VBFNLO
NLO QCD corrections for processes with electroweak bosons in the final state

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in collaboration with:
D. Zeppenfeld and the VBFNLO group

- VBF processes
- NLO for triboson production
- phenomenology and results for LHC
- conclusions

QCD corrections to VBF processes

Precise predictions require QCD corrections

$qq \to qqH$ Han, Valencia, Willenbrock; Figy, Oleari, Zeppenfeld; Campbell, Ellis, Berger

- Higgs coupling measurements

$qq \to qqZ$ and $qq \to qqW$ Oleari, Zeppenfeld

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

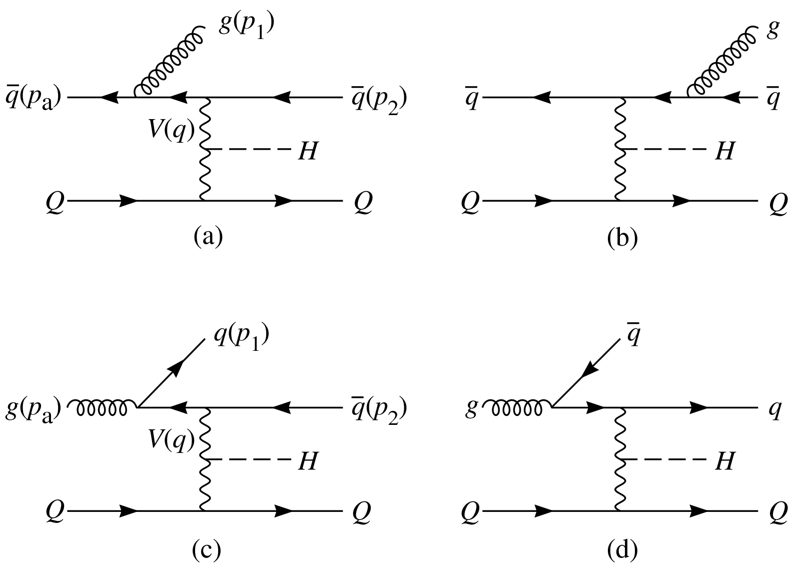
$qq \to qqWW$, $qq \to qqZZ$, $qq \to qqWZ$ Jäger, Oleari, Bozzi, Zeppenfeld

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

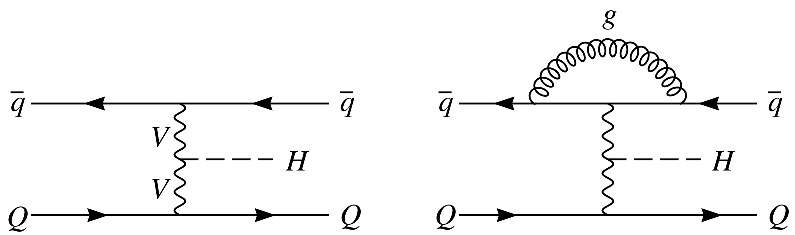
Generic features of QCD corrections to VBF

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

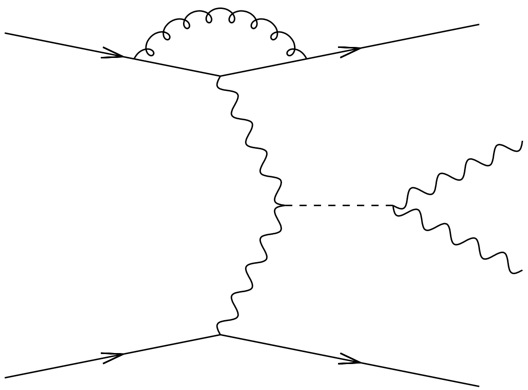
$$\frac{\alpha_s}{2\pi} C_F \left(\frac{4\pi\mu_R^2}{Q^2}\right)^{\epsilon} \Gamma(1+\epsilon) |\mathcal{M}_{\rm Born}|^2 \left[\frac{2}{\epsilon^2} + \frac{3}{\epsilon} + 9 - \frac{4}{3}\pi^2\right] \delta(1-x)$$

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

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

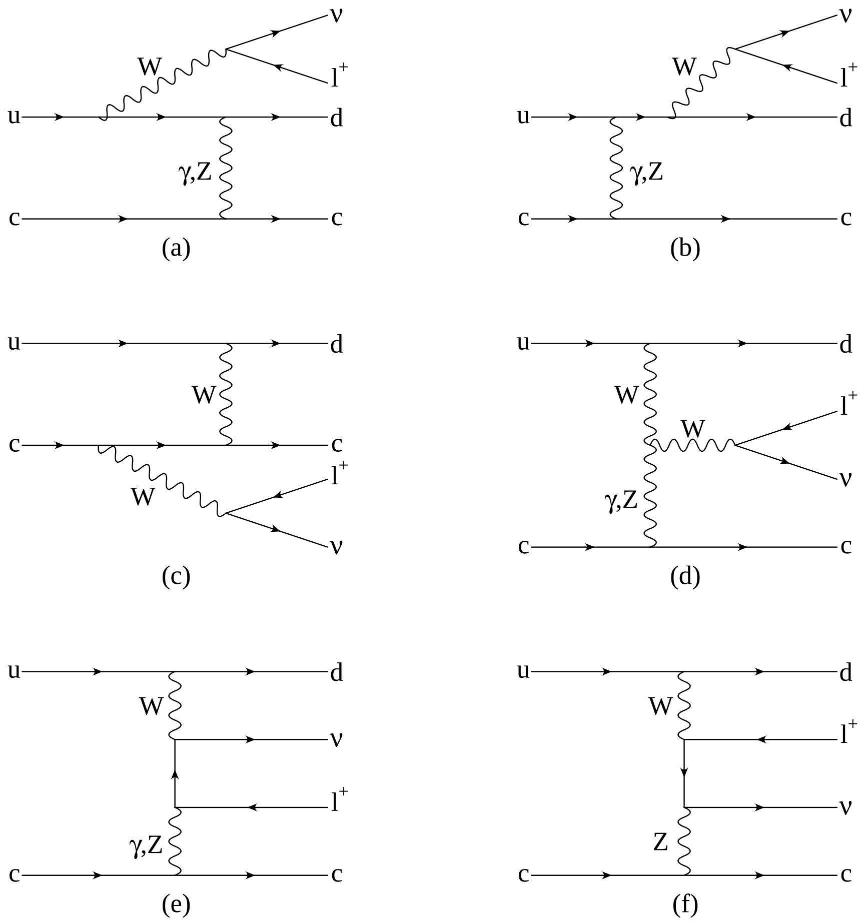
- Divergent piece canceled via Catani Seymour algorithm

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

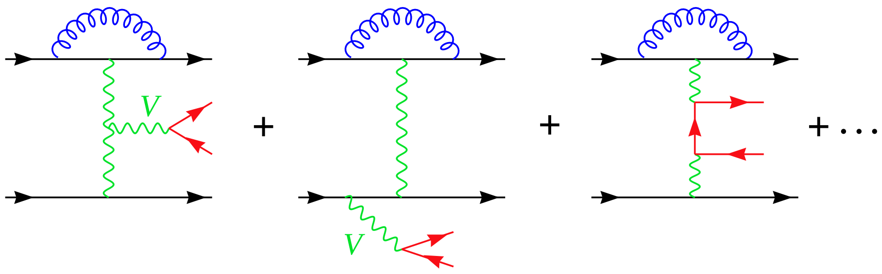
W and Z production



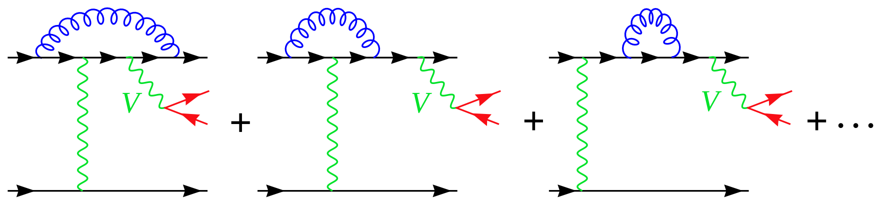
- $10 \cdots 24$ Feynman graphs
- $\Rightarrow$ use amplitude techniques, i.e. numerical evaluation of helicity amplitudes
- However: numerical evaluation works in d=4 dimensions only

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

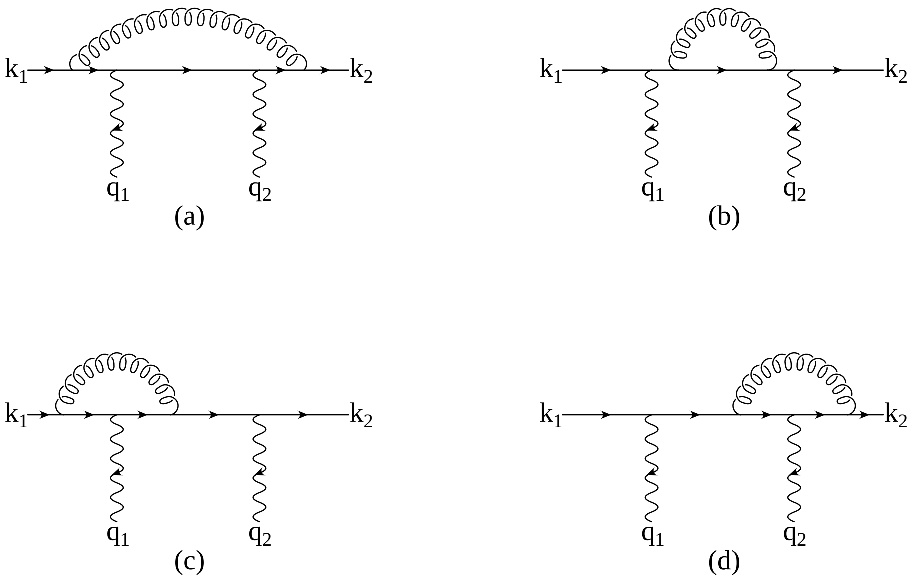
$$\mathcal{M}_V^{(i)} = \mathcal{M}_B^{(i)} \frac{\alpha_s(\mu_R)}{4\pi} C_F \left(\frac{4\pi\mu_R^2}{Q^2}\right)^\epsilon \Gamma(1+\epsilon) \left[-\frac{2}{\epsilon^2} - \frac{3}{\epsilon} + \frac{\pi^2}{3} - 7\right]$$

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

Boxline corrections

Virtual corrections for quark line with 2 EW gauge bosons



The external vector bosons correspond to $V \to l_1 \bar{l}_2$ 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 $F(Q) = \frac{\alpha_s(\mu_R)}{4\pi} C_F \left(\frac{4\pi\mu_R^2}{Q^2}\right)^\epsilon \Gamma(1+\epsilon)$

$\widetilde{\mathcal{M}}_\tau(q_1,q_2) = \widetilde{\mathcal{M}}_{\mu\nu}\epsilon_1^\mu \epsilon_2^\nu$ 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

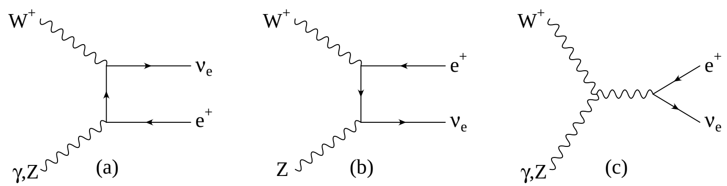
$$2\,\mathrm{Re}\,[\mathcal{M}_V \mathcal{M}_B^*] = |\mathcal{M}_B|^2 F(Q) \left[-\frac{2}{\epsilon^2} - \frac{3}{\epsilon} + \frac{\pi^2}{3} - 7 \right] + 2\,\mathrm{Re}\left[\widetilde{\mathcal{M}}_V \mathcal{M}_B^* \right]$$

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

3 weak bosons on a quark line: $qq \to qqWW$, $qqZZ$, $qqWZ$ at NLO

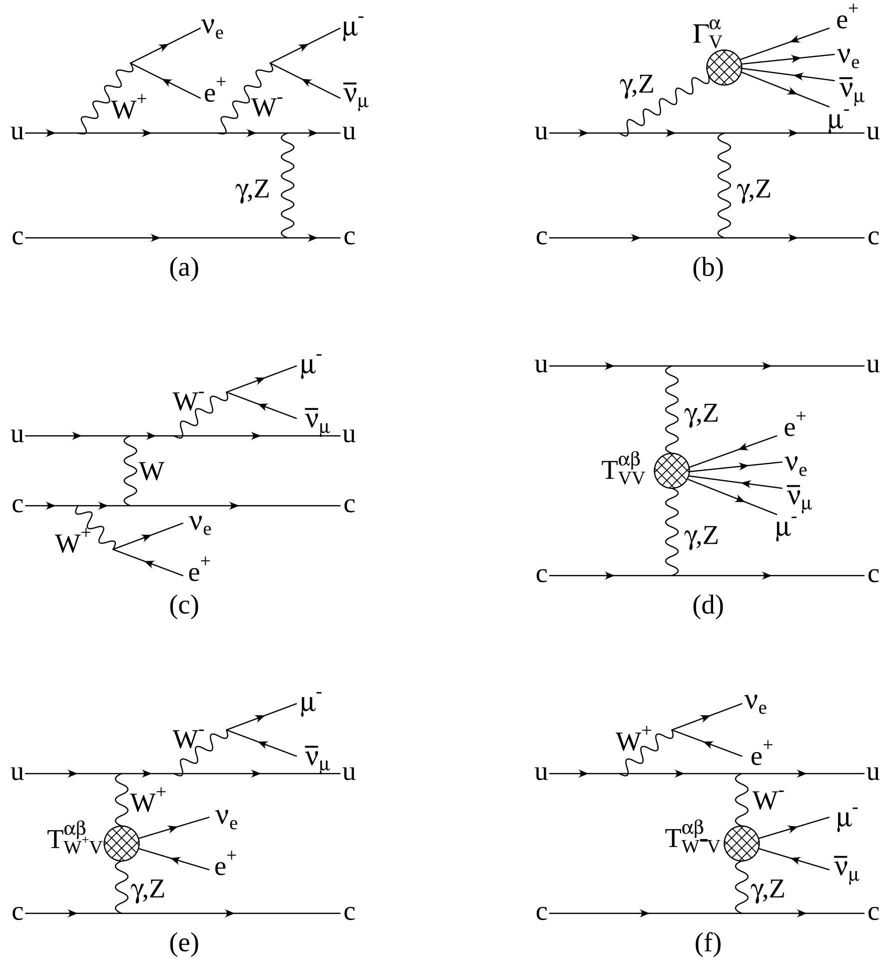
- example: WW production via VBF with leptonic decays: $pp \to e^+ \nu_e \mu^- \bar{\nu}_\mu + 2j$
- Spin correlations of the final state leptons
- All resonant and non-resonant Feynman diagrams included
- NC $\Longrightarrow$ 181 Feynman diagrams at LO
- CC $\Longrightarrow$ 92 Feynman diagrams at LO

Use modular structure, e.g. leptonic tensor



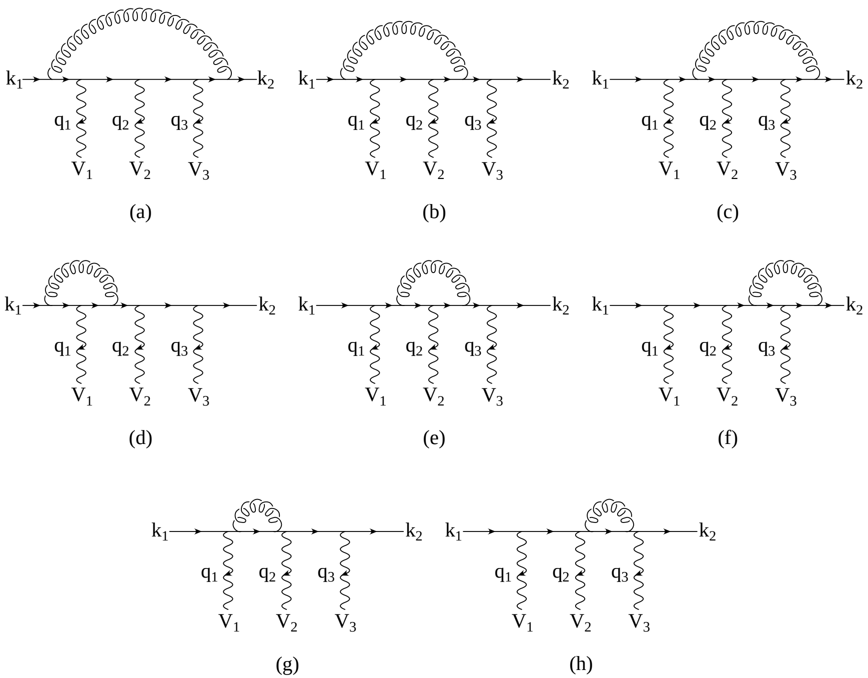
Calculate once, reuse in different processes

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

$$\begin{aligned}\mathcal{M}_V^{(i)} &= \mathcal{M}_B^{(i)} \frac{\alpha_s(\mu_R)}{4\pi} C_F \left(\frac{4\pi\mu_R^2}{Q^2}\right)^{\epsilon} \Gamma(1+\epsilon) \\ &\quad \left[-\frac{2}{\epsilon^2} - \frac{3}{\epsilon} + c_{\text{virt}}\right] \\ &+ \widetilde{\mathcal{M}}^{(i)}_{V_1 V_2 V_{3,\tau}}(q_1, q_2, q_3) + \mathcal{O}(\epsilon)\end{aligned}$$

- 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

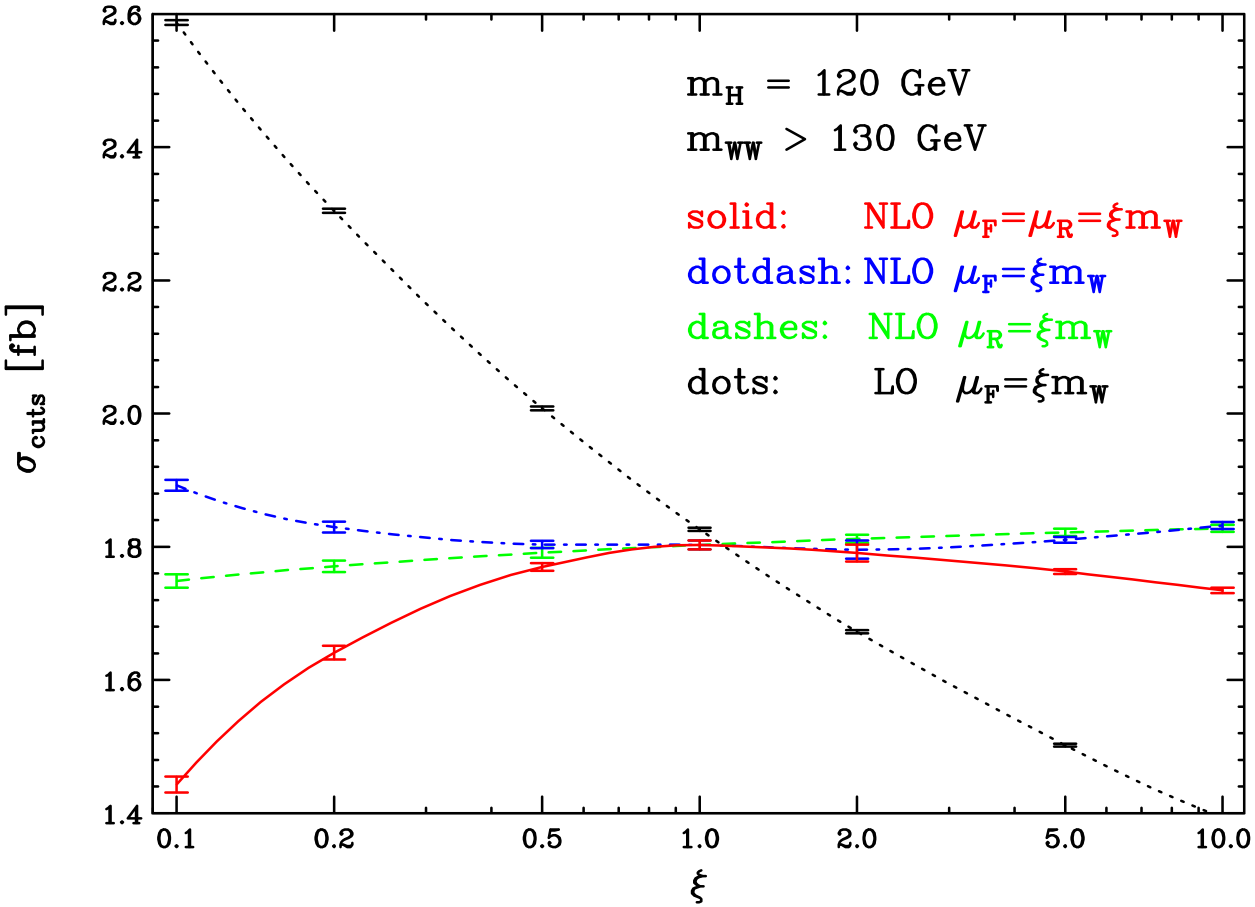
$$y_{j,min} < \eta_\ell < y_{j,max}$$

For scale dependence studies we have considered

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

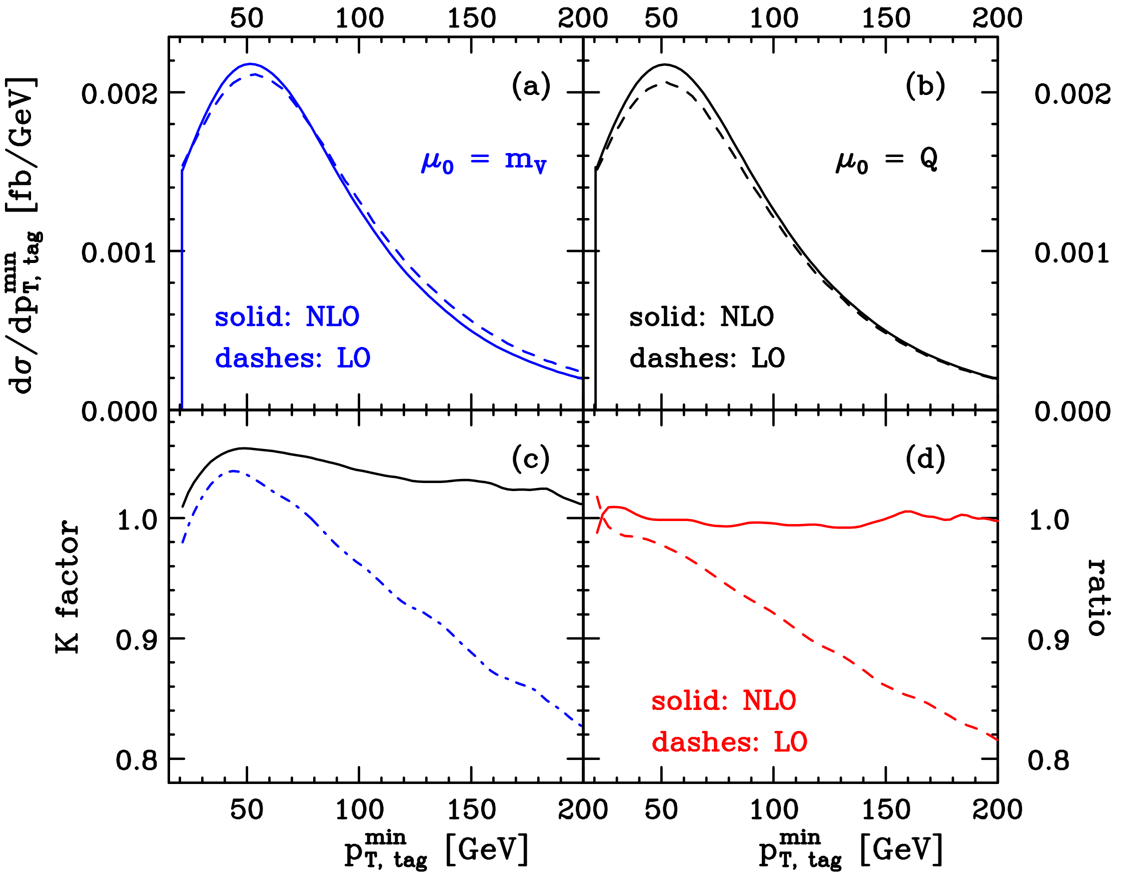
WW production: $pp \to jje^+\nu_e\mu^-\bar{\nu}_\mu X$ @ LHC

Stabilization of scale dependence at NLO



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

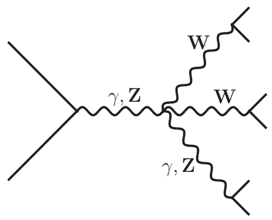
Use $\mu_F = Q$ at LO to best approximate the NLO results

Crossing: VVV Production

- The pentline graphs directly correspond to production of three (virtual) electroweak bosons in $q\bar{q}\to VVV$
- Virtual QCD corrections fully contained in modules for boxline and pentline routines (and a trivial overall factor for the vertex amplitudes)
- Crossing is trivial for the basic helicity amplitudes of the fermion lines. Analytic continuation implemented for all scalar integrals: boxline and pentline routines work directly for crossed processes.
- New: subtraction of real emission singularities. Use Catani Seymour for Drell-Yan type processes. Implemented by Vera Hankele and tested against $q\bar{q}\to W^+W^-$ as implemented in MCFM.

Motivation

- Standard Model background for SUSY processes with multi-lepton + $\not{p}_T$ signature
- Possibility to obtain information about quartic electroweak couplings.



- QCD corrections to $pp \rightarrow$ VVV + X on experimentalist's wishlist:

  [The QCD, Electroweak and Higgs Working Group 2006]

process ($V \in \{Z, W, \gamma\}$)	relevant for
1. $pp \rightarrow V\,V$ jet	$t\bar{t}H$, new physics
2. $pp \rightarrow t\bar{t}\,b\bar{b}$	$t\bar{t}H$
3. $pp \rightarrow t\bar{t} + 2\,\text{jets}$	$t\bar{t}H$
4. $pp \rightarrow V\,V\,b\bar{b}$	VBF$\rightarrow H \rightarrow VV$, $t\bar{t}H$, new physics
5. $pp \rightarrow V\,V + 2\,\text{jets}$	VBF$\rightarrow H \rightarrow VV$
6. $pp \rightarrow V + 3\,\text{jets}$	various new physics signatures
7. $pp \rightarrow V\,V\,V$	SUSY trilepton

Status of the VVV calculations in VBFNLO

- W^+W^-Z production with leptonic decays and full $H \to WW$ and $H \to ZZ$ contributions
  [Hankele, Zeppenfeld]

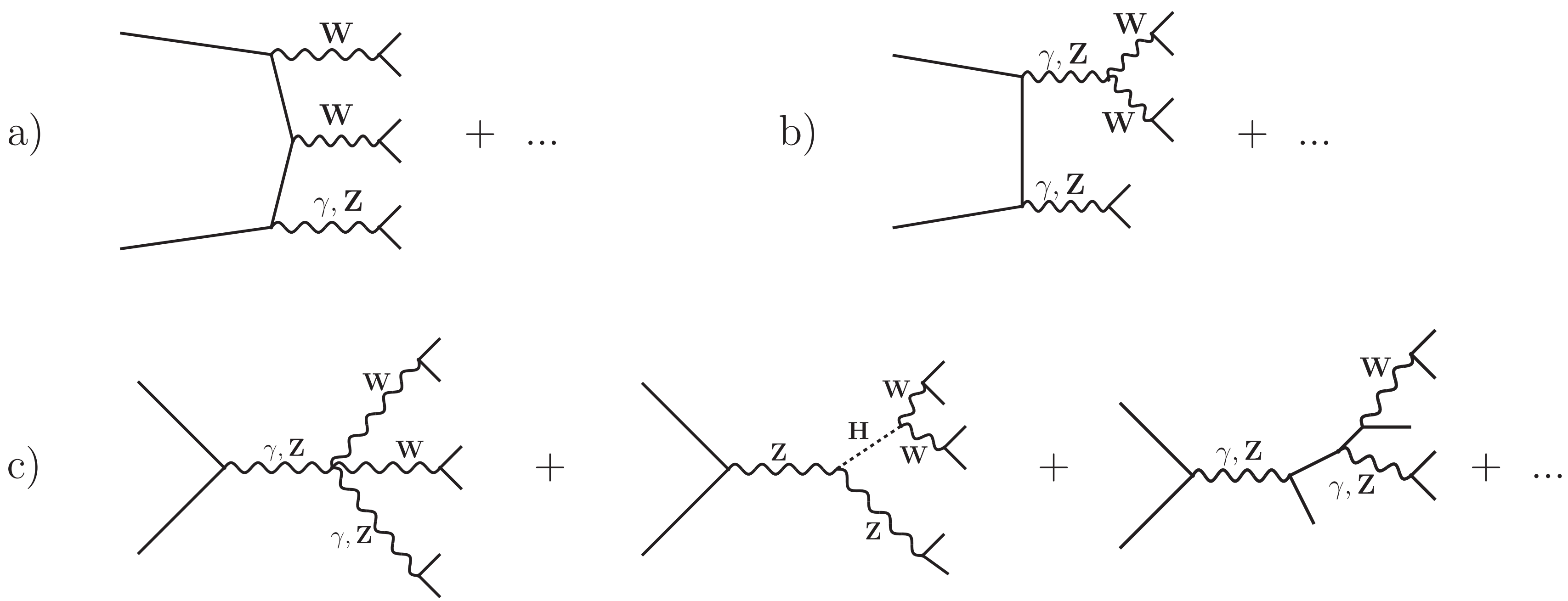
- $ZZW^\pm$ and $W^\pm W^\mp W^\pm$ production with leptonic decays.
  [Campanario, Hankele, Oleari, Prestel, Zeppenfeld]

- $W^+W^-\gamma$ and $ZZ\gamma$ production with leptonic decays.
  [Bozzi, Campanario, Hankele, Zeppenfeld]

- $W^\pm\gamma j$, $W^\pm Z j$ and $Z\gamma j$ production with leptonic decays and final state photon radiation
  [Englert, Campanario, Kallweit, Spannowsky, Zeppenfeld]

Code is available at
http://www-itp.particle.uni-karlsruhe.de/~vbfnloweb

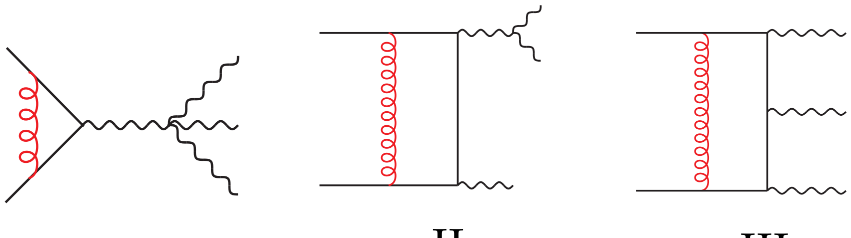
Contributions to WWZ production



- All resonant and non-resonant matrix elements as well as spin correlations of final state leptons and Higgs contribution included.
- Interference terms due to identical particles in the final state have been neglected.
- All fermion mass effects neglected. ($H\tau\tau$-coupling = 0)

1-loop matrix elements and real emission matrix elements

Three different topologies:



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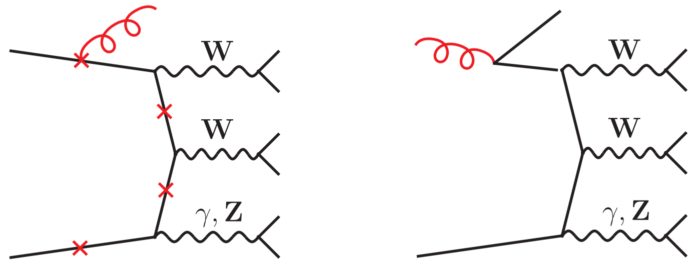


I Vertex correction proportional to Born matrix element.

II Maximally 4-point integrals appear.

III Up to five external legs (Pentagons):

- Two independent calculations.
- Numerically stable results with Denner Dittmaier method.

- Two different classes: final state gluon and initial state gluon.
- Each of them consists of several hundred Feynman-Graphs.
- No initial state gluon contribution at LO.

Input variables for LHC phenomenology

- **PDFs**: CTEQ6L1 at LO and CTEQ6M, $\alpha_S(m_Z) = 0.118$ at NLO.

- **Cuts and Masses**:

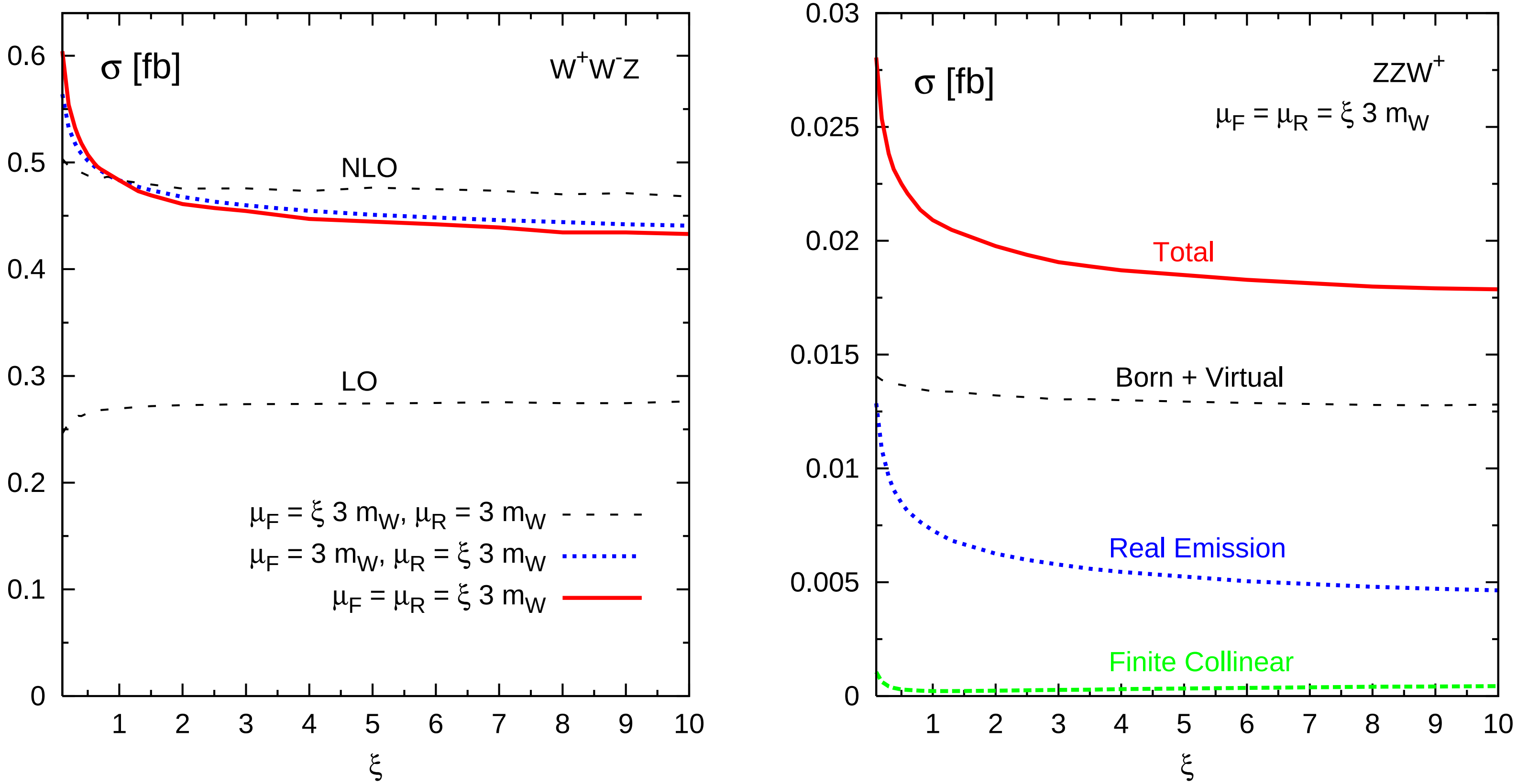
$$p_{T_\ell} > 10 \text{ GeV}, \qquad |\eta_\ell| < 2.5, \qquad m_{\ell^+\ell^-} > 15 \text{ GeV}, \qquad m_H = 120 \text{ GeV}.$$

- **Renormalization- and Factorization Scale**: $\mu_F = \mu_R = 3\, m_W$.

Following results are for electrons and/or muons in the final state:

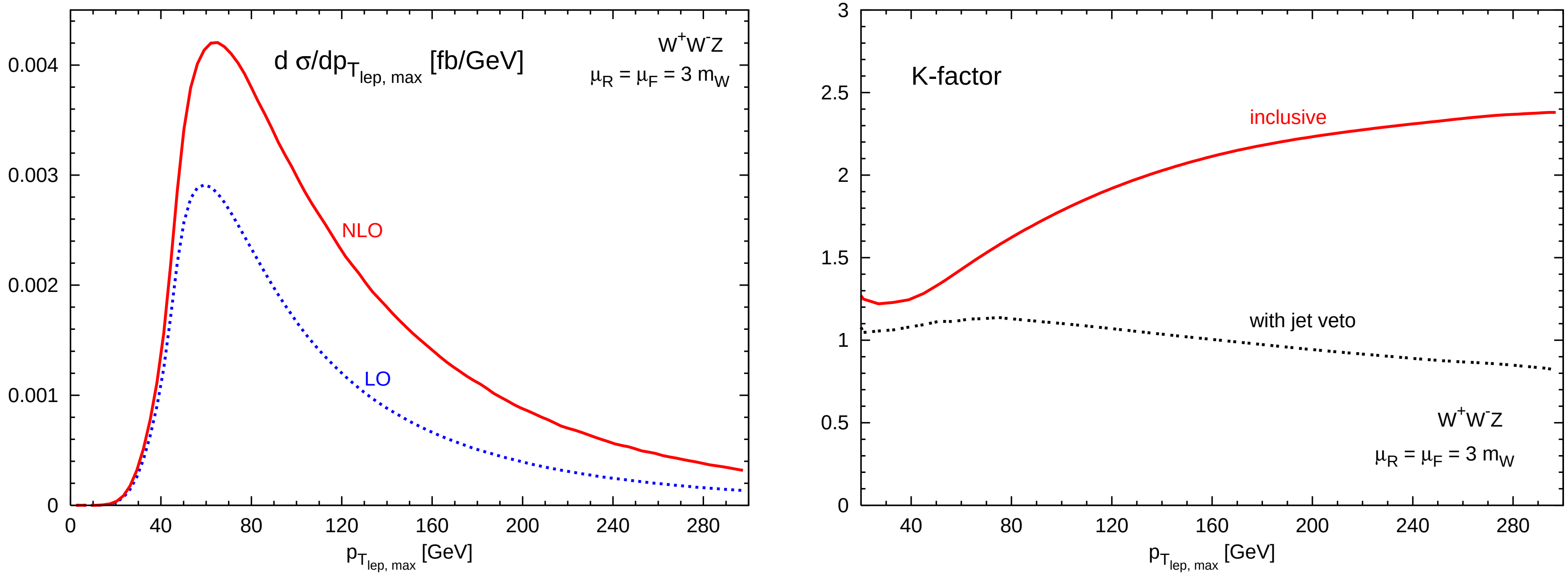
$\Longrightarrow$ Combinatorial factor of 8/4 for the $W^+W^-Z/ZZW^\pm$ production compared to three different lepton families in the final state.

Scale Dependence



- At LO only small μ_F-dependence, no $\alpha_s(\mu_R)$.
- At NLO scale dependence is dominated by $\alpha_s(\mu_R)$.
- Real emission contribution drives overall scale dependence at NLO.

Differential cross section and K-factor for the highest-p_T-lepton



- K-factor increases with transverse momentum (p_T) by almost a factor of 2.
- Strong phase space dependence due to events with high p_T jets recoiling against the leptons.
- Veto on jets with $p_T > 50$ GeV leads to flat K-factor.

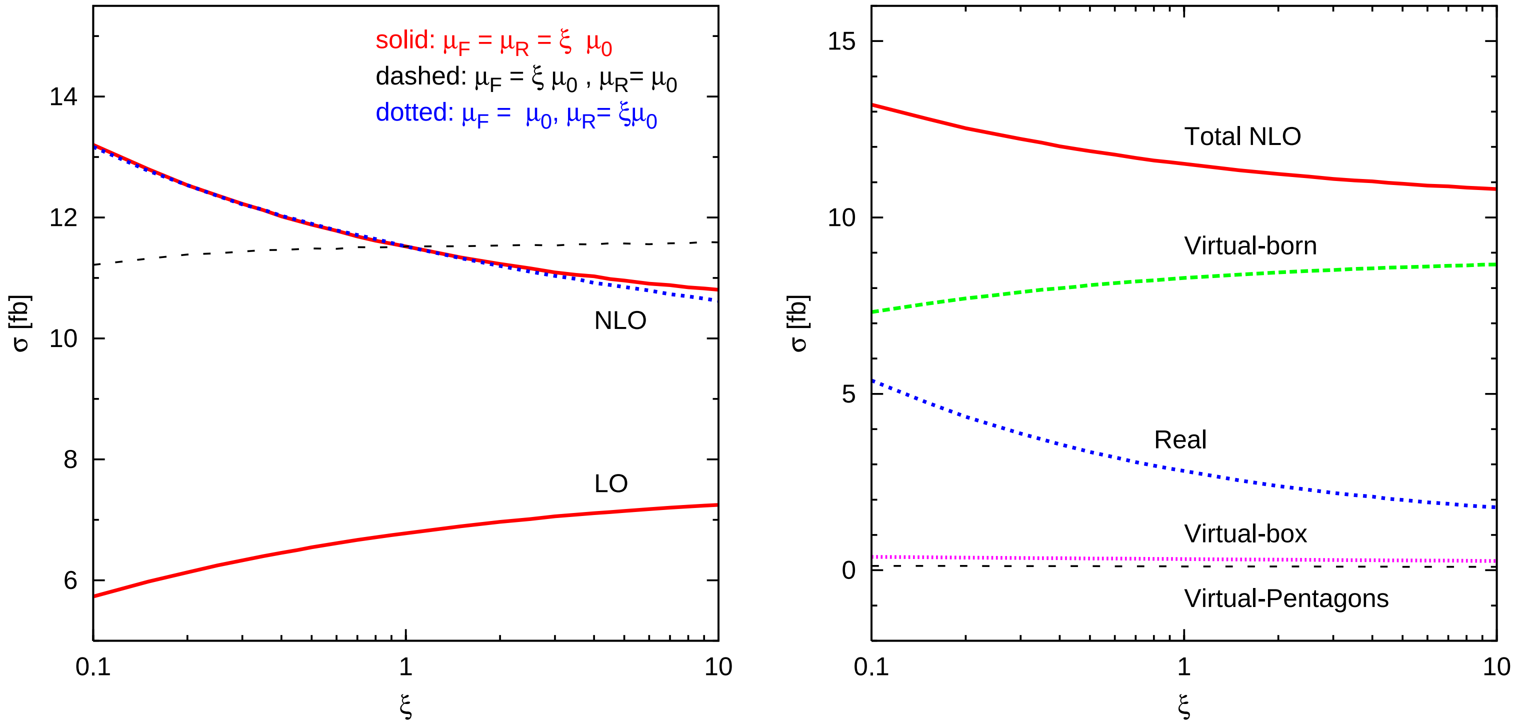
Extension to $W^+W^-\gamma$ and $ZZ\gamma$ production

- DIfferent infrared divergence structure of individual loop integrals but same finite virtual expressions in terms of finite parts od C_{ij}, D_{ij}, E_{ij} functions
- Photon isolation from jets for real emission contributions: use Frixione isolation

$$\Sigma_i E_{T_i} \theta(\delta - R_{i\gamma}) \leq p_{T_\gamma} \frac{1 - \cos\delta}{1 - \cos\delta_0}$$

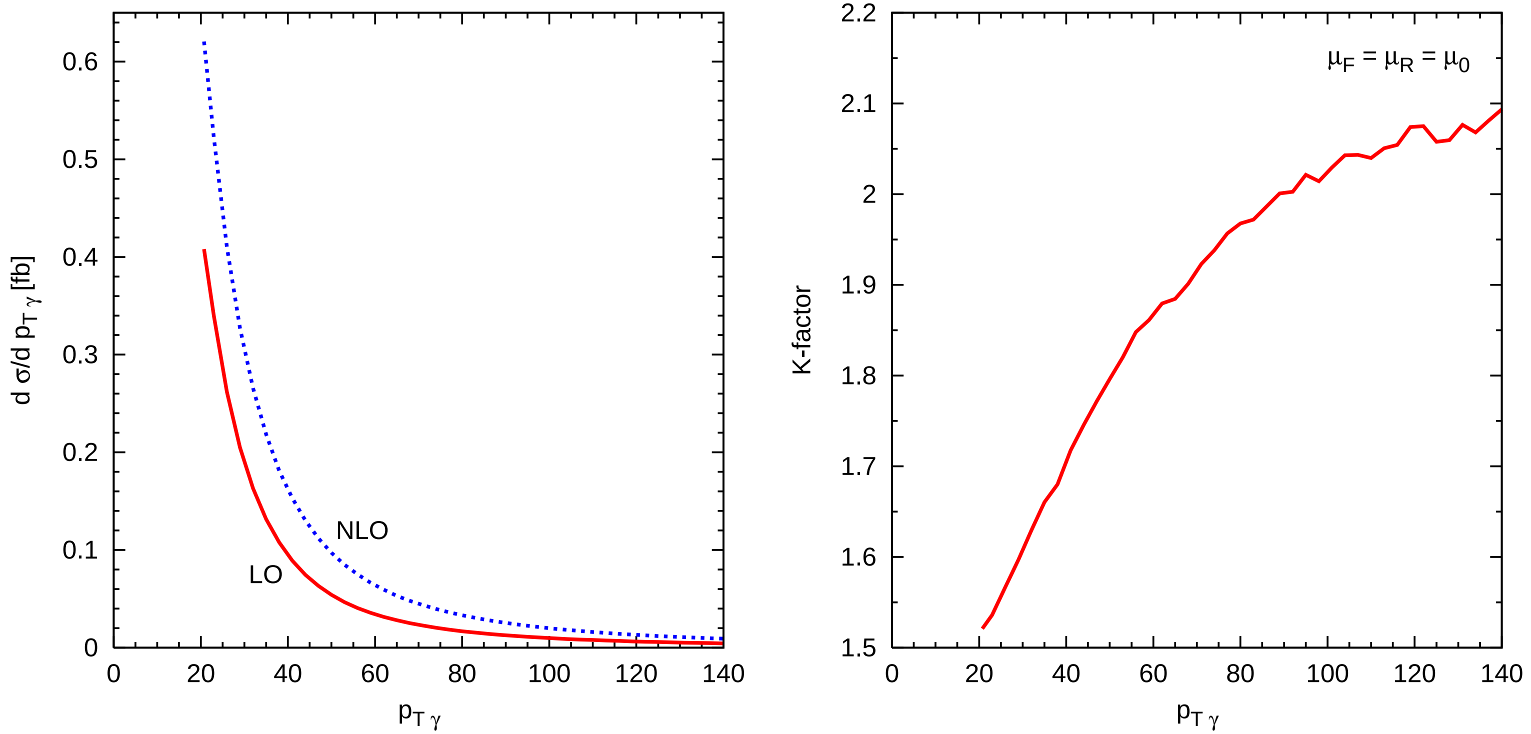
- Final state photon radiation becomes important: adapt phase space to this

Scale dependence of integrated cross sections



- Behaviour similar to VVV production: LO scale variation much smaller than NLO correction
- NLO scale dependence largely due to real emission contributions → jet veto will reduce it
- Box and pentagon contributions are quite small: 3% and 1% of total

NLO Corrections to distributions: p_T of photon



- Strong phase space dependence of K-factors (depends on LO scale choice)

Conclusions

- NLO QCD corrections to $pp \to$ VVV + X are Standard Model background processes for new-physics searches and are sensitive to quartic electroweak couplings.
- All off-shell diagrams as well as the Higgs-contributions have been considered.
- The K-factor is sizeable and NLO corrections lead to substantial shape changes of lepton distributions.
- Sizable scale dependence of the NLO cross section, small scale dependence at LO.
- New release of `VBFNLO` includes NLO QCD corrections for W^+W^-Z, $ZZW^\pm$, $W^\pm W^\mp W^\pm$, $WW\gamma, ZZ\gamma.WZ\gamma$ production at hadron colliders
- Ongoing activity: $pp \to W\gamma\gamma, Z\gamma\gamma.WZ\gamma$

Code is available at http://www-itp.particle.uni-karlsruhe.de/~vbfnloweb

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