

WW SCATTERING: NLO CORRECTIONS IN VBFNLO

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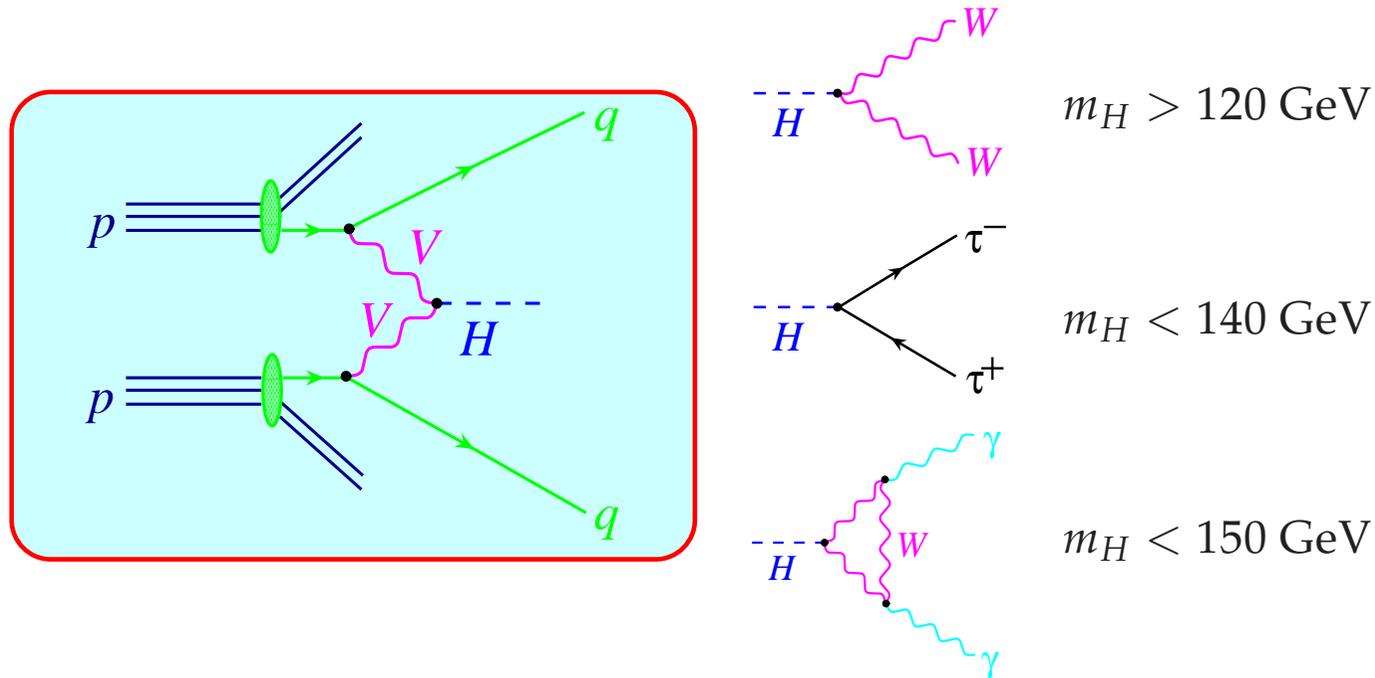


Bundesministerium
für Bildung
und Forschung

Implications of LHC results for TeV-scale physics, CERN, March 26-30, 2012

- Vector Boson Fusion
- NLO QCD corrections to VV scattering
- BSM effects in VBFNLO
- Signal definition for heavy Higgs
- Conclusions

Vector Boson Fusion

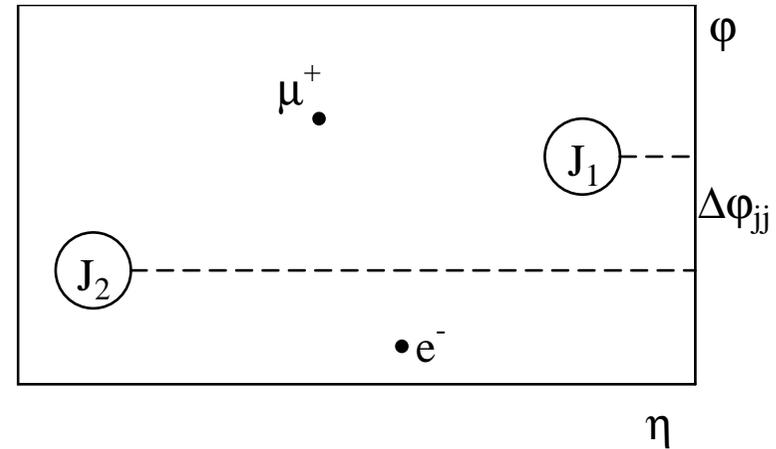
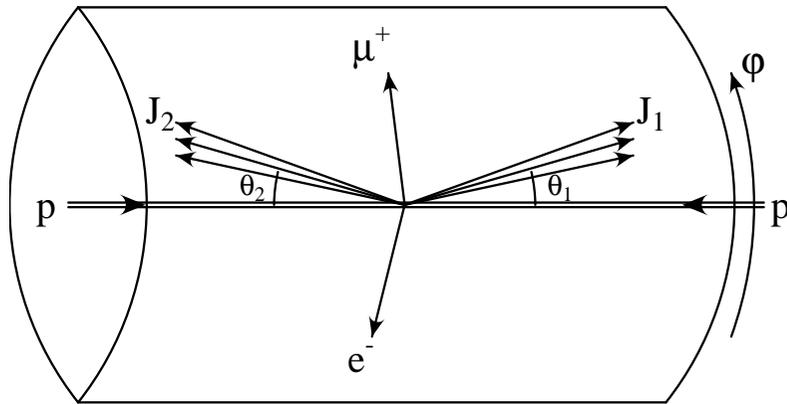


[Eboli, Hagiwara, Kauer, Plehn, Rainwater, D.Z. ...]

Most measurements can be performed at the LHC with **statistical accuracies** on the measured cross sections times decay branching ratios, $\sigma \times \text{BR}$, of **order 10%**.

Would like theory errors below 5% \implies 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)

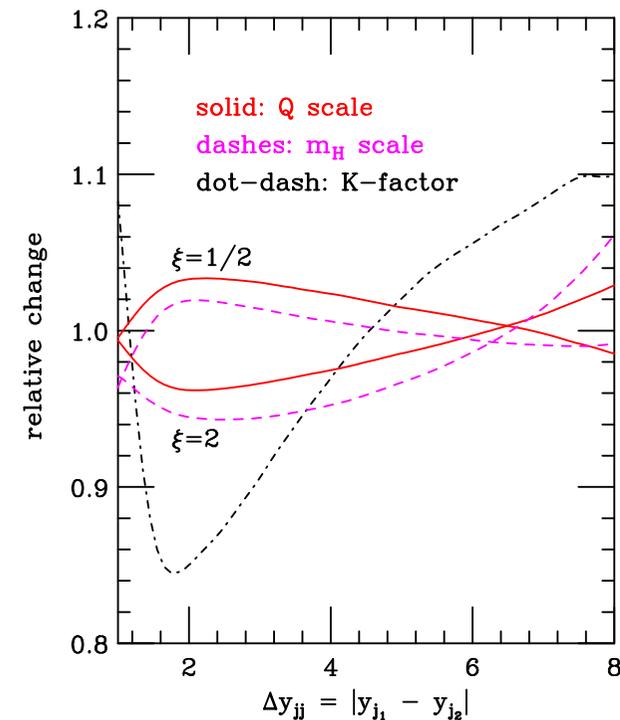
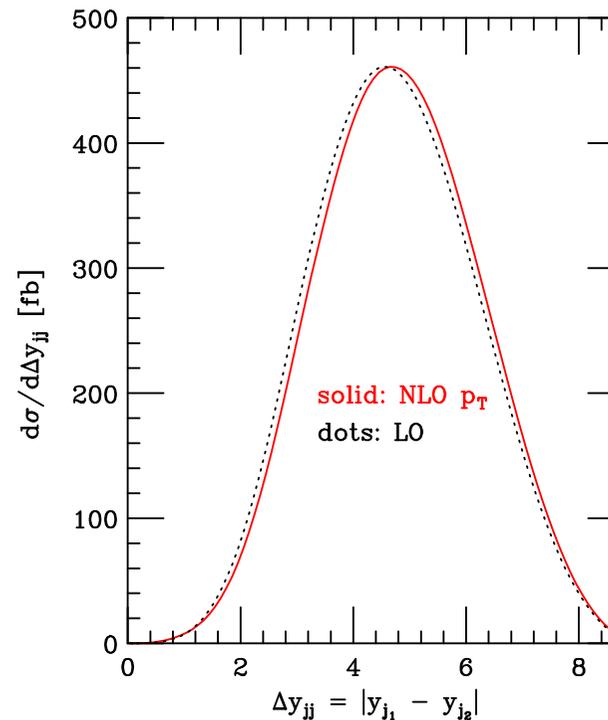
NLO QCD corrections to VBF

- 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

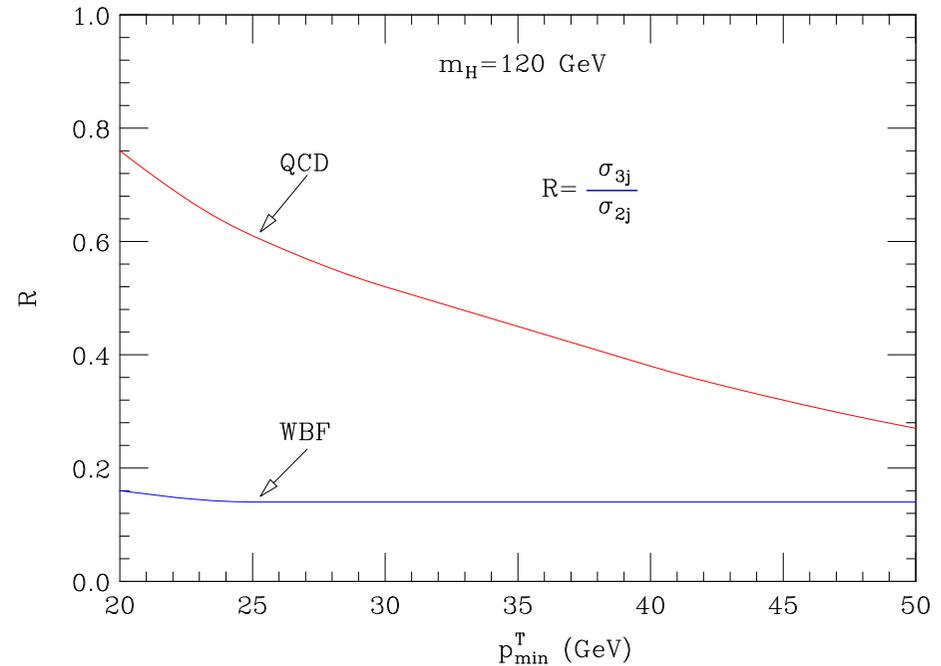
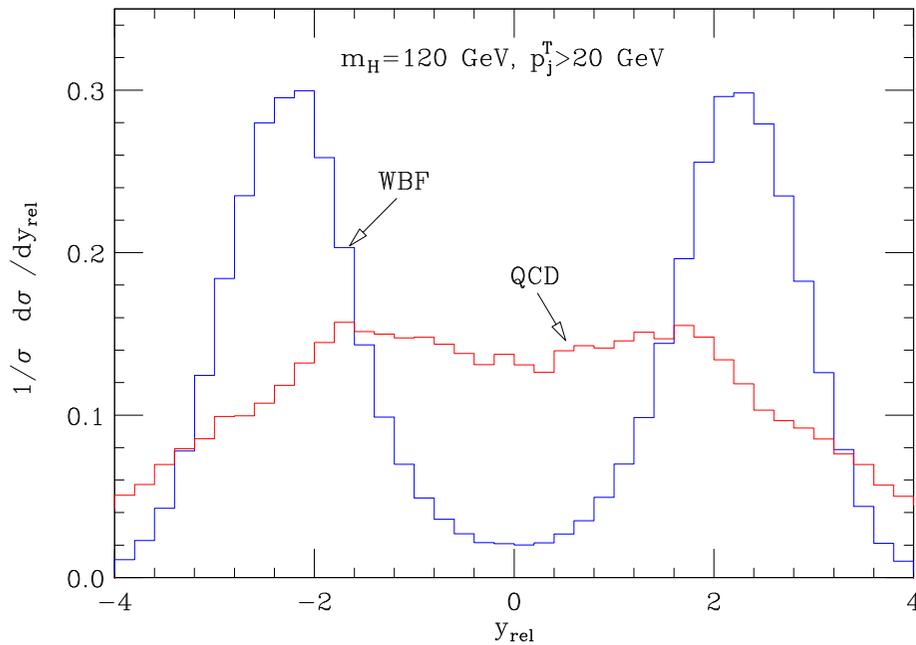
Ciccolini, Denner, Dittmaier, 0710.4749

Figy, Palmer, Weiglein arXiv:1012.4789



$m_H = 120 \text{ GeV}$, typical VBF cuts

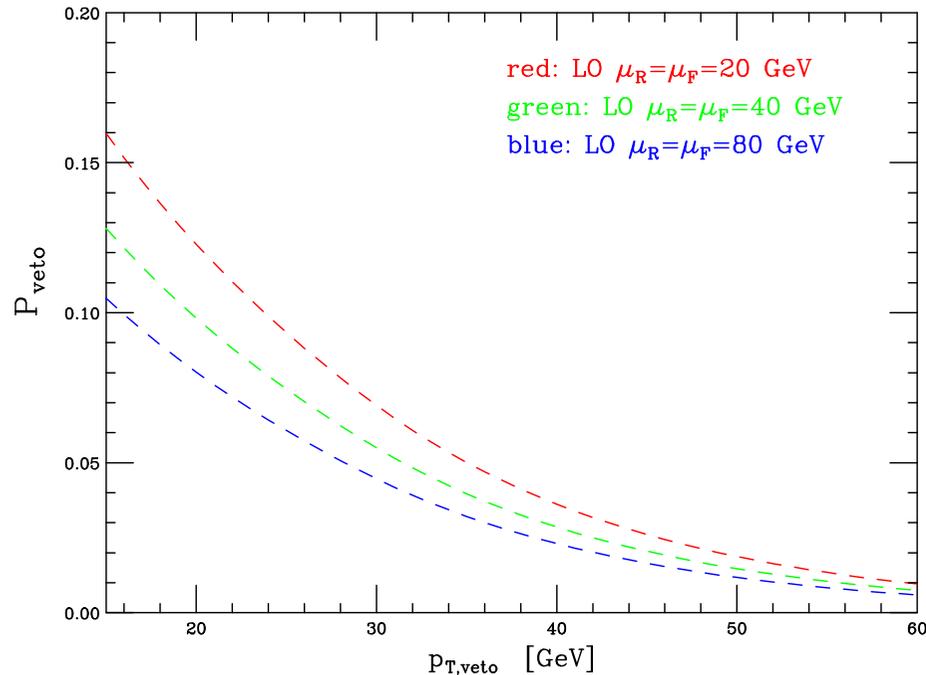
Central Jet Veto: $Hjjj$ from VBF vs. gluon fusion



[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



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

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

- 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)

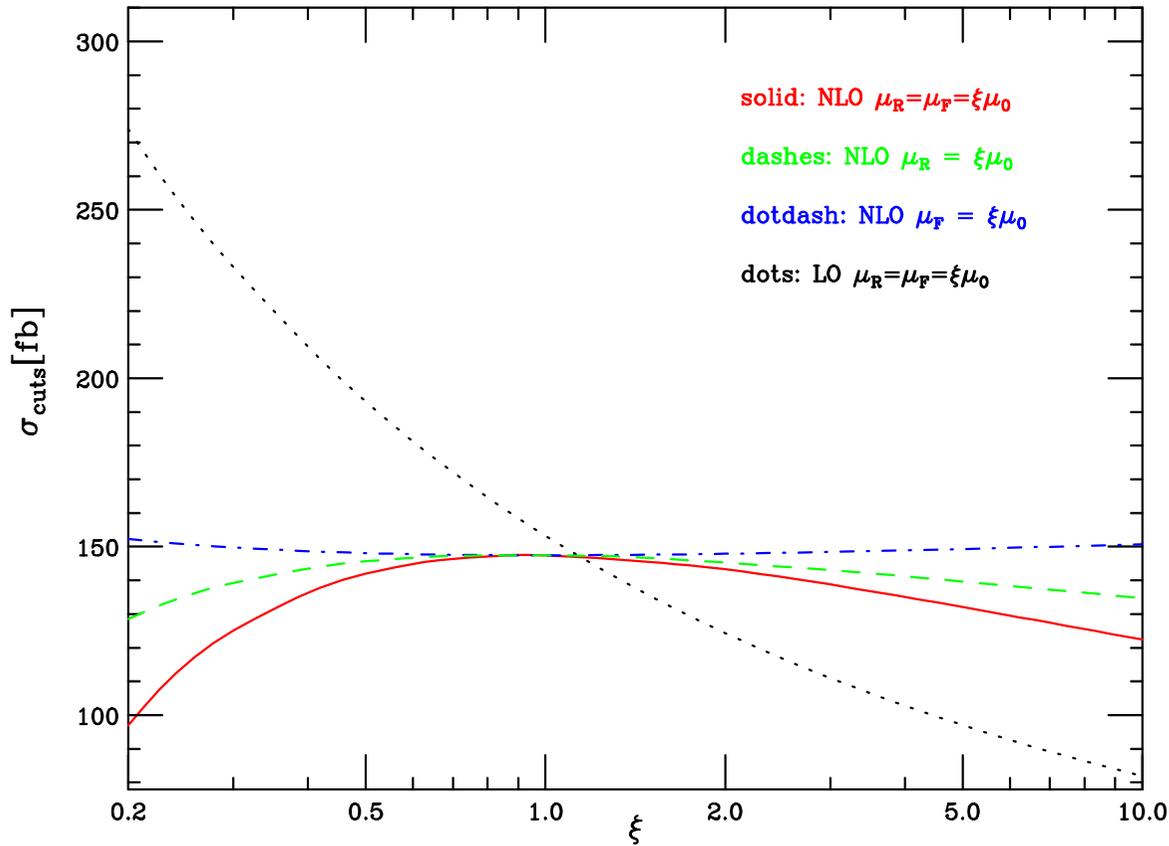
Ingredients of the NLO Calculation

- Born: 3 final state partons + Higgs via VBF

$$\mathcal{M}_B = \delta_{i_2 i_b} t_{i_1 i_a}^{a_3} \left[\begin{array}{c} \mathcal{M}_{B,1a} : \\ \begin{array}{cc} \begin{array}{c} 3 \\ \text{---} \\ a \end{array} \begin{array}{c} \text{---} \\ \text{---} \\ b \end{array} \\ \begin{array}{c} \text{---} \\ \text{---} \\ 1 \\ \text{---} \\ \text{---} \\ 2 \end{array} \\ \begin{array}{c} \text{---} \\ \text{---} \\ H \end{array} \end{array} & \begin{array}{cc} \begin{array}{c} 3 \\ \text{---} \\ a \end{array} \begin{array}{c} \text{---} \\ \text{---} \\ b \end{array} \\ \begin{array}{c} \text{---} \\ \text{---} \\ 1 \\ \text{---} \\ \text{---} \\ 2 \end{array} \\ \begin{array}{c} \text{---} \\ \text{---} \\ H \end{array} \end{array} \end{array} \right] \\
 + \delta_{i_1 i_a} t_{i_2 i_b}^{a_3} \left[\begin{array}{c} \mathcal{M}_{B,2b} : \\ \begin{array}{cc} \begin{array}{c} a \end{array} \begin{array}{c} \text{---} \\ \text{---} \\ b \end{array} \\ \begin{array}{c} \text{---} \\ \text{---} \\ 1 \\ \text{---} \\ \text{---} \\ 2 \end{array} \\ \begin{array}{c} \text{---} \\ \text{---} \\ H \end{array} \end{array} & \begin{array}{cc} \begin{array}{c} a \end{array} \begin{array}{c} \text{---} \\ \text{---} \\ b \end{array} \\ \begin{array}{c} \text{---} \\ \text{---} \\ 1 \\ \text{---} \\ \text{---} \\ 2 \end{array} \\ \begin{array}{c} \text{---} \\ \text{---} \\ H \end{array} \end{array} \end{array} \right]$$

- 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**

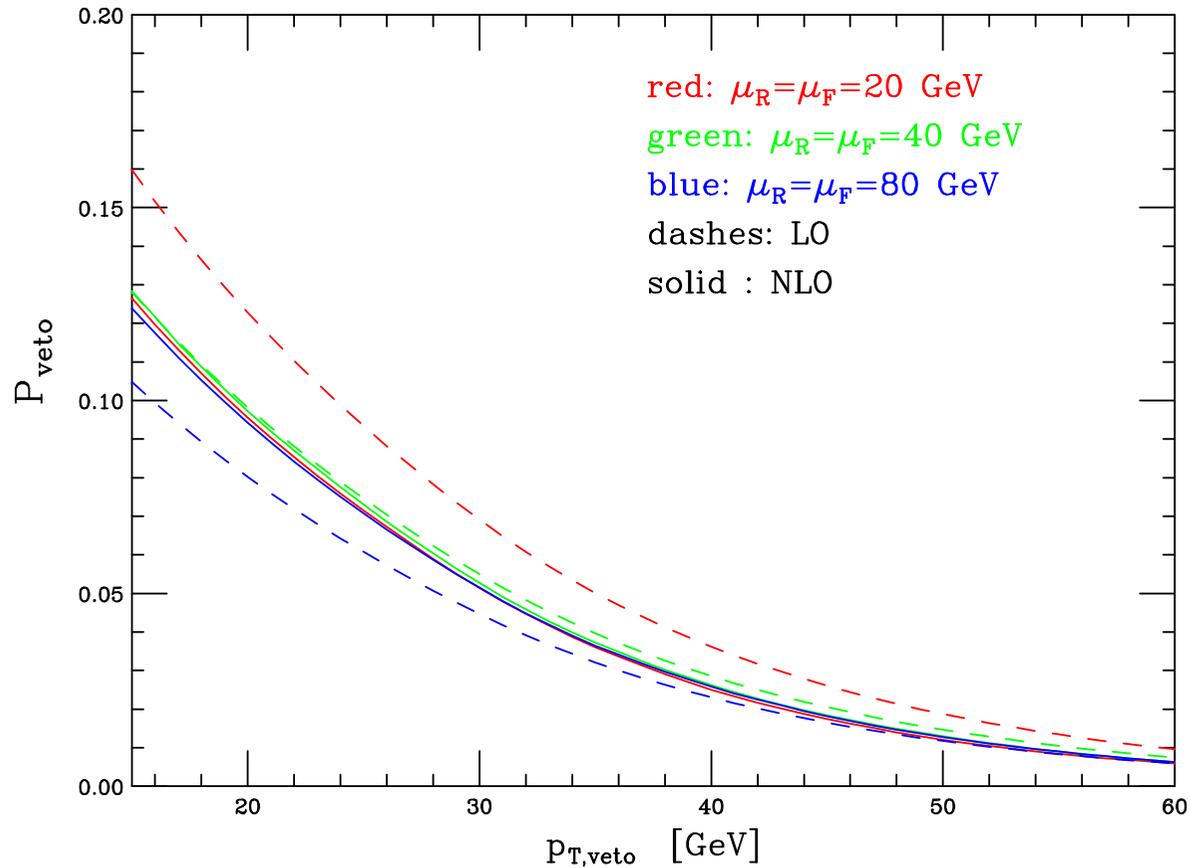
Total $Hjjj$ Cross Section at the LHC: NLO vs LO



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

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

Veto Probability for the VBF Signal



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

Scale variations, $p_{T,\text{veto}} = 15$ 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/~vbfnlweb/>

Limitations of the $qq \rightarrow qqH$ 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 $qq \rightarrow qqVV$ or $qq \rightarrow qq\bar{f}_1 f_2 \bar{f}_3 f_4$
- s-channel Higgs exchange graph with inverse propagator

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

is just one contribution.

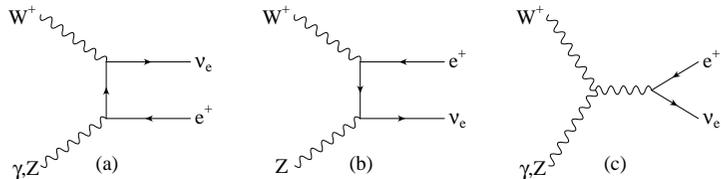
Note: m_H and Γ_H should be treated as free parameters for heavy Higgs

(Γ_H should not necessarily be calculated in SM because EW precision tests give $m_H < 152$ GeV: for much 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: $qq \rightarrow qqWW, qqZZ, qqWZ$ at NLO

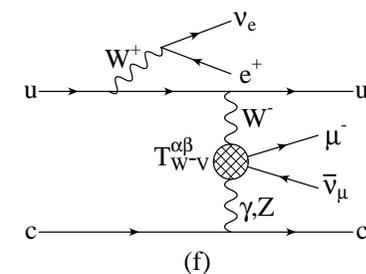
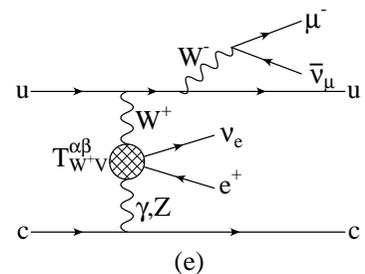
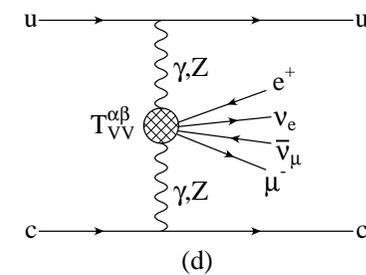
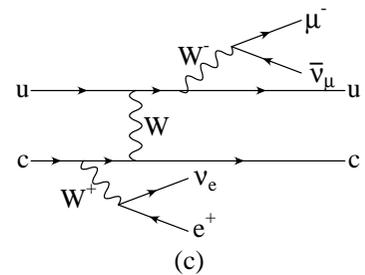
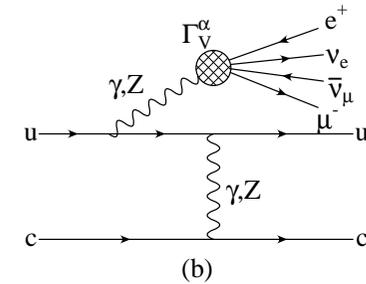
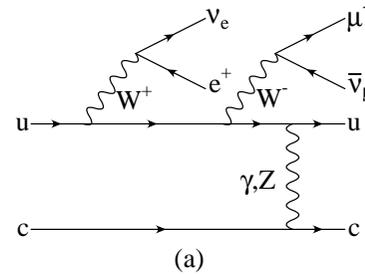
- example: WW production via VBF with leptonic decays: $pp \rightarrow e^+ \nu_e \mu^- \bar{\nu}_\mu + 2j$
- Spin correlations of the final state leptons
- All resonant and non-resonant Feynman diagrams included
- NC \implies 181 Feynman diagrams at LO
- CC \implies 92 Feynman diagrams at LO

Use modular structure, e.g. leptonic tensor



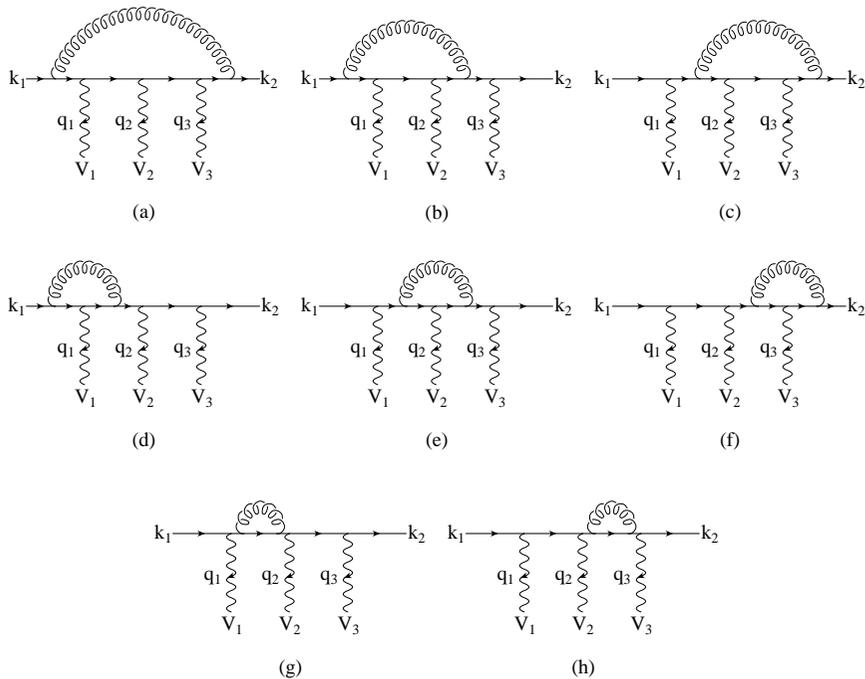
Calculate once, reuse in different processes

Speedup factor ≈ 70 compared to 2005 version of MadGraph for real emission corrections



Most challenging for virtual: pentagon corrections

Virtual corrections involve up to pentagons



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

$$\mathcal{M}_V^{(i)} = \mathcal{M}_B^{(i)} \frac{\alpha_s(\mu_R)}{4\pi} C_F \left(\frac{4\pi\mu_R^2}{Q^2} \right)^\epsilon \Gamma(1 + \epsilon) \left[-\frac{2}{\epsilon^2} - \frac{3}{\epsilon} + c_{\text{virt}} \right] + \widetilde{\mathcal{M}}_{V_1 V_2 V_3, \tau}^{(i)}(q_1, q_2, q_3) + \mathcal{O}(\epsilon)$$

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

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

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 ($D = 0.8$)

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

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

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

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

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

and leptons must lie between the tagging jets

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

For scale dependence studies we have considered

$$\mu = \xi m_V \quad \text{fixed scale}$$

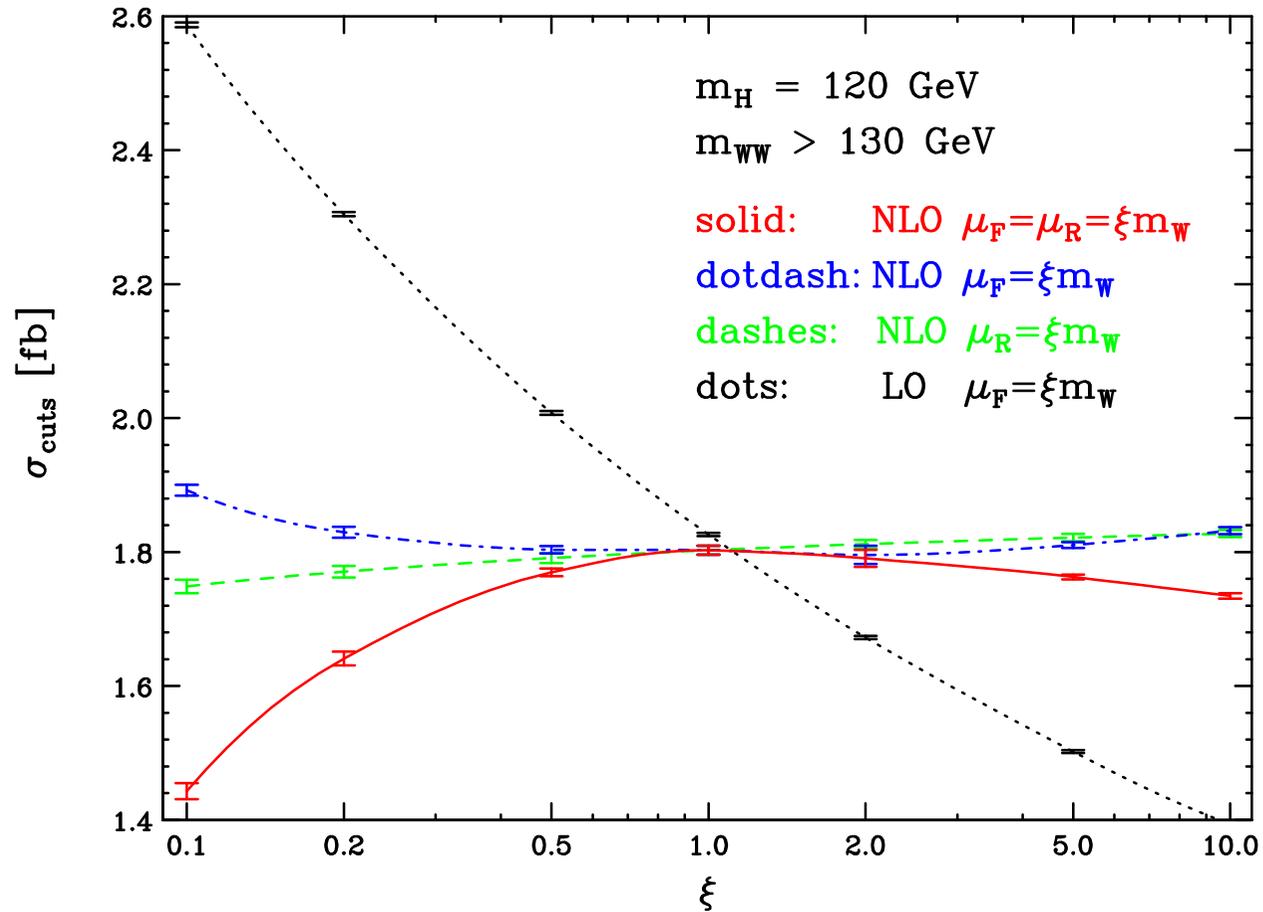
$$\mu = \xi Q_i$$

$$\text{weak boson virtuality : } Q_i^2 = 2k_{q_1} \cdot k_{q_2}$$

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

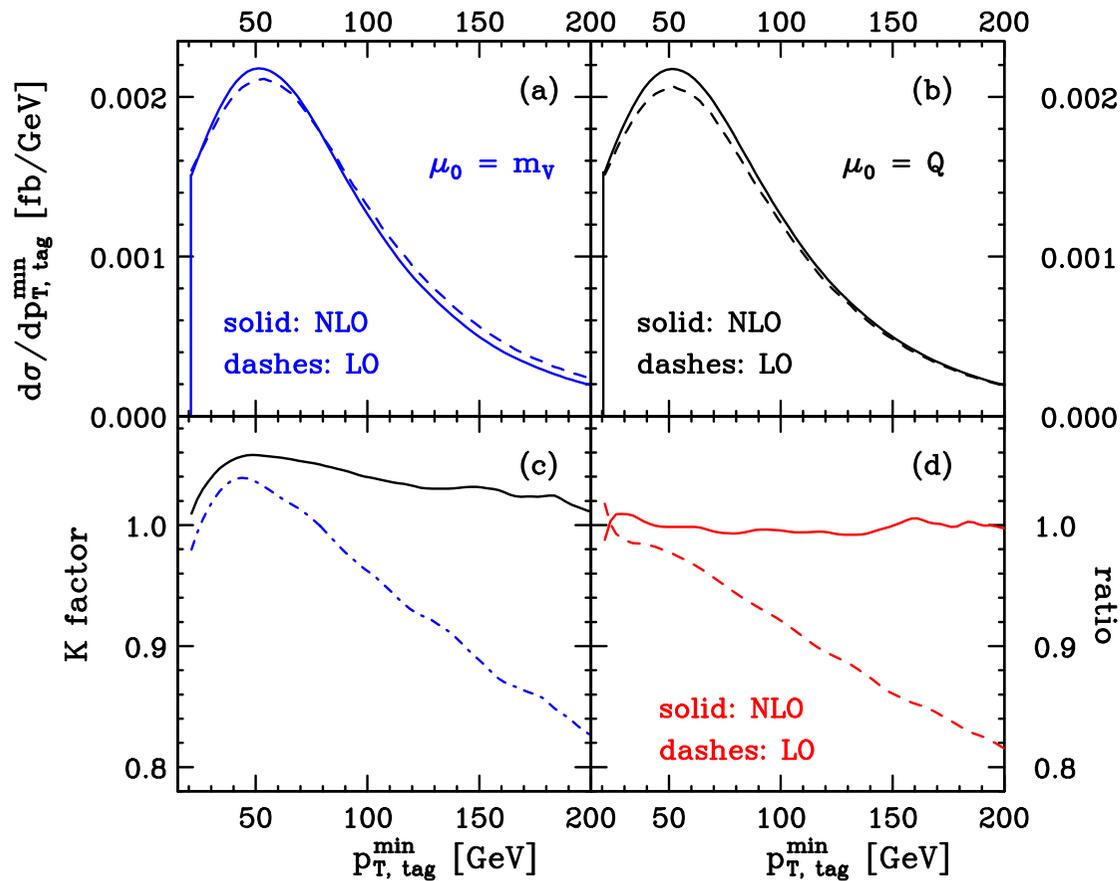
Stabilization of scale dependence at NLO

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

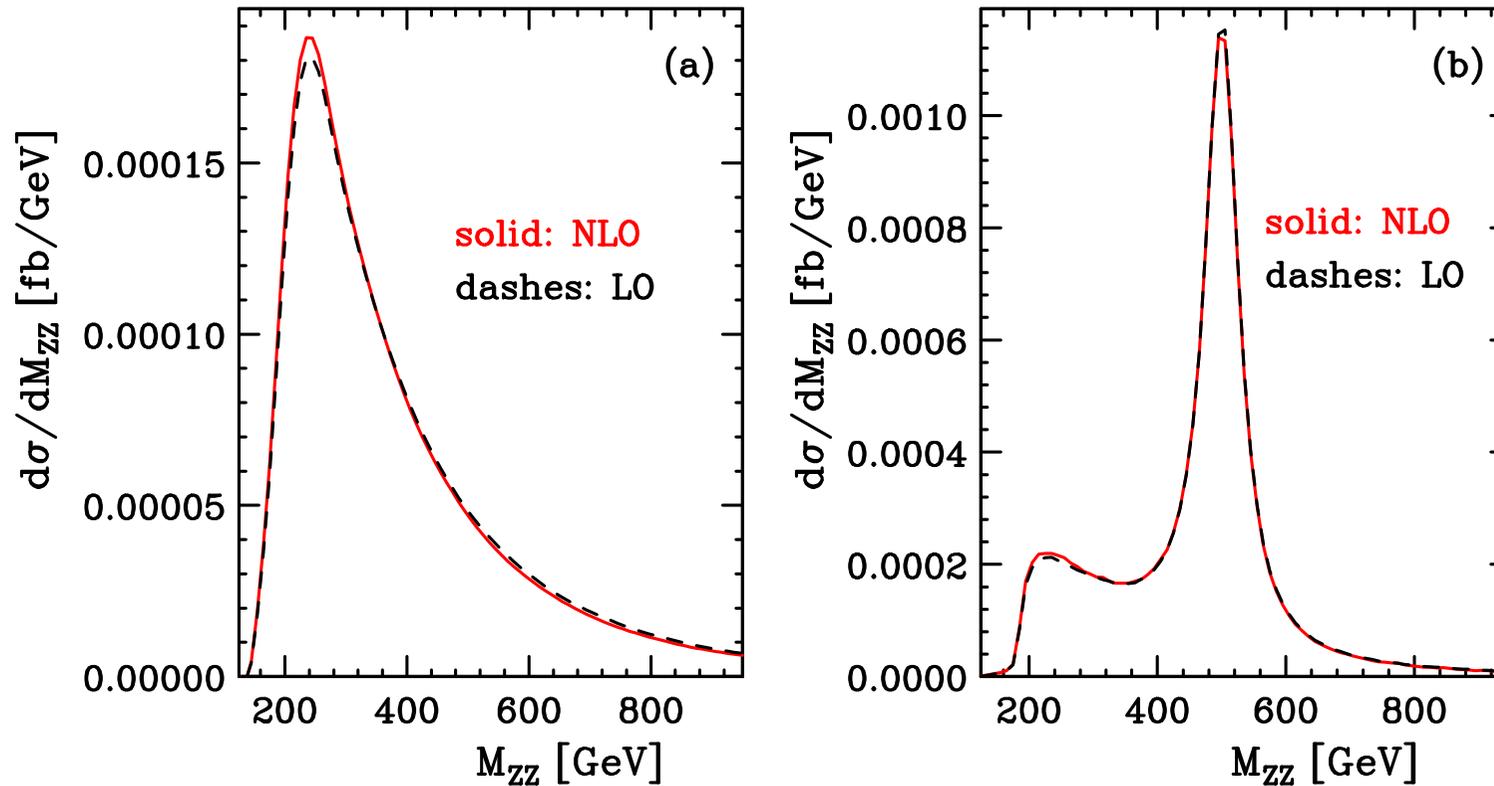


- Shape comparison LO vs. NLO depends on scale
- Scale choice $\mu = Q$ produces approximately constant K -factor
- Ratio of NLO curves for different scales is unity to better than 2%: scale choice matters very little at NLO

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

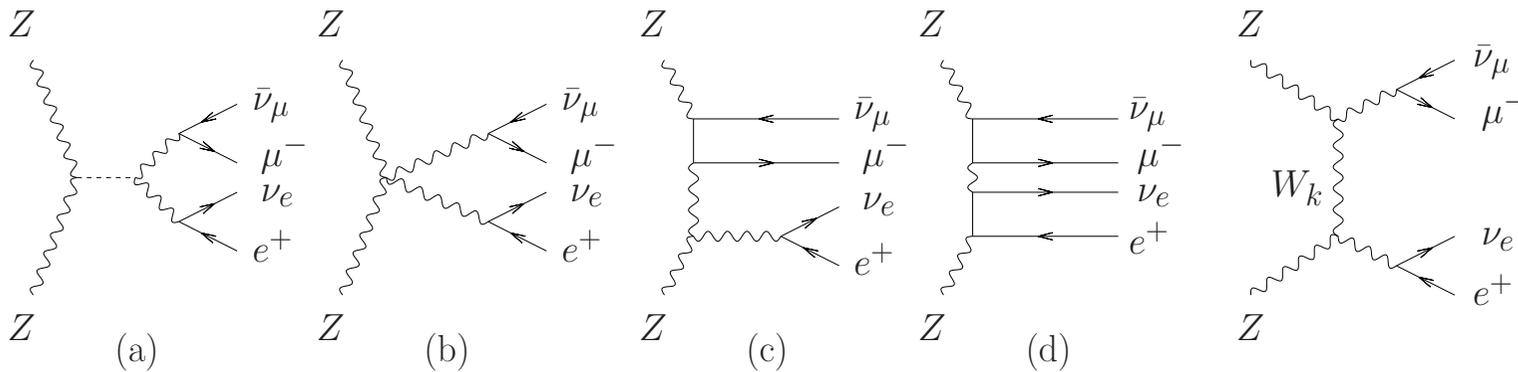
ZZ production in VBF, $ZZ \rightarrow e^+ e^- \mu^+ \mu^-$

4-lepton invariant mass distribution without/with Higgs resonance



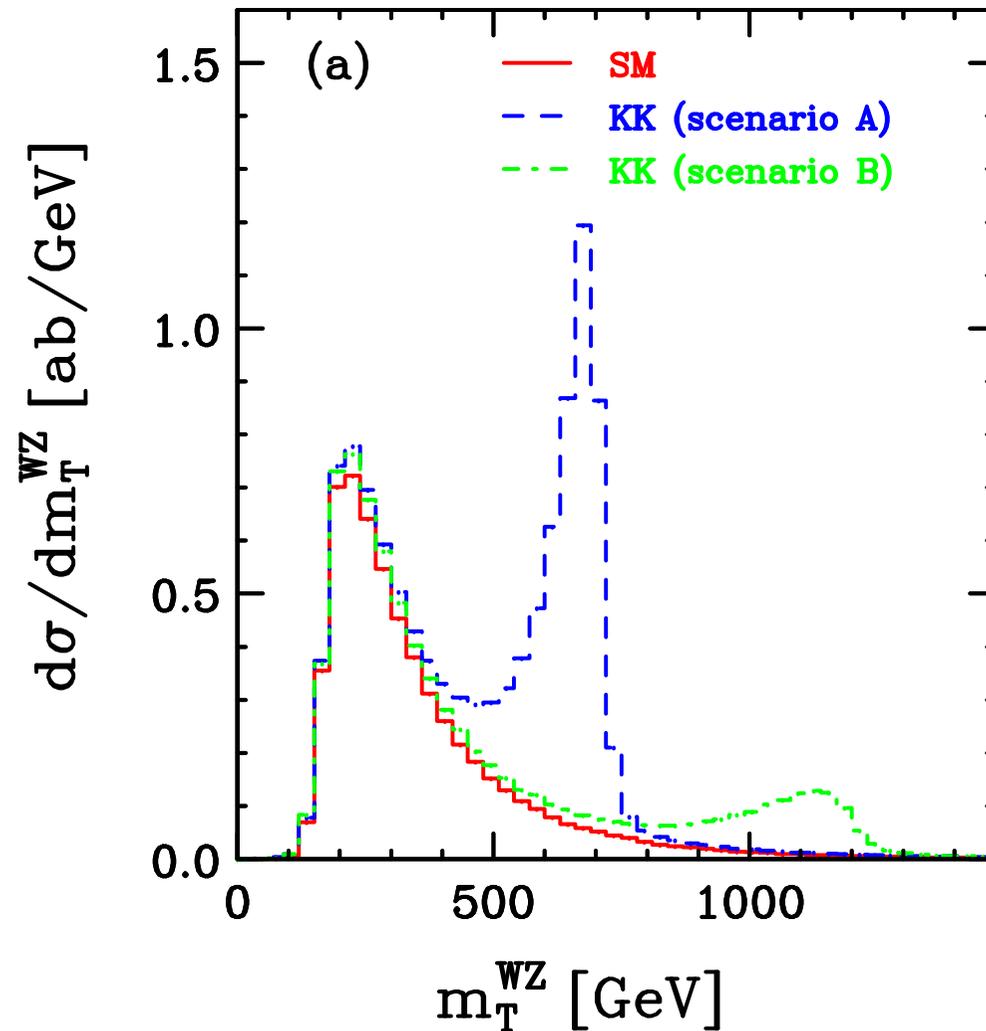
Good agreement of LO and NLO due to low scale choice $\mu = m_Z$. Alternative choice $\mu = m_H$ or $\mu = m_{4\ell}$ leads to smaller LO cross section at high $m_{4\ell}$

Exploiting the leptonic tensors for BSM



- Entire weak boson scattering amplitude implemented via leptonic tensor: same for LO and NLO QCD cross section.
- Easy to modify: include contribution from extra vector boson exchange or
- Implemented: Kaluza-Klein towers of vector resonances in higgsless models
- In progress: implementation of anomalous WWV , HVV and $VVVV$ couplings from dimension 6 and 8 operators in \mathcal{L}_{eff}

Technirho or KK resonance in WZ scattering at NLO QCD



- Extra vector resonance clearly visible in transverse mass distribution
- Implementation of NLO QCD corrections
- Parameters of extra vector resonance can be chosen by user

Signal definition in VV scattering

Problem: heavy Higgs or technirho or interferes with continuum electroweak background
How do we take **interference** into account in our definition of the signal?

Notation:

$\mathcal{M}_X = \mathcal{M}_X(m_X) \sim \frac{s}{v^2}$ Signal amplitude for s-, t- and u-channel exchange of new particle X
 $\mathcal{M}_B \sim \frac{-s}{v^2}$ continuum electroweak background amplitude

$\implies B = \int d\Phi |\mathcal{M}_B|^2$ or $S = \int d\Phi [|\mathcal{M}_X|^2 + 2\text{Re}\mathcal{M}_X\mathcal{M}_B^*]$ violate unitarity at large s

Compare to SM light Higgs scenario with $m_h = 125$ GeV or $m_h = 100$ GeV, i.e. define electroweak background: $B = \int d\Phi |\mathcal{M}_B + \mathcal{M}_h(m_h)|^2$ and

signal: $S = \int d\Phi |\mathcal{M}_B + \mathcal{M}_X(m_X)|^2 - B$

Integrate over suitable mass range $[m_X - \Gamma_1, m_X + \Gamma_2]$

Advantages:

- S and B are well defined and do not violate unitarity
- B is minimized since early onset of cancellations for light Higgs SM are taken into account
- Avoid potentially negative signal cross section due to dominance of (negative) interference terms

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

New release of VBFNLO planned for early summer 2012

Conclusions

- VBFNLO provides NLO QCD corrections to a host of processes, in particular Higgs production via vector boson fusion and weak boson scattering
- All off-shell diagrams as well as the Higgs-contributions have been considered.
- QCD corrections are usually modest (order 10%) but beware simulation of additional jets for central jet veto: **must** be included at matrix element level

Code of 2011 release of VBFNLO is available at

<http://www-itp.particle.uni-karlsruhe.de/~vbfnlweb>

- VBFNLO is collaborative effort! Thanks to
V. Hankele, B. Jäger, M. Worek, S. Palmer, M. Rauch, C. Oleari, K. Arnold, J. Bellm, G. Bozzi, F. Campanario, C. Englert, B. Feigl, T. Figy, J. Frank, M. Kerner, G. Klämke, M. Kubocz, S. Plätzer, S. Prestel, H. Rzehak, F. Schissler, M. Spannowsky