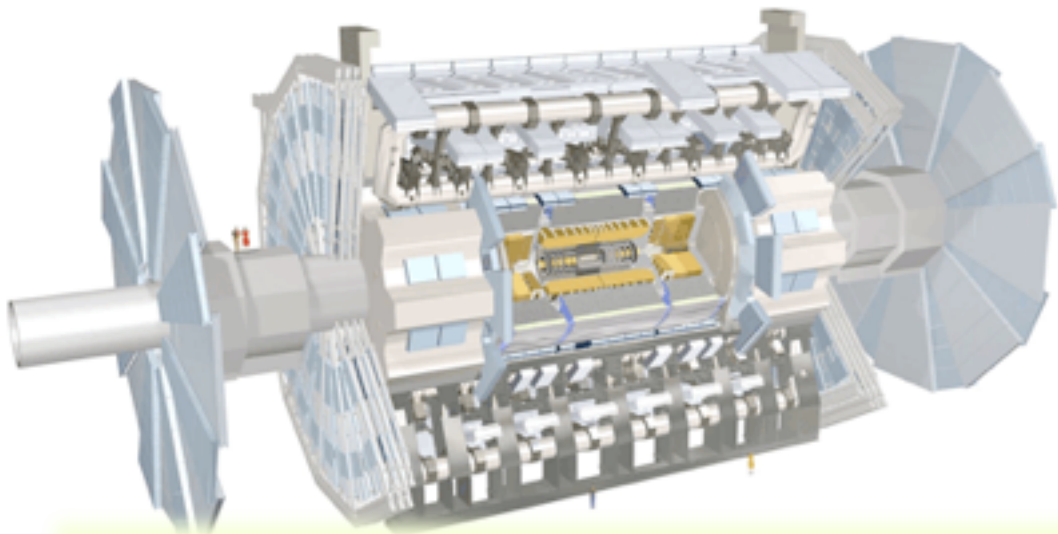

Measurements of vector boson with associated jet production with the ATLAS detector

Stefania Spagnolo
INFN Lecce and
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on behalf of the **ATLAS** Collaboration

Lake Louise Winter Institute 2015 - 15-21 Feb 2015

ATLAS results on W/Z+jets

- ***Jet production in association with gauge bosons***
  - Z+jets differential cross section JHEP07(2013)032
  - W+jets differential cross section arXiv:1409.8639, accepted by EPJC
  - W+jets / Z+jets cross section ratio: EPJC(2014)74:3168

in Summer Conf, 2014

- ***Heavy quark production in association with Gauge bosons***
  - W+b(b): JHEP06(2013)084
  - W+c: JHEP05(2014)068
  - Z+b(b): JHEP10(2014)141

part of it presented at LLWI2014

in Summer Conf, 2014

2011 Dataset: 4.6 fb^{-1} $\sqrt{s}$ = 7 TeV

Z,W reconstructed from leptonic final state with $e^{\pm}$ or $\mu^{\pm}$ (combined)

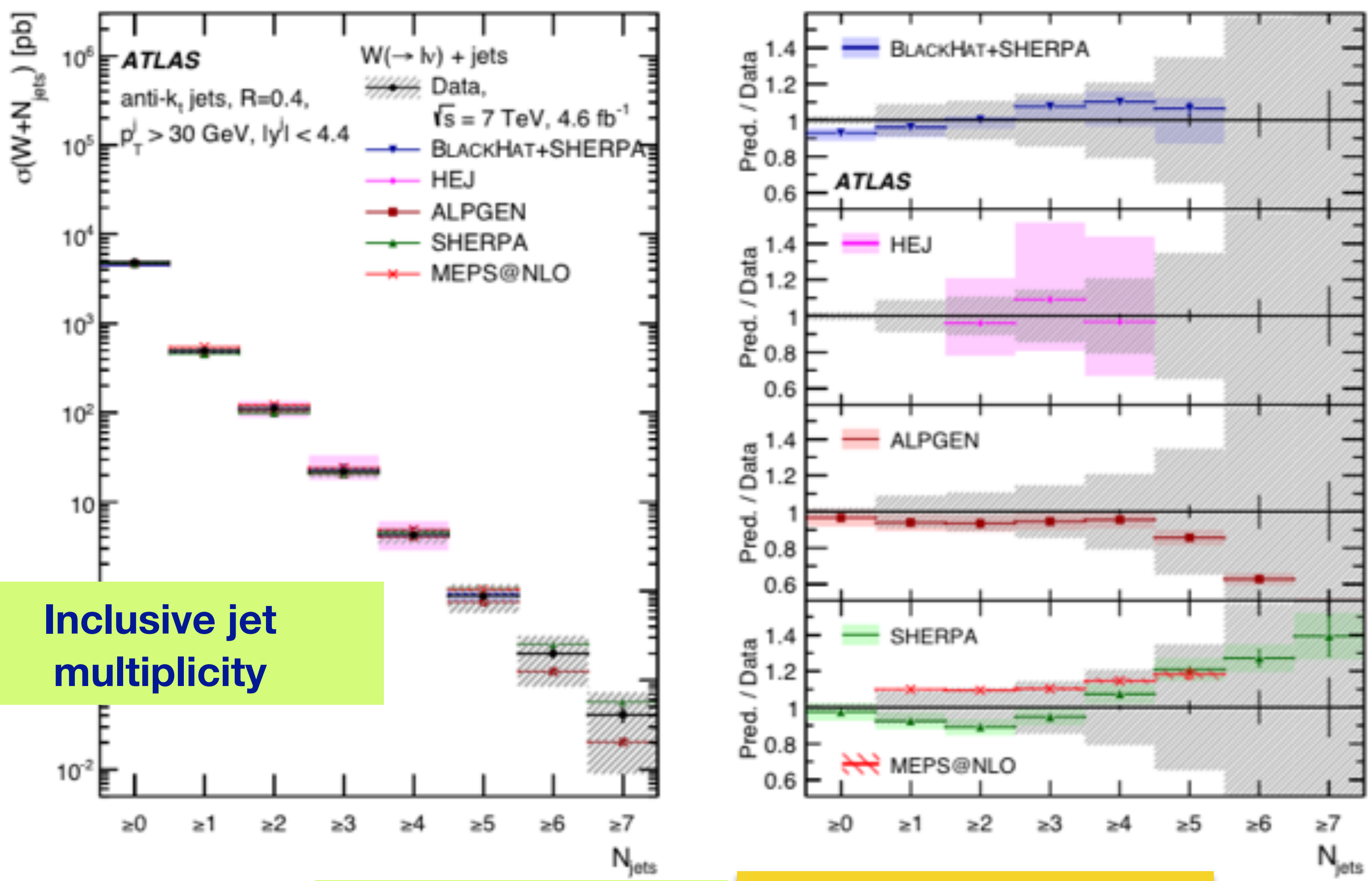
Results are corrected for detector effects and quoted at the particle (hadron) level for easy comparison with predictions

Motivations → ***Precise test and tuning of predictions for accurate modeling of SM background to searches and improved understanding of QCD***

V+jets vs Predictions

- Large phase space explored, N_{jet} up to 7, p_T^{jet} up to 1 TeV challenging predictions
- Measurements well described over 5 orders of magnitude

A large variety of Theory Predictions compared to data



Inclusive jet multiplicity

from **W+jet** arXiv:1409.8639

Multi-parton LO + PS **Alpgen** (up to 5 partons), **Sherpa** 1.4 (up to 4 partons)

Fixed order calculations: **BlackHat+SHERPA** (NLO for V+up to 5 jets)

NLO for V+up to 2 partons and LO for W+up to 4 jets merged to PS: **MEPS@NLO**

calculations of higher orders with approximations: **HEJ** (resummation), **LoopSim** (approx. NNLO)

arXiv:1409.8639

Summer 2014

W+jets: a plethora of distributions

	BlackHat +Sherpa	BlackHat +Sherpa **exclusive sum**	HEJ	MEPS@NLO	Loopsim	ALPGEN	SHERPA
jet multiplicity	😀		😀 test for N= or ≥2,3,4	😀		😀 some discr. at N>4	😀 some discr. at N>4
jet kinematics: p_T	😐 for N≥1 😀 for N≥2,3 and exclusive	does not help for N≥1	😟 N≥2 😀 N≥3,4	😐 for N≥1 😀 for N≥2,3 and exclusive	😐 for N≥1	😀	😀, 😐
jet kinematics: y	😀 *		😀	😀 *		😀	😀 * overest. large y
jet p_T scalar sum S_T	😐	😀😐 test for N≥1	😟	😀	😀😐 test for N≥1	😐	😐😟
angular variables for N≥2	😀 ϕ,y 😟 m_{jj}		😀 ϕ, m_{jj} 😟 y	😟 y, m_{jj} 😐 ϕ		😐 ϕ, m_{jj} 😟 y	😟 y, m_{jj} 😐 ϕ

arXiv:1409.8639

W+jets: a plethora of distributions

	BlackHat +Sherpa	BlackHat +Sherpa **exclusive sum**	HEJ	MEPS@NLO	Loopsim	ALPGEN	SHERPA
jet multiplicity	😀		😀 test for N= or ≥2,3,4	😀		😀 some discr. at N>4	😀 some discr. at N>4
jet kinematics: p_T	😐 for N≥1 😀 ... and exclusive	do...	😀 ...	😀 ... for N≥2,3 and exclusive	😐 for N≥1	😀	😀, 😐
jet kinematics: y	😀 *		😀	😀 *		😀	😀 * overest. large ...
jet p_T scalar sum H_T	😐	😀 😐 ... N≥1	😟	😀	😀 😐 test for N≥1	😐	
angular variables for N≥2	😀 ϕ,y 😟 m_{jj}		😀 ... m_{jj}	😟 y, m_{jj} 😐 ϕ		😐 ϕ, m_{jj} 😟 y	😟 y, m_{jj} 😐 ϕ

difficult to reach high accuracy;

EWK corr do not help

confirms Z+jets

diff w.r.t. ALPGEN from PS

remarkably better m_{jj} modeling

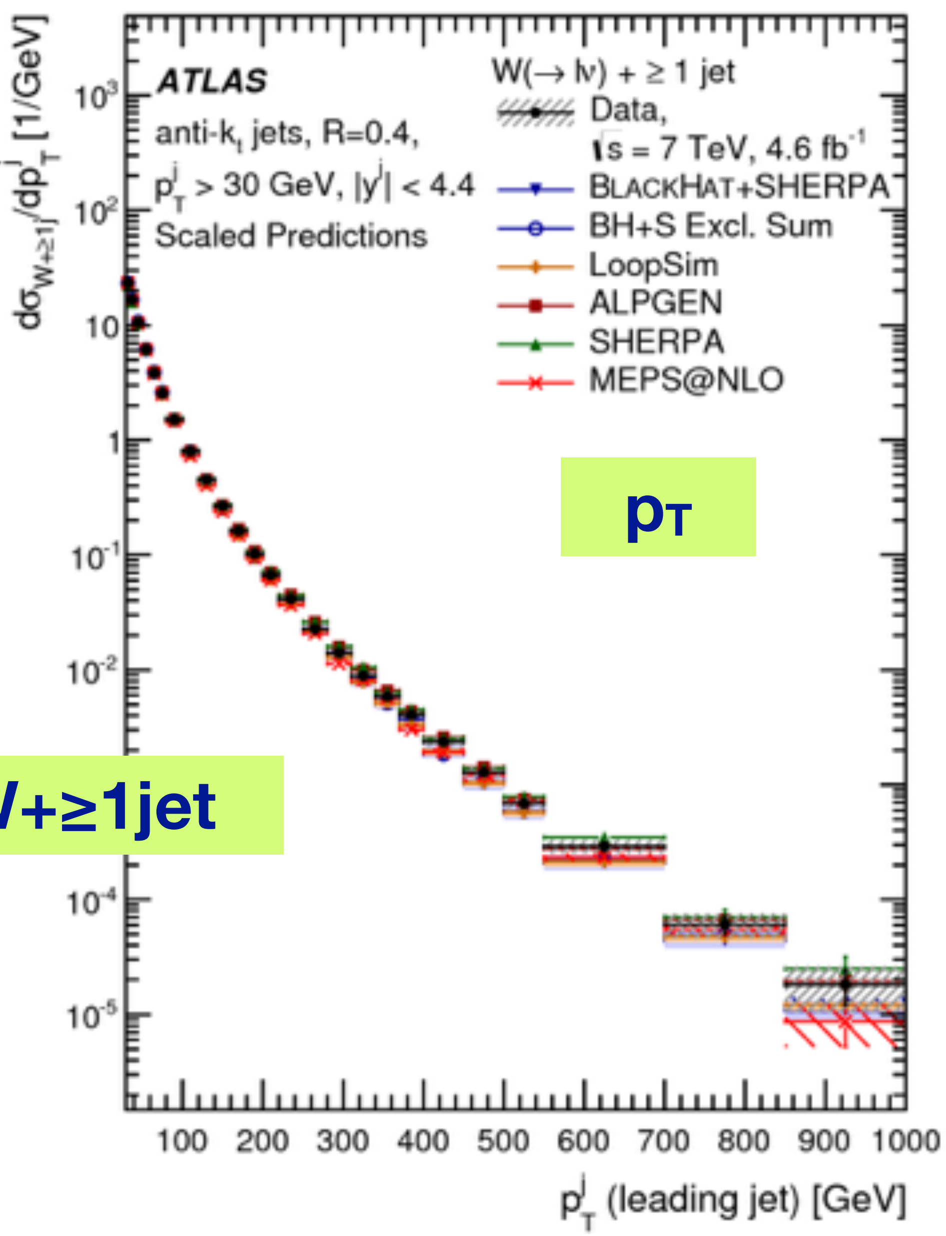
W+jets: p_T of leading jet

- High accuracy of measurements uncover limitations of the predictions at high p_T
- EWK corrections (missing) do not help (negative and large at high p_T)

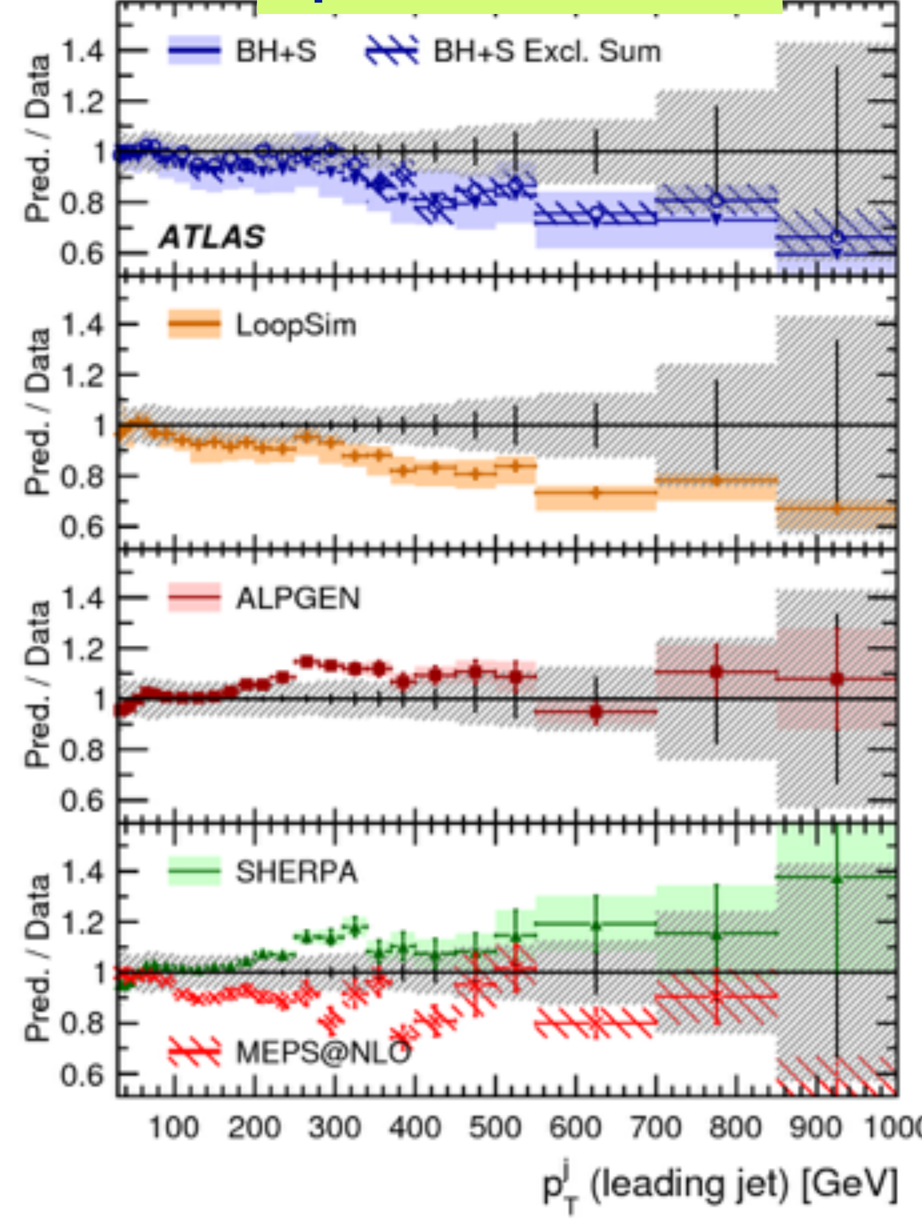
JHEP08(2009)075

PRL111 12(2013) 121801

W+≥1jet



predictions/data



BH+S

LoopSim

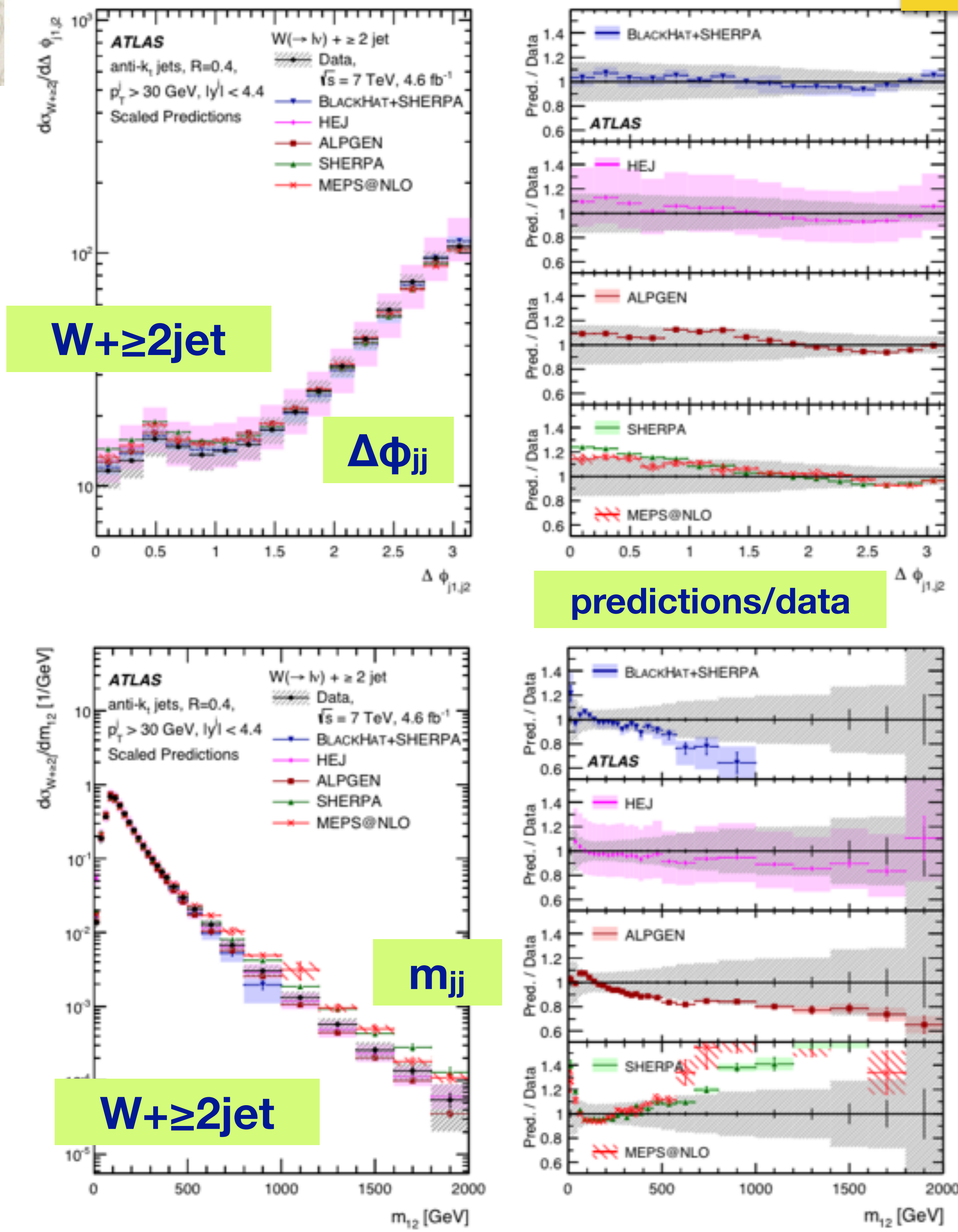
ALPGEN

SHERPA

MEPS@NLO

arXiv:1409.8639

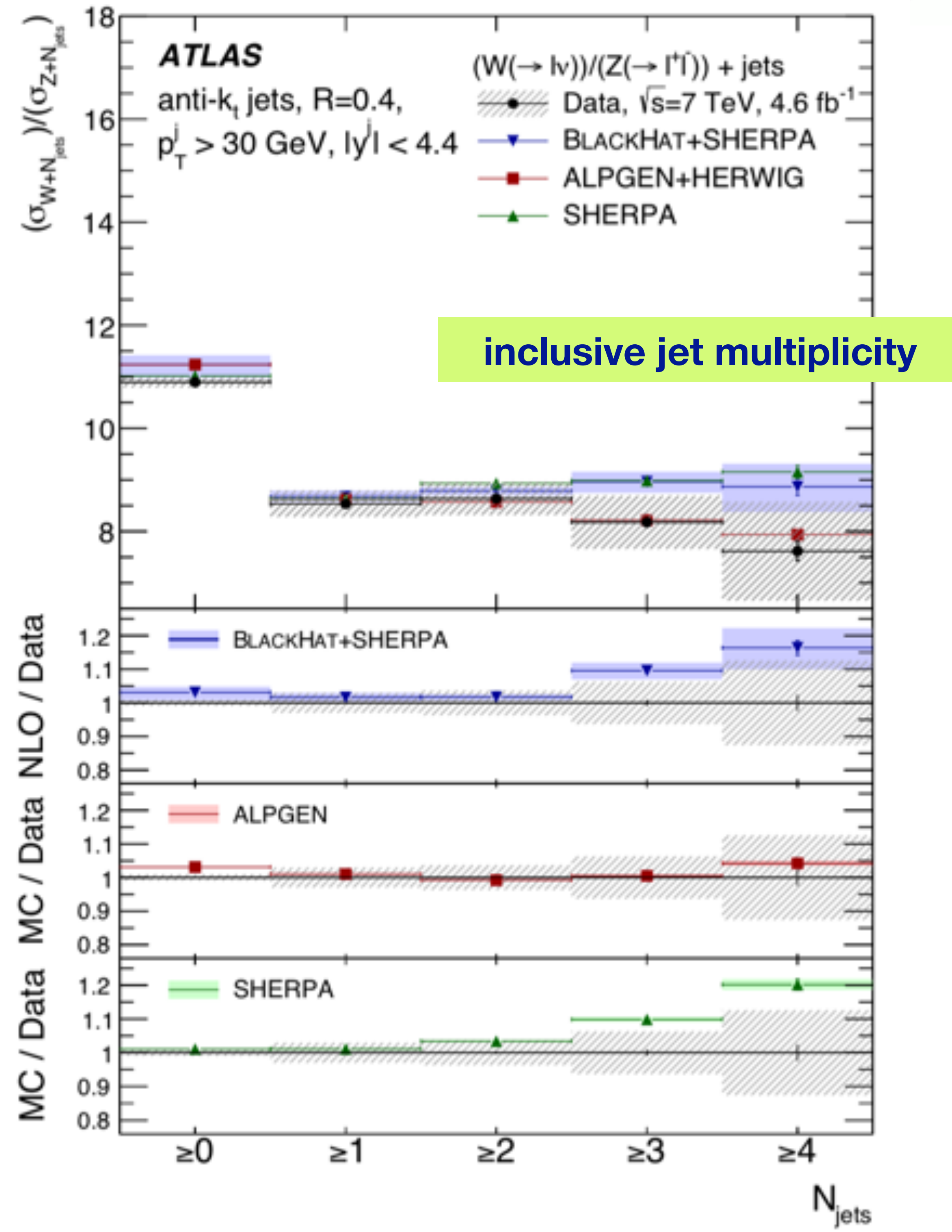
W+jets:
angular variables

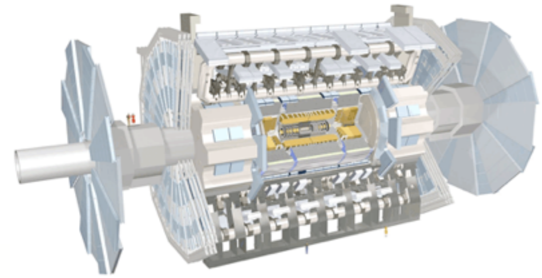


- *test large angle hard (ME) and soft-collinear (PS) radiation; important to model, background to searches, VBF and VBS*
- **BlackHat+SHERPA** provides the best description the Δϕ and Δy of the two leading jets, but fails to describe m_{jj}
- **HEJ,** approx. ME (valid for high Δy) resummed to all orders, gives the best modeling of m_{jj}
- **ALPGEN** within 1 sigma from data
- **SHERPA** and **MEPS@NLO** fail to reproduce large Δy and, as a consequence, m_{jj}

$R_{jets} = \sigma(W+N_{jets})/\sigma(Z+N_{jets})$

- At low p_T sensitive to **qg vs qq-bar** content of the proton; at high p_T test new physics leading to W or Z production
  - **non perturbative QCD effects and experimental errors (jet scale and resol., luminosity) cancel out**
  - **correlated systematic theory errors cancel in the ratio** (0.3 - 1.8% for Njet in 0-4; 2-6% for pT in 30-700GeV)
- **Distributions**: jet multiplicity (inclusive and exclusive), p_T and y of 1st, 2nd and 3rd leading jet; scalar sum of jet p_T S_T; angular variables





Heavy flavor production in association with Gauge Bosons

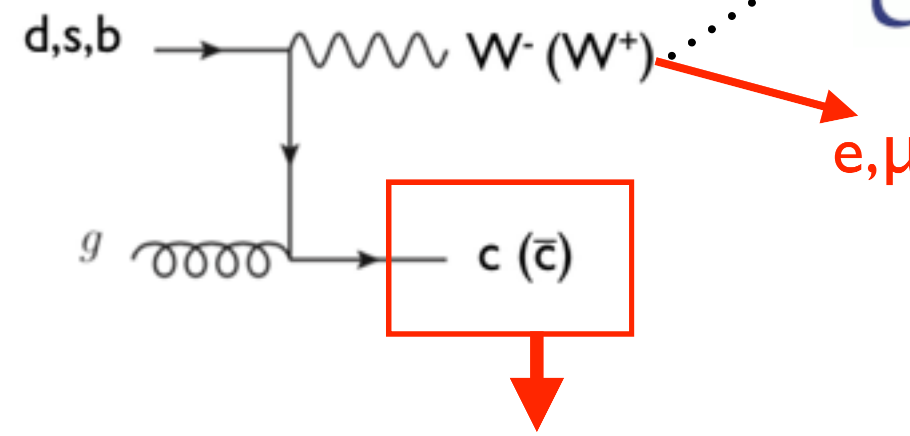
in ATLAS at 7 TeV

W+charm

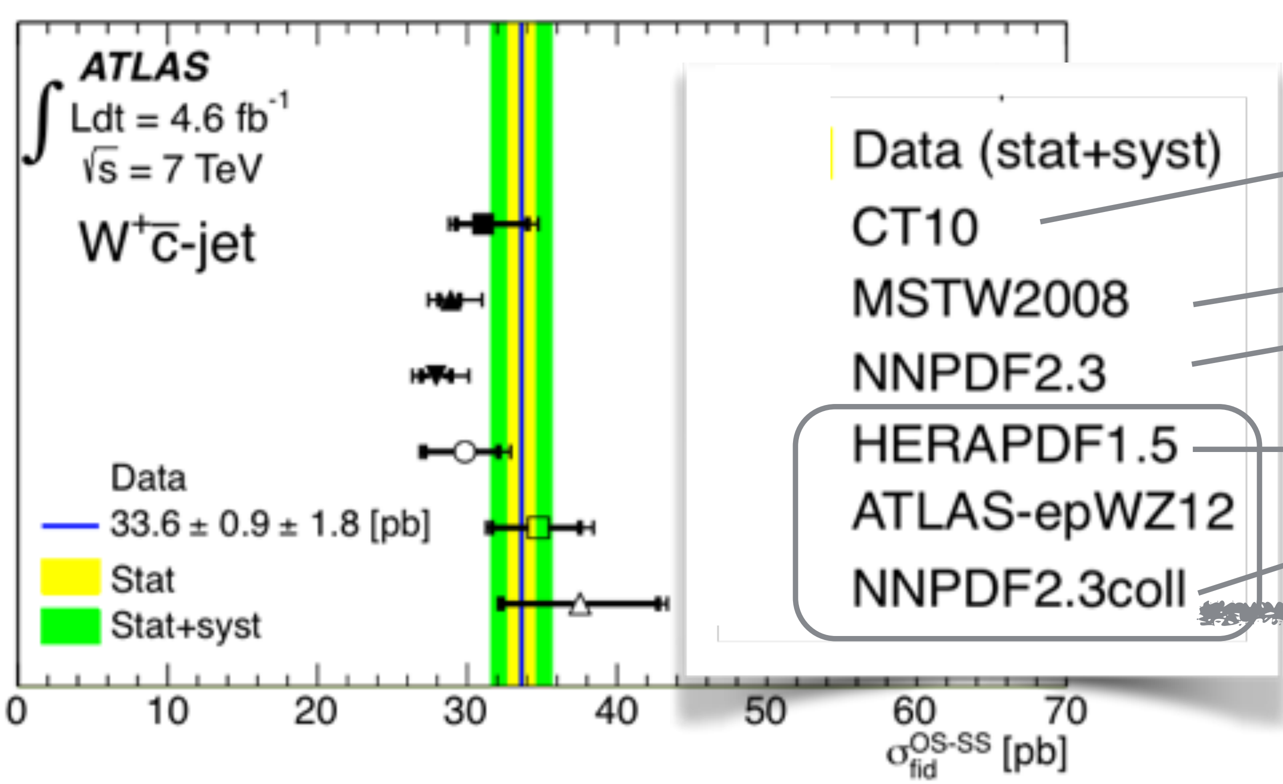
Z+b(b)

W+charm: cross section

- Probe of $s,\bar{s}$ content of the proton
  - *PDFs using νN DIS describe suppressed s/d in the sea, ATLAS W/Z cross section + HERA indicate SU(3) symmetric sea* ***(assuming $\bar{s}/s$ =1)***
- main systematics:
  - tracking efficiency and modeling , c-fragmentation and decay , background, Branching Ratios



A) soft-μ in a jet from semilept. decay
B) a decay chain of $D^{\pm}$, $D^{\pm *}$
W/c charge anti-correlation:
yield from OS-SS



mild s-suppression

s-suppressed w.r.t. d at all x

SU(3) symmetric PDF at x ~0.01

NO νN DIS data

W+charm cross section in agreement with predictions from aMC@NLO

JHEP05(2014)068

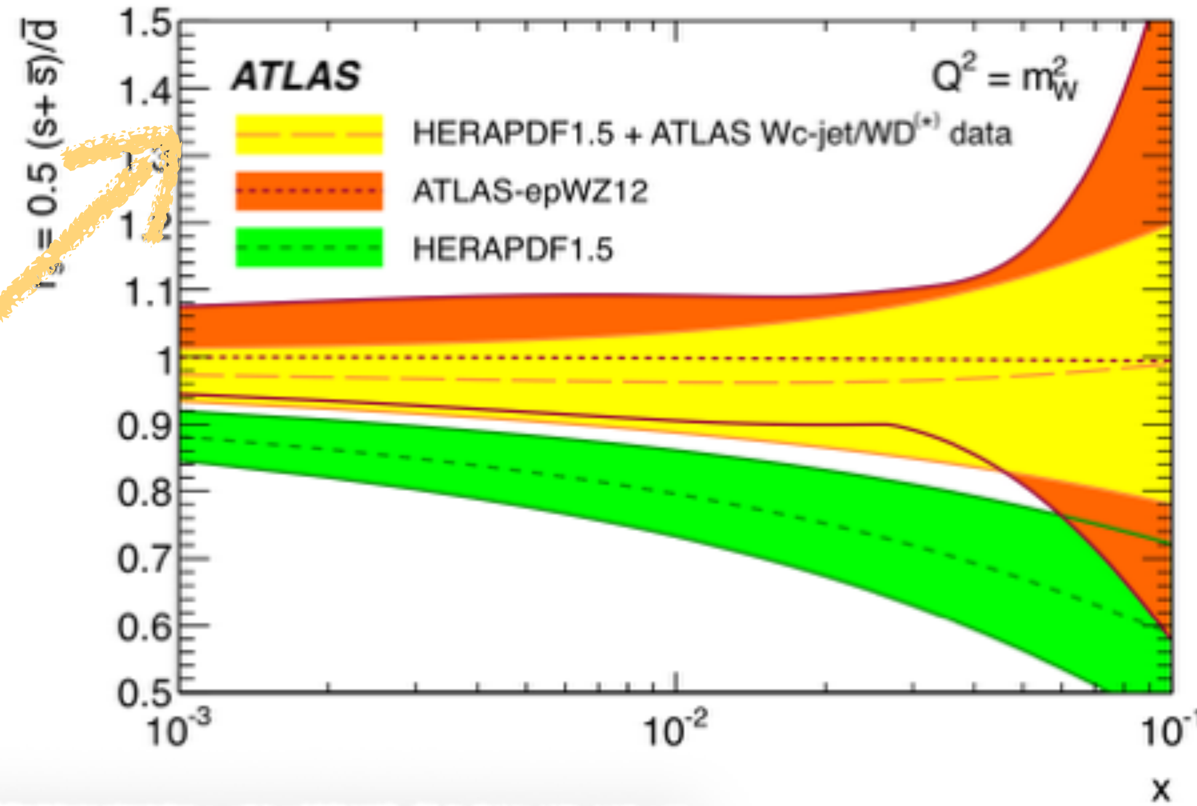
W+charm

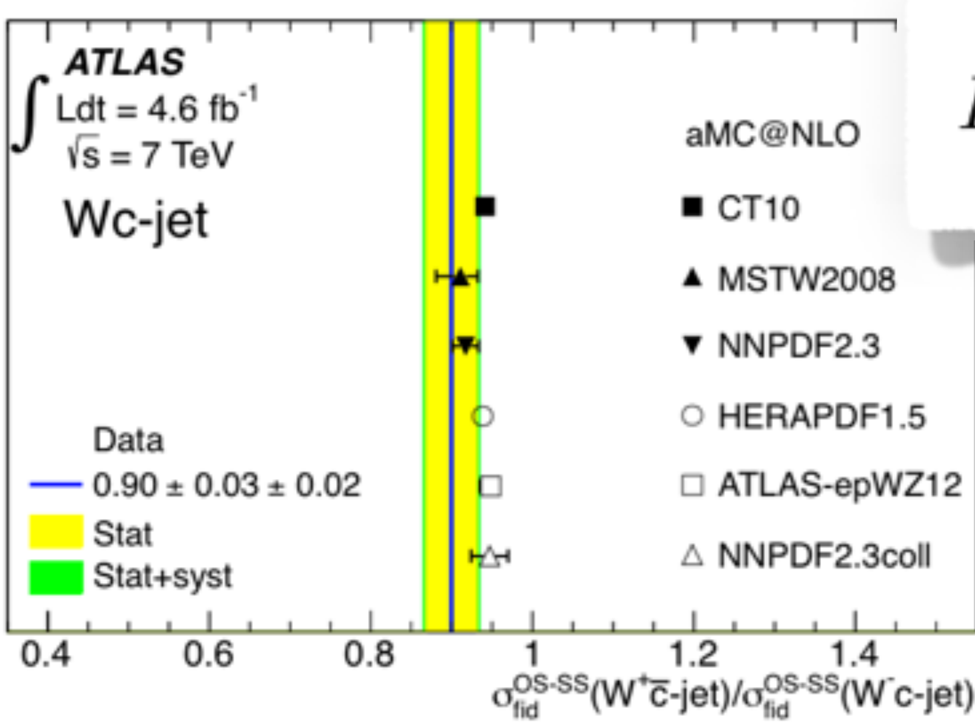
s/d ratio r^s — $\bar{s}$/s asymmetry $A_{s\bar{s}}$

- The W+charm measurements can be used to fit the s/d ratio (through a free parameter in the HERAPDF1.5 set); at Q^2=1.9 GeV^2

$$r^s \equiv 0.5(s+\bar{s})/\bar{d} = f_s/(1-f_s) = 0.96\,^{+0.16}_{-0.18}\,^{+0.21}_{-0.24}$$

  - in agreement with s PDF from ATLAS W/Z cross sections (*PRL109 (2012) 012001*) +HERA, in some tension with NuTeV





$$R_c^{\pm} \equiv \sigma(W^+ + \bar{c})/\sigma(W^- + c)$$

$$A_{s\bar{s}} = \frac{\langle s(x,Q^2)\rangle - \langle \bar{s}(x,Q^2)\rangle}{\langle s(x,Q^2)\rangle}$$ =(2±3) %

A statistically limited measurement, can benefit from Run 2

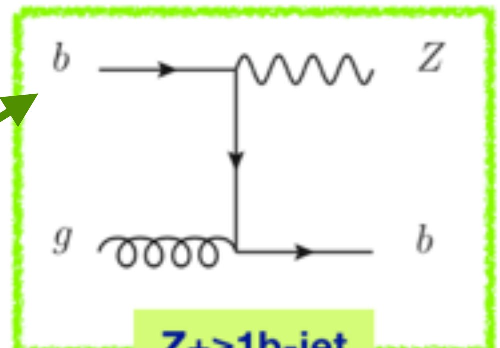
Summer 2014 JHEP10(2014)141

Z+b(b)

- pQCD + flavor number schema (**FNS**) and b-content of the proton + treatment of b-mass (in ME and PS); Several calculation techniques on the market
- Measurements: Total and differential cross sections for Z+≥1b and Z+≥2b testing different physics

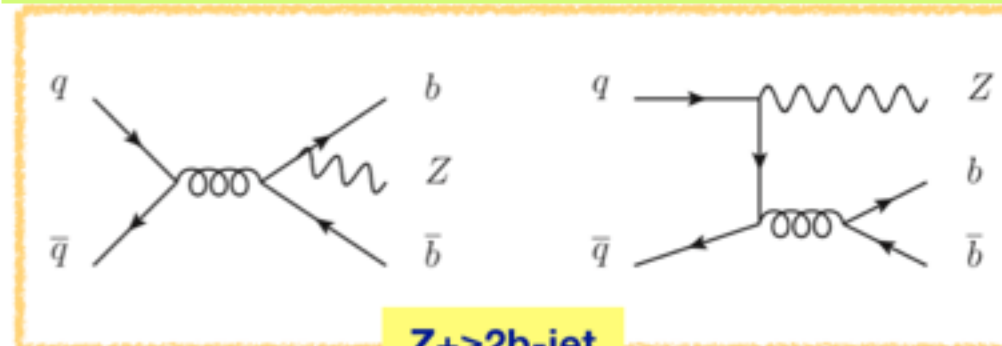
b as initial state parton from DGLAP evolution **5FNS**

b from initial state gluon splitting to bb **4FNS**

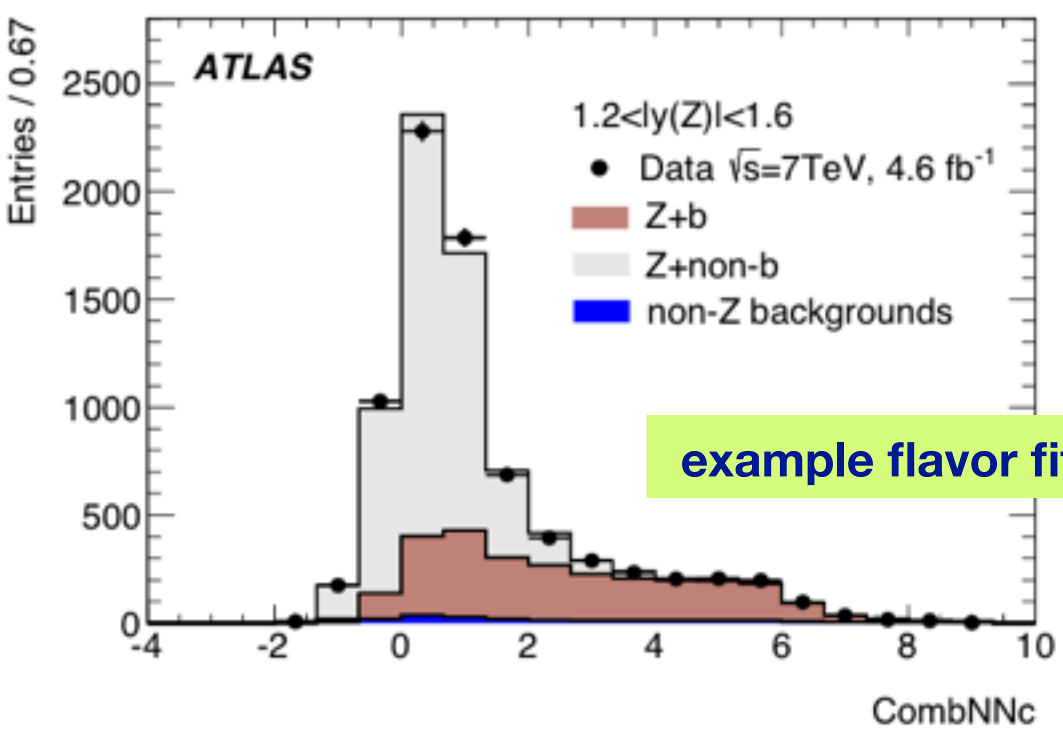


Z+≥1b-jet

not a b-initiated process **FNS is NOT relevant**



Z+≥2b-jet



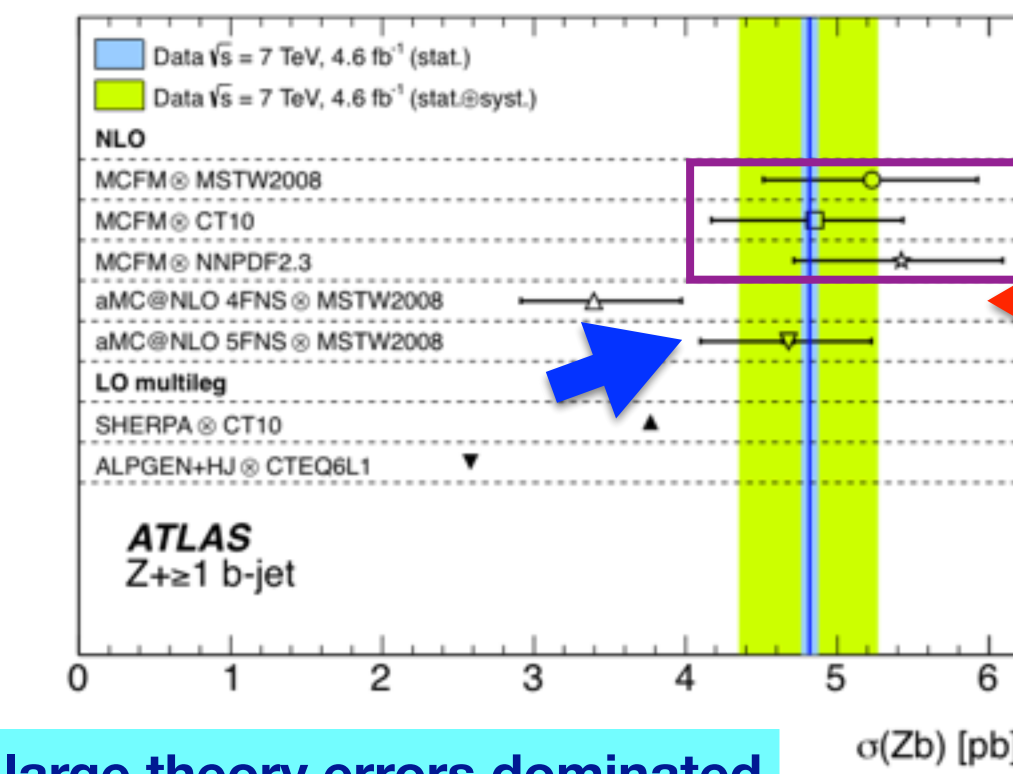
example flavor fit

- Low background Z+jet selection
  - b-tagging (@75%efficiency) and **fit to distributions of flavor-sensitive discriminant** (predicted by simulation) to reduce Z+c and Z+light
  - dominant systematics
- Z+≥1b error dominated by systematics; Z+≥2b still statistically limited in differential distributions

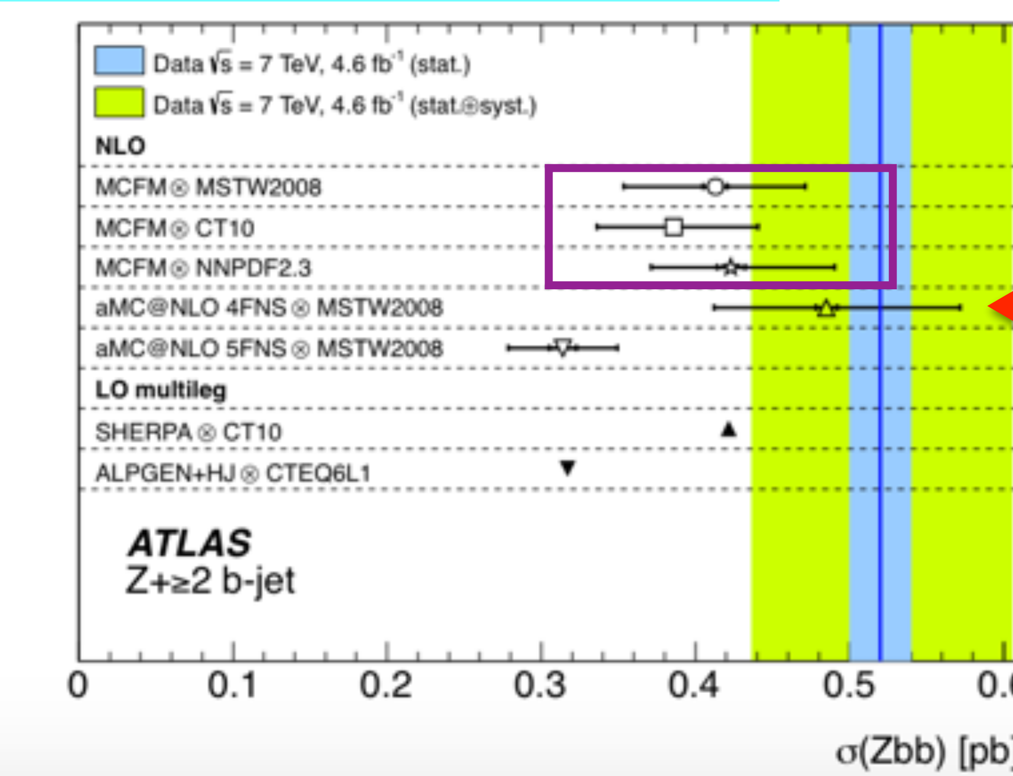
JHEP10(2014)141

Z+b(b) Integrated Cross Section

- **MCFM** (fixed order NLO for Z+≥1b and Z +≥2b, 5FNS, massless b) in agreement with data
  - differences from PDF sets ~1 σ_{exp}, < 1σ_{theory}
- ***aMC@NLO with NLO ME for Zbb and 4FNS, merged to PS, massive b***
  - **good for Z+≥2b,** better than MCFM (massive treatment of b-quark ?)
  - *at more than 2 experimental standard deviations from data for Z+≥1b*
- ***aMC@NLO with NLO ME for Zb and 5FNS, merged to PS, massless b*** in good agreement with Z+≥1b cross section
- LO-multiparton shown without k-factors (ALPGEN 4FNS, SHERPA 5FNS)



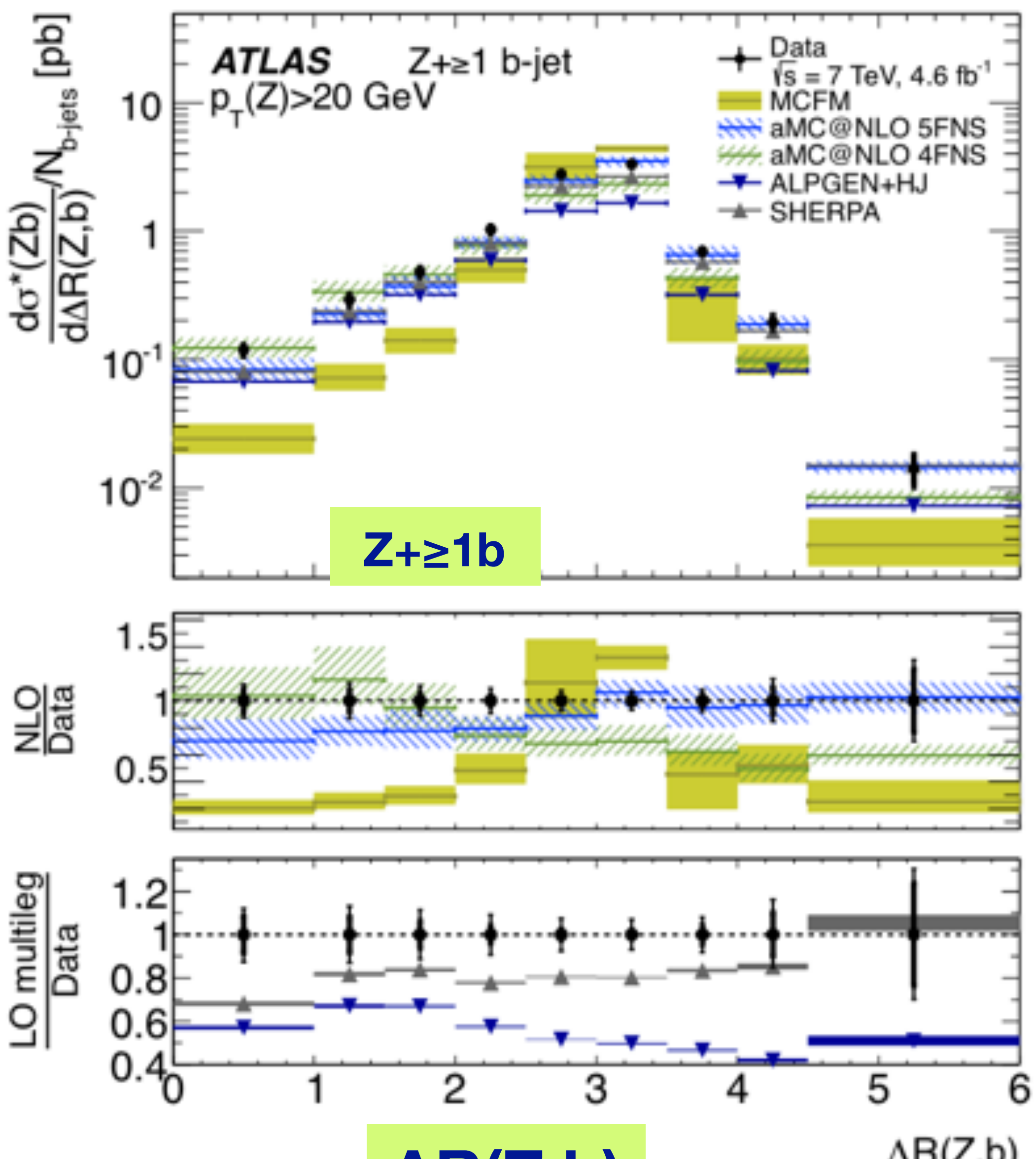
large theory errors dominated by scale dependence



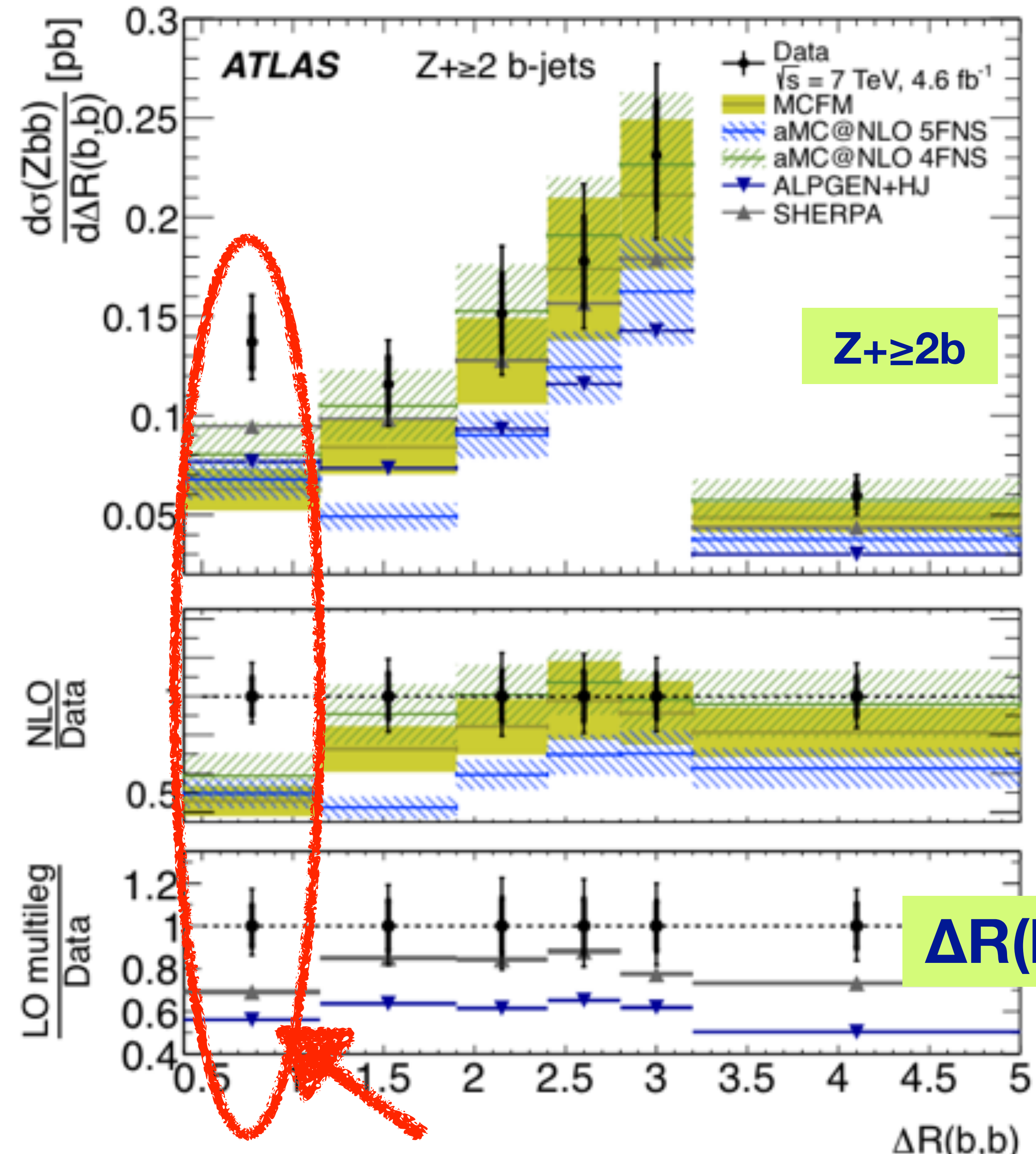
JHEP10(2014)141

Z+b(b) - differential cross sections

generally well reproduced, unless expected, like in angular variables



ΔR(Z,b)



ΔR(b,b)

in Z+≥2bjets interesting excess at low ΔR(bb), seen also by CMS, *testing gluon splitting to b quark pairs*

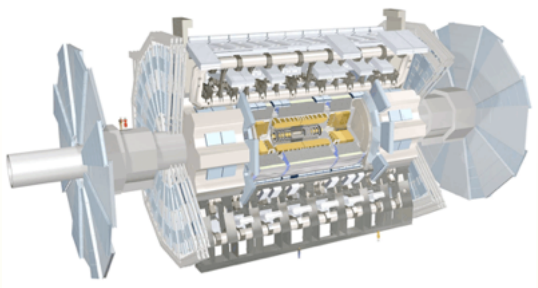
to be followed up in Run 2

Conclusions

- Many interesting results
  - validation of SM background modeling for searches and Higgs physics
  - … but also
    - better understanding of SM processes
    - and many interesting fundamental measurements

More in backup

- **All ATLAS SM results at**
  - https://twiki.cern.ch/twiki/bin/view/AtlasPublic/StandardModelPublicResults



Extra Material

auxiliary slide

Reconstruction and Observables

- Leptons
  - $e^{\pm}$ $p_T > 25$ GeV (20 GeV if Z sel.), $|\eta| < 2.47$ (excluding $1.37 < |\eta| < 1.52$)
  - $\mu^{\pm}$ $p_T > 25$ GeV (20 GeV if Z sel.), $|\eta| < 2.4$
- $W^{\pm}$
  - $E_T^{miss} > 25$ GeV, $m_T > 40$GeV
- Z/γ
  - $66 \leq m_{ll}$ (GeV) ≤ 116, $\Delta R_{ll} > 0.2$
- jets: from energy clusters in the calorimeter processed with the anti-k_T jet finding algorithm with distance parameter R=0.4
  - $p_T > 30$ GeV, $|y| < 4.4$, $\Delta R_{lj} > 0.5$
  - for b-jets, b-tagging based on secondary vertex and properties of tracks originating from it

particle level fiducial cross sections
for detector independent measurements and
easy comparison with theory

in a phase space very similar to reconstruction phase space

e/μ, dressed with γ at $\Delta R < 0.1$: extrapolation to pseudorapidity $|\eta| < 2.5$

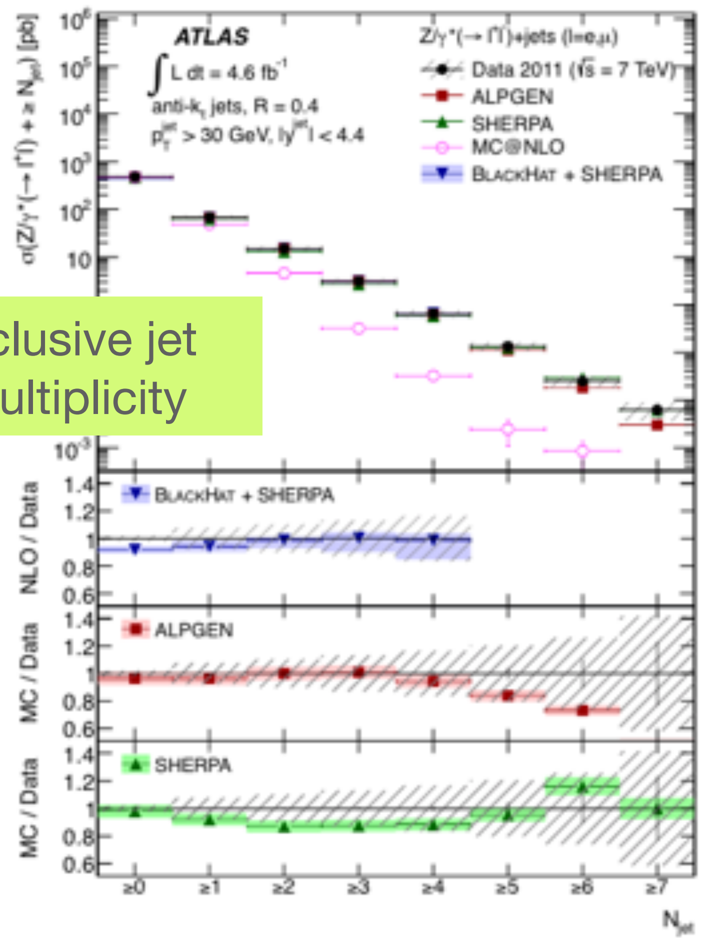
particle jets form all stable particles (excluding dressed-leptons from W/Z) with $c\tau > 10$mm (anti k_T, R=0.4)

Contributions to the observed cross section from multi-parton interactions are included in the signal definition

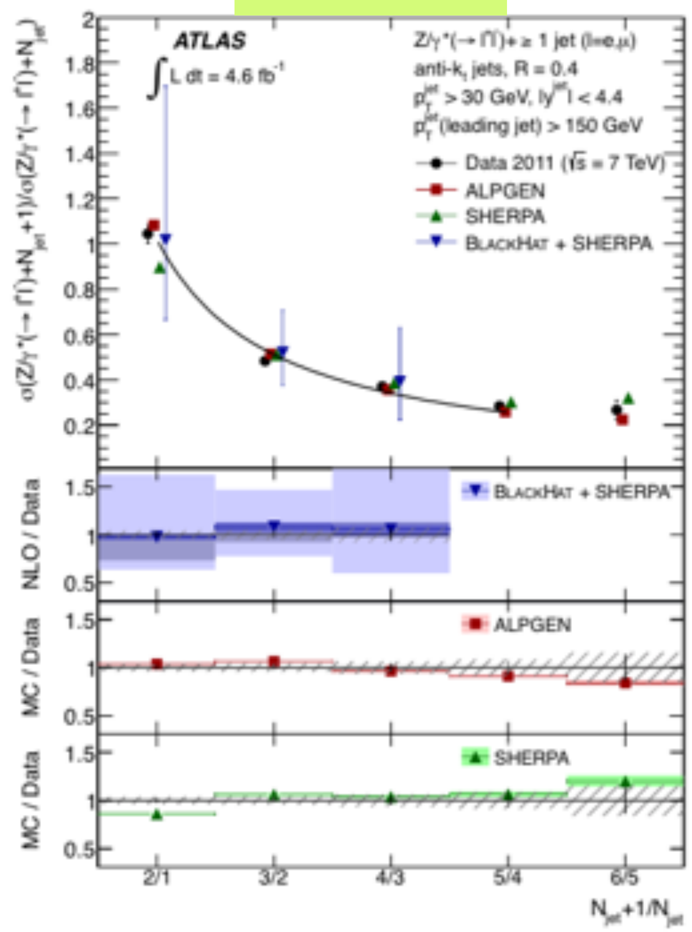
Spring 2013 JHEP07(2013)032

Z+jets not presented in detail here

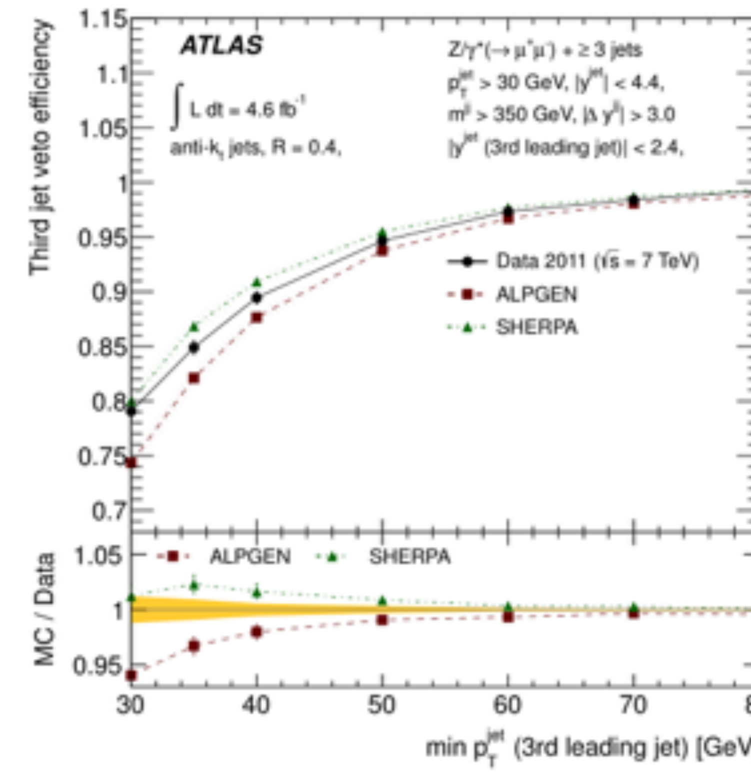
inclusive jet multiplicity



$R_{N+1/N}$



VBF topology; efficiency of veto on central jet



- V+Njet NLO and multi-leg LO matched to parton shower generally give a good description of data
- **MC@NLO (DY at NLO merged to parton shower [HERWIG])** fails to describe data

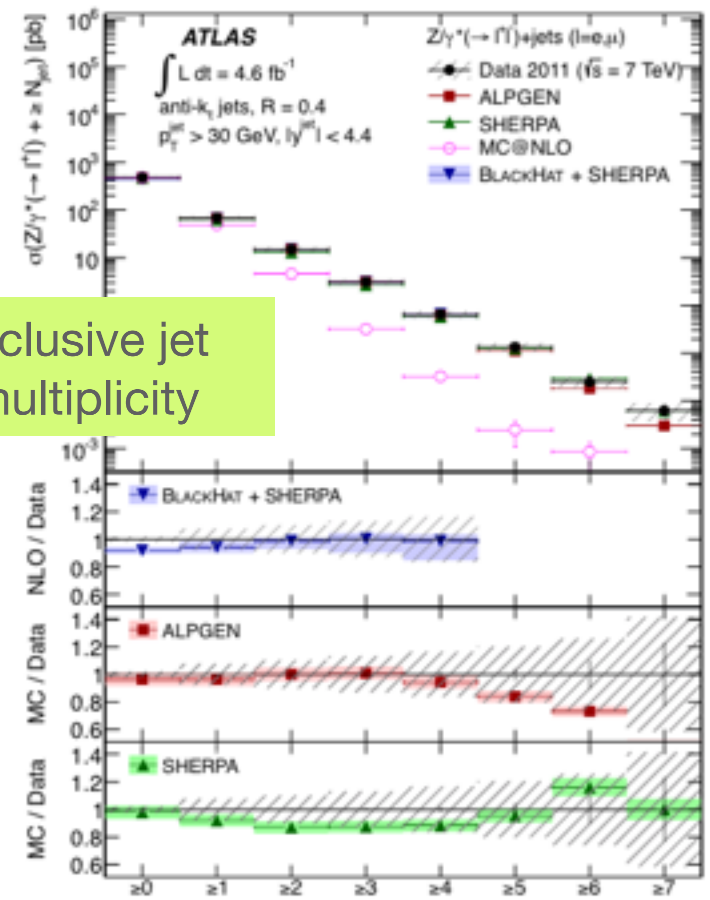
- fundamental features of QCD interactions verified
  - poissonian scaling of exclusive jet multiplicity ratio: **σ[(N+1)jet]/σ[Njet]** for leading jet $p_T > 150$GeV
  - BlackHat+Sherpa and multi-leg in good agreement with data

- **modeling** of Z+jets background in interesting / rare topologies: **Vector Boson Fusion**
  - **ALPGEN** underestimates the efficiency for Z+jets to pass the typical veto on central jets for p_T<60GeV of the vetoed jet

Spring 2013

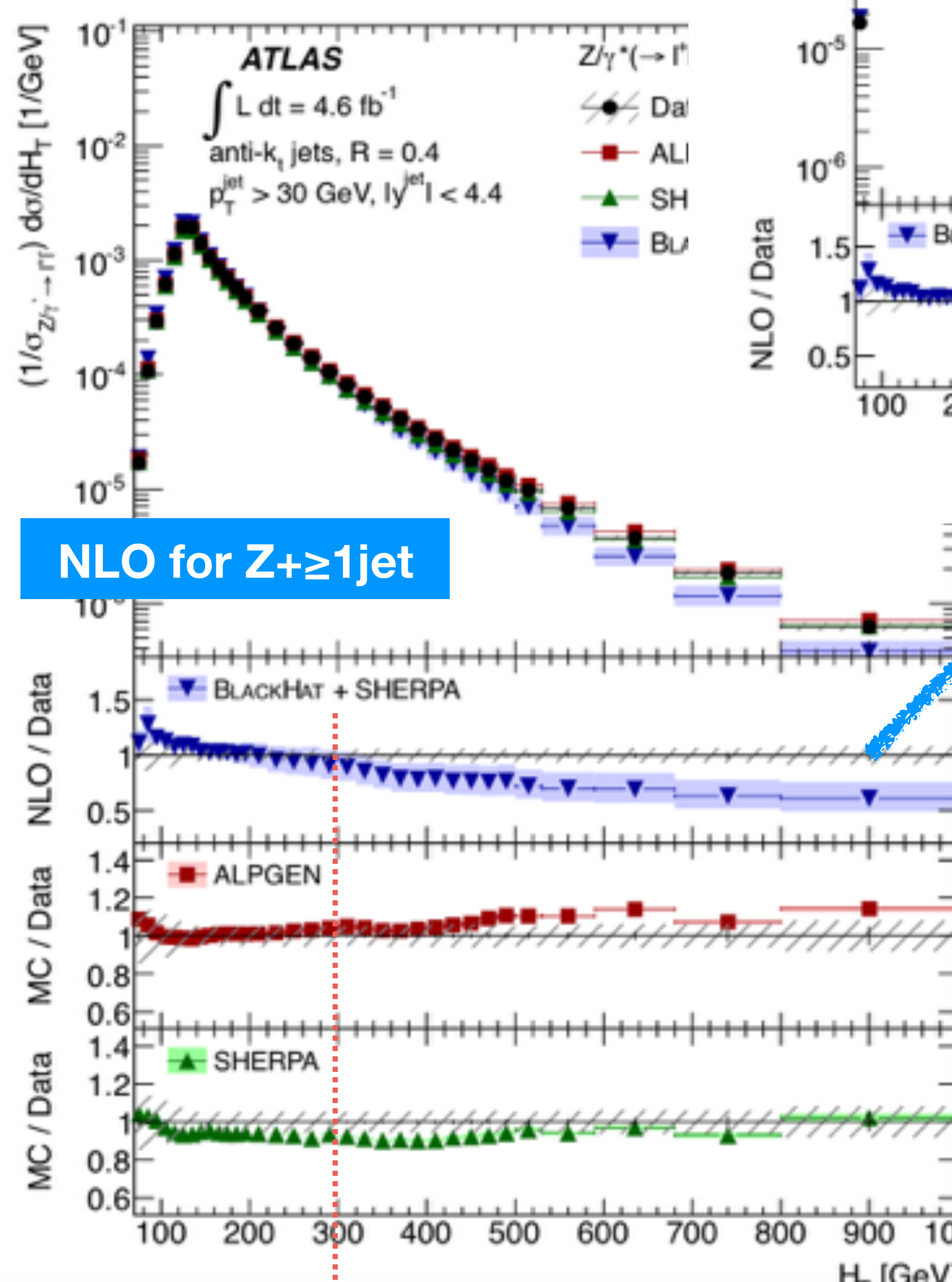
Z+jets legacy

JHEP07(2013)032

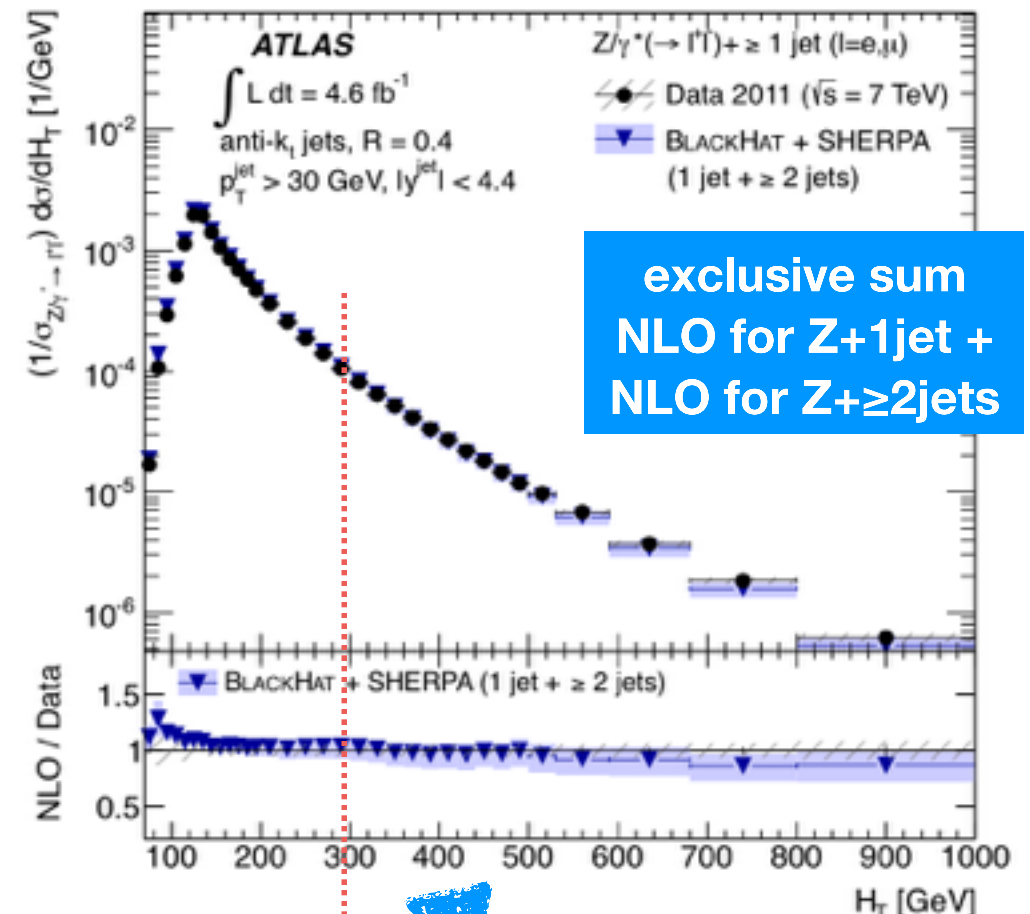


inclusive jet multiplicity

N_{jet}



NLO for Z+≥1jet



exclusive sum NLO for Z+1jet + NLO for Z+≥2jets

- **MC@NLO** (DY at NLO merged to parton shower [HERWIG]) ruled out by data
- **BlackHat+Sherpa** established as benchmark for high/moderate jet multiplicity
  - ***limitations understood***
- ***exclusive sum*** cures the *expected* mis-modeling of inclusive variables, when Njets > n+1(LO + real emission), in predictions for V+≥n jets (most relevant for n=1)
  - *significant discrepancy is seen at* H_T > 300GeV, where $<N_{jets}>$ >2

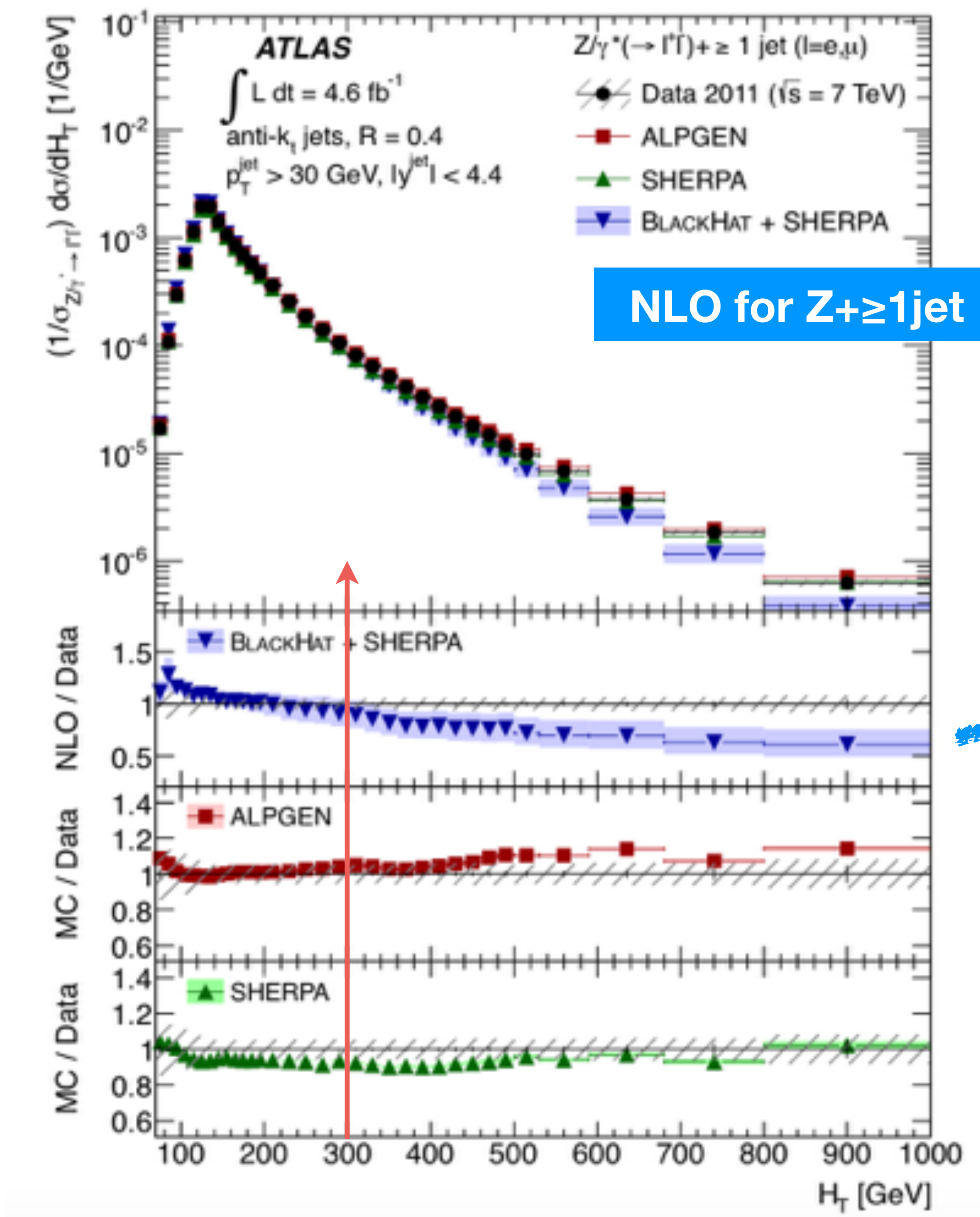
H_T scalar sum of all p_T (including leptons)

Z+jets not presented in detail here

Spring 2013

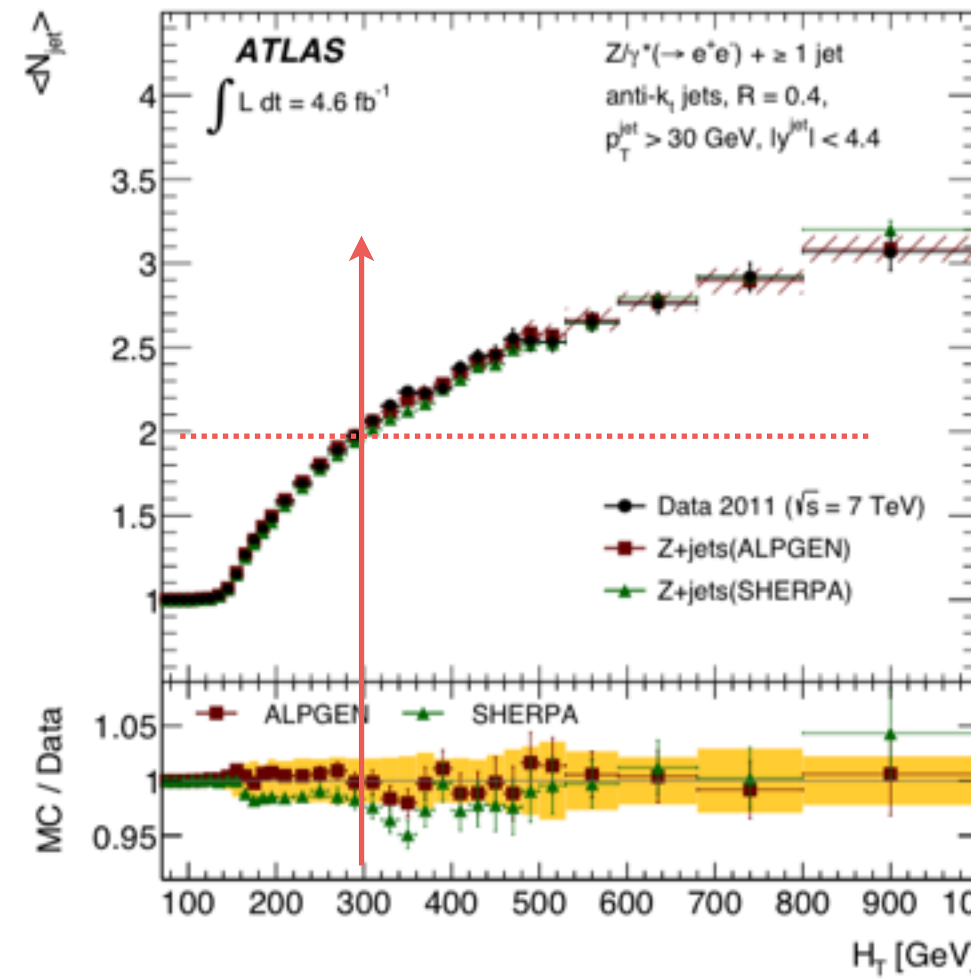
JHEP07(2013)032

H_T scalar sum of all p_T for events with Z+≥1jet



differential cross section normalised to total

<Njets> vs H_T for events with Z+≥1jet



- large discrepancy for HT > 300GeV, where <Njets> >2

- large discrepancy for HT > 300GeV, where <Njets> >2

V+jets: Theory Predictions

- Monte Carlo **ALPGEN** (interfaced to Herwig+Jimmy with AUET2-CTEQ61L and PHOTOS) and **SHERPA** with CT10 (***LO ME for up to 5 partons in the final state in addition to W/Z matched to parton shower***)
  - including all non perturbative (NP) effects of QCD + final state QED radiation; *quoted uncertainty is MC statistics only*
- Parton-level: ***Fixed-order pQCD calculation at NLO (for V+≥1jet and up to V+≥4jet)*** from **BlackHat**+**Sherpa** and CT10 pdf-set

  $\mu_R = \mu_F = H_T / 2$

  virtual one-loop ME | real emission + integration

  - corrections for NP effects from ALPGEN (δ_{had} = ratio of predictions with fragmentation and multiparton interaction on/off, bin by bin of diff. cross sections); SHERPA or ALPGEN+PYTHIA with PERUGIA2011C for systematics; δ_{had} ~3-4% on inclusive jet multiplicity distributions, error added in quadrature to the other sources
  - corrections for QED effects (~2%) from ALPGEN (δ_{FSR} = ratio of predictions with Born-level leptons / dressed leptons); SHERPA (QED FSR with YFS approach) for systematics (~0.1%)
  - ***quoted uncertainty is generator stat. ⊕ μ_R, μ_F uncertainties (dominant term) ⊕ PDF (eigenvectors ⊕ α_s) ⊕ errors on corrections to particle level***

BlackHat+Sherpa
exclusive sum
arXiv:1203.6803 [hep-ph]
(for ≥njets):

prediction for V+n-jet (exclusive) summed to prediction for V+≥(n+1)jets

used in Z+jets, W+jets, Rjets

MEPS@NLO
more rigorous merging of NLO (for W+1j and W+2j virtual contributions from BlackHat) and LO ME (W+up to 4j) + parton shower from Sherpa + fragmentation and full MC

used in W+jets

LoopSim

approximate NNLO prediction for W+≥1jet (missing only non-div. two-loop NNLO term)

used in W+jets

HEJ

approximate ME for W +≥2jets (valid for high Δy_{jets}) resummed to all orders in α_s

used in W+jets

V+jets: Theory Predictions

Program	Max. number of partons at approx. NNLO ($\alpha_s^{N_{\text{jets}}+2}$)	NLO ($\alpha_s^{N_{\text{jets}}+1}$)	LO ($\alpha_s^{N_{\text{jets}}}$)	Parton/Particle level	Distributions shown
LoopSim	1	2	3	parton level with corrections	Leading jet p_{T} and H_{T} for $W + \geq 1$ jet
BLACKHAT+SHERPA	–	5	6	parton level with corrections	All
BLACKHAT+SHERPA exclusive sums	1	2	3	parton level with corrections	Leading jet p_{T} and H_{T} for $W + \geq 1$ jet
HEJ	all orders, resummation			parton level	All for $W + \geq 2, 3, 4$ jets
MEPS@NLO	–	2	4	particle level	All
ALPGEN	–	–	5	particle level	All
SHERPA	–	–	4	particle level	All

- W+jets differential cross section arXiv:1409.8639 auxiliary slide

V+jets: Theory Predictions

Program	
LoopSim	M. Rubin, G. P. Salam, and S. Sapeta, J. High Energy Phys. 1009 (2010) 084, arXiv:1006.2144 [hep-ph]
BlackHat+SHERPA	Z. Bern et al., Phys. Rev. D 88 (2013) 014025, 32. arXiv:1304.1253 [hep-ph]
BlackHat+SHERPA exclusive sums	J. Alcaraz Maestre et al., arXiv:1203.6803 [hep-ph].
HEJ	J. R. Andersen, T. Hapola, and J. M. Smillie, J. High Energy Phys. 1209 (2012) 047, arXiv:1206.6763 [hep-ph]; J. R. Andersen and J. M. Smillie, J. High Energy Phys. 1001 (2010) 039, arXiv:0908.2786 [hep-ph].
MEPS@NLO	T. Gleisberg et al., J. High Energy Phys. 0902 (2009) 40. 007, arXiv:0811.4622 [hep-ph]; S. Hoeche, F. Krauss, M. Schonherr, and F. Siegert, J. 41. High Energy Phys. 1304 (2013) 027, arXiv:1207.5030 [hep-ph].
ALPGEN	M. L. Mangano et al., J. High Energy Phys. 0307 39. (2003) 001, arXiv:hep-ph/0206293 [hep-ph].
SHERPA	T. Gleisberg et al., J. High Energy Phys. 0902 (2009) 40. 007, arXiv:0811.4622 [hep-ph]; S. Hoeche, F. Krauss, M. Schonherr, and F. Siegert, J. 41. High Energy Phys. 1304 (2013) 027, arXiv:1207.5030 [hep-ph].

- W+jets differential cross section arXiv:1409.8639

arXiv:1409.8639

W+jets: sample composition and systematic errors

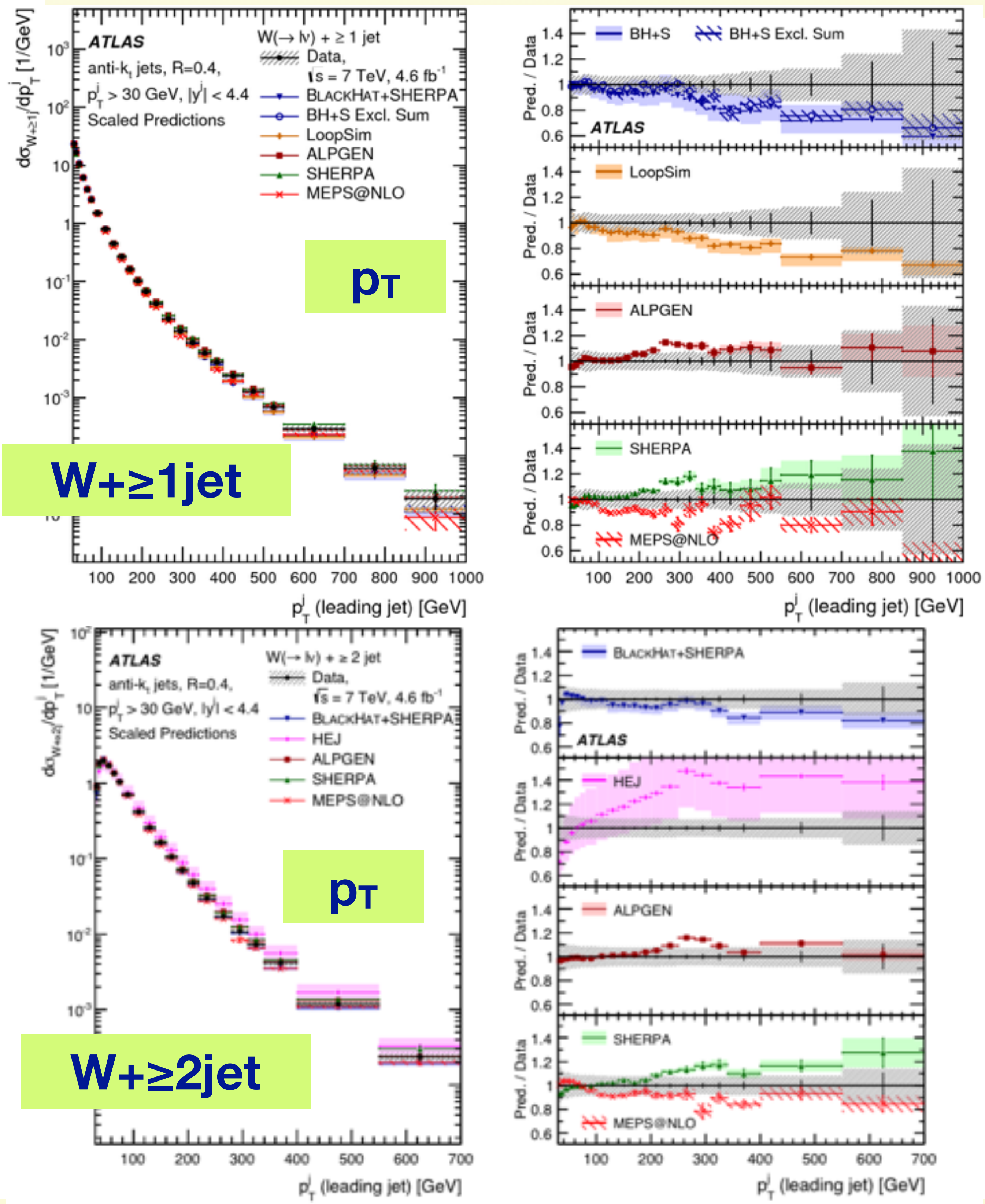
	$W \to \mu\nu$							
$W \to \mu\nu$	93%	82%	78%	62%	40%	25%	17%	11%
Multijet	2%	11%	10%	9%	7%	5%	4%	3%
$t\bar{t}$	$< 1\%$	$< 1\%$	3%	19%	46%	64%	75%	83%
Single top	$< 1\%$	$< 1\%$	2%	3%	4%	3%	2%	2%
$W \to \tau\nu$, diboson	2%	3%	3%	3%	2%	1%	1%	$< 1\%$
$Z \to \mu\mu$	3%	4%	3%	3%	2%	1%	1%	1%
Total Predicted	13 300 000 ± 770 000	1 710 000 ± 100 000	384 000 ± 24 000	96 700 ± 6100	30 100 ± 1600	8990 ± 480	2400 ± 180	627 ± 66
Data Observed	13 414 400	1 758 239	403 146	99 749	30 400	9325	2637	663

($W \to \mu\nu$)								
Muon	1.5%	1.7%	1.7%	1.4%	1.5%	2.1%	3.7%	4.4%
Jets	0.1%	8%	9%	13%	16%	20%	29%	60%
$t\bar{t}$ backgrounds	$< 0.1\%$	0.2%	0.9%	4.1%	11%	26%	47%	60%
Multijet backgrounds	0.1%	0.5%	0.8%	1.4%	2.2%	4.2%	4.6%	9%
$E_{\mathrm{T}}^{\mathrm{miss}}$	0.3%	1.0%	0.9%	1.0%	1.0%	0.6%	0.9%	1.1%
Unfolding	0.2%	1.7%	0.9%	1.0%	1.2%	1.3%	2.6%	11%
Luminosity	1.9%	2.0%	2.0%	2.1%	2.1%	2.1%	2.0%	2.0%
Total Syst.	2.5%	8%	10%	14%	20%	34%	60%	80%

Table 3 Systematic uncertainties on the measured W + jets cross section in the electron and muon channels as a function of the inclusive jet multiplicity in percent.

[arXiv:1409.8639](https://arxiv.org/abs/1409.8639)

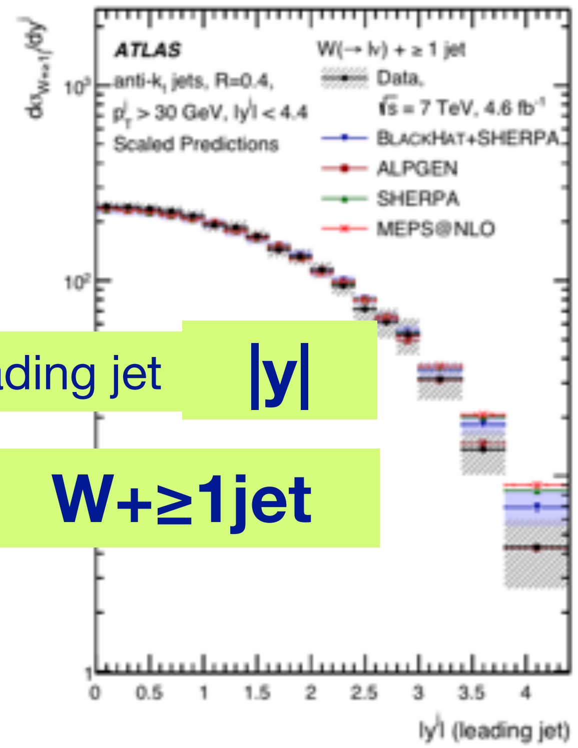
W+jets: p_T of leading jet

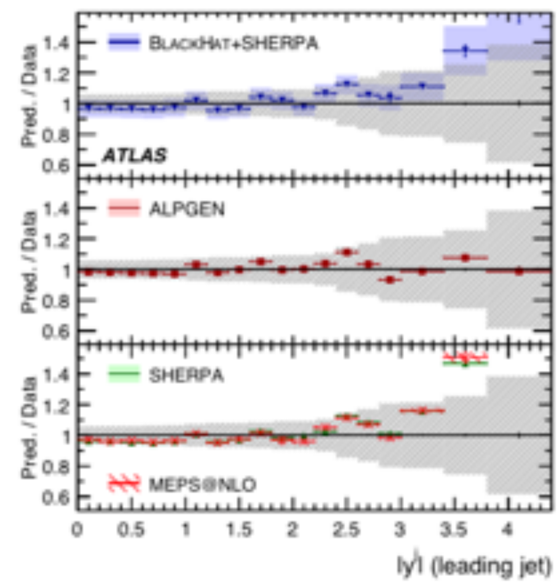


- all predictions inaccurate for p_T > 200 GeV
- **BlackHat+SHERPA** at 2 sigma from data; better in W≥2j
  - **exclusive sum** of does not improve significantly the agreement
- **LoopSim**: at 2 sigma
- best shape from **ALPGEN**;
- **SHERPA** too hard spectrum
- **MEPS@NLO**: better for W+≥2j than W+≥1j
- **HEJ** bad shape in W+≥2j

arXiv:1409.8639

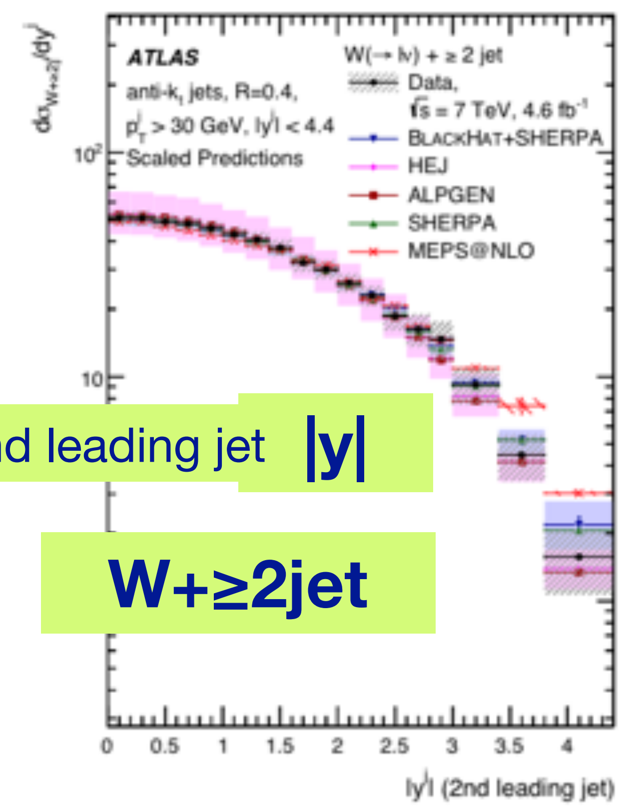
W+jets: jet |y|

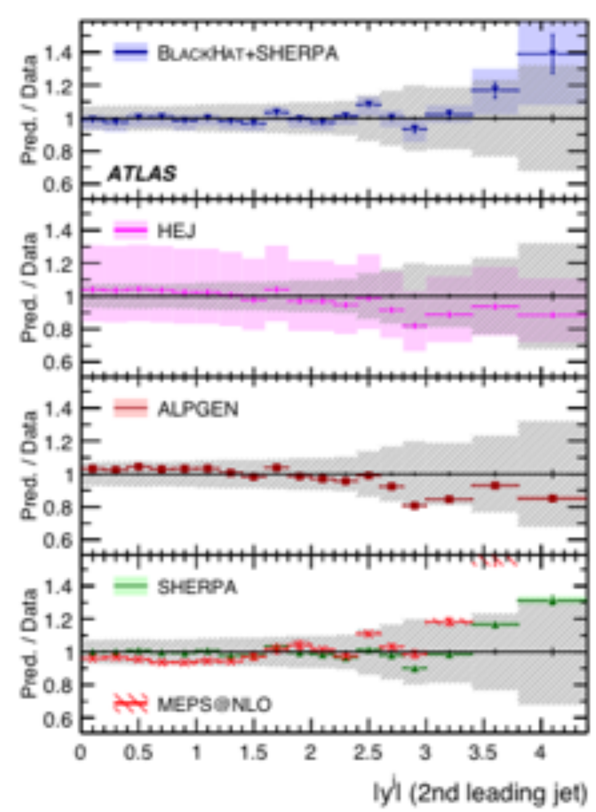




leading jet |y|

W+≥1jet



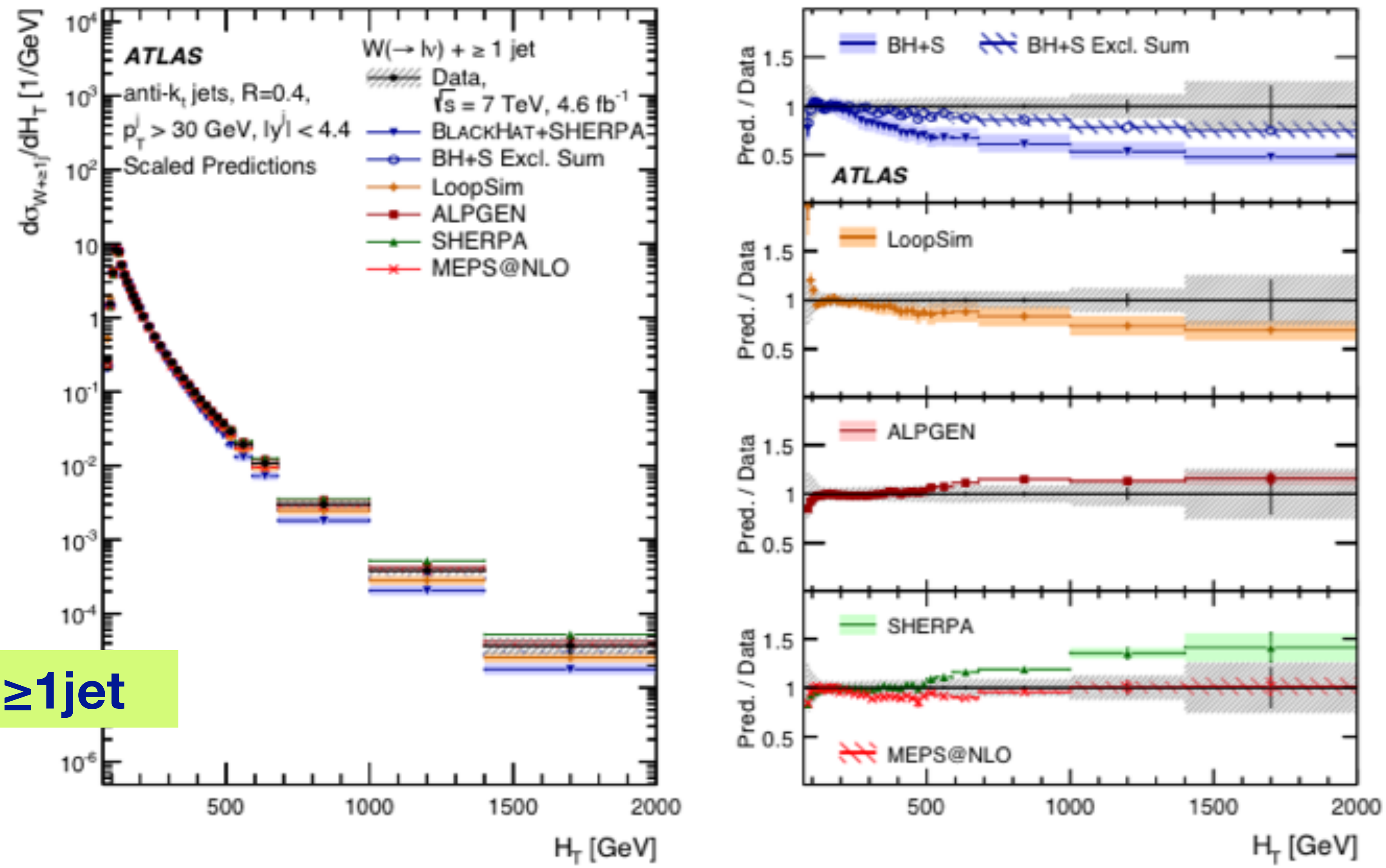


2nd leading jet |y|

W+≥2jet

- **SHERPA** too wide |y| distribution w.r.t. data (same feature in **BlackHat+SHERPA** and **MEPS@NLO**
- difference w.r.t. **ALPGEN** have been investigated:
  - ALPGEN reweighed to the NLO pdf set used by SHERPA (CT10) do not exhibit the feature
- ***high rapidity jets are generated by parton shower (different between ALPGEN and SHERPA)***

W+jets: global variables S_T



W+≥1jet

S_T

S_T scalar sum of all jet p_T for events with W+≥1jet

- **BlackHat+SHERPA *exclusive sum*** improves **BlackHat+SHERPA** for W+≥1jet; similar accuracy of **LoopSim**
- **ALPGEN** within 1 sigma from data, better than **SHERPA**
- **MEPS@NLO** very good at high H_T, in spite of some mis-modeling at low H_T

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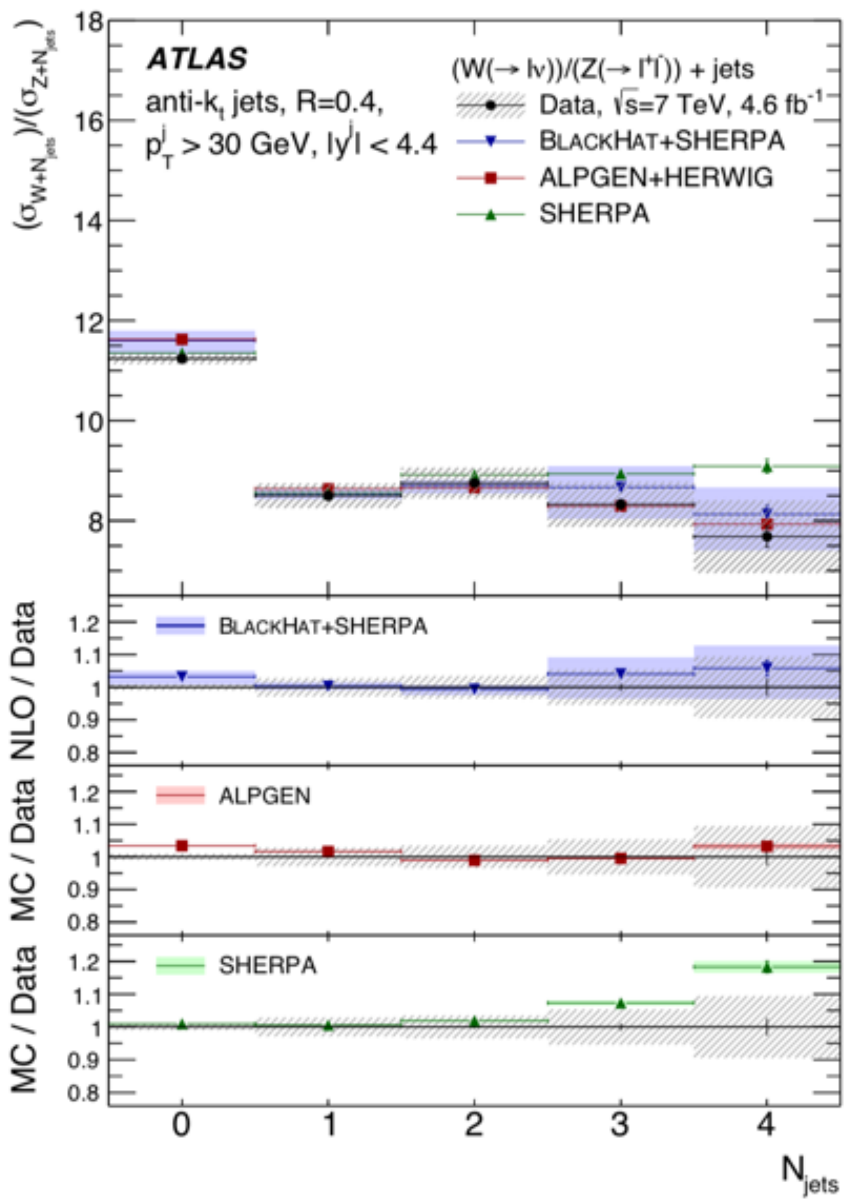
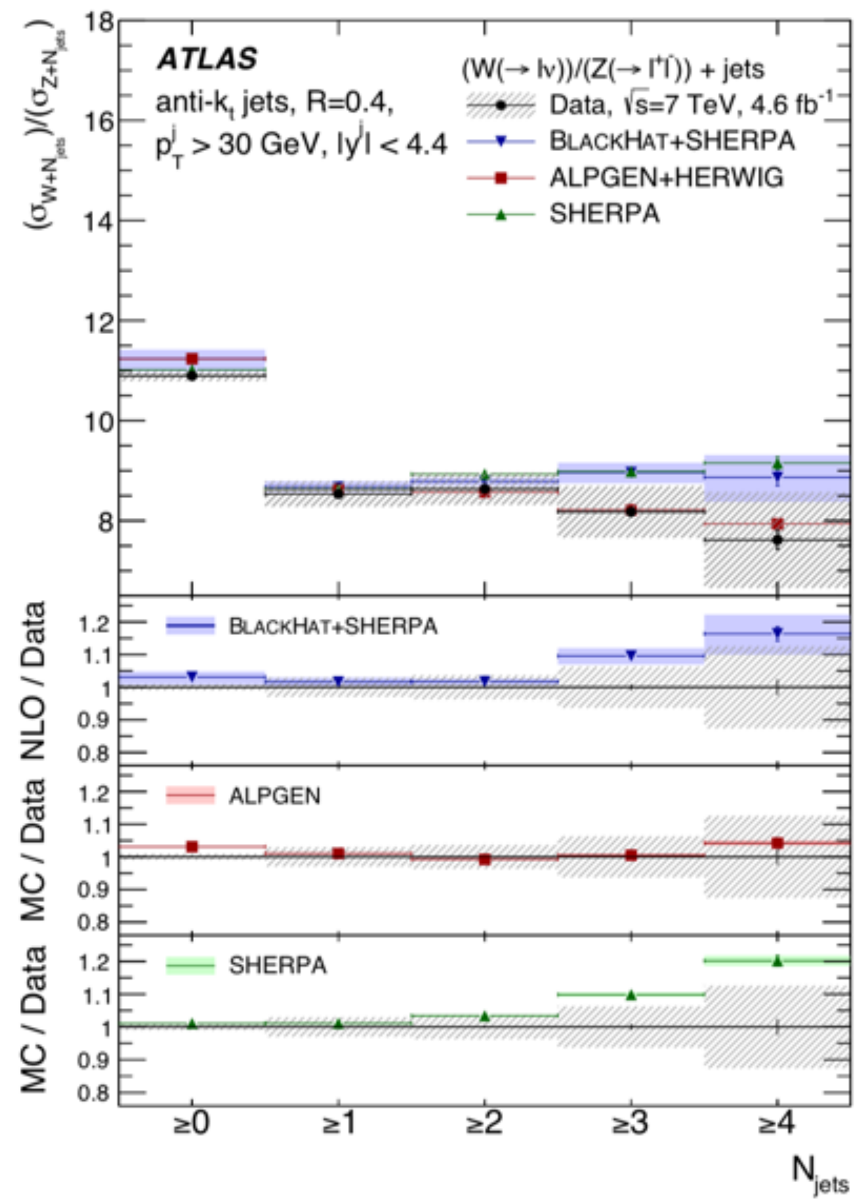
R_{jets} as a function of jet multiplicity



R_{jets} vs exclusive jet multiplicity



R_{jets} vs inclusive jet multiplicity

- **BlackHat +SHERPA** at 1 sigma (experimental error) from data at high inclusive jet multiplicity
- **ALPGEN** in good agreement with data
- **SHERPA** too large Rjets at large multiplicity

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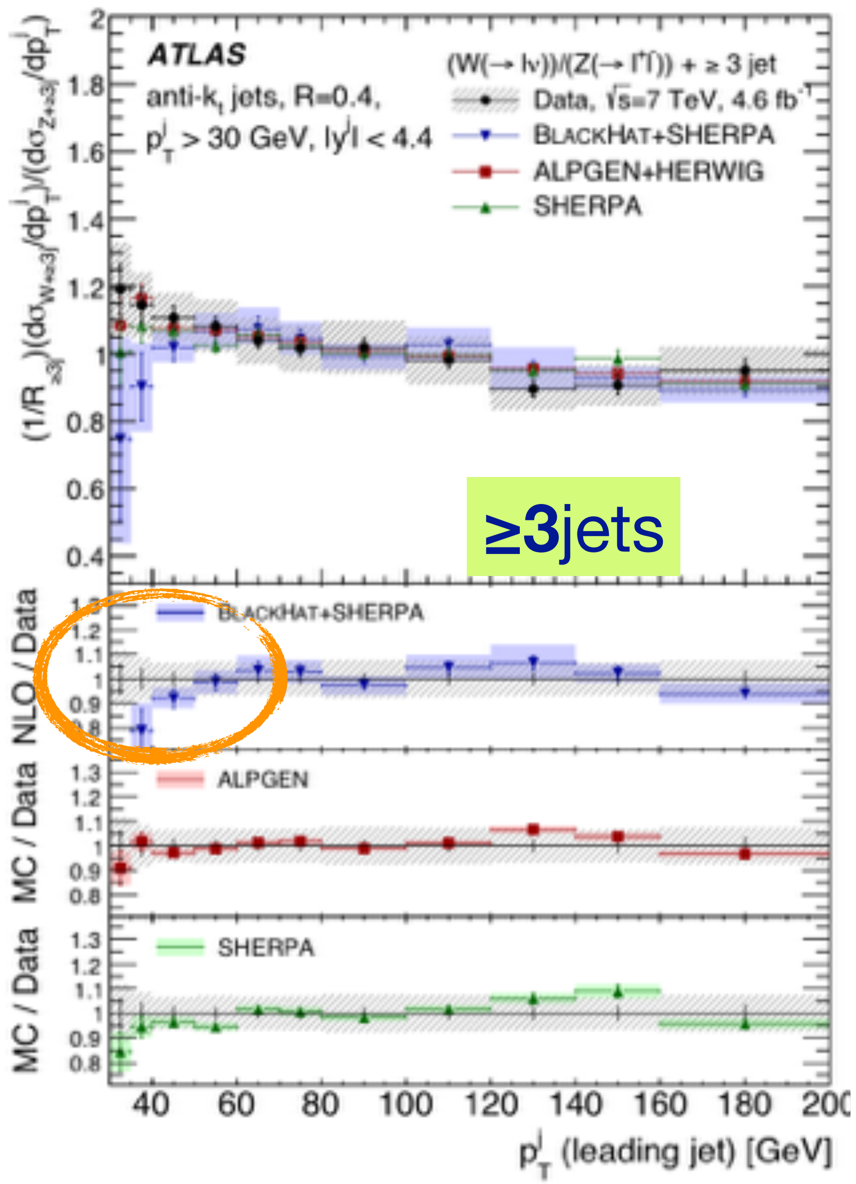
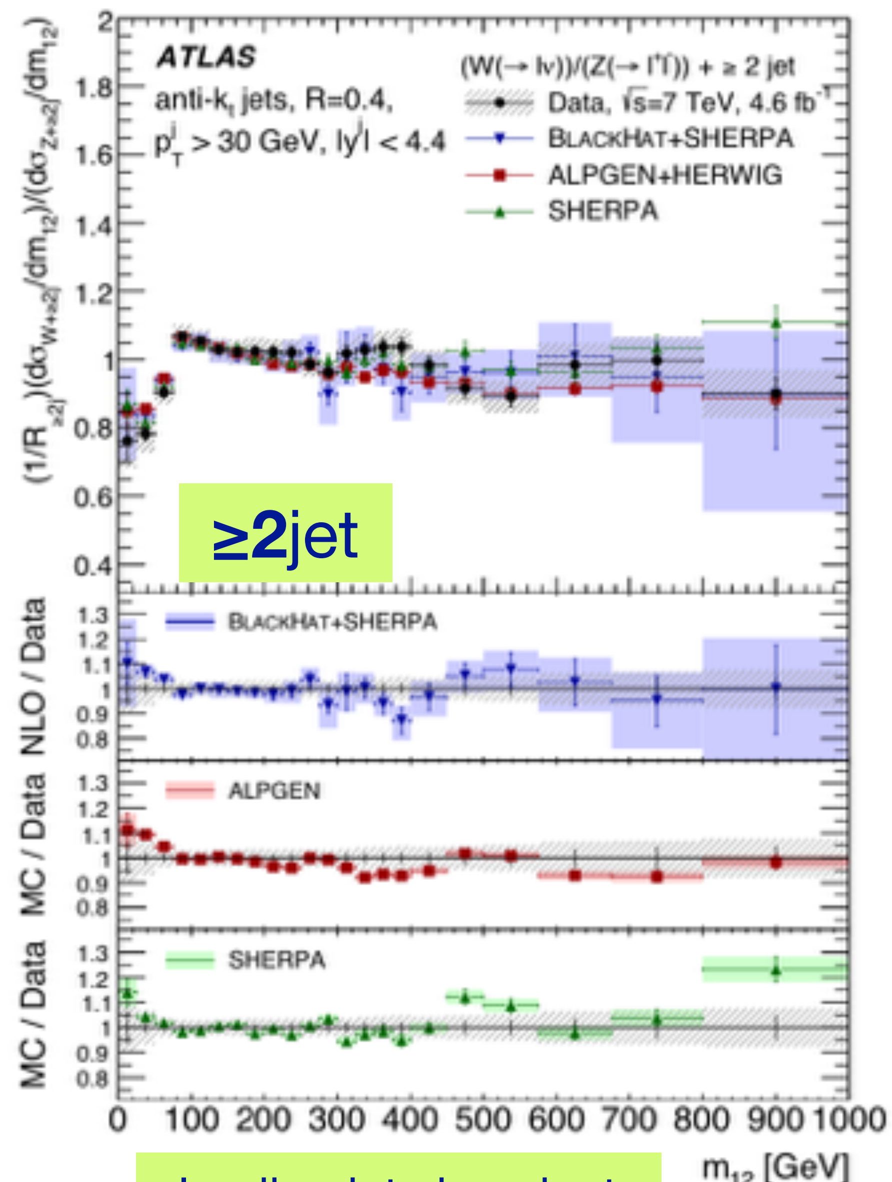
R_{jets} as a function of p_T^{jet} and shape variables

The data/theory discrepancies observed in W+jets and Z+jets are cured by the ratio

- **leading jet p_T** described well over a wide range for N>=1jet and N>=2 jets
  - some mismodeling at low p_T for N≥3jets in **BlackHat+SHERPA** (missing resummation of soft and collinear radiation)
- shapes and global variables OK



leading jet p_T (N≥3jets)



leading jets invariant mass (N≥2jets)

A successful validation with data of state-of-the-art NLO pQCD predictions by BlackHat+SHERPA (as good as tuned Monte Carlo over a wide phase space)

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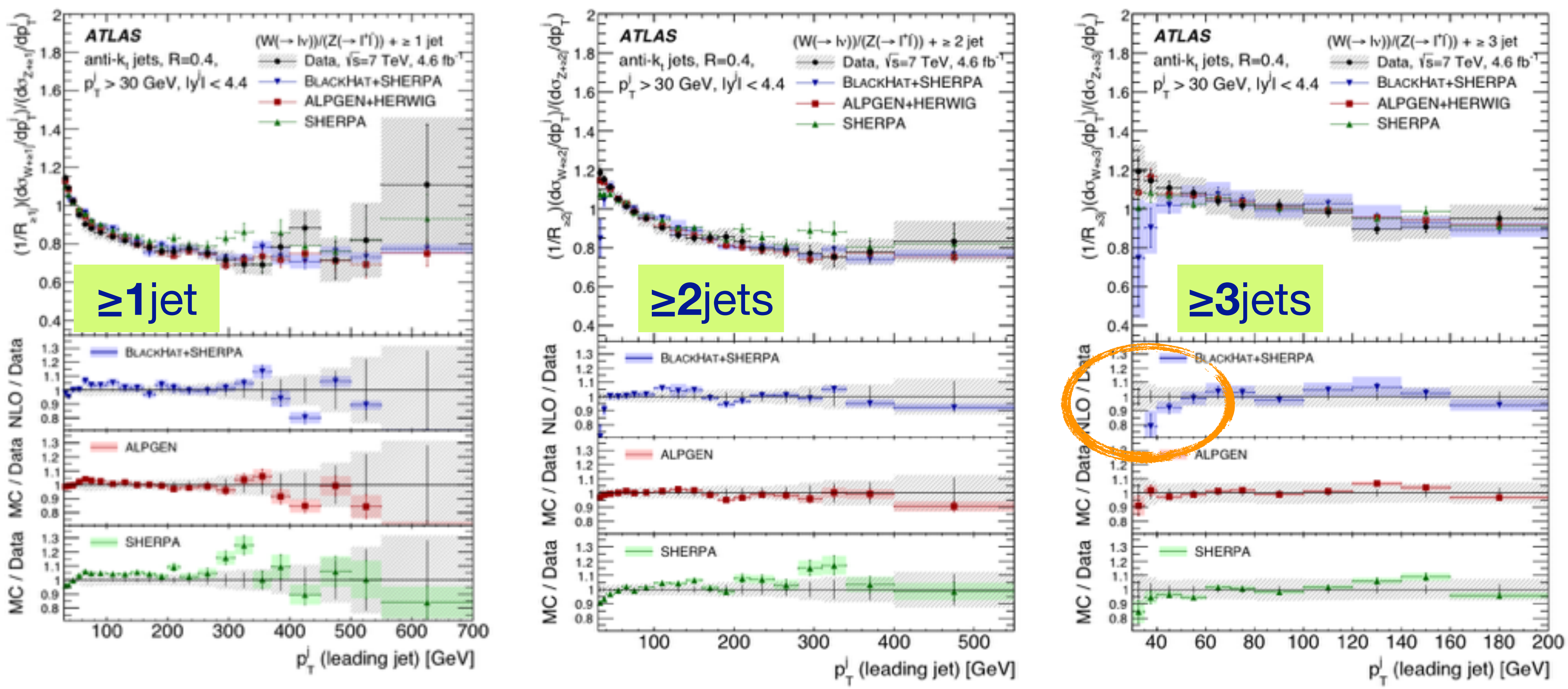
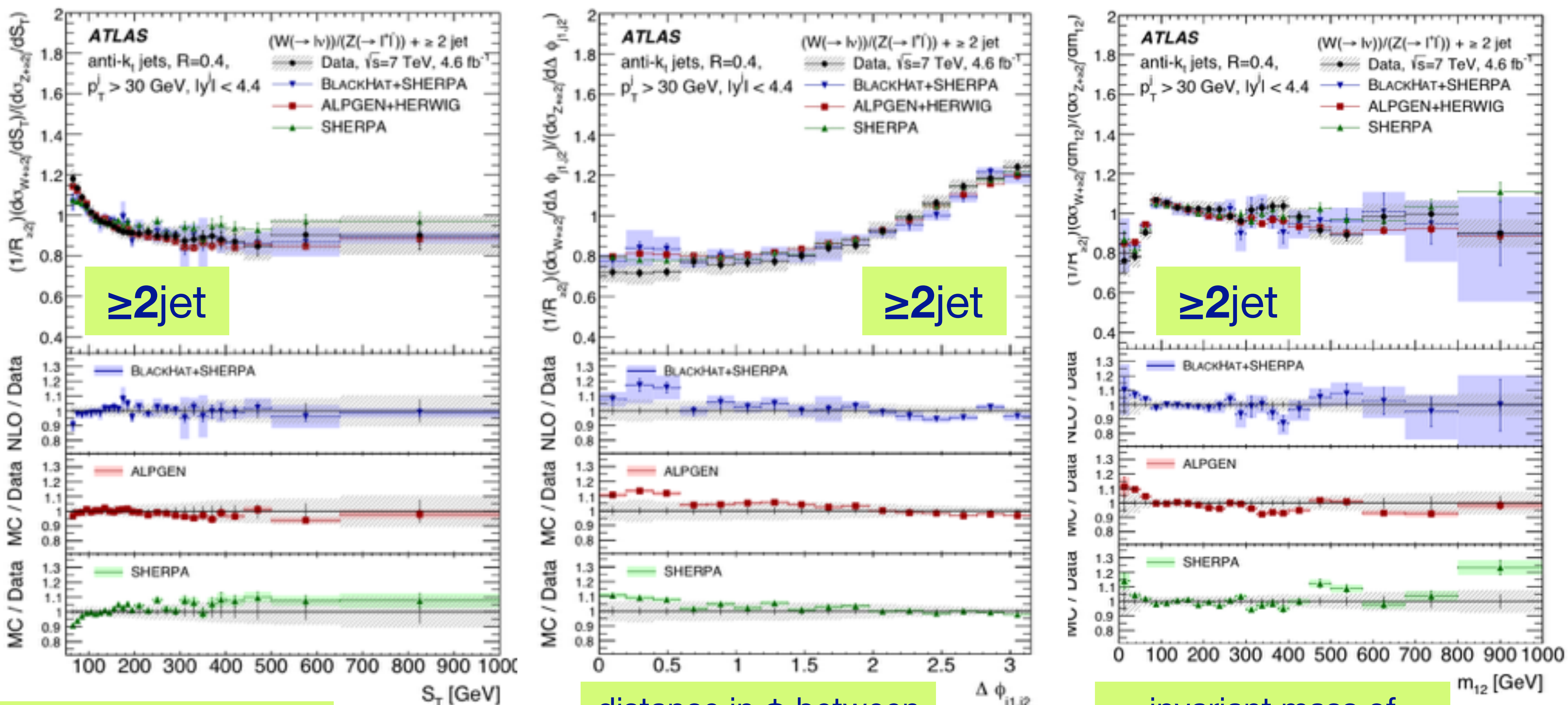
R_{jets} as a function of leading jet p_T



- **leading jet p_T** described well over a wide range for N>=1jet and N>=2 jets
- some mismodeling at low p_T for N≥3jets (particularly for the **BlackHat +SHERPA** caused by missing resummation of soft and collinear parton emission

R_{jets} as a function of global and shape variables



scalar sum of jet p_T

distance in ϕ between the two leading jets

invariant mass of the two leading jets

In summary, a successful validation with data of state-of-the-art NLO pQCD predictions for W+Njets/Z+Njets by **BlackHat+SHERPA** (as good as tuned Monte Carlo over a wide phase space)

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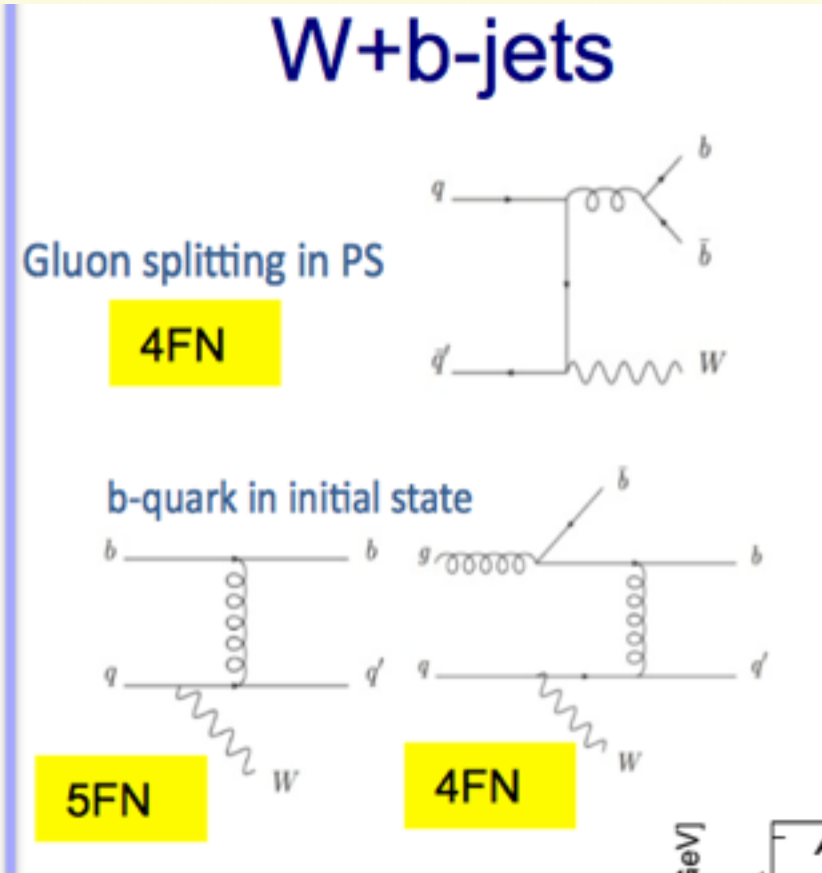
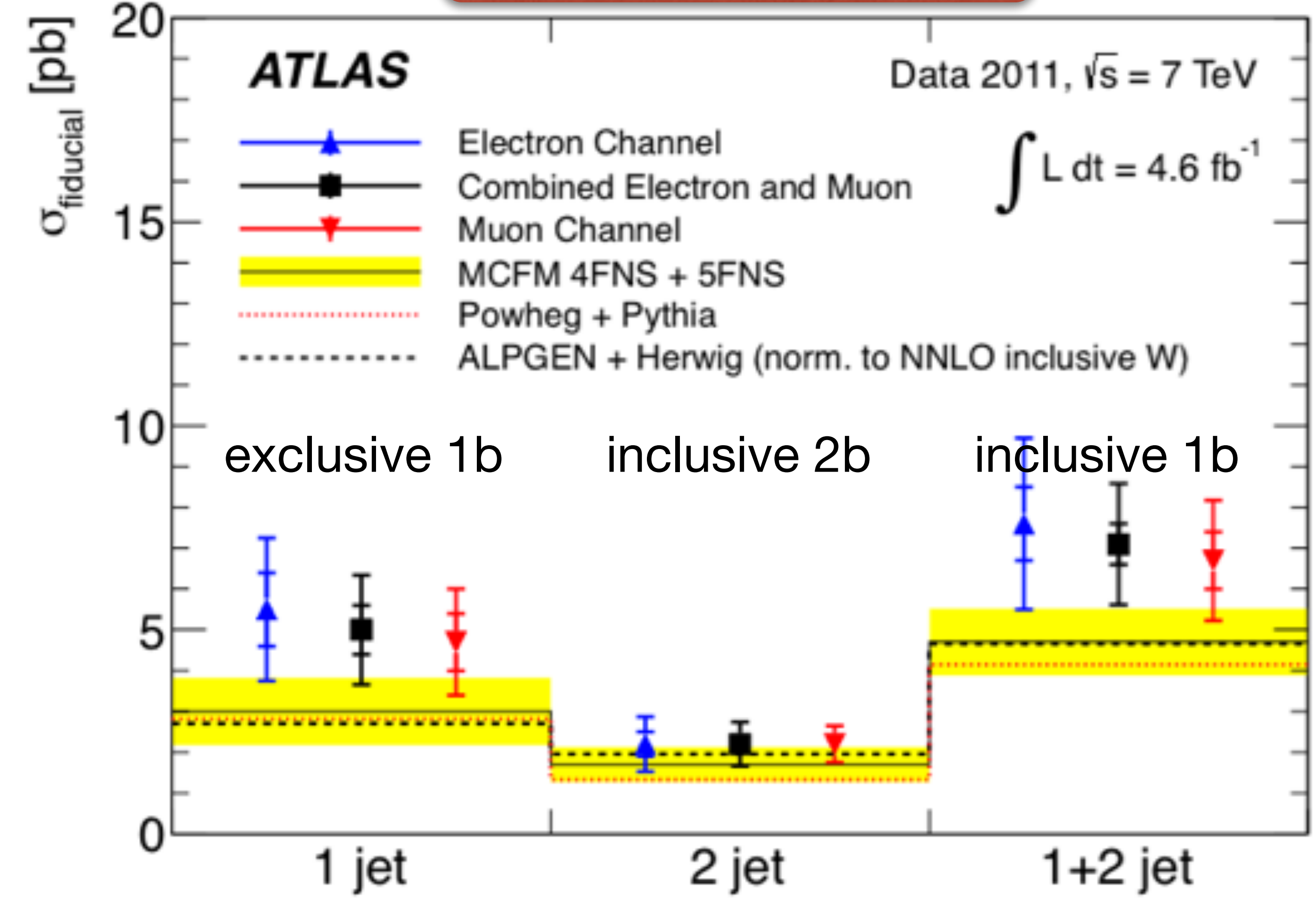
W+bb

qq→Wbb

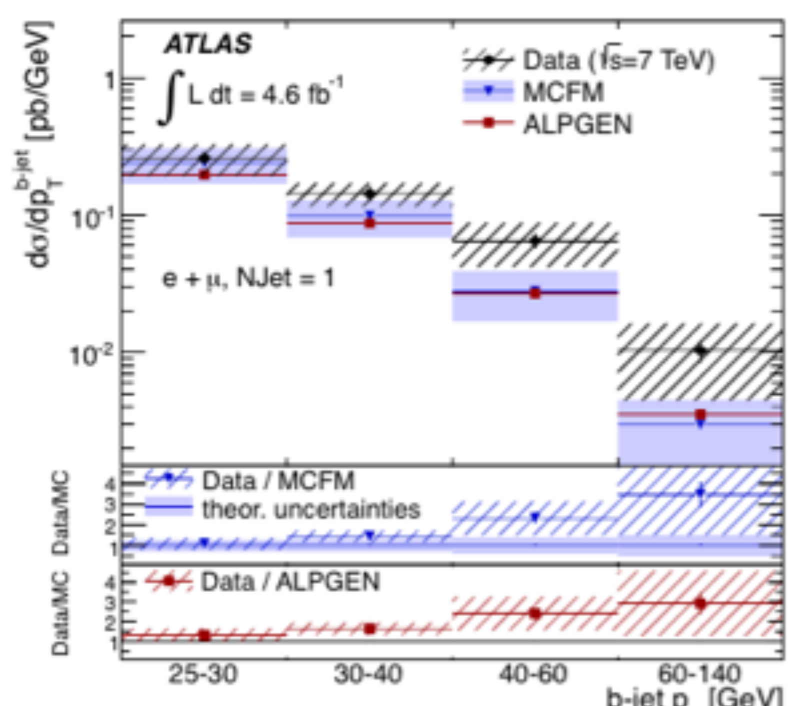
bq→Wbq
gq→Wbbq



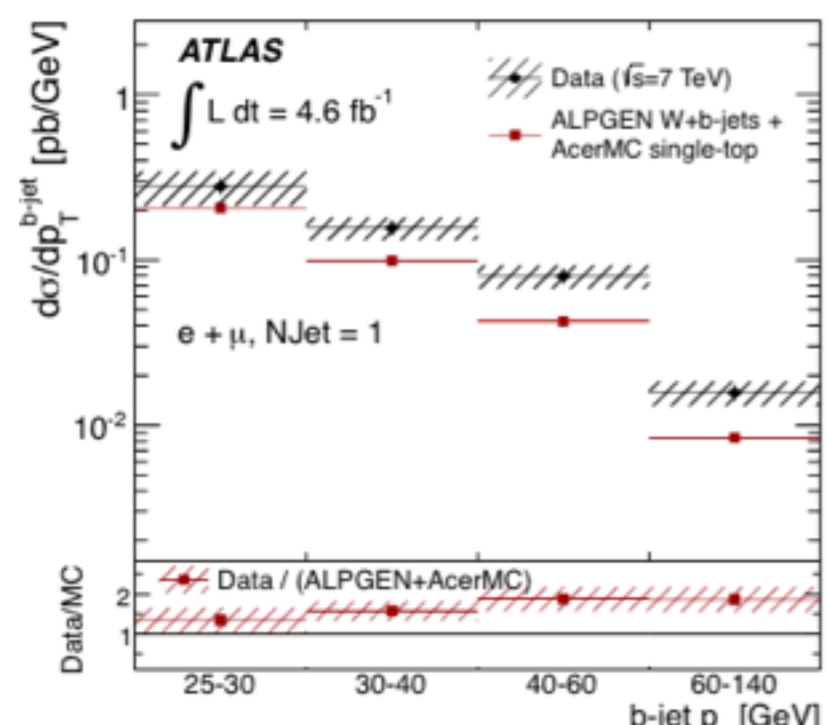
single top subtracted



- important background to WH(bb)
- MCFM NLO 5FNS +4FNS Powheg NLO 4FNS



single top subtracted

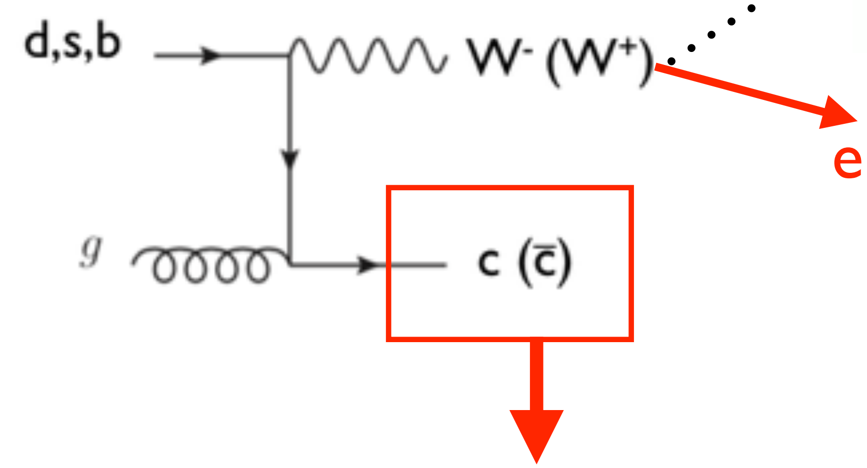


single top included

W+charm

JHEP05(2014)068

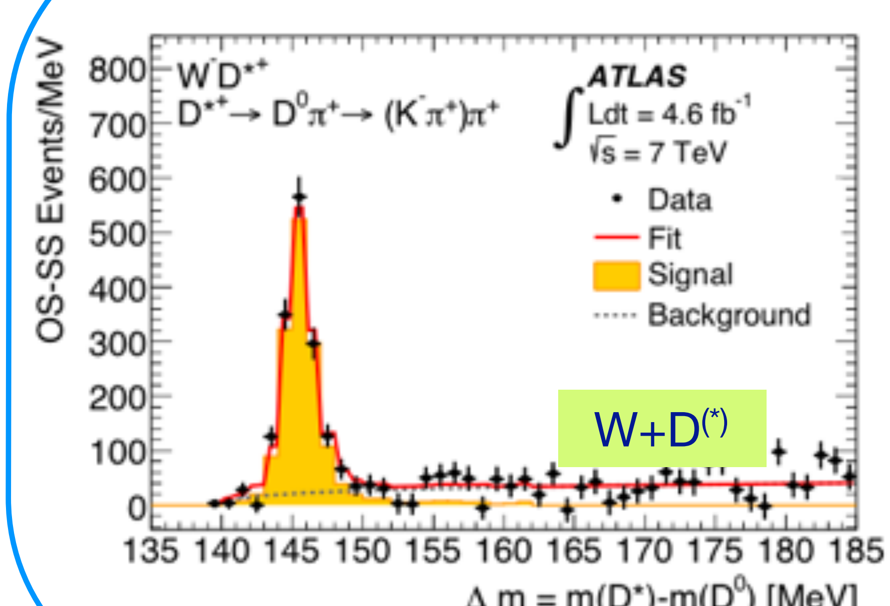
- Total cross section and dσ/dη (of the lepton from W)
- Leading order process: sg ➛Wc a direct probe of the s,s-bar content of the proton
- main systematics:
  - tracking efficiency and modeling , c-fragmentation and decay , background, Branching Ratios

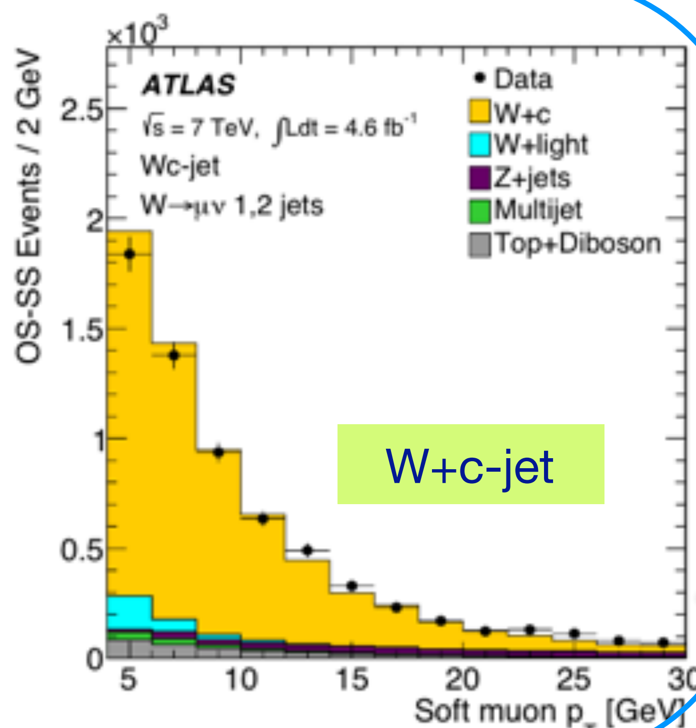


A) soft-μ in a jet from semileptonic c decay
or
B) a decay chain of $D^{\pm}$, $D^{\pm *}$

(in both cases **charge anti-correlation** with the lepton from the W allows to reduce the background)

examples of OS-SS yield



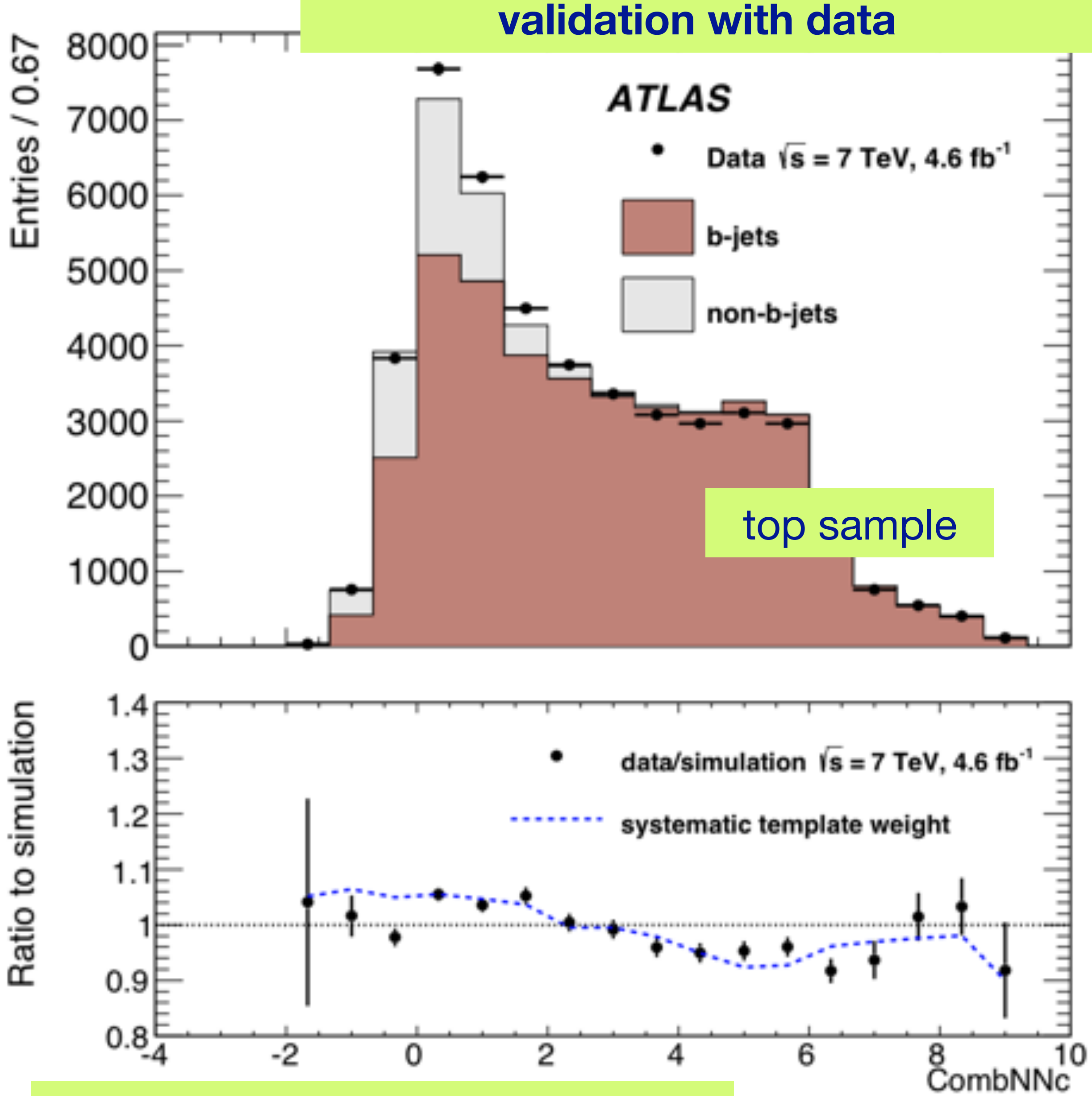


W+c yield from OS-SS selection

Z+b(b) - Reconstruction

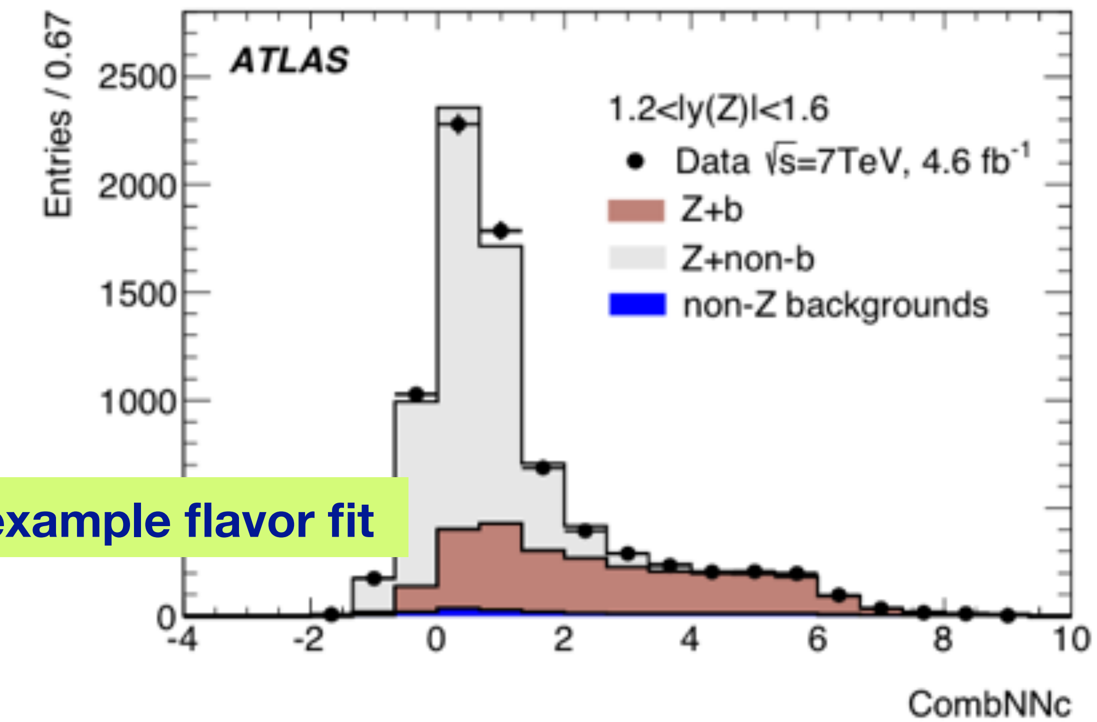
- **fit to distributions of flavor-sensitive discriminant** (predicted by simulation) to separate Z+b from contamination of Z+c and Z+light

validation with data



top sample

diff.s to MC used for systematics



example flavor fit

main sources of experimental systematic uncertainty

- ☐ uncertainty on **flavor-sensitive discriminant** (predicted by simulation and validated with data)
- ☐ b-tagging efficiency

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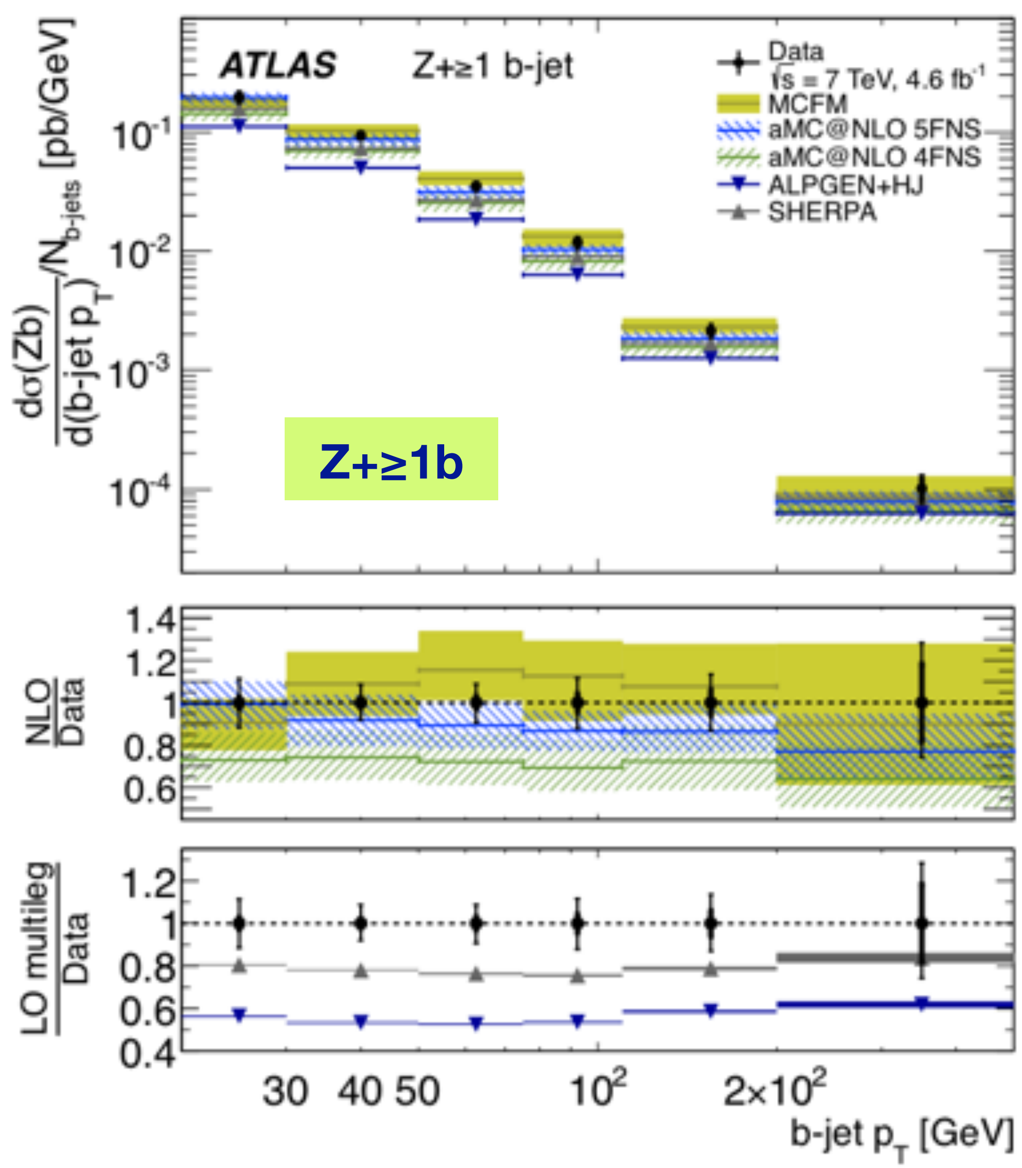
Z+b(b) - More on Predictions



$\mu_R = \mu_F = \text{sqrt}[\, M(Z)^2 + p_T(Z)^2 \,]$

in all NLO predictions

- Theory predictions:
  - **fixed order NLO** predictions for Zb and for Zbb (parton level) **MCFM** [5FNS always used]+ *corrections to particle level*
    - *various NLO PDF sets tested:* CT10, NNPDF2.3, and MSTW2008
  - Monte Carlo (aMC@NLO+Herwig) based on
    - **NLO ME for Z+≥1b-jet in 5FNS**, massless b
      - a LO prediction for Z+≥2b-jets can be derived, in addition to the NLO prediction for Z+≥1b-jet
    - **NLO ME for Z+≥2b-jets in 4FNS** merged to parton shower
      - fully massive b-quark treatment in ME allows for no kinematic cuts on b-jets: samples can be used to extract predictions for Z≥1b-jet (at NLO in 4FNS) in addition to Z+≥2b-jets
- Multi-leg MC matched to parton shower **ALPGEN** (4F-NS) and **SHERPA** (5F-NS)

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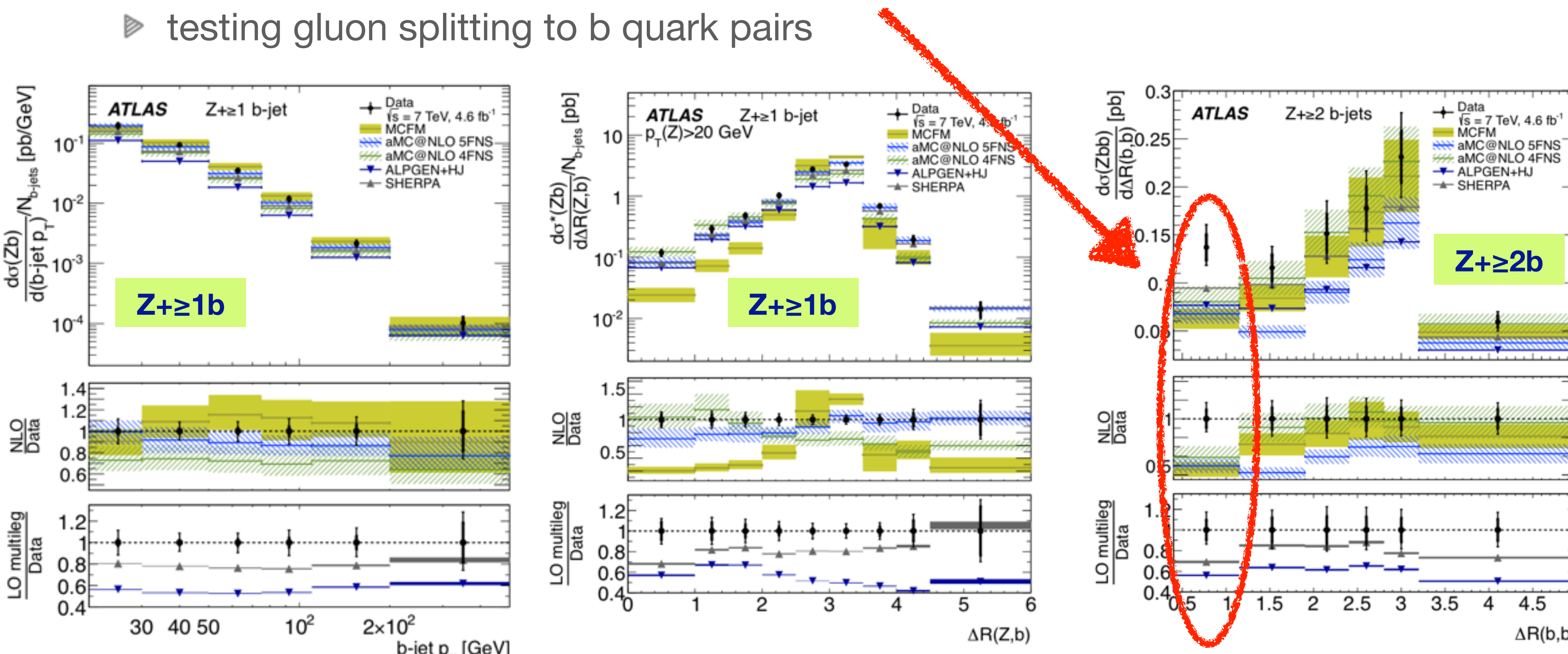
Z+b(b) results

- Differential cross sections
  - generally well reproduced, unless expected (angular variables need higher order corrections, fixed order NLO clearly not enough, multileg still not optimal)
  - in Z+≥2bjets interesting excess at low ΔR(bb)
    - testing gluon splitting to b quark pairs



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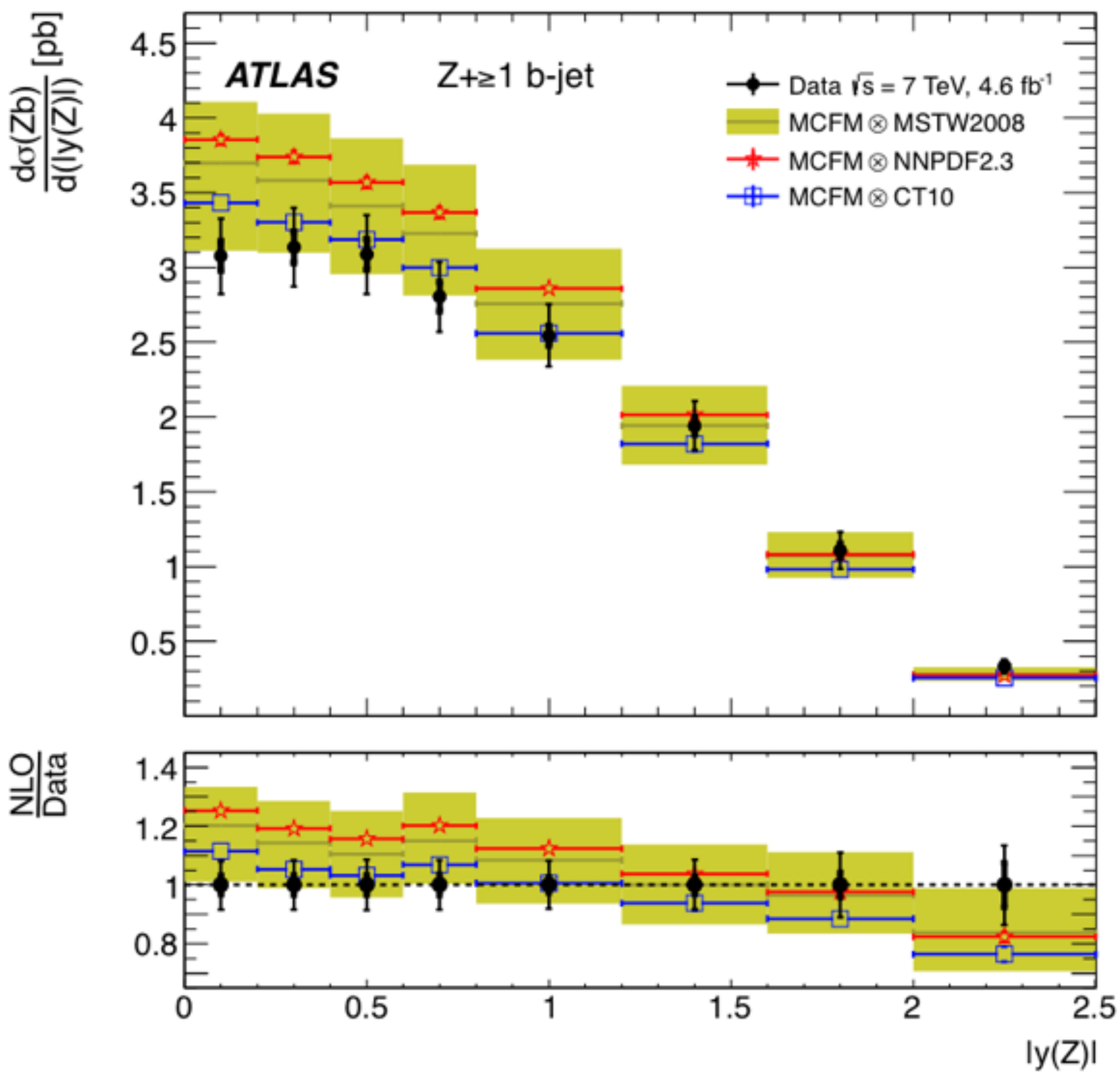
Z+b(b) input to PDF



Any sensitivity to PDF ?

- experimental error is small enough to observe possible patterns
  - for Z+≥1b-jet some indication can be seen in y(Z)
- large theory errors, dominated by scale dependence, cover the entire range of variations