QCD CORRECTIONS IN VBFNLO

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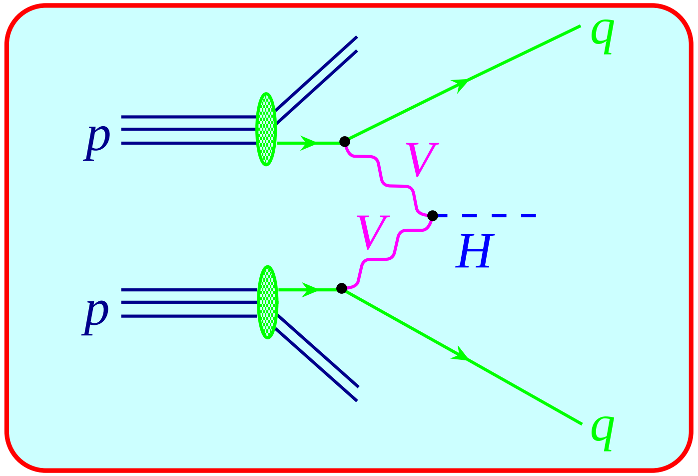
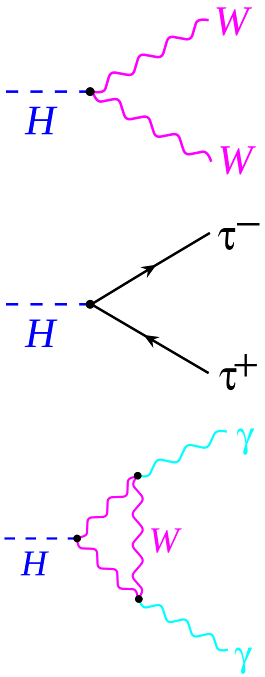
Mini-Workshop on PDFs and Standard Candles at the LHC

Karlsruhe, March19, 2012

- Vector Boson Fusion
- NLO QCD corrections to VV scattering
- Other NLO QCD processes in VBFNLO
- Conclusions

Vector Boson Fusion





$m_H > 120$ GeV

$m_H < 140$ GeV

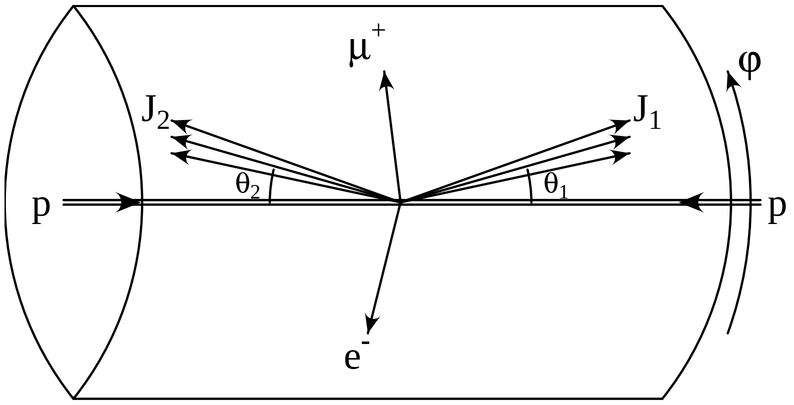
$m_H < 150$ GeV

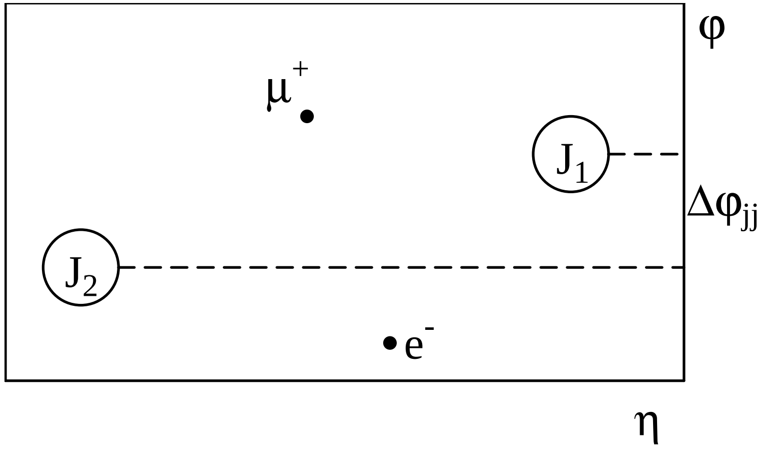
[Eboli, Hagiwara, Kauer, Plehn, Rainwater, D.Z. . . .]

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%.

Would like theory errors below 5% $\Longrightarrow$ Need NLO corrections

VBF signature





Characteristics:

- energetic jets in the forward and backward directions ($p_T > 20$ GeV)
- large rapidity separation and large invariant mass of the two tagging jets
- 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 between tagging jets)

NLO QCD corrections to VBF

- Small QCD corrections of $\mathcal{O}(10\%)$
- Tiny scale dependence at NLO
  - $\pm 5\%$ for distributions
  - $< 2\%$ for σ_{total}
- K-factor is phase space dependent
- QCD corrections under excellent control

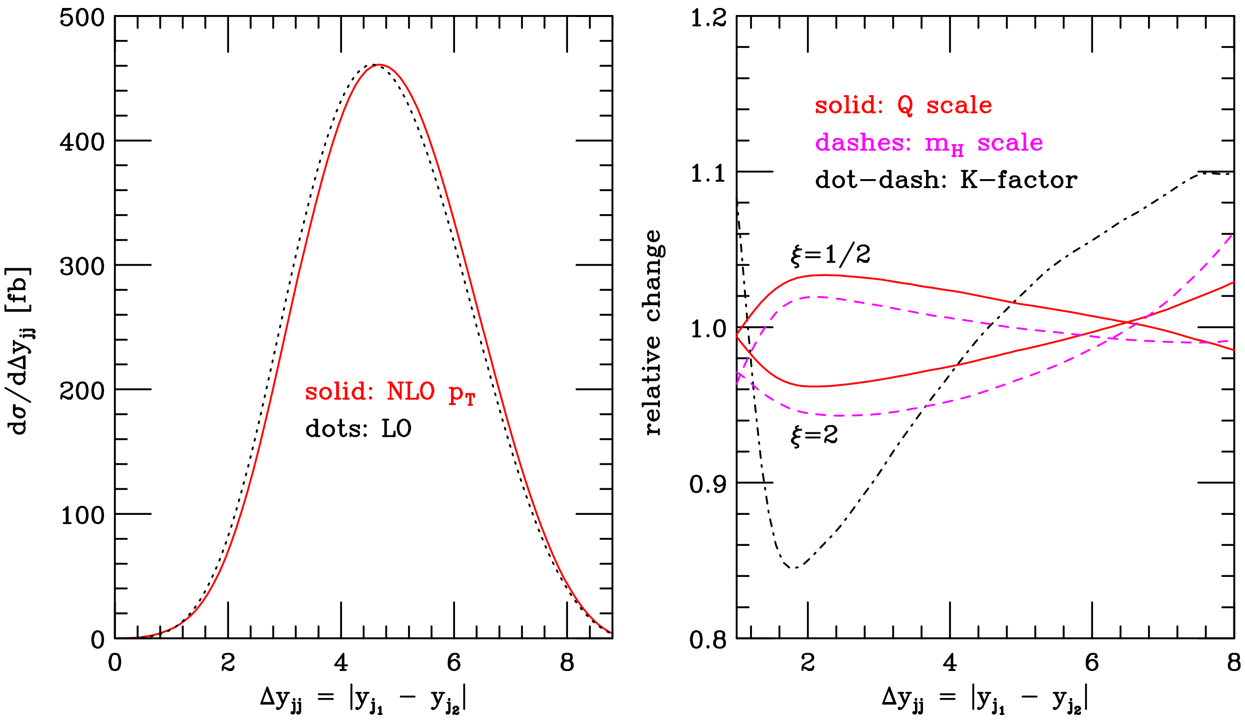
  confirmed by NNLO corrections to inclusive VBF cross section

  Bolzoni, Maltoni, Moch, Zaro arXiv:1003.4451

✗ Need electroweak corrections for 5% uncertainty

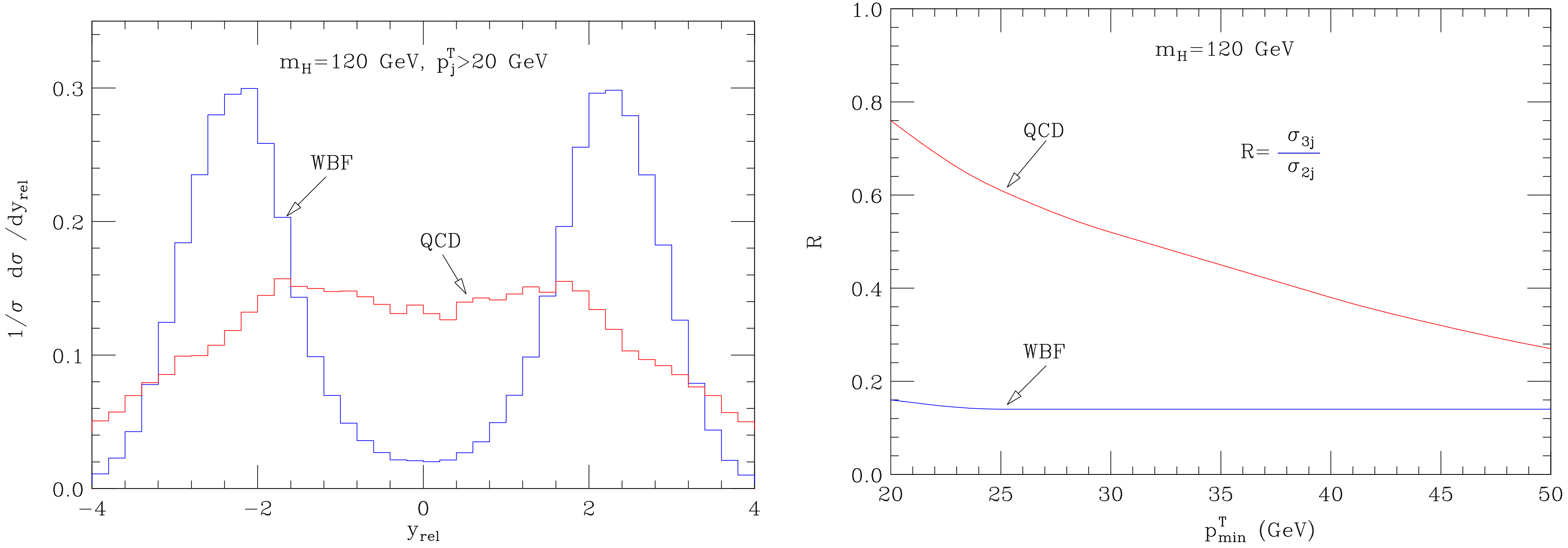
Ciccolini, Denner, Dittmaier, 0710.4749

Figy, Palmer, Weiglein arXiv:1012.4789



$m_H = 120$ GeV, typical VBF cuts

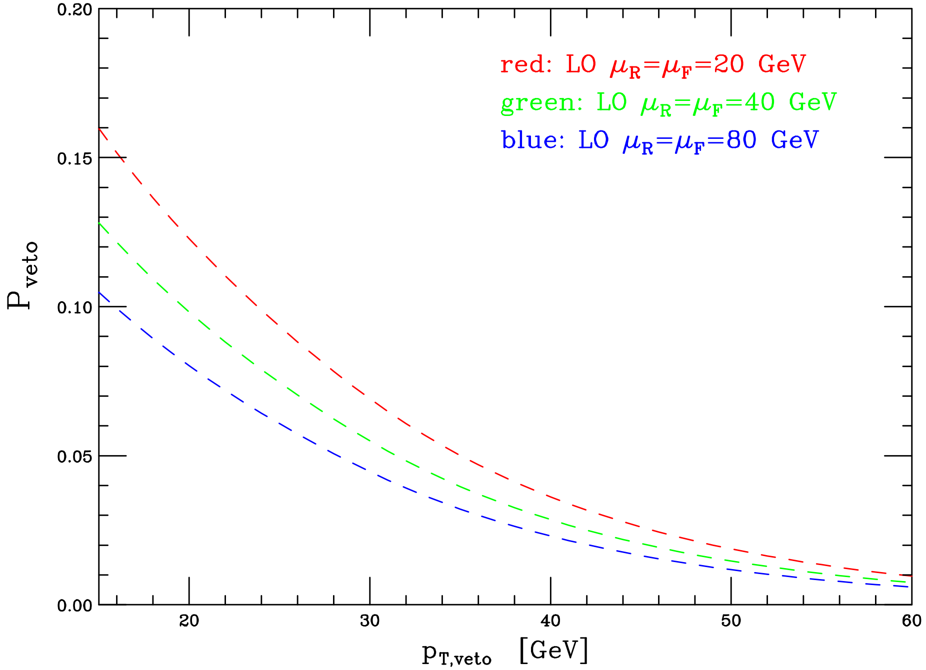
Central Jet Veto: $Hjjj$ from VBF vs. gluon fusion



[Del Duca, Frizzo, Maltoni, JHEP 05 (2004) 064]

- Angular distribution of third (softest) jet follows classically expected radiation pattern
- QCD events have higher effective scale and thus produce harder radiation than VBF (larger three jet to two jet ratio for QCD events)
- Central jet veto can be used to distinguish Higgs production via GF from VBF

VBF Higgs signal and CJV



$$p_{Tj}^{veto} > p_{T,veto}, \quad \eta_j^{veto} \in (\eta_j^{\text{tag 1}}, \eta_j^{\text{tag 2}})$$

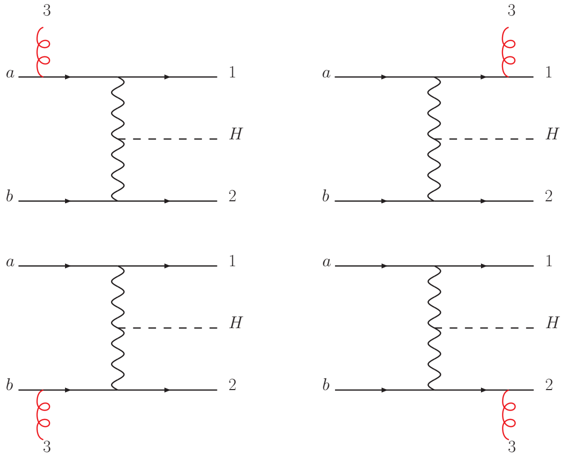
$$P_{\text{veto}} = \frac{1}{\sigma_2^{NLO}} \int_{p_{T,veto}}^{\infty} dp_{Tj}^{veto} \frac{d\sigma_3^{LO}}{dp_{Tj}^{veto}}$$

- Scale variation at LO for σ_{3j}: $+33\%$ to -17% for $p_{T,veto} = 15$ GeV
- The uncertainty in P_{veto} feeds into the uncertainty of coupling measurements at the LHC
- In order to constrain couplings more precisely, the NLO QCD corrections to $Hjjj$ are needed: T. Figy, V. Hankele, and DZ, arXiv:0710.5621 (JHEP)

Ingredients of the NLO Calculation

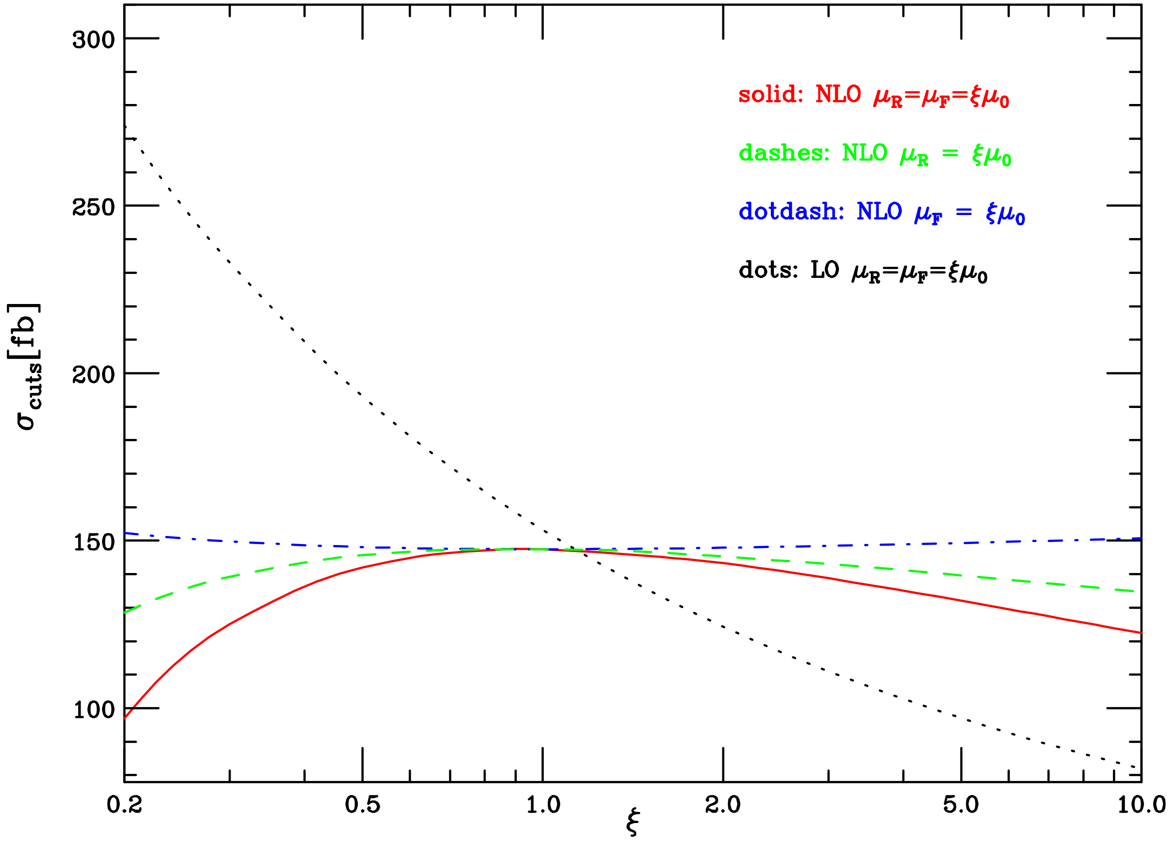
- Born: 3 final state partons + Higgs via VBF

$$\mathcal{M}_B = \delta_{i_2 i_b} t^{a_3}_{i_1 i_a} \Big[\mathcal{M}_{B,1a} : \qquad \Big] + \delta_{i_1 i_a} t^{a_3}_{i_2 i_b} \Big[\mathcal{M}_{B,2b} : \qquad \Big]$$



- Catani, Seymour subtraction method
- Real: 4 final state partons + Higgs via VBF
- Virtual: Two classes of gauge invariant subsets
  - Box + Vertex + Propagator
  - Pentagon + Hexagon are small and can be neglected

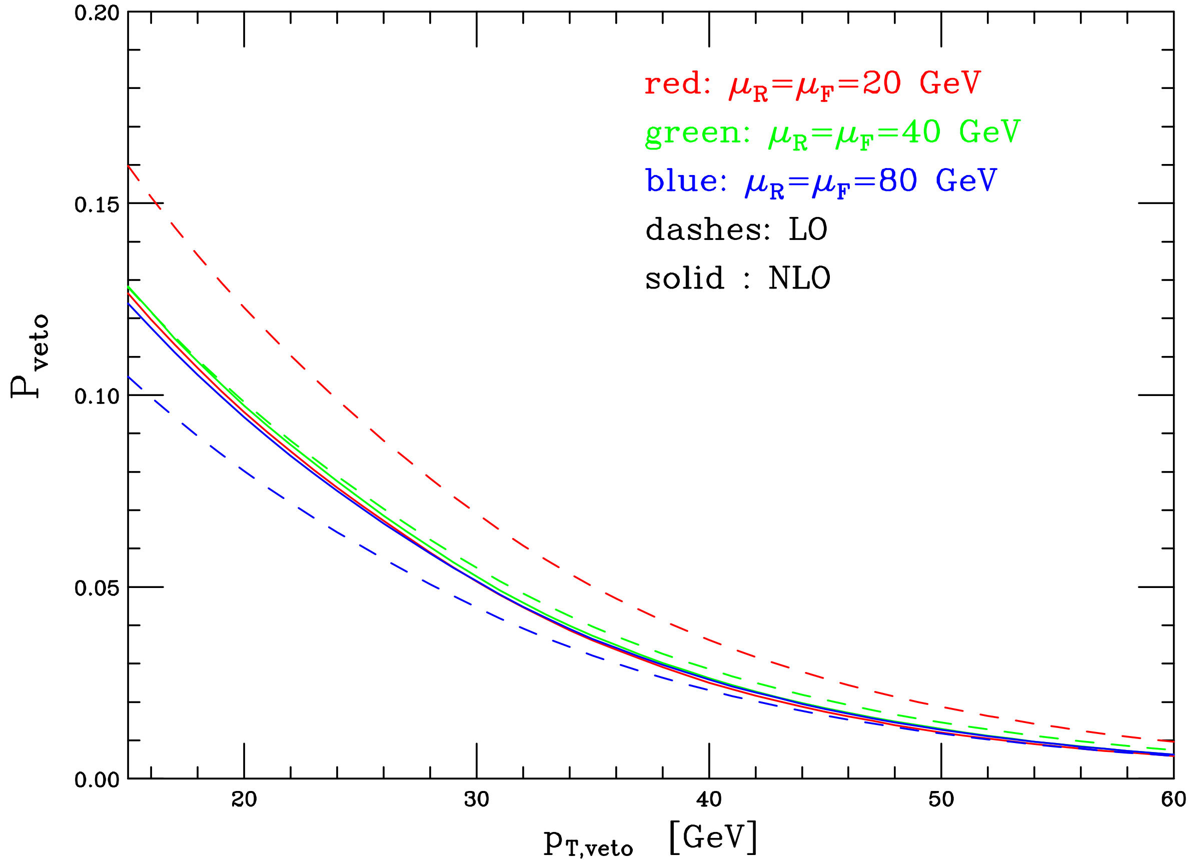
Total $Hjjj$ Cross Section at the LHC: NLO vs LO



$\mu_0 = 40$ GeV
$\xi = 2^{\mp 1}$ scale variations:

- LO: $+26\%$ to -19%
- NLO: less than 5%

Veto Probability for the VBF Signal



$$P_{\text{veto}} = \frac{1}{\sigma_2^{NLO}} \int_{p_{T,veto}}^{\infty} dp_{Tj}^{veto} \frac{d\sigma_3}{dp_{Tj}^{veto}}$$

Scale variations, $p_{T,veto} = 15$ GeV:

- LO: +33% to −17%
- NLO: −1.4% to −3.4%

Reliable prediction for perturbative part of veto probability at NLO

NLO corrections available in VBFNLO

Parton level Monte Carlo programs for various NLO calculations, including

- QCD corrections for Higgs production via VBF

  Figy, Oleari, DZ

  Now includes electroweak and SUSY corrections to VBF Higgs production

  Figy,Palmer,Weiglein

- QCD corrections to Higgs plus 3 jet production in VBF

  Figy,Hankele, DZ

- QCD corrections to VBF W and Z production ($qq \rightarrow qqV$)

  Oleari, DZ

- QCD corrections to weak boson scattering processes ($qq \rightarrow qqVV$)

  Jäger, Oleari, DZ

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

Limitations of the $qq \to qqH$ picture

At $m_H >$ few hundred GeV (for say $\Gamma_H/m_H > 0.1$) we need to take interference with continuum electroweak into account

Implication:

- Consider full processes $qq \to qqVV$ or $qq \to qq\bar{f}_1 f_2 \bar{f}_3 f_4$
- s-channel Higgs exchange graph with inverse propagator

$$\Delta_H(s) = s - s_H = s - m_H^2 + i m_H \Gamma_H$$

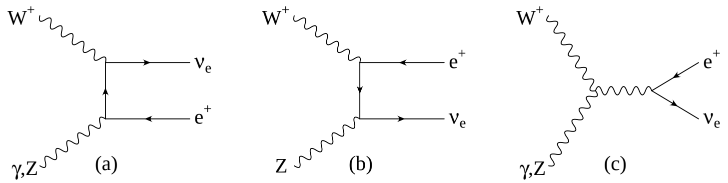
is just one contribution.

Note: m_H and Γ_H should be treated as free parameters for heavy Higgs
(Γ_H should not necessarily be calculated in SM because EW precision tests give $m_H < 152$ GeV: for larger m_H there must be BSM effects which should also affect the relation between m_H and Γ_H as well as HVV couplings)

Weak boson scattering: $qq\to qqWW$, $qqZZ$, $qqWZ$ at NLO

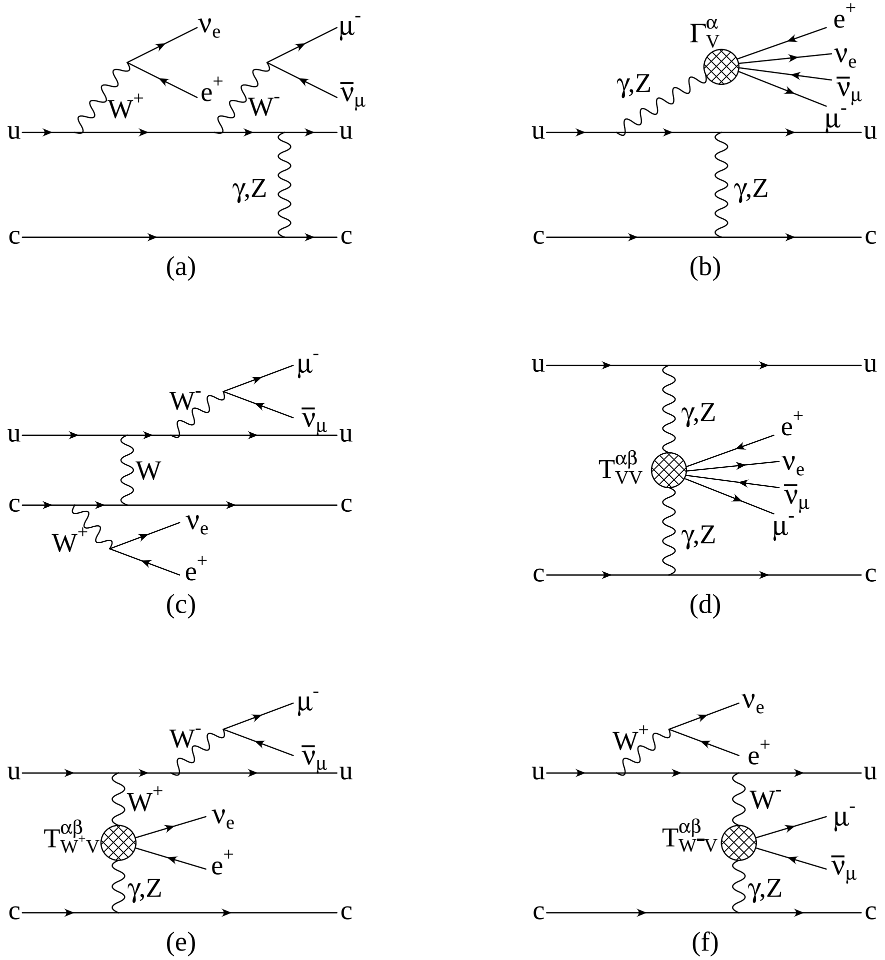
- example: WW production via VBF with leptonic decays: $pp \to e^+\nu_e\mu^-\bar{\nu}_\mu + 2j$
- Spin correlations of the final state leptons
- All resonant and non-resonant Feynman diagrams included
- NC $\Longrightarrow$ 181 Feynman diagrams at LO
- CC $\Longrightarrow$ 92 Feynman diagrams at LO

Use modular structure, e.g. leptonic tensor



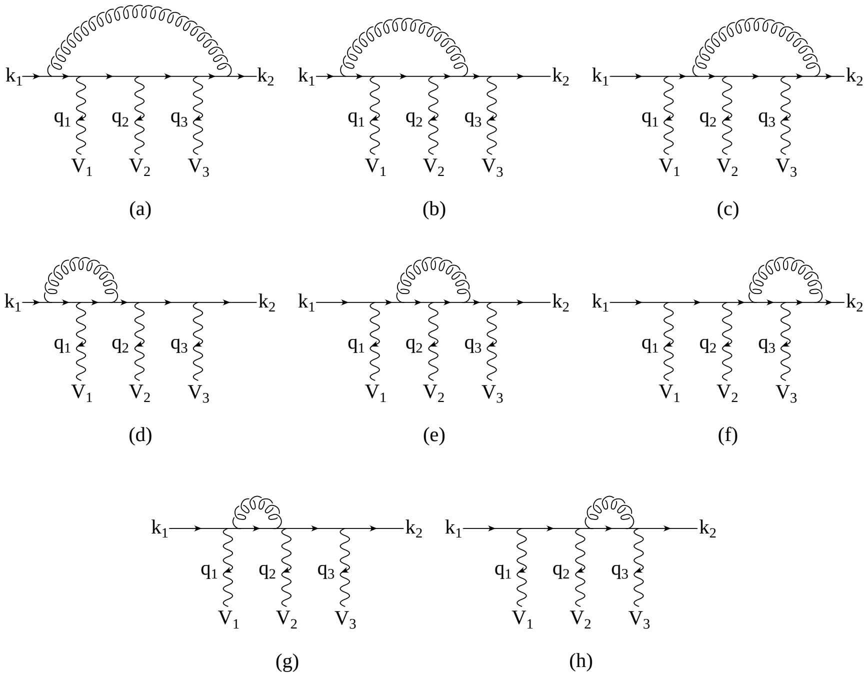
Calculate once, reuse in different processes

Speedup factor ≈ 70 compared to MadGraph for real emission corrections



Most challenging for virtual: pentagon 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

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

- 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

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

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

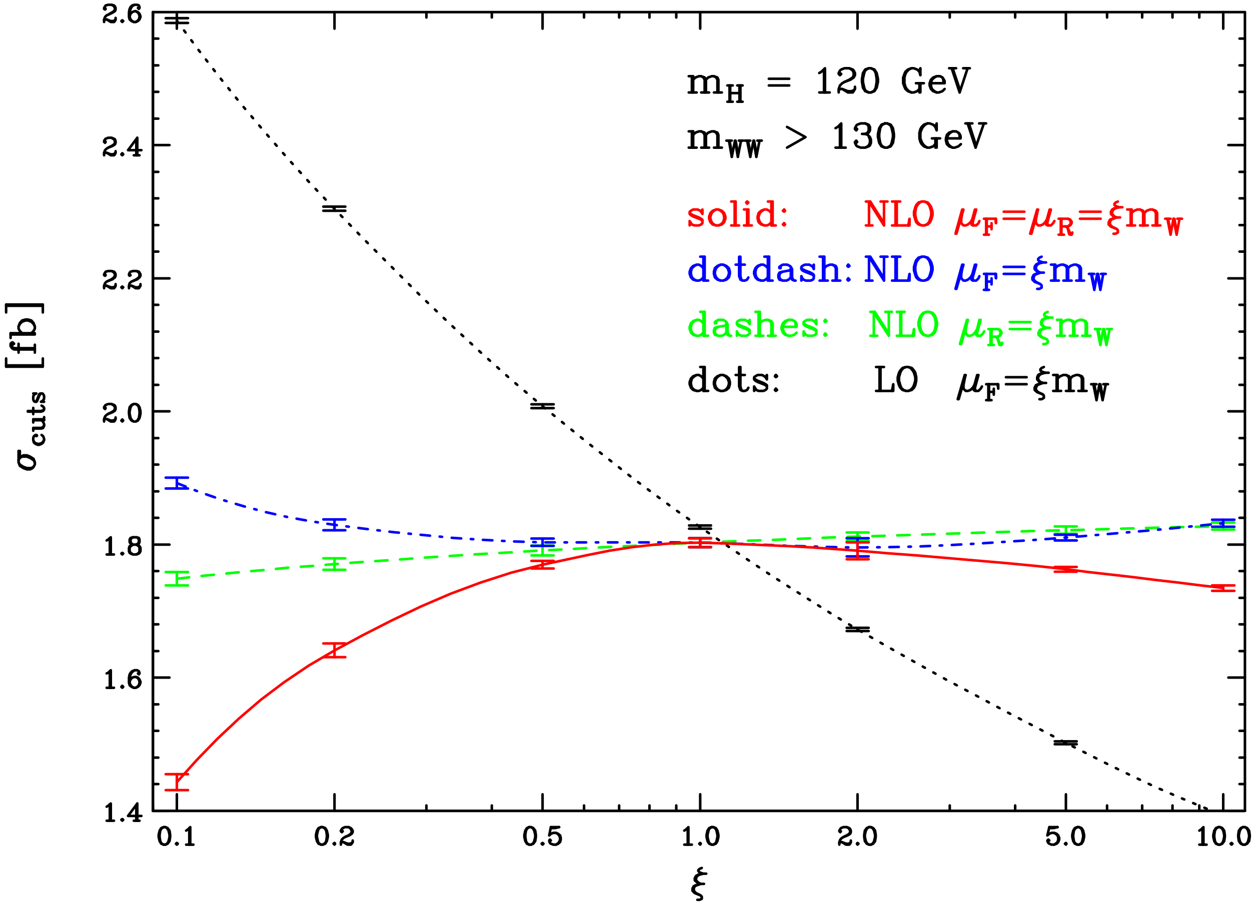
For scale dependence studies we have considered

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

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

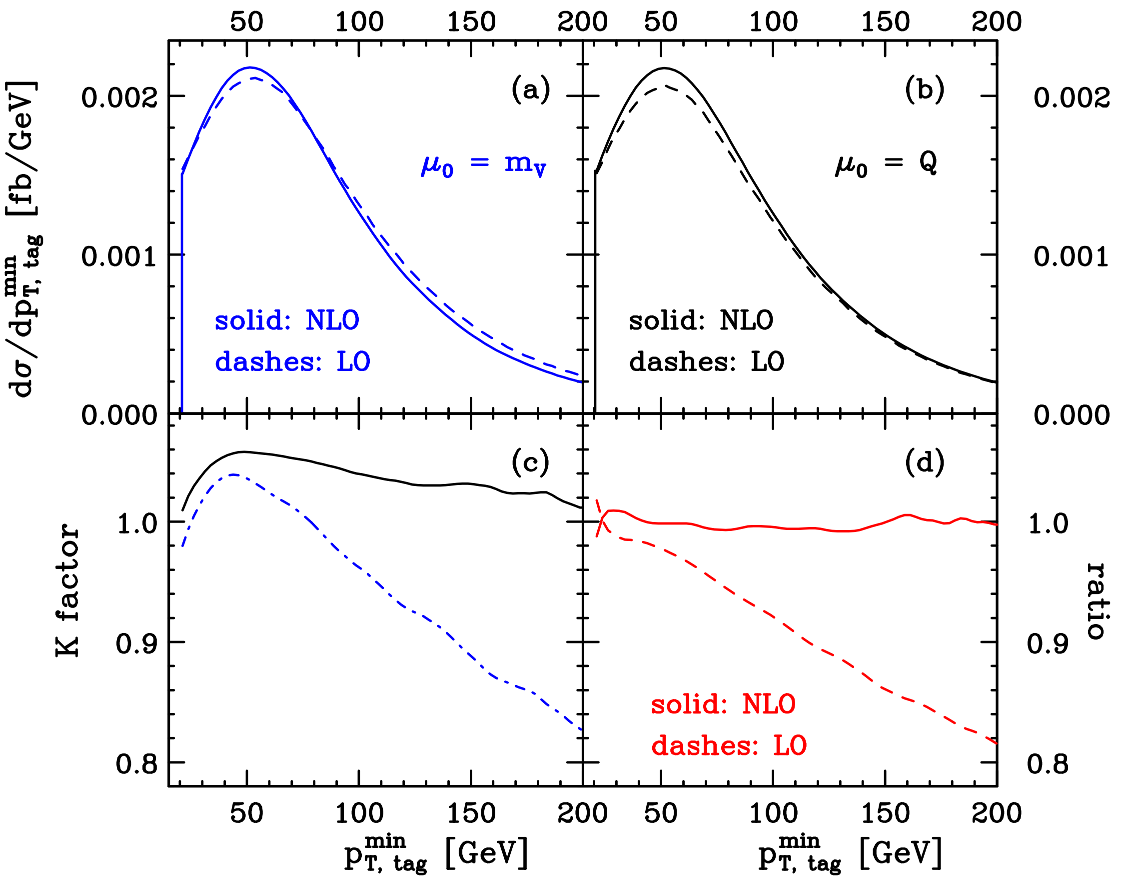
Stabilization of scale dependence at NLO

Jäger, Oleari, DZ hep-ph/0603177



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

Transverse momentum distribution of the softer tagging jet

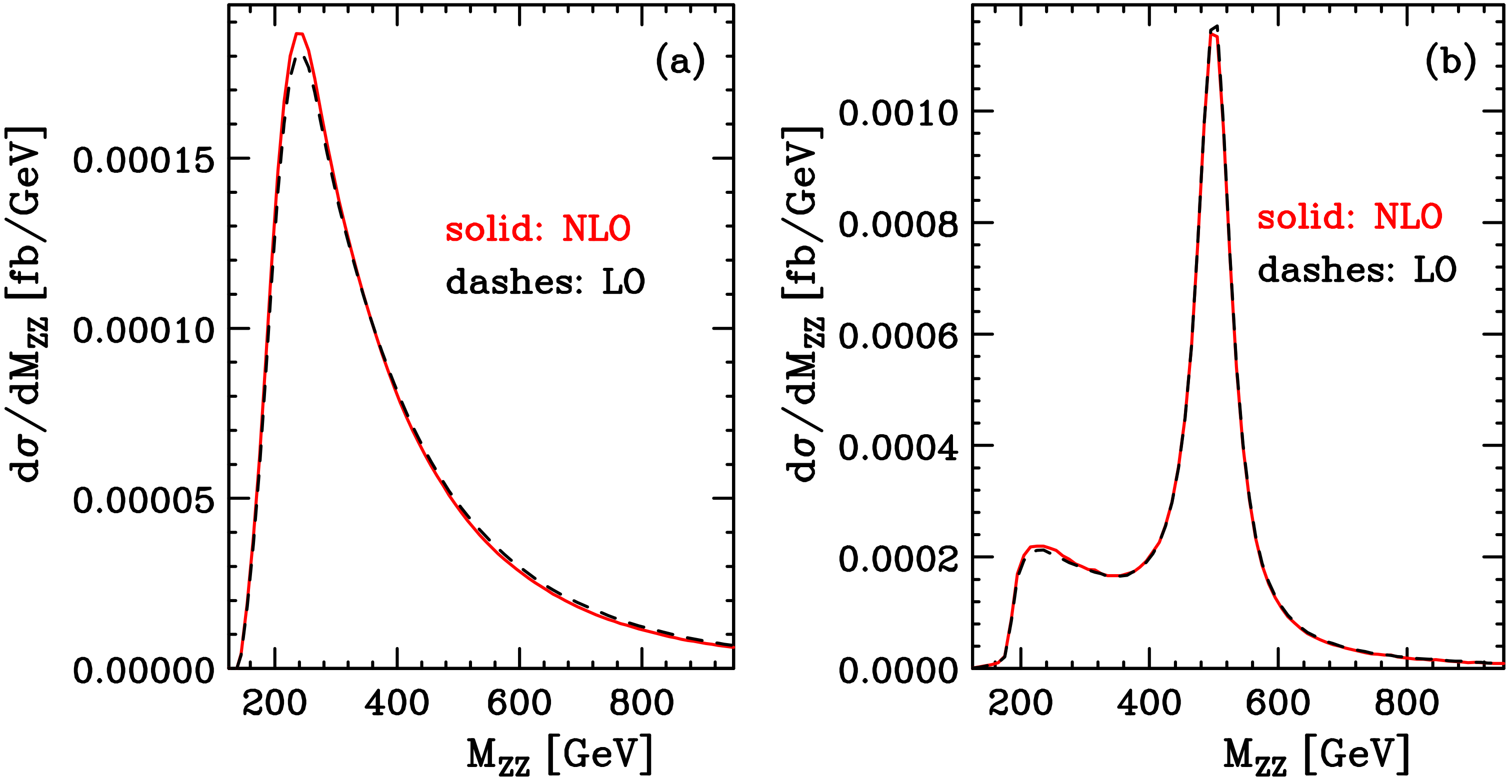


- Shape comparison LO vs. NLO depends on scale
- Scale choice $\mu = Q$ produces approximately constant K-factor
- Ratio of NLO curves for different scales is unity to better than 2%: scale choice matters very little at NLO

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

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

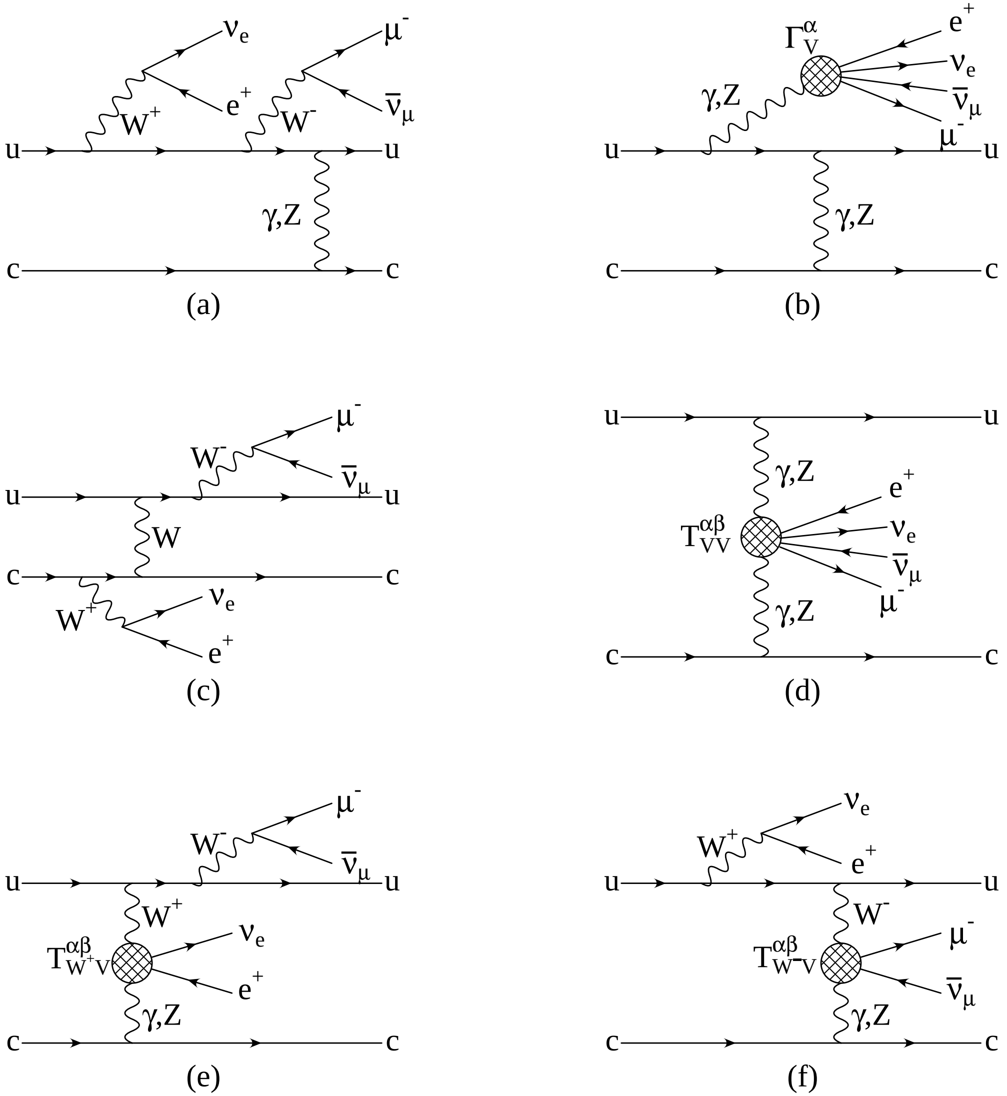
4-lepton invariant mass distribution without/with Higgs resonance



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 $m_{4\ell}$

$qq\to qqVV$: 3 weak bosons on a quark line

- NLO corrections to $qq\to qqVV$ contain all loops with a virtual gluon attached to a quark line with one, two or three weak bosons
- Crossing and replacing one quark line by a lepton line yields $q\bar{q}\to VVV$ production processes with leptonic decays of the weak bosons
- Recycle virtual contributions from NLO corrections to VBF
- Decompose calculation into modules which can be used in different NLO calculations



Extending VBFNLO: VVV and VVj Production at NLO QCD

Additional processes implemented in 2008 release of VBFNLO:

- Triple weak boson production: $VVV = W^\pm W^\mp W^\pm$, W^+W^-Z and $W^\pm ZZ$ with leptonic decay of the weak bosons and full $H \rightarrow WW$ and $H \rightarrow ZZ$ contributions
  Work in collaboration with V. Hankele, S. Prestel, C. Oleari and F. Campanario

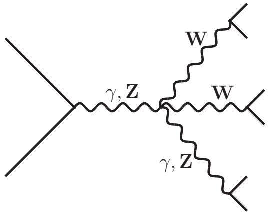
New processes which were made available in 2011 release:

- $W^+W^-\gamma$, $ZZ\gamma$ $WZ\gamma$, $W\gamma\gamma$ production with leptonic decay of weak bosons
  Work in collaboration with G. Bozzi, F. Campanario, M. Rauch, H. Rzehak
- $W^\pm\gamma j$ and WZj production (with W, Z leptonic decay and final state photon radiation)
  Work with C.Englert, F. Campanario, S. Kallweit, M. Spannowsky
- $H\gamma jj$ production in VBF
  Work in collaboration with K. Arnold, B. Jäger, T. Figy
- BSM effects like anomalous couplings and heavy vector resonances

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

VVV Production: Motivation

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

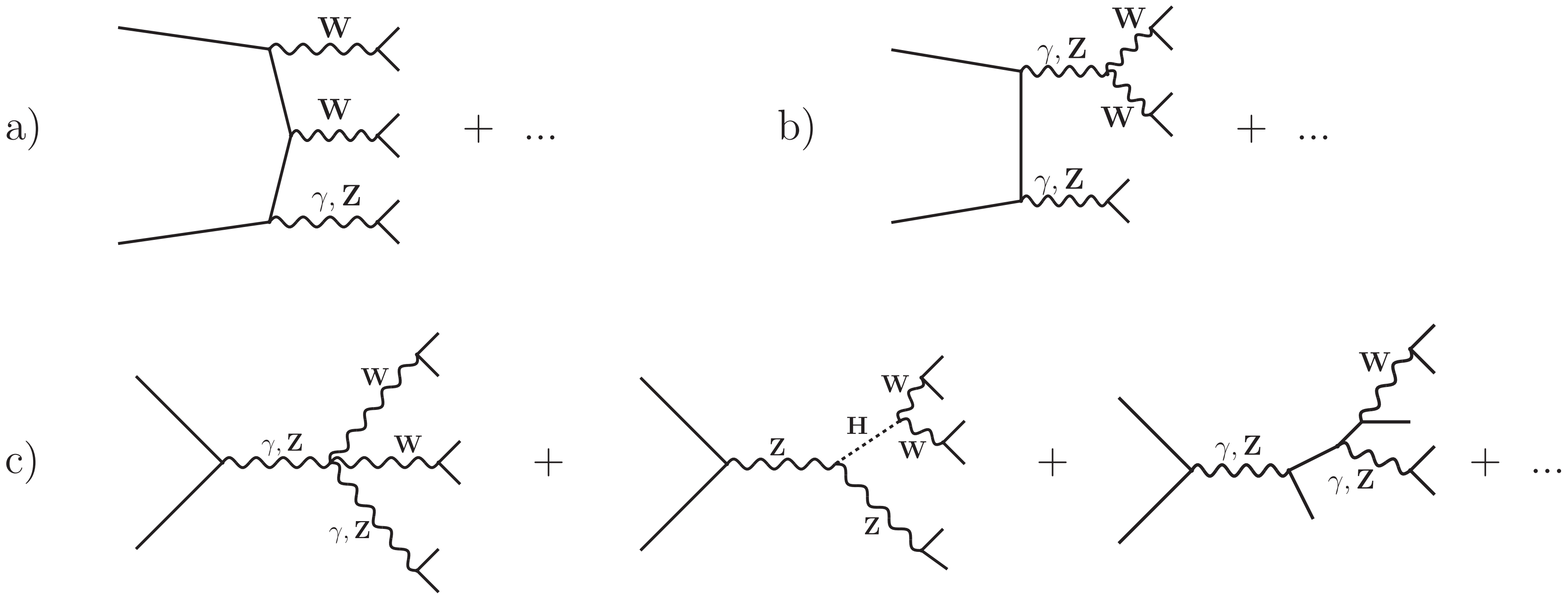


- QCD corrections to $pp\rightarrow$ VVV + X on experimentalist's wishlist:

[The QCD, EW, and Higgs Working Group: hep-ph/0604120]

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

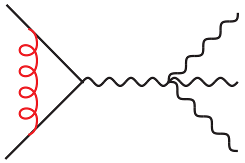
Example: Contributions to WWZ production



- 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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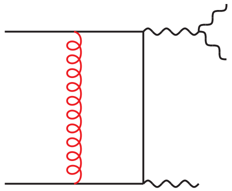

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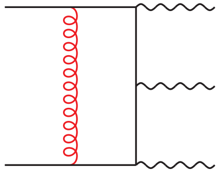
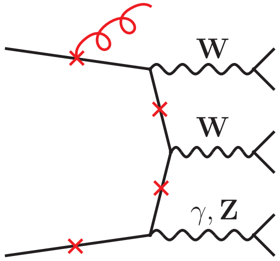
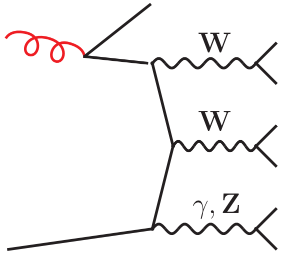


III

- 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.
- Soft and collinear singularities subtracted with Catani-Seymour presription

Input variables for LHC phenomenology

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

- **Cuts and Masses**:

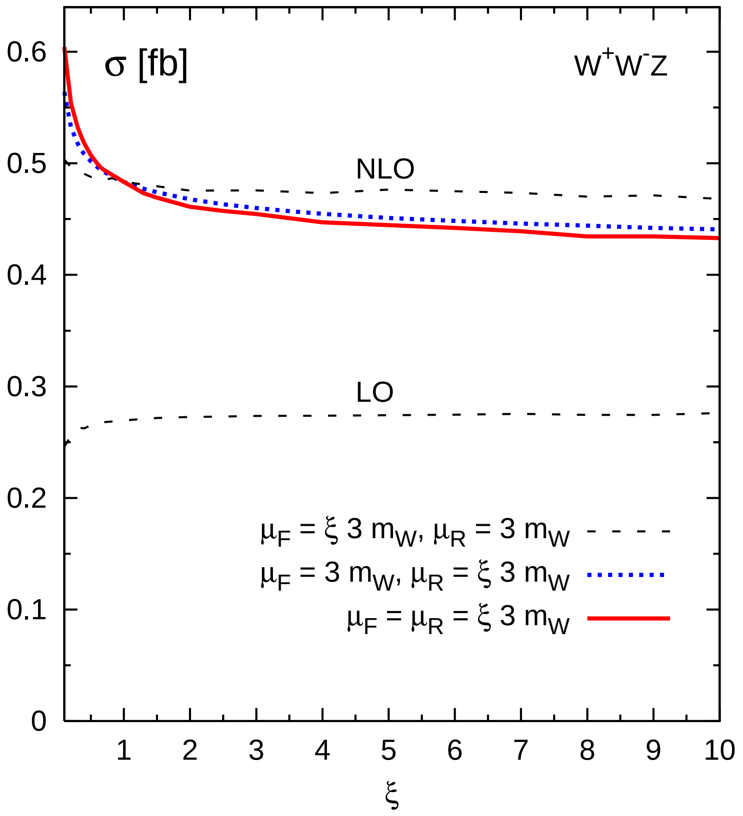
$$p_{T_\ell} > 10\ \text{GeV}, \qquad |\eta_\ell| < 2.5, \qquad m_{\ell^+\ell^-} > 15\ \text{GeV}, \qquad m_H = 120\ \text{GeV}.$$

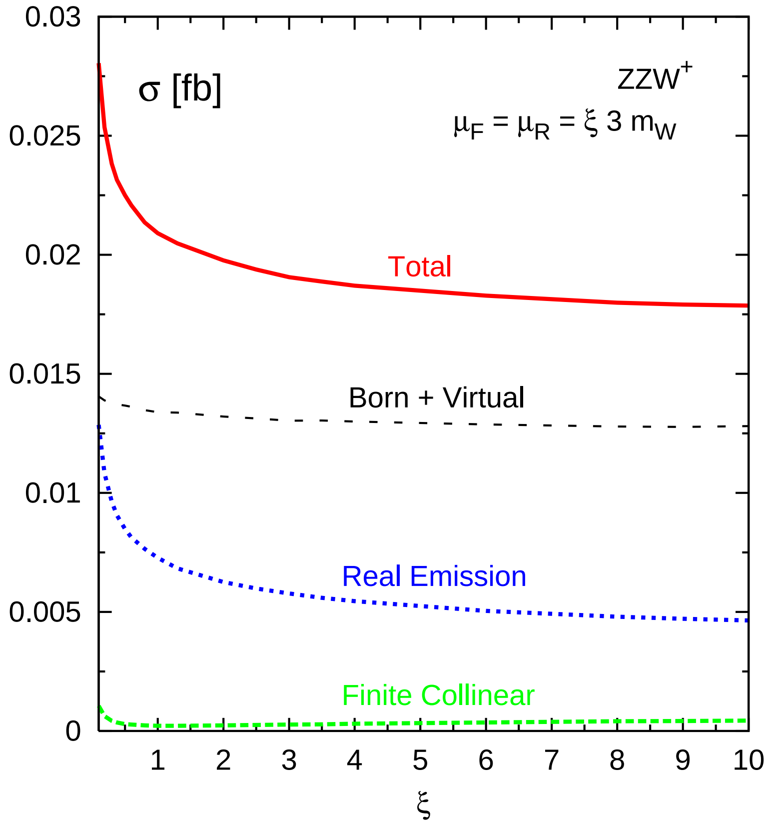
- **Renormalization- and Factorization Scale**: $\mu_F = \mu_R = 3\, m_W$.

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.

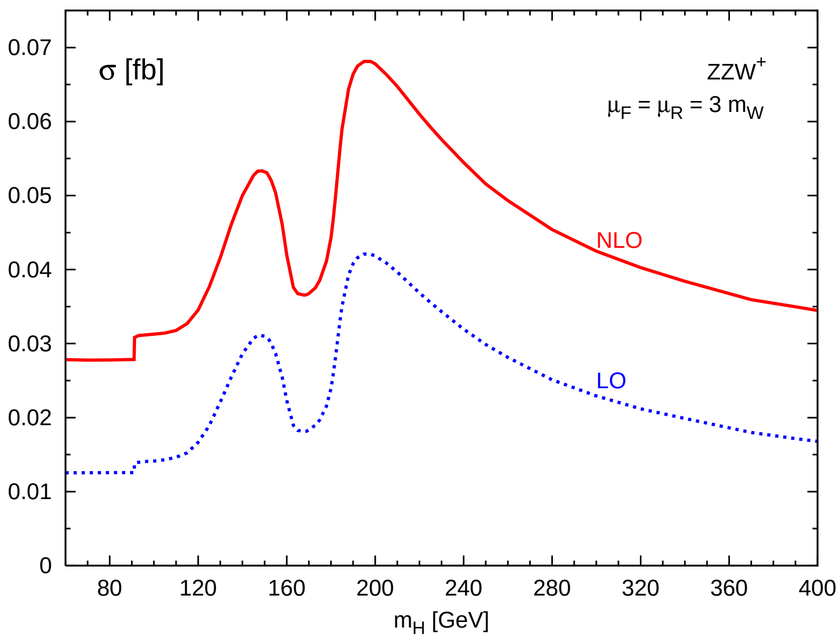
Scale Dependence

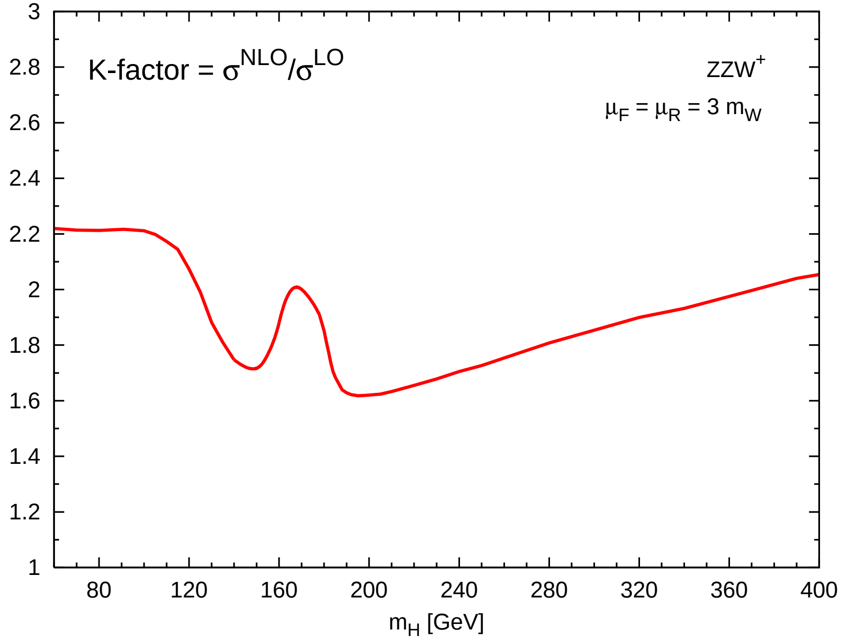


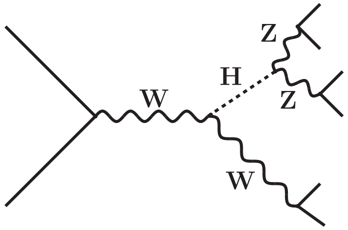


- At LO only small μ_F-dependence, no $\alpha_s(\mu_R)$.
- At NLO scale dependence is dominated by $\alpha_s(\mu_R)$.
- Real emission contribution drives overall scale dependence at NLO.

Higgs mass dependence

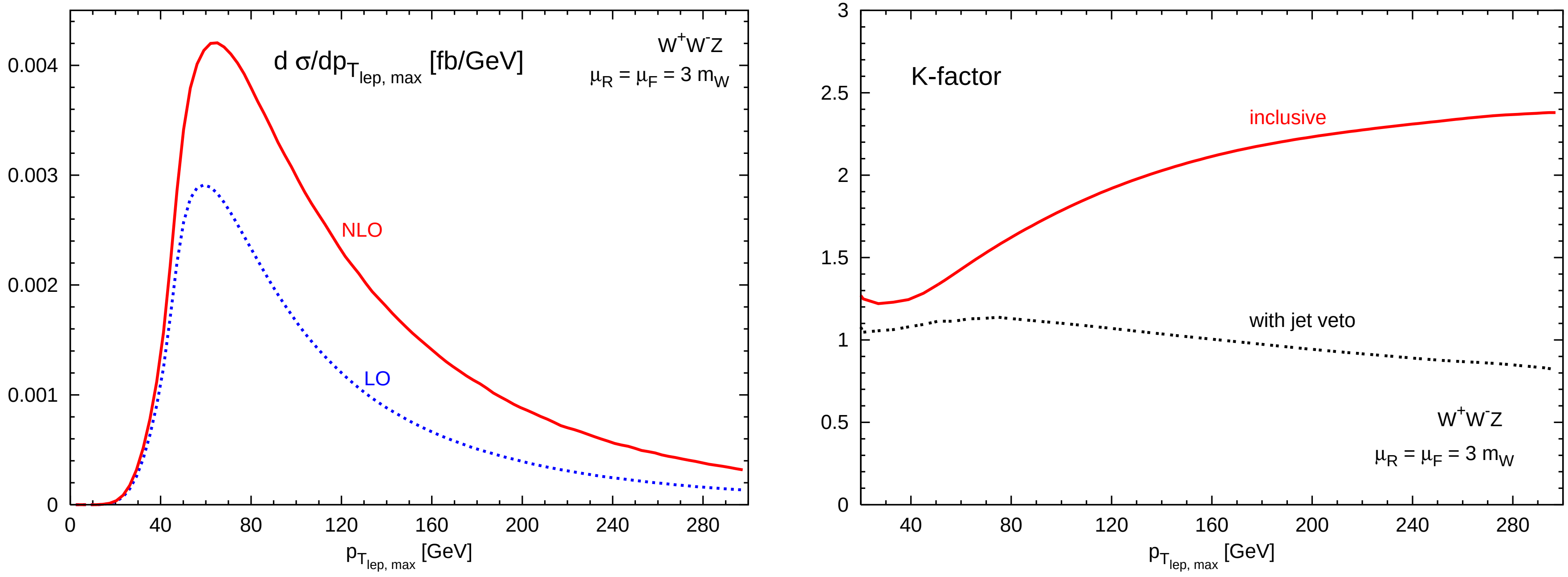






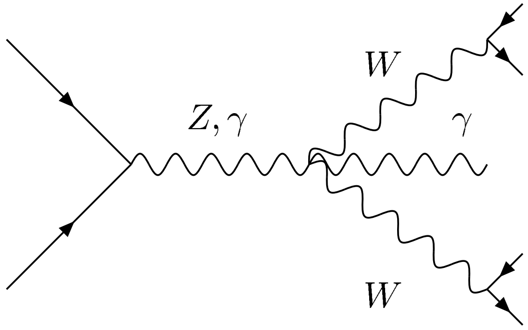
- Cross section reflects behavior of $BR(H \to ZZ)$
- K-factor is reduced by Higgs contribution.
  K-factor for $pp \to ZH$ production is about K = 1.3
  $\Longrightarrow$ Different K-factor for resonance production

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 fairly flat K-factor.

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



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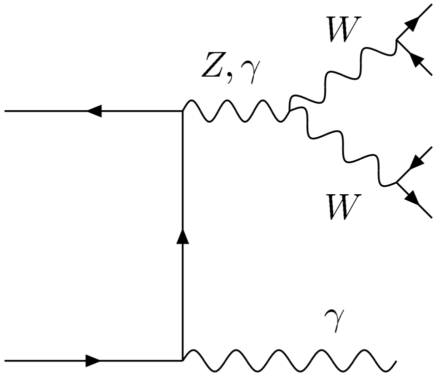

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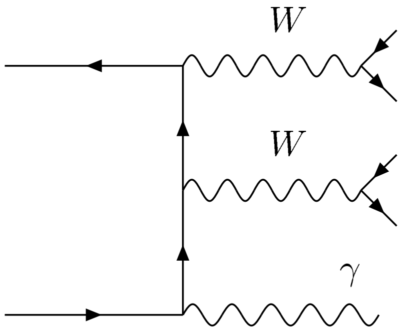


III

New elements of calculation:

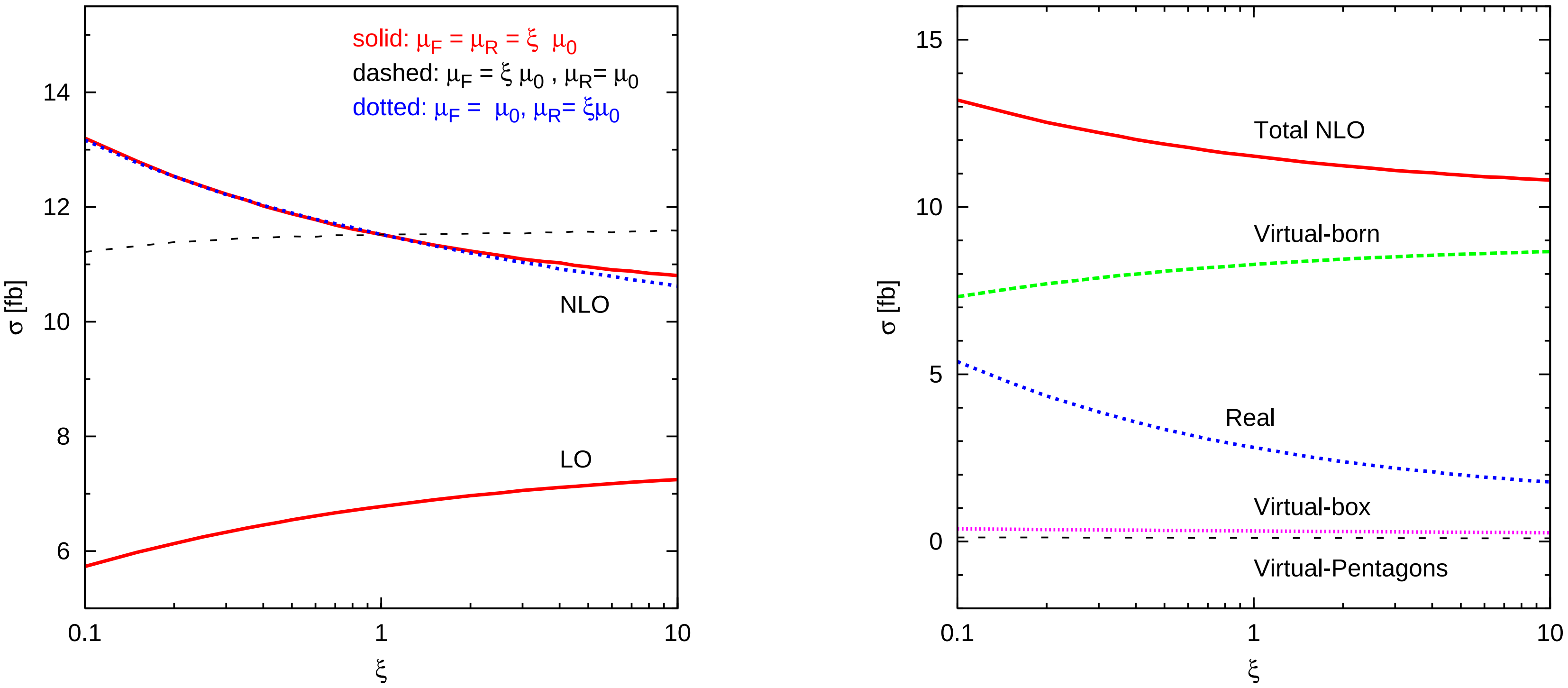
- Different infrared divergence structure of individual loop integrals but same final virtual expressions in terms of finite parts of C_{ij}, D_{ij}, and E_{ij} functions
- Photon isolation from jets for real emission contributions: use Frixione isolation

$$\Sigma_i\, E_{T_i}\, \theta(\delta - R_{i\gamma}) \;\leq\; p_{T_\gamma}\, \frac{1-\cos\delta}{1-\cos\delta_0} \qquad (\text{for all} \quad \delta \leq \delta_0)$$

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

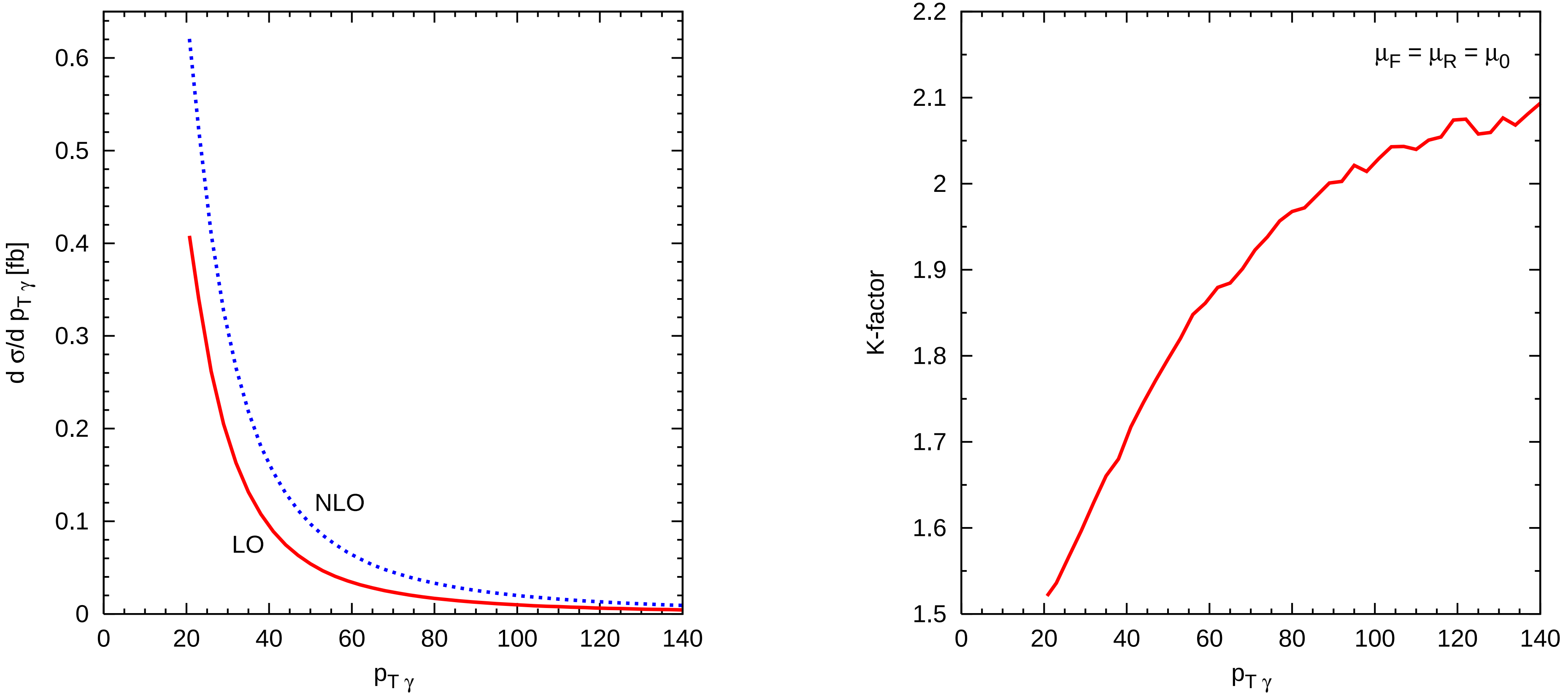
Scale dependence of integrated cross sections

Variation of μ_F, μ_R about $\mu_0 = m_{WW\gamma}$



- Behaviour similar to VVV production: LO scale variation much smaller than NLO correction
- NLO scale dependence largely due to real emission contributions $\Longrightarrow$ jet veto will reduce it
- Box and pentagon contributions ($\tilde{\mathcal{M}}_V$ terms) are quite small: 3% and $< 1\%$ of total

NLO Corrections to Distributions: p_T of photon



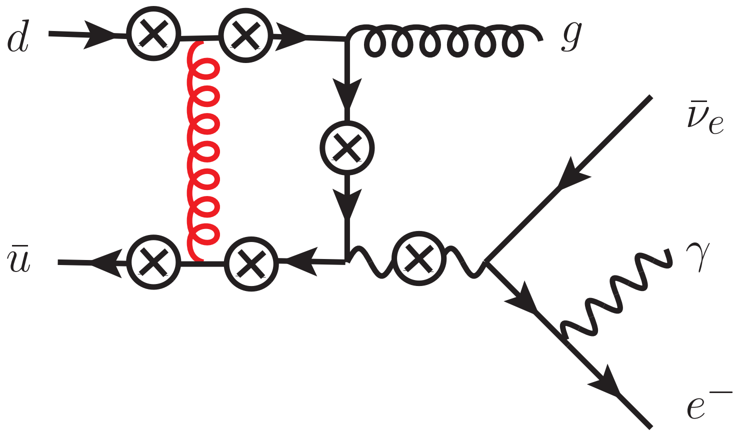
Strong phase space dependence of K-factors (depends on LO scale choice)

NLO QCD Corrections to $W\gamma j$ Production

- Provide NLO QCD corrections including leptonic W decay, e.g.

$$pp \to e^+ \nu_e \gamma j\,, \qquad pp \to e^- \bar{\nu}_e \gamma j$$

- Sizable cross section at LHC (1.2 pb) and Tevatron (15 fb) for $p_{Tj}, p_{T\gamma} > 50$ GeV and separation cuts (later)
- Measurement of anomalous $WW\gamma$ coupling: veto on jets in $W\gamma$ events requires good knowledge of cross section and distributions: want NLO
- Photon isolation à la Frixione probed at NLO level



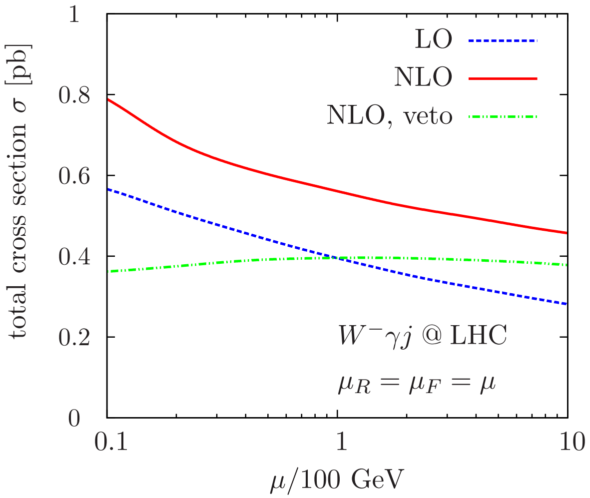
- Initial and final state photon radiation. Final radiation from lepton is important
- Virtual corrections up to pentagons
- External gluon already at tree level $\Longrightarrow$ *nonabelian* boxes with three gluon vertex
- Larger number of subtraction terms

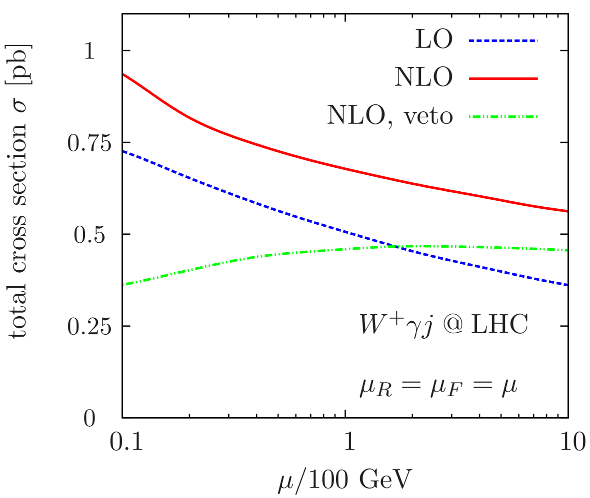
Scale dependence: LHC and Tevatron

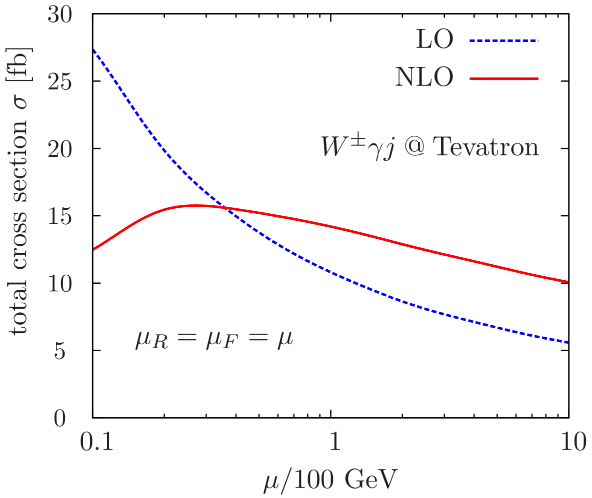
Identify lepton, photon and one or more jets with k_T-algorithm ($D = 0.7$)

$p_{Tj,\gamma} \geq 50\,\mathrm{GeV}\,, \quad |y_j| \leq 4.5\,, |\eta_\gamma| \leq 2.5,$ $\qquad p_{Tl} \geq 20\,\mathrm{GeV}\,, \quad |\eta_l| \leq 2.5$ $\qquad R_{l,\gamma}, R_{l,j} > 0.2$

Frixione isolation of photons with $\delta_0 = 1$ Cross sections are for $W \rightarrow e\nu_e$ only





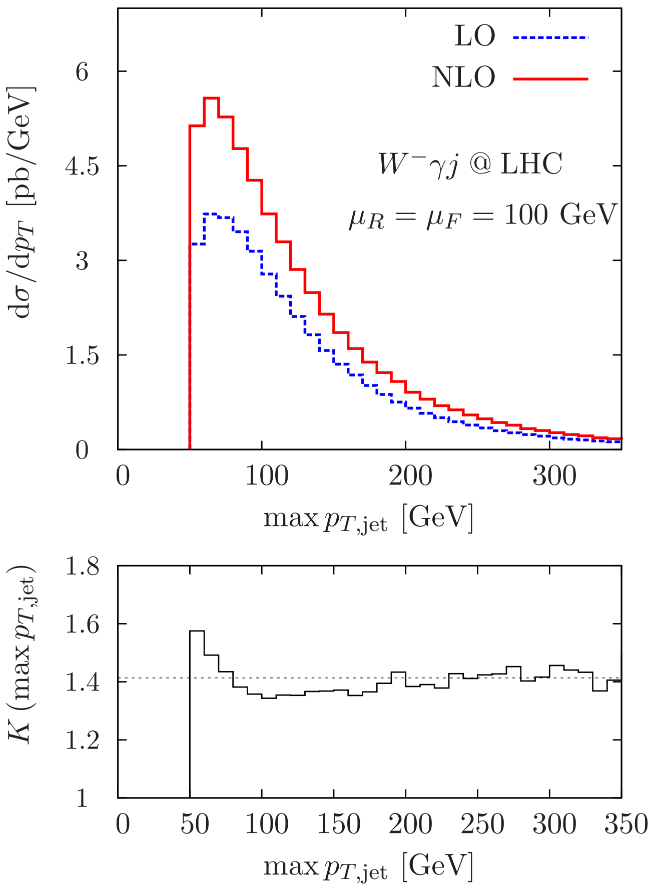


Scale variation at LHC for $\mu_F = \mu_R = 2^{\pm 1} \cdot 100$ GeV: ±11% at LO reduced to ±7% at NLO

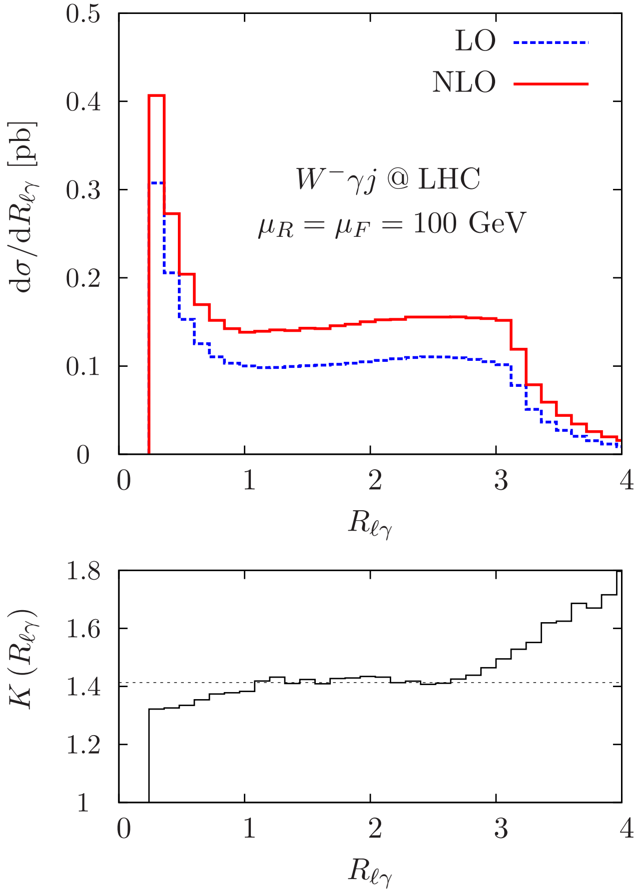
Almost flat behaviour for veto of additional jets of $p_T > 50$ GeV should be taken as accidental and not as a measure of NLO uncertainties

NLO corrections to distributions

p_T of hardest jet



lepton photon separation



- Clear shape changes of distributions when going from LO to NLO
- Average K-factor of 1.4 at LHC is significantly larger than LO scale variation

Conclusions

- VBFNLO provides NLO QCD corrections to a host of processes, in particular vector boson fusion, VVV production and VVj production

- All off-shell diagrams as well as the Higgs-contributions have been considered.

- VBFNLO also contains hjj production from gluon fusion at LO with full quark and squark mass dependence

  Code of 2011 release is available at
  http://www-itp.particle.uni-karlsruhe.de/∼vbfnloweb

- Upcoming extensions include $W\gamma\gamma$ jet production at NLO and WZ and $W\gamma$ production with anomlous triple gauge interactions

- VBFNLO is collaborative effort! Thanks to
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