NLO QCD corrections to W and Z production via vector boson fusion

Carlo Oleari

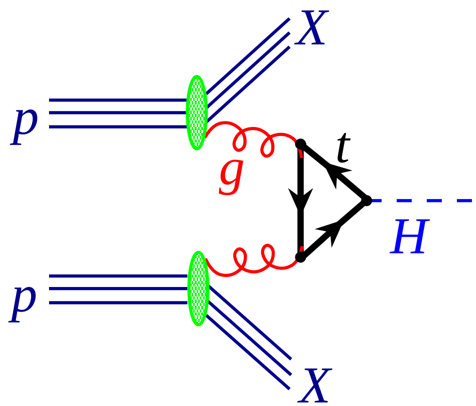
Università di Milano-Bicocca, Milan

LoopFest III

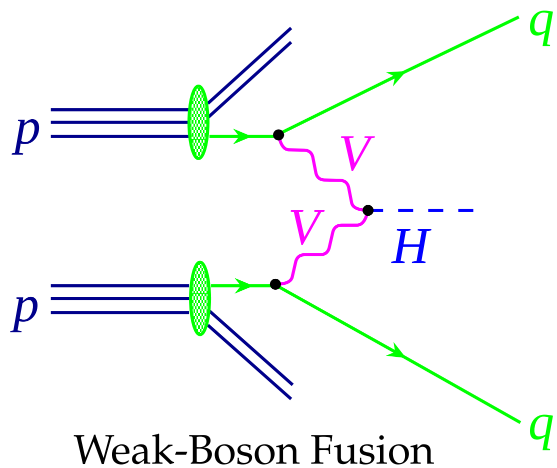
Santa Barbara, April 1, 2004

- Introduction: production modes
- Higgs production and (some) backgrounds
- Total cross sections and distributions
- Conclusions

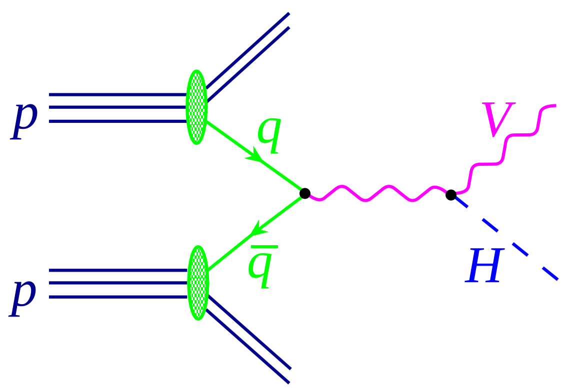
Production Modes



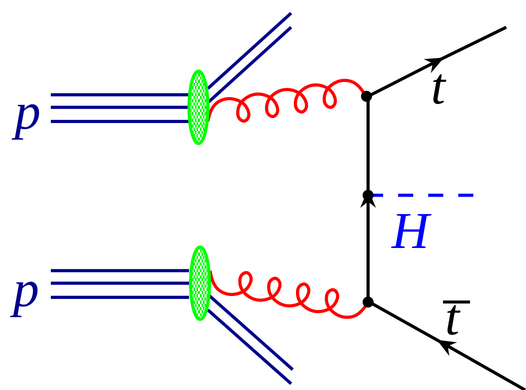
Gluon fusion



Weak-Boson Fusion

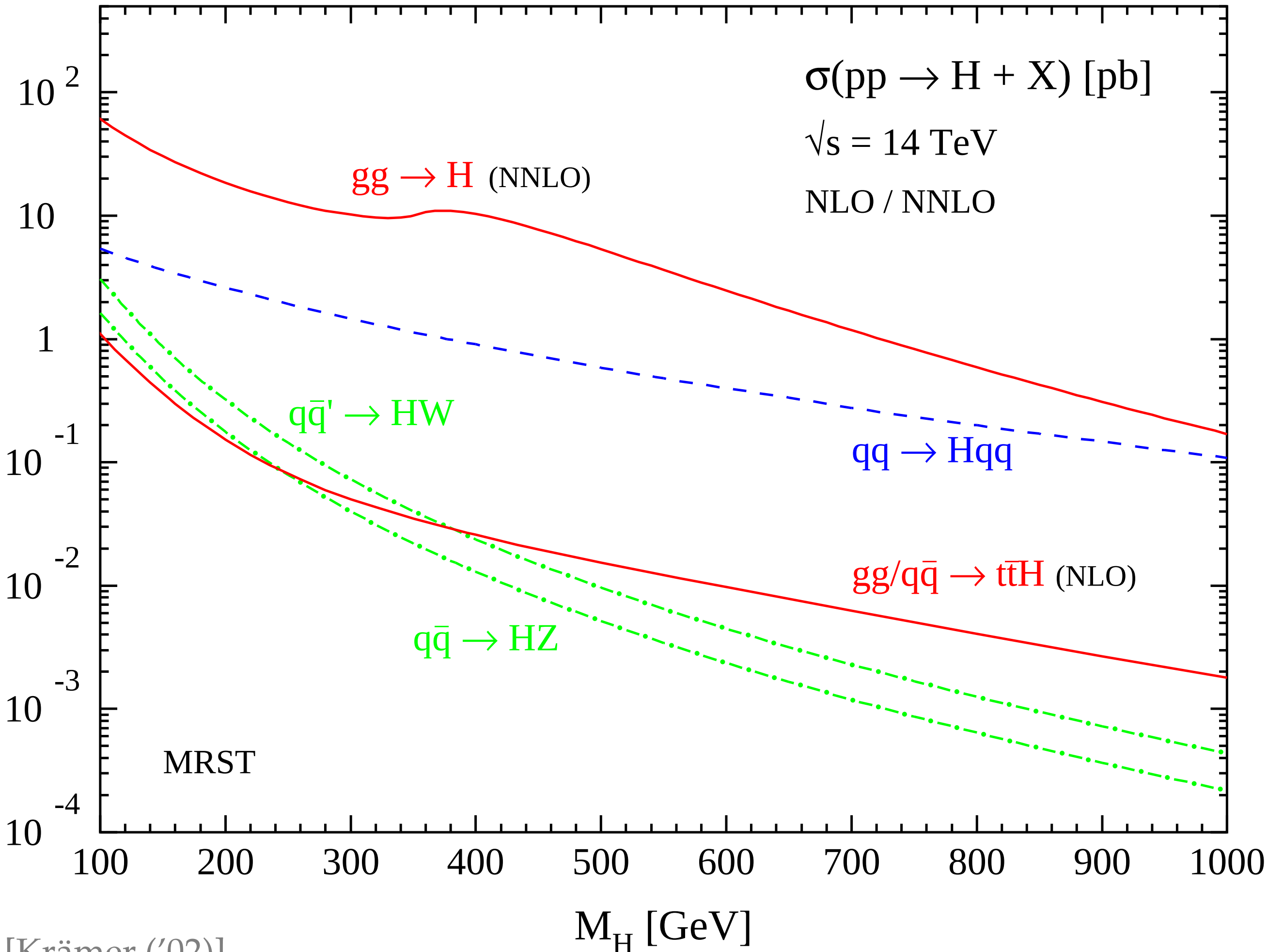


Higgs Strahlung

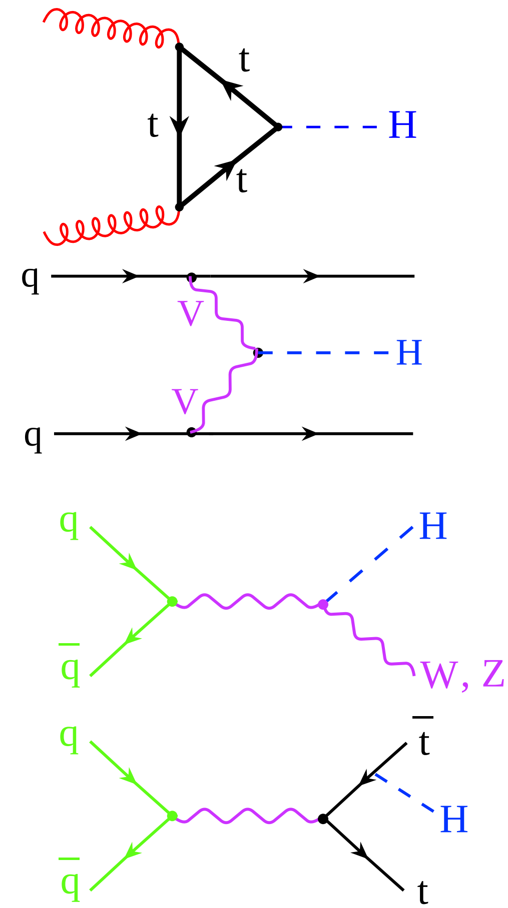


$t\bar{t}H$

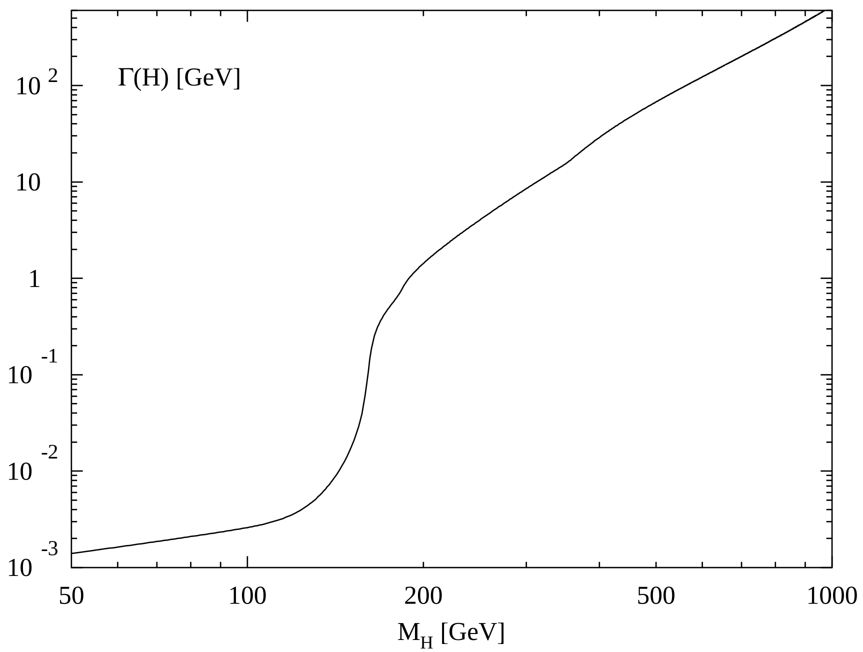
Total cross sections at the LHC

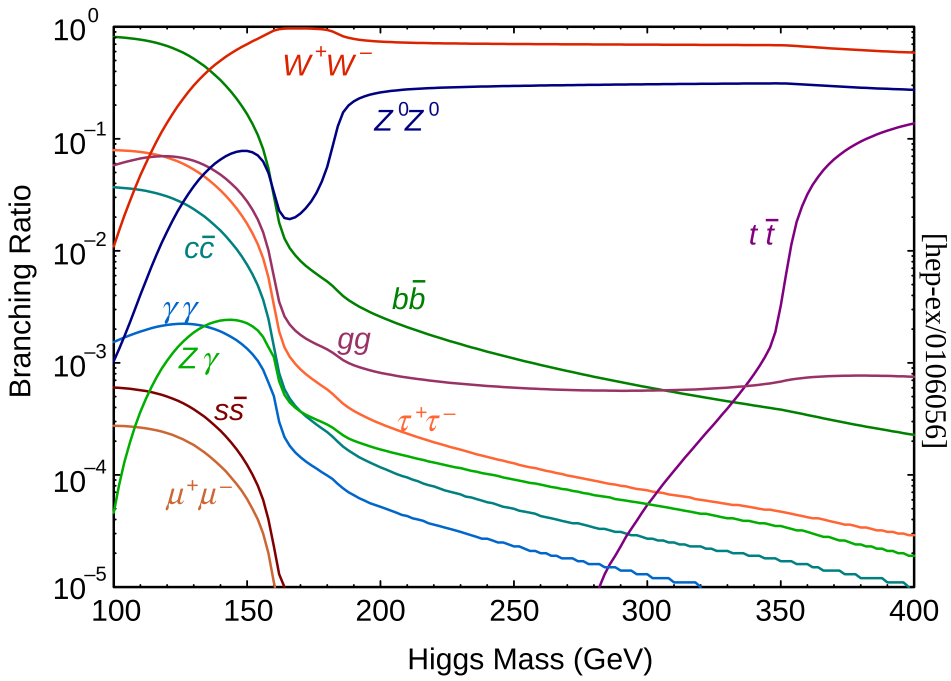


[Krämer ('02)]



Decay width and branching fractions of the SM Higgs





[Spira and 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.

Weak-boson fusion (WBF) is of central importance since it allows a precise coupling measurement of the HWW and HZZ vertex interactions and to check the mechanism of symmetry breaking.

The HVV (V vector boson) vertex is NOT present in the Lagrangian if the interaction with the scalar Higgs field were not generated by vacuum-expectation value.

Gauge interactions of not vacuum-expectation value scalar fields are proportional (at tree level) to: $\Phi\Phi^\dagger V$, $\Phi\Phi^\dagger VV$

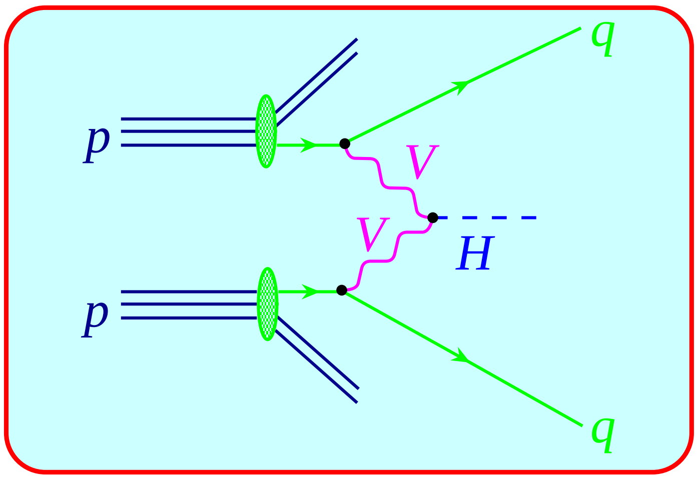
Coupling measurements

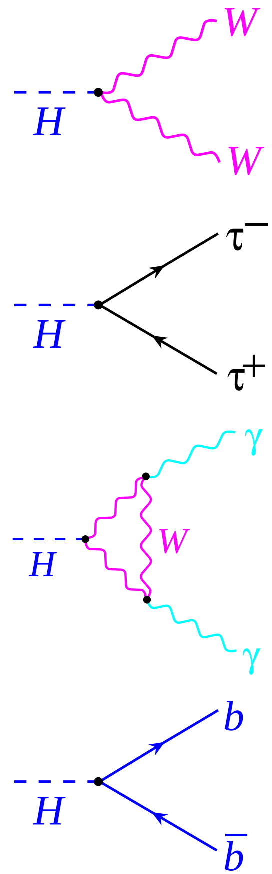
In addition, WBF will allow for independent observations of

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

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.

Weak Boson Fusion





$m_H > 120$ GeV

$m_H < 140$ GeV

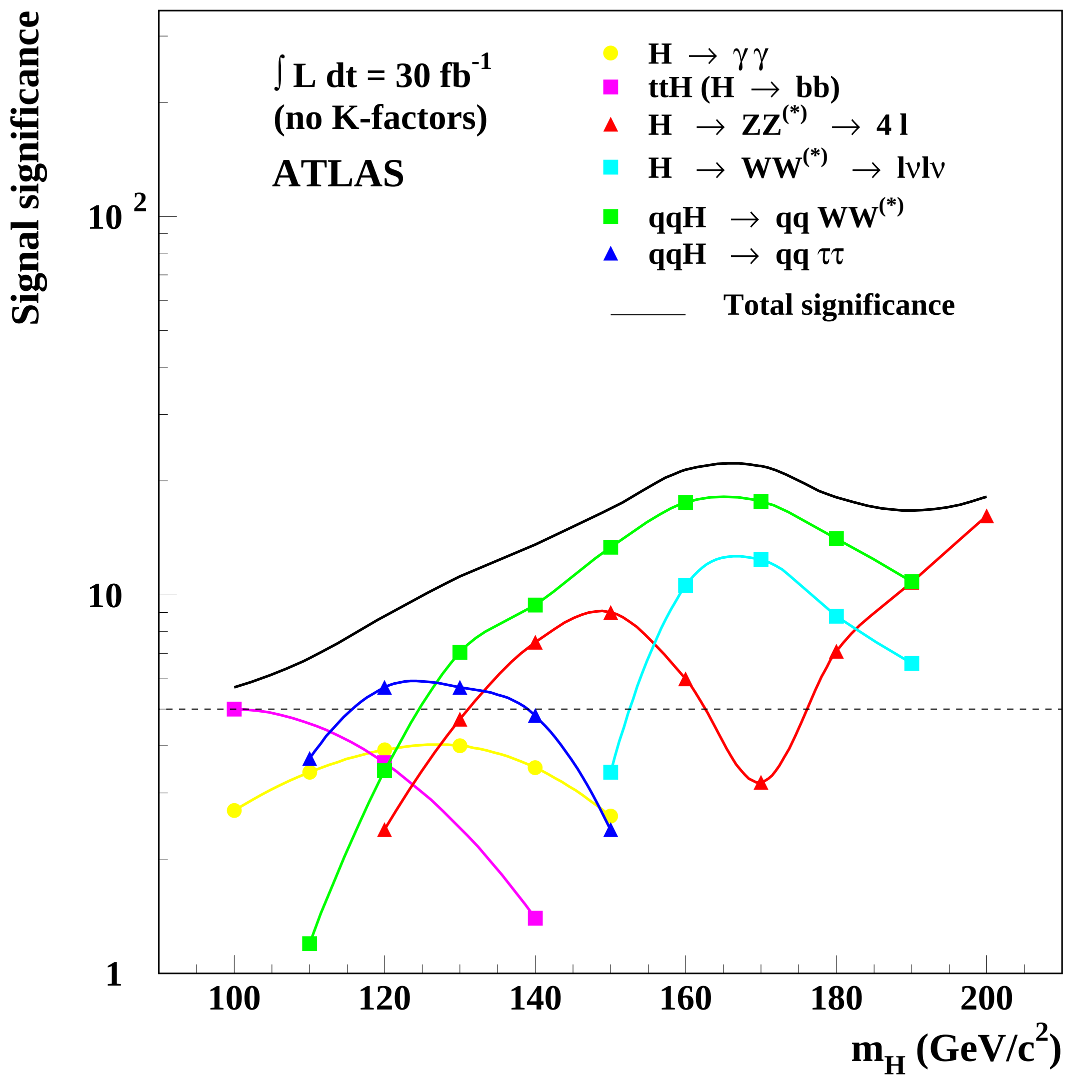
$m_H < 150$ GeV

$m_H < 140$ GeV

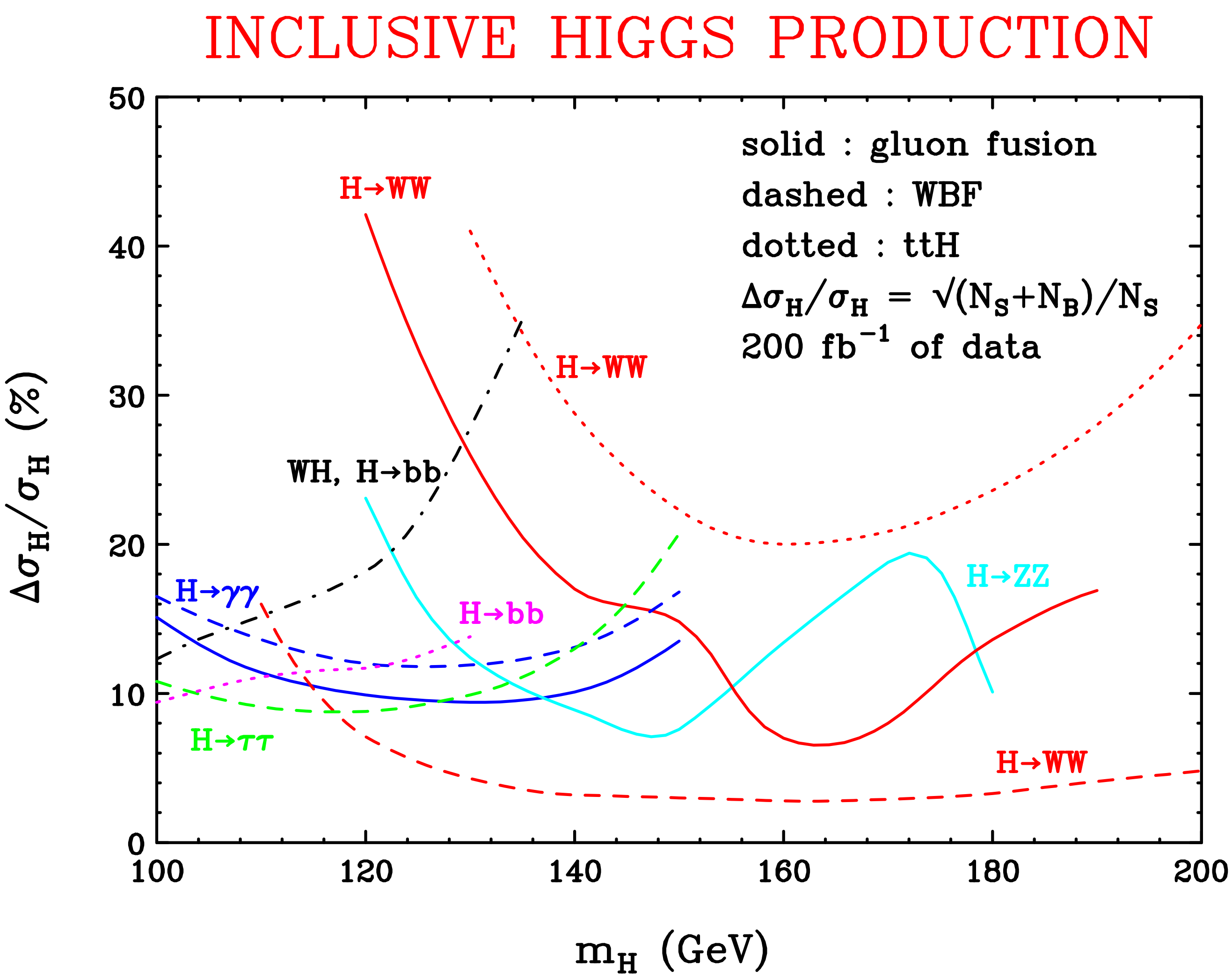
[Eboli, Hagiwara, Kauer, Plehn, Rainwater, Zeppenfeld . . .]

[Mangano, Moretti, Piccinini, Pittau, Polosa ('03)]

Higgs discovery potential

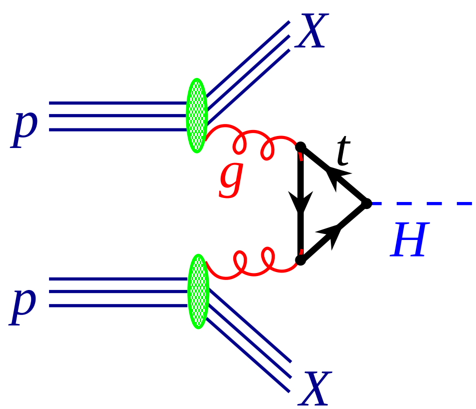


Statistical and systematic errors at LHC

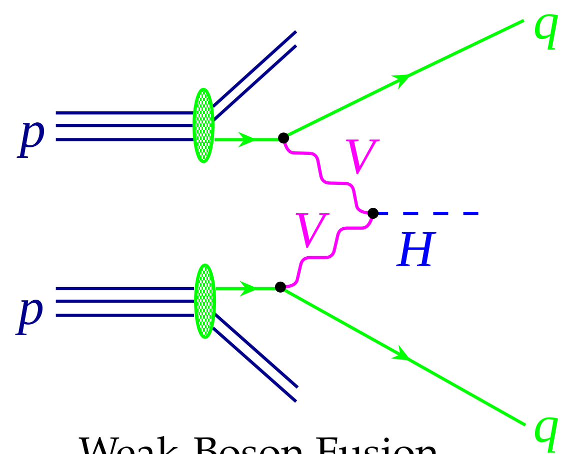


- QCD/PDF uncertainties
  - ±5% for WBF
  - ±20% for gluon fusion
- luminosity/acceptance uncertainties
  - ±5%

Gluon fusion vs. WBF



Gluon fusion

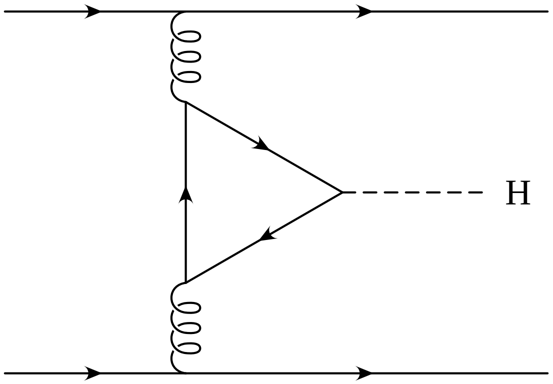


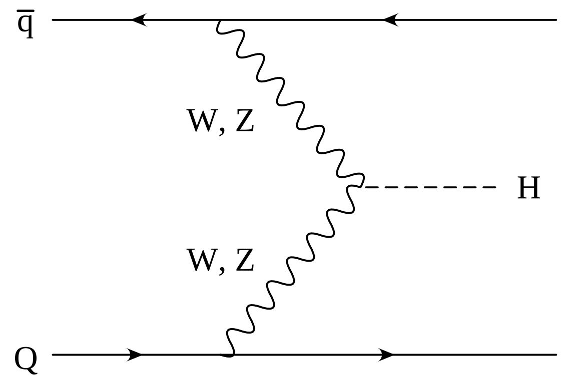
Weak-Boson Fusion

Signal vs. backgrounds

Can we impose a set of kinematics cuts on a final-state configuration in such a way that we can distinguish between the WBF signal and the backgrounds?

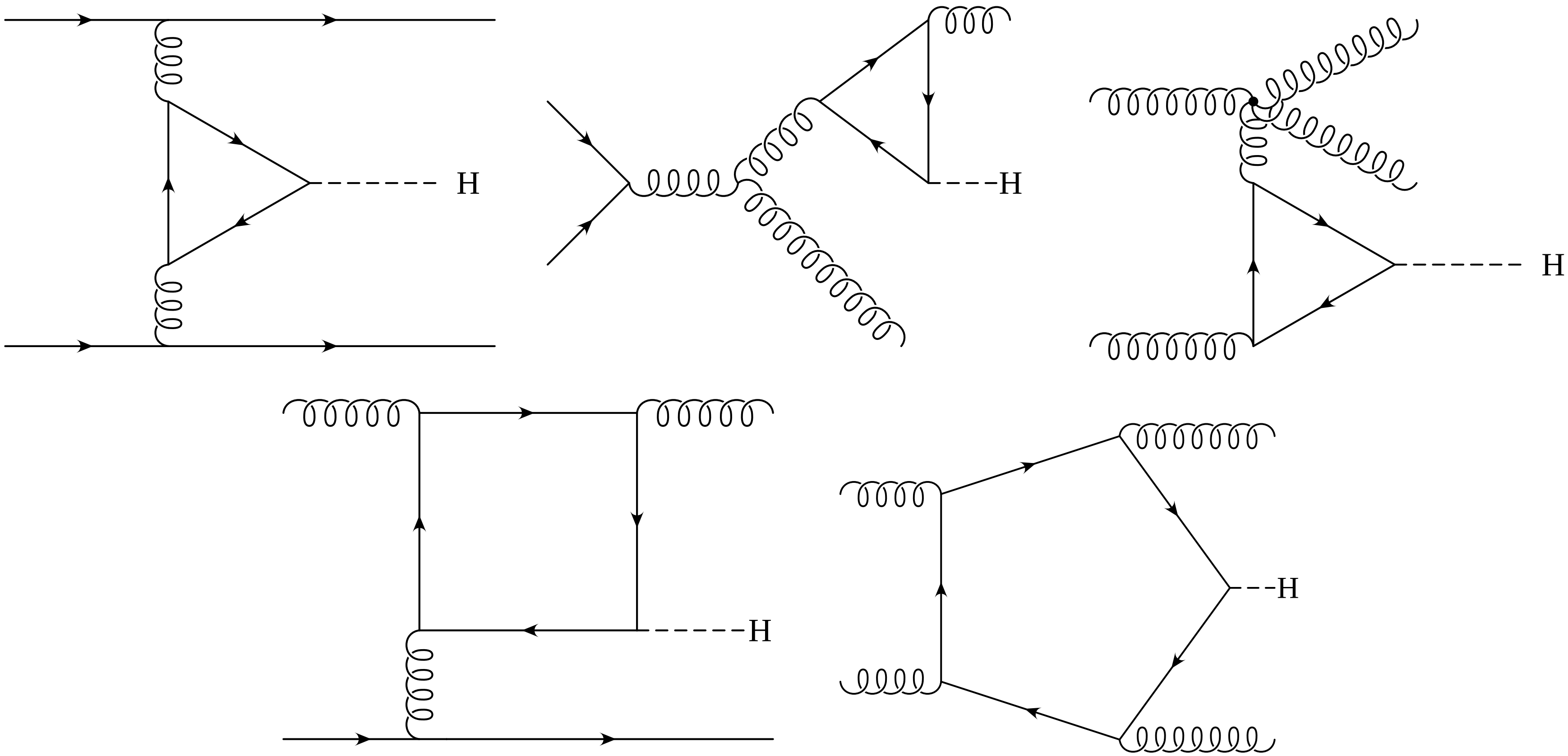
For example: double real corrections to $gg \to H$ can "fake" WBF





They **BOTH** contribute to Higgs boson discovery, but only one is the "WBF signal".

Double real corrections to gluon fusion



$q\,Q \to q\,Q\,H \qquad Q = q, q'$ $\qquad q\,g \to q\,g\,H \qquad g\,g \to g\,g\,H$

plus crossed processes. In total 61 independent diagrams.

Applied cuts

The cross section for Higgs production plus 2 jets diverges when

- final-state partons become collinear with one another
- final-state partons become collinear with initial-state partons
- final-state partons become soft

- INCLUSIVE cuts to define $H + 2$ jets

$$p_{Tj} > 20 \text{ GeV} \qquad |\eta_j| < 5 \qquad R_{jj} > 0.6$$

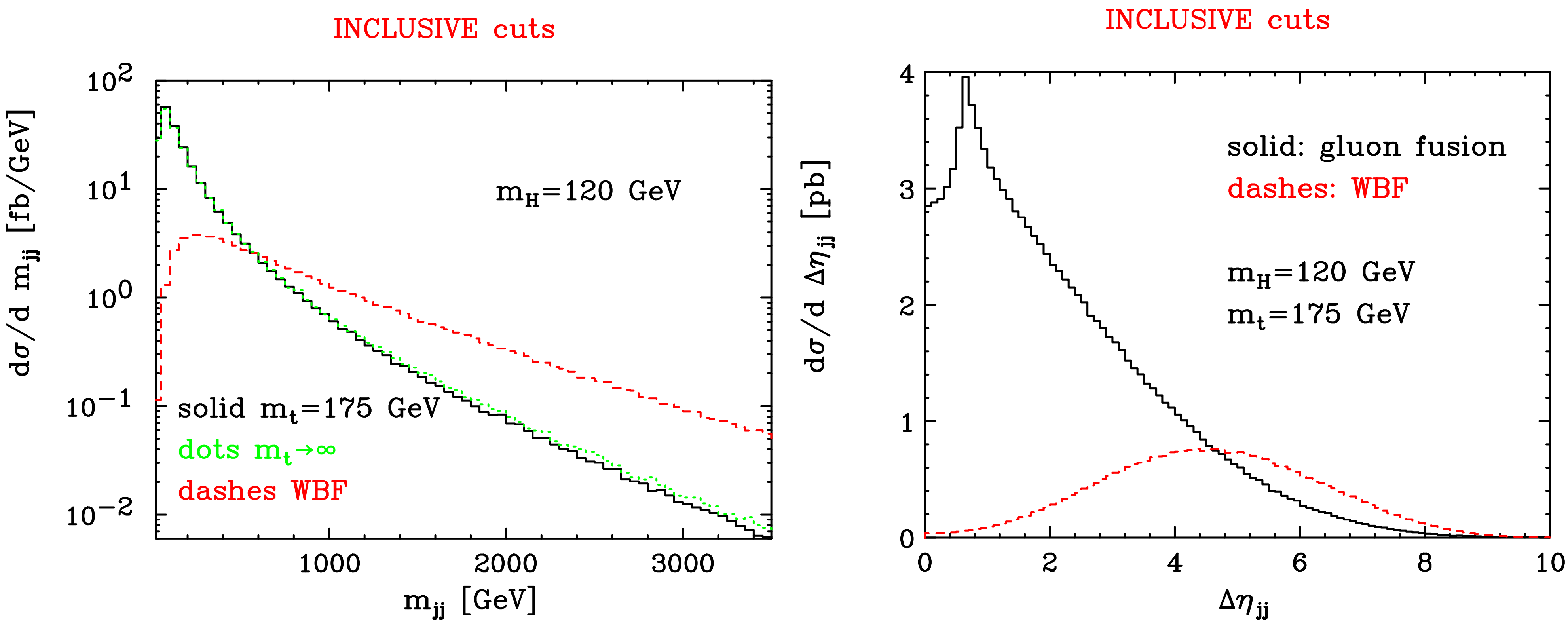
- WBF cuts. In addition to the previous ones, we impose

$$|\eta_{j_1} - \eta_{j_2}| > 4.2 \qquad \eta_{j_1} \cdot \eta_{j_2} < 0 \qquad m_{jj} > 600 \text{ GeV}$$

  – the two tagging jets must be well separated in rapidity
  – they must reside in opposite detector hemispheres
  – they must possess a large dijet invariant mass.

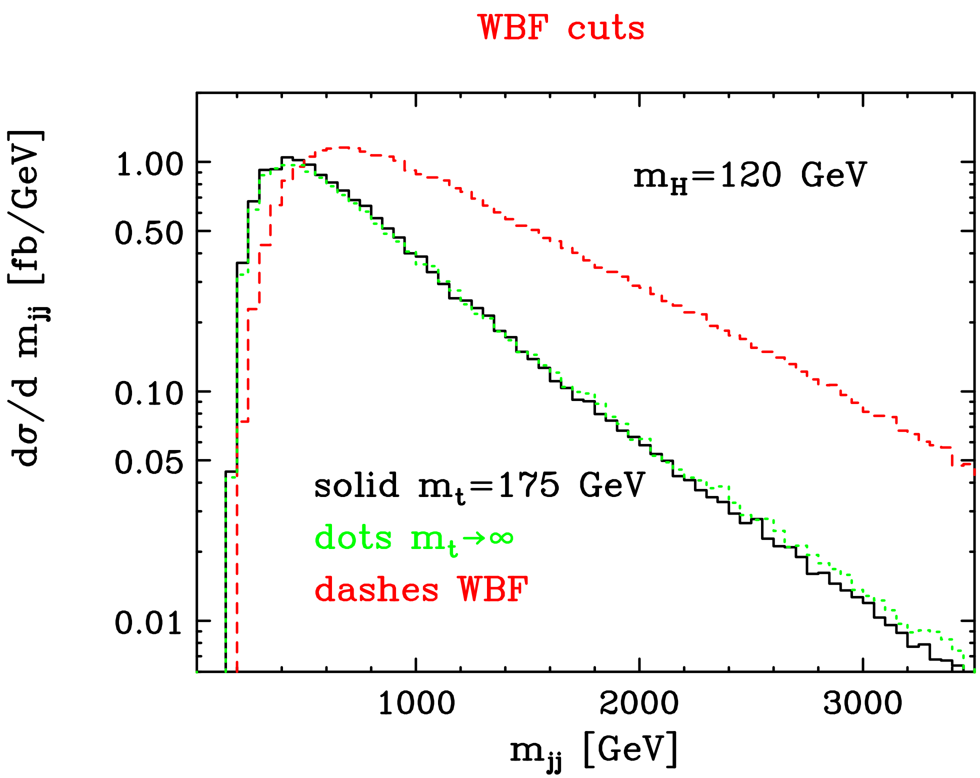
$$R_{jj} = \sqrt{\left(\eta_{j_1} - \eta_{j_2}\right)^2 + \left(\phi_{j_1} - \phi_{j_2}\right)^2}$$

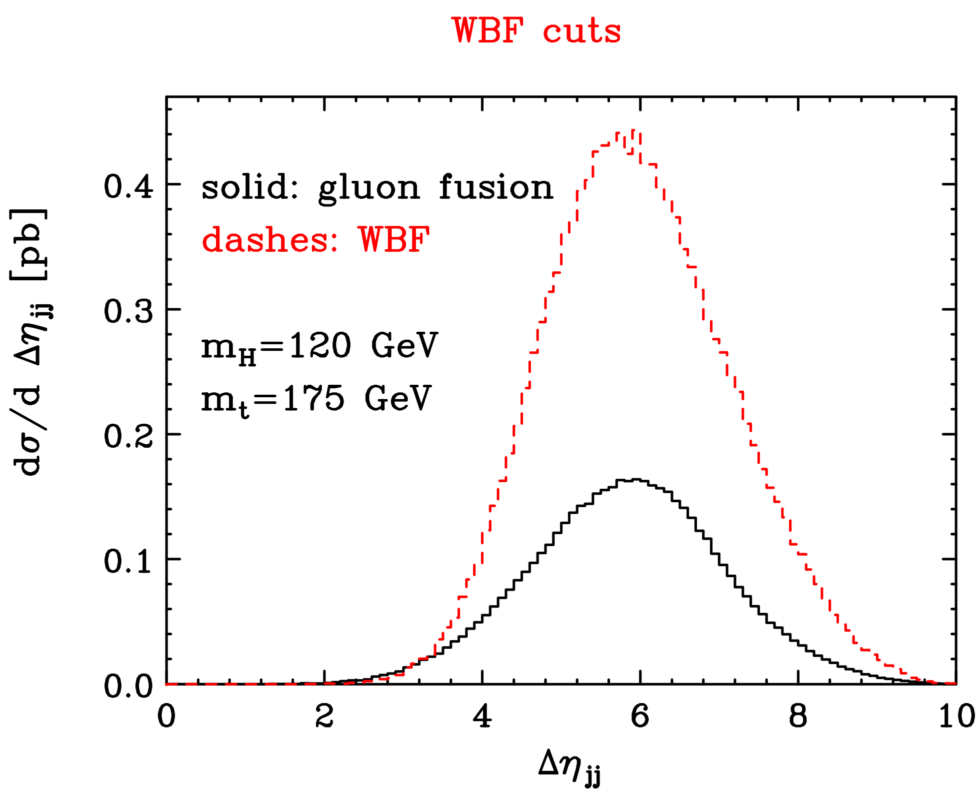
Inclusive cuts (LHC)



In gluon fusion, jets tend to have a small invariant dijet mass and tend to be close in rapidity. Note the rapidity separation of the jets in WBF processes.

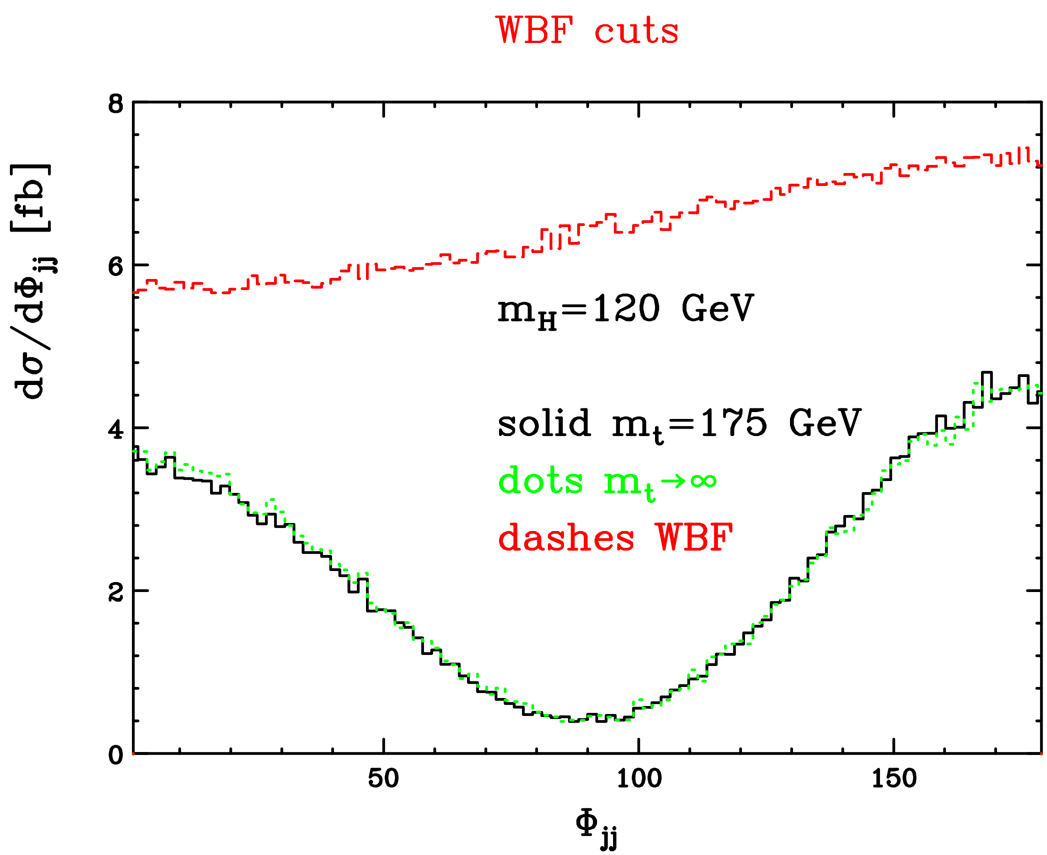
WBF cuts (LHC)





WBF cuts : $|\eta_{j_1} - \eta_{j_2}| > 4.2 \qquad m_{jj} > 600$ GeV

Azimuthal angle between jets ϕ_{jj} (LHC)



WBF

$$|\mathcal{A}|^2 \quad \propto \quad \frac{1}{\left(2\, p_{q,\text{in}} \cdot p_{q,\text{out}} + M_W^2\right)^2} \times \frac{1}{\left(2\, p_{Q,\text{in}} \cdot p_{Q,\text{out}} + M_W^2\right)^2}\, \hat{s}\, m_{jj}^2$$

CP even

$$H\, G_{\mu\nu}\, G^{\mu\nu}$$

CP odd

$$H\, G_{\mu\nu}\, G_{\alpha\beta}\, \epsilon^{\mu\nu\alpha\beta}$$

where $G_{\mu\nu} = \partial^\mu A^\nu - \partial^\nu A^\mu$

Important to identify the two jets!

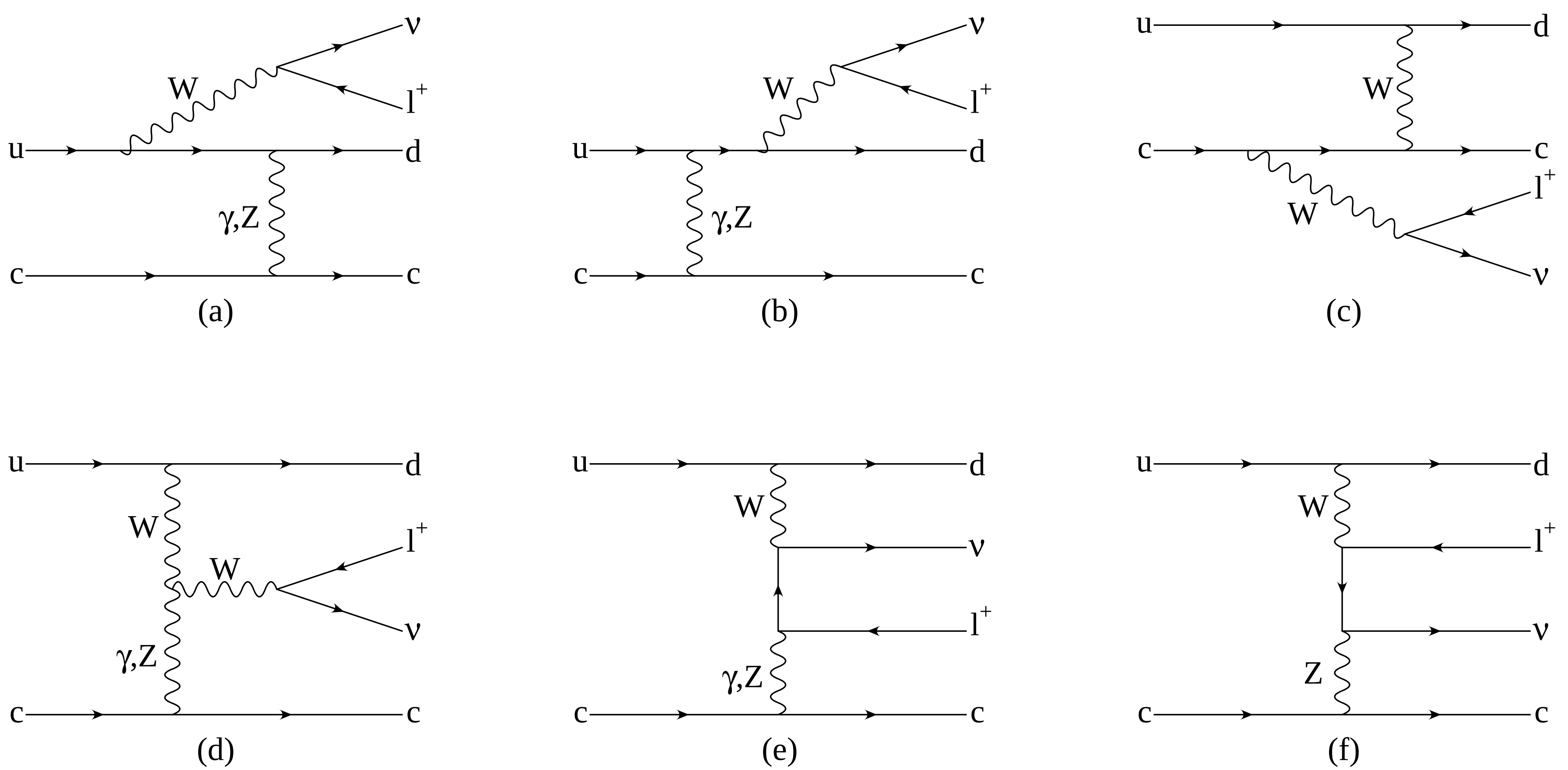
W and Z production via VBF

The production of $\ell\nu_\ell jj$ or $\ell^+\ell^- jj$ is another important background to the Higgs boson search in vector-boson fusion (VBF) at the LHC.

- $\tau^+\tau^- jj$ is a background to $H\to\tau^+\tau^-$ and $H\to W^+W^-$, when W's and τ's decay leptonically.

- $\ell\nu_\ell jj$ final state with an unidentified charged lepton, or $\nu_\ell\bar{\nu}_\ell jj$ events from $Z\to\nu_\ell\bar{\nu}_\ell$ decay, form a background to invisible Higgs boson decay

Leading order diagrams



Neglect annihilation and conversion diagrams (where both the two bosons are time-like): very suppressed by VBF cuts.

Why compute NLO QCD corrections?

- To exploit W and Z production via VBF as calibration processes for Higgs boson production
  - as a tool to understand the tagging of forward jets or the distribution. Understanding the gap-survival probability in the known case of W and Z production can give insight on the gap survival for the case of Higgs boson production.
  - to investigate veto of additional central jets in VBF.

- To study anomalous triple-gauge-boson couplings

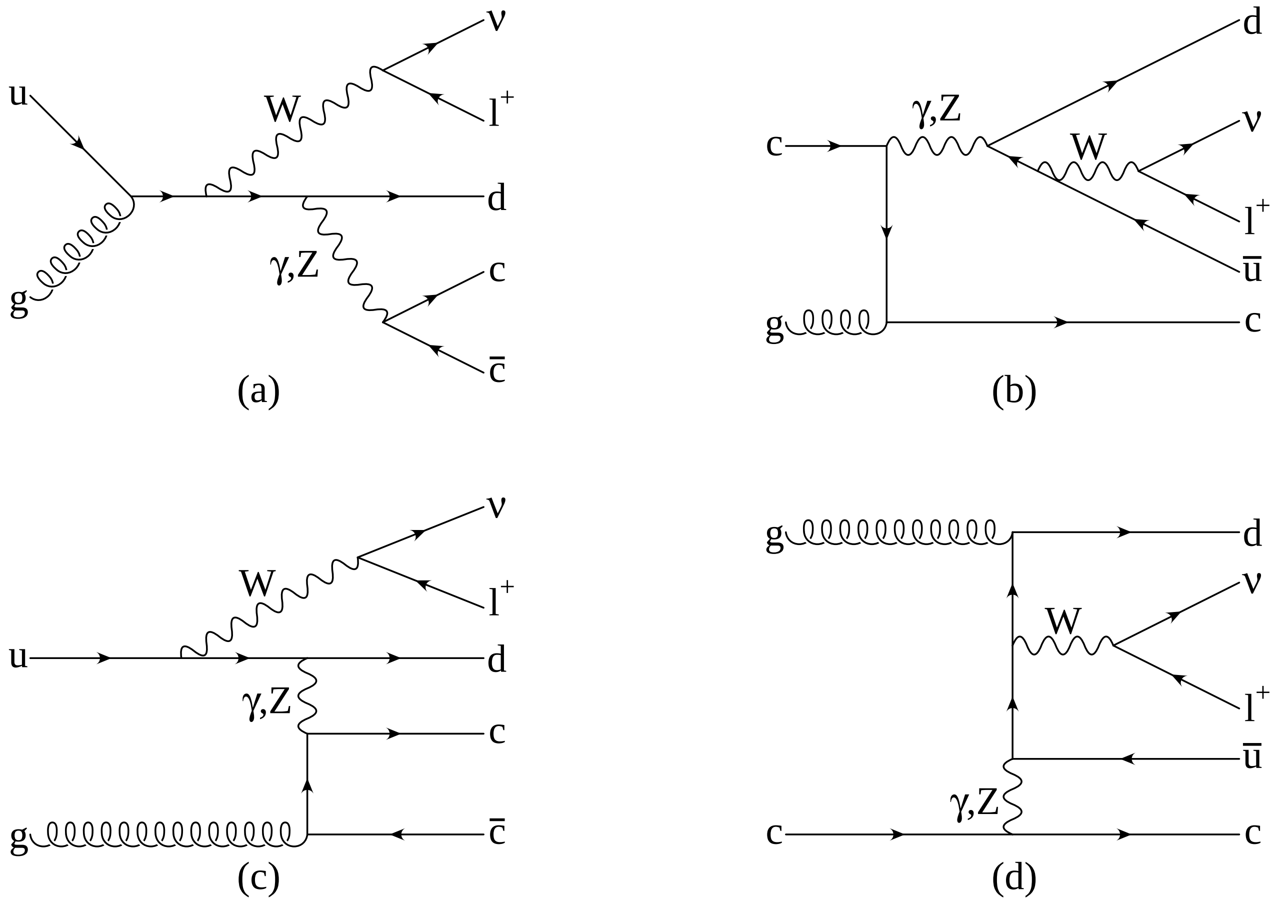
Contributions NOT included

- diagrams where both the virtual vector bosons are time-like.
- interference effects from diagrams obtained by interchange of identical initial- or final-state (anti)quarks

In the phase-space region where VBF can be observed experimentally, the neglected terms are strongly suppressed by large momentum transfer in one or more weak-boson propagators. Color suppression further reduces any interference

At LO, the diagrams that we have not considered and interference effects contribute less than 0.3%.

Some real-correction diagrams



Tagging jets

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

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.

The p_T method has smaller QCD NLO corrections than the E method.

VBF Higgs production: NLO total cross is 3-5% higher than the LO one with p_T method, and it is 6-9% higher with E method.

The larger cross section for the E method is due to events with a fairly energetic extra (gluon) central jet.

Applied cuts

We calculate the partonic cross sections for events where the two tagging jets 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 $|\eta| < 5$.

In addition, we impose the rapidity-gap separation

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

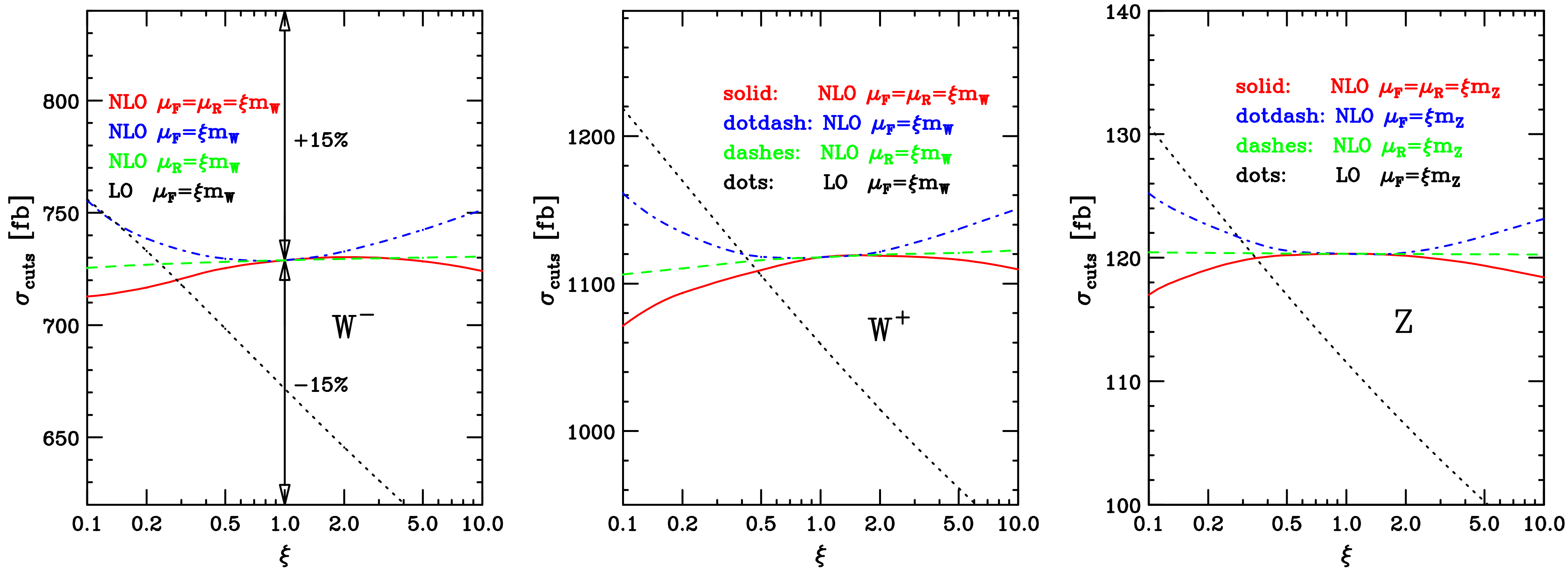
The charged lepton(s) from $Z \to l^+ l^-$ and $W \to l\nu$ must satisfy

$$p_{T\ell} \geq 20 \text{ GeV} \,, \quad |\eta_\ell| \leq 2.5 \,, \quad \triangle R_{j\ell} \geq 0.4 \,,$$

$$y_{j,min} < \eta_\ell < y_{j,max}$$

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

Total cross section (LHC)



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

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

Considering the range $0.5 < \xi < 2$, the NLO cross sections change by less than 1% in all cases.

[Zeppenfeld and C.O.]

PDFs and PDFs uncertainties

- 30 PDFs of MRST2001E set
- 40 PDFs1 of CTEQ6M set

- W^-
  - MRST $\sigma_{\text{NLO}} = 755.2 \pm 20.2$ fb 2.7%
  - CTEQ $\sigma_{\text{NLO}} = 728.9 \pm 29.4$ fb 4%

$$\frac{\delta\sigma_{\text{pdfs}}}{\sigma} = 3.5\%$$

- W^+
  - MRST $\sigma_{\text{NLO}} = 1159.4 \pm 16.1$ fb 1.4%
  - CTEQ $\sigma_{\text{NLO}} = 1117.8 \pm 40.5$ fb 3.6%

$$\frac{\delta\sigma_{\text{pdfs}}}{\sigma} = 3.6\%$$

Results

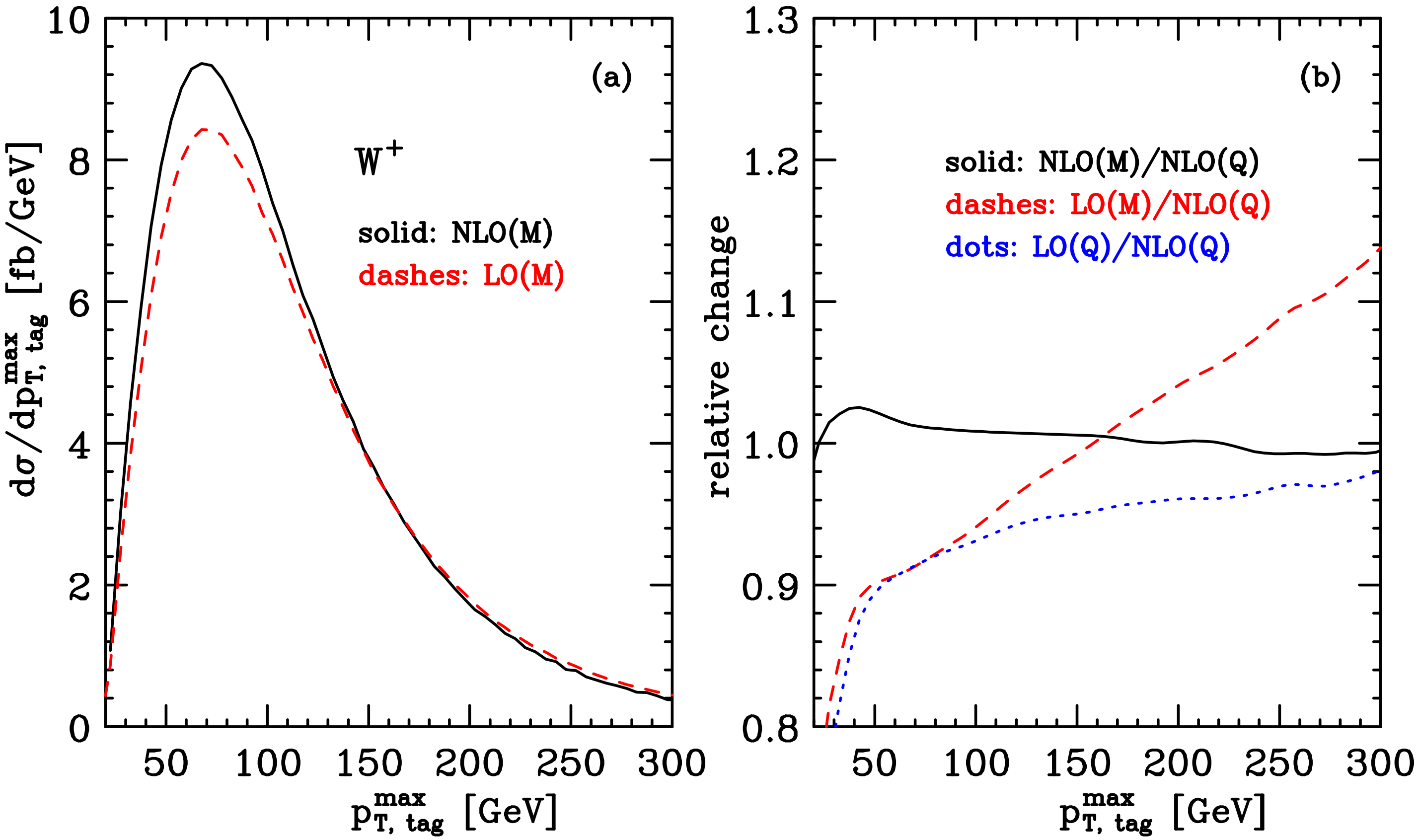
- K factors

$$K(x) = \frac{d\sigma_{NLO}/dx}{d\sigma_{LO}/dx}$$

  flat for all the distributions we have checked, and QCD corrections affect distributions for less than a few percent.

- CAVEAT: but only if tagging jets are considered, and not any of the jets that has passed the cuts!

Transverse momentum

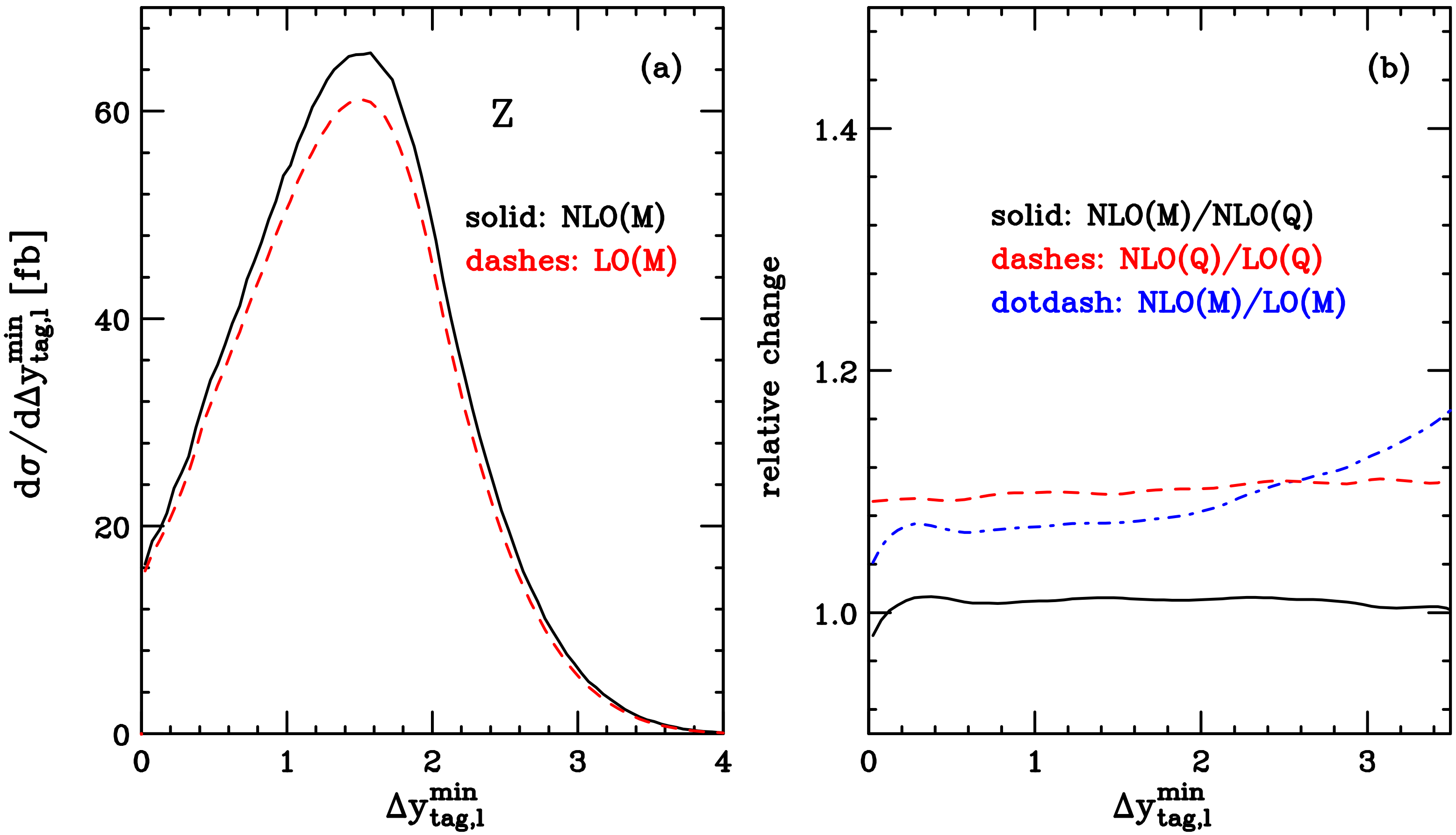


$M: \quad \mu_R = \mu_F = m_W$

$Q: \quad \mu_R = \mu_F = Q_i$

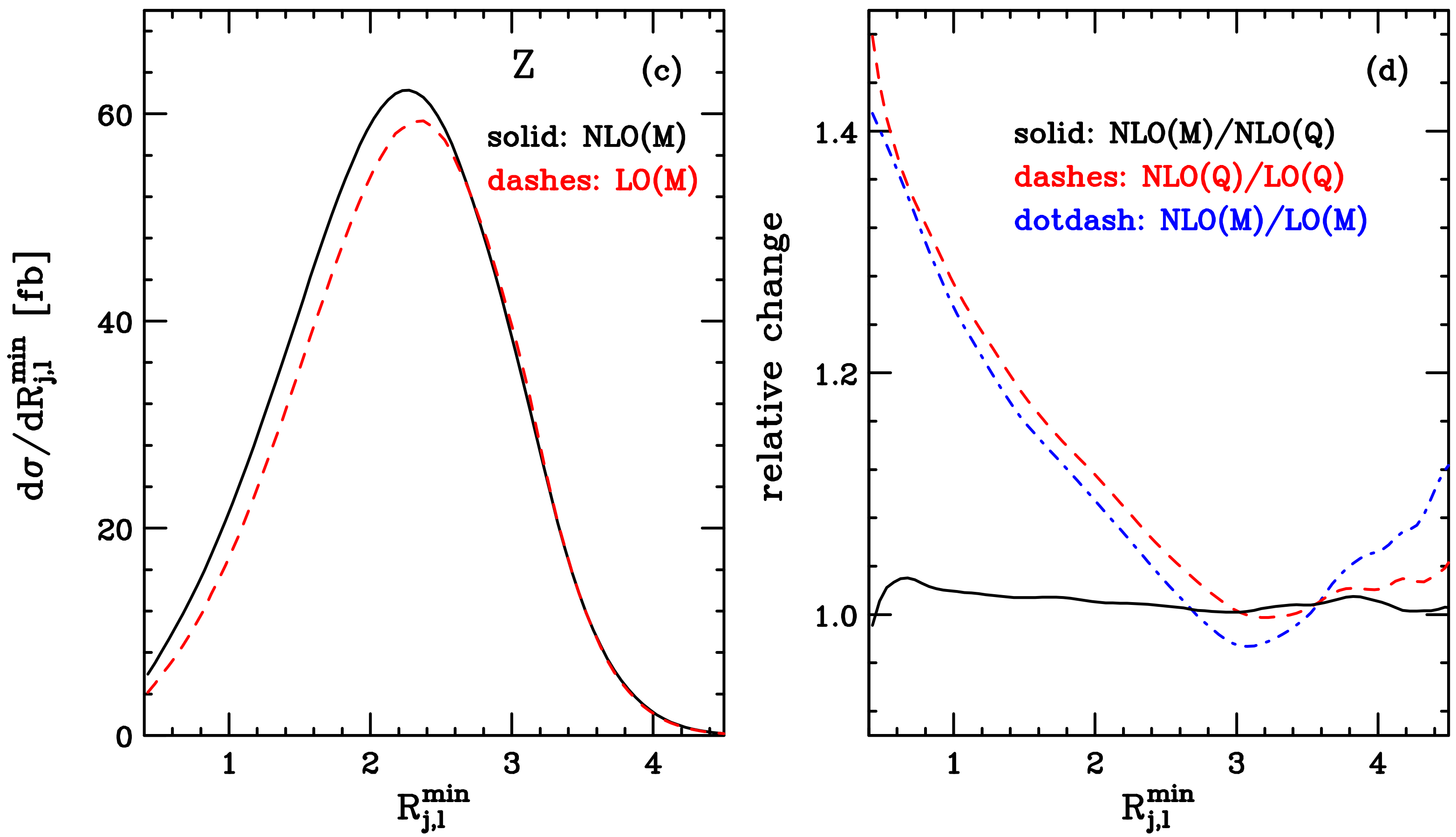
- NLO(M)/NLO(Q) deviates from unity by 2% $\Longrightarrow$ small QCD corrections.
- the "dynamical" scale choice $\mu_F = Q_i$ at LO better reproduces the NLO results.

Angular correlations of leptons and jets



K factor small and flat.

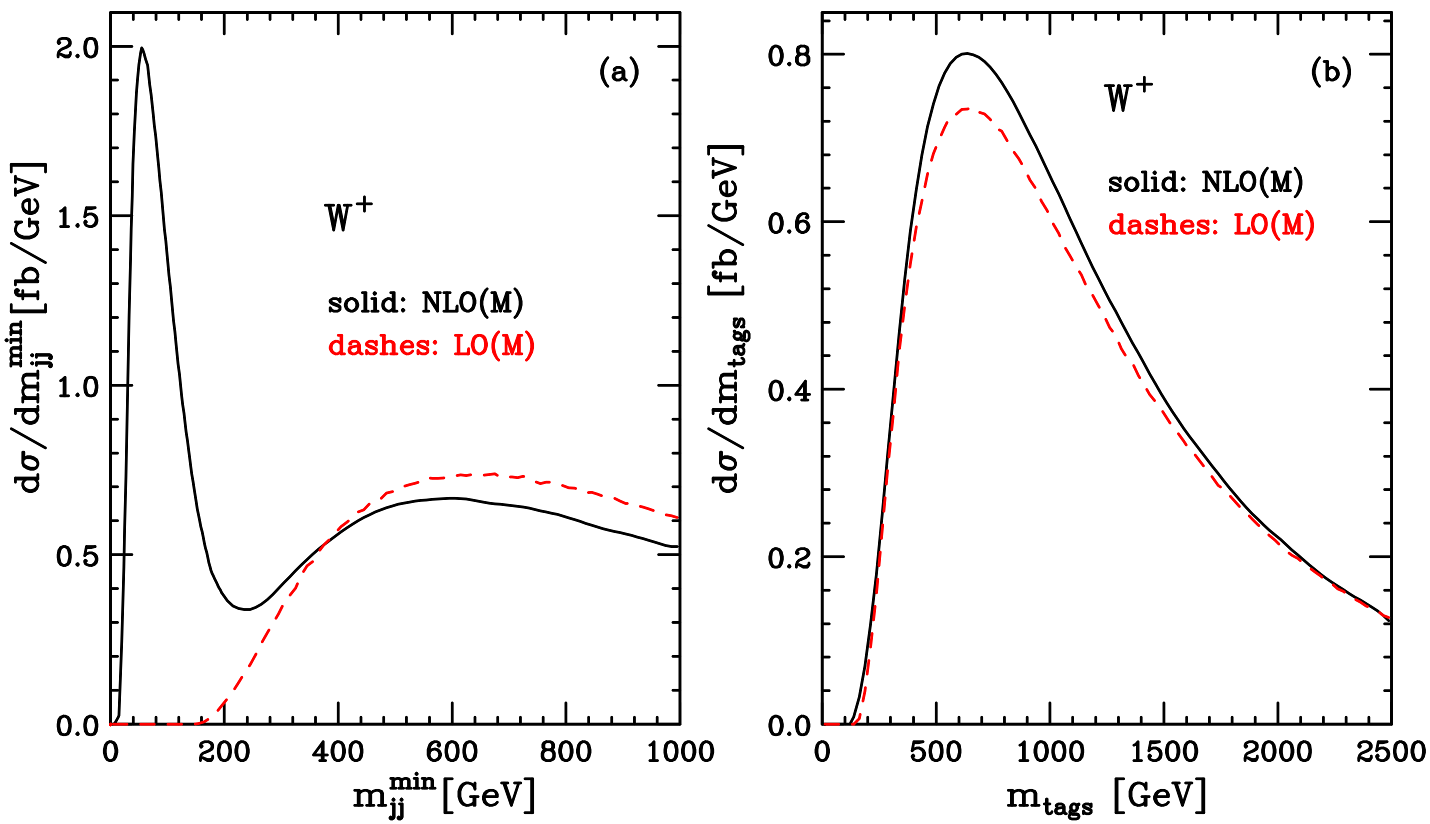
Angular correlations of leptons and jets



$$R_{jl} = \sqrt{\Delta\eta_{jl}^2 + \phi_{jl}^2}$$

Additional parton emission at NLO reduces lepton isolation.

Dijet invariant-mass



At LO, there are only two final-state quarks of $p_T > 20$ GeV.

At NLO, additional parton emission provides for soft third jets which form low invariant-mass pairs with one of the 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.

- This clearly requires knowledge of the next-to-leading order QCD corrections for signal and backgrounds. These corrections, in the case of H, W and Z production in WBF processes, are in general small, but one must be careful about the definition of jet.