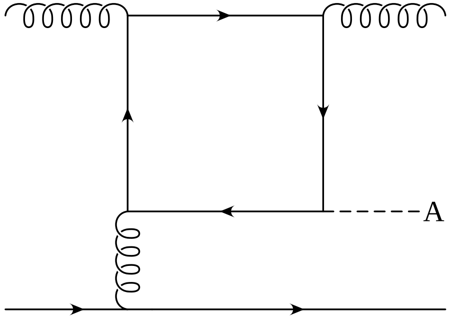
Available at http://www-itp.physik.uni-karlsruhe.de/~vbfnloweb/

Feynman graphs for (pseudo)scalar Higgs production

$pp\rightarrow\Phi jjX$ including top and bottom loops + interference [Del Duca et al., Michael Kubocz]



(a)



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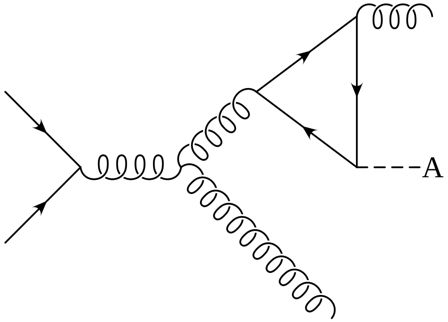

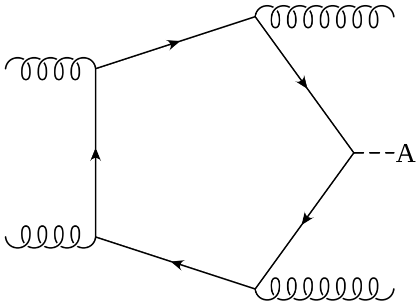

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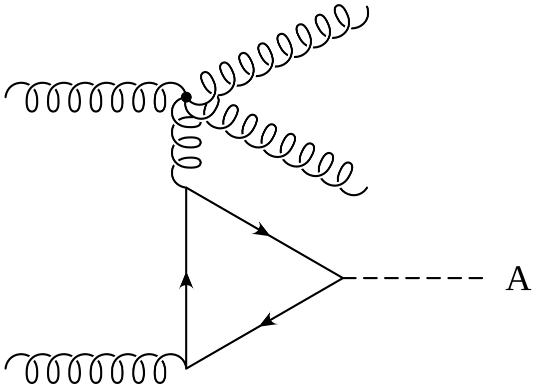
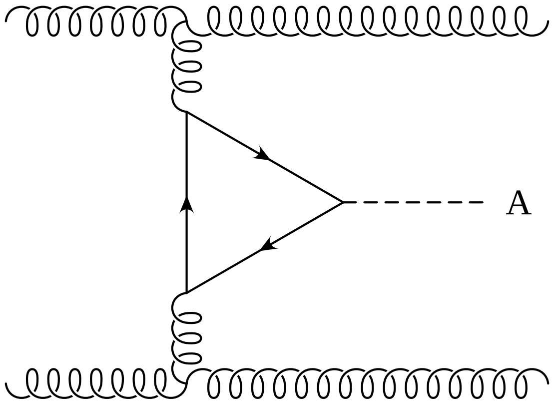
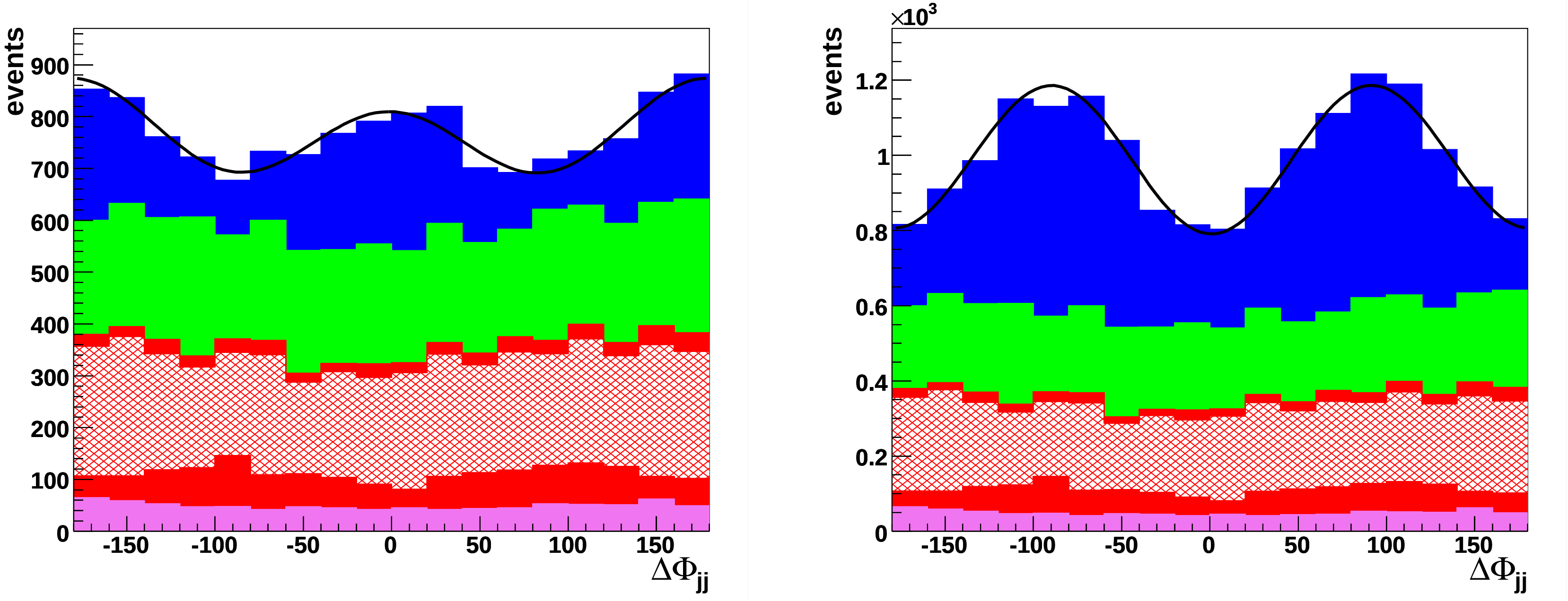




$\Delta\Phi_{jj}$-Distribution in gluon fusion: WW case, $m_H = 160$ GeV

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



Signal

VBF

$t\bar{t}$+Jets

QCD-WW

$L = 300\ \text{fb}^{-1}$

($\Delta\eta_{jj} > 3.0$)

CP-even

$A = 0.100 \pm 0.039$

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

CP-odd

$A = 0.199 \pm 0.034$

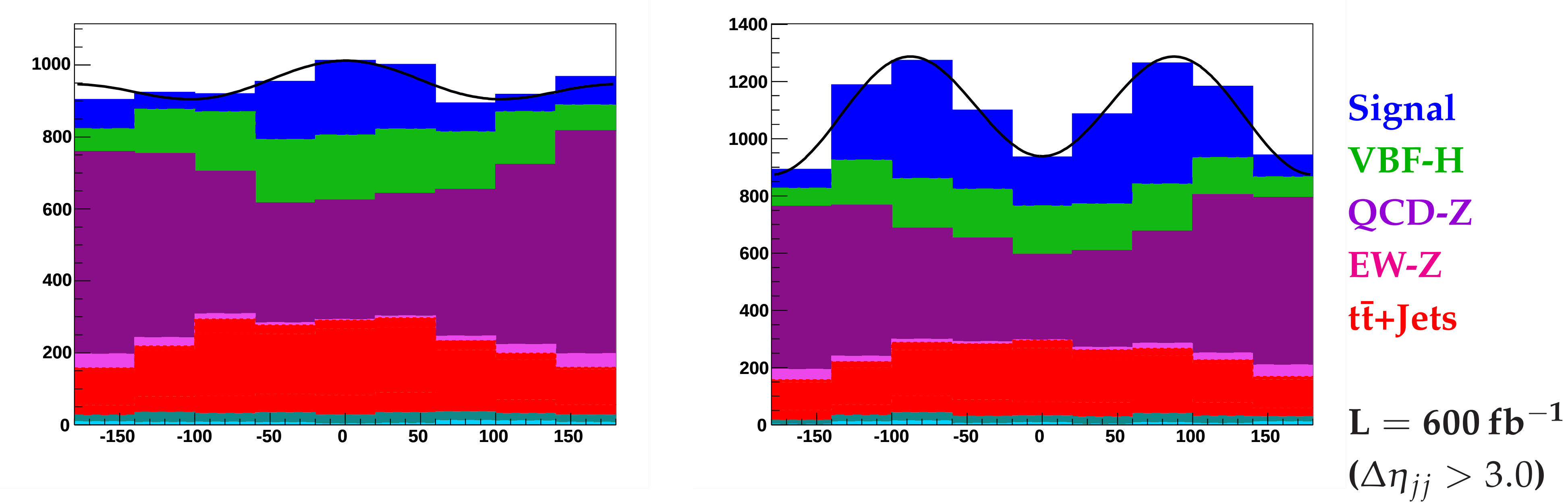
$\Delta\Phi_{max} = 93.7 \pm 5.1$

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)

$H \to \tau\tau$ case: $\Delta\Phi_{jj}$-distribution with backgrounds, $m_H = 120$ GeV

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



L = 600 fb^{-1}

($\Delta\eta_{jj} > 3.0$)

CP-even

$A = 0.004 \pm 0.015$

CP-odd

$A = -0.161 \pm 0.014$

fit of the background only : -0.043 ± 0.016

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

Conclusions

- LHC will observe a SM-like Higgs boson in multiple channels,
  $\Longrightarrow$ great source of information on Higgs couplings
- Many other fascinating searches and measurements....
- Loop corrections particularly important for multileg processes: reduce scale variation from factor of two estimate to order 10% precision
- it will be great to have actual LHC data