Precision Multiboson Phenomenology: Status and Prospects

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Outline

- Vector-Boson Fusion (*Vjj*) / Vector-Boson Scattering (*VVjj*)

- Triboson Production (*VVV*)

VBF event topology

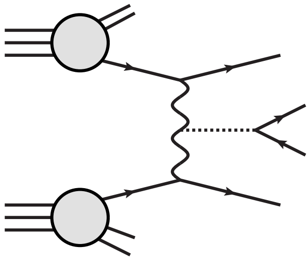
VBF (vector-boson fusion) topology shows distinct signature

- two tagging jets in forward region
- reduced jet activity in central region
- leptonic decay products typically between tagging jets

→ two-sided DIS

First studied in context of Higgs searches [Han, Valencia, Willenbrock; Figy, Oleari, Zeppenfeld; . . .]

- $\sim$ 10% compared to main production mode gluon fusion
- NLO QCD corrections moderate ($\mathcal{O}(\lesssim 10\%)$)
- NLO EW same size, opposite sign as QCD for $M_H \sim 126$ GeV [Ciccolini *et al.* , Figy *et al.*]
- NNLO QCD known for subsets: no significant contributions [Harlander *et al.* , Bolzoni *et al.*]
- advantageous scale choice: momentum transfer q^2 of intermediate vector bosons



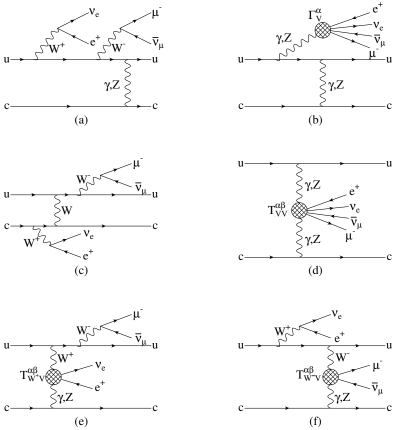
Diboson-VBF production

[Bozzi, Jäger, Oleari, Zeppenfeld (VV); Campanario, Kaiser, Zeppenfeld ($W^{\pm}\gamma$)]
[Denner, Hosekova, Kallweit ($W^{+}W^{+}$)]

- Part of the NLO wish list
  [Les Houches 2005]
- background to Higgs searches
- access to triple and quartic gauge couplings

Available tools:

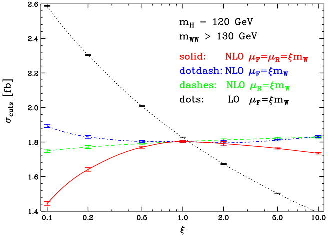
- VBFNLO [Zeppenfeld, MR et al.]
  NLO QCD, VBF approximation
- Phantom [Ballestrero et al.]
  LO, $pp \to 6f$
- automated tools, e.g.
  GoSam [Cullen et al.]
  MadGraph5_aMC@NLO
  [Artoisenet et al.]



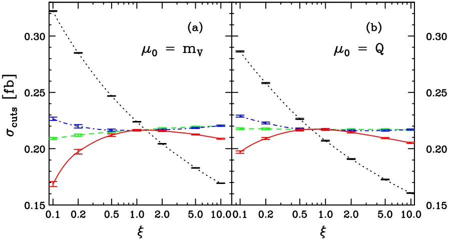
Scale dependence

Dependence on factorization and renormalization scale [Bozzi, Jäger, Oleari, Zeppenfeld]

$pp \to W^+W^-jj$



$pp \to W^+Zjj$



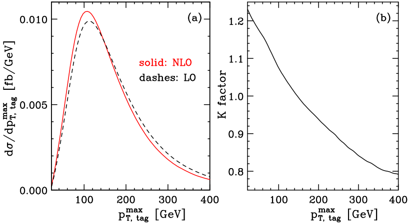
- sizable scale dependence at LO: $\sim \pm$ 10%
- strongly reduced at NLO: $\sim \pm$ 2% (up to 6% in distributions)
- K-factor around 0.98 for $\mu = m_V$, 1.04 for $\mu = Q$ (momentum transfer)

Distributions

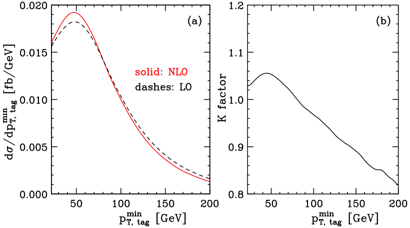
[Jäger, Oleari, Zeppenfeld]

Differential distributions: $p_T(j)$ ($W^+ W^-$)

p_T of the leading tagging jet



p_T of the second tagging jet

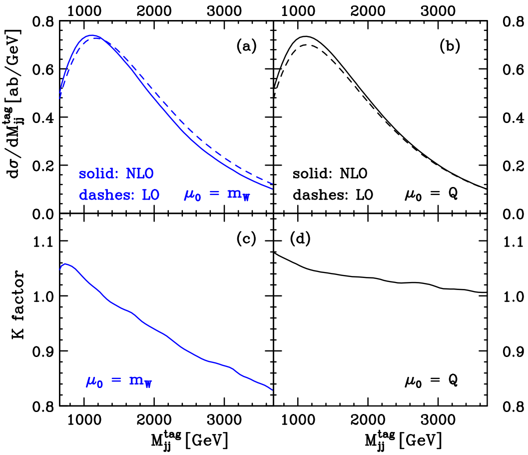


- K factor not constant over range of distribution
- → shape of distributions changes
- → simple rescaling with K factor not sufficient

Distributions

Differential distributions: m_{jj} ($W^+ W^+$)

[Jäger, Oleari, Zeppenfeld]



→ scale choice $\mu_0 = Q$ leads to flatter differential K factor

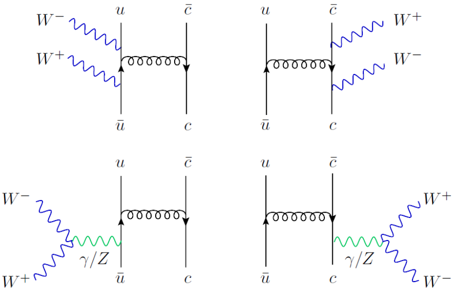
QCD-Diboson production

Most important background: QCD-Diboson Production
All combinations available at NLO QCD:

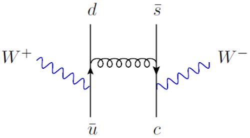
[Melia, Melnikov, Röntsch, Zanderighi; Greiner, Heinrich, Mastrolia, Ossola, Reiter, Tramontano]

[Campanario, Kerner, Ninh, Zeppenfeld; Gehrmann, Greiner, Heinrich]

W^+W^-jj



W^+W^-jj & W^+W^+jj
(latter after changing quark flavors appropriately)



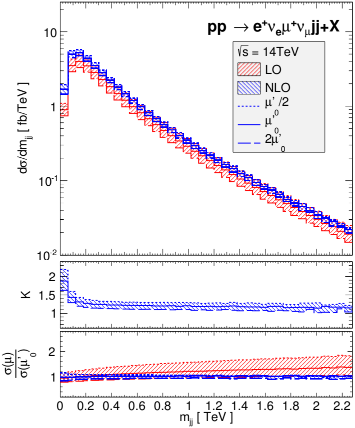
+ diagrams where quark line without attached vector bosons is replaced by gluons

QCD-Diboson production

$pp \to e^+\nu_e\mu^+\nu_\mu$

[Campanario, Kerner, Ninh, Zeppenfeld]

Impact of NLO QCD corrections



- K factors typically between 1 and 1.5
- corrections $<$ 20% for invariant mass of two leading jets $>$ 200 GeV
- huge correction for small m_{jj} due to new phase-space region (almost collinear quark-gluon splitting)
- good scale choice (interpolates between different regions):

$$\mu_0' = \frac{1}{2}\left(\sum_{\text{jets}} p_{T,i} \exp|y_i - y_{12}| + \sum_{W} \sqrt{p_{T,i}^2 + m_{W,i}^2} \right)$$

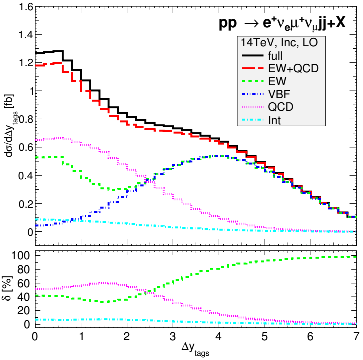
$(y_{12} = (y_1 + y_2)/2)$

QCD-EW interference

$pp \to e^+ \nu_e \mu^+ \nu_\mu$

[Campanario, Kerner, Ninh, Zeppenfeld]

Comparing contributions at LO



EW: full $\mathcal{O}(\alpha^6)$ calculation
VBF: VBF approximation
(only t-/u-channel diagrams)

- QCD and EW contributions of similar size
  (destructive interference for QCD, no gluon-initiated contributions)
- QCD-EW interference largest for large $p_{T,j}$, small Δy_{tags}
  up to 20% reducing to 10% (3%) for loose (tight) VBF cuts
- VBF contribution by far dominant in VBF region (96%)
  $\to$ good approximation

Definition of VBF region:

- $m_{jj} > 500$ GeV
- $\Delta y_{\text{tags}} > 4$
- $y_{j_1} \times y_{j_2} < 0$

Matching with parton shower

NLO calculation

- normalization correct to NLO
- additional jet at high-p_T accurately described
- theoretical uncertainty reduced
- low-p_T jet emission badly modeled
- parton level description

LO + parton shower

- LO normalization only
- further high-p_T jets badly described
- Sudakov suppression at small p_T
- events at hadron level possible

$\Rightarrow$ combine both approaches $\rightarrow$ NLO + parton shower

POWHEG-BOX [Alioli, Hamilton, Nason, Oleari, Re]

currently available VBF implementations:

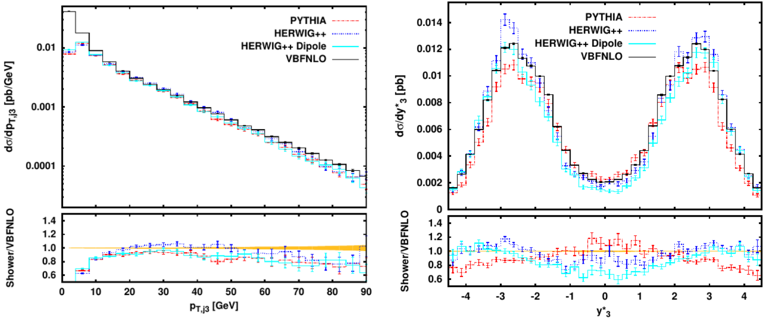
Z	[Jäger, Schneider, Zanderighi]
$W^\pm$, Z	[Schissler, Zeppenfeld]
$W^\pm W^\pm$, $W^\pm W^\mp$	[Jäger, Zanderighi]
ZZ	[Jäger, Karlberg, Zanderighi]

Matching with parton shower

W^+ via VBF (similar results for W^- and Z) [Schissler, Zeppenfeld]

$p_{T,j} > 30$ (tag), 20 GeV, $R = 0.5$, $m_{jj}^{\text{tag}} > 600$ GeV, $y_{j,\min}^{\text{tag}} - 0.2 < y_\ell < y_{j,\max}^{\text{tag}} + 0.2$

Relative position of third jet with respect to the two tagging jets: $y^\star = y_{j_3} - \frac{y_{j_1} + y_{j_2}}{2}$



Comparison of three different showers: Pythia, Herwig++-Default, Herwig++-Dipole

low-p_T region: damping due to Sudakov factor

hard 3rd jet $\gtrsim$ 75 GeV: lower rates than NLO from additional hard/wide-angle radiation

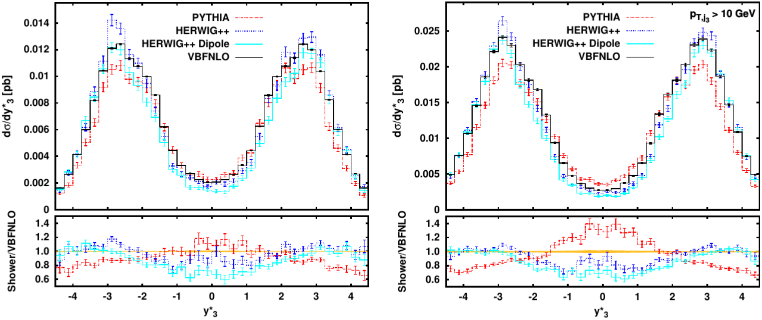
$y^\star$: relevant differences between shower algorithms

Matching with parton shower

W^+ via VBF

[Schissler, Zeppenfeld]

Relative position of third jet with respect to the two tagging jets: $y^\star = y_{j_3} - \frac{y_{j_1} + y_{j_2}}{2}$



Typical $|y_j^{\rm tag}| \simeq 2.7 \rightarrow |y^\star| < 2.7$ corresponds to rapidity gap

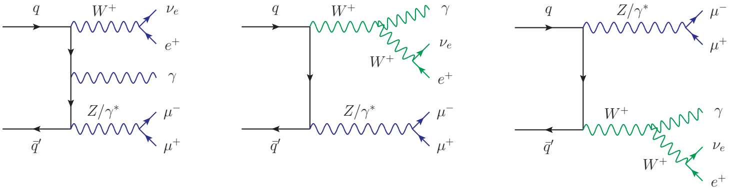
Pythia: more radiation inside rapidity gap than NLO $\leftrightarrow$ Herwig++ (both showers): less
even more pronounced when lowering $p_{T,j3}$ cut to 10 GeV
origin: more soft partons predicted by Pythia, mostly collinear radiation by Herwig++

Even bigger differences for additional jets generated solely by parton shower

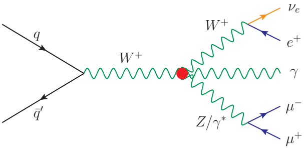
$\rightarrow$ Uncertainty of prediction

Triboson production

e.g. $pp \to W^+ Z\gamma \to \ell_1^+ \nu_1\, \ell_2^+ \ell_2^-\, \gamma$



- background to new-physics searches
  $\to$ signature: multilepton
  + possibly missing E_T
- gives access to triple and quartic gauge couplings (e.g. *WWWW*, $WW\gamma\gamma$)
- processes with all bosons massive contain intermediate Higgs
  $\to$ background to *VH*, $H \to VV$



Triboson production

All combinations $V \in \{W^\pm, Z, \gamma\}$ at NLO QCD discussed in literature:

- ZZZ production (no leptonic decays, no Higgs contribution) [Lazopoulos, Melnikov, Petriello]
- W^+W^-Z production [Hankele, Zeppenfeld]
- ZZZ, W^+W^-Z, $ZZW^\pm$, $W^\pm W^\mp W^\pm$ (no leptonic decays, no Higgs contributions) [Binoth, Ossola, Papadopoulos, Pittau]
- $ZZW^\pm$, $W^\pm W^\mp W^\pm$ [Campanario, Hankele, Oleari, Prestel, Zeppenfeld]
- ZZZ
- $W^+W^-\gamma$, $ZZ\gamma$ [Bozzi, Campanario, Hankele, Zeppenfeld]
- $W^\pm Z\gamma$ [Bozzi, Campanario, MR, Rzehak, Zeppenfeld]
- $W^\pm\gamma\gamma$ production (no leptonic decays, including CKM and fragmentation) [Baur, Wackeroth, Weber]
- $W^\pm\gamma\gamma$ [Bozzi, Campanario, MR, Zeppenfeld]
- $Z\gamma\gamma$, $\gamma\gamma\gamma$ [Bozzi, Campanario, MR, Zeppenfeld]
- W^+W^-Z (no leptonic decays, NLO QCD+EW) [Nhung, Ninh, Weber]

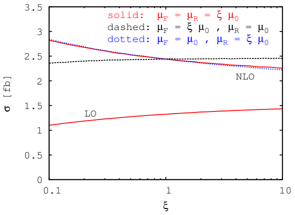
VBFNLO approximations: [Zeppenfeld, MR, et al.]

- fermion mass effects neglected, CKM matrix effects neglected
- Interference terms due to identical particles in the final state neglected

$W^{\pm}Z\gamma$ distributions

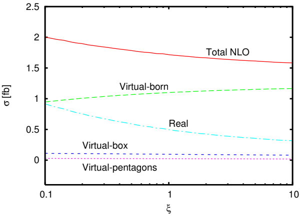
Scale dependence

$W^{+}Z\gamma$ ($\mu_0 = m_{WZ\gamma}$)



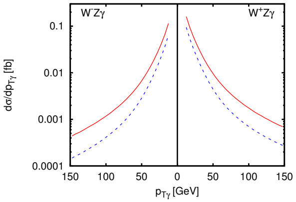
[Bozzi, Campanario, MR, Rzehak, Zeppenfeld]

Individual contributions $W^{-}Z\gamma$

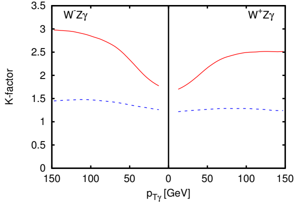


Transverse momentum of the photon

Total cross section NLO/LO



Differential K-factor without/with jet veto

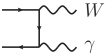


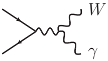
⇒ Sizable K-factor $\sim$ 1.9, strongly dependent on phase-space region

⇒ Fully differential NLO Monte Carlo necessary

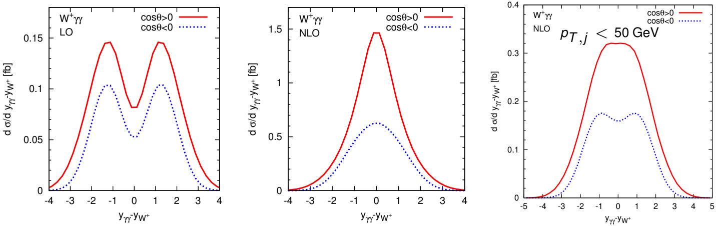
$W\gamma\gamma$

Radiation Zero in $W\gamma\gamma$ at LO

- SM amplitude for $q\bar{Q} \to W^{\pm}\gamma(\gamma)$ vanishes for $\cos\theta^*_W = \pm\frac{1}{3}$
  (for $W^{\pm}\gamma\gamma$ photons must be collinear) [Baur, Han, Kauer, Sobey, Zeppenfeld]
- Negative interference between 

and 

- LHC symmetric $\Rightarrow$ radiation dip at 0
- spoiled by
  - final-state radiation (photon emission off final-state lepton)
  - gluon-initiated processes (NLO real emission contribution)
- look at rapidity difference $y_{\gamma\gamma} - y_W$ for $\cos\theta_{\gamma\gamma} > 0$ and $\cos\theta_{\gamma\gamma} < 0$
- final-state radiation suppressed by cut $M_{T,\ell\nu} > 70$ GeV



$\Rightarrow$ radiation zero not present at NLO, not restored by jet veto

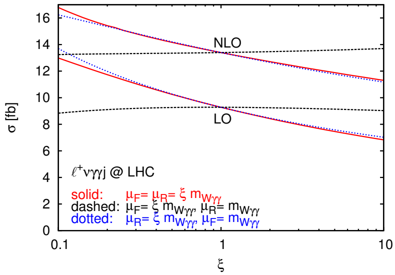
$W\gamma\gamma$ + jet

- Large K factors in $W^{\pm}\gamma\gamma$ calculation
- $\Rightarrow$ need higher orders in perturbation theory
- NLO calculation of real emission part important ingredient for NNLO precision

$\Rightarrow$ $W^{\pm}\gamma\gamma$ + jet calculation at NLO QCD [Campanario, Englert, MR, Zeppenfeld]

- First triboson + jet process at NLO QCD
- Leptonic decays of $W^{\pm}$ and all off-shell effects included

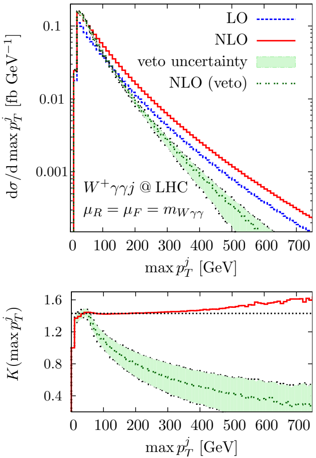
Scale dependence of $W^{+}\gamma\gamma j$



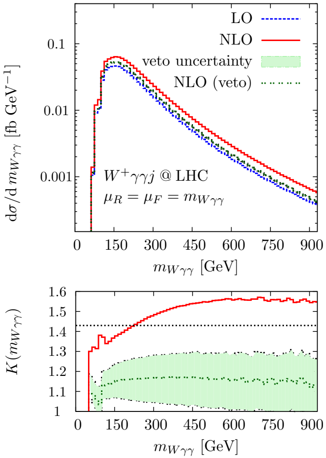
$\sigma_{\text{LO}} = 2 \cdot 4.6398(1)$ fb $\quad \sigma_{\text{NLO}} = 2 \cdot 6.5026(8)$ fb $\quad K = 1.40$

Distributions

Differential max p_T^j distribution



Invariant $W\gamma\gamma$ mass

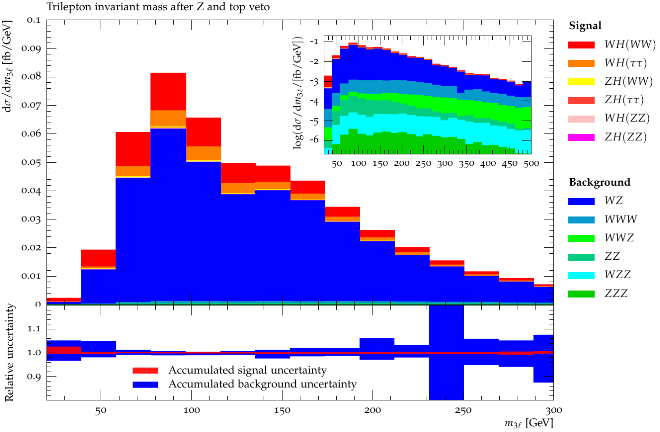


$\Rightarrow$ results consistent with NLO QCD corrections for *VVj*
$\Rightarrow$ global *K* factor not a good approximation $\rightarrow$ need full NLO calculation
$\Rightarrow$ large scale variation uncertainties for exclusive sample $p_{T,j_2} < 50$ GeV

Triboson + Parton Shower

Study of $pp \to 3\ell + \not{E}_T$ with VH, $H \to VV, \tau\tau$ as signal [Sherpa+OpenLoops (Höche et al.)]

Triboson processes appearing as background, simulated up to merging of VVV, $VVVj$ at NLO QCD and $VVVjj$ at LO, plus parton shower



→ non-trivial application of multi-jet merging at NLO

Conclusions

Multi-boson production important processes for LHC:

- access to triple/quartic gauge couplings
- background to Higgs searches

Vector-Boson Fusion/Scattering:

- modest NLO QCD corrections, small remaining scale uncertainties
- state-of-the-art: NLO QCD + parton shower
- enhance over irred. QCD background by VBF cuts
- $\leftrightarrow$ significant discrepancies in predicting central jet activity
  $\rightarrow$ needs further studies

Triboson production:

- large NLO QCD K factors due to new channels
- $\rightarrow$ merging with higher jet multiplicities
- fixed jet vetoes can induce large theory uncertainties

Experimental cuts for $W\gamma\gamma$

Experimental values used:

$p_j^T > 20$ GeV $\quad |\eta_{\text{parton}}| < 5.0 \quad |\eta_j| < 4.5$

$p_l^T > 20$ GeV $\quad |\eta_l| < 2.5$

$p_\gamma^T > 20$ GeV $\quad |\eta_\gamma| < 2.5$

$\Delta R_{l\gamma} > 0.4 \quad \Delta R_{\gamma\gamma} > 0.4 \quad \Delta R_{j\gamma} > 0.4$

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

$m_W = 80.398$ GeV $\quad m_Z = 91.1876$ GeV

PDFs : LO : CTEQ6l1 $\quad$ NLO : CT10

LHC : $\sqrt{S} = 14$ TeV