

Electroweak and QCD corrections to Higgs production in vector-boson fusion at the LHC

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Radcorr 2007, Florence, Italy, October 1-5, 2007

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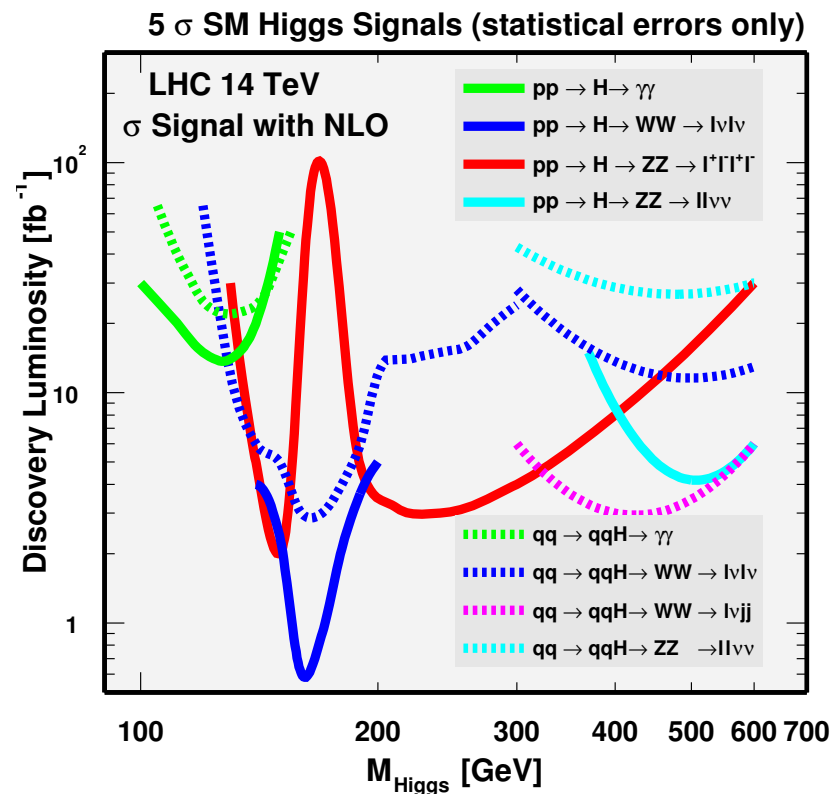
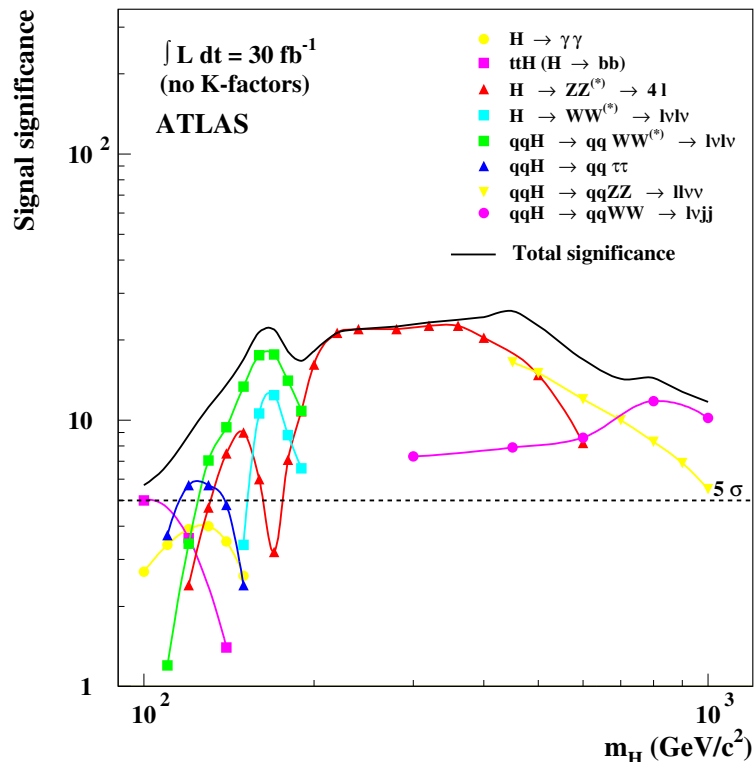
partially published in arXiv:0707.0381 [hep-ph] (to appear in PRL)

- Motivation
- Some details of the calculation
- Numerical results

Introduction — Significance of Higgs signal at LHC

ATLAS '04

CMS



Importance of vector-boson fusion (VBF) $pp \rightarrow H + 2\text{jets} + X$:

- important Higgs-production process for $100 \text{ GeV} \lesssim M_H \lesssim 200 \text{ GeV}$ and large Higgs boson masses
- measurement of HVV couplings

Experimental versus theoretical uncertainties for vector boson fusion

expected statistical uncertainty for $\sigma \times B$: 5–10% Zeppenfeld et al '00

NLO QCD corrections to $pp \rightarrow H + 2\text{jets} + X$

neglecting all interferences \Rightarrow only vertex corrections (structure functions)

- total cross section:

Han, Valencia, Willenbrock '92; Spira '98; Djouadi, Spira '00

corrections change LO by $\sim 5\text{--}10\%$

residual scale dependence: few per cent

leading corrections absorbed in PDFs

- cross section with realistic vector-boson fusion (VBF) cuts, jet distributions:

Figy, Oleari, Zeppenfeld '03, Berger, Campbell '04

corrections of the order of 10–20%, strongly phase-space dependent

- theoretical uncertainty from QCD: $\pm 4\%$ Figy, Oleari, Zeppenfeld '03

Size of electroweak (EW) corrections?

First results for electroweak corrections

Ciccolini, Denner, Dittmaier '07

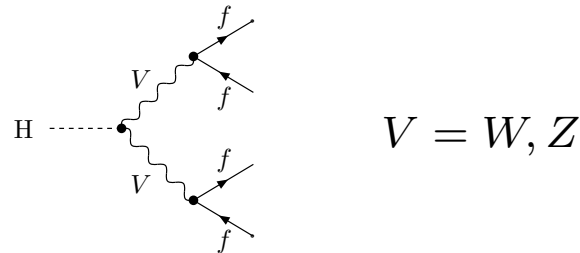
- complete NLO electroweak corrections to $pp \rightarrow H + 2\text{jets} + X$ including photon-induced processes (using MRST2004QED PDFs)
- recalculation and extension of NLO QCD correction (complete set of diagrams and interference contributions)

calculation follows closely the one for $H \rightarrow 4f$

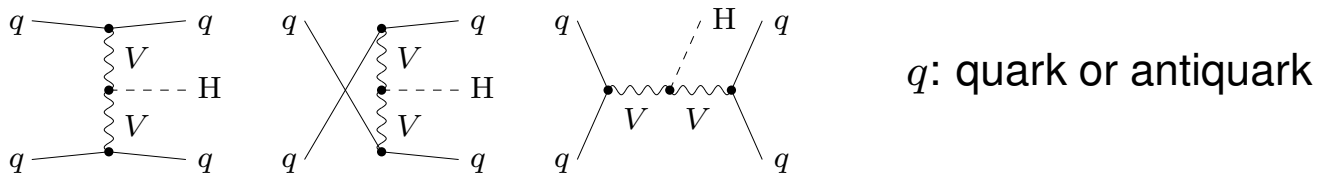
Bredenstein, Denner, Dittmaier, Weber '06/'07

diagrams can be obtained via crossing symmetry

LO topology for $H \rightarrow 4f$

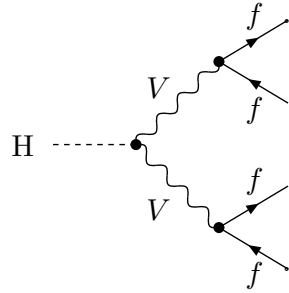


topologies for t -, u -, and s -channel contributions to $qq \rightarrow qqH$ in LO



Survey of Feynman diagrams

Lowest order:



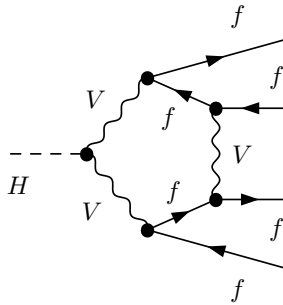
$$V = W, Z$$

electroweak $\mathcal{O}(\alpha)$ corrections:

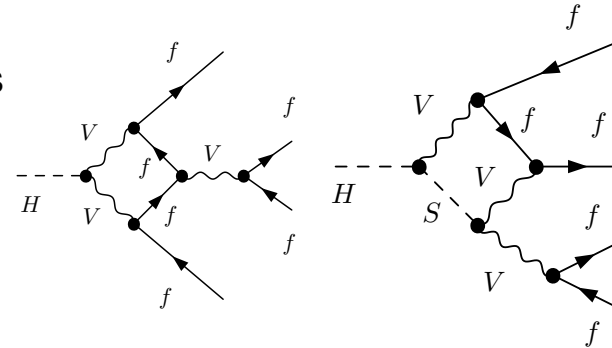
typical one-loop diagrams:

diagrams = $\mathcal{O}(200)$ per tree diagram

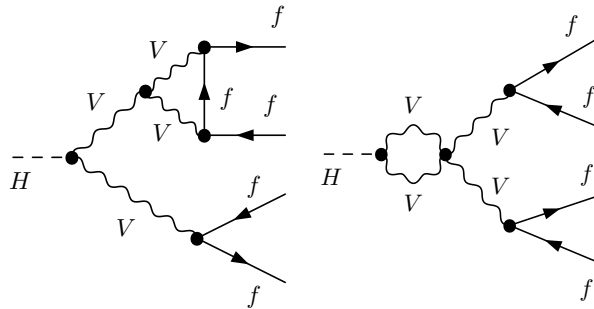
pentagons



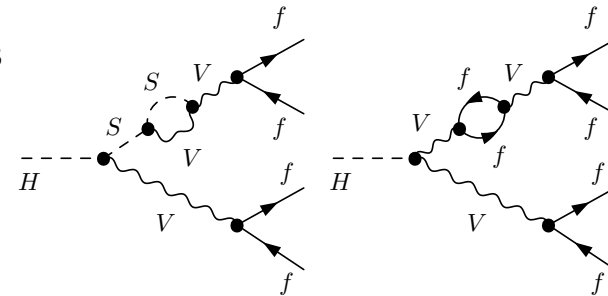
boxes



vertices



self-energies



Comments on the $\mathcal{O}(\alpha)$ calculation

Main complications in loop calculation:

- numerically stable evaluation of one-loop tensor integrals
↪ improved reduction methods Denner, Dittmaier '05
- gauge-invariant treatment of W and Z resonances
↪ complex-mass scheme Denner, Dittmaier, Roth, Wieders '05

new concepts already used in

$\mathcal{O}(\alpha)$ corrections to $e^+e^- \rightarrow 4f$

Denner, Dittmaier, Roth, Wieders '05

and $\mathcal{O}(\alpha)$ and $\mathcal{O}(\alpha_s)$ corrections to $H \rightarrow 4f$

Bredenstein, Denner, Dittmaier, Weber '06/'07

Calculation of virtual corrections

Tools

- generation of Feynman diagrams with FeynArts version 1 and 3
Küblbeck, Böhm, Denner, Eck '90,'92 Hahn '01
- algebraic simplifications using two independent in-house programs implemented in *Mathematica*, one building upon FORMCALC
Hahn, Perez-Victoria '99, Hahn '00
- reduction of tensor integrals according to
Denner, Dittmaier, NPB658 (2003)175 [hep-ph/0212259], NPB734 (2006) 62 [hep-ph/0509141]
↪ numerically stable results
- scalar integrals: evaluated with standard techniques and analytic continuation for complex masses

contributions

- complete NLO QCD and electroweak corrections
- two-loop corrections $\propto G_\mu^2 M_H^4$ to VVH vertex in large M_H limit
Ghinculov '95, Frink et al. '96

Algebraic reduction of tensor integrals

For details see [NPB734 \(2006\) 62 \[hep-ph/0509141\]](#)

- **2-point integrals**: numerically stable direct calculation
- **3-point and 4-point integrals**: **Passarino–Veltman reduction**
↔ inverse Gram determinants of up to three momenta
↔ **serious numerical instabilities where $\det G \rightarrow 0$**
(at phase-space boundary, but also within phase space !)

two hybrid methods

- (i) Passarino–Veltman \oplus **expansions in small Gram and other kinematical determinants**
 - (ii) Passarino–Veltman \oplus analytical special cases
 \oplus **seminumerical method** (in this calculation for checks only)
(numerical calculation of logarithmic Feynman-parameter integral and algebraic reduction to this basis integral)
- **5-point integrals** \rightarrow five 4-point integrals Melrose '65; Denner, Dittmaier '02, '05
stable reduction without inverse Gram determinants

Real corrections

Contributions

- real gluon radiation, processes with gq and $g\bar{q}$ initial states (like $gq \rightarrow Hqq\bar{q}$)
- real photon radiation, **photon-induced processes** (γq and $\gamma\bar{q}$ initial states)

Matrix elements

- evaluated with **Weyl-van der Waerden spinor technique** Dittmaier '99
↔ compact expressions

soft and collinear singularities:

- regularized with infinitesimal photon and quark masses
- dipole subtraction formalism Dittmaier '99; Diener, Dittmaier, Hollik '05
- initial-state collinear singularities absorbed via factorization in PDFs

phase-space integration

- multi-channel Monte Carlo integration with adaptive optimization
Berends, Kleiss, Pittau '94; Kleiss, Pittau '94

Checks on the calculation for $pp \rightarrow H + 2\text{jets} + X$

- **UV structure** of virtual corrections
 - ↔ independence of reference mass μ of dimensional regularization
- **IR structure** of virtual + soft-gluon/photon corrections
 - ↔ independence of $\ln m_\gamma$ ($m_\gamma =$ infinitesimal photon mass)
- **mass singularities** of virtual + collinear gluon/photon corrections
 - ↔ independence of $\ln m_{f_i}$ ($m_{f_i} =$ small masses of external fermions)
- **gauge invariance** of amplitudes with $\Gamma_W, \Gamma_Z \neq 0$
 - ↔ identical results in 't Hooft–Feynman and background-field gauge
Denner, Dittmaier, Weiglein '94
- **real corrections**
 - ↔ squared amplitudes compared with MADGRAPH Stelzer, Long '94
- **combination of virtual and real corrections**
 - ↔ identical results with two-cutoff slicing and dipole subtraction
- **two completely independent calculations of all ingredients !**

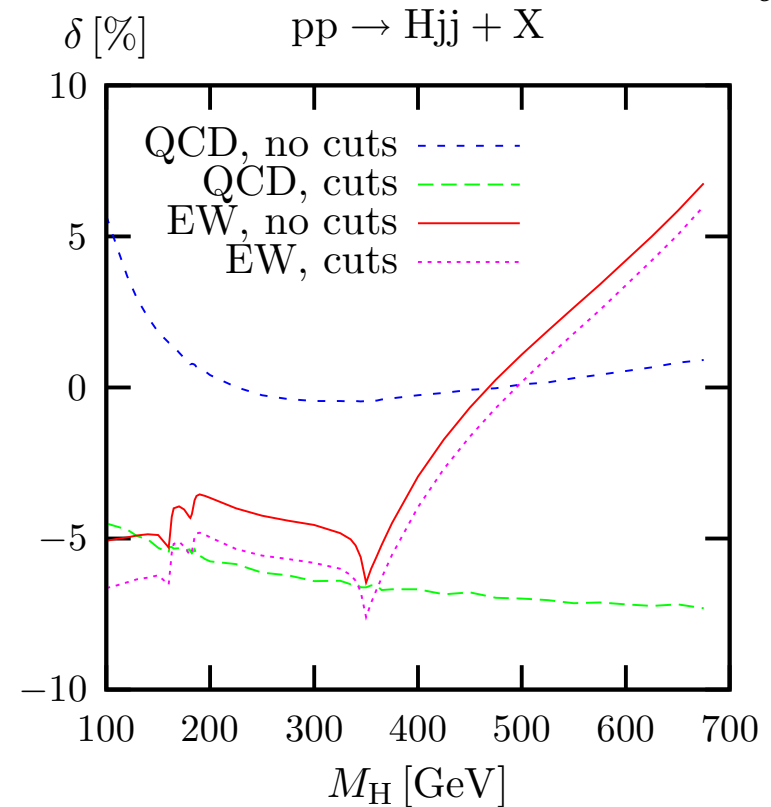
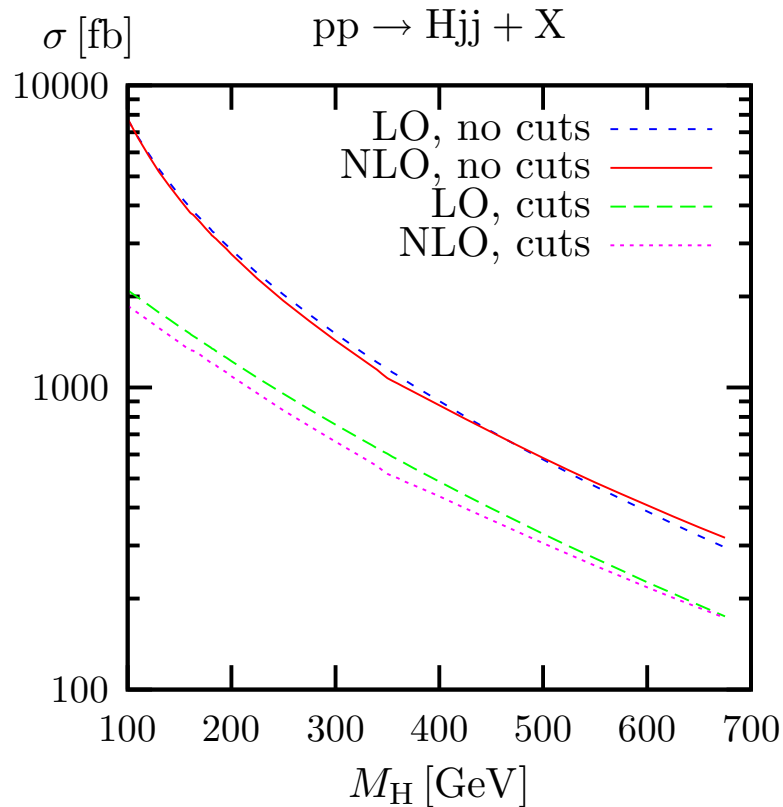
Set-up for numerical calculation

- Vector-boson fusion cuts following Figy, Zeppenfeld '04
 - jets defined via Tevatron run II k_T -algorithm Blazey et al '00
 - cluster jets from partons with $|\eta| < 5$
 - jet resolution parameter $D = 0.8$
 - real photons are recombined with jets
 - require ≥ 2 hard jets with
 - $p_{Tj} > 20 \text{ GeV}$, $|y_j| < 4.5$
 - define tagging jets
 - $p_{Tj_1} > p_{Tj_2} (> p_{Tj_3})$
 - require large rapidity separation of tagging jets
 - $|y_{j_1} - y_{j_2}| > 4$, $y_{j_1} \cdot y_{j_2} < 0$
- Higgs boson considered stable
- renormalization and factorization scale: default $\mu_F = \mu_R = M_W$

Total cross section for $pp \rightarrow H + 2\text{jets} + X$

Ciccolini, Denner, Dittmaier

$$\delta = \frac{\sigma}{\sigma_{\text{LO}}} - 1$$



\uparrow WW/ZZ thresholds for $M_H \sim 2M_{W,Z}$
 \uparrow $t\bar{t}$ threshold for $M_H \sim 2m_t$

electroweak (EW) corrections of similar size as QCD corrections
 EW corrections $\sim -4\% - -7\%$ for small M_H

Total cross section for $pp \rightarrow H + 2\text{jets} + X$

VBF cuts

Ciccolini, Denner, Dittmaier

M_H [GeV]	120	150	200	400	700
σ_{LO} [fb]	1876.3(5)	1589.8(4)	1221.1(3)	487.31(9)	160.67(2)
σ_{NLO} [fb]	1665(1)	1407.5(8)	1091.3(5)	435.4(2)	160.36(5)
δ_{EW} [%]	-6.47(2)	-6.27(2)	-4.98(1)	-3.99(1)	6.99(2)
$\delta_{\text{EW},qq}$ [%]	-7.57(2)	-7.42(2)	-6.19(1)	-5.37(1)	5.44(2)
$\delta_{\gamma\text{-induced}}$ [%]	1.10	1.15	1.22	1.38	1.55
δ_{QCD} [%]	-4.77(4)	-5.20(4)	-5.65(3)	-6.67(3)	-7.18(2)
$\delta_{\text{QCD,diag}}$ [%]	-4.75(4)	-5.17(4)	-5.66(4)	-6.63(3)	-7.18(2)
$\delta_{\text{QCD,nondiag}}$ [%]	-0.011	-0.0052(1)	0.0032(1)	0.0030	0.0022
$\delta_{g\text{-split}}$ [%]	-0.0085(1)	0.0084(1)	0.027	0.014	0.0074
$\delta_{gg\text{-fusion}}$ [%]	-0.030	-0.030	-0.028(1)	-0.020	-0.014
$\delta_{G_\mu^2 M_H^4}$ [%]	0.0035	0.0086(1)	0.027	0.43	4.06(1)

electroweak corrections $-6.5\% - +7\%$

photon-induced corrections $\sim 1\%$

interference corrections $\sim 0.02\%$

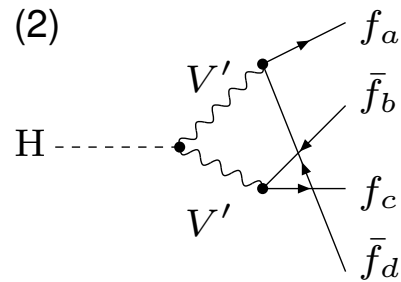
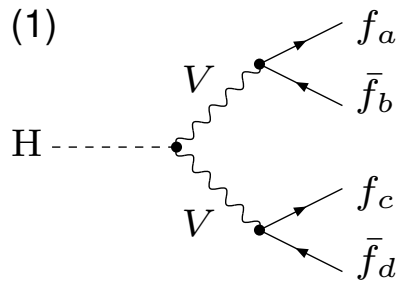
10^8 weighted events

~ 100 CPU h on Xeon 3 GHz PC

per cross section

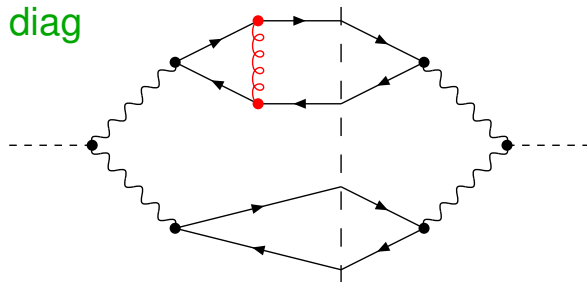
Classification of QCD corrections

Possible Born diagrams:

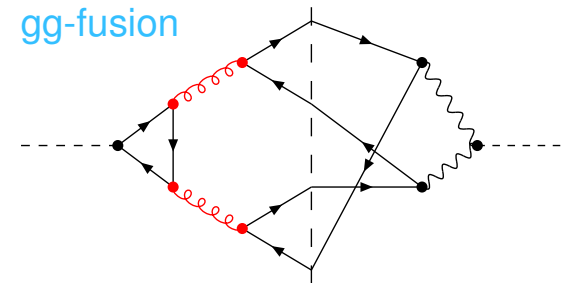
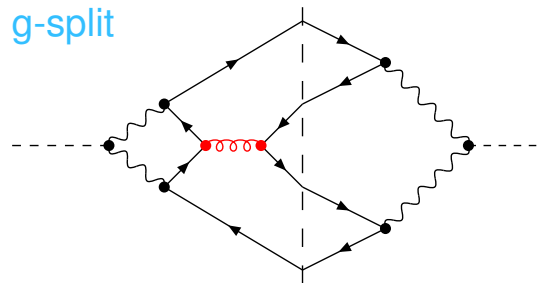
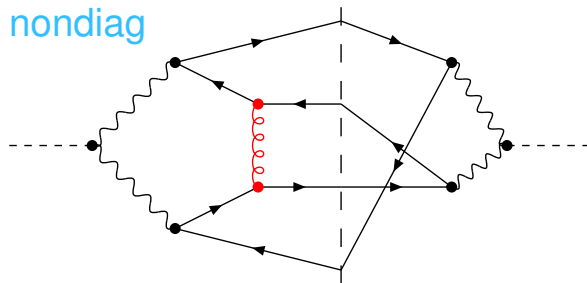


diagrams (2) only for $q\bar{q}q\bar{q}$ and $q\bar{q}q'\bar{q}'$ channels
(q' = weak-isospin partner of q)

Classification of QCD corrections into four categories: (typical diagrams shown)



diag = correction to W/Z decays



nondiag, g-split, gg-fusion = corrections to interferences (only for $q\bar{q}q\bar{q}$ and $q\bar{q}q'\bar{q}'$ channels)

s -channel and interference contributions to $pp \rightarrow H + 2\text{jets} + X$

no cuts

Ciccolini, Denner, Dittmaier

M_H [GeV]	120	150	200	400	700
σ_{NLO} [fb]	5872(2)	4202(2)	2765(1)	871.8(3)	294.33(9)
$\sigma_{\text{LO},s}$ [fb]	1294.4(2)	639.4(1)	244.26(4)	19.69	2.11
$\sigma_{\text{NLO},s}$ [fb]	1582.1(4)	769.4(2)	289.80(9)	21.72(1)	2.29(1)
$\sigma_{\text{LO},t/u\text{-int}}$ [fb]	-9.2	-5.6	-2.7	-0.32	-0.041
$\sigma_{\text{NLO},t/u\text{-int}}$ [fb]	-27.6	-9.4	0.04(1)	-1.08(1)	-0.19

no cuts: s -channel contributes up to 27%, interference below 0.5%

VBF cuts

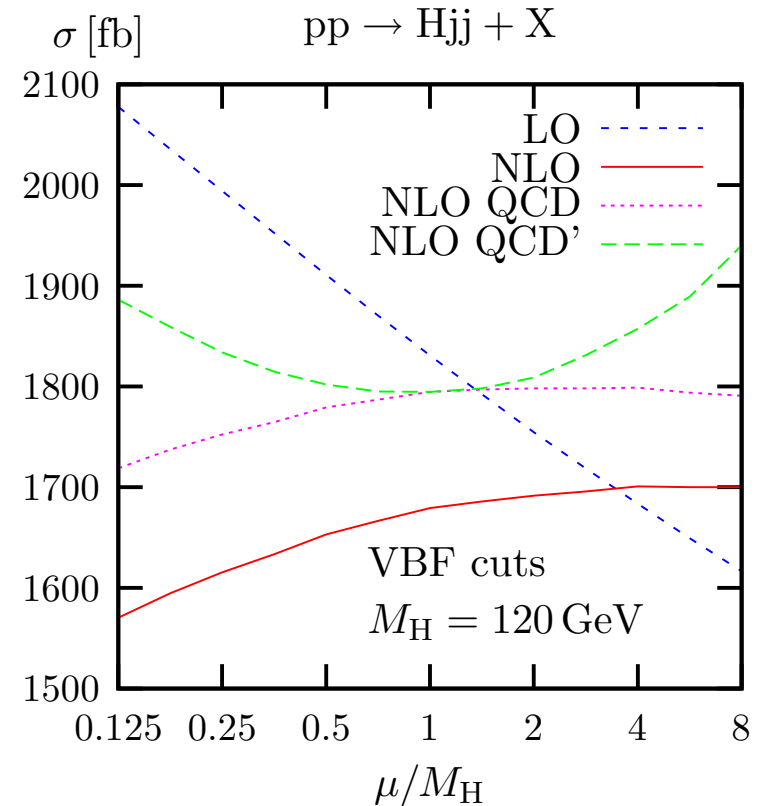
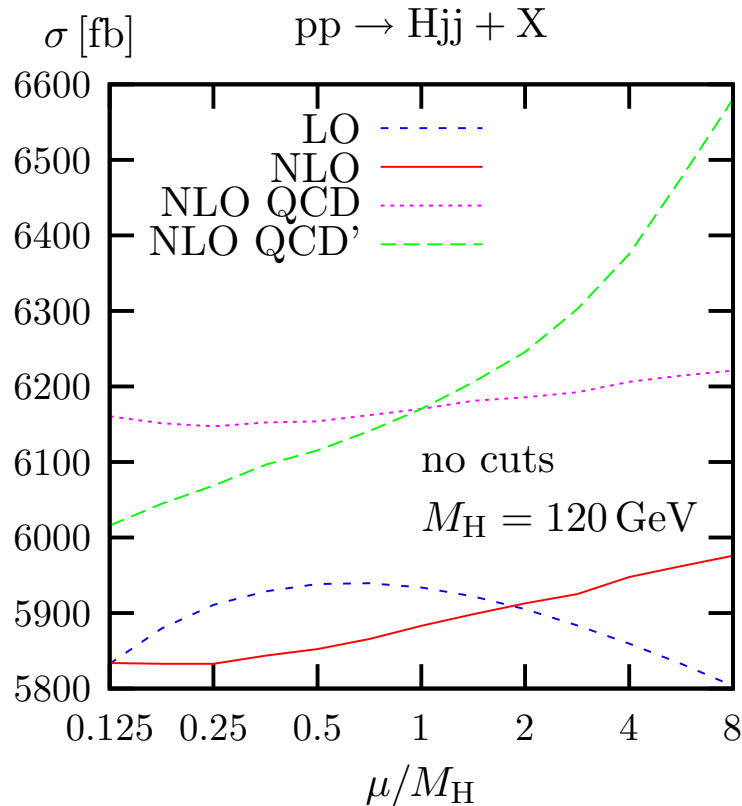
M_H [GeV]	120	150	200	400	700
σ_{NLO} [fb]	1665(1)	1407.5(8)	1091.3(5)	435.4(2)	160.36(5)
$\sigma_{\text{LO},s}$ [fb]	0.0025	0.0015	0.00071	0.000072	0.0000069
$\sigma_{\text{NLO},s}$ [fb]	9.45(1)	5.21(1)	2.33	0.29	0.044
$\sigma_{\text{LO},t/u\text{-int}}$ [fb]	-0.12	-0.091	-0.060	-0.016	-0.0034
$\sigma_{\text{NLO},t/u\text{-int}}$ [fb]	-0.75	0.17	0.76	0.089	0.0044(1)

VBF cuts: s channel and interference contributions below 0.5%

Scale dependence of total cross section for $pp \rightarrow H + 2\text{jets} + X$

$M_H = 120 \text{ GeV}$

Ciccolini, Denner, Dittmaier



$\mu_R = \mu_F \equiv \mu$ for LO, NLO and NLO QCD

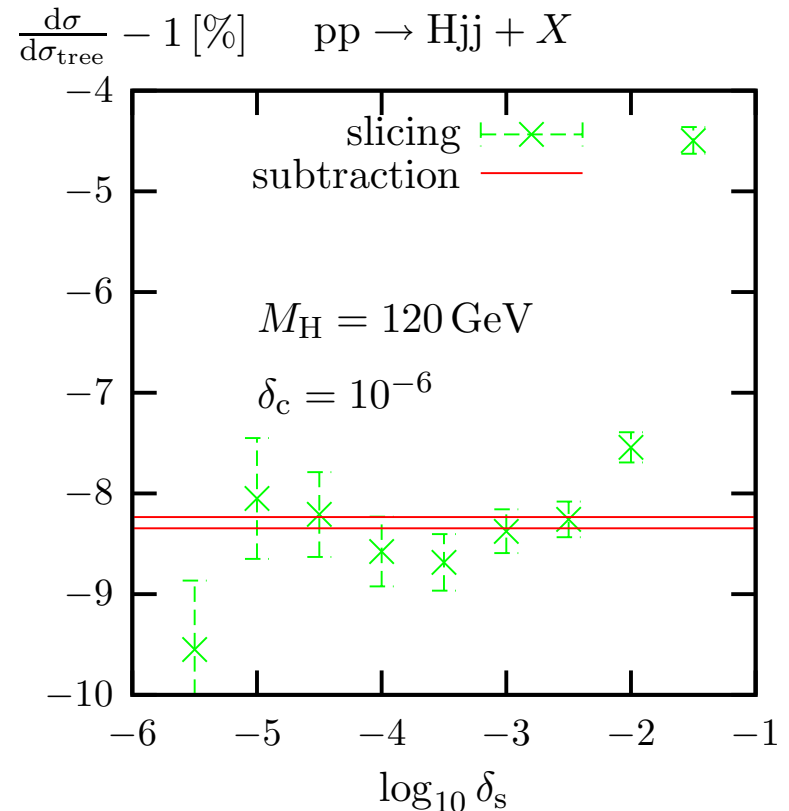
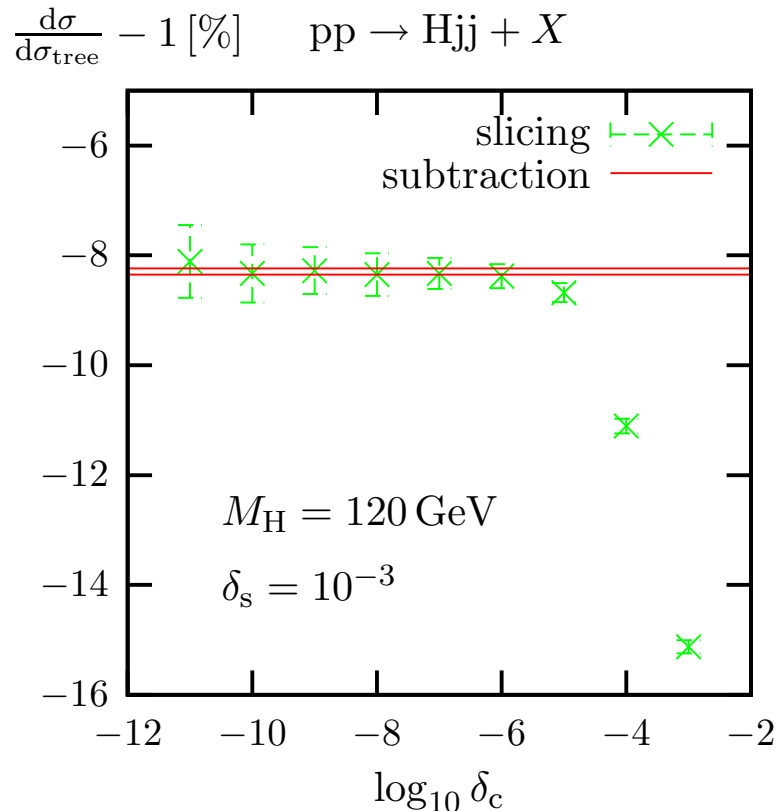
$\mu_R = M_H^2/\mu$ for NLO QCD'

scale dep. at NLO: $\sim 10\text{--}20\%$ for $M_H/8 < \mu < 8M_H$ ($\sim 30\%$ at LO)
 $\sim 3\%$ for $M_H/2 < \mu < 2M_H$ ($\sim 10\%$ at LO)

Comparison between slicing and subtraction methods

VBF cuts (10⁹ events)

Ciccolini, Denner, Dittmaier



soft photon/gluon cut: $\delta_s = \Delta E_{\text{cut}} / E_{\text{parton}}$
 collinear photon/gluon cut: $\delta_c = 1 - \cos \theta_{\text{cut}}$
 cuts are applied in CMS of incoming partons

Comparison with existing NLO QCD calculations

VVH2 by M. Spira based on [Hahn, Valencia, Willenbrock '92](#) no cuts, $\mu_R = \mu_F = M_H$

M_H [GeV]	120	150	170	200	400	700
σ_{LO} [fb]	4194.8(6)	3292.2(5)	2826.8(4)	2277.8(3)	707.8(1)	196.74(3)
$\sigma_{\text{LO}}^{\text{VV}2\text{H}}$ [fb]	4193.6(6)	3291.3(5)	2826.5(4)	2277.6(4)	707.6(1)	196.65(3)
σ_{NLO} [fb]	4432(3)	3540(2)	3071(2)	2511(1)	842.5(4)	251.7(1)
$\sigma_{\text{NLO}}^{\text{VV}2\text{H}}$ [fb]	4437(4)	3538.8(8)	3071.1(7)	2511.9(6)	842.7(2)	251.69(6)

agreement within 0.1% \sim statistical error

VBF cuts: VBFNLO [Zeppenfeld et al.](#) VBF cuts, isotropic Higgs-boson decay into massless particles included

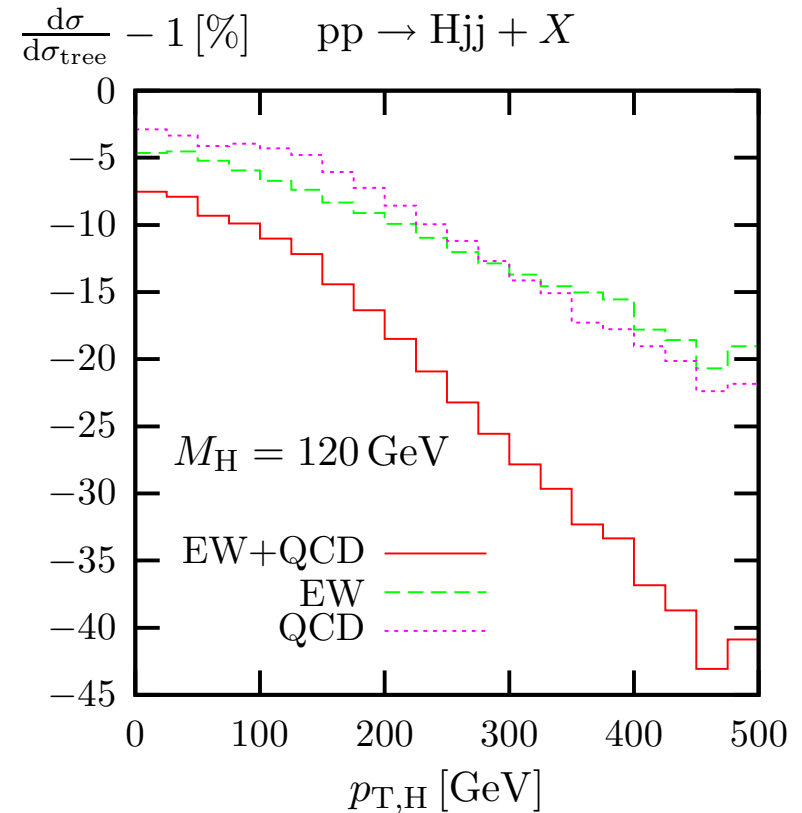
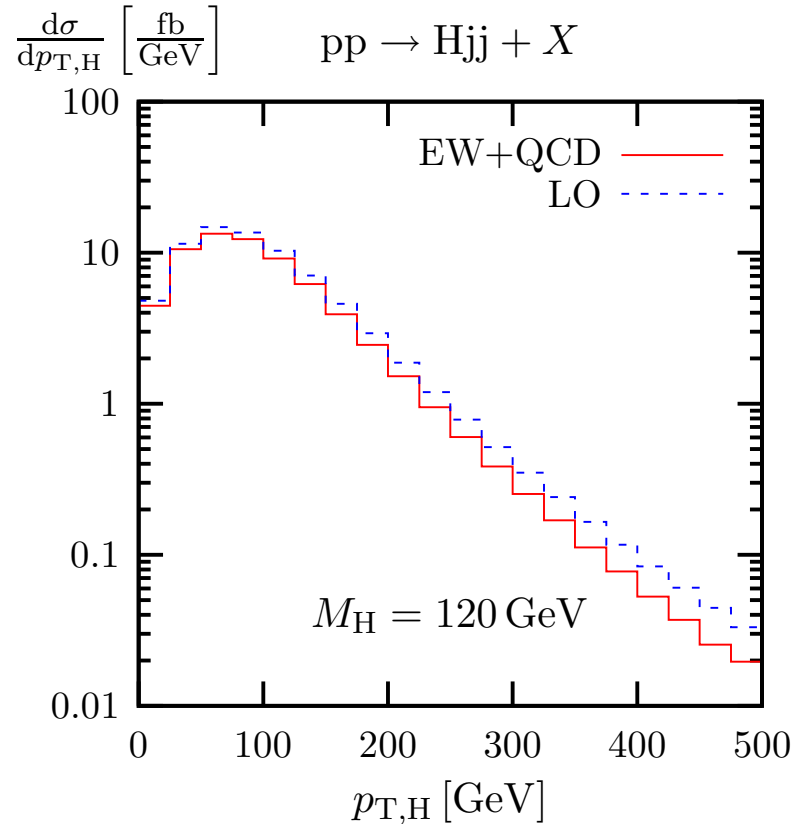
M_H [GeV]	120	150	170	200	400	700
σ_{LO} [fb]	1644.4(4)	1374.2(3)	1223.5(2)	1033.0(2)	383.10(7)	124.71(4)
$\sigma_{\text{LO}}^{\text{VBFNLO}}$ [fb]	1644.8(3)	1374.32(6)	1223.57(5)	1033.30(4)	383.12(2)	124.722(6)
σ_{NLO} [fb]	1737(3)	1470(3)	1322(2)	1132(2)	443.9(5)	151.9(2)
$\sigma_{\text{NLO}}^{\text{VBFNLO}}$ [fb]	1734.8(2)	1470.1(2)	1319.5(2)	1127.0(1)	442.60(5)	151.62(2)

agreement within 0.4% \sim 2–3 \times statistical error

Distribution in the transverse momentum of the Higgs boson

VBF cuts

Ciccolini, Denner, Dittmaier



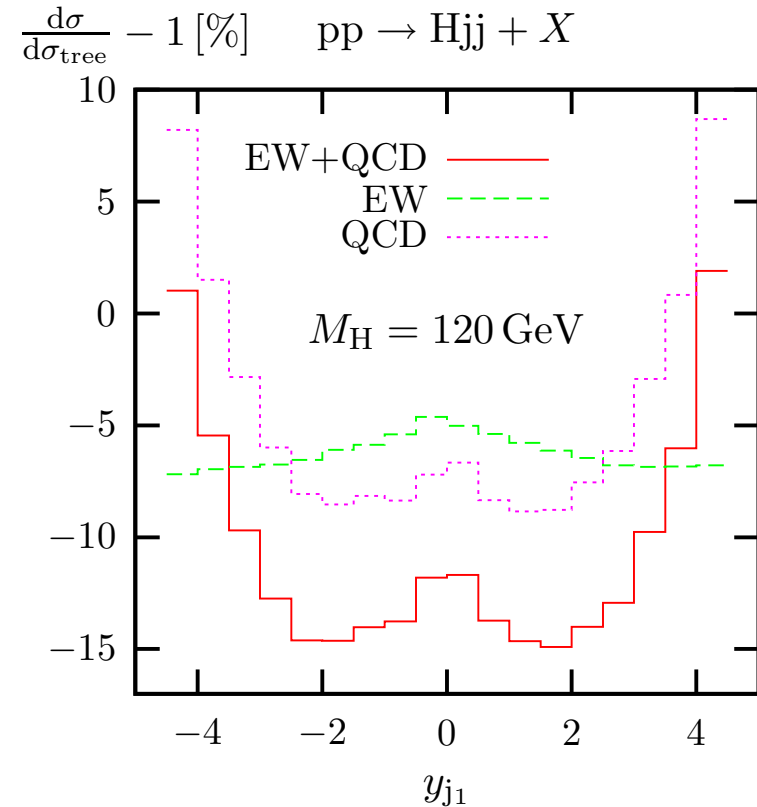
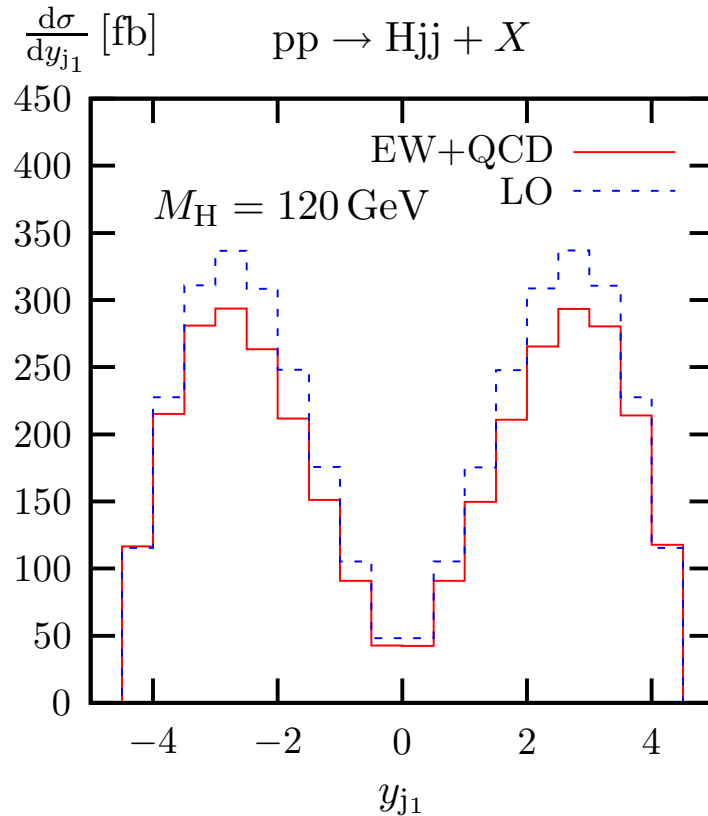
EW and QCD corrections similar

EW corrections -20% at $p_{T,H} = 500 \text{ GeV}$

Distribution in the rapidity of the harder tagging jet

VBF cuts

Ciccolini, Denner, Dittmaier



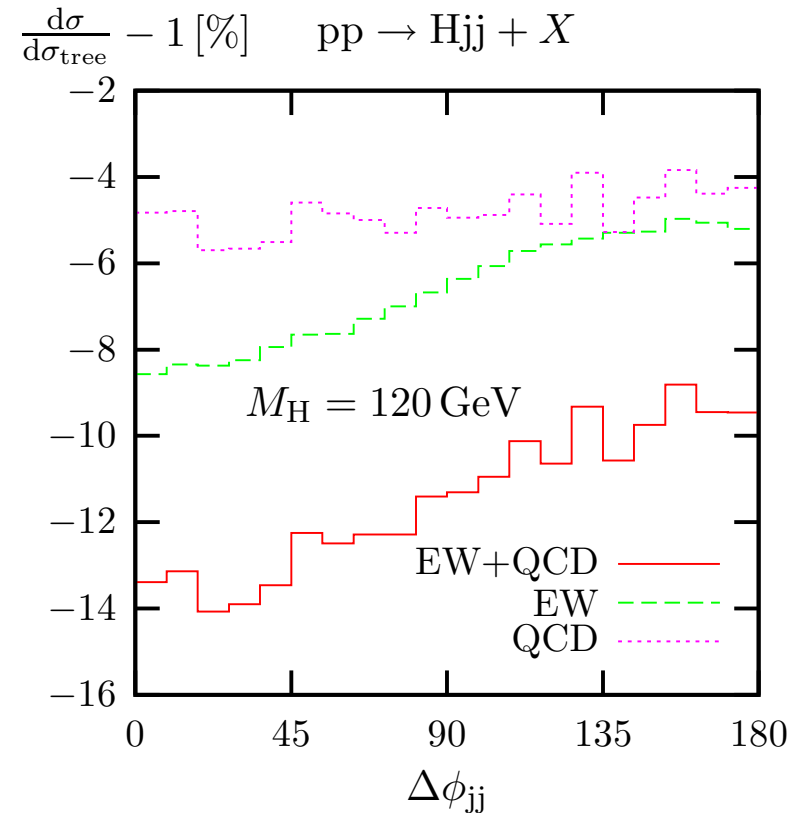
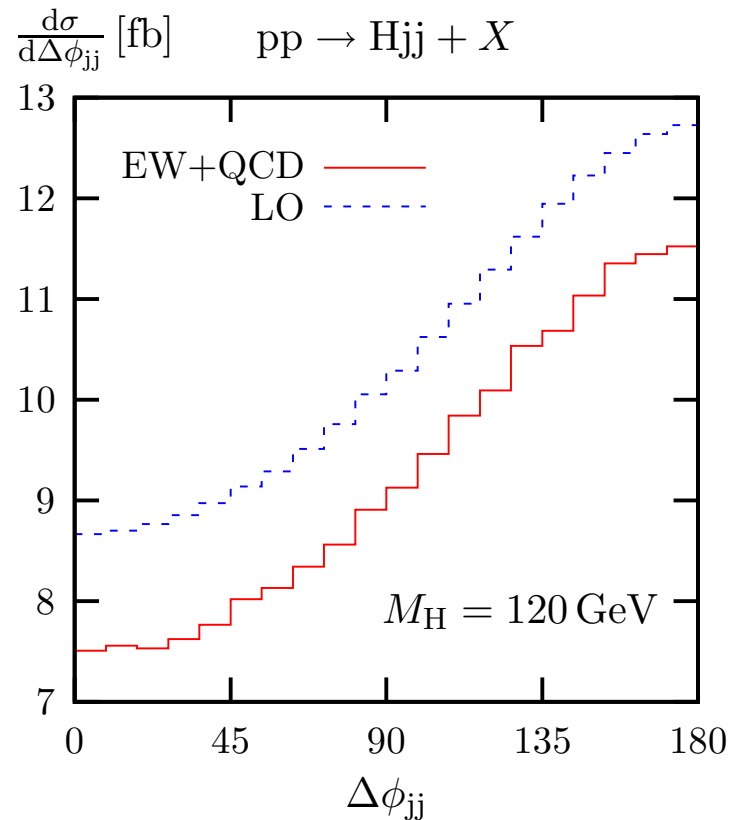
tagging jets forward–backward

EW corrections depend only weakly on rapidity y_{j_1} (-4% – -7%)

Distribution in the azimuthal angle separation of the tagging jets

VBF cuts

Ciccolini, Denner, Dittmaier



distribution in $\Delta\phi_{jj}$ sensitive to non-standard HVV couplings

EW corrections yield distortion of distribution by 4%

Conclusions

Higgs production in vector-boson fusion $pp \rightarrow H + 2\text{jets} + X$ important for

- Higgs-boson discovery at the LHC and Higgs-mass measurement
- measurement of HVV couplings

NEW: MC generator for $pp \rightarrow H + 2\text{jets} + X$ including

- full $\mathcal{O}(\alpha)$ electroweak corrections including photon-induced processes
- full $\mathcal{O}(\alpha_s)$ QCD corrections including s -channel diagrams and interferences

results for the NLO corrections to $pp \rightarrow H + 2\text{jets} + X$

- **electroweak corrections:** $\mathcal{O}(5\%)$ and negative for $100 \text{ GeV} \lesssim M_H \lesssim 200 \text{ GeV}$
comparable to QCD corrections, reach $+7\%$ for $M_H = 700 \text{ GeV}$
- **real corrections due to initial-state photons** $\sim 1\%$
- **QCD corrections** in agreement with previous calculations
- **s -channel diagrams and interference contributions** $< 0.5\%$ for VBF cuts

Backup slides

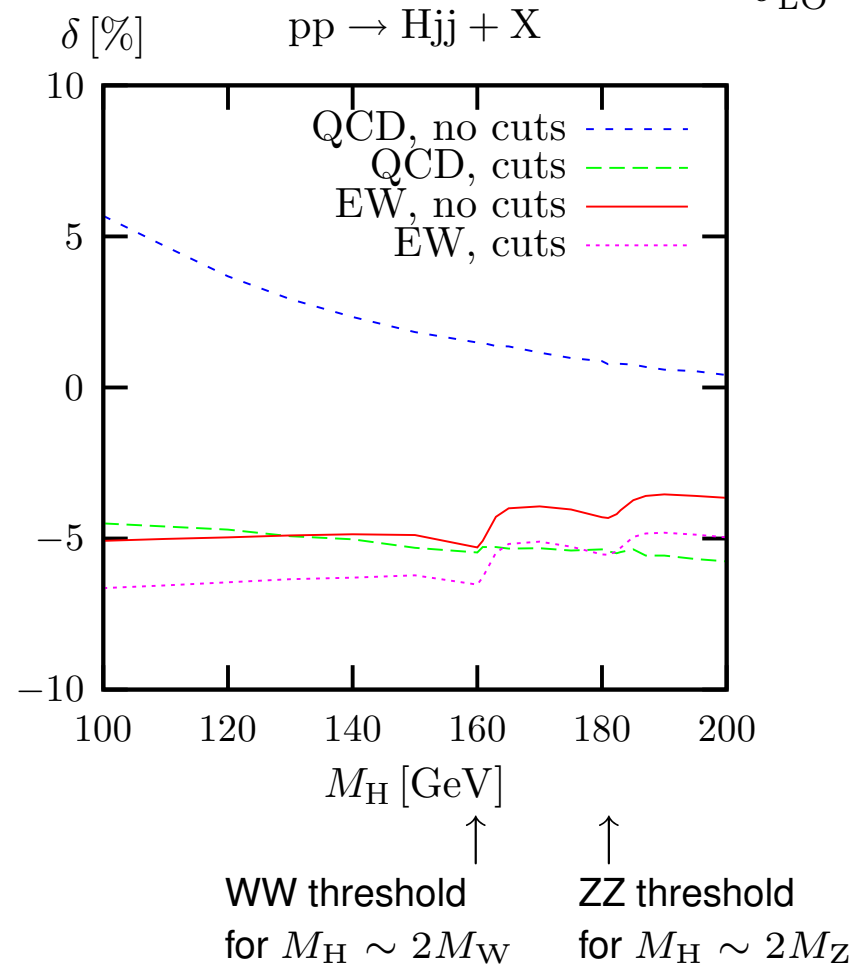
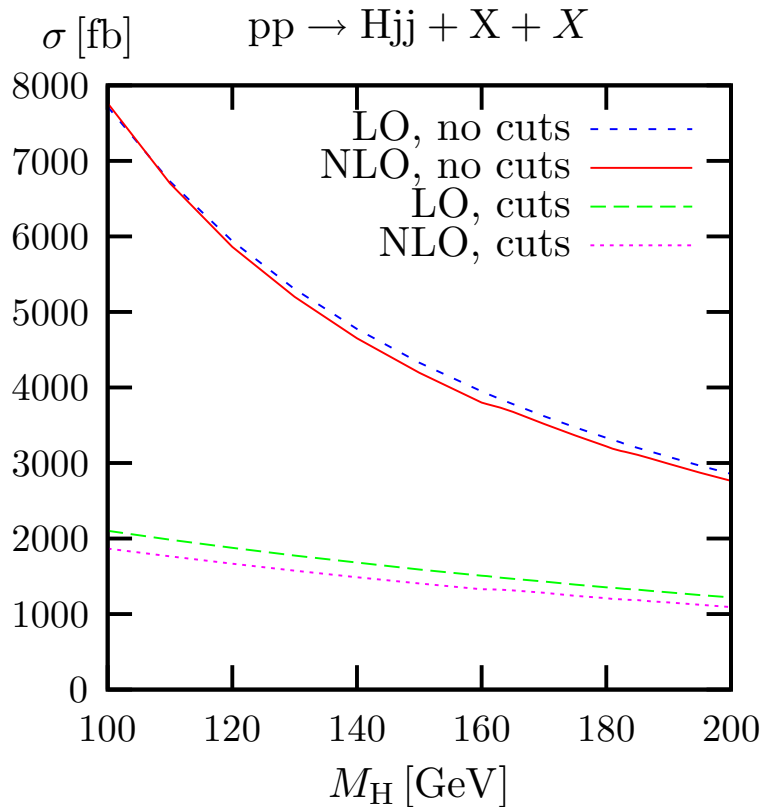
Set-up of the calculation

- external fermion masses neglected whenever possible (everywhere but in mass-singular logarithms)
- (complex) on-shell renormalization scheme
- G_μ scheme for electromagnetic couplings ($\alpha_{G_\mu} = \sqrt{2}G_\mu M_W^2 s_w^2 / \pi$) accounts for electromagnetic running effects and universal corrections $\propto G_\mu m_t^2$ from the ρ parameter
- unit quark-mixing matrix (effect of realistic CKM $< 0.1\%$)
- MRST2004QED PDFs (include $\mathcal{O}(\alpha)$ QED corrections) photon distribution function for proton
- running α_s with 5 flavours and $\alpha_s(M_Z) = 0.1187$
- renormalization and factorization scale: default $\mu_F = \mu_R = M_W$
- no Higgs-boson decay included
- 5×10^7 weighted events without cuts, 10^8 events with VBF cuts (~ 100 CPU h on Xeon 3 GHz PC)

Total cross section for $pp \rightarrow H + 2\text{jets} + X$

Ciccolini, Denner, Dittmaier

$$\delta = \frac{\sigma}{\sigma_{\text{LO}}} - 1$$



electroweak (EW) corrections of similar size as QCD corrections

EW corrections -4% – -7%

Total cross section for $pp \rightarrow H + 2\text{jets} + X$

no cuts

Ciccolini, Denner, Dittmaier

M_H [GeV]	120	150	200	400	700
σ_{LO} [fb]	5943(1)	4331(1)	2855.4(6)	900.7(1)	270.51(4)
σ_{NLO} [fb]	5872(2)	4202(2)	2765(1)	871.8(3)	294.33(9)
δ_{EW} [%]	-4.94(2)	-4.91(2)	-3.67(1)	-2.97(1)	7.74(2)
$\delta_{\text{EW},qq}$ [%]	-5.79(2)	-5.92(2)	-4.85(1)	-4.50(1)	5.99(2)
$\delta_{\gamma\text{-induced}}$ [%]	0.85	1.00	1.18	1.53	1.75
δ_{QCD} [%]	3.75(5)	1.94(3)	0.49(3)	-0.24(3)	1.06(3)
$\delta_{\text{QCD,diag}}$ [%]	3.97(3)	2.04(3)	0.55(3)	-0.06(3)	1.14(3)
$\delta_{\text{QCD,nondiag}}$ [%]	0.010(2)	0.027(2)	0.050(1)	0.026	0.013
$\delta_{g\text{-split}}$ [%]	-0.015(1)	0.059(1)	0.110(1)	0.040(1)	0.017(1)
$\delta_{gg\text{-fusion}}$ [%]	-0.19(1)	-0.20	-0.22	-0.24	-0.11(1)
$\delta_{G_\mu^2 M_H^4}$ [%]	0.0027	0.0073	0.025	0.42	4.03(1)

electroweak corrections $-5\% - +8\%$

photon-induced corrections $\sim 1\%$

interference corrections $\sim 0.1\%$

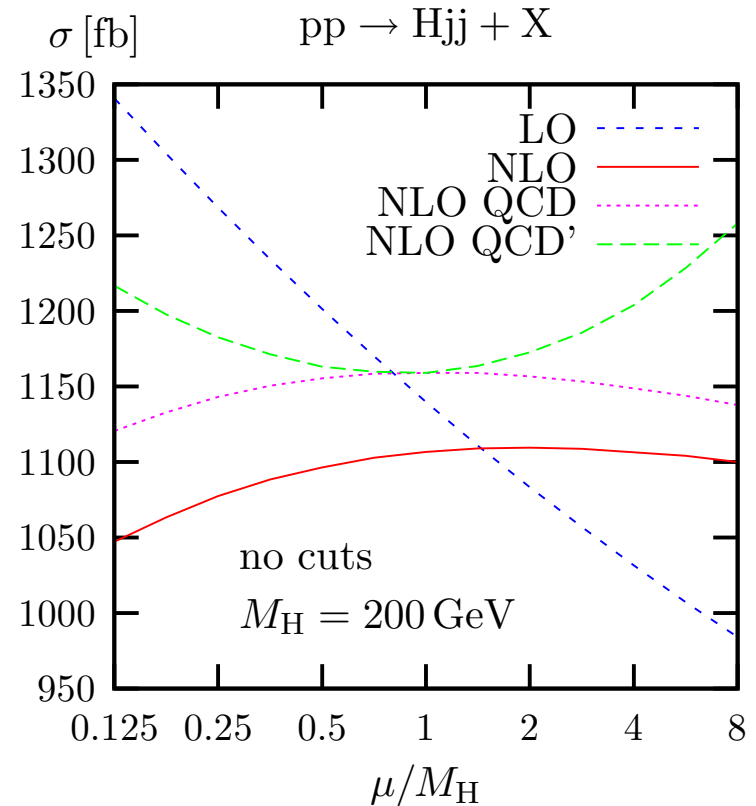
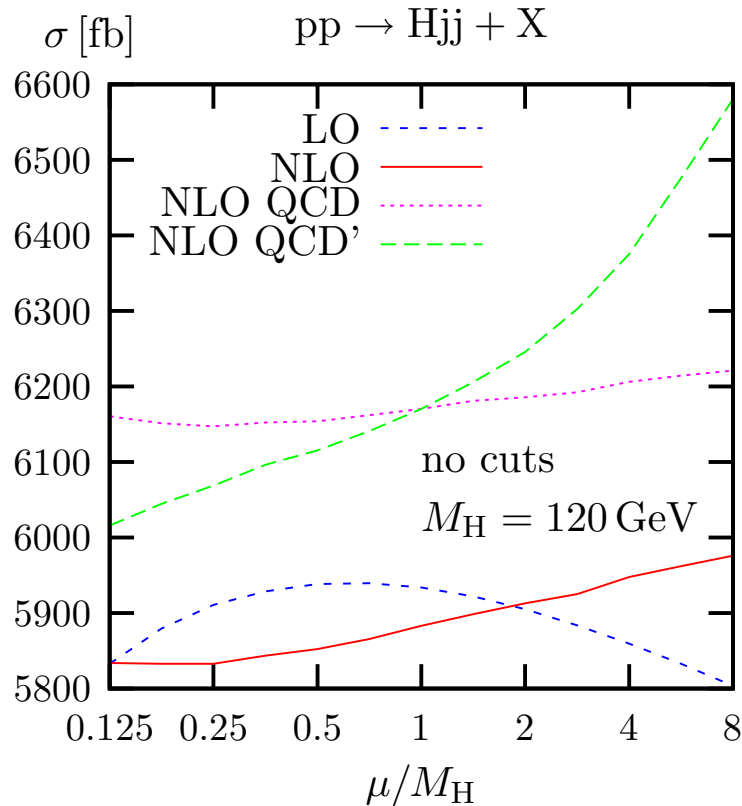
5×10^7 weighted events

~ 100 CPU h on Xeon 3 GHz PC
per cross section

Scale dependence of total cross section for $pp \rightarrow H + 2\text{jets} + X$

$M_H = 200 \text{ GeV}$

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$\mu_R = \mu_F \equiv \mu$ for LO, NLO and NLO QCD

$\mu_R = M_H^2/\mu$ for NLO QCD'

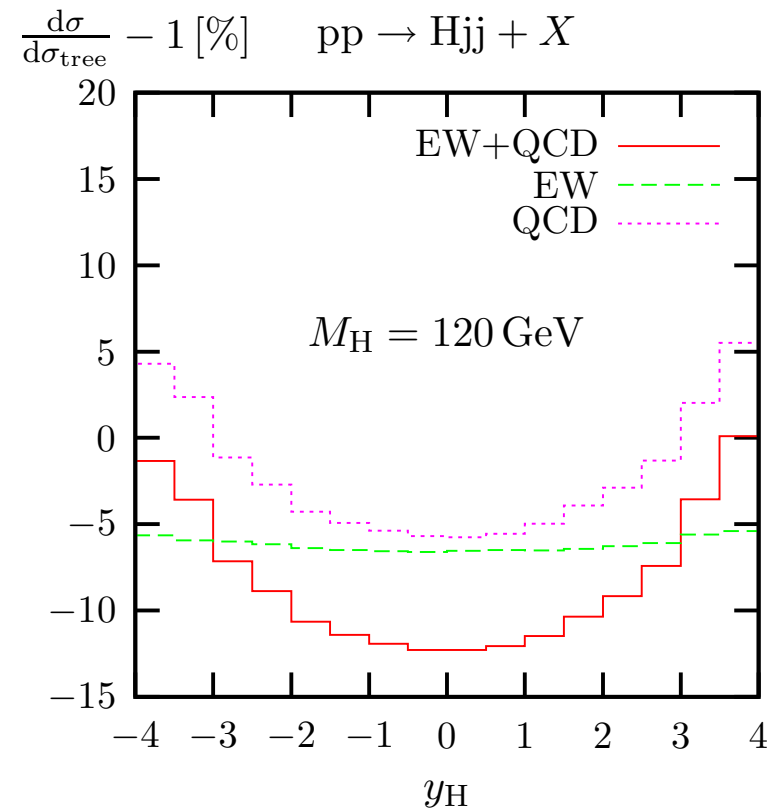
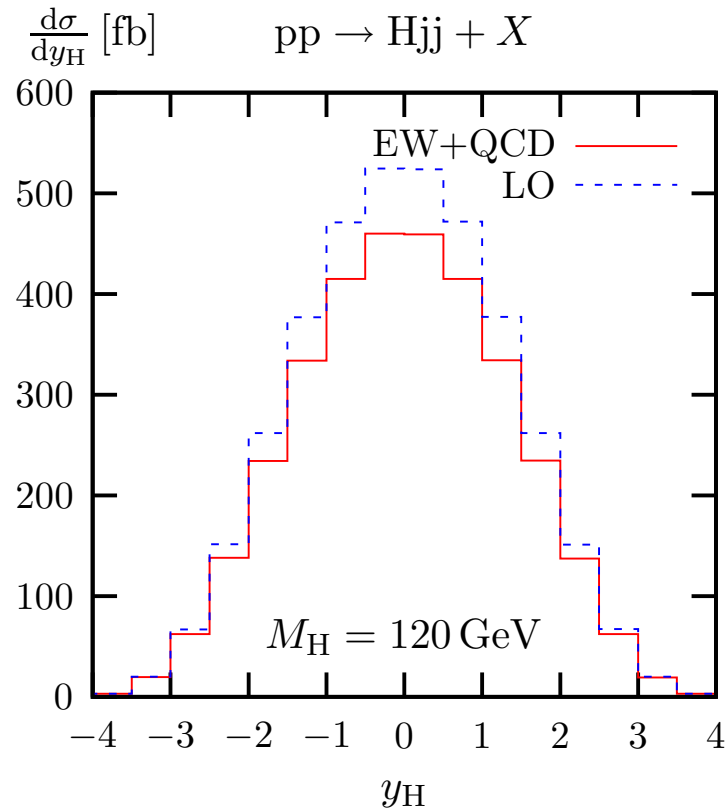
scale dep. at NLO: $\sim 5\text{--}10\%$ for $M_H/8 < \mu < 8M_H$ ($\sim 20\text{--}30\%$ at LO)

$\sim 2\text{--}3\%$ for $M_H/2 < \mu < 2M_H$ ($\sim 10\text{--}15\%$ at LO)

Distribution in the rapidity of the Higgs boson

VBF cuts

Ciccolini, Denner, Dittmaier



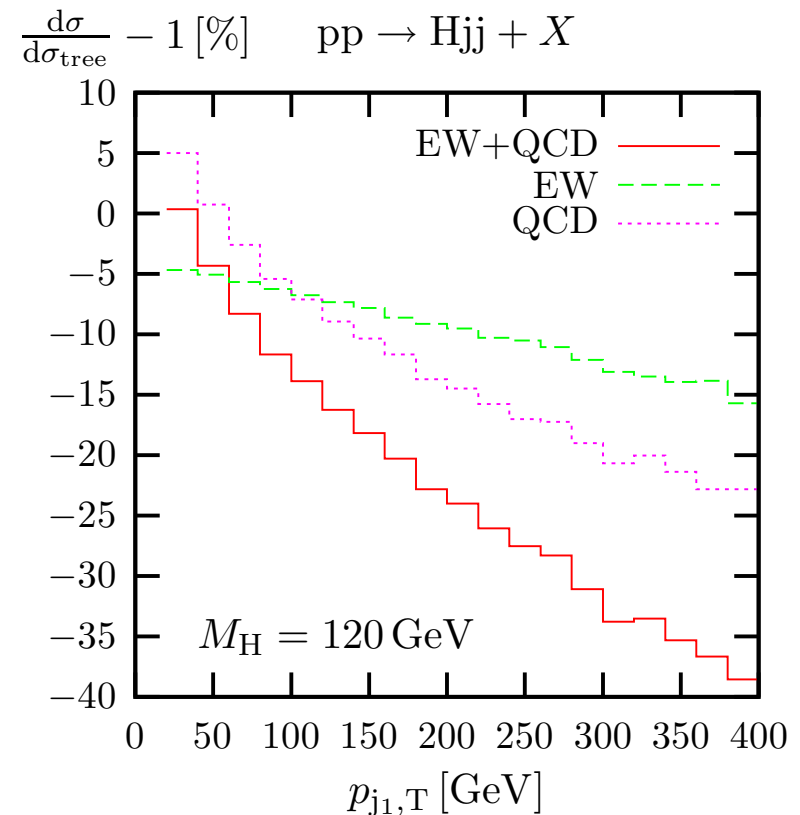
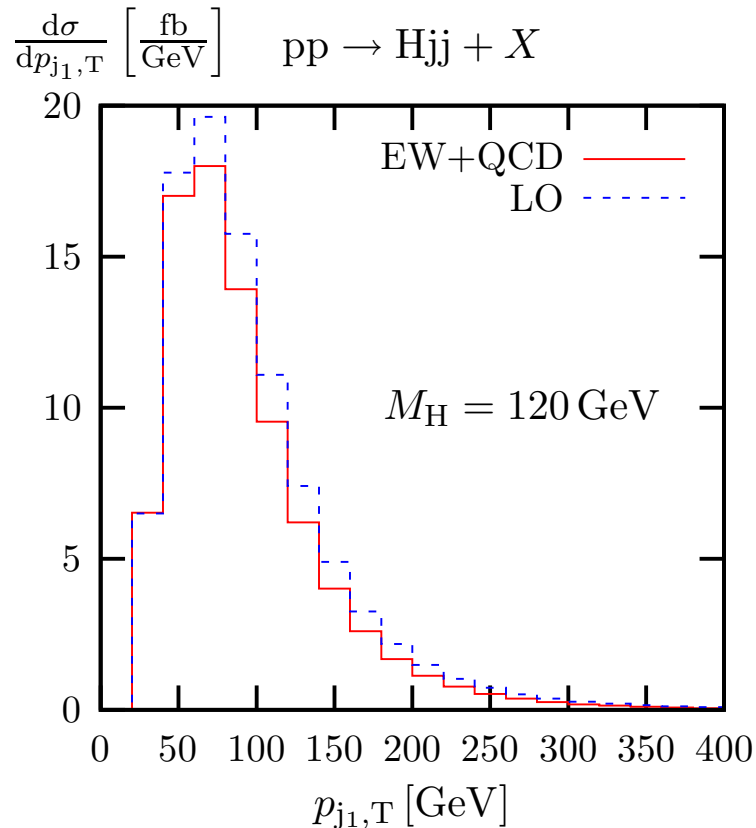
QCD corrections peak in forward and backward direction

EW corrections depend weakly on y_H

Distribution in the transverse momentum of the harder tagging jet

VBF cuts

Ciccolini, Denner, Dittmaier



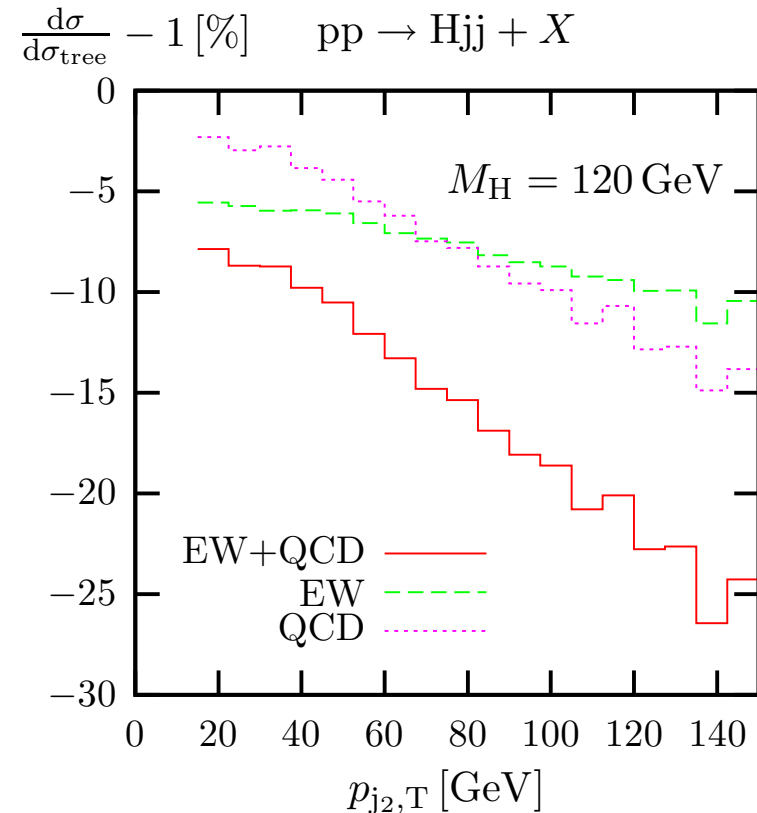
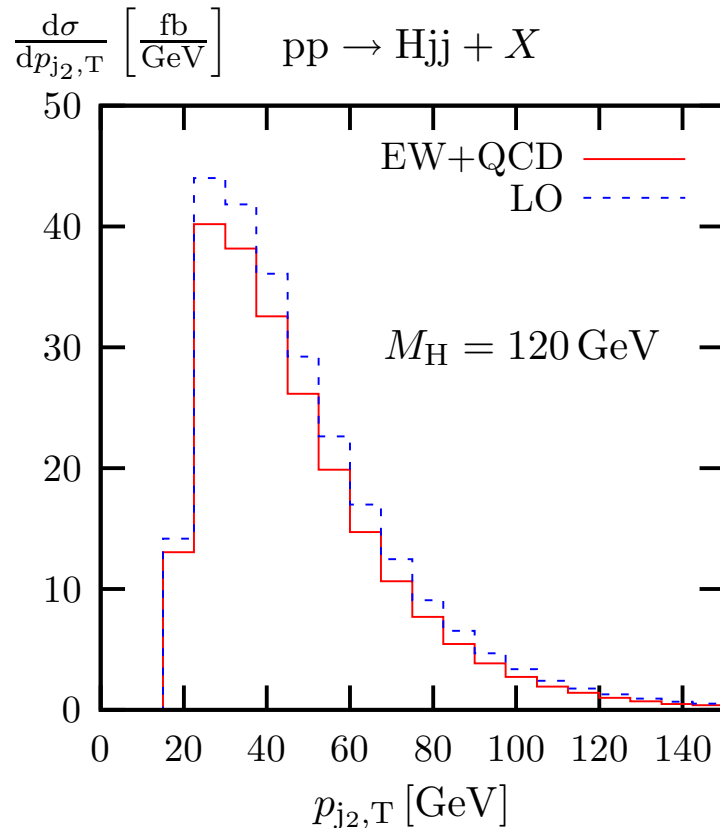
QCD and EW corrections become more and more negative for large p_{T,j_1}

QCD and EW corrections add up for large p_{T,j_1}

Distribution in the transverse momentum of the softer tagging jet

VBF cuts

Ciccolini, Denner, Dittmaier



QCD and EW corrections become more and more negative for large p_{T,j_2}

QCD and EW corrections add up for large p_{T,j_1}