Associated production of a vector boson and jets with ATLAS and CMS

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On the behalf of the ATLAS and CMS Collaboration

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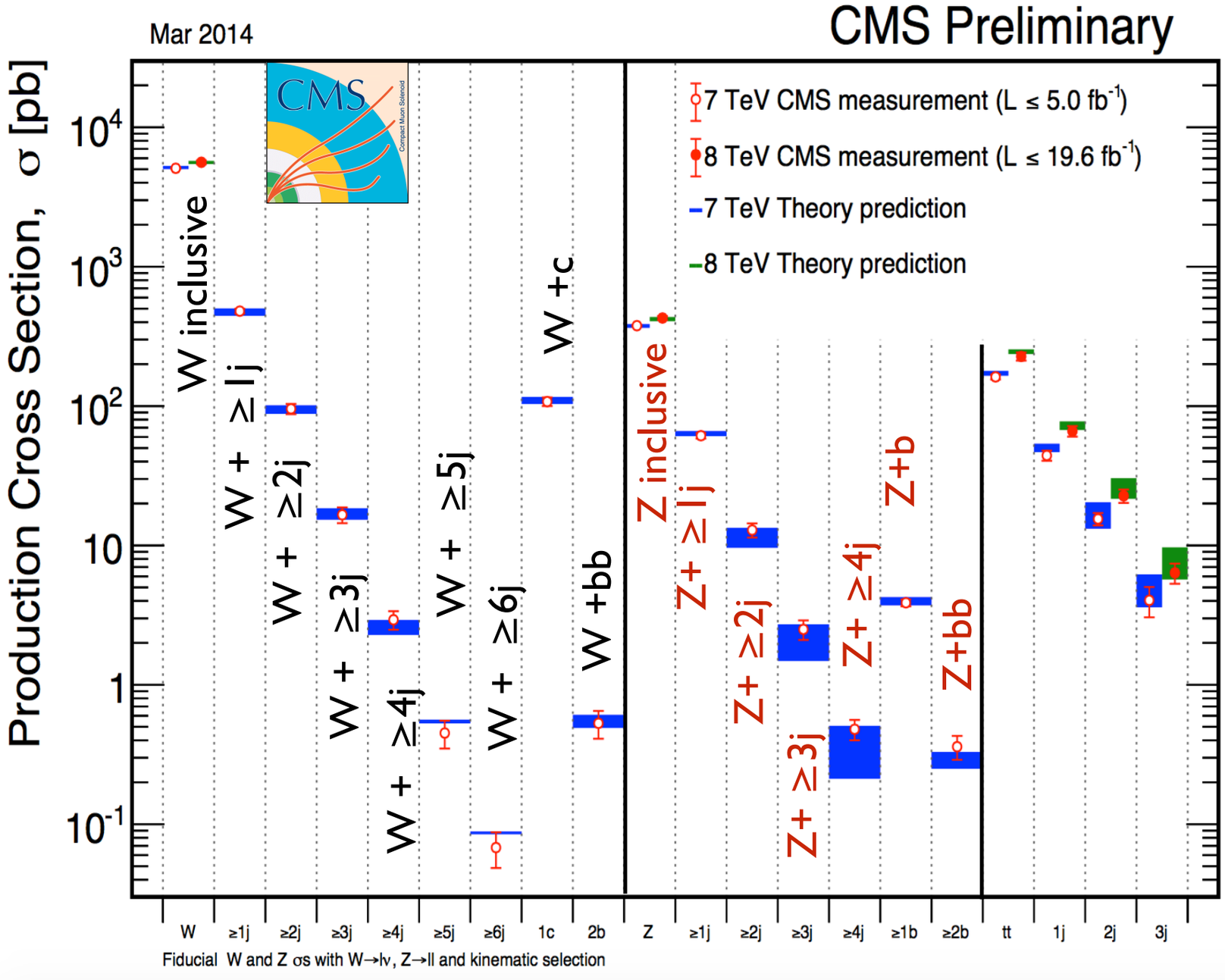
Vector bosons + jets at LHC

Physics of V(=*W/Z/γ*) + jets is an essential part of ATLAS/CMS physics program



- powerful tool to deeply test the perturbative **QCD predictions**:

  - PDFs

  - new generation MC generators

  - NLO effects

  - Flavour schemes, b/c mass effects

- **Higgs and BSM background**

  - *HZZ, HWW,* SM backgrounds

  - SUSY with hadronic final states constraining MET modelling

  - 4th generations of heavy quarks

  - 2HDMs

<u>Very good agreement for inclusive V+jets cross sections at 7 and 8 TeV in ATLAS and CMS</u>

$W + jets$

$\int Ldt = 4.6\,\text{fb}^{-1}$ $\sqrt{s} = 7$ TeV

[EPJC 75:82 (2015)]

selection criteria

- isolated electron(muon) $p_T > 25$ GeV $|\eta| < 2.47(2.4)$

- ≥1 antiKT04 jet with $p_T > 30$ GeV, $|y| < 4.4$

- $MT(\mu, \not{E}_T) > 40$ GeV and $\not{E}T > 25$ GeV

backgrounds

- ***tt*** (high multiplicities, ~80% of 7jets)
- ***QCD*** (low multiplicities 11% of 1jet)

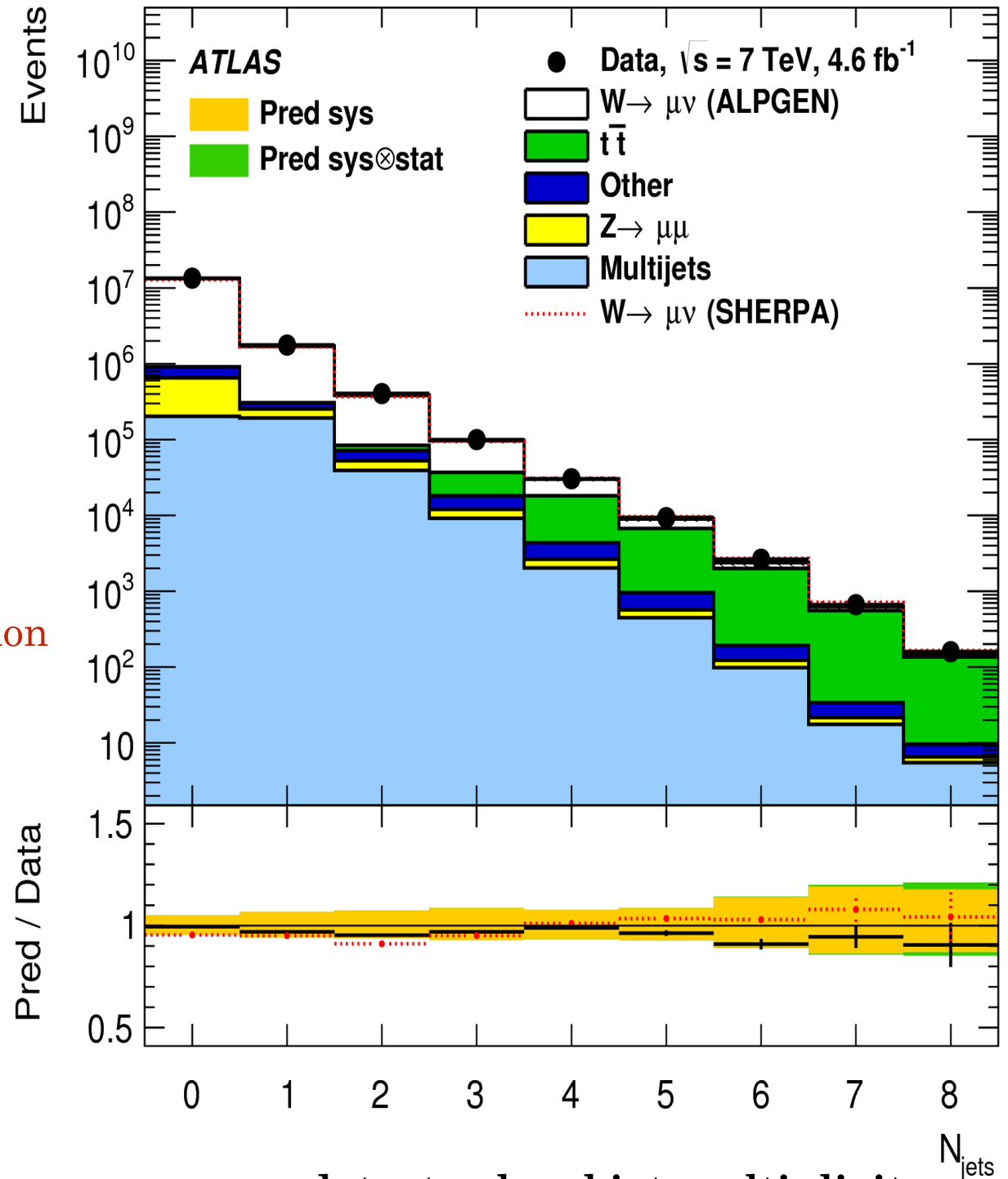
data driven estimation for both shape and normalization

cross sections

- *unfolding* data to account detector effects using the Bayesian algorithm and compare to particle level MC

theoretical predictions (see next page…)

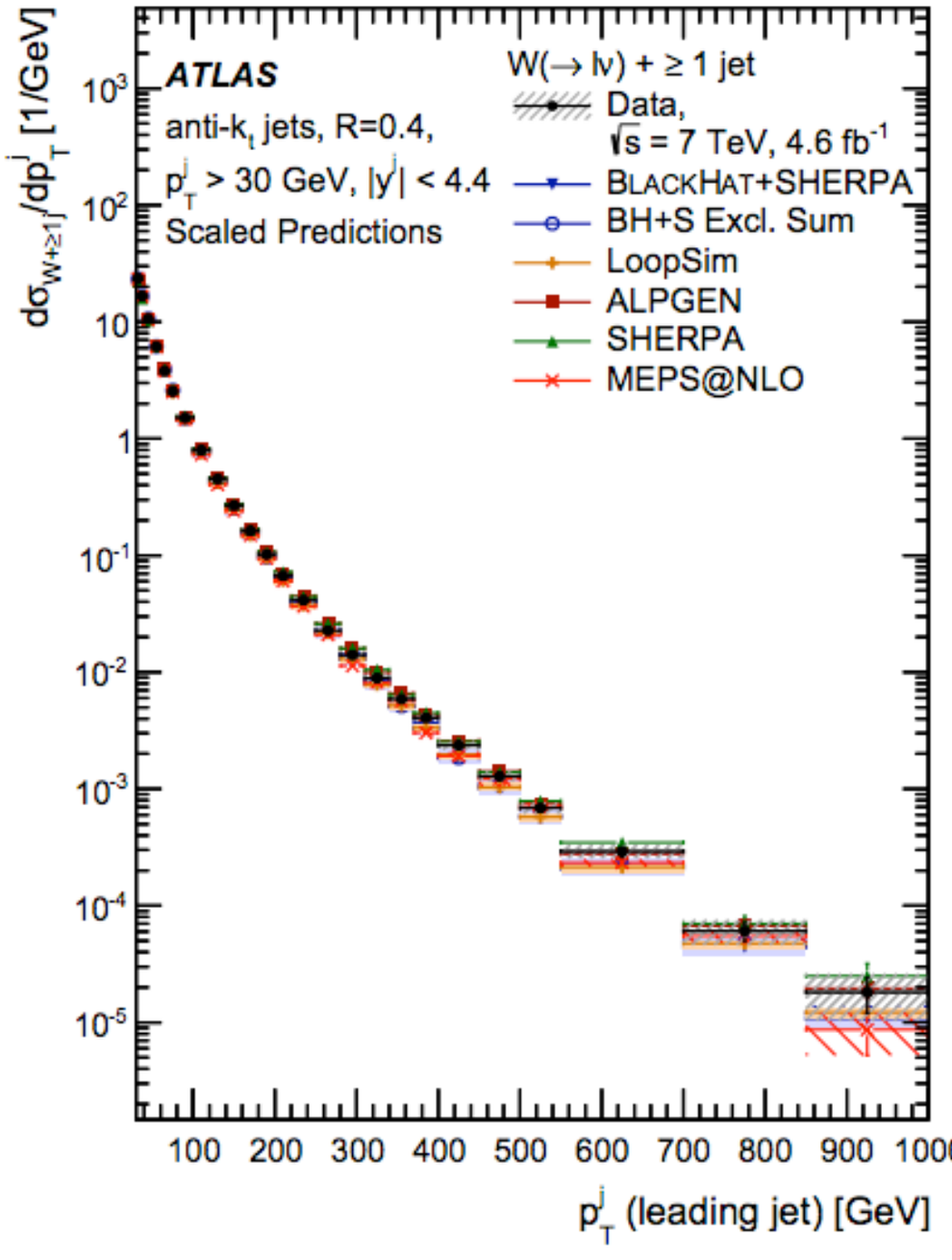
- MadGraph5+Pythia6 (LO)
- BlackHat+Sherpa (NLO)
- ALPGEN (LO)
- SHERPA (LO)
- Sherpa v2 MEPS@NLO (NLO up to 2 partons)
- HEJ@NLO (parton level >1 jet)

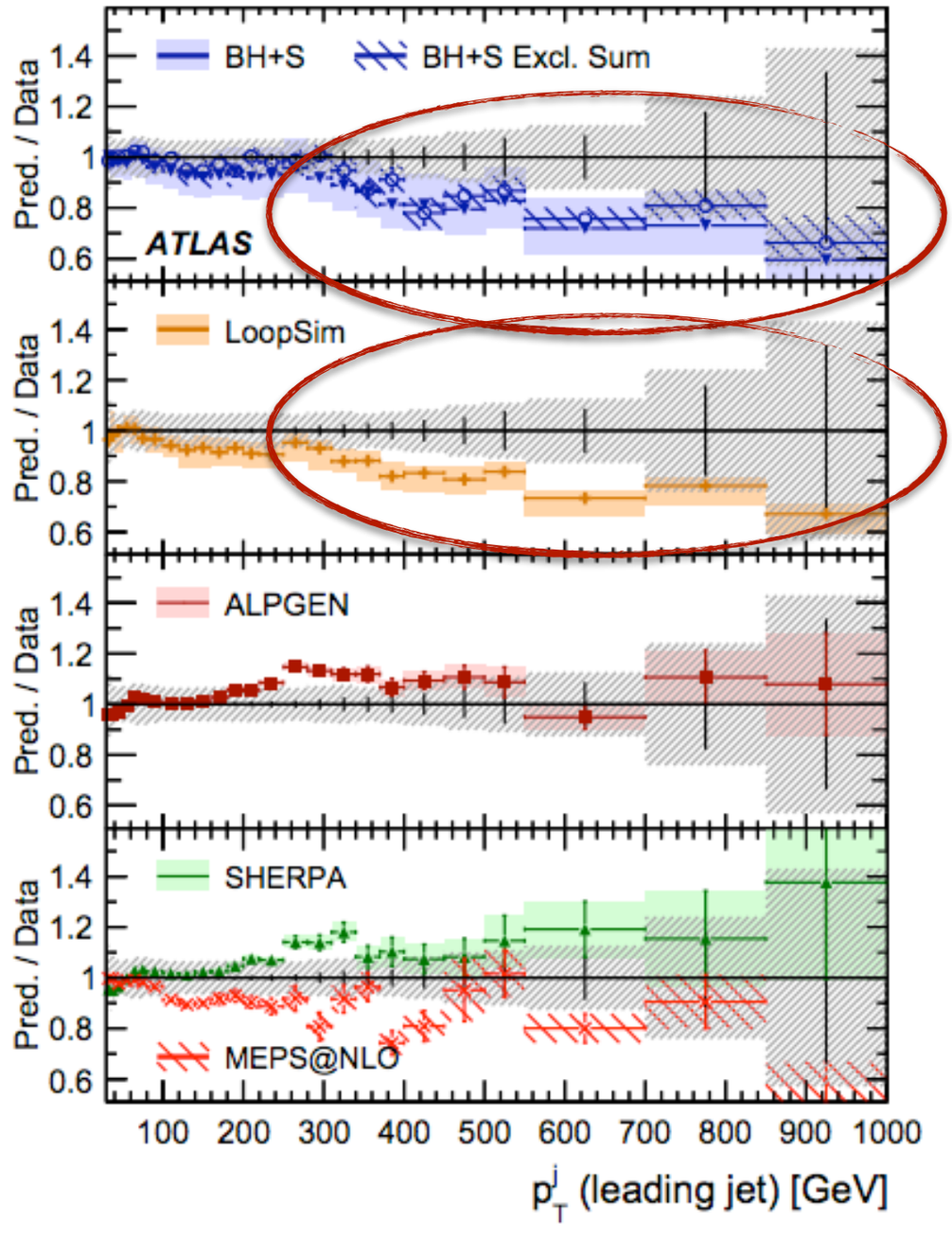


detector level jet multiplicity showing the background composition

W + jets - unfolded differential cross sections

leading jet momentum

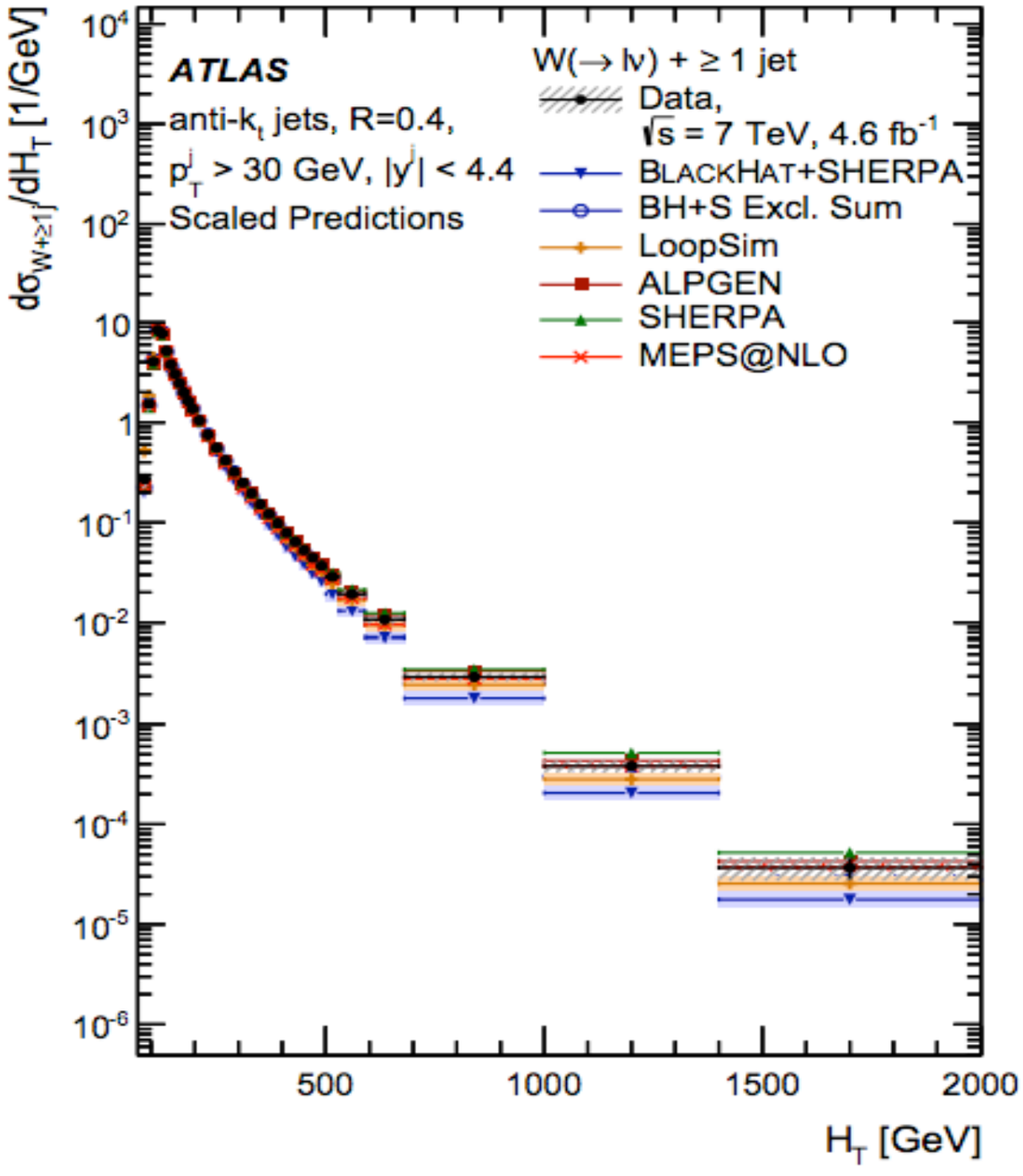


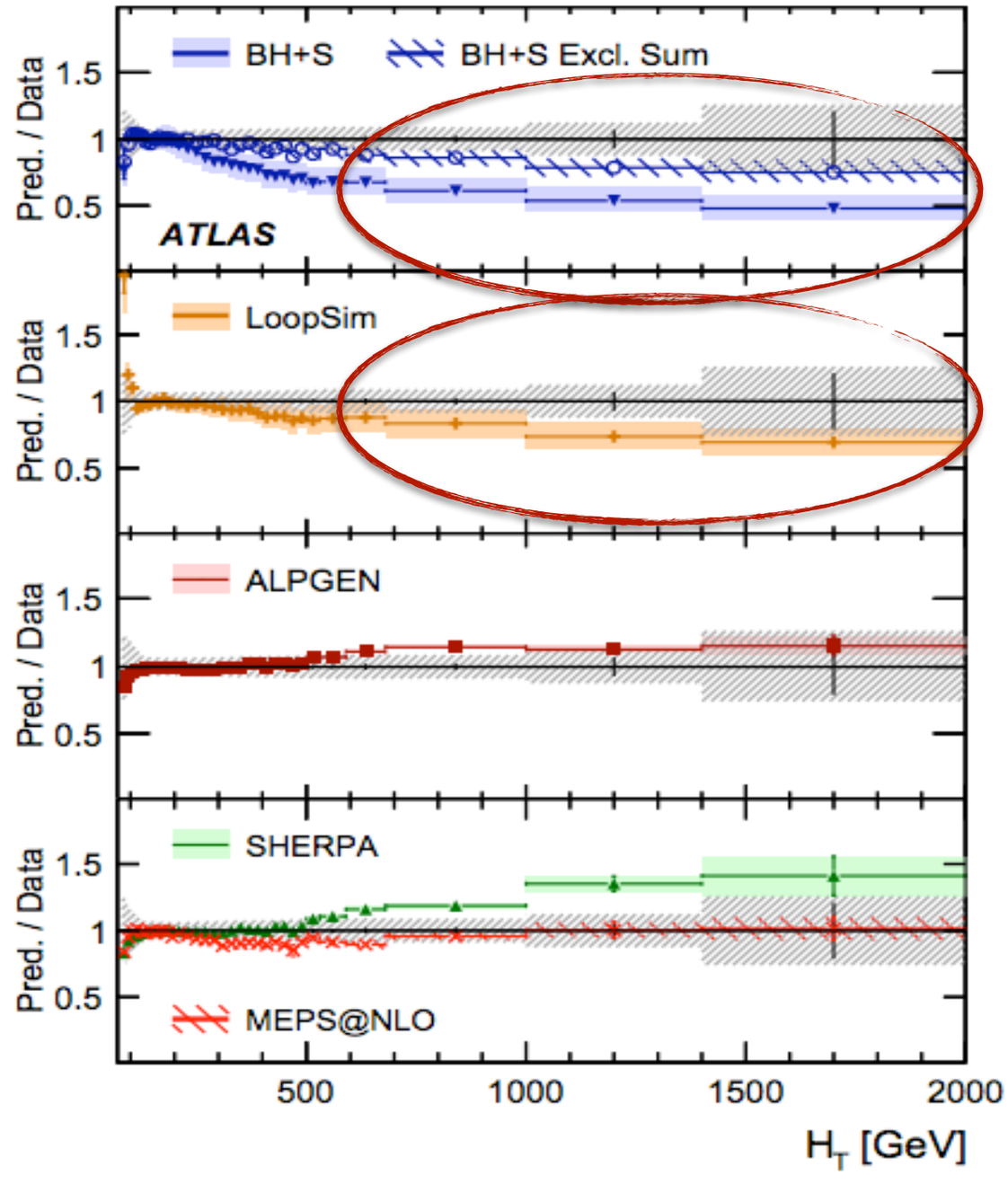


- BH+Sherpa and LoopSim underestimate at high pt

W + jets - unfolded differential cross sections

HT = ∑pT(j)



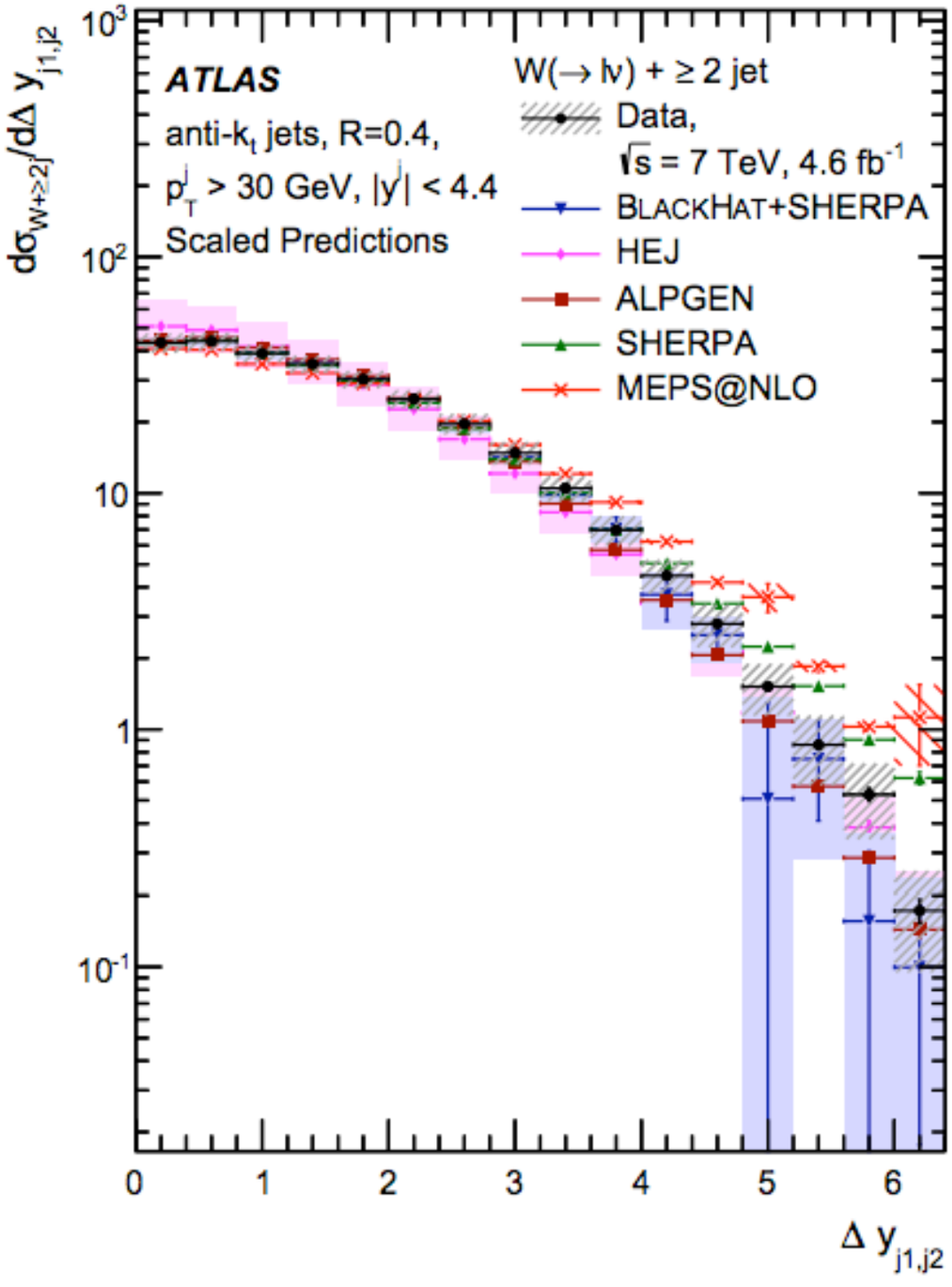


- BH+Sherpa and LoopSim underestimate at high pt

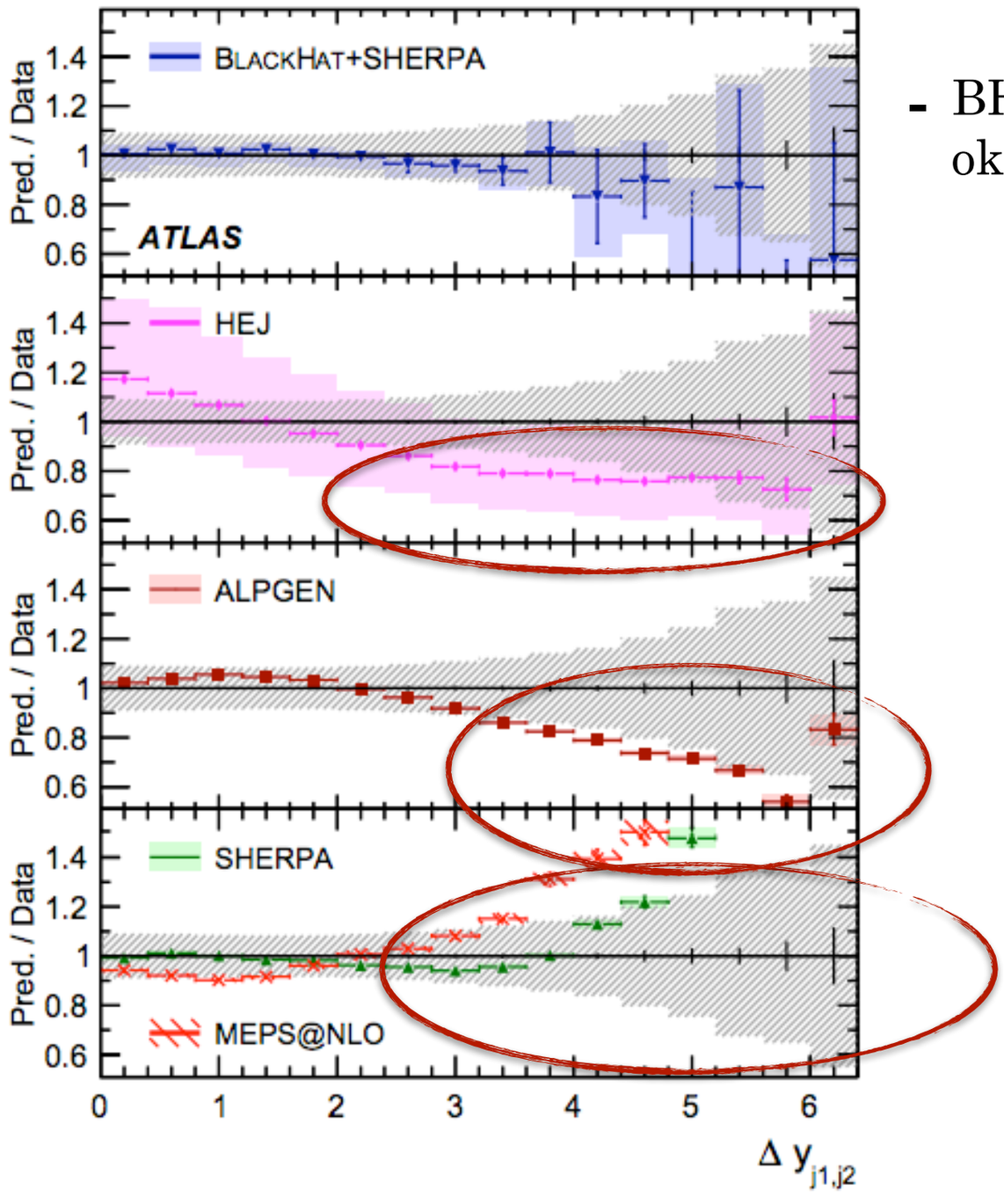
- impact of adding higher orders QCD (LoopSim) improve the description of multi-leg observables

W + jets - unfolded differential cross sections

Δy (j1, j2)



- ALPGEN and HEJ underestimate data at Δy>2



- Sherpa LO and Sherpa v2 (MEPS@NLO) overestimate data at Δy>2

- BH+Sherpa ok

$W + jets$

$\int Ldt = 5\ \text{fb}^{-1}$ $\sqrt{s} = 7\ \text{TeV}$

[PLB 741 (2015) 12]

selection criteria

- isolated muon $p_T > 25$ GeV $|\eta| < 2.1$

- ≥1 antiKT05 jet with $p_T > 30$ GeV, $|\eta| < 2.1$

- $MT(\mu, E_T) > 50$ GeV

backgrounds

- ***tt***: dominant for high multiplicity, suppressed with a *b-tag veto*

- ***QCD***: estimated with a *data-driven* method requiring reverting the isolation cut

cross sections

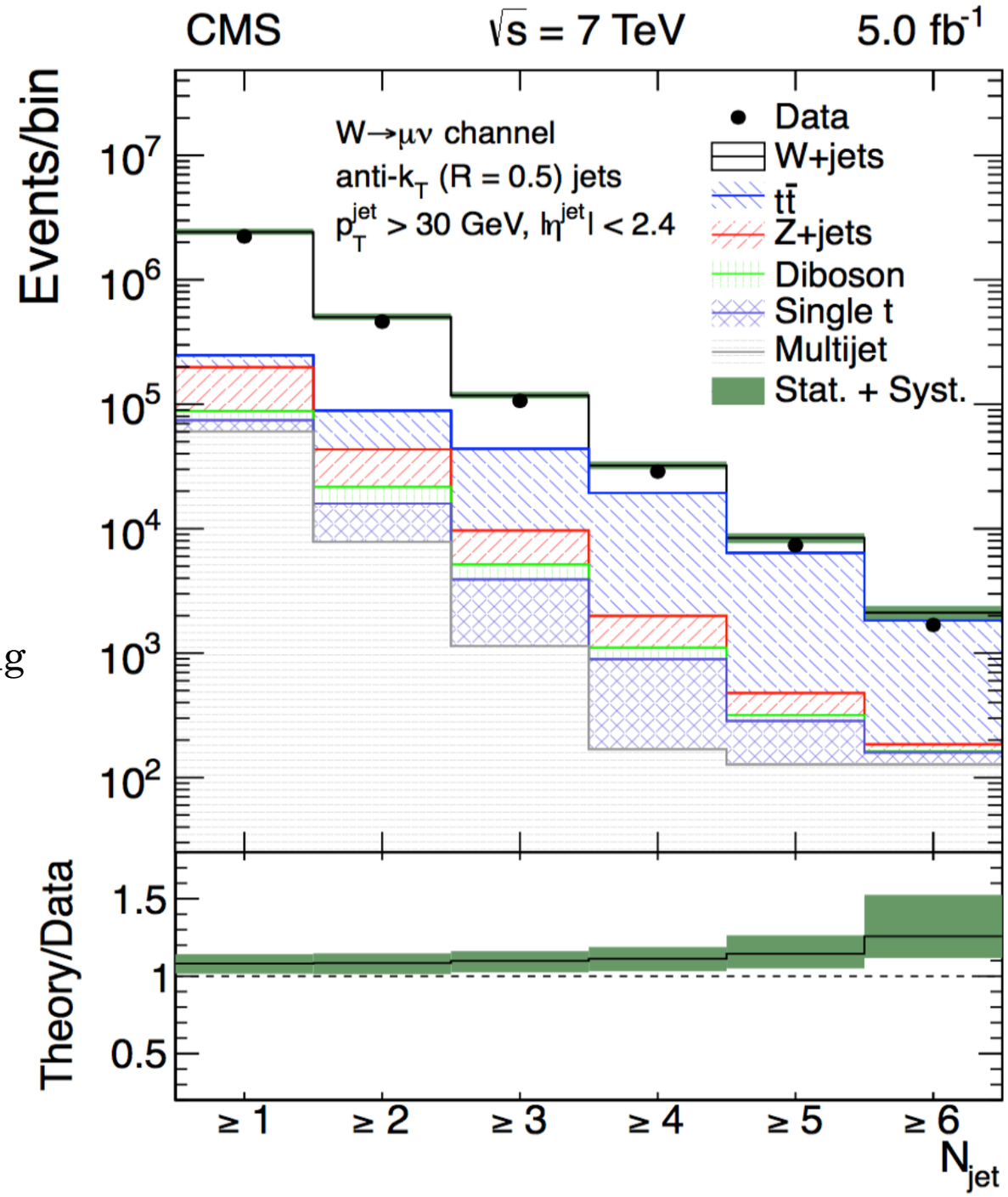
- *unfolding* data to account detector effects using the SVD algorithm and compare to particle level MC

theoretical predictions (see next page…)

- MadGraph5+Pythia6 (LO)

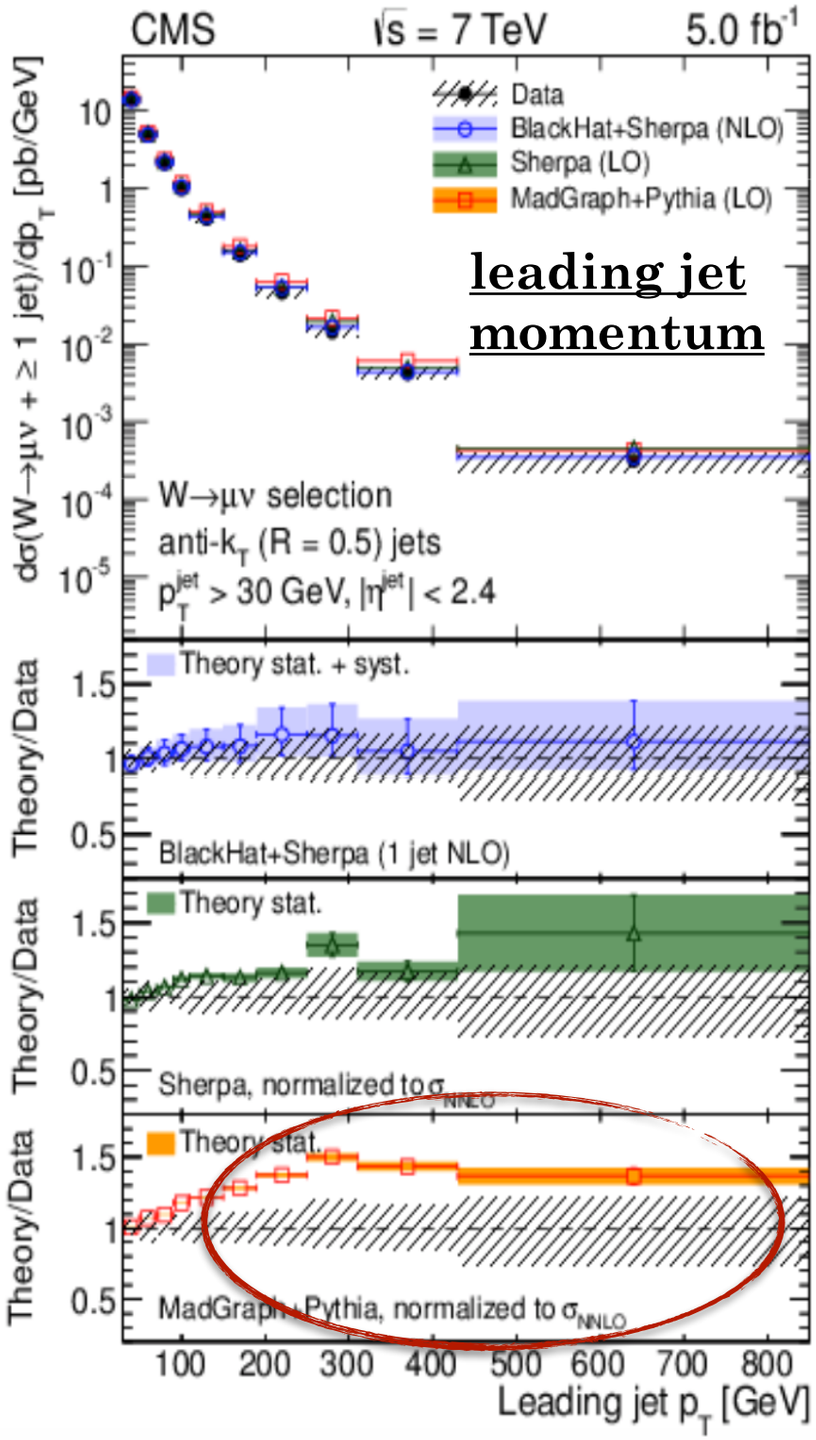
- BlackHat+Sherpa (NLO)

- Sherpa (LO)

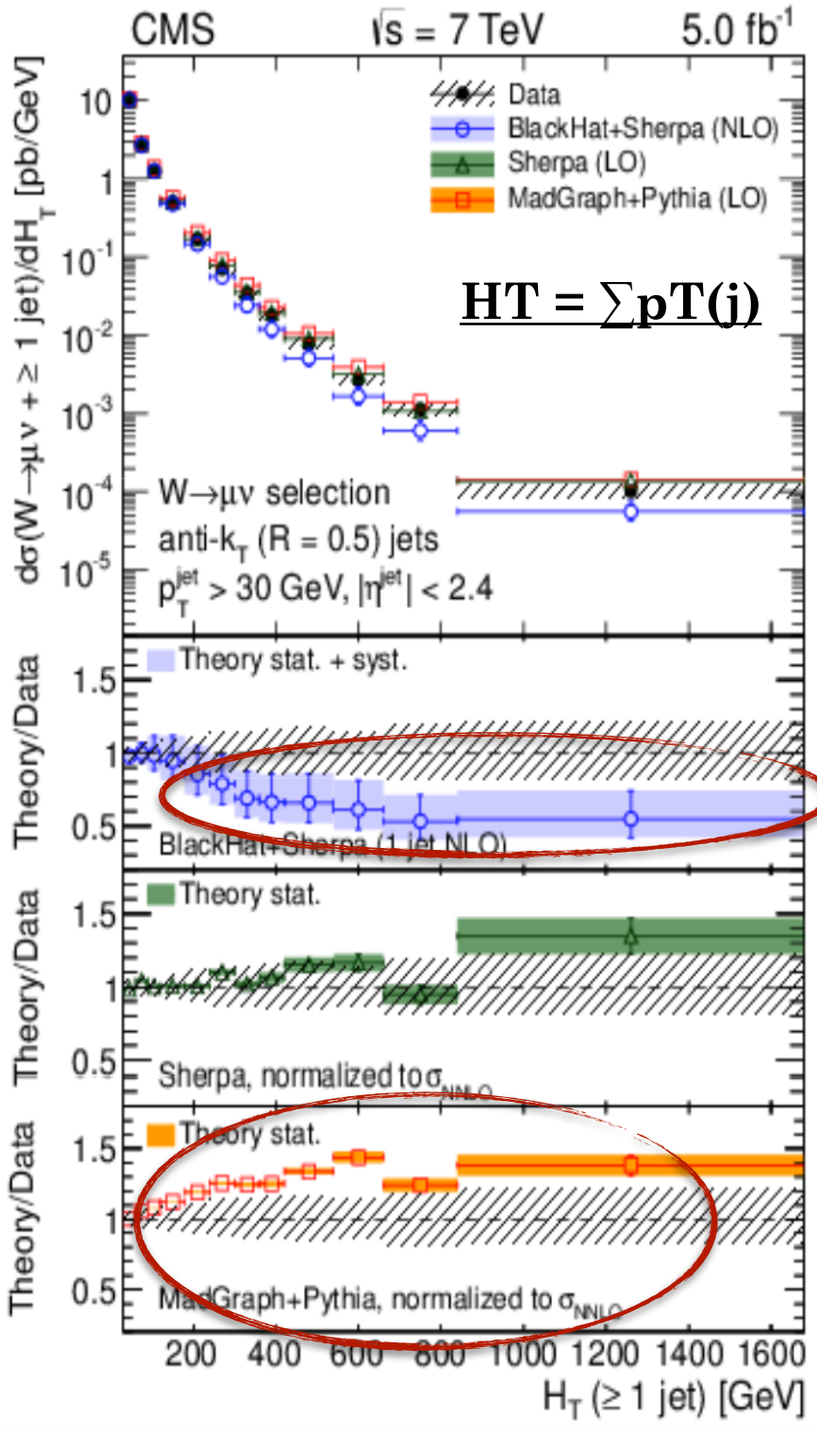


detector level jet multiplicity showing the background composition

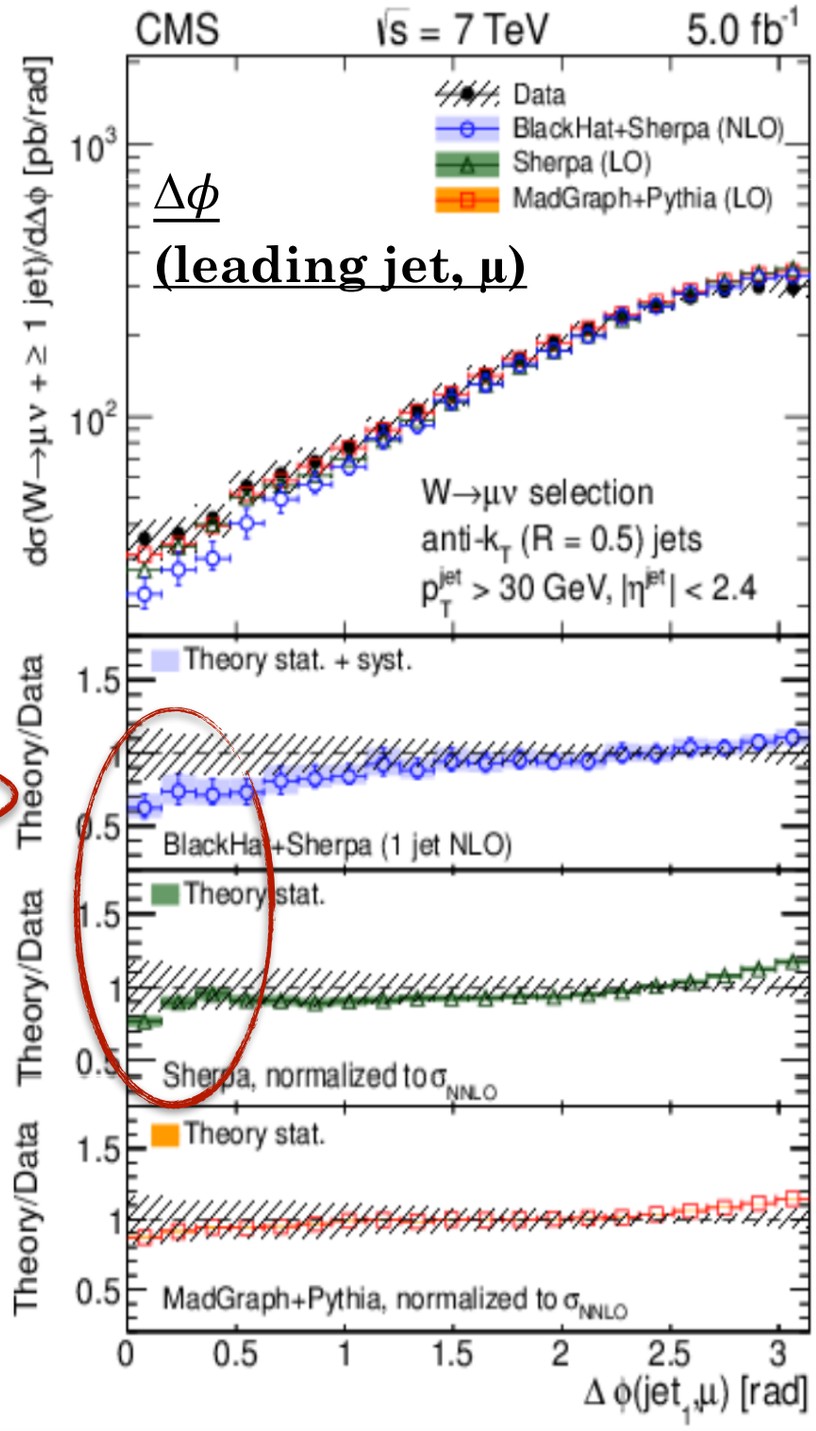
W + jets - unfolded differential cross sections



- LO predictions over-estimate data
- good agreement with NLO



- known discrepancy in NLO due to the limitation of higher order contributions



- discrepancy in the collinear j-μ system for both LO and NLO

$Z + jets$ differential

$\int Ldt = 20\ \text{fb}^{-1}$ $\sqrt{s} = 8$ TeV

selection criteria

- ee, μμ with p_T>20 GeV and $|\eta|$<2.4
- ≥1 antiKT05 jet with p_T > 30 GeV, $|\eta|$<2.1
- dilepton mass 71 < M(ll) < 111 GeV

cross sections

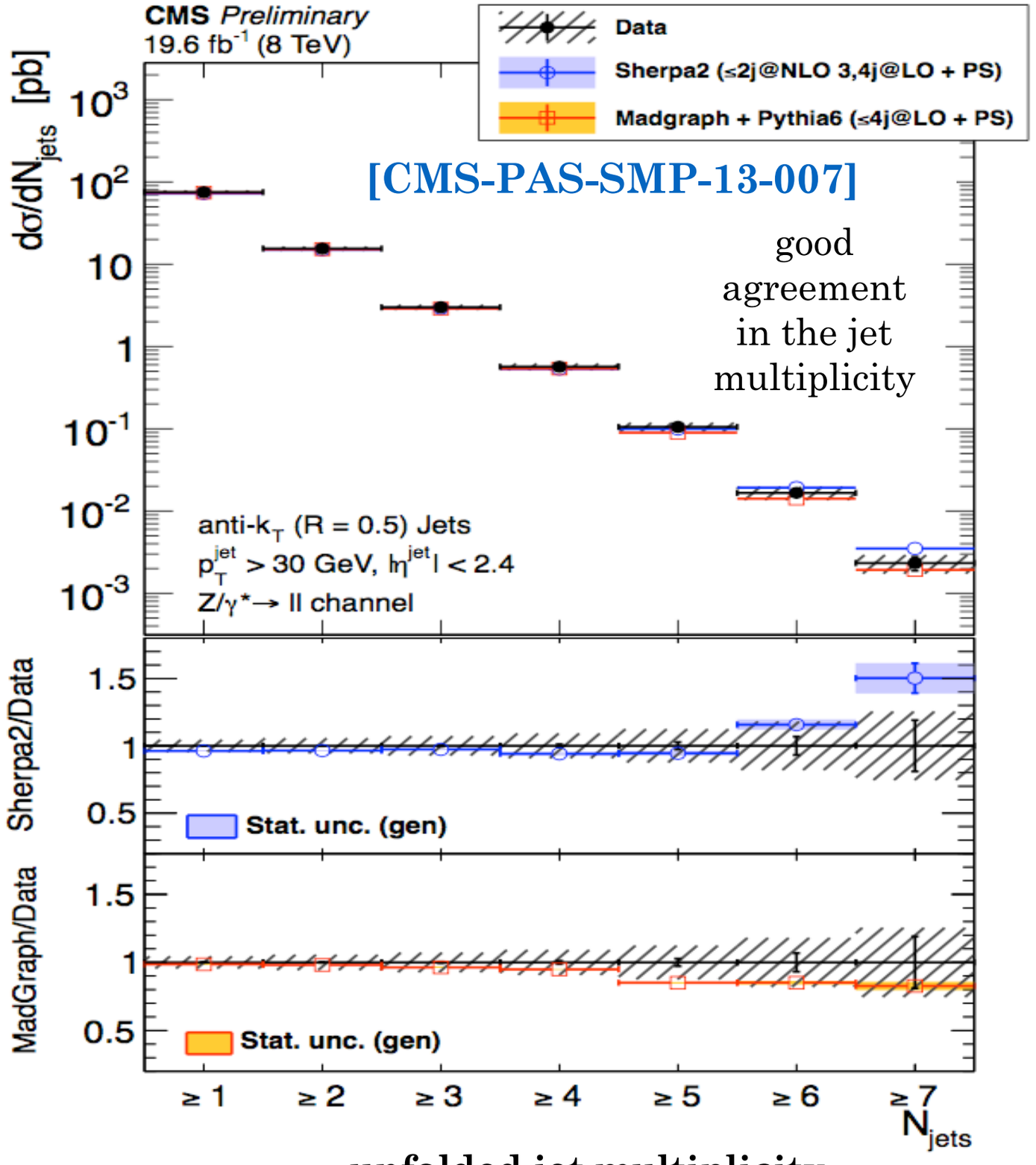
- *unfolding* data to account detector effects using the Bayes Iterative algorithm and compare to particle level MC

theoretical predictions

- MadGraph5+Pythia6 (LO up to 4jets)
- Sherpa(v2) (NLO for 0/1/2 jets)

systematics

- Jet Energy Correction/Resolution
- Unfolding



unfolded jet multiplicity

$Z + jets$ differential

$\int Ldt = 20\ \text{fb}^{-1}$ $\sqrt{s} = 8$ TeV

selection criteria

- ee, μμ with p_T>20 GeV and $|\eta|$<2.4
- ≥1 antiKT05 jet with p_T > 30 GeV, $|\eta|$<2.1
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cross sections

- *unfolding* data to account detector effects using the Bayes Iterative algorithm and compare to particle level MC

theoretical predictions

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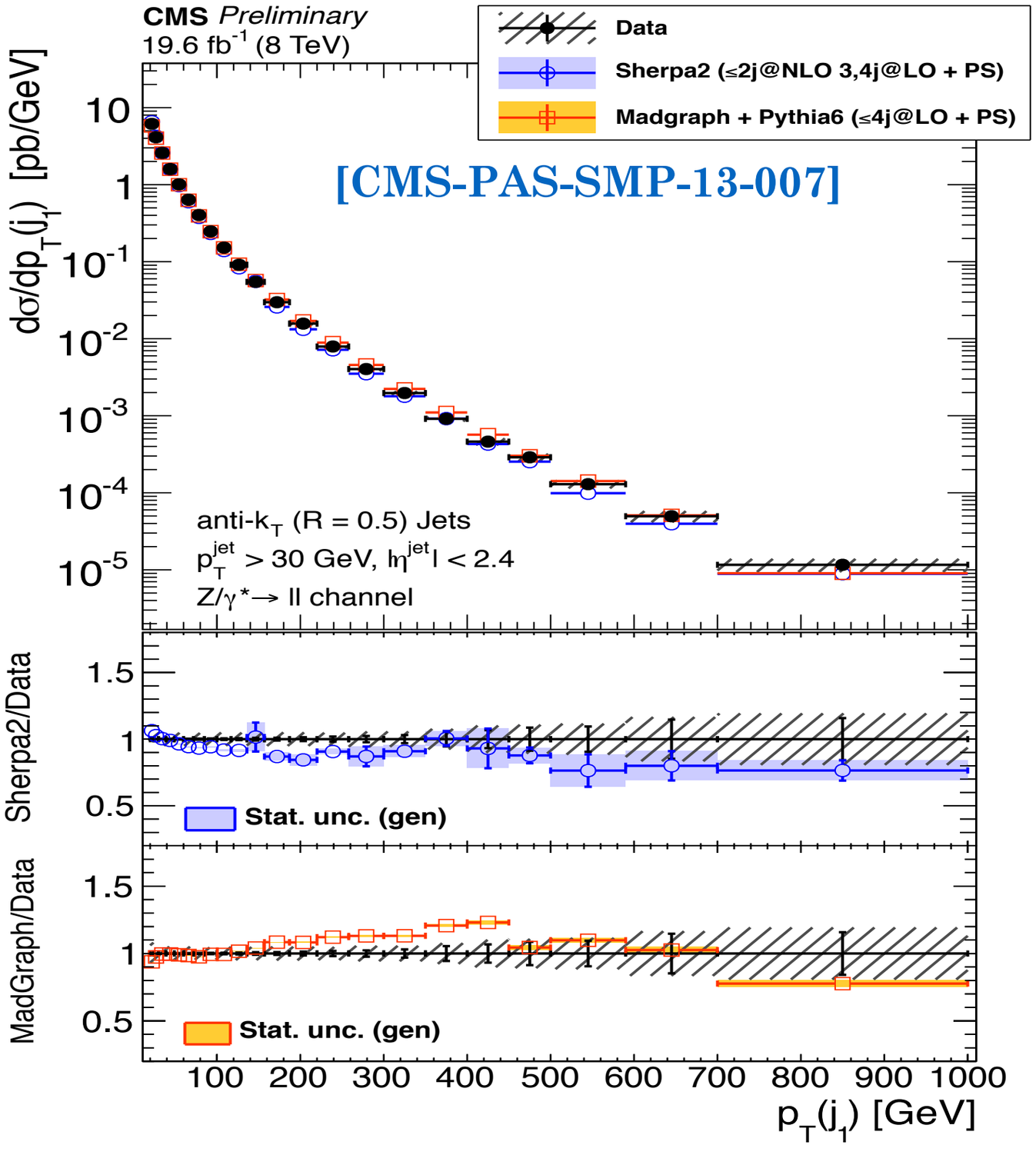
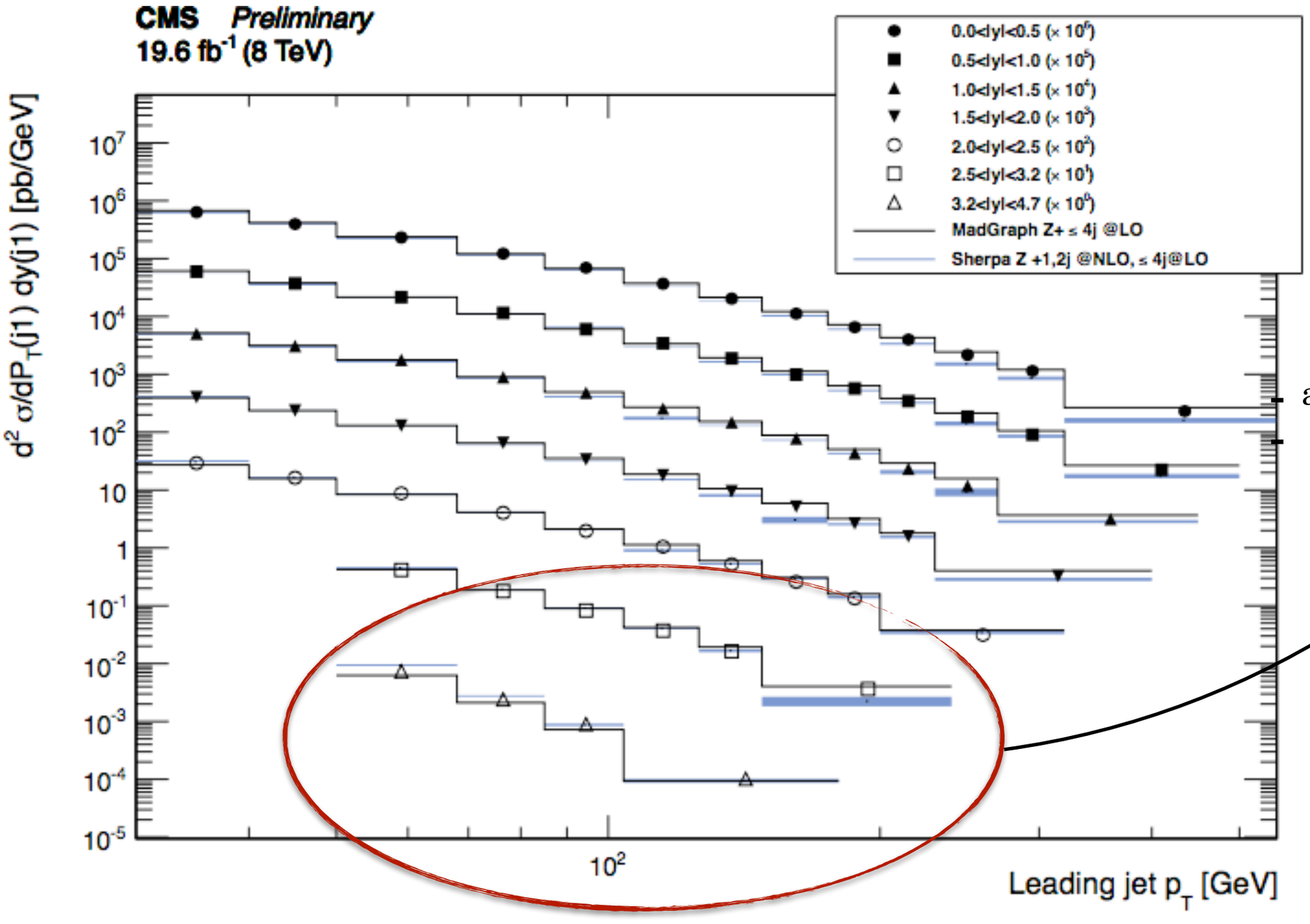


unfolded leading jet momentum

$Z + jets$ double differential

$\int Ldt = 20\ \text{fb}^{-1}$ $\sqrt{s} = 8$ TeV



[CMS PAS SMP-14-009]

<u>similar selection as 1D *Z*+jets measurements</u>

(but only μμ final state)

access to the forward region: rapidity up to 4.7

<u>unfolded double differential cross sections as a function of the leading jet momentum and rapidity</u>

<u>theoretical predictions</u>

- Sherpa(v2) (NLO 0/1/2 jets)

- MadGraph+Pythia6 (LO)

R=σ(W+jets)/σ(Z+jets)

$\int Ldt = 4.6\,\text{fb}^{-1}$ $\sqrt{s} = 7$ TeV

selection criteria

- isolated electron(muon)
p_T > 25 GeV
$|\eta|$<2.47(2.4)

- ≥1 antiKT04 jet with p_T > 30 GeV, $|y|$<4.4

- MT(μ,E_T) > 40 GeV and ET > 25 GeV

theoretical predictions

- Alpgen (LO)

- BlackHat+Sherpa (NLO)

- Sherpa (LO)

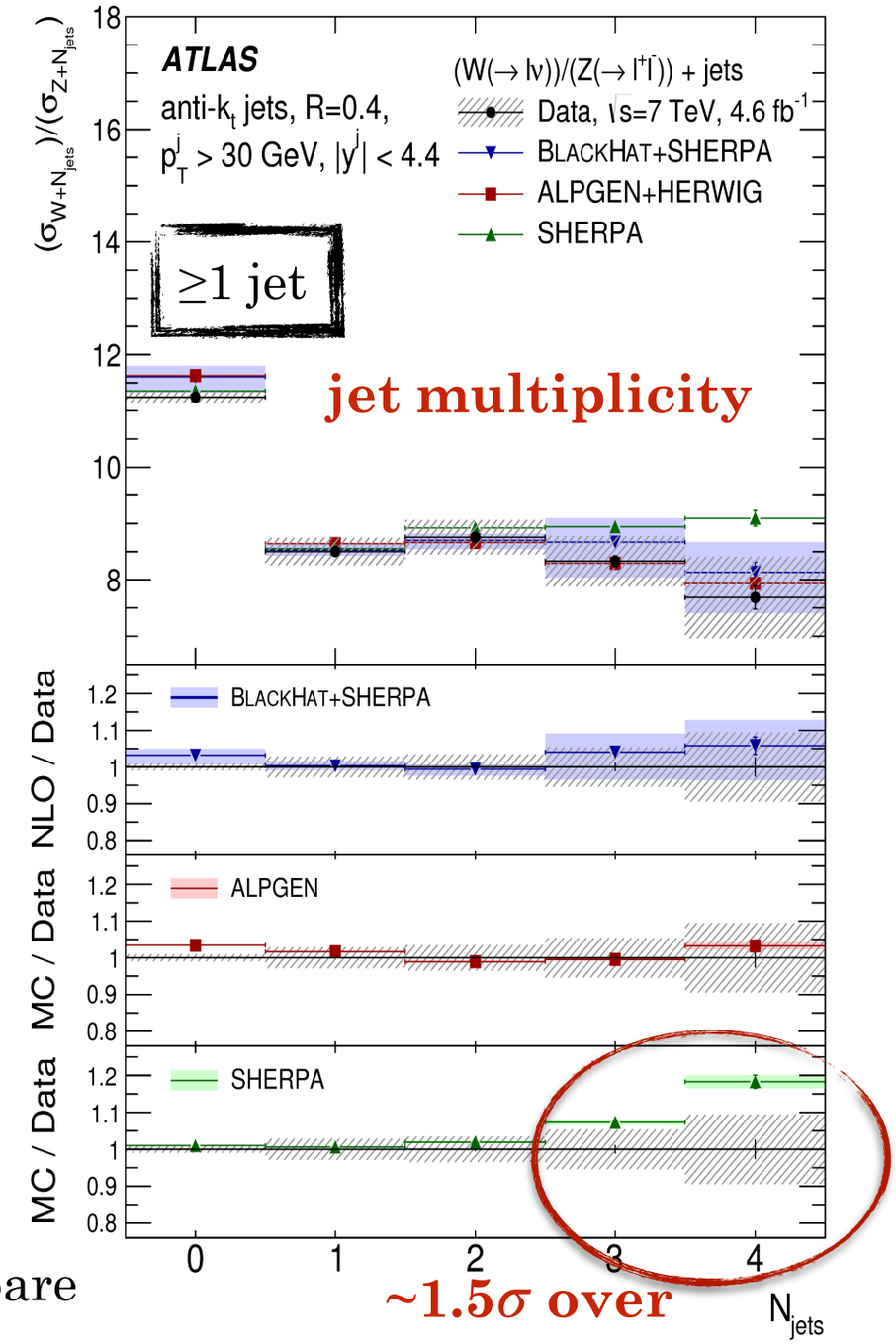
cross sections

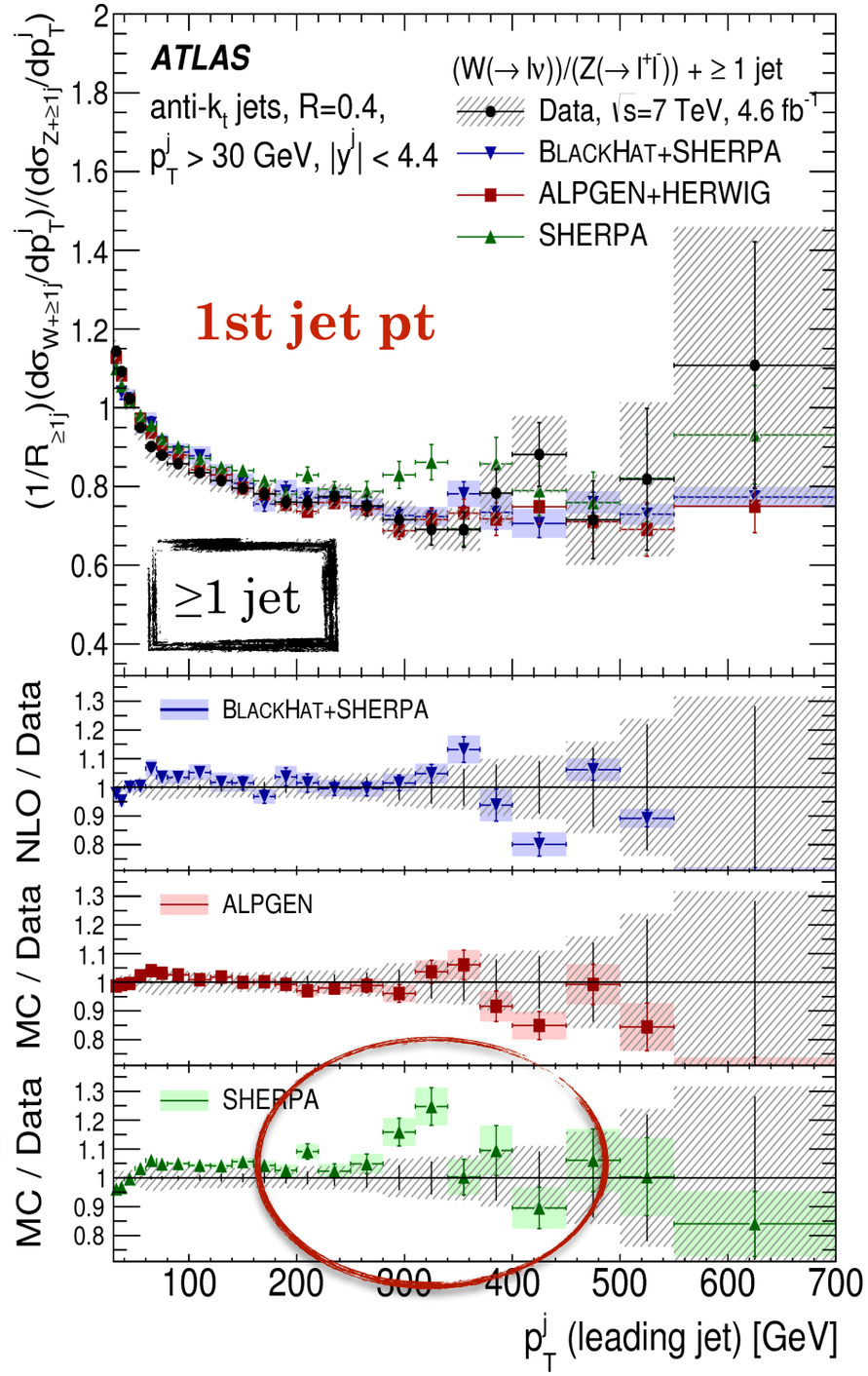
- *unfolding* data to account detector effects using the Bayesian algorithm and compare to particle level MC

- Increased precision pQCD test as many large systematics cancel in the ratio

- model the jet recoil against W/Z as a function of the boson momentum

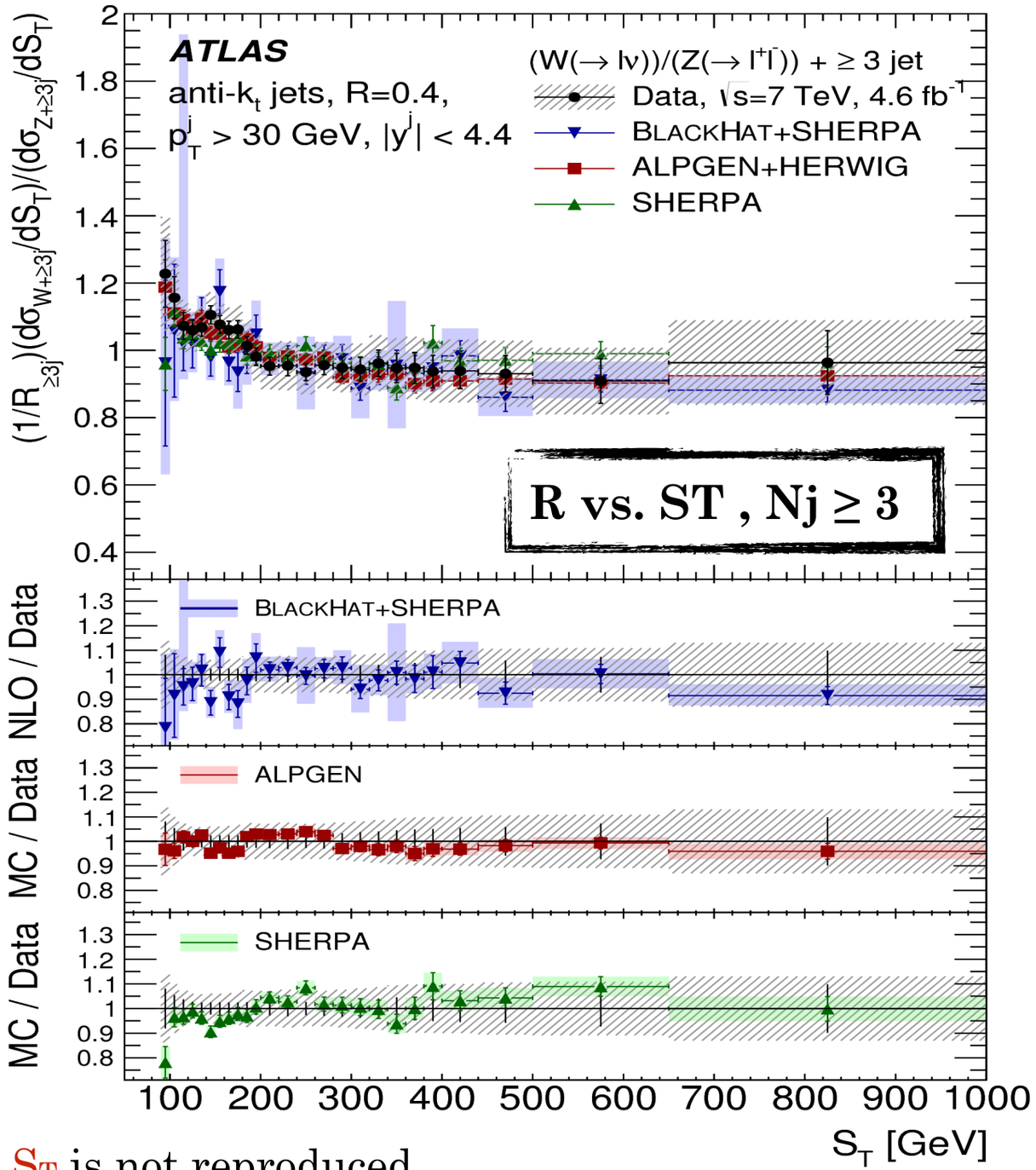
[EPJC (2014) 74:3168]





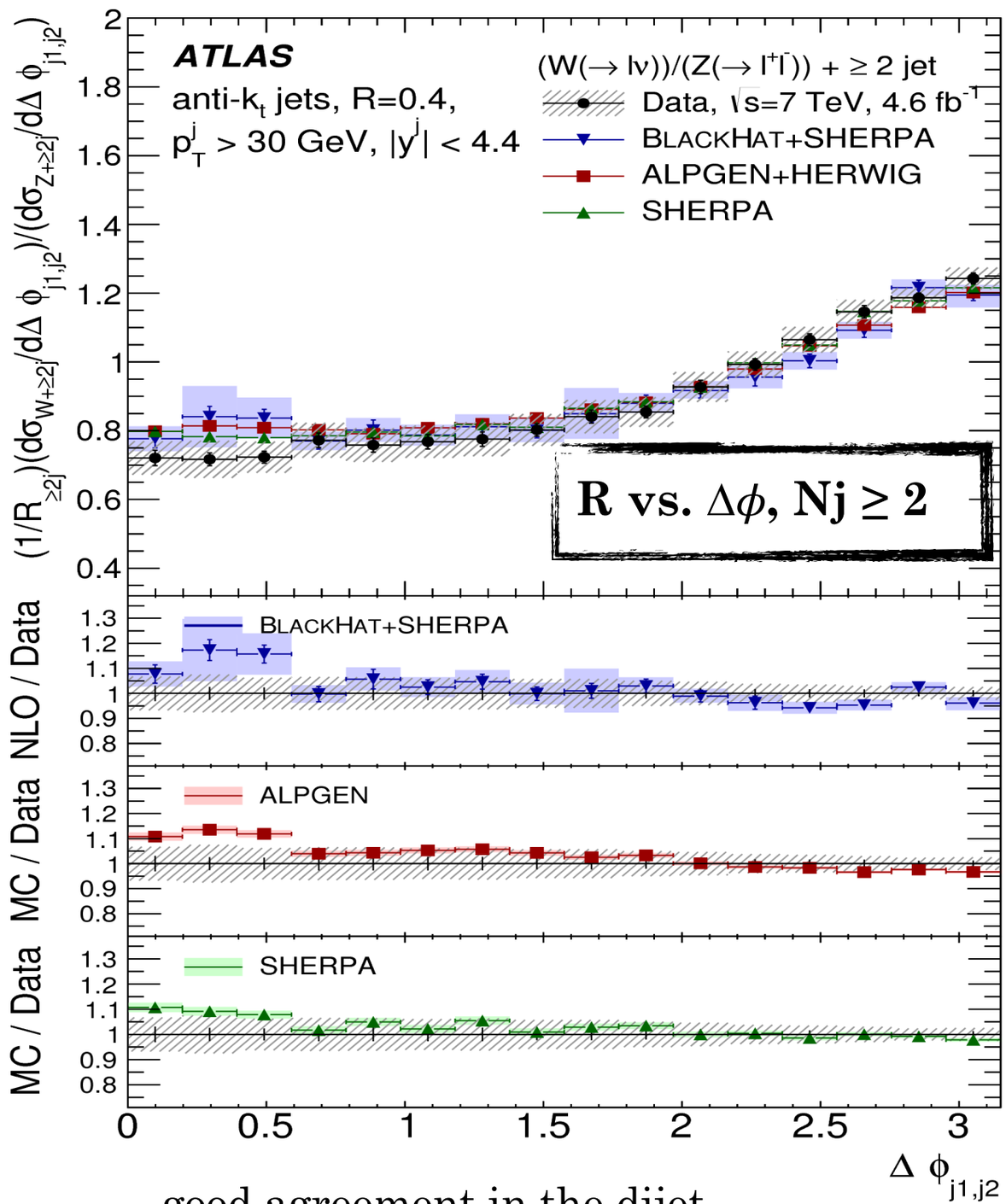
R=σ(W+jets)/σ(Z+jets)

$\int Ldt = 4.6\,\text{fb}^{-1}$ $\sqrt{s} = 7$ TeV



- S_T is not reproduced independently in W+jets and Z +jets (cfr.slide 4) but in the ratio missing high order effects cancel out!

[S_T = *sum of jet pt (equivalent of CMS's HT)*]



- good agreement in the dijet azimuthal separation

Z/γ differential ratio

$\int Ldt = 20\ \text{fb}^{-1}\ \sqrt{s} = 8\ \text{TeV}$

[arXiv.1505.06250]

selection criteria

- same Z+jets selection as 8 TeV measurement
- γ+jets: $\geq 1\gamma$ with $p_T>100$GeV $|\eta|<1.4$,
  ≥ 1 jet (anti-k_T $\Delta R=0.5$), $p_T>30$ GeV, $|\eta|<2.4$

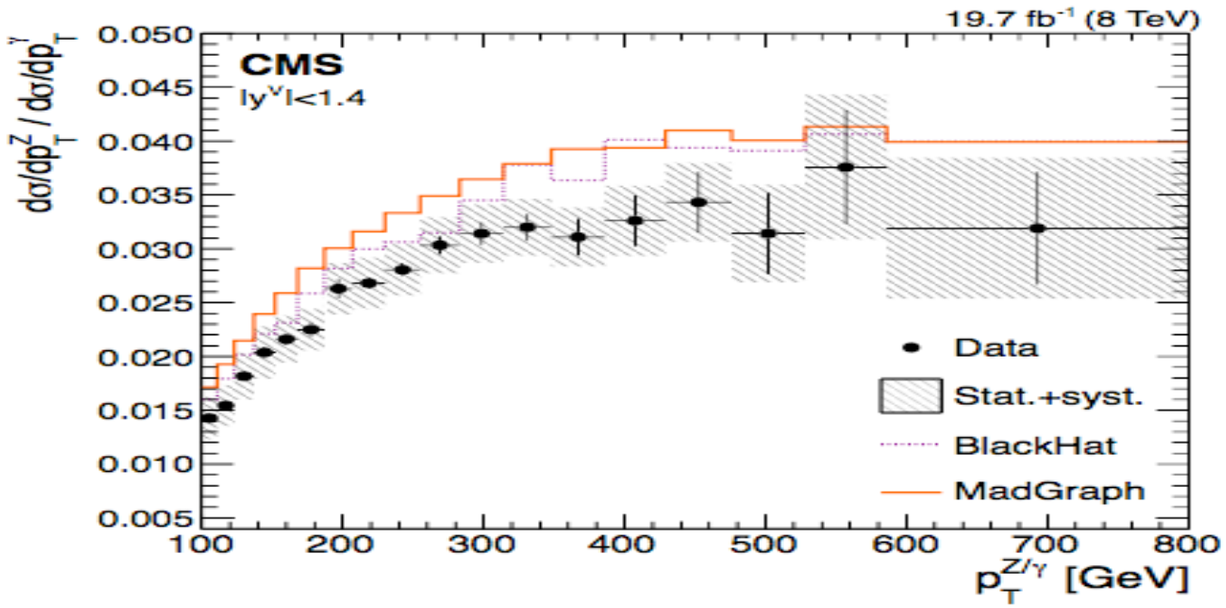
cross sections

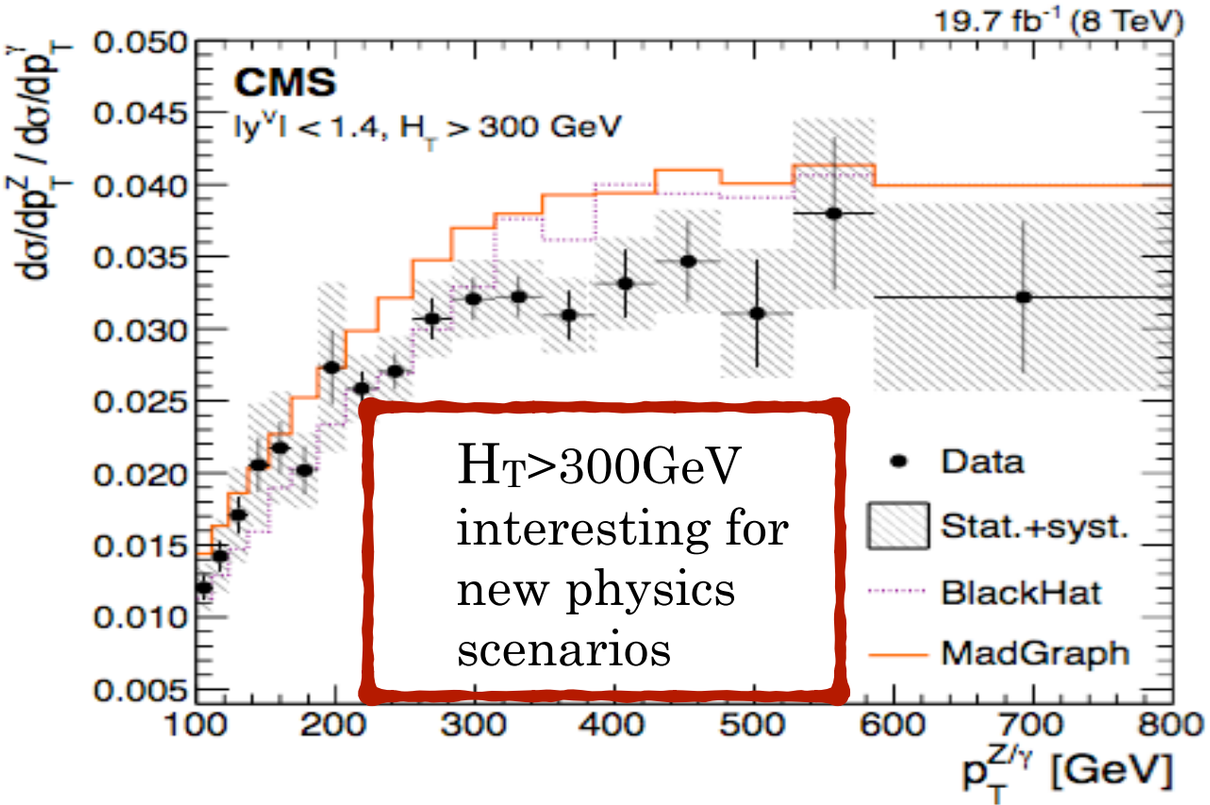
- differential cross section for the Z+jets/γ+jets vs. Z boson p_T

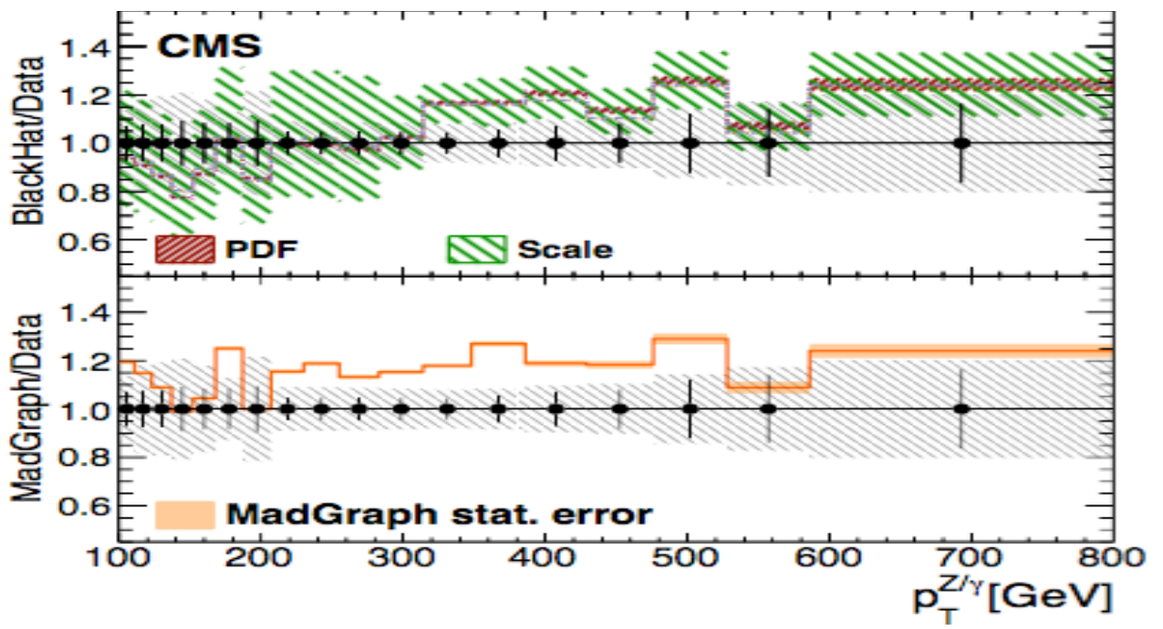
theoretical predictions

- BlackHat+Sherpa (parton level NLO)
- MadGraph5+Pythia6 (LO up to 4jets)

- important test of NLO predictions
- important tool to model $Z\rightarrow\nu\nu$ from data (dark matter searches, susy…)
- at LO and high pT , the ratio is expected to reach a plateau

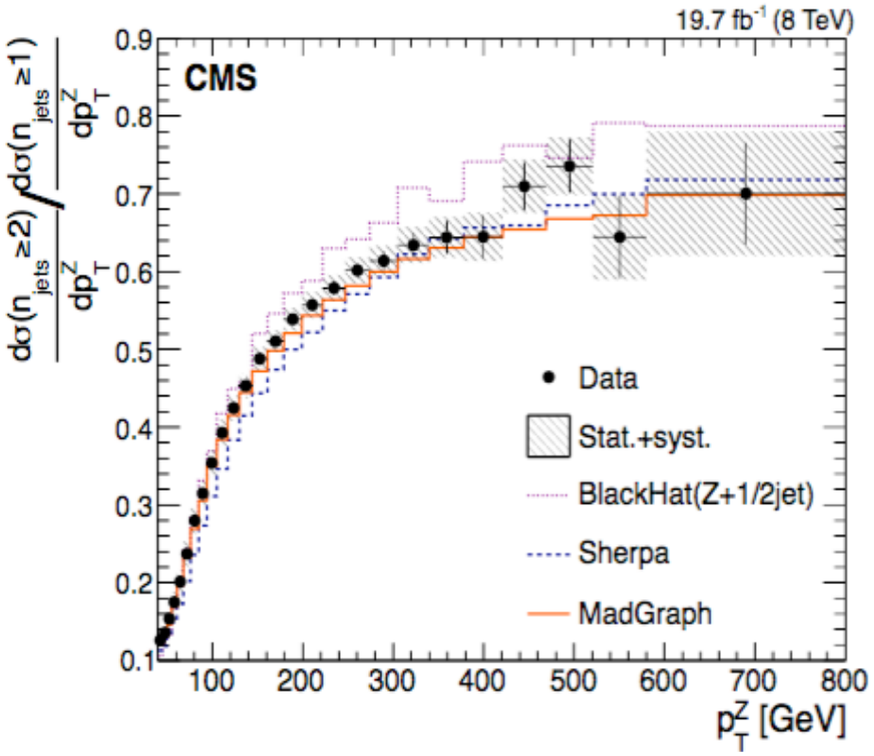


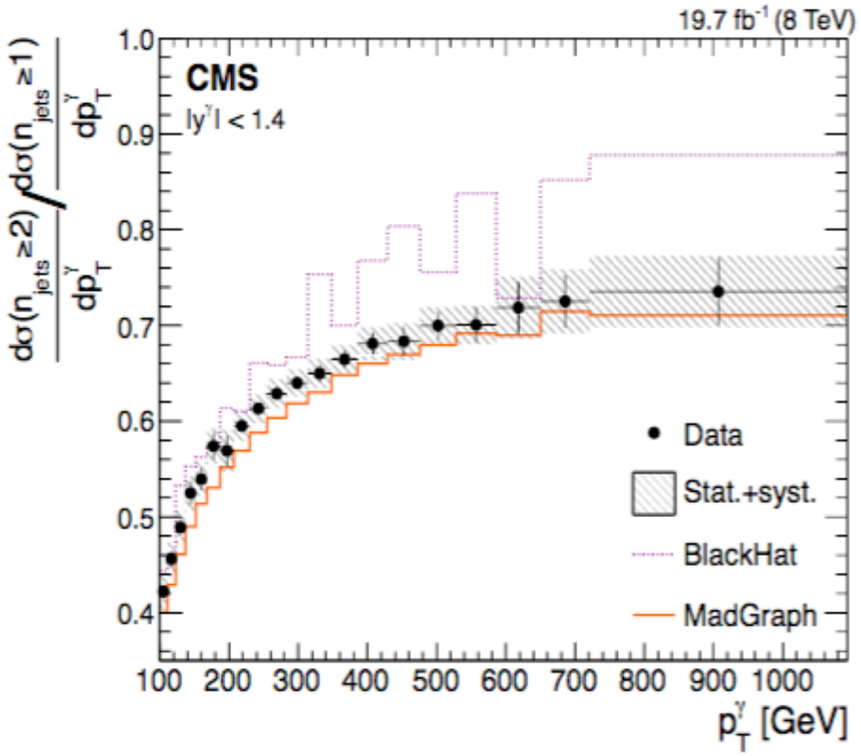




Z/γ differential ratio

$$\int Ldt = 20\ \text{fb}^{-1} \quad \sqrt{s} = 8\ \text{TeV}$$



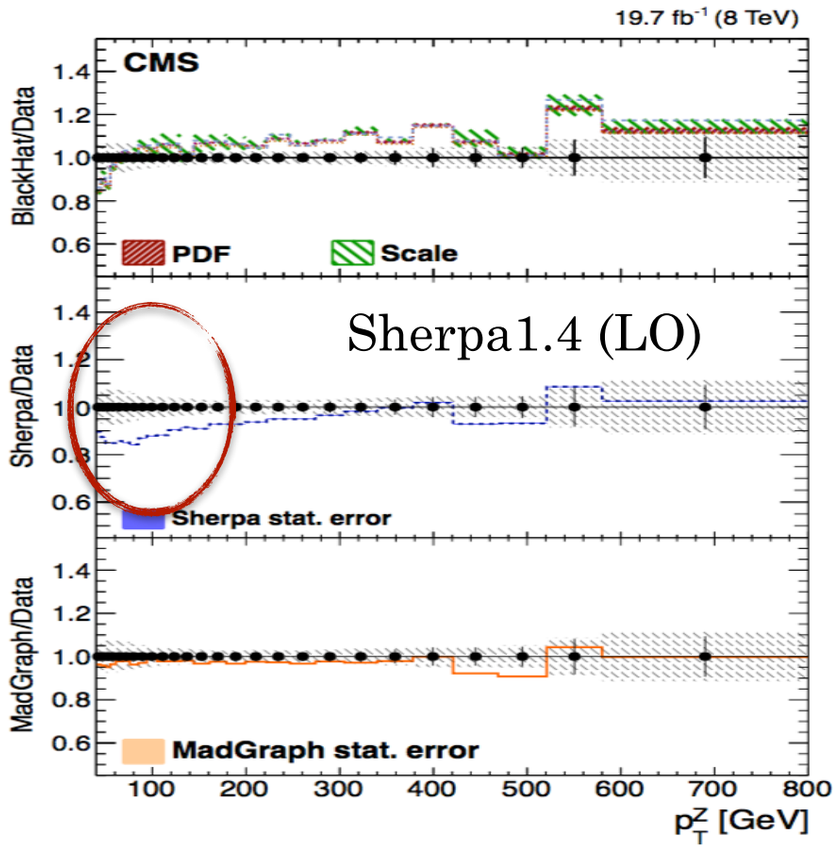


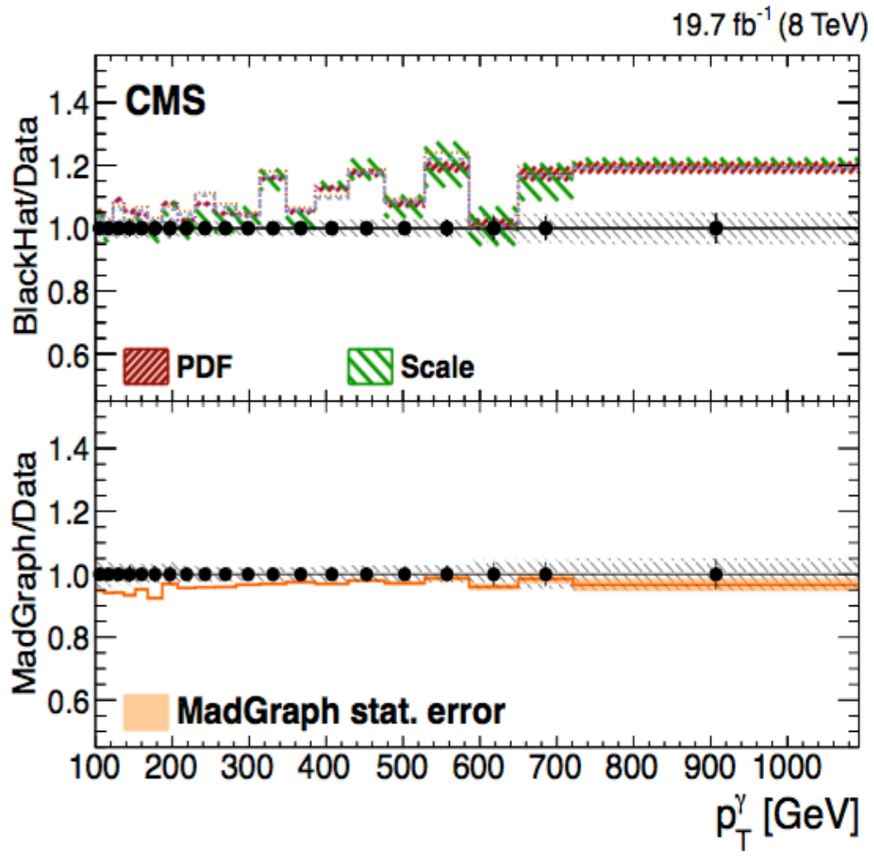
Z+ N≥2 jets over Z+ N≥1 jets unfolded cross sections vs. Z boson p_T

(left)

Z+ N≥2 jets over Z+ N≥1 jets unfolded cross sections vs. γ p_T

(right)





<u>theoretical predictions</u>

BlackHat+Sherpa (NLO)

MadGraph5+Pythia6 (LO up to 4jets)

$Z + b,\ Z + bb$

NEW!

$\int Ldt = 20\ \text{fb}^{-1}\ \sqrt{s} = 8\ \text{TeV}$

[CMS-PAS-SMP-14-010]

selection criteria

- ≥1 antiKT05 jet with $p_T > 30$ GeV, $|\eta| < 2.4$
- b-tagging: exploiting SV mass discriminator
- ≥1/2 b-tagged jet with $p_T > 30$ GeV, $|\eta| < 2.4$
- dilepton mass $71 < M(ll) < 111$ GeV

two samples: Z+ ≥1b and Z+ ≥2b

background

- ttbar: ***data-driven*** estimation in an eμ+jets control sample: extract both shape and normalization

- *Z+c, Z+light-* flavor MC templates extracted from SV mass fit and subtracted

- *dibosons taken from MC*

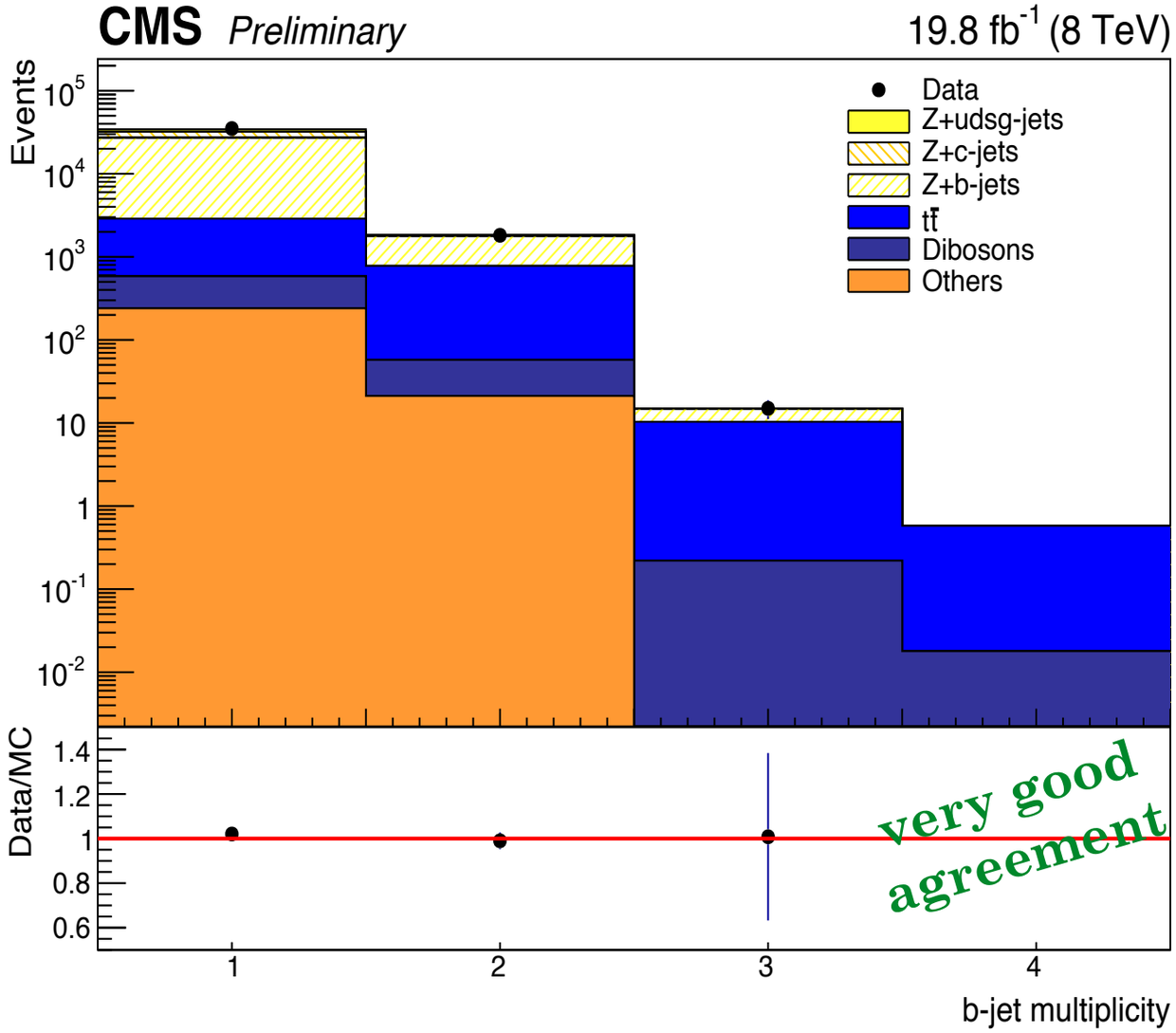
cross sections

- *unfolded* (SVD) data compared with:
  - MadGraph5+Pythia6 (LO) 5FS
  - MadGraph5 4FS
  - Powheg (NLO for 1jet)

systematics
- Jet Energy Correction
- Unfolding

- important test of pQCD with heavy flavors: 4 flavor scheme (b massive) and 5 flavor schemes (b massless)

- important background for new physics and Higgs: HZZ, SUSY, 4th generation…



detector-level inclusive b-jet multiplicity

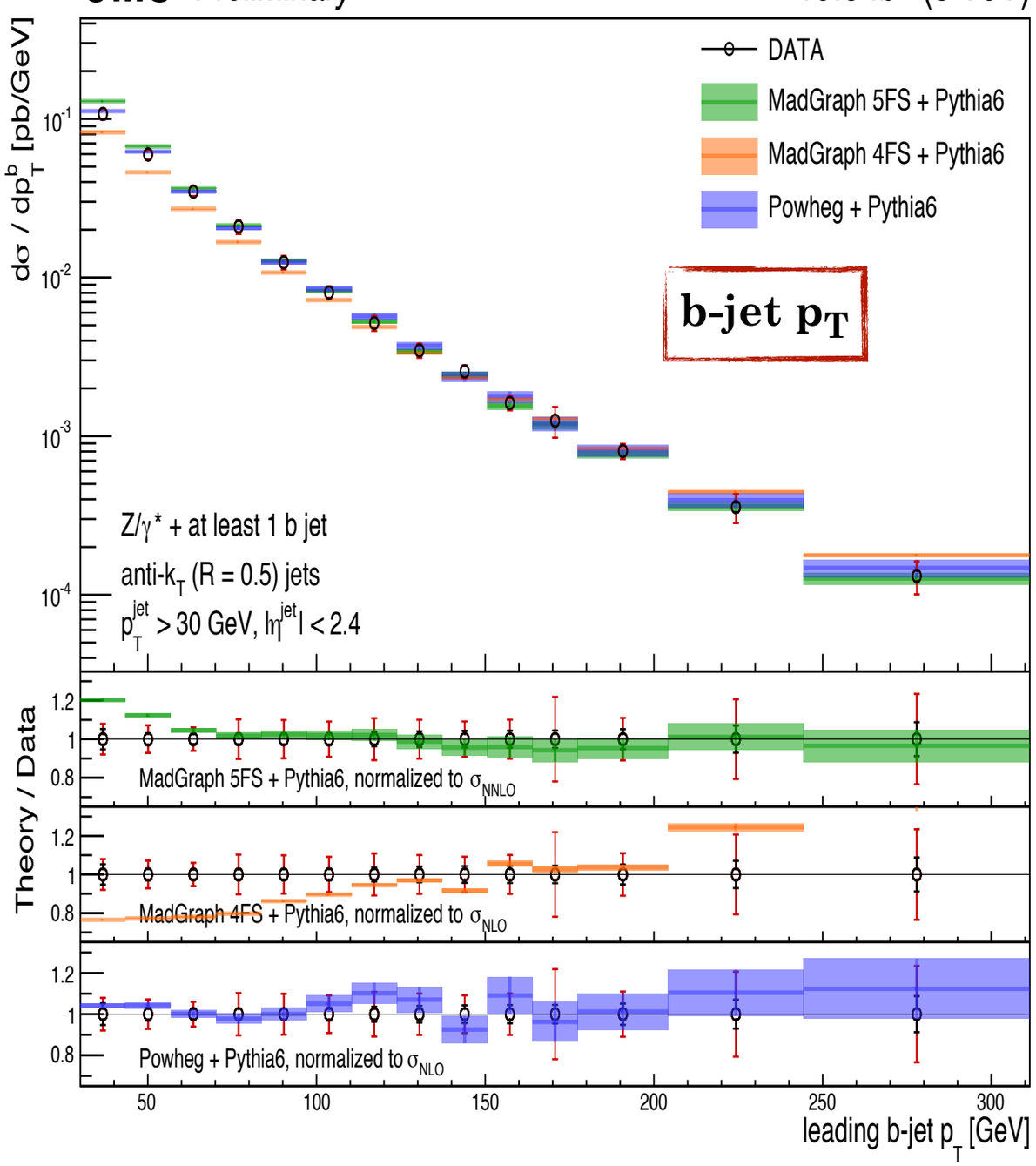
$Z + b,\ Z + bb$

NEW!

$\int Ldt = 20\ \text{fb}^{-1}\ \sqrt{s} = 8\ \text{TeV}$

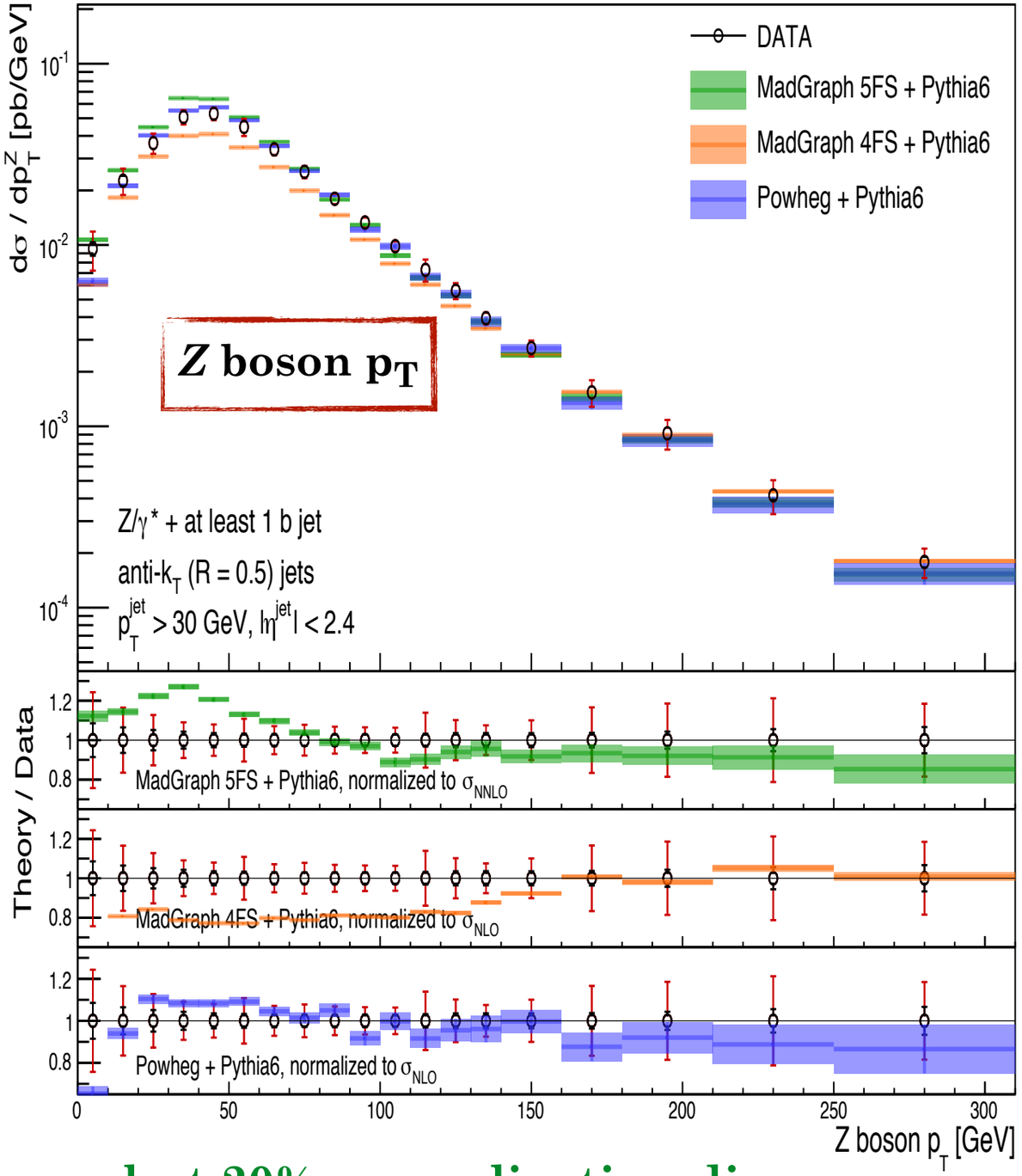
unfolded leading b-jet p_T cross section

(Z + at least 1 b jet selection)



unfolded Z boson p_T cross section

(Z + at least 1 b jet selection)



4FS overall better agreement in shape, but 20% normalization discrepancy

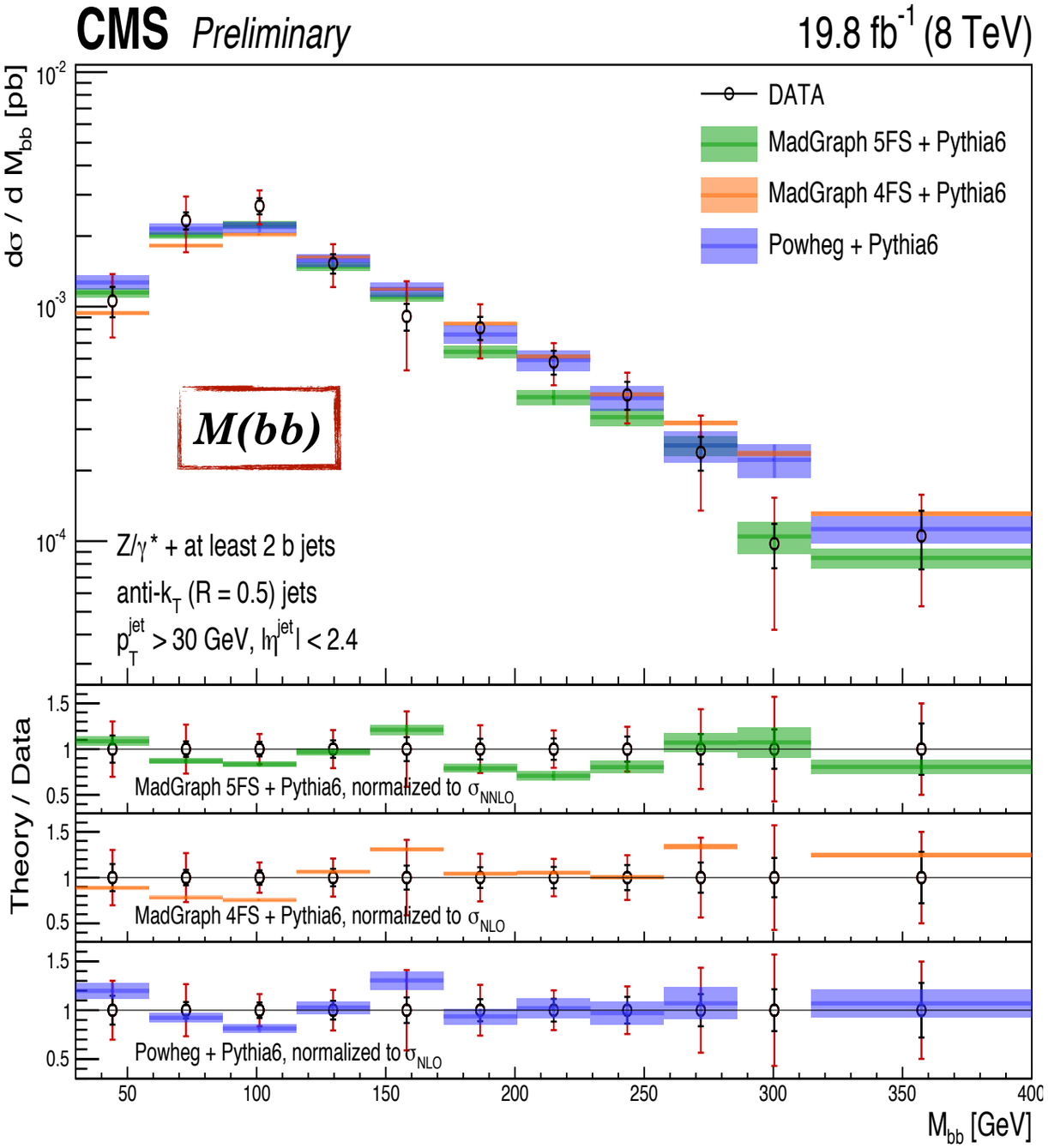
$Z + b,\ Z + bb$

NEW!

$\int Ldt = 20\ \text{fb}^{-1}\ \sqrt{s} = 8\ \text{TeV}$

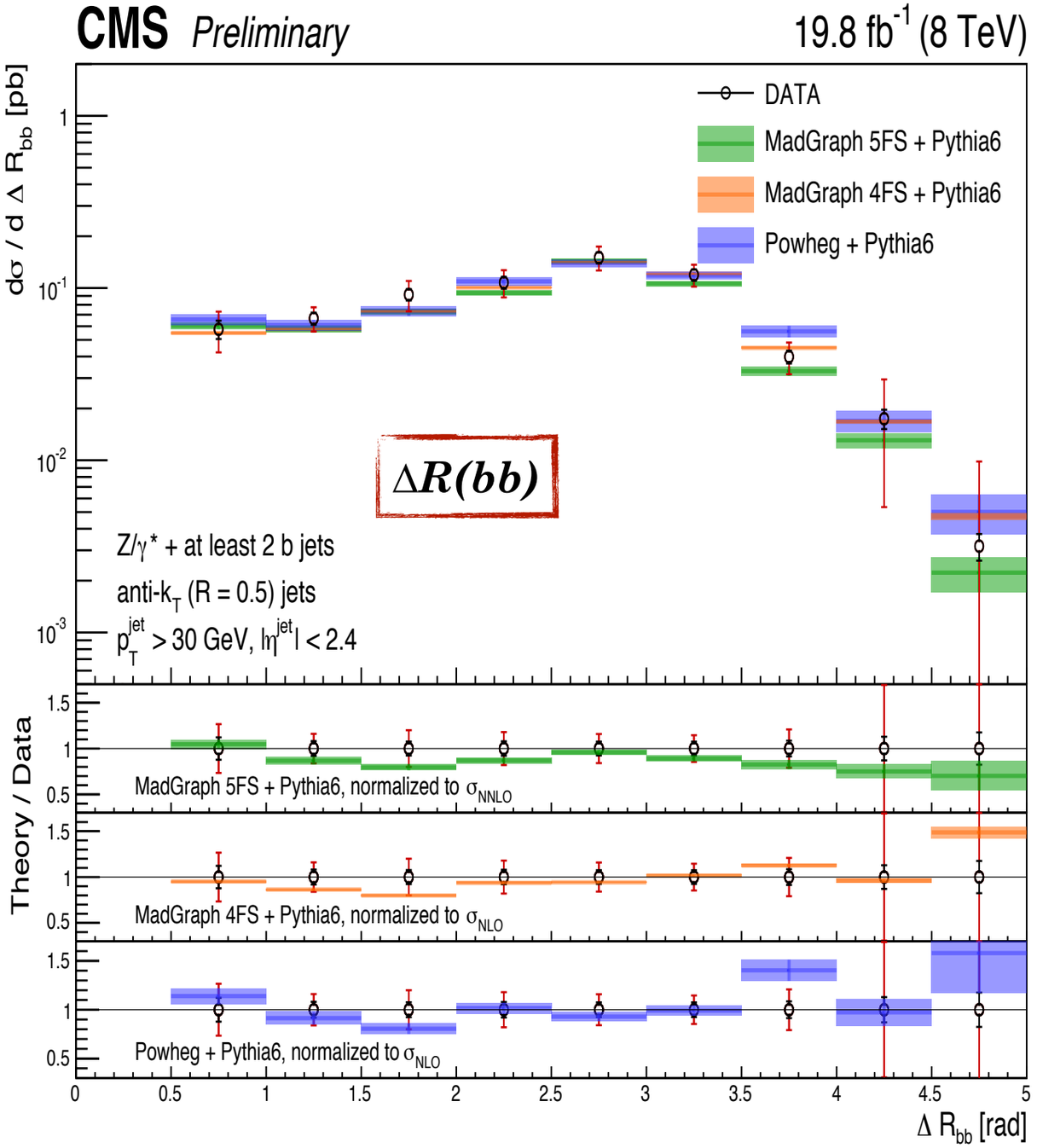
unfolded M(bb) cross section

(Z + at least 2 b jet selection)



unfolded ΔR(bb) cross section

(Z + at least 2 b jet selection)



good agreement with both MadGraph 4FS, 5FS and Powheg

$Z + b,\ Z + bb$

NEW!

$\int Ldt = 20\ \text{fb}^{-1}\ \sqrt{s} = 8\ \text{TeV}$

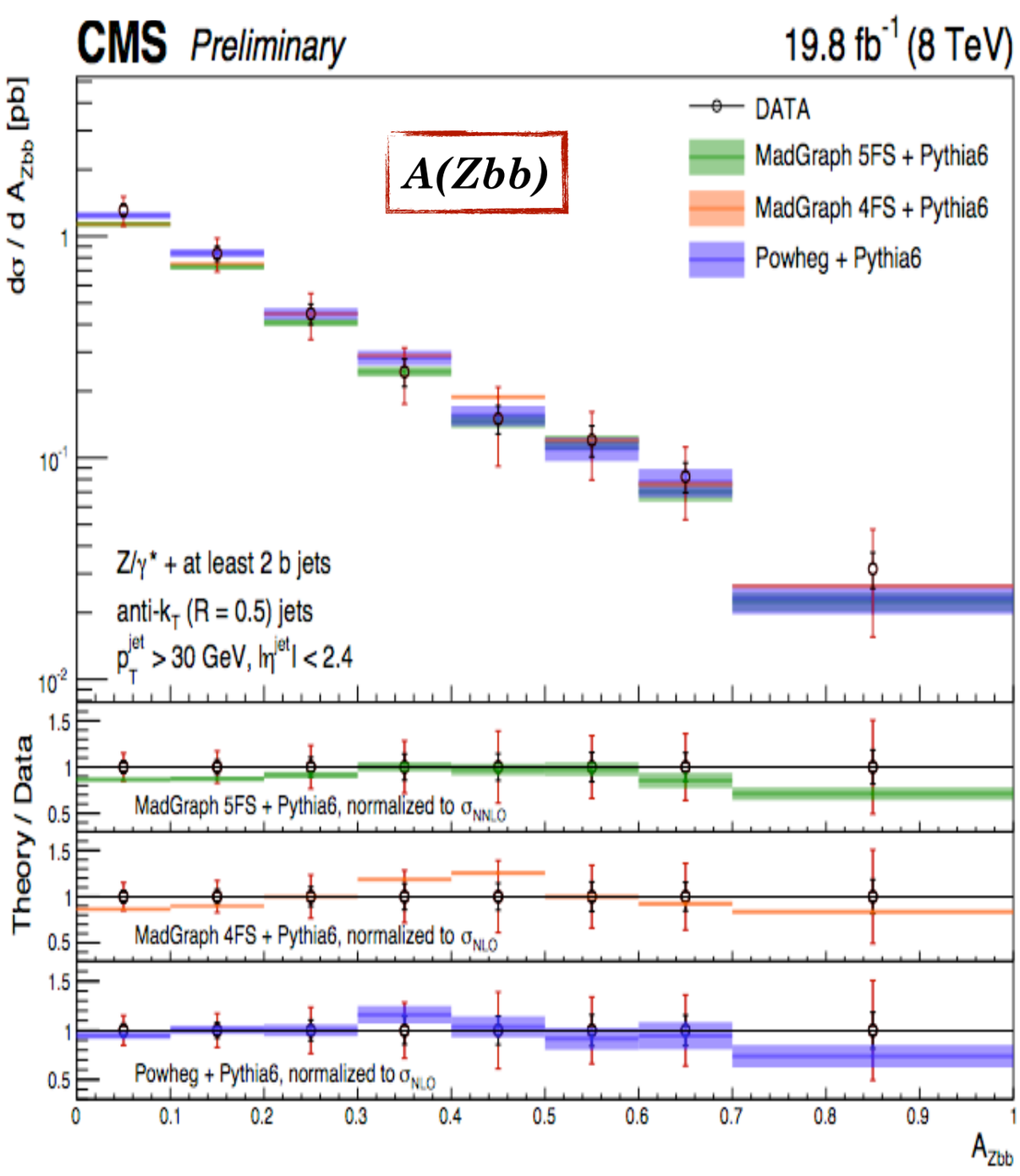
$$A_{Zbb} = \frac{(\Delta R_{Zb}^{max} - \Delta R_{Zb}^{min})}{(\Delta R_{Zb}^{max} + \Delta R_{Zb}^{min})}.$$

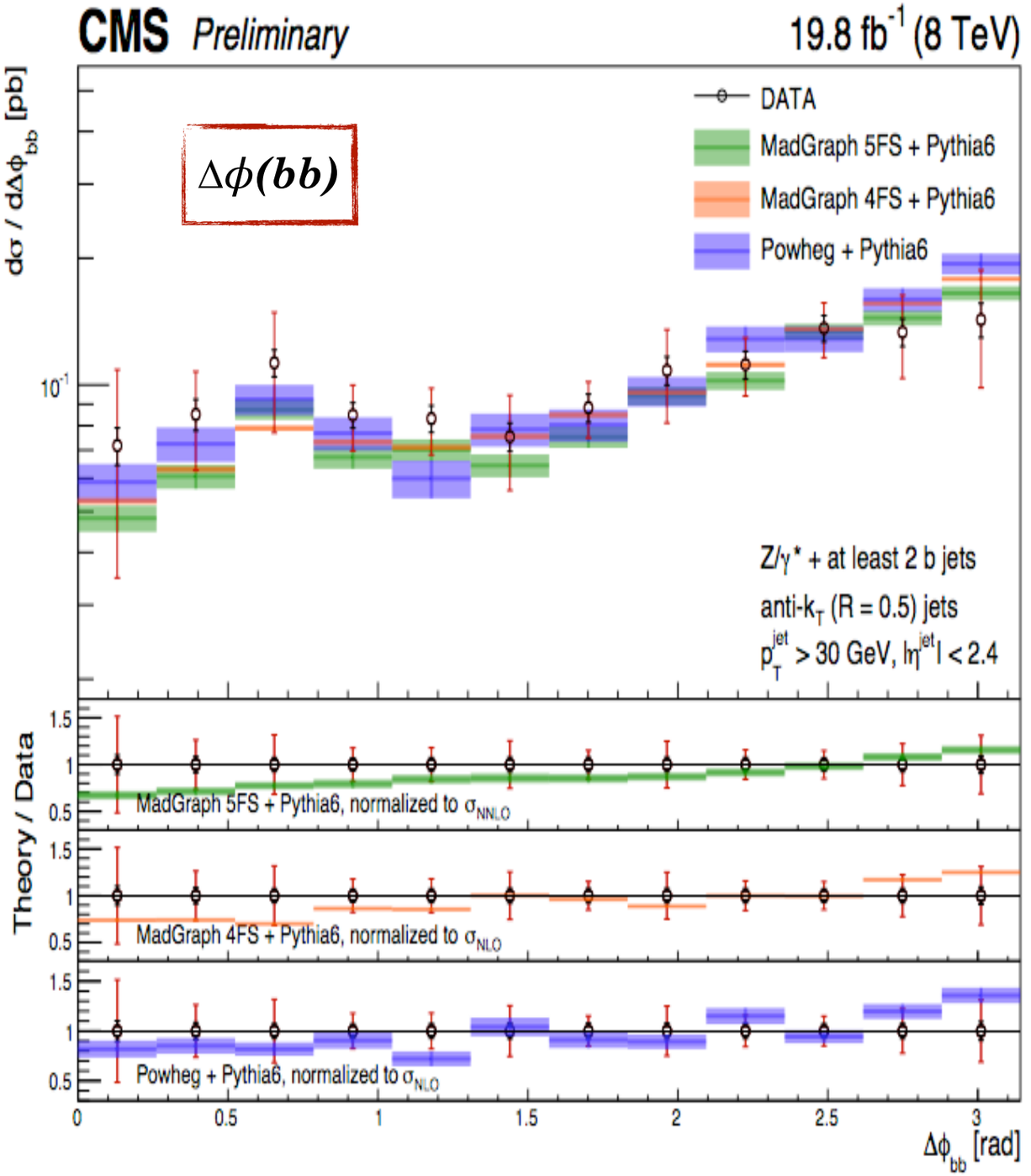
_Zb_ Asymmetry

(Z + at least 2 b jet selection)

unfolded $\Delta\phi$(bb) cross section

(Z + at least 2 b jet selection)





MadGraph 4FS, 5FS ok within the systematics, Powheg shows better agreement

$Z + jets$ @ 13 TeV

NEW!

$\int Ldt = 85\ \text{pb}^{-1}\ \sqrt{s} = 13\ \text{TeV}$

[ATLAS-CONF-2015-051]

selection criteria

- isolated e/μ with p_T>25 GeV, $|\eta|$<2.47 / 2.4
- ≥1 antiKT04 jet p_T > 30 GeV, $|y|$<2.5
- di-lepton mass 66 < M(ll) < 116 GeV

PU<μ> = 19 σ(L) = ±9%

cross sections

- corrected to particle level using a ***C*** factor (Sherpa)

systematics

- Jet Energy Scale and Resolution dominant, up to 4-5%

(extrapolated from RunI)

theoretical predictions

- MadGraph5_aMC@NLO + Pythia8 (up to 4 partons at LO)
- Sherpa v2 (NLO up to 2 partons)

$$\sigma^{\text{fid}}_{Z\to e^+e^-+\geq \text{N}_{\text{jets}}} \equiv A \cdot \sigma_{Z\to e^+e^-+\geq \text{N}_{\text{jets}}} \cdot BR(Z \to \ell^+\ell^-) \equiv \frac{N^{\text{sig}}_{Z\to e^+e^-+\geq \text{N}_{\text{jets}}}}{C_{Z\to e^+e^-+\geq \text{N}_{\text{jets}}} \cdot \mathcal{L}}$$

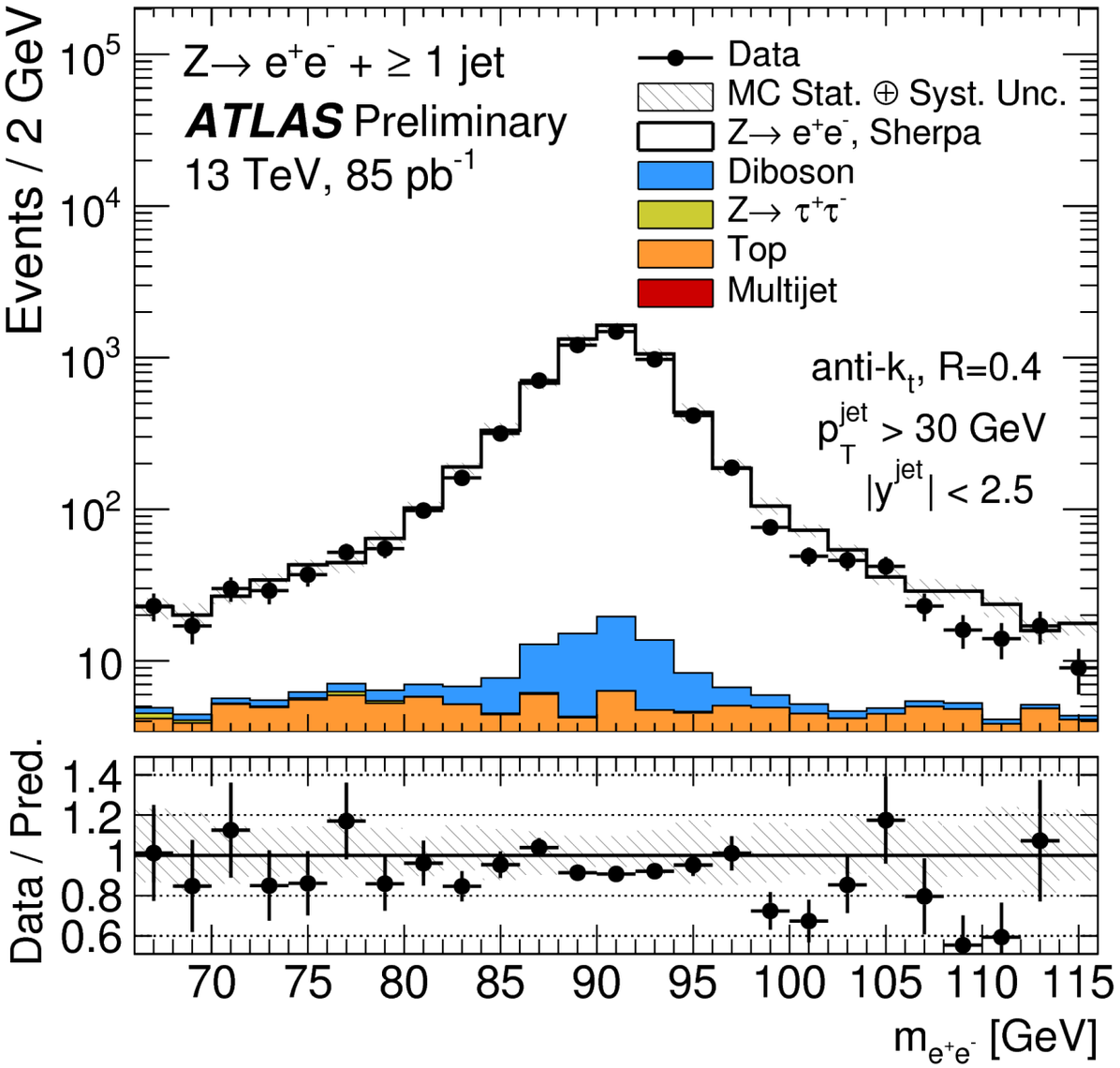
$\delta\sigma_{Z\to e^+e^-+\geq \text{N}_{\text{jets}}}/\sigma_{Z\to e^+e^-+\geq \text{N}_{\text{jets}}}$ (%)

	$Z \to e^+e^-$			
Systematic source	+ ≥ 1 jet	+ ≥ 2 jets	+ ≥ 3 jets	+ ≥ 4 jets
Electron Trigger	0.5	0.5	0.5	0.5
Electron Reconstruction, Identification	5.2	6.0	6.8	7.8
Electron Isolation	1.2	1.4	1.6	1.8
Electron Scale and Resolution	0.4	0.5	0.4	0.7
JES and JER	4.4	5.9	8.5	7.7
Pileup	0.3	0.5	1.0	2.0
Backgrounds	0.2	0.5	1.0	1.2
Total	7.1	8.5	12.4	11.7
	$Z \to \mu^+\mu^-$			
Systematic source	+ ≥ 1 jet	+ ≥ 2 jets	+ ≥ 3 jets	+ ≥ 4 jets
Muon Trigger	1.0	1.0	1.1	1.2
Muon Reconstruction and Identification	0.9	1.0	1.0	1.2
Muon Isolation	0.7	0.9	1.3	1.8
Muon Scale and Resolution	0.2	0.2	0.3	0.6
JES and JER	4.9	6.5	8.4	10.5
Pileup	0.7	0.6	1.7	6.0
Backgrounds	0.2	0.5	1.1	1.9
Total	5.2	6.7	8.9	12.6

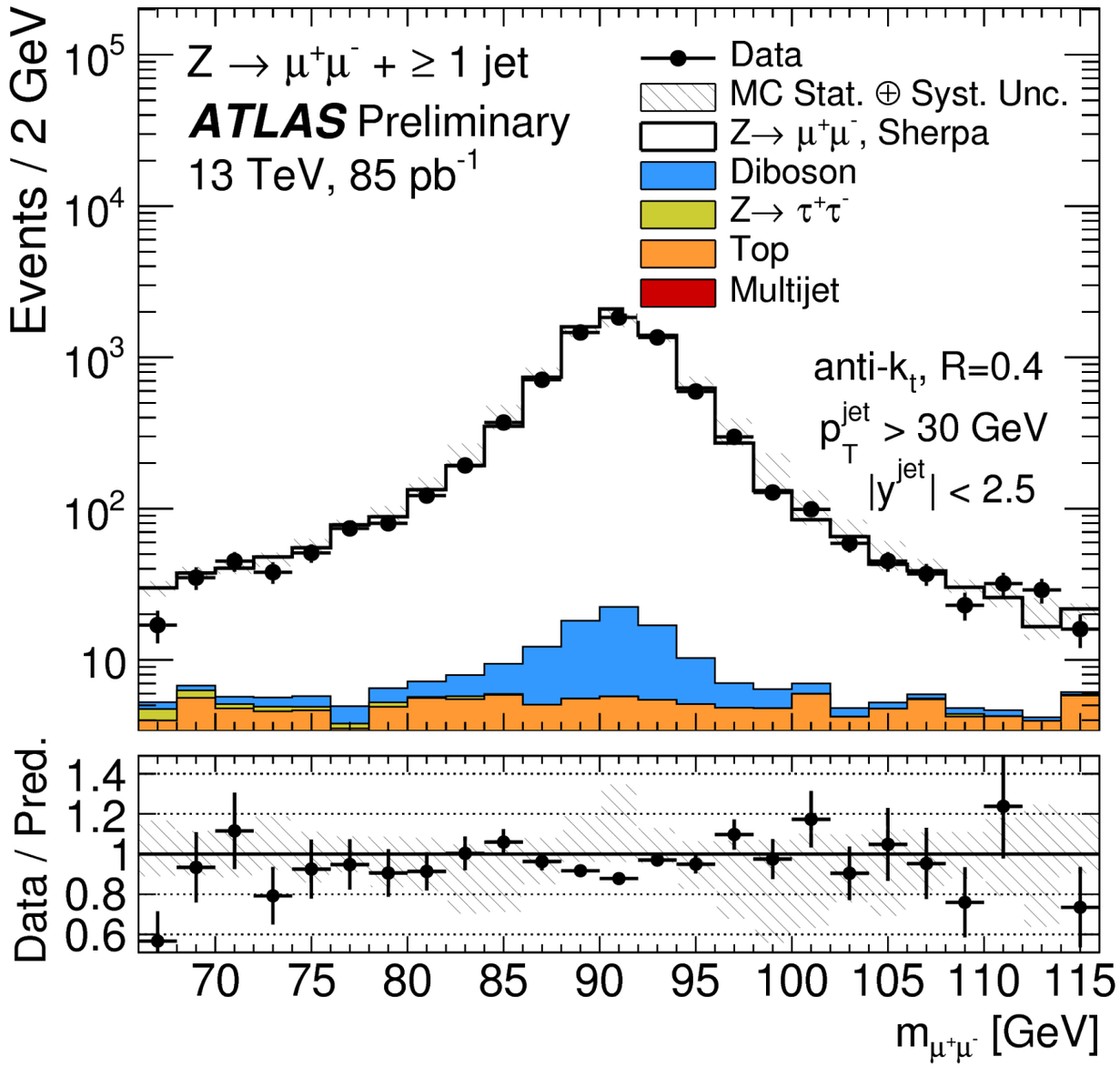
$Z + jets$ @ 13 TeV

NEW!

$\int Ldt = 85\ \text{pb}^{-1}\ \sqrt{s} = 13\ \text{TeV}$



detector level dielectron mass

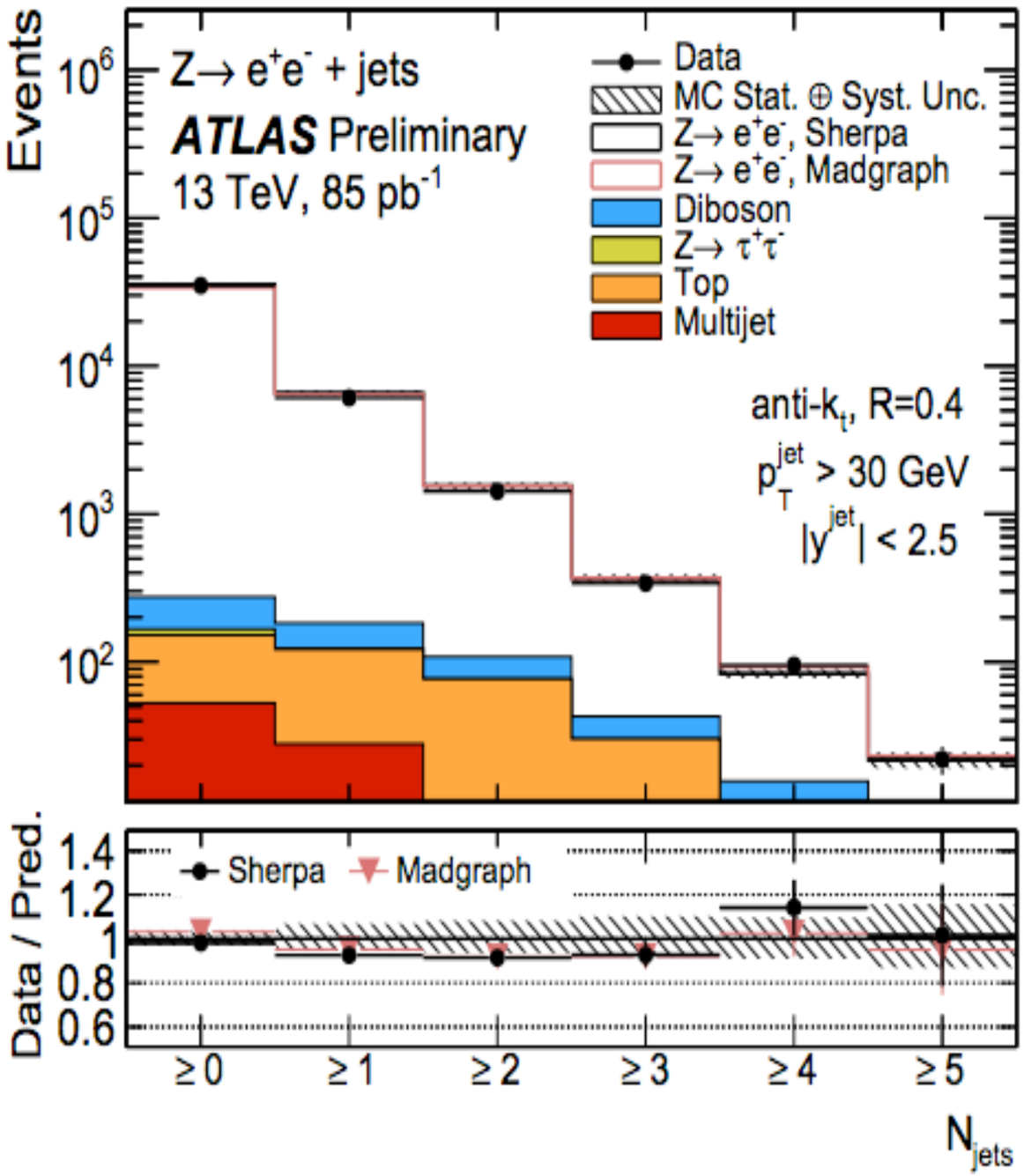


detector level dimuon mass

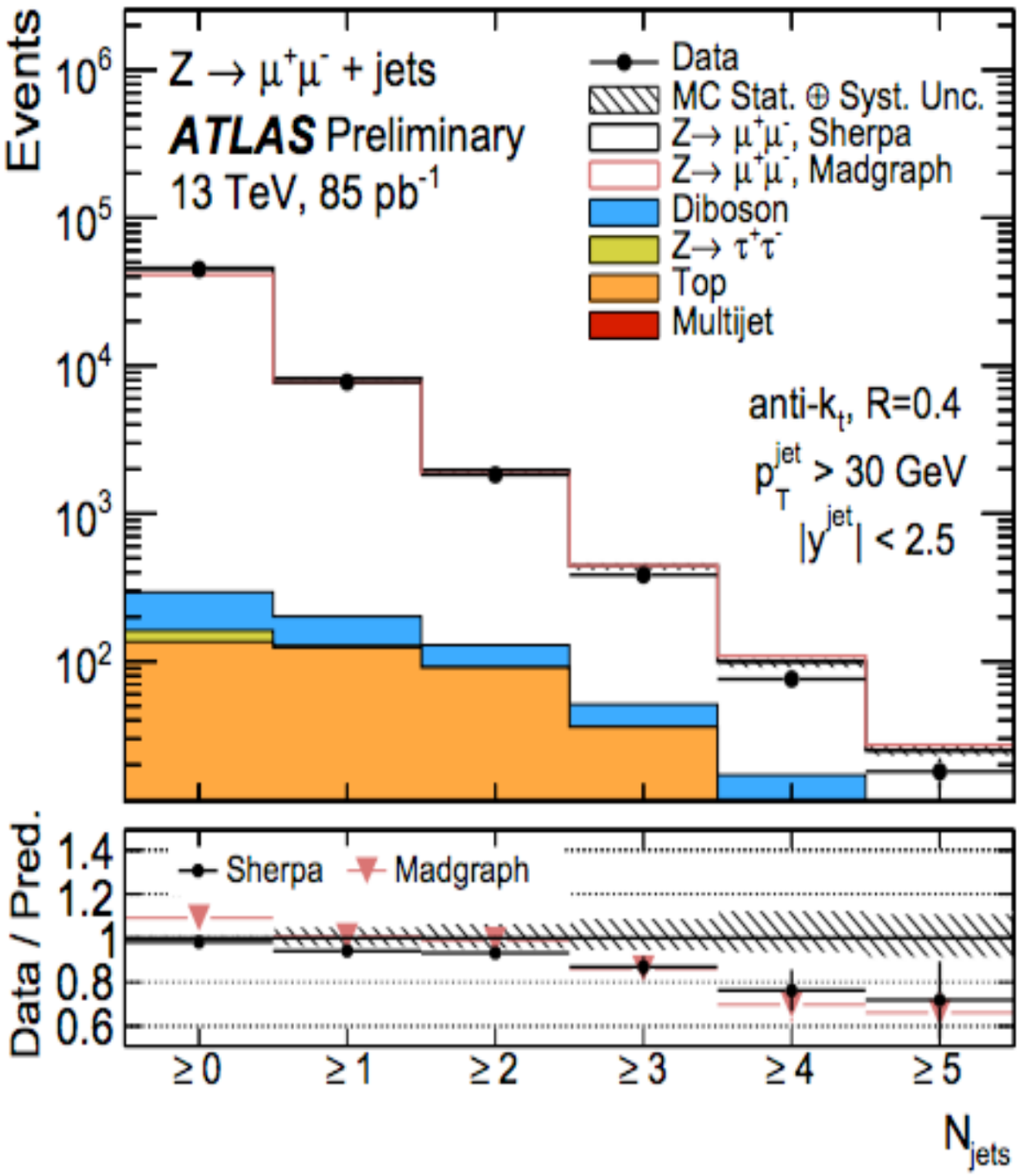
$Z + jets$ @ 13 TeV

NEW!

$\int Ldt = 85\ \text{pb}^{-1}\ \sqrt{s} = 13\ \text{TeV}$



detector level inclusive jet multiplicity



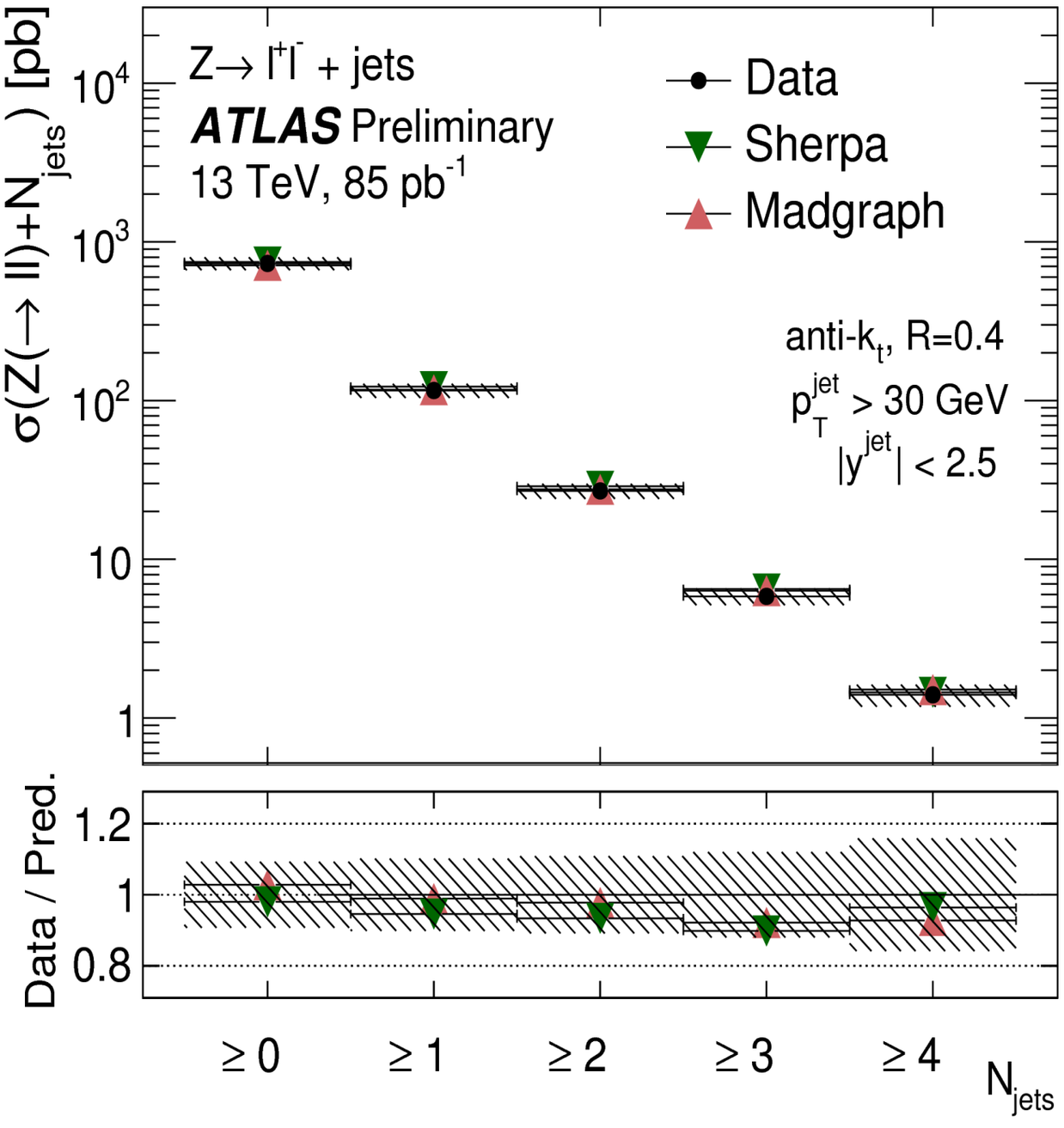
detector level inclusive jet multiplicity

$Z + jets$ @ 13 TeV

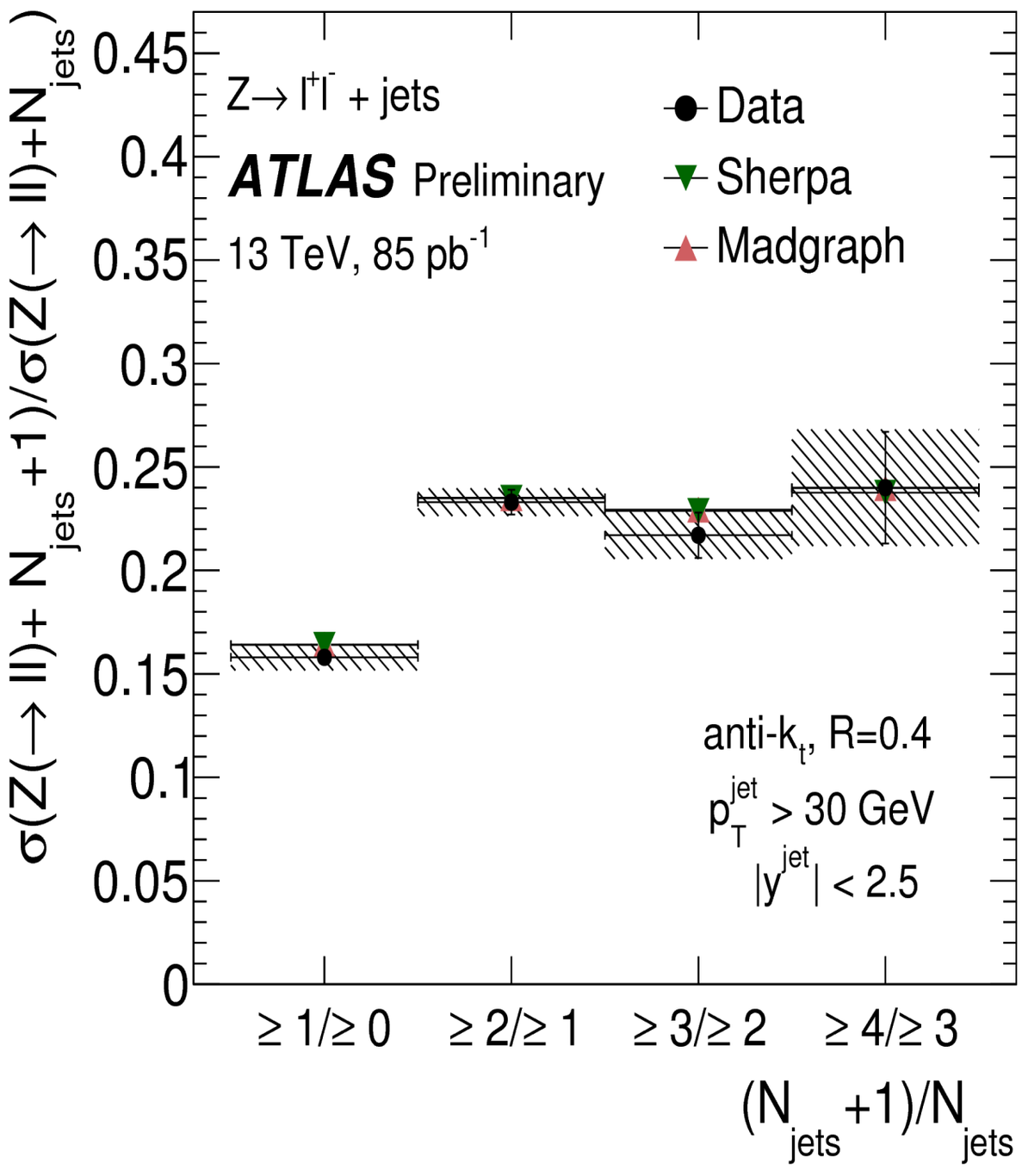
NEW!

$\int Ldt = 85\ \text{pb}^{-1}\ \sqrt{s} = 13\ \text{TeV}$

unfolded inclusive jet multiplicity



unfolded Nj+1/Nj cross section



MadGraph and Sherpa consistent with data

Summary and perspectives

The *V+jets* production is an important and wide part of the SM physics program of LHC

- *W+jets* @ 7 TeV differential cross sections compared to LO and NLO predictions
- *Z+jets* @ 8 TeV 1D and 2D differential cross sections compared to NLO predictions
- *Z+b, Z+bb* @ 8 TeV differential cross sections compared to 4, 5 FS LO and to 5 FS NLO
- R(*W/Z + jets)* @ 7 TeV differential cross section compared with LO predictions
- *Z+jets* @ 13 TeV differential cross sections compared to NLO predictions

More *V+jets* analyses at 8 TeV with 20/fb will be ready soon!

The full 13 TeV V+jets physics program is on the way so… stay tuned!!!

backup

Full List of Public V+Jets Results in CMS

- V + light flavors
  http://cms-results.web.cern.ch/cms-results/public-results/publications/SMP/VLF.html

Standard Model Physics Publications			V+Light-Flavour Production	
67	SMP-12-017	Measurements of jet multiplicity and differential production cross sections of Z+jets events in proton-proton collisions at $\sqrt{s}$ = 7 TeV	PRD 91 (2015) 052008	13 August 2014
65	SMP-12-023	Differential cross section measurements for the production of a W boson in association with jets in proton-proton collisions at $\sqrt{s}$ = 7 TeV	PLB 741 (2015) 12	30 June 2014
55	QCD-11-005	Measurement of the triple-differential cross section for photon+jets production in proton-proton collisions at $\sqrt{s}$ = 7 TeV	JHEP 06 (2014) 009	24 November 2013
52	SMP-12-004	Rapidity distributions in exclusive Z + jet and photon + jet events in pp collisions at $\sqrt{s}$ = 7 TeV	PRD 88 (2013) 112009	11 October 2013
44	SMP-12-019	Studies of jet mass in dijet and W/Z+jet events	JHEP 05 (2013) 090	20 March 2013
42	EWK-11-021	Event shapes and azimuthal correlations in Z + jets events in pp collisions at $\sqrt{s}$ =7 TeV	PLB 722 (2013) 238-261	9 January 2013
39	SMP-12-015	Measurement of the sum of WW and WZ production with W+dijet events in pp collisions at $\sqrt{s}$ = 7 TeV	EPJC 73 (2013) 2283	29 October 2012
37	EWK-11-017	Study of the dijet mass spectrum in pp → W + jets events at $\sqrt{s}$ = 7 TeV	PRL 109 (2012) 251801	17 August 2012
28	EWK-10-012	Jet Production Rates in Association with W and Z Bosons in pp Collisions at $\sqrt{s}$ = 7 TeV	JHEP 01 (2012) 010	17 October 2011
19	EWK-10-014	Measurement of the Polarization of W Bosons with Large Transverse Momenta in W+Jets Events at the LHC	PRL 107 (2011) 021802	20 April 2011

- V + heavy flavors
  http://cms-results.web.cern.ch/cms-results/public-results/publications/SMP/VHF.html

Standard Model Physics Publications			V+Heavy-Flavour Production	
59	SMP-13-004	Measurement of the production cross sections for a Z boson and one or more b jets in pp collisions at $\sqrt{s}$ = 7 TeV	JHEP 06 (2014) 120	7 February 2014
57	SMP-12-026	Measurement of the production cross section for a W boson and two b jets in pp collisions at $\sqrt{s}$ = 7 TeV	PLB 735 (2014) 204	23 December 2013
51	SMP-12-002	Measurement of associated W + charm production in pp collisions at $\sqrt{s}$ = 7 TeV	JHEP 02 (2014) 013	6 October 2013
50	EWK-11-015	Measurement of the cross section and angular correlations for associated production of a Z boson with b hadrons in pp collisions at $\sqrt{s}$ = 7 TeV	JHEP 12 (2013) 039	4 October 2013
32	EWK-11-012	Measurement of the Z/γ^* +b-jet cross section in pp collisions at $\sqrt{s}$ = 7 TeV	JHEP 06 (2012) 126	8 April 2012

Full List of Public V+Jets Results in ATLAS

W/Z Physics

Short Paper Title	Published	Date	√s (TeV)	Run (year)	Lumi	Links
W+jets cross sections	EPJC	9/2014	7	2011	4.6 fb^{-1}	HepData, Rivet
Rjets (W+jets/Z+jets ratio) cross sections	EPJC	8/2014	7	2011	4.6 fb^{-1}	HepData,Rivet
Z boson in association with b-jets	JHEP	7/2014	7	2011	4.6 fb^{-1}	HepData Rivet
High pT vector bosons reconstructed as single jets and studies of jet substructure	NJP	7/2014	7	2011	4.6 fb^{-1}	
Z transverse momentum distribution	JHEP	6/2014	7	2011	4.7 fb^{-1}	HepData Rivet
Z->bb cross section	PLB	4/2014	8	2012	19.5 fb^{-1}	
Low-mass Drell–Yan differential cross section	JHEP	4/2014	7	2011, 2010	1.6 fb^{-1}, 35 pb^{-1}	HepData Rivet
W plus D/D* and c-jet	JHEP	2/2014	7	2011	4.6 fb^{-1}	HepData Rivet
High-mass Drell-Yan differential cross-section	PLB	5/2013	7	2011	4.9 fb^{-1}	HepData
Production of jets in association with a Z boson	JHEP	4/2013	7	2011	4.6 fb^{-1}	HepData, Rivet
W boson production in association with b-jets	JHEP	2/2013	7	2011	4.6 fb^{-1}	HepData,Rivet
Measurement of kt splitting scales in W->lnu events	EPJC	2/2013	7	2010	36 pb^{-1}	HepData, Rivet
Phi* distribution of Drell-Yan lepton pairs to probe Z/gamma* boson transverse momentum	PLB	11/2012	7	2011	4.6 fb^{-1}	HepData, Rivet
Measurement of tau polarization in W->taunu decays	EPJC	4/2012	7	2010	24 pb^{-1}	
Determination of the strange-quark density from measurements of W and Z cross-sections	PRL	3/2012	7	2010	36 pb^{-1}	LHAPDF EIG,LHAPDF VAR
Polarisation of W bosons produced at large momentum transfer	EPJC	2/2012	7	2010	35 pb^{-1}	
Study of jets produced in association with a W boson	PRD	1/2012	7	2010	36 pb^{-1}	HepData, Rivet
Z/ gamma* in association with jets (superseded)	PRD	11/2011	7	2010	36 pb^{-1}	HepData, Rivet
W and Z/gamma* cross sections in the e and μ decay channels	PRD	9/2011	7	2010	36 pb^{-1}	HepData Rivet Z Rivet W
b-jets produced in association with a Z boson (superseded)	PLB	9/2011	7	2010	36 pb^{-1}	

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/StandardModelPublicResults#W_Z_Physics

γγ+*jets* differential

$\int Ldt = 5\ \text{fb}^{-1}$ $\sqrt{s} = 7\ \text{TeV}$

selection criteria

- isolated γ with p_T>40 GeV and
- $|\eta|$<1.44 or 1.57<$|\eta|$<2.5
- at least1 antiKT05 jet
  p_T > 25 GeV, $|\eta|$<2.4

signal extraction

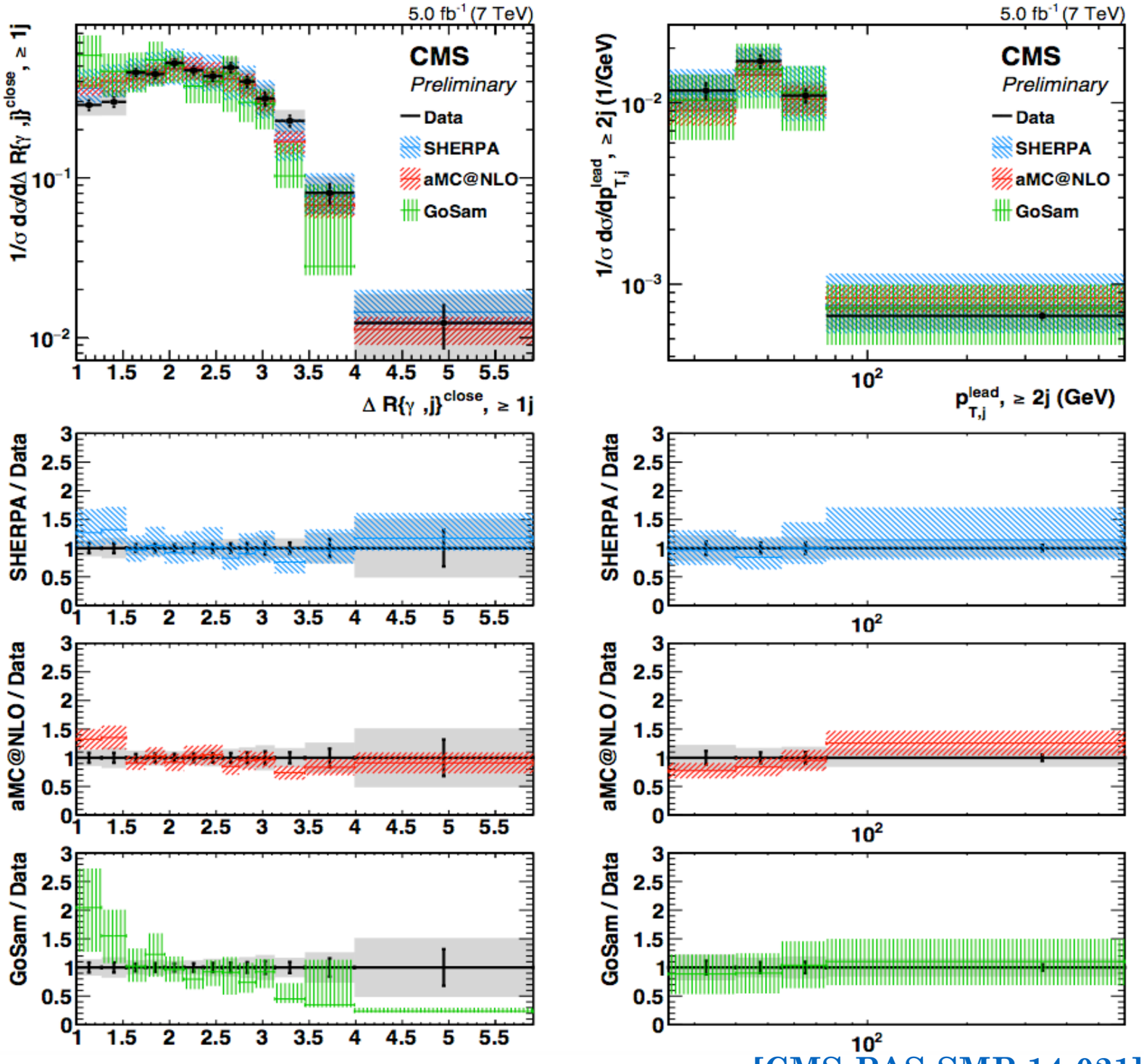
- data-driven method: 2D fit the particle flow isolation variable to discriminate prompt γγ from neutral mesons decays (π,η → γ γ)

unfolding

- data unfolded using
  Bayesian d'Agostini Iterative method

theoretical predictions

- Sherpa1.4 (LO up to 3 jets)
- aMC@NLO (NLO up to 2jets)
- GoSam (NLO for 1 or 2 jets)



[CMS-PAS-SMP-14-021]

good agreement w.r.t. the three predictions

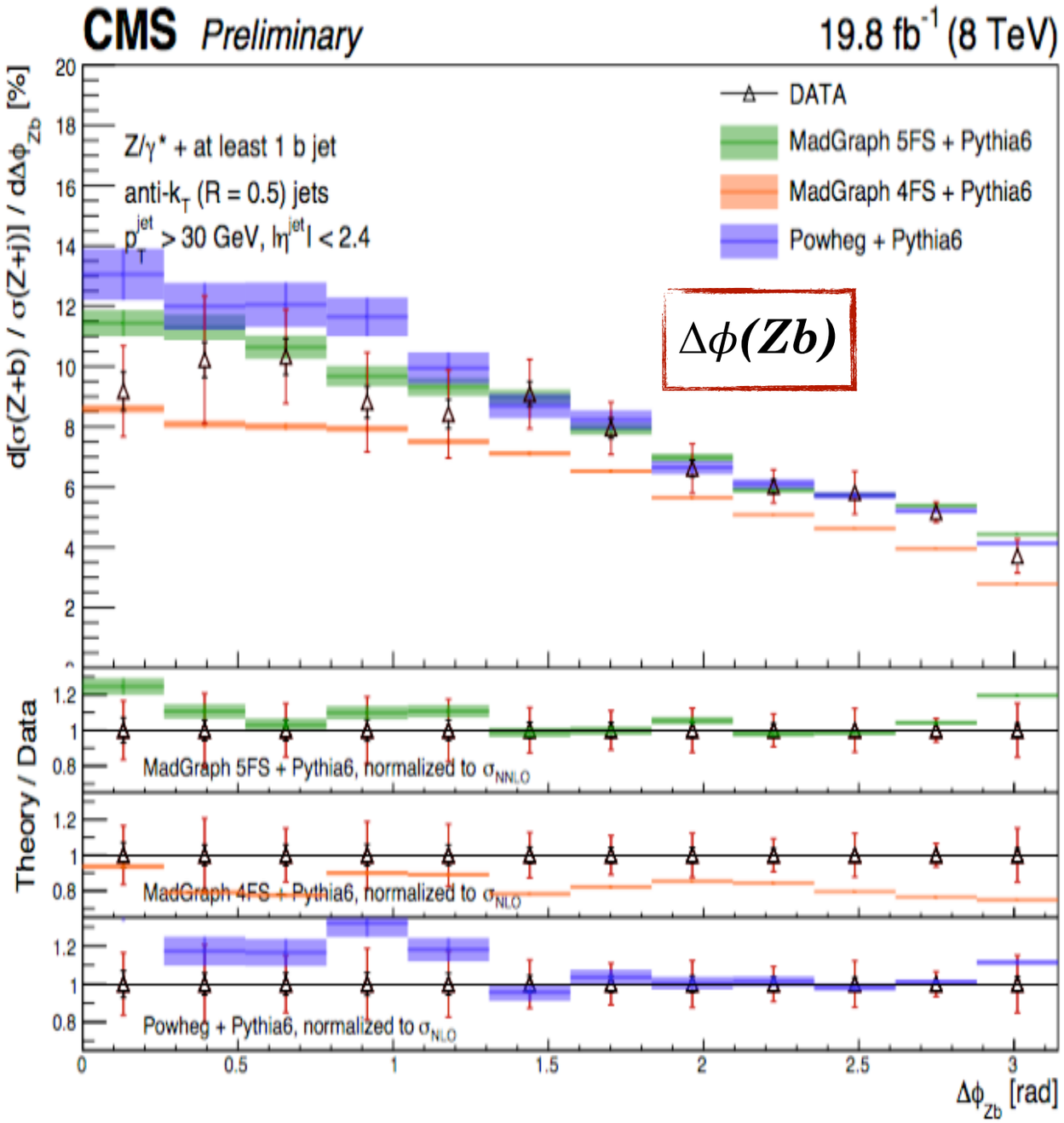
$Z + b,\ Z + bb$

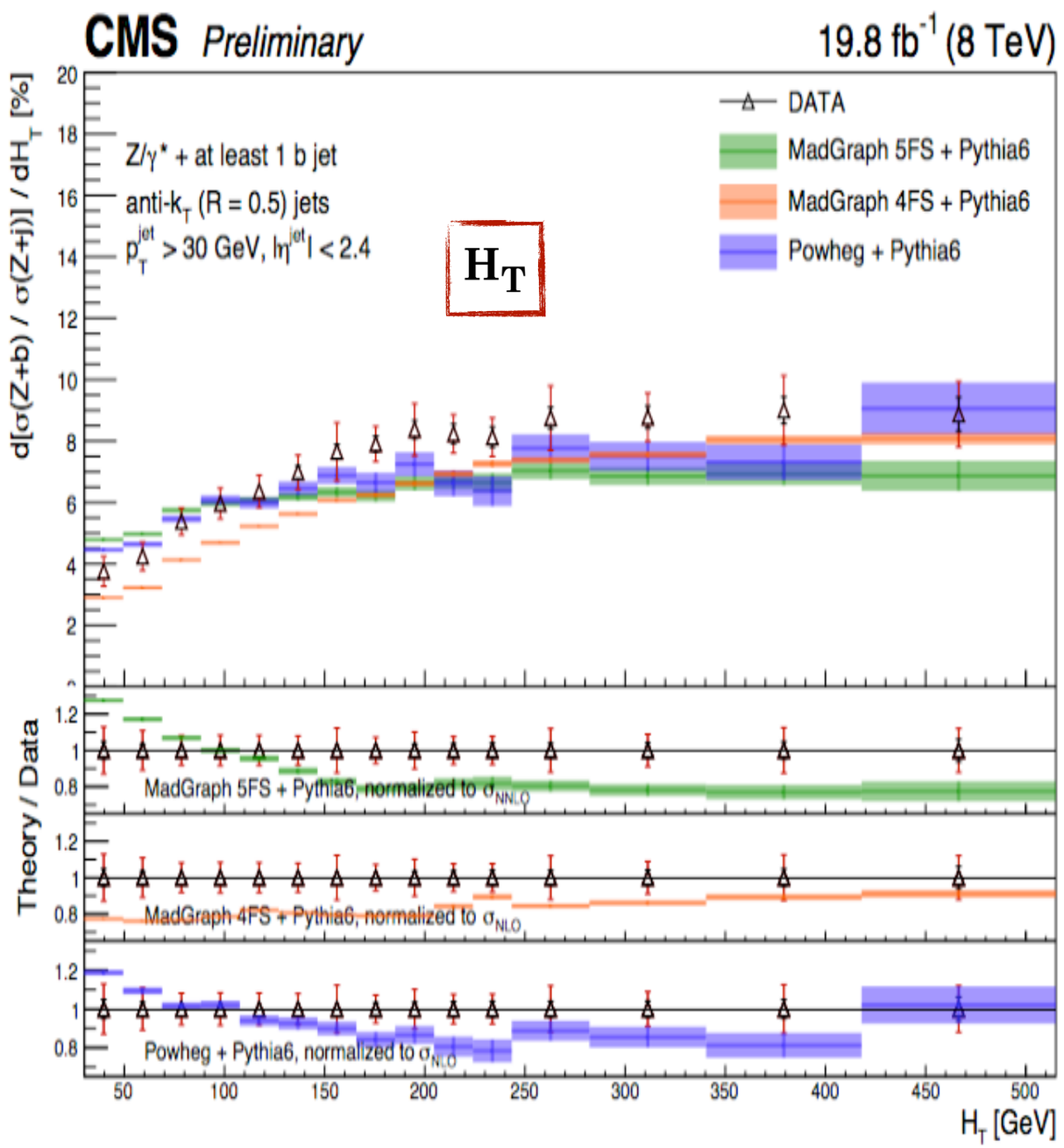
NEW!

$\int Ldt = 20\ \text{fb}^{-1}\ \sqrt{s} = 8\ \text{TeV}$

$$R(x) = \frac{d\sigma(Z+b)/dx}{d\sigma(Z+\text{jets})/dx} \qquad \frac{Z + at\ least\ 1\ b\ jet}{Z + at\ least\ 1\ jet}$$

unfolded cross section ratios





4FS overall better agreement in shape, but 20% normalization discrepancy