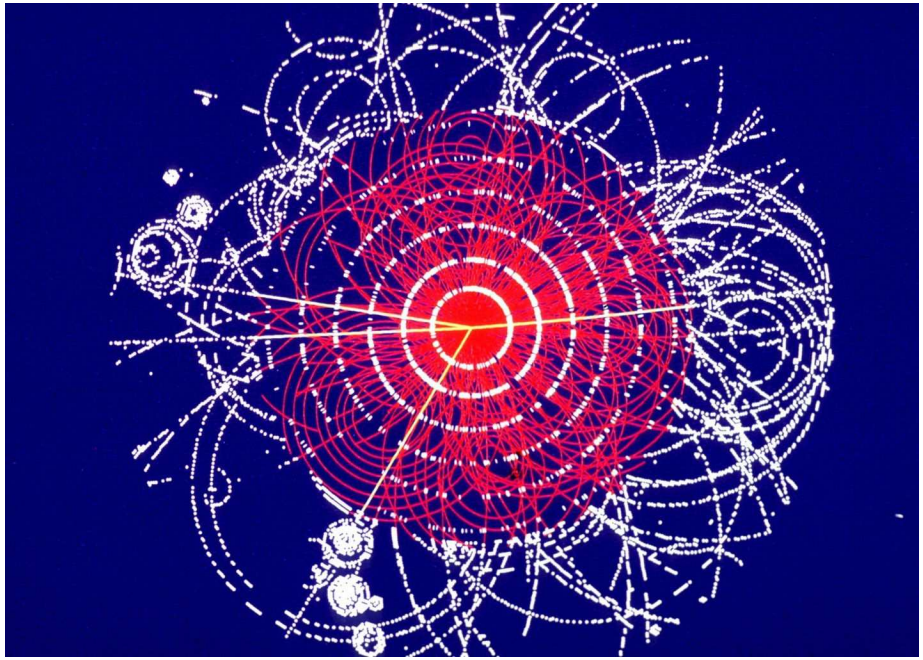
QCD corrections to Higgs and vector bosons production

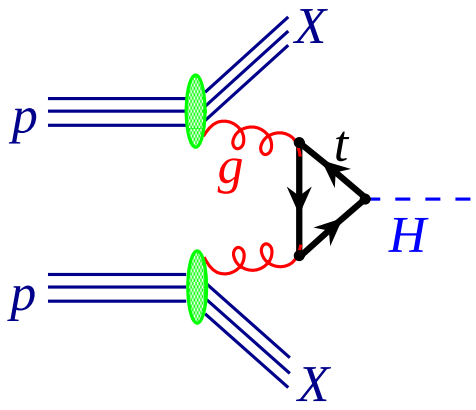
Carlo Oleari
Università di Milano-Bicocca, Milan

DIS2006, Tzukuba
21 April 2006

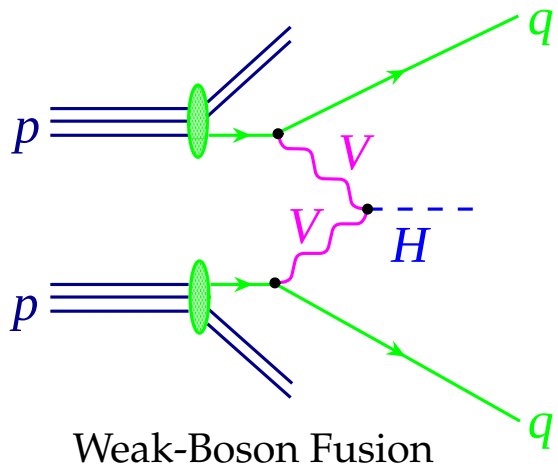
- Higgs production
- QCD corrections to vector-boson-fusion (VBF) production of
  - Higgs boson
  - W/Z
  - WW/ZZ
- Conclusions



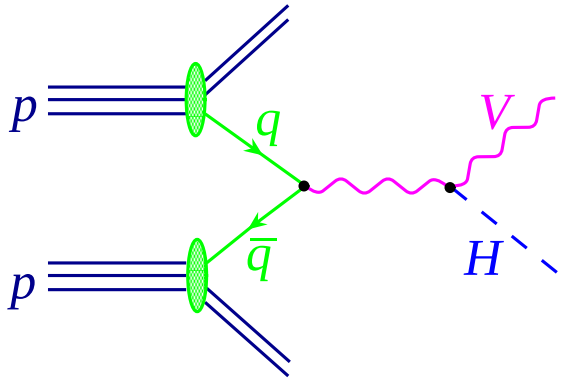
Production Modes



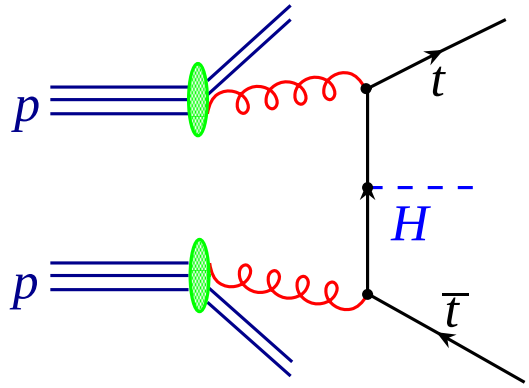
Gluon fusion



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

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

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

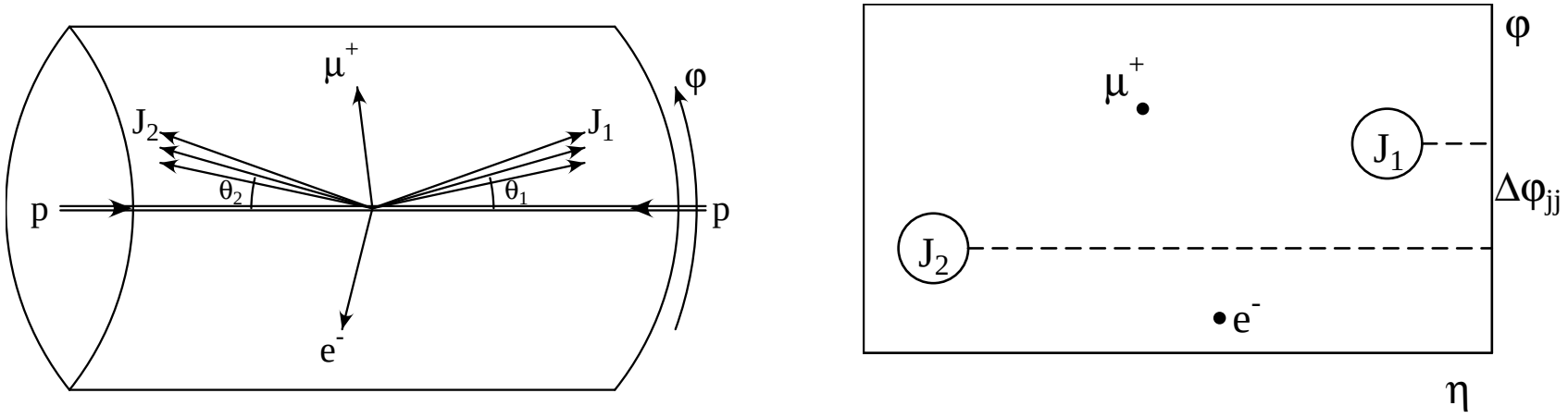
After spontaneous symmetry breaking $\Phi(x) \to \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + H(x) \end{pmatrix}$

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

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

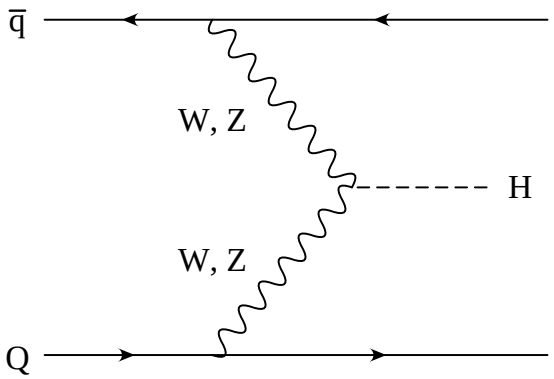
To extract Higgs-boson coupling constants with full experimental precision, a theoretical prediction of the SM production cross sections with error well below 10% is required, and this clearly entails knowledge of the next-to-leading order QCD corrections.

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.

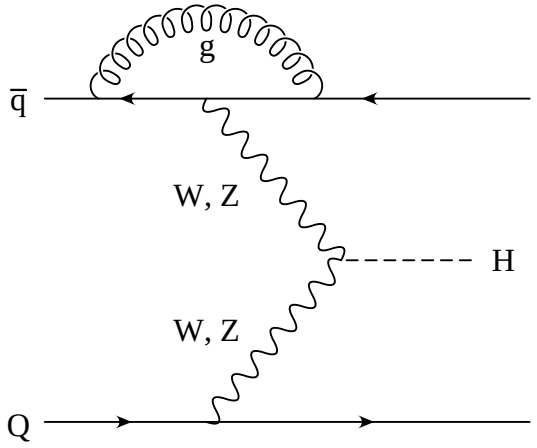
To address this question, we have implemented the QCD corrections to VBF in a fully flexible NLO parton-level Monte Carlo program: VBFNLO.

NLO QCD correction diagrams

Leading order diagrams

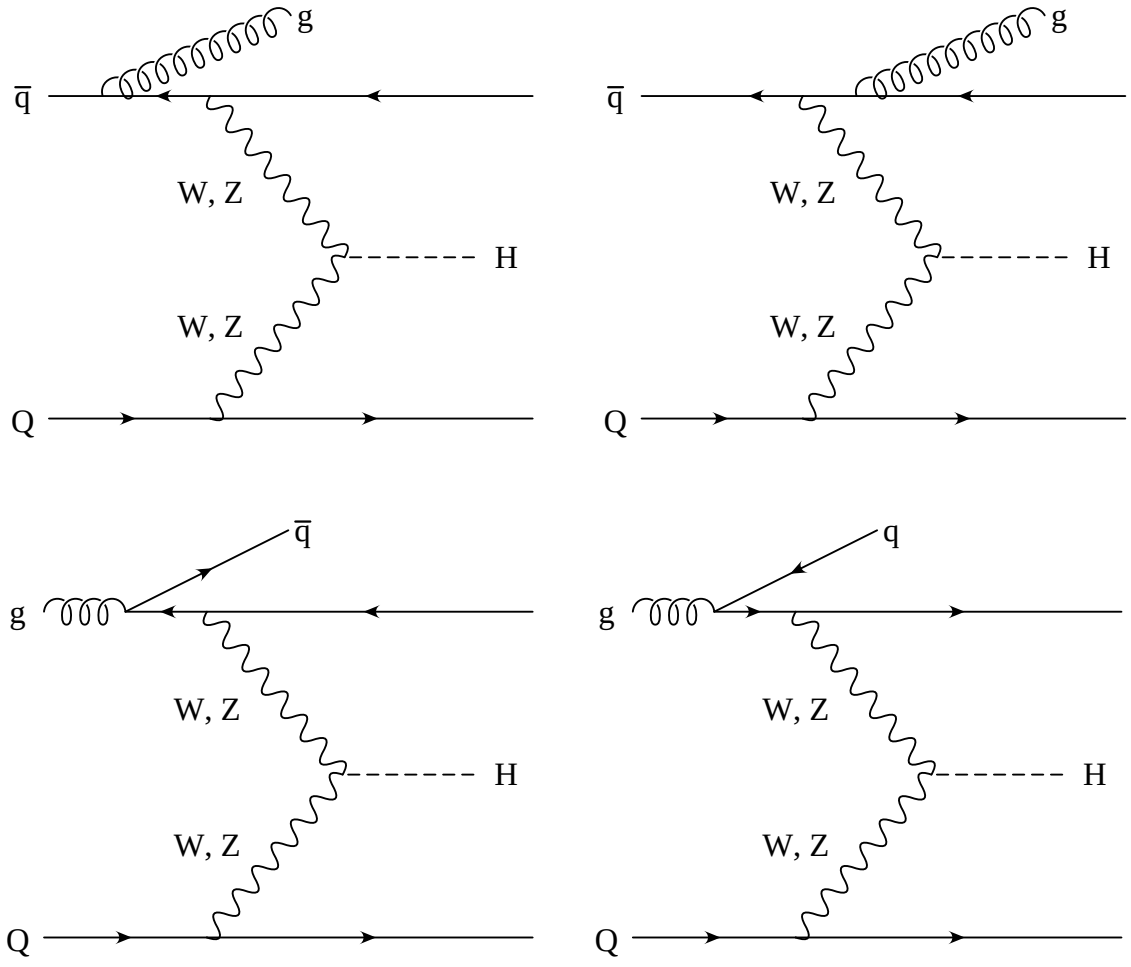


NLO: virtual diagrams



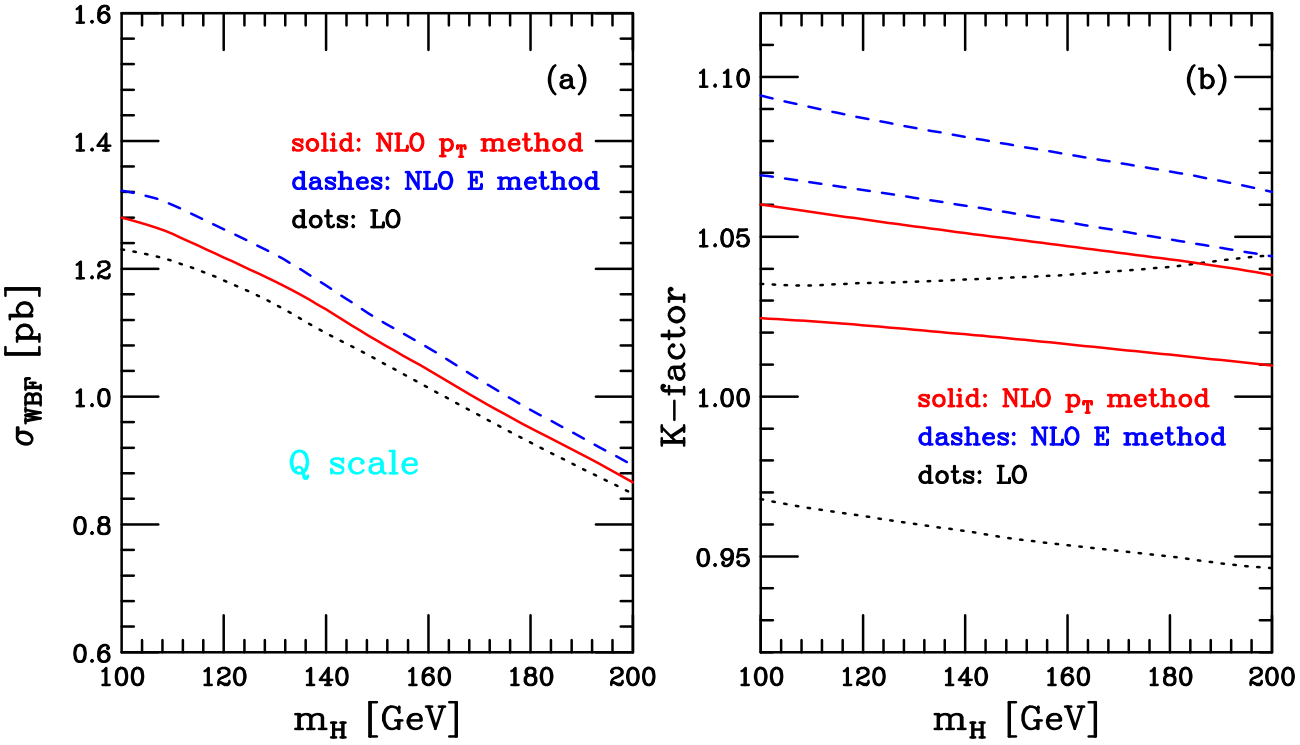
NLO QCD correction diagrams

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]

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

To test scale dependence we use two different scales

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

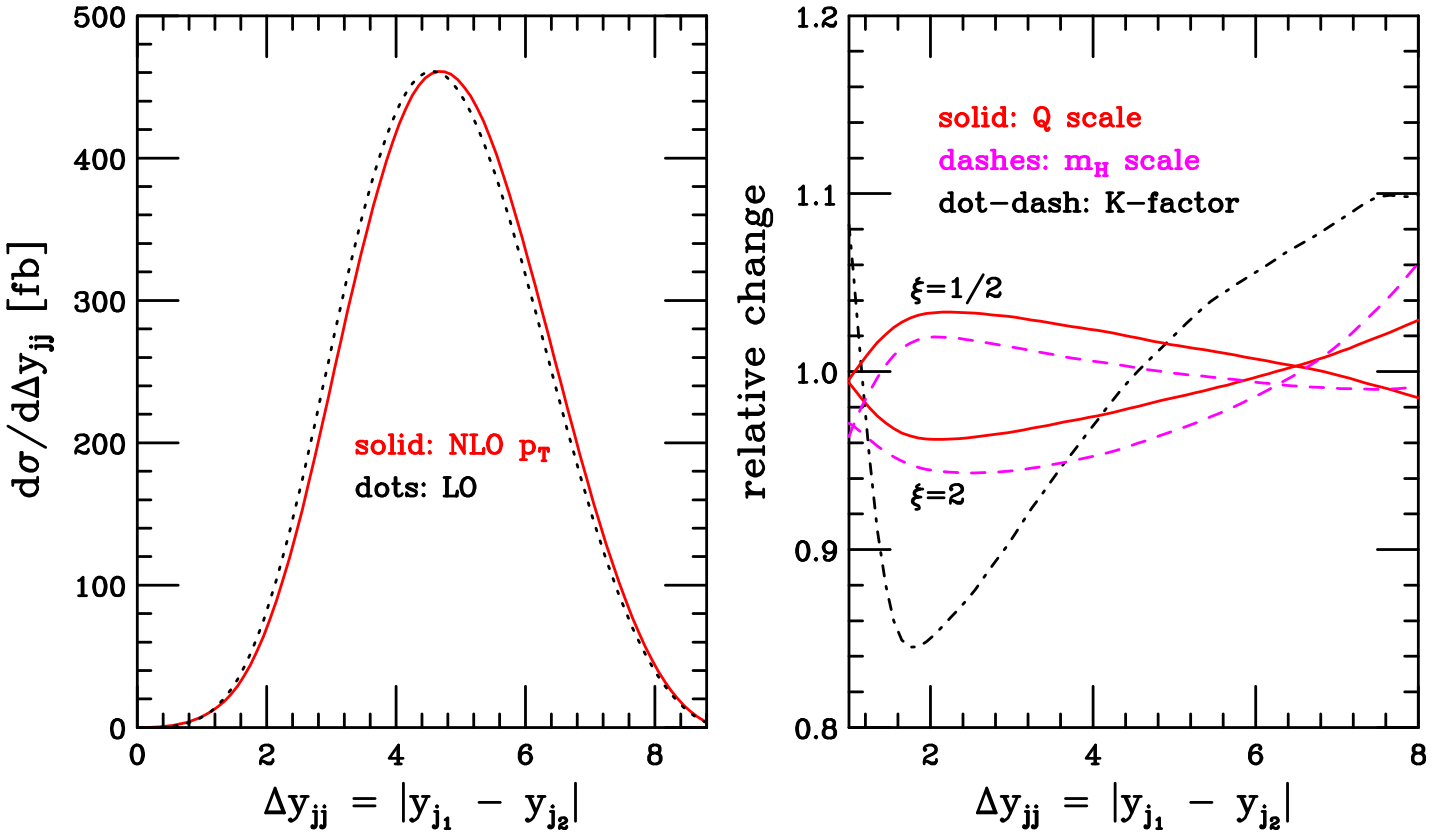
$$\mu_{Fi} = \xi_F Q_i \qquad \mu_{Ri} = \xi_R Q_i$$

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

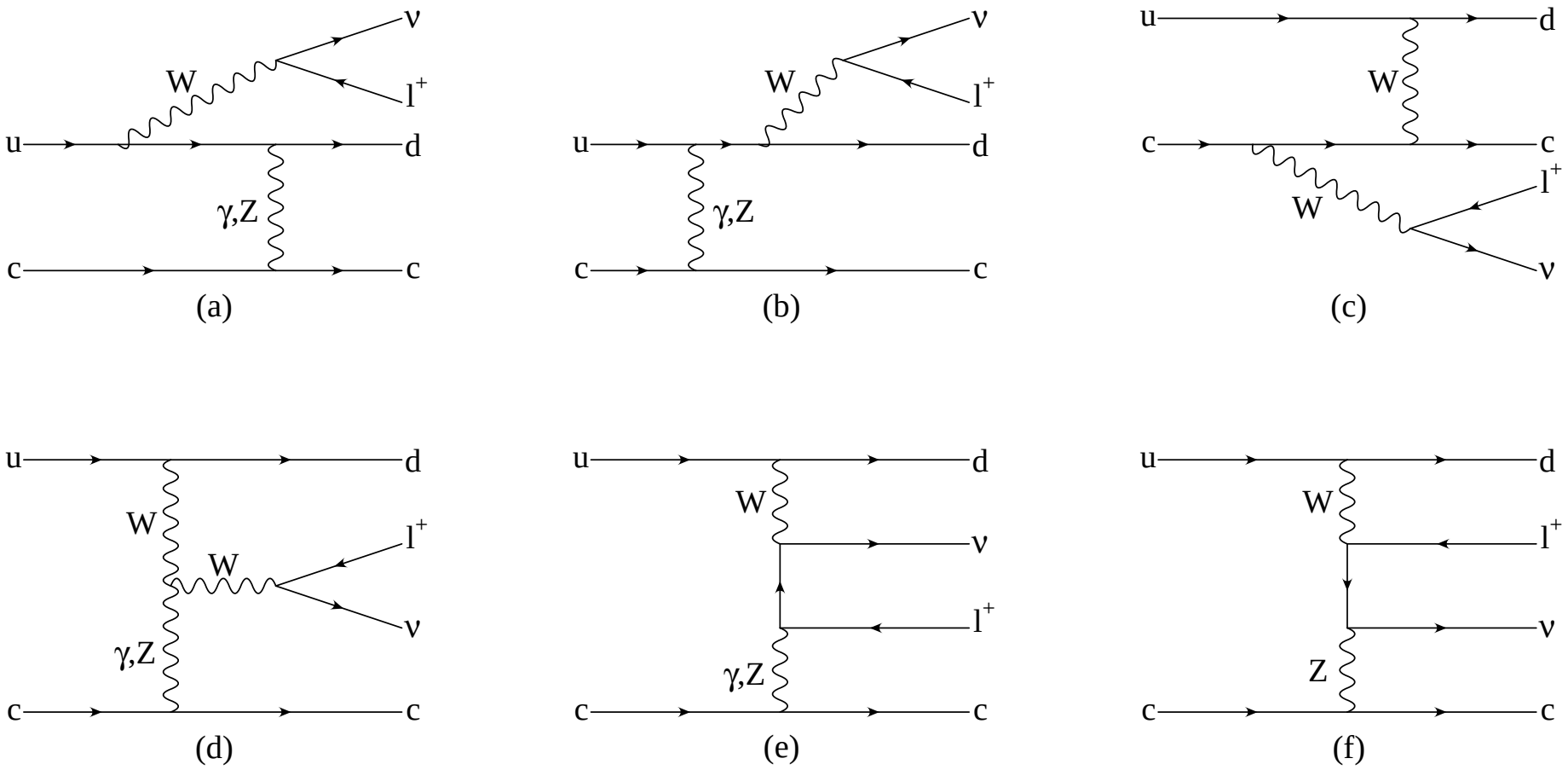
NLO QCD corrections to W and Z production via VBF

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

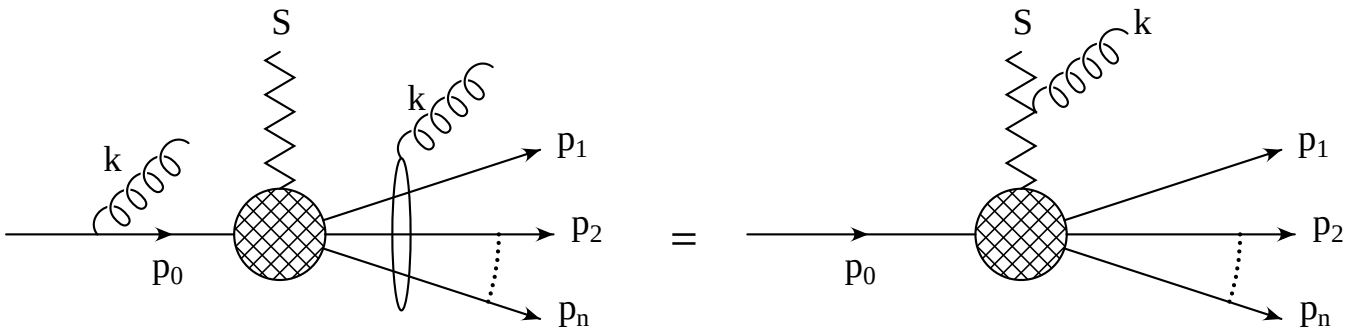


Neglect annihilation and conversion diagrams (where both the two bosons are time-like): very suppressed by VBF cuts.

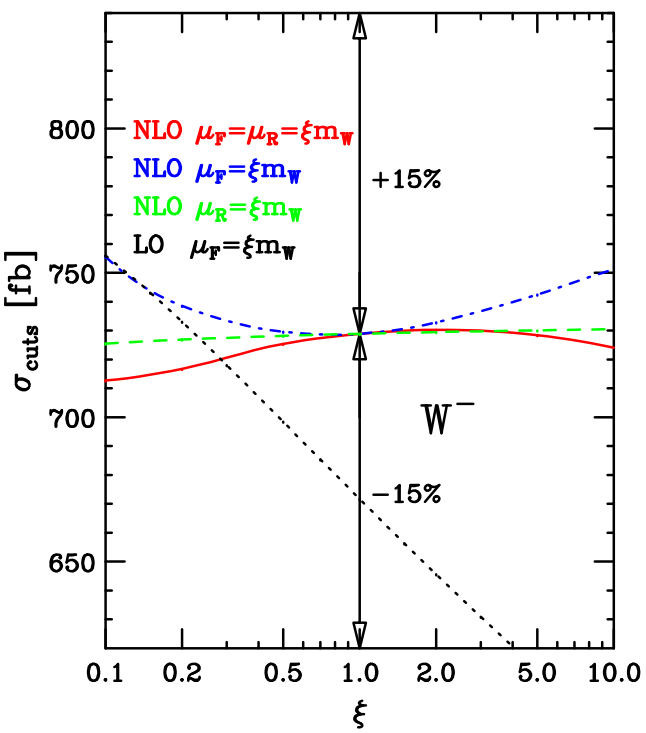
Why compute NLO QCD corrections?

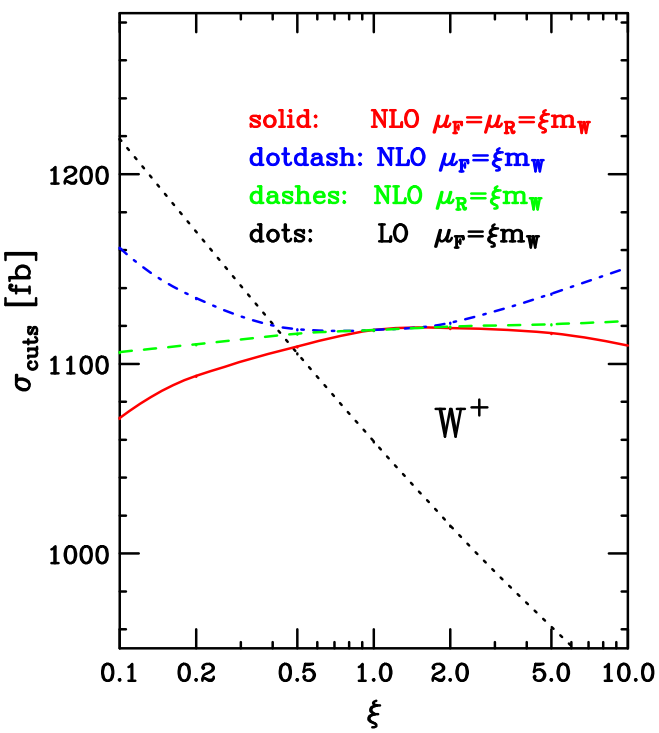
To exploit W and Z production via VBF as calibration processes for Higgs boson production

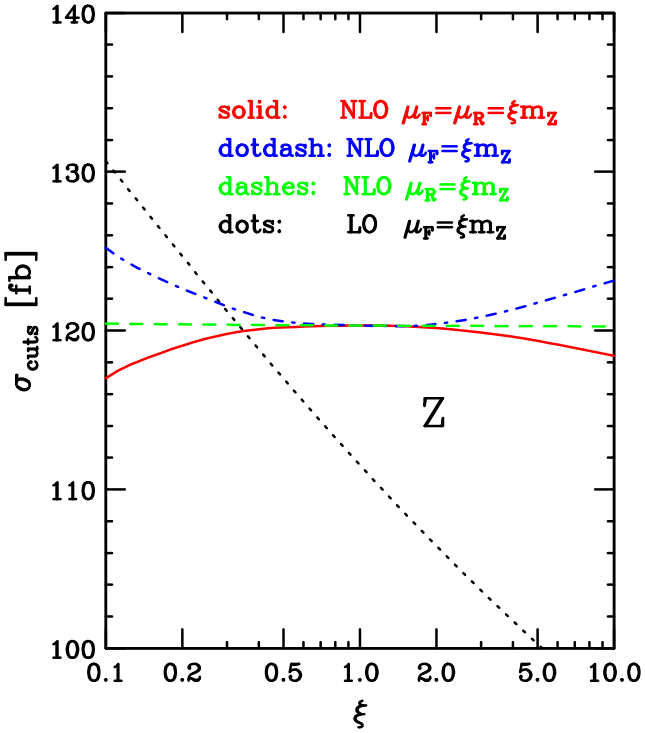
- as a tool to understand the tagging of forward jets
- to investigate veto of additional central jets in VBF: no extra jets with $p_T > 20$ GeV and $|\eta| < 2.5$



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]

Results

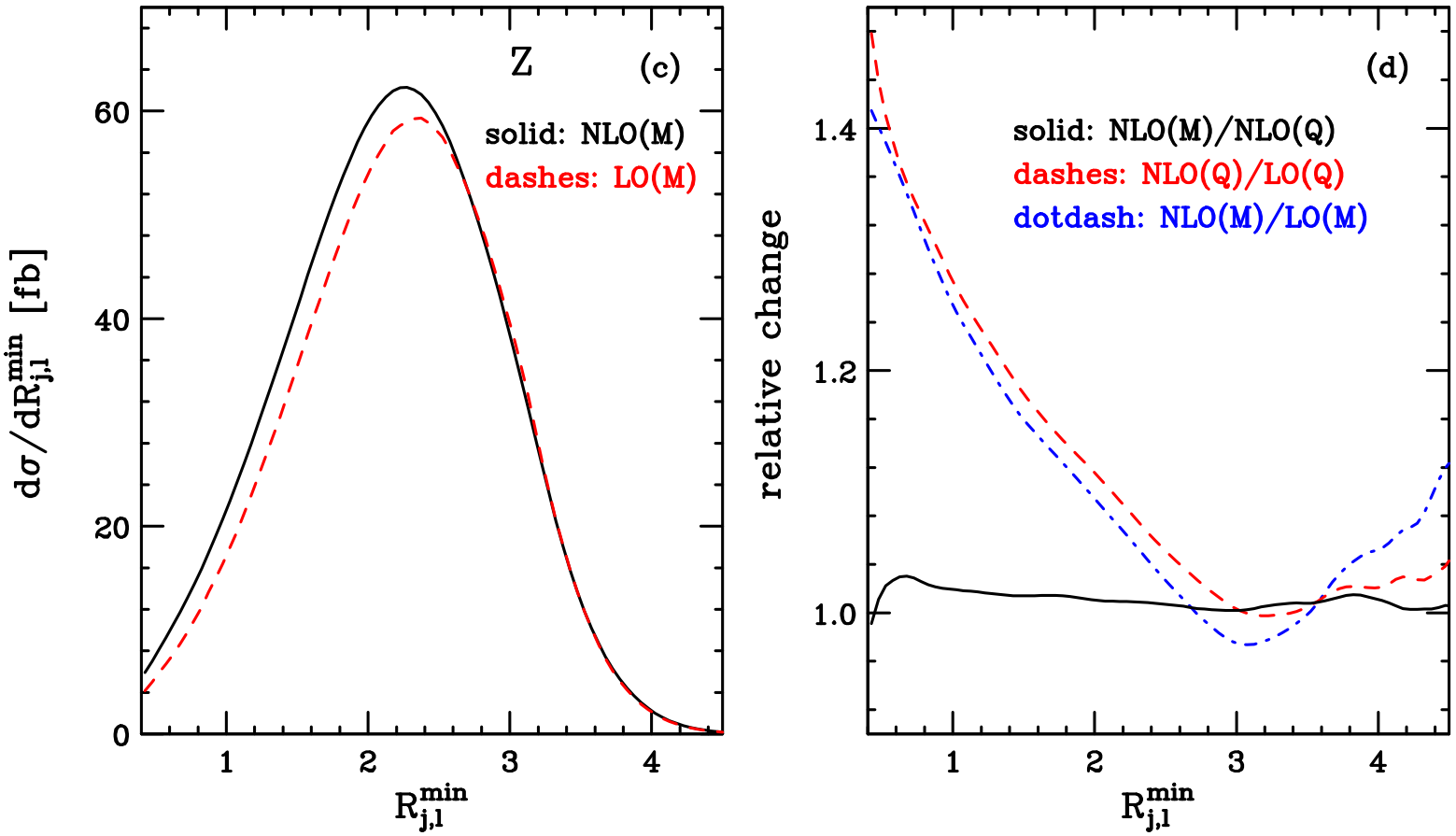
- PDF scale dependence of the total cross section within VBF cuts less than $\pm 4\%$

- 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

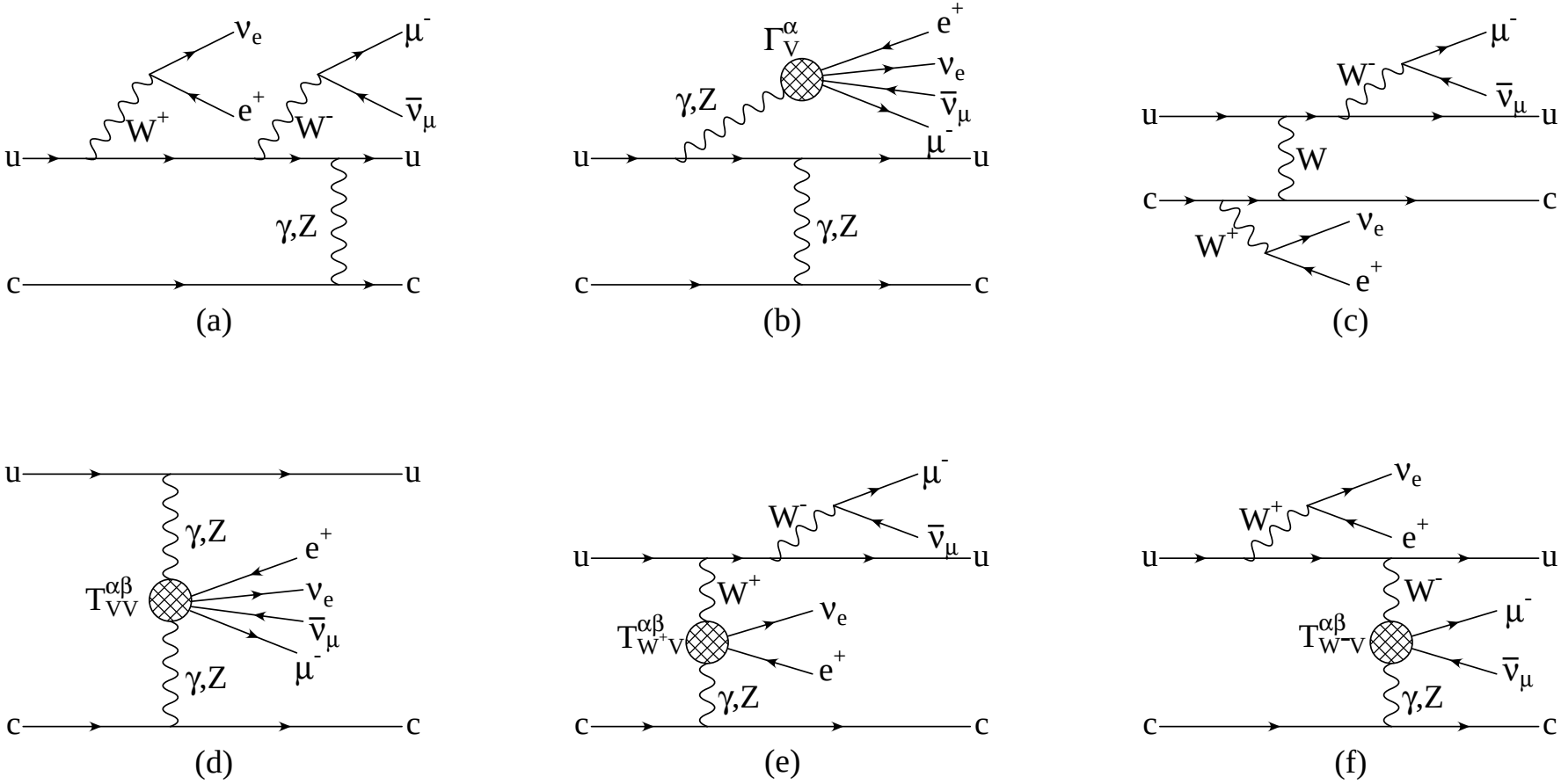
$pp \to e^+\nu_e\,\mu^-\bar{\nu}_\mu + 2\,\text{jets}$ and $pp \to e^+e^-\mu^+\mu^- + 2\,\text{jets}$ or $pp \to e^+e^-\nu_\mu\bar{\nu}_\mu + 2\,\text{jets}$

- ✗ 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] since:

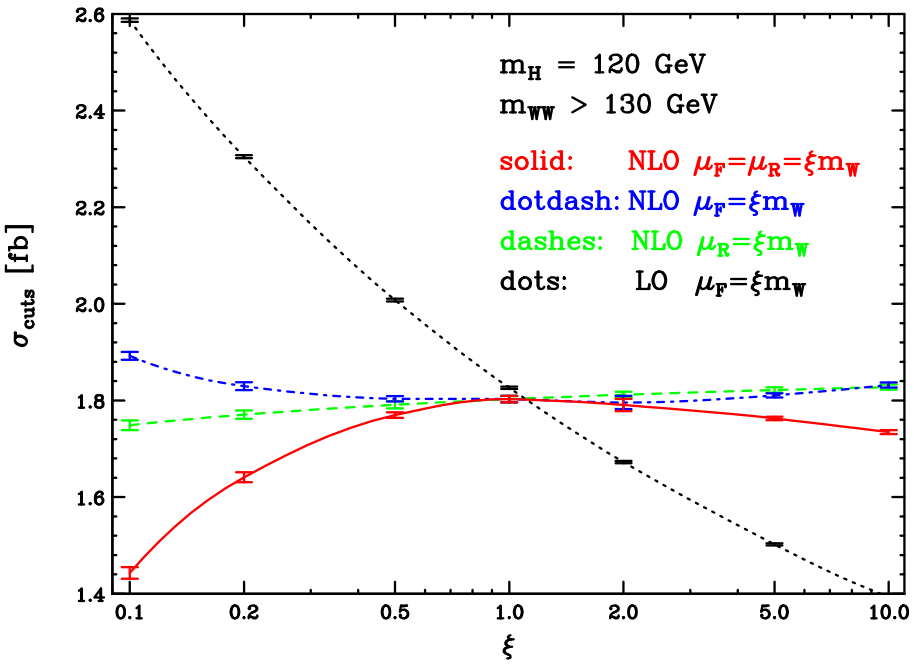
- ✓ W^+W^- contribution ranges between 15% and 3.5% of the Higgs signal, for Higgs boson masses between 115 and 160 GeV $\Longrightarrow$ important in the extraction of Higgs boson couplings
- ✓ one can use weak-boson scattering processes $VV \to V'V'$, and more precisely the absence of strong enhancements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

Leading order diagrams



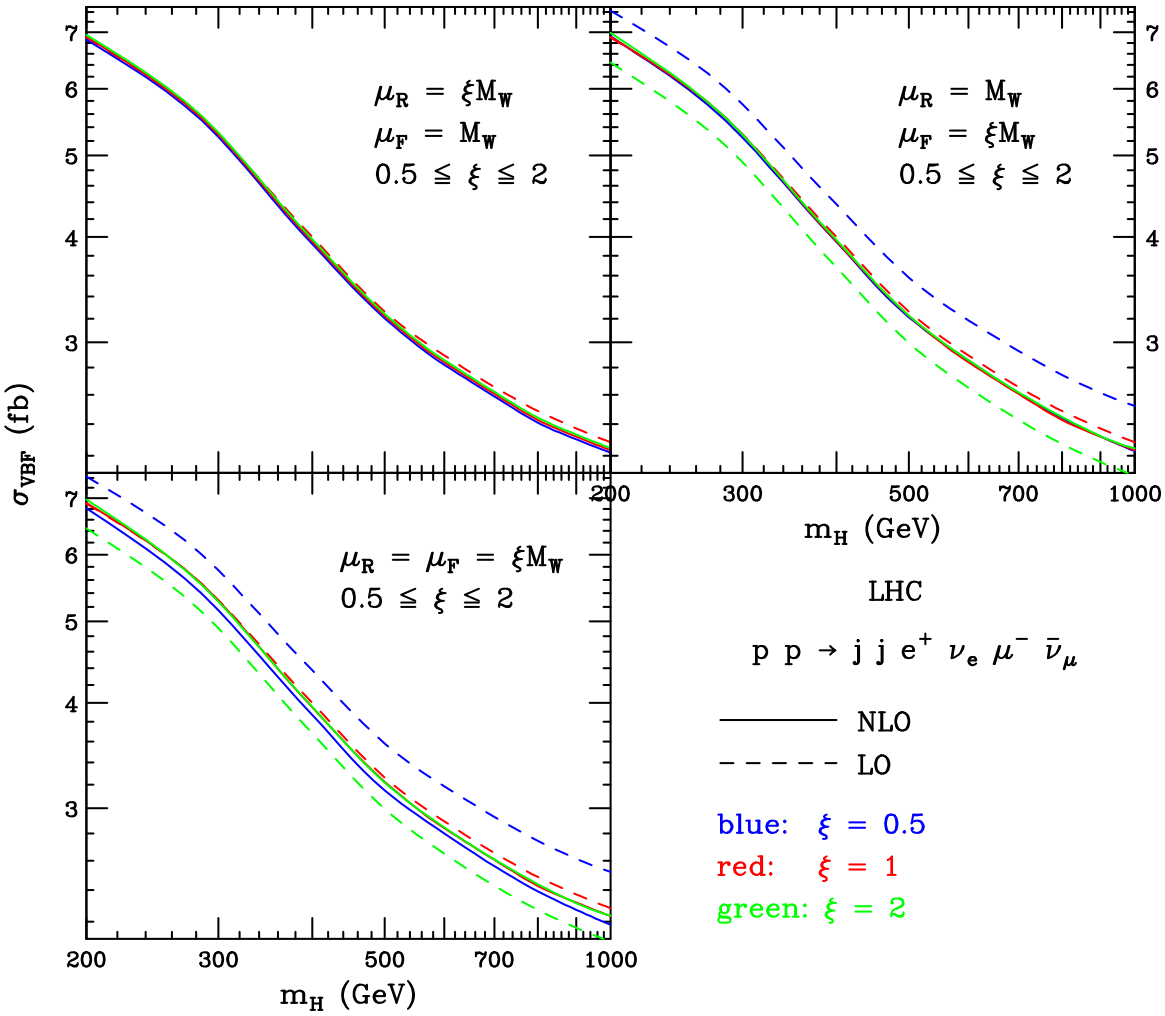
Neglect annihilation and conversion diagrams (where all the three bosons are time-like): very suppressed by VBF cuts.

Total cross section (LHC)

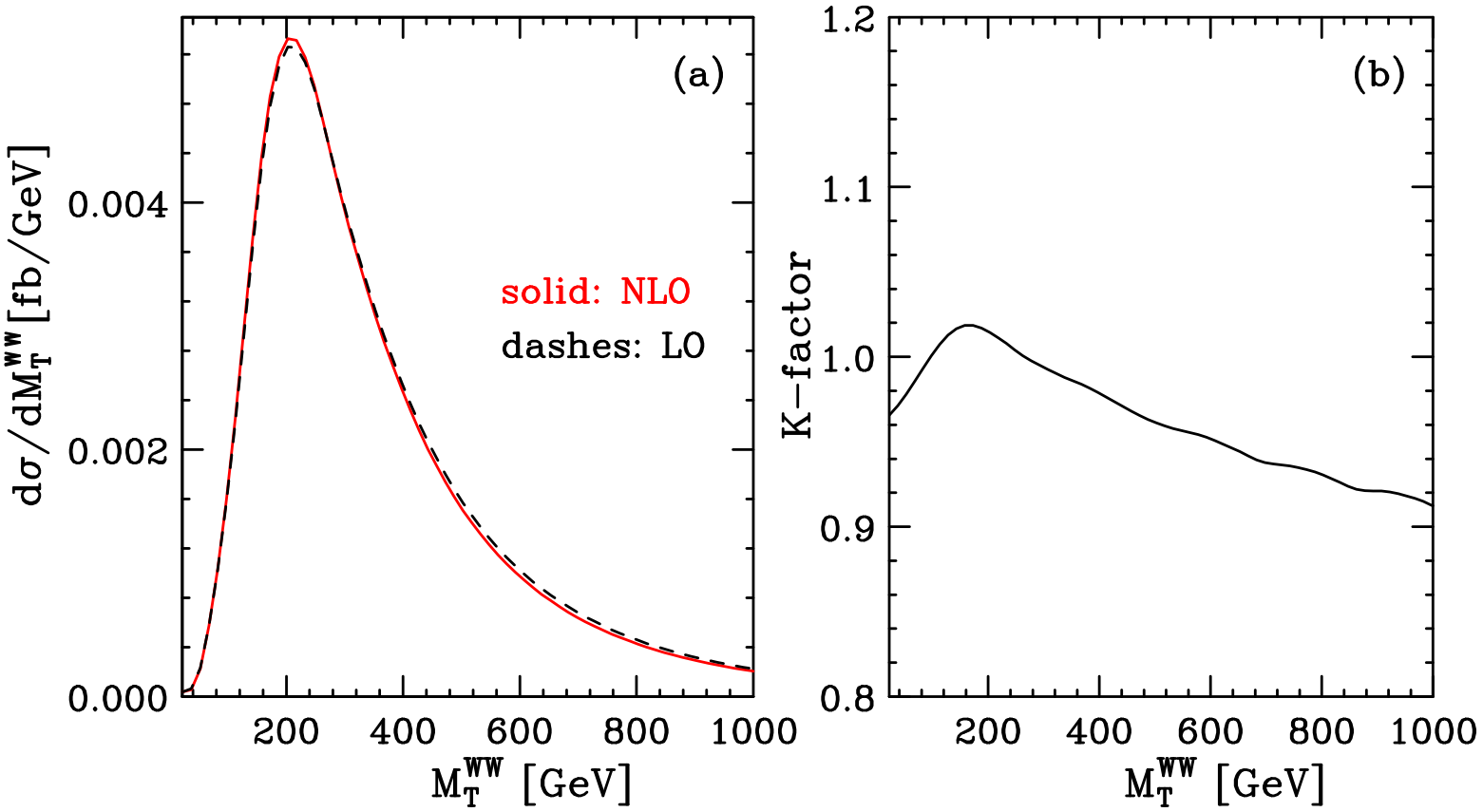


Scale variation less than 2%

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



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



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

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!
- But jet veto and forward-jet tagging still need more investigation.