QCD corrections to Higgs and vector-boson production

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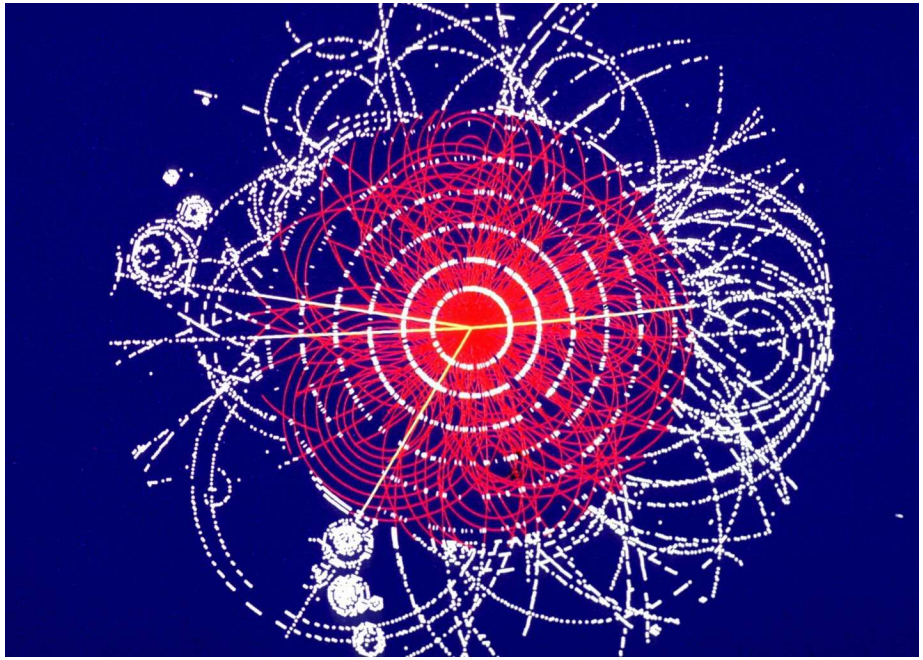
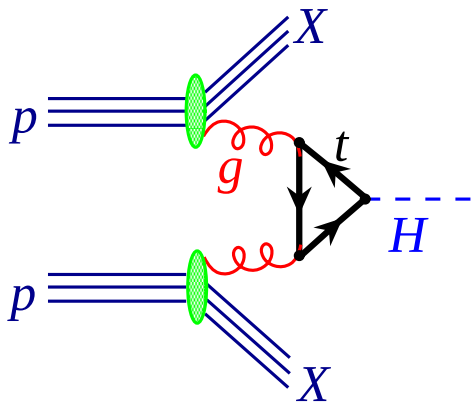
Pheno2006, Madison

16 May 2006

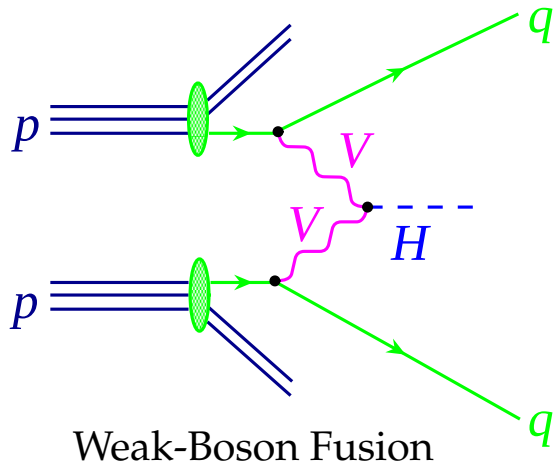
- Higgs production
- QCD corrections to vector-boson-fusion (VBF) production of
  - Higgs boson
  - W/Z
  - WW/ZZ
- Conclusions



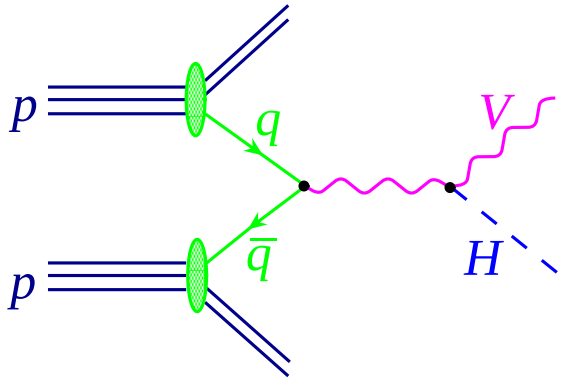
Production Modes



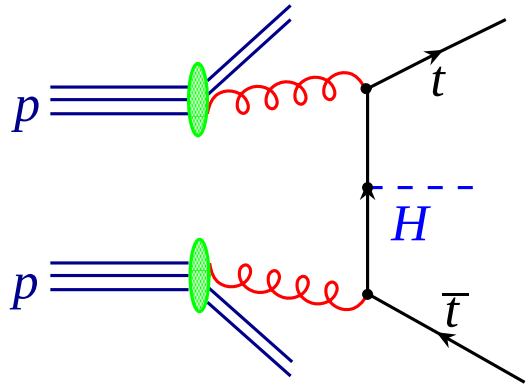
Gluon fusion



Weak-Boson Fusion



Higgs Strahlung



$t\bar{t}H$

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

- mass
- gauge couplings
- Yukawa couplings
- self couplings
- charge
- color
- spin
- CP quantum numbers
- ...

VBF: spontaneous symmetry breaking

$$\mathcal{L}_{\text{Higgs, kin}} = (D_\mu \Phi)^\dagger (D^\mu \Phi) \qquad \Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$$

$$D^\mu = \partial^\mu - igW_i^\mu \frac{\sigma^i}{2} - ig' \frac{Y(\Phi)}{2} B^\mu$$

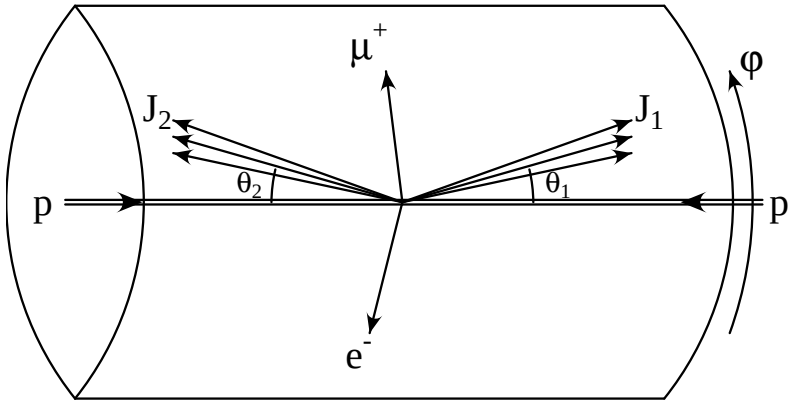
After spontaneous symmetry breaking $\Phi(x) \to \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + H(x) \end{pmatrix}$

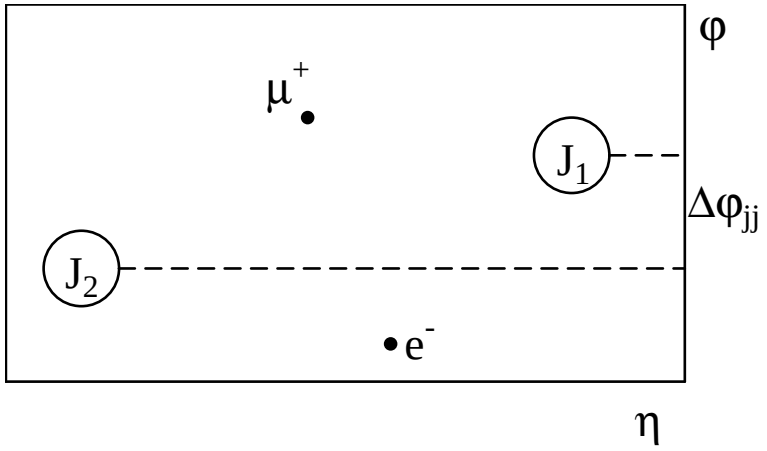
$$(D^\mu \Phi)^\dagger D_\mu \Phi = \frac{1}{2} \partial^\mu H \partial_\mu H + \left[\left(\frac{g}{2} \right)^2 W^{\mu +} W_\mu^- + \frac{1}{2} \frac{(g^2 + g'^2)}{4} Z^\mu Z_\mu \right] (v + H)^2$$

Tree-level HWW and HZZ couplings require vacuum-expectation value

Gauge interactions of non-VEV scalars are bilinear in Φ

VBF signature





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

Characteristics and detector requirements:

- 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 $|\eta| < 2.5$)

NLO QCD corrections to Higgs production in VBF

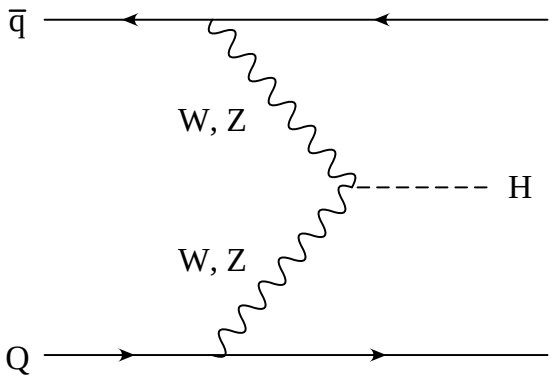
To extract Higgs-boson coupling constants with full experimental precision, a theoretical prediction of the SM production cross sections with error well below 10% is required, and this clearly entails knowledge of the next-to-leading order QCD corrections.

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.

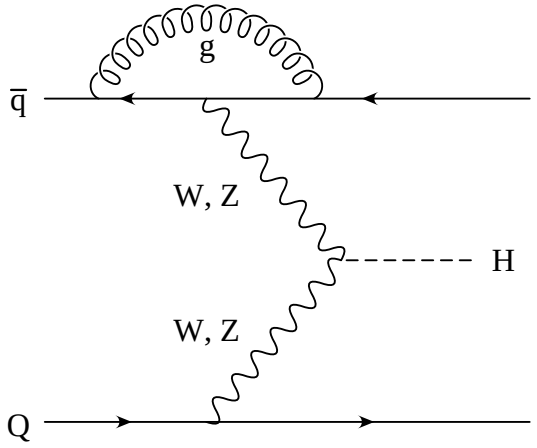
To address this question, we [Figy, C.O. and Zeppenfeld, `hep-ph/0306109`] have implemented the QCD corrections to VBF in a fully flexible NLO parton-level Monte Carlo program: VBFNLO.

NLO QCD correction diagrams

Leading order diagrams

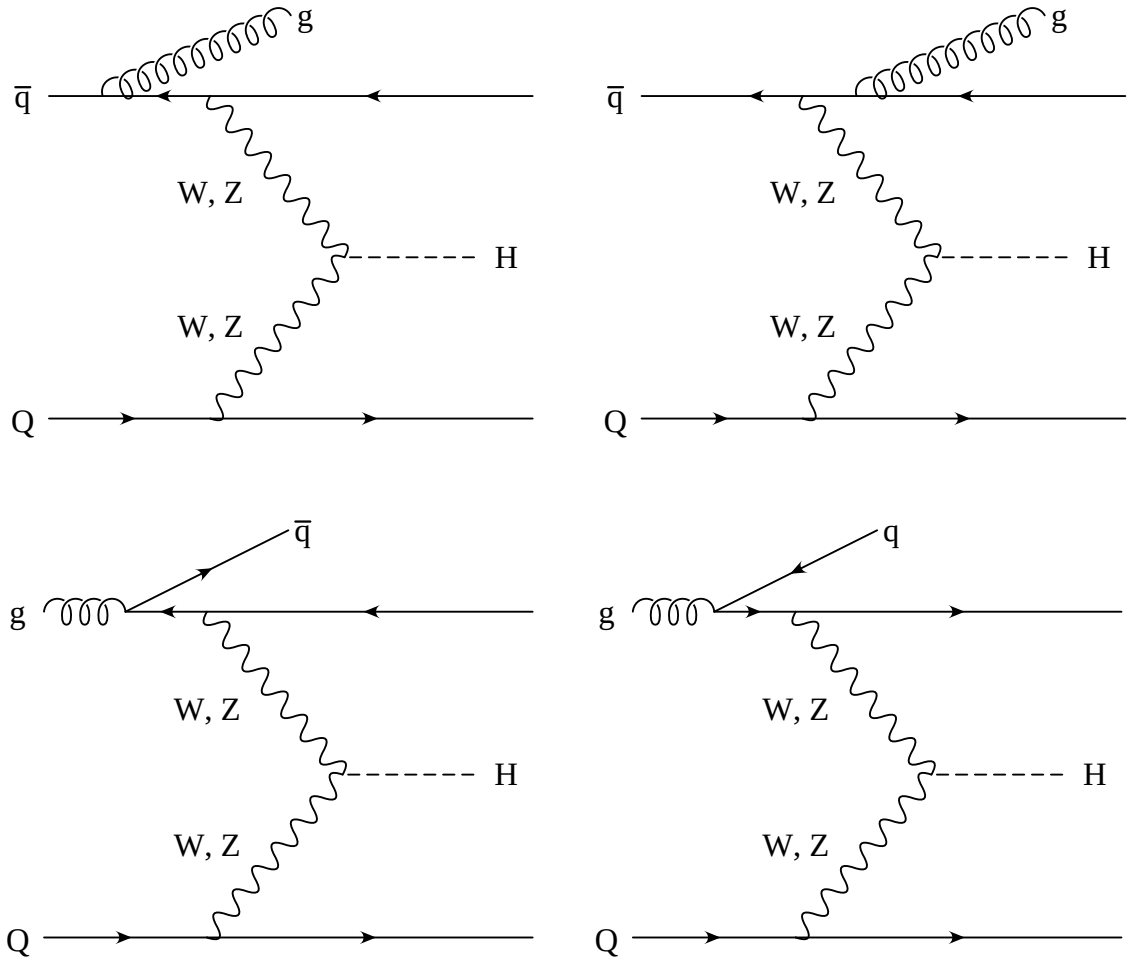


NLO: virtual diagrams



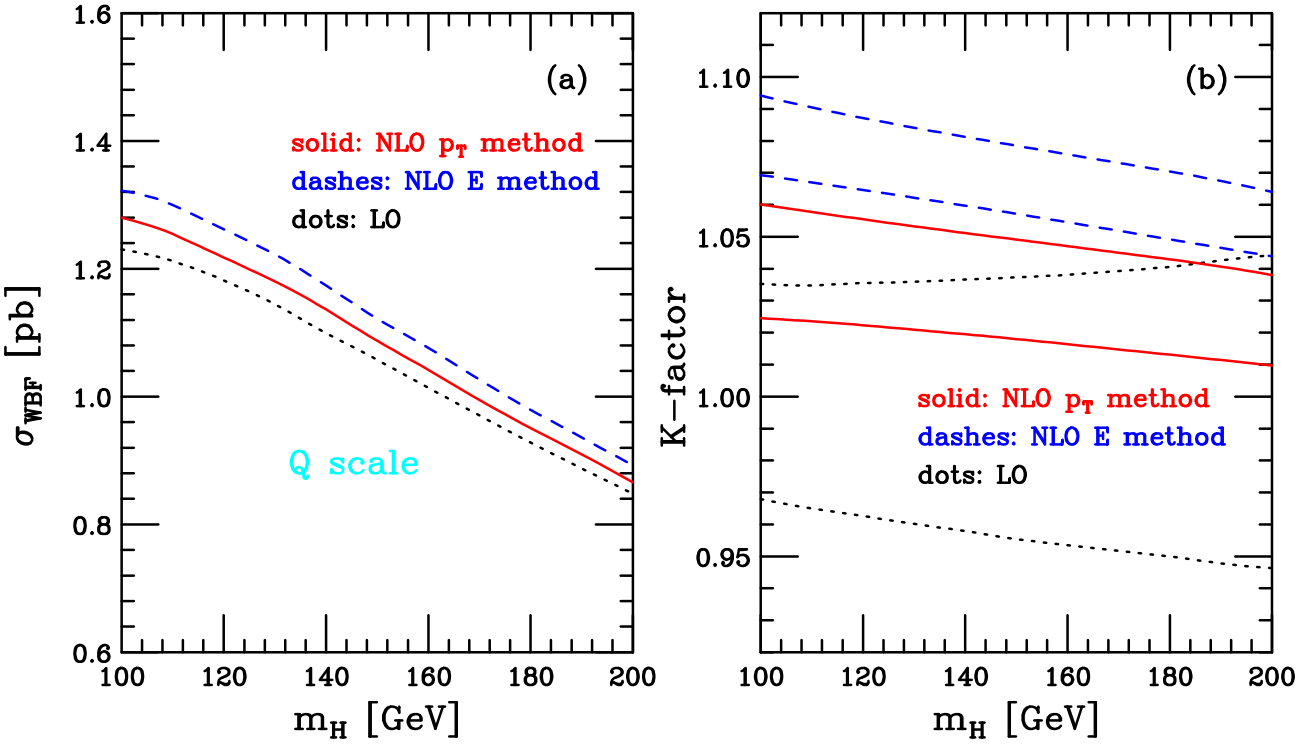
NLO QCD correction diagrams

NLO: real diagrams



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

Total cross section (LHC)



[Figy, C.O. and Zeppenfeld, hep-ph/0306109]

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

To test scale dependence we use two different scales

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

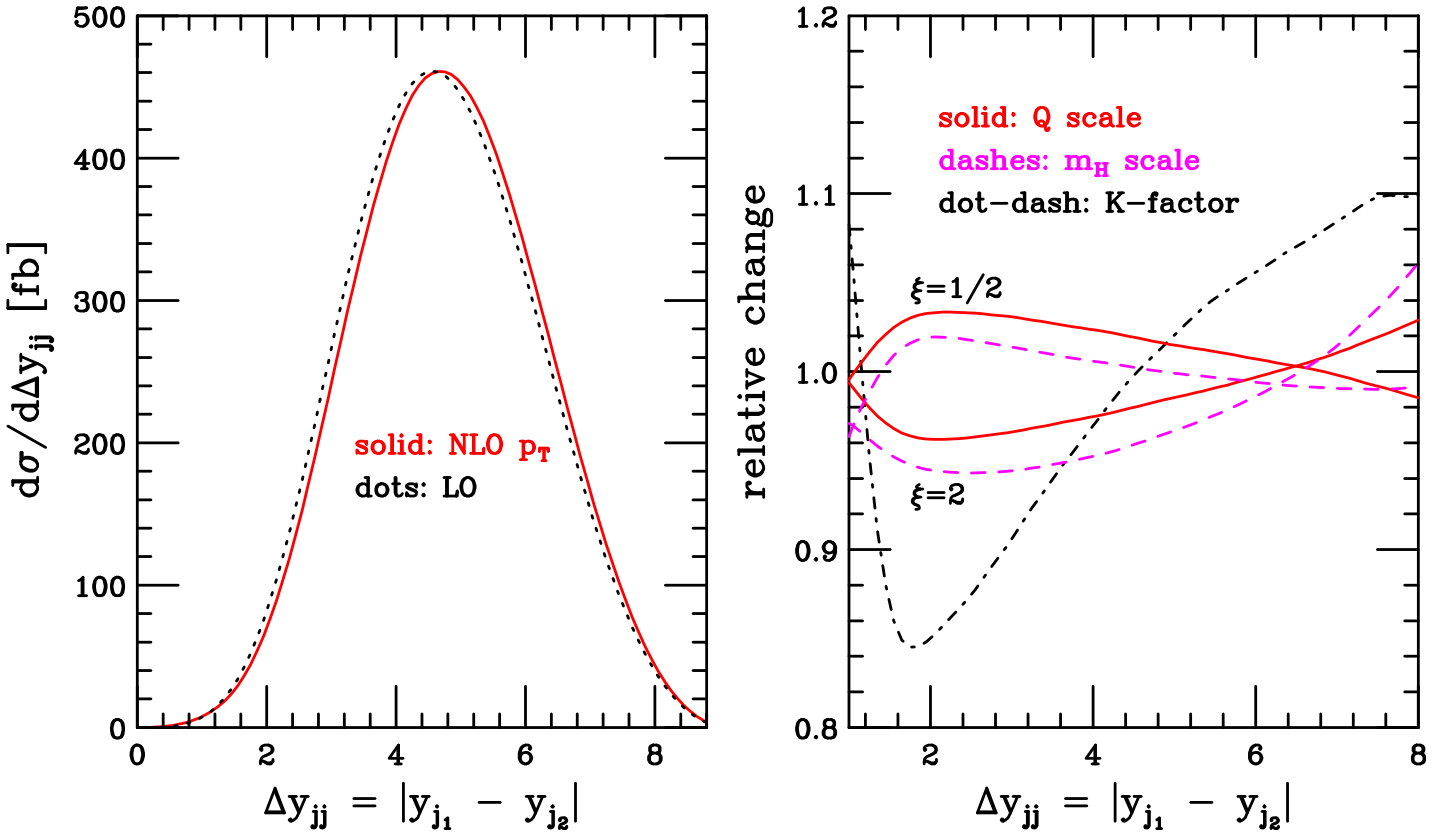
$$\mu_{Fi} = \xi_F Q_i \qquad \mu_{Ri} = \xi_R Q_i$$

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

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

A uniform $\pm 3.5\%$ PDF uncertainty of the total cross section over the entire range of m_H.

Does the rapidity gap survive?



Tagging jets are slightly more forward at NLO than at LO

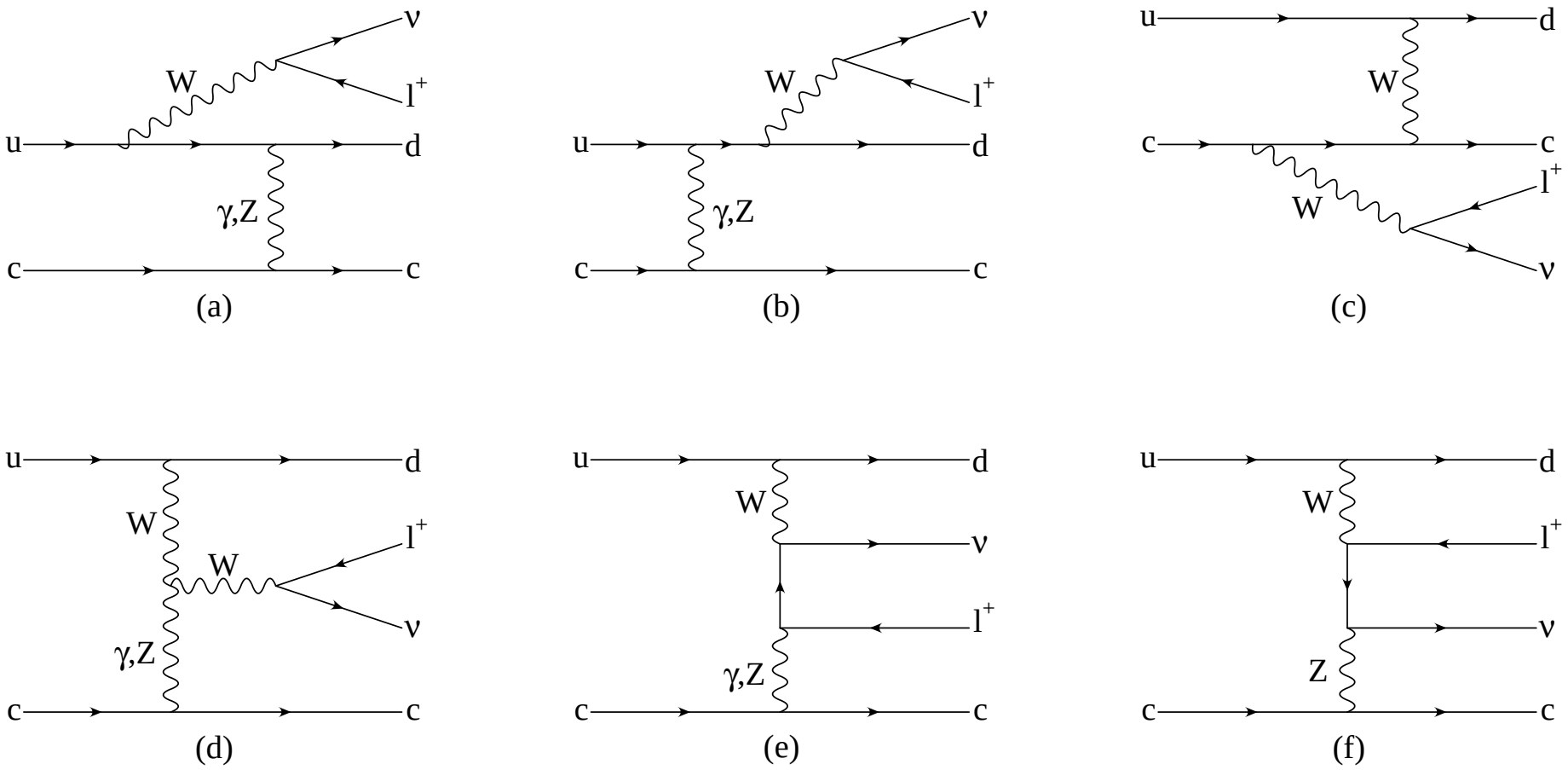
NLO QCD corrections to W and Z production via VBF

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
  - Higgs to the lightest neutralinos or gravitinos (in some region of the parameter space of SUSY models, these branching rates are large)
  - in large extra dimensions, where the Higgs boson mixes with scalar fields arising from gravity

Leading order diagrams

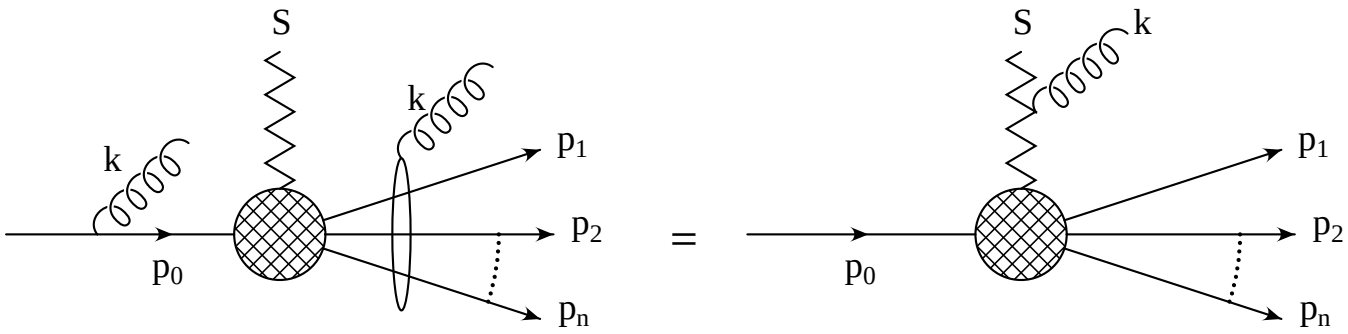


Neglect annihilation and conversion diagrams (where both the two bosons are time-like): very suppressed by VBF cuts.

Why compute NLO QCD corrections?

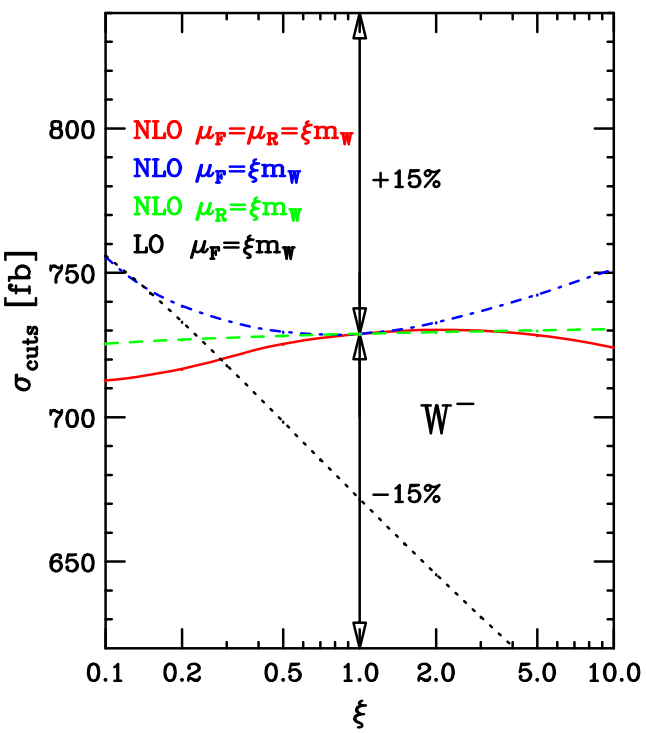
To exploit W and Z production via VBF as calibration processes for Higgs boson production

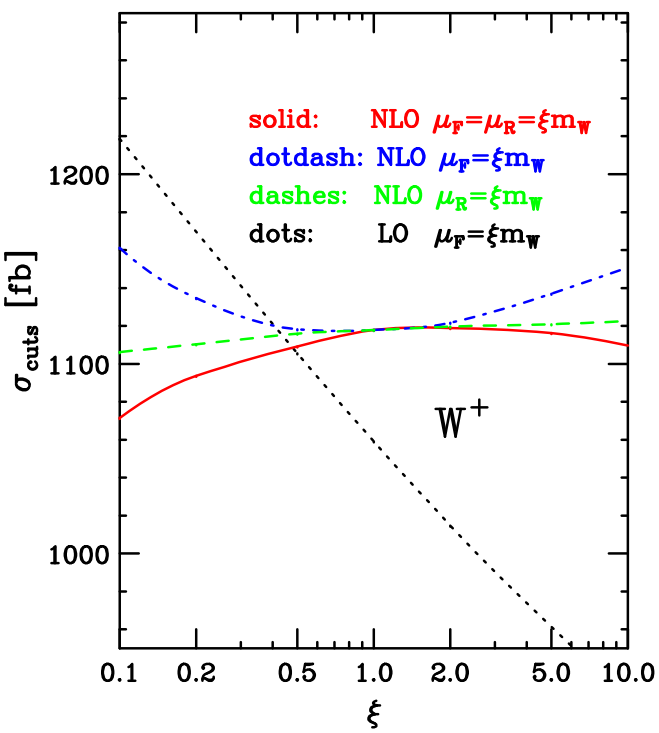
- as a tool to understand the tagging of forward jets
- to investigate veto of additional central jets in VBF: no extra jets with $p_T > 20$ GeV and $|\eta| < 2.5$

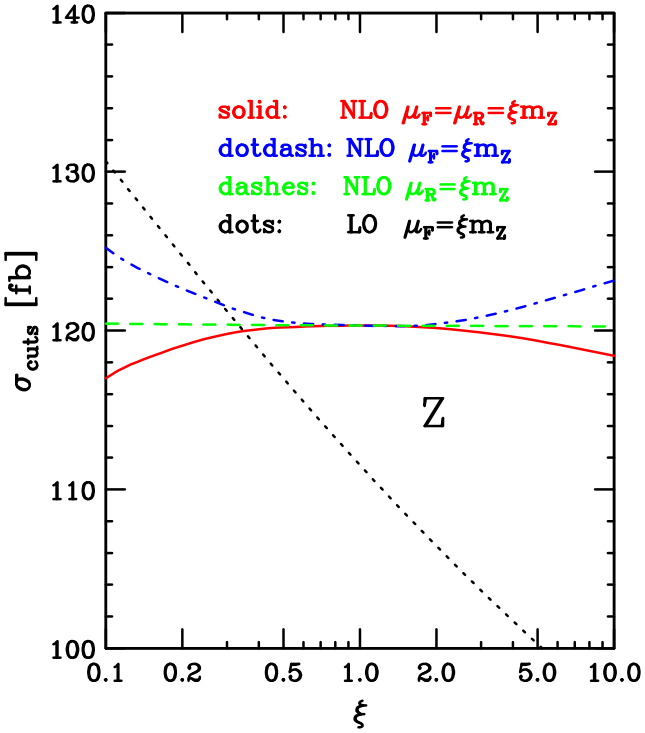


Color coherence and angular ordering

Total cross sections (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.

[C.O. and Zeppenfeld, hep-ph/0310156]

Results

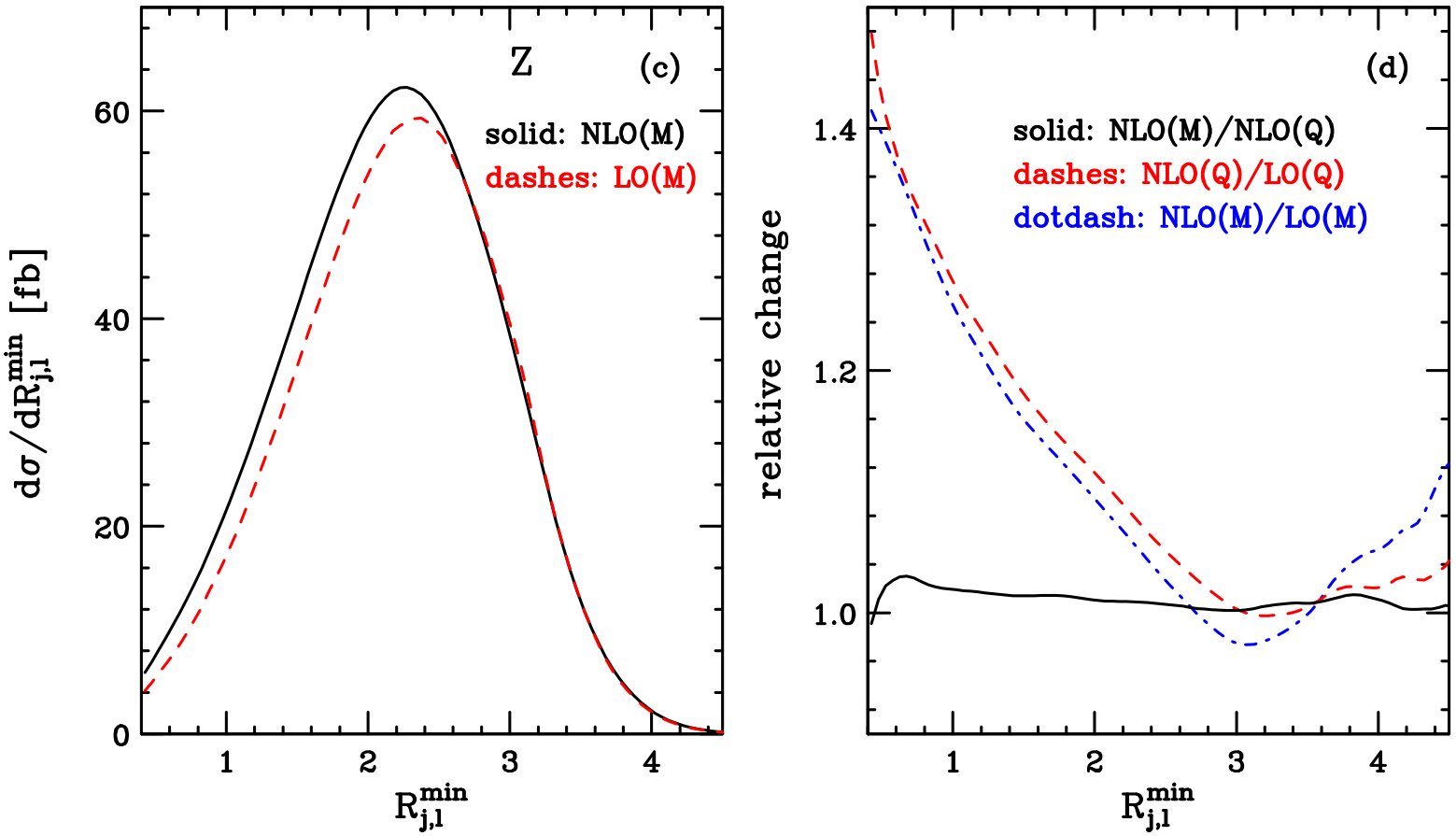
- PDF scale dependence of the total cross section within VBF cuts less than $\pm 4\%$

- 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.

Angular correlations of leptons and jets



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

Additional parton emission at NLO reduces lepton isolation.

NLO QCD corrections to W^+W^- and ZZ production via VBF

An important irreducible background to Higgs searches at the LHC, in particular to the search for $H \to VV$ ($V = W, Z$) decays in VBF, is caused by continuum VV production, or more precisely, by

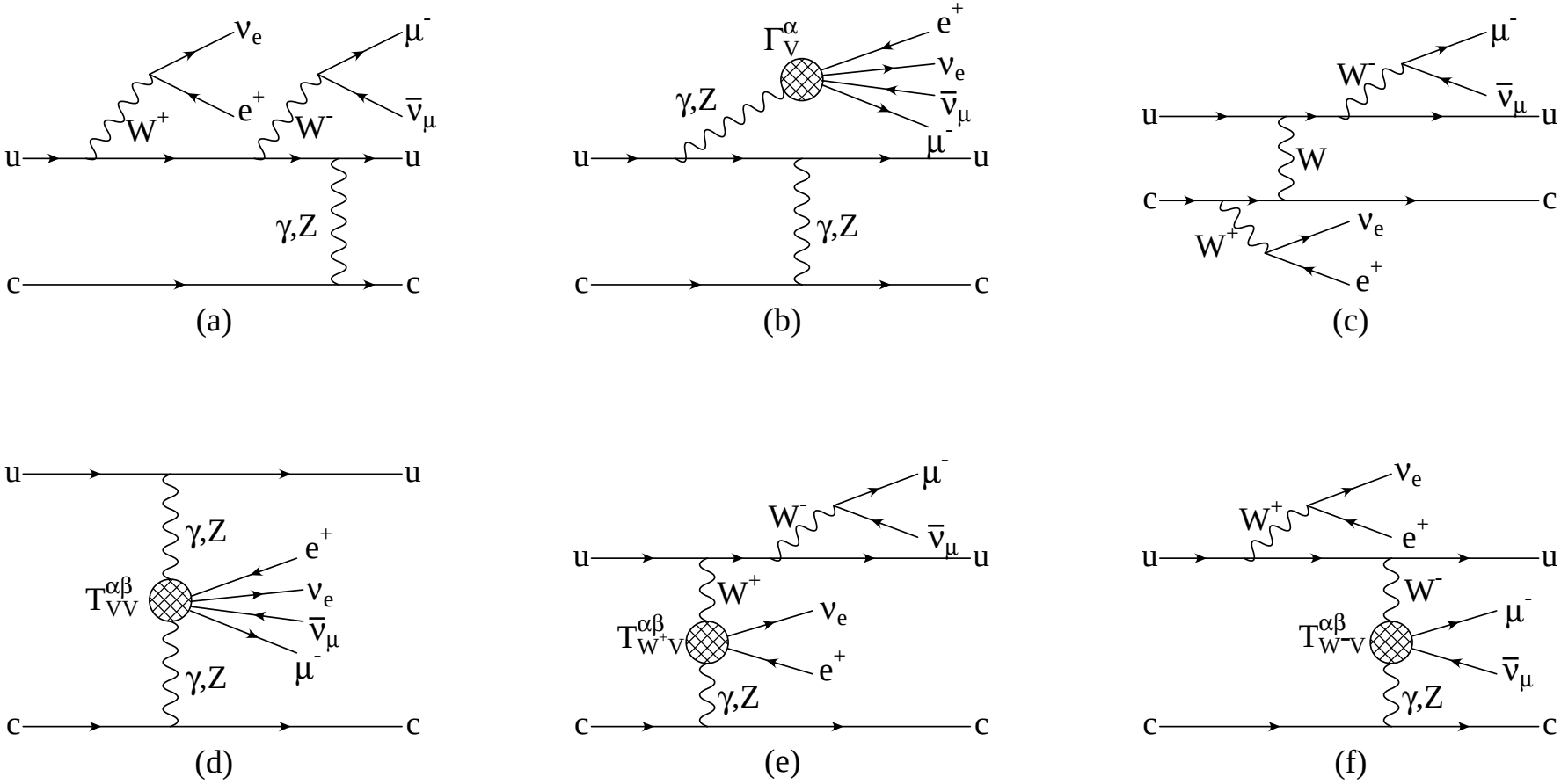
$$pp \to e^+\nu_e\,\mu^-\bar{\nu}_\mu + 2\,\text{jets} \quad \text{and} \quad pp \to e^+e^-\mu^+\mu^- + 2\,\text{jets} \quad \text{or} \quad pp \to e^+e^-\nu_\mu\bar{\nu}_\mu + 2\,\text{jets}$$

- ✗ similar tagging-jet and leptonic distributions
- ✗ suppression of gluon radiation in the central region (due to the t-channel color-singlet exchange nature of the VBF process)

Compute QCD corrections [Jäger, C.O. and Zeppenfeld, `hep-ph/0603177` and `hep-ph/0604200`] since:

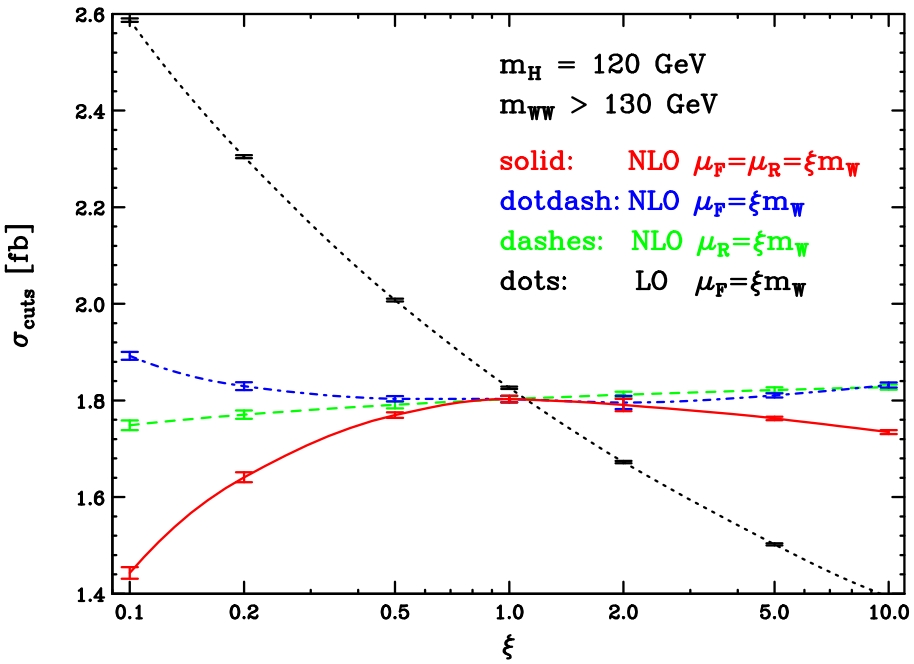
- ✓ W^+W^- contribution ranges between 15% and 3.5% of the Higgs signal, for Higgs boson masses between 115 and 160 GeV $\Longrightarrow$ important in the extraction of Higgs boson couplings
- ✓ one can use weak-boson scattering processes $VV \to V'V'$, and more precisely the absence of strong enhancements in these cross sections, as a probe for the existence of a light Higgs boson.

Leading order diagrams



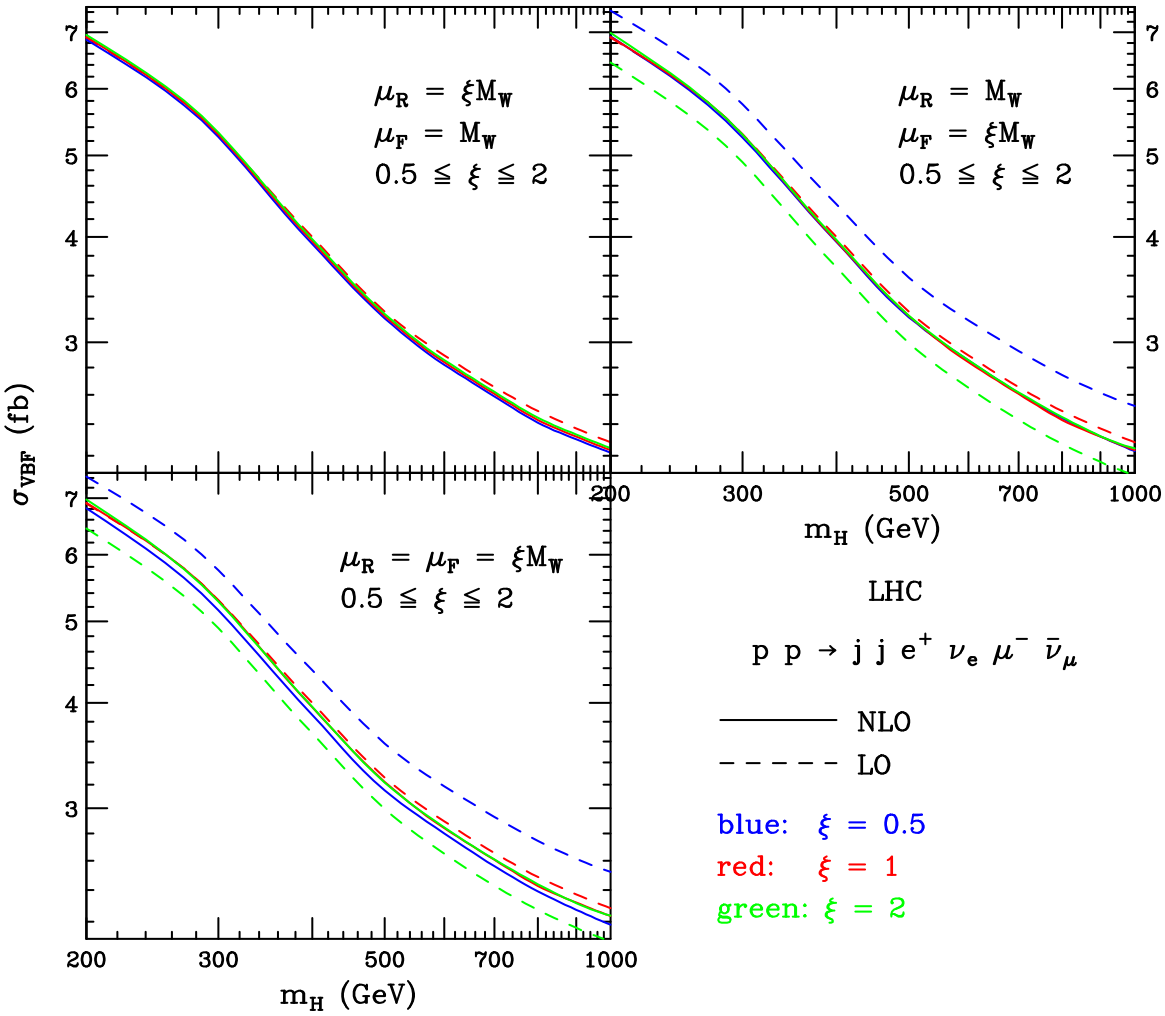
Neglect annihilation and conversion diagrams (where all the three bosons are time-like): very suppressed by VBF cuts.

Total cross section (LHC)

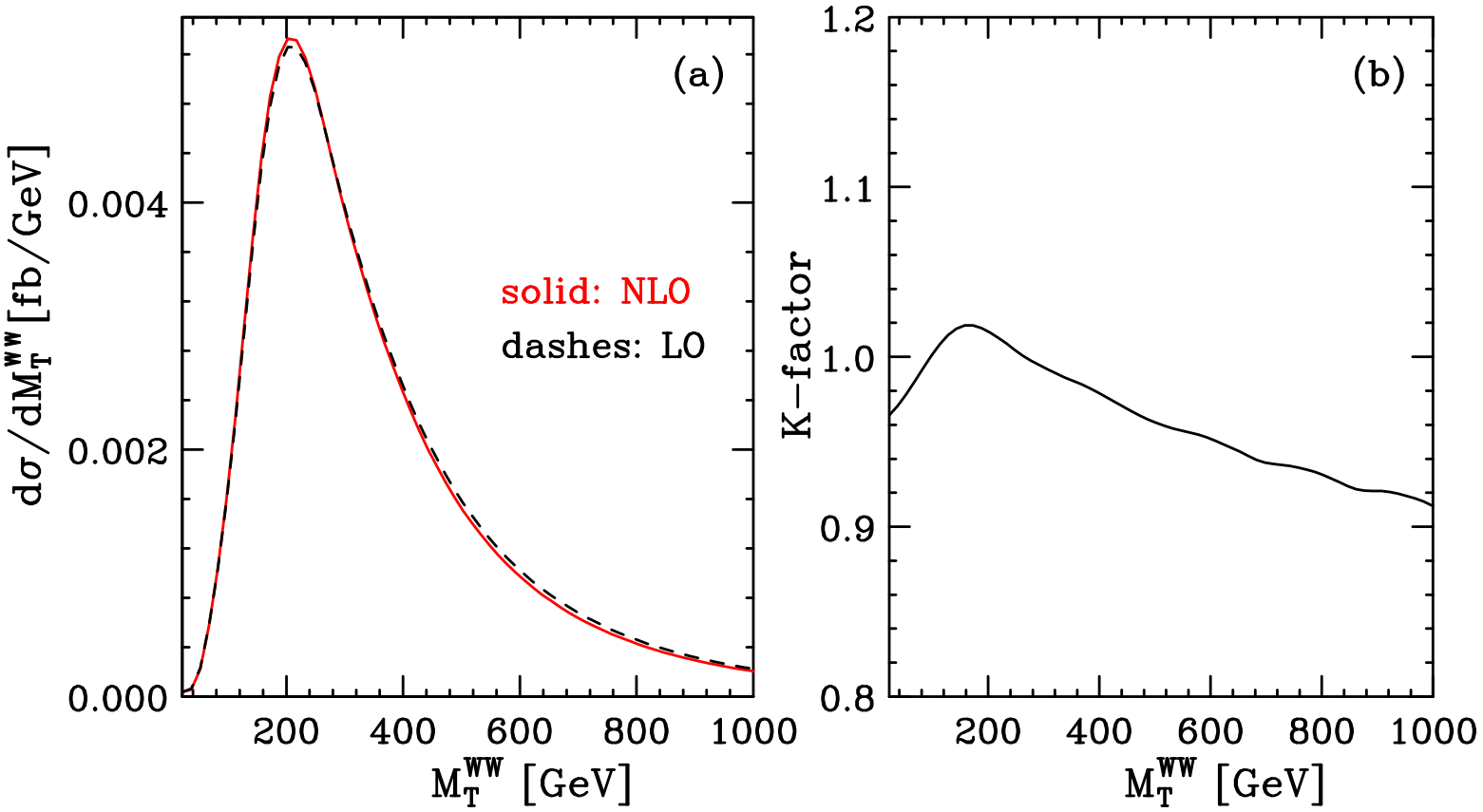


Scale variation less than 2%

$$m_{WW} = \sqrt{(p_e + p_\mu + p_{\nu_e} + p_{\nu_\mu})^2}$$

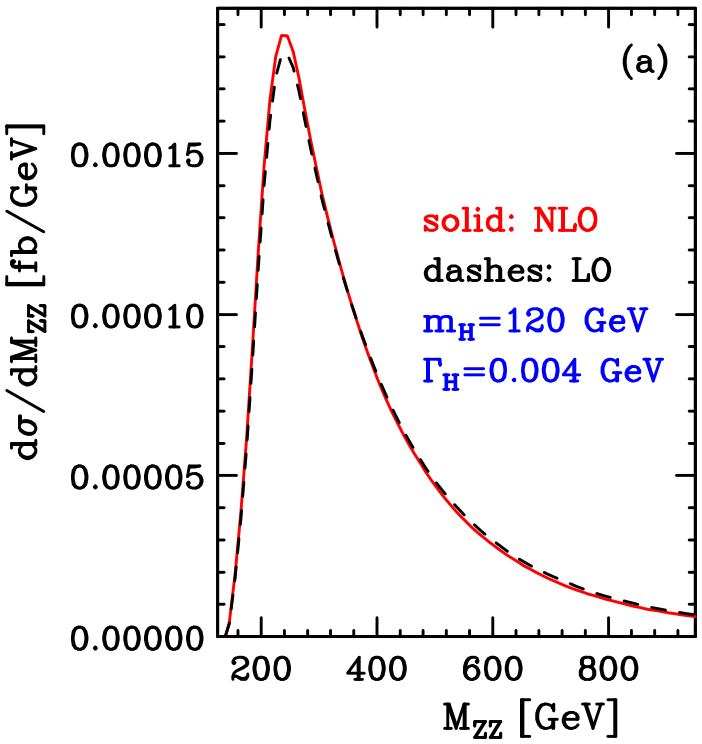


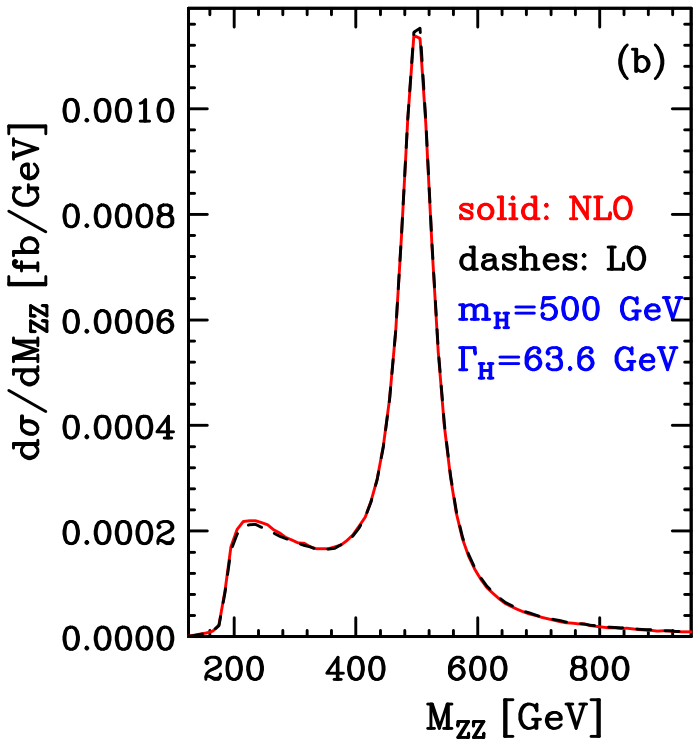
Transverse mass distribution for $e^+\nu_e\,\mu^-\bar{\nu}_\mu$



$$M_T^{WW} = \sqrt{(\not{E}_T + E_{T,ll})^2 - (\mathbf{p}_{T,ll} + \not{\mathbf{p}}_T)^2} \qquad E_{T,ll} = \sqrt{\mathbf{p}_{T,ll}^2 + m_{ll}^2} \qquad \not{E}_T = \sqrt{\not{\mathbf{p}}_T^2 + m_{\nu\nu}^2} \approx \sqrt{\not{\mathbf{p}}_T^2 + m_{ll}^2}$$

Lepton-mass distribution for $e^+e^-\,\mu^+\mu^-$





- $\mu_F = \mu_r = m_Z$
  $\mu_F = \mu_r = m_{ZZ}$
- $\sigma^{\rm LO}/\sigma^{\rm LO} = 1.8$
  $\sigma^{\rm NLO}/\sigma^{\rm NLO} = 1.13$
  at $M_{ZZ} = 1.5$ TeV

$$M_{ZZ} = \sqrt{(p_{\ell+} + p_{\ell-} + p_{\ell'+} + p_{\ell'-})^2}$$

✓ very sensitive to a light Higgs boson: pronounced resonance behavior for $m_H \lesssim 800$ GeV

✓ for $m_H \sim 1$ TeV, the peak is diluted ($\Gamma_H \approx 500$ GeV) and the signal is distributed over a wide range in M_{ZZ}

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 vector-boson fusion will be of central importance since it allows for independent observation in the $H \to \tau\tau$, $H \to WW$ and $H \to \gamma\gamma$.
- These measurements can be performed at the LHC with statistical accuracies on the measured cross sections times decay branching ratios, $\sigma \times B$, 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/Z and WW/ZZ production in VBF processes, are in general small, but distributions at LO and NLO have different shapes!
- Jet veto and forward-jet tagging still need more investigation.