Radiative corrections to triple gauge boson production at the LHC

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Precision Theory, Quy Nhon, Sep 25 - Oct 1, 2016

Bundesministerium
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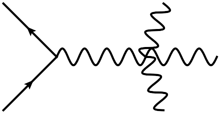
Outline

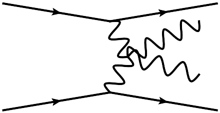
- Motivation
- What has been done?
- Main points of NLO QCD, NLO EW corrections to VVV production.
- Summary

Motivation

- quartic-gauge-boson couplings, studies of anomalous gauge couplings:



1 quark line



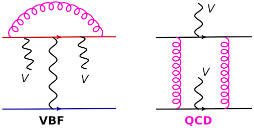
2 quark lines

- in SM: only $WWVV$ exists at tree level. (same-sign $W^{\pm}W^{\pm}jj$ is interesting!).
- backgrounds to new physics searches.

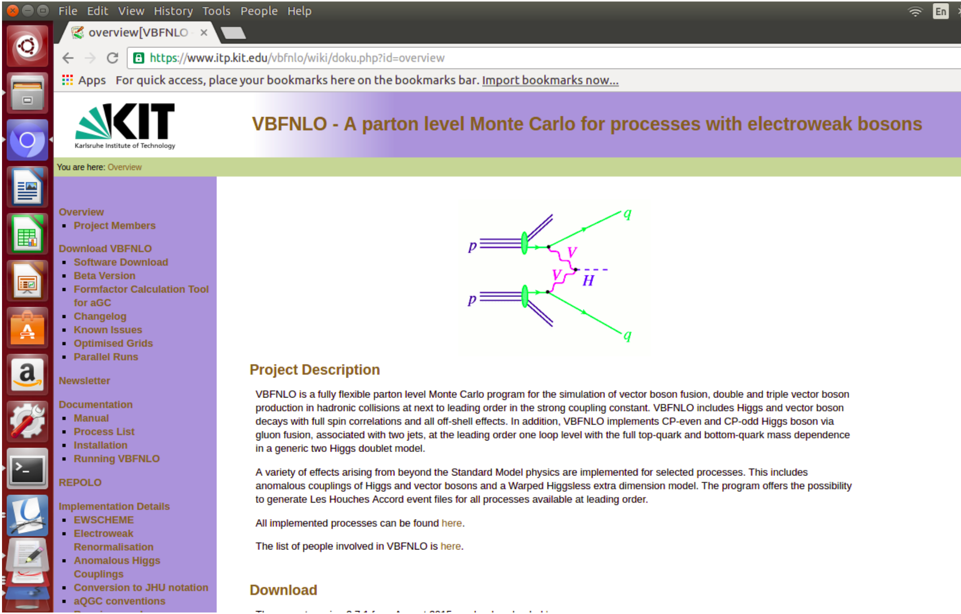
VVV@LHC: What has been done?

- all VVV (leptonic decays, semi-leptonic decays with approximations) at NLO QCD have been done in VBFNLO (a parton-level MC program, with anomalous couplings); and OS production [Binoth et al. arXiv:0804.0350].
- NLO EW (OS level): W^+W^-Z [Nhung et al. arXiv:1307.7403], $W^\pm ZZ$ [Shen et al. arXiv:1507.03693], WWW [Shen et al. arXiv:1605.00554].
- NLO: many automated tools (Gosam+Sherpa/Herwig, MadGraph5, OpenLoops+Sherpa/Herwig, RECOLA+In-house-Real, ...).
  NLO EW $pp \to b\bar{b}e^+\nu_e\mu^-\nu_\mu$ [RECOLA, arXiv:1607.05571]!!!
  Problem nearly solved?
- Next aim: full NLO EW corrections to $pp \to VVV \to 6l$ (2018?).

$VVjj$@LHC: What has been done?



- EW mechanism (VBF):
  - W^+W^-jj: [Jager, Oleari, Zeppenfeld, 2006]
  - $ZZjj$: [Jager, Oleari, Zeppenfeld, 2006]
  - $W^\pm Zjj$: [Bozzi, Jager, Oleari, Zeppenfeld, 2007]
  - $W^\pm W^\pm jj$: [Jager, Oleari, Zeppenfeld, 2009], [Denner, Hosekova, Kallweit, 2012]
  - $W^\pm \gamma jj$: [Campanario, Kaiser, Zeppenfeld, 2013]
- QCD mechanism:
  - $W^\pm W^\pm jj$: [Melia, Melnikov, Rontsch, Zanderighi, 2010], [Campanario, Kerner, LDN, Zeppenfeld, 2013]
  - W^+W^-jj: [Melia, Melnikov, Rontsch, Zanderighi, 2011], [Greiner, Heinrich, Mastrolia, Ossola, et al, 2012]
  - $W^\pm Zjj$, $W^\pm \gamma jj$, $ZZjj$, $Z\gamma jj$: [Campanario, Kerner, LDN, Zeppenfeld, 2013, 2014]
- almost all processes are included in VBFNLO program (very fast!).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VBFNLO - A parton level Monte Carlo for processes with electroweak bosons
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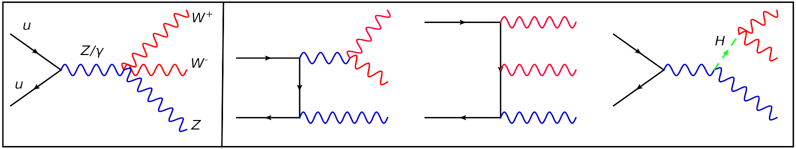
REPOLO
Implementation Details
EWSCHEME
Electroweak Renormalisation
Anomalous Higgs Couplings
Conversion to JHU notation
aQGC conventions
p
p
q
q
V
V
H
Project Description
VBFNLO is a fully flexible parton level Monte Carlo program for the simulation of vector boson fusion, double and triple vector boson production in hadronic collisions at next to leading order in the strong coupling constant. VBFNLO includes Higgs and vector boson decays with full spin correlations and all off-shell effects. In addition, VBFNLO implements CP-even and CP-odd Higgs boson via gluon fusion, associated with two jets, at the leading order one loop level with the full top-quark and bottom-quark mass dependence in a generic two Higgs doublet model.
A variety of effects arising from beyond the Standard Model physics are implemented for selected processes. This includes anomalous couplings of Higgs and vector bosons and a Warped Higgsless extra dimension model. The program offers the possibility to generate Les Houches Accord event files for all processes available at leading order.
All implemented processes can be found here.
The list of people involved in VBFNLO is here.
Download

NLO EW: main issues

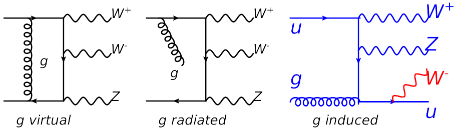
- amplitudes are complicated (a lot of Feynman diags)
- time-consuming
- numerical instabilities

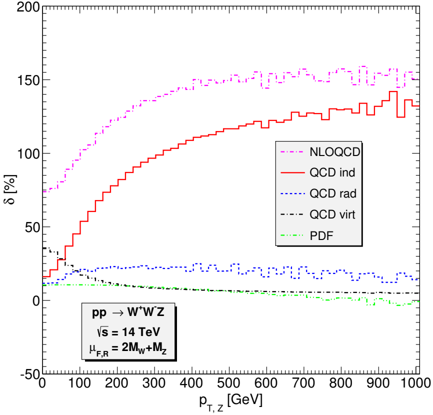
A typical example: W^+W^-Z [Nhung, LDN, Weber, arXiv:1307.7403]



- NLO QCD ?
- NLO EW ?

Huge QCD correction: p_T distributions





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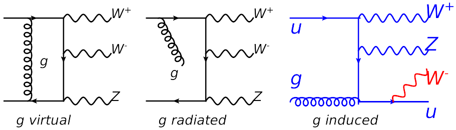

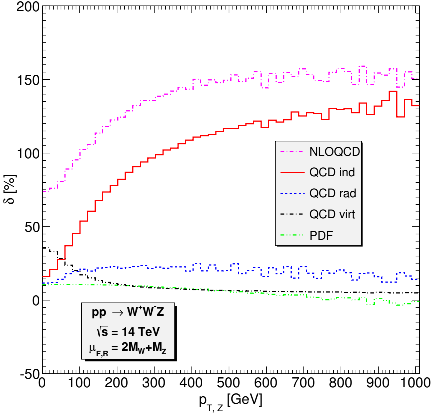

- Huge gluon induced correction: $\propto g(x)\alpha_s \log(p^2_{T,Z}/M^2_Z)$, a new mechanism!

EW correction: huge or tiny?

QCD

- Virtual gluon ($m_g = 0$)
- Real gluon emission
- Quark-gluon induced
- $\alpha_s \approx 0.1$
- gluon PDF: large at the LHC

EW

- Virtual photon, Z, $W^\pm$ ($m_\gamma = 0$, $M_Z = 90\,\text{GeV}$)
- Real photon emission
- Quark-photon induced
- $\alpha_s \approx 0.01$
- photon PDF: small at the LHC

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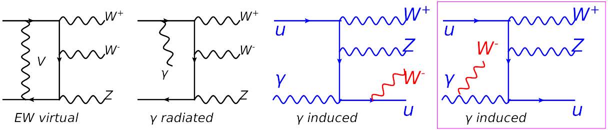


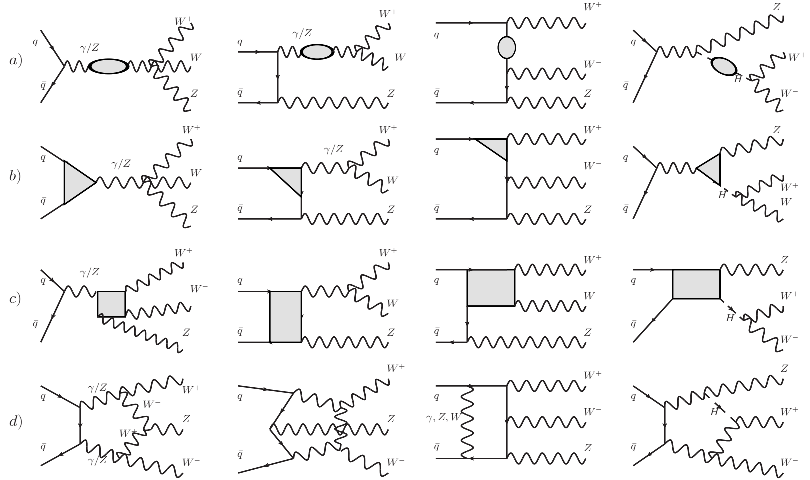
- real W, Z emission not included (different final states, finite since $M_V > 0$):
  $\rightsquigarrow$ Sudakov Double Logarithms $-\alpha \log^2(Q^2/M_V^2)$ from the virtual part survive.

- photon can radiate W: $\rightsquigarrow$ new (compared to QCD) mechanism in quark-photon induced processes.

$\Longrightarrow$ What is the size of EW corrections?

Feynman diagrams

Use input-parameter and renormalization scheme such that $|A|^2_{\text{virt}}$ is independent of light m_f!



Checks of the calculation

Bugs are everywhere!

- Check UV, IR finiteness
- Two independent calculations are in good agreement
  [Using FeynArt, FormCalc, in-house LoopInts]
- Numerical instabilities occur in the integration of the virtual part. This requires that the scalar and tensor integrals have to be stably calculated:
  - 5-point integrals: method of Denner and Dittmaier (2005), no explicit Gram determinant.
  - 3 and 4 point integrals: Passarino and Veltman reduction method,

$$D_{ijkl} = f(p_i, m_i)/\det(G_N)^4. \quad (1)$$

  - Using quadruple precision if

$$\frac{\det(G_N)}{(2p_{\max}^2)^{N-1}} < 10^{-3}, \quad N = 3, 4. \quad (2)$$

Scale dependence: LHC14

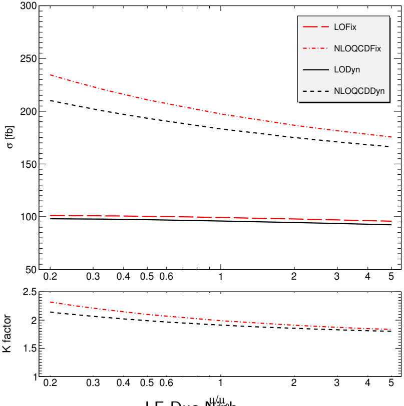
- $\sigma_{\text{LO}}(\mu_F)$: dominant region $x_1 = x_2 \approx 0.03$ ($M_{WWZ}^{\text{max}} \approx 400\,\text{GeV}$) $\rightsquigarrow$ small μ_F dependence.
- $\sigma_{\text{NLO}}(\mu_F, \mu_R) \propto \alpha_s(\mu_R)$: μ_R dependence is dominant.
- Fixed scale: $\mu = \mu_R = \mu_F, \mu_0 = (2M_W + M_Z)$.
- Dynamic scale: $\mu = \mu_R = \mu_F, \mu_0 = M_{WWZ}$.

$$\delta = \frac{|\sigma(2\mu_0) - \sigma(\mu_0/2)|}{\sigma(\mu_0)}$$

LO: 2.5% (Fix), 2.7% (Dyn)

NLO:12.2% (Fix), 10% (Dyn)

No better choice for the scale.

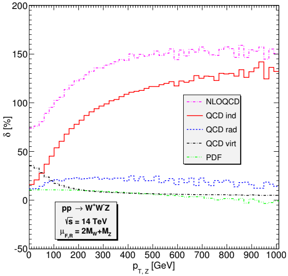


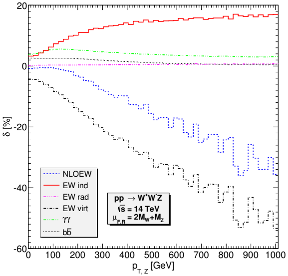
Total cross section: LHC14

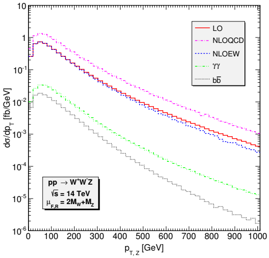
- quark PDFs: MSTW2008
- photon PDFs: MRST2004qed

		Fixed scale		Dynamic scale	
		$\sigma[fb]$	$\delta[\%]$	$\sigma[fb]$	$\delta[\%]$
LO		99.29(2)	...	95.91(2)	...
$\bar{b}b$		2.4173	2.4	2.6915	2.8
$\gamma\gamma$		4.852	4.9	5.559	5.8
Δ_{QCD}	$q\bar{q}$	48.83(3)	49.2	53.33(3)	55.6
	$qg, \bar{q}g$	49.29(1)	49.6	34.07(1)	35.5
Δ_{EW}	$q\bar{q}$	-8.74(1)	-8.8	-8.05(1)	-8.4
	$q\gamma, \bar{q}\gamma$	6.81(1)	6.8	5.854(9)	6.1
Δ_{NLO}		103.46(4)	104.2	93.46(4)	97.4

P_T distributions: QCD vs. EW







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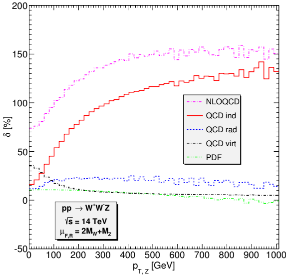
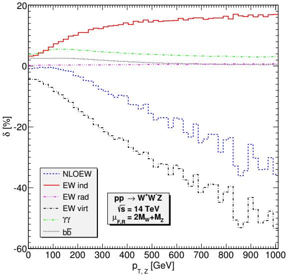
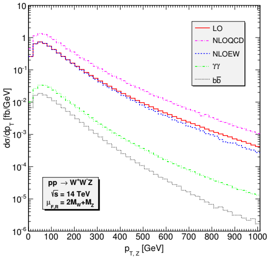


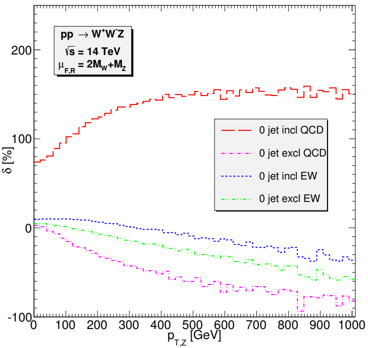




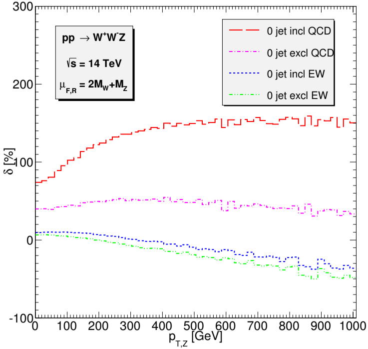
- Virtual EW: Sudakov Double Logarithms $-\alpha \log^2(p_{T,Z}^2/M_W^2)$, as expected, -53% at 1 TeV.
- The quark-photon induced correction is NOT small (17% at 1 TeV)!

P_T distributions with jet-veto

- need jet-veto to kill $t\bar{t}Z$ background (remind W^+W^-).
- Fixed jet veto: veto all events with $p_{T,j} > 25$ GeV and $\eta_j < 4.5$
- Dynamic jet veto: veto all events with $p_{T,j} > \max(M_{T,W^+}, M_{T,W^-}, M_{T,Z})/2$



Fixed jet veto



Dynamic jet veto

Summary

- $pp \to VVV$: NLO QCD and EW corrections are similar to the case of VV.
- p_T^Z distribution at 1 TeV: QCD $\rightsquigarrow 20 + 130 = 150\%$, EW $\rightsquigarrow -53 + 17 = -36\%$.
- Large corrections due to new subprocesses (gluon- and photon-quark induced) opening up at NLO.
- For EW correction: significant cancellation between virtual and photon-quark induced corrections.
- Dynamic jet veto seems better than fixed jet veto (BUT remember: jet veto always increases theoretical uncertainty).

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THANK YOU FOR YOUR ATTENTION