Parton Shower matching for VBS

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Monte Carlo description of VBS
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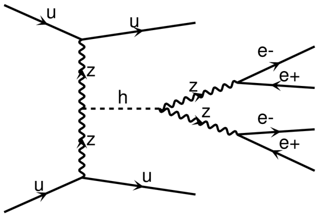
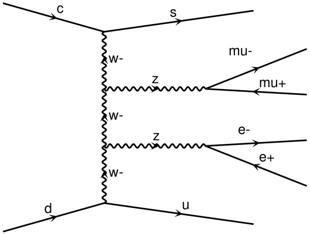
Vector Boson Scattering

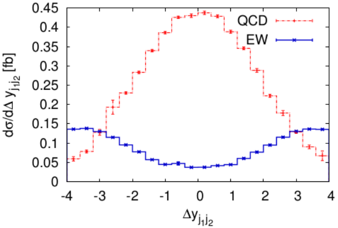


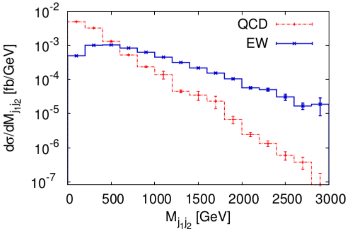


Topology

- Forward tagging jets
- Little central jet activity
- Leptonic decay products (typically) between jets

VBS cuts

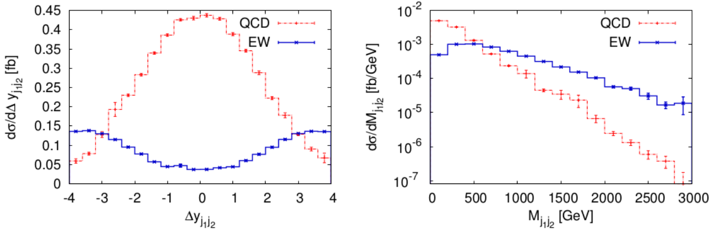




[Jäger, Zanderighi (2011)]

- Central leptons
  - $\eta_{j,min} < \eta_l < \eta_{j,max}$
- High invariant jet mass
  - $M_{jj} > 600\ GeV$
- Separated jets
  - $\eta_{j_1} \cdot \eta_{j_2} < 0$
  - $|\eta_{j_1} - \eta_{j_2}| > 4.0$

VBS cuts



[Jäger, Zanderighi (2011)]

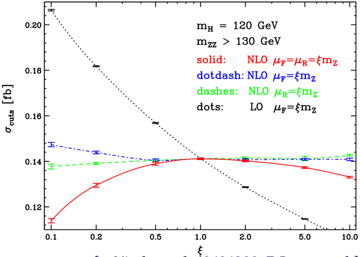
Inclusive NLO results ($p_T^{jet} > 20$ GeV)

$\sigma_{QCD}^{inc} \sim 2.1$ fb $\qquad$ $\sigma_{EW}^{inc} \sim 1.1$ fb

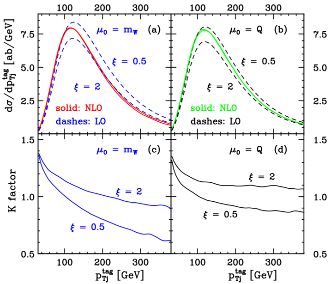
VBF NLO results

$\sigma_{QCD}^{VBF} \sim 0.007$ fb $\qquad$ $\sigma_{EW}^{VBF} \sim 0.2$ fb

Why study NLO?



[arXiv:hep-ph/0604200, B.Jäger et al.]



[B.Jäger et al. (2010)]

- Precision
- Stability
  - Normalisation of LO results arbitrary
  - Scale dependence reduced to $\sim 2\%$

VBS@NLO-QCD

Fixed order NLO-QCD result for

- $pp \rightarrow ZZjj, \quad W^{\pm}W^{\mp}jj, \quad W^{\pm}W^{\pm}jj, \quad W^{\pm}Zjj$

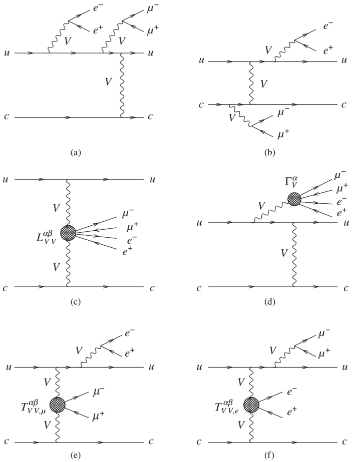
available through VBFNLO. [Figy, Oleari, Zeppenfeld (2003)]

- Includes
  - off-shell effects
  - spin correlations
  - s-channel contributions (version used for mathcing did not)
- Excludes
  - t/u-channel interference

S-channel and interference effects found to contribute at the permille level under VBF cuts

[G. Bozzi, C. Oleari, D. Zeppenfeld, B. Jäger (2006-2009)]

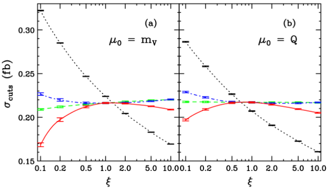
Elements of the calculation

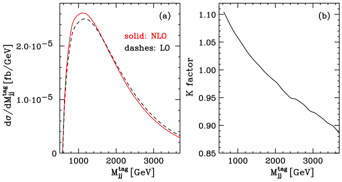


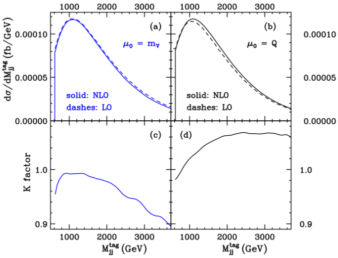
- Leptonic tensors for different topologies
- Only corrections to quark lines - self-energy, triangle, box and pentagon
- New physics does not change the QCD structure of amplitudes
- Can implement BSM at NLO-QCD for free

[Bozzi, Jäger, Oleari, Zeppenfeld (2006)]

VBFNLO







- Integrated k-factor of few percent
- Shapes can change $\sim 10\%$
- NLO corrections very stable

VBS@NLOPS

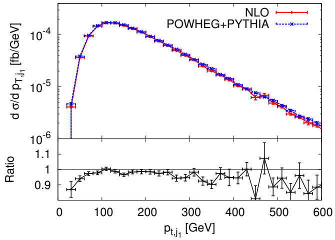
Many EW $VVjj$ processes and some QCD $VVjj$ processes implemented in the

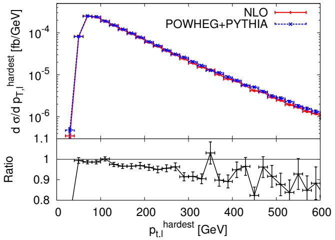
POWHEG-BOX [Alioli, Nason, Oleari, Re (2010)]

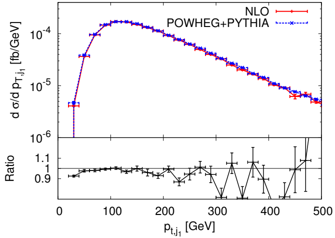
- In general high performance clusters are needed to achieve good results
- Uses features of Version 2 of the POWHEG-BOX code
  - the possibility to produce grids in parallel and combine them;
  - the option to modify scales and parton distribution functions a posteriori, through a reweighting procedure of Les Houches events;
  - a faster calculation of upper bounds, and the possibility to store upper bounds and combine them;
  - an improvement in the separation of regions for the real radiation, which results in smoother distributions.
- Here focus on $ZZjj$ but results very similar for all $VVjj$ processes

- EW $WWjj$: Jäger, Zanderighi (2011-2013)
- EW $ZZjj$: Jäger, Zanderighi, AK (2013)
- QCD W^+W^+jj: Melia, Nason, Rontsch, Zanderighi (2011)

Parton Shower Effects I

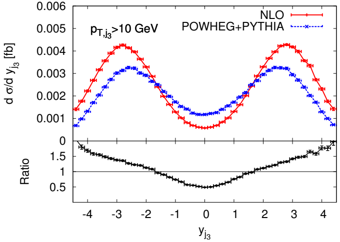


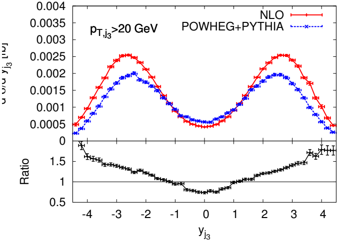


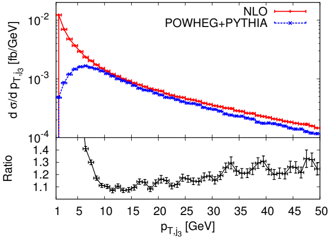


Parton shower does not change leptonic observables or hard QCD observables significantly

Parton Shower Effects II

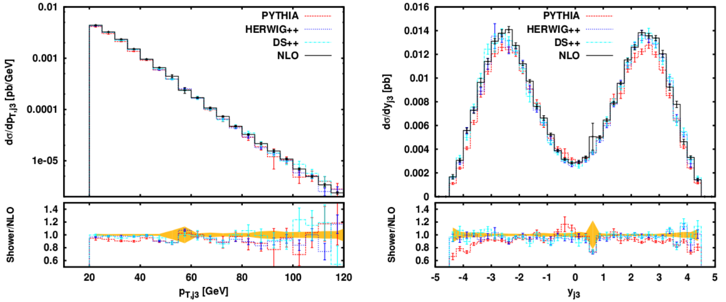






Third jet made finite by Sudakov factor. Central rapidity region populated.

Third jet @ NLO-QCD



[Jäger, Schissler, Zeppenfeld (2014)]

- No *VVjjj* processes at NLO-QCD but VBF *Hjjj*
- Third jet becomes more stable under PS
- Needed for central-jet veto

Dimension 6 operators

- Possible to extend SM $\leftarrow SU(3) \times SU(2) \times U(1)$

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_i \frac{c_i^{(6)}}{\Lambda^2} \mathcal{O}_i^{(6)} + \cdots$$

- Only valid up to Λ (scale of new physics)
- Model *independent* expansion
  - $\rightarrow$ Can compute coefficients in BSM model
- Limits on $\frac{c_i}{\Lambda^2}$ not on c_i and Λ independently
- Focus on dimension 6 only

Dimension 6 operators

$$\mathcal{L}_{eft} = \frac{c_{WWW}}{\Lambda^2}\mathrm{Tr}[W_{\mu\nu}W^{\nu\rho}W_{\rho}^{\nu}] + \frac{c_W}{\Lambda^2}(D_\mu\Phi)^\dagger W^{\mu\nu}(D_\nu\Phi) + \frac{c_B}{\Lambda^2}(D_\mu\Phi)^\dagger B^{\mu\nu}(D_\nu\Phi)$$

$$\mathcal{L}_{eft} = \frac{c_{\tilde{W}WW}}{\Lambda^2}\mathrm{Tr}[\tilde{W}_{\mu\nu}W^{\nu\rho}W_{\rho}^{\nu}] + \frac{c_{\tilde{W}}}{\Lambda^2}(D_\mu\Phi)^\dagger \tilde{W}^{\mu\nu}(D_\nu\Phi)$$

$$\tilde{W}_{\mu\nu} = \left[\frac{1}{2}\right]\epsilon_{\mu\nu\rho\sigma}W^{\rho\sigma}$$

Implementation

- Adopted code from `MadGraph` [Degrande et al. (2012)]
- Dim6 couplings implemented for $e^+e^-\mu^+\mu^-$ and $e^+e^-\bar{\nu}_\mu\nu_\mu$ decay channels

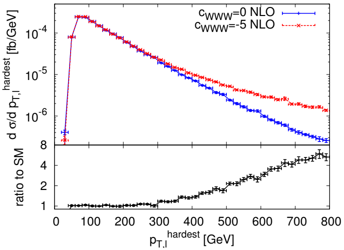
LEP limits (68% CL - not up-to-date)

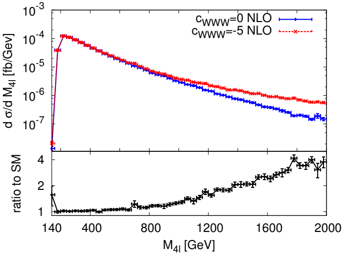
$$-11.9\ \text{TeV}^{-2} < \frac{c_{WWW}}{\Lambda^2} < -1.94\ \text{TeV}^{-2},$$

$$-19.4\ \text{TeV}^{-2} < \frac{c_{\tilde{W}WW}}{\Lambda^2} < -2.42\ \text{TeV}^{-2},$$

	WWZ	$WW\gamma$	WWH	ZZH	γZH	$WWWW$	$WWZZ$	$WWZ\gamma$	$WW\gamma\gamma$
$\mathcal{O}_{WWW}$	x	x				x	x	x	x
$\mathcal{O}_W$	x	x	x	x	x	x	x	x	
$\mathcal{O}_B$	x	x		x	x				
$\mathcal{O}_{\tilde{W}WW}$	x	x				x	x	x	x
$\mathcal{O}_{\tilde{W}}$	x	x	x	x	x				

Plots





- Enhancement of tails of transverse momentum distributions
- Only few events with 300fb^{-1} at 14 TeV
- Cross section increases dramatically with energy

Predictions for the LHC

At LO

	events @ 300 fb^{-1}	significance	events @ 3000 fb^{-1}	significance
SM	0.599		5.99	
$\frac{c_{WWW}}{\Lambda^2} = -5\ \text{TeV}^{-2}$	1.22	0.80	12.2	2.5
$\frac{c_{\tilde{W}WW}}{\Lambda^2} = -5\ \text{TeV}^{-2}$	3.03	3.1	30.3	9.9

At NLO-QCD

	events @ 300 fb^{-1}	significance	events @ 3000 fb^{-1}	significance
SM	0.692		6.92	
$\frac{c_{WWW}}{\Lambda^2} = -5\ \text{TeV}^{-2}$	1.49	0.96	14.9	3.0
$\frac{c_{\tilde{W}WW}}{\Lambda^2} = -5\ \text{TeV}^{-2}$	3.76	3.7	37.6	11.64

LO→NLO

- Significance improves $\sim 20\%$

→ Watch out for *spurious* new physics effects

Summary

- NLO-QCD results very stable
  - Corrections typically 10%
  - Scale dependence of 2%
- NLOPS known for many processes
  - Leptonic variables and hard QCD variables (un)affected by PS
  - Third jet more central
  - Systematics of parton showers need to be investigated
- VBS can be used to study EWSB in a model independent environment
  - Can include NLO-QCD effect
  - Affects hard leptonic variables