Divector Boson Production in Association with Jets at the LHC

W^+W^-+Jets at NLO QCD with BlackHat+Sherpa

Fernando Febres Cordero
Department of Physics, University of Freiburg

Theory Seminar, DESY, Zeuthen

September 2015

With Philipp Hofmann and Harald Ita [to appear]

ALBERT-LUDWIGS-
UNIVERSITÄT FREIBURG

Alexander von Humboldt
Stiftung/Foundation

Outline

MOTIVATION

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

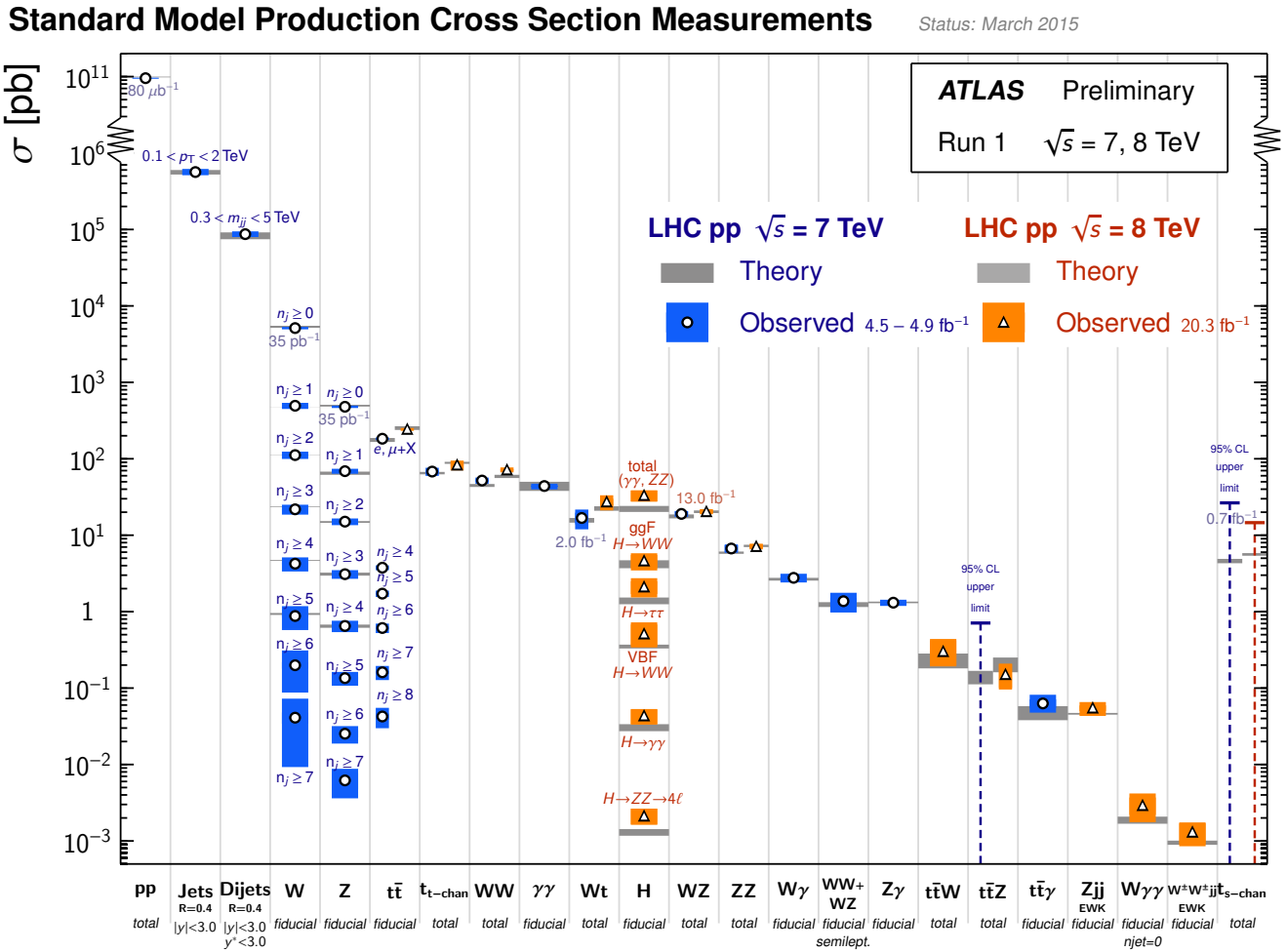
NLO QCD WITH BlackHat+Sherpa

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

CORRECTIONS TO $W^+W^- + 3$ JETS

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

SM Cross Sections at ATLAS

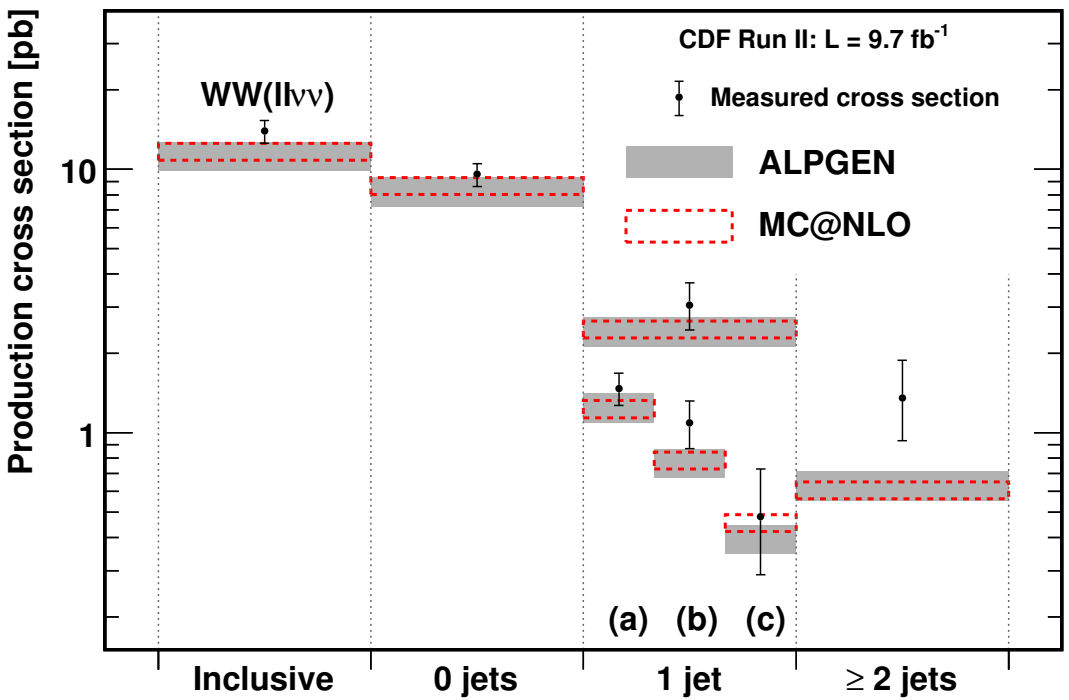


- Summary plot of SM cross sections
- Impressive agreement between theory and experiment
- Di-vector boson measurements
- Jet towers to deeply test QCD
- Smallest cross section from $W^{\pm}W^{\pm} + 2$ jets
- Similar results from CMS

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

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

Outline

MOTIVATION

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

NLO QCD WITH BlackHat+Sherpa

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

CORRECTIONS TO $W^+W^- + 3$ JETS

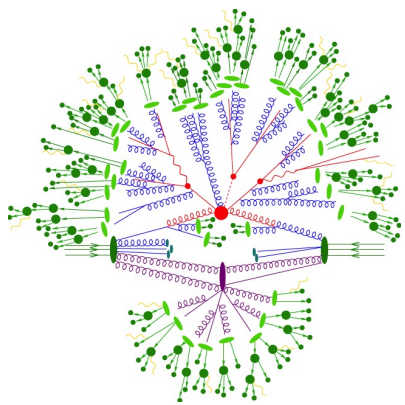
Scale sensitivity, Jet bins, Total/diff cross sections, Radiation gap

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

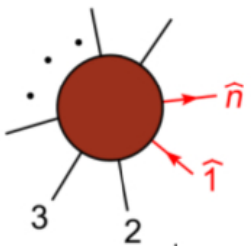
Trees from On-Shell Information

[Britto, Cachazo, Feng, Witten, hep-th/0501052]

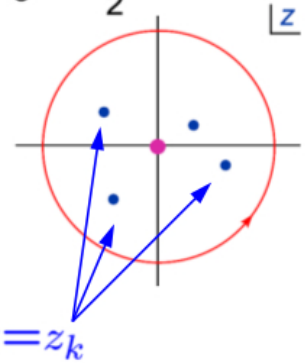
Introduce complex momentum at leg 1, remove it at leg *n*.

$$k_1(z) + k_n(z) = k_1 + k_n$$
$$k_1^2(z) = k_n^2(z) = 0$$

$$\Rightarrow \quad A(0) \rightarrow A(z)$$



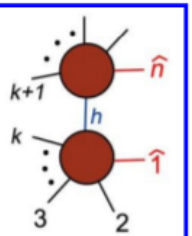
special limits $\Leftrightarrow$ poles in *z*



Cauchy: If $A(\infty) = 0$ then

$$0 = \frac{1}{2\pi i}\oint dz\,\frac{A(z)}{z} = A(0) + \sum_k \text{Res}\left[\frac{A(z)}{z}\right]\Big|_{z=z_k}$$

residue at z_k = [k^{th} factorization limit] =

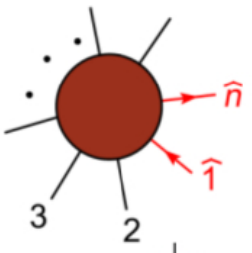


Trees from On-Shell Information

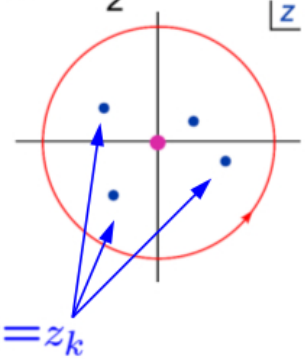
[Britto, Cachazo, Feng, Witten, hep-th/0501052]

Introduce complex momentum at leg 1, remove it at leg *n*.

$$k_1(z) + k_n(z) = k_1 + k_n$$
$$k_1^2(z) = k_n^2(z) = 0$$
$$\Rightarrow \quad A(0) \rightarrow A(z)$$



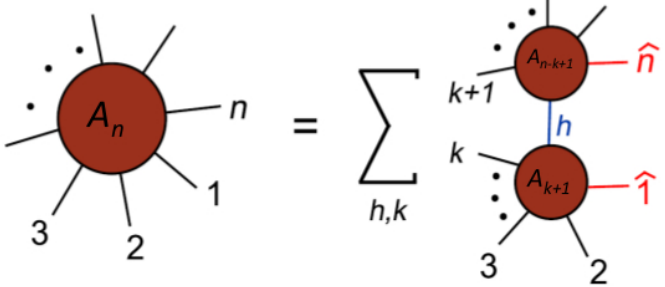
special limits $\Leftrightarrow$ poles in *z*



Cauchy: If $A(\infty) = 0$ then

$$0 = \frac{1}{2\pi i}\oint dz\,\frac{A(z)}{z} = A(0) + \sum_k \text{Res}\left[\frac{A(z)}{z}\right]\Big|_{z=z_k}$$

On-shell Recursion



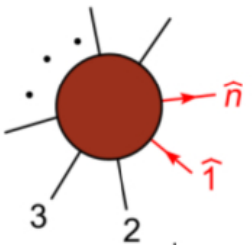
Trees from On-Shell Information

[Britto, Cachazo, Feng, Witten, hep-th/0501052]

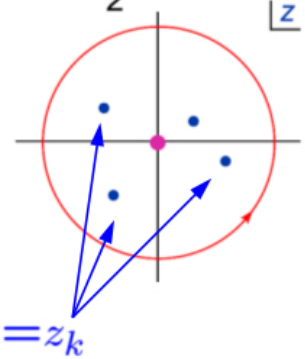
Introduce complex momentum at leg 1, remove it at leg *n*.

$$k_1(z) + k_n(z) = k_1 + k_n$$
$$k_1^2(z) = k_n^2(z) = 0$$

$$\Rightarrow \quad A(0) \rightarrow A(z)$$



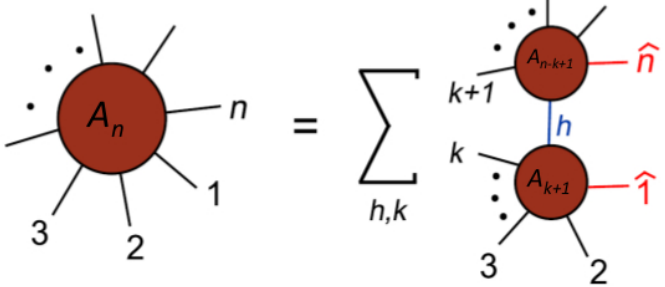
special limits $\Leftrightarrow$ poles in *z*



Cauchy: If $A(\infty) = 0$ then

$$0 = \frac{1}{2\pi i}\oint dz\,\frac{A(z)}{z} = A(0) + \sum_k \text{Res}\left[\frac{A(z)}{z}\right]\Big|_{z=z_k}$$

On-shell Recursion



Recursion: Amplitudes from amplitudes!

Scalar Integral Basis at One Loop

At one loop complex plane looks a bit messier: Appearance of branch cuts and un-physical poles. Nevertheless, we get a little help...

[See Bern, Dixon, Dunbar, Kosower, hep-ph/9212308]

All external momenta in *D=4*, loop momenta in *D=4-2ε* (dimensional regularization)

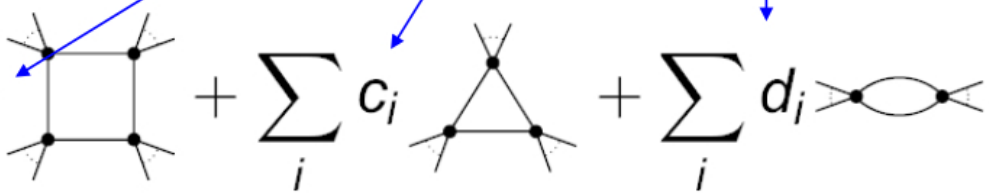
Rational part

Cut part

Process dependent D=4 rational integral coefficients

$$A = R + C$$

$$C = \sum_i b_i \; + \sum_i c_i \; + \sum_i d_i$$

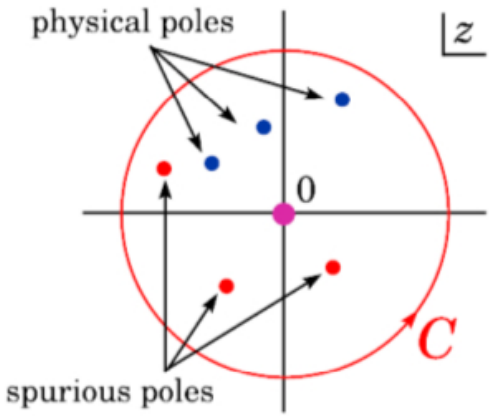


- Cut Part from unitarity cuts in 4 dimensions
- Rational part from recurrence relations or D-dim unitarity

We end up with an expression for the amplitude in terms of scalar integrals (known) and a series of coefficients and the rational part

Rational Terms

• If we subtract from the Amplitude the Cut part in 4-dim, the left over is a purely rational part
• In principle one can apply a BCFW approach to extract this piece recursively

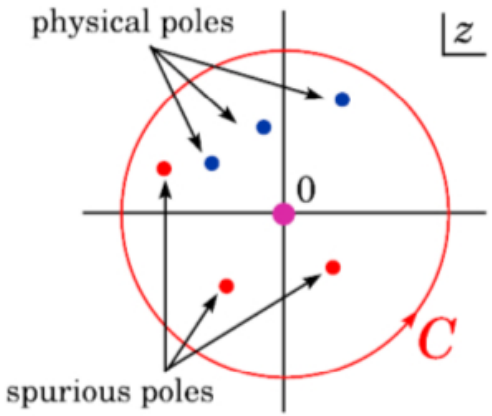


• But one finds that spurious (un-physical) poles appear, actually related to the integral basis
• They are related to Gram determinants
• These terms cancel actually against the Cut part (they are un-physical)
• Employing Taylor expansions of integrals around Gram determinants one indeed can extract the related poles

- BlackHat has implemented this recursive approach

Rational Terms

• If we subtract from the Amplitude the Cut part in 4-dim, the left over is a purely rational part
• In principle one can apply a BCFW approach to extract this piece recursively

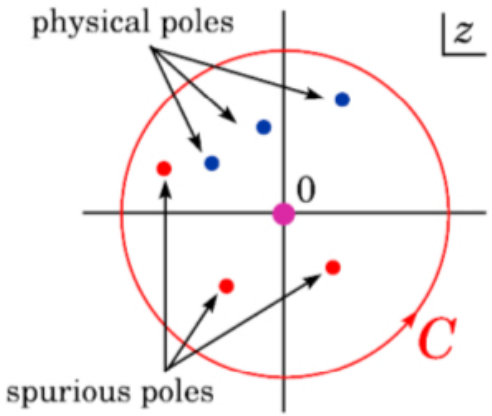


• But one finds that spurious (un-physical) poles appear, actually related to the integral basis
• They are related to Gram determinants
• These terms cancel actually against the Cut part (they are un-physical)
• Employing Taylor expansions of integrals around Gram determinants one indeed can extract the related poles

- BlackHat has implemented this recursive approach
- Alternatives include the OPP approach $R = R_1 + R_2$

Rational Terms

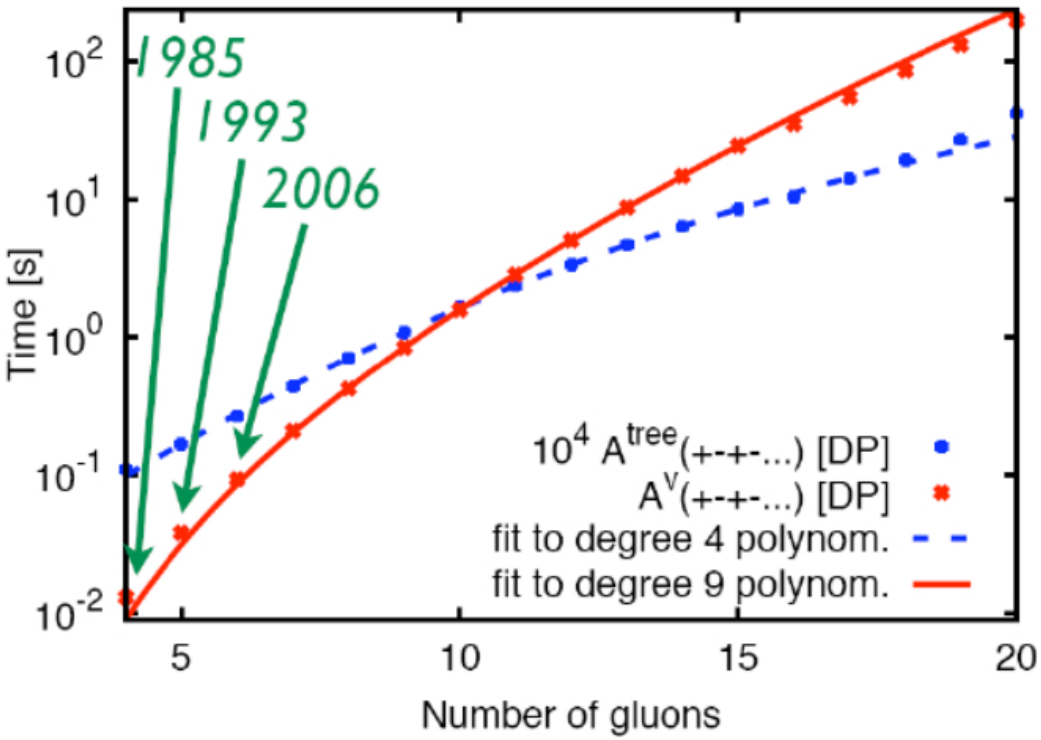
• If we subtract from the Amplitude the Cut part in 4-dim, the left over is a purely rational part
• In principle one can apply a BCFW approach to extract this piece recursively

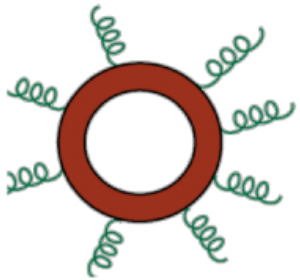


• But one finds that spurious (un-physical) poles appear, actually related to the integral basis
• They are related to Gram determinants
• These terms cancel actually against the Cut part (they are un-physical)
• Employing Taylor expansions of integrals around Gram determinants one indeed can extract the related poles

- BlackHat has implemented this recursive approach
- Alternatives include the OPP approach $R = R_1 + R_2$
- Also D-dim unitarity is employed. BlackHat has implemented a variant of Badger and Forde's approach

A Powerful Technique!





[Giele, Zanderighi arXiv:0806.2152]

BUT STILL VERY COMPUTER INTENSIVE **[BlackHat + Sherpa]**

NTUPLES: STORE AS MUCH INFO AS POSSIBLE DURING YOUR COMPUTATION!

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
  - $\gamma\gamma + 2$ jets

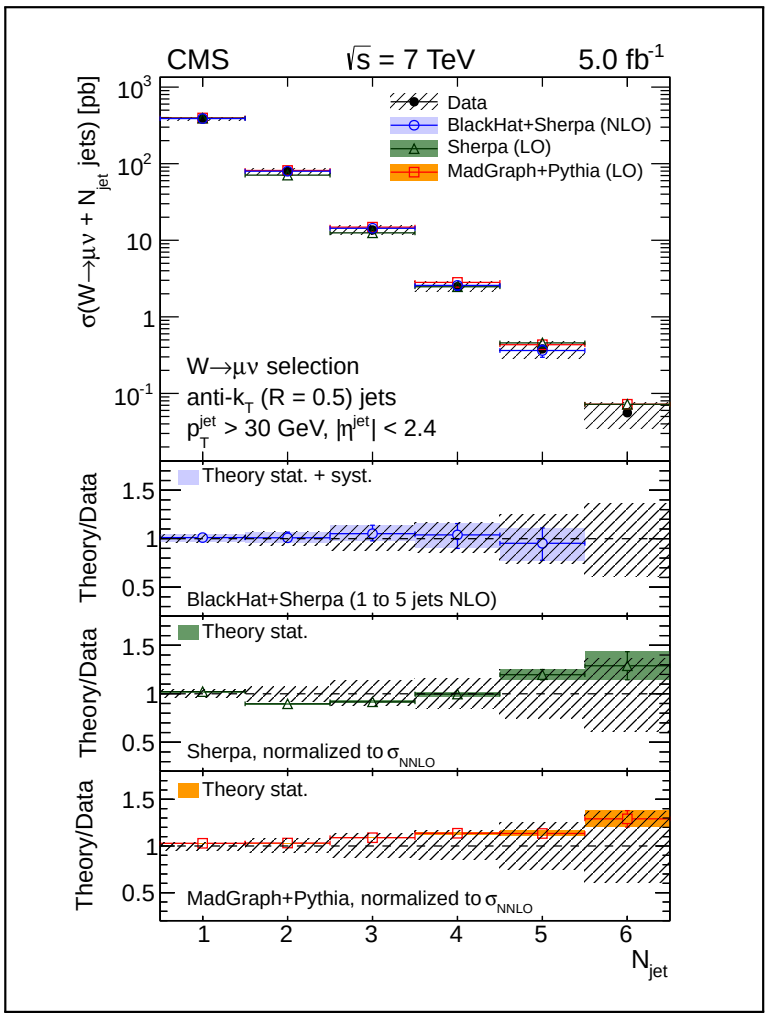
NTuples: Full Flexibility for NLO

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
  - $\gamma\gamma + 2$ jets
  - $W^+W^- + 0, 1, 2, 3$ jets $\rightarrow$ to appear!

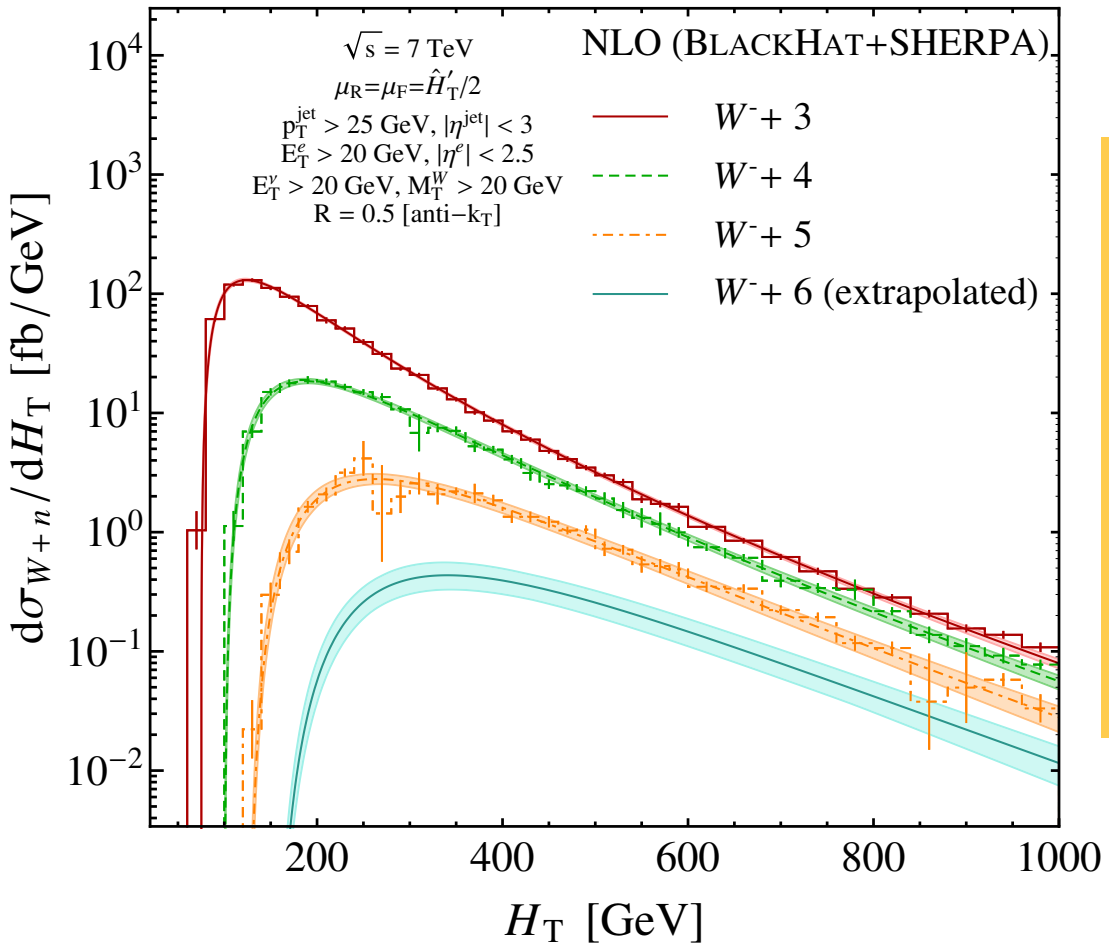
NLO at Work at the LHC

CMS arXiv:1406.7533 [hep-ex]



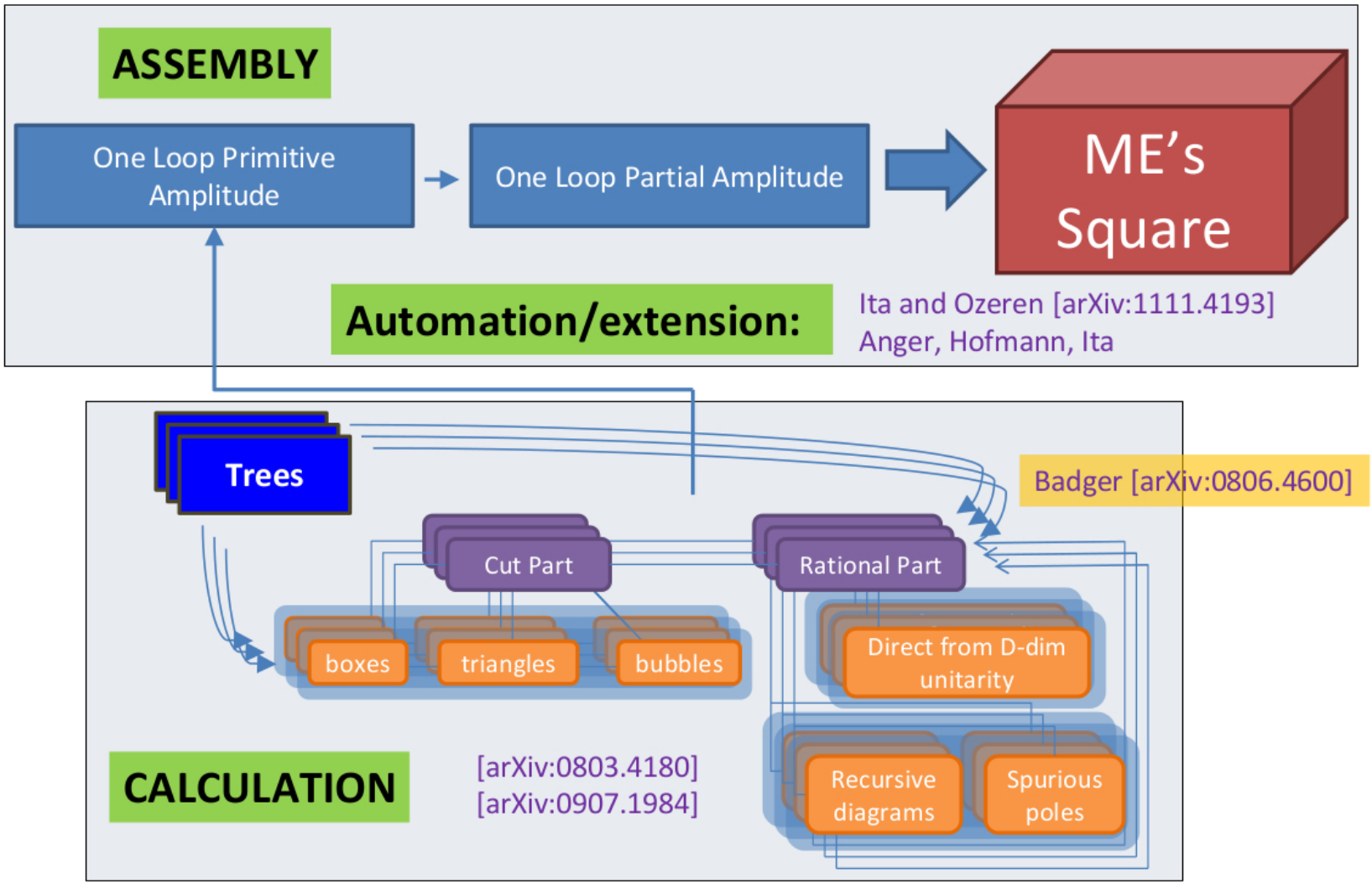
- CMS has performed a full study of $W^{\pm}$ production in association with jets
- Several theory predictions compared with data
- NLO QCD results produced directly employing BH NTuples (including small non perturbative corrections)
- Similar study by ATLAS on arXiv:1409.8639 [hep-ex]
- Also similar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

Exploring Very High Multiplicity Observables



- Fit ratios of distributions
- Extrapolate parameters of fit
- Fit lower multiplicity distribution
- There is good agreement between LO $W + 6$ result and extrapolated distribution

BlackHat in a Nutshell



New Developments in BlackHat

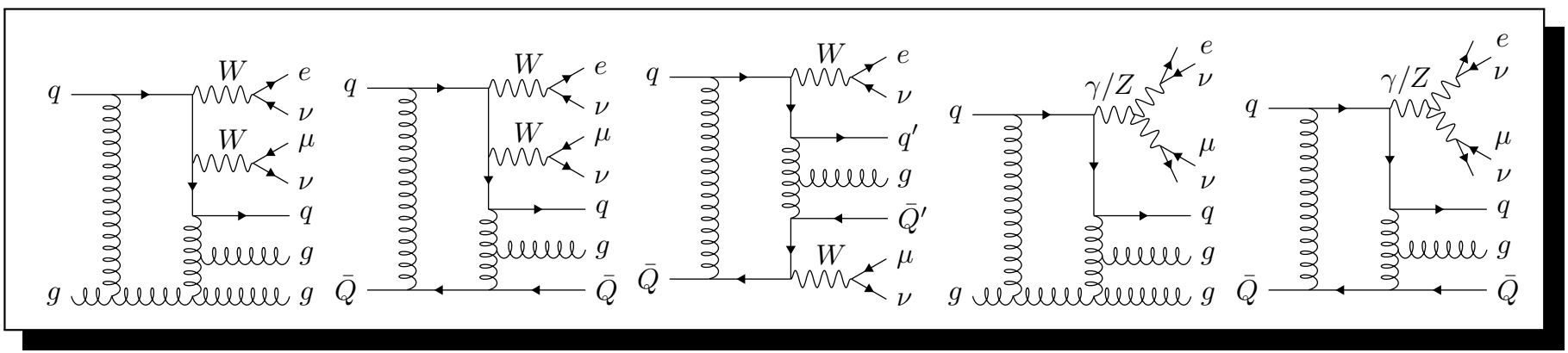
Produced NLO QCD results for V+3,4,5 Jets; 4 Jets; $\gamma\gamma$+2jets; Universality in jet ratios; Ntuples for NLO QCD

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

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 $\alpha_{\rm dipole}$ independence of the real corrections
- Fully integrated results for $W^+W^-+0, 1, 2$ jets being carried out employing Madgraph5_aMC@NLO

Outline

MOTIVATION

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

NLO QCD WITH BlackHat+Sherpa

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

CORRECTIONS TO $W^+W^- + 3$ JETS

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

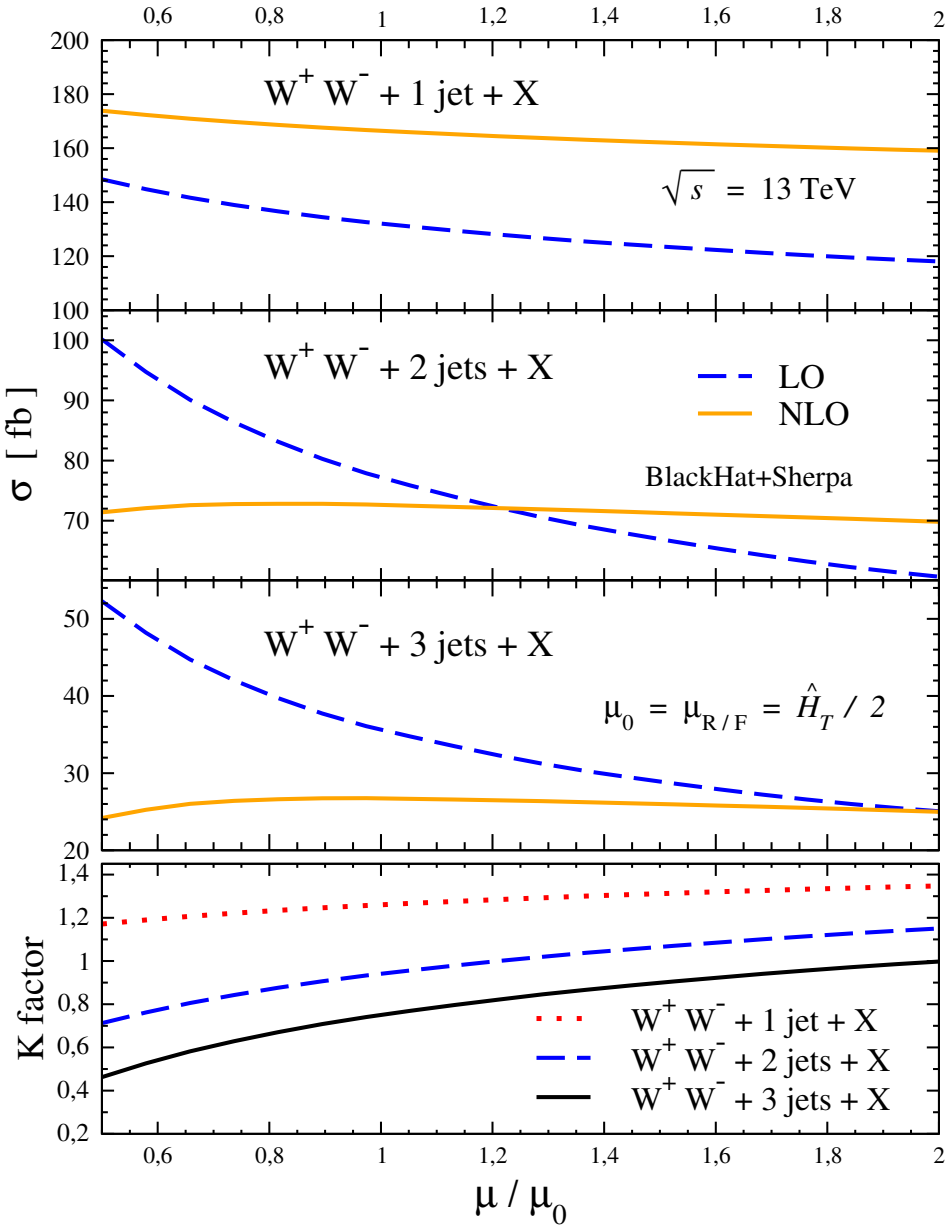
Phenomenology

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)
- 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		$(W^+W^- + n$ jet$)$ / $(W^+W^- + (n-1)$ 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

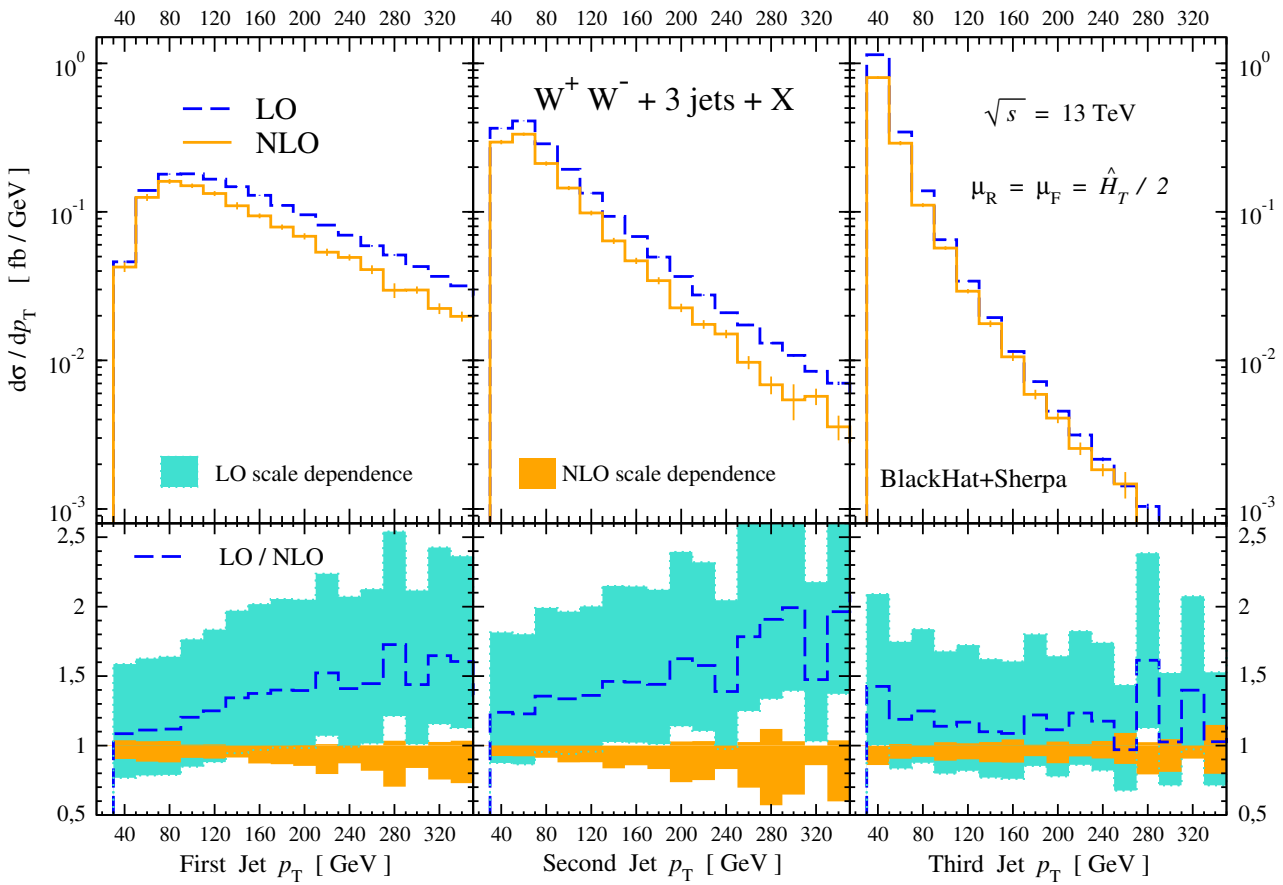
(in fb)

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	$77.2(2)^{+23.0}_{-16.5}$	$72.7(4)^{+0.1}_{-2.8}$	$0.585(2)$	$0.438(4)$
3	$35.62(7)^{+16.68}_{-10.56}$	$26.8(3)^{+0.0}_{-2.5}$	$0.462(2)$	$0.367(6)$
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

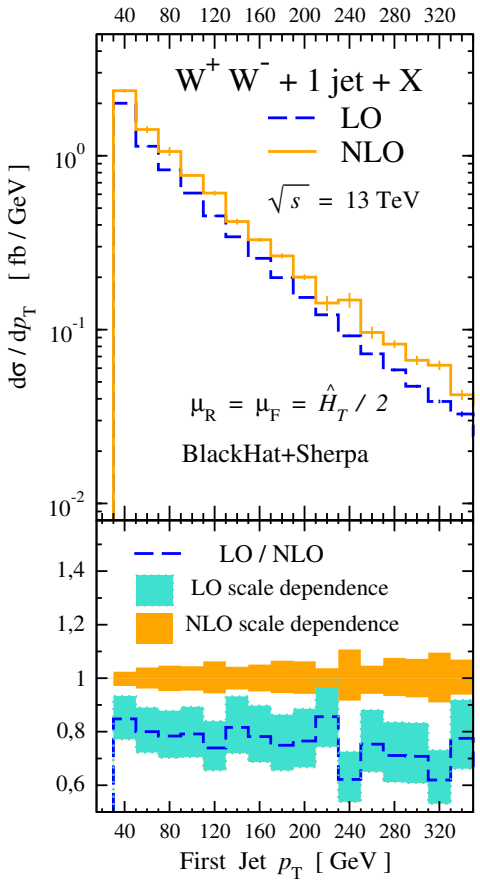
Jet p_{T} Spectra



- p_{T} distributions for softer jets fall more steeply
- Quantum corrections only shift softest jet p_{T} distribution
- 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

PRELIMINARY

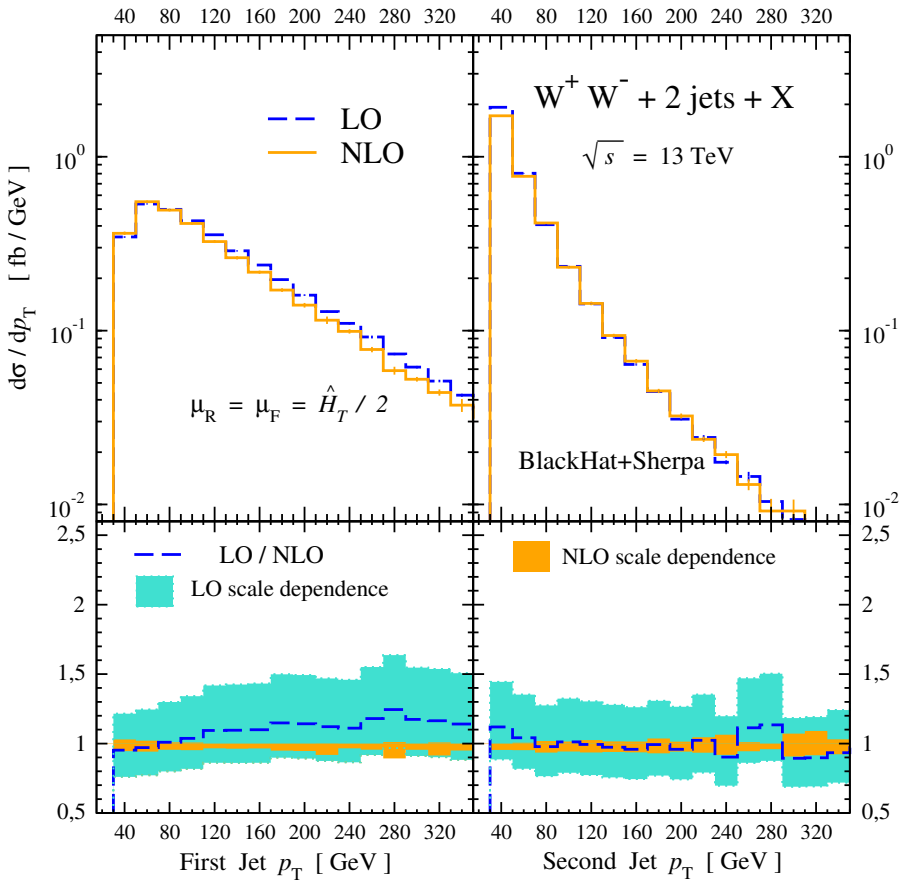
Jet p_{T} Spectra



- 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

PRELIMINARY

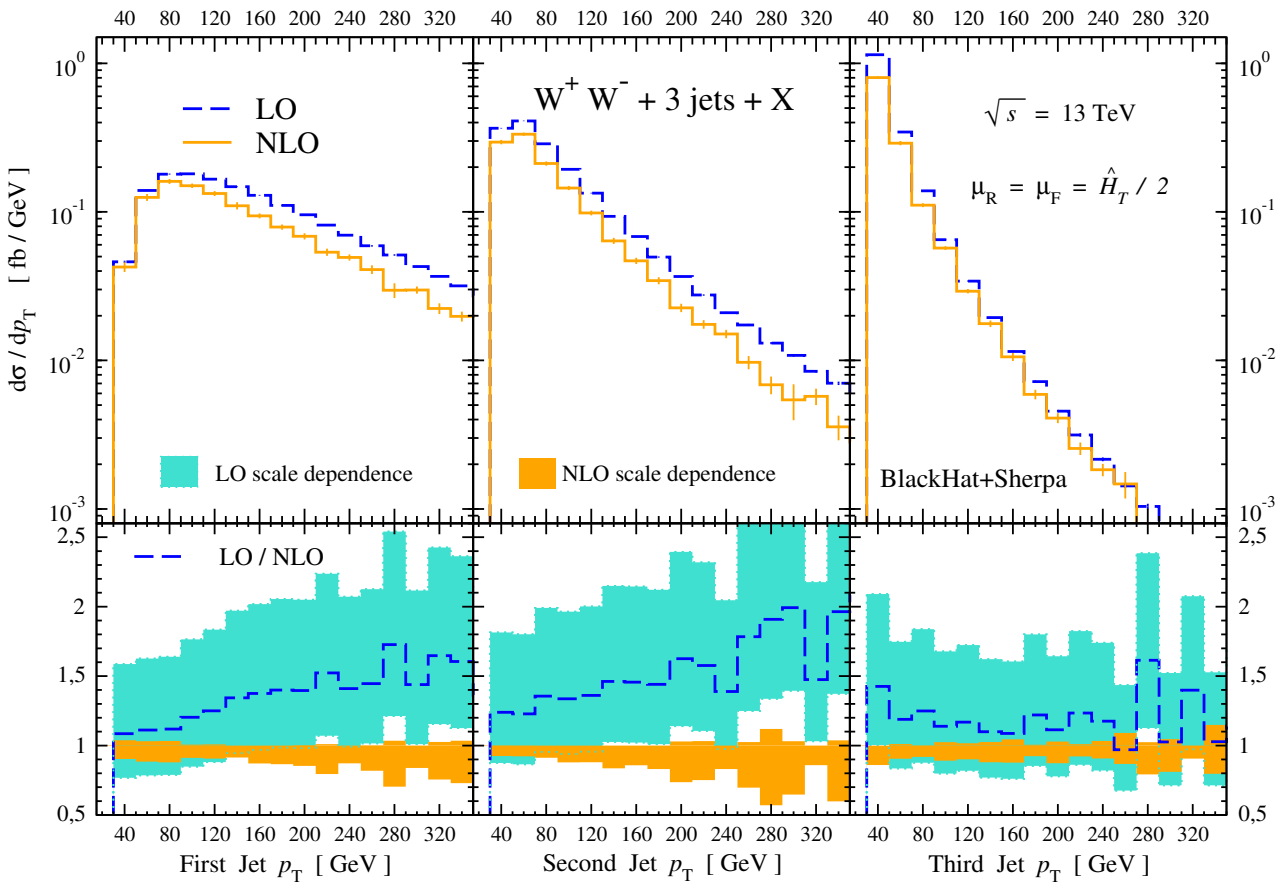
Jet p_{T} Spectra



- 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

PRELIMINARY

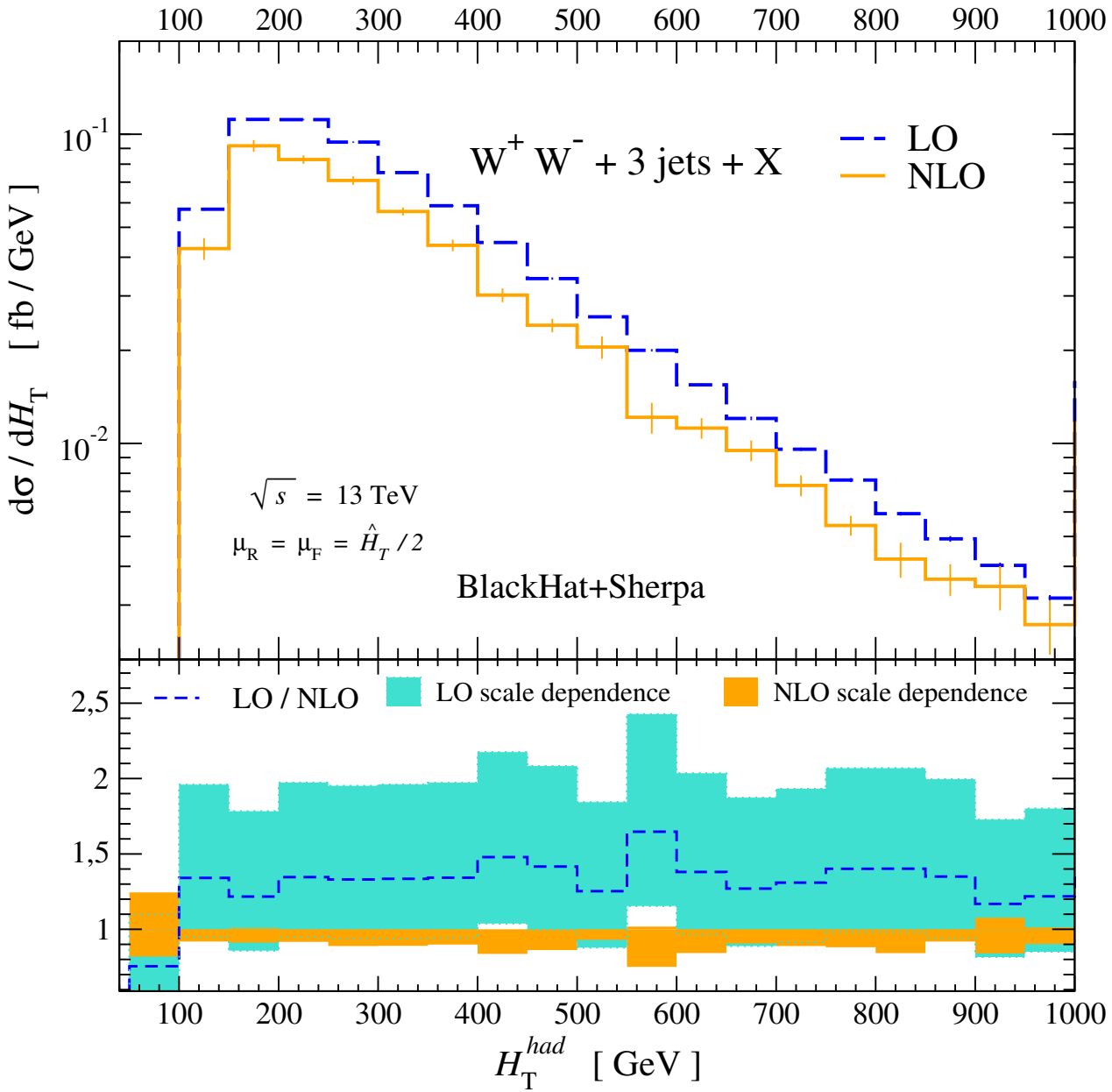
Jet p_{T} Spectra



- 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

PRELIMINARY

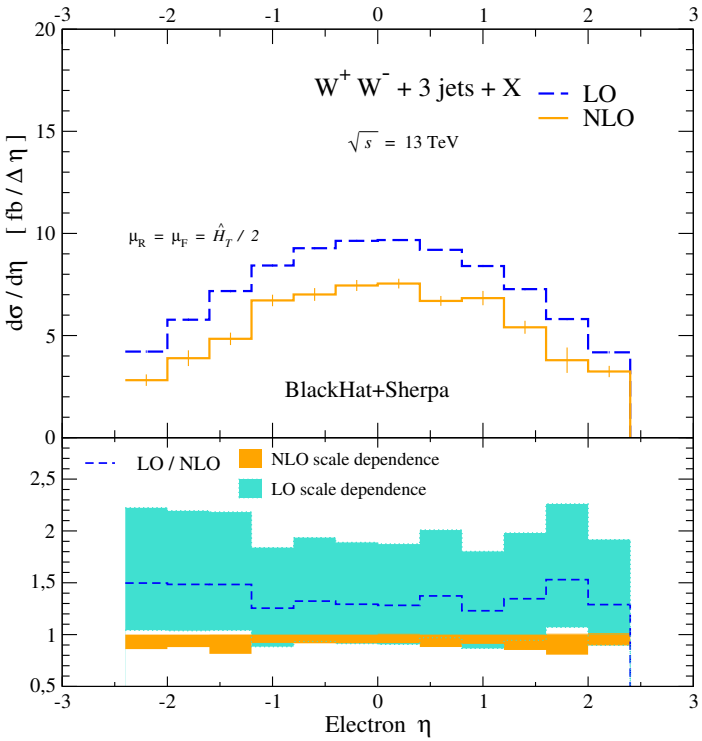
Hadronic Transverse Energy

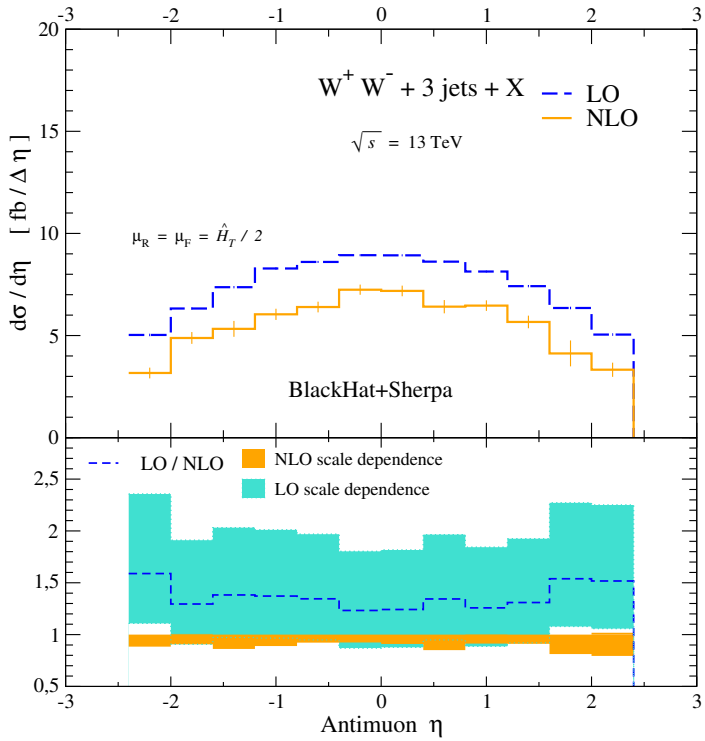


- Sum of transverse energy of jets
- Important for BSM searches
- The dynamical scale choosen appears as natural
- Considerable reduction of scale sensitivity

PRELIMINARY

Lepton Rapidities

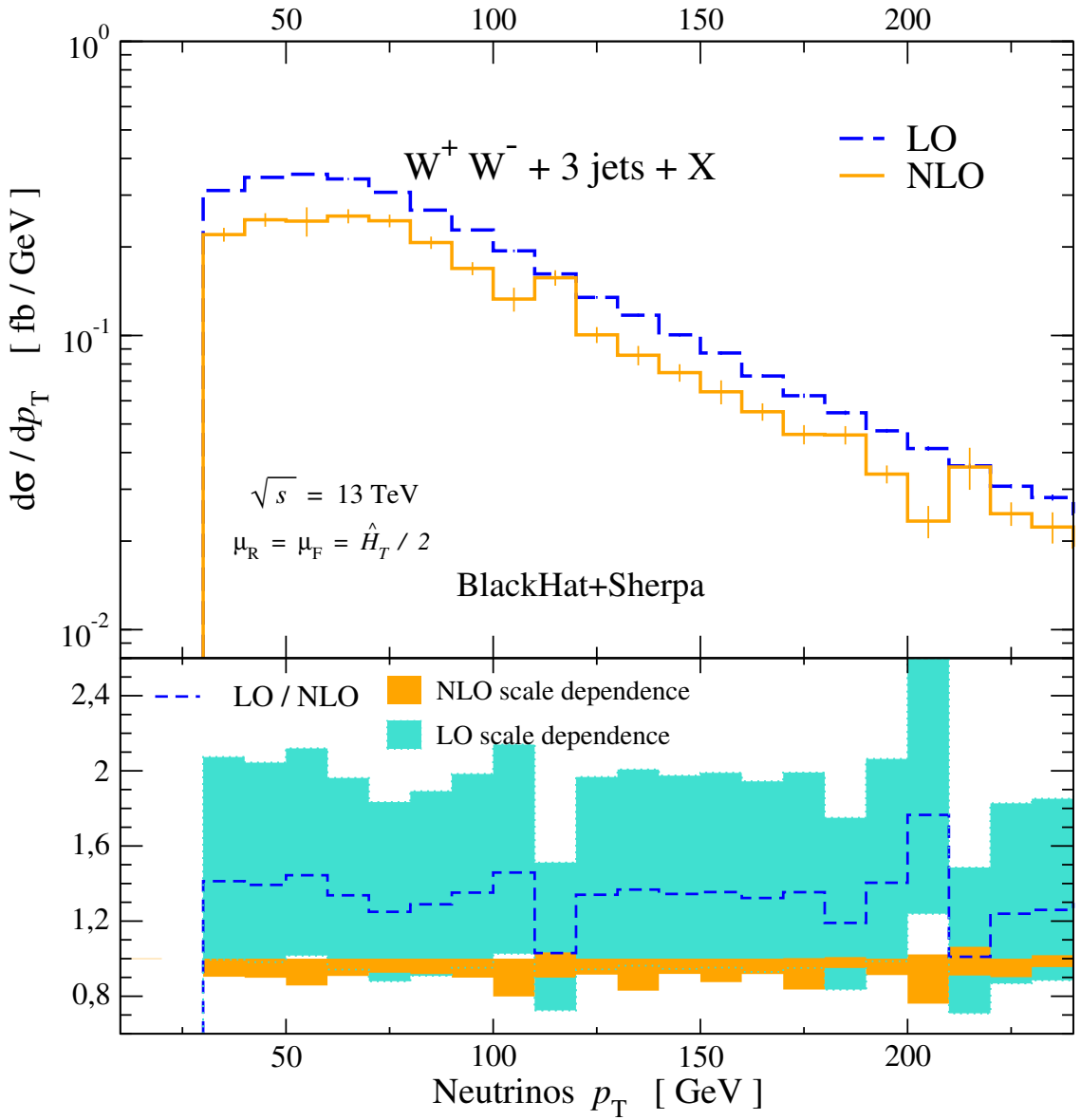




- Lepton η distributions shapes not affected by corrections
- Very similar distributions (both leptons are treated massless)
- Considerable reduction of scale sensitivity

PRELIMINARY

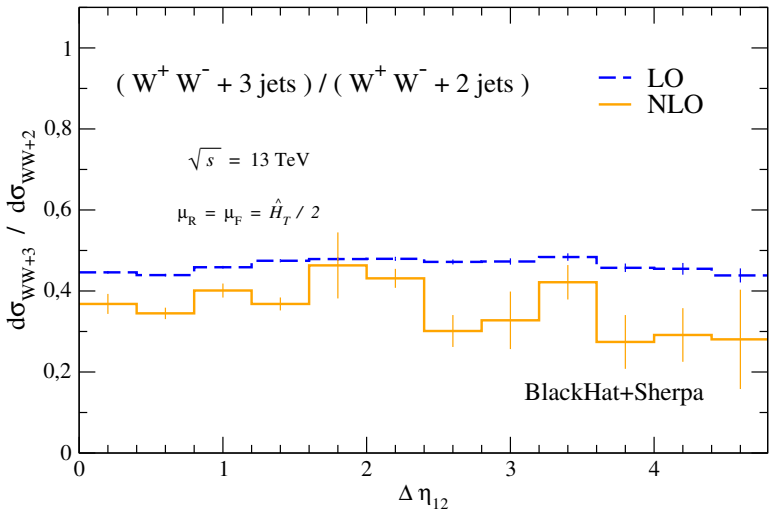
Missing Transverse Energy

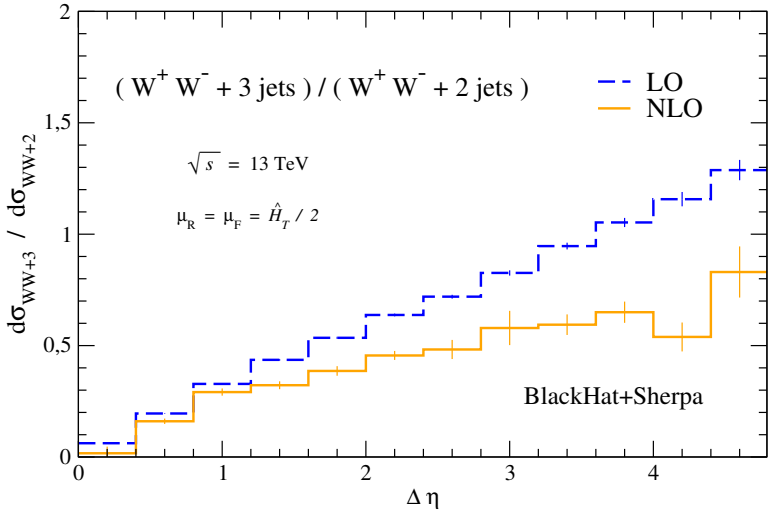


- Neutrinos scape detector, and produce $\not{E}_{\mathrm{T}}$
- Important observable for BSM searches
- Experimental analyses favor $\not{E}_{\mathrm{T}}^{\mathrm{rel}}$, to avoid instrumental backgrounds

PRELIMINARY

Radiation Gap



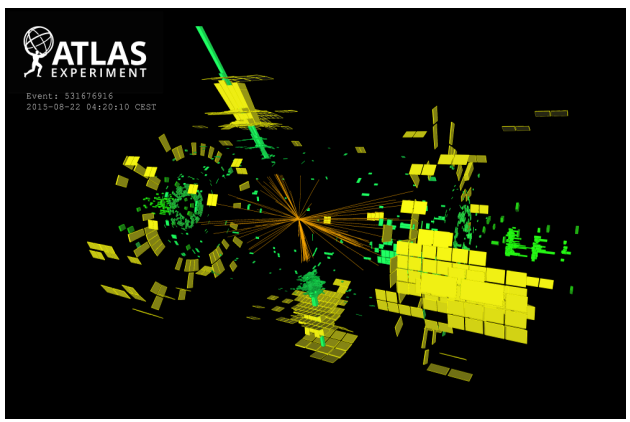


- A clear signature of VBF processes is a low rate of radiation in the gap between *tagging* forward and backward jets
- Background processes can have very different features
- A way to study this: look at ratios of $W^+W^- + 3$ Jets to $W^+W^- + 2$ Jets
- Left plot jets p_{T} ordered and right are η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

PRELIMINARY

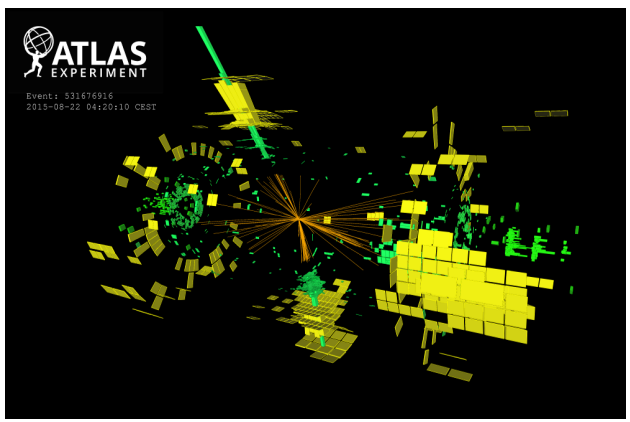
Outlook

- 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, 5-Jet Production and fully off-shell $Ht\bar{t}$ production)
- 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 processes
- More dedicated results will follow, including jet ratio observables



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, 5-Jet Production and fully off-shell $Ht\bar{t}$ production)
- 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 processes
- More dedicated results will follow, including jet ratio observables



Thanks!