NLO QCD corrections to vector boson fusion processes

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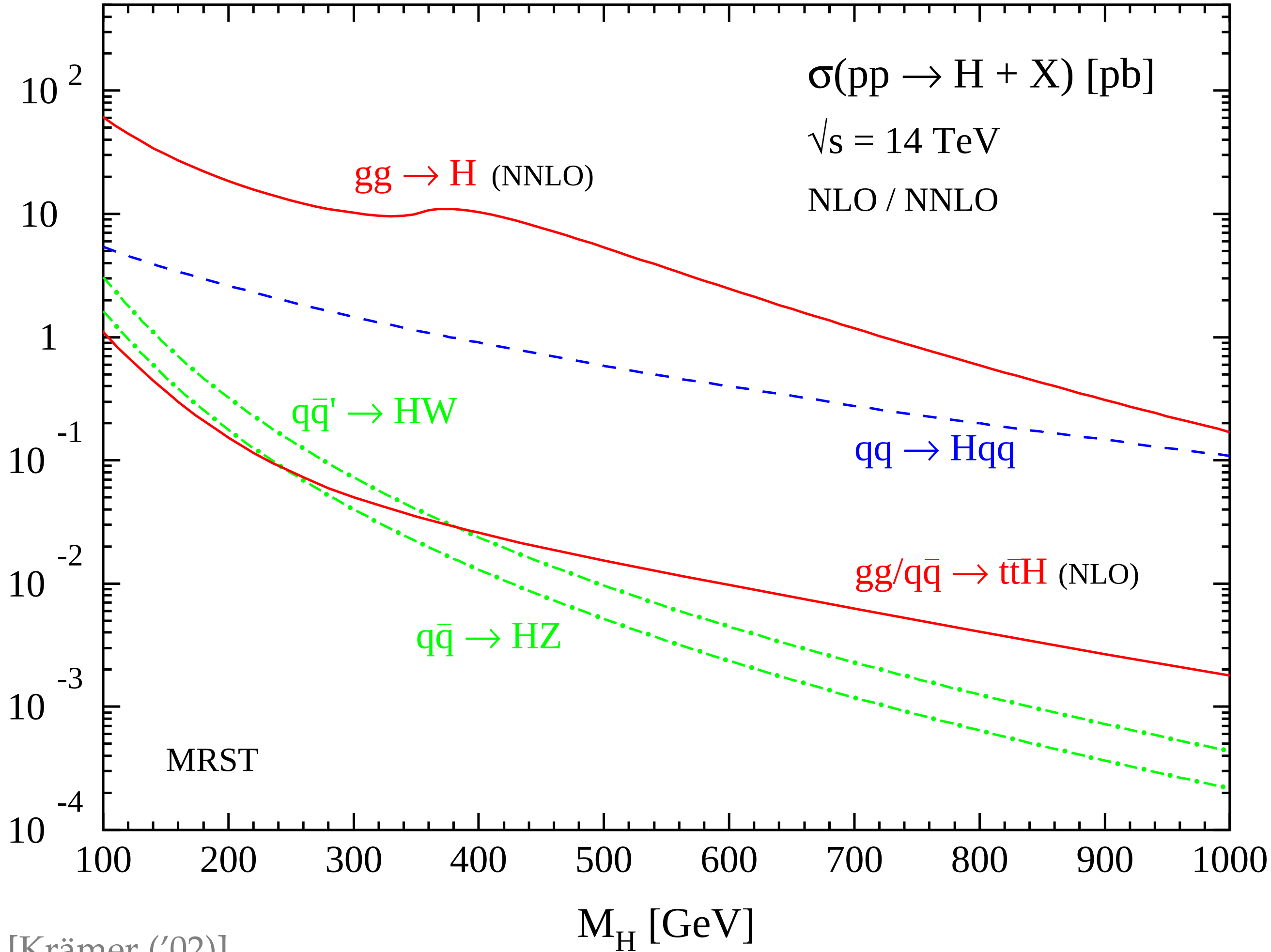
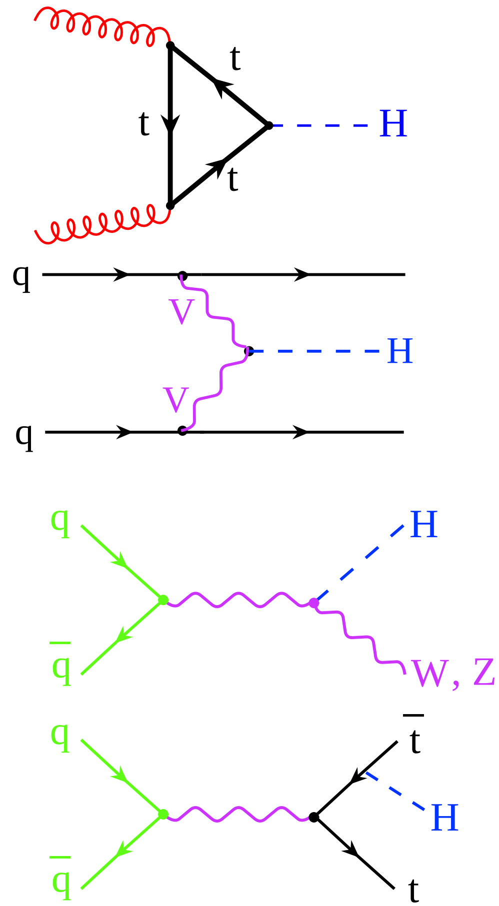
- VBF and Higgs Physics
- Wjj and Zjj production
- Vector boson pairs in VBF
- Virtual corrections
- Phenomenological implications
- Conclusions

Total Higgs production cross sections at the LHC

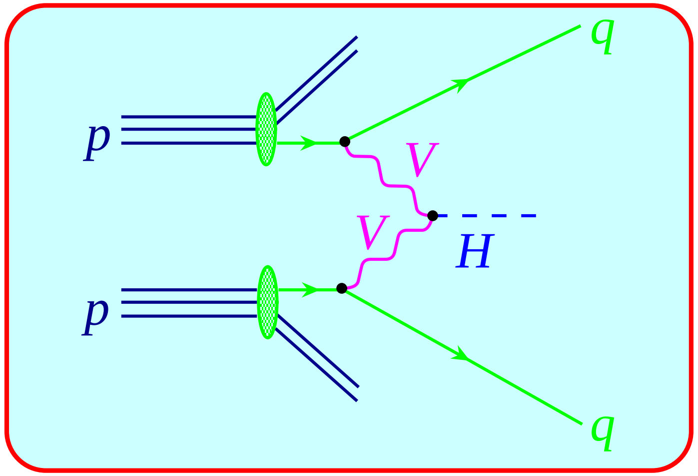
Vector boson fusion is an important ingredient in Higgs search at the LHC

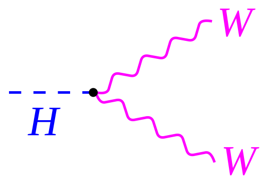




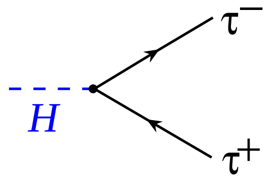
[Krämer ('02)]

Higgs Search in Vector Boson Fusion

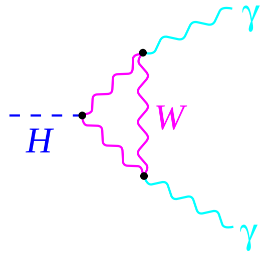




$m_H > 120$ GeV



$m_H < 140$ GeV

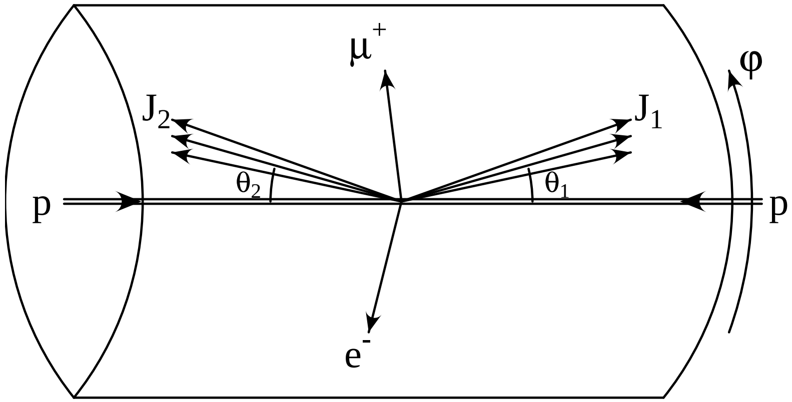


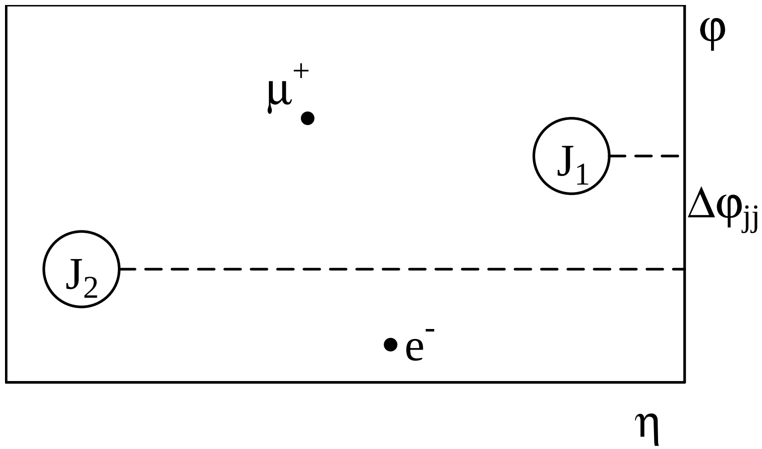
$m_H < 150$ GeV

[Eboli, Hagiwara, Kauer, Plehn, Rainwater, D.Z. . . .]

Most measurements can be performed at the LHC with statistical accuracies on the measured cross sections times decay branching ratios, $\sigma\times$ BR, of order 10% (sometimes even better).

VBF signature



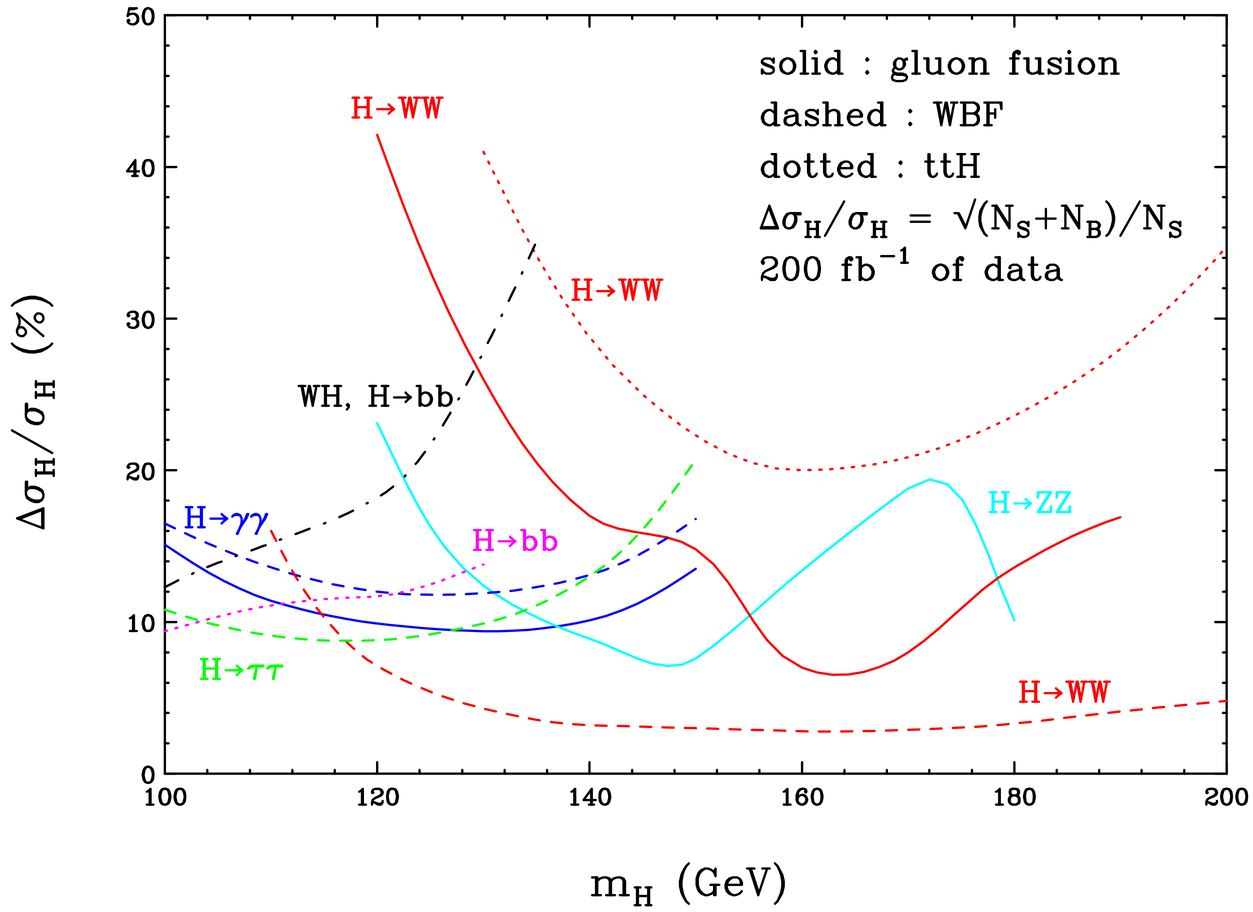


$$\eta = \frac{1}{2} \log \frac{1 + \cos\theta}{1 - \cos\theta}$$

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 $|\eta| < 2.5$)

Statistical and systematic errors at LHC



Assumed errors in fits to couplings:

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

Some of the lowest errors are achievable in VBF production of the Higgs boson

VBF processes at LHC

$qq \to qqH$ Han, Valencia, Willenbrock (1992); Figy, Oleari, DZ: hep-ph/0306109; Campbell, Ellis, Berger (2004)

- Higgs coupling measurements

$qq \to qqZ$ and $qq \to qqW$ Oleari, DZ: hep-ph/0310156

- $Z \to \tau\tau$ as background for $H \to \tau\tau$
- measure central jet veto acceptance at LHC

$qq \to qqWW$, $qq \to qqZZ$, $qq \to qqWZ$ Jäger, Oleari, Bozzi, DZ: hep-ph/0603177, hep-ph/0604200, hep-ph/0701105

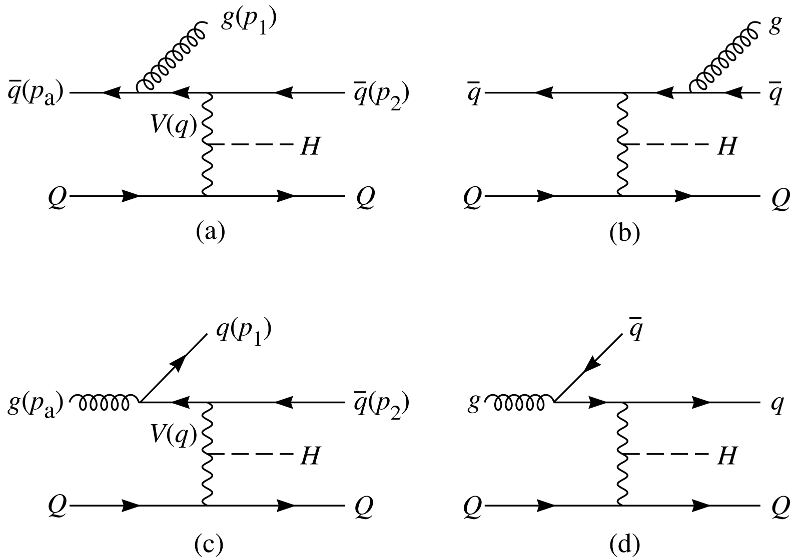
- $qqWW$ is background to $H \to WW$ in VBF
- underlying process is weak boson scattering:
  $WW \to WW$, $WW \to ZZ$, $WZ \to WZ$ etc.
  $\Longrightarrow$ measure weak boson scattering

Precise predictions require QCD corrections

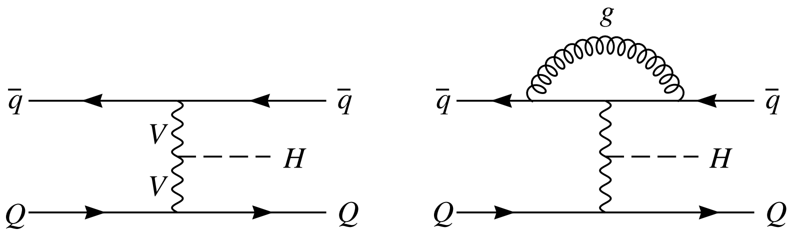
Generic features of QCD corrections to VBF

t-channel color singlet exchange $\Longrightarrow$ QCD corrections to different quark lines are independent

real emission contributions: upper line



Born and vertex corrections to upper line



No t-channel gluon exchange at NLO

Features are generic for all VBF processes

Real emission

Calculation is done using Catani-Seymour subtraction method

Consider $q(p_a)Q \to g(p_1)q(p_2)QH$. Subtracted real emission term

$$|\mathcal{M}_{\rm emit}|^2 - 8\pi\alpha_s \frac{C_F}{Q^2}\frac{x^2+z^2}{(1-x)(1-z)}|\mathcal{M}_{\rm Born}|^2 \qquad \text{with } 1-x = \frac{p_1\cdot p_2}{(p_1+p_2)\cdot p_a}, \quad 1-z = \frac{p_1\cdot p_a}{(p_1+p_2)\cdot p_a}$$

is integrable $\Longrightarrow$ do by Monte Carlo

Integral of subtracted term over $d^3\mathbf{p}_1$ can be done analytically and gives

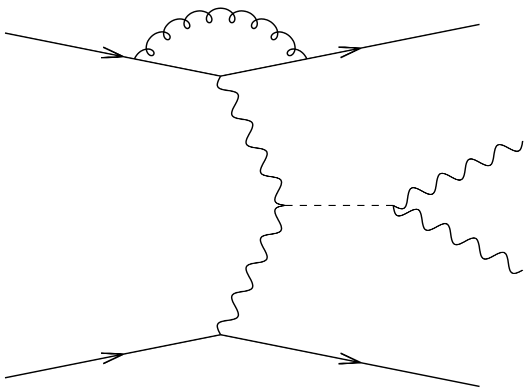
$$\frac{\alpha_s}{2\pi}C_F \left(\frac{4\pi\mu_R^2}{Q^2}\right)^{\epsilon} \Gamma(1+\epsilon)|\mathcal{M}_{\rm Born}|^2 \left[\frac{2}{\epsilon^2}+\frac{3}{\epsilon}+9-\frac{4}{3}\pi^2\right]\delta(1-x)$$

after factorization of splitting function terms (yielding additional “finite collinear terms”)

The divergence must be canceled by virtual corrections for all VBF processes
only variation: meaning of Born amplitude $\mathcal{M}_{\rm Born}$

Higgs production

Most trivial case: Higgs production
Virtual correction is vertex correction only



virtual amplitude proportional to Born

$$\mathcal{M}_V = \mathcal{M}_{\text{Born}} \frac{\alpha_s(\mu_R)}{4\pi} C_F \left(\frac{4\pi\mu_R^2}{Q^2}\right)^{\epsilon} \Gamma(1+\epsilon) \left[-\frac{2}{\epsilon^2} - \frac{3}{\epsilon} + \frac{\pi^2}{3} - 7\right] + \mathcal{O}(\epsilon)$$

- Divergent piece canceled via Catani Seymour algorithm

Remaining virtual corrections are accounted for by trivial factor multiplying Born cross section

$$|\mathcal{M}_{\text{Born}}|^2 \left(1 + 2\alpha_s \frac{C_F}{2\pi} c_{\text{virt}}\right)$$

- Factor 2 for corrections to upper and lower quark line
- Same factor to Born cross section absorbs most of the virtual corrections for other VBF processes

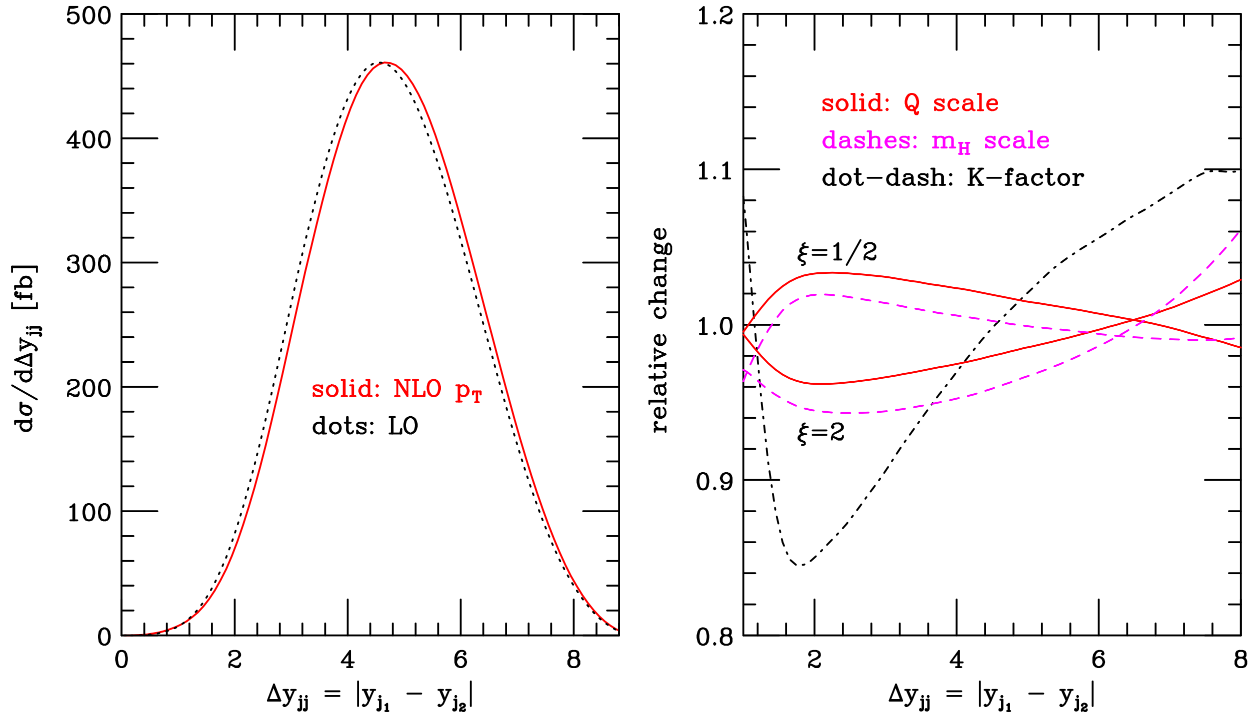
Results for Higgs production

- ✓ Small QCD corrections of order 10%
- ✓ Tiny scale dependence of NLO result
  - $\pm 5\%$ for distributions
  - $< 2\%$ for σ_{total}
- ✓ K-factor is phase space dependent
- ✓ QCD corrections under excellent control
- ✗ Need electroweak corrections for 5% uncertainty

  Solved now $\Longrightarrow$

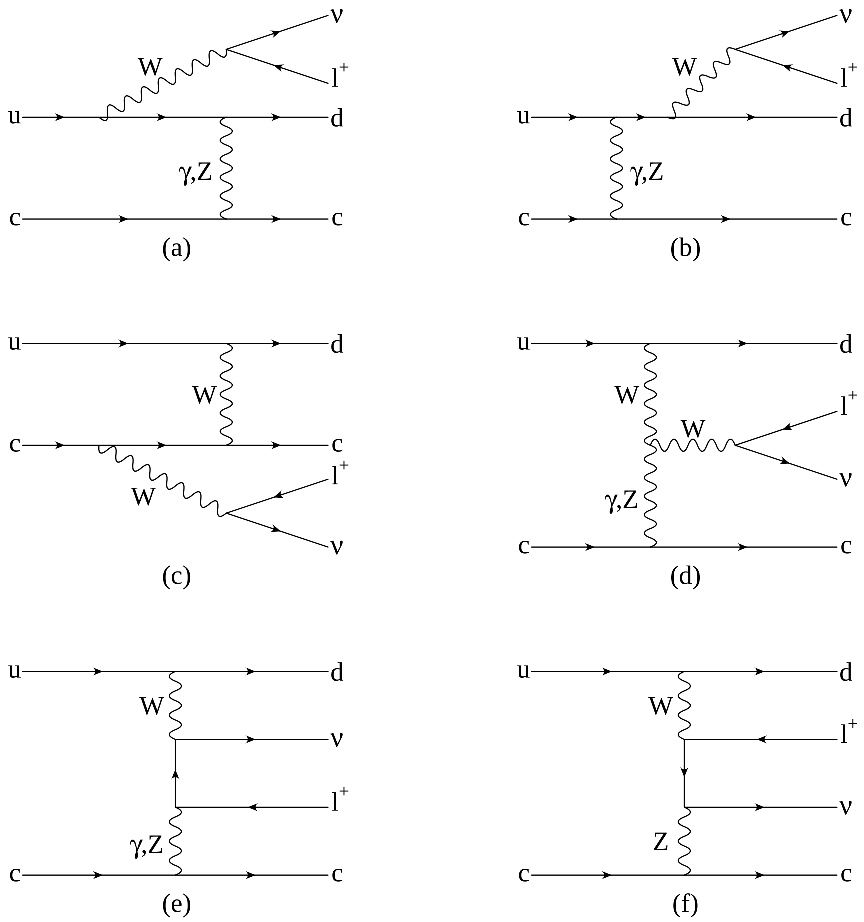
  talk by Denner

Figy, Oleari, DZ: hep-ph/0306109



$m_H = 120$ GeV, typical VBF cuts

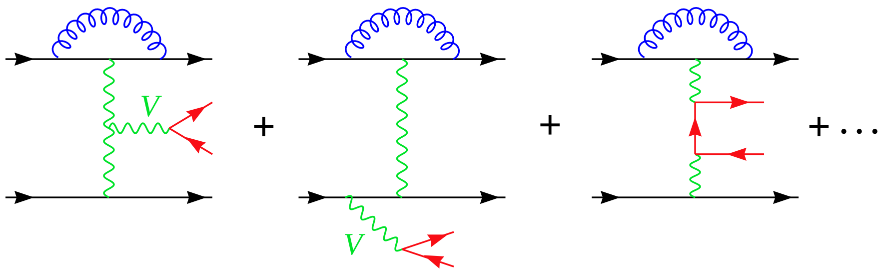
W and Z production



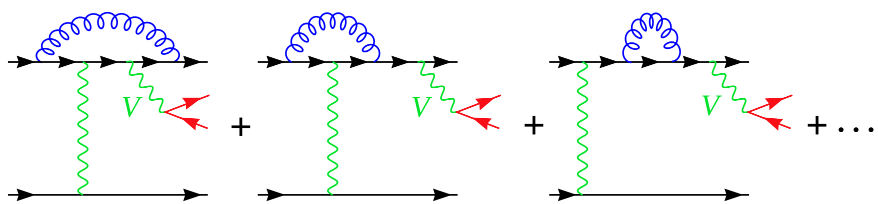
- $10 \cdots 24$ Feynman graphs
- $\Rightarrow$ use amplitude techniques, i.e. numerical evaluation of helicity amplitudes
- However: numerical evaluation works in d=4 dimensions only

Virtual contributions

Vertex corrections: same as for Higgs case



New: Box type graphs (plus gauge related diagrams)



For each individual pure vertex graph $\mathcal{M}^{(i)}$ the vertex correction is proportional to the corresponding Born graph

$$\mathcal{M}_V^{(i)} = \mathcal{M}_B^{(i)} \frac{\alpha_s(\mu_R)}{4\pi} C_F \left(\frac{4\pi\mu_R^2}{Q^2}\right)^{\epsilon} \Gamma(1+\epsilon) \left[-\frac{2}{\epsilon^2} - \frac{3}{\epsilon} + \frac{\pi^2}{3} - 7\right]$$

Vector boson propagators plus attached quark currents are effective polarization vectors

build a program to calculate the finite part of the sum of the graphs

Handling of IR and collinear divergences

Use tensor decomposition a la Passarino-Veltman

Split $B_0 \quad \cdots \quad D_{ij}$ functions into divergent and finite parts

With $s = (q_1 + q_2)^2$, $t = (k_2 + q_2)^2 = (k_1 - q_1)^2$ we get, for example,

$$B_0(q^2) = \frac{\Gamma(1+\epsilon)}{(-s)^\epsilon}\left[\frac{1}{\epsilon} + 2 - \ln\frac{q^2 + i0^+}{s} + \mathcal{O}(\epsilon)\right]$$

$$= \frac{\Gamma(1+\epsilon)}{(-s)^\epsilon}\left[\frac{1}{\epsilon} + \widetilde{B}_0(q^2) + \mathcal{O}(\epsilon)\right]$$

$$D_0(k_2, q_2, q_1) = \frac{\Gamma(1+\epsilon)}{(-s)^\epsilon}\left[\frac{1}{st}\left(\frac{1}{\epsilon^2} + \frac{1}{\epsilon}\ln\frac{q_1^2 q_2^2}{t^2}\right) + \widetilde{D}_0(k_2, q_2, q_1) + \mathcal{O}(\epsilon)\right]$$

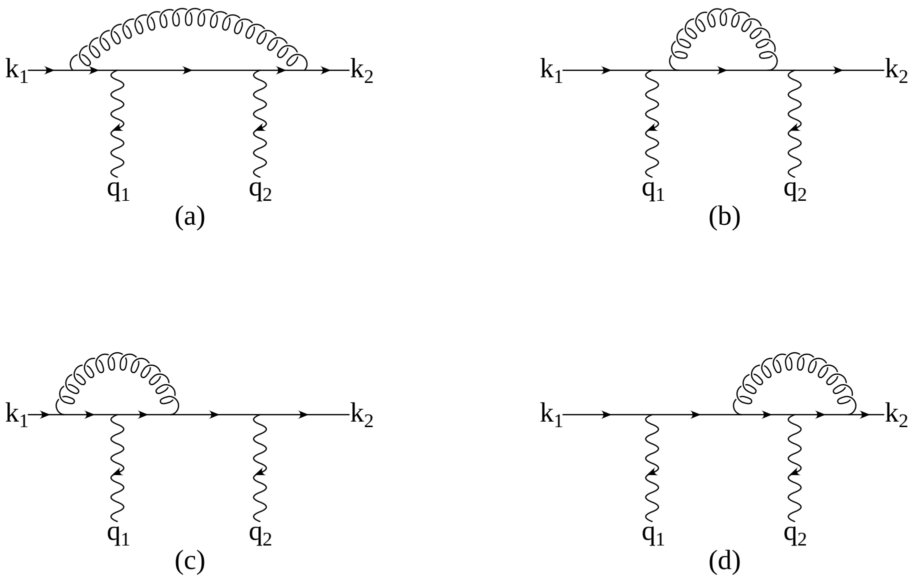
$$D^{\mu\nu}(k_2, q_2, q_1) = \frac{\Gamma(1+\epsilon)}{(-s)^\epsilon}\left(\frac{1}{\epsilon}\left(k_1^\mu k_1^\nu d_2(q_1^2, t) + k_2^\mu k_2^\nu d_2(q_2^2, t)\right) + \widetilde{D}^{\mu\nu}(k_2, q_2, q_1) + \mathcal{O}(\epsilon)\right)$$

with $d_2(q^2, t) = 1/(s(q^2 - t)^2)\,\left[t \ln(q^2/t) - (q^2 - t)\right]$

Finite $\widetilde{D}_{ij}$ have standard PV recursion relations $\Longrightarrow$ determine them numerically

Boxline corrections

Virtual corrections for quark line with 2 EW gauge bosons



The external vector bosons correspond to $V \rightarrow l_1 \bar{l}_2$ decay currents or quark currents

Divergent terms in 4 Feynman graphs combine to multiple of corresponding Born graph

$$\mathcal{M}^{(i)}_{\text{boxline}} = \mathcal{M}^{(i)}_B F(Q) \left[-\frac{2}{\epsilon^2} - \frac{3}{\epsilon} + \frac{\pi^2}{3} - 7 \right]$$

$$+ \frac{\alpha_s(\mu_R)}{4\pi} C_F \widetilde{\mathcal{M}}_\tau(q_1, q_2)(-e^2) g_\tau^{V_1 f_1} g_\tau^{V_2 f_2}$$

$$+ \mathcal{O}(\epsilon)$$

with $F(Q) = \frac{\alpha_s(\mu_R)}{4\pi} C_F \left(\frac{4\pi\mu_R^2}{Q^2}\right)^\epsilon \Gamma(1+\epsilon)$

$\widetilde{\mathcal{M}}_\tau(q_1, q_2) = \widetilde{\mathcal{D}}_{\mu\nu} \epsilon_1^\mu \epsilon_2^\nu$ is universal virtual $qqVV$ amplitude: use like HELAS calls in MadGraph

Virtual corrections

Born sub-amplitude is multiplied by same factor as found for pure vertex corrections
$\Rightarrow$ when summing all Feynman graphs the divergent terms multiply the complete $\mathcal{M}_B$

Complete virtual corrections

$$\mathcal{M}_V = \mathcal{M}_B \; F(Q) \left[-\frac{2}{\epsilon^2} - \frac{3}{\epsilon} + \frac{\pi^2}{3} - 7 \right] + \widetilde{\mathcal{M}}_V$$

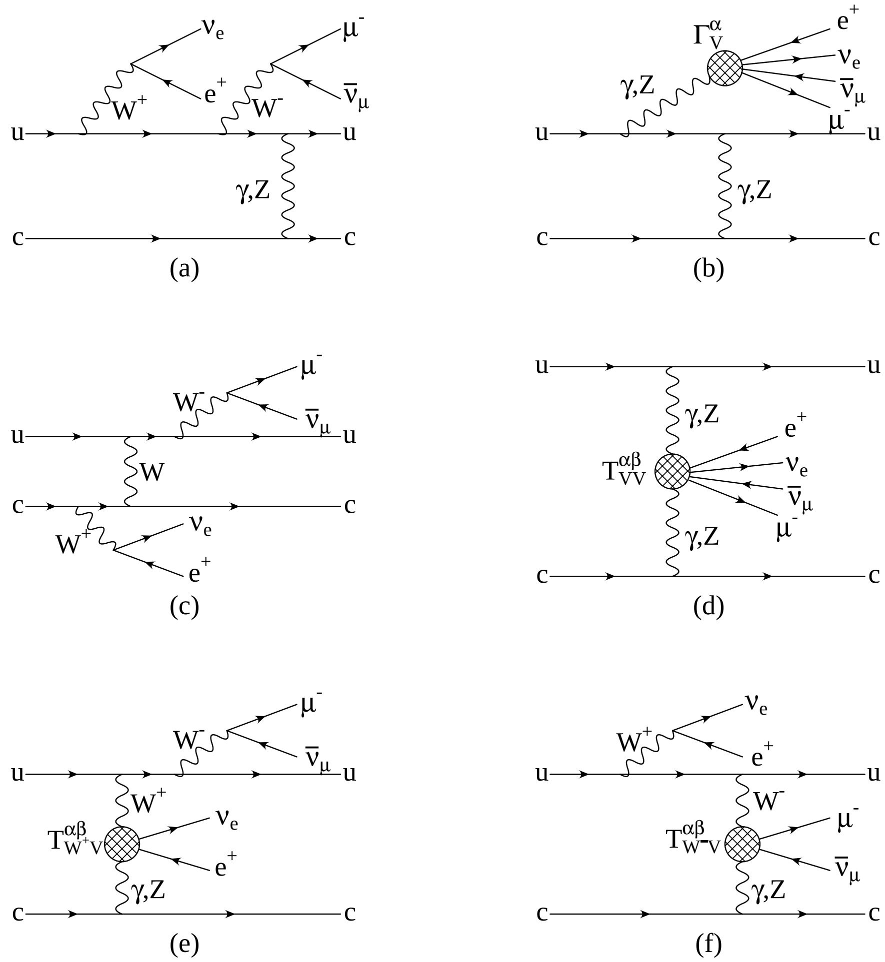
where $\widetilde{\mathcal{M}}_V$ is finite, and is calculated with amplitude techniques.
The interference contribution in the cross-section calculation is then given by

$$2\,\mathrm{Re}\,[\mathcal{M}_V \mathcal{M}_B^*] = |\mathcal{M}_B|^2 F(Q) \left[-\frac{2}{\epsilon^2} - \frac{3}{\epsilon} + \frac{\pi^2}{3} - 7 \right] + 2\,\mathrm{Re}\left[\widetilde{\mathcal{M}}_V \mathcal{M}_B^* \right]$$

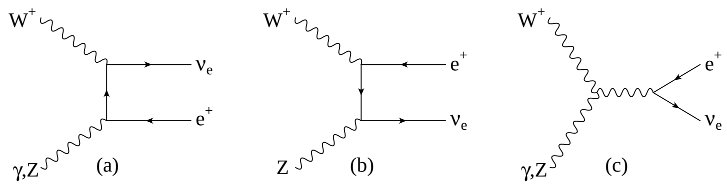
The divergent term, proportional to $|\mathcal{M}_B|^2$, cancels against the subtraction terms just like in the Higgs case.

Most recent: $qq \to qqWW$, $qqZZ$, $qqWZ$ at NLO

- example: WW production via VBF with leptonic decays: $pp \to e^+\nu_e\mu^-\bar{\nu}_\mu + 2j$
- Spin correlations of the final state leptons
- All resonant and non-resonant Feynman diagrams included
- NC $\Longrightarrow$ 181 Feynman diagrams at LO
- CC $\Longrightarrow$ 92 Feynman diagrams at LO



Use modular structure, e.g. leptonic tensor

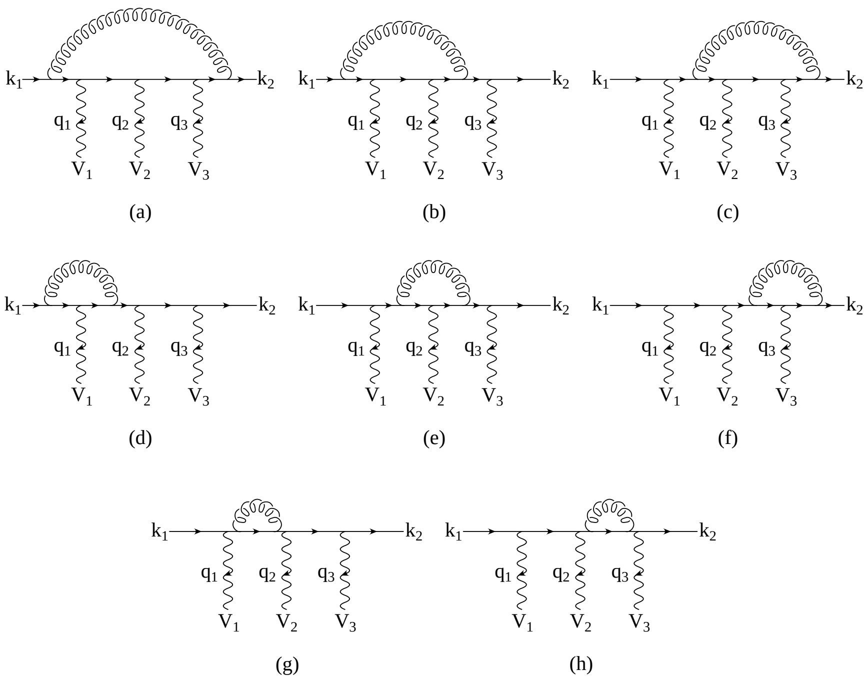


Calculate once, reuse in different processes

Speedup factor ≈ 70 compared to MadGraph for real emission corrections

New for virtual: pentline corrections

Virtual corrections involve up to pentagons



The external vector bosons correspond to $V \to l_1 \bar{l}_2$ decay currents or quark currents

The sum of all QCD corrections to a single quark line is simple

$$\mathcal{M}_V^{(i)} = \mathcal{M}_B^{(i)} \frac{\alpha_s(\mu_R)}{4\pi} C_F \left(\frac{4\pi\mu_R^2}{Q^2}\right)^\epsilon \Gamma(1+\epsilon) \left[-\frac{2}{\epsilon^2} - \frac{3}{\epsilon} + c_{\text{virt}}\right] + \widetilde{\mathcal{M}}^{(i)}_{V_1V_2V_3,\tau}(q_1, q_2, q_3) + \mathcal{O}(\epsilon)$$

- Divergent pieces sum to Born amplitude: canceled via Catani Seymour algorithm
- Use amplitude techniques to calculate finite remainder of virtual amplitudes

Pentagon tensor reduction with Denner-Dittmaier is stable at 0.1% level

Gauge invariance tests

Numerical problems flagged by gauge invariance test: use Ward identities for pentline and boxline contributions

$$q_2^{\mu_2}\,\widetilde{\mathcal{E}}_{\mu_1\mu_2\mu_3}(k_1,q_1,q_2,q_3) = \widetilde{\mathcal{D}}_{\mu_1\mu_3}(k_1,q_1,q_2+q_3) - \widetilde{\mathcal{D}}_{\mu_1\mu_3}(k_1,q_1+q_2,q_3)$$

With Denner-Dittmaier recursion relations for E_{ij} functions the ratios of the two expressions agree with unity (to 10% or better) at more than 99.8% of all phase space points.

Ward identities reduce importance of computationally slow pentagon contributions when contracting with $W^{\pm}$ polarization vectors

$$J_{\pm}^{\mu} = x_{\pm}\, q_{\pm}^{\mu} + r_{\pm}^{\mu}$$

choose $x_{\pm}$ such as to minimize pentagon contribution from remainders $r_{\pm}$ in all terms like

$$J_{+}^{\mu_1} J_{-}^{\mu_2}\,\widetilde{\mathcal{E}}_{\mu_1\mu_2\mu_3}(k_1,q_+,q_-,q_0) = r_{+}^{\mu_1}\, r_{-}^{\mu_2}\,\widetilde{\mathcal{E}}_{\mu_1\mu_2\mu_3}(k_1,q_+,q_-,q_0) + \text{box contributions}$$

Resulting true pentagon piece contributes to the cross section at permille level $\Longrightarrow$ totally negligible for phenomenology

Phenomenology

Study LHC cross sections within typical VBF cuts

- Identify two or more jets with k_T-algorithm ($D = 0.8$)

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

- Identify two highest p_T jets as tagging jets with wide rapidity separation and large dijet invariant mass

$$\Delta y_{jj} = |y_{j_1} - y_{j_2}| > 4, \qquad M_{jj} > 600\ \text{GeV}$$

- Charged decay leptons ($\ell = e,\ \mu$) of W and/or Z must satisfy

$$p_{T\ell} \geq 20\ \text{GeV}\,, \qquad |\eta_\ell| \leq 2.5\,, \qquad \triangle R_{j\ell} \geq 0.4\,,$$
$$m_{\ell\ell} \geq 15\ \text{GeV}\,, \qquad \triangle R_{\ell\ell} \geq 0.2$$

and leptons must lie between the tagging jets

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

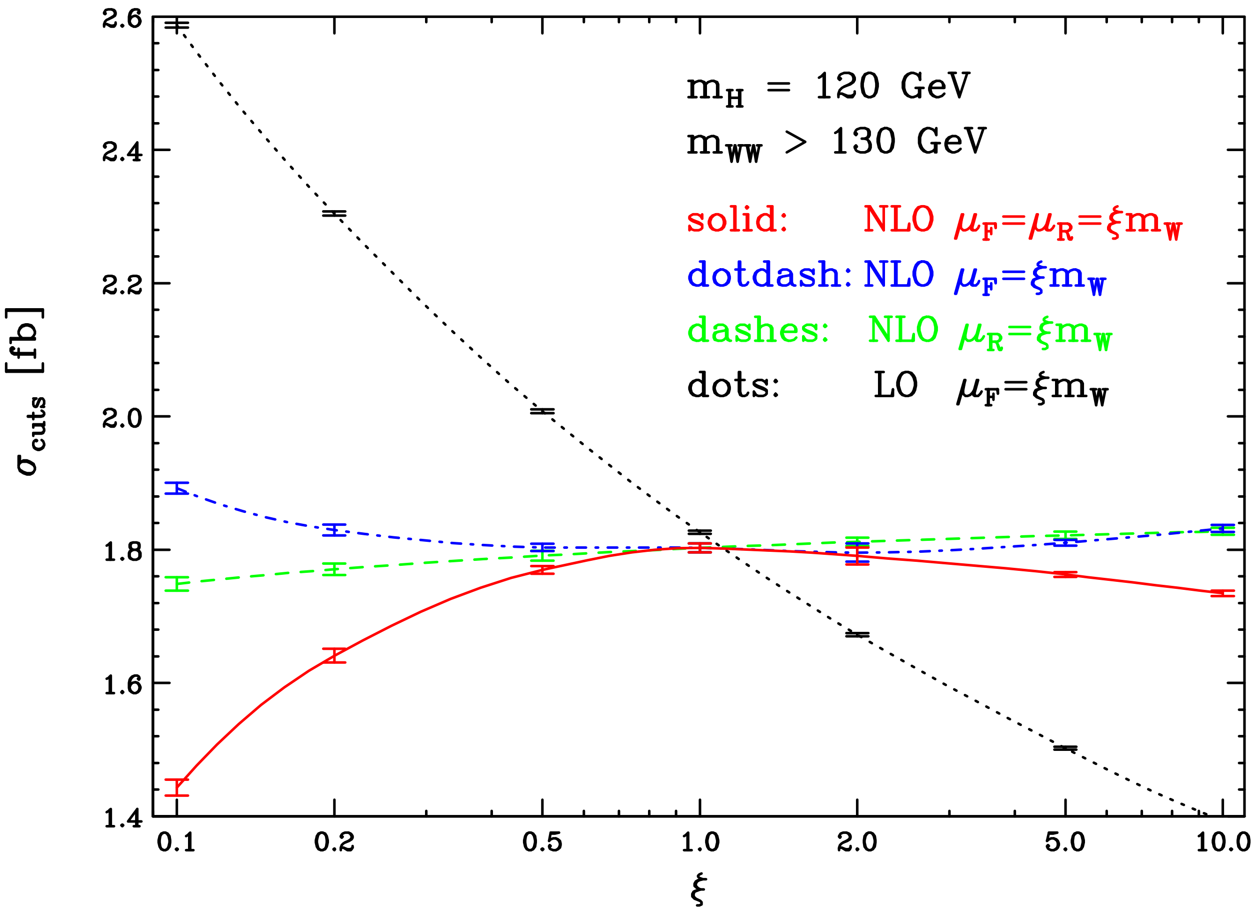
For scale dependence studies we have considered

$\mu = \xi\ m_V$ fixed scale $\qquad$ $\mu = \xi\ Q_i$ weak boson virtuality : $Q_i^2 = 2k_{q_1} \cdot k_{q_2}$

WW production: $pp \to jje^+\nu_e\mu^-\bar{\nu}_\mu X$ @ LHC

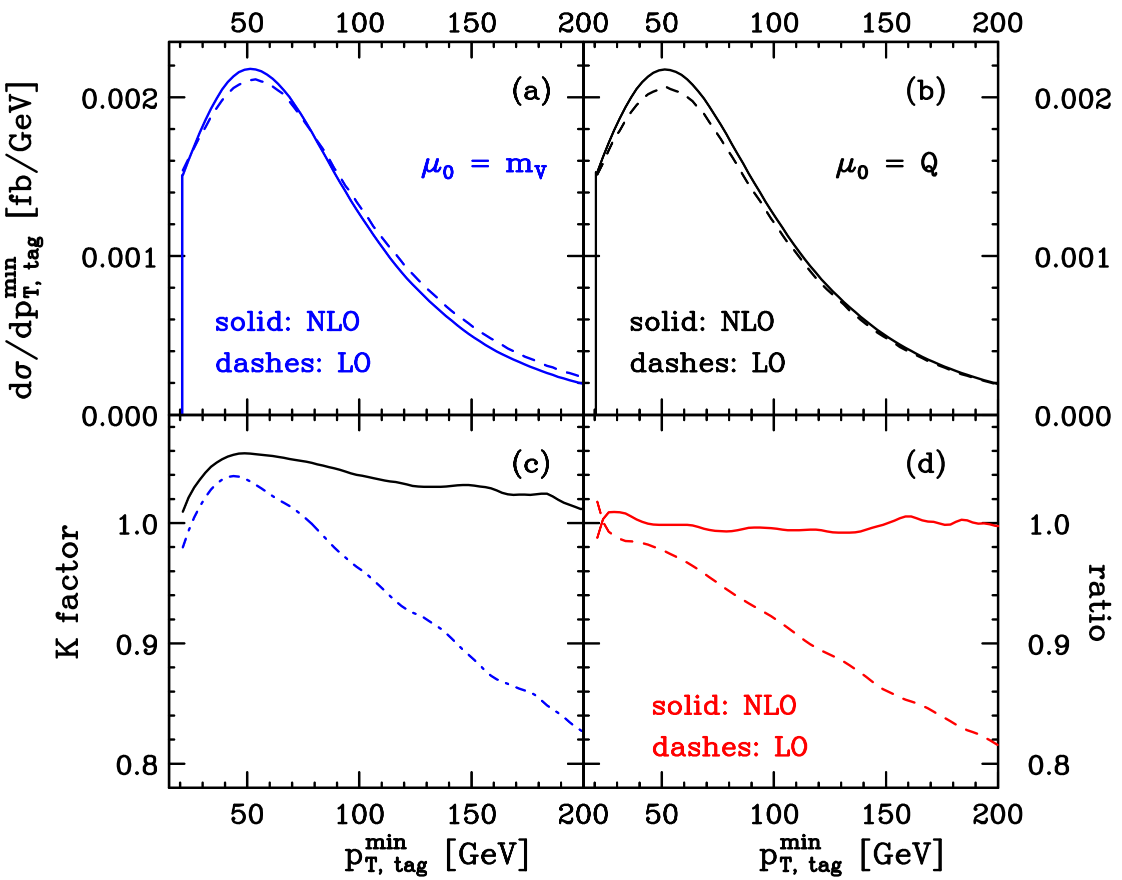
Stabilization of scale dependence at NLO

Jäger, Oleari, DZ hep-ph/0603177



WZ production in VBF, $WZ \to e^+\nu_e\mu^+\mu^-$

Transverse momentum distribution of the softer tagging jet

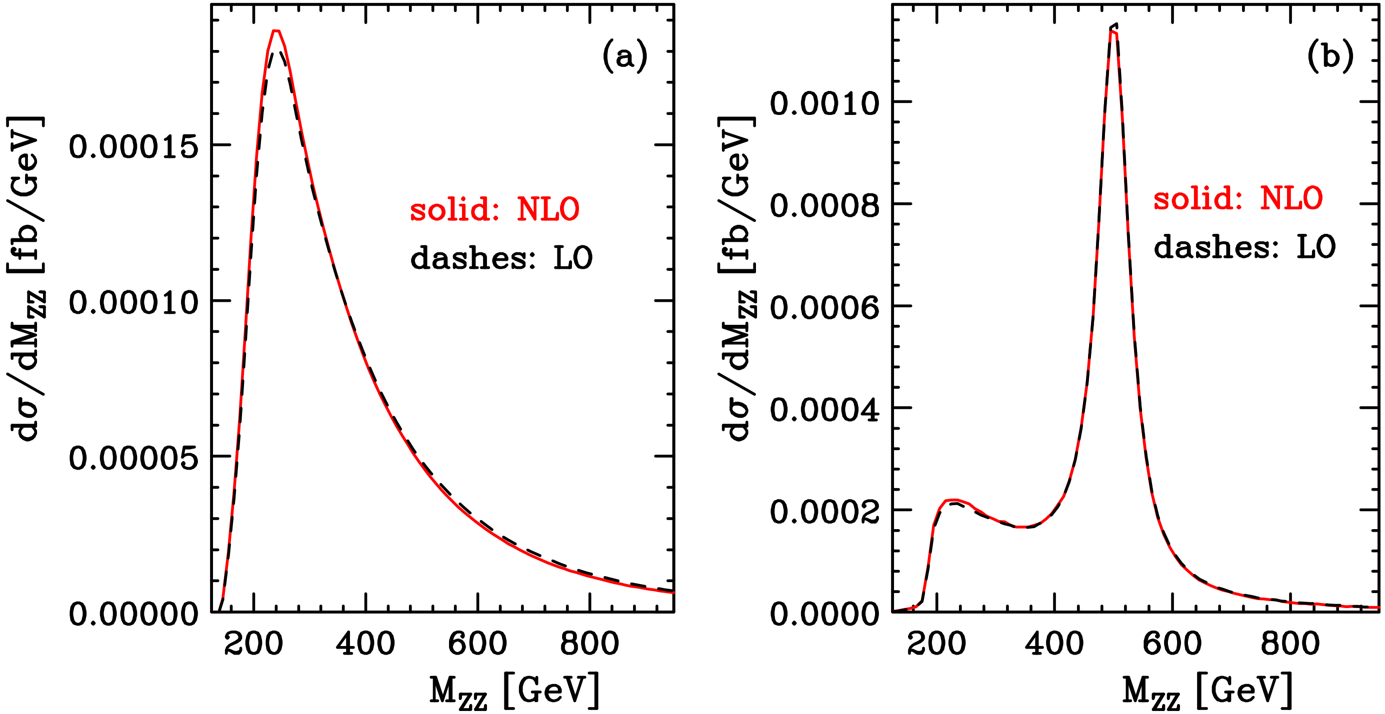


- Shape comparison LO vs. NLO depends on scale
- Scale choice $\mu = Q$ produces approximately constant K-factor
- Ratio of NLO curves for different scales is unity to better than 2%: scale choice matters very little at NLO

Use $\mu_F = Q$ at LO to best approximate the NLO results

ZZ production in VBF, $ZZ \to e^+e^-\mu^+\mu^-$

4-lepton invariant mass distribution without/with Higgs resonance



Good agreement of LO and NLO due to low scale choice $\mu = m_Z$. Alternative choice $\mu = m_H$ or $\mu = m_{4\ell}$ leads to smaller LO cross section at high $m_{4\ell}$

Conclusions

- LHC will observe a SM-like Higgs boson in multiple channels, with $5 \ldots 20\%$ statistical errors
  $\Longrightarrow$ great source of information on Higgs couplings
- Whether or not a light Higgs is observed, weak boson scattering, i.e. $VVjj$ production by VBF, is an important testing ground for the physics underlying $SU(2) \times U(1)$ breaking
- NLO QCD corrections and improved simulation tools are crucial for precise measurements with full LHC data.

NLO QCD correction for VBF now available in VBFNLO:
parton level Monte Carlo for Hjj, Wjj, Zjj, W^+W^-jj, $ZZjj$ production
by Bozzi, Figy, Hankele, Jäger, Klämke, Oleari, Worek, DZ, ...

http://www-itp.physik.uni-karlsruhe.de/∼vbfnloweb/