W^+W^- Production with Many Jets at the LHC

NLO QCD with BlackHat+Sherpa

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With Philipp Hofmann and Harald Ita [to appear]

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Outline

MOTIVATION

$t\bar{t}$, VBF, Gauge couplings, Experimental results, Previous calculations

NLO QCD WITH BlackHat+Sherpa

New developments, Cross checks, Pheno setup, LHC $\sqrt{s} = 7, 8, 13$ TeV

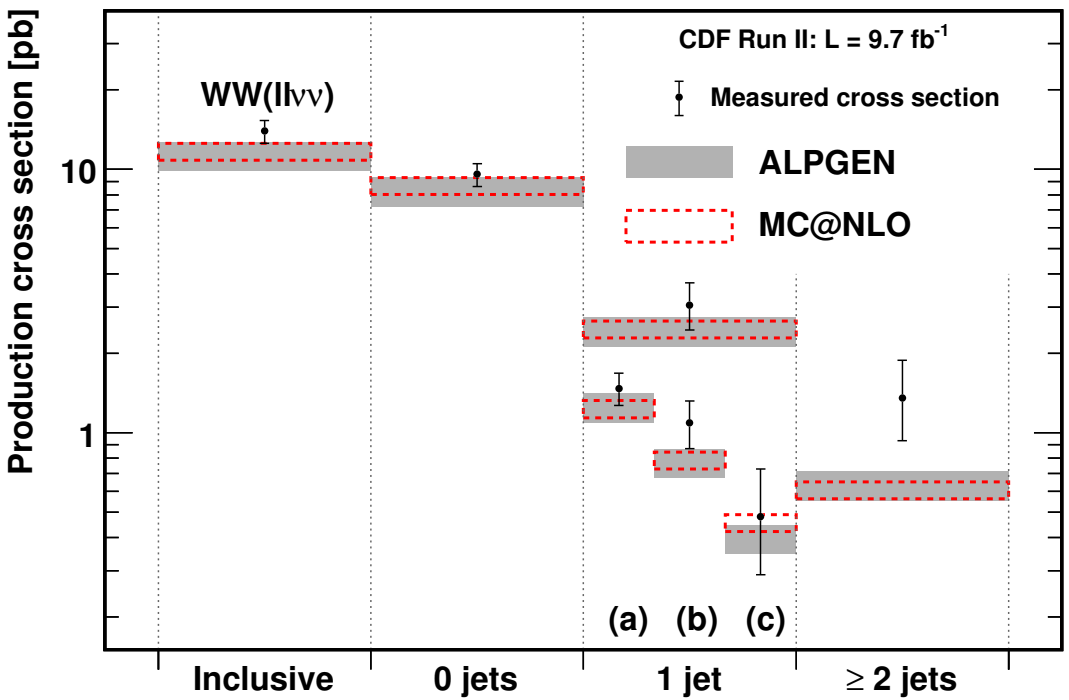
CORRECTIONS TO W^+W^- + 3 JETS

Scale sensitivity, Jet bins, Total/diff cross sections, Radiation gap

W^+W^-+Jets Signatures

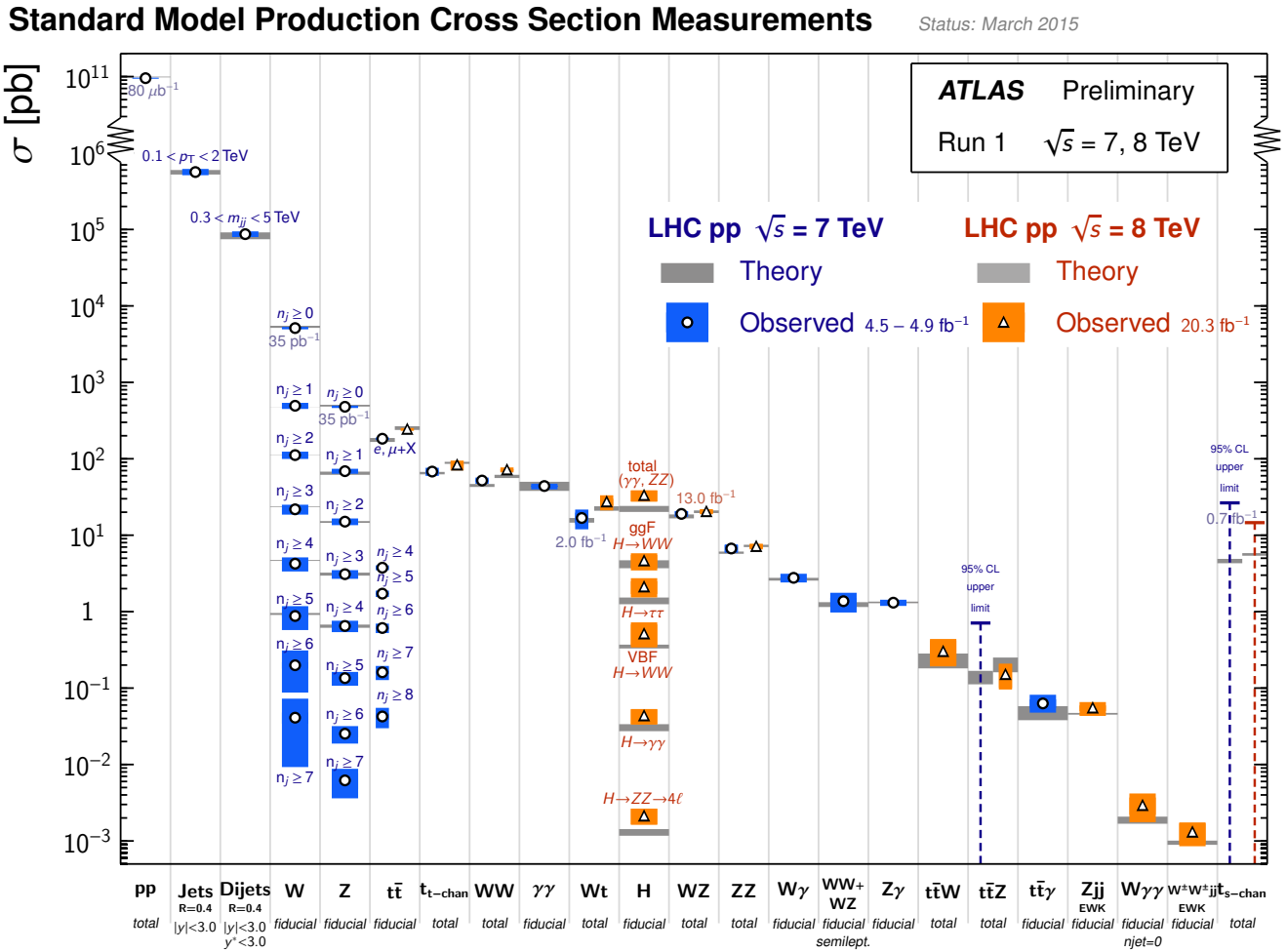
- Measurement of **trilinear and quartic couplings**
- In **$t\bar{t}$** production, as the top quarks decay $t \to W + b$
- In vector boson scattering, **vector boson fusion** (VBF)
- In **Higgs** phenomenology, when it decays into W^+W^-
- Scenarios of **BSM**, in which heavy colored particles decay in chains of leptons and jets
- In particular, W^+W^- + 3-Jet production is of relevance to understand **radiation gap** in and as background to VBF

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

SM Cross Sections at ATLAS



- Summary plot of SM cross sections
- Impressive agreement between theory and experiment
- Di-vector boson measurements
- Jet towers to deeply test QCD
- Smallest cross section from $W^{\pm}W^{\pm} + 2$ jets
- Similar results from CMS

Parton Level Calculations for $WW + n$ Jets

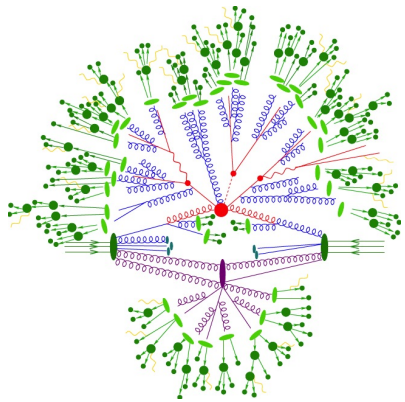
W^+W^-	LO (1979)	Brown, Mikaelian
	NLO (1991)	Ohnemus; Frixione; Campbel, Ellis; Dixon, Kunszt, Signer; Campbel, Ellis, Williams
	NNLO (2014)	Gehrmann, Grazzini, Kallweit, Maierhfer, von Manteuffel, Pozzorini, Rathlev, Tancreedi
$W^+W^- + 1$ Jet	NLO (2007)	Campbell, Ellis, Zanderighi; Dittmaier, Kallweit, 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.*
$W^\pm W^\pm + 2$ Jets	NLO (2010)	Melia, Melnikov, Rontsch, Zanderighi; Campanario, Kerner, Ninh, Zeppenfeld

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. We record Ntuple files for sharing and analysing results

New Developments in BlackHat

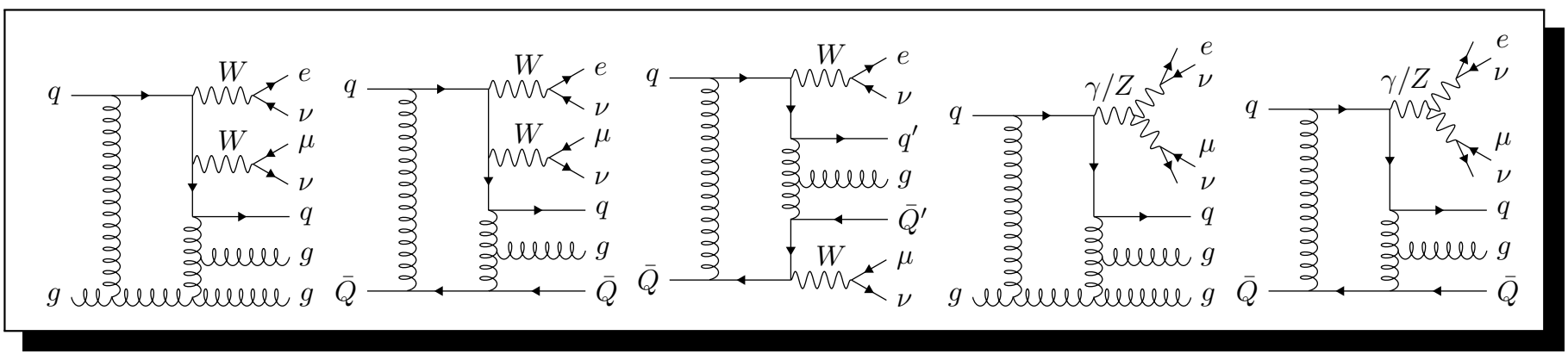
Produced NLO QCD results for V+3,4,5 Jets; 4 Jets; $\gamma\gamma$+2jets; Universality in jet ratios; Ntuples for NLO QCD
$\rightarrow$ (See Daniel Maître's talk!)

In order to extend the library to handle Di-vector boson processes, we have made the following extensions:

- Tree on-shell recursion relations with quarks, gluons and several vector bosons (with leptonic decay products)
- To cross check, tree level off-shell recursions (Berends-Giele) have been implemented
- Added infrastructure to compute loop amplitudes based on new tree amplitudes
- Automated assembly of tree- and loop-level MEs

Our Setup

- We employ a leading-color approximation (only) for the virtual correction of $W^+W^- + 3$ Jet. We have checked that this approximation works well, at the level of 1%, in the lower point cases
- We consider double resonant contributions and include Breit-Wigner propagator for intermediate W and Z bosons
- Top quark contributions are excluded. We drop also finite bottom quark contributions
- We work with a diagonal CKM matrix
- We decay the W bosons into different lepton flavors (e & μ)



Cross Checks of Results

- We have checked IR/UV poles of (full-color) virtual matrix elements
- We have checked collinear limits
- We have cross checked lower point ($n = 0, 1, 2$) one-loop matrix elements with GOSAM
- We have cross checked our results with independent implementations within BlackHat
- We have checked α_{dipole} independence of the real corrections

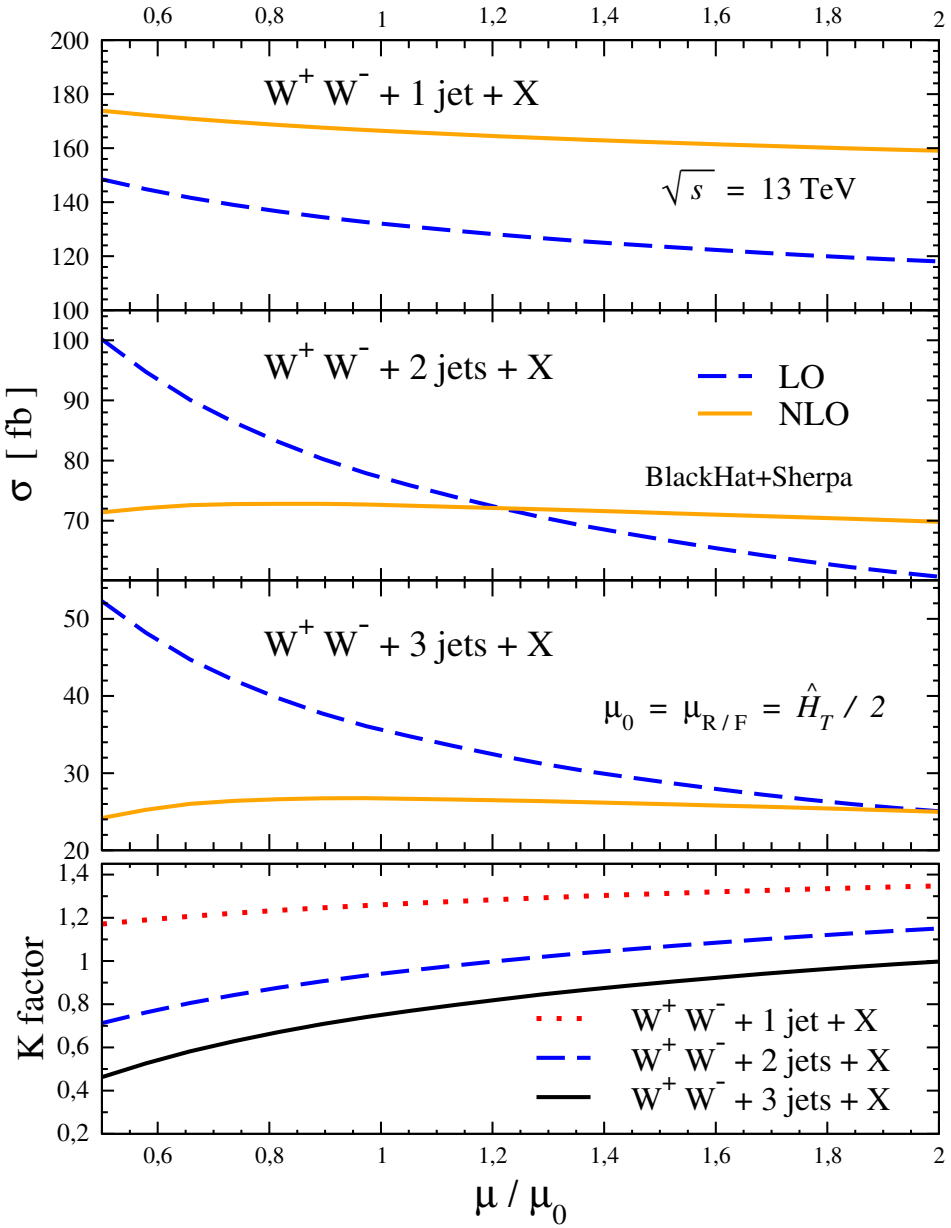
Phenomenology

We employ a dynamical scale $\mu = \mu_r = \mu_f = \hat{H}_{\rm T}$ 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. For the results we present 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 $\sqrt{s} = 7, 8$ and 13 TeV.

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



- Total cross sections as function of unphysical scales
- W^+W^-+0 Jet not shown (corrections very large, NNLO needed $\rightarrow$ (See D. Rathlev's talk!)
- Small scale sensitivity at NLO
- Large multiplicity needs NLO

PRELIMINARY

Total Cross Section and Jet Ratios at $\sqrt{s} = 8$ TeV

(in fb)

PRELIMINARY

	$W^+W^- + n$ jet		$(W^+W^- + n \text{ jet}) \,/\, (W^+W^- + (n-1) \text{ jet})$	
n	LO	NLO	LO	NLO
0	$141.7(4)^{+3.7}_{-5.3}$	$207.9(7)^{+5.4}_{-3.5}$	—	—
1	$61.1(2)^{+9.8}_{-8.0}$	$76.4(4)^{+3.6}_{-4.0}$	0.431(2)	0.367(2)
2	$29.44(7)^{+9.99}_{-6.92}$	$28.8(2)^{+0.3}_{-1.9}$	0.482(2)	0.377(3)
3	$11.12(2)^{+5.74}_{-3.51}$	$9.22(16)^{+0.17}_{-1.05}$	0.378(1)	0.320(1)
4	$3.59(2)^{+2.50}_{-1.37}$	—	0.323(2)	—

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

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

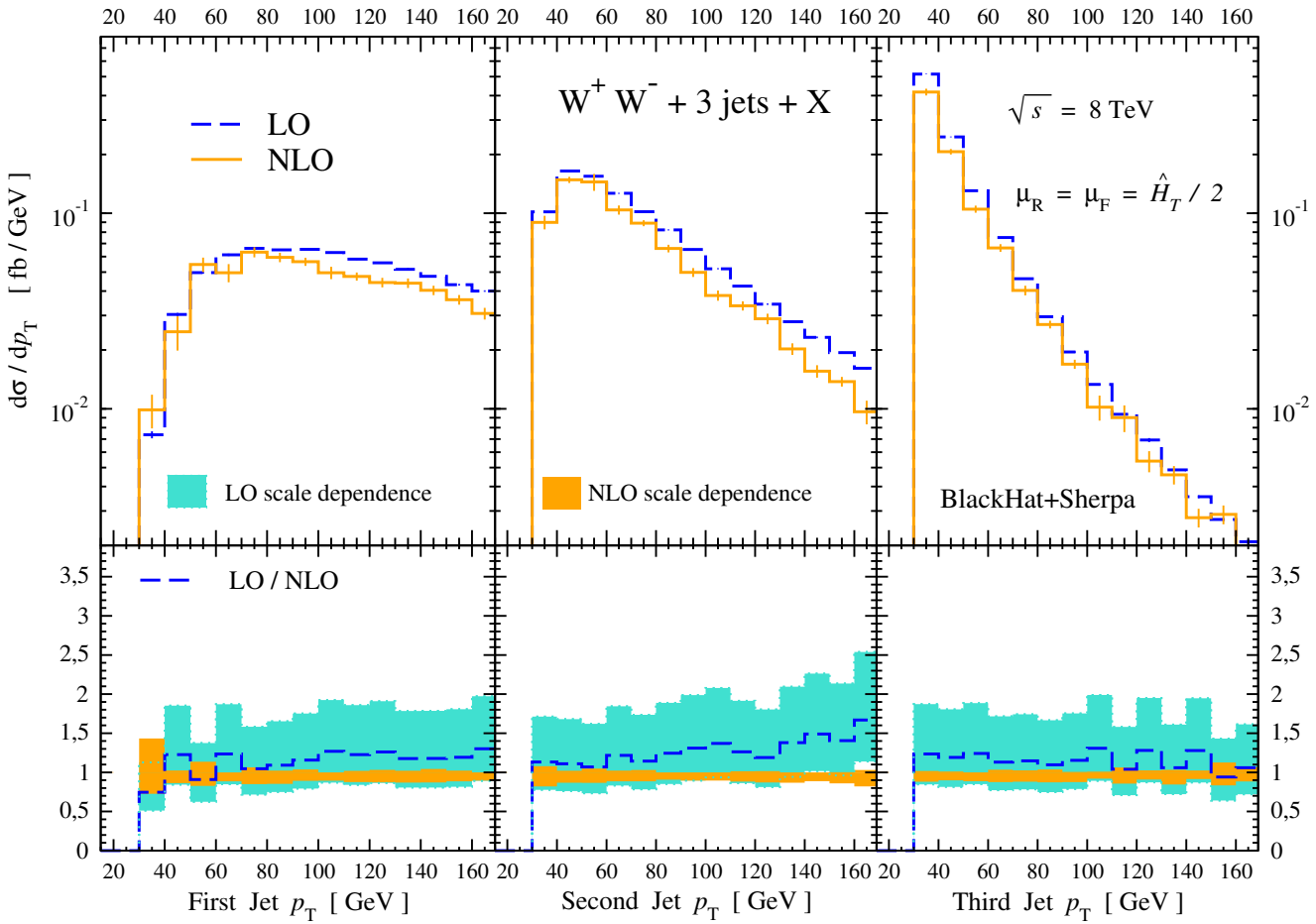
(in fb)

PRELIMINARY

	$W^+W^- + n$ jet		$(W^+W^- + n$ jet$)$ / $(W^+W^- + (n-1)$ jet$)$	
n	LO	NLO	LO	NLO
0	$231.7(6)^{+13.7}_{-16.8}$	$363(2)^{+7.7}_{-4.8}$	—	—
1	$132.0(3)^{+16.4}_{-14.0}$	$166(1)^{+7.4}_{-7.4}$	0.570(2)	0.458(4)
2	$77.2(2)^{+23.0}_{-16.5}$	$72.6(4)^{+0.1}_{-2.8}$	0.585(2)	0.436(4)
3	$35.62(7)^{+16.68}_{-10.56}$	$26.7(4)^{+0.0}_{-2.5}$	0.462(2)	0.368(6)
4	$14.15(9)^{+9.08}_{-5.15}$	—	0.397(3)	—

- With more jets, cross sections increase more with energy
- Jet ratios increase, as more energy available for radiation
- Need to explore jet ratios behavior more detailed

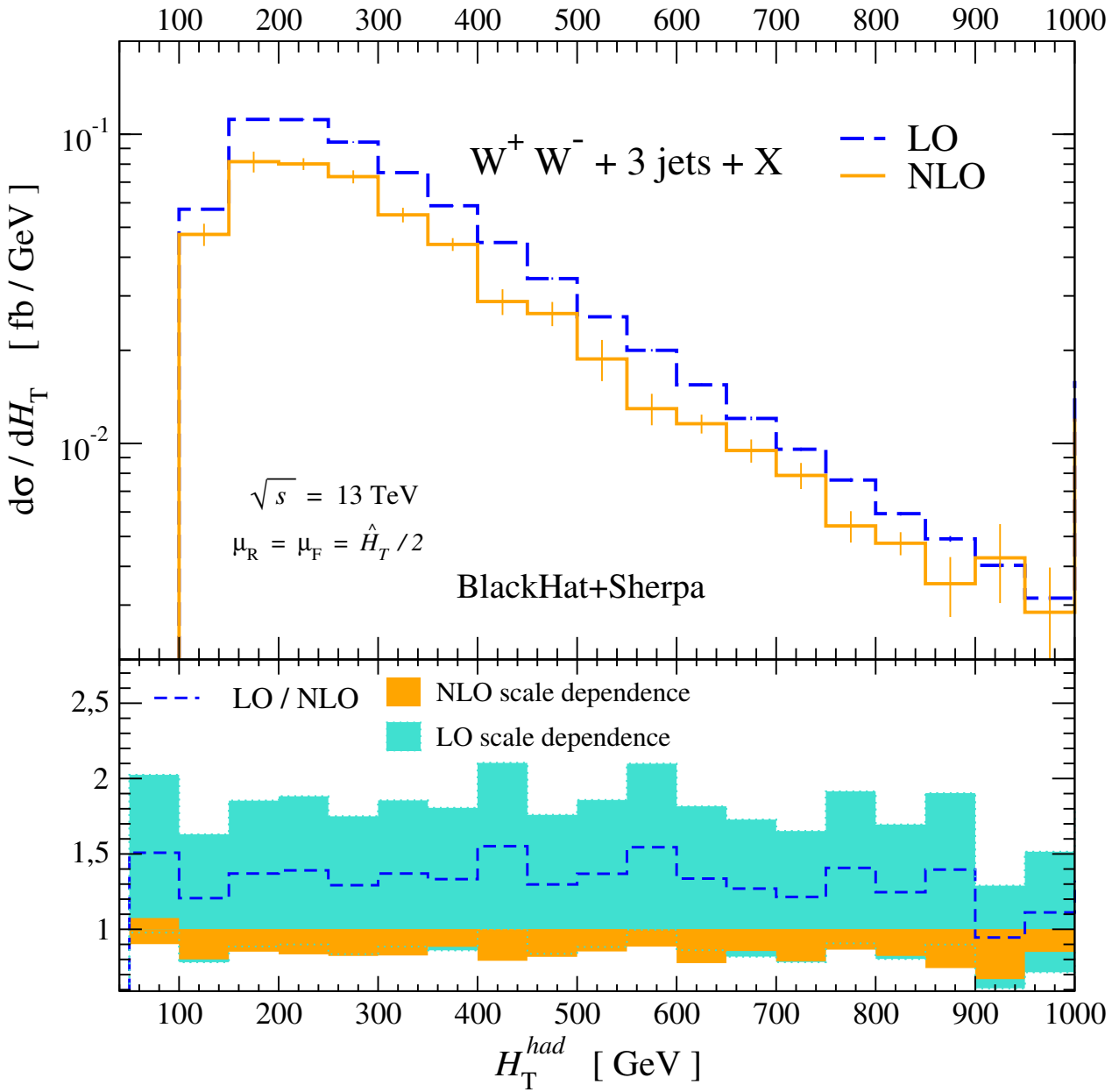
Jet p_{T} Spectra



- p_{T} distributions for softer jets fall more steeply
- Quantum corrections only shift softest jet p_{T} distribution
- More structure for harder jet emeissions
- Similar trends to what is observed in NLO QCD corrections to V+Jets

PRELIMINARY

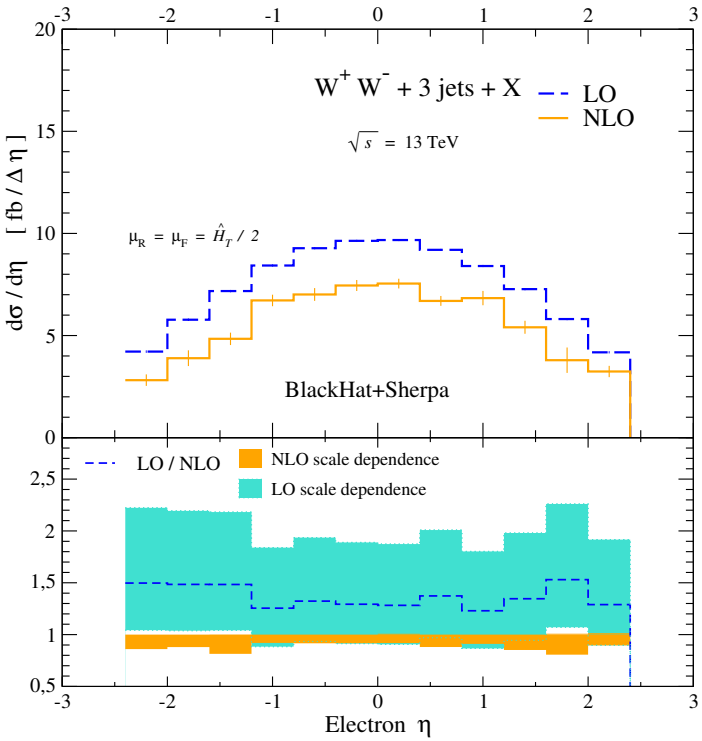
Hadronic Transverse Energy

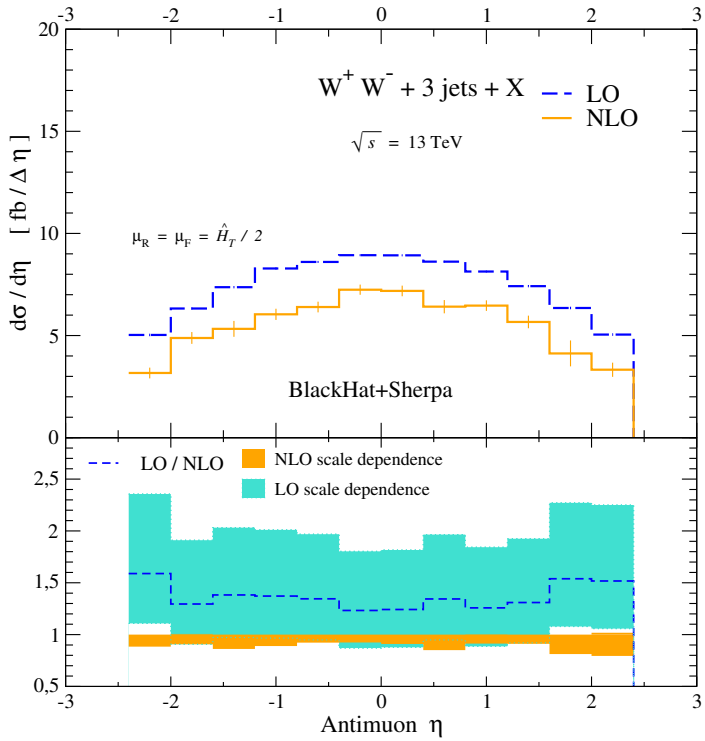


- Sum of transverse energy of jets
- Important for BSM searches
- The dynamical scale choosen appears as natural
- Considerable reduction of scale sensitivity

PRELIMINARY

Lepton Rapidities

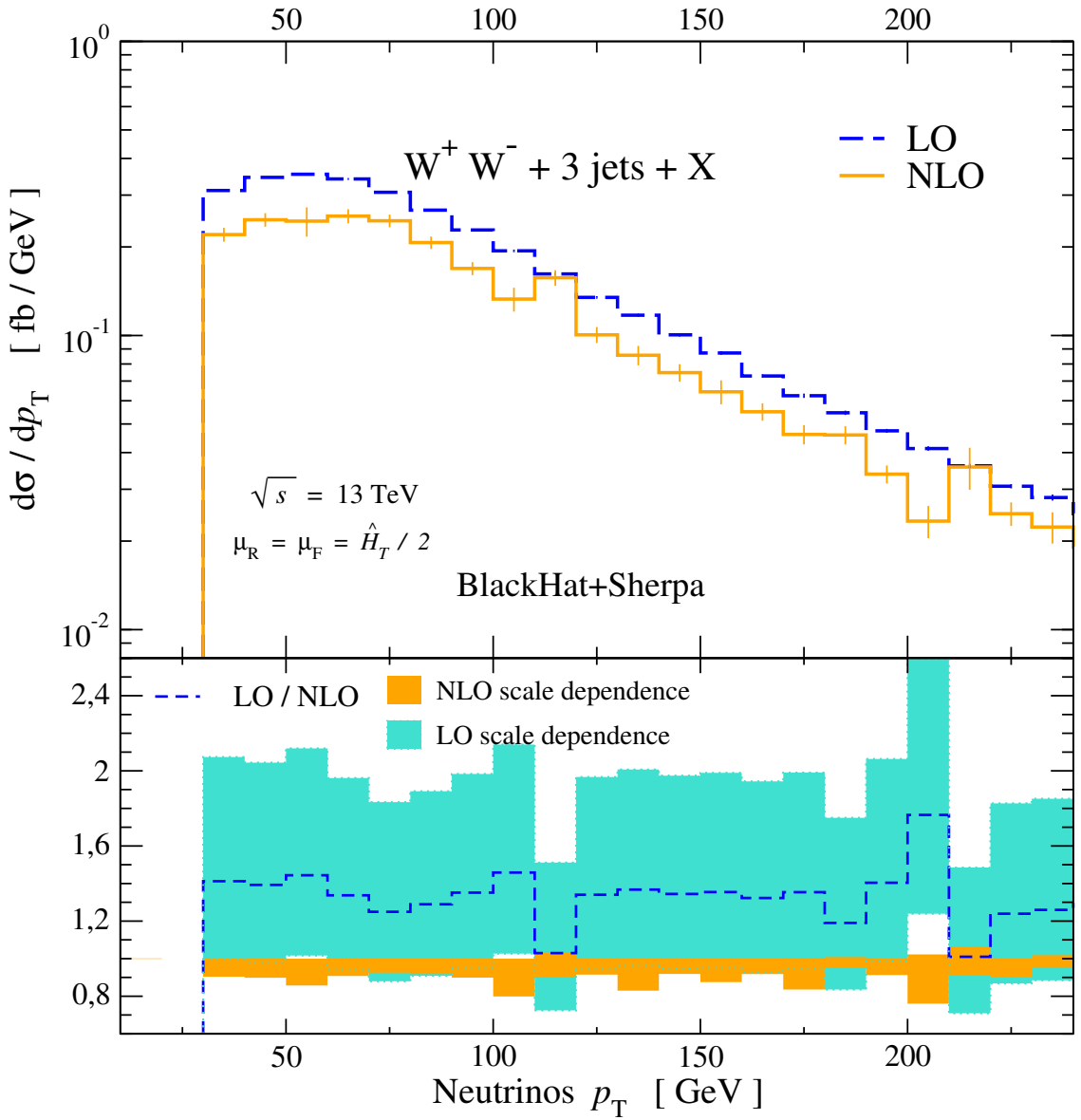




- Lepton η distributions shapes not affected by corrections
- Very similar distributions (both leptons are treated massless)
- Considerable reduction of scale sensitivity

PRELIMINARY

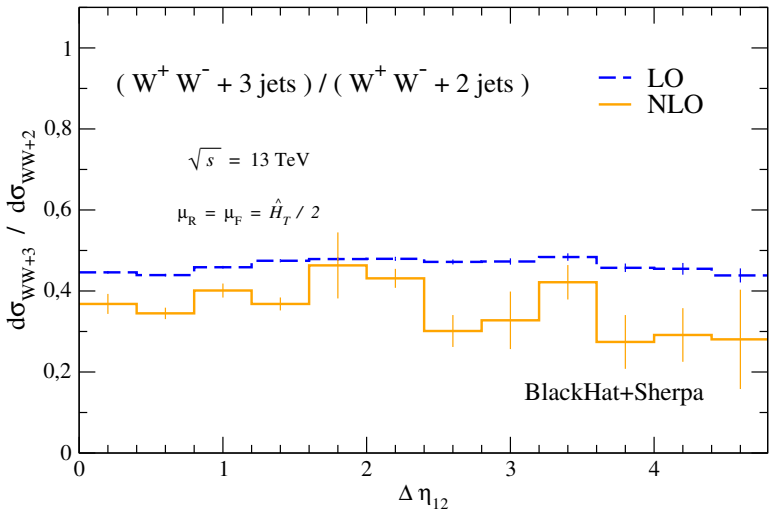
Missing Transverse Energy

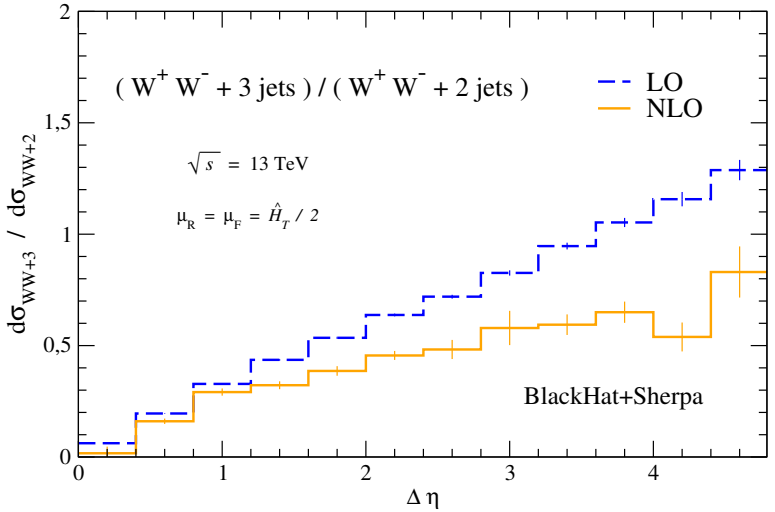


- Neutrinos scape detector, and produce $\not{E}_{\mathrm{T}}$
- Important observable for BSM searches
- Experimental analyses favor $\not{E}_{\mathrm{T}}^{\mathrm{rel}}$, to avoid instrumental backgrounds

PRELIMINARY

Radiation Gap



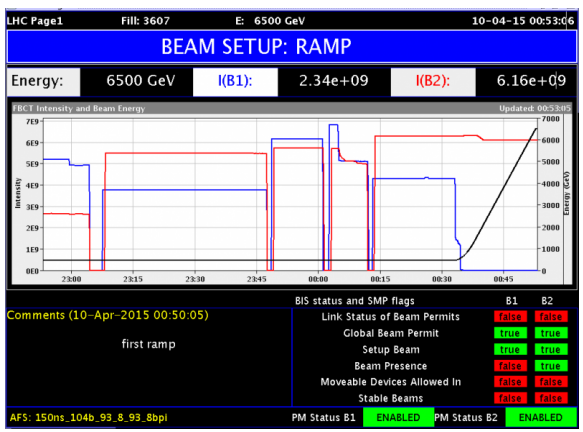


- A clear signature of VBF processes is a low rate of radiation in the gap between *tagging* forward and backward jets
- Background processes can have very different features
- A way to study this: look at ratios of $W^+W^- + 3$ Jets to $W^+W^- + 2$ Jets
- Left plot jets p_{T} ordered and right are η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

PRELIMINARY

Outlook

- We presented first NLO QCD correction to $W^+W^- + 3$-Jet production. This results joins the few NLO QCD results for processes with more than 5 objects in the final state ($V + 4, 5$ Jets from BlackHat+Sherpa and 5-Jet Production from NJet)
- We are ready to explore in general NLO QCD production of Di-vector bosons with jets
- Ntuple sets are ready for phenomenological studies
- NLO QCD corrections provide reliable predictions for large multiplicity predictions
- More dedicated results will follow, including jet ratio observables



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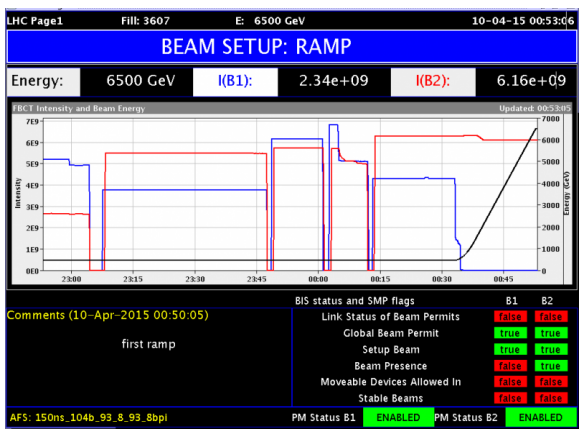

Thanks!