VBS & anomalous couplings - $ZZjj$ production in the POWHEG-BOX

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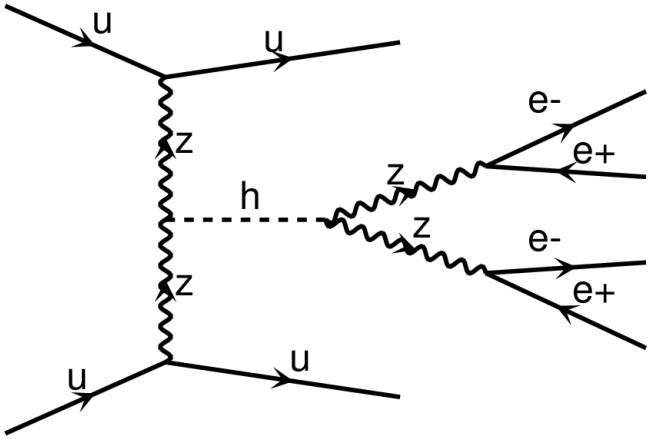
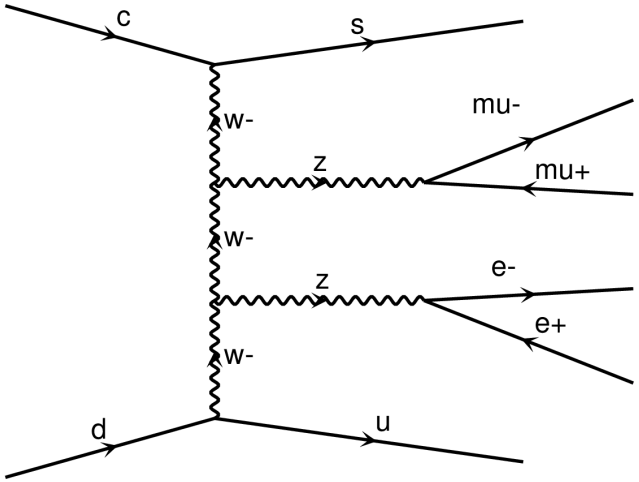
St Petersburg

Why study VBF/VBS?

- probes directly the triple and quartic vector boson vertices
- sensistive to new physics
- essential production channel for the Higgs
  - probes EWSB and CP properties of the weak sector
- low cross section but very clean after VBF cuts
  - distinct signature of two forward jets
- pertubatively well-behaved

Vector Boson Fusion

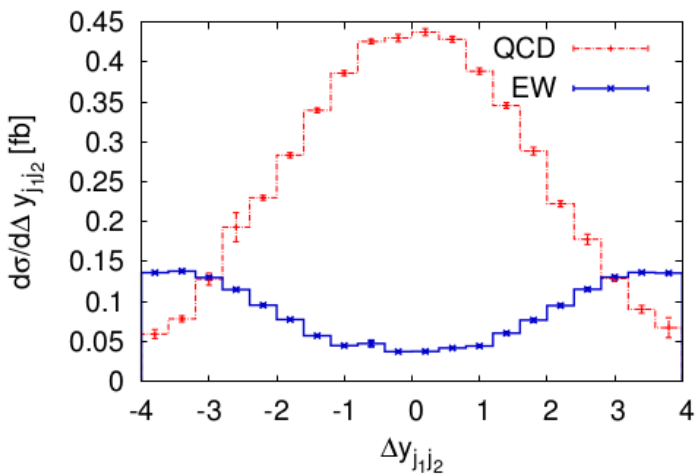


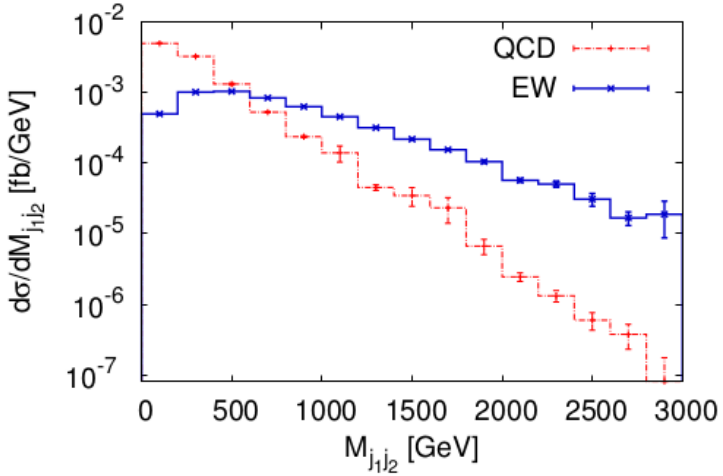


Topology

- forward tagging jets
- little central jet activity
- leptonic decay products (typically) between jets

VBF cuts

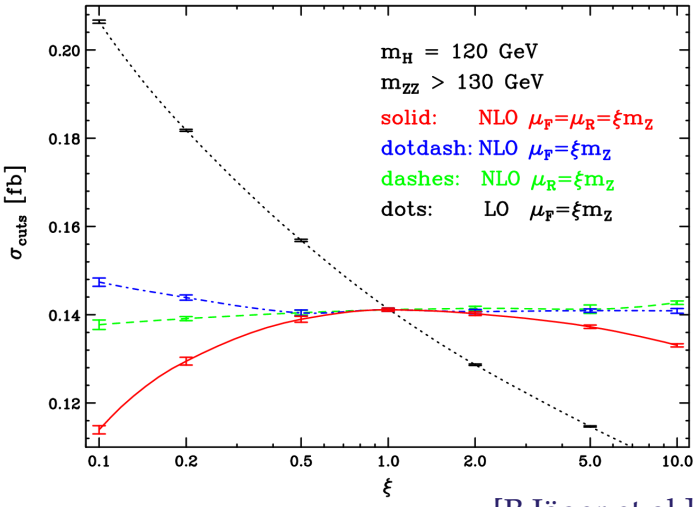




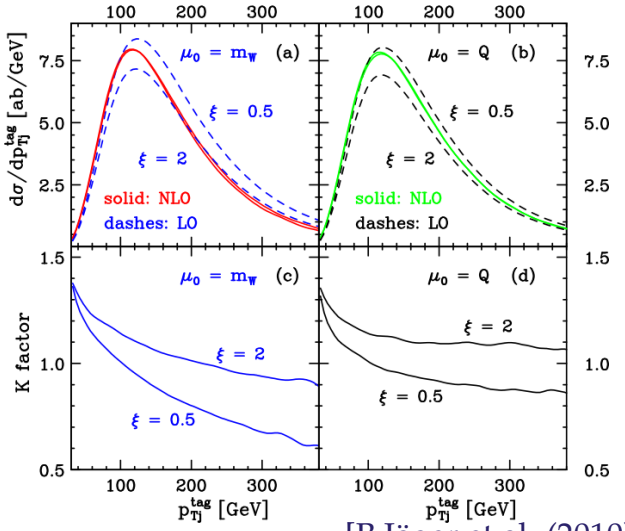
[Jäger, Zanderighi (2011)]

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

Why study NLO?



[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

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

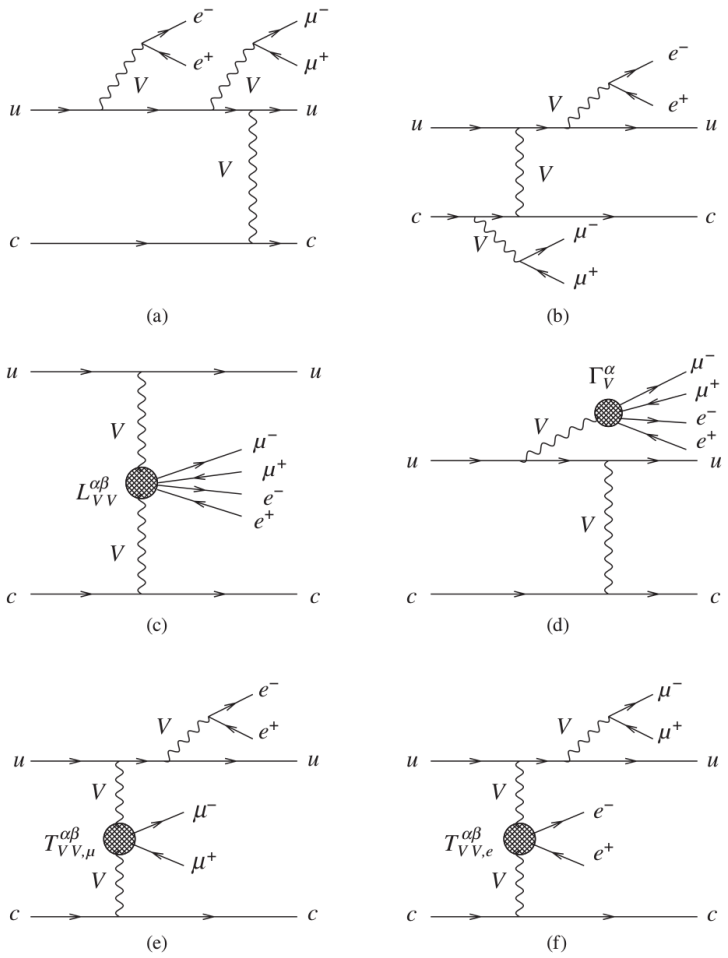
available through `VBFNLO`. [Figy, Oleari, Zeppenfeld (2003)]

- 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)]

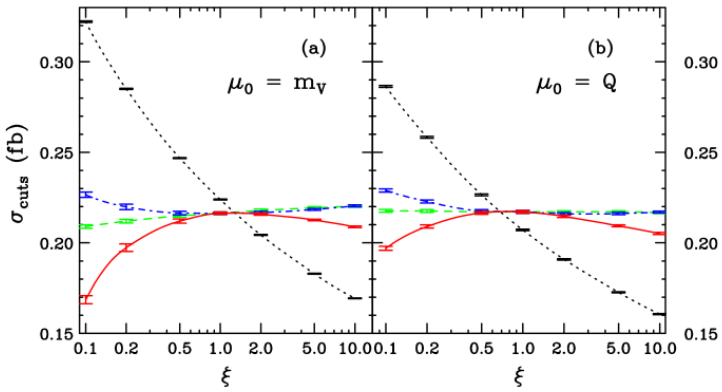
Elements of the calculation

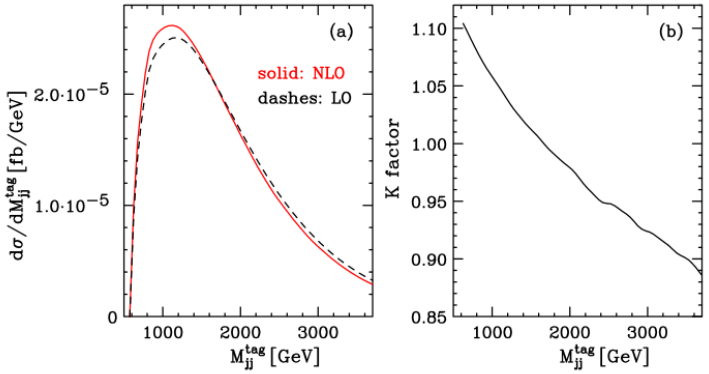


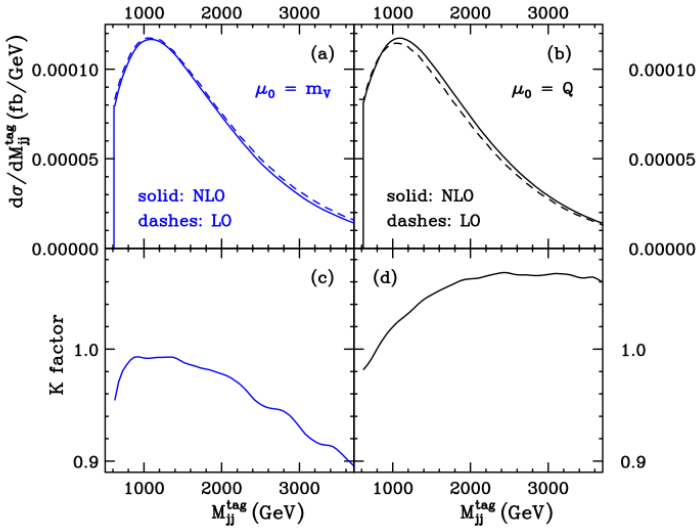
- leptonic tensors for different topologies
- only corrections to quark lines - self-energy, triangle, box and pentagon
- new physics does not change the QCD structure of amplitudes
- can implement BSM at NLO-QCD for free

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

VBFNLO



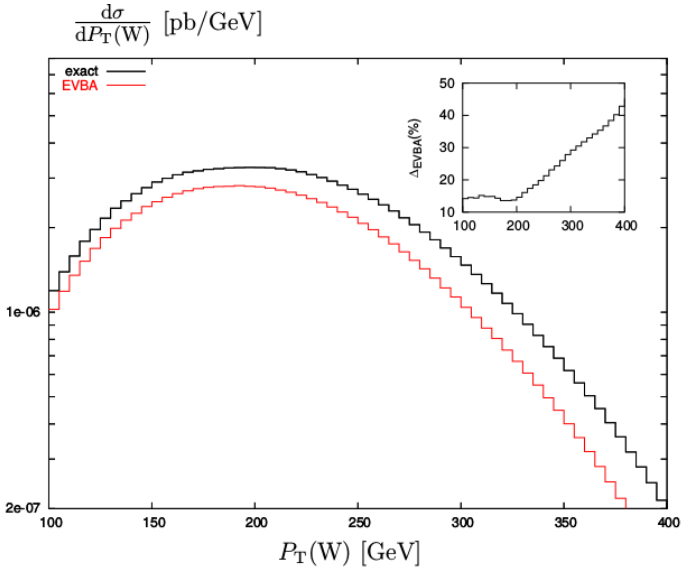




- integrated k-factor of few percent
- shapes can change $\sim 10\%$
- NLO corrections very stable

What about NLO-EW?

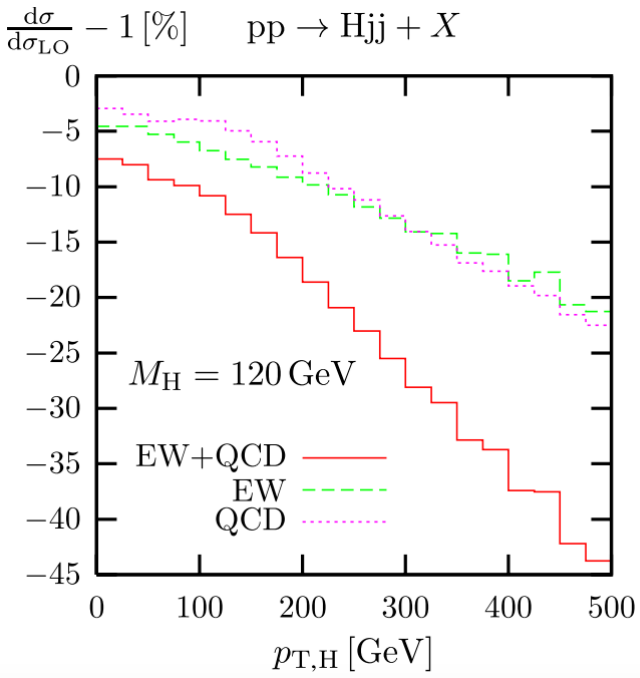
?



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

[Accomando, Denner, Pozzorini (2006)]

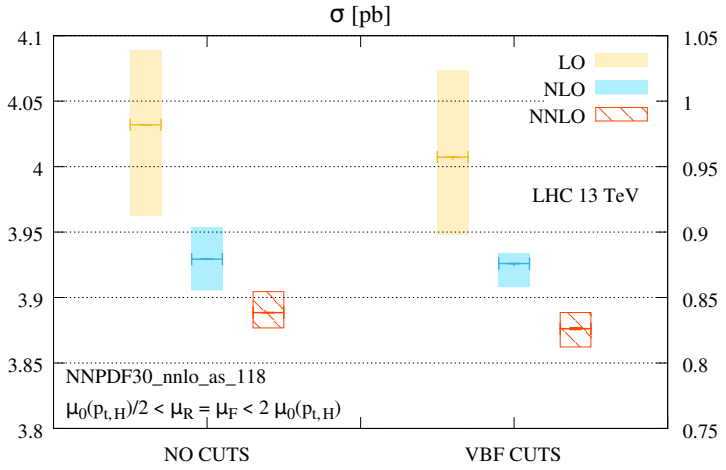
What about NLO-EW?



However for Higgs VBF production EW corrections are modest and comparable to QCD corrections

[Ciccolini, Denner, Dittmaier (2007)]

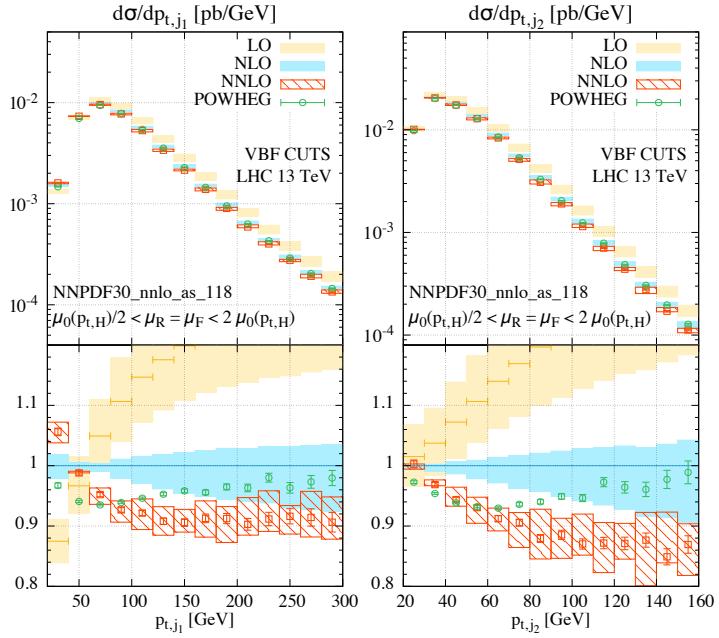
NNLO-QCD?



NNLO-QCD corrections not yet know. From residual scale uncertainties they are believed to be small.

Recent results for VBF Higgs production suggest that the NLO residual scale uncertainties underestimate the NNLO corrections.

[Cacciari, Dreyer, AK, Salam, Zanderighi (2015)]



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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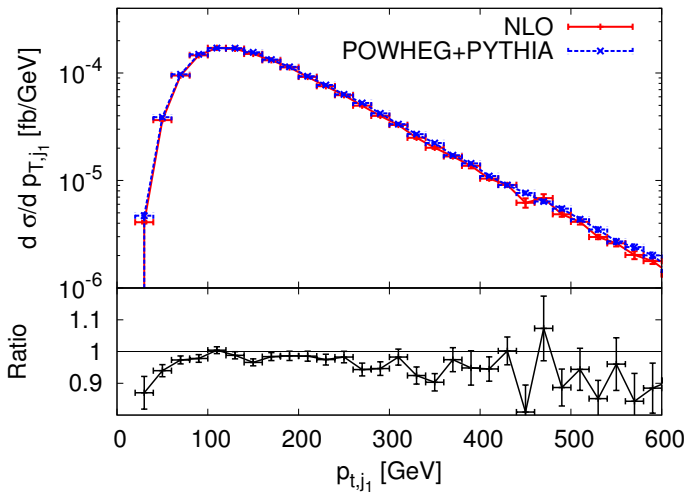
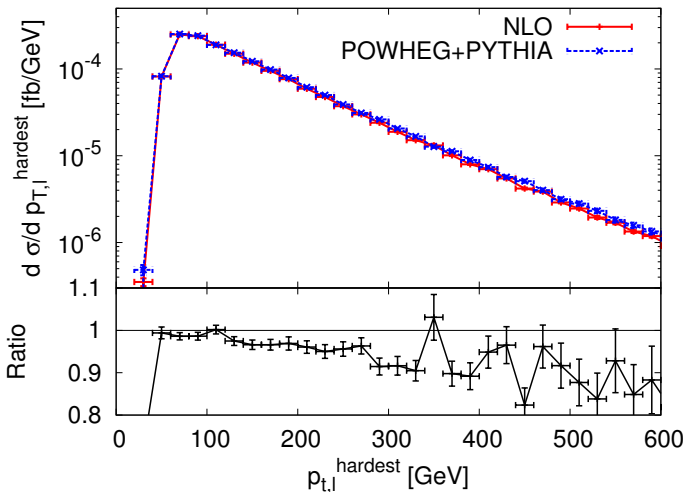
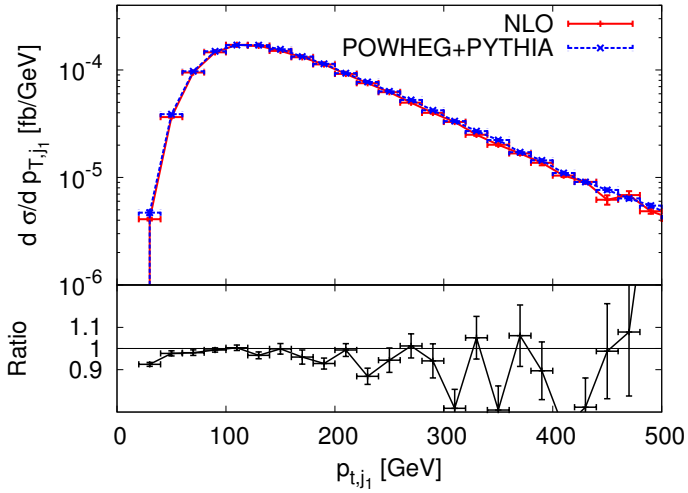
Parton Shower Effects I

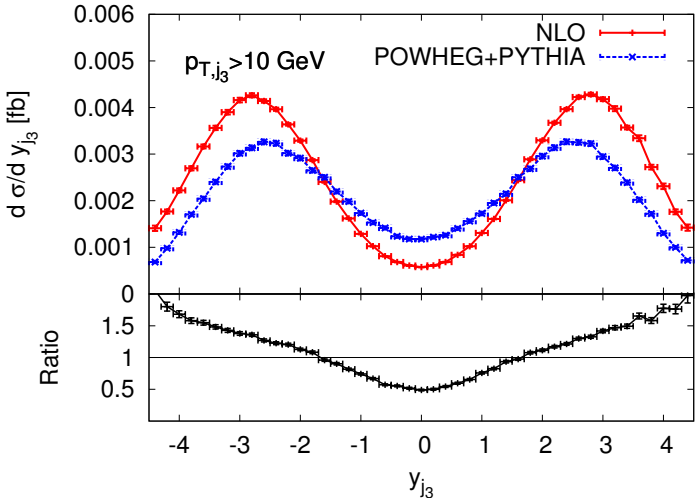


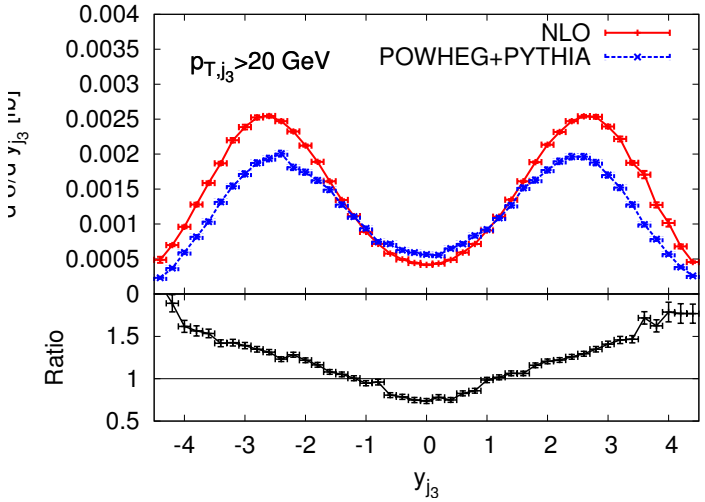


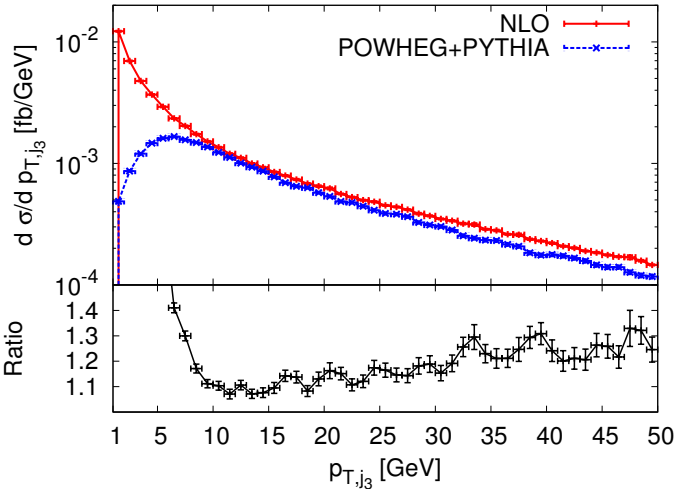


Parton shower does not change leptonic observables or hard QCD observables significantly

Parton Shower Effects II

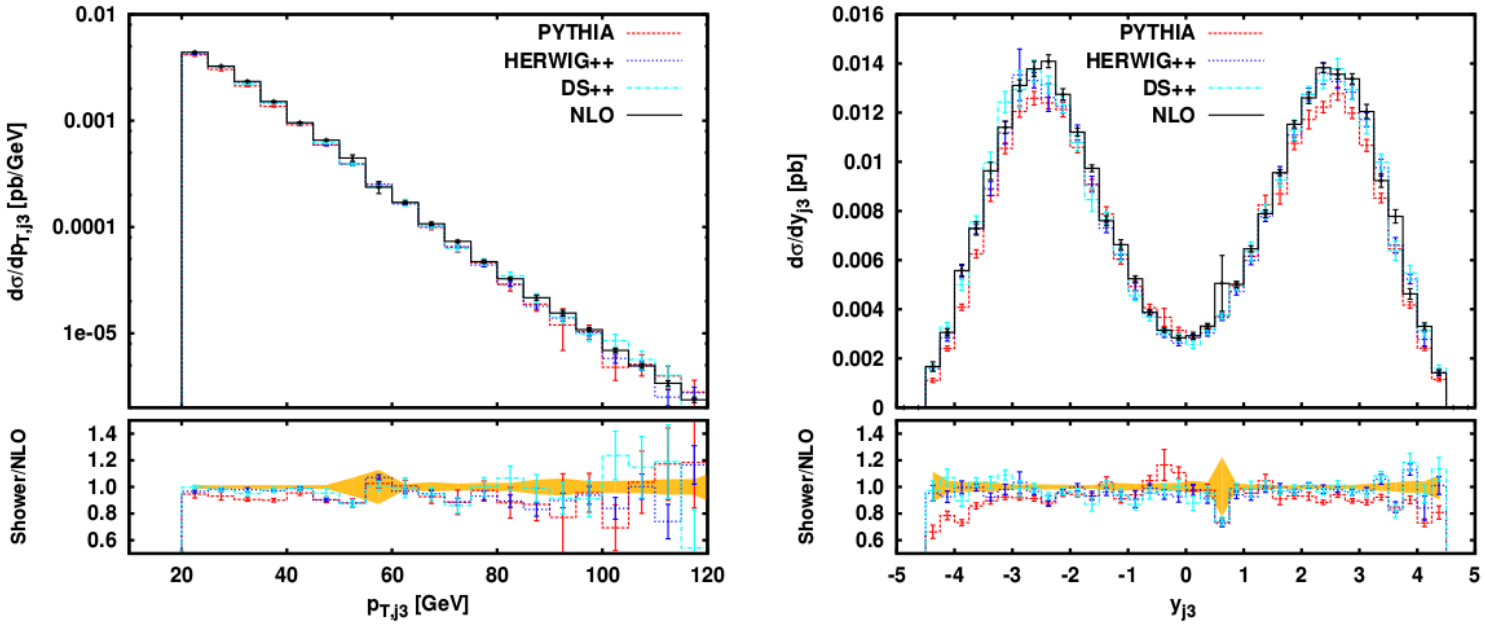






Third jet made finite by Sudakov factor. Central rapidity region populated.

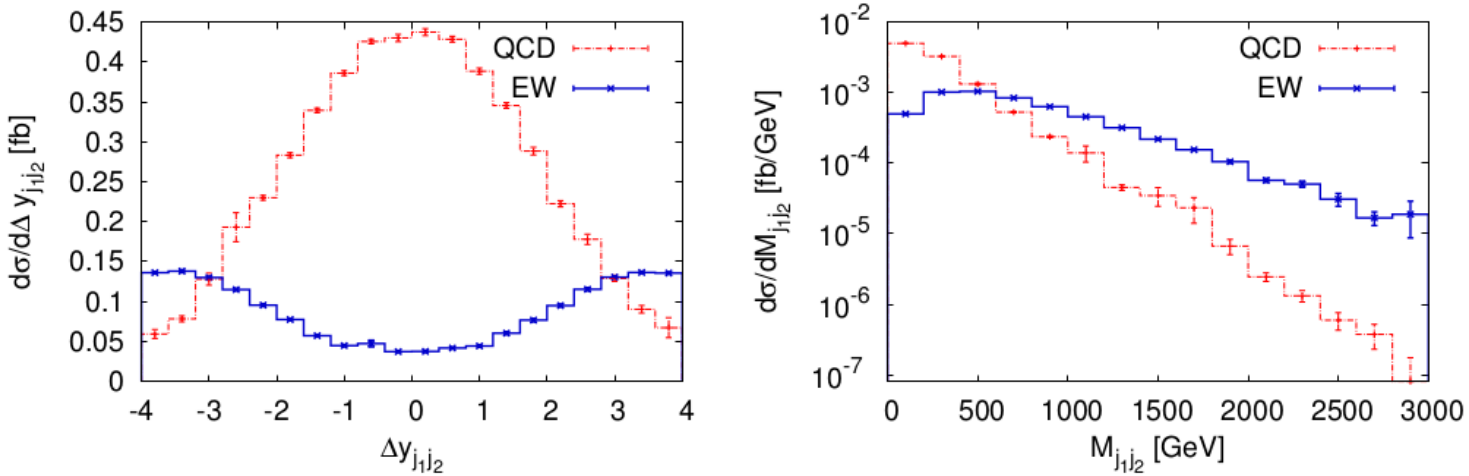
Third jet @ NLO-QCD



[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

VBF cuts revisited



[Jäger, Zanderighi (2011)]

- central leptons
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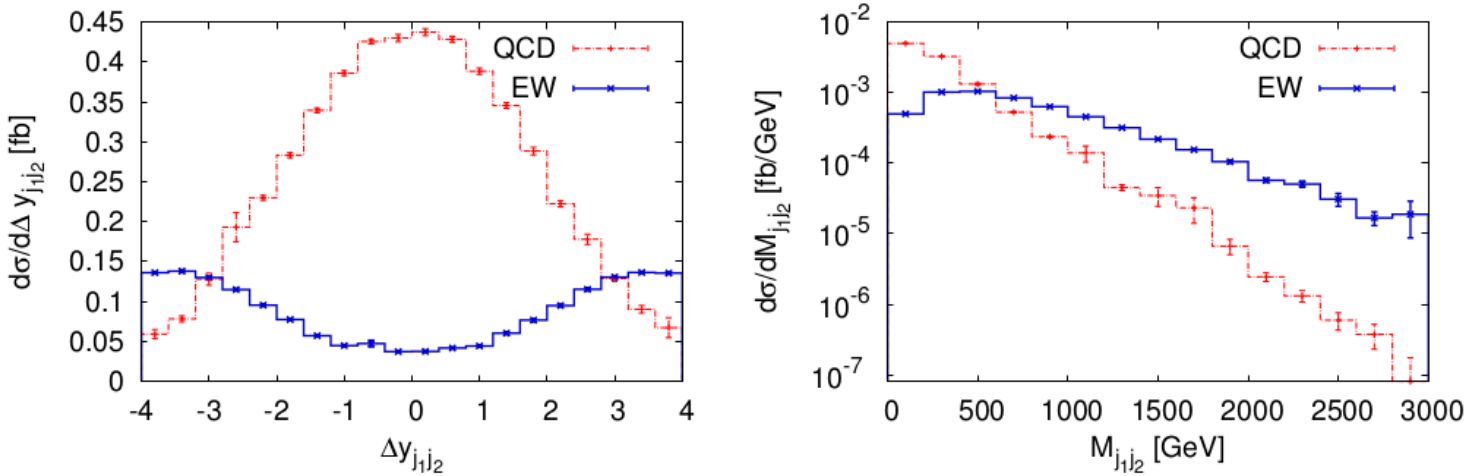


[Jäger, Zanderighi (2011)]

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

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

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

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

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

Implementation

- adapted 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

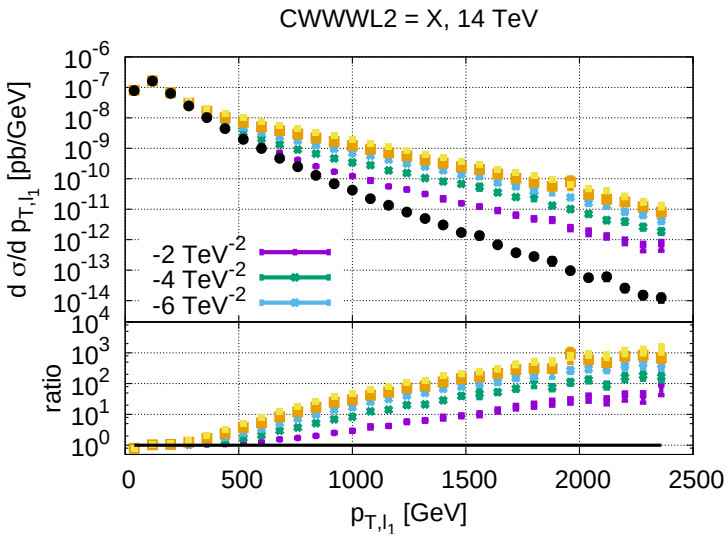
Current limits (68% CL)

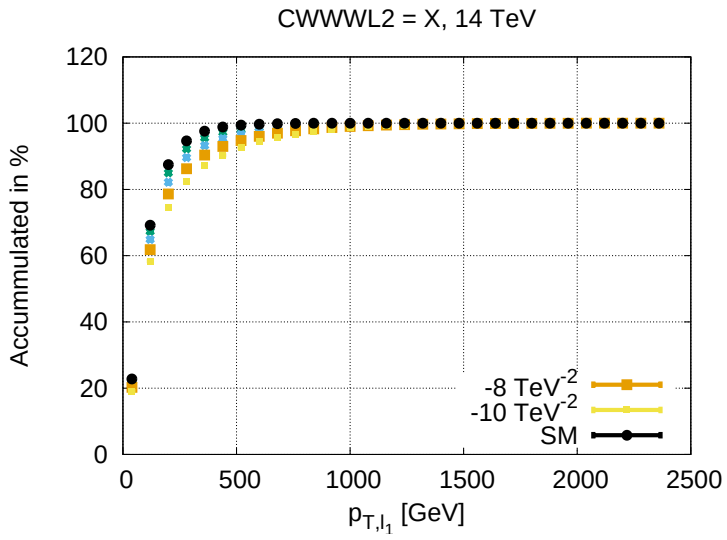
$$-11.9\ \text{TeV}^{-2} < \frac{c_{WWW}}{\Lambda^2} < -1.94\ \text{TeV}^{-2},$$

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

	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				

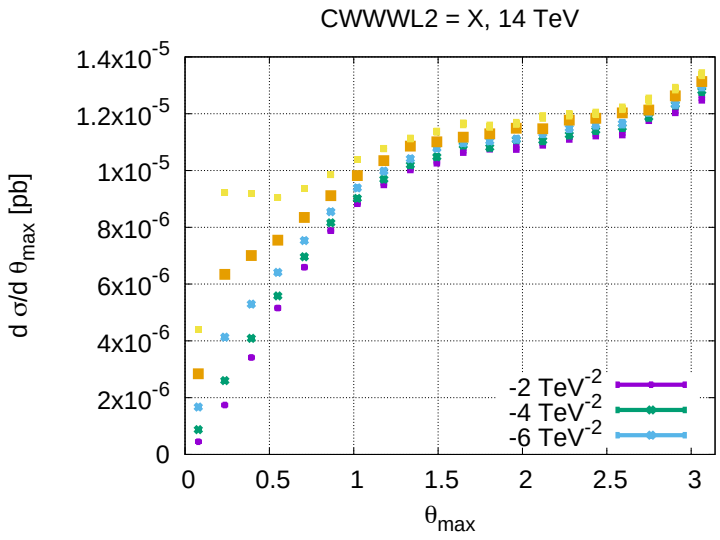
Plots I

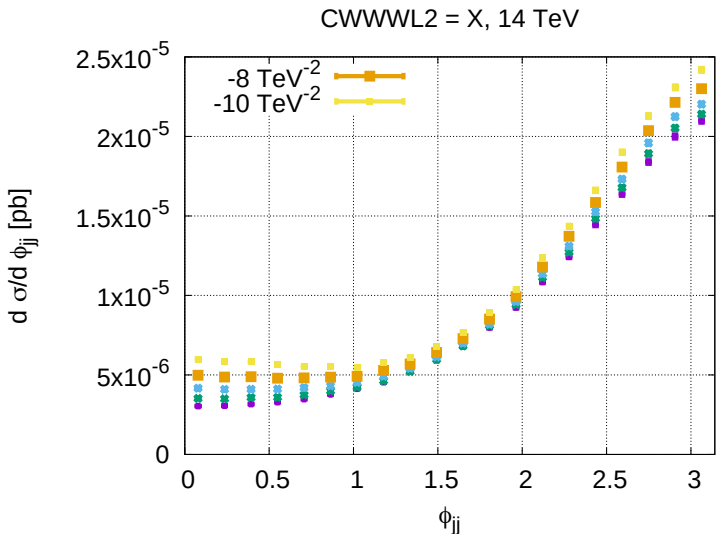




- enhancement of tails of transverse momentum distributions
- only few events with 300fb^{-1} at 14 TeV
- cross section increases dramatically with energy

Plots II





- dimensionless distributions also receive non-trivial corrections
- non-leptonic variables somewhat sensitive to the couplings

Predictions for the LHC

At LO

	events @ 300 fb^{-1}	significance	events @ 3000 fb^{-1}	significance
SM	0.599		5.99	
$\frac{c_{WWW}}{\Lambda^2} = -5$ TeV^{-2}	1.22	0.80	12.2	2.5
$\frac{c_{\tilde{W}WW}}{\Lambda^2} = -5$ 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	
$\frac{c_{WWW}}{\Lambda^2} = -5$ TeV^{-2}	1.49	0.96	14.9	3.0
$\frac{c_{\tilde{W}WW}}{\Lambda^2} = -5$ TeV^{-2}	3.76	3.7	37.6	11.64

LO→NLO

- significance improves $\sim 20\%$

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

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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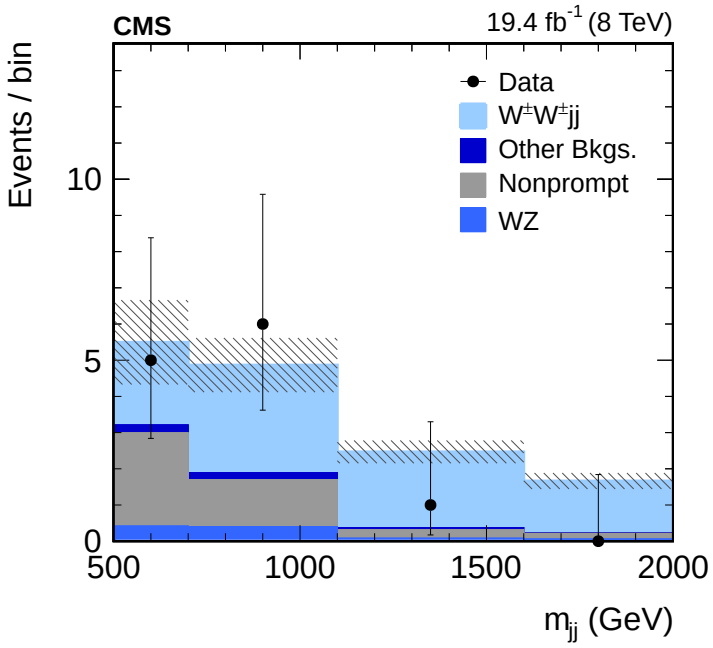
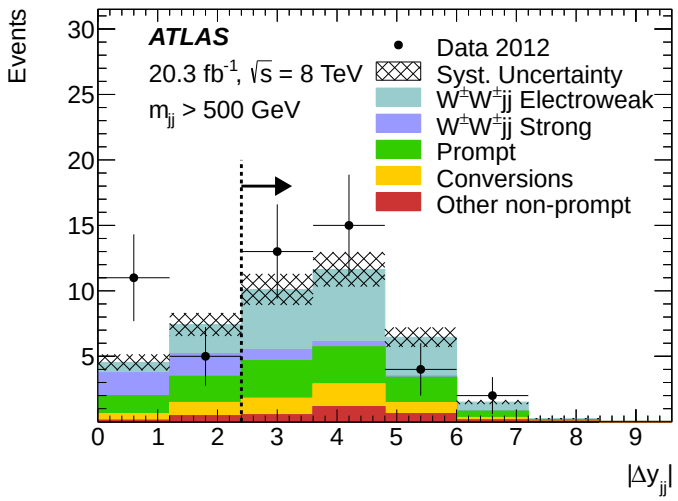
First physics results!

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





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Summary I

- NLO-QCD results very stable
  - corrections typically 10%
  - scale dependence of 2%
- NLO+PS 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 $l^+l^- \to WW\nu\bar{\nu}$ 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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