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

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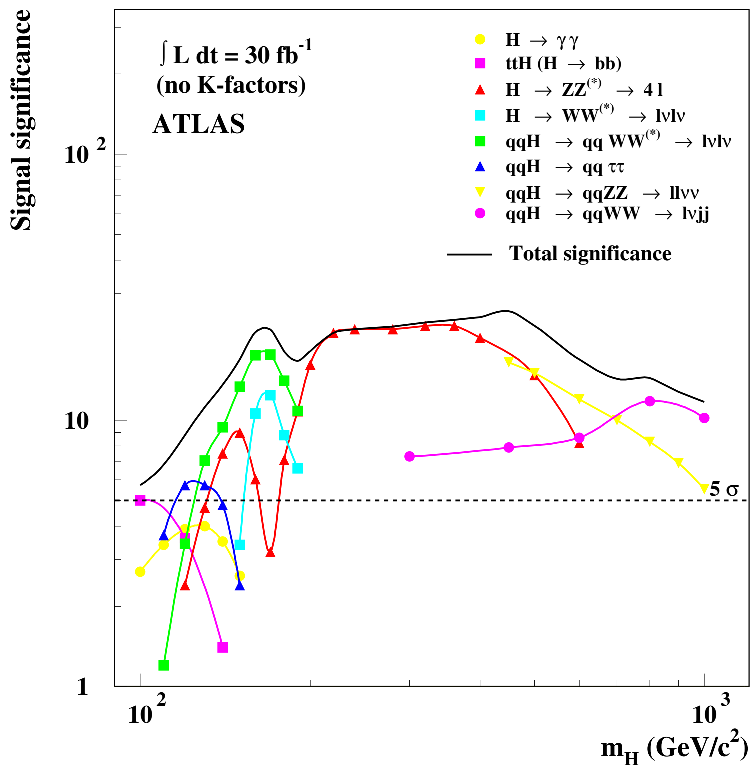
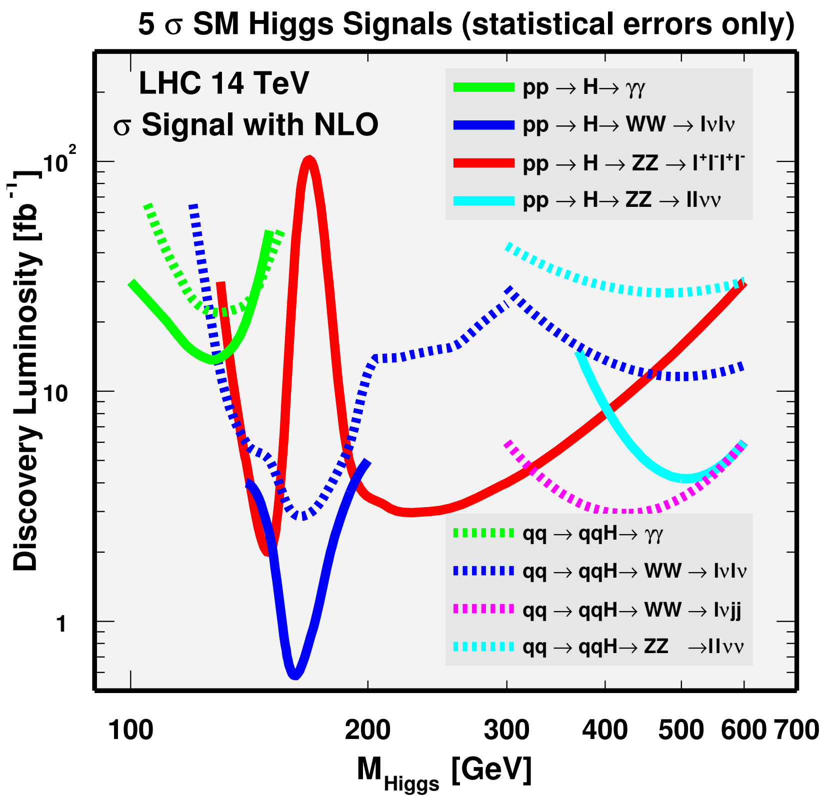
- Motivation
- Some details of the calculation
- Numerical results

ATLAS '04



CMS



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

– important Higgs-production process for $100\,\mathrm{GeV} \lesssim M_\mathrm{H} \lesssim 200\,\mathrm{GeV}$ 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 $\mathrm{pp} \to \mathrm{H} + 2\mathrm{jets} + X$

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 ~ 5–10%
  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

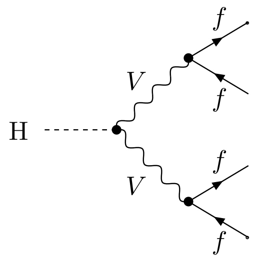
- complete NLO electroweak corrections to $\mathrm{pp} \to \mathrm{H} + 2\mathrm{jets} + X$ including photon-induced processes (using MRST2004QED PDFs)
- recalculation and extension of NLO QCD correction (complete set of diagrams and interference contributions)

calculation follows closely the one for $\mathrm{H} \to 4f$

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

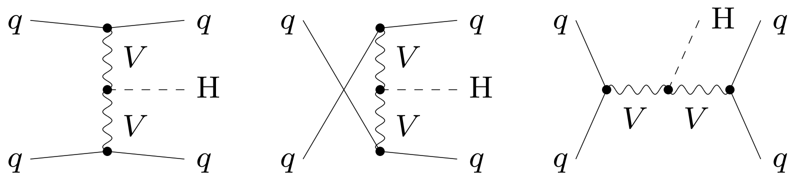
diagrams can be obtained via crossing symmetry

LO topology for $\mathrm{H} \to 4f$



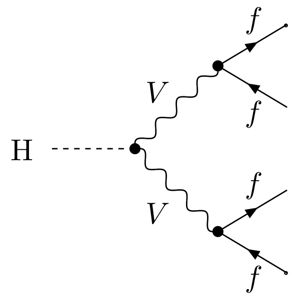
$V = W, Z$

topologies for t-, u-, and s-channel contributions to $qq \to qq\mathrm{H}$ in LO



q: quark or antiquark

Survey of Feynman diagrams

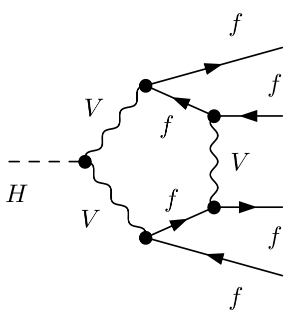
Lowest order: 

$V = W, Z$

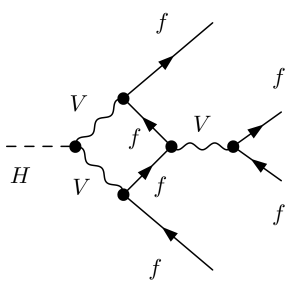
electroweak $\mathcal{O}(\alpha)$ corrections:

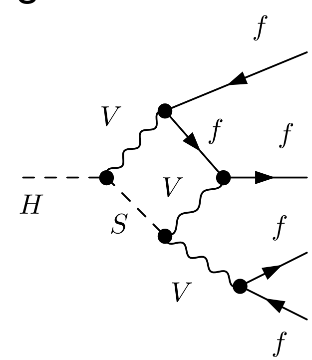
typical one-loop diagrams: # diagrams = $\mathcal{O}(200)$ per tree diagram

pentagons

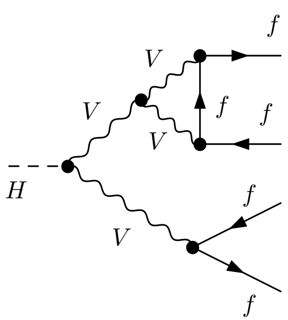


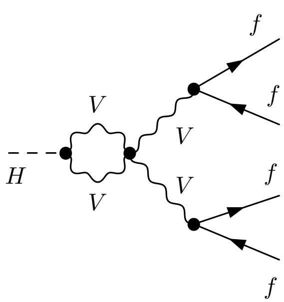
boxes



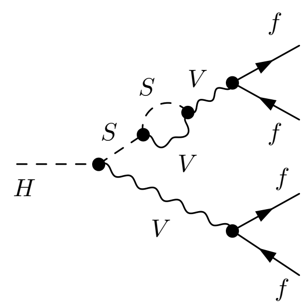


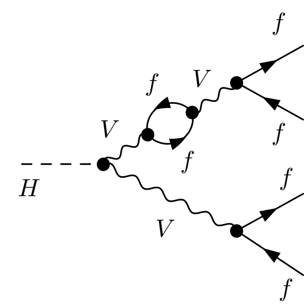
vertices





self-energies





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

Main complications in loop calculation:

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

new concepts already used in
$\mathcal{O}(\alpha)$ corrections to $\mathrm{e}^+\mathrm{e}^- \to 4f$ Denner, Dittmaier, Roth, Wieders ’05
and $\mathcal{O}(\alpha)$ and $\mathcal{O}(\alpha_\mathrm{s})$ corrections to $\mathrm{H} \to 4f$
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]

  $\hookrightarrow$ 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 $\propto G_\mu^2 M_{\mathrm{H}}^4$ to VVH vertex in large M_{H} limit

  Ghinculov '95, Frink et al. '96

Algebraic reduction of tensor integrals

For details see Denner, Dittmaier NPB734 (2006) 62 [hep-ph/0509141]

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

  two hybrid methods

  (i) Passarino–Veltman $\oplus$ expansions in small Gram and other kinematical determinants (see also Ellis et al. '05)

  (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) (see also Binoth et al. '05, Ferroglia et al. '02)

- 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 $gq \to \mathrm{H}q q\bar{q}$)
- 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
  $\hookrightarrow$ compact expressions

soft and collinear singularities:

- regularized with infinitesimal photon/gluon and quark masses
- dipole subtraction formalism Catani, Seymour '96, 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 $\mathrm{pp} \to \mathrm{H} + 2\mathrm{jets} + X$

- UV structure of virtual corrections
  $\hookrightarrow$ independence of reference mass μ of dimensional regularization
- IR structure of virtual + soft-gluon/photon corrections
  $\hookrightarrow$ independence of $\ln m_\gamma$ (m_γ = infinitesimal photon mass)
- mass singularities of virtual + collinear gluon/photon corrections
  $\hookrightarrow$ independence of $\ln m_{f_i}$ (m_{f_i} = small masses of external fermions)
- gauge invariance of amplitudes with $\Gamma_\mathrm{W}, \Gamma_\mathrm{Z} \neq 0$
  $\hookrightarrow$ identical results in 't Hooft–Feynman and background-field gauge
  Denner, Dittmaier, Weiglein '94
- real corrections
  $\hookrightarrow$ squared amplitudes compared with MADGRAPH Stelzer, Long '94
- combination of virtual and real corrections
  $\hookrightarrow$ 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
    $p_{\mathrm{Tj}} > 20\,\mathrm{GeV}, \qquad |y_{\mathrm{j}}| < 4.5$
  - define tagging jets
    $p_{\mathrm{Tj}_1} > p_{\mathrm{Tj}_2} \,(> p_{\mathrm{Tj}_3})$
  - require large rapidity separation of tagging jets
    $|y_{\mathrm{j}_1} - y_{\mathrm{j}_2}| > 4, \qquad y_{\mathrm{j}_1} \cdot y_{\mathrm{j}_2} < 0$

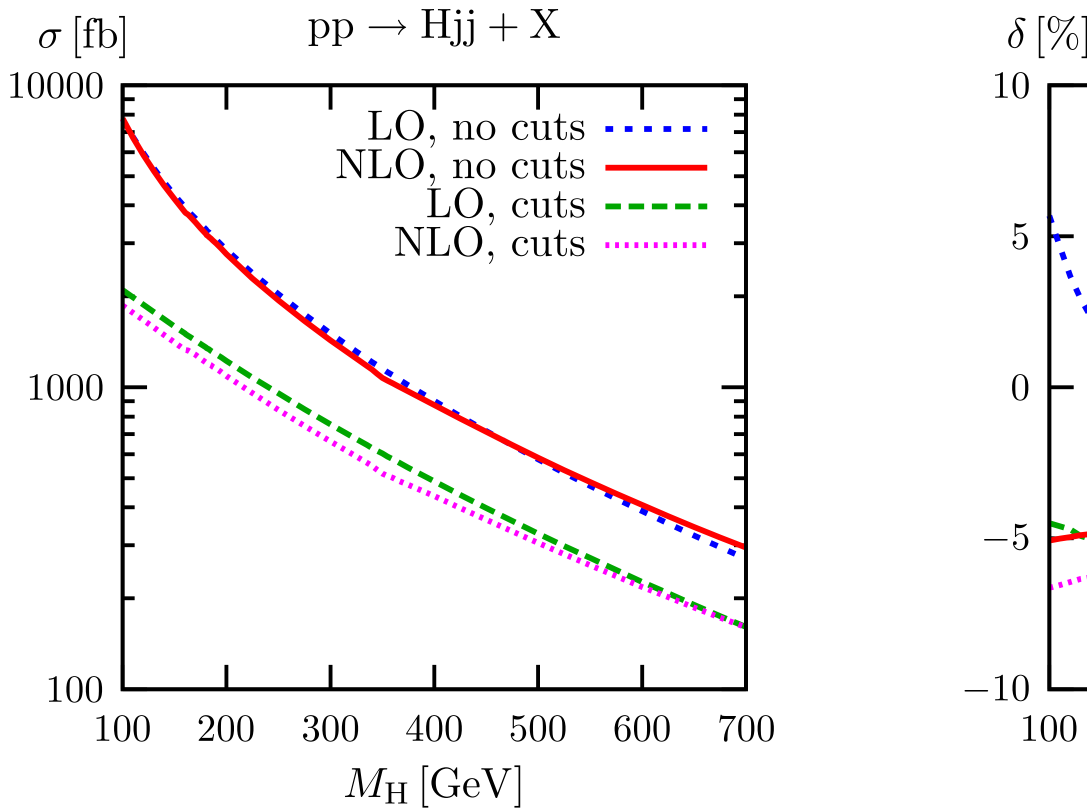
- Higgs boson considered stable

- renormalization and factorization scale: default $\mu_{\mathrm{F}} = \mu_{\mathrm{R}} = M_{\mathrm{W}}$

Total cross section for pp $\longrightarrow$ H + 2jets + X

Ciccolini, Denner, Dittmaier

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



↑ WW/ZZ thresholds for $M_{\mathrm{H}} \sim 2M_{\mathrm{W,Z}}$

↑ $\mathrm{t\bar{t}}$ threshold for $M_{\mathrm{H}} \sim 2m_{\mathrm{t}}$

electroweak (EW) corrections of similar size as QCD corrections
EW corrections $\sim -4\%$ – -7% for small M_{H}

Total cross section for pp $\longrightarrow$ H + 2jets + 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} [%]	$-6.47(2)$	$-6.27(2)$	$-4.98(1)$	$-3.99(1)$	$6.99(2)$
$\delta_{\mathrm{EW},qq}$ [%]	$-7.57(2)$	$-7.42(2)$	$-6.19(1)$	$-5.37(1)$	$5.44(2)$
$\delta_{\gamma\text{-induced}}$ [%]	1.10	1.15	1.22	1.38	1.55
δ_{QCD} [%]	$-4.77(4)$	$-5.20(4)$	$-5.65(3)$	$-6.67(3)$	$-7.18(2)$
$\delta_{\mathrm{QCD,diag}}$ [%]	$-4.75(4)$	$-5.17(4)$	$-5.66(4)$	$-6.63(3)$	$-7.18(2)$
$\delta_{\mathrm{QCD,nondiag}}$ [%]	-0.011	$-0.0052(1)$	$0.0032(1)$	0.0030	0.0022
$\delta_{\text{g-split}}$ [%]	$-0.0085(1)$	$0.0084(1)$	0.027	0.014	0.0074
$\delta_{\text{gg-fusion}}$ [%]	-0.030	-0.030	$-0.028(1)$	-0.020	-0.014
$\delta_{G_\mu^2 M_{\mathrm{H}}^4}$ [%]	0.0035	$0.0086(1)$	0.027	0.43	$4.06(1)$

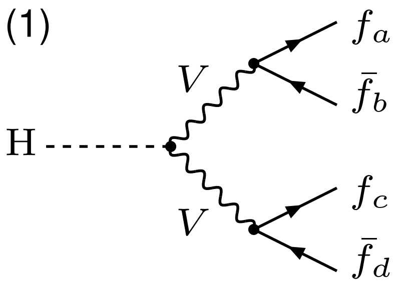
electroweak corrections $-6.5\% - +7\%$
photon-induced corrections $\sim 1\%$
interference corrections $\sim 0.02\%$

10^8 weighted events
~ 100 CPU h on Xeon 3 GHz PC
per cross section

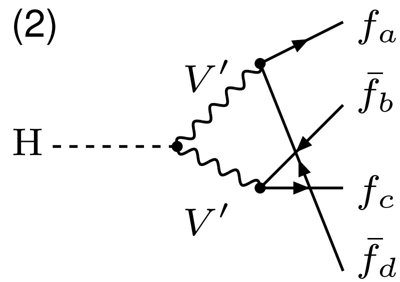
Classification of QCD corrections

Possible Born diagrams:

(1)



(2)



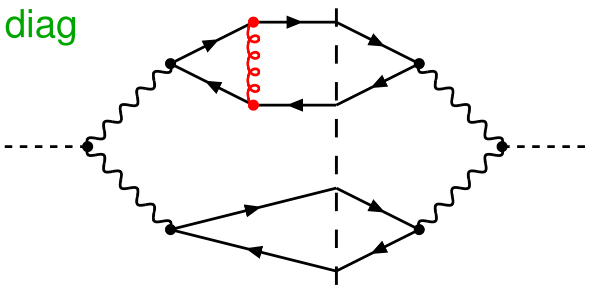
diagrams (2) only for

$q\bar{q}q\bar{q}$ and $q\bar{q}q'\bar{q}'$ channels

(q' = weak-isospin partner of q)

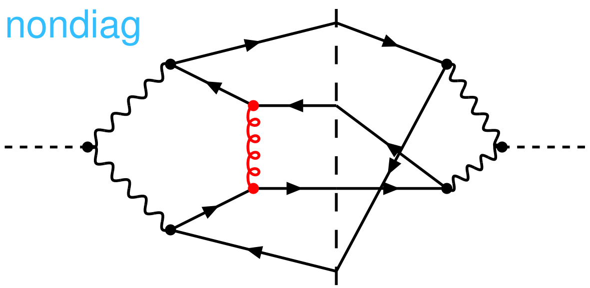
Classification of QCD corrections into four categories: (typical diagrams shown)

diag

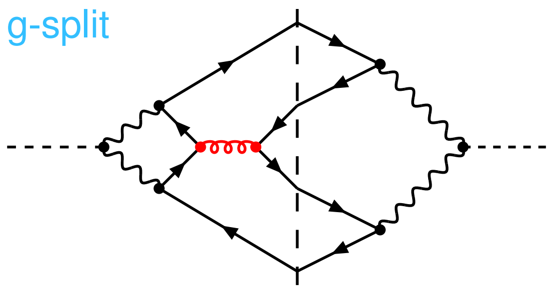


diag = corrections squared tree diagrams

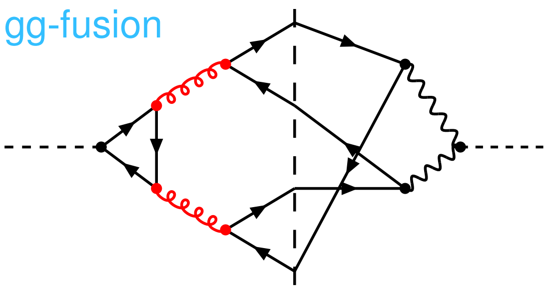
nondiag



g-split



gg-fusion



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

gg-fusion int.: see also Anderson, Smillie '06 and in $\mathcal{O}(\alpha^2\alpha_s^3)$ Anderson et al. '07, Bredenstein et al. '08

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)
$\sigma_{\mathrm{LO},s}$ [fb]	1294.4(2)	639.4(1)	244.26(4)	19.69	2.11
$\sigma_{\mathrm{NLO},s}$ [fb]	1582.1(4)	769.4(2)	289.80(9)	21.72(1)	2.29(1)
$\sigma_{\mathrm{LO},t/u\text{-int}}$ [fb]	-9.2	-5.6	-2.7	-0.32	-0.041
$\sigma_{\mathrm{NLO},t/u\text{-int}}$ [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

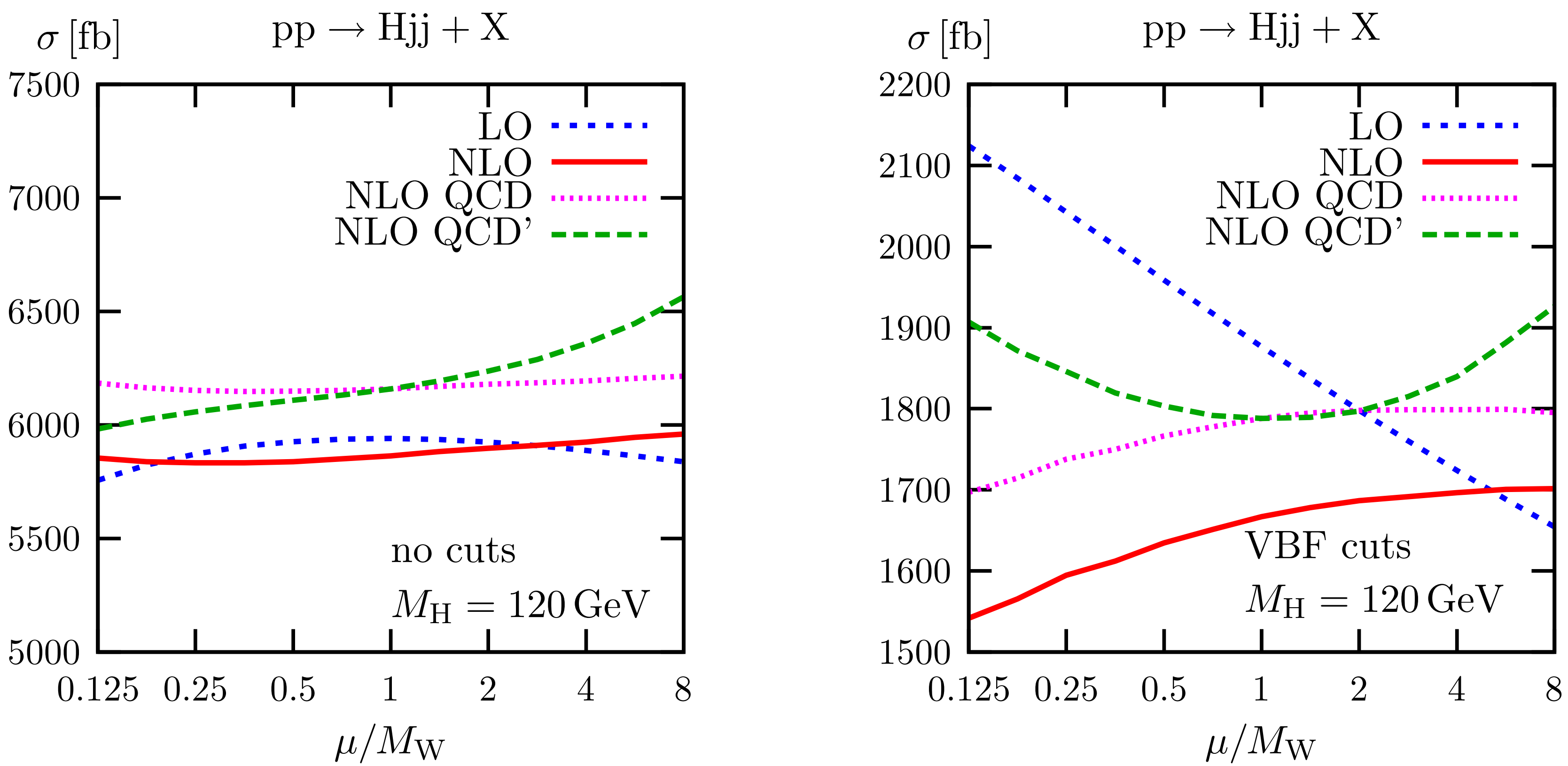
M_H [GeV]	120	150	200	400	700
σ_NLO [fb]	1665(1)	1407.5(8)	1091.3(5)	435.4(2)	160.36(5)
$\sigma_{\mathrm{LO},s}$ [fb]	0.0025	0.0015	0.00071	0.000072	0.0000069
$\sigma_{\mathrm{NLO},s}$ [fb]	9.45(1)	5.21(1)	2.33	0.29	0.044
$\sigma_{\mathrm{LO},t/u\text{-int}}$ [fb]	-0.12	-0.091	-0.060	-0.016	-0.0034
$\sigma_{\mathrm{NLO},t/u\text{-int}}$ [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 $\mathrm{pp} \to \mathrm{H} + 2\mathrm{jets} + X$

$M_\mathrm{H} = 120\,\mathrm{GeV}$

Ciccolini, Denner, Dittmaier



$\mu_\mathrm{R} = \mu_\mathrm{F} \equiv \mu$ for LO, NLO and NLO QCD

$\mu_\mathrm{R} = M_\mathrm{W}^2/\mu$ for NLO QCD'

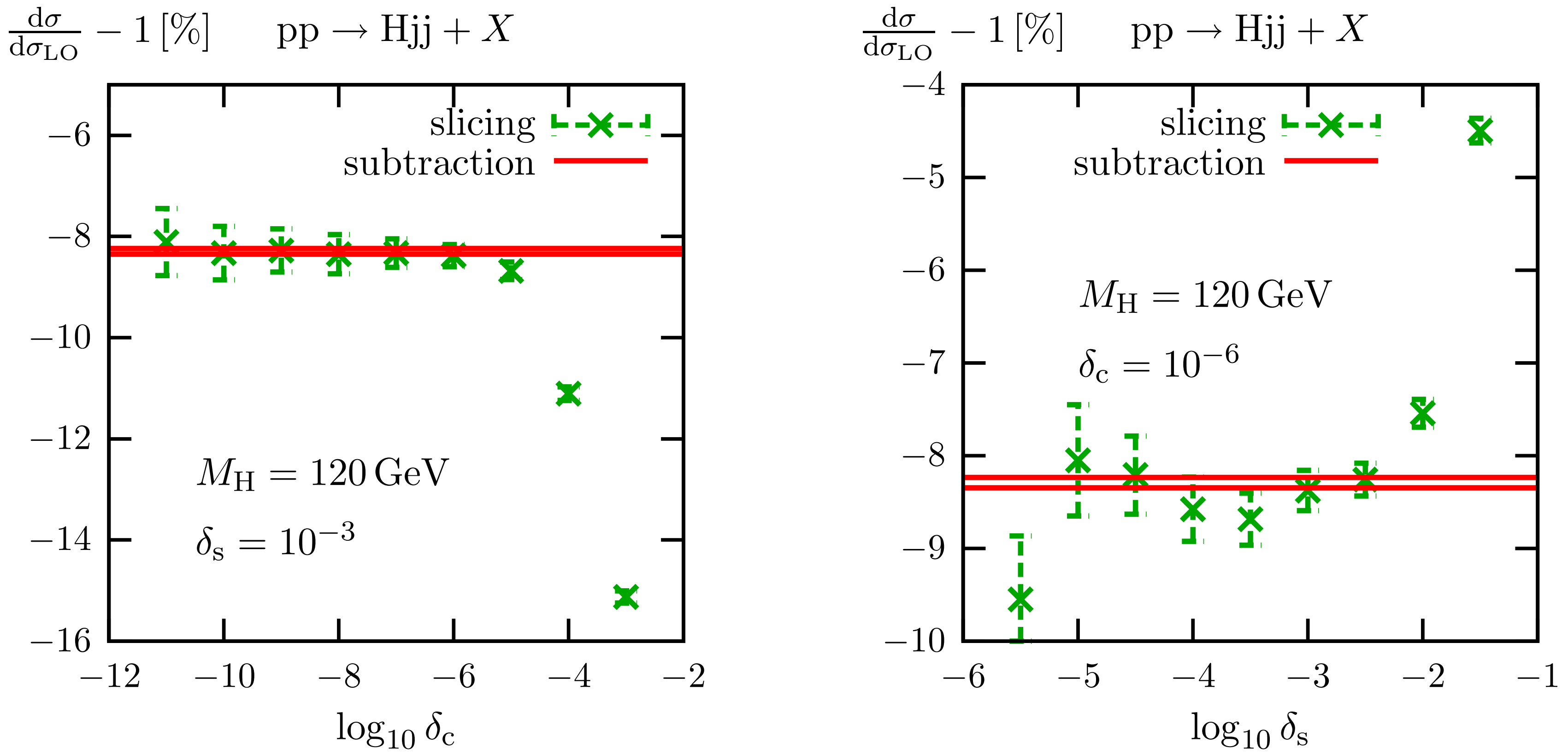
scale dep.: $M_\mathrm{W}/8 < \mu < 8M_\mathrm{W}$: NLO $\pm 8\%$, $\pm 9\%$ (LO $\pm 14\%$)

$M_\mathrm{W}/2 < \mu < 2M_\mathrm{W}$: NLO $\pm 2\%$, $\pm 2\%$ (LO $\pm 5\%$)

Comparison between slicing and subtraction methods

VBF cuts $(10^9/10^8$ events)

Ciccolini, Denner, Dittmaier



soft photon/gluon cut: $\delta_s = \Delta E_{cut}/E_{parton}$

collinear photon/gluon cut: $\delta_c = 1 - \cos\theta_{cut}$

cuts are applied in CMS of incoming partons

Comparison with existing NLO QCD calculations

tuned comparison: only squared t- and u-channel diagrams, no interferences

VVH2 by M. Spira based on Hahn, Valencia, Willenbrock '92 no cuts

$M_\mathrm{H}\ [\mathrm{GeV}]$	120	150	170	200	400	700
$\sigma_\mathrm{LO}\ [\mathrm{fb}]$	4226.3(6)	3357.8(5)	2910.7(4)	2381.6(3)	817.6(1)	257.49(4)
$\sigma_\mathrm{LO}^\mathrm{VV2H}\ [\mathrm{fb}]$	4226.2(4)	3357.3(3)	2910.2(3)	2380.4(2)	817.33(8)	257.40(3)
$\sigma_\mathrm{NLO}\ [\mathrm{fb}]$	4424(4)	3520(3)	3052(3)	2505(2)	858.4(7)	268.2(2)
$\sigma_\mathrm{NLO}^\mathrm{VV2H}\ [\mathrm{fb}]$	4415(1)	3519.7(8)	3055.8(7)	2503.4(6)	858.8(2)	268.03(6)

agreement within 0.2% $\sim$ statistical error

VBF cuts: VBFNLO Zeppenfeld et al. VBF cuts

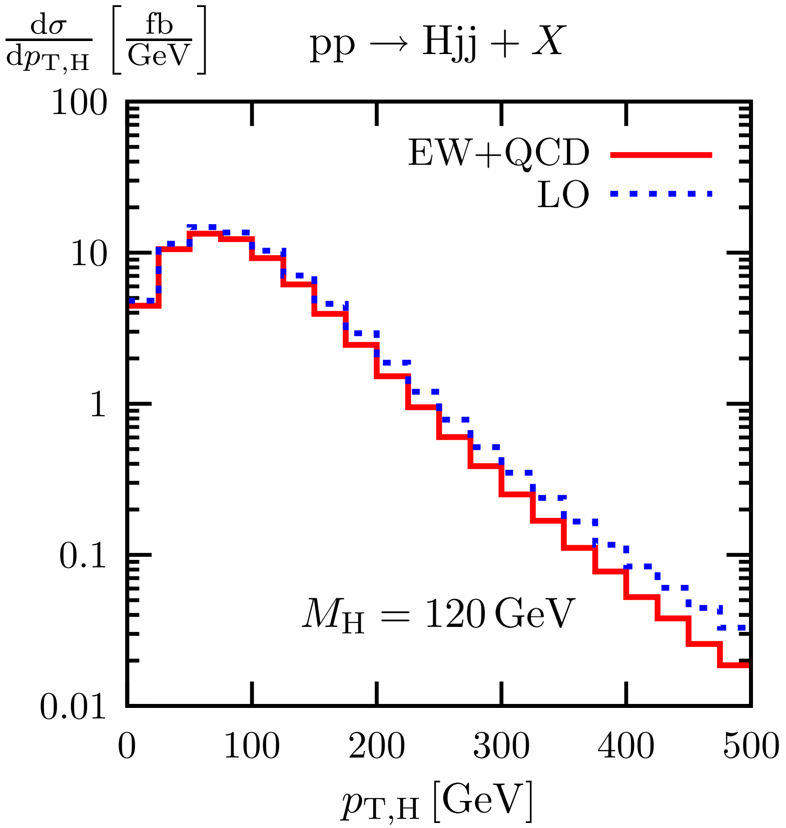
$M_\mathrm{H}\ [\mathrm{GeV}]$	120	150	170	200	400	700
$\sigma_\mathrm{LO}\ [\mathrm{fb}]$	1686.2(3)	1433.4(2)	1290.3(2)	1106.8(1)	451.27(5)	153.68(2)
$\sigma_\mathrm{LO}^\mathrm{VBFNLO}\ [\mathrm{fb}]$	1686.90(5)	1433.79(4)	1290.42(4)	1106.97(3)	451.31(1)	153.689(4)
$\sigma_\mathrm{NLO}\ [\mathrm{fb}]$	1728(2)	1463(1)	1313(2)	1121(1)	444.8(3)	147.2(1)
$\sigma_\mathrm{NLO}^\mathrm{VBFNLO}\ [\mathrm{fb}]$	1728.8(2)	1461.7(2)	1311.7(1)	1119.8(1)	444.71(3)	147.14(1)

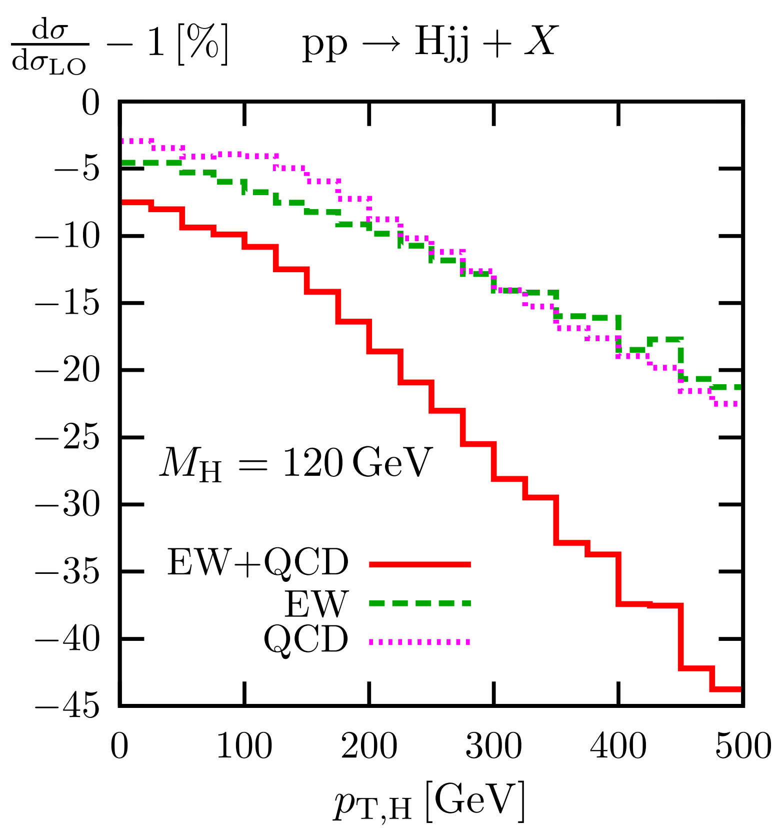
agreement within 0.1% $\sim$ statistical error

Distribution in the transverse momentum of the Higgs boson

VBF cuts

Ciccolini, Denner, Dittmaier





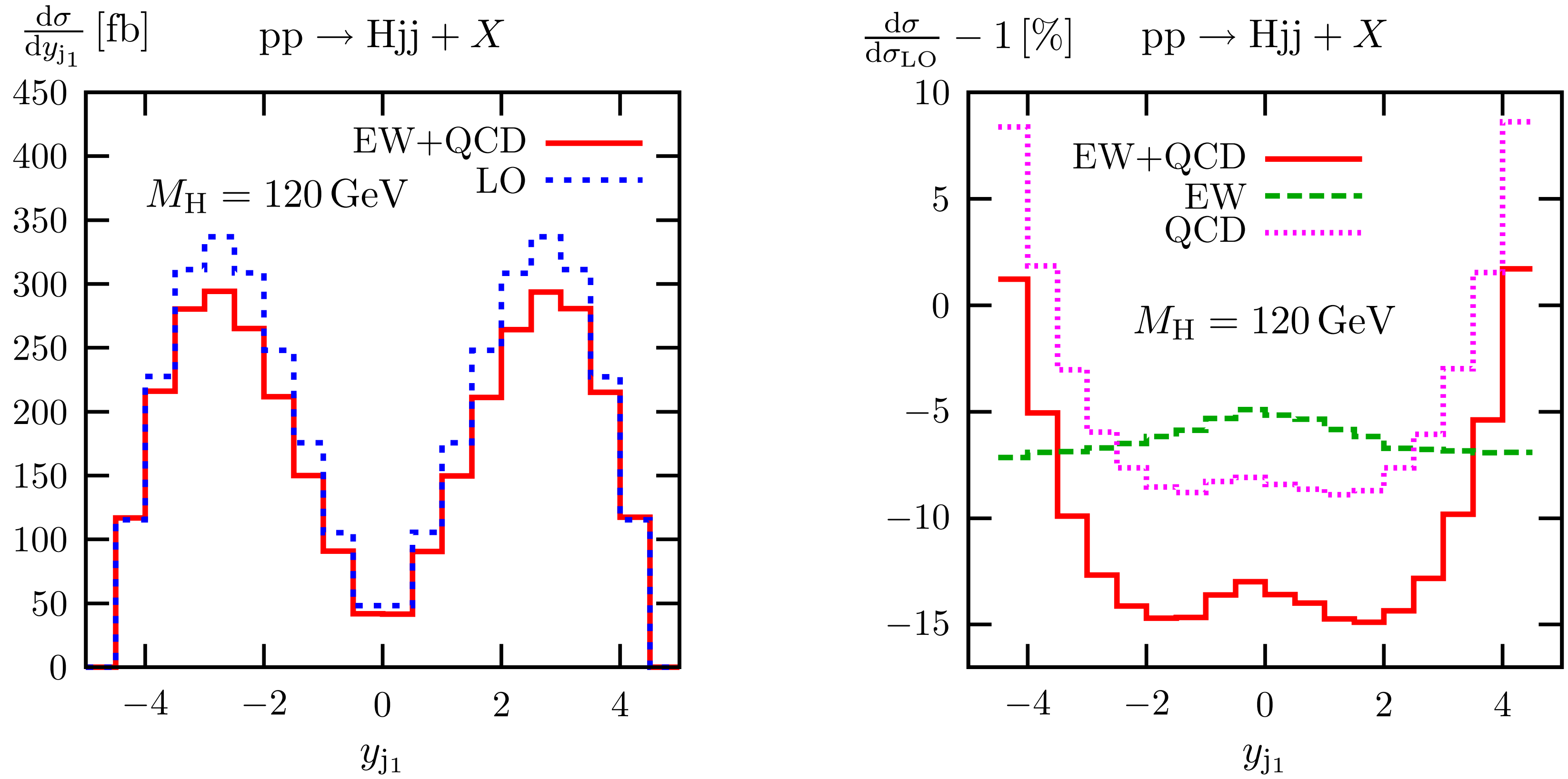
EW and QCD corrections similar

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

Distribution in the rapidity of the harder tagging jet

VBF cuts

Ciccolini, Denner, Dittmaier



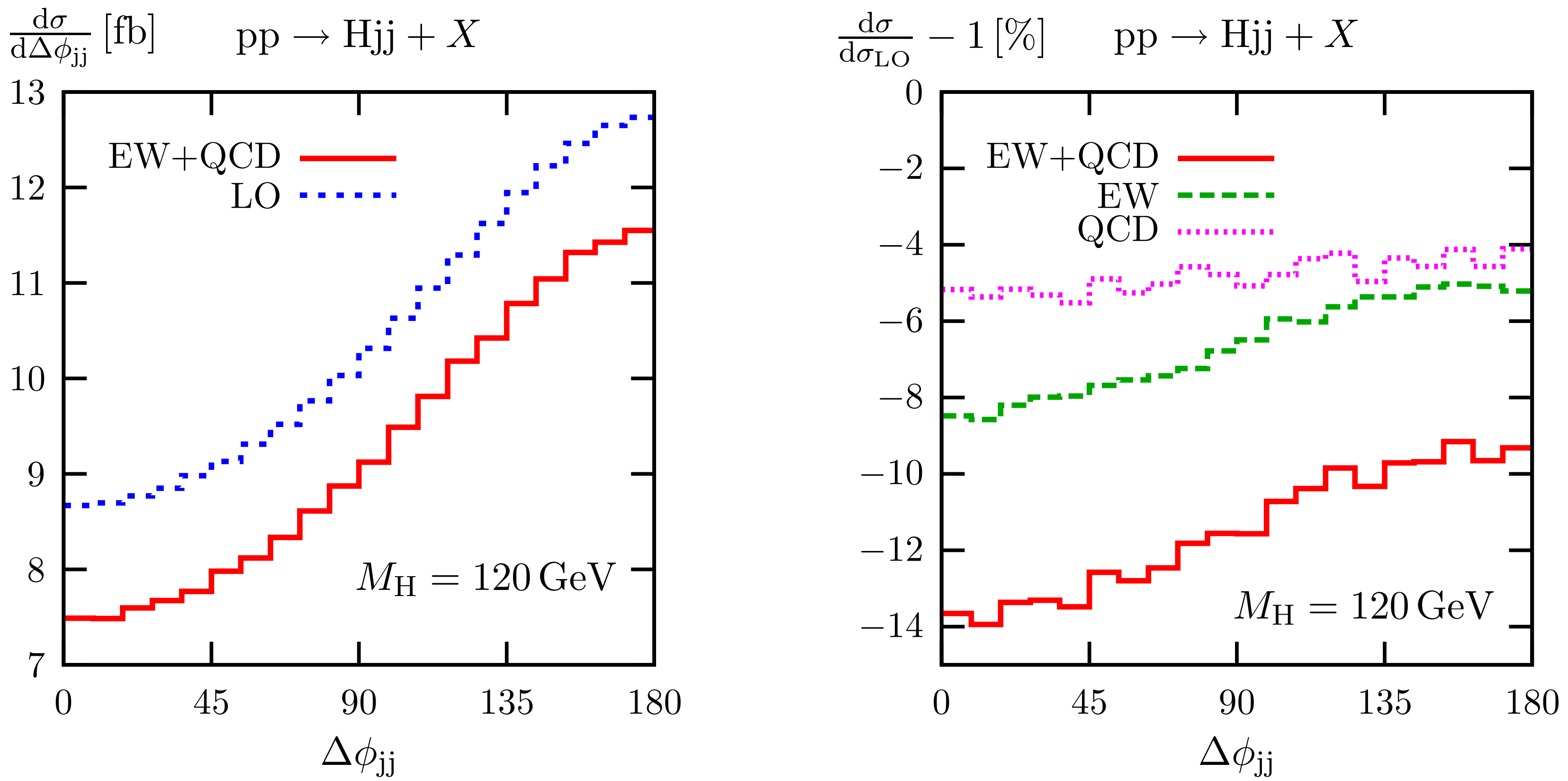
tagging jets forward–backward

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 Figy, Zeppenfeld '04

EW corrections yield distortion of distribution by 4%

Conclusions

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

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

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

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

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

- electroweak corrections: $\mathcal{O}(5\%)$ and negative for $100\,\mathrm{GeV} \lesssim M_\mathrm{H} \lesssim 200\,\mathrm{GeV}$
  comparable to QCD corrections, reach $+7\%$ for $M_\mathrm{H} = 700\,\mathrm{GeV}$
- real corrections due to initial-state photons $\sim 1\%$
- QCD corrections: $\mathcal{O}(5\%)$, in agreement with previous calculations
- s-channel diagrams and interference contributions $< 0.5\%$ for VBF cuts
- supersymmetric corrections: $\mathcal{O}(1\%)$ Hollik, Plehn, Rauch, Rzehak '08

Backup slides

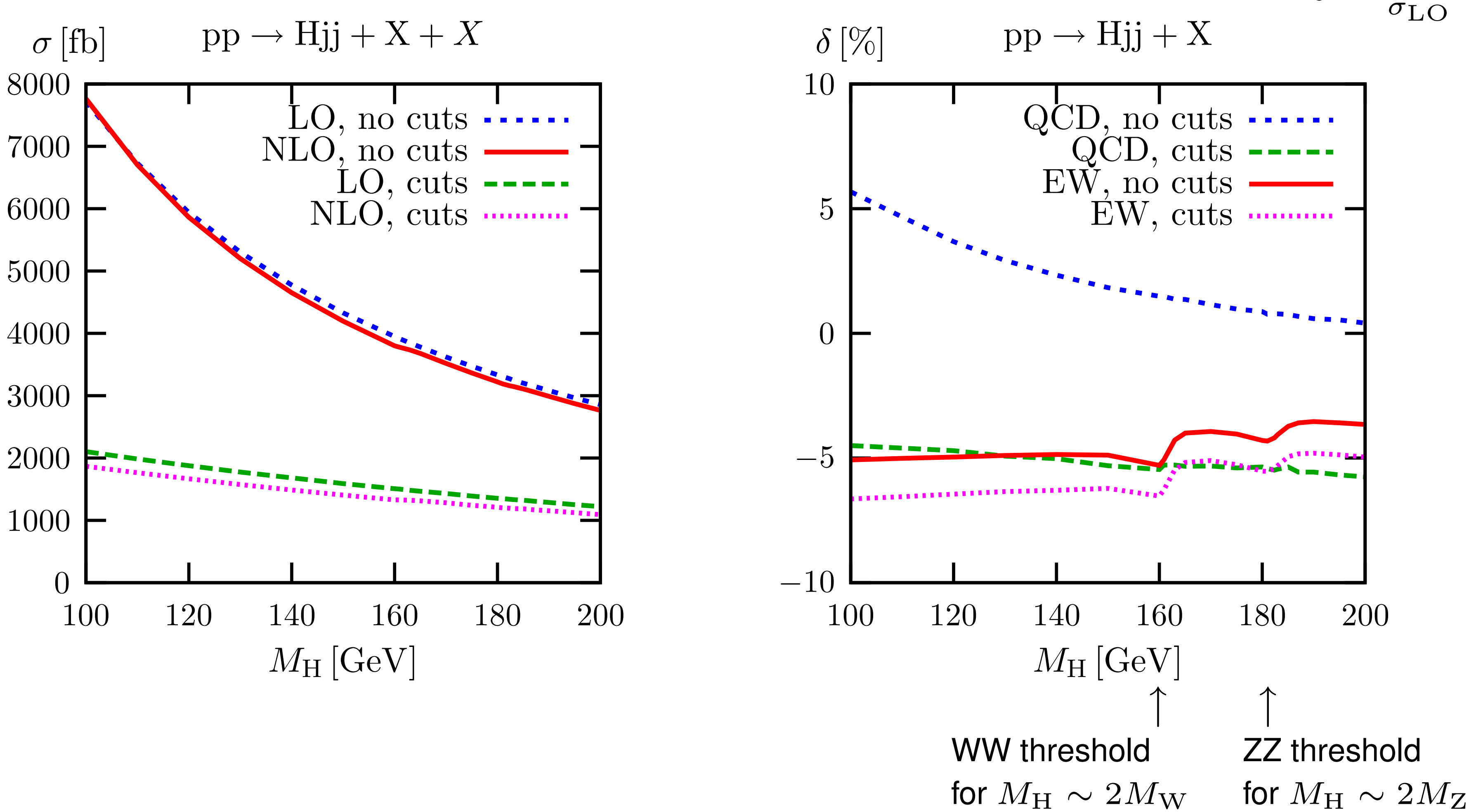
Set-up of the calculation

- external fermion masses neglected whenever possible
  (everywhere but in mass-singular logarithms)
- (complex) on-shell renormalization scheme
- G_μ scheme for electromagnetic couplings ($\alpha_{G_\mu} = \sqrt{2} G_\mu M_\mathrm{W}^2 s_\mathrm{w}^2/\pi$)
  accounts for electromagnetic running effects and universal corrections
  $\propto G_\mu m_\mathrm{t}^2$ 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 $\alpha_\mathrm{s}(M_\mathrm{Z}) = 0.1187$
- renormalization and factorization scale: default $\mu_\mathrm{F} = \mu_\mathrm{R} = M_\mathrm{W}$
- 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 $\longrightarrow$ H + 2jets + X

Ciccolini, Denner, Dittmaier

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



electroweak (EW) corrections of similar size as QCD corrections

EW corrections -4% – -7%

Total cross section for pp $\to$ H + 2jets + X

no cuts

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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} [%]	$-4.94(2)$	$-4.91(2)$	$-3.67(1)$	$-2.97(1)$	$7.74(2)$
$\delta_{\mathrm{EW},qq}$ [%]	$-5.79(2)$	$-5.92(2)$	$-4.85(1)$	$-4.50(1)$	$5.99(2)$
$\delta_{\gamma\text{-induced}}$ [%]	0.85	1.00	1.18	1.53	1.75
δ_{QCD} [%]	$3.75(5)$	$1.94(3)$	$0.49(3)$	$-0.24(3)$	$1.06(3)$
$\delta_{\mathrm{QCD,diag}}$ [%]	$3.97(3)$	$2.04(3)$	$0.55(3)$	$-0.06(3)$	$1.14(3)$
$\delta_{\mathrm{QCD,nondiag}}$ [%]	$0.010(2)$	$0.027(2)$	$0.050(1)$	0.026	0.013
$\delta_{\text{g-split}}$ [%]	$-0.015(1)$	$0.059(1)$	$0.110(1)$	$0.040(1)$	$0.017(1)$
$\delta_{\text{gg-fusion}}$ [%]	$-0.19(1)$	-0.20	-0.22	-0.24	$-0.11(1)$
$\delta_{G_\mu^2 M_{\mathrm{H}}^4}$ [%]	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 $pp \to H + 2\text{jets} + X$

$M_H = 200$ GeV

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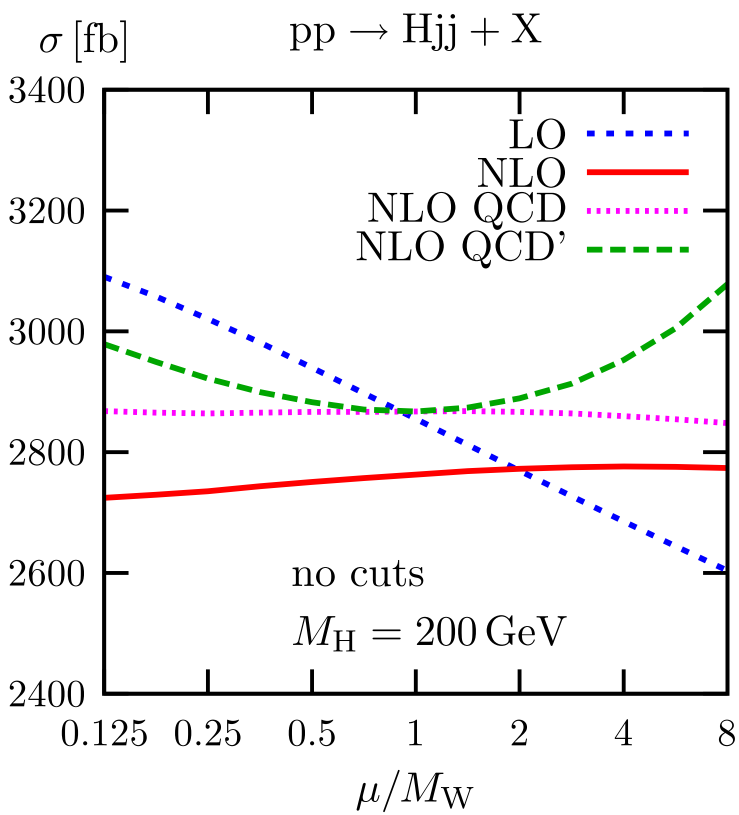

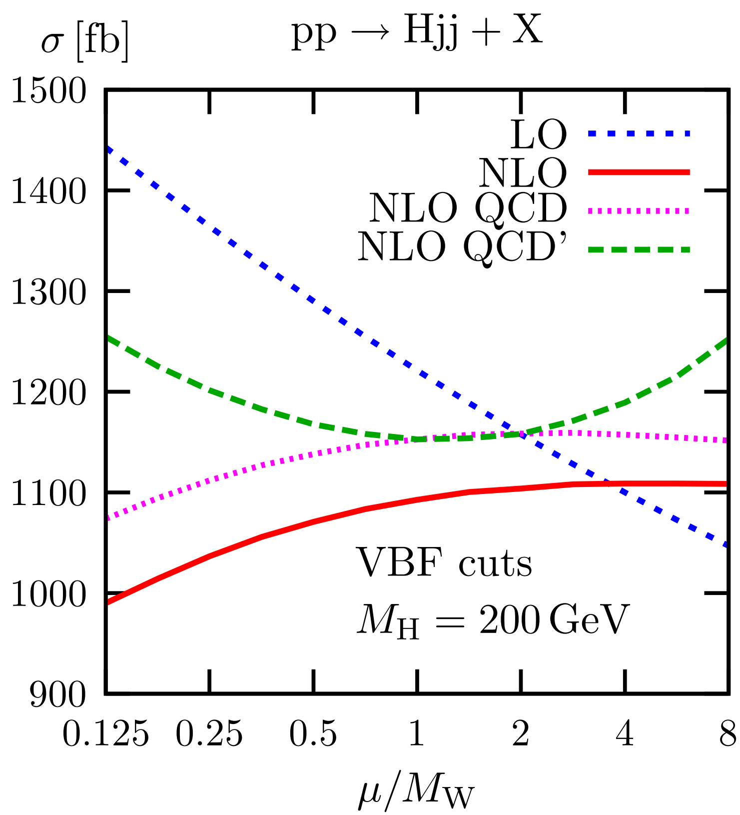

$\mu_R = \mu_F \equiv \mu$ for LO, NLO and NLO QCD

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

scale dep.: $M_W/8 < \mu < 8M_W$: NLO ${}^{-2\%}_{+9\%}$, $\pm 11\%$ (LO $\pm 9\%$, $\pm 18\%$)

$M_W/2 < \mu < 2M_W$: NLO $\pm 1\%$, $\pm 2\%$ (LO $\pm 3\%$, $\pm 6\%$)

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

$M_H = 400$ GeV

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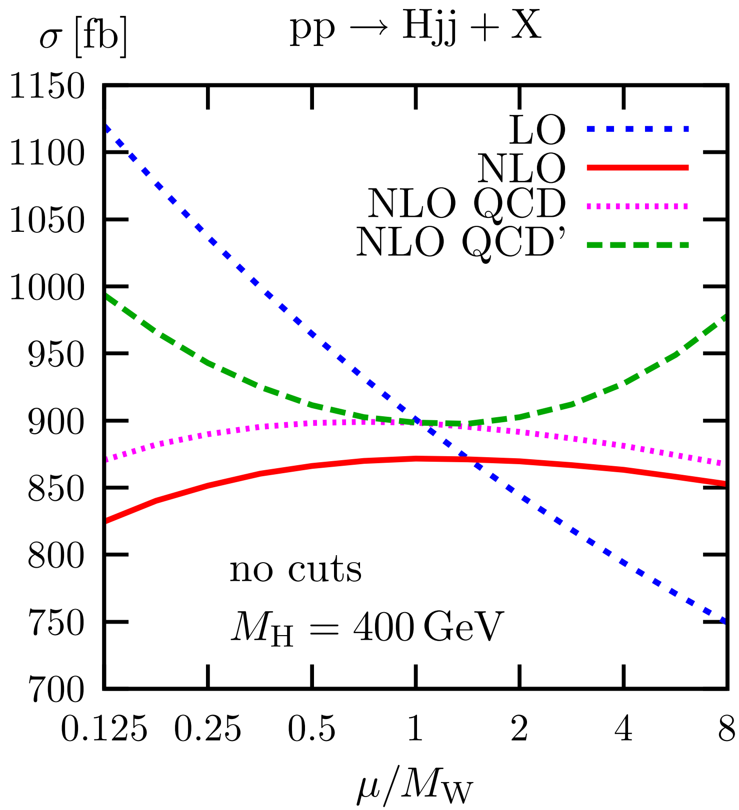
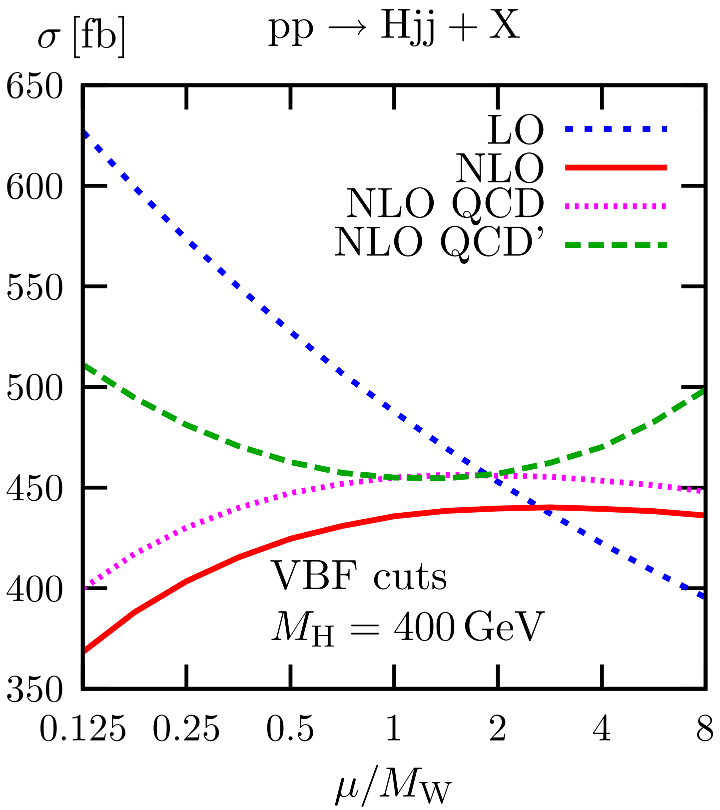




$\mu_R = \mu_F \equiv \mu$ for LO, NLO and NLO QCD

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

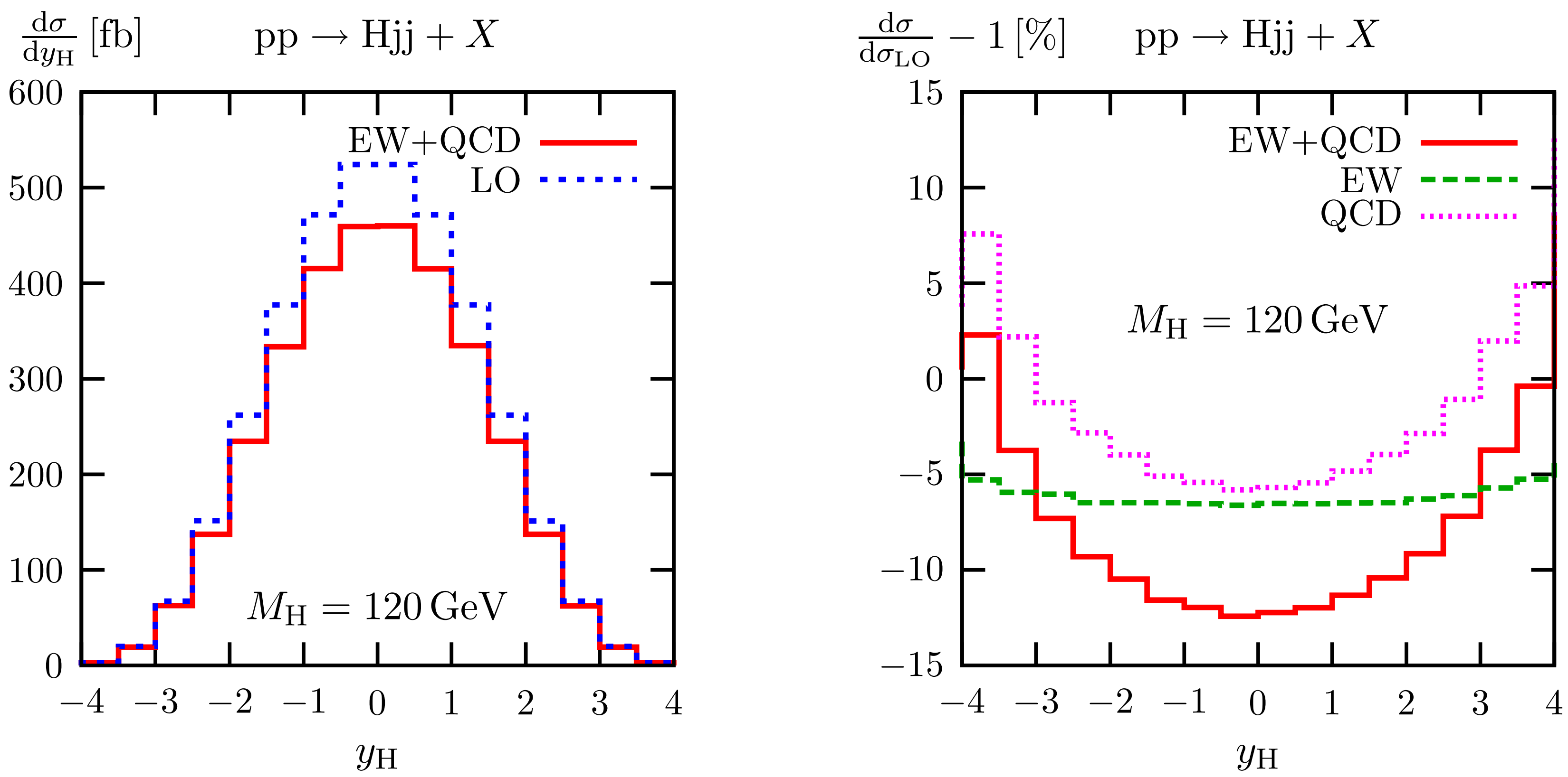
scale dep.: $M_W/8 < \mu < 8M_W$: NLO $\pm 11\%$, $\pm 15\%$ (LO $\pm 24\%$, $\pm 29\%$)

$M_W/2 < \mu < 2M_W$: NLO $\pm 1\%$, $\pm 3\%$ (LO $\pm 7\%$, $\pm 8\%$)

Distribution in the rapidity of the Higgs boson

VBF cuts

Ciccolini, Denner, Dittmaier



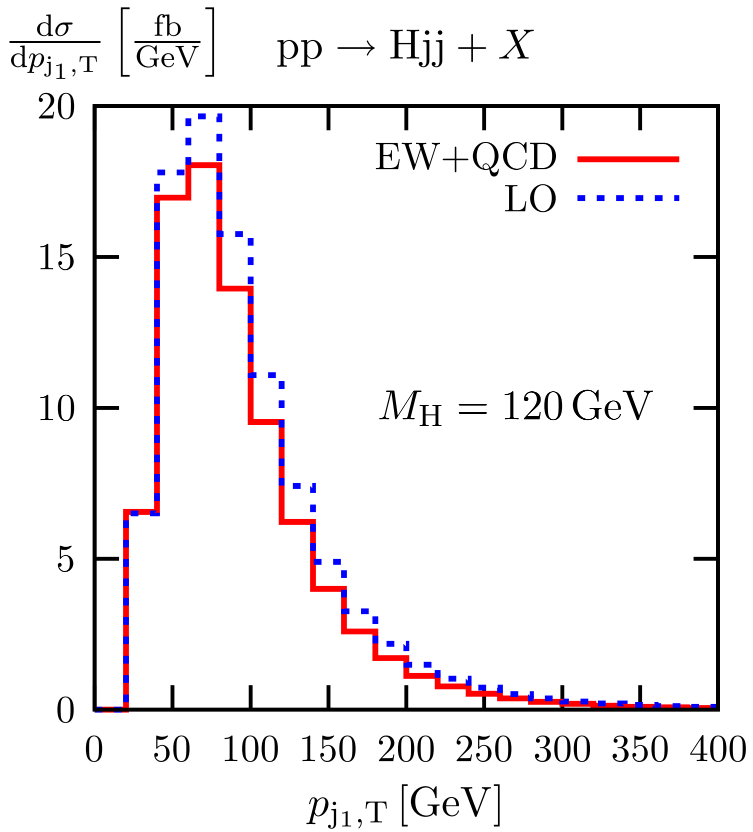
QCD corrections peak in forward and backward direction

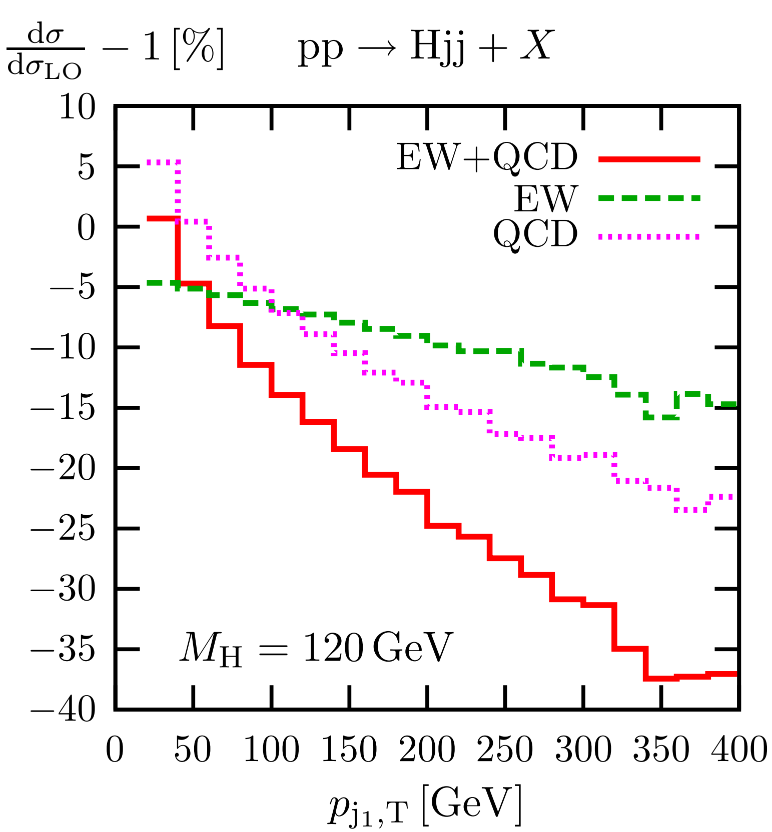
EW corrections depend weakly on y_H

Distribution in the transverse momentum of the harder tagging jet

VBF cuts

Ciccolini, Denner, Dittmaier





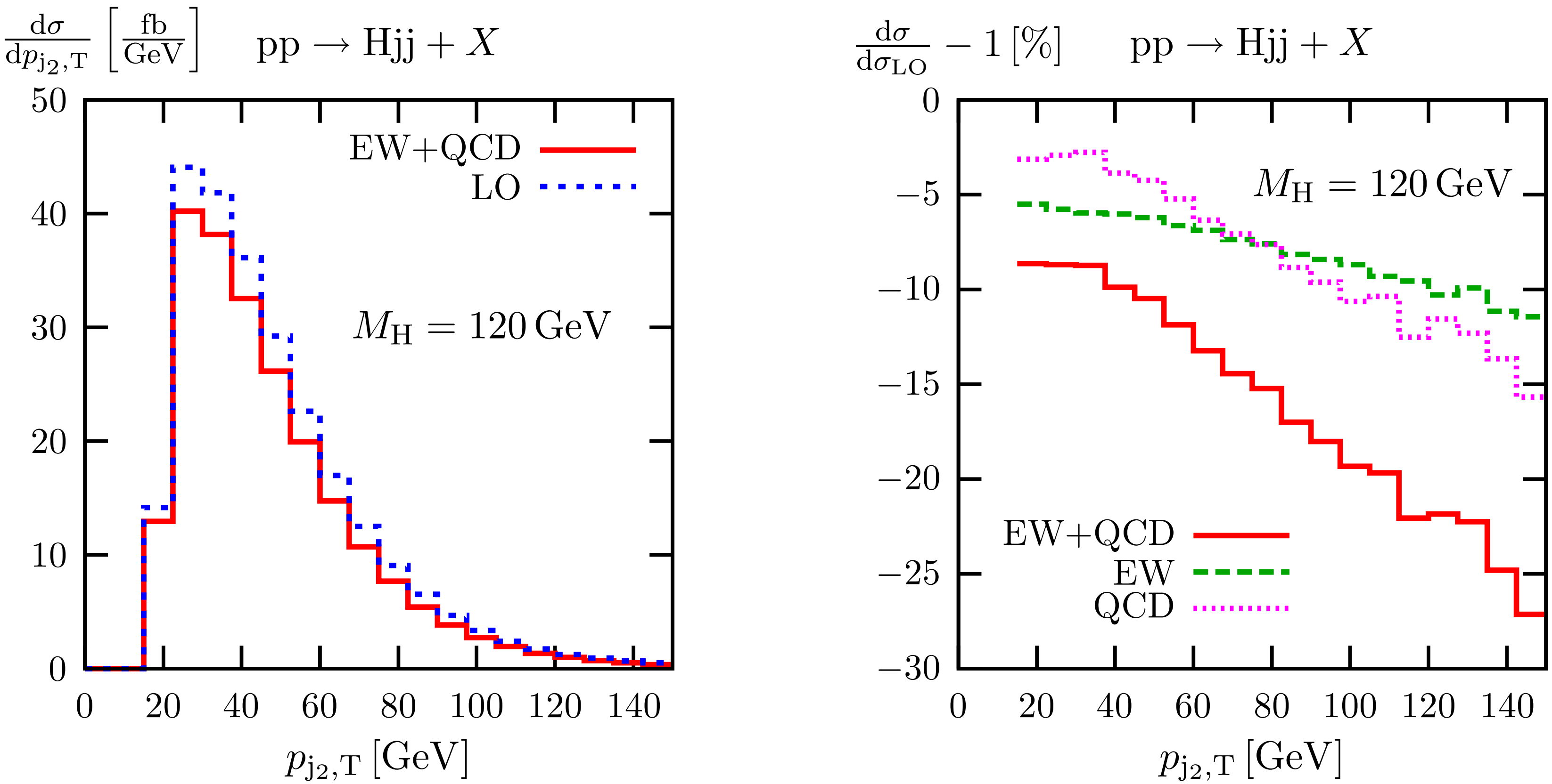
QCD and EW corrections become more and more negative for large p_{T,j_1}

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}