Divector Boson Production with Jets at the LHC

W^+W^-+3-Jets at NLO QCD

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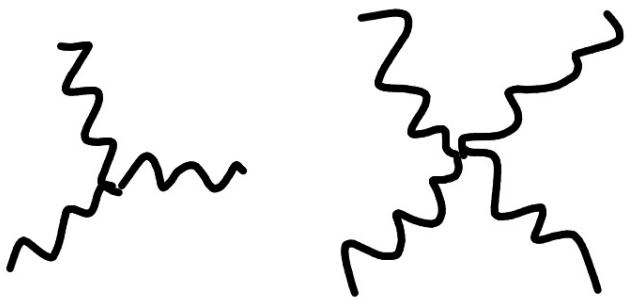
Loops & Legs, Leipzig, April 2016

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

Divector Boson Signatures in the SM

Test of EW gauge structure



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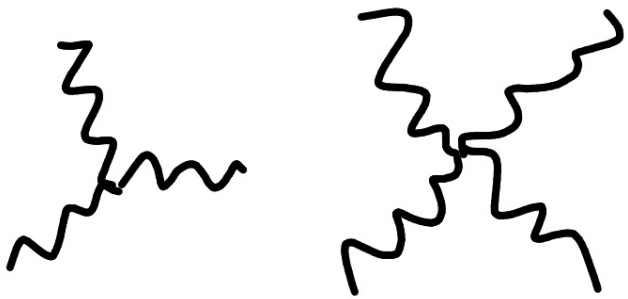
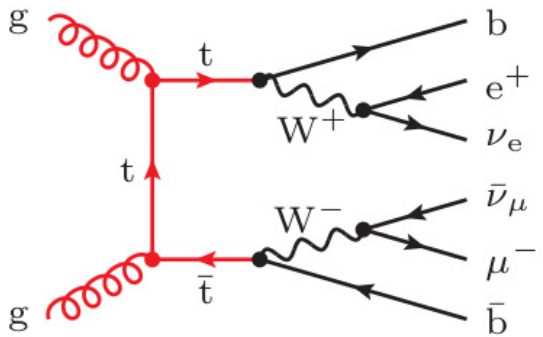


Associated to top-pair Production



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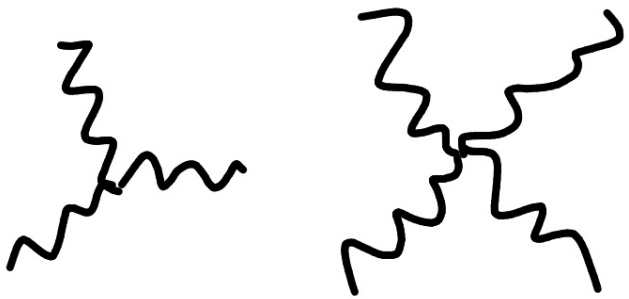

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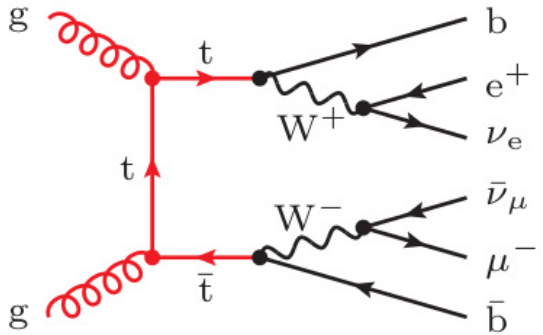
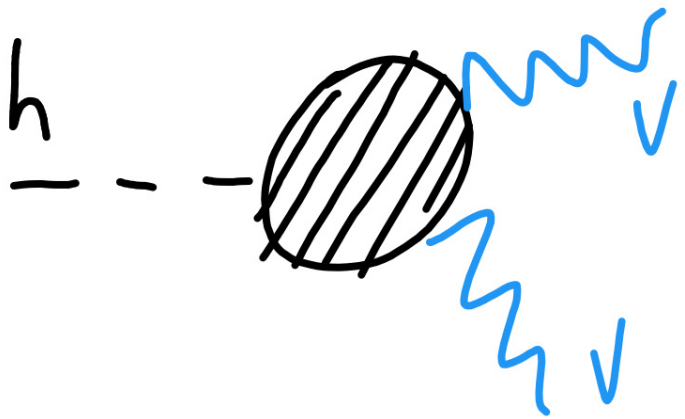
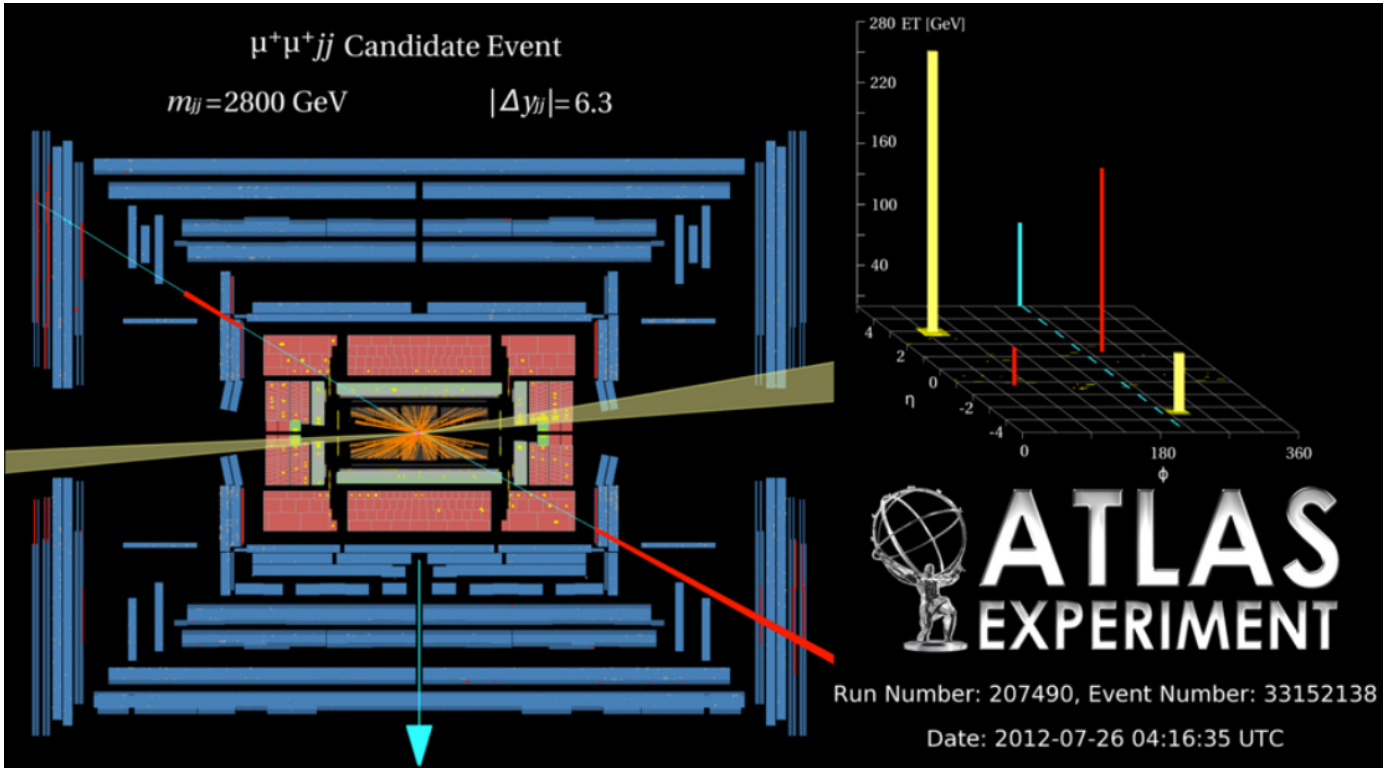


Background to $h \to VV$ signals



Vector Boson Scattering



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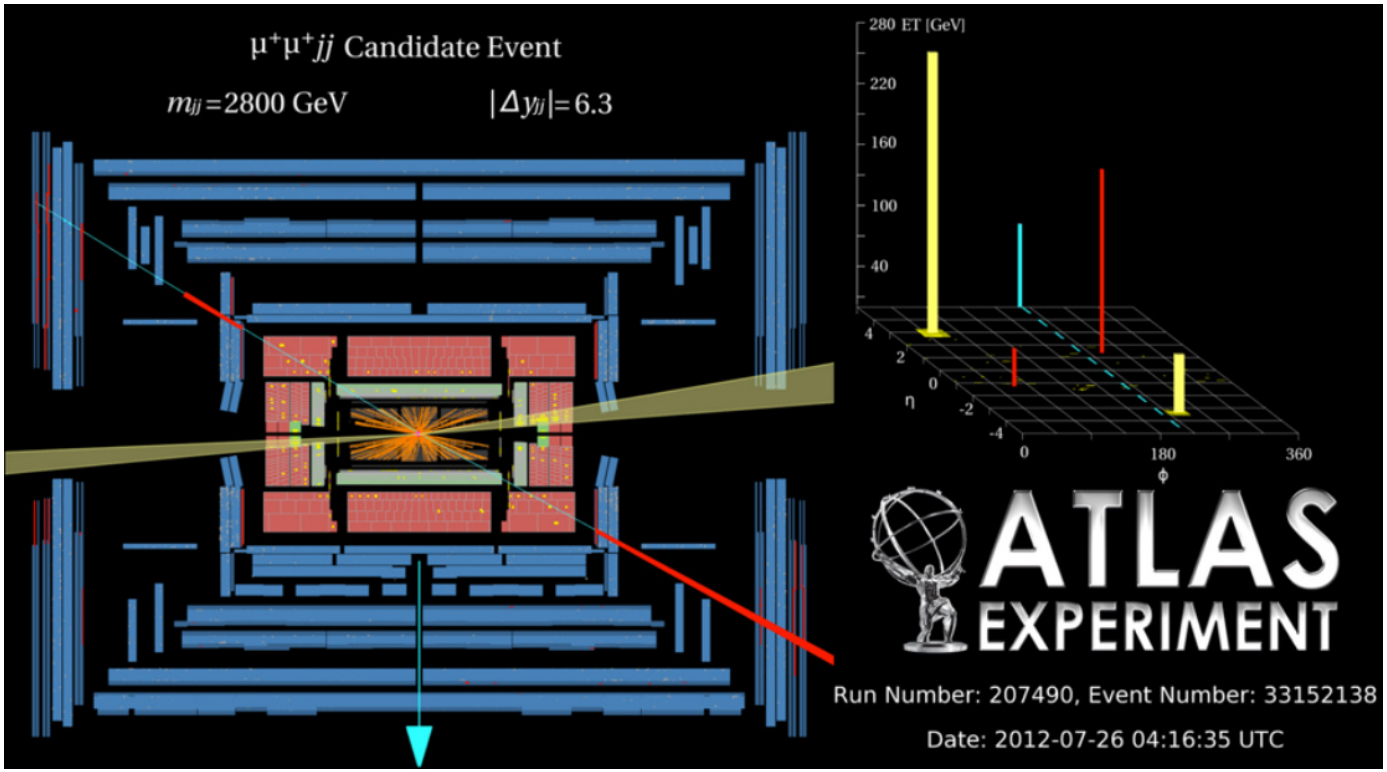
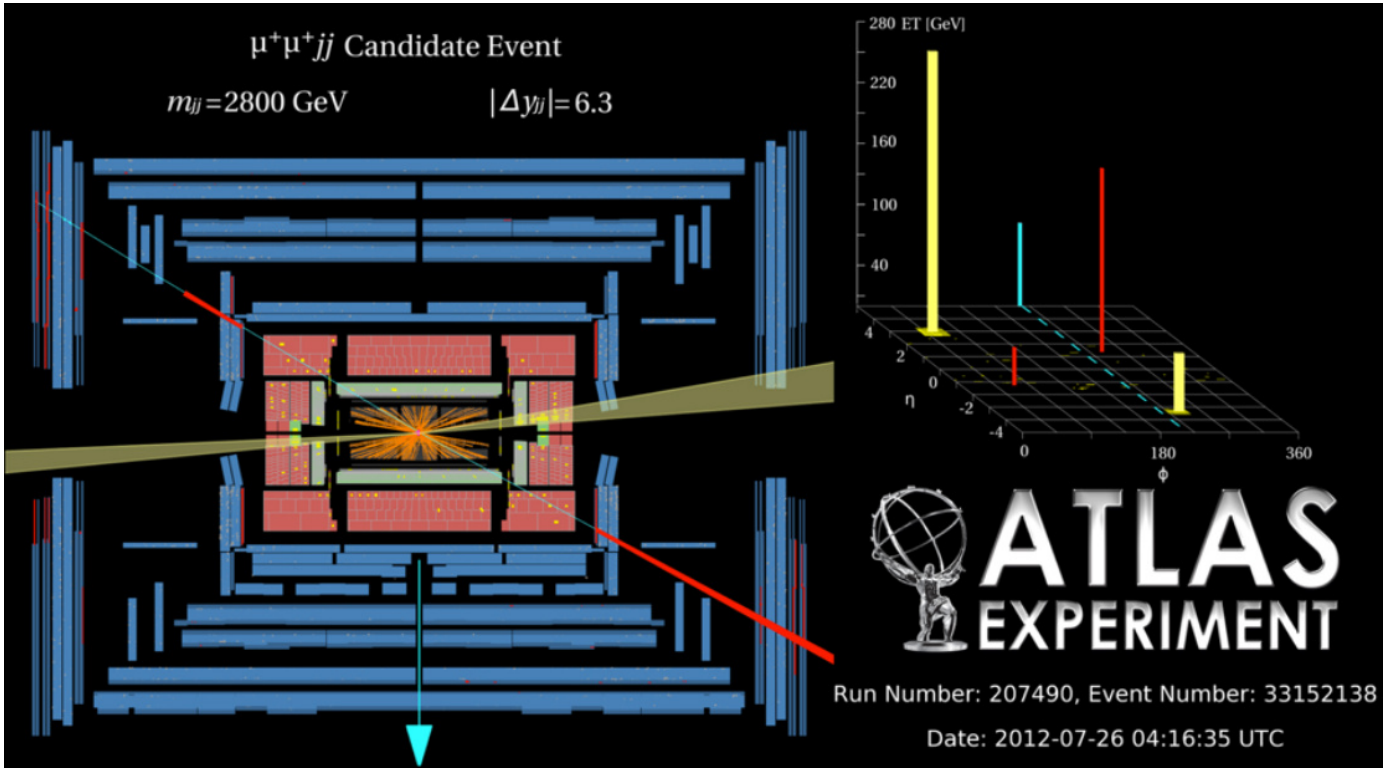


$VV \to VV$ scattering has a clear detector signature with two very forward jets

Vector Boson Scattering

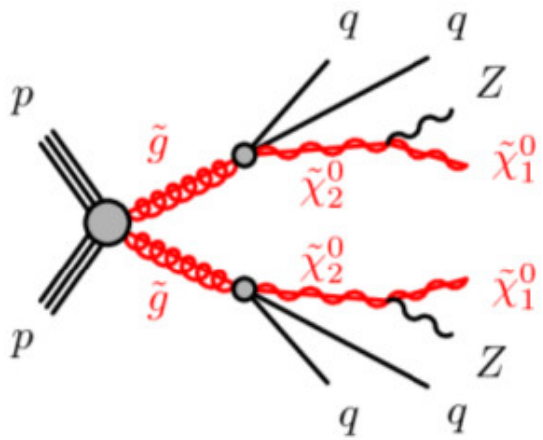


$VV \to VV$ scattering has a clear detector signature with two very forward jets

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



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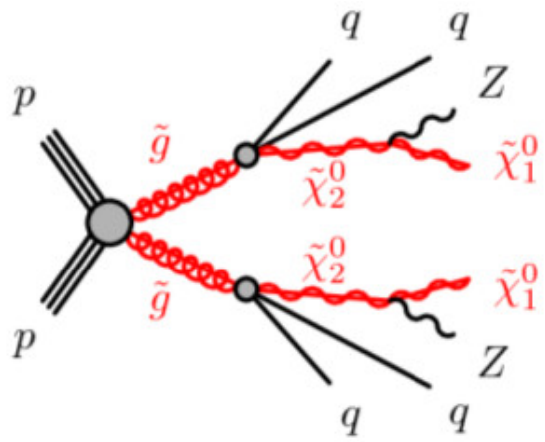
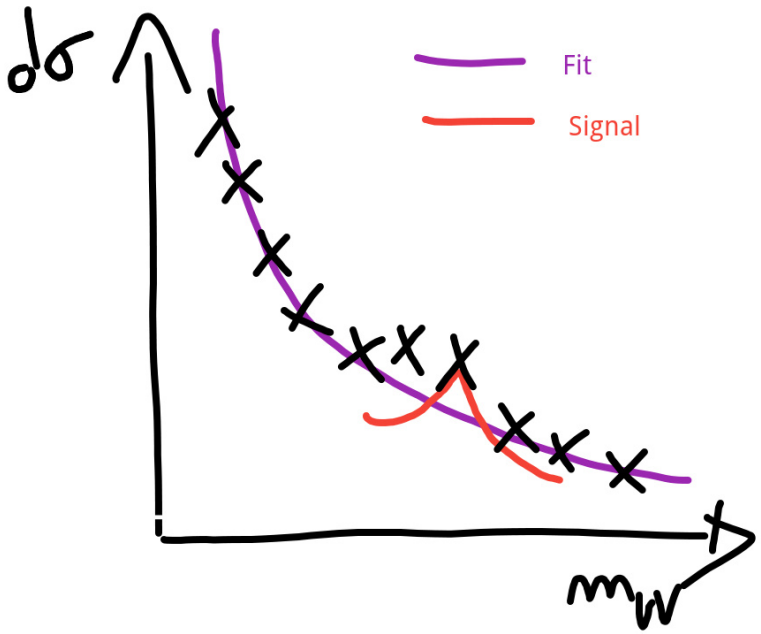
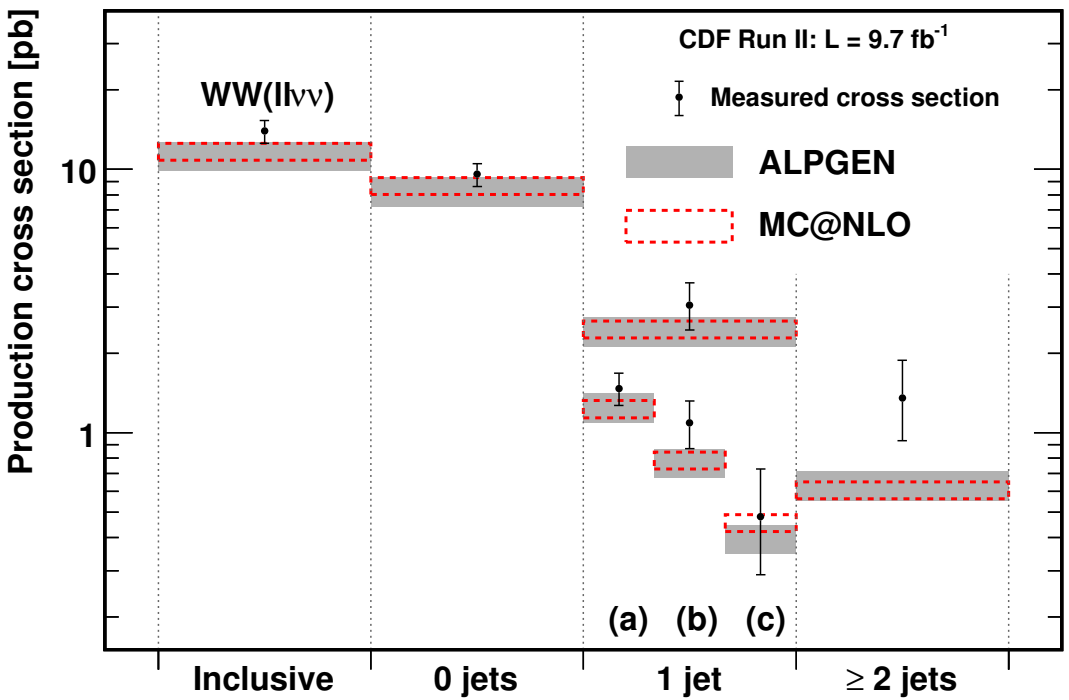


Divector boson resonances and their radiation patterns

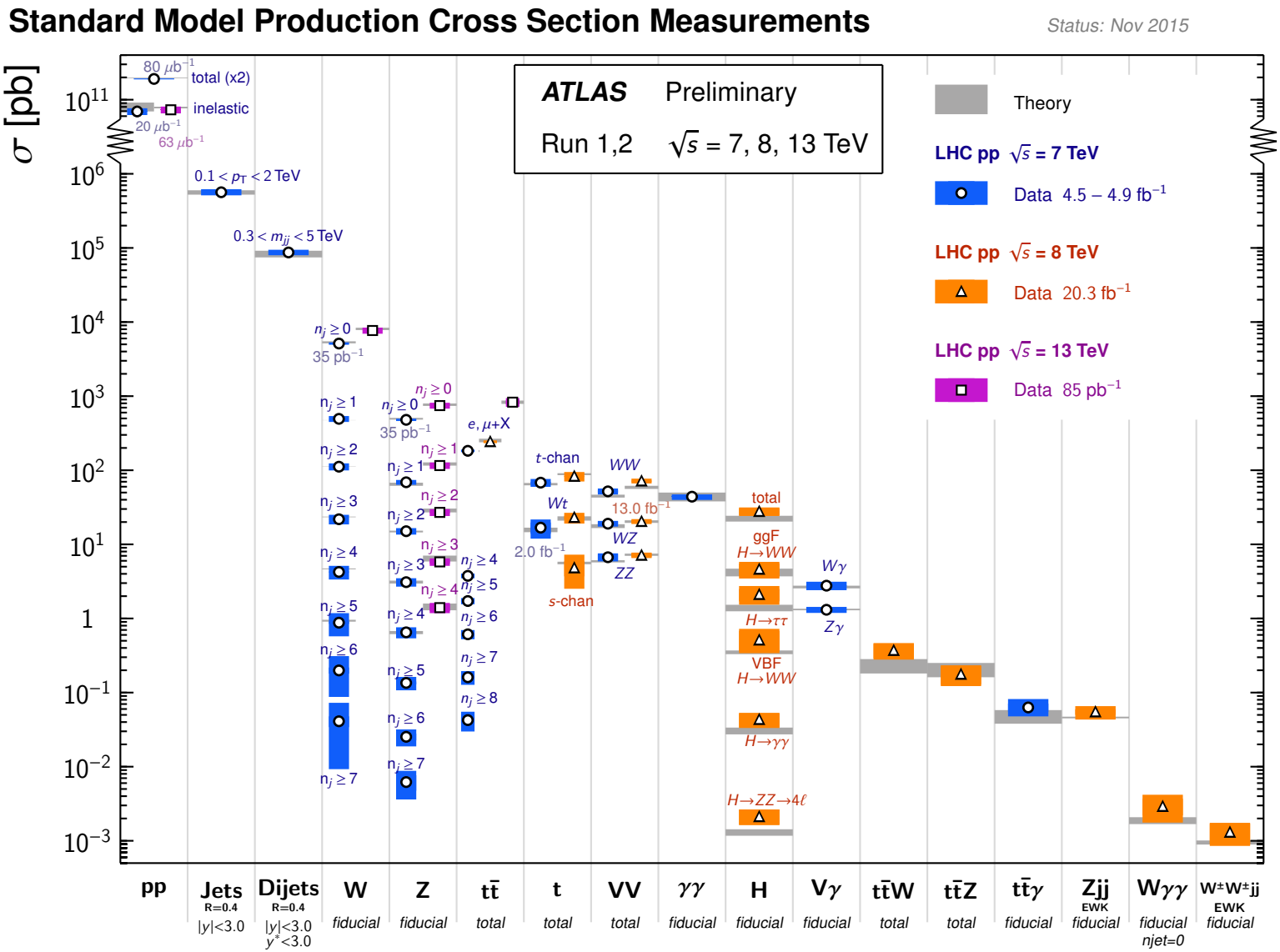


$W^+W^- + n$-Jet Measurement at CDF

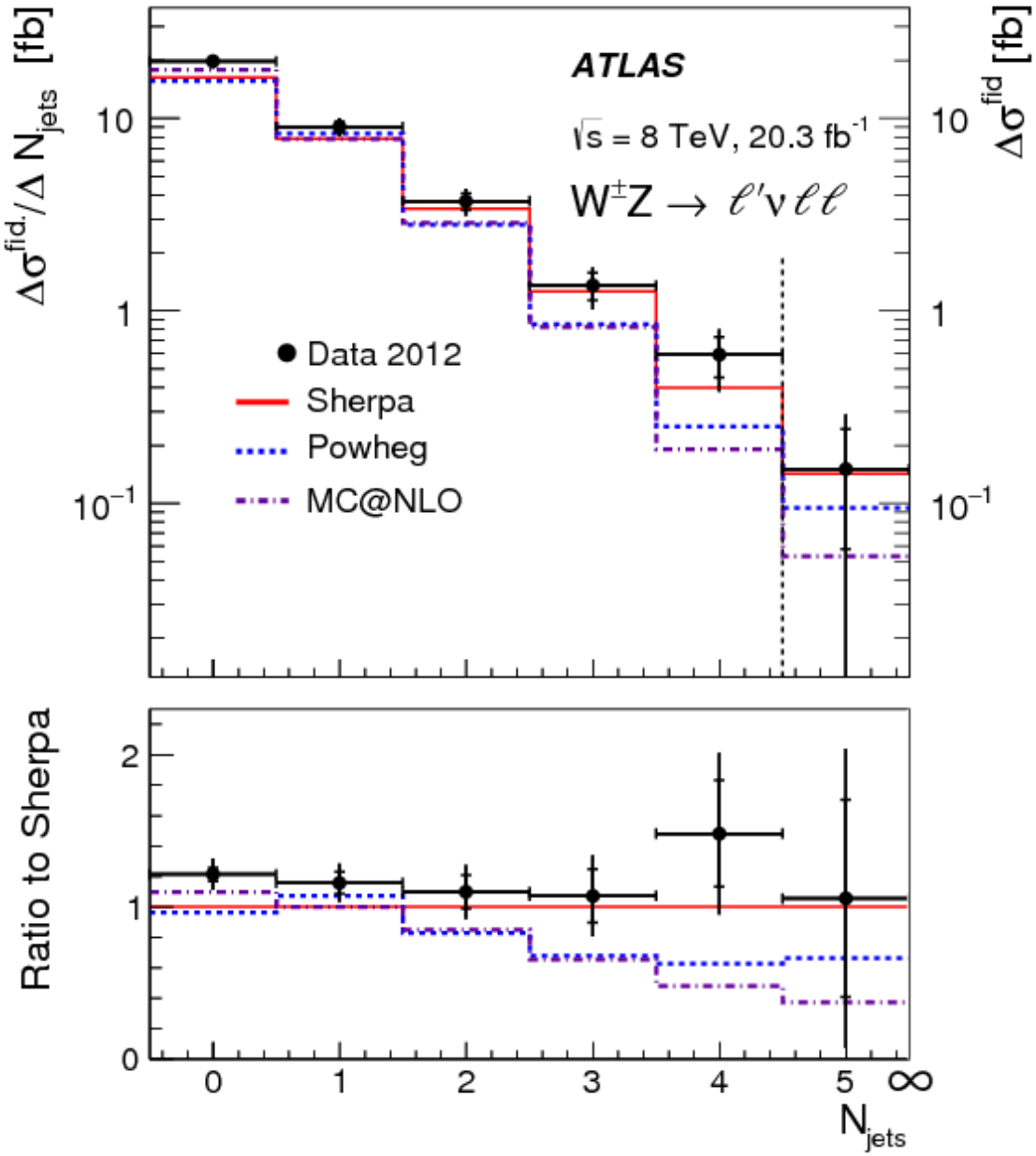


- arXiv:1505.00801
- Full dataset analyzed
- Total and differential cross sections
- Relative good agreement between theory and data
- At the Tevatron $t\bar{t}$ background is small

Same Sign WW Pair Measurement



$WZ + n$-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-Jet Production ($n = 0, 1, 2, 3$) at NLO QCD

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

W^+W^-	LO (1979)	Brown, Mikaelian
	NLO (1991)	Ohnemus; Frixione; Campbel, Ellis; Dixon, Kunszt, Signer; Campbel, Ellis, Williams
	NNLO (2014)	Gehrmann, Grazzini, Kallweit, Maierhöfer, von Manteuffel, Pozzorini, Rathlev, Tancreedi
$W^+W^- + 1$ 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, ...)

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$W^\pm W^\pm + 2$ Jets	NLO (2010)	Melia, Melnikov, Rontsch, Zanderighi; Campanario, Kerner, Ninh, Zeppenfeld

High Multiplicity NLO QCD Calculations

Full automation for $2 \to 4$ SM processes: Gosam, HELAC-NLO, Madgraph, OpenLoops, ...

$W + 4$-Jet Production	2010	Berger, Bern, Dixon, FFC, Forde, Gleisberg, Ita, Kosower, Maitre – **BlackHat**
$Z + 4$-Jet Production	2011	Ita, Bern, Dixon, FFC, Kosower, Maitre – **BlackHat**
5-Jet Production	2013	Badger, Biedermann, Uwer, Yundin – **NJet**
Diphoton+3 Jets	2013	Badger, Guffanti, Yundin – **NJet**
$t\bar{t}$+Higgs	2015	Denner, Feger, Scharf
$t\bar{t}$+Jet	2015	Bevilacqua, Hartanto, Kraus, Worek
W^+W^-+3-Jets	2015	FFC, Hofmann, Ita

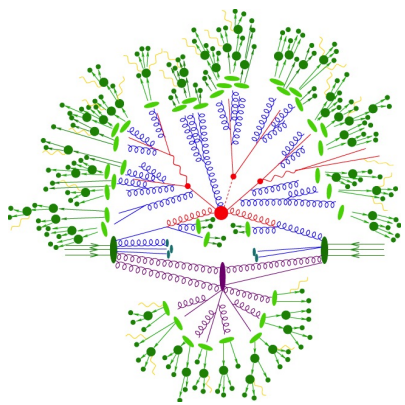
$W + 5$-Jet Production	2013	Bern, Dixon, FFC, Hoeche, Ita, Kosower, Maitre, Ozeren – **BlackHat**

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

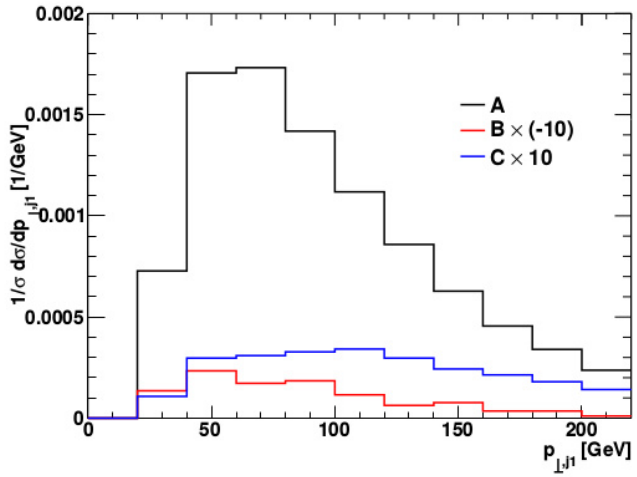


We employ the Catani-Seymour Dipole subtraction implementation of Sherpa, together with their integration algorithms

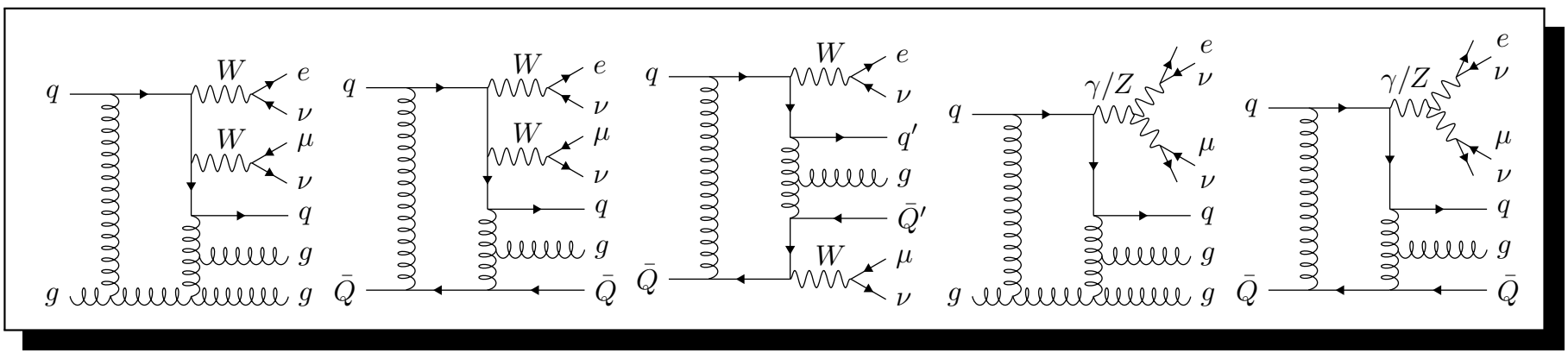
Our Setup

- We decay the W bosons into different lepton flavors (e & μ)

- We employ a leading-color approximation only for the virtual correction of $W^+W^- + 3$ Jet
- Diagrams with close massive loops are dropped
- We work with a diagonal CKM matrix



Gosam: arXiv:1202.6004



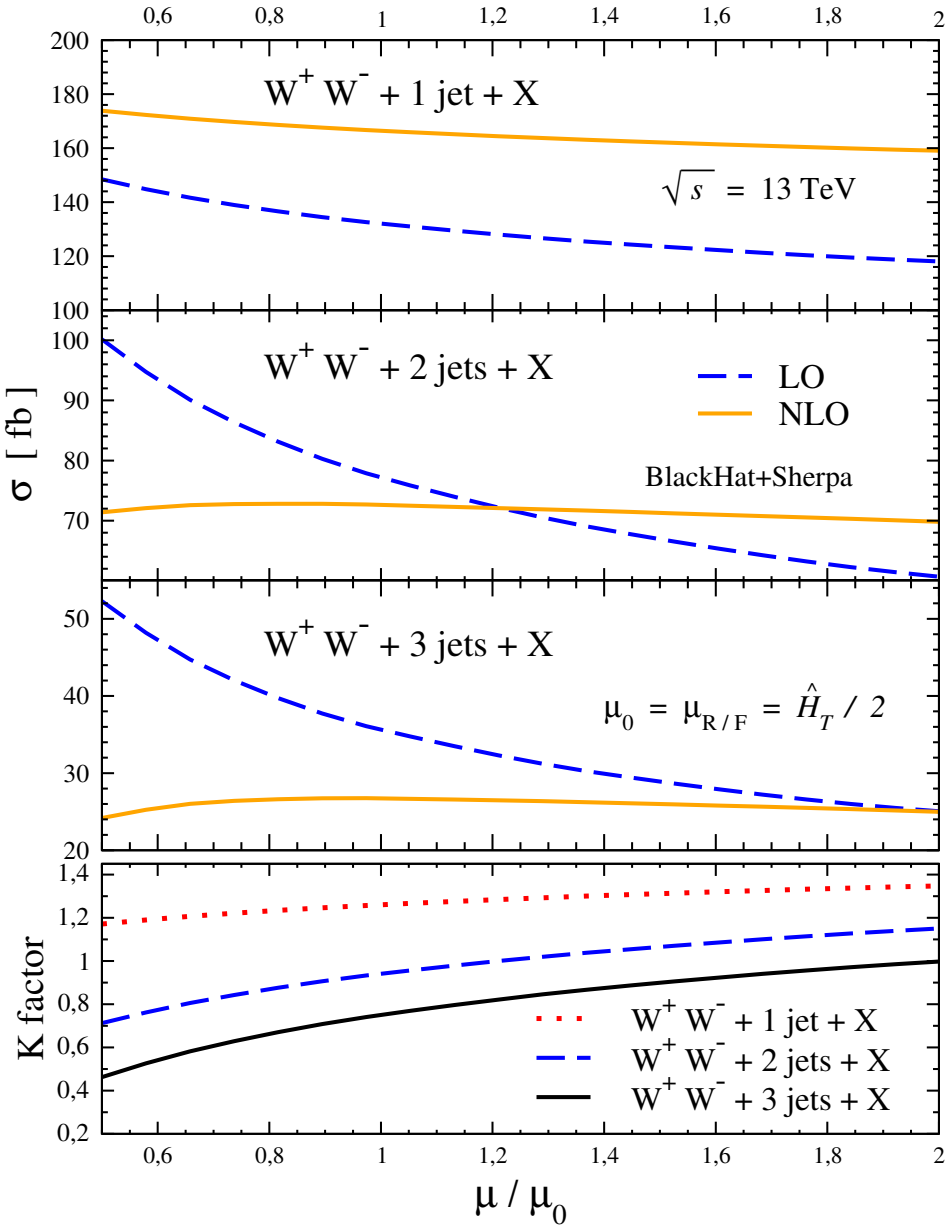
W^+W^-+Jet Phenomenology

We employ a dynamical scale $\mu = \mu_r = \mu_f = \hat{H}_{\rm T}/2$ 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:

- $p_{\rm T}^{e,\mu} > 20$ GeV
- $|\eta^{e,\mu}| < 2.4$
- $\not{E}_{\rm T} > 30$ GeV
- $p_{\rm T}^{e\mu} > 30$ GeV
- $m_{e\mu} > 10$ GeV
- Jets defined with anti-$k_{\rm T}$ algorithm
- $R = 0.4$
- $p_{\rm T}^{jet} > 30$ 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

Total Cross Section and Jet Ratios at $\sqrt{s} = 13$ TeV

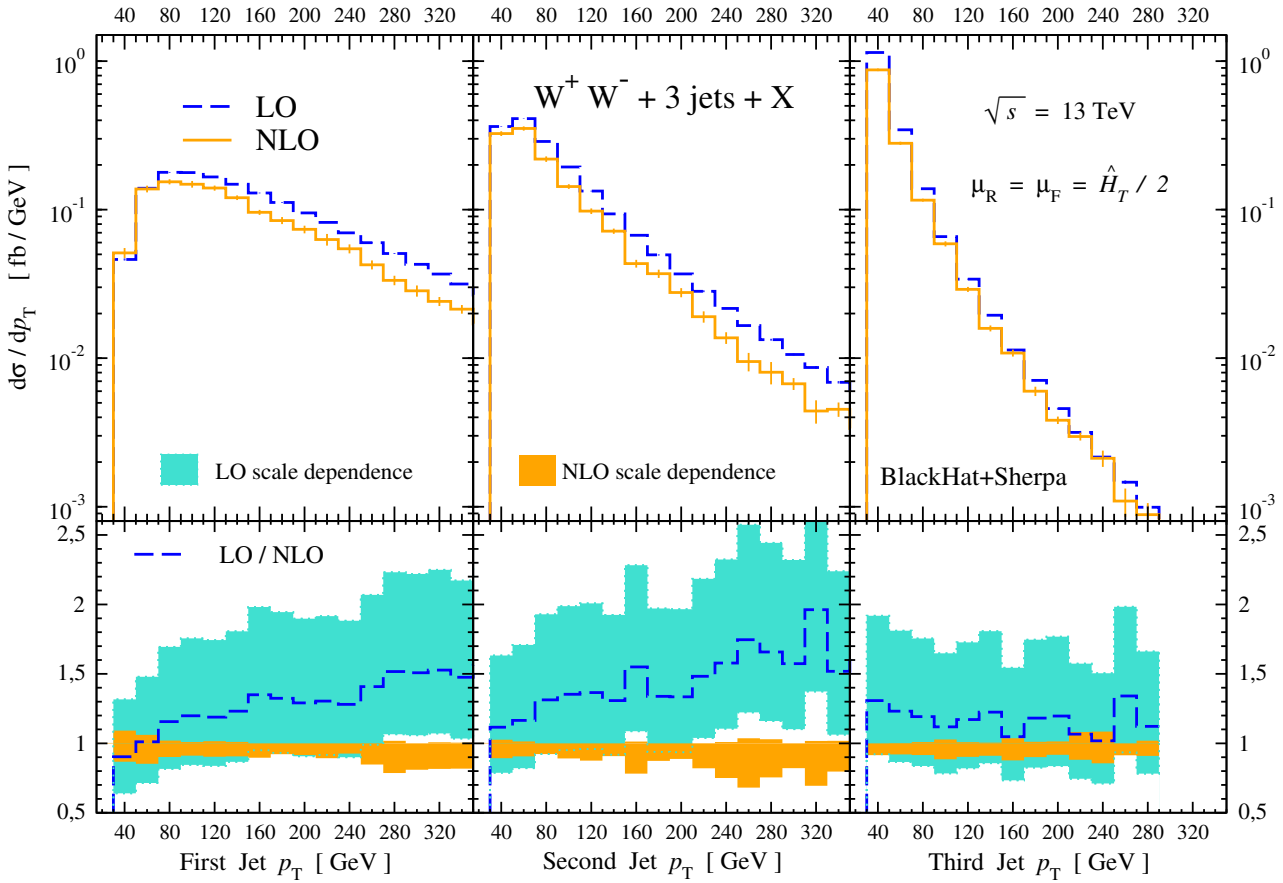
(in fb)

arXiv:1512.07591 [hep-ph]

	$W^+W^- + n$ jet		$(W^+W^- + n$ jet$)$ / $(W^+W^- + (n-1)$ jet$)$	
n	LO	NLO	LO	NLO
0	$230.7(5)^{+13.7}_{-16.7}$	$358(2)^{+7.3}_{-4.5}$	—	—
1	$131.6(2)^{+16.3}_{-14.0}$	$165.1(6)^{+7.2}_{-7.1}$	$0.571(2)$	$0.462(3)$
2	$77.5(2)^{+23.1}_{-16.6}$	$72.7(4)^{+0.2}_{-3.2}$	$0.589(2)$	$0.440(3)$
3	$35.59(6)^{+16.66}_{-10.55}$	$28.1(3)^{+0.0}_{-2.1}$	$0.459(1)$	$0.386(5)$
4	$14.12(8)^{+9.05}_{-5.14}$	—	$0.397(2)$	—

- Sizable reduction of scale sensitivity
- For $W^+W^- + 3$ Jets goes from 45% to 15%
- Jet ratios decrease for larger multiplicities

Jet p_{T} Spectra

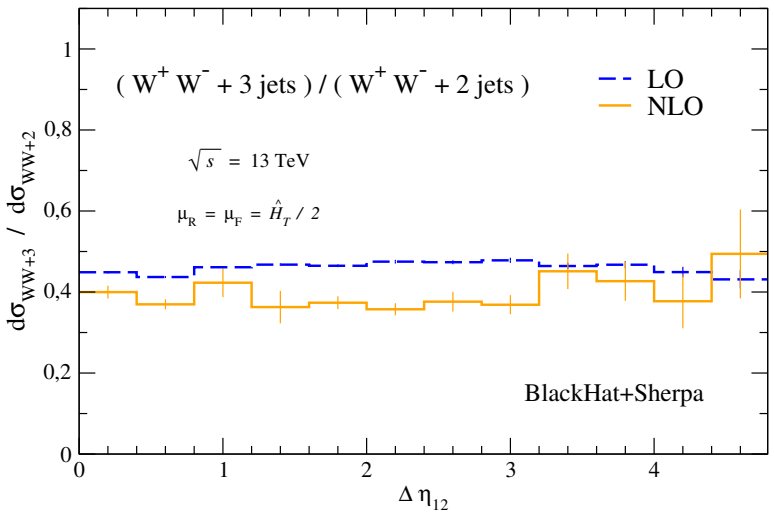


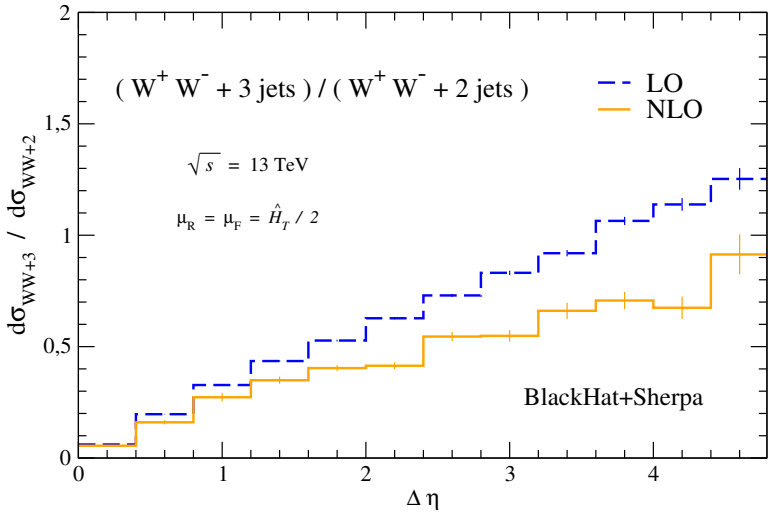
arXiv:1512.07591 [hep-ph]

- 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+Jets

Radiation into the Gap for VBF background

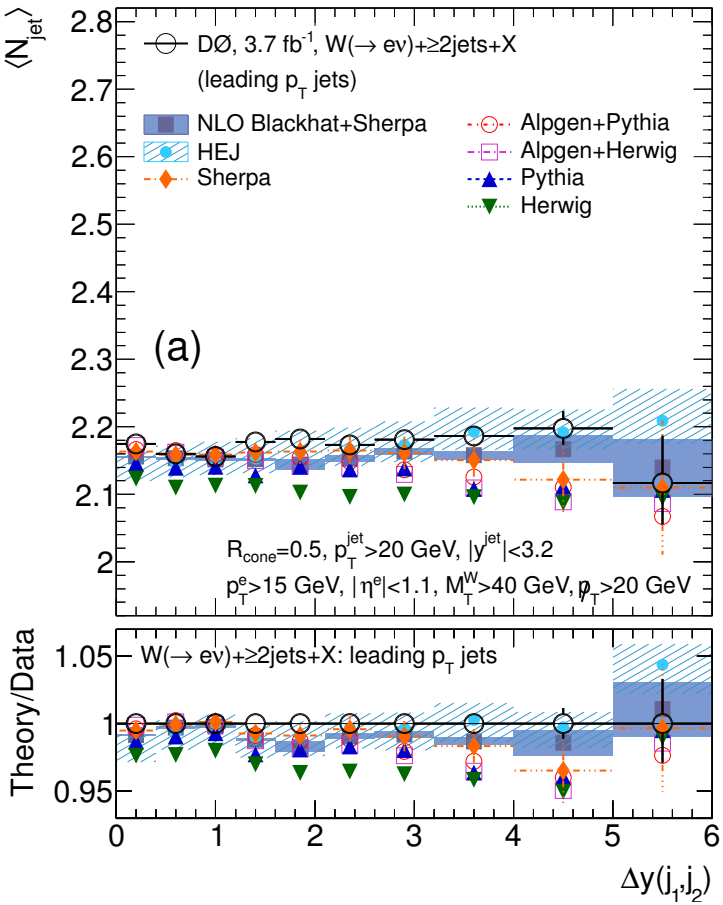
Radiation Gap

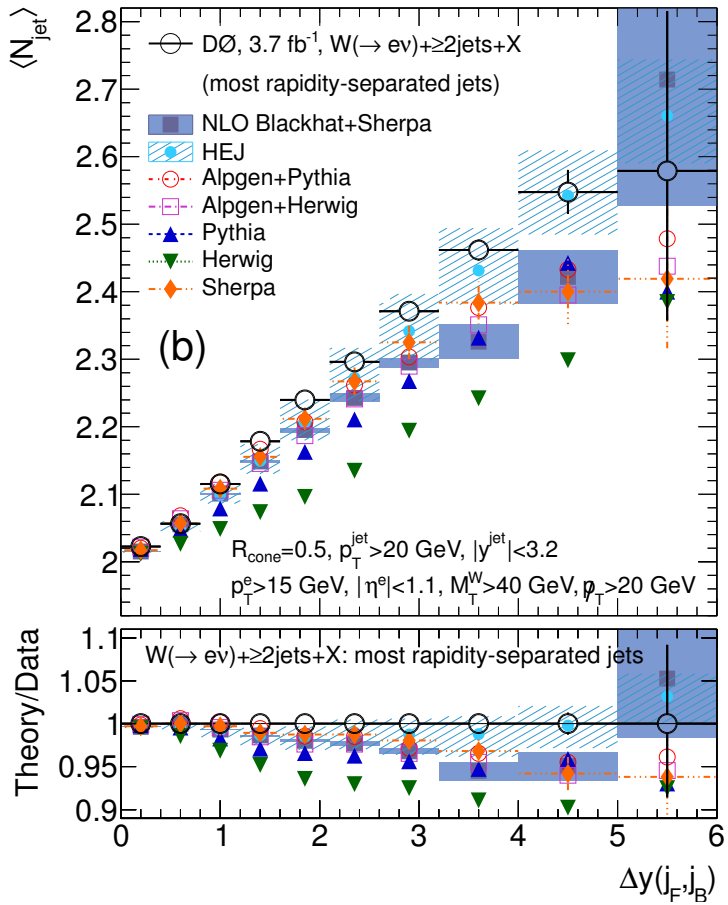




- A clear signature of VBF processes is a low rate of radiation in the gap between *tagging* forward and backward jets
- Background processes can have very different features
- A way to study this: look at ratios of $W^+W^- + 3$ Jets to $W^+W^- + 2$ Jets
- Left plot jets p_{T} ordered and right are η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

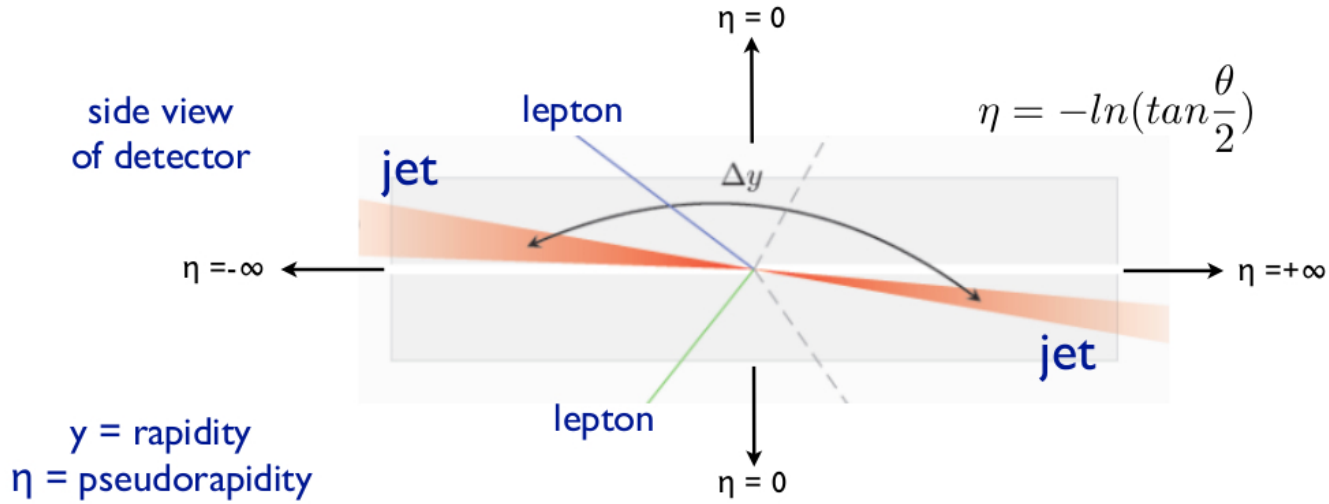
Radiation Gap at D0 in W+Jets





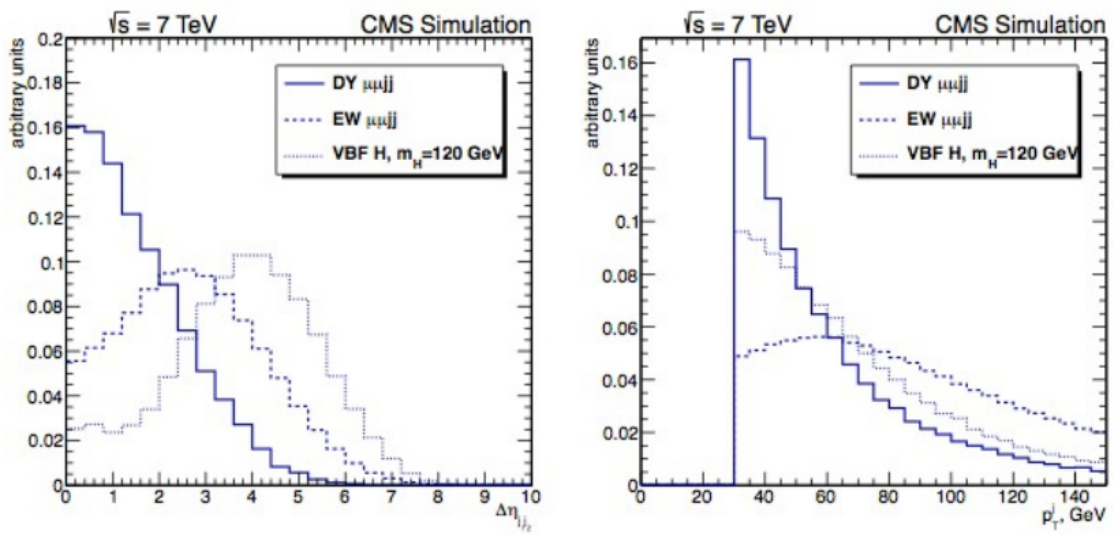
D0 Measurement [arXiv:1302.6508 [hep-ph]]

VBF - Distinguishing Topology



y = rapidity
η = pseudorapidity
y ~ η

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



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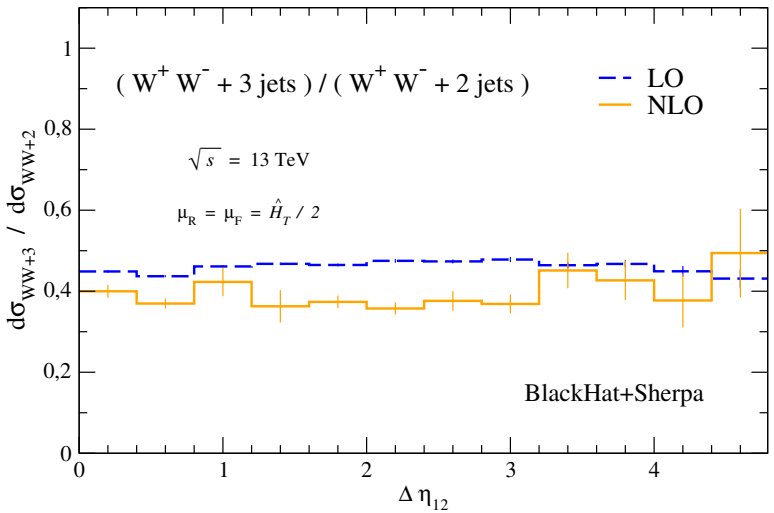
Slide from Sabine Lammers

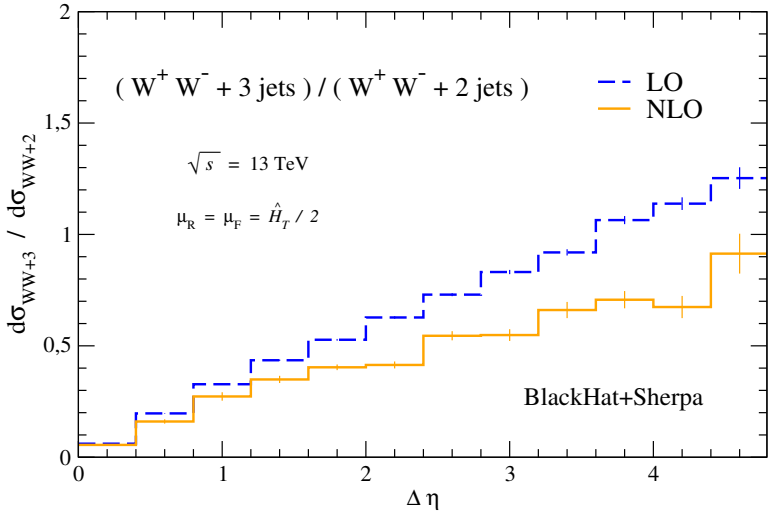
VBF Cuts

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

- Invariant mass for tagging jets: $M_{j_1 j_2} > 500$ GeV
- Jet separation: $\Delta R_{j_1 j_2} > 3.2$
- Different hemispheres: $\eta_{j_1} \eta_{j_2} < 0$

Radiation Gap: non VBF vs. VBF





Adding VBF cuts:

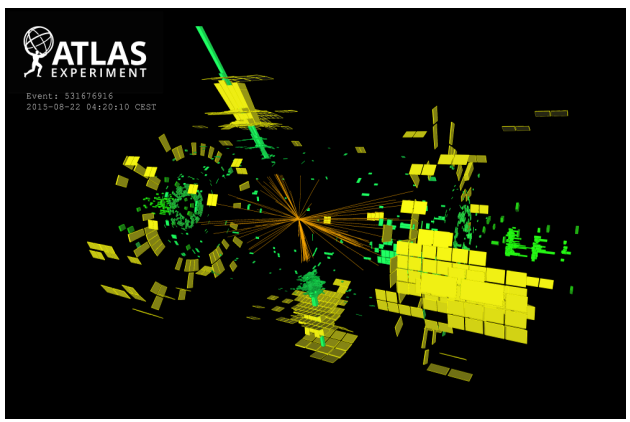
n	LO	NLO
j_1, j_2 ordered by p_{T}		
2	$1.589(4)^{+0.573}_{-0.379}$	$1.484(27)^{+0.002}_{-0.074}$
3	$1.135(5)^{+0.590}_{-0.353}$	$0.728(83)^{+0.015}_{-0.179}$
ratio:	$0.714(4)$	$0.49(6)$

n	LO	NLO
j_1, j_2 ordered by η		
2	$1.589(4)^{+0.573}_{-0.379}$	$2.492(27)^{+0.417}_{-0.360}$
3	$2.480(7)^{+1.260}_{-0.762}$	$2.17(13)^{+0.02}_{-0.24}$
ratio:	$1.561(6)$	$0.87(5)$

PRELIMINARY

Outlook

- We have computed NLO QCD corrections to W^+W^-+3-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 compared against data collected at the LHC



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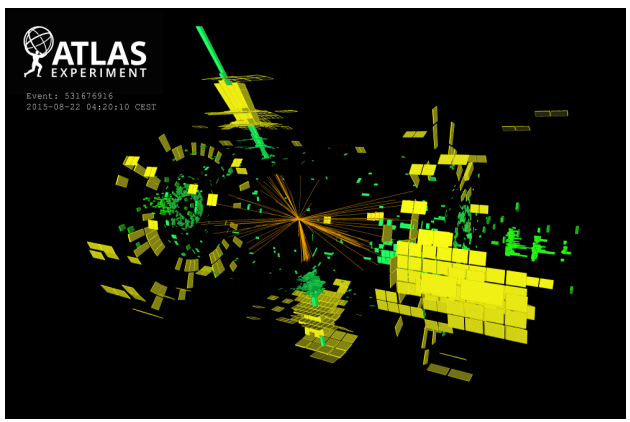

Thanks!