Associated production of a vector boson and jets in CMS

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On the behalf of the CMS Collaboration

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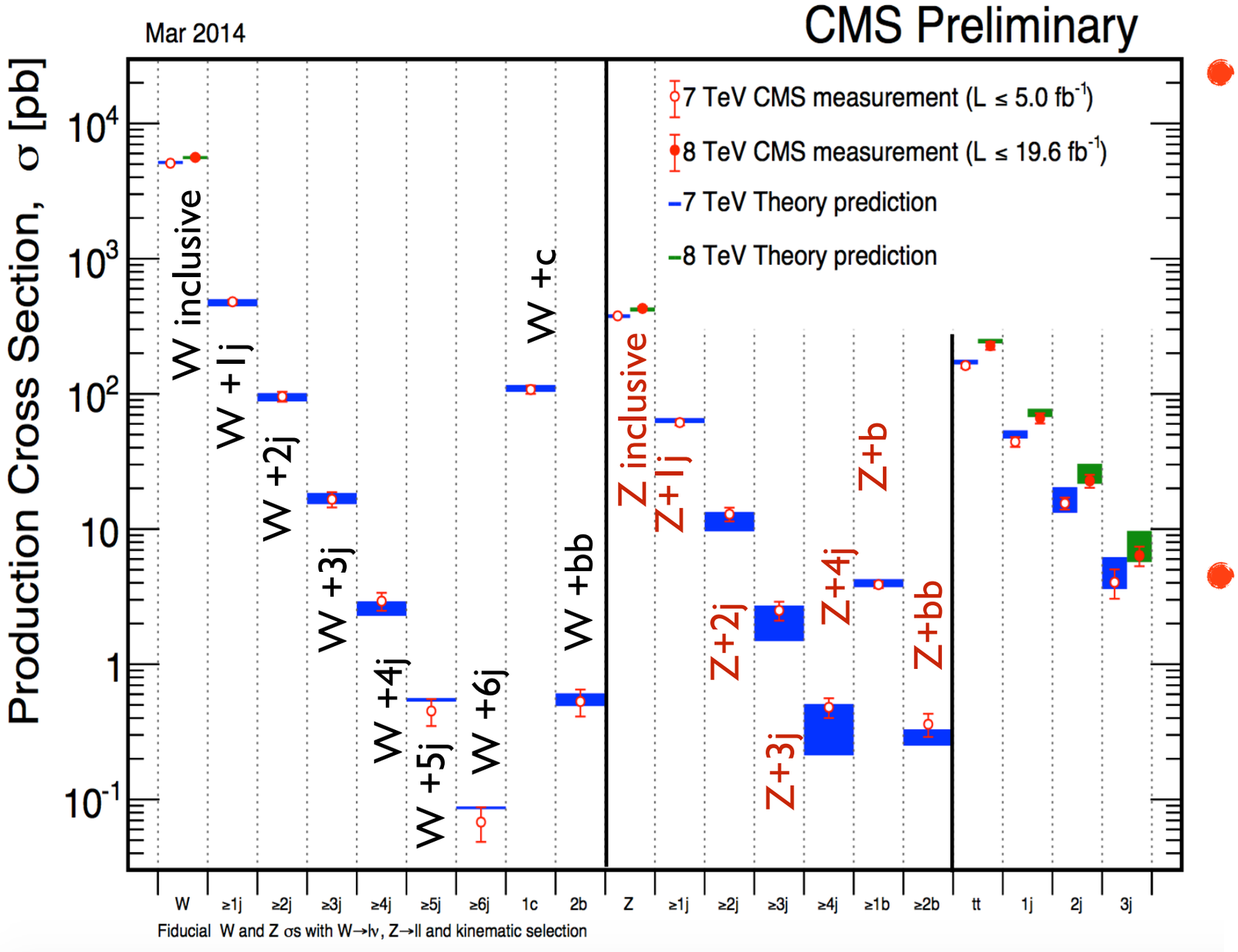
Vector bosons + jets at LHC

Physics of V(=*W/Z/γ*) + jets is an essential part of the 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
  - 4th generations of heavy quarks
  - 2HDMs

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

$W + jets$

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

[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

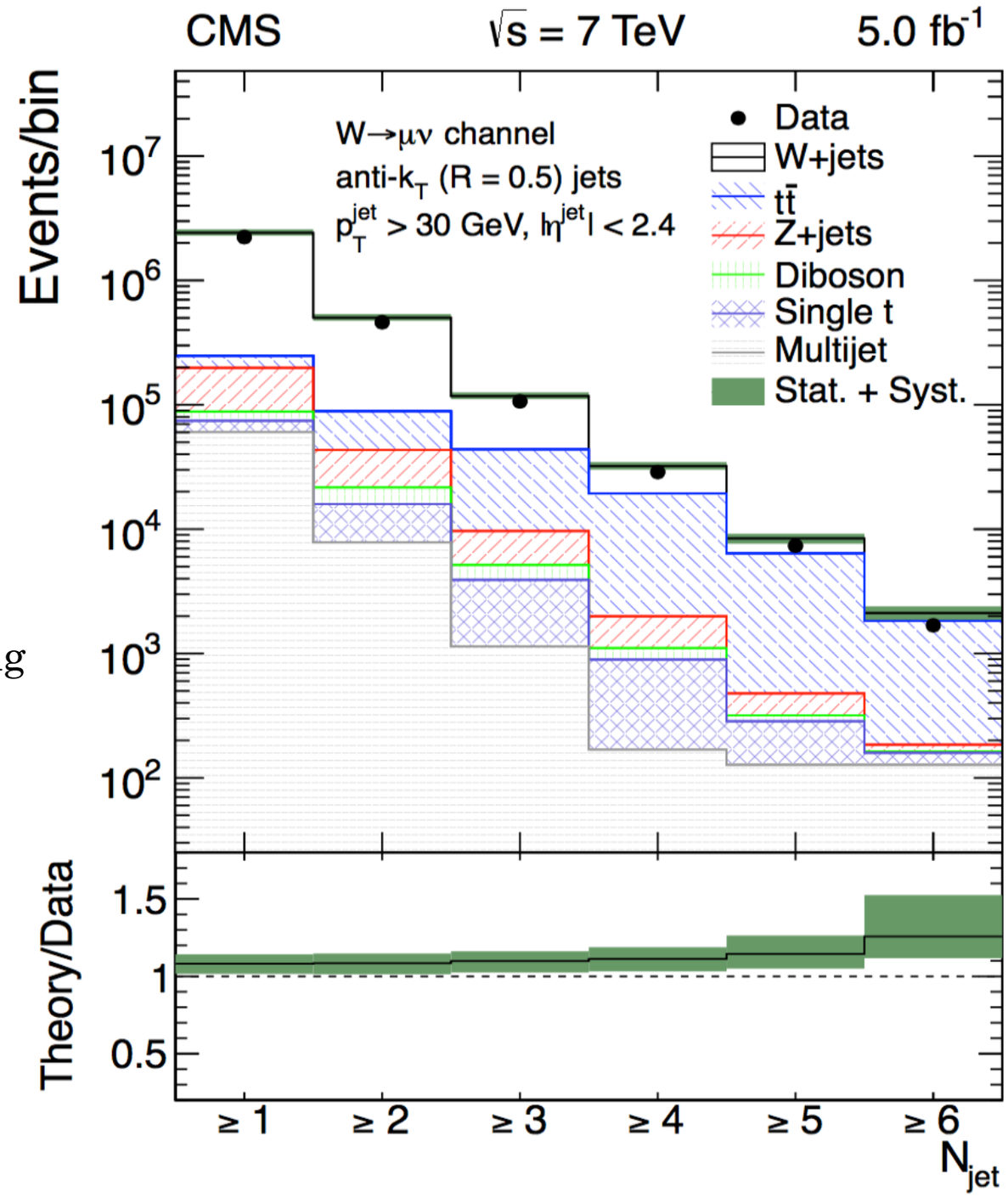
- *unfolding* data to account detector effects using the SVD algorithm and compare to particle level MC

theoretical predictions (see next page…)

- MadGraph5+Pythia6 (LO)

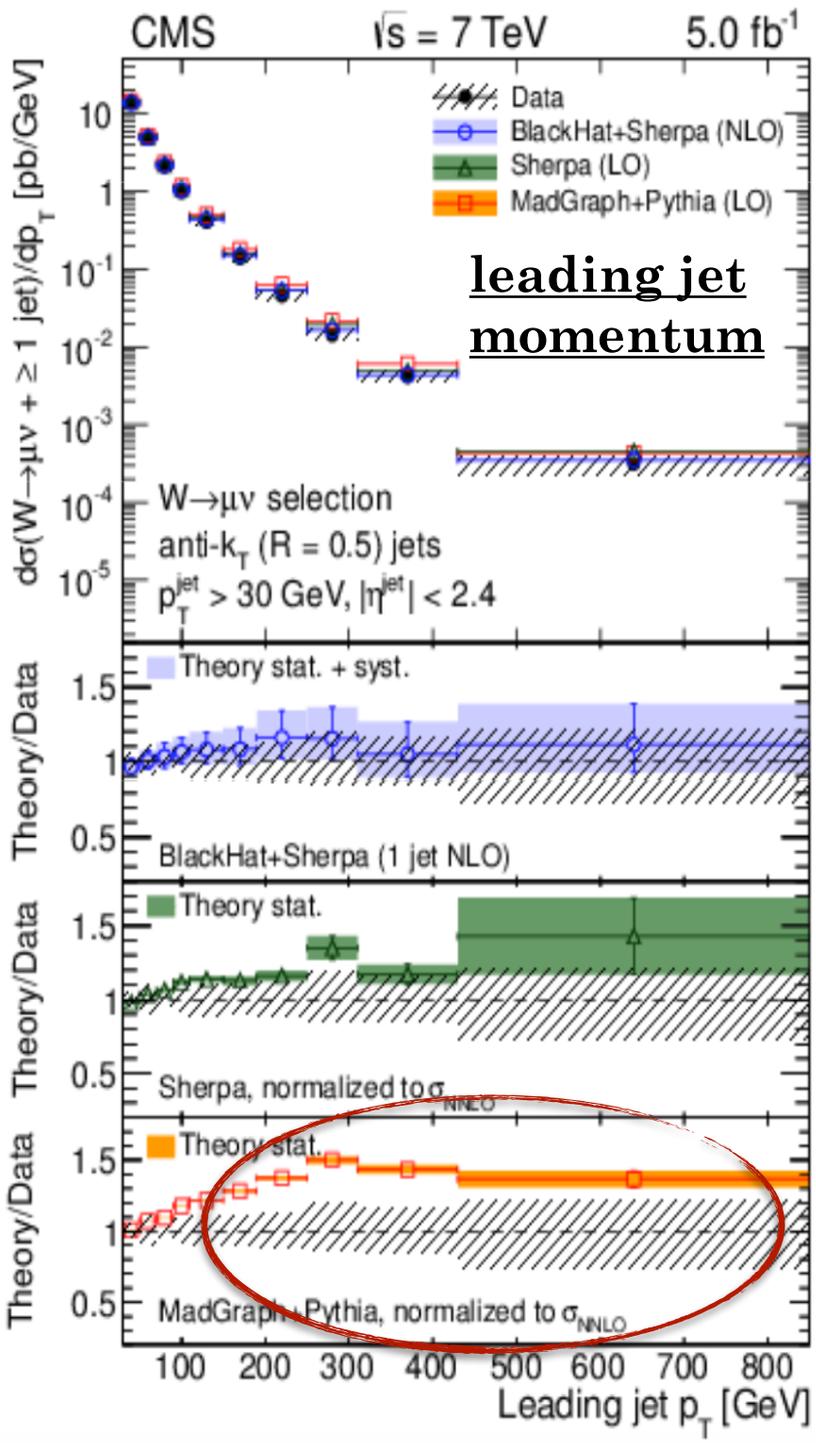
- BlackHat+Sherpa (NLO)

- Sherpa (LO)

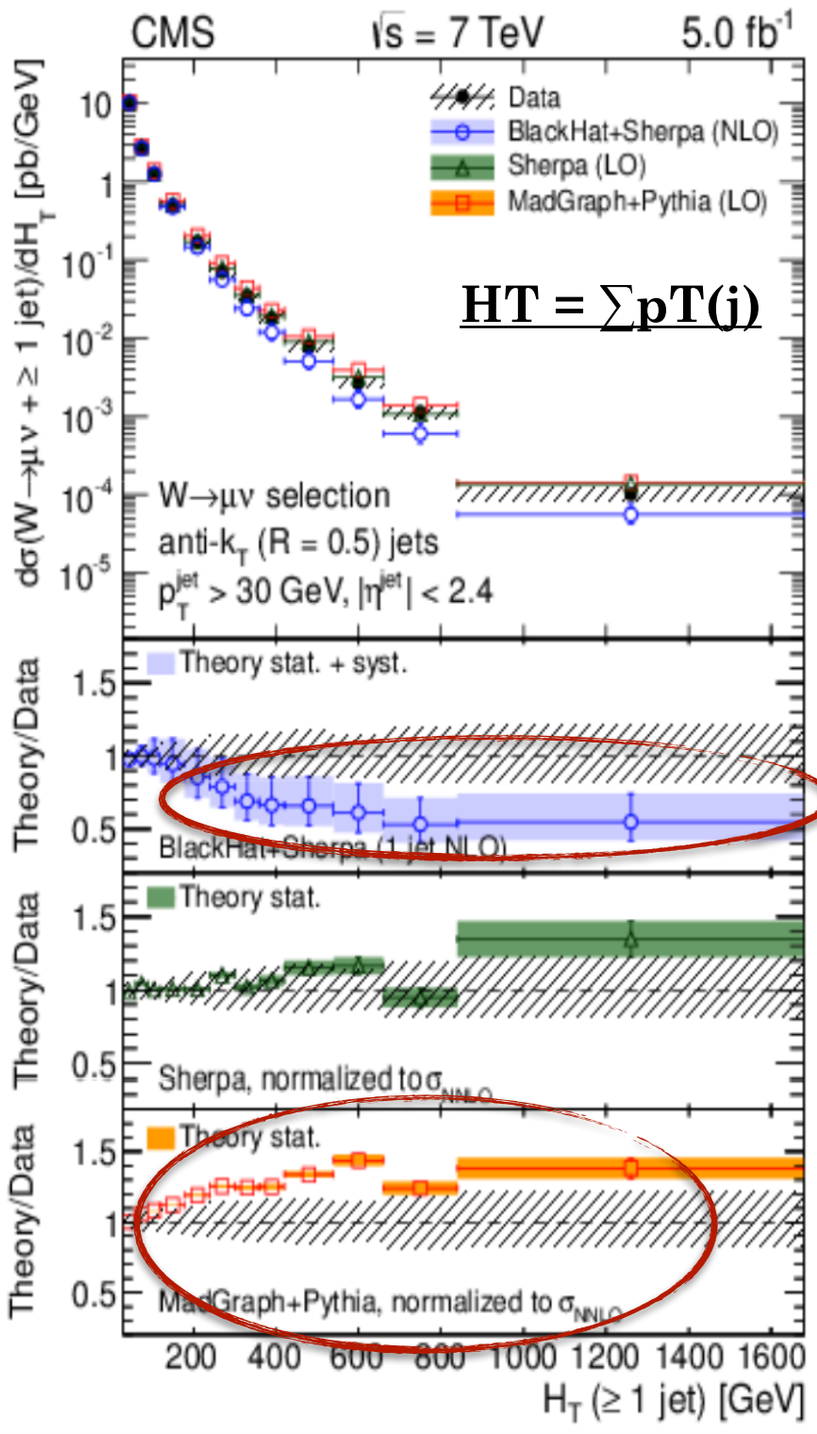


detector level jet multiplicity showing the background composition

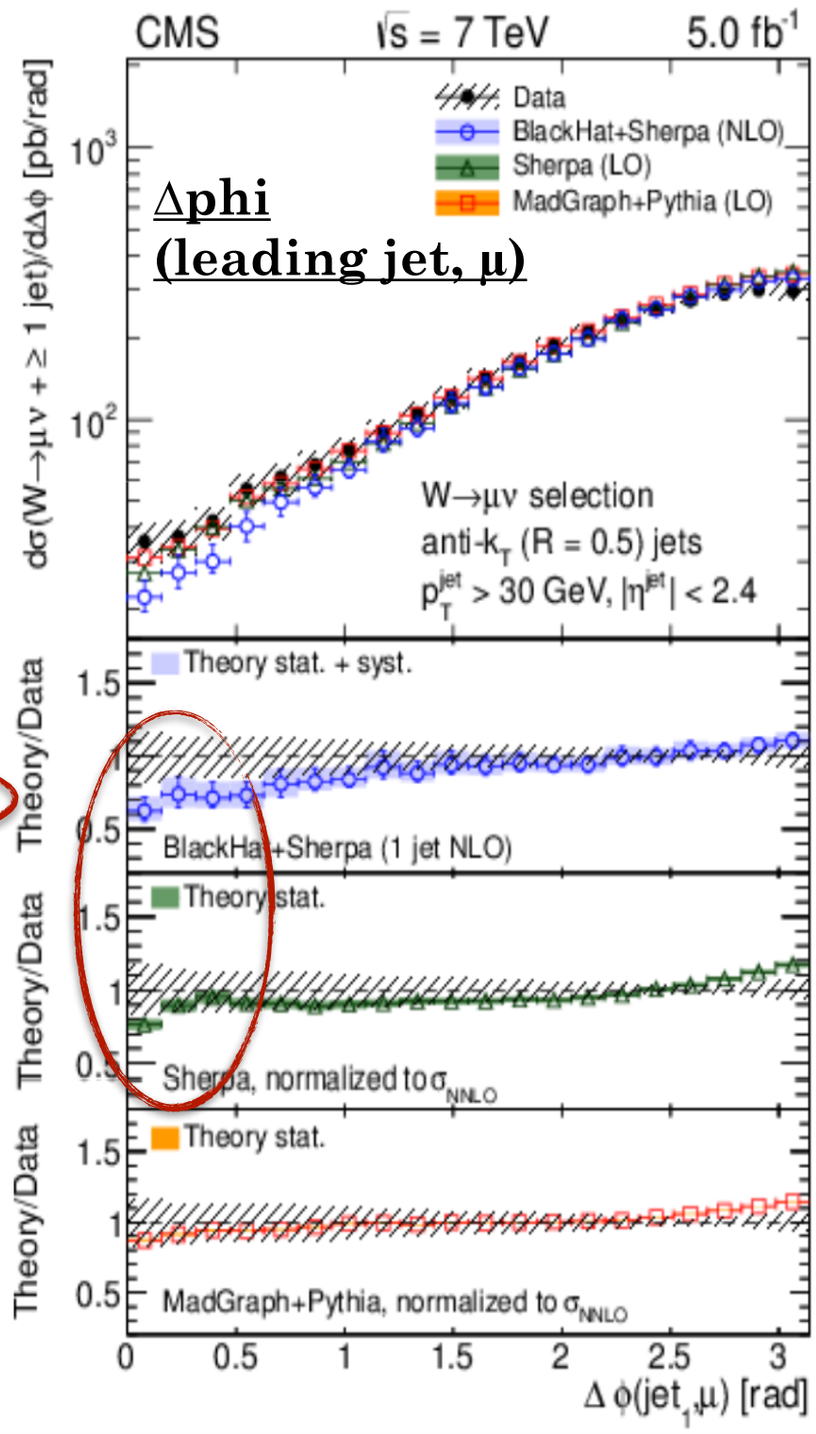
W + jets - unfolded differential cross sections



- 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

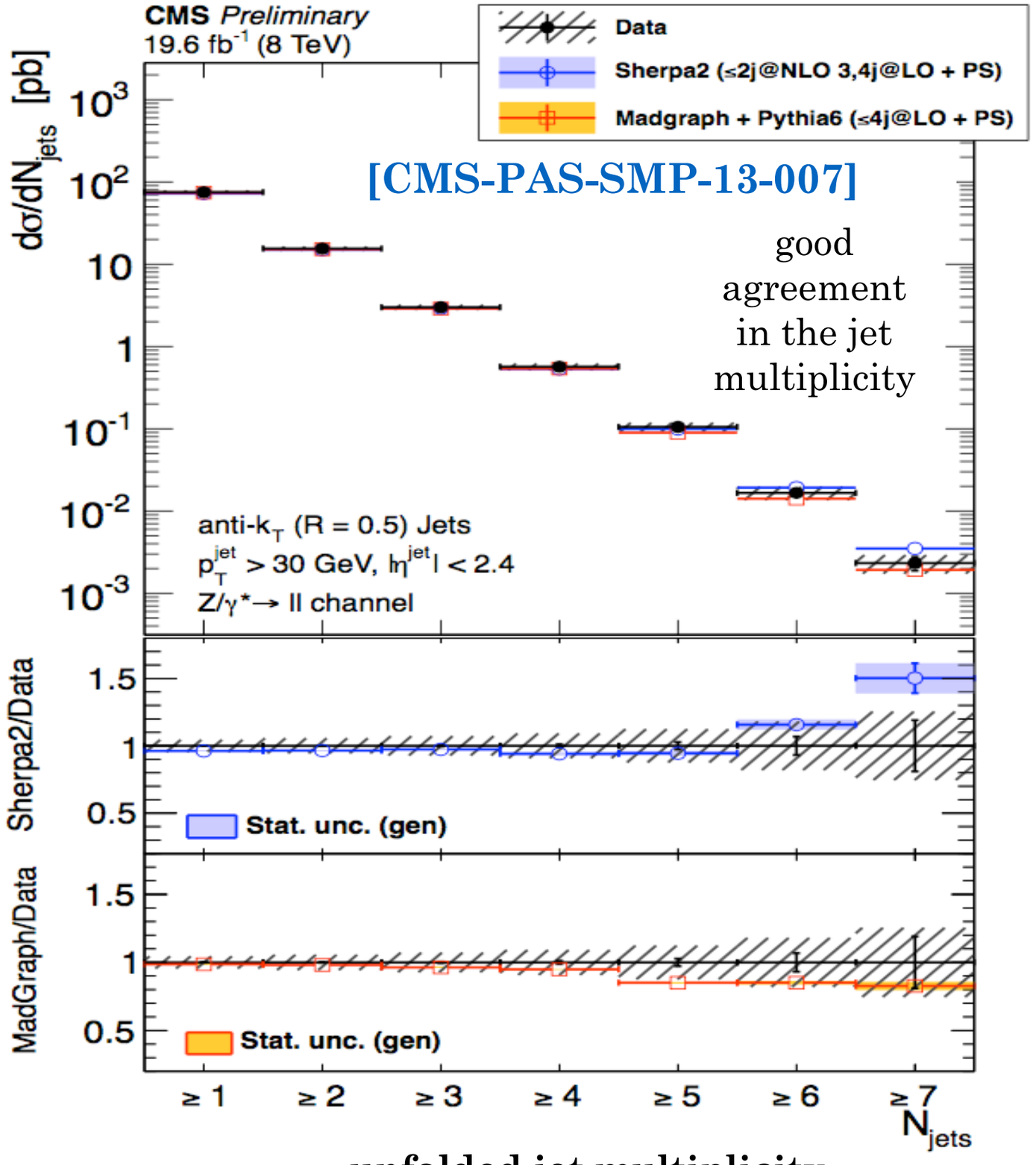
- *unfolding* data to account detector effects using the Bayes Iterative algorithm and compare to particle level MC

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

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

selection criteria

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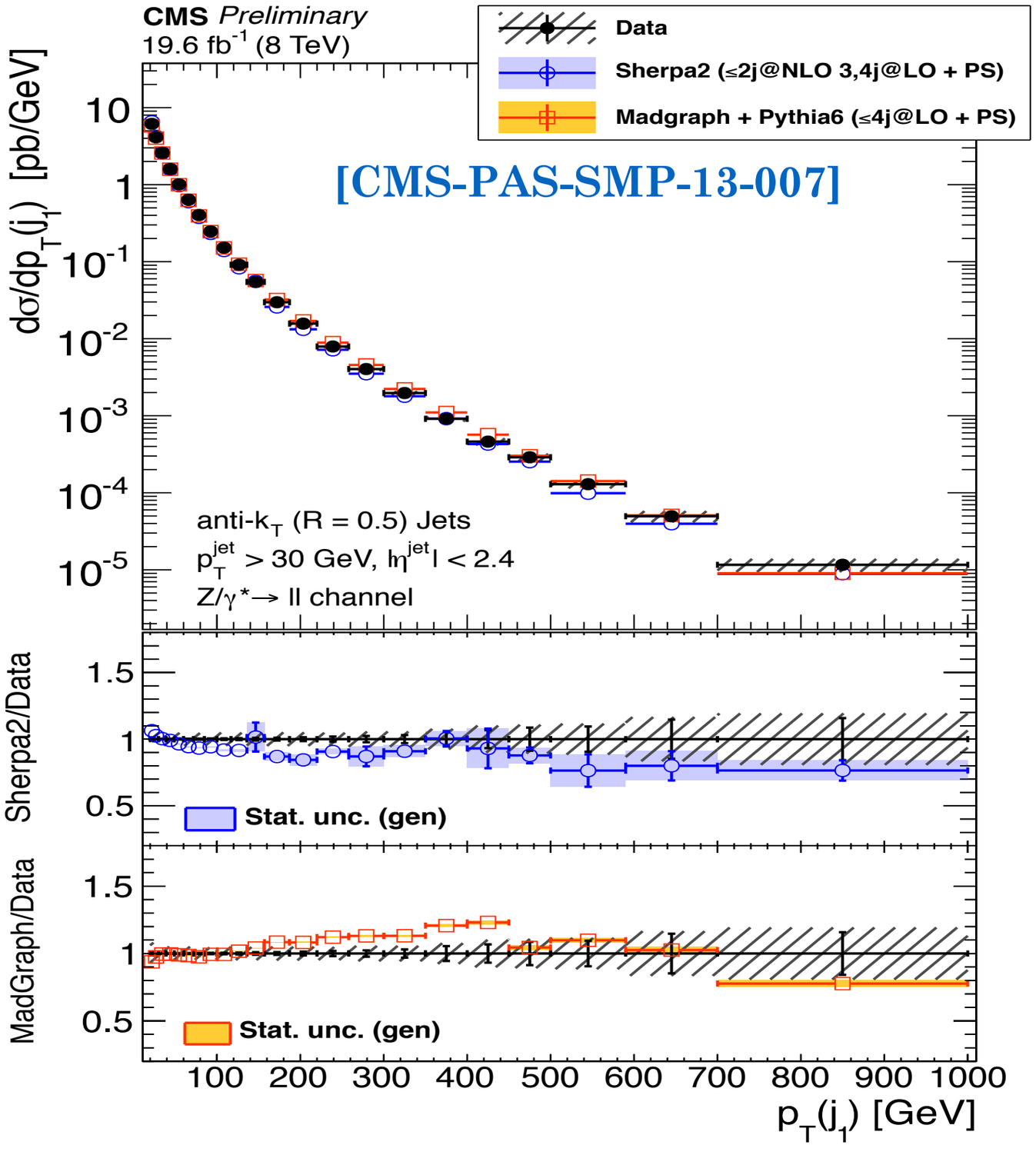
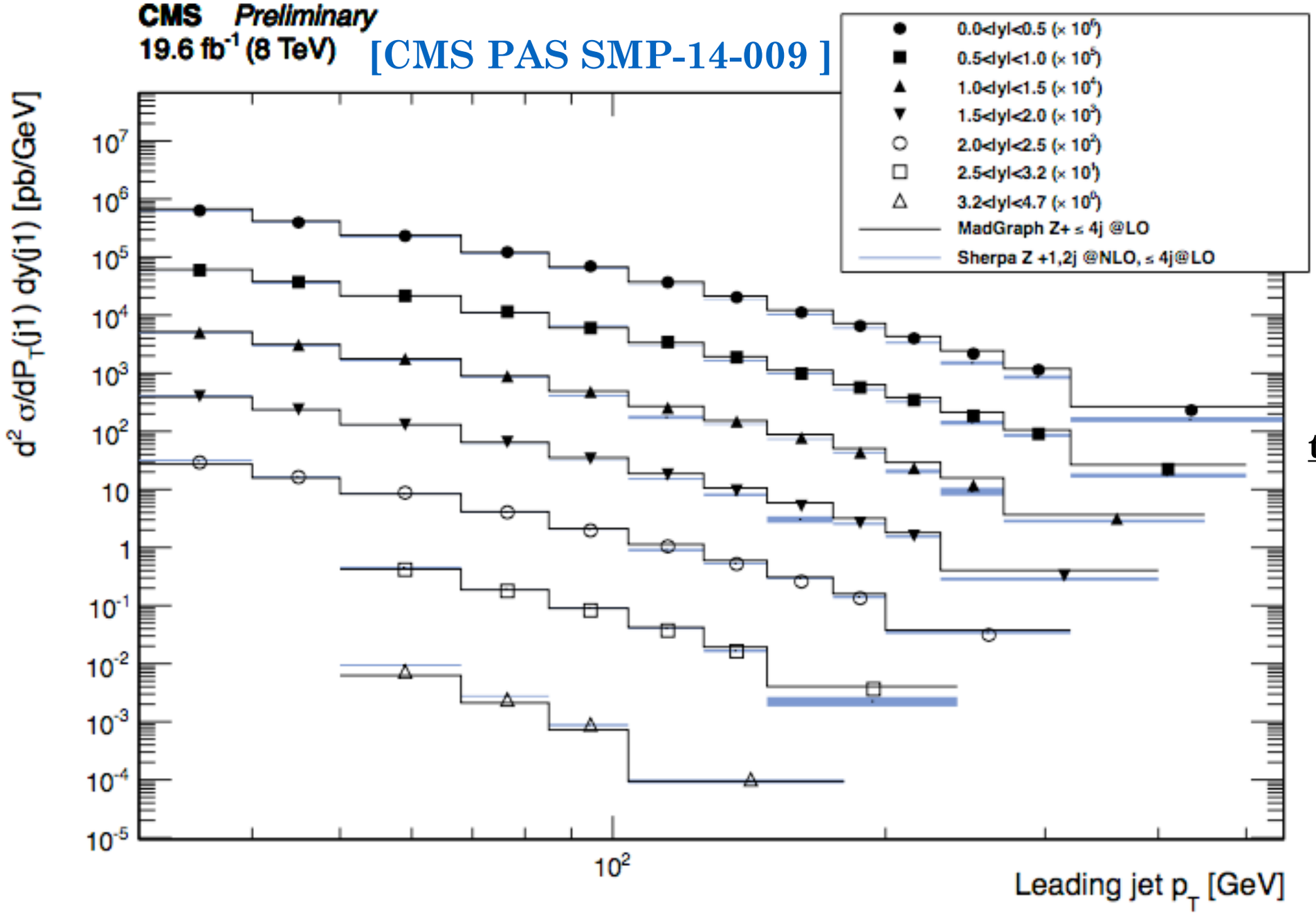


unfolded leading jet momentum

$Z + jets$ double differential

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



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

- only μμ final state
- pseudorapidity up to 4.7

<u>theoretical predictions</u>

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

- MadGraph+Pythia6 (LO)

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

$Z + b,\ Z + bb$

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*

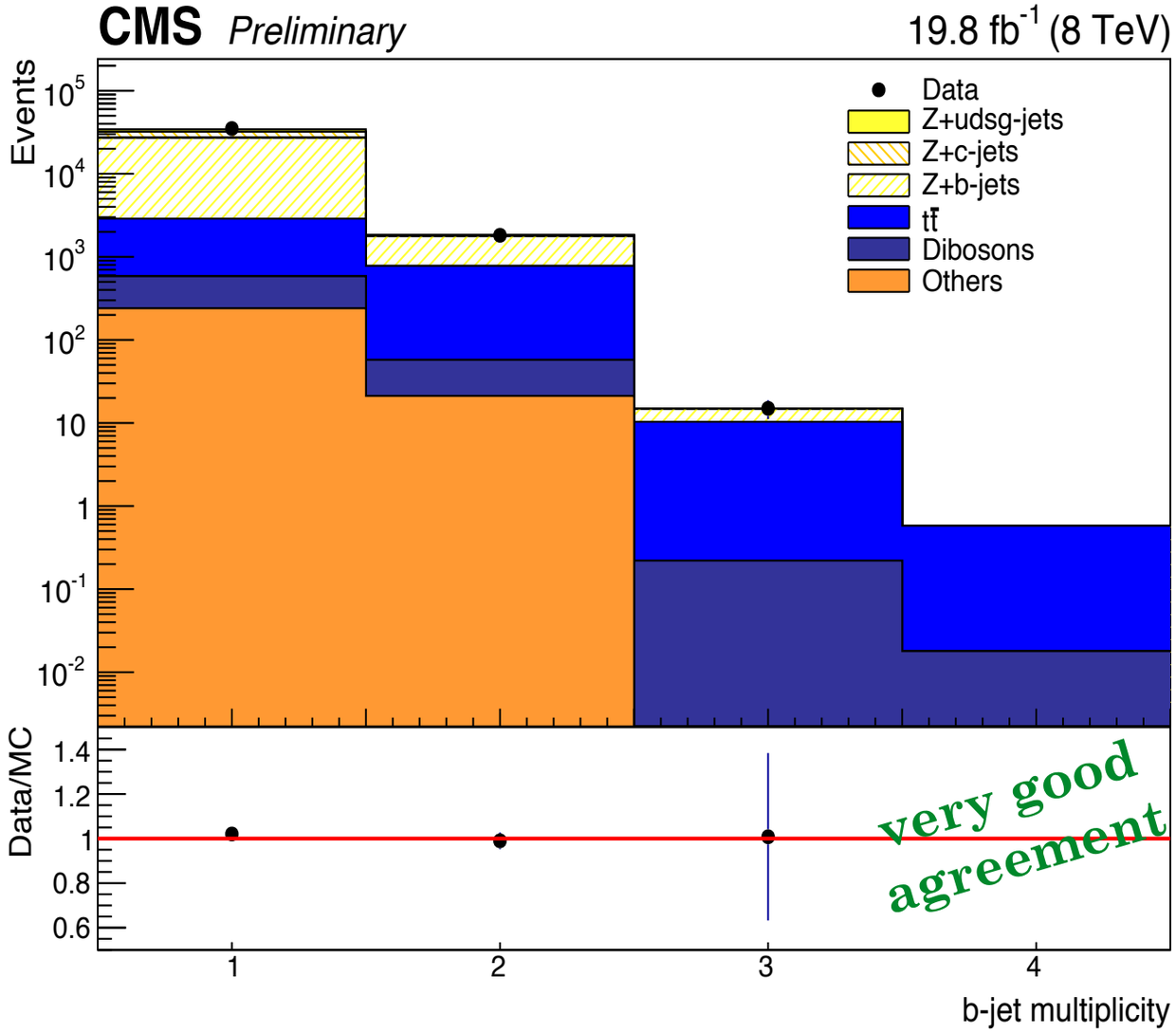
cross sections

- *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

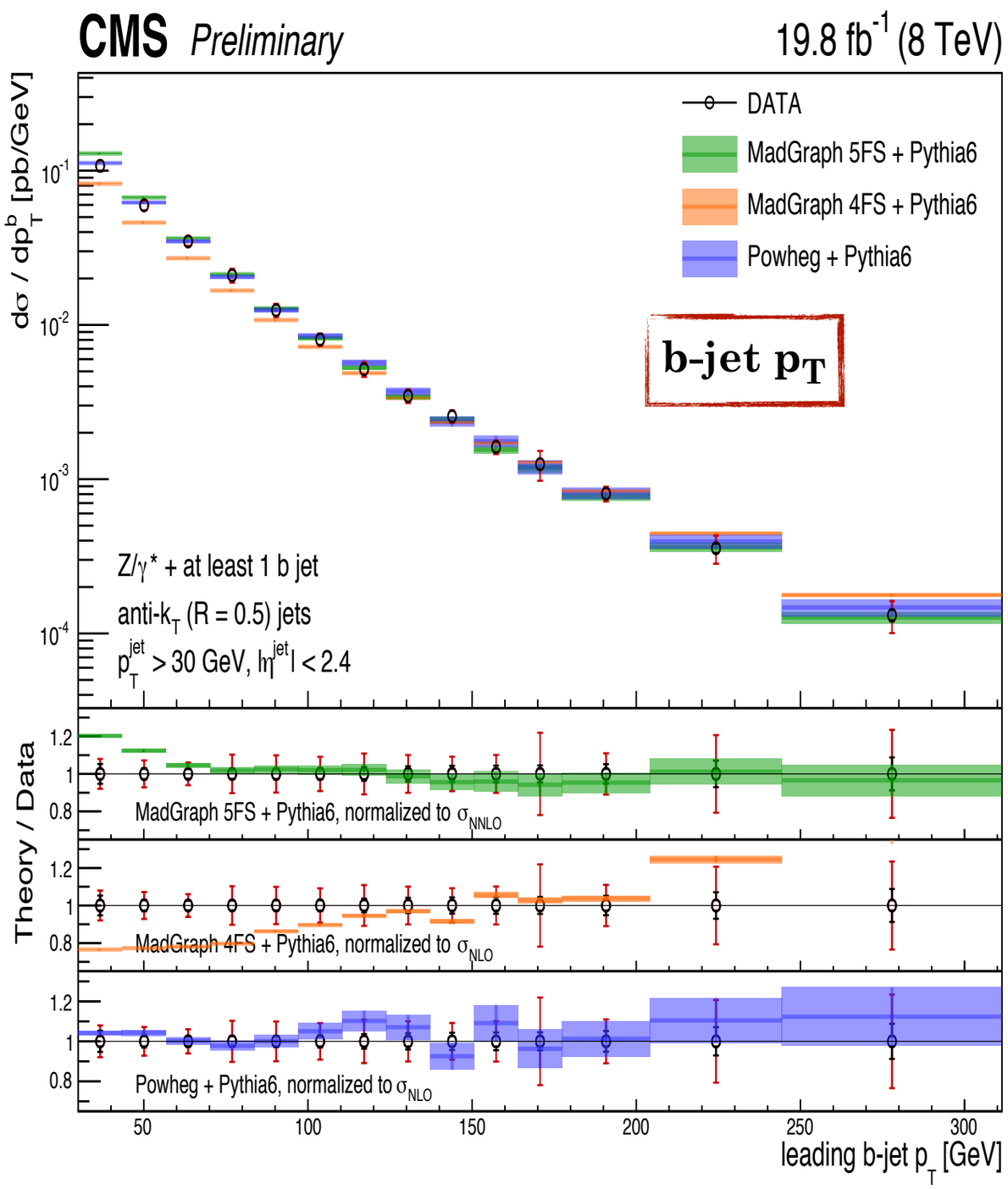
$Z + b,\ Z + bb$

NEW!

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

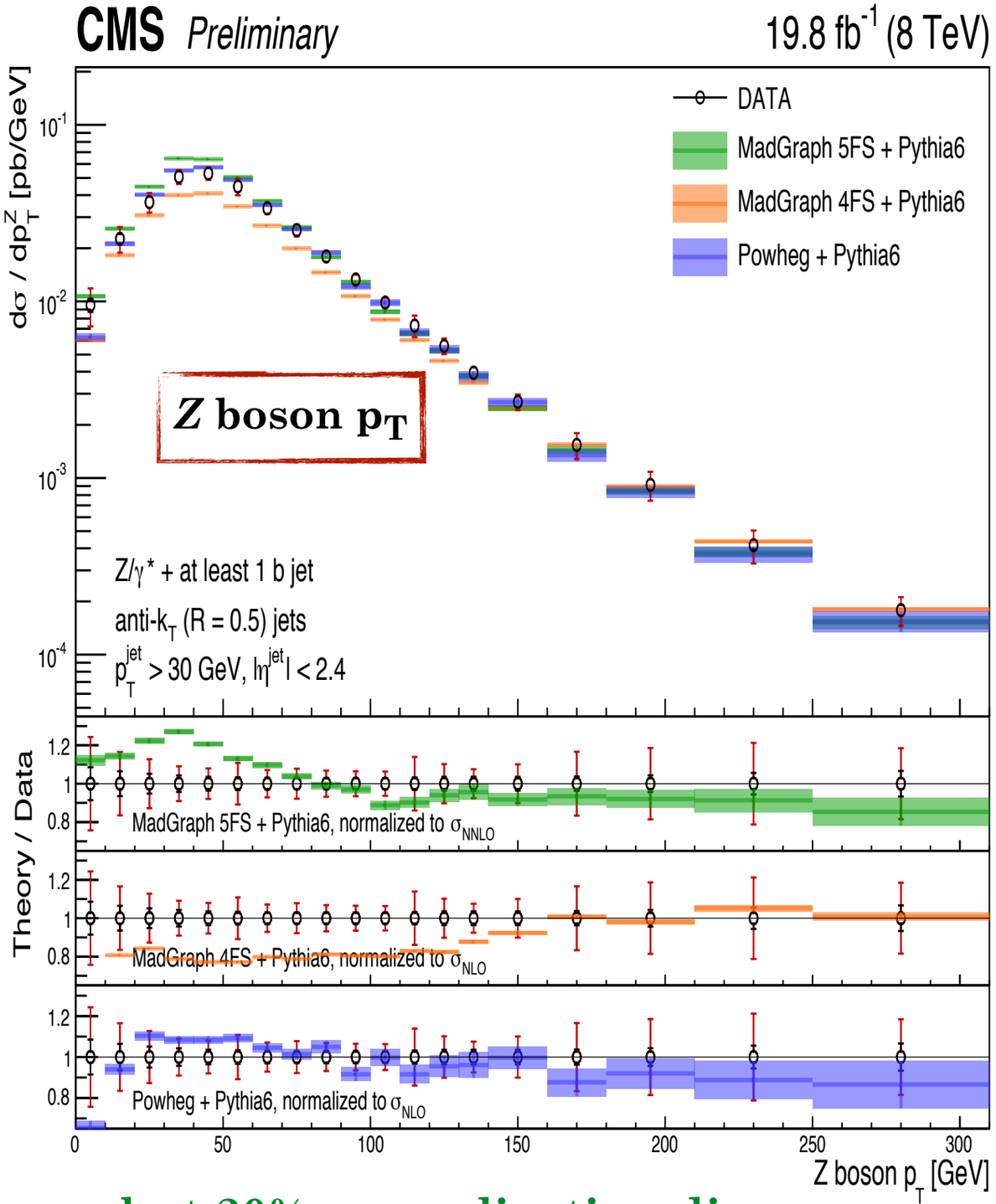
unfolded leading b-jet p_T cross section

(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

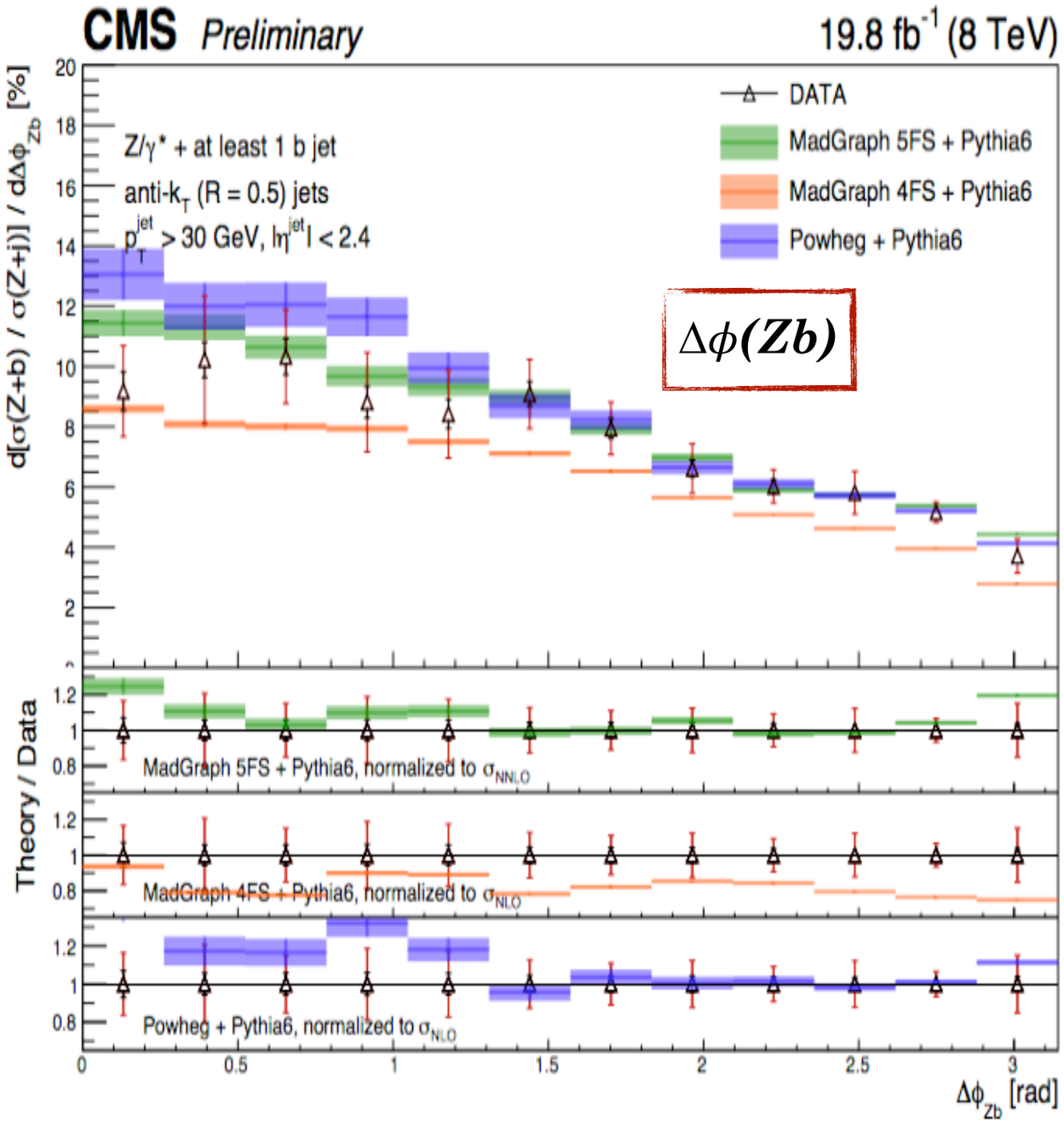
$Z + b,\ Z + bb$

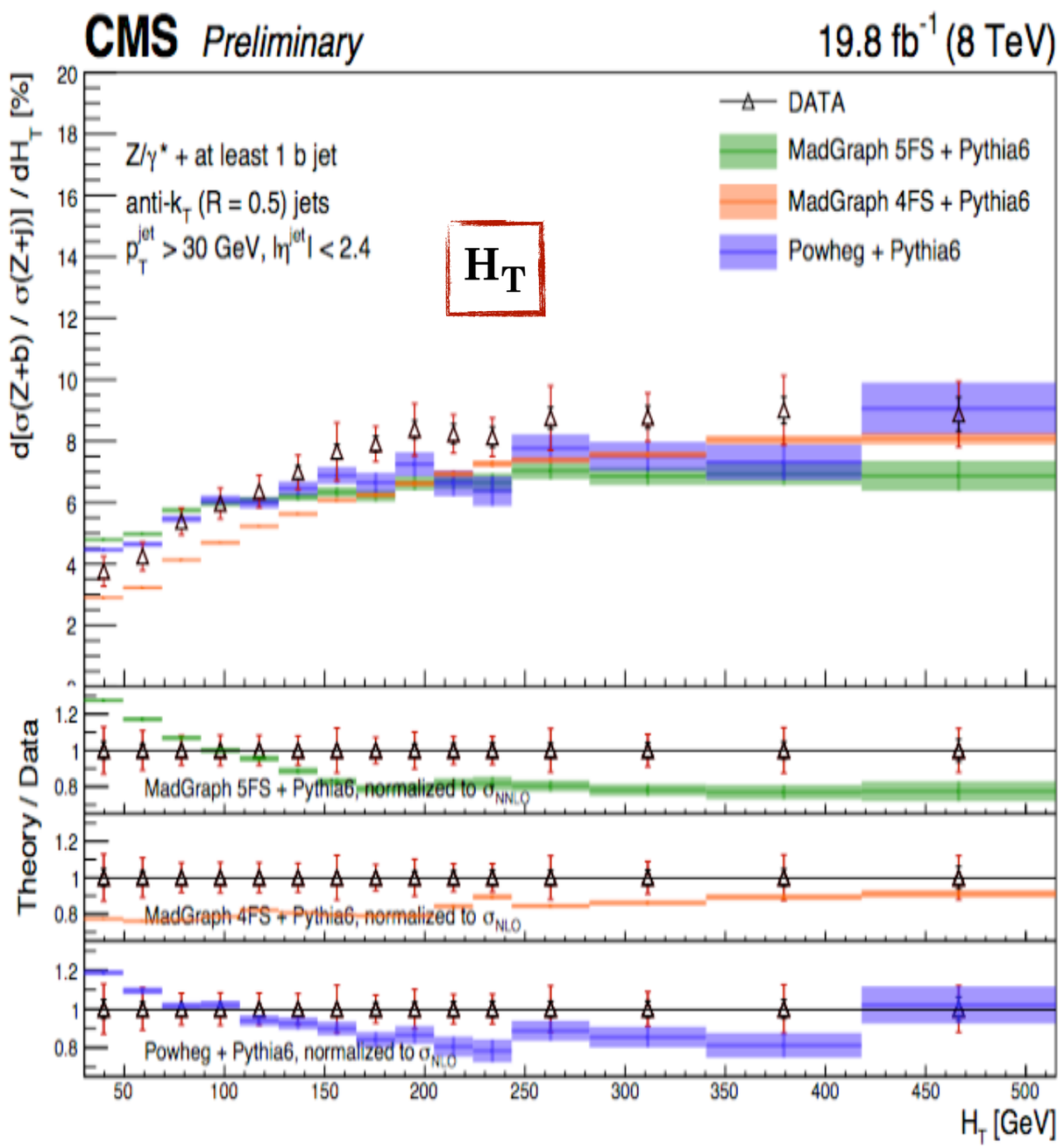
NEW!

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

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

unfolded cross section ratios





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

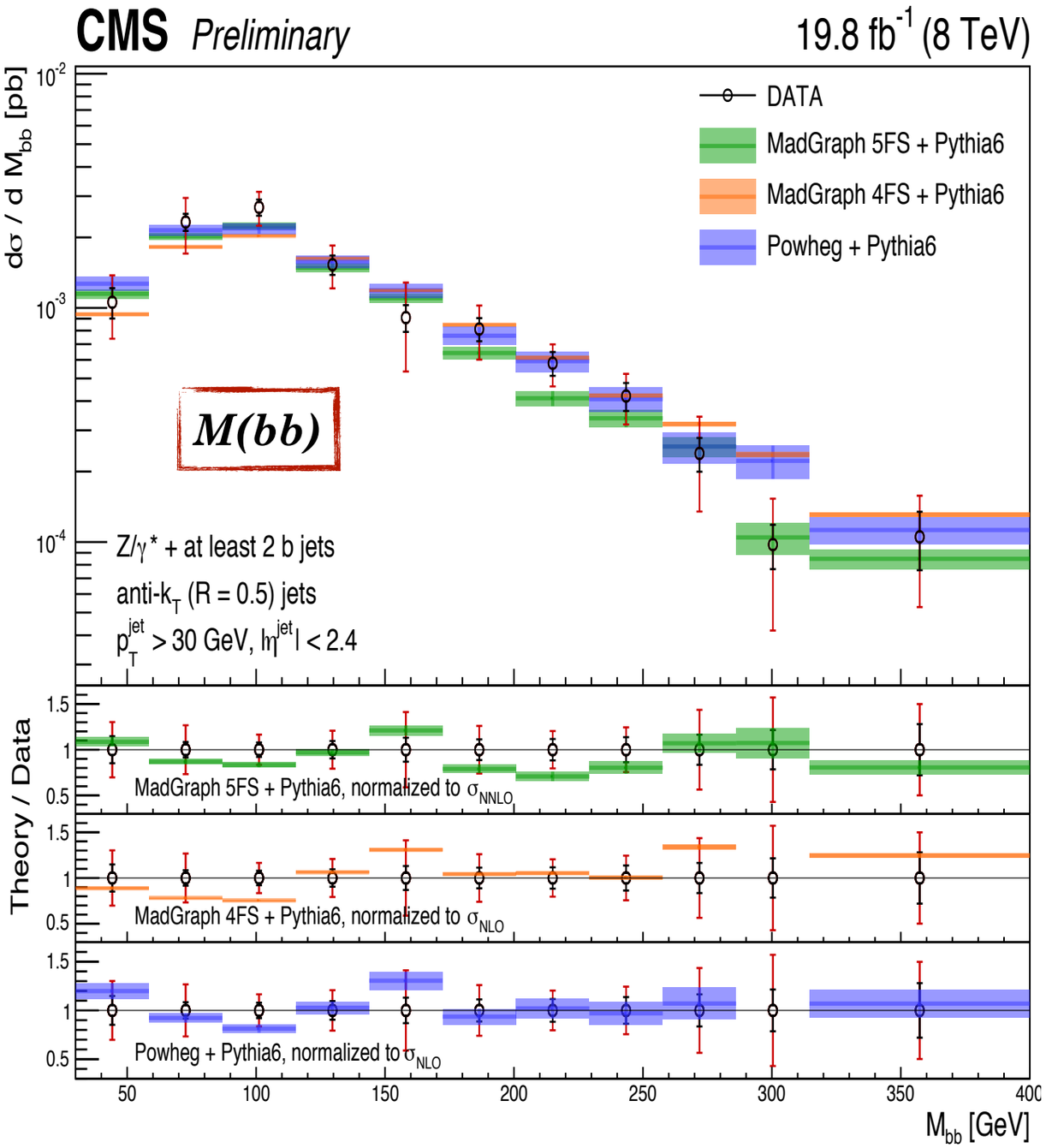
$Z + b,\ Z + bb$

NEW!

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

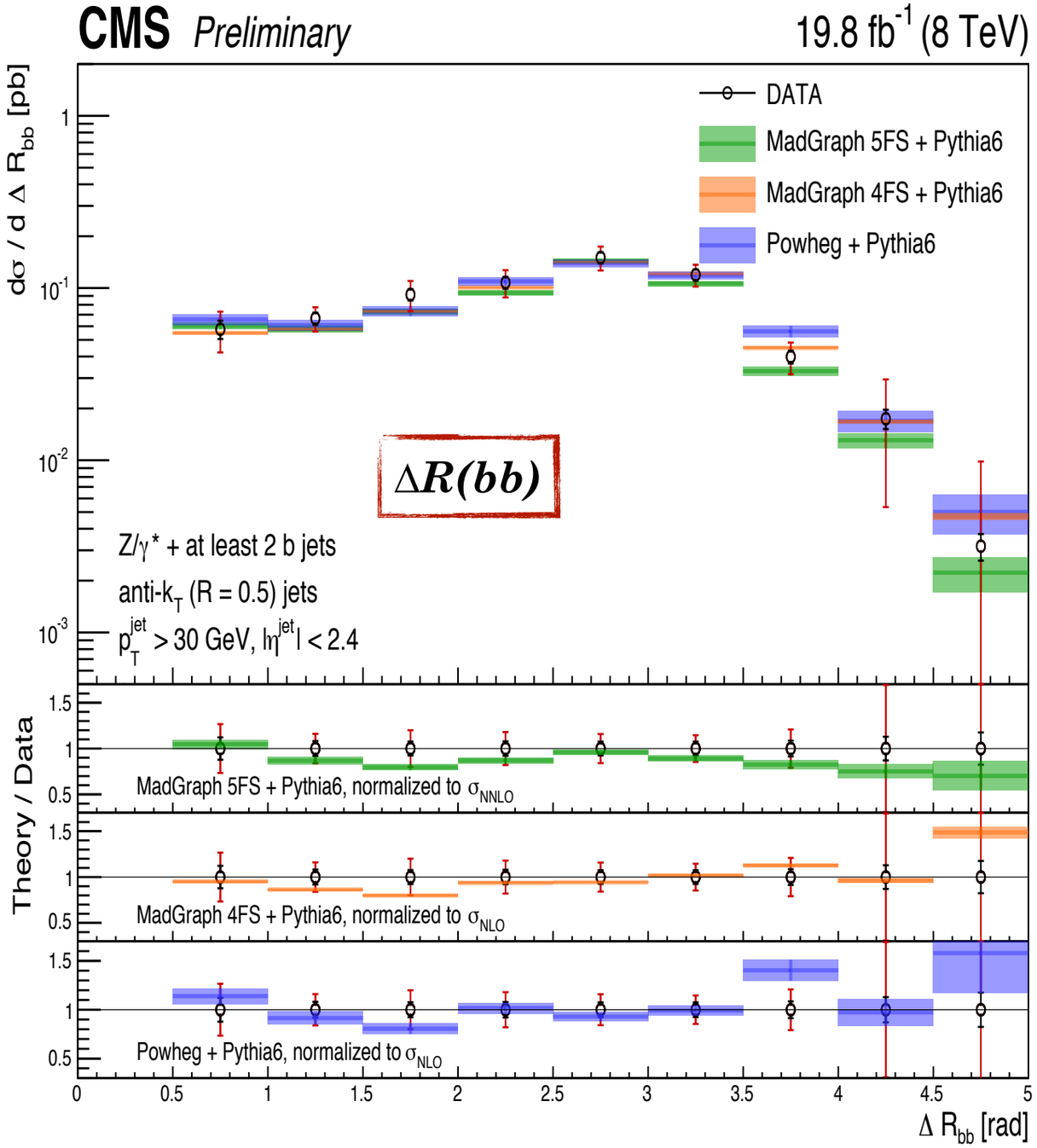
unfolded M(bb) cross section

(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

$Z + b,\ Z + bb$

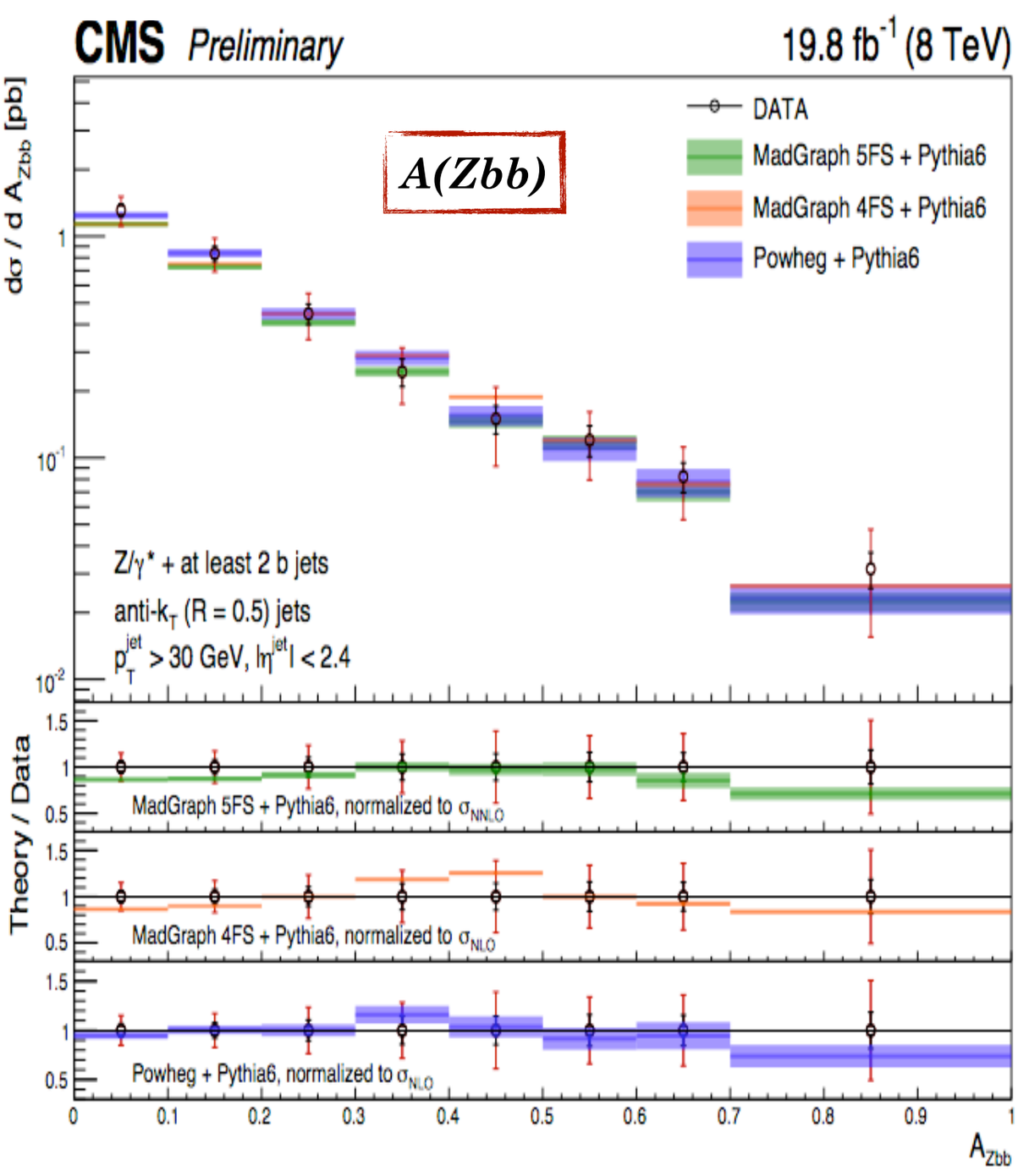
NEW!

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

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

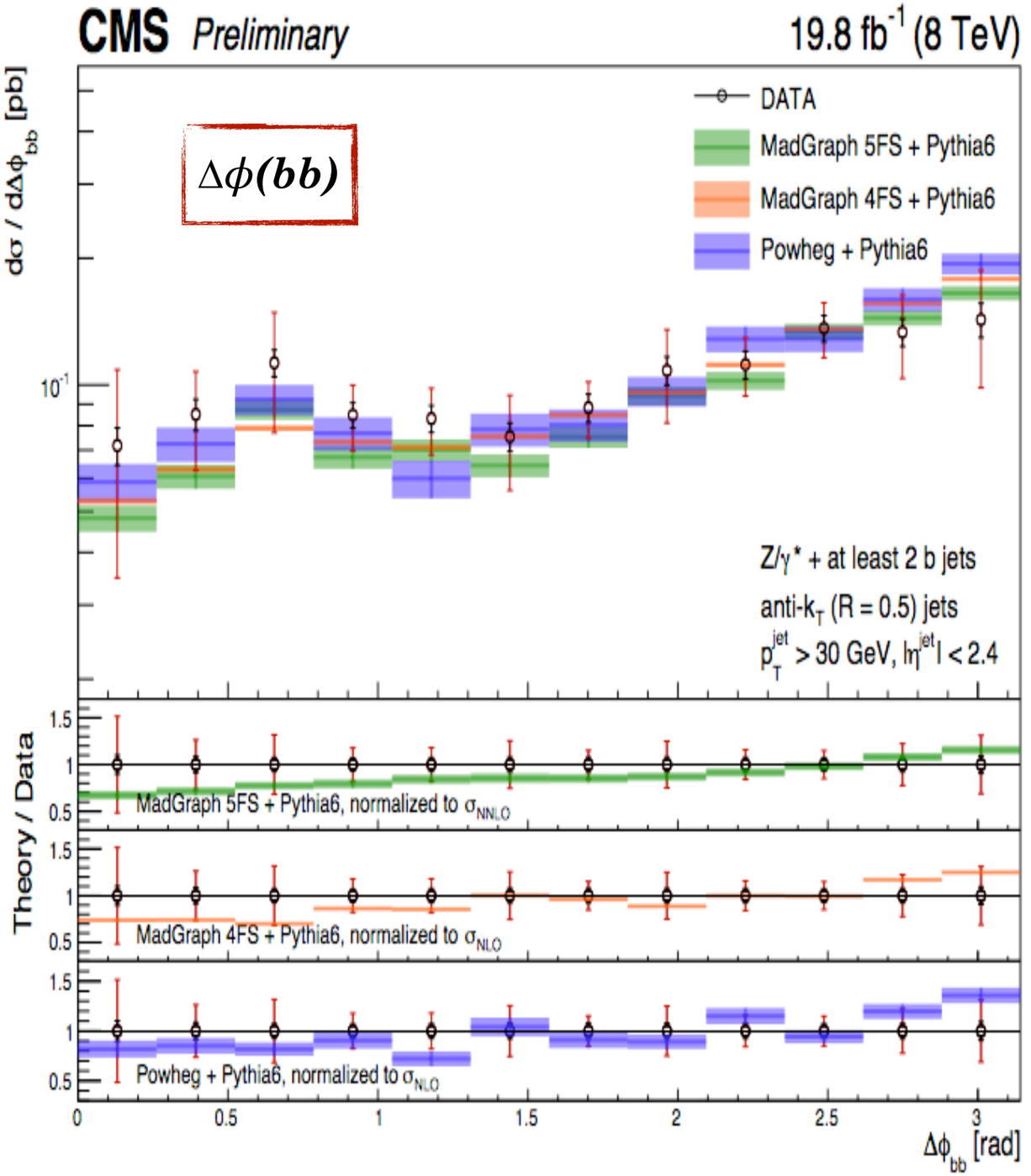
Zb Asymmetry

(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/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, $|\eta|<2.4$

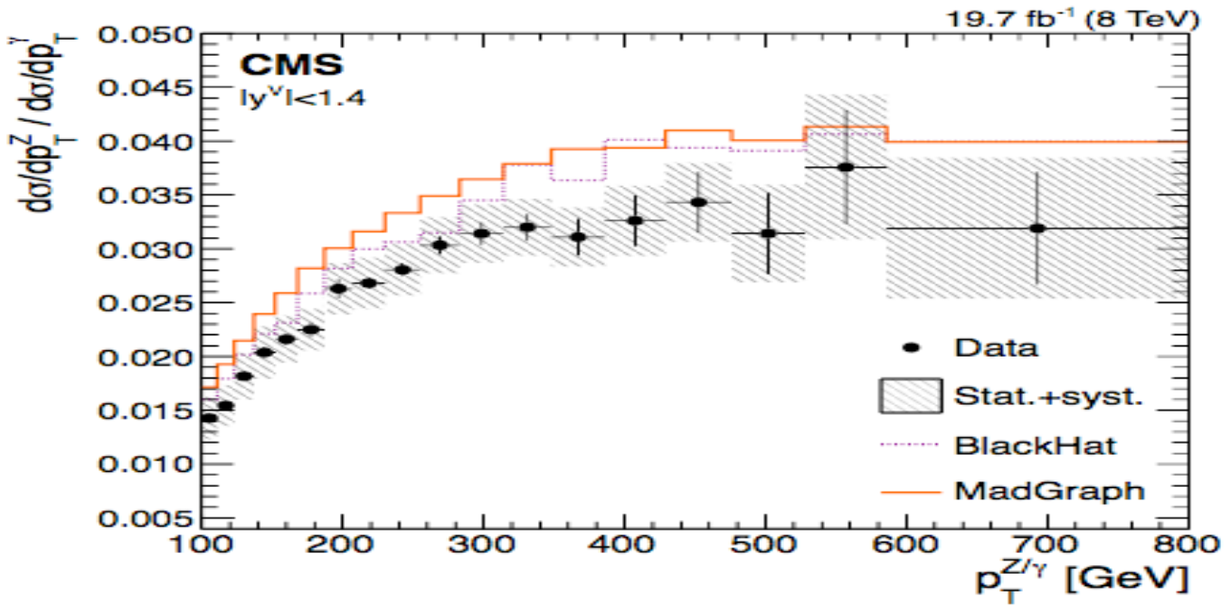
cross sections

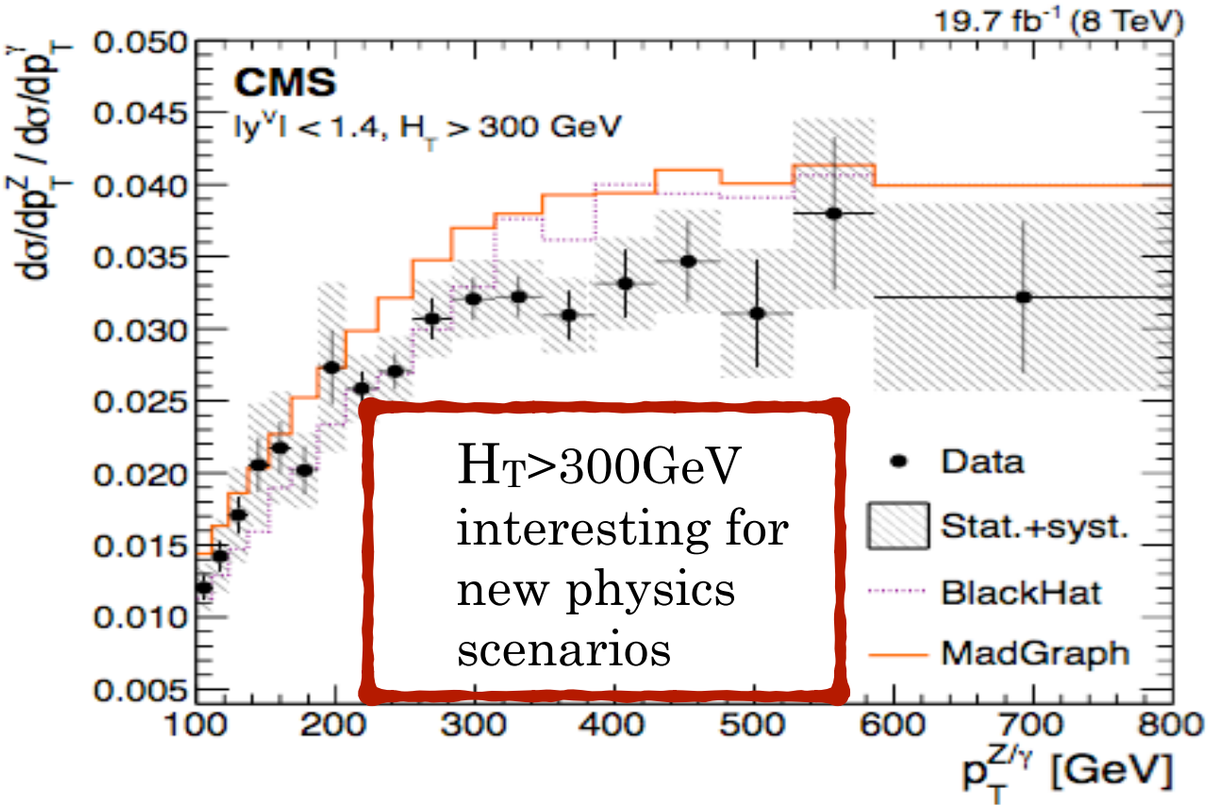
- differential cross section for the Z+jets/γ+jets vs. Z boson p_T

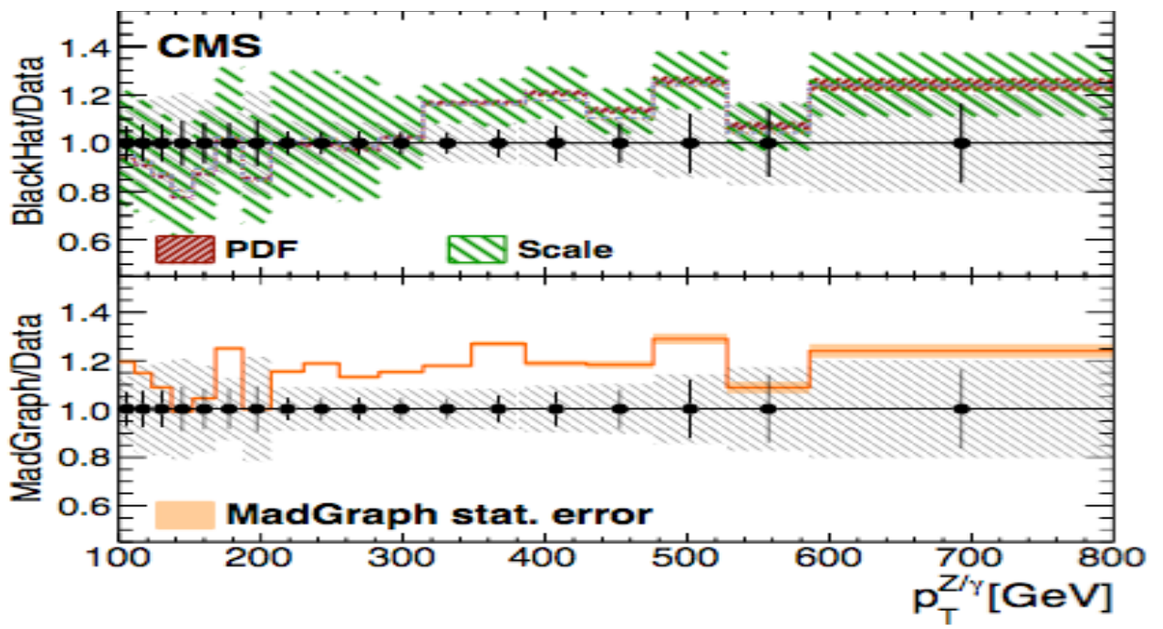
theoretical predictions

- 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

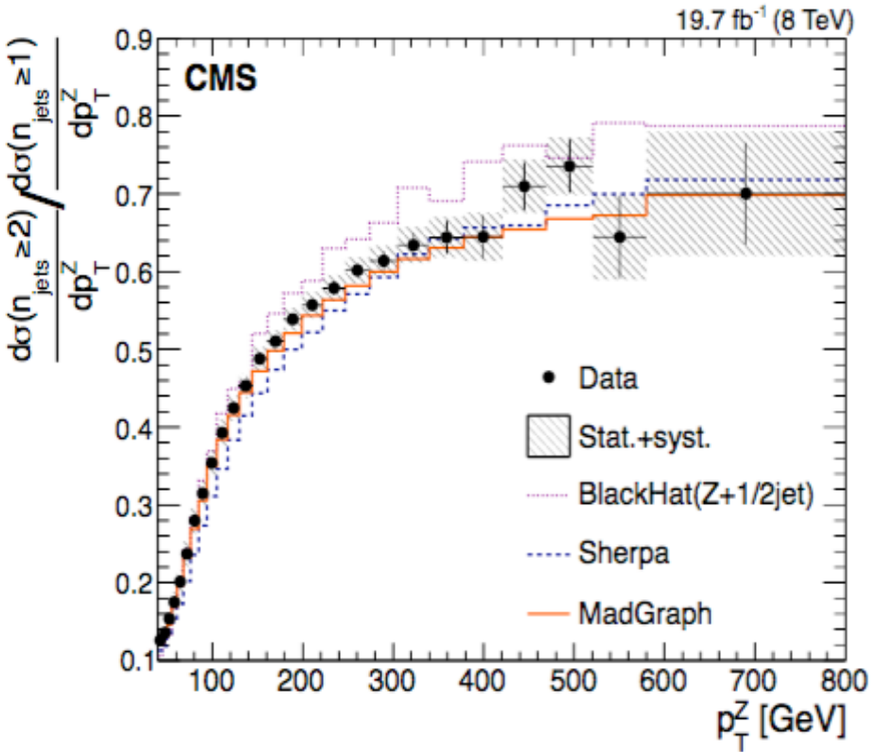


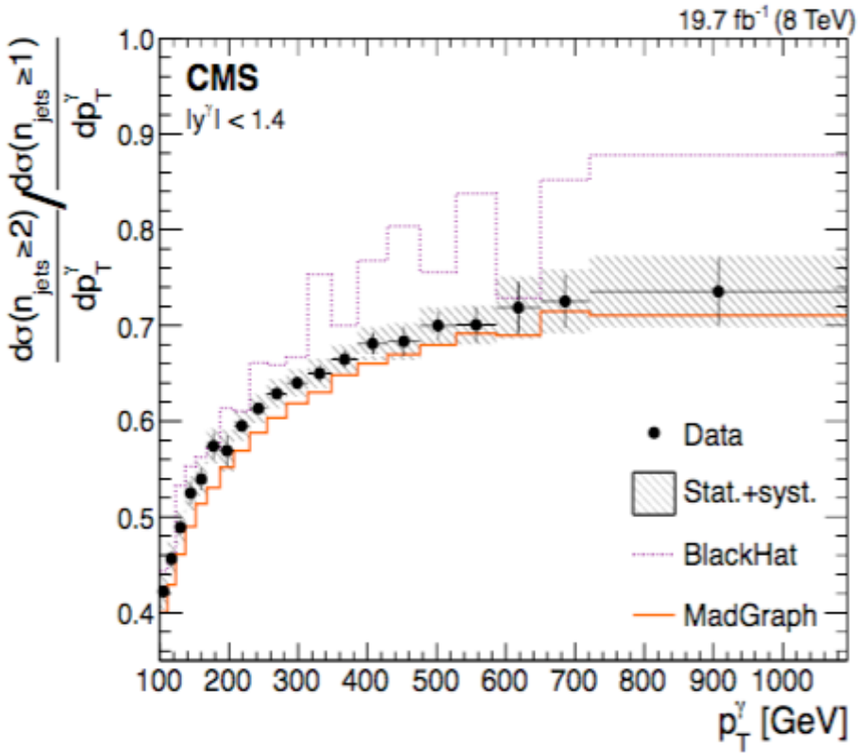




Z/γ differential ratio

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



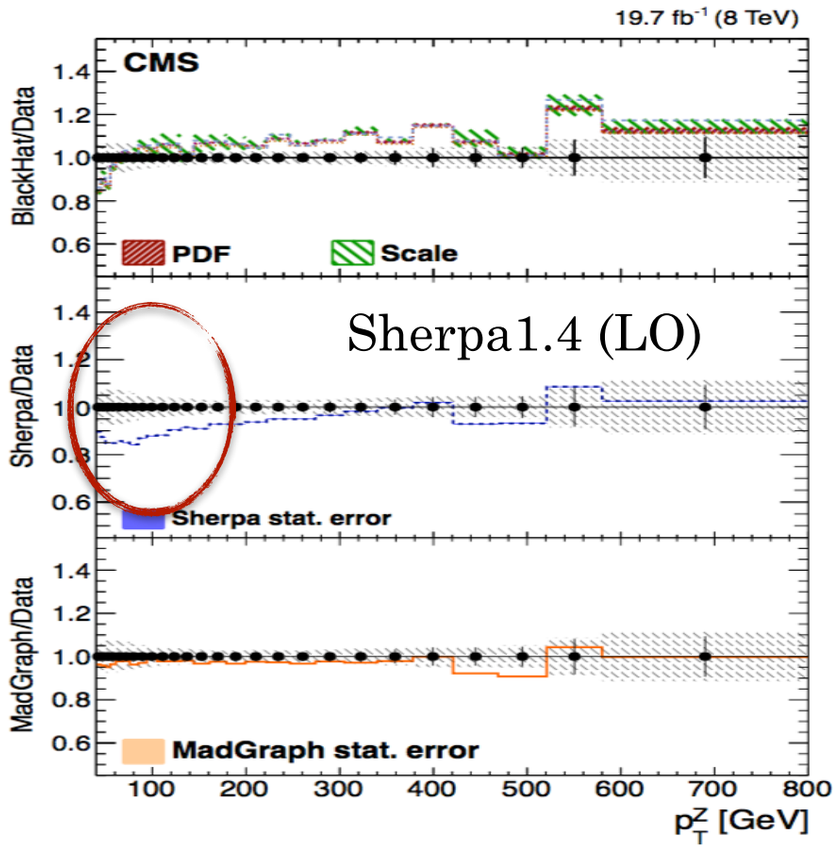


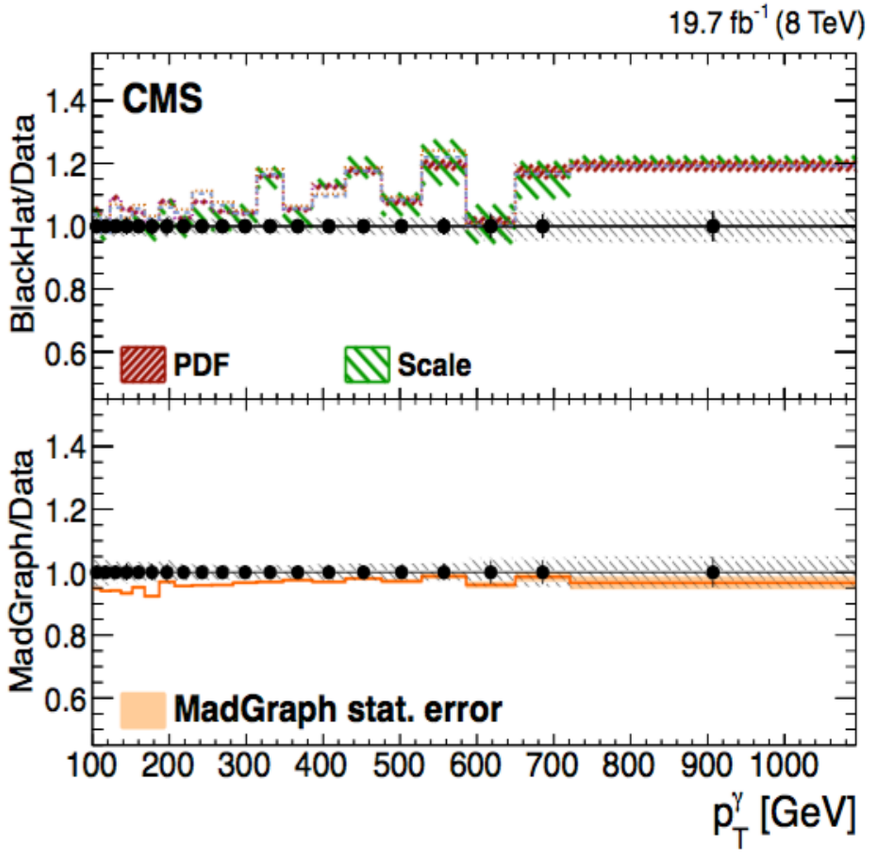
Z+ N≥2 jets over Z+ N≥1 jets unfolded cross sections vs. Z boson p_T

(left)

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

(right)





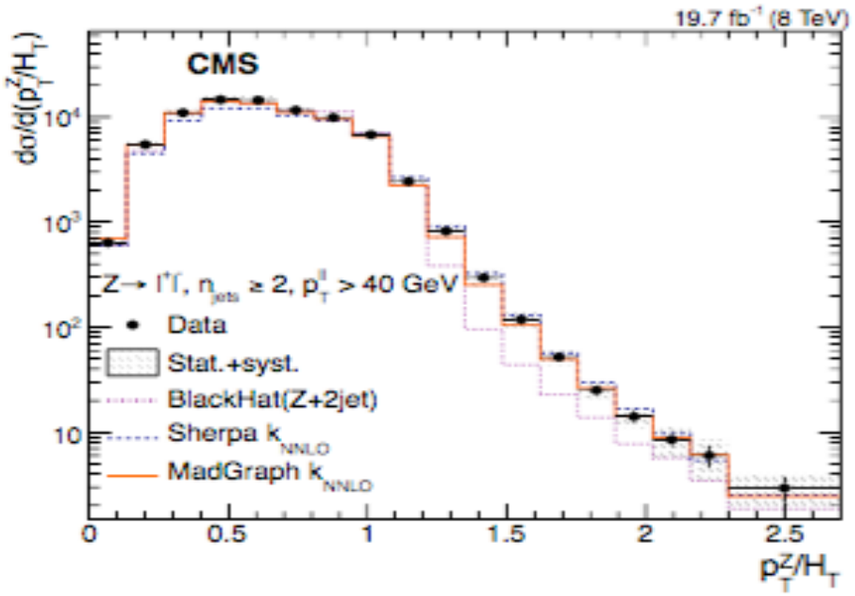
<u>theoretical predictions</u>

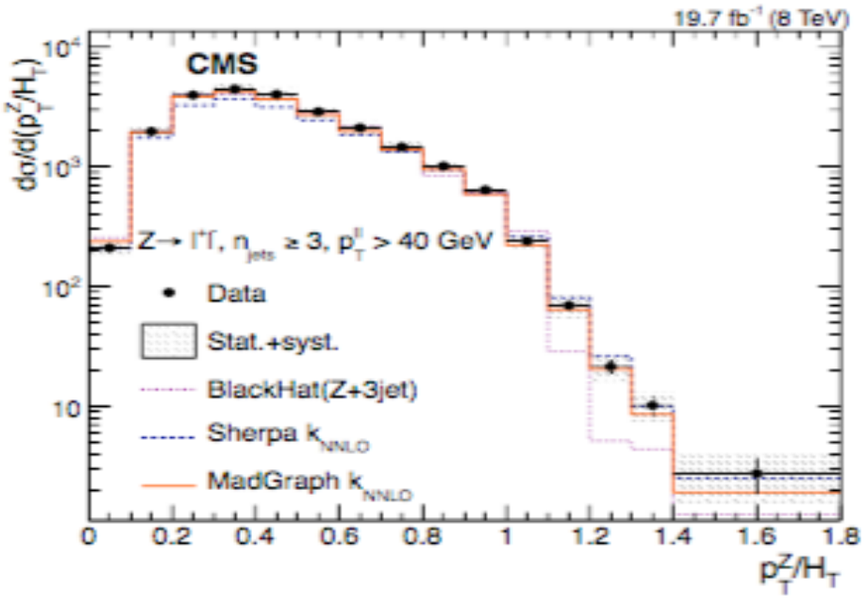
BlackHat+Sherpa (NLO)

MadGraph5+Pythia6 (LO up to 4jets)

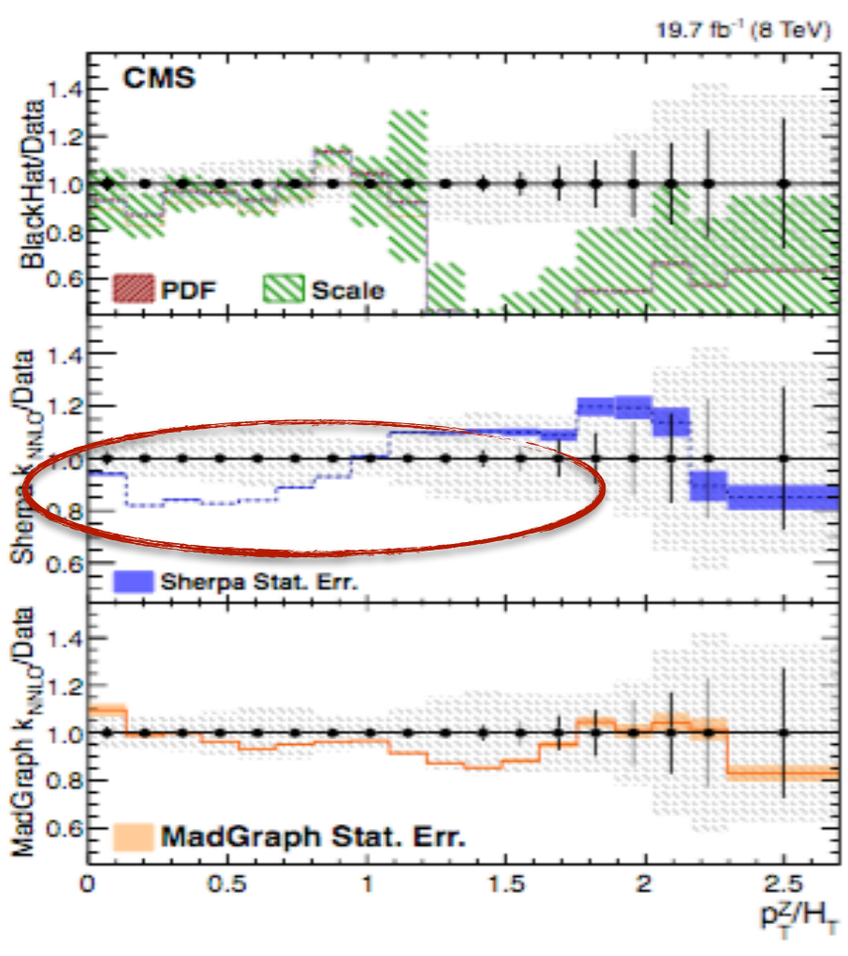
Z/γ differential ratio

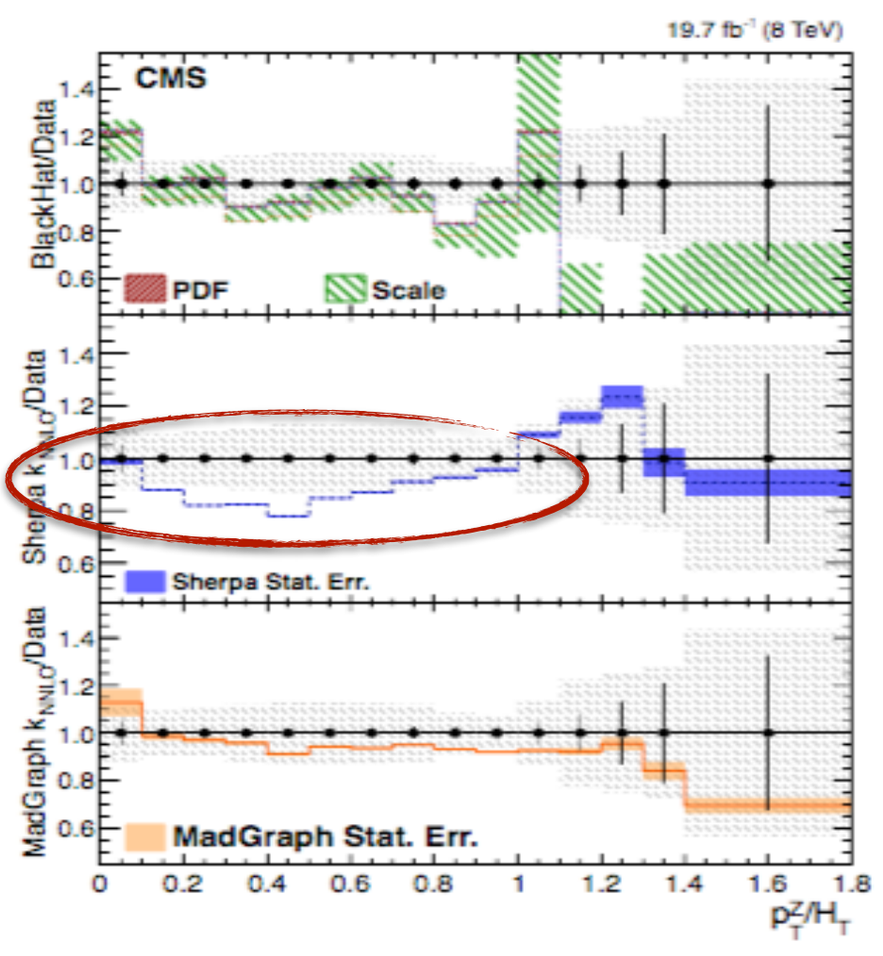
$$\int Ldt = 20\ \text{fb}^{-1} \quad \sqrt{s} = 8\ \text{TeV}$$





Differential Z+ >2 (left) and >3 (right) jets cross sections as a function of $\mathbf{p_T / H_T}$





<u>theoretical predictions</u>

BlackHat+Sherpa (NLO)

Sherpa1.4 (LO)

MadGraph5+Pythia6
(LO up to 4jets)

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

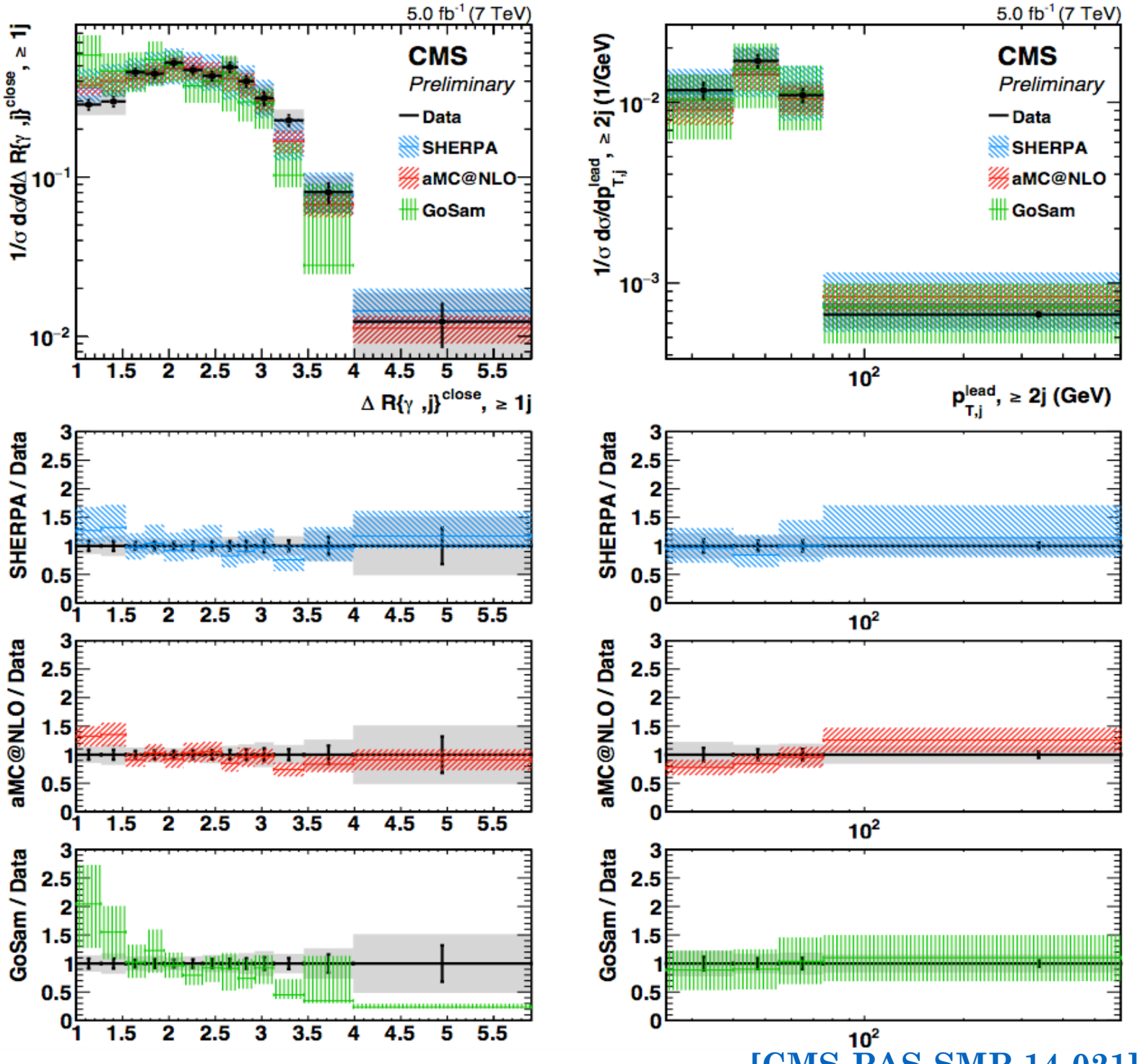
- data-driven method: 2D fit the particle flow isolation variable to discriminate prompt γγ from neutral mesons decays (π,η → γ γ)

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

Summary and perspectives

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

- *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
- *Z/g ratio* @ 8 TeV differential cross section compared with LO predictions (HT ranges)
- γγ + *jets* @ 8 TeV differential cross sections compared to NLO predictions

More *V+jets* analyses at 8 TeV with 20/fb almost ready:
W+jets at 8 TeV, *W+bb at 8 TeV, W/Z + c-jets, Z+J/ψ…*

The first ***13 TeV*** W/Z+jets analyses will come very soon, 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