
# Higgs production via vector-boson fusion

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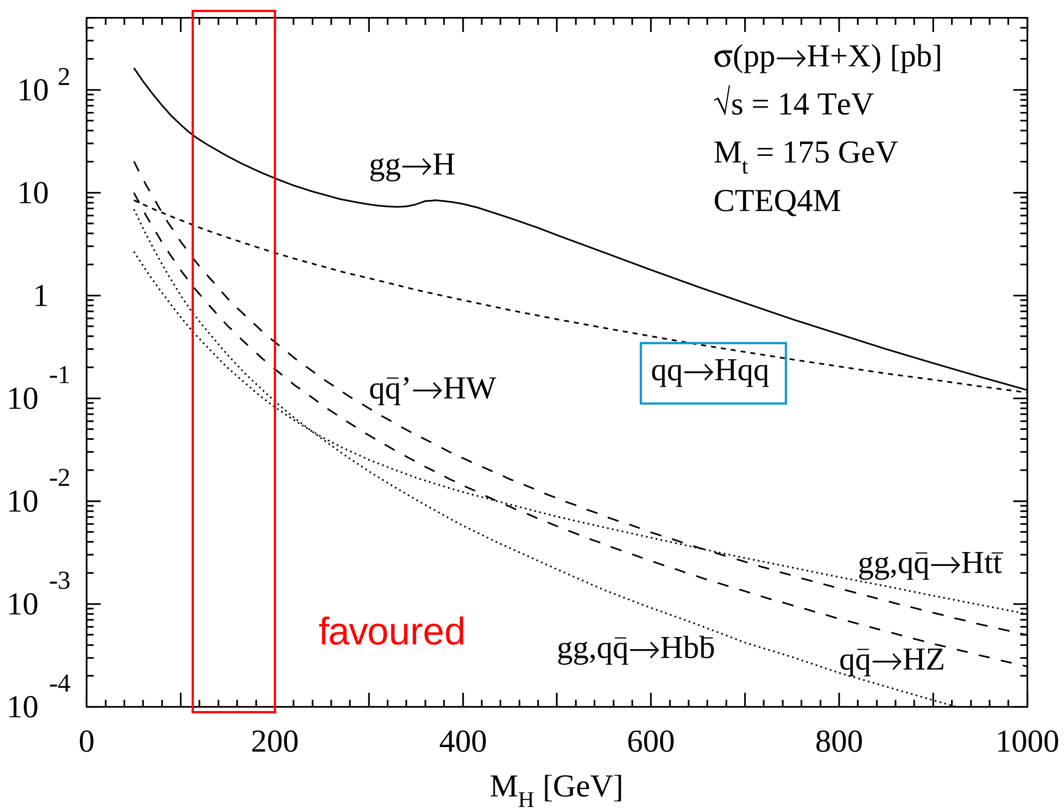
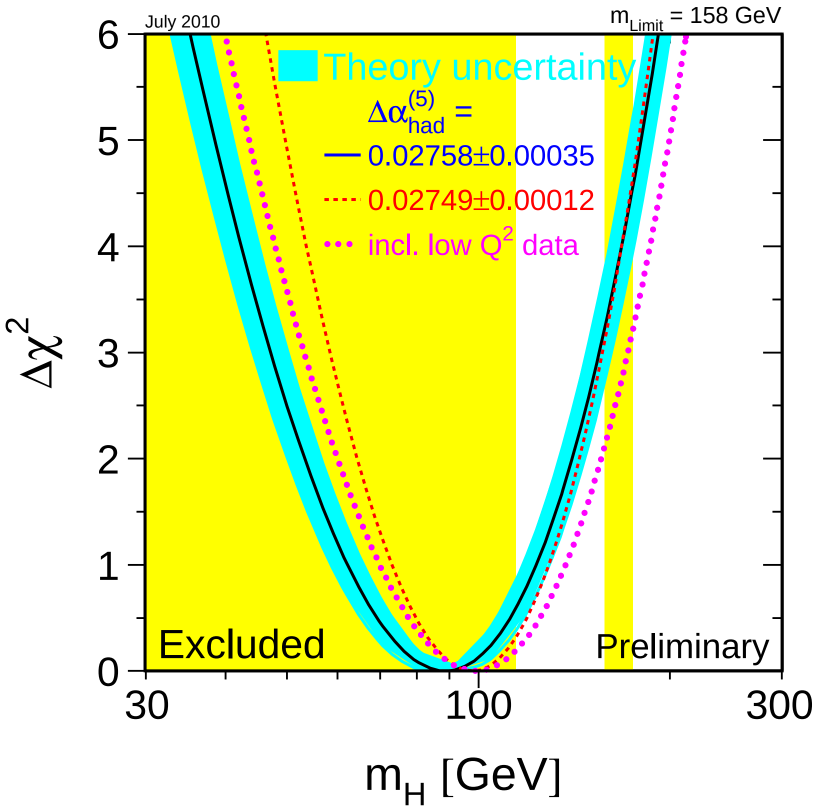
## Contents

# Introduction – overview

# Cross sections and significance of the Higgs signal at the LHC

(not only) Spira et al. ’98

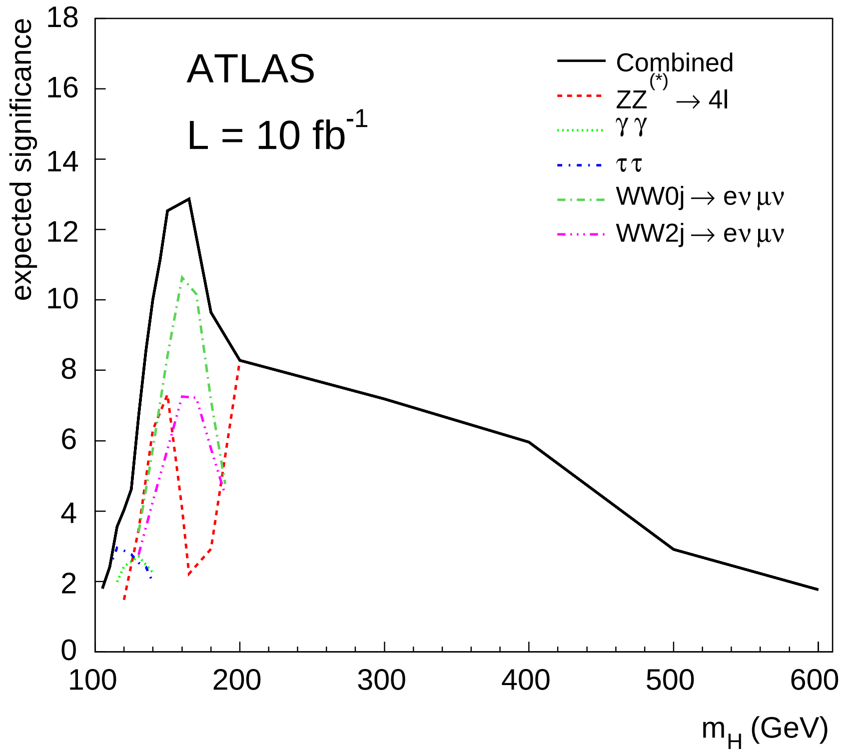


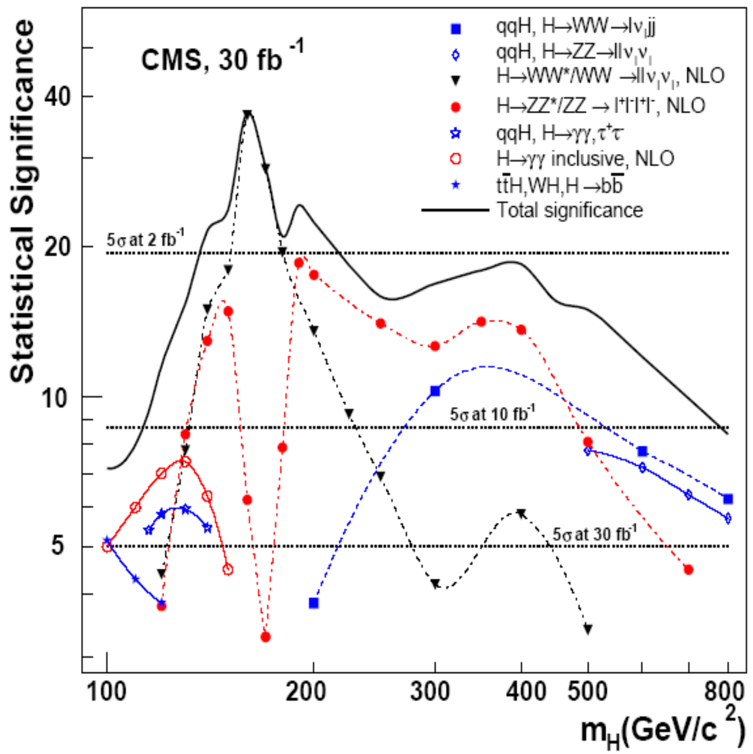




## Higgs production via VBF (“qqH”)

represents second largest cross section in entire $M_{\mathrm{H}}$ range

# Significance of the Higgs signal at the LHC

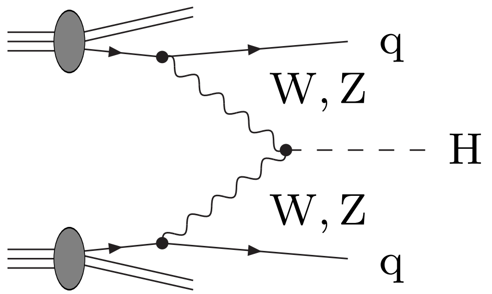



Higgs production via VBF ("qqH") is cornerstone in Higgs search in entire $M_{\mathrm{H}}$ range

$\hookrightarrow$ calculate / control higher orders to reduce theoretical uncertainty down to the level of PDF ($\sim 3{-}4\%$) and experimental uncertainties ($\sim 5{-}10\%$)

# Process topology of Higgs production via VBF




colour exchange between quark lines suppressed

$\Rightarrow$ small QCD corrections

$\hookrightarrow$ "DIS-like approximation" (vertex corrections)

## VBF cuts and background suppression:

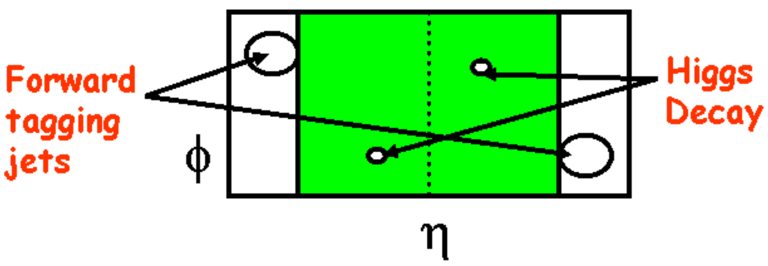
- 2 hard "tagging" jets demanded:

  $p_{\mathrm{Tj}} > 20\,\mathrm{GeV}, \quad |y_{\mathrm{j}}| < 4.5$

- tagging jets forward–backward directed:

  $\Delta y_{\mathrm{jj}} > 4, \quad y_{\mathrm{j1}} \cdot y_{\mathrm{j2}} < 0$

signature $=$ Higgs + 2jets




$\hookrightarrow$ Suppression of background

- from other (non-Higgs) processes,
  such as $\mathrm{t\bar{t}}$ or $\mathrm{WW}$ production Zeppenfeld et al. '94-'99

- induced by Higgs production via gluon fusion,
  such as $gg \to gg\mathrm{H}$ Del Duca et al. '06; Campbell et al. '06

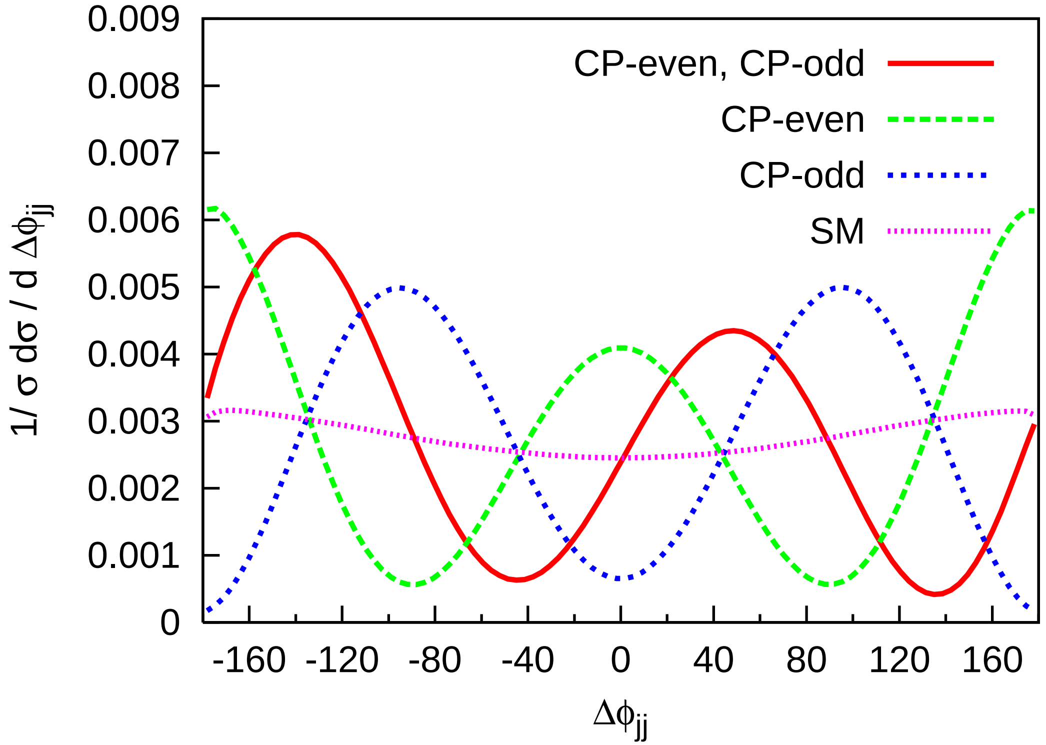
# WWH and ZZH coupling analyses

- Higgs via VBF plays important role in global Higgs couplings analysis

Dührssen et al. ’04

- azimuthal angle difference $\Delta\phi_{\mathrm{jj}}$ of tagging jets is sensitive to BSM effects:

Hankele, Klämke, Zeppenfeld, Figy ’06
Ruwiedel, Schumacher, Wermes ’07




(Individual contributions without SM; plot from Hankele et al.)

CP-even: $\mathcal{L} \propto HW^+_{\mu\nu}W^{-,\mu\nu}, \qquad \Gamma^{HW^+W^-}_{\mu\nu} \propto g_{\mu\nu}(k_+k_-) - k_{+,\nu}k_{-,\mu}$

CP-odd: $\mathcal{L} \propto H\tilde{W}^+_{\mu\nu}W^{-,\mu\nu}, \qquad \Gamma^{HW^+W^-}_{\mu\nu} \propto \epsilon_{\mu\nu\rho\sigma}k^\rho_+k^\sigma_-$

## Work on radiative corrections to the production of Higgs+2jets

- NLO QCD corrections to VBF in DIS-like approximation
  - ◇ total cross section — Han, Valencia, Willenbrock ’92; Spira ’98; Djouadi, Spira ’00
  - ◇ distributions — Figy, Oleari, Zeppenfeld ’03; Berger, Campbell ’04
  - ◇ matching with parton shower (POWHEG) — Nason, Oleari ’09

- (full) NLO QCD+EW corrections to VBF — Ciccolini, Denner, S.D. ’07

  $\hookrightarrow$ NLO QCD $\sim$ NLO EW $\sim 5{-}10\%$

- NNLO QCD corrections to VBF in DIS-like approximation — Bolzoni, Maltoni, Moch, Zaro ’10

  $\hookrightarrow$ NNLO QCD $\sim 1{-}2\%$

- NLO QCD corrections to $\mathrm{gg} \to \mathrm{Hgg}$, etc. — Campbell, R.K.Ellis, Zanderighi ’06

  $\hookrightarrow$ contribution to VBF $\sim 5\%$ — Nikitenko, Vazquez ’07 (NLO scale uncertainty $\sim 35\%$)

- QCD loop-induced interferences between VBF and $\mathrm{Hgg}$-initiated channels

  $\hookrightarrow$ impact $\lesssim 10^{-3}\,\%$ (negligible!) — Andersen, Binoth, Heinrich, Smillie ’07; Bredenstein, Hagiwara, Jäger ’08

- loop-induced VBF in $\mathrm{gg}$ scattering — Harlander, Vollinga, Weber ’08

  $\hookrightarrow$ impact $\sim 0.1\%$

- SUSY QCD+EW corrections — Hollik, Plehn, Rauch, Rzehak ’08

  $\hookrightarrow$ $|\mathrm{MSSM} - \mathrm{SM}| \lesssim 1\%$ for SPS points $(2{-}4\%$ for low SUSY scales)

## Work on related processes:

- NLO QCD corrections to $\mathrm{H}+3\mathrm{jets}$ via VBF  Figy, Hankele, Zeppenfeld ’07
- NLO QCD corrections to $\mathrm{HH}$ production via VBF  Figy ’08
- NLO QCD corrections to $\mathrm{H}+\gamma$ production via VBF  Arnold, Figy, Jäger, Zeppenfeld ’10

# LHC-Higgs cross section group → mandate for theory update

CrossSections < LHCPhysics < TWiki - Mozilla Firefox

https://twiki.cern.ch/twiki/bin/view/LHCPhysics/CrossSections

## Organization

### Overall Contacts

| ATLAS | CMS | THEORY | |
|---|---|---|---|
| Reisaburo Tanaka (LAL) | Chiara Mariotti (Torino) | Stefan Dittmaier (Freiburg) | Giampiero Passarino (Torino) |

### Subgroup Contacts and Link for Subgroup Wiki

* We are organized in 10 subgroups, with 2 experimental contacts (one from ATLAS and one from CMS) and 2 theoretical contacts.

* LHCb collaboration participates in WH/ZH group.

| Group | ATLAS | CMS | LHCb | THEORY | |
|---|---|---|---|---|---|
| 1. *ggF* | Jianming Qian (Michigan) | Fabian Stöckli (CERN) | | Massimiliano Grazzini (Firenze) | Frank Petriello (Wisconsin) |
| 2. *VBF* | Daniela Rebuzzi (Pavia) Sinead Farrington (Oxford) | Christoph Hackstein (Karlsruhe) | | Ansgar Denner (PSI) | Carlo Oleari (Milano-Bicocca) |
| 3. *WH/ZH* | Giacinto Piacquadio (CERN) | Jim Olsen (Princeton) | Clara Matteuzzi (Milano-Bicocca) | Stefan Dittmaier (Freiburg) | Robert Harlander (Wuppertal) |
| 4. *ttH* | Simon Dean (UCL) | Chris Neu (Virginia) | | Laura Reina (Florida) | Michael Spira (PSI) |
| 5. *MSSM neutral* | Markus Warsinsky (Freiburg) | Monica Vazquez Acosta (IC) | | Michael Spira (PSI) | Georg Weiglein (DESY) |
| 6. *MSSM charged* | Martin Flechl (Freiburg) | Sami Lehti (Helsinki) | | Michael Krämer (Aachen) | Tilman Plehn (Heidelberg) |
| 7. *PDF* | Joey Huston (Michigan State) | Kajari Mazumdar (TIFR) | | Stefano Forte (Milano) | Robert Thorne (UCL) |
| 8. *Branching ratios* | Daniela Rebuzzi (Pavia) | Ivica Puljak (Split) | | Ansgar Denner (PSI) | Sven Heinemeyer (IFCA) |
| 9. *NLO MC* | Jae Yu (Texas) | Marta Felcini (UCD) | | Fabio Maltoni (Louvain) | Paolo Nason (Milano-Bicocca) |
| 10. *Pseudo-observables* | Michael Dührssen (CERN) | Martin Grünewald (Ghent) | | Sven Heinemeyer (IFCA) | Giampiero Passarino (Torino) |

## Available tools

- VV2H Spira

  NLO QCD for inclusive cross section

- VBF@NNLO Bolzoni, Maltoni, Moch, Zaro

  NNLO QCD for inclusive cross section

- PHANTOM Ballestrero et al.

  LO MC with PS for VBF $\to \mathrm{H} \to \mathrm{WW/ZZ} \to 4f$

- VBFNLO Zeppenfeld et al.

  MC with NLO QCD corrections, including Higgs decays

- HAWK Denner, S.D., Mück

  MC with NLO QCD and EW corrections, including $s$-channel

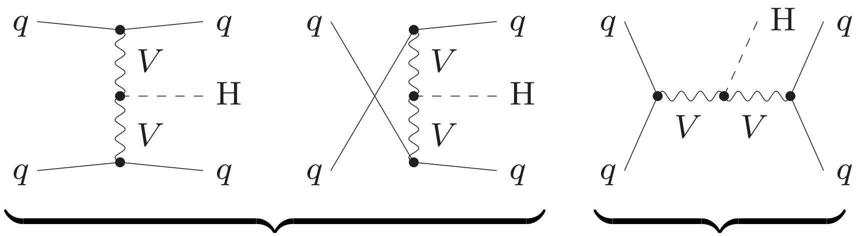
- POWHEG Frixione, Nason, Oleari, Ridolfi

  MC with matching of NLO QCD with PS

# NLO QCD and EW corrections to VBF

# Higgs production via VBF in LO

- $\sigma_{\mathrm{LO}} \propto \alpha^3$, no $\alpha_{\mathrm{s}}$ dependence
  $\hookrightarrow$ no $\mu_{\mathrm{ren}}$ dependence, scale dependence not a good measure of uncertainties
- many subcontributions from $qq$, $q\bar{q}$, and $\bar{q}\bar{q}$ channels
- each channel receives contributions from one or two topologies ("$t$, $u$, $s$"):




- $s$-channel involves $\mathrm{W/Z}$ resonances

## Size of specific contributions:

| | no cuts | | VBF cuts | | |
|---|---|---|---|---|---|
| $M_{\mathrm{H}}\,[\,\mathrm{GeV}]$ | $120{-}200$ | $700$ | $120{-}200$ | $700$ | |
| $\Delta_{s-\mathrm{channel}}[\%]$ | $30{-}10$ | $1$ | $< 0.6$ | $< 0.1$ | negligible with VBF cuts |
| $\Delta_{t/u-\mathrm{interference}}[\%]$ | $< 0.5$ | $< 0.1$ | $< 0.1$ | $< 0.1$ | negligible |
| $\Delta_{\mathrm{b-quarks}}[\%]$ | $\approx 4$ | $1$ | $\approx 2$ | $1$ | |

## Higgs production via VBF in NLO:

- partonic channels
  - ◇ one-loop diagrams: $qq$, $q\bar{q}$, $\bar{q}\bar{q}$
  - ◇ real QCD corrections $qq$, $q\bar{q}$, $\bar{q}\bar{q}$ (gluon emission), $qg$, $\bar{q}g$ (gluon induced)
  - ◇ real QED corrections $qq$, $q\bar{q}$, $\bar{q}\bar{q}$ (photon emission), $q\gamma$, $\bar{q}\gamma$ (photon induced)
- collinear initial-state singularities

  $\hookrightarrow$ factorization and PDF redefinition for QCD and QED singularities

  Note: MRSTqed2004 = the only PDF set including $\mathcal{O}(\alpha)$ effects
  but: $\mathcal{O}(\alpha)$ effects in PDFs $\lesssim 1\%$

  $\hookrightarrow$ better use up-to-date PDFs without $\mathcal{O}(\alpha)$ effects than miss PDF updates
- $\mathrm{W}/\mathrm{Z}$ resonances in $s$-channel

  $\hookrightarrow$ respect gauge invariance when introducing $\mathrm{W}/\mathrm{Z}$ decay widths !

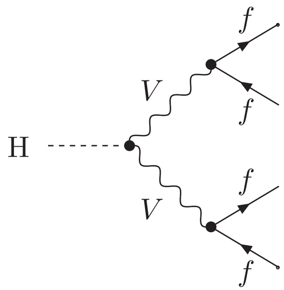
  Possible solution: "complex-mass scheme" Denner, S.D., Roth, Wieders '05
  i.e. consistent use of complex $\mathrm{W}/\mathrm{Z}$ masses
  and complex weak mixing angle
- EW input parameter scheme

  define $\alpha$ in $G_\mu$ scheme: $\alpha_{G_\mu} = \sqrt{2} G_\mu M_\mathrm{W}^2 (1 - M_\mathrm{W}^2/M_\mathrm{Z}^2)/\pi$

  $\hookrightarrow$ absorbs running of $\alpha$ from $Q = 0$ to EW scale and $\Delta\rho$ in $Wq\bar{q}'$ coupling

# Survey of Feynman diagrams for NLO corrections

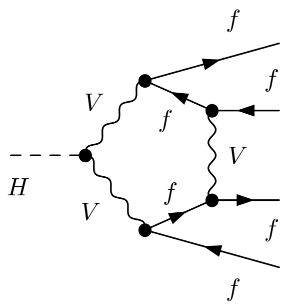
Lowest order:



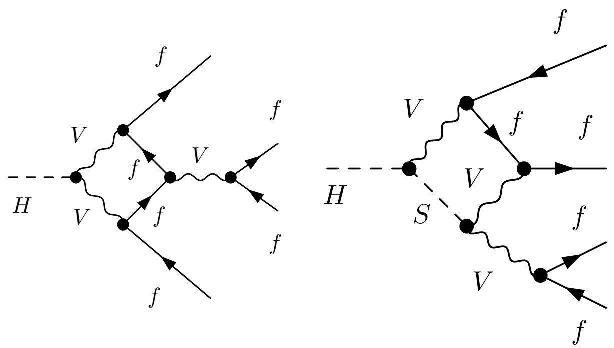

(one or two diagrams per flavour channel)

Typical one-loop diagrams: # diagrams = $\mathcal{O}(200\!-\!400)$

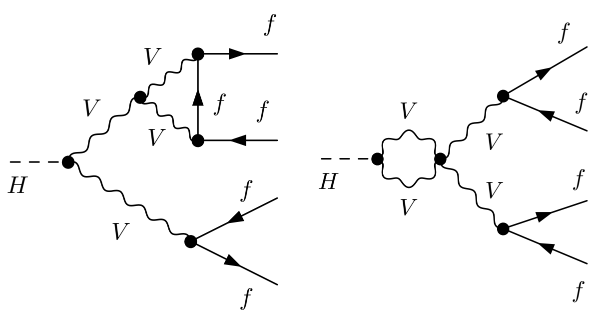
pentagons



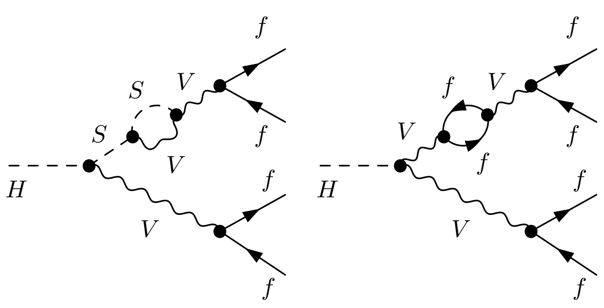

boxes




vertices




self-energies

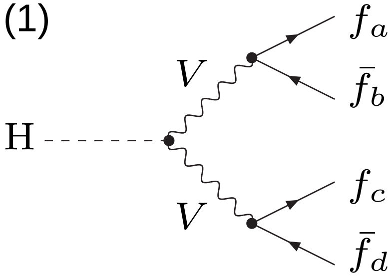



$+$ tree graphs with real gluon or photons

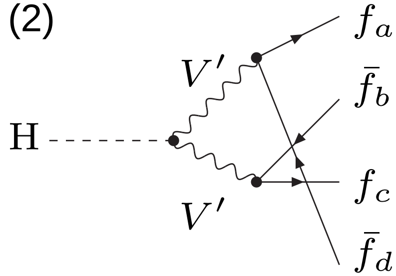
# Classification of NLO QCD corrections

Possible Born diagrams:

(1)




(2)



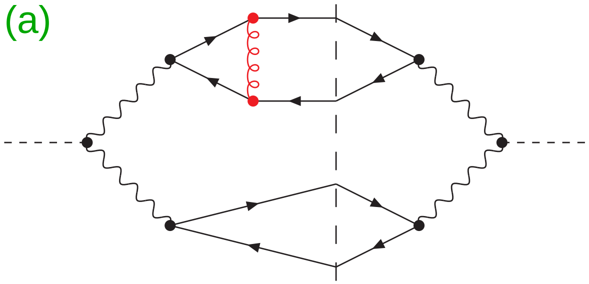

diagrams (2) only for

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

($q'$ = weak-isospin partner of $q$)

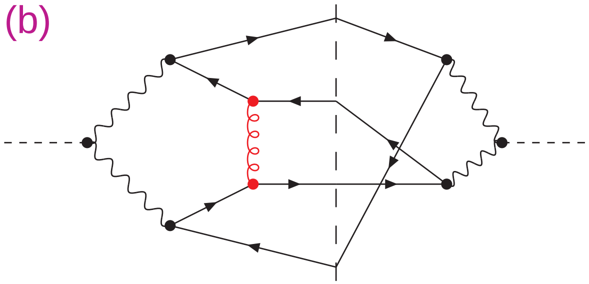
Classification of QCD corrections into four categories: (typical diagrams shown)

(a)

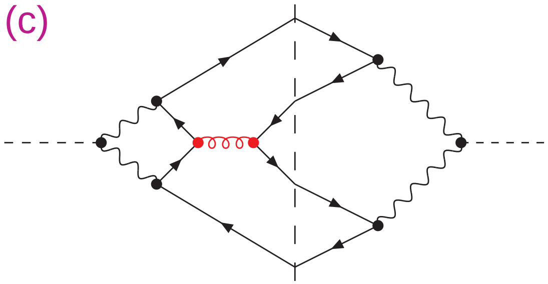


(a) defines DIS-like approximation

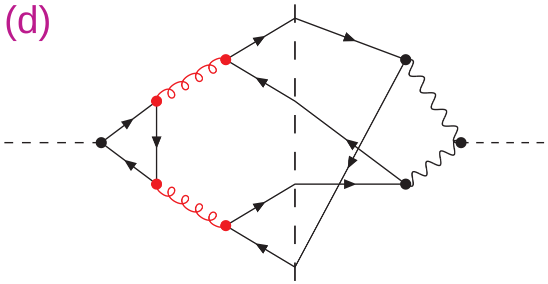
(b)



(c)

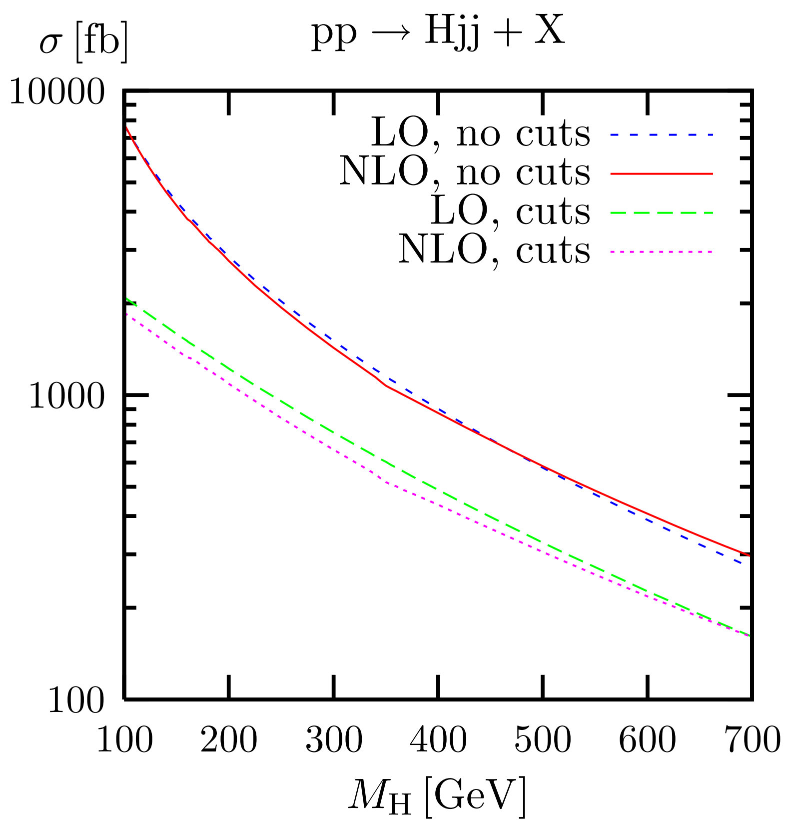


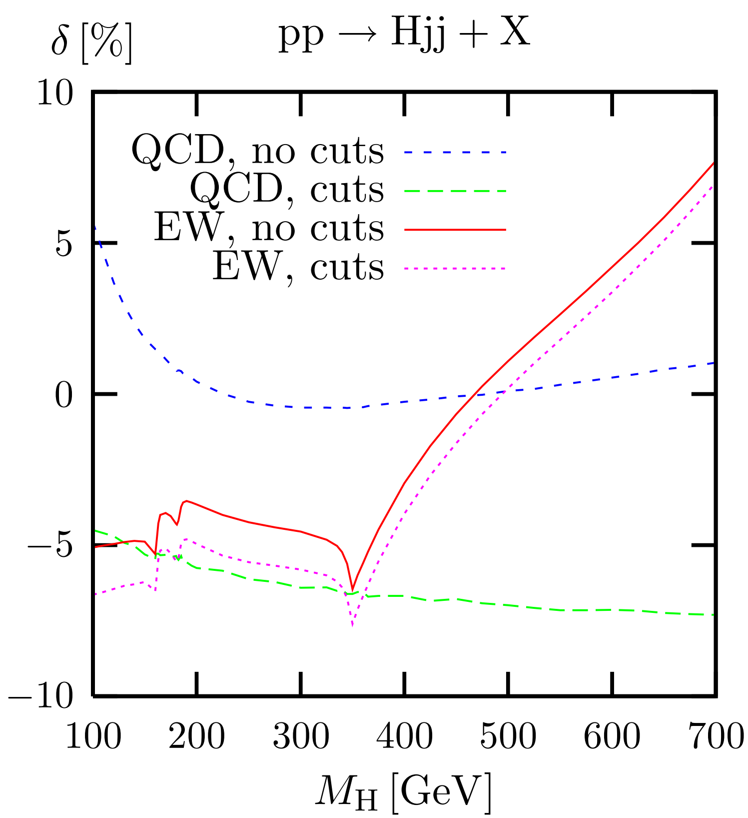
(d)



(b,c,d) = corrections to interferences (only for $q\bar{q}q\bar{q}$ and $q\bar{q}q'\bar{q}'$ channels)

# Results on integrated cross sections




Ciccolini, Denner, S.D. '07

- QCD and EW corrections are of same generic size
- reasonable scale choice: $\mu_{\mathrm{ren/fact}} \sim M_\mathrm{W} \sim \mathrm{W/Z}$ virtuality (rather than $M_\mathrm{H}$)
- scale uncertainty $\sim 3\%$ within $M_\mathrm{W}/2 < \mu_{\mathrm{ren/fact}} < 2M_\mathrm{W}$ in NLO ($\sim 10\%$ in LO)
- sensitivity to cuts: large for QCD, small for EW corrections

## Size of specific corrections to cross sections:

| | no cuts | | VBF cuts | | |
|---|---|---|---|---|---|
| $M_{\rm H}\,[\,{\rm GeV}]$ | $120{-}200$ | $700$ | $120{-}200$ | $700$ | |
| $\delta_{\rm QCD(a)}\,[\%]$ | $4{-}0.5$ | $+1$ | $\approx -5$ | $-7$ | $\mathcal{O}(5{-}10\%)$ |
| $\delta_{\rm QCD(b+c+d)}\,[\%]$ | $\lesssim 0.2$ | $-0.1$ | $< 0.1$ | $< 0.1$ | negligible |
| $\delta_{{\rm EW},qq}\,[\%]$ | $\approx -6$ | $+6$ | $\approx -7$ | $+5$ | $\mathcal{O}(5{-}10\%)$ |
| $\delta_{{\rm EW},q\gamma}\,[\%]$ | $\approx +1$ | $+2$ | $\approx +1$ | $+2$ | |
| $\delta_{G_\mu^2 M_{\rm H}^4}\,[\%]$ | $< 0.1$ | $+4$ | $< 0.1$ | $+4$ | negligible for $M_{\rm H} < 400\,{\rm GeV}$ |

Heavy-Higgs corrections at $M_{\rm H} \sim 700\,{\rm GeV}$: $\underbrace{G_\mu M_{\rm H}^2}_{\text{1-loop}} \sim \underbrace{(G_\mu M_{\rm H}^2)^2}_{\text{2-loop}} \sim 4\%$

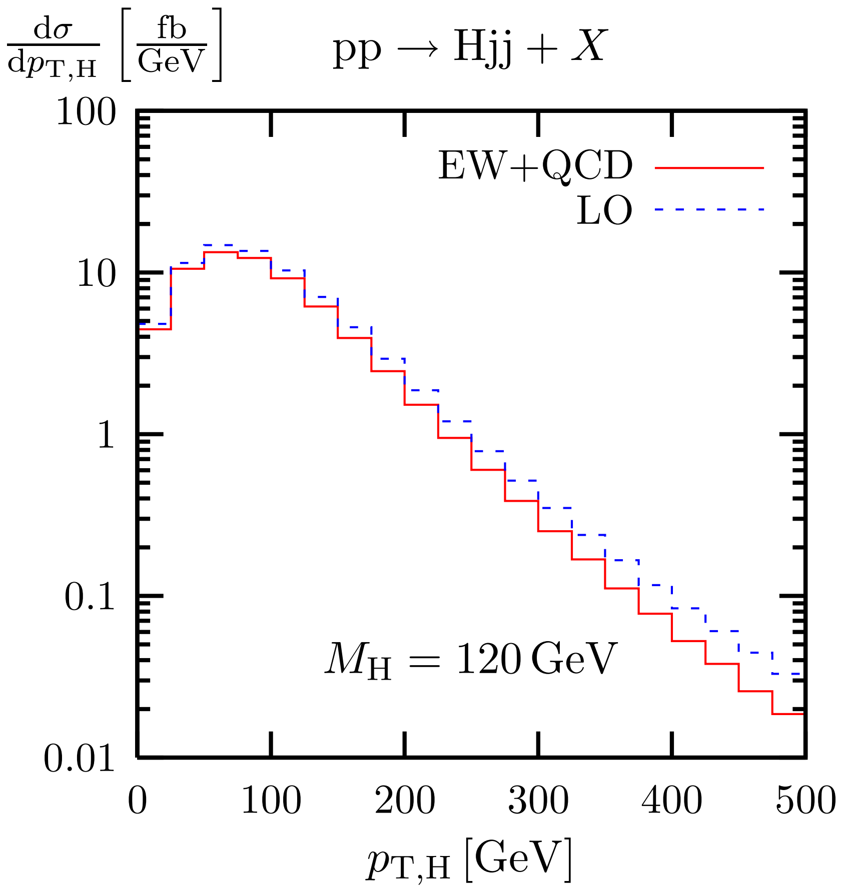
$\hookrightarrow$ breakdown of perturbation theory

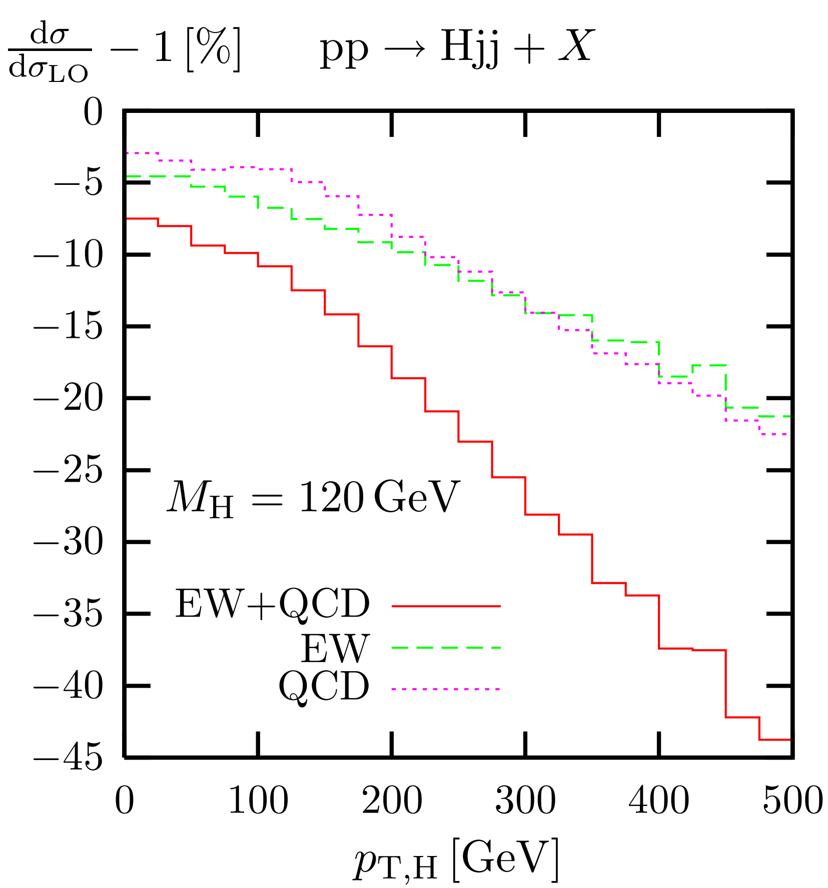
$\uparrow$

taken from Ghinculov '95; Frink et al. '96

## Distribution in the Higgs transverse momentum $p_{\mathrm{T,H}}$

Ciccolini, Denner, S.D. '07



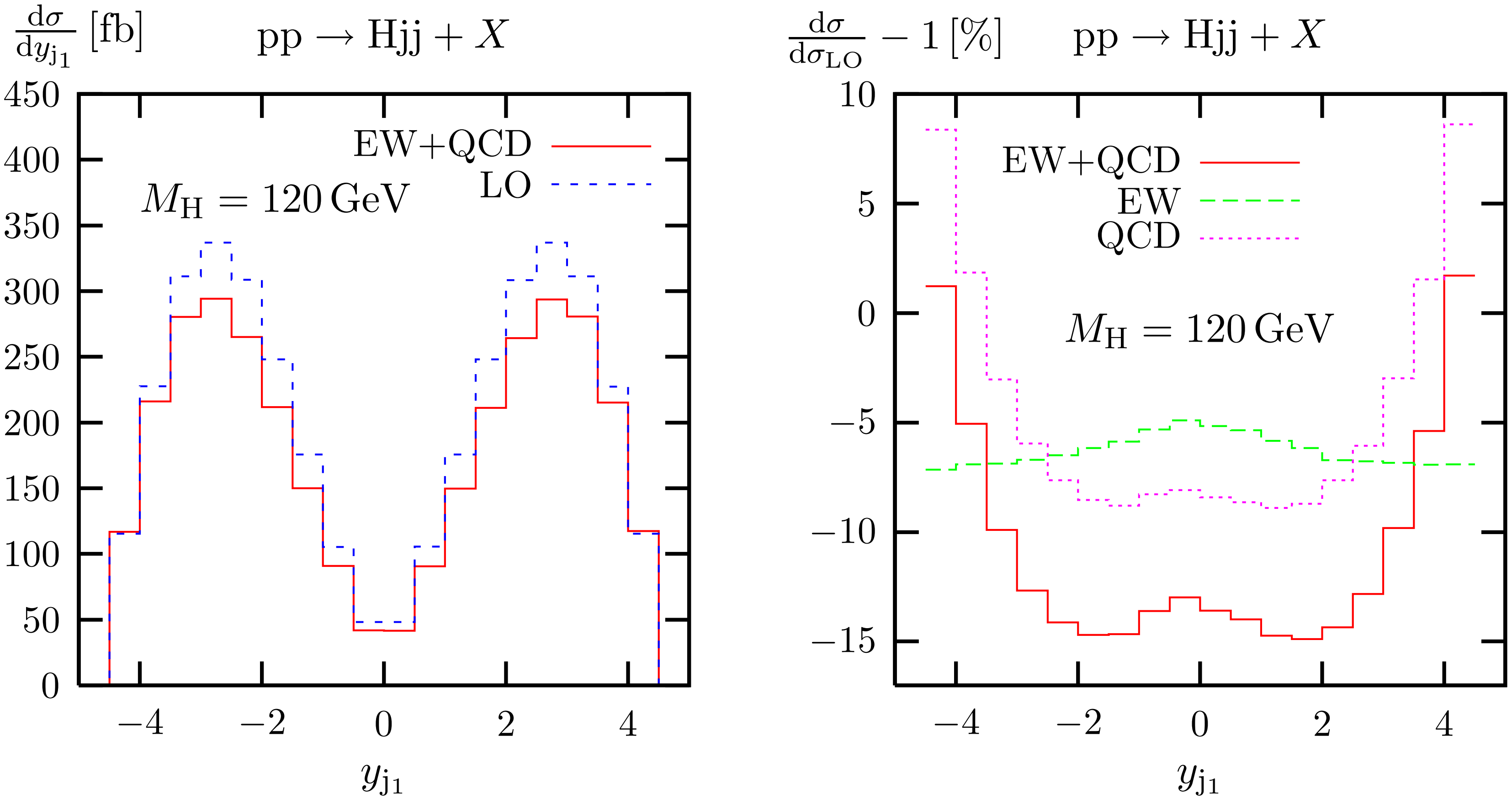




$\hookrightarrow$ QCD and EW corrections distort shapes

QCD+EW $\sim$ $20\%(40\%)$ at $p_{\mathrm{T,H}} = 200\,\mathrm{GeV}(500\,\mathrm{GeV})$

## Distribution in the rapidity $y_{j_1}$ of the leading tagging jet

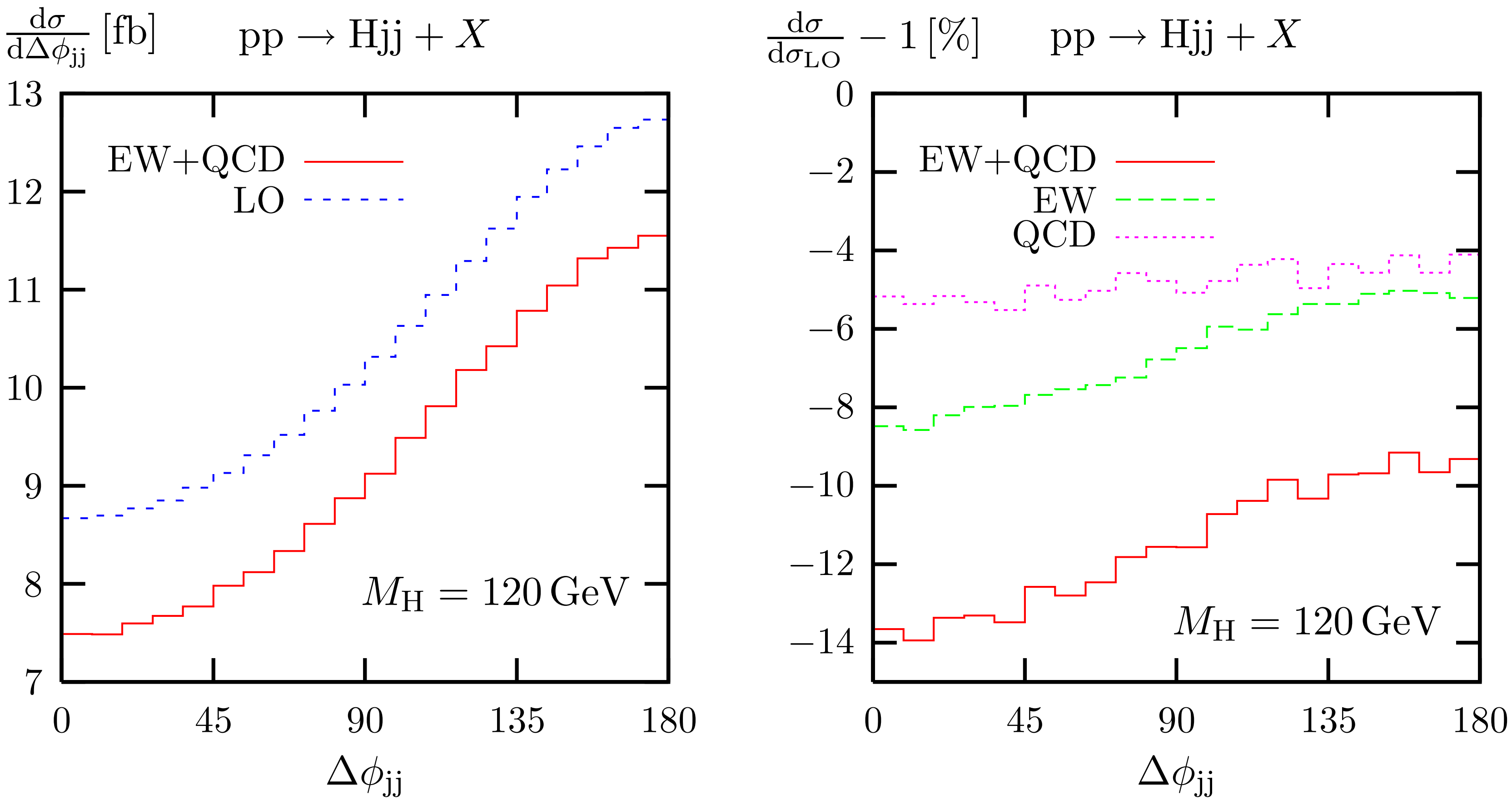
Ciccolini, Denner, S.D. ’07




$\hookrightarrow$ Significant shape distortions by QCD effects, but EW effects almost uniform

## Distribution in the azimuthal angle difference $\Delta\phi_{\rm jj}$ of the tagging jets

Ciccolini, Denner, S.D. '07




$\hookrightarrow$ QCD+EW corrections induce small distortions similar to BSM effects

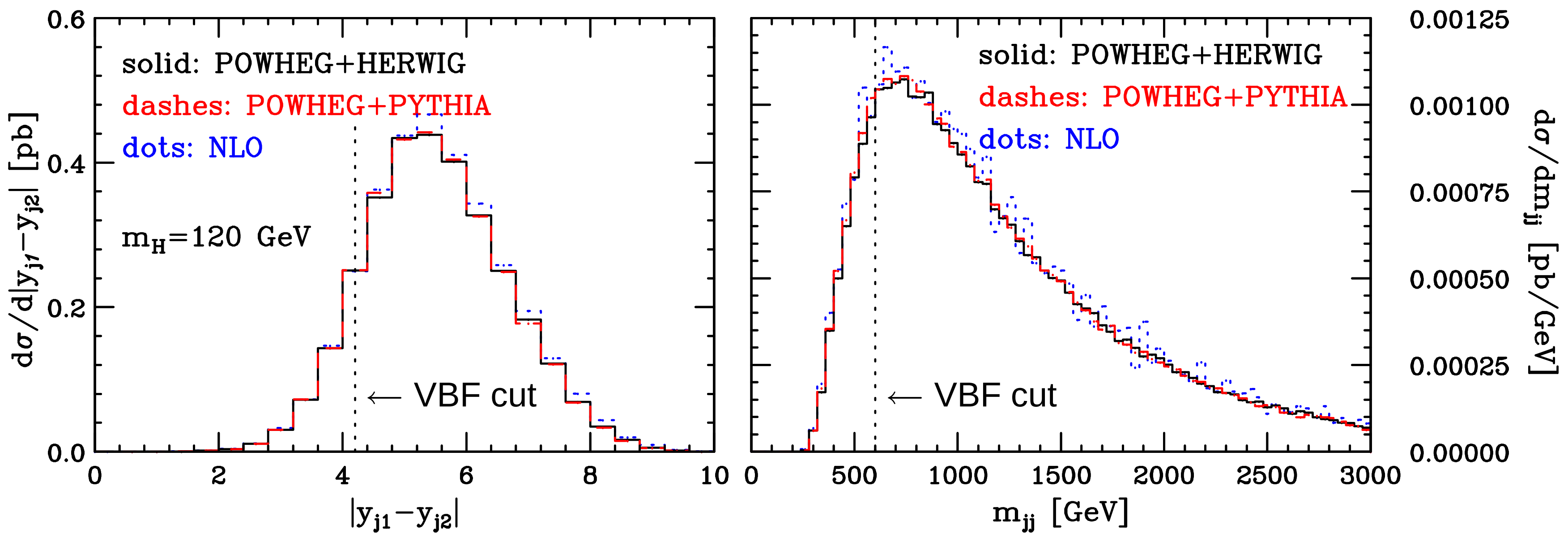
# Effects beyond NLO

# Matching fixed order with partons shower at NLO QCD

## POWHEG matching of NLO with HERWIG/PYTHIA: Nason, Oleari ’09

- hardest radiation is generated first (largest $p_{\mathrm{T}}$) using exact matrix elements
- POWHEG output transferred to parton shower
- concept independent of shower algorithm
- unweighted events

## Results on VBF:

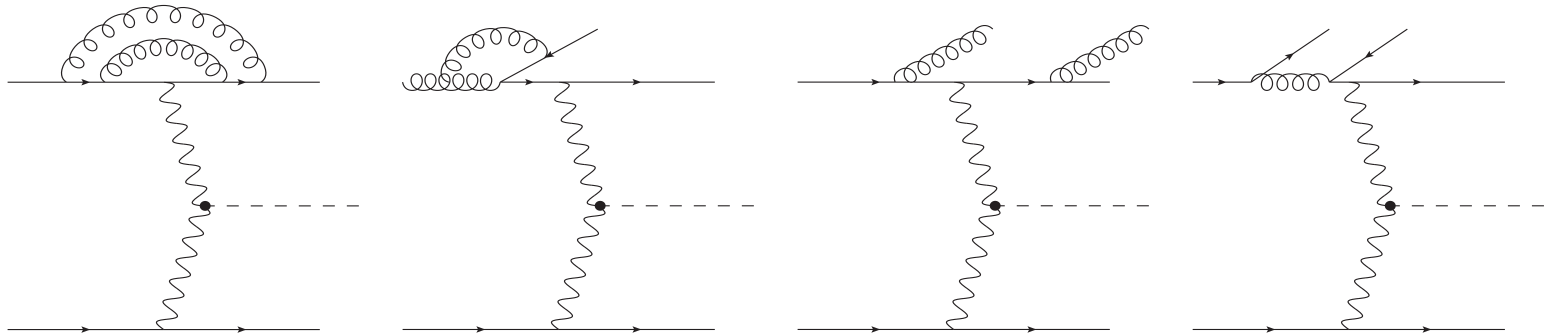



$\hookrightarrow$ Characteristic features not changed by parton shower

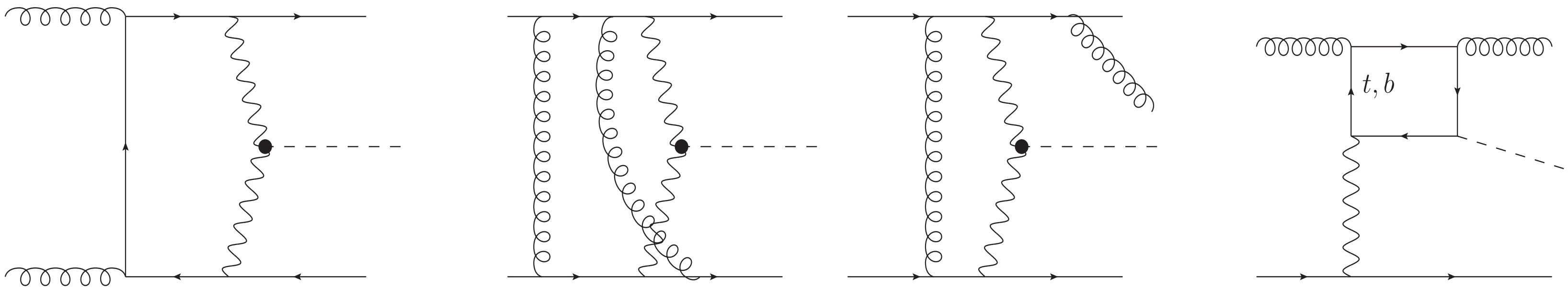
# NNLO QCD corrections

## DIS-like corrections $\longrightarrow$ structure-function approach

Bolzoni, Maltoni, Moch, Zaro '10



## Non-DIS-like corrections:



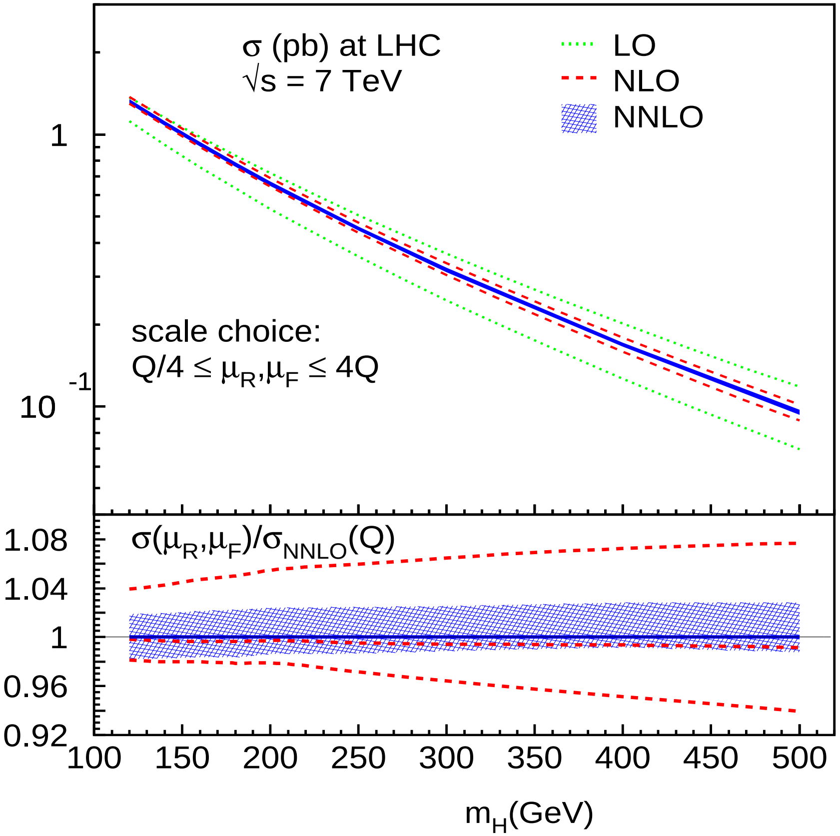

loop-induced contributions with
ext. gluons and $\mathrm{HVV}$ couplings
Harlander, Vollinga, Weber '08

colour-exchange diagrams and
Higgs radiation off quark loops
expected small $\longrightarrow$ neglected

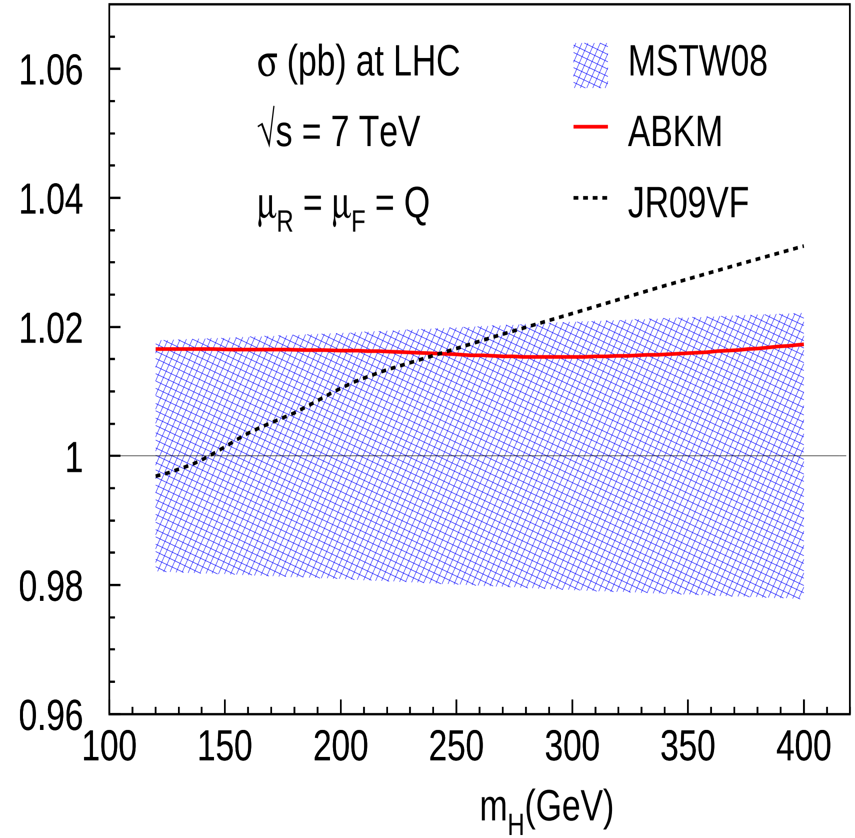
# DIS-like NNLO QCD corrections to the total VBF cross section

Bolzoni, Maltoni, Moch, Zaro '10

## Scale uncertainty:




## PDF uncertainty: (68% C.L.)




Results for $\sigma_{\text{tot}}$ at the LHC:

- NNLO QCD corrections $\sim\ 1\%$ with scale $Q$ = $\mathrm{W/Z}$ virtuality = $\mathcal{O}(M_{\mathrm{W}})$
- scale uncertainty $\sim$ PDF uncertainty $\sim\ 2\%$

Implementation of VBF cuts $\rightarrow$ work in progress

# Loop-induced contributions with ext. gluons and $\mathrm{HVV}$ couplings

Harlander, Vollinga, Weber '08

## LO/NLO for VBF

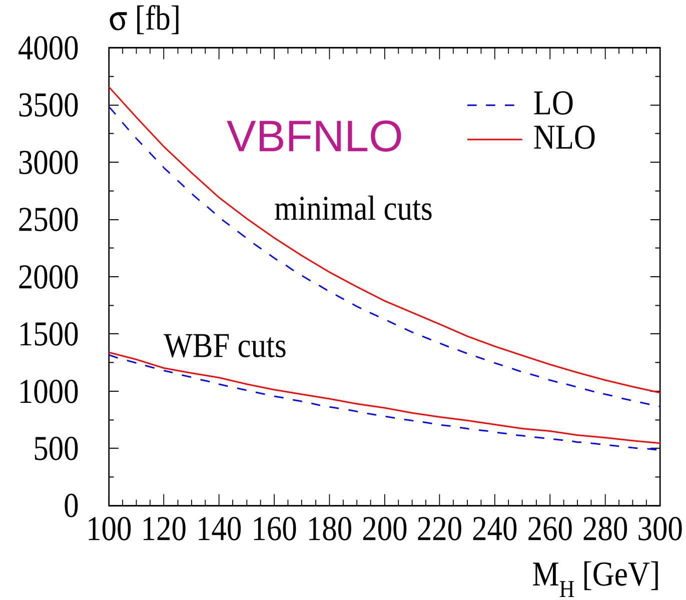
"minimal" cuts $(p_{\mathrm{T,j}}>20\,\mathrm{GeV},\ |\eta_{\mathrm{j}}|<5,\ R>0.6)$

$\downarrow$

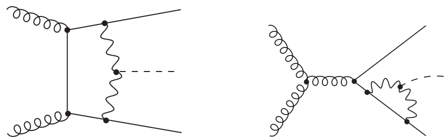
WBF cuts = miminal cuts

+ $(\eta_1 \cdot \eta_2<0,\ |\Delta\eta|>4.2,\ m_{\mathrm{jj}}>600\,\mathrm{GeV})$

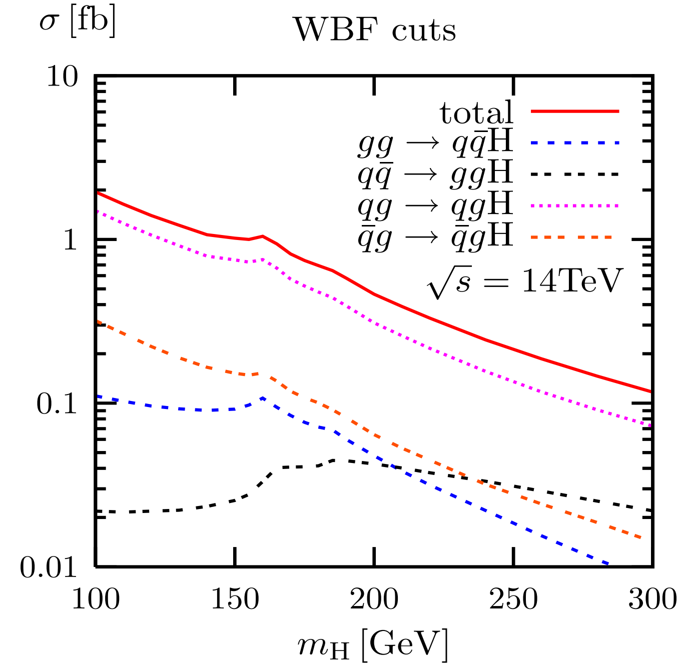
$\hookrightarrow$ reduction of $\sigma$ by factor $2-3$




## Loop-induced parts with ext. gluons:



etc. + crossed




minimal cuts $\rightarrow$ WBF cuts

$\hookrightarrow$ reduction of $\sigma$ by factor $\sim 30$

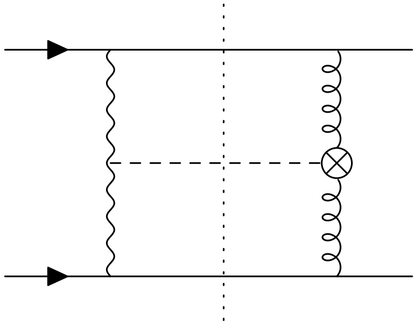
Impact $\lesssim 0.1\%$ $\rightarrow$ negligible

## Mixed QCD–EW interferences

Andersen, Binoth, Heinrich, Smillie '07
Bredenstein, Hagiwara, Jäger '08

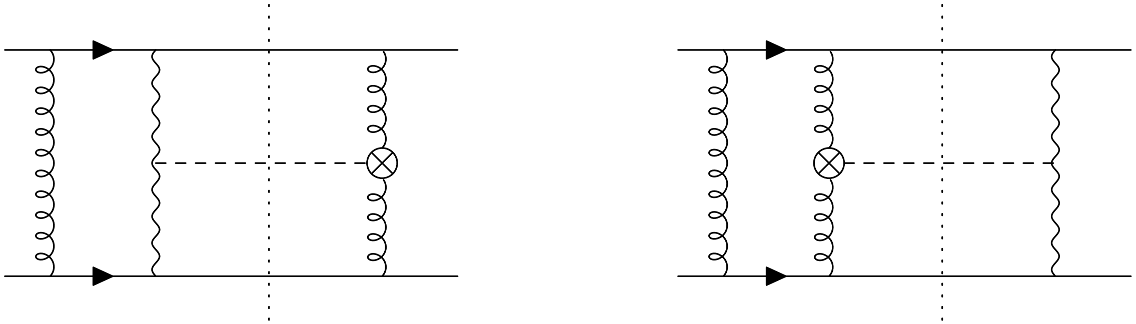
$\hookrightarrow$ cross-talk between $\mathrm{HVV}$- and $\mathrm{Hgg}$-initiated production

Interference at LO:



$= 0$

But at NLO QCD:



$\neq 0$

Explicit result:

- various suppression mechanisms at work (PDF weights, weak couplings, etc.)
- impact $\lesssim 10^{-3}\%$ $\rightarrow$ negligible

# Conclusions

## Higgs production via VBF is important at the LHC

- for Higgs discovery
- for Higgs coupling analyses

## Status of VBF predictions – size of higher-order effects:

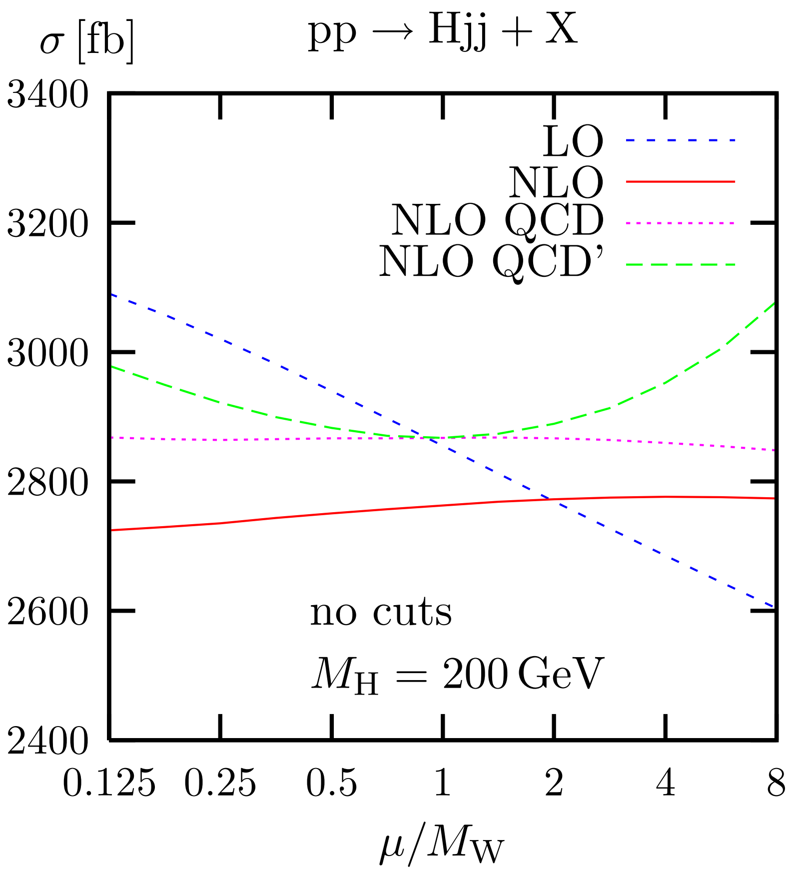
- significant corrections: $\sim 5{-}10\%$
  - ◇ NLO QCD (DIS-like) and NLO EW
  - ◇ $\mathrm{gg}$ fusion via effective $\mathrm{Hgg}$
- small corrections: $\sim 1{-}2\%$
  - ◇ NNLO QCD ($\sigma_{\mathrm{tot}}$ available, VBF cuts in progress)
  - ◇ initial states with $\mathrm{b}$-quarks or photons
- negligible effects: $< 1\%$ (after VBF cuts)
  $s$-channel contributions, interferences, non-DIS-like NLO QCD,
  QCD–EW interferences, loop-induced $\mathrm{gg}$-fusion
- Heavy-Higgs effects negligible for $M_{\mathrm{H}} < 400\,\mathrm{GeV}$
  but 1-loop $\sim$ 2-loop at $M_{\mathrm{H}} \sim 700\,\mathrm{GeV}$ $\rightarrow$ breakdown of perturbation theory

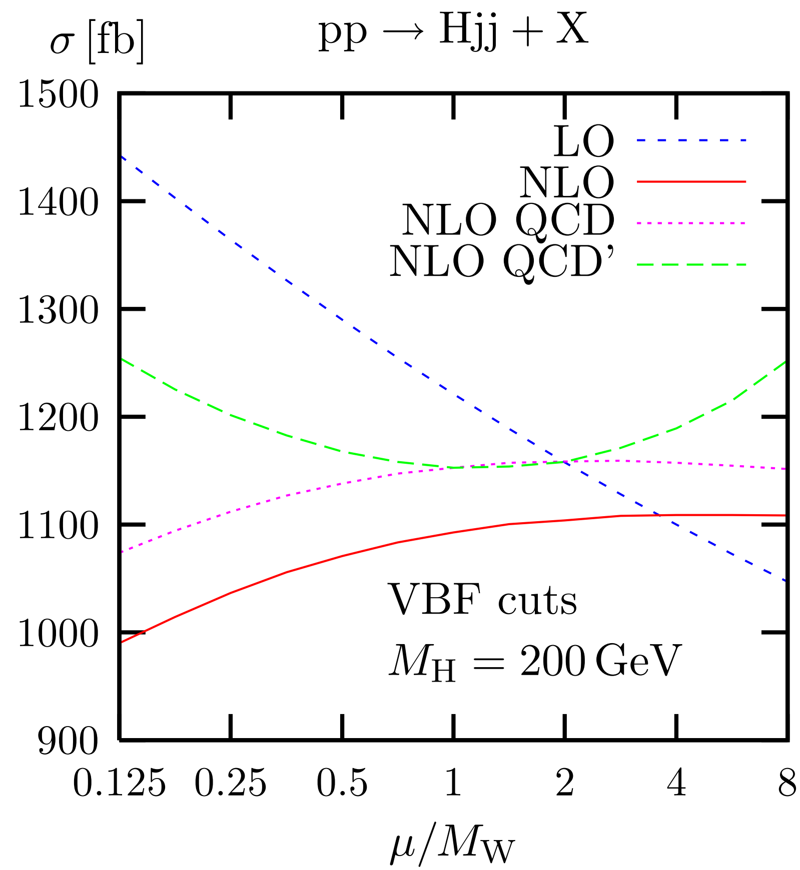
Theoretical accuracy of cross section $\sim 2\%$ (for intermediate Higgs masses)
matches uncertainties from PDFs and expected experimental errors

# Extra slides

# Scale dependence of LO and NLO cross sections

Ciccolini, Denner, S.D. '07



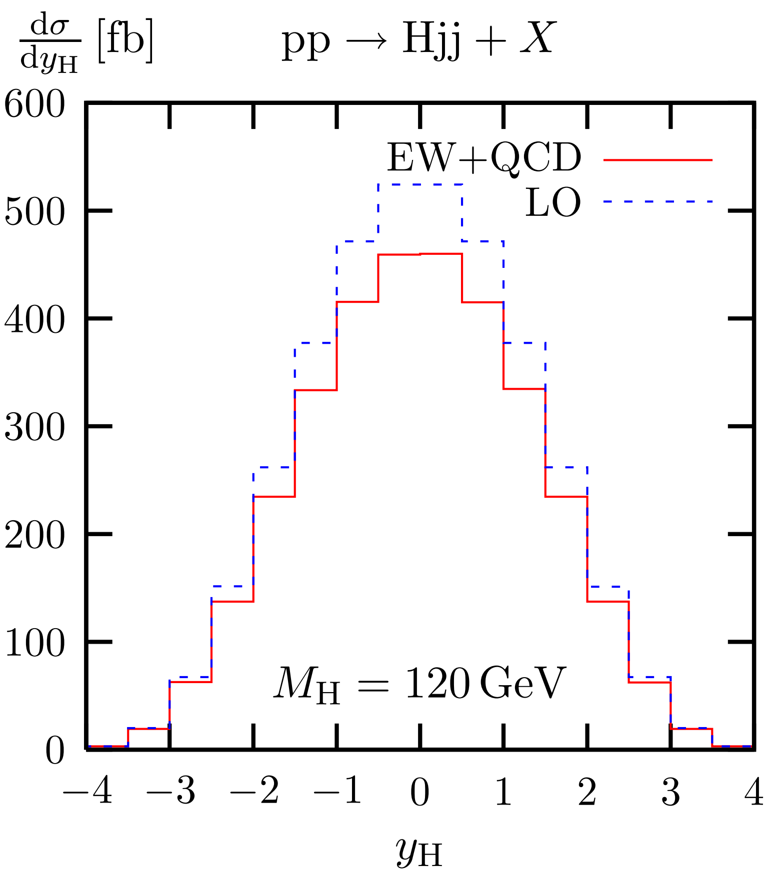



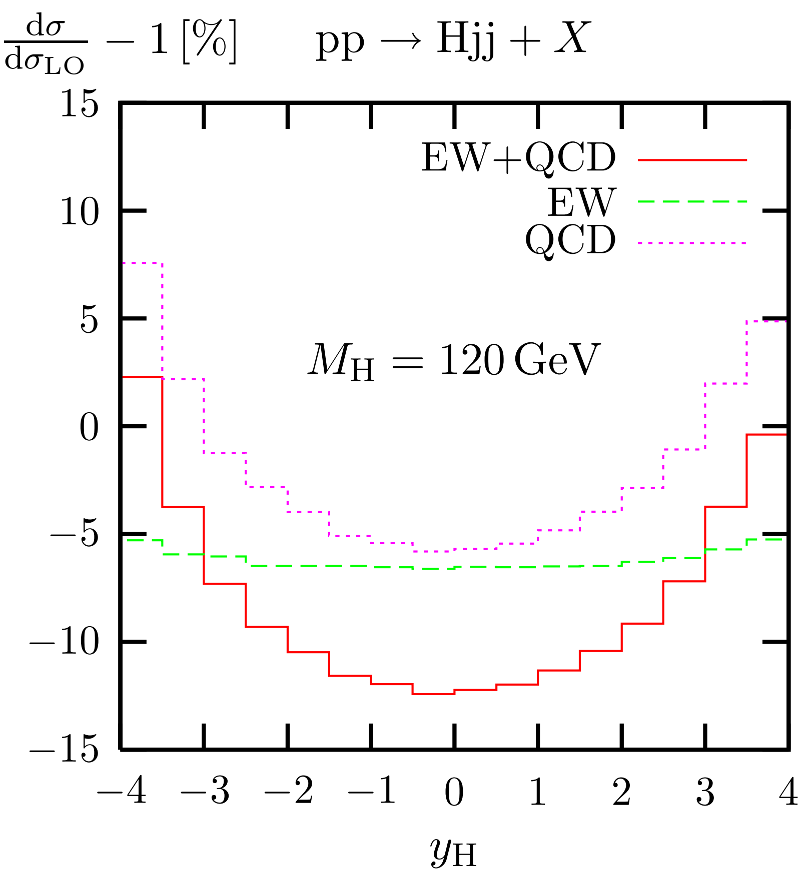

QCD: $\mu = \mu_{\mathrm{fact}} = \mu_{\mathrm{ren}}$

QCD': $\mu = \mu_{\mathrm{fact}} = M_W^2/\mu_{\mathrm{ren}}$

# Higgs rapidity distribution at NLO

Ciccolini, Denner, S.D. '07

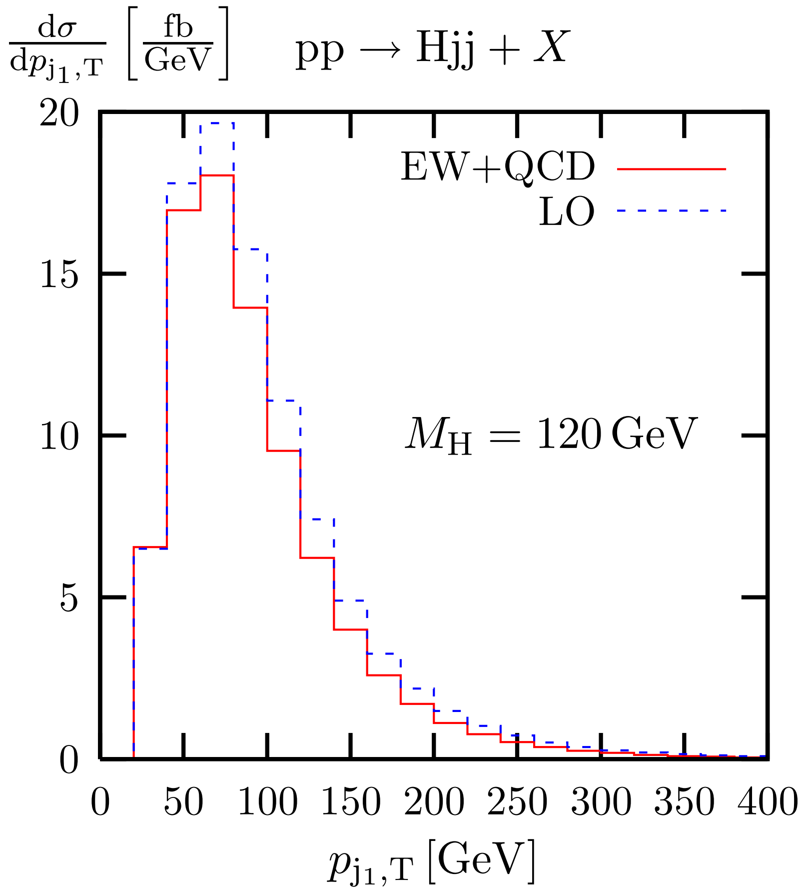


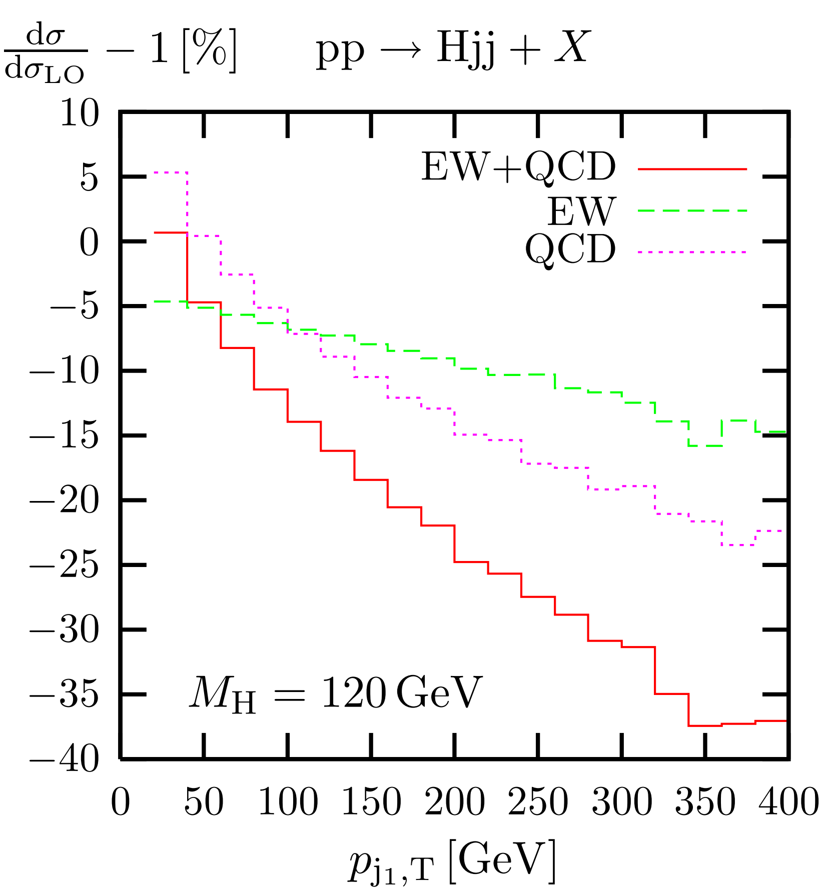




$\hookrightarrow$ Significant shape distortions by QCD effects, but EW effects almost uniform

## Distribution in the transverse momentum $p_{\mathrm{Tj}_1}$ of the leading tagging jet at NLO

Ciccolini, Denner, S.D. '07




$\hookrightarrow$ QCD and EW corrections distort shapes

QCD+EW $\sim$ $25\%(40\%)$ at $p_{T,H} = 200\,\mathrm{GeV}(500\,\mathrm{GeV})$