NLO Corrections for Higgs Boson Production via Weak-Boson Fusion

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In collaboration with:
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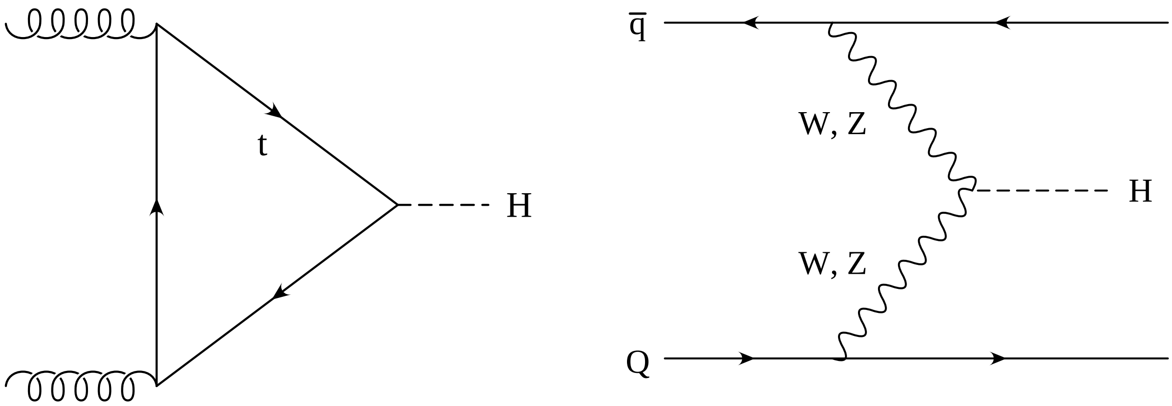
- Introduction: weak-boson fusion and gluon fusion
- Calculation of next-to-leading order corrections to weak-boson fusion
- Cuts and distributions
- Conclusions

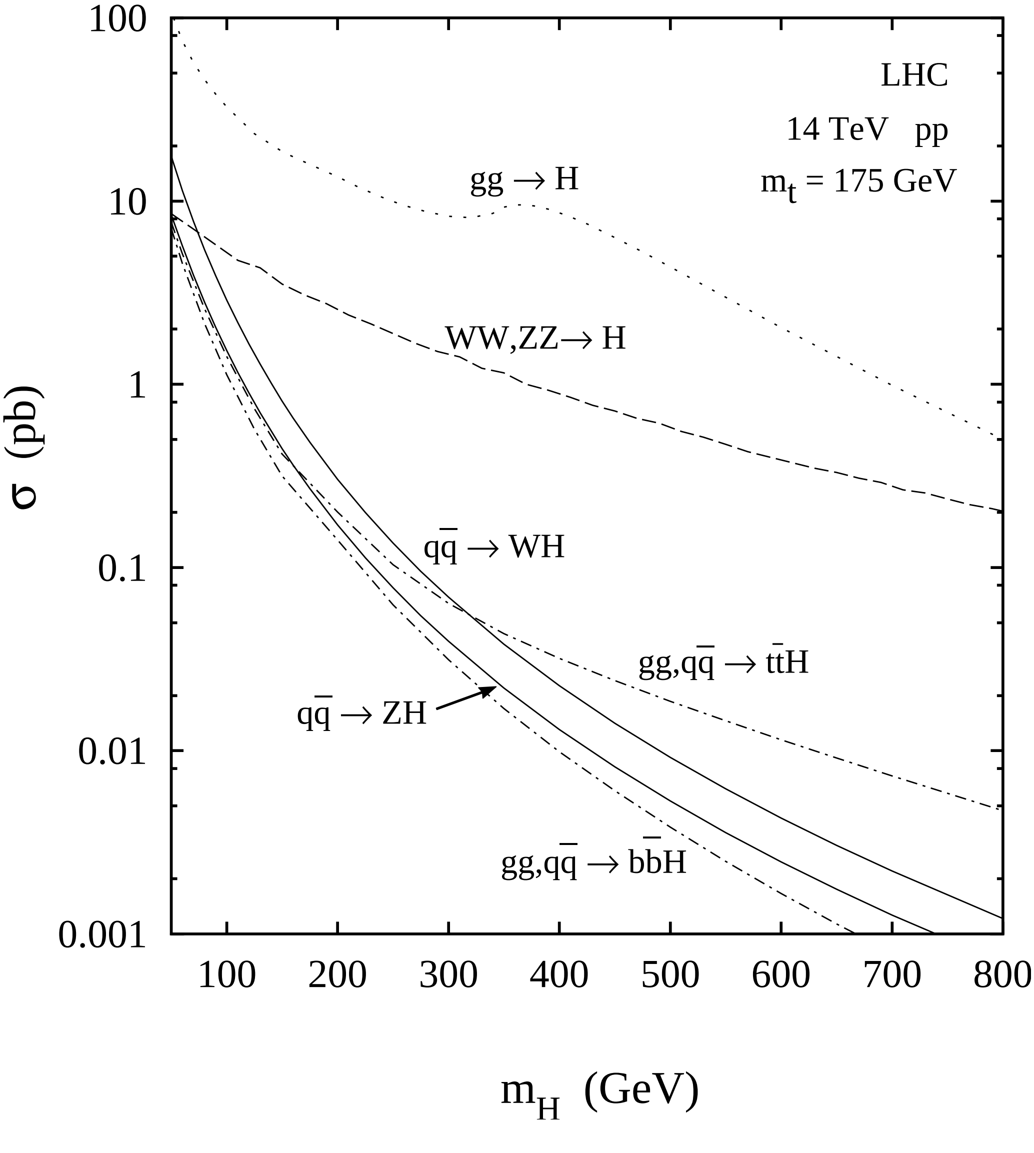
Gluon Fusion and Weak-Boson Fusion



At values of $m_H > 100$ GeV, and at LHC energies, these are the two dominant processes for inclusive Higgs production: gg fusion and weak-boson fusion (WBF).

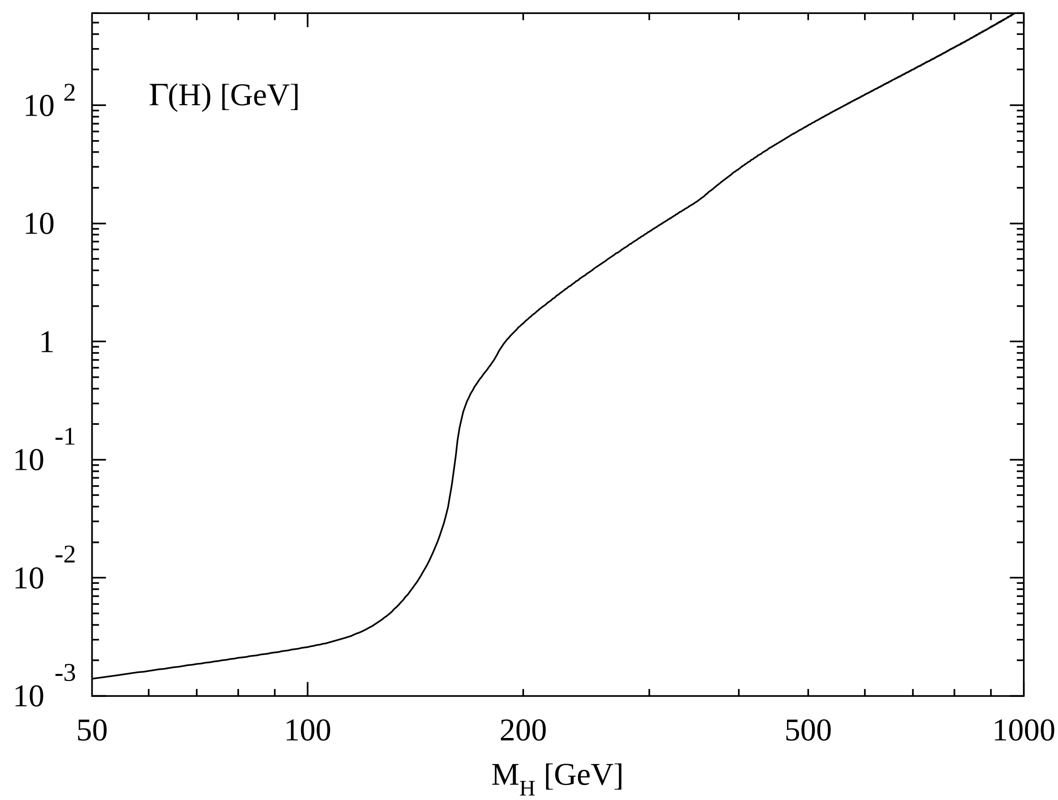
- Both the two processes are important from the point of view of the discovery of the Higgs.
- In the intermediate Higgs mass region, WBF cross section is $\sim 3-5$ pb while gluon fusion cross section is $\sim 10-30$ pb.

  WH and $t\bar{t}H$ associated production have cross sections in the range $\sim 0.2-2$ pb.

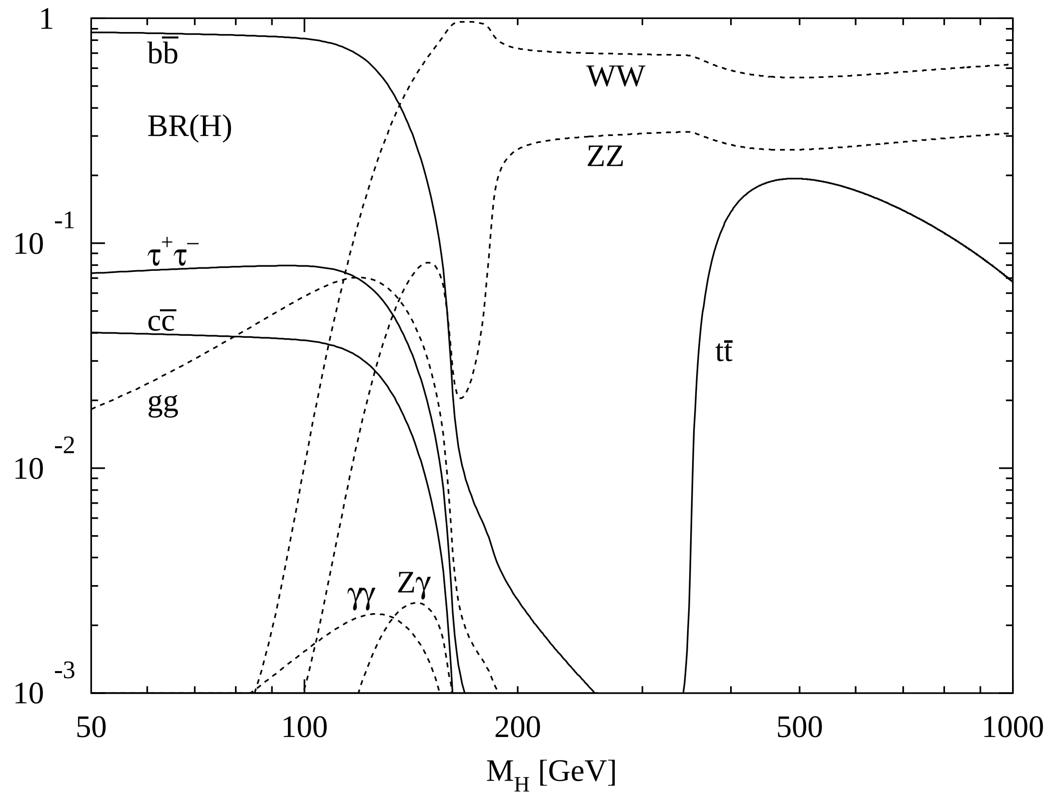


100
10
1
0.1
0.01
0.001
σ (pb)
100
200
300
400
500
600
700
800
m_H (GeV)
LHC
14 TeV pp
m_t = 175 GeV
gg → H
WW,ZZ→ H
qq̄ → WH
gg,qq̄ → tt̄H
qq̄ → ZH
gg,qq̄ → bb̄H

Total decay width (in GeV) of the SM Higgs



Branching fractions of the SM Higgs



Spira & Zerwas

Discovery is not the whole story!!

At least as important as the discovery, is the detailed study of the properties of the Higgs-like resonance: determination of all the quantum numbers and couplings of the state. These include the mass, the gauge, Yukawa and self couplings as well as the charge, color, spin and CP quantum numbers.

WBF is of central importance since it allows a precise coupling measurement of the HWW and HZZ vertex interactions.

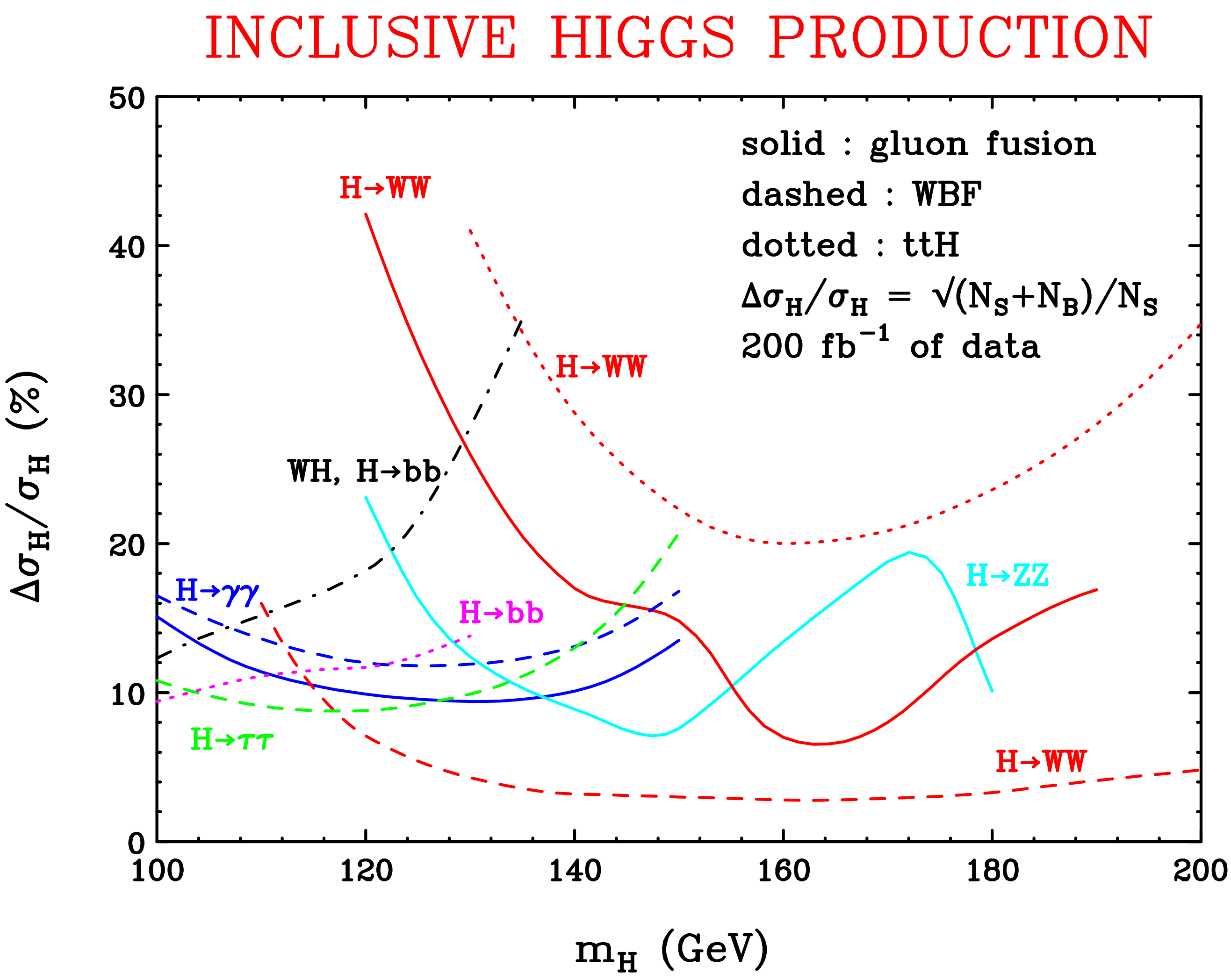
In addition, WBF will allow for independent observations[a] of

$$H \to \begin{cases} \tau\tau & m_H \leq 140\mathrm{GeV} \\ WW & m_H > 120\mathrm{GeV} \\ \gamma\gamma & m_H \leq 150\mathrm{GeV} \end{cases}$$

These measurements can be performed at the LHC with statistical accuracies on the measured cross sections times decay branching ratios, $\sigma \cdot B$, of order 10% or even better.

[a] K. Hagiwara, N. Kauer, T. Plehn, D. Rainwater and D. Zeppenfeld

Statistical errors at LHC



Systematic errors

- QCD/pdf uncertainties
  - $\pm 5\%$ for WBF
  - $\pm 20\%$ for gluon fusion
- luminosity/acceptance uncertainties
  - $\pm 5\%$

NLO jet distribution in weak-boson fusion

To extract Higgs-boson coupling constants with this full experimental precision, a theoretical prediction of the SM production cross sections with error well below 10% is required, and this clearly entails knowledge of the next-to-leading order QCD corrections.

The question then arises whether the K-factors (the ratio between the next-to-leading and the leading-order cross section) and the scale dependence, determined for the inclusive production cross section, are valid for less inclusive quantities.

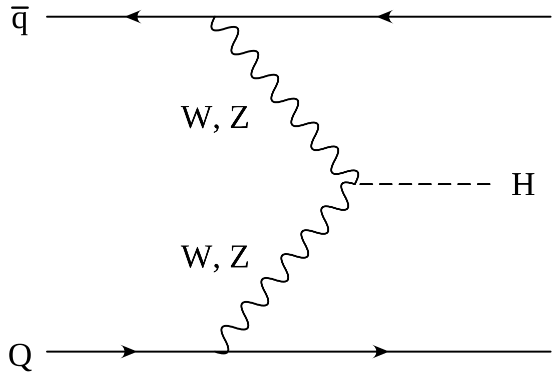
To address this question, we[a] have implemented the one-loop QCD corrections to WBF in a fully flexible NLO parton-level Monte Carlo program.

We are presently developing such programs for a collection of relevant WBF processes, of which Higgs boson production, in the narrow resonance approximation, is the simplest example.

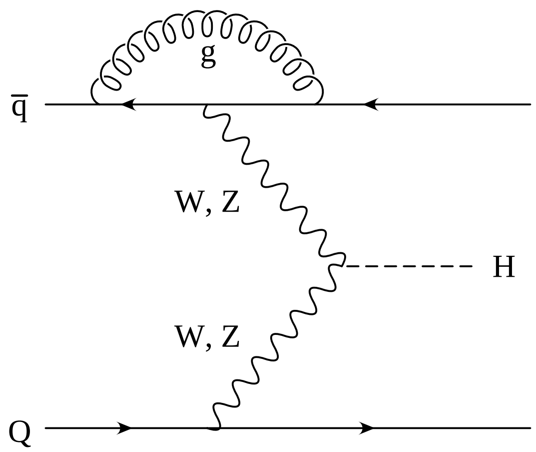
[a] T. Figy, D. Zeppenfeld and C.O.

Diagrams

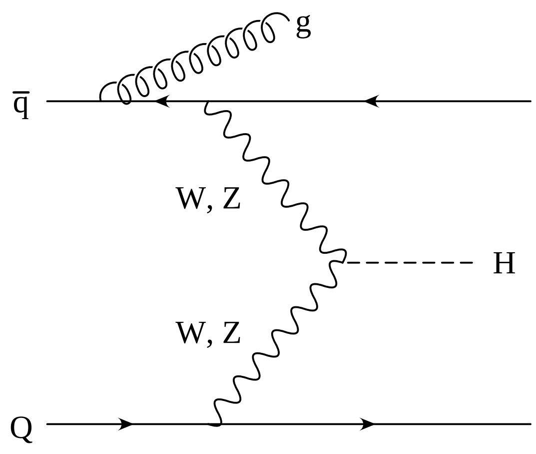
Leading order diagrams

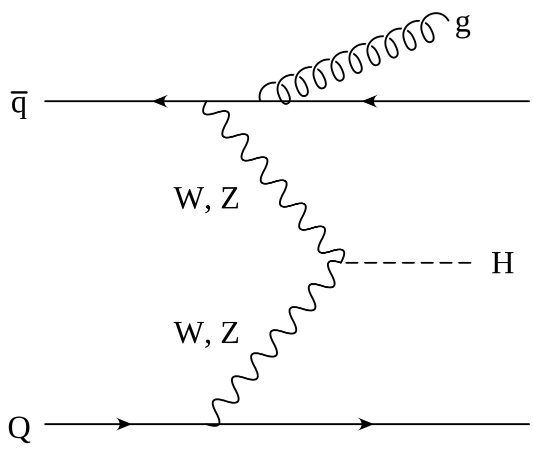


NLO: virtual diagrams



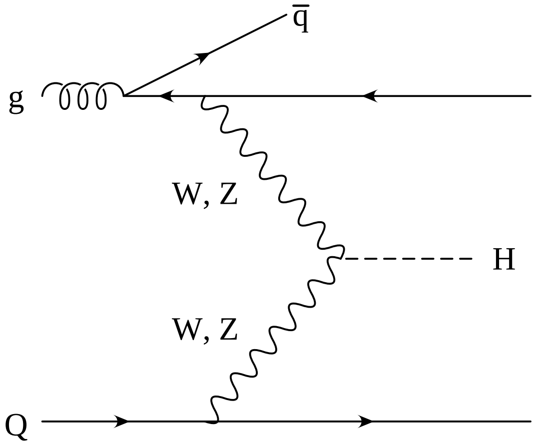
NLO: real diagrams

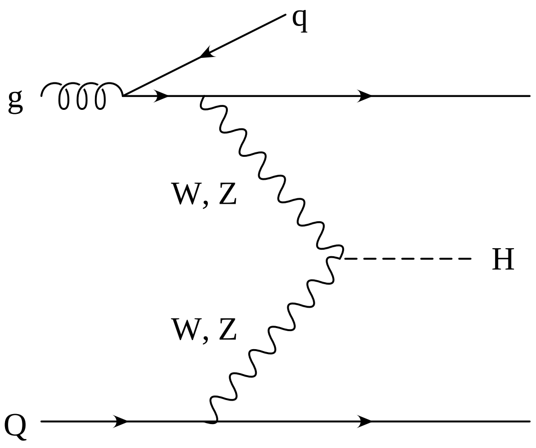




Diagrams

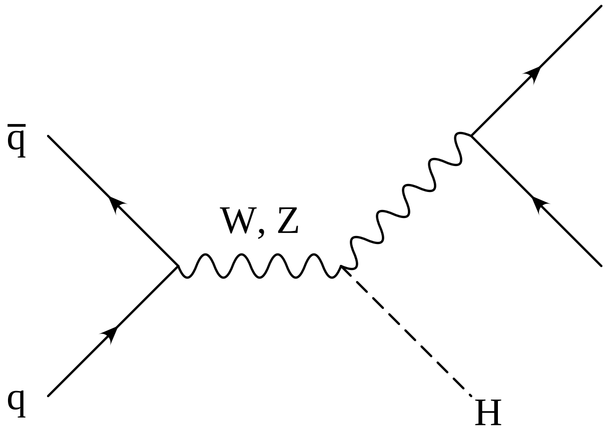
NLO: real diagrams





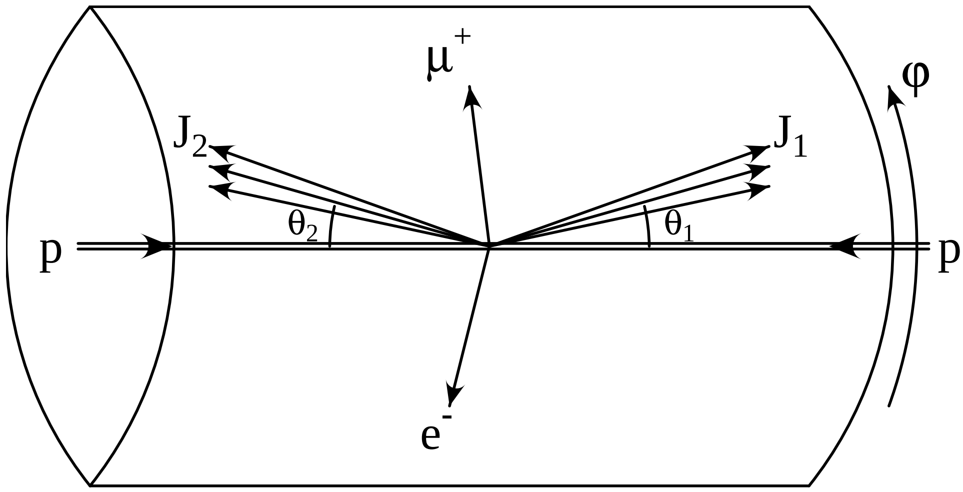
plus crossed processes: $\bar{q} \to q$, and/or $Q \to \overline{Q}$

Not included...

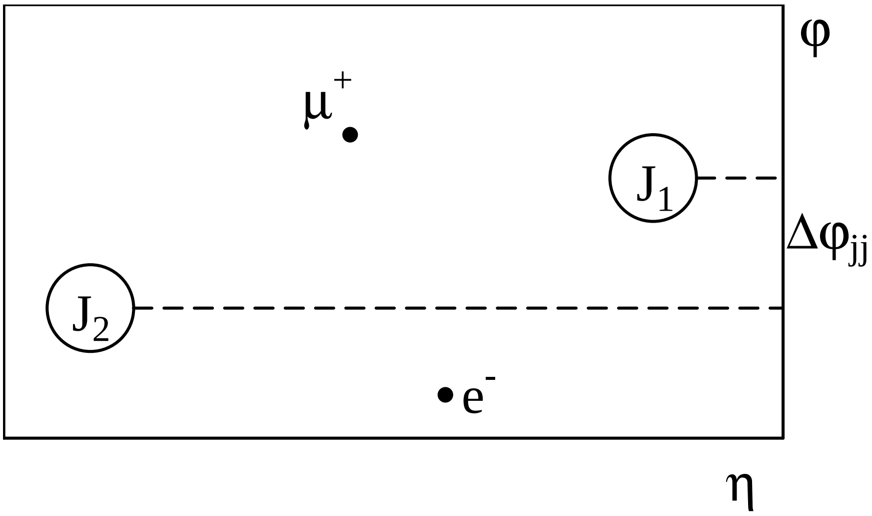


...suppressed by WBF cuts!

Generic WBF event



Legoplot



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

Characteristics:

- energetic jets in the forward and backward directions ($p_T > 20$ GeV)
- Higgs decay products between tagging jets
- Little gluon radiation in the central-rapidity region, due to colorless W/Z exchange (central jet veto: no extra jets with $p_T > 20$ GeV and $|\eta| < 2.5$)

Applied cuts

For the NLO corrections, we expect cuts on the Higgs boson decay products to play a minor role, with respect to WBF cuts.

We use the k_T-algorithm to recombine partons and create jets, with resolution parameter $D = 0.8$.

We calculate the partonic cross sections for events with at least two hard jets, which are required to have

$$p_{Tj} \geq 20 \text{ GeV} \qquad\qquad |y_j| \leq 4.5$$

y_j = rapidity of the (massive) jet momentum which is reconstructed as the four-vector sum of massless partons of pseudorapidity $|\eta| < 5$.

The Higgs boson decay products, called "leptons" (which represent $\tau^+\tau^-$ or $\gamma\gamma$ or $b\bar{b}$ final states), must satisfy

$$p_{T\ell} \geq 20 \text{ GeV} , \quad |\eta_\ell| \leq 2.5 , \quad \triangle R_{j\ell} \geq 0.6 ,$$

where

$$\Delta R_{jl} = \sqrt{(\eta_j - \eta_l)^2 + (\phi_j - \phi_l)^2}$$

In addition

$$y_{j,min} < \eta_{\ell_{1,2}} < y_{j,max}$$

We do not specifically require the two tagging jets to reside in opposite detector hemispheres for the present analysis.

No reduction due to branching ratios for specific final states is included.

Tagging jets

Two methods to select the tagging jets:

1. "p_T-method": the tagging jets are the two highest p_T jets in the event. This ensures that the tagging jets are part of the hard scattering event.

2. "E-method": the tagging jets are the two highest energy jets in the event. This selection favors the very energetic forward jets which are typical for weak-boson fusion processes.

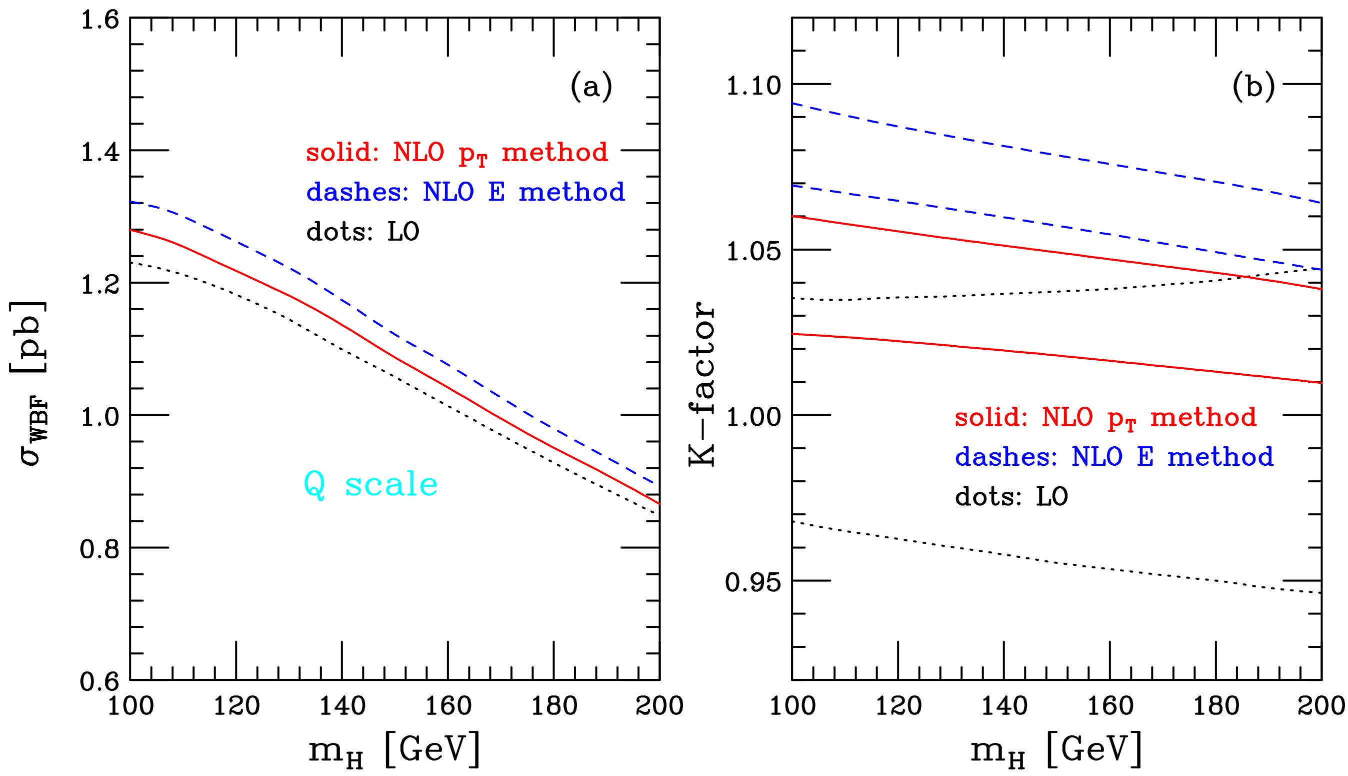
In addition, to further suppress backgrounds for WBF, we impose a "rapidity gap cut"

$$\Delta y_{jj} = |y_{j_1} - y_{j_2}| > 4$$

PDF

We have used CTEQ6L1 for LO and CTEQ6M for NLO results

Total cross section (LHC)



$$K = \frac{\sigma(\mu_R, \mu_F)}{\sigma^{LO}(\mu_F = Q)}$$

Two different scales to test scale dependence

$$\mu_F = \xi_F m_H \qquad \mu_R = \xi_R m_H$$

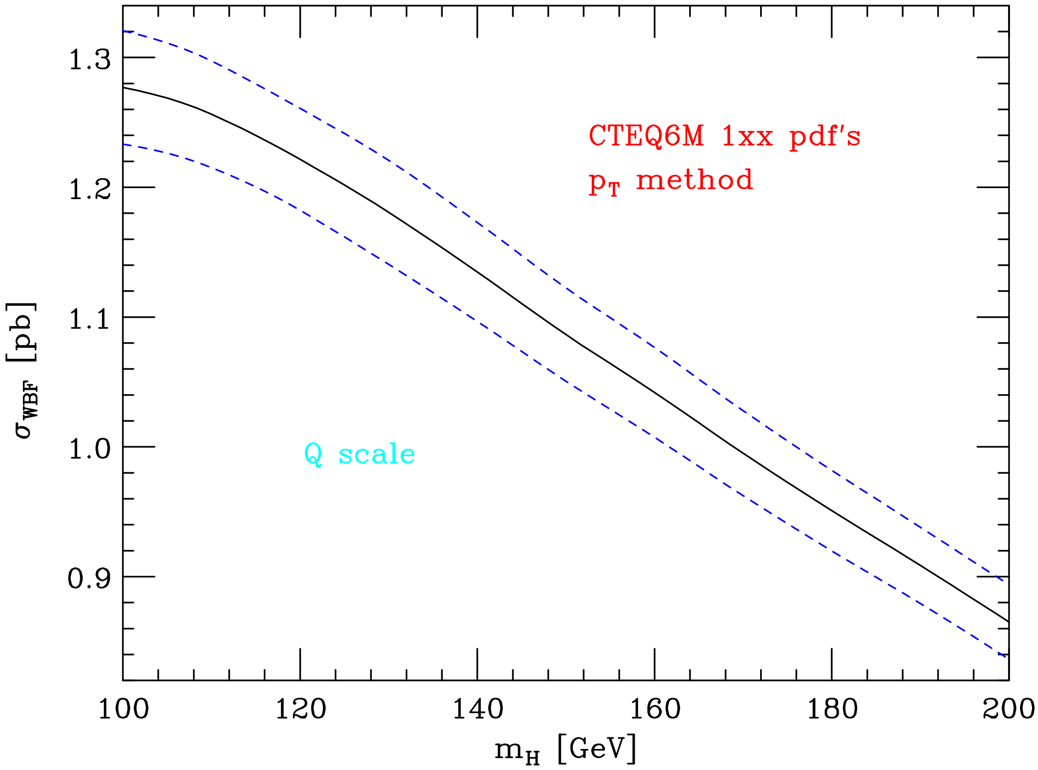
$$\mu_{Fi} = \xi_F Q_i \qquad \mu_{Ri} = \xi_R Q_i$$

Q_i = virtuality of the exchanged weak boson (on upper or lower quark line)

WBF as two independent DIS events, with independent radiative corrections on the two electroweak boson vertices.

The largest scale variations when we vary the renormalization and the factorization scale in the same direction $\Longrightarrow \xi = \xi_R = \xi_F$ with $1/2 \leq \xi \leq 2$.

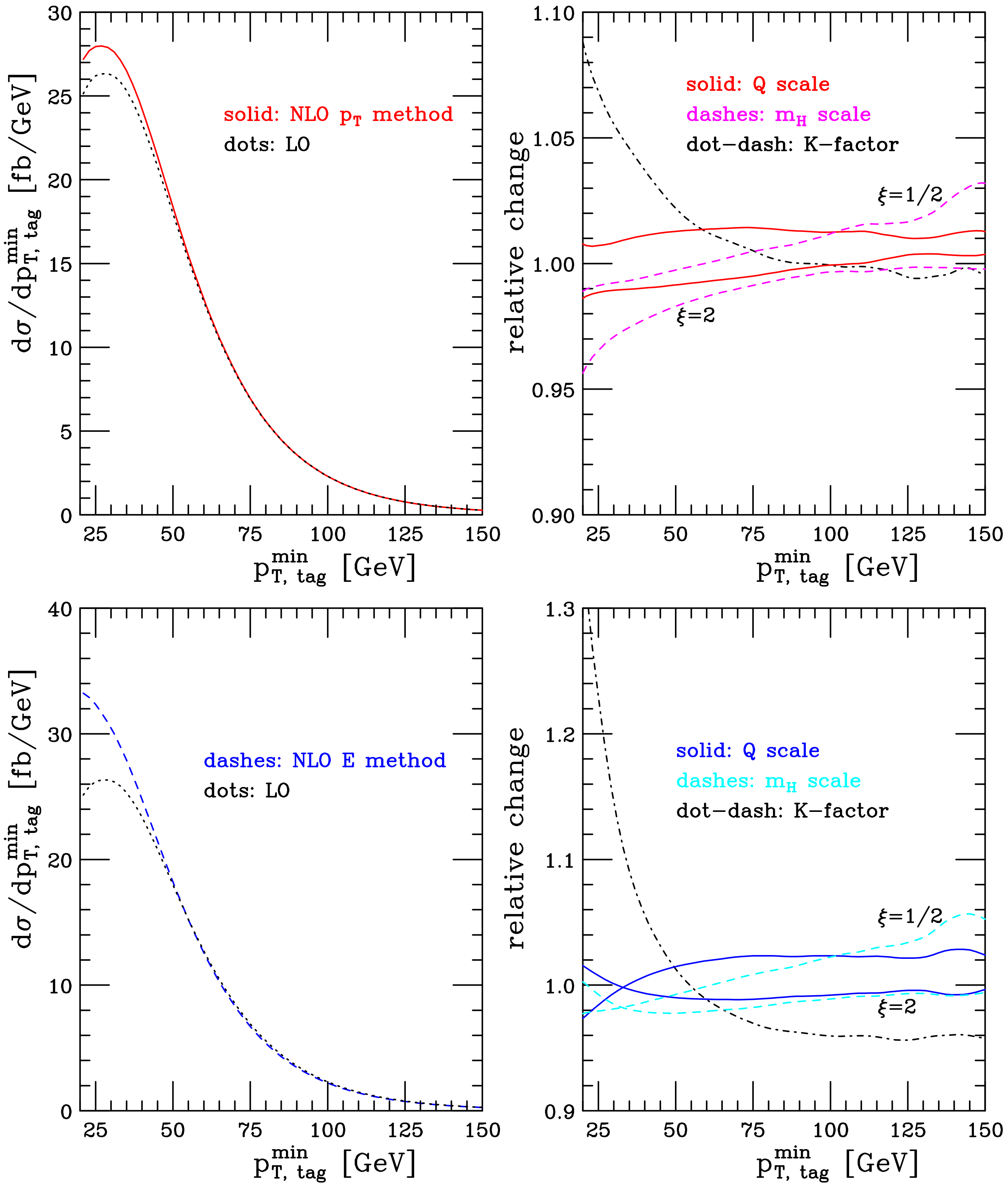
PDF uncertainties



PDF set CTEQ6Mxxx (xxx = 101–140)

They correspond to extremal plus/minus variations in the directions of the 20 error eigenvectors of the Hessian of the CTEQ6M fitting parameters.

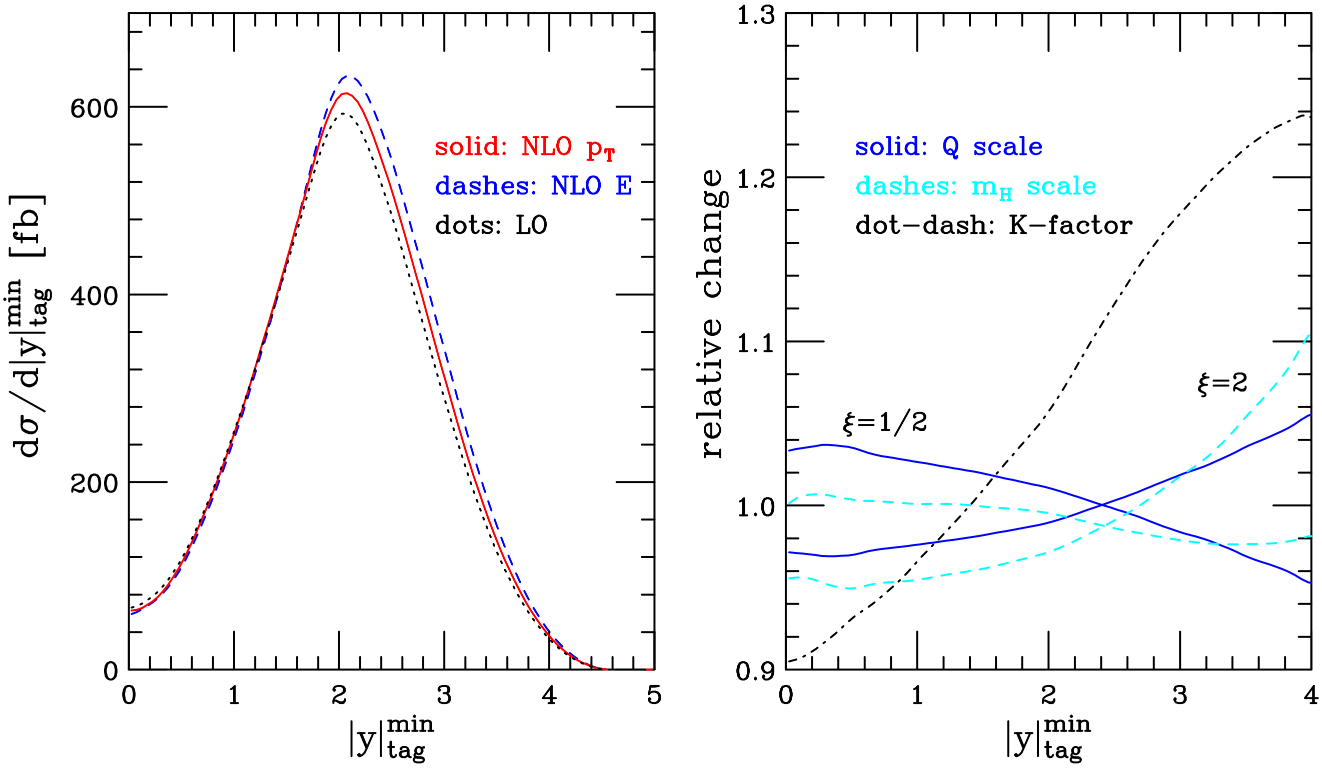
We find a uniform $\pm 3.5\%$ pdf uncertainty of the total cross section over the entire range of m_H shown.



$$m_H = 120 \text{ GeV}$$

$$R = \frac{d\sigma^{NLO}(\mu_F = \mu_R = Q)}{d\sigma^{NLO}(\mu_F = \mu_R = \mu)}$$

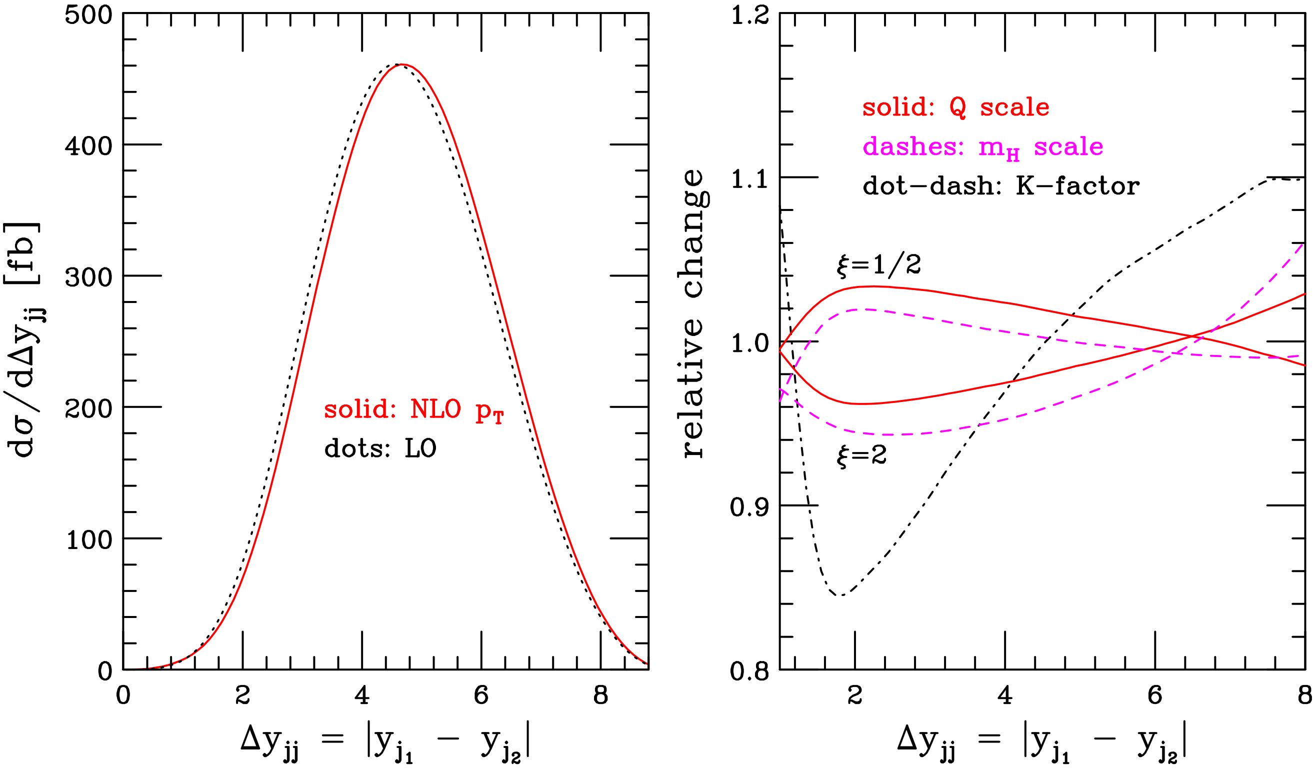
where $\mu = \xi Q$ (solid) and $\mu = \xi m_H$ (dashes) with $\xi = 1/2$ and 2.



K-factor strongly phase-space dependent.

But scale dependence modest, in particular in the important region around $|y|^{\rm min}_{\rm tag} \approx 2$.

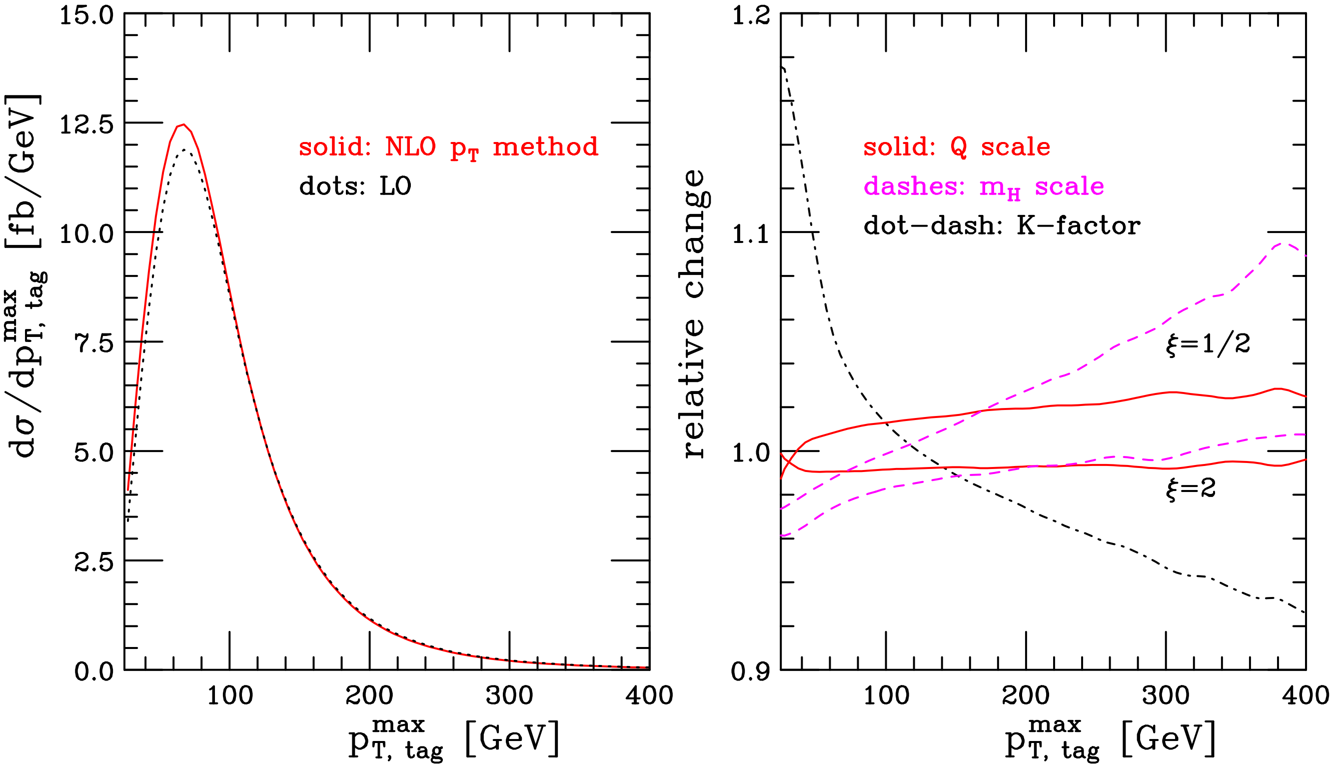
Scale variation below 4% .



Tagging jets are slightly more forward at NLO than at LO

$\Downarrow$

motivates $\Delta y_{jj} > 4$ cut.



K-factor reaches 1.18

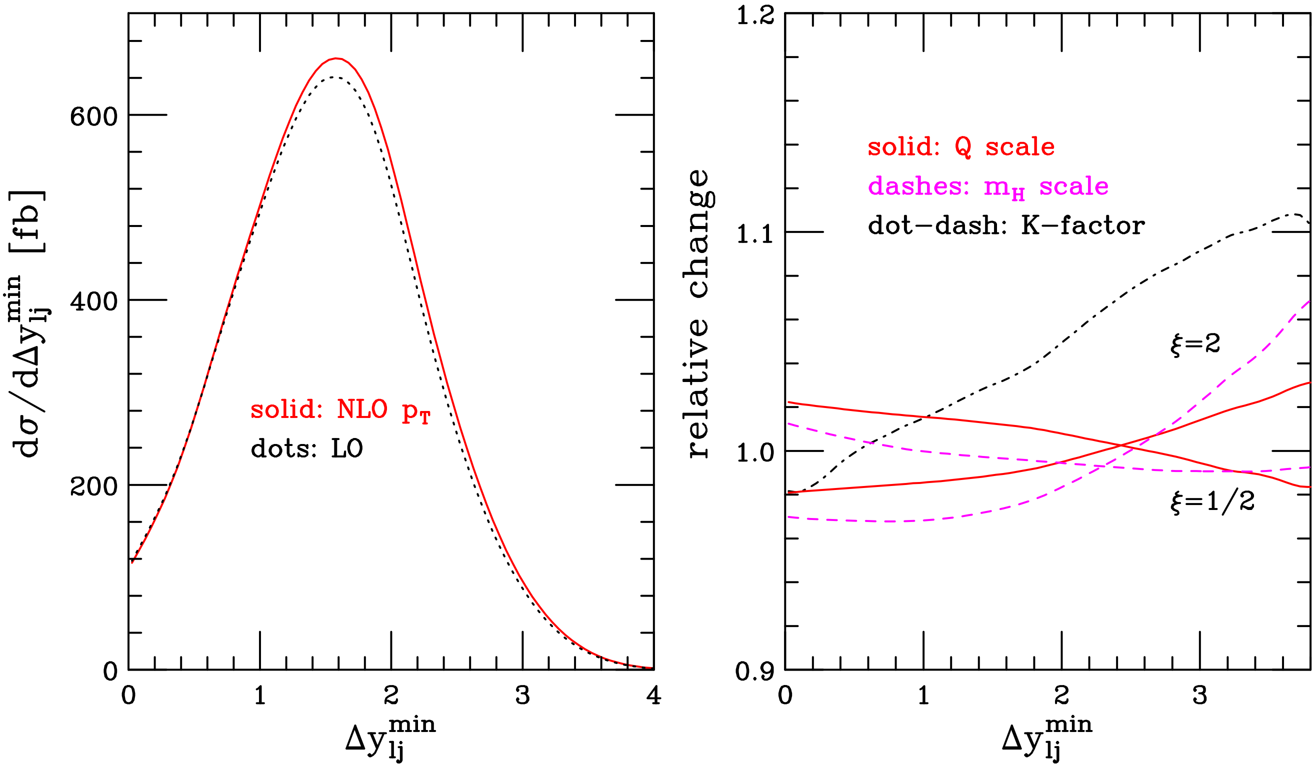
Scale variations:

- $-1\% \div 3\%$ with Q_i scales
- $-4\% \div 10\%$ with m_H scales

Smaller scale variations for $\mu = \xi Q$

$\Downarrow$

Best default scale $\mu = \xi Q$



where $\Delta y_{jl}^{\rm min} = \min\{|y_j - y_l|\}$ is the absolute value of the minimal rapidity separation of the two Higgs-boson decay "leptons" from either of the two tagging jets.

Conclusions

- Once the Higgs boson has been found and its mass determined, the measurement of its couplings to gauge bosons and fermions will be of main interest. Here weak-boson fusion will be of central importance since it allows for independent observation in the $H \to \tau\tau$, $H \to WW$ and $H \to \gamma\gamma$ channels.

- These measurements can be performed at the LHC with statistical accuracies on the measured cross sections times decay branching ratios, $\sigma \cdot B$, of order 10% or even better.

- We have shown that QCD corrections are modest, of order 5 to 10% in most cases, but reaching 30% occasionally.

  Remaining scale uncertainties range from order 5% or less for distributions to below $\pm 2\%$ for the Higgs boson cross section in typical weak-boson fusion search regions.