

Divector Boson Production with Jets at the LHC

QCD Radiation into the Gap

Fernando Febres Cordero

Department of Physics, University of Freiburg

ICHEP, Chicago, August 2016

Based on arXiv:1512.07591, with P. Hofmann and H. Ita



ALBERT-LUDWIGS-
UNIVERSITÄT FREIBURG



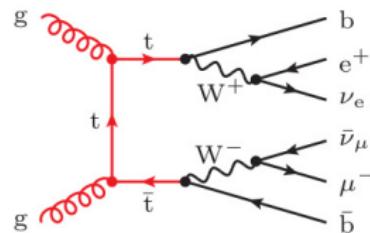
Alexander von Humboldt
Stiftung / Foundation

Divector Boson Signatures in the SM

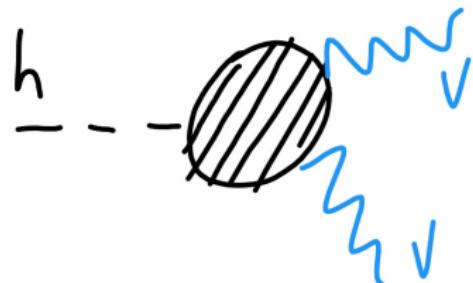
Test of EW gauge structure



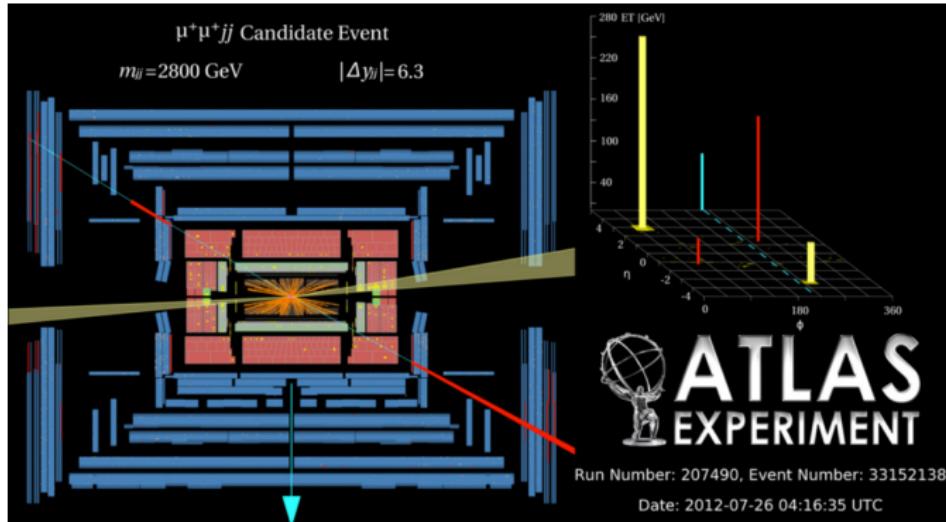
Associated to top-pair
Production



Background to $h \rightarrow VV$ signals



Vector Boson Scattering

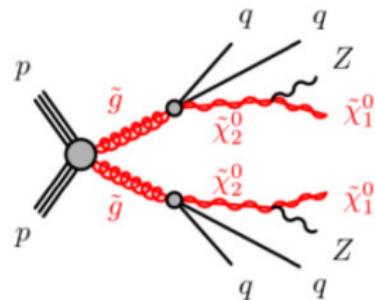


$VV \rightarrow VV$ scattering has a clear detector signature with two very forward jets

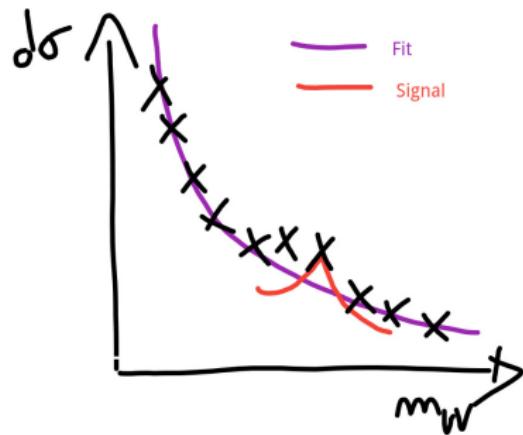
Direct VV production can mimic these processes, but often with more *central radiation*

Divector Bosons and BSM

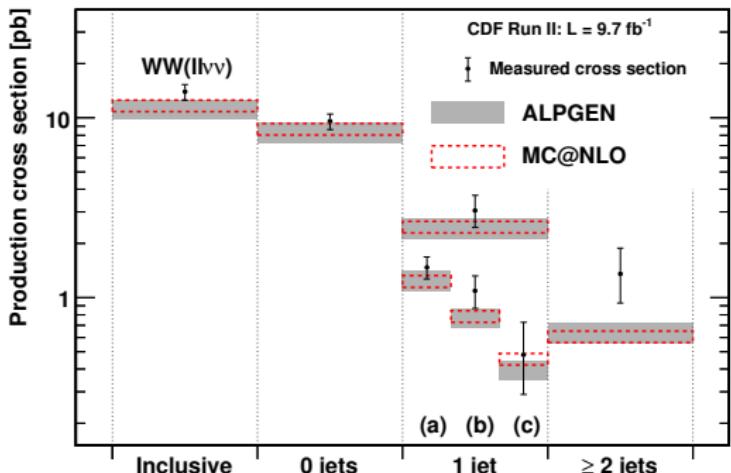
Heavy colored pairs decaying in chain of jets and vector bosons



Divector boson resonances and their radiation patterns

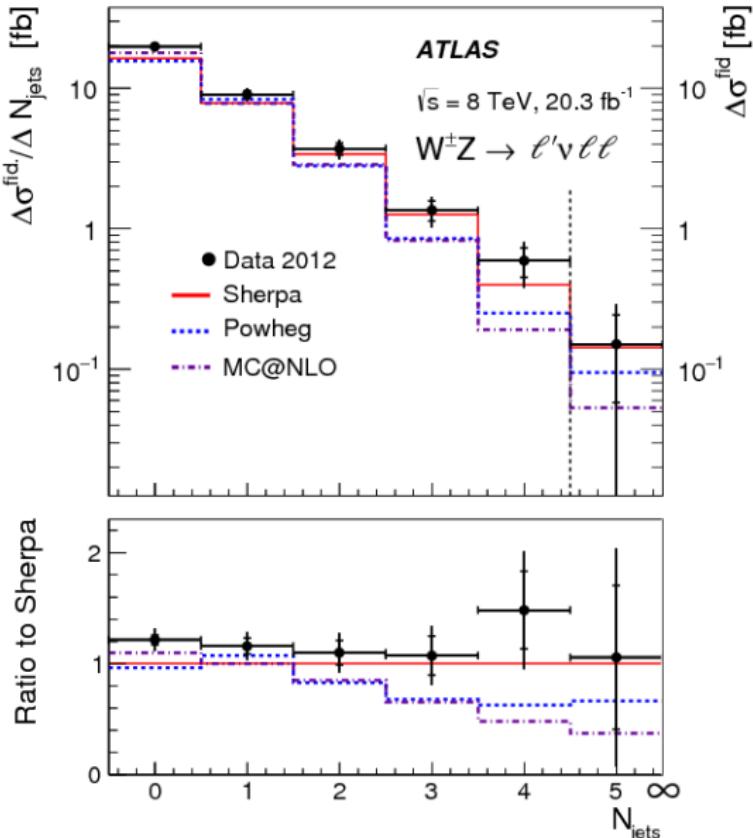


$W^+W^- + n\text{-Jet}$ Measurement at CDF



- arXiv:1505.00801
- Full dataset analyzed
- Total and differential cross sections
- Relative good agreement between theory and data
- At the Tevatron $t\bar{t}$ background is small

$WZ + n\text{-Jet}$ Measurement at ATLAS



- arXiv:1603.02151
- Full 8 TeV dataset
- Impressive reach of up to 5 jets
- Statistical errors relatively large (to be improved!)
- Good comparison with Sherpa prediction

$W^+W^- + n\text{-Jet}$ Production ($n = 0, 1, 2, 3$) at NLO QCD

QCD Parton Level Calculations for $W^+W^- + n$ Jets

	LO (1979)	Brown, Mikaelian
W^+W^-	NLO (1991)	Ohnemus; Frixione; Campbell, Ellis; Dixon, Kunszt, Signer; Campbell, Ellis, Williams
	NNLO (2014)	Gehrmann, Grazzini, Kallweit, Maierhofer, von Manteuffel, Pozzorini, Rathlev, Tancredi
$W^+W^- + 1$ Jet	NLO (2007)	Campbell, Ellis, Zanderighi; Dittmaier, Kallweit, Uwer; Campbell, Miller, Robens
$W^+W^- + 2$ Jets	NLO (2011)	Melia, Melnikov, Rontsch, Zanderighi; Greiner, Heinrich, Mastrolia, Ossola, Reiter, Tramontano; Alwall, Frederix, Frixione, Hirschi, Maltoni, et al.

In this signatures it is assumed that $t\bar{t}$ contributions are always dropped (through initial b suppression, anti- b -jet tagging, kinematical cuts, ...)

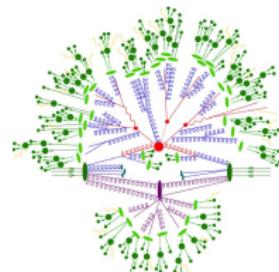
NLO QCD with BlackHat+Sherpa



BlackHat: Zvi Bern, Lance Dixon, FFC, Stefan Höche, Harald Ita, David Kosower, Adriano Lo Presti and Daniel Maitre; Berger, Diana, Forde, Gleisberg, Ozeren

We employ the BlackHat library, based on unitarity and on-shell techniques, for the computation of the one-loop MEs

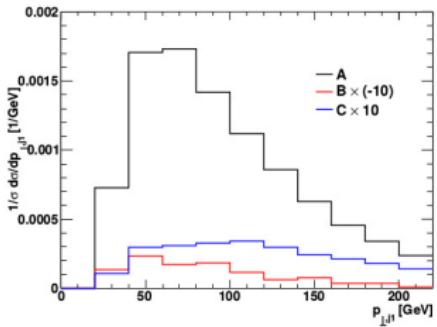
SHERPA: Höche, Krauss, Kuttimalai, Schoenherr, Schumann, Siegert, Thompson, Winter and Zapp



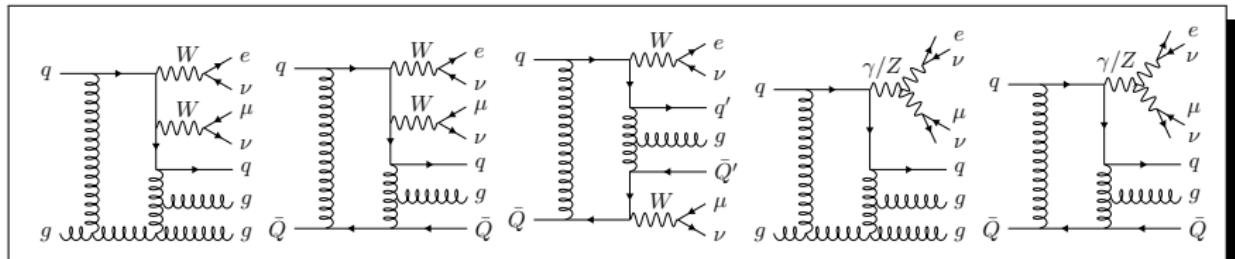
We employ the Catani-Seymour Dipole subtraction implementation of Sherpa, together with their integration algorithms

Our Setup

- We decay the W bosons into different lepton flavors (e & μ)
- We employ a leading-color approximation only for the virtual correction of $W^+W^- + 3 \text{ Jet}$
- Diagrams with close massive loops are dropped
- We work with a diagonal CKM matrix



Gosam: arXiv:1202.6004



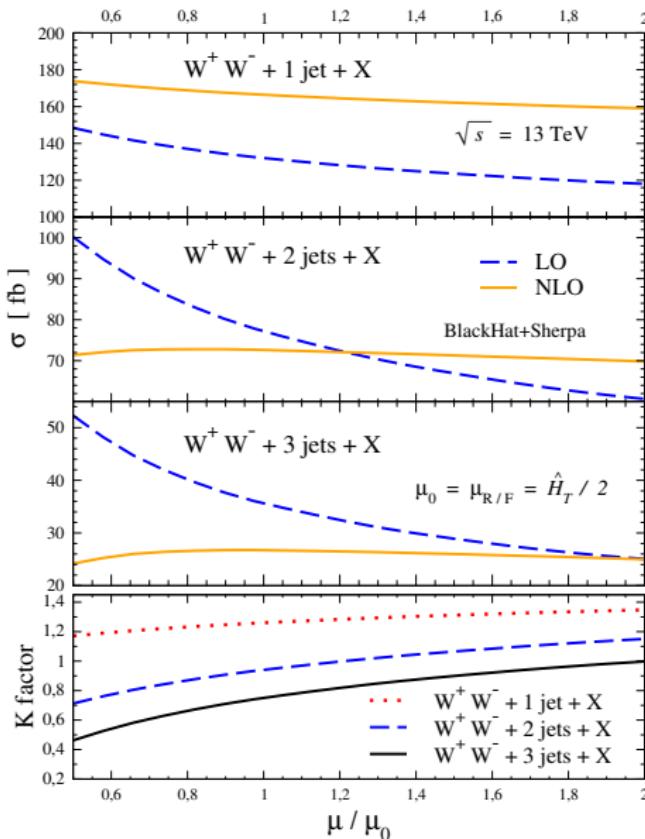
$W^+W^- + \text{Jet}$ Phenomenology

We employ a dynamical scale $\mu = \mu_r = \mu_f = \hat{H}_T/2$ and the MSTW2008 set of PDFs. We take the α_s provided by the PDF sets and employ $M_W = 80.399$ GeV, $M_Z = 91.188$ GeV, $\Gamma_W = 2.085$ GeV and $\Gamma_Z = 2.4952$ GeV. We employ the following kinematical cuts:

- ▶ $p_T^{e,\mu} > 20$ GeV
- ▶ $|\eta^{e,\mu}| < 2.4$
- ▶ $\cancel{E}_T > 30$ GeV
- ▶ $p_T^{e\mu} > 30$ GeV
- ▶ $m_{e\mu} > 10$ GeV
- ▶ Jets defined with anti- k_T algorithm
- ▶ $R = 0.4$
- ▶ $p_T^{jet} > 30$ GeV
- ▶ $|\eta^{jet}| < 4.5$

We have collected results for the LHC with $\sqrt{s} = 8$ and 13 TeV

Scale Sensitivity for $W^+W^- + n$ -Jet Production

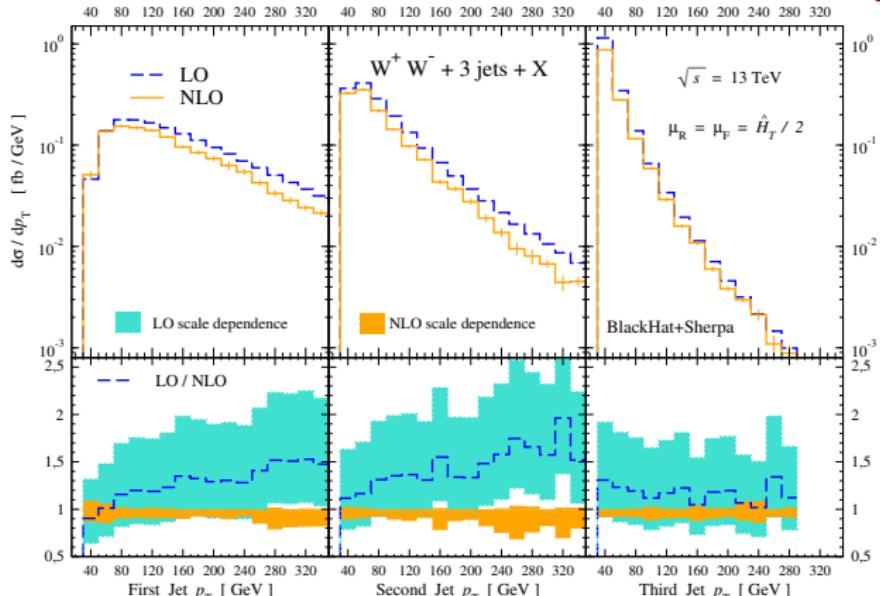


arXiv:1512.07591 [hep-ph]

- ▶ Total cross sections as function of unphysical scales
- ▶ $W^+W^- + 0$ Jet not shown (corrections very large, NNLO needed)
- ▶ Small scale sensitivity at NLO
- ▶ Large multiplicity needs NLO

Jet p_T Spectra

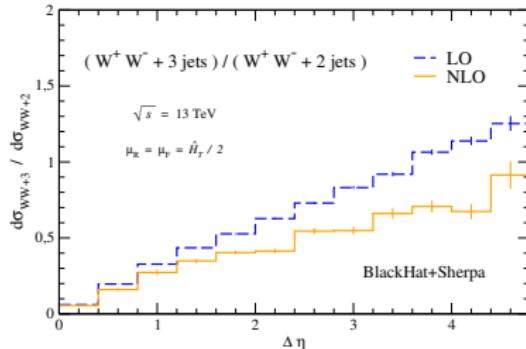
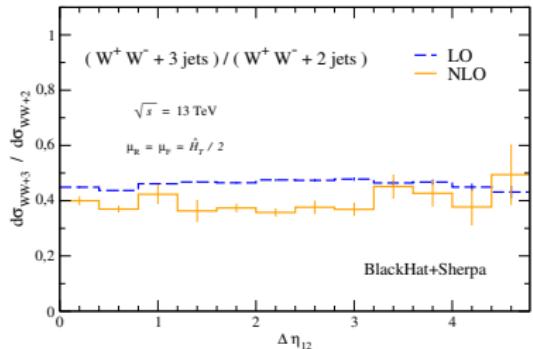
arXiv:1512.07591 [hep-ph]



- p_T distributions for softer jets fall more steeply
- Quantum corrections only shift softest jet p_T distribution
- Scale bands considerably reduced over phase space
- Similarities in corrections for different (large) multiplicities
- Similar trends to what is observed in NLO QCD corrections to $V + \text{Jets}$

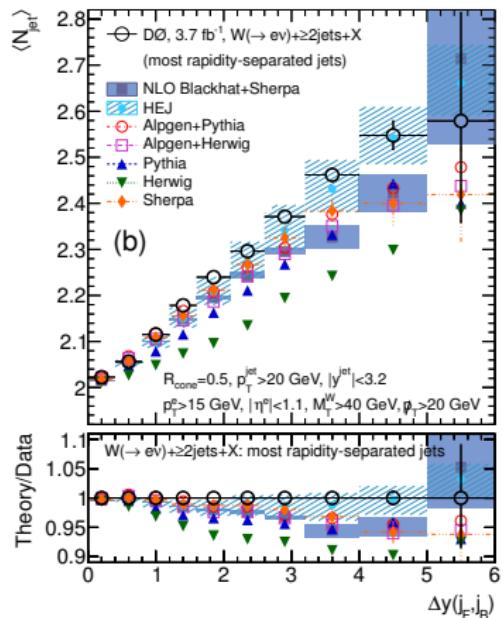
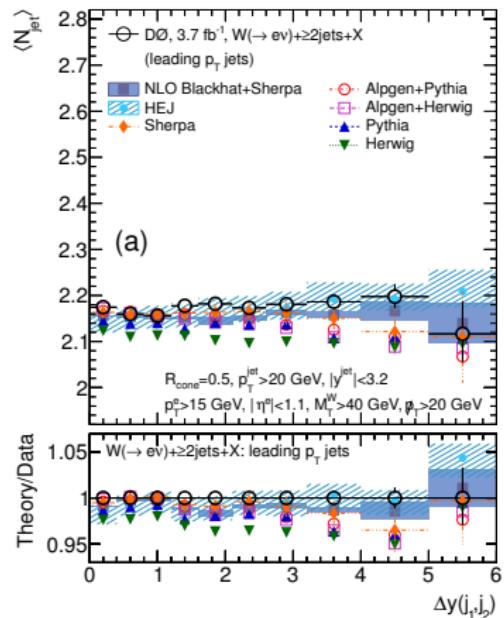
Radiation into the Gap for VBF background

Radiation Gap



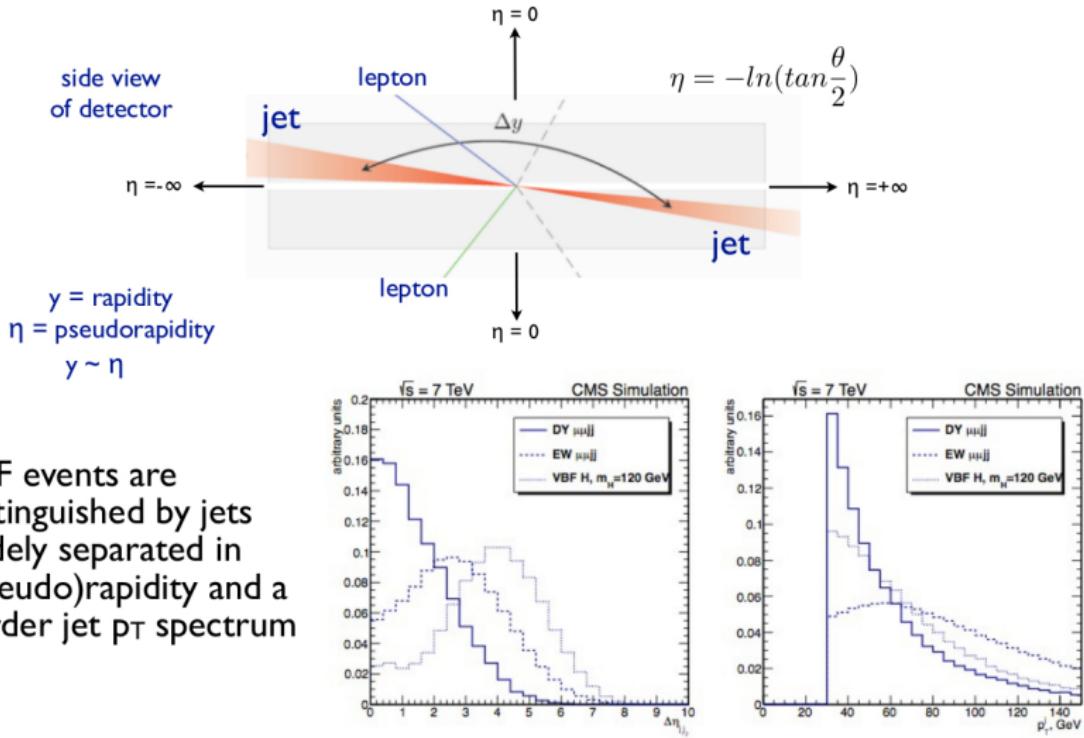
- ▶ A clear signature of VBF processes is a low rate of radiation in the gap between tagging forward and backward jets
- ▶ Background processes can have very different features
- ▶ A way to study this: look at ratios of $W^+W^- + 3$ Jets to $W^+W^- + 2$ Jets
- ▶ Left plot jets p_T ordered and right are η ordered (forward-backward)
- ▶ Noticeable reduction for large $\Delta\eta$ when η ordered

Radiation Gap at D0 in $W+J$ ets



D0 Measurement [arXiv:1302.6508 [hep-ph]]

VBF - Distinguishing Topology



VBF events are distinguished by jets widely separated in (pseudo)rapidity and a harder jet p_T spectrum

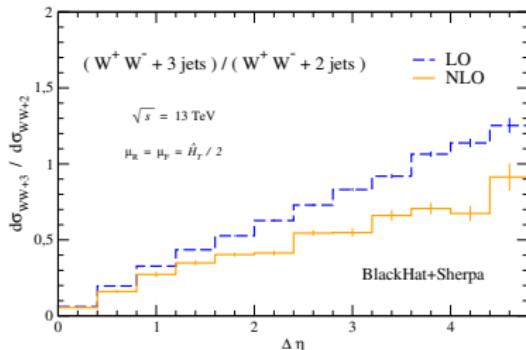
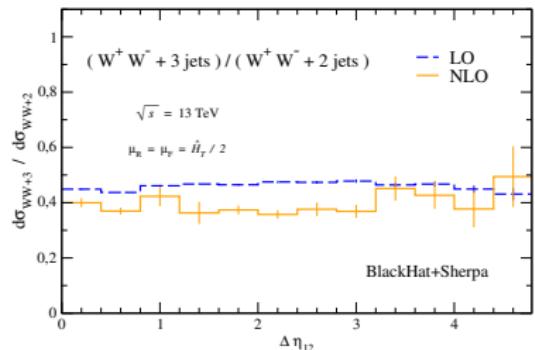
Slide from Sabine Lammers

VBF Cuts

In order to explore radiation patterns of background signals to VBF processes, we add the following cuts:

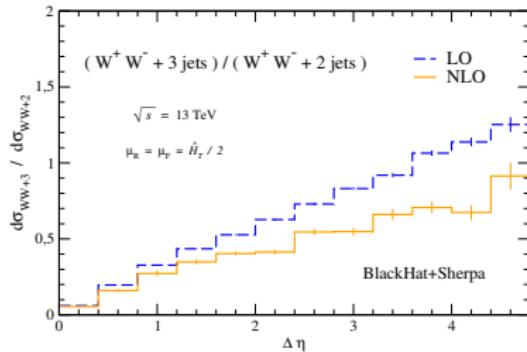
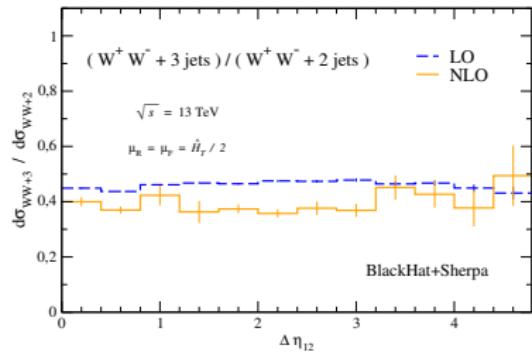
- ▶ Invariant mass for tagging jets: $M_{j_1 j_2} > 500 \text{ GeV}$
- ▶ Different hemispheres: $\eta_{j_1} \eta_{j_2} < 0$

Radiation Gap: non VBF vs. VBF

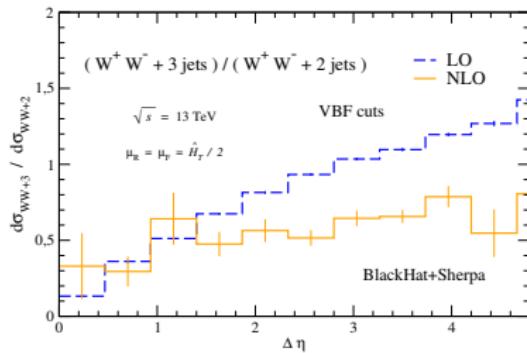
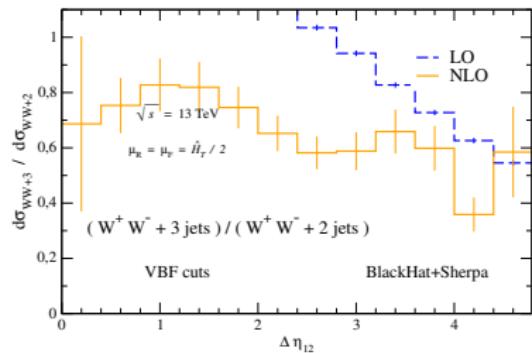


Adding VBF cuts:

Radiation Gap: non VBF vs. VBF

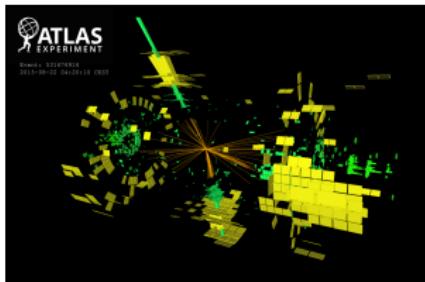


Adding VBF cuts:



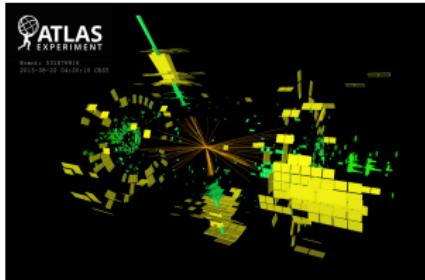
Outlook

- ▶ We have computed NLO QCD corrections to $W^+W^- + 3\text{-jet}$ production at hadron colliders
- ▶ We observe considerable reduction on dependence on the renormalization and factorization scales
- ▶ We can explore patterns of radiation into the gap for backgrounds to VBF
- ▶ We will extend the presented results to other diboson combinations to compare against data collected at the LHC



Outlook

- ▶ We have computed NLO QCD corrections to $W^+W^- + 3\text{-jet}$ production at hadron colliders
- ▶ We observe considerable reduction on dependence on the renormalization and factorization scales
- ▶ We can explore patterns of radiation into the gap for backgrounds to VBF
- ▶ We will extend the presented results to other diboson combinations to compare against data collected at the LHC



Thanks!