NLO QCD Predictions for Vector-Boson Production

Harald Ita
Albert-Ludwigs-Universität-Freiburg

in collaboration with BlackHat-authors: C. Berger, Z. Bern, L. Dixon, F. Febres Cordero, D. Forde, T. Gleisberg, S. Höche, D. Kosower, D.Maitre, K. Ozeren

ZPW 2013: Particle Physics in the LHC Era

Outline

1. Introduction
2. Setup of NLO QCD Computation
3. W/Z+jets results
4. Summary

Introduction

Physics Motivation

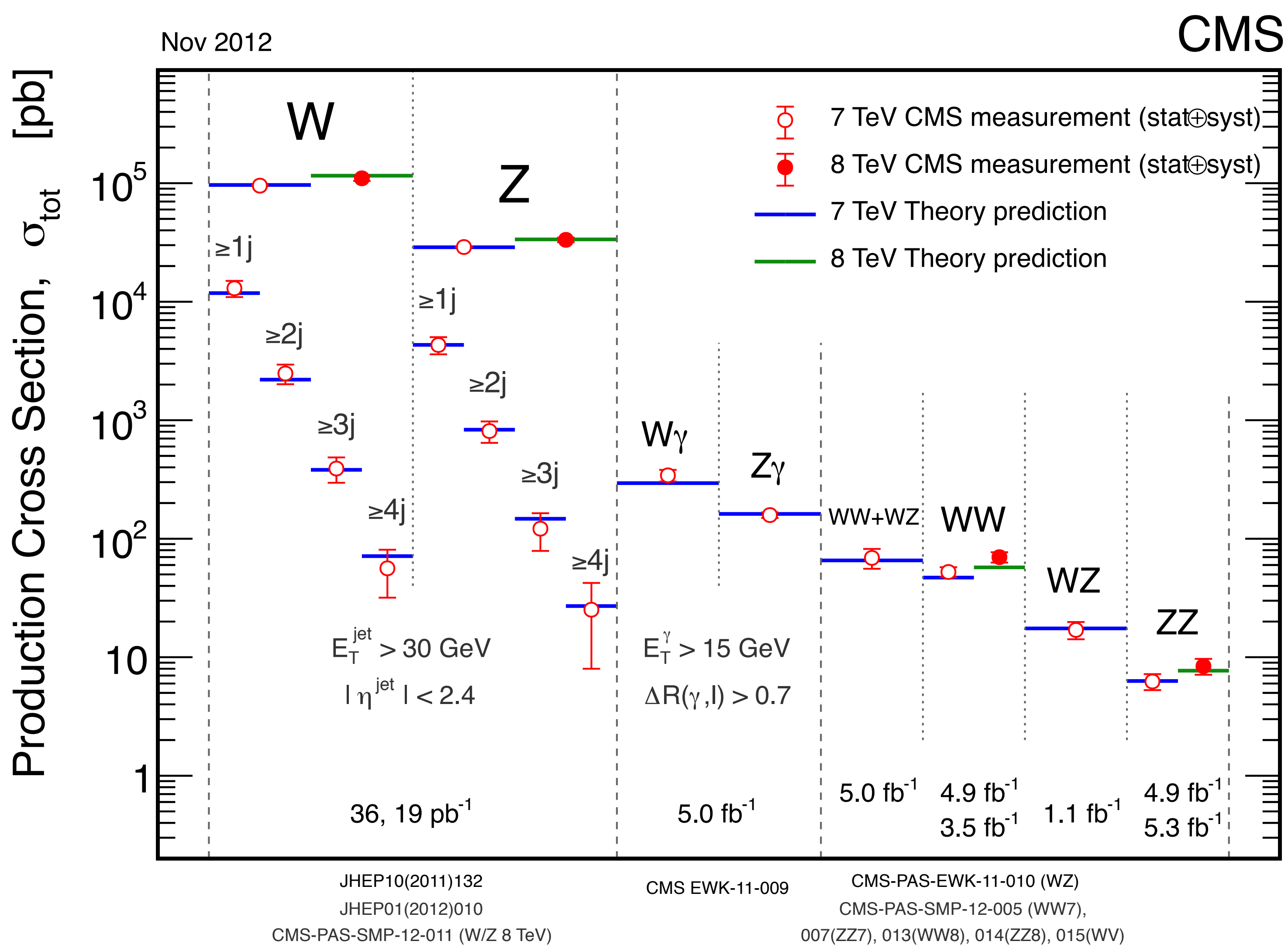
High-multiplicity events common @ LHC.

W/Z+n-jets:

- *test of perturbative QCD*
- *significant background (BSM, tt, Higgs)*

Many interesting observables:

- *jet-production ratios, conversion factors, jet substructure (see talk by D.Kosower)*

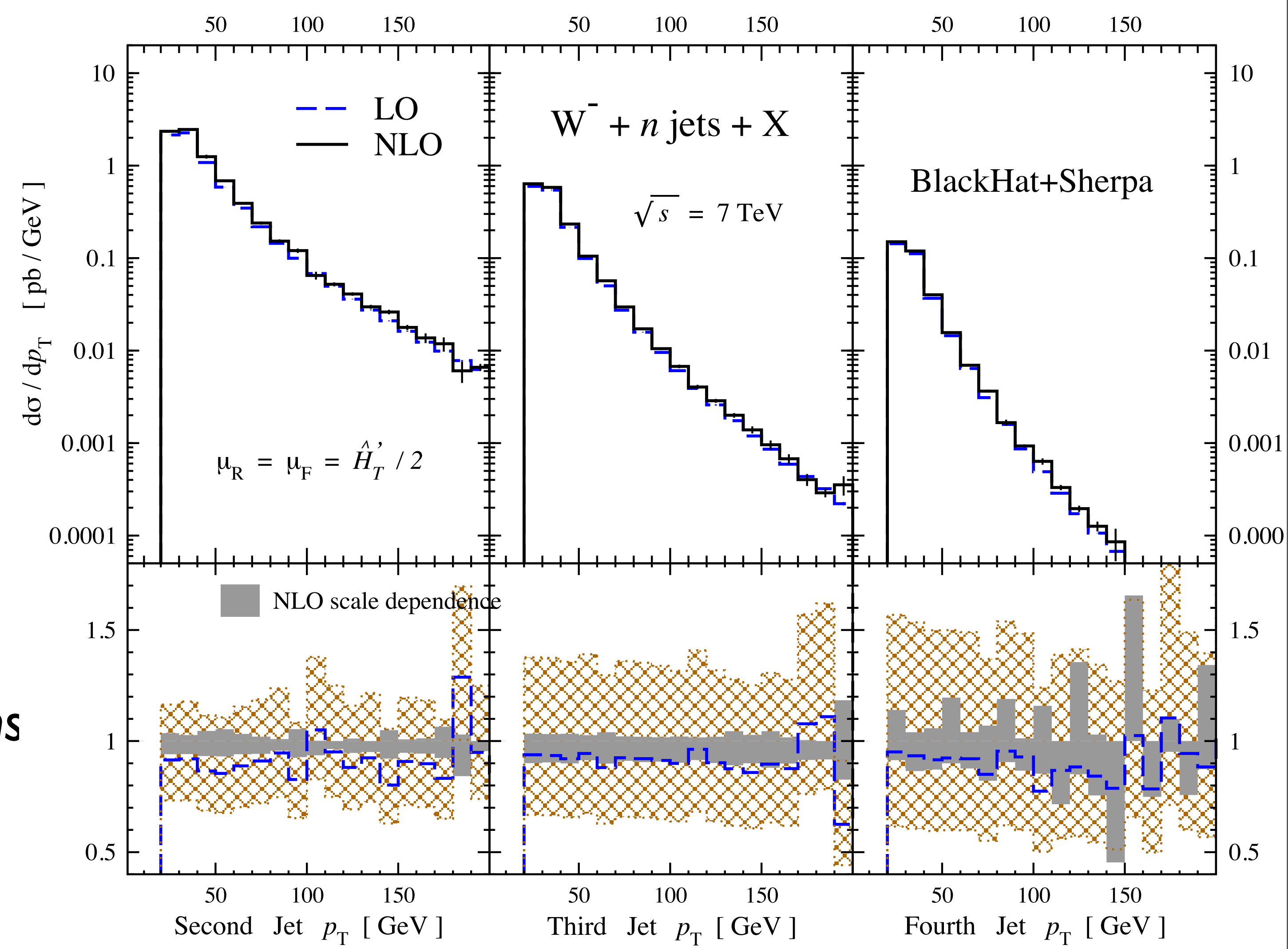


Impact of Precision Theory

Consider here parton-level @ NLO:

- Normalizations & shapes of cross sections:
  - *Large multiplicity ⇒ high powers of strong coupling*
  - *unphysical renormalization-scale dependence stabilizes at NLO*
- Inclusion of QCD effects: *multiple partons merged into jets, initial state radiation*
- Important ingredient for NLO parton shower

[BlackHat 1109.6527]



BlackHat: Recent Progress

Pushed state-of-the-art in precision QCD:

- pp $\rightarrow$ W/Z/γ+4-jets and presently W+5jets [BlackHat:1108.2229, 1009.2338]
- pp $\rightarrow$ 4-jets (see also talk by S.Badger) [BlackHat:1112.3940; Badger, Biedermann, Uwer, Yundin 1209.0100]

Automated methods for dealing with color d.o.f. [HI, Ozeren: 1111.4193]

Dissemination of results:

- Helped CMS experimenters with supersymmetry search [CMS-PAS-SUS-08-002 & 10-005; BlackHat 1206.6064 &1106.1423]
- n-tuple event files (used by ATLAS) [ATLAS: 1111.2690 & 1201.1276]

Public BlackHat (manual on hepforge) for:

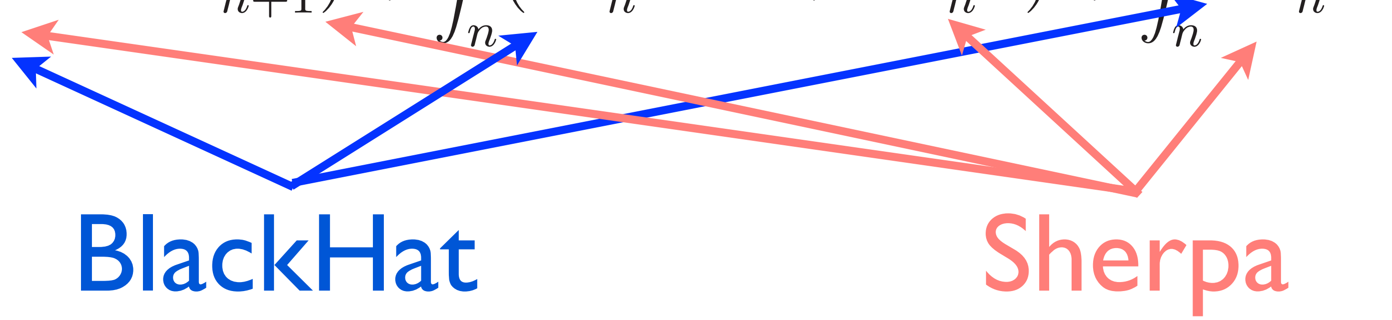
- pp $\rightarrow$ W/Z/γ+($n \leq 3$)-jets and pp $\rightarrow$ ($n \leq 4$) jets

Setup of NLO QCD Computation

BlackHat + Sherpa collaboration

Fixed-order parton-level cross section @ NLO:

$$\sigma_n^{NLO} = \int_{n+1} (d\sigma_n^{real} - d\sigma_{n+1}^{sub}) + \int_n (d\sigma_n^{virtual} + d\Sigma_n^{sub}) + \int_n d\sigma_n^{born}$$



Loop-matrix-element generator:

- *BlackHat* [Berger, Bern, Dixon, Febres Cordero, Forde, HI, Maitre, Kosower, Ozeren]

Tree-matrix-element generators:

- *AMEGIC (Feynman diagram based), COMIX (color flow + Berends Giele recursion)*

- *BlackHat (on-shell methods & N=4 inspired)*

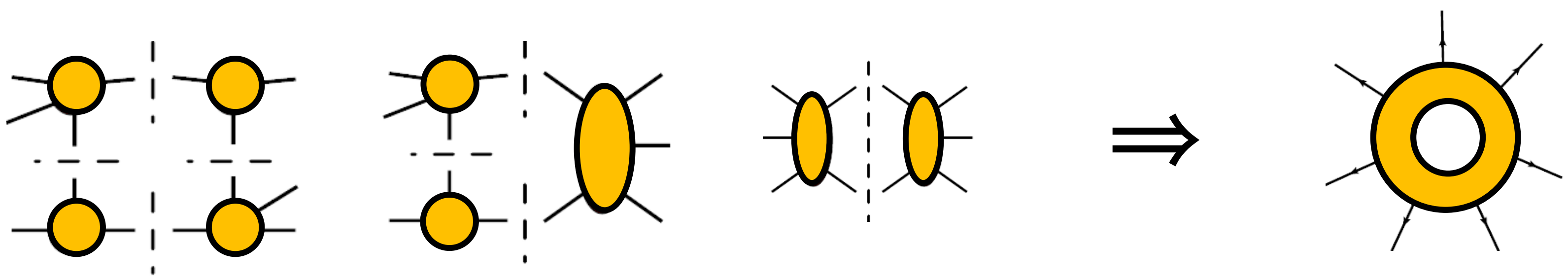
Soft & collinear singularities:

- *dipole subtraction formalism* [Catani, Seymour '96; Dittmaier '99; Phaf, Weinzierl '01; Catani, Dittmaier, Seymour, Trocsanyi '02]

- *implementations: AMEGIC* [Gleisberg, Krauss] *and COMIX* [Hoeche]

Sherpa's multi-channel integration and analysis framework; BlackHat n-tuple analysis

On-shell Methods



Key features:

- multiplicity independent setup
- on-shell tree amplitudes as input
- numerically stable

For details see recent reviews: [Britto `11; HI '11; Ellis, Kunszt, Melnikov, Zanderighi `11]

- Tensor reduction with on-shell loop momenta: [Ossola, Papadopoulos, Pittau; Harmeren]
- Unitarity methods: [Bern, Dixon, Kosower; Britto, Cachazo, Feng; Ellis, Giele, Kunszt, Melnikov]
- Recursive on-shell methods for loops: [Berger, Bern, Dixon, Febres-Cordero, Forde, HI, Kosower, Maitre]
- Numerical unitarity methods: [Berger, Bern, Dixon, Febres-Cordero, Forde, HI, Kosower, Maitre; Ossola, Papadopoulos, Pittau,Hameren; Giele, Kunszt, Melnikov]

BlackHat-library

[Berger, Bern, Dixon, Forde, Febres Cordero, HI, Kosower, Maitre, Ozeren]

Tree & loop matrix-element generator

Aim: computation of multi-leg loop matrix elements

Key: New field-theory methods important for LHC phenomenology @ LHC; these provide efficiency and numerical stability

Further recent programs giving collider cross sections:

- Helac-NLO: Bevilacqua, Czakon, Hameren, Ossola, Papadopoulos, Pittau, Worek
- Rocket+MCFM: Ellis, Giele, Kunszt, Melnikov, Zanderighi
- MadLoop: Hirchi, Maltoni, Frixione, Frederix, Garzelli, Pittau
- GoSam & Samurai: Cullen, Greiner, Heinrich, Luisoni, Mastrolia, Ossola, Reiter, Tramontano
- NJet: Badger, Biedermann, Uwer, Yundin
- OpenLoops: Cascioli, Maierhofer, Pozzorini
- Recola: Actis, Denner, Hofer, Scharf, Uccirati

BlackHat: Loop Setup

Express loop-matrix elements in terms of primitive loop amplitudes:

$$\mathcal{A}^{1-\text{loop}} = \sum_{\text{color traces } \rho} C_\rho[(T^a)^j_{\bar{k}}]\ \mathcal{A}_\rho^{\text{partial}}$$

$$\hookrightarrow \sum_{\text{ordered amplitudes } \sigma} g_{\rho\sigma}(N_c, N_f)\ A_\sigma^{\text{primitive}}$$

Key features:

- explicit color dependence exposed $\Rightarrow$ *color expansion in powers of $(1/N_c)$*
- primitive amplitude contain gauge invariant subset of Feynman diagrams

Convenient for on-shell methods:

- depend on ordered kinematic variables; s_{12}, s_{123} *but not* s_{13}, s_{134} $\Rightarrow$ *simplifies on-shell methods*
- fine division into physical objects $\Rightarrow$ *excellent control over numerical stability*

BlackHat: Color

Needed: partial loop amplitudes in terms of primitive amplitudes

$$\mathcal{A}_\rho^{\text{partial}} = \sum_{\text{ordered amplitudes } \sigma} g_{\rho\sigma}(N_c, N_f) \; A_\sigma^{\text{primitive}}$$

Decompositions have been well known for some amplitudes:

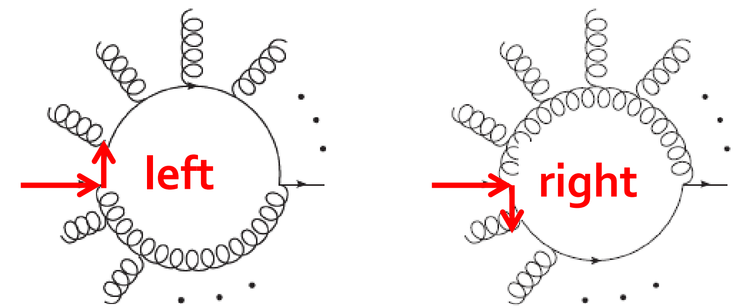
- n-gluons, 2-quarks & n-gluons, 4-quarks [Bern, Kosower '91; Kunszt Signer, Trocsanyi '94; Bern, Dixon, Kosower '94; Bern, Dixon, Kosower, Weinzierl '96]
- 4-quark & 1-gluon [Ellis, Giele, Kunszt, Melnikov, Zanderighi '08]; see also review by [Ellis, Kunszt, Melnikov, Zanderighi '11].

Explicit expressions given for various quark and gluon amplitudes [HI, Ozeren: 1111.4193]

BlackHat: Color

Primitive amplitudes [Bern, Dixon, Kosower '94]:

- Ordered amplitudes (as for adjoint fermions and gluons)
- Further split up into left-turners and right-turners.
  Following fermion as it moves towards loop.



Color algorithm: [HI, Ozeren: 1111.4193]

Feynman diagrams
$\{D_i\}$

collect diagrams of given color structure, e.g. $(T^{a_1}\cdots T^{a_n})_k{}^i$

adjoint color dressing
collect diagrams with $Tr(T^{a_1}\cdots T^{a_n})$

Partial amplitudes

$$\mathcal{A}_\rho{}^{\text{partial}} = \sum_{i\in\,\text{diagrams}} K_\rho^i \; D_i$$

Primitive amplitudes

$$A_\sigma{}^{\text{primitive}} = \sum_{i\in\,\text{diagrams}} L_\sigma^i \; D_i$$

Inversion gives color assembly

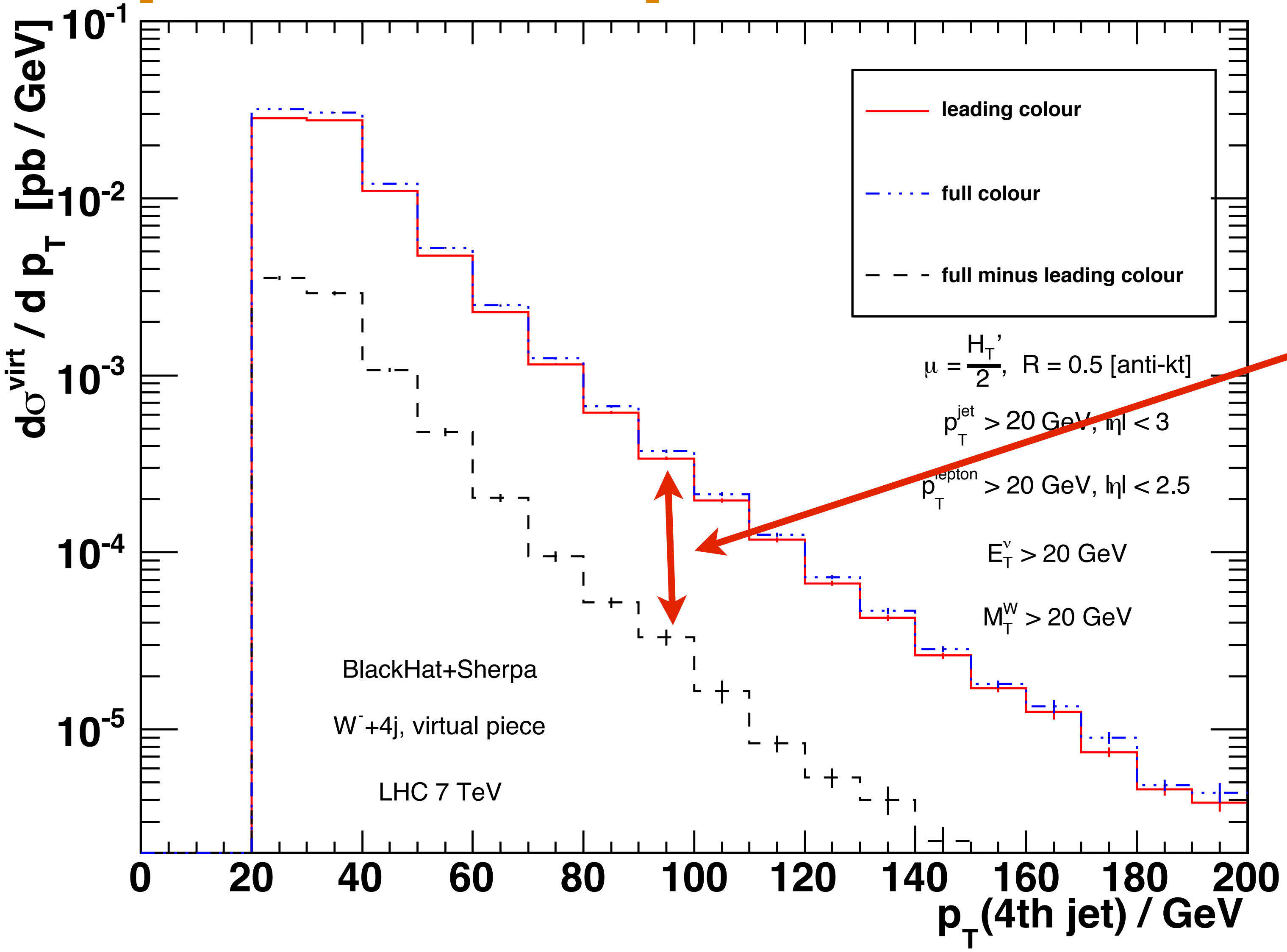
$$\mathcal{A}_\rho{}^{\text{partial}} = \sum_{\text{primitives}\ \sigma} g_{\rho\sigma} \; A_\sigma{}^{\text{primitive}}$$

BlackHat: Color - W+4jets

Color organization in powers of $(1/N_c)$ useful for efficiency:

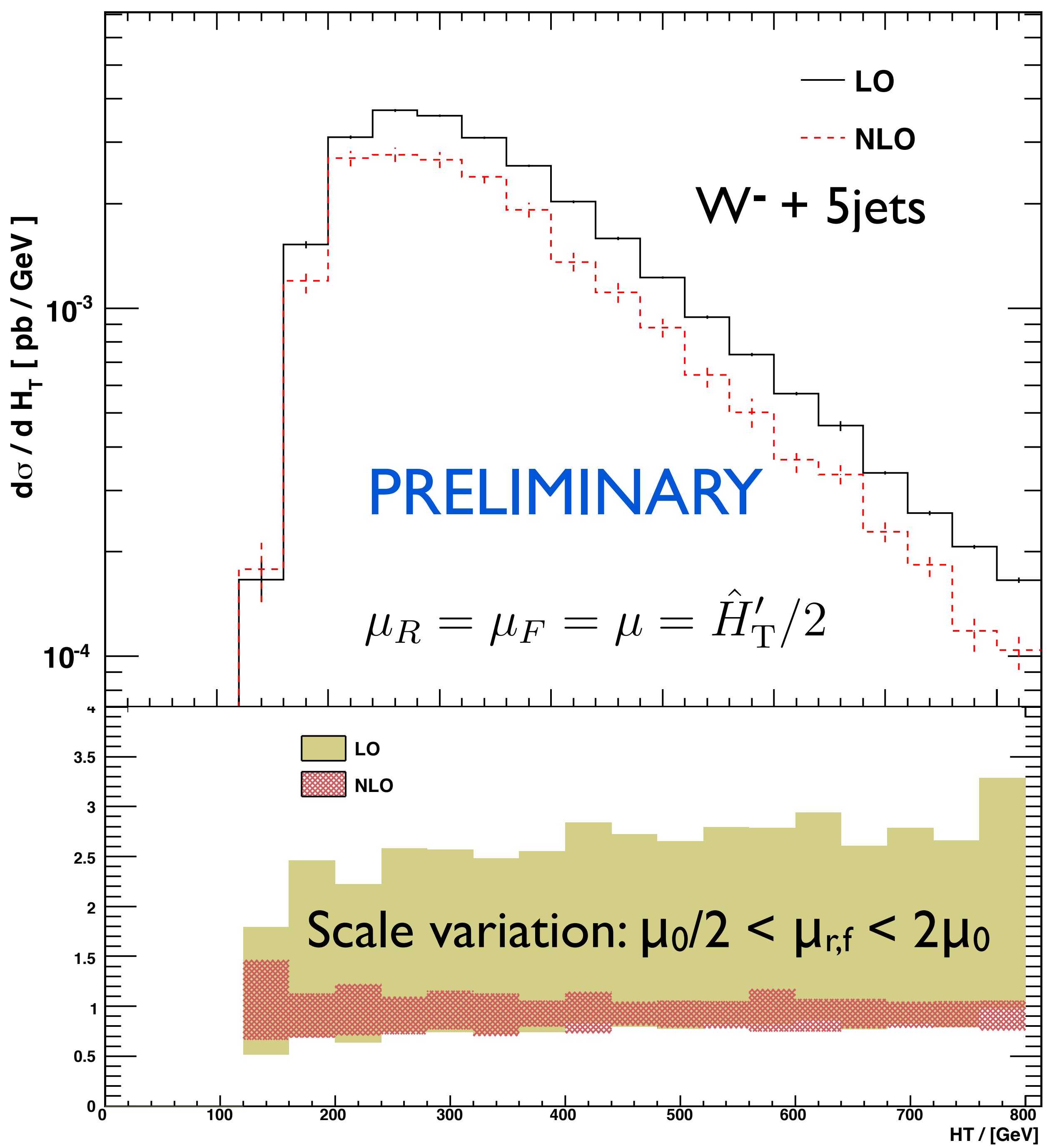
- mostly evaluate bigger, leading-color contributions
- reduced number of evaluations of demanding sub-leading color terms

[HI, Ozeren: 1111.4193]



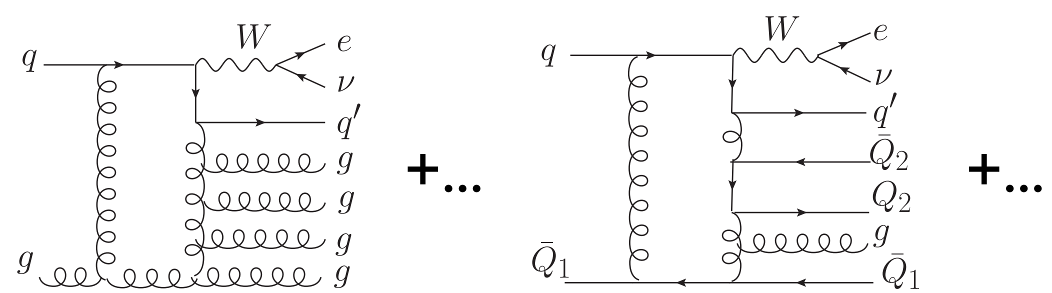
- confirm expected $(1/N_c)^2$ suppression
- leading-color approximation excellent in bulk of distribution

BlackHat: W+5-jets - Work in Progress



Bern, Dixon, Febres Cordero, Hoeche, HI, Kosower, Maitre, Ozeren

First NLO QCD 2 → 6 process @ LHC.



Leading-color approximation of virtual part. Good to about 3% based on W+ (n≤4)-jet experience.

Scale variation reduction:

- 50% @ LO → 15% @ NLO

BlackHat: Public Event Files - Work in Progress

Bern, Dixon, Febres Cordero, Hoeche, HI, Kosower, Maitre, Ozeren

Public event files: $pp \rightarrow W/Z/\gamma$+n-jets, n-jets with ($n \leq 4$) @ NLO

Event files: Standardized ROOT-format n-tuples for NLO fixed order predictions. (Can be generated by Sherpa.)

Analysis library: used to change renormalization and factorization scale setting and PDFs of events.

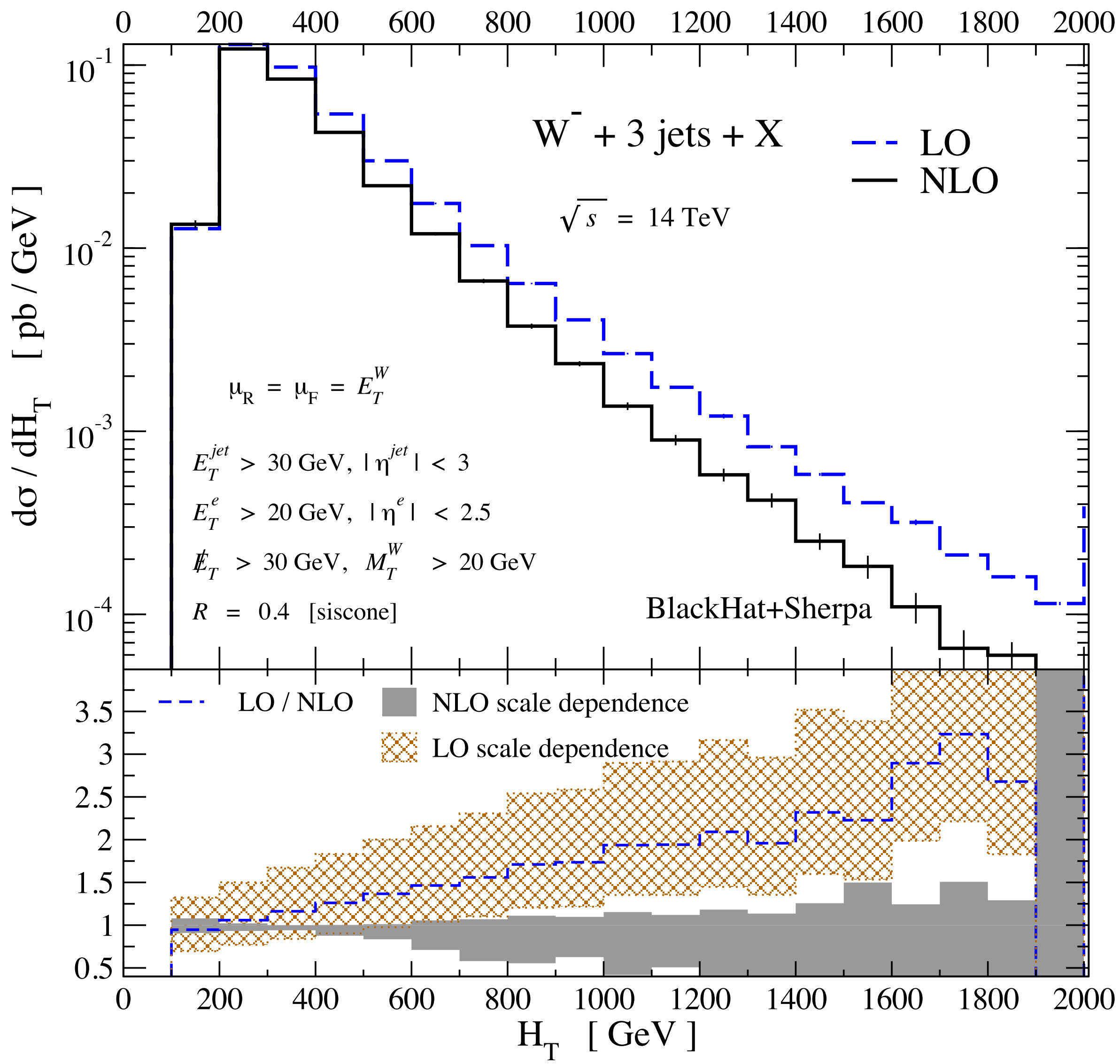
Key features of n-tuple approach:

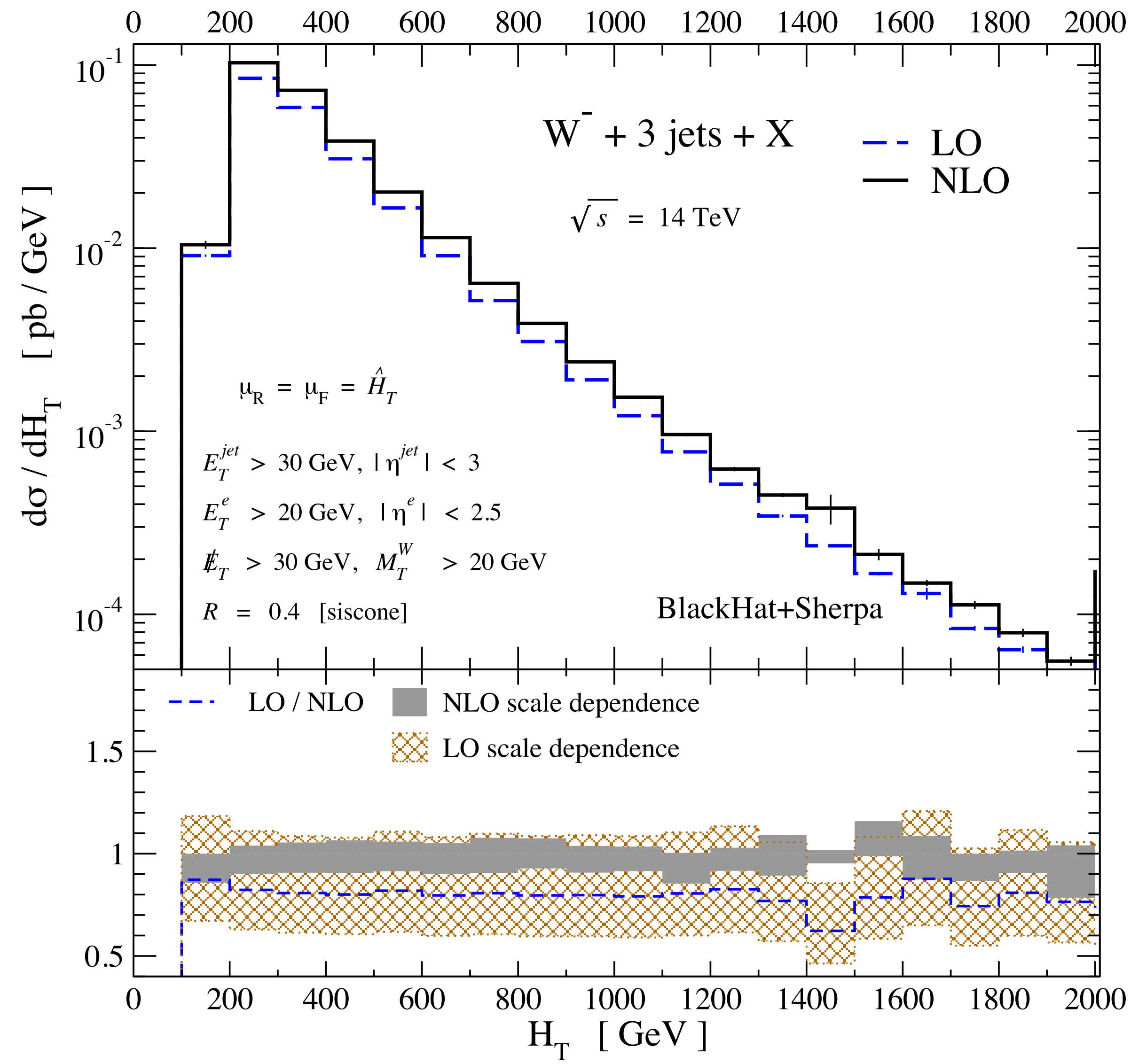
- makes available NLO results to experimenters (used by ATLAS in [1111.2690 & 1201.1276])
- change scales and PDFs cheaply (without re-evaluating real/loop/born parts and dipole-terms)
- tighten cuts and study new distributions

W/Z-results

Renormalization Scale

[BlackHat: 0907.1984]



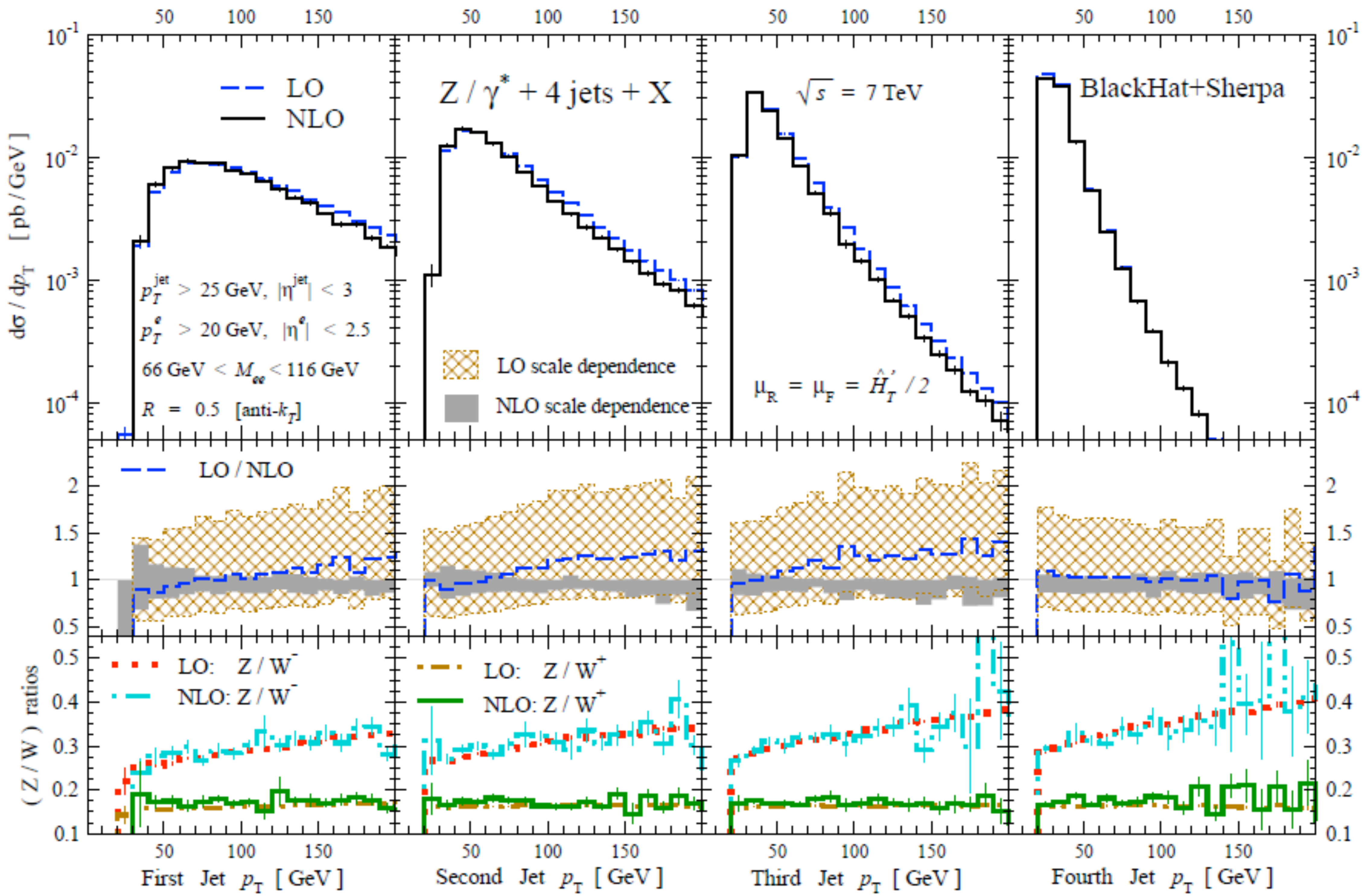


$$\mu = E_T^W \equiv \sqrt{M_W^2 + p_T^2(W)}$$

$$\mu = \hat{H}_T = \sum_p E_T^p + E_T^e + E_T^\nu$$

W/Z+jets @ NLO

[BlackHat: 1108.2229]



Jet-Parameter Dependence

[BlackHat 1090.2338]

anti-kt, R=0.5

no. jets	W^- LO	W^- NLO
0	$1614.0(0.5)^{+208.5}_{-235.2}$	$2077(2)^{+40}_{-31}$
1	$264.4(0.2)^{+22.6}_{-21.4}$	$331(1)^{+15}_{-12}$
2	$73.14(0.09)^{+20.81}_{-14.92}$	$78.1(0.5)^{+1.5}_{-4.1}$
3	$17.22(0.03)^{+8.07}_{-4.95}$	$16.9(0.1)^{+0.2}_{-1.3}$
4	$3.81(0.01)^{+2.44}_{-1.34}$	$3.55(0.04)^{+0.08}_{-0.30}$

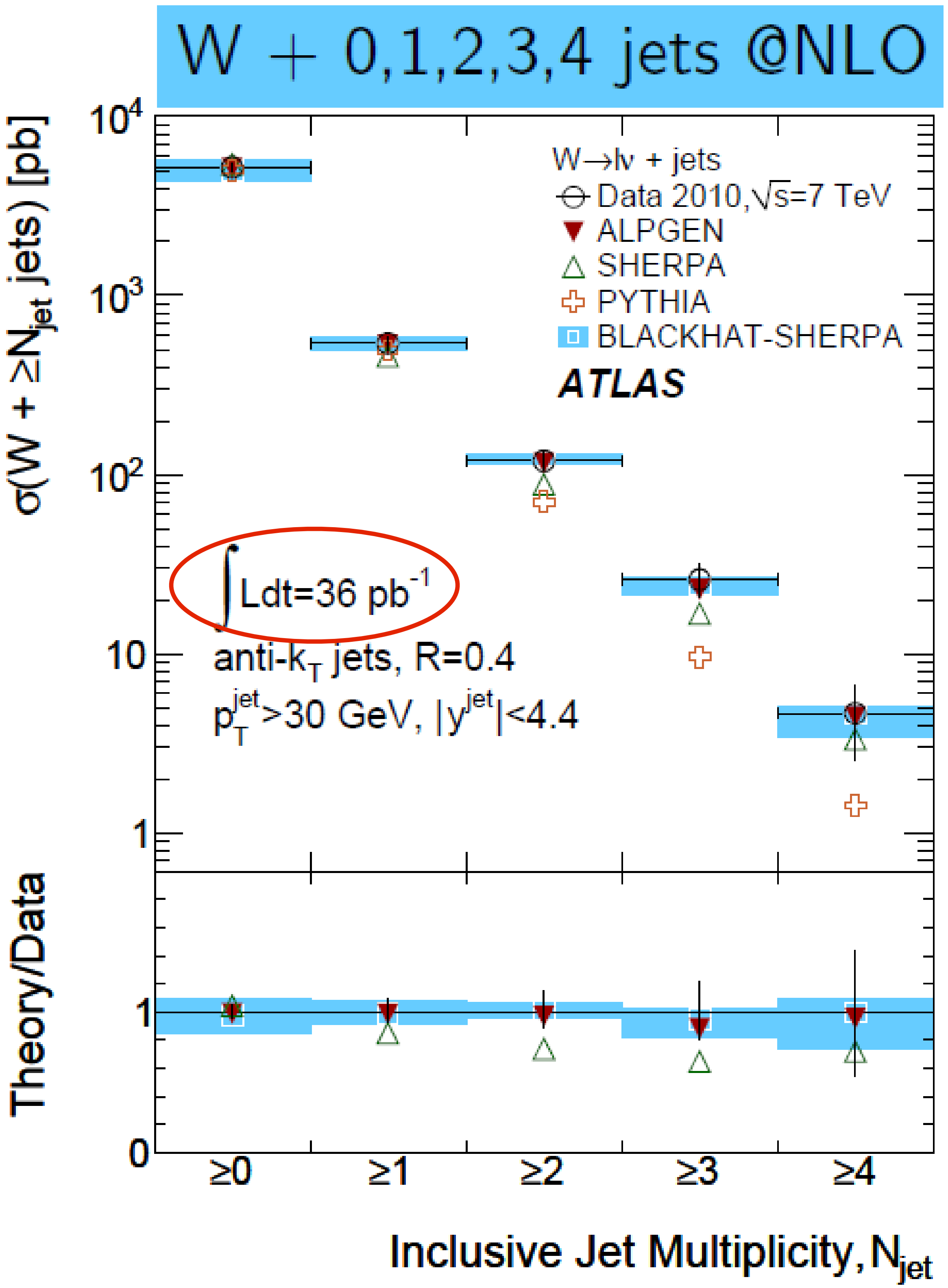
NLO decreasing

LO increasing

anti-kt, R=0.4

no. jets	W^- LO	W^- NLO
0	$1614.0(0.5)^{+208.5}_{-235.2}$	$2077(2)^{+40}_{-31}$
1	$264.4(0.2)^{+22.6}_{-21.4}$	$324(1)^{+14}_{-11}$
2	$74.17(0.09)^{+21.08}_{-15.12}$	$76.2(0.5)^{+0.8}_{-3.4}$
3	$18.42(0.03)^{+8.61}_{-5.29}$	$17.0(0.1)^{+0.0}_{-1.0}$
4	$4.41(0.01)^{+2.82}_{-1.55}$	$3.81(0.04)^{+0.00}_{-0.44}$

ATLAS Comparison



Data: [ATLAS 1201.1276]

Theory: [BlackHat 1090.2338]

Excellent agreement between data and theory.

Particle level; ~3% non-perturbative corrections included by ATLAS.

Theory limited by scale dependence (<15%).
Data limited my JES uncertainty (<30%).

New methods work!

Conclusions

- New theory developments in order to deal with color d.o.f in QCD. Automated sub-leading color of one-loop matrix elements in BlackHat.

- Discussed recent NLO computations in NLO QCD: Z+4 jets, W+4/5-jets.

- Precision theory can play a central role in order to fully exploit the LHC potential.

- Recently made BlackHat matrix elements publicly available to experimenters.

- Advertised n-tuple event files.

Thanks.