$W\,Z\,\gamma$ production at NLO QCD

in collaboration with F. Campanario, H. Rzehak and D. Zeppenfeld

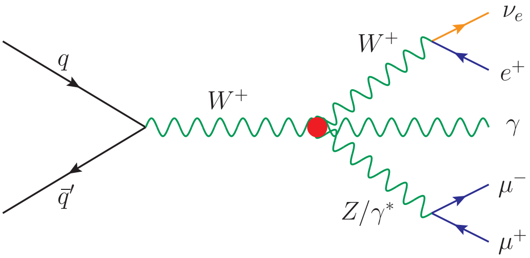
Michael Rauch | March 2010

INSTITUTE FOR THEORETICAL PHYSICS

Motivation

Physics motivation:

- Trilepton final state with missing transverse energy
  $\Rightarrow$ Background to searches beyond the Standard Model (e.g. SUSY)
- Possibility to obtain information about quartic gauge-boson couplings ($W\,W\,Z\,\gamma$ and $W\,W\,\gamma\,\gamma$)



Current Status

Triple vector-boson production part of NLO wishlist

- NLO QCD corrections to ZZZ production

  [Lazopoulos, Melnikov,Petriello 07]

- NLO QCD corrections to WWZ production
  with leptonic decays $\longrightarrow$ VBFNLO

  [Hankele, Zeppenfeld 08]

- NLO QCD corrections to ZZZ, WWZ, ZZW, WWW production

  [Binoth, Ossola, Papadopoulos, Pittau 08]

- NLO QCD corrections to ZZW, WWW production
  with leptonic decays $\longrightarrow$ VBFNLO

  [Campanario, Hankele, Oleari, Prestel, Zeppenfeld 08]

- NLO QCD corrections to $WW\gamma$, $ZZ\gamma$ production
  with leptonic decays $\longrightarrow$ VBFNLO

  [Bozzi, Campanario, Hankele, Zeppenfeld 09]

- NLO QCD corrections to $W\gamma\gamma$ production

  [Baur, Wackeroth, Weber in progress]

- This Talk:
  NLO QCD corrections to $WZ\gamma$ production
  with leptonic decays $\longrightarrow$ VBFNLO

Current Status

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- NLO QCD corrections to $Z\,Z\,Z$ production
  [Lazopoulos, Melnikov,Petriello 07]
- NLO QCD corrections to $W\,W\,Z$ production
  with leptonic decays → VBFNLO
  [Hankele, Zeppenfeld 08]
- NLO QCD corrections to $Z\,Z\,Z$, $W\,W\,Z$, $Z\,Z\,W$, $W\,W\,W$ production
  [Binoth, Ossola, Papadopoulos, Pittau 08]
- NLO QCD corrections to $Z\,Z\,W$, $W\,W\,W$ production
  with leptonic decays → VBFNLO
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- NLO QCD corrections to $W\,W\,Z$ production
  with leptonic decays $\longrightarrow$ VBFNLO

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- NLO QCD corrections to $Z\,Z\,Z$, $W\,W\,Z$, $Z\,Z\,W$, $W\,W\,W$ production

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- NLO QCD corrections to $Z\,Z\,W$, $W\,W\,W$ production
  with leptonic decays $\longrightarrow$ VBFNLO

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- NLO QCD corrections to $W\,W\,\gamma$, $Z\,Z\,\gamma$ production
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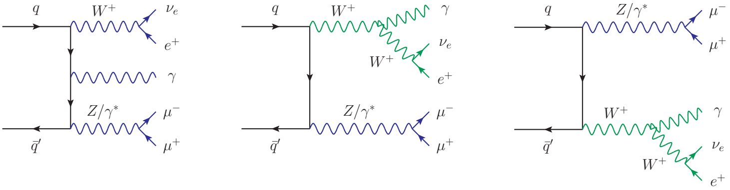
$W\,Z\,\gamma$ production



...

- All resonant and non-resonant matrix elements as well as spin correlations of final state leptons included
- γ taken as real (otherwise part of $W\,Z\,Z$)
- Interference terms due to identical particles in the final state neglected
- All fermion mass effects neglected
- In total 71 Feynman graphs for LO and 194 for LO plus jet ($\rightarrow$ real emission part) $\Rightarrow$ helicity amplitude method [Hagiwara, Zeppenfeld]
- Same building blocks for different Feynman graphs $\Rightarrow$ Compute only once per phase-space point and reuse ("leptonic tensors")
- Hand-written code up to factor 10 faster than SHERPA

Checks – LO and LO+j Comparison

- Comparison with MadGraph pointwise in phase-space ($W^+Z\gamma$):
  - Three qqV vertices

VBFNLO	$2.67043931319751927 \cdot 10^{-6} + 7.93930367436647552 \cdot 10^{-6}$ i
MadGraph	$2.67043931319726770 \cdot 10^{-6} + 7.93930367436614009 \cdot 10^{-6}$ i
ratio of absolute values	$1.0000000000000953 \simeq 1 + 10^{-13}$

  - Two qqV vertices

VBFNLO	$1.68921080432822916 \cdot 10^{-5} - 1.82679493447941318 \cdot 10^{-5}$ i
MadGraph	$1.68921080432817664 \cdot 10^{-5} - 1.82679493447928884 \cdot 10^{-5}$ i
ratio of absolute values	$1.0000000000001021 \simeq 1 + 10^{-13}$

  - One qqV vertex (s-channel)

VBFNLO	$-1.72717755320785464 \cdot 10^{-5} + 1.65363967675760989 \cdot 10^{-5}$ i
MadGraph	$-1.72717755320779500 \cdot 10^{-5} + 1.65363967675749198 \cdot 10^{-5}$ i
ratio of absolute values	$1.0000000000001041 \simeq 1 + 10^{-13}$

  - Similar accuracy for all other process types ($W^-Z\gamma, W^+Z\gamma j, W^-Z\gamma j$)

- Comparison with Sherpa and MadGraph/MadEvent integrated over phase-space (cross sections in ab)

process	VBFNLO	Sherpa	MadEvent
$W^+Z\gamma$	327.87 ± 0.21	327.83 ± 0.19	325.95 ± 1.13
$W^-Z\gamma$	219.04 ± 0.13	219.20 ± 0.13	217.58 ± 0.70
$W^+Z\gamma j$	378.20 ± 0.68	379.42 ± 0.72	—
$W^-Z\gamma j$	268.32 ± 0.25	268.02 ± 0.55	—

Catani-Seymour Dipole Subtraction

Karlsruhe Institute of Technology

$$\sigma_{\rm NLO} = \int d\sigma_{\rm NLO} = \underbrace{\int_{m+1} d\sigma^R}_{\text{real emission}} + \underbrace{\int_m d\sigma^V}_{\text{virtual contributions}}$$

$\int_{m+1} d\sigma^R$ and $\int_m d\sigma^V$ are separately infrared divergent in 4 dimensions

Divergences cancel in sum [Kinoshita, Lee, Nauenberg]

$\Rightarrow$ Introduce local counterterm $d\sigma^A$ with the same singular behaviour as $d\sigma^R$

$$\sigma_{\rm NLO} = \int_{m+1} [d\sigma^R|_{\epsilon=0} - d\sigma^A|_{\epsilon=0}] + \int_m [d\sigma^V + \int_1 d\sigma^A]_{\epsilon=0} + \underbrace{\int_m d\sigma^C}_{\text{finite collinear term}}$$

Numerical integration in 4 dimensions

Poles cancel analytically

[Catani, Seymour 96]

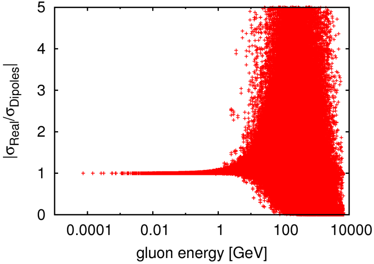
Checks – Cancellation of infrared divergencies

Catani-Seymour subtraction formalism:

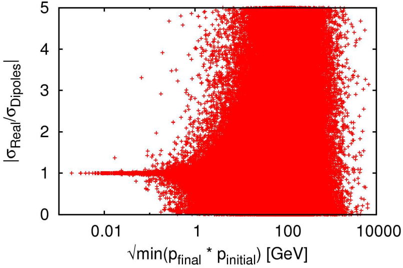
$$\sigma_{\text{NLO}} = \int_{5+1} [\mathrm{d}\sigma^R|_{\epsilon=0} - \mathrm{d}\sigma^A|_{\epsilon=0}] + \ldots$$

About 1 million phase-space points

- Soft Divergencies



- Collinear Divergencies



Exact cancellation as we approach the relevant limits

Checks – Correspondence between (5) and (5+1)-particle PS

Constant terms can be shifted between
virtual (`cvirt`) and finite-collinear (`creal`) part

Only sum physically meaningful: $\texttt{csum} = \texttt{cvirt} + \texttt{creal} = \frac{\pi^2}{3} - 3$

Process $W^+ Z \gamma$, c.s. in ab

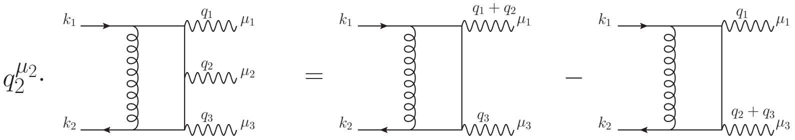
	$cvirt = \frac{4}{3}\pi^2 - 8$	$cvirt = -30$	$cvirt = +30$
σ_{virt}	450.32 ± 0.33	160.83 ± 0.16	654.85 ± 0.46
σ_{real}	184.81 ± 0.84	473.44 ± 0.84	-20.06 ± 0.74
σ_{tot}	635.13 ± 0.90	634.27 ± 0.86	634.79 ± 0.86

Comparison checks

- mapping of finite collinear terms onto (5+1)-particle PS
- consistency of settings between virtual and real emission calculation (α_s, colour factors, ...)

Checks & Tricks – Shifting Polarization Vectors

Effective polarization vector of the vector boson can be split: $\epsilon_V^\mu = x_V q_V^\mu + \tilde{\epsilon}_V^\mu$
Use identity



to shift contributions from pentagons to boxes
Box integration quicker
Can use less MC points for pentagons for same final accuracy

Best choice (by trying): $\tilde{\epsilon}_V^\mu \cdot (q_\mu^W + q_\mu^Z) = 0$

Cross-check (Process $W^+ Z \gamma$, c.s. in ab):

c.s. in ab	with shift	no shift	single int.
born-virtual	402.6	402.6	–
boxes	38.7	33.6	–
pentagons	9.0	13.9	–
sum	450.3	450.2	450.2
error	0.3	0.3	0.3

Photon Isolation

Simple (e.g. R) separation cut between photon and jet not infrared safe:

- Complete divergence in virtual part (integration over loop momentum)
- Part of divergence in real part removed by separation cuts
- $\Rightarrow$ Cancellation of infrared divergencies between virtual and real part broken

Use Frixione cut (infrared safe): [Frixione 98]

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

$\delta_0 = 0.7$ is fixed separation cut

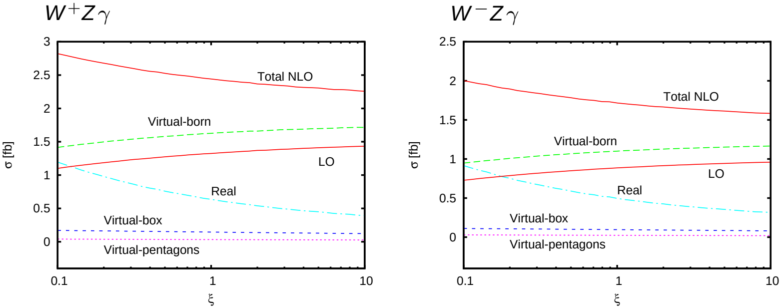
- Sufficiently soft parton (E_{T_i} small)
  $\longrightarrow$ arbitrarily close to photon axis possible
- Collinear parton ($R_{i\gamma} = 0$)
  $\longrightarrow$ only accepted for vanishing energy

Numerical Results – Gauge dependence

No distinction between *e* and μ in the final state $\Rightarrow$ multiplicity factor 4

Scale choice $\mu_0 =$ invariant mass of $WZ\gamma$ system

Combined factorization and renormalization scale dependence $\mu = \mu_F = \mu_R = \xi\mu_0$

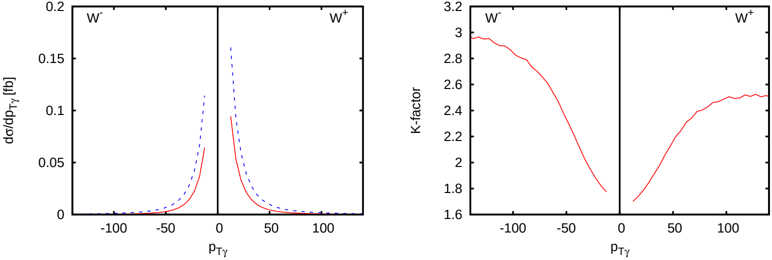


K-factor($\xi = 1$) = 1.84

K-factor($\xi = 1$) = 1.94

Numerical Results – Distributions

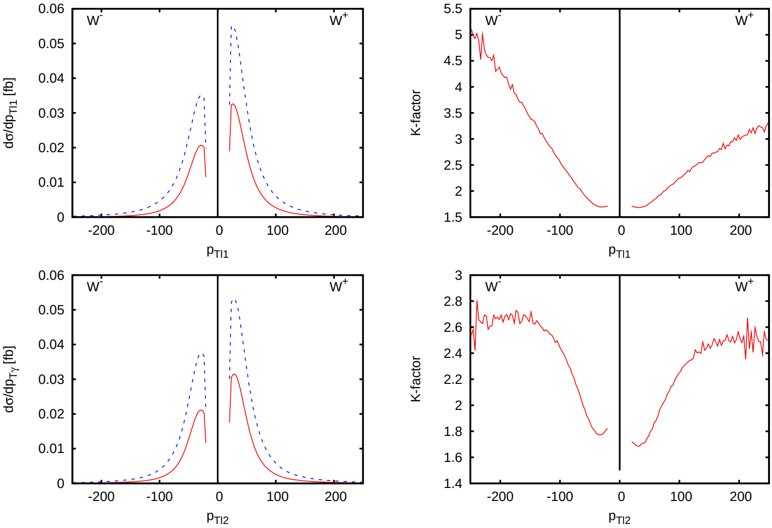
Transverse momentum distribution of the photon
(solid red: LO; dashed blue: NLO)



- K-factor varies strongly over photon momentum
- Simple rescaling of LO cross section not a good approximation
- $\Rightarrow$ Need NLO differential distributions

Numerical Results – Distributions

Transverse momentum of lepton 1 and 2 (p_T-ordered)
(solid red: LO; dashed blue: NLO)



Conclusions

- NLO QCD corrections to $W^{\pm} Z \gamma$ with leptonic decays evaluated
- All off-shell effects included
- Important background for supersymmetry
  Test of $W W Z \gamma$ and $W W \gamma \gamma$ gauge couplings in SM
- Sizable K-factors, strong variation within distributions
  $\Rightarrow$ simple multiplication of LO result with K-factor
  not a good approximation

Outlook:

- Calculation of $W^{\pm} \gamma \gamma$, $Z \gamma \gamma$ and $\gamma \gamma \gamma$ in progress [Bozzi, Campanario, MR, Zeppenfeld]

Experimental cuts

Experimental values:

$$p_j^T > 20\ \text{GeV} \qquad |\eta_j| < 4.5$$
$$p_l^T > 20\ \text{GeV} \qquad |\eta_l| < 2.5$$
$$p_\gamma^T > 10\ \text{GeV} \qquad |\eta_\gamma| < 2.5$$

$$\Delta m_{ll} > 15\ \text{GeV} \qquad \Delta R_{ll} > 0.3 \qquad \Delta R_{l\gamma} > 0.4 \qquad \Delta R_{j\gamma} > 0.4$$

$$\Delta R_{p\gamma,\text{Frixione}} = 0.7 \qquad \text{Eff.}_{\text{Frixione}} = 1.0$$

$$m_W = 80.398\ \text{GeV} \qquad m_Z = 91.1876\ \text{GeV}$$

$$\text{PDFs}:\ \text{LO}:\ \text{CTEQ6l1} \qquad \text{NLO}:\ \text{CTEQ6m}$$
$$\text{LHC}:\ \sqrt{S} = 14\ \text{TeV}$$

Numerical Results – Distributions

Missing transverse momentum
(solid red: LO; dashed blue: NLO)