Karlsruher Institut für Technologie

WZjj production @ NLO QCD

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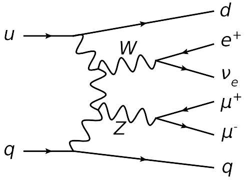
KIT - INSTITUT FÜR THEORETISCHE PHYSIK

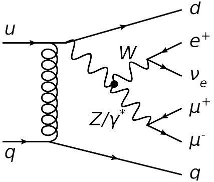
Outline

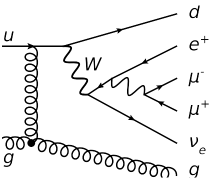
1. *WZjj* production mechanisms
2. NLO caluclations in parton level Monte-Carlos
3. Implementation in VBFNLO
   - Real emissions
   - Virtual corrections
   - Performance
4. Results
5. Summary

WZjj production mechanisms

EW (VBF) *WZjj* (α^6) [VBFNLO, 2007]	QCD *WZjj* ($\alpha_s^2\alpha^4$)







- triple and quartic EW vector boson couplings
- two jets with high separation/invariant mass
- precision measurements of EW sector

- irreducible background to VBF process
- large cross section
- high scale uncertainty (α_s^2)
- nontrivial color structure

Motivation

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QCD $pp \to WZjj$ is a background to various processes:

- EW *WZjj* production via Vector Boson Scattering
  - Probe mechanism of EW symmetry breaking
    $\to$ precision measurement
  - Central Jet Veto $\to$ reduce QCD background
- SUSY searches

precision measurements of *VVjj* production at the LHC require predictions with next to leading order accuracy (NLO) in α_s

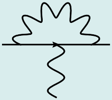
First NLO implementation of this process
(W^+W^+jj, W^+W^-jj known)

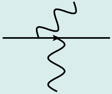
[Melia, Melnikov, Rontsch, Zanderighi 2010/2011]
[Greiner, Heinrich, Mastrolia, Ossola, Reiter, Tramontano 2012]

NLO contributions

Virtual corrections | Real emissions

E.g.: Drell-Yan process





- UV-divergent
  $\rightarrow$ renormalization
- IR-divergent

- IR-divergent

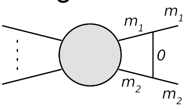
KLN theorem:
All IR singularities cancel in the sum of virtual and real contributions for sufficiently inclusive observables.

[T. Kinoshita 1962; T.D. Lee, M Naunberg 1964]

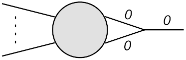
IR divergencies

Virtual corrections

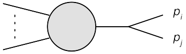
- soft divergencies



- collinear divergencies



Real emissions



- soft divergencies:
  $p_i \rightarrow 0$ oder $p_j \rightarrow 0$
- collinear divergencies:
  $p_i \,||\, p_j$

Regularization: Continuation of the phase space to $d = 4 - 2\varepsilon$ space-time dimensions
$\rightarrow$ divergencies = $\frac{1}{\varepsilon^2}$- and $\frac{1}{\varepsilon}$- poles

Subtraction methods

$$\sigma^{NLO} = \underbrace{\underbrace{\int_{m+1} d\sigma^R}_{\text{divergent}} + \underbrace{\int_m d\sigma^V}_{\text{divergent}} + \underbrace{\int_m d\sigma^C}_{\text{divergent}}}_{\text{finite}}$$

Monte-Carlo integration (in $d = 4$ dimensions)
$\rightarrow$ insert additional term $d\sigma^A$:

$$\sigma^{NLO} = \int_{m+1} \left[d\sigma^R|_{\epsilon=0} - d\sigma^A|_{\epsilon=0} \right] + \int_m \left[d\sigma^V + d\sigma^C + \int_1 d\sigma^A \right]_{\epsilon=0}$$

with

$$d\sigma^A \xrightarrow[\text{regions}]{\text{soft/coll.}} d\sigma^R$$

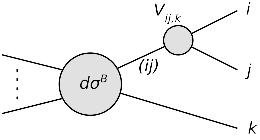
$$\int_1 d\sigma^A = (\mathbf{I} + \mathbf{P} + \mathbf{K}) \otimes d\sigma_B$$

Both phase-space integrals are finite!

Real emissions

Catani-Seymour dipole subtraction: [S. Catani, M.H. Seymour 1996]

$$d\sigma^A = \sum_{\substack{\text{pairs } (ij)= \\ (q\bar{q}),(qg),(gg)}} \sum_{k \neq i,j} d\sigma^B \otimes \mathbf{V_{ij,k}}$$

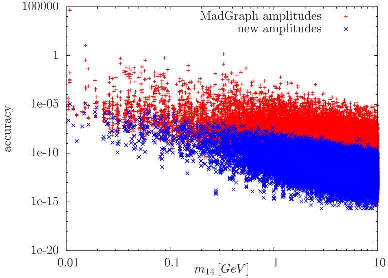


Real emission calculation of *WZjj* production:

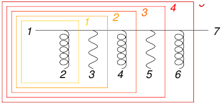
- 146 subprocesses
- with leptonc decays: 2 $\rightarrow$ 7 processes
- up to 27 dipoles per subprocess
- optimizations:
  - combine subprocesses
  - cache Born amplitudes, used in different dipoles
  - ...

Real emissions

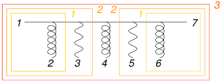
numerically stable implementation of matrix elements needed

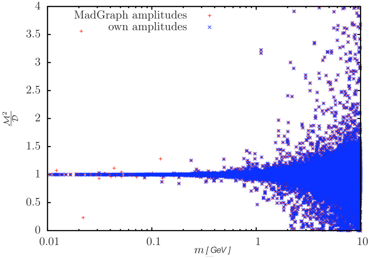


MadGraph 4:
bad precision when
6 || 7



Own implementation:
numerically stable

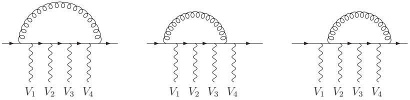




Virtual amplitude

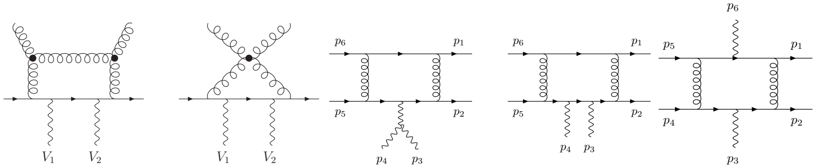
- up to hexagon diagrams
- split into universal building blocks, e.g.

HexLine
Abelian



+ 3 boxes
+ 4 vertices
+ 3 self energies

- most building blocks already used in other processes
- new topologies:

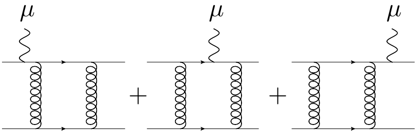


- tensor reduction
  - Passarino-Veltman (up to boxes) [G. Passarino, M. Veltman 1979]
  - Denner-Dittmaier (pentagons, hexagons) [A. Denner, S. Dittmaier 2005]

Gauge tests

- Use Ward identities to identify numerical instabilities, e.g.

$$p_V^\mu \mathrm{PenBox}_\mu = p^\mu \cdot \left(\quad (1) + (2) + (3) \quad \right) = 0$$



(1) (2) (3)

$\rightarrow$ Gauge test: $\left| \frac{(1)+(2)}{(3)} + 1 \right| = \mathit{GaugePrec.} \overset{?}{<} \mathit{GaugeLimit}$

- Most amplitudes can be calculated with *double precision*
- If gauge test fails:
  - Recalculate scalar integrals and tensor reduction using *quad precision*
  - If gauge test still fails $\rightarrow$ discard phase space point

Performance

- Percentage of unstable phase space points
  (only 2q2g-subprocesses, GaugeLimit = 0.01)

	double precision	*quad precision*
hexagons	1.2%	$\sim 10^{-4}$
pentagons	0.6%	$\sim 10^{-6}$

- Runtime of amplitudes
  0.4-25 ms (depending on subprocess)
- Total runtime
  2-3 h to get 1% accuracy on one processor

Scale variation

$pp \to e^+ \nu_e \mu^+ \mu^- jj$ @ 14 TeV

- Cuts:

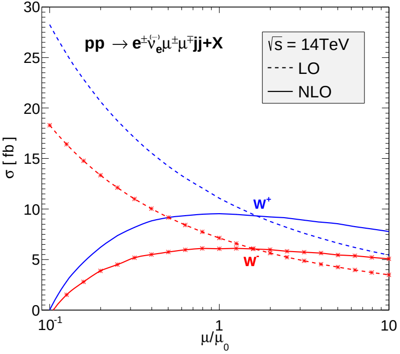
$$p_{Tj} > 20 \text{ GeV}, \quad |\eta_j| < 4.5,$$
$$p_{Tl} > 20 \text{ GeV}, \quad |\eta_l| < 2.5,$$
$$R_{jj} > 0.4, \quad R_{ll} > 0.4, \quad R_{jl} > 0.4,$$
$$m_{l^+l^-} > 15 \text{ GeV}, \quad \not{p}_T > 30 \text{ GeV}$$

- PDF:

MSTW2008 with $N_f = 4$

- Scale:

$$\mu_F = \mu_R = \mu_0$$
$$= \frac{1}{2}\left(\sum_{\text{jet}} p_{T,\text{jet}} + E_{T,W} + E_{T,Z}\right)$$
with $E_{T,V} = \sqrt{p_{T,V}^2 + m_V^2}$



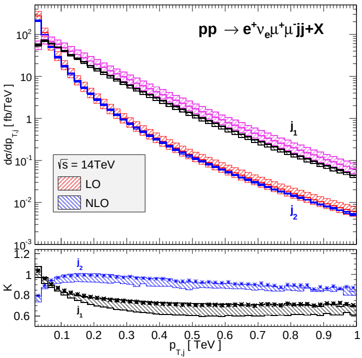
scale dependence reduced

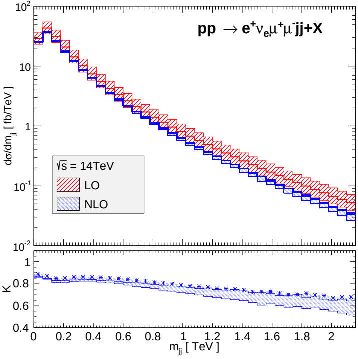
$$\sigma_{LO}^{W^+Zjj} = 11.1^{+3.2}_{-2.3} \; fb$$

$$\sigma_{NLO}^{W^+Zjj} = 9.5^{+0.0}_{-0.4} \; fb$$

Differential cross section

$p_{T,j}$ m_{jj}





- scale uncertainty reduced
- K-factor (NLO/LO): 0,6-1
  depending on phase space region

Summary

- *WZjj* production: QCD und EW mechanism
- Imlementation of QCD process @ NLO QCD
  - numerically stable
  - fast
  - checked with 2^{nd} independent implementation
- Scale uncertainty: 50% (LO) $\rightarrow$ 5% (NLO)
- K-factor depending on phase space region

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Thank you for your attention!