Precision Predictions for *VV* Scattering

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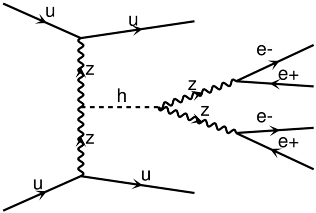
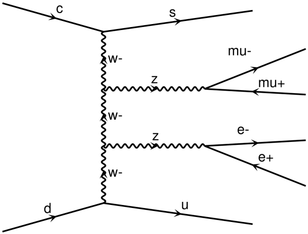
Brookhaven National Laboratory

Why study VBF/VBS?

- Probes directly the triple and quartic vector boson vertices
- Sensitive to new physics
- Essential production channel for the Higgs
  - Probes EWSB and CP properties of the weak sector
- Very low cross section but very clean after VBF cuts
- Pertubatively well-behaved

Vector Boson Fusion

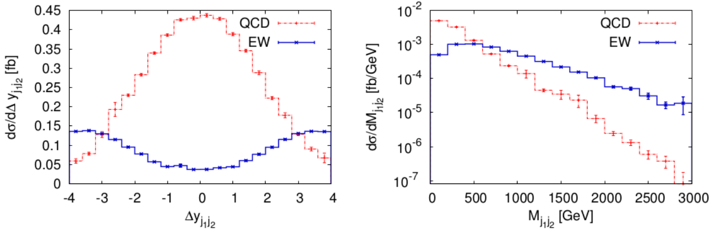




Topology

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

VBF cuts



[Jäger, Zanderighi (2011)]

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

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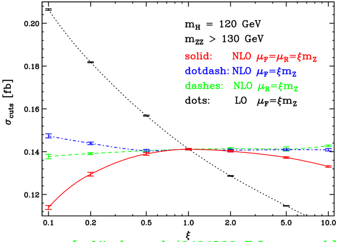
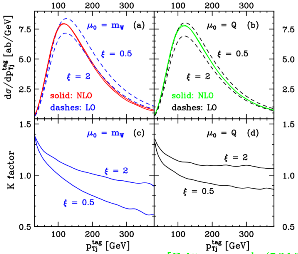
Why study NLO?



[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
- x Excludes
  - s-channel contributions
  - 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)]

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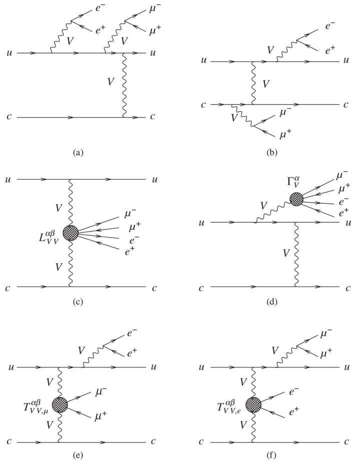
Elements of the calculation



- 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)]

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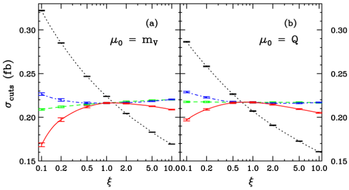
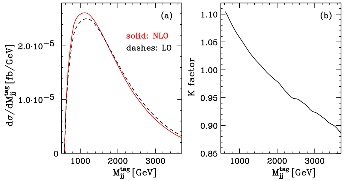
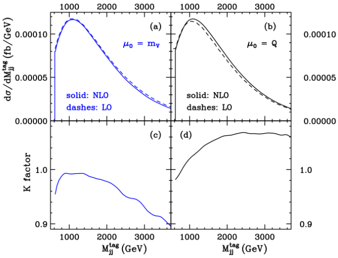
VBFNLO



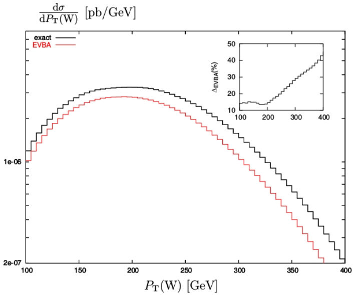




- Integrated k-factor of few percent
- Shapes can change $\sim 10\%$
- NLO corrections very stable

What about NLO-EW?

?



Calculated in
$e^+e^- \to \nu_e\bar{\nu}_e W^+W^-$
NLO-EW corrections
could potentially be huge

[Accomando, Denner, Pozzorini (2006)]

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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)

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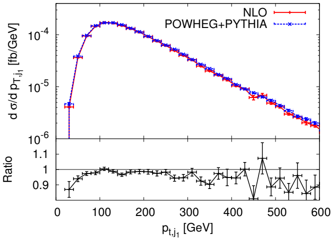
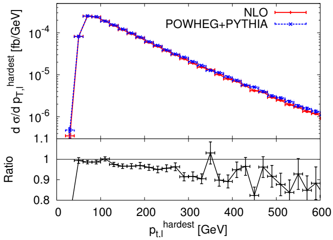
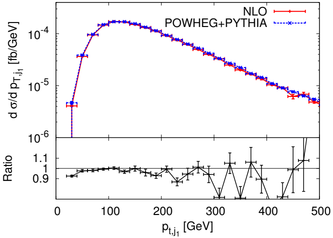
Parton Shower Effects I







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

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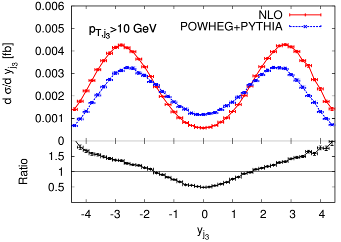
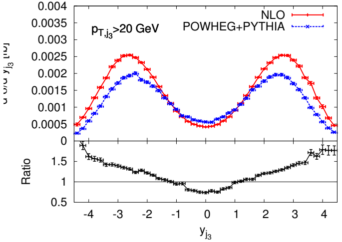
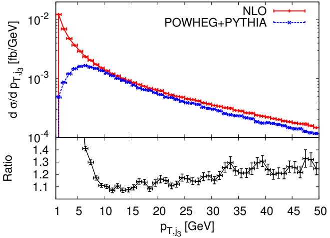
Parton Shower Effects II







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

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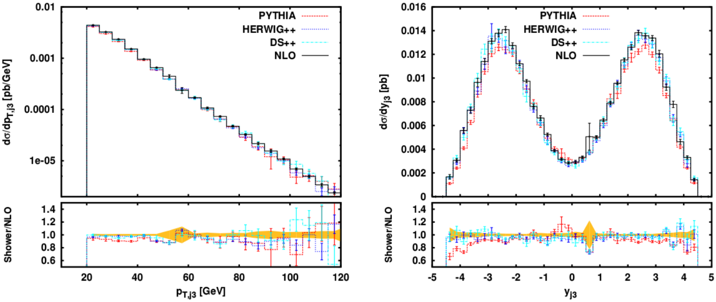
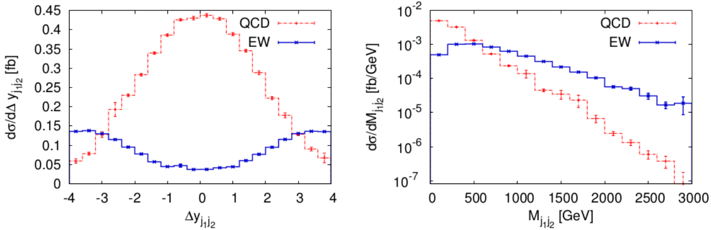
Third jet @ NLO-QCD



[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

VBF cuts revisited



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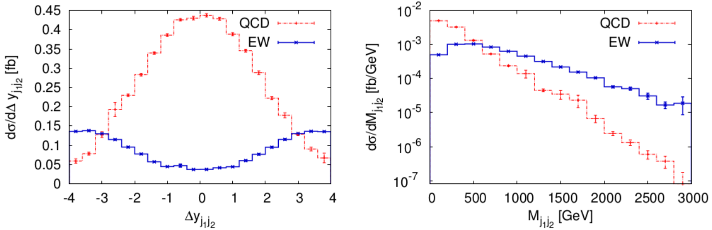

[Jäger, Zanderighi (2011)]

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

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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

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Dimension 6 operators

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

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

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

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

Current limits (68% CL)

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

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

	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				

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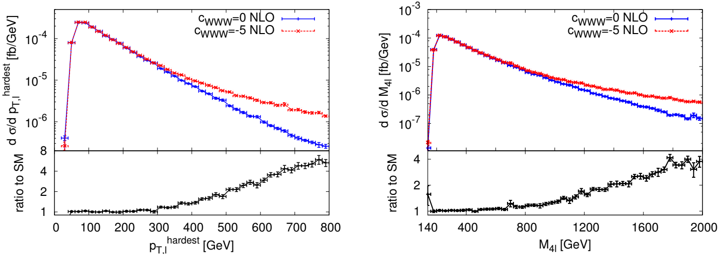
Plots



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

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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$\rightarrow$NLO

- Significance improves $\sim 20\%$

$\rightarrow$ Equivalent to increase in luminosity of $\sim 44\%$

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VLHC and HE-LHC

c_{WWW}/Λ^2

$\frac{c_{WWW}}{\Lambda^2}$	events @ 14 TeV	significance	events @ 33 TeV	significance	events @ 100 TeV	significance
0.0 TeV^{-2}	0.200		3.26		32.1	
−2.0 TeV^{-2}	0.234	0.0765	4.47	0.671	74.6	7.51
−4.0 TeV^{-2}	0.334	0.301	8.12	2.70	203	30.2
−6.0 TeV^{-2}	0.496	0.663	14.3	6.10	419	68.3
−8.0 TeV^{-2}	0.725	1.18	22.8	10.8	720	122
−10.0 TeV^{-2}	1.01	1.82	33.7	16.9	1110	190

$c_{\tilde{W}WW}/\Lambda^2$

$\frac{c_{\tilde{W}WW}}{\Lambda^2}$	events @ 14 TeV	significance	events @ 33 TeV	significance	events @ 100 TeV	significance
0.0 TeV^{-2}	0.200		3.26		32.1	
−2.0 TeV^{-2}	0.331	0.293	8.12	2.70	205	30.3
−4.0 TeV^{-2}	0.717	1.16	22.8	10.9	723	121
−6.0 TeV^{-2}	1.36	2.60	47.3	24.4	1580	272
−8.0 TeV^{-2}	2.27	4.64	81.7	43.5	2790	484
−10.0 TeV^{-2}	3.43	7.23	125	67.7	4350	759

- Significance grows faster than E_{cm}^2

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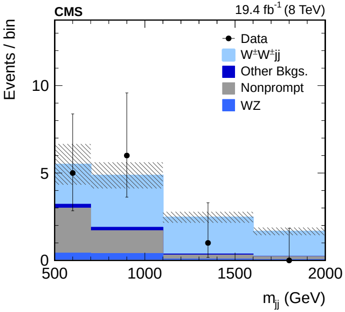
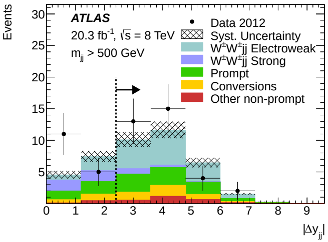
First physics results!

Both ATLAS and CMS have published results on $W^{\pm}W^{\pm}jj$





See talk by L. Liu and R. Lopes de Sa

Summary I

- 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
- NLO-EW to VBS not available yet
  - From $l^+l^- \rightarrow WW\nu\bar{\nu}$ it is known that they can be large
- NLO-QCD corrections to QCD induced $VVjj$ only exists for one case
  - Even after VBF cuts the background can be spoil precision

Summary II

- VBS important for measurement of Higgs properties
  - Can probe triple and quartic gauge couplings
- VBS can be used to study EWSB in a model independent environment
  - Can include NLO-QCD effect
  - Affects hard leptonic variables
- Limits on Dim6 operators to improve
  - Energy more potent in improving couplings than luminosity
- First analysis from CMS and ATLAS just released. Stay tuned for run II!

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