NLO QCD corrections to *WZjj* production at the LHC

Francisco Campanario, Matthias Kerner, LE Duc Ninh, Dieter Zeppenfeld | Windows on the universe, Aug 2013, Quy Nhon

INSTITUT FÜR THEORETISCHE PHYSIK

Outline

- *VVjj* production (with leptonic decays) at the LHC: motivation
- *WZjj* @ NLO QCD : some calculational details
- Numerical results
- Summary

VVjj production at the LHC: why?

- Motivation:
  - Sensitive to $VV \to VV$ scattering, quartic quage-boson couplings.
  - Important background for new physics searches.
  - *WVjj* with one charged lepton unobserved: background to W^+W^+jj production.

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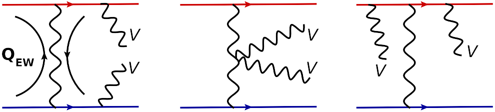
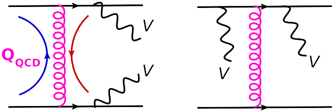
  - Important background for new physics searches.
  - *WVjj* with one charged lepton unobserved: background to W^+W^+jj production.
- Classification at LO: 2 mechanisms
  - EW mechanism (vector boson fusion, VBF): $\sigma_{EW} \propto \alpha^6$

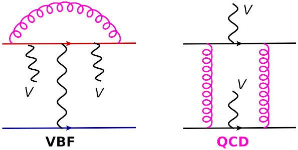


  - QCD mechanism: $\sigma_{QCD} \propto \alpha_s^2\alpha^4$



  - Interference: color and kinematically suppressed.
    $\rightsquigarrow$ can be neglected for a-few-percent precision measurements at the LHC.

What have been done at NLO QCD?



- EW mechanism (VBF): consider QCD corrections to each quark lines separately $\rightsquigarrow$ pentagons at most.
  - W^+W^-jj: [Jager, Oleari, Zeppenfeld, 2006]
  - $ZZjj$: [Jager, Oleari, Zeppenfeld, 2006]
  - $W^\pm Zjj$: [Bozzi, Jager, Oleari, Zeppenfeld, 2007]
  - W^+W^+jj/W^-W^-jj: [Jager, Oleari, Zeppenfeld, 2009], [Denner, Hosekova, Kallweit, 2012], good agreement!

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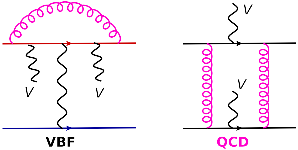

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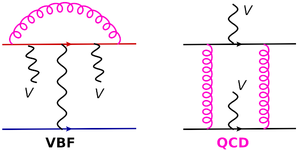

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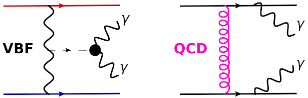
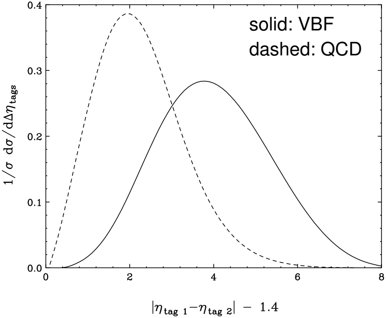
  - $ZZjj$: not done
- all VBF processes and QCD W^+W^+jj/W^-W^-jj, $W^\pm Zjj$ are included in VBFNLO program. Available soon.

VBF vs. QCD background: a Higgs example

[Rainwater, hep-ph/9908378]

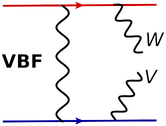


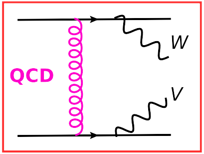
LHC $\sqrt{s} = 14$ TeV, $p_{Tj} \geq 20$ GeV, $|\eta_j| < 5$, $\Delta R_{jj} \geq 0.7$,
$|\eta_\gamma| < 2.5$, $\Delta R_{j\gamma} \geq 0.7$;
$\eta_{j,min} + 0.7 < \eta_\gamma < \eta_{j,max} - 0.7$, $\eta_{j_1}\eta_{j_2} < 0$



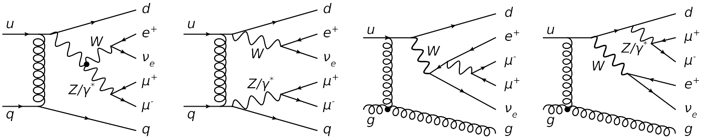
The two tagging jets are more separated in VBF than in QCD background!

$pp \to W^{\pm}Zjj$: QCD mechanism





The problem

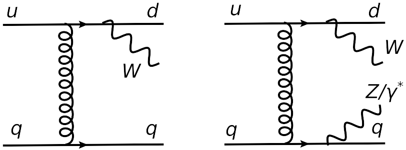


$+\ldots$

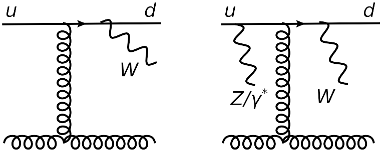
- Q: What is the NLO QCD correction to this process?
- A: Before answering this question, some classifications are needed.

LO: subprocesses

- 2-quark lines [4q]: $q_1 + q_2 \to q_3 + q_4 + (WV)$

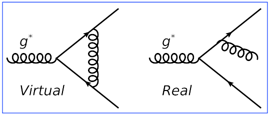


  - 76 subprocesses (2 generations).
  - 12 crossings.
- 1-quark line [2g]: $q_1 + q_2 \to g + g + (WV)$



  - 14 subprocesses (2 generations).
  - 7 crossings.
- 4 QCD gauge invariant groups: $4q(W)$, $4qWV$, $2g(W)$, $2gWV$.

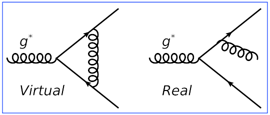
NLO calculation: theory

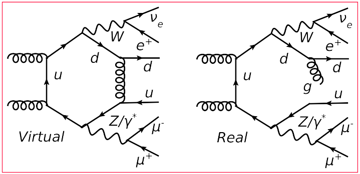


$$d\sigma_{NLO} = d\sigma^{\text{virt}}_{2\to N} + d\sigma^{\text{real}}_{2\to N+1}.$$

- Both terms are IR divergent. The sum is finite for IR-safe observables (e.g. jet distributions)

NLO calculation: theory vs. practice





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- Real: IR divergences can be separated using Catani-Seymour dipole subtraction method.
- Virtual: 1-loop amplitude is, unfortunately, much more complicated than tree-level one. Use Feynman-diagram and tensor reduction methods. The most difficult part.

Counting diagrams: 2 generations

- LO: 4840
- NLO real emission: 79784
- NLO virtual: 116896 (up to 6-point rank 5)

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This calculation can be done with:

- good classifications: effective currents $V \to l_1 l_2$, $V \to l_1 l_2 l_3 l_4$, building blocks (hexlines, penlines, ...), ...
- use crossing symmetry (to a minimum extent to reduce computing time): subprocesses are not completely independent (diagrams share common parts).
- two independent calculations:
  - manual implementation using VBFNLO framework
  - more automated approach using HELAS/MadGraph, FeynArts, FormCalc
  - loop integrals: 2 different codes
- numerical instabilities in the virtual part: difficult $\rightsquigarrow$ gauge tests

Numerical instabilities: gauge test

$$\mathcal{B}^{\mathcal{N}} = T^N_\mu \epsilon^\mu(k),\ \epsilon^\mu \to k^\mu,$$

$$\frac{1}{\not{q}+\not{k}}\not{k}\frac{1}{\not{q}} = \frac{1}{\not{q}} - \frac{1}{\not{q}+\not{k}},$$

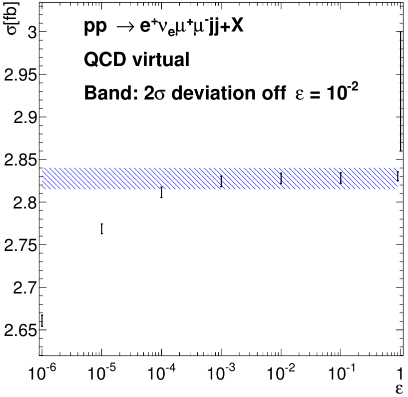
$$T^N_\mu k^\mu - \mathcal{A}^{N-1} = 0,$$

$$Q = 1 - \frac{\mathcal{A}^{N-1}}{T^N_\mu k^\mu},$$

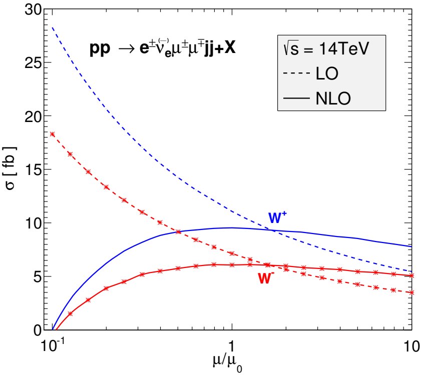
if $Q < \varepsilon$: accept the point.

if $Q > \varepsilon$: use quadruple precision,

$\rightsquigarrow$ $Q < \varepsilon$? accept or discard points.



Results: inclusive cuts



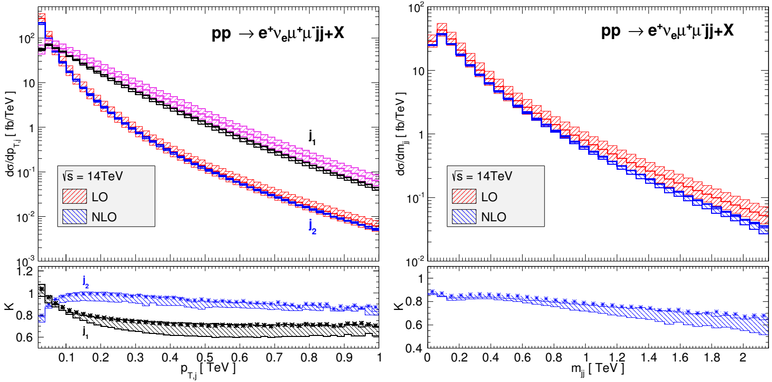
speed: 1% statistical error in 2.5h on a normal PC (Intel i5-3470) with 1 core.

[Campanario, Kerner, LDN, Zeppenfeld, arXiv: 1305.1623]

$$p_{T,j} > 20\text{ GeV}, \quad |\eta_j| < 4.5, \quad R_{jj}^{anti-k_t} = 0.4, \quad R_{jl} > 0.4;$$
$$p_{T,l} > 20\text{ GeV}, \quad |\eta_l| < 2.5, \quad R_{ll} > 0.4, \quad M_{l^+l^-} > 15\text{ GeV}.$$

Dynamic scale: $\mu_F = \mu_R = \mu_0 = \left(\sum_{\text{jet}} p_{T,\text{jet}} + \sqrt{p_{T,W}^2 + m_W^2} + \sqrt{p_{T,Z}^2 + m_Z^2}\right)/2$,
$p_{T,V}$ (m_V) are reconstructed from leptons, jets pass all cuts.

Distributions of leading jets



- scale uncertainty: significantly reduced
- K factor (NLO/LO): 0.6–1 in a large range
- ⇝ regular NLO QCD corrections (as expected)

Summary

- *VVjj* is a special class of processes: sensitive to $VV \to VV$ scatterings, quartic gauge couplings, background for new physics searches, ...
- Two mechanisms: EW (VBF), QCD, interference effects are very small.
- For *WZjj* with leptonic decays, QCD mechanism:
    - K factor: from 0.6–1 with a dynamic scale choice for many distributions
    - scale uncertainty: from 50% at LO to 5% at NLO for inclusive cross section
- Virtual amplitude: difficult part, gauge tests are good to deal with numerical instabilities.
- The code will be available in the next release of the VBFNLO program.

Thank you!

Dipole subtraction method

$$\begin{aligned}
\int_{N+1} d\sigma^{\text{real}}_{N+1}(p)J^{N+1}(p) &= \int_{N+1}\left[\left(d\sigma^{\text{real}}_{N+1}(p)J^{N+1}(p) - \sum_{i,j} S^N_{ij}(\tilde{p}_{ij})J^N_{ij}(\tilde{p}_{ij}\right)\right] \quad (1)\\
&+ \underbrace{\int_{N+1}\sum_{i,j} S^N_{ij}(\tilde{p}_{ij})J^N_{ij}(\tilde{p}_{ij})}_{\text{PK+I}}\\
\text{PK} &= \int_0^1 dx \int_N \sum_{j\neq a} S^N_{aj}(x,p)J^N_a(x,p) + (a \leftrightarrow b) \quad (2)\\
\text{I} &= \int_N \sum_{i,j} S^N_{ij}(p)J^N(p). \quad (3)
\end{aligned}$$

Dipole subtraction method

$$\int_{N+1} d\sigma^{\text{real}}_{N+1}(p)J^{N+1}(p) = \int_{N+1}\left[(d\sigma^{\text{real}}_{N+1}(p)J^{N+1}(p) - \sum_{i,j} S^N_{ij}(\tilde{p}_{ij})J^N_{ij}(\tilde{p}_{ij})\right] \quad (1)$$

$$+ \underbrace{\int_{N+1}\sum_{i,j} S^N_{ij}(\tilde{p}_{ij})J^N_{ij}(\tilde{p}_{ij})}_{\text{PK+I}}$$

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The Jet function: a cut, a histogram, PDF(Q), $\alpha_s(Q)$, ...

- IR safety: $J^N \to J^{N+1}$ in the IR singular limits.
- An easy mistake: in Eq. (1), set $\alpha_s^N(\tilde{Q}) = \alpha_s^{N+1}(Q)$: the result is finite, BUT wrong (almost correct) because the integrated part $\neq$ the subtraction part.
- If we do $J^N = J^{N+1}$ in Eq. (1), then PK term will get more complicated. [arXiv: 0802.1405]

Tree-level, virtual and real matching

- Partonic level:

$$\begin{aligned} d\sigma^{\mathrm{I}}_{\mathrm{soft}} + d\sigma^{\mathrm{virt}}_{\mathrm{soft}} &= 0, \\ d\sigma^{\mathrm{I}}_{\mathrm{coll}} + d\sigma^{\mathrm{virt}}_{\mathrm{coll}} &= 0, \\ d\sigma^{\overline{PK}}_{\mathrm{coll}} &\neq 0. \end{aligned}$$

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- Hadronic level:

$$\begin{aligned} d\sigma^{\mathrm{NLO}} &= d\sigma^{\mathrm{tree}} + d\sigma^{\mathrm{virt}} + d\sigma^{\mathrm{real}}, \\ \mathrm{PDF}^{\mathrm{NLO}} \otimes d\sigma^{\mathrm{NLO}} &= \int dx_1 \int dx_2 f_a(x_1, Q) f_b(x_2, Q) d\sigma^{\mathrm{NLO}} + \delta_{\mathrm{PDF}}(d\sigma^{\mathrm{tree}}, 1/\epsilon), \\ d\sigma^{\mathrm{PK}} &\equiv d\sigma^{\overline{PK}}(1/\epsilon) + \delta_{\mathrm{PDF}}(d\sigma^{\mathrm{tree}}, 1/\epsilon) : \quad \text{finite} \end{aligned}$$

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- Virtual: use 't Hooft-Veltman (HV) scheme (external momenta in 4D)

$$d\sigma^{\mathrm{virt}}_{\mathrm{HV}} = d\sigma^{\mathrm{virt}}_{\mathrm{CDR}}, \quad \alpha_s^{\mathrm{HV}} = \alpha_s^{\mathrm{CDR}}.$$

- Dimensional regularization scheme (DRS) independence [Catani, Seymour, Trócsányi 1997]:

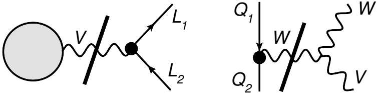
$$d\sigma^{\mathrm{tree}} + d\sigma^{\mathrm{virt}} + d\sigma^{\mathrm{I}} : \notin \text{DRS at partonic level!}$$

- 4 flavors (no b/t) or 5 flavors (b and t loop): α_s, PDF, tree, virtual, real.

Fermion loops

- Include V decays:

$$\epsilon^\mu(k,\lambda) \to J^\mu_{\text{eff}}/(k^2 - M_V^2 + iM_V\Gamma_V), \quad \text{Or}$$



$$g^{\mu\nu} = -\sum_{\lambda=-1,0,1} \epsilon^\mu(k,\lambda)\epsilon^{*\nu}(k,\lambda) + \underbrace{\frac{k^\mu k^\nu}{k^2}}_{=0},$$

$$k^\mu \bar{F}_1\gamma_\mu(a+b\gamma_5)F_2 = 0, \quad \text{since} : m_1 = m_2 = 0 \ \text{(no Goldstones)}.$$

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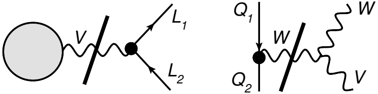

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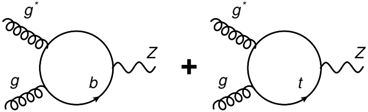
- Fermion loop with γ_5: anomaly free (need both b and t)



⇝ 2.5 generations not OK (we cannot decouple the top quark).