Vector Bosons and Jets at the LHC

NLO QCD with BlackHat+Sherpa

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LHC Run II and the Precision Frontier

KITP, UCSB, March 2016

With F. Anger, P. Hofmann, H. Ita and D. Maitre
arXiv:1512.07591, arXiv:16xx.xxxxx
Based on collaboration with Z. Bern, L. Dixon, D. Kosower, S. Höche

ALBERT-LUDWIGS-UNIVERSITÄT FREIBURG

Alexander von Humboldt Stiftung/Foundation

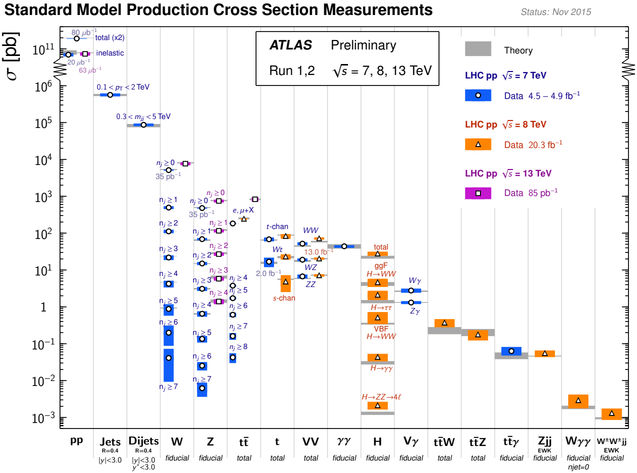
Outline

INTRODUCTION
Jets at the LHC, NLO QCD, BlackHat+Sherpa, Data comparisons

Weak Vector Boson and Jets
Production at the LHC with $\sqrt{s} = 13\ (14)$ TeV

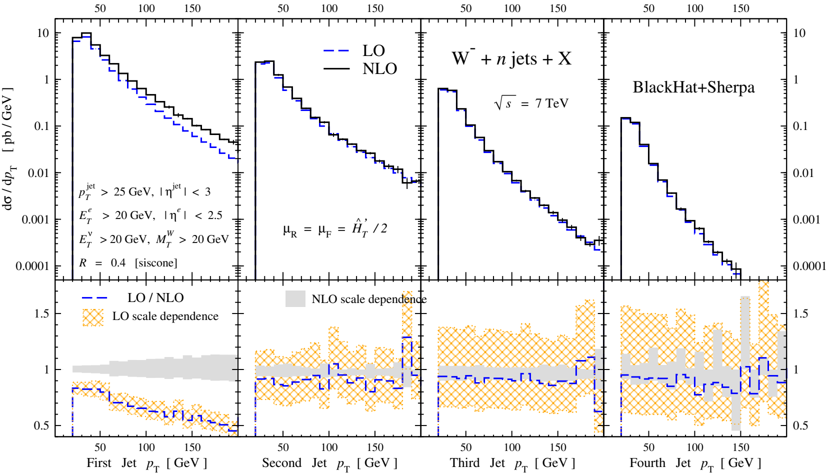
Divector Boson and Jets
W^+W^- with many jets, Cross sections, Radiation gap

SM Cross Sections at ATLAS



- Summary plot of SM cross sections
- Includes recent $\sqrt{s} = 13$ TeV results
- Impressive agreement between theory and experiment
- Jet towers deeply testing QCD
- Similar results from CMS

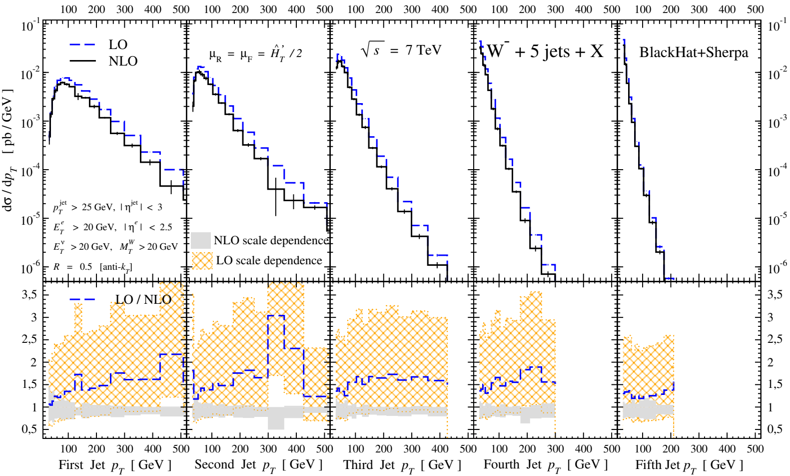
N^{th} Jet p_T Spectra at NLO



- NLO QCD predictions to Jet p_T in inclusive W Production
- Long history of advancements in perturbative calculations

- NLO QCD first numerically reliable prediction
- With BlackHat+Sherpa we were able to access even softer jets ...

Jet p_T Spectra at NLO for $W + 5$-Jet Production



- Involves 1-loop amplitudes with 6 particles attached to the loop
- Real radiation with integration over PS of 6(7) particles

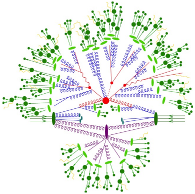
- Impressive improvement on the perturbative prediction
- Allows for tests of QCD in highly complex kinematic configurations

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

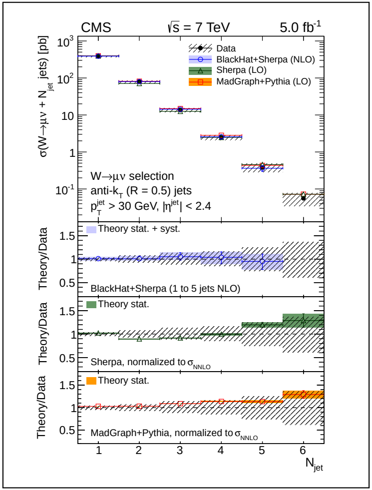
NTuples: Full Flexibility for NLO

BH Ntuples arXiv:1310.7439 [hep-ex]

- Generate files containing:
  - Kinematic information
  - Information needed to change factorization and renormalization scales
  - PDF weights
  - Information for multiple jet algorithms (type, R's, f-parameter, etc)
- Publicly available ($CASTOR$, LHC Grid)
  - Full implementation in SHERPA
  - We also provide a C++ library to read and handle them
- Many processes provided for the LHC
  - $W + 0, 1, 2, 3, 4, 5$ jets
  - $Z + 0, 1, 2, 3, 4$ jets
  - $2, 3, 4$ jet production
  - $\gamma\gamma + 1, 2$ jets
  - $W^+W^- + 0, 1, 2, 3$ jets

NLO at Work at the LHC

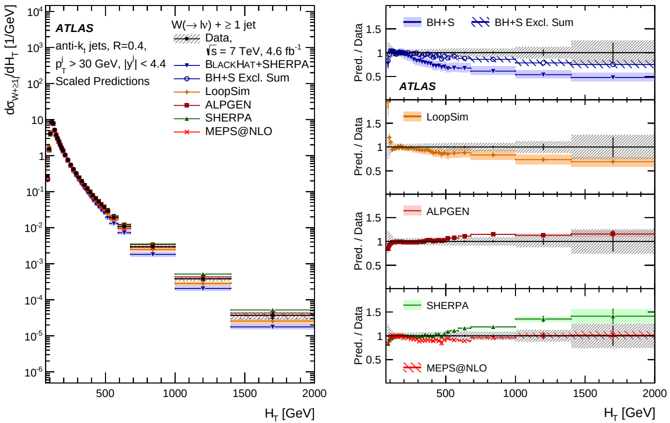
CMS arXiv:1406.7533 [hep-ex]



- CMS has performed a full study of $W^{\pm}$ production in association with jets
- Several theory predictions compared with data
- NLO QCD results produced directly employing BH NTuples (including small non perturbative corrections)
- Similar study by ATLAS on arXiv:1409.8639 [hep-ex]
- Also similar studies performed with Z bosons

LHC Measurements of $W + n$ Jets Production

ATLAS arXiv:1409.8639 [hep-ex]



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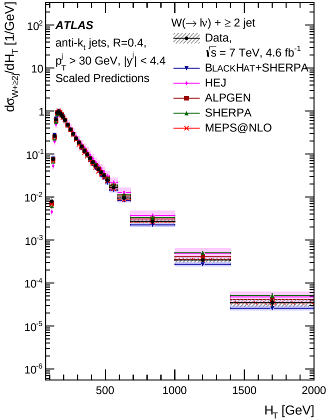

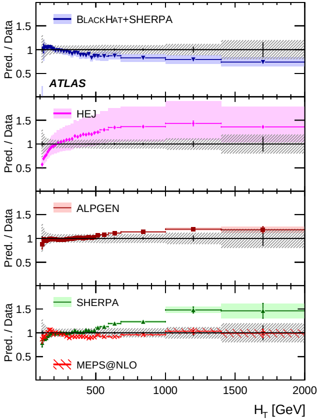

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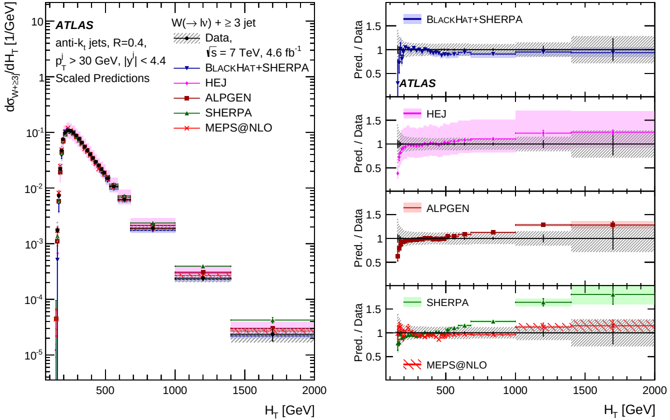

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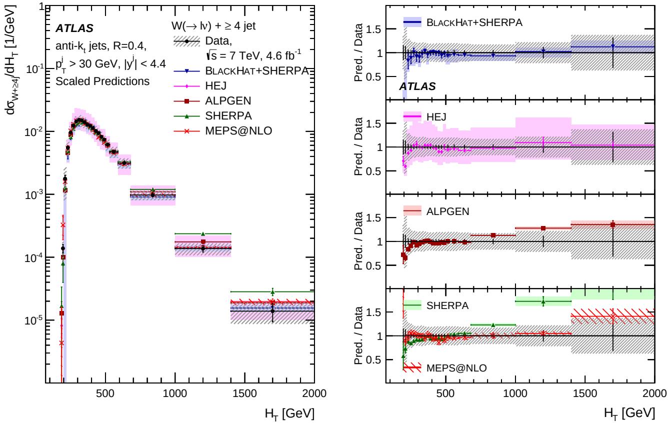

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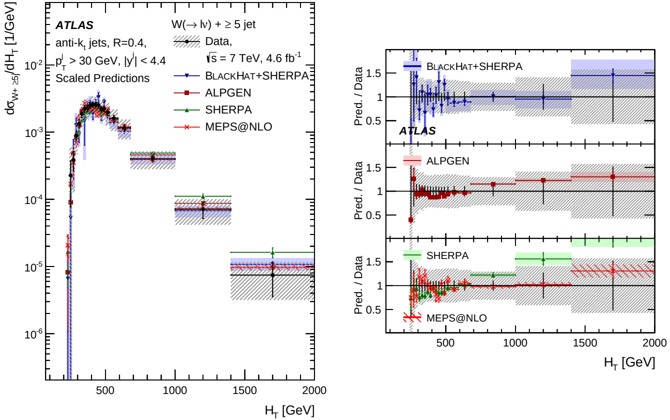

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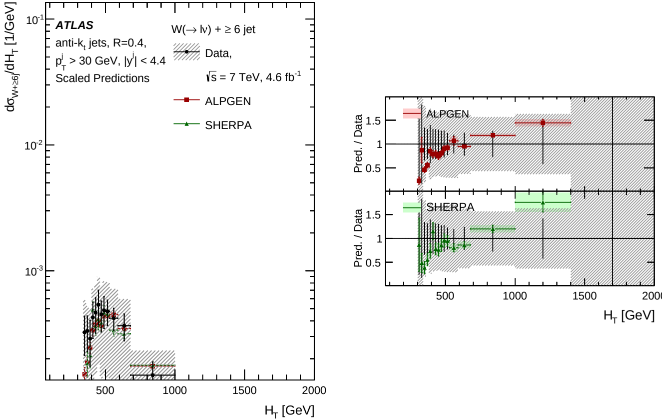
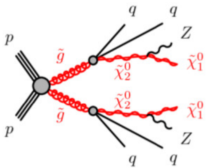


Studying High Multiplicity Processes

- High multiplicity processes allow to test our understanding of QCD in a complex multi-scale environment
- Combination of vector bosons and jets mix all ingredients of the SM
- Many escenarios of physics BSM predict excesses in related signatures



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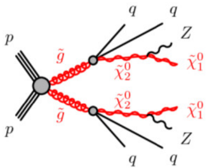

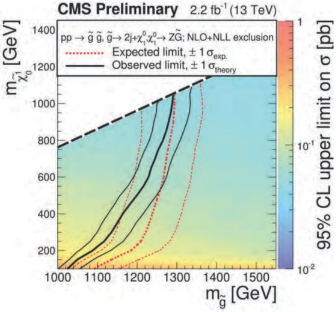

High Multiplicity NLO QCD Calculations

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

$W + 4$-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

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

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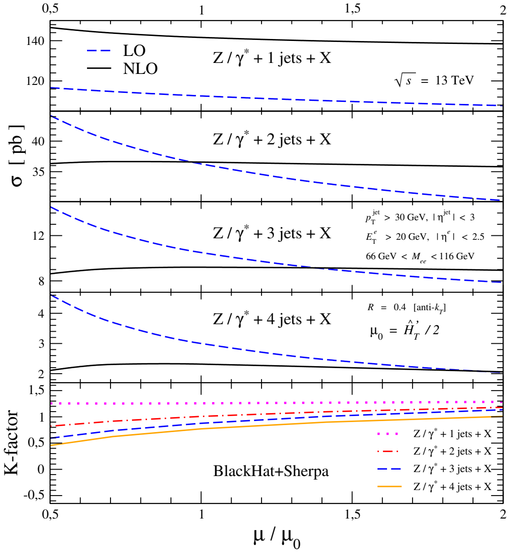
V+Jet Phenomenology at $\sqrt{s} = 13$ TeV

We employ a dynamical scale $\mu = \mu_r = \mu_f = \hat{H}'_{\mathrm{T}}/2$ and the CT14 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:

- $p_{\mathrm{T}}^{l} > 20$ GeV
- $|\eta^l| < 2.5$
- W: $\not{E}_{\mathrm{T}} > 30$ GeV, $M_{\mathrm{T}}^{W} > 20$ GeV
- Z: $66 \text{ GeV} < M_{ll} < 116 \text{ GeV}$

- Jets defined with anti-k_{T} algorithm
- $R = 0.4$
- $p_{\mathrm{T}}^{jet} > 30$ GeV
- $|\eta^{jet}| < 3$

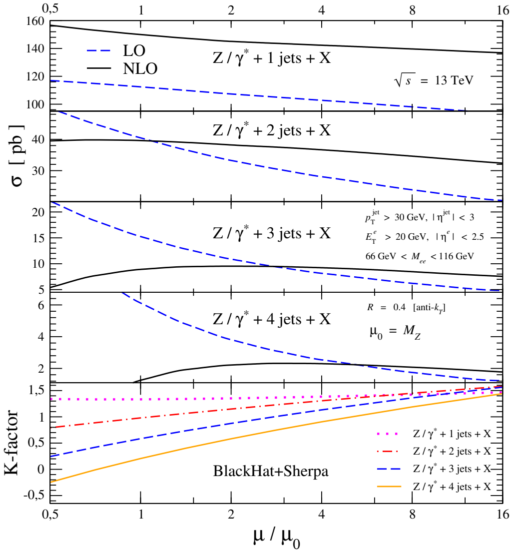
Scale Sensitivity for Z-Jet Production: *Dynamical*



- Total cross sections as function of unphysical scales
- $\mu = \mu_r = \mu_f = \hat{H}'_{\mathrm{T}}/2$
- Dynamical scale appears as natural
- Small scale sensitivity at NLO
- Large multiplicity needs NLO

PRELIMINARY

Scale Sensitivity for Z-Jet Production: *Fixed*



- Total cross sections as function of unphysical scales
- $\mu = \mu_r = \mu_f = M_Z$
- Larger multiplicities tend to prefer larger scales
- Nevertheless, NLO stable in large range of scales

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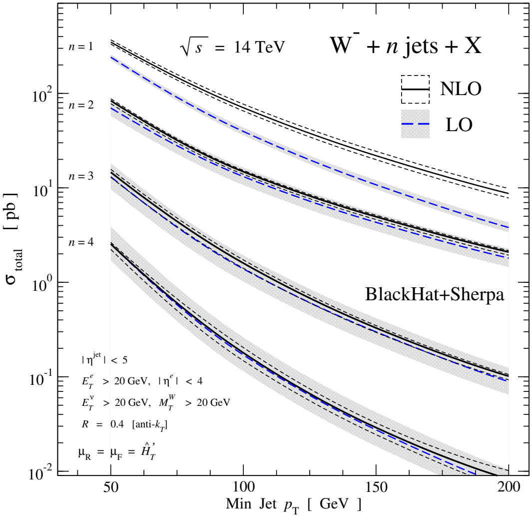
Stability of Predictions ($\sqrt{s} = 14$ TeV)



- Total cross sections as function of minimum Jet p_T
- Well behaved perturbative series for large multiplicities
- $\hat{H}_T'$ is a good choice in many different kinematical regimes

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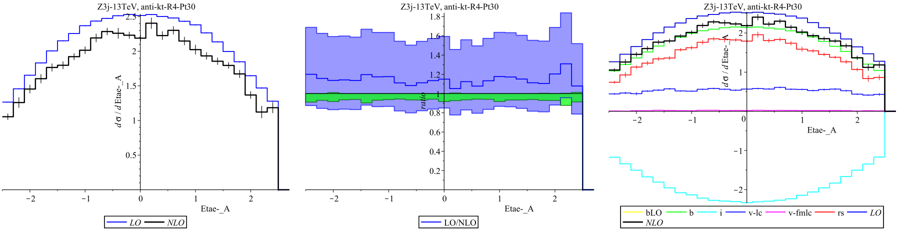
Dissecting NLO: An Example



- NLO predictions build of many pieces
- Typical scale sensitivity at LO $30-60\%$, at NLO $10-20\%$
- Subleading color pieces below 1% (with Ita and Ozeren decomposition [arXiv:1111.4193])
- Computer intensive, but full results stored in NTuple files
- Ntuple sizes around $100, 400, 800$ TB for $V+3,4,5$ jets

Total Cross Section at $\sqrt{s} = 13$ TeV for W^-+Jets

(in pb)

	$W^- + n$ jets			
n	LO	NLO	K factor	PDF err
1	$446.68(22)^{+17.48}_{-20.29}$	$582.0(1.1)^{+25.6}_{-18.6}$	$1.3030(25)$	1.52%
2	$141.67(14)^{+31.89}_{-24.67}$	$144.51(51)^{+1.04}_{-5.48}$	$1.0200(38)$	1.43%
3	$39.029(55)^{+15.653}_{-10.448}$	$34.35(23)^{+0.00}_{-2.07}$	$0.8801(61)$	1.37%
4	$10.513(23)^{+6.035}_{-3.585}$	$8.26(22)^{+0.00}_{-0.88}$	$0.786(21)$	1.61%

- Mild K factors, with LO predicting larger rates
- PDF uncertainties very small at around 1.5%

PRELIMINARY

Total Cross Section at $\sqrt{s} = 13$ TeV for W^++Jets

(in pb)

	$W^+ + n$ jets		
n	LO	NLO	K factor
1	$588.49(33)^{+23.77}_{-27.06}$	$759.9(5.7)^{+37.3}_{-26.6}$	$1.2913(97)$
2	$197.23(27)^{+44.64}_{-34.42}$	$197.33(91)^{+1.72}_{-7.70}$	$1.0005(48)$
3	$57.07(10)^{+22.82}_{-15.23}$	$50.48(70)^{+0.00}_{-2.96}$	$0.885(12)$
4	$16.408(50)^{+9.344}_{-5.566}$	$12.25(53)^{+0.00}_{-1.36}$	$0.746(32)$

- W^+ rates larger, due to charge assymetry. Ratios to W^- stable and around 1.4
- Work in progress to add $n = 5$ case

PRELIMINARY

Total Cross Section at $\sqrt{s} = 13$ TeV for Z+Jets

(in pb)

n	$Z+n$ jets LO	NLO	K factor
1	$112.264(60)^{+4.121}_{-4.876}$	$142.79(15)^{+5.12}_{-3.70}$	$1.2719(15)$
2	$36.140(38)^{+7.931}_{-6.178}$	$36.790(93)^{+0.226}_{-1.336}$	$1.0180(28)$
3	$10.4844(76)^{+4.1227}_{-2.7703}$	$9.212(61)^{+0.000}_{-0.561}$	$0.8786(59)$
4	$2.9597(37)^{+1.6698}_{-0.9989}$	$2.326(47)^{+0.000}_{-0.243}$	$0.786(16)$

- Similar trends as for $W^\pm$
- More detailed studies will follow

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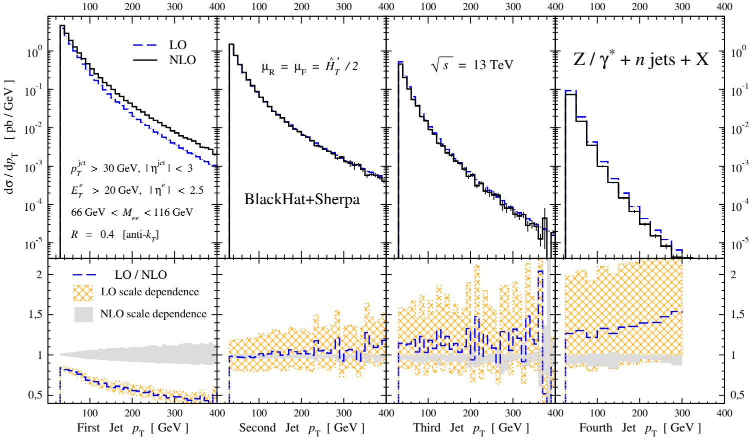
Jet p_T in $Z + n$ Jets at $\sqrt{s} = 13$ TeV

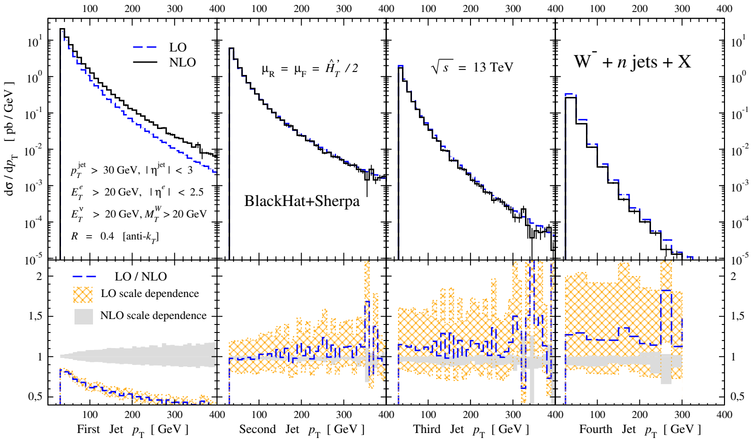


- Prediction for Jet p_T spectra in inclusive Z production at $\sqrt{s} = 13$ TeV
- Residual scale dependence at NLO minimal, even below 10%. Need for a better estimation of uncertainty?

- First Jet p_T spectrum suffers from large correntions
- Now NNLO QCD results available!

PRELIMINARY

Jet p_T in $W^- + n$ Jets at $\sqrt{s} = 13$ TeV

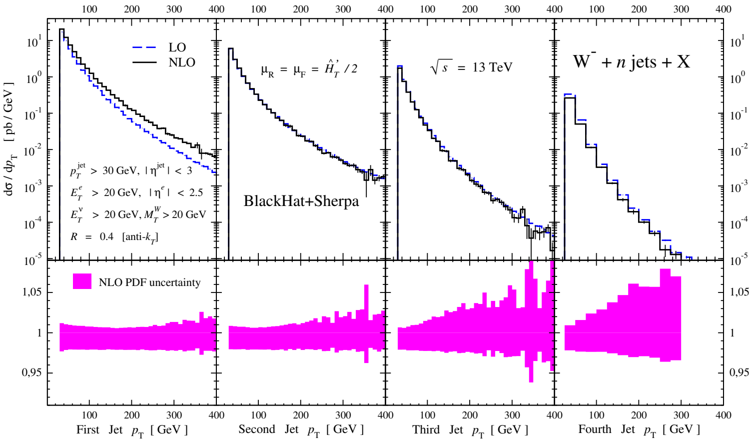


- Prediction for Jet p_T spectra in inclusive W^- production at 13 TeV
- Scale uncertainty? What about PDF errors?

- First Jet p_T spectrum suffers from large correntions
- Now NNLO QCD results available!

PRELIMINARY

Jet p_T with PDF Uncertainty



- PDF uncertainties marginal, at around $1-5\%$ in the shown regimes
- Testing wide range of x

- Marginal increase for harder jet p_{T}
- Marked increase for softer jet p_{T}

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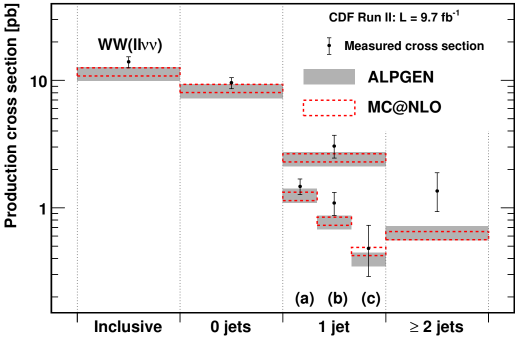
W^+W^- with many jets, Cross sections, Radiation gap

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

QCD 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, 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.*

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

W^+W^-+Jet Phenomenology

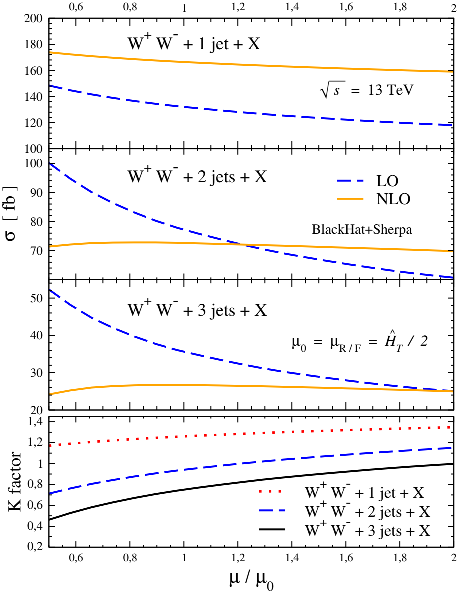
We employ a dynamical scale $\mu = \mu_r = \mu_f = \hat{H}_\mathrm{T}/2$ and the MSTW2008 set of PDFs. We take the α_s provided by the PDF sets and employ $M_W = 80.399$ GeV, $M_Z = 91.188$ GeV, $\Gamma_W = 2.085$ GeV and $\Gamma_Z = 2.4952$ GeV. We employ the following kinematical cuts:

- $p_\mathrm{T}^{e,\mu} > 20$ GeV
- $|\eta^{e,\mu}| < 2.4$
- $\not{E}_\mathrm{T} > 30$ GeV
- $p_\mathrm{T}^{e\mu} > 30$ GeV
- $m_{e\mu} > 10$ GeV

- Jets defined with anti-k_T algorithm
- $R = 0.4$
- $p_\mathrm{T}^{jet} > 30$ 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 $\sqrt{s} = 8$ 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	$142.2(3)^{+3.7}_{-5.3}$	$207.4(7)^{+5.1}_{-3.3}$	—	—
1	$60.9(1)^{+9.8}_{-8.0}$	$76.0(2)^{+3.6}_{-3.9}$	$0.428(1)$	$0.366(2)$
2	$29.43(6)^{+9.99}_{-6.91}$	$28.5(1)^{+0.4}_{-1.8}$	$0.483(1)$	$0.376(2)$
3	$11.11(2)^{+5.73}_{-3.51}$	$9.05(12)^{+0.08}_{-0.90}$	$0.378(1)$	$0.317(5)$
4	$3.58(1)^{+2.49}_{-1.37}$	—	$0.322(1)$	—

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

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

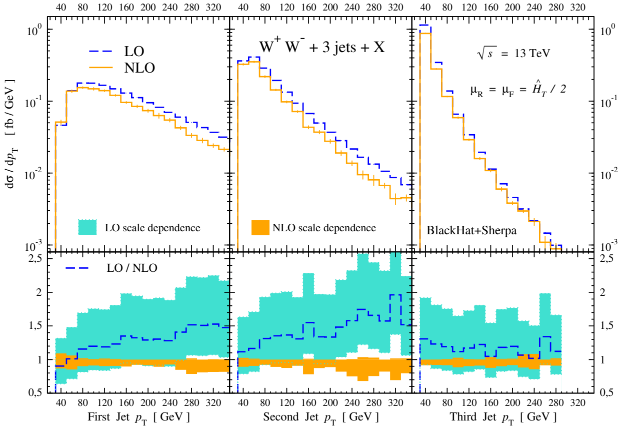
(in fb)

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	$14.12(8)^{+9.05}_{-5.14}$	—	$0.397(2)$	—

- The increase of cross sections grows with jet multiplicity
- Ratios increase, as more energy available for radiation
- Need to explore jet ratios behavior in more detail

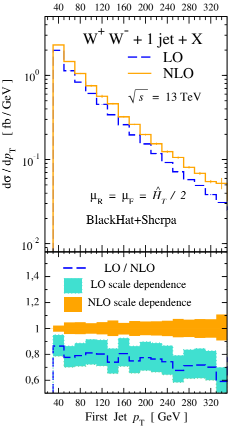
Jet p_{T} Spectra



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

Jet p_{T} Spectra



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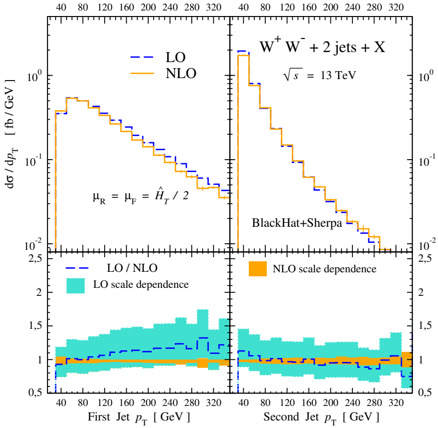

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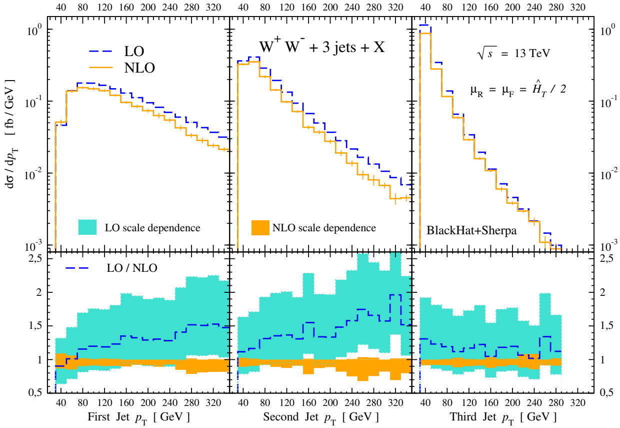

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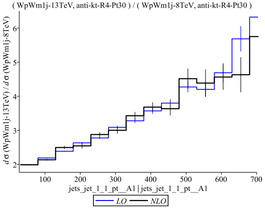
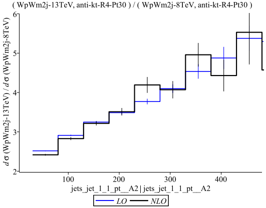
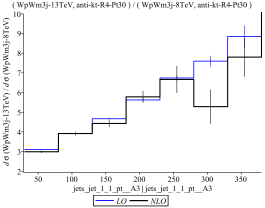
- Scale bands considerably reduced over phase space
- Similarities in corrections for different (large) multiplicities
- Similar trends to what is observed in NLO QCD corrections to V+Jets

E_{CM} Energy Ratios

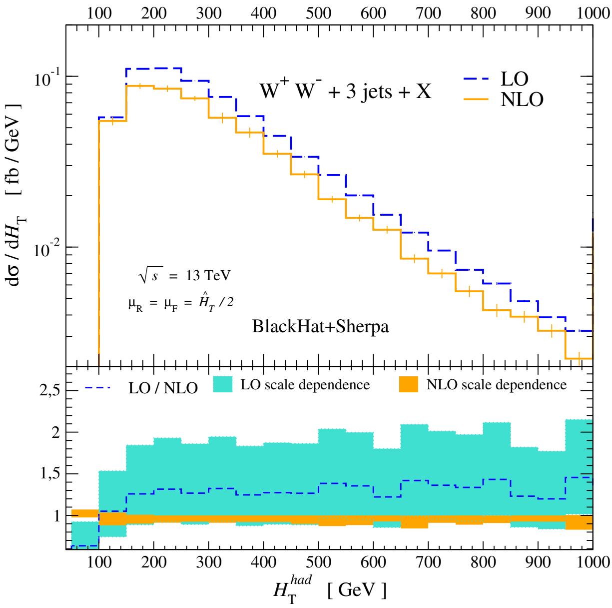






- Ratios for n^{th}-jet p_{T} for $(W^+W^- + X)$@ 13 TeV to $(W^+W^- + X)$@ 8 TeV
- Stable to quantum corrections
- Larger increase for softer jet

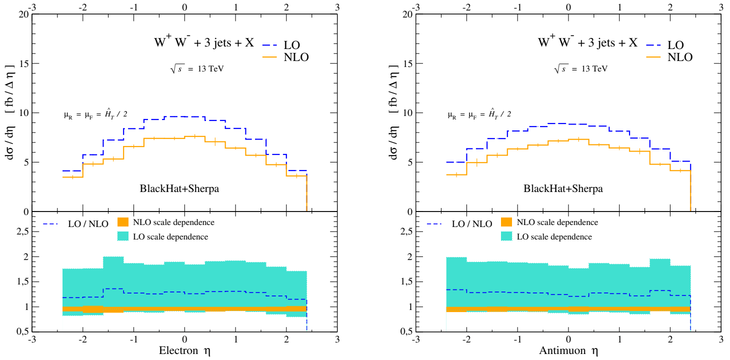
Hadronic Transverse Energy



arXiv:1512.07591 [hep-ph]

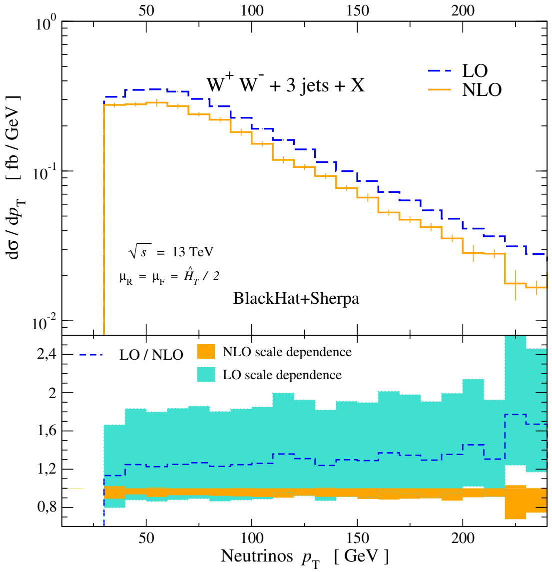
- Sum of transverse energy of jets
- Important for BSM searches
- The dynamical scale choosen appears as natural
- Considerable reduction of scale sensitivity

Lepton Rapidities



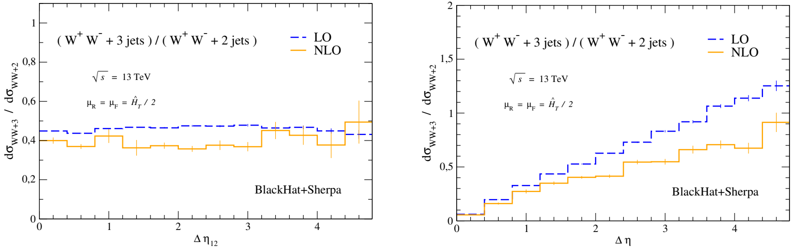
- Lepton η distributions shapes not affected by corrections
- Very similar distributions (both leptons are treated massless)
- Considerable reduction of scale sensitivity

Missing Transverse Energy



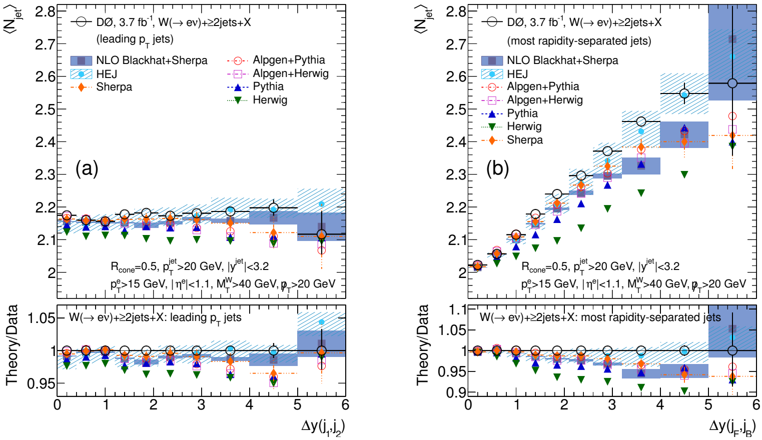
- Neutrinos scape detector, and produce $\not{E}_{\mathrm{T}}$
- Important observable for BSM searches
- Experimental analyses favor $\not{E}_{\mathrm{T}}^{\mathrm{rel}}$, to avoid instrumental backgrounds

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 $p_{\rm T}$ ordered and right are η ordered (forward-backward)
- Noticeable reduction for large $\Delta\eta$ when η ordered

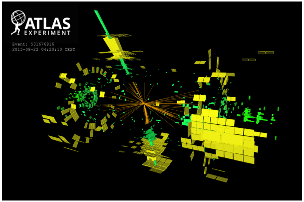
Radiation Gap at D0 in W+Jets



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

Outlook

- Robust tools exist now to compute NLO QCD corrections to high multiplicity processes
- Fixed order results give valuable predictions to gain confidence on complex signatures (though they are limited, of course)
- Important to explore ways for estimate theoretical uncertainties
- In the future we hope to extend calculations with BlackHat+Sherpa to other diboson combinations, as well as other processes



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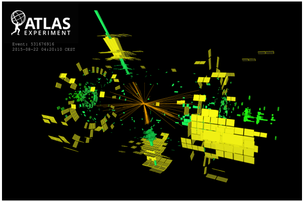

Thanks!