V plus Jets and MC Modeling at LHC

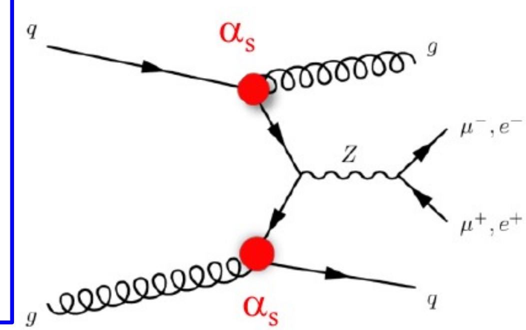
38th International Conference on High Energy Physics
3-10 August 2016, Chicago

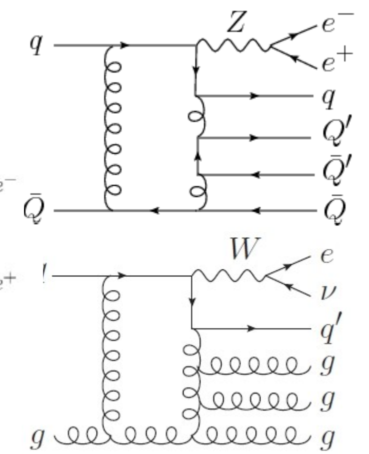
Federico Sforza (CERN)

on behalf of ATLAS and CMS Collaborations

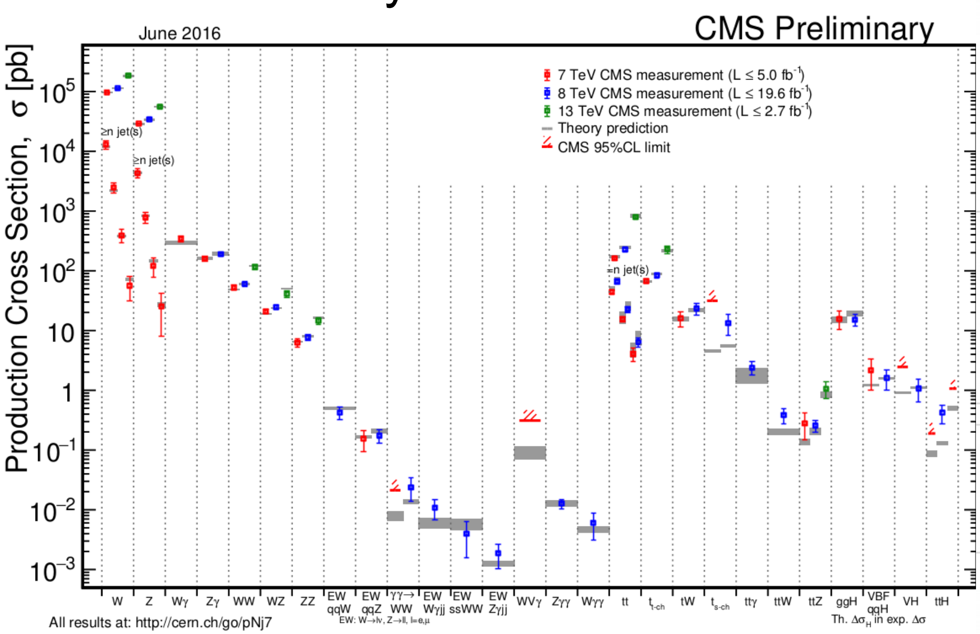
W or Z plus Jets at ATLAS and CMS

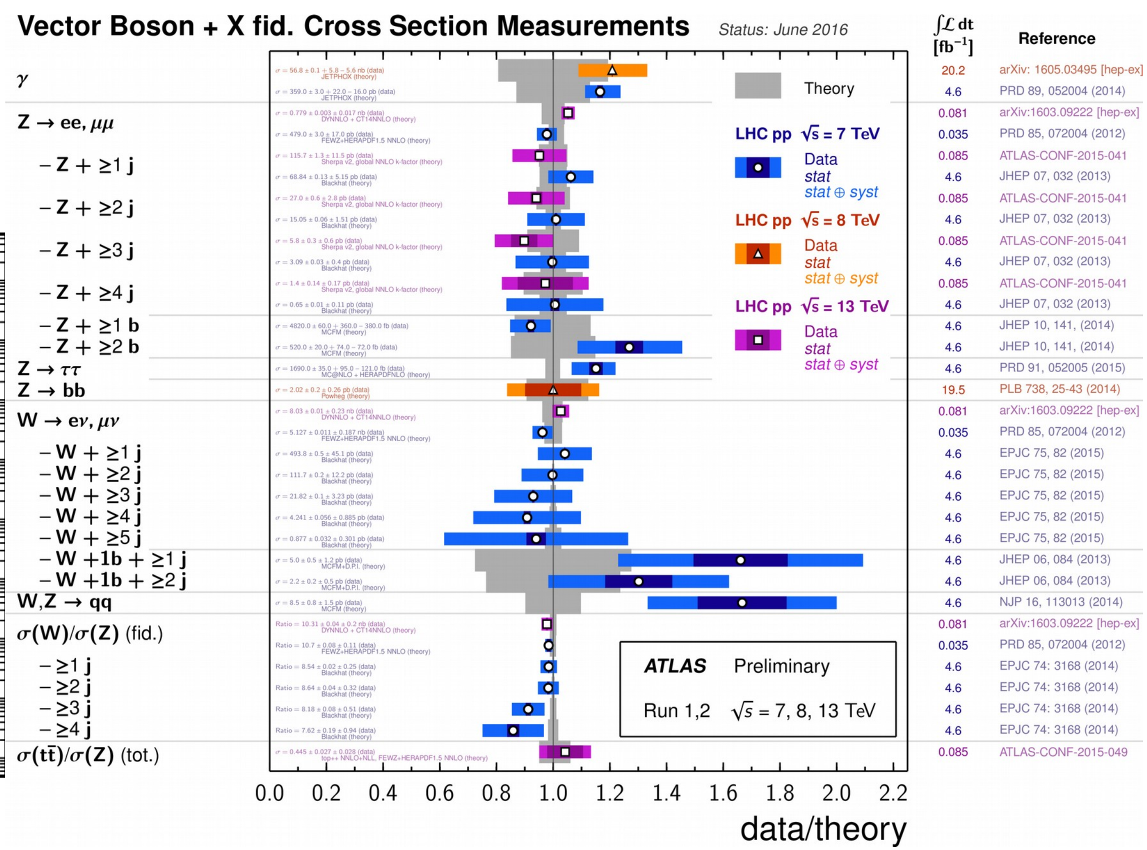
- **Dominated by QCD interaction → abundant production**
- **Measurement is test of perturbative QCD (pQCD)**
- **Sensitive to PDFs models**
- **Large background to BSM and Higgs searches**





Many available measurements of V+jets cross-sections spanning several orders of magnitude, often used in the differential analysis of observables





Z or W plus Jets: Recent Results

Recent ***Run II*** results discussed in this presentation:

- ATLAS Z + jets at 13 TeV, ATLAS-CONF-2016-046 (2016) → **Today for 1st time!**
- CMS Z + jets at 13 TeV, SMP-15-010 (2015)
- CMS W + jets at 13 TeV, SMP-16-005 (2016) → **Today for 1st time!**

Recent ***Run I*** results discussed in this presentation:

- CMS W + jets 8 TeV, SMP-14-023 (2016)
- ATLAS W + jets 7 TeV, EPJC(2015) 75:82 (2015)
- ATLAS W + jets 8 TeV W boson angular distributions in event with high-p_T jets, STDM-2015-16 (2016) → **Today for 1st time!**
- CMS W + b-jets 8 TeV, SMP-14-020 (2016)
- CMS Z + b-jets 8 TeV, SMP-14-010 (2015)
- CMS Z + c-jets 8 TeV, SMP-15-009 (2016) → **Today for 1st time!**

A complete set of V+jets SM measurements is available at:

- https://twiki.cern.ch/twiki/bin/view/AtlasPublic/StandardModelPublicResults
- http://cms-results.web.cern.ch/cms-results/public-results/publications/SMP/index.html
- http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/SMP/index.html

Step 1: Detector Level Analysis

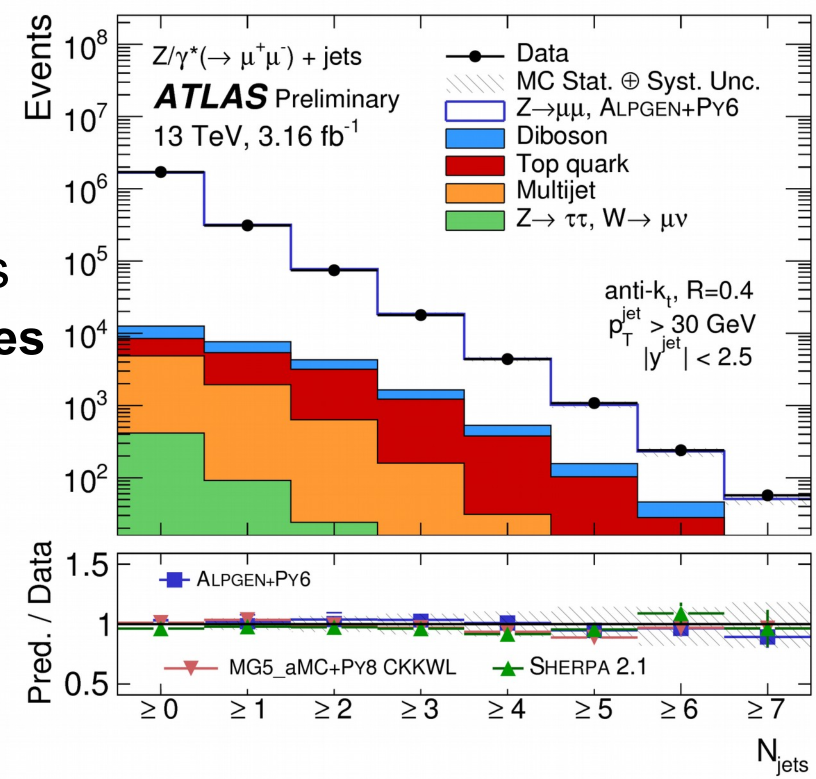
Selection of W(e/μ+ν) or Z(ee/μμ) candidates:

- Single lepton triggers used *for online selection*
- Reconstruction of isolated charged leptons of p_T > 20 or 25 GeV in detector acceptance
  - Electron up to $|\eta|$ = 2.4 CMS, $|\eta|$ = 2.47 ATLAS
  - Muon up to $|\eta|$ = 2.4 CMS and ATLAS
- In W analyses: identify escaping neutrino using *missing transverse energy:* $\mathbf{E_T^{miss}}$

Reconstruct and select jets:

- Anti-k_t ΔR = 0.4 CMS and ATLAS (=0.5 CMS Run I)
- Typical jet p_T > 25 or 30 GeV
- Acceptance up to $|y|<2.5$ ATLAS, $|\eta|$ = 2.4 CMS
  - Up to $|y|$ = 4.4 in several ATLAS Run I analyses
- **Heavy-Flavor (HF) jets selected in specific analyses**
  - Analysis of long-living HF-hadrons within jets
  - Information combined using light-to-HF-jets MVA

E.g. n-jets for data, signal, backgrounds:



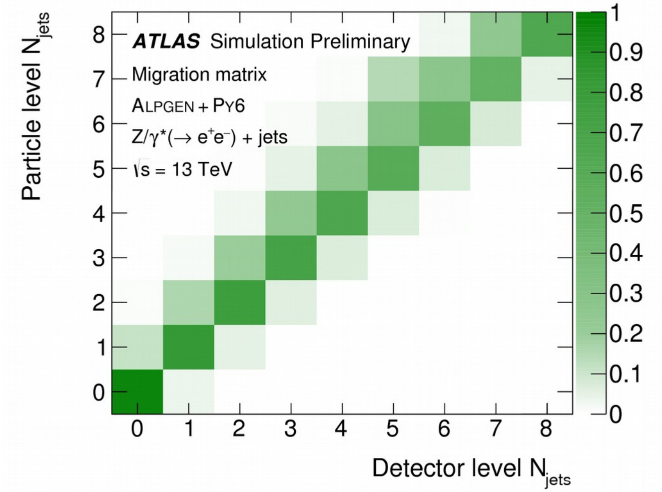
Extract signal as function of "x"

- *Signal (x)= Data (x) - Backgrounds (x)*

Step 2: Unfolding, Comparison with Predictions

- Define fiducial volume of the measurement in phase space similar to experimental acceptance
- Use signal MC to remove *detector* effects (efficiencies, resolution, scales) on background subtracted data
- Compare unfolded data to available MC simulations or to fixed-order calculations (after correction for non-perturbative effects as fragmentation, underling event, etc.)

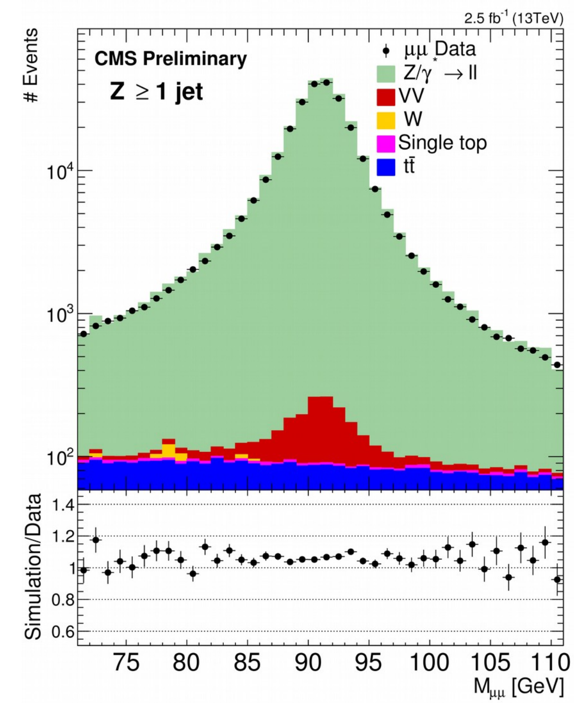
E.g. n-jets reco-vs-particle jets:



Type of Prediction	MCs & Calculations "label"	Usage & Notes
multi-partons (Np) LO ME+PS	Sherpa 1.X (up to Np = 4)	Wide usage in ATLAS Run I analyses
	Madgraph5 (up to Np = 4)	Wide usage in CMS Run I analyses
	ALPGEN (up to Np = 5)	Run I (and Run II) "workhorse"
multi-parton (Np) NLO and LO ME+PS	Madgraph5 aMC@NLO (NLO up to Np = 2)	"Standard" in many Run II CMS analyses
	Sherpa 2.X (NLO up to Np = 2)	"Standard" in many Run II ATLAS analyses
	Powheg (NLO Np = 1)	Tested in Run I by CMS
Fixed order NLO calculation	BlackHat + Sherpa (NLO up to Np = 5)	Tested in Run I, II (both ATLAS and CMS)
Approximate NNLO	LoopSim (approx. NNLO for W+>=1jets)	Tested in Run I by ATLAS
	HEJ (approx. to all orders for W+>=2 jets)	
Fixed order NNLO calculation	N-Jettiness (full NNLO QCD)	**!! NEW !! Tested for fist time in Run II**

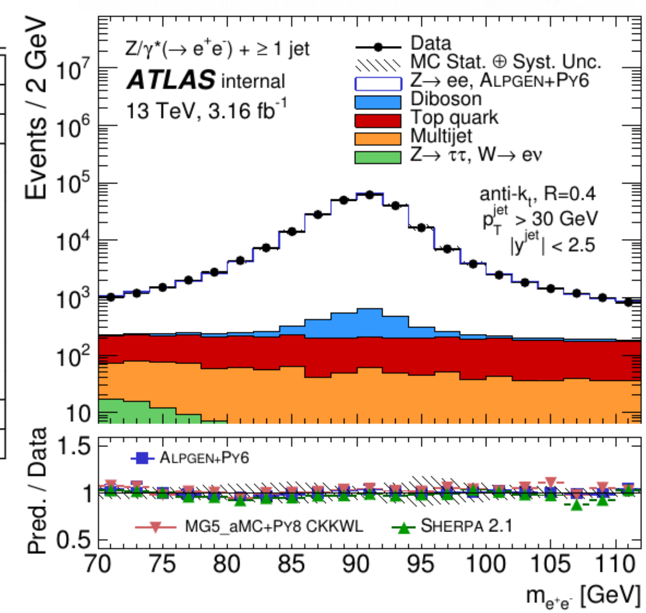
The Very First V+jets Measurement at 13 TeV:
Z+jets Using 2015 Run II Data

- Two opposite-sign same-flavour leptons within M_{ll} window around M_Z :
  → **Clean probe, small backgrounds**
- Irreducible backgrounds (top-quark, diboson) give % level contamination and are estimated using MC
- Multi-jet contamination often negligible, extracted with data-driven methods
- *Main systematic uncertainty from jet energy-scale calibration and resolution*



CMS SMP-15-010, Z→μμ

Relative uncertainty on $\sigma(Z(\rightarrow \ell^+\ell^-) + \geq \mathrm{N_{jets}})$ (%)								
	$Z \rightarrow e^+e^-$							
Systematic source	$+ \geq 0$ jet	$+ \geq 1$ jet	$+ \geq 2$ jets	$+ \geq 3$ jets	$+ \geq 4$ jets	$+ \geq 5$ jets	$+ \geq 6$ jets	$+ \geq 7$ jets
Electron Trigger	0.1	0.1	0.1	0.1	0.2	0.3	0.4	0.8
Electron Selection	1.2	1.6	1.8	2.0	2.2	2.7	2.9	4.1
JES	< 0.1	6.1	8.0	10.3	12.8	15.0	21.7	23.7
JER	< 0.1	3.1	3.0	3.6	4.5	5.5	4.7	2.4
JVT	< 0.1	1.3	2.0	2.7	3.3	3.8	5.4	6.5
Pile-up	0.4	< 0.1	< 0.1	0.2	0.3	0.7	0.3	1.5
Luminosity	2.1	2.2	2.2	2.3	2.4	2.5	2.6	2.8
Unfolding	2.0	2.0	2.0	2.1	2.0	2.0	2.1	2.6
Background	0.1	0.3	0.5	1.0	1.5	3.2	6.0	12.5
Syst. uncertainty	3.2	7.8	9.4	11.9	14.6	17.3	24.0	28.3
Stat. uncertainty	0.1	0.2	0.5	1.0	1.9	3.9	8.2	17.7



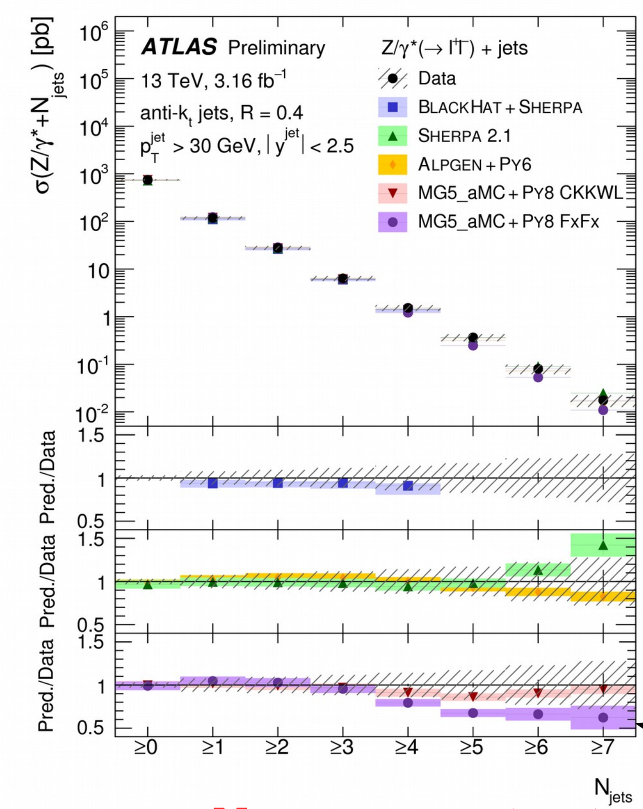
ATLAS-CONF-2016-046, Z→ee

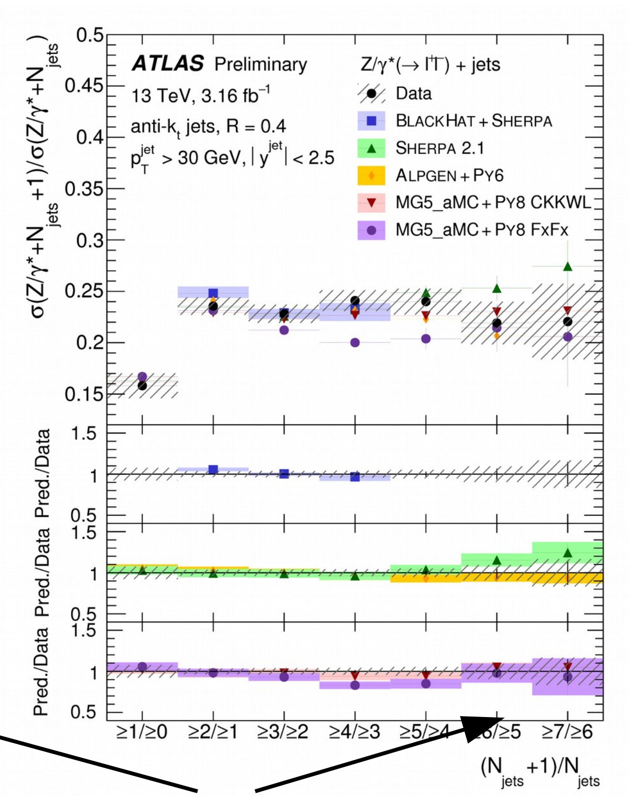
- *Statistical uncertainty negligible with ~3 fb^{-1} of data*

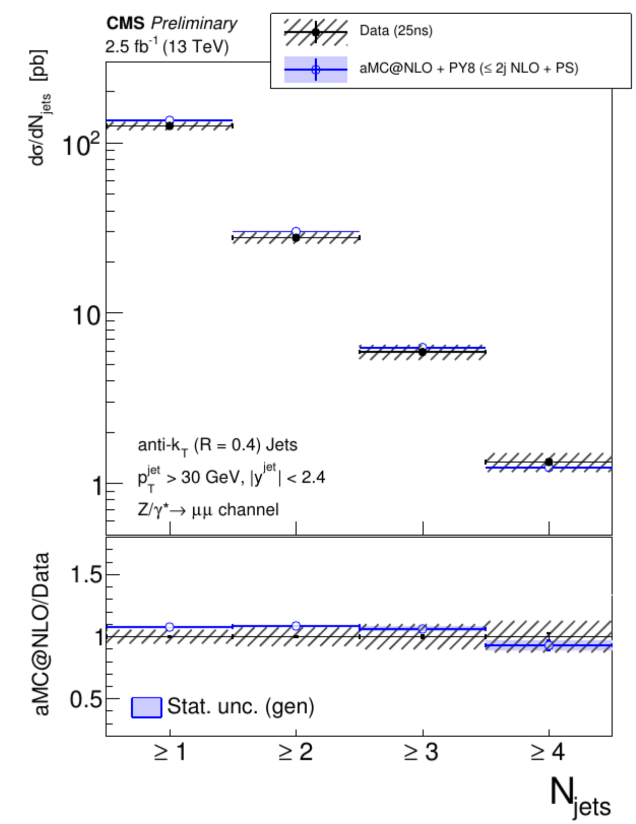
Jet multiplicity and ratio of jet multiplicities:

- Main figure of merit of QCD predictions
- Discriminating variable for Higgs and BSM searches

Data distribution unfolded at particle level using Bayesian iterative method







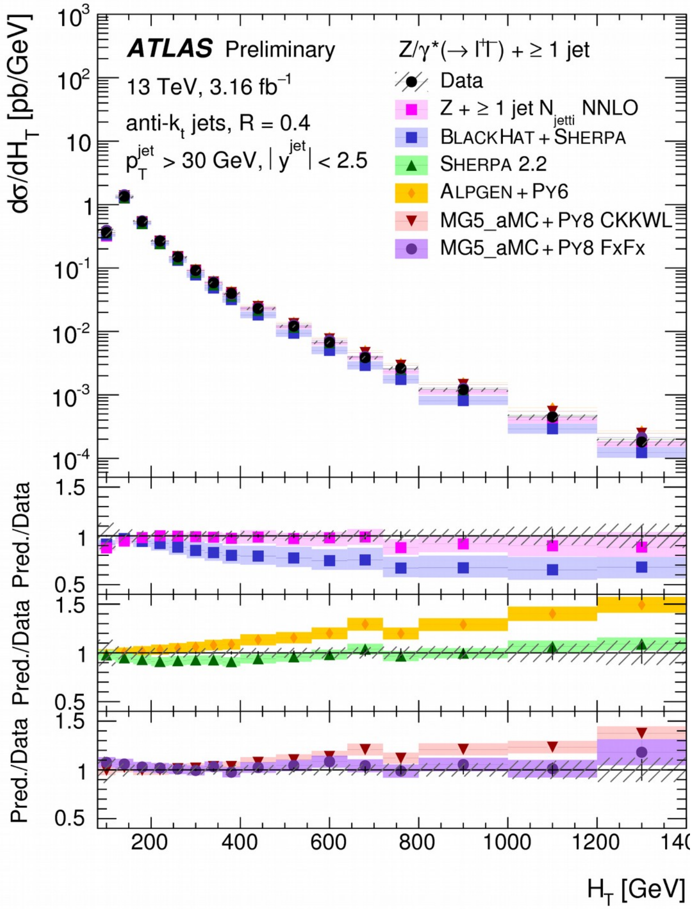
Measurement extends up to Z+7 jets!

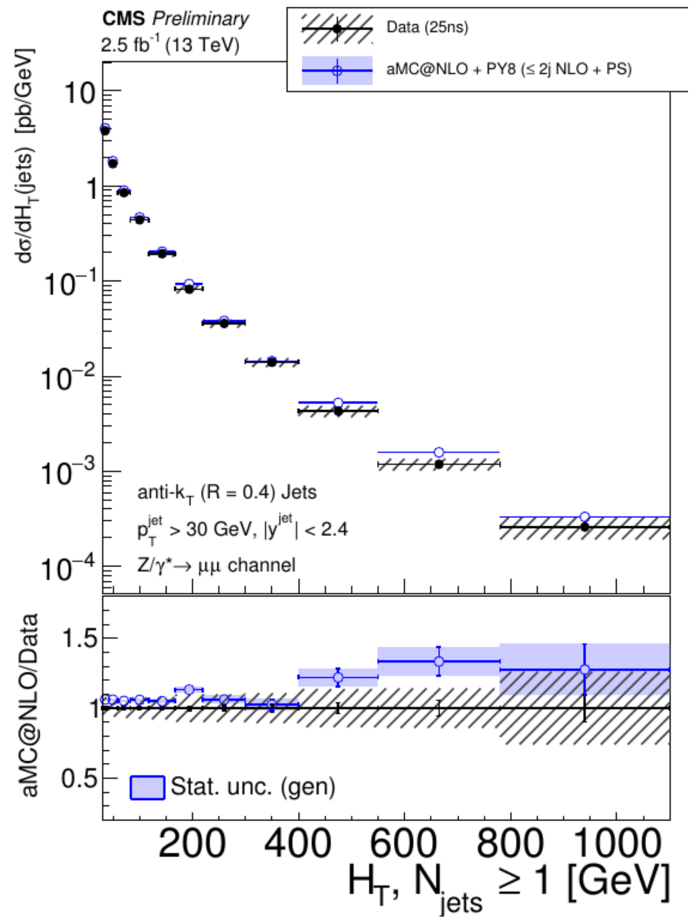
- *Multiplicity up to 4 jets → well reproduced by most of available predictions*
- Early Run II results allow validation and further tuning MC generators, this is of primary importance for a successful analysis of very large LHC data set soon available

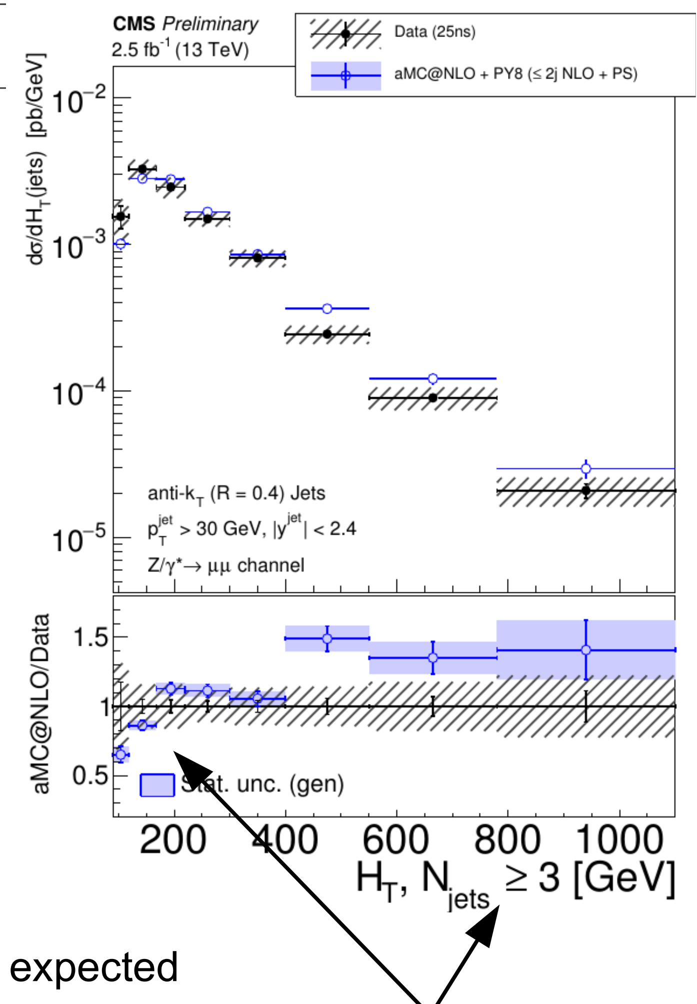
Z+jets at 13 TeV: H_T

$H_T = \Sigma_{l,jets} |p_T|$

- Actual QCD scale of the event
- Used in searches for BSM topologies with large jet activity

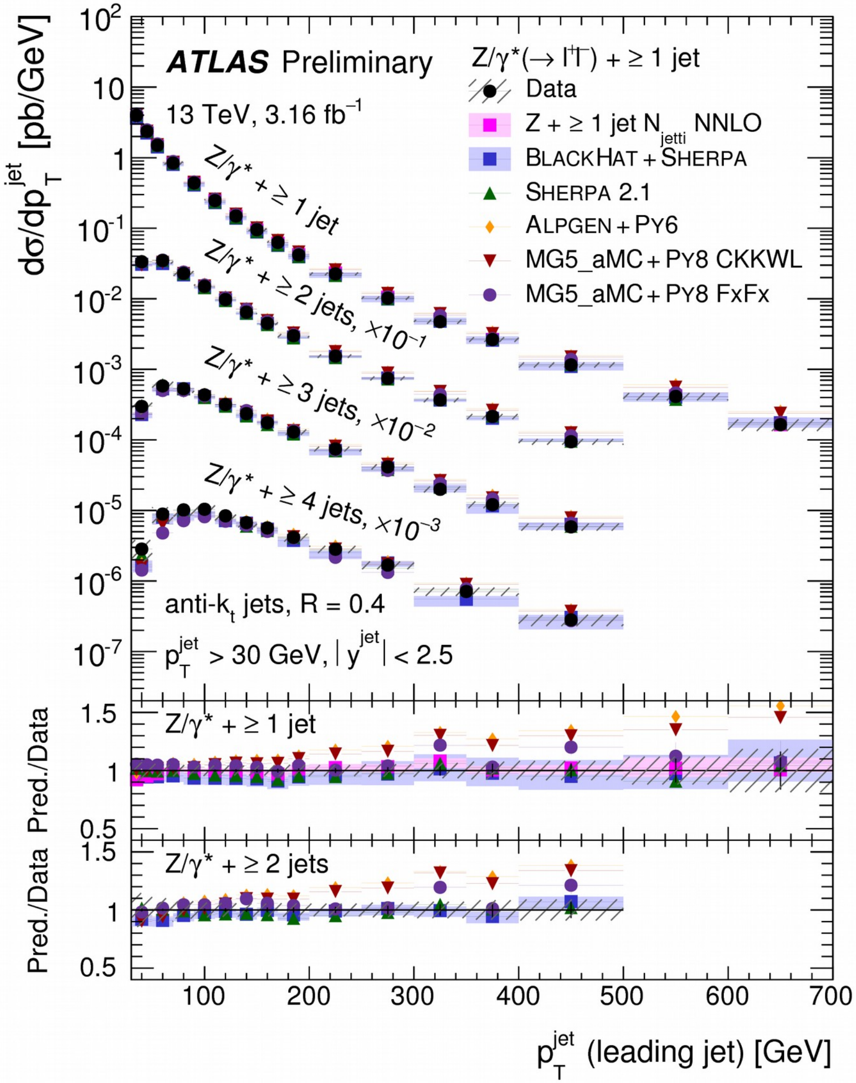


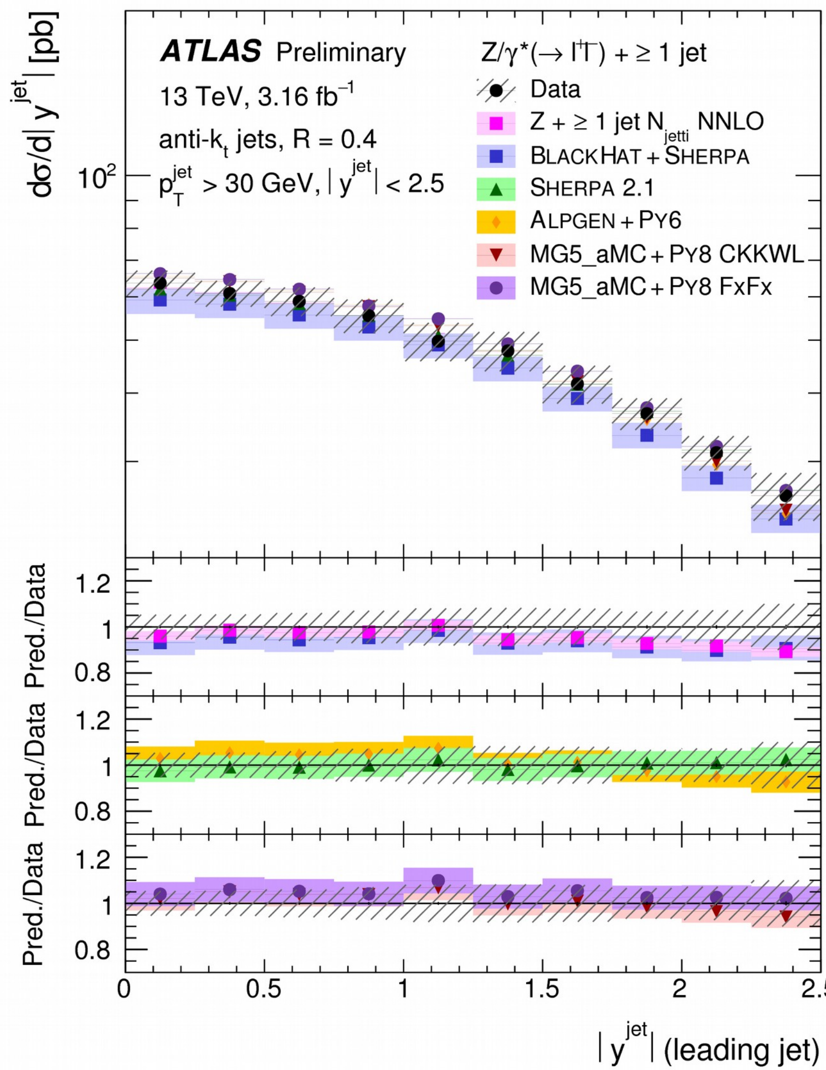




- LO generators over-shooting at large H_T → large scale uncertainty also expected
- Good data description from NLO (1,2 jets) + PS, may still have issues in events dominated by > 2 partons
- Very good agreement from NNLO predictions at all scales!

Z+jets at 13 TeV: Jet Kinematics





- Leading jet p_T in > 1,2 jets too hard for LO generators at high p_T → large scale uncertainty also expected
- Leading jet rapidity (sensitive to PDFs) modeled within uncertainties by all predictions up to $|y| = 2.5$
- *NLO and new NNLO calculations show very good modeling!*

W+Jets Analyses

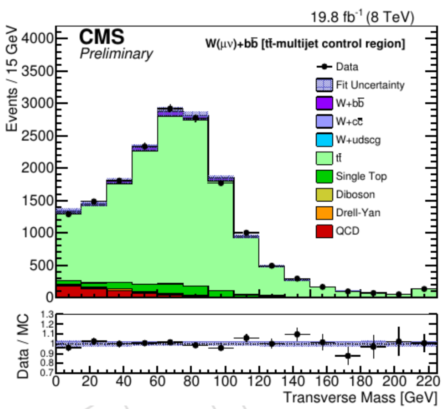
Cons:

- Partial reconstruction of W(e/μ+ν) decay final state because of escaping neutrino
- Large backgrounds:
  → multijet (MJ) typically up to 10% for N_{jets}>2
  → top-pair-production > 50% for N_{jets} > 4

Pros: σ_{W+jets} ~ 10 x σ_{Z+jets}:

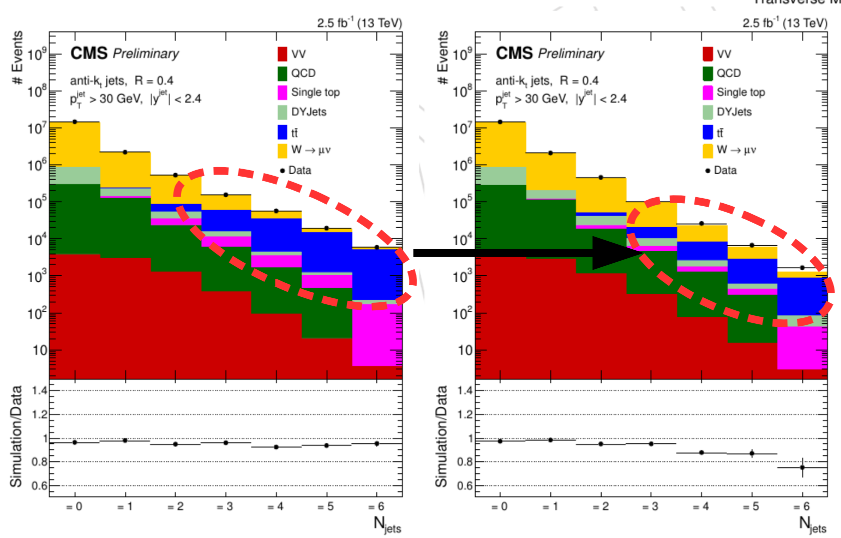
- Very large sample available
- Explore wider kinematic regimes
- Probe different final state and process
  → important in many other analyses

- E.g. 1) extraction of MJ by fitting m_T or E_T^{miss} data templates
- E.g 2) Top rejection using with "anti" b-tag



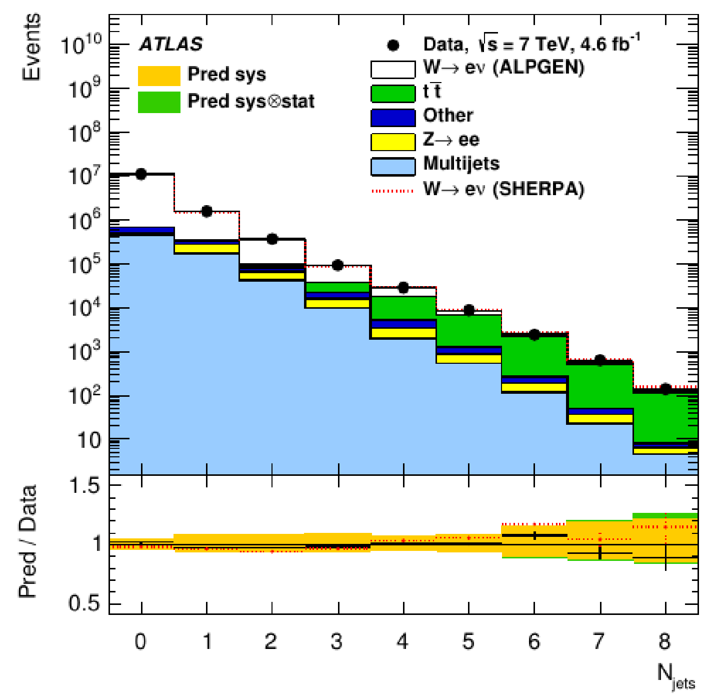
Fit of m_T for MJ extraction

Before *anti b-tag*



After *anti b-tag*

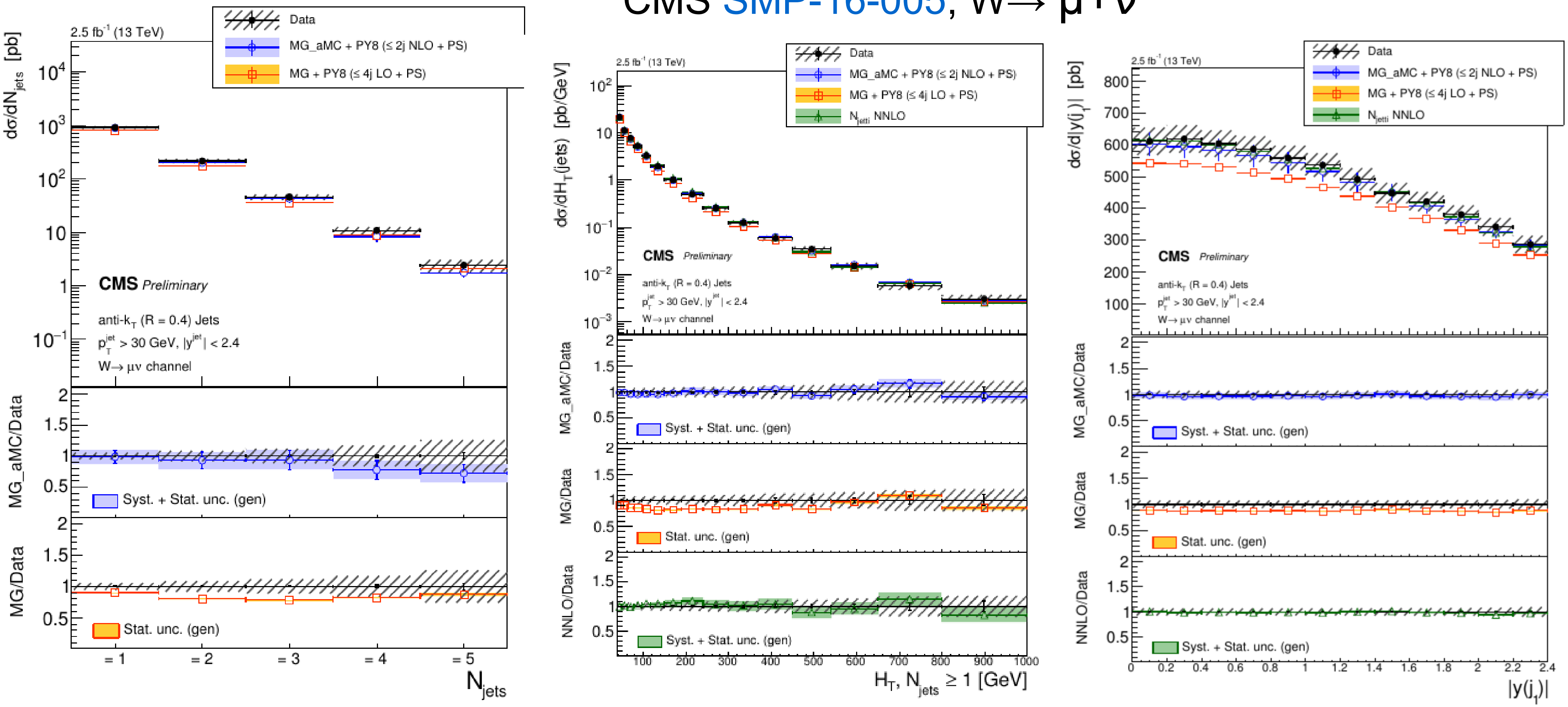
8-jets final states on 7 TeV dataset!



Challenging but extremely interesting analyses!

W+jets at 13 TeV Now Available!

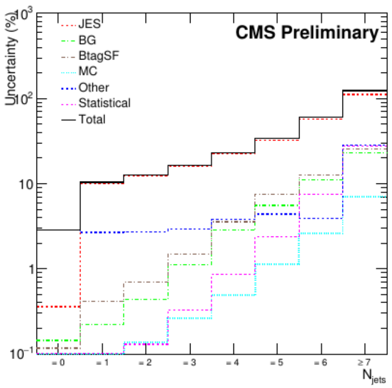
CMS SMP-16-005, W→ μ+ν



- Reasonable agreement of LO+PS and NLO+PS tested generators for N-jets and kinematic distributions for low jet multiplicities
- *NNLO predictions available for W + 1 jet processes show remarkable agreement with studied data distribution*

W + N-jets in Run I

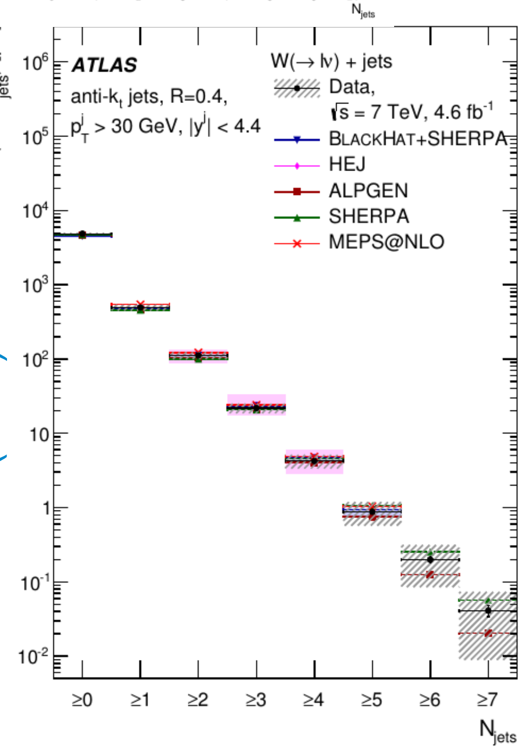
A wide set of differential distributions and different predictions is available when looking at 7 and 8 TeV W+jets analyses

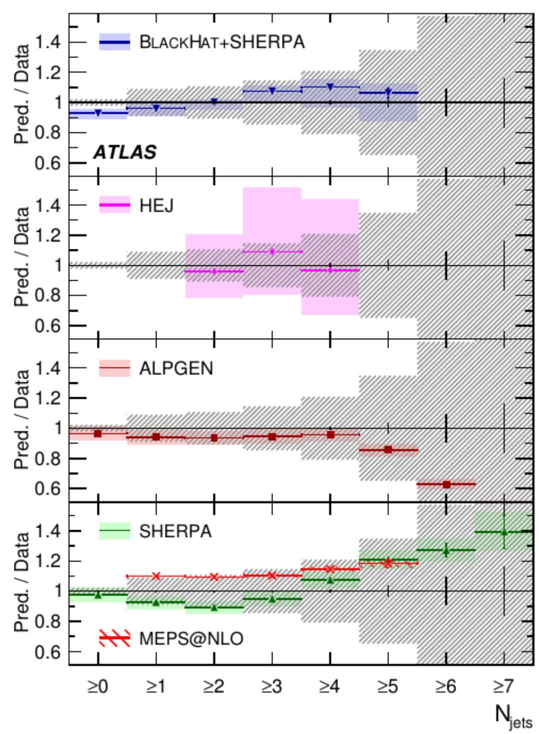


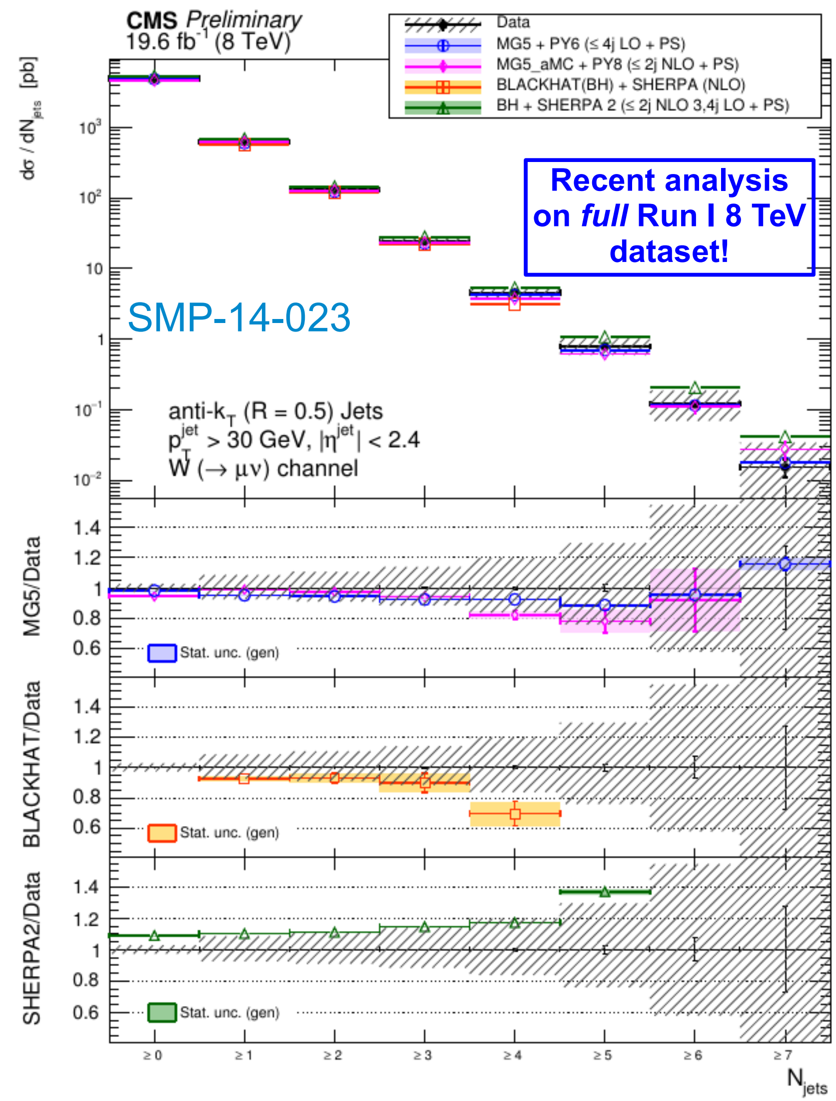
Main systematic uncertainties:

- Jet energy scale for $N_{jets} > 0$
- Backgrounds extraction and rejection methods become sizable for $N_{jets} > 4$

EPJC(2015) 75:82







Recent analysis on *full* Run I 8 TeV dataset!

SMP-14-023

- Data/predictions agreement slightly worse than Z+jets case

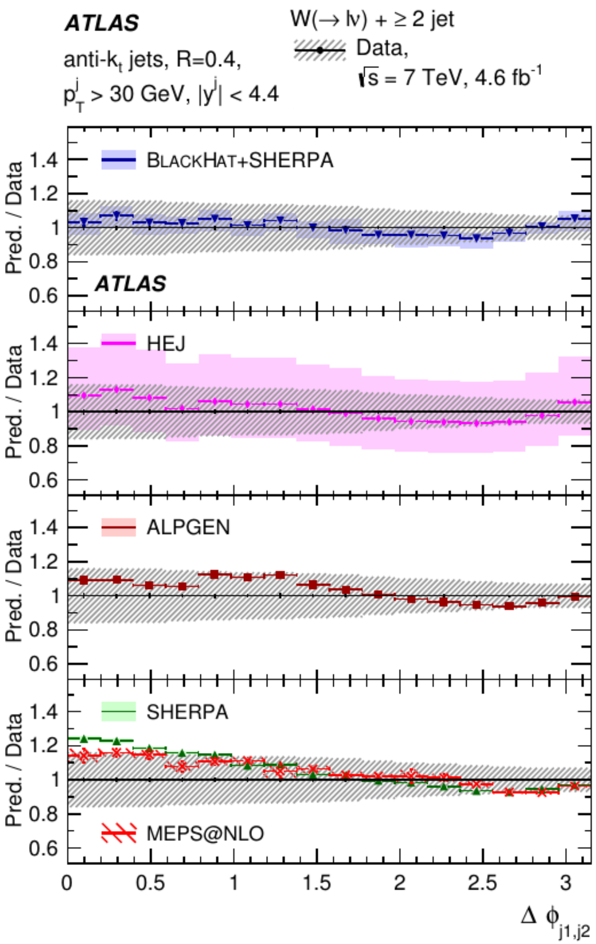
W+jets in Run I: Angular Variables

Δφ (j_1,j_2) is a test of QCD and MC modeling:

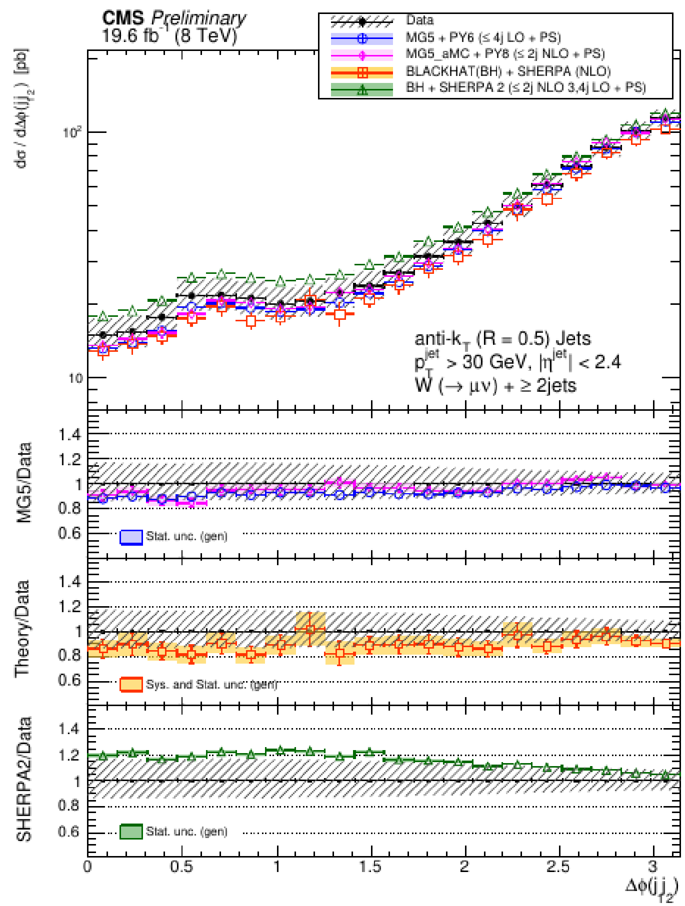
- Hard radiation at large angles from matrix element
- Soft collinear radiation from PS

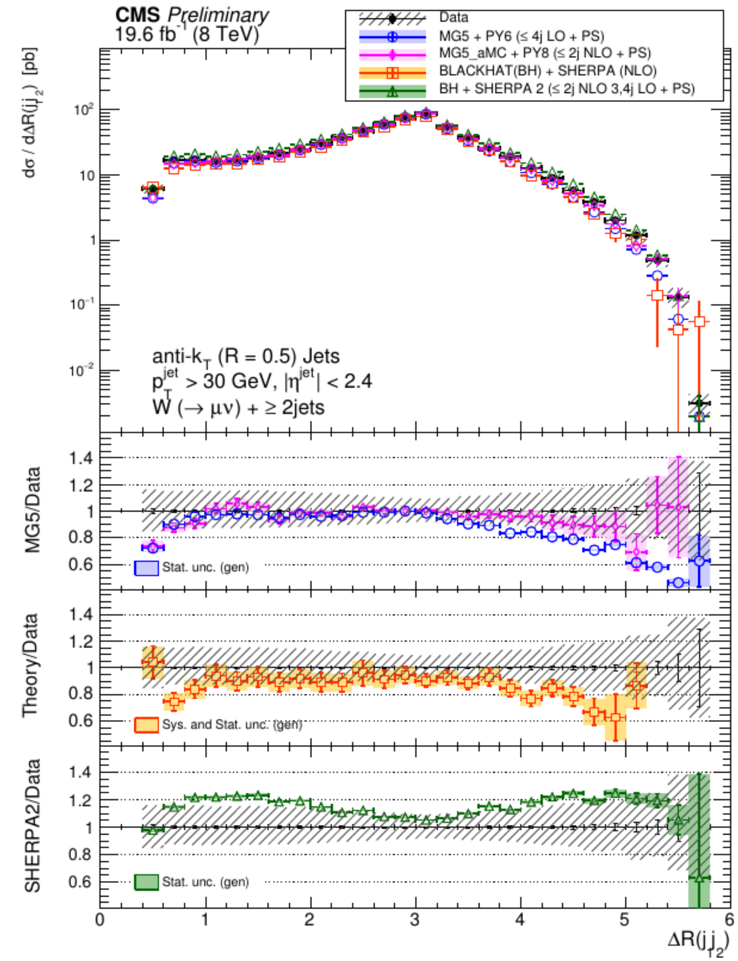
ΔR (j_1,j_2)

EPJC(2015) 75:82



SMP-14-023



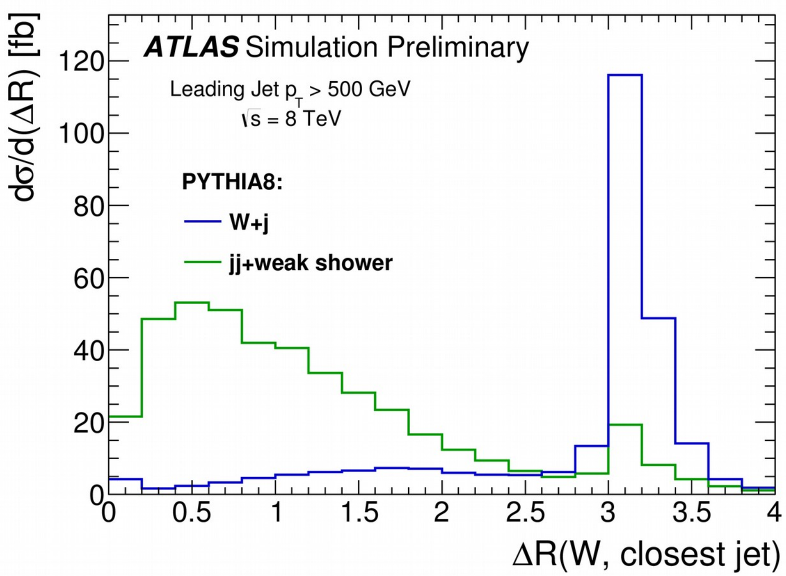


- Various predictions show different trends but data is modeled within uncertainties

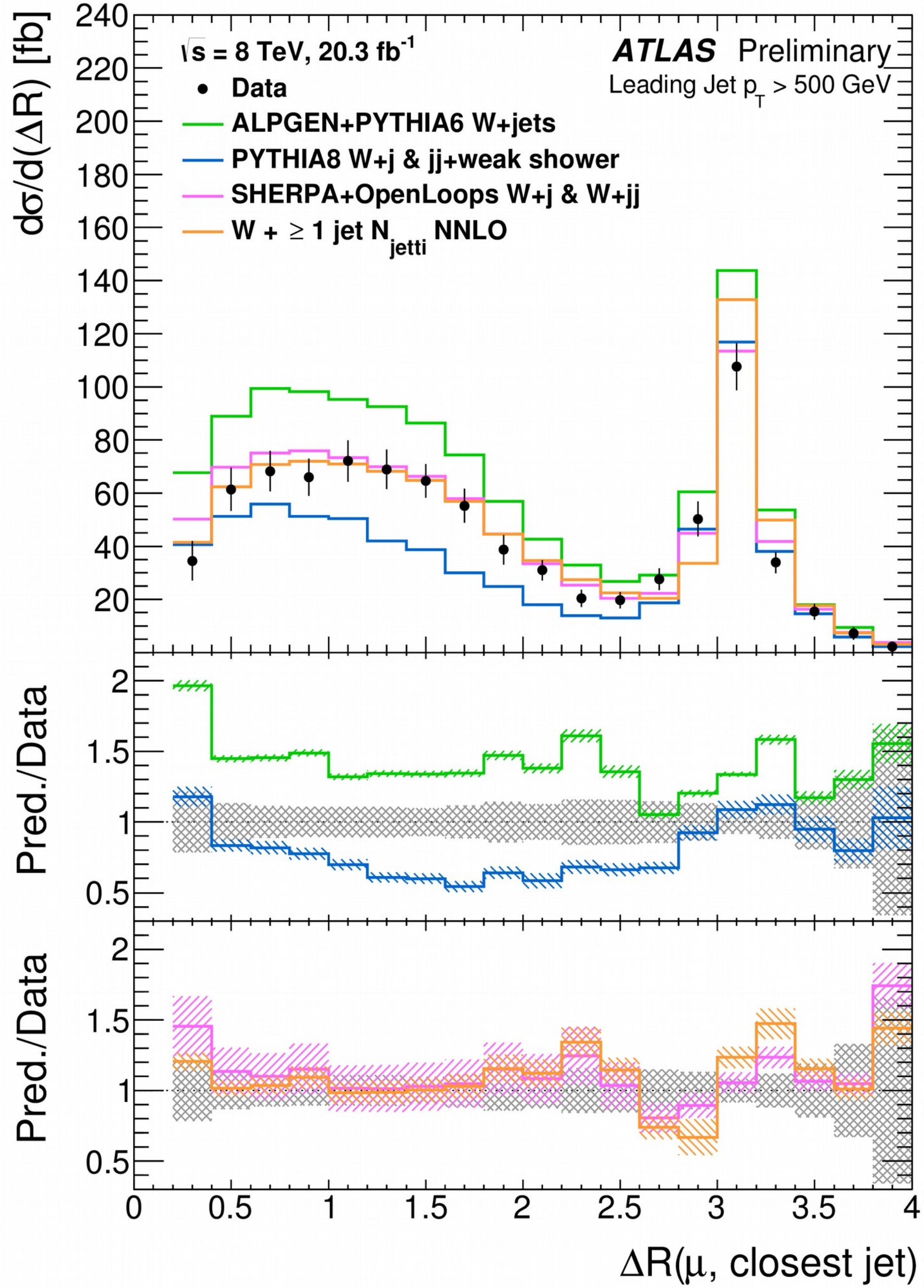
W + Jets in Events with High-p_T Jets

- Large 8 TeV dataset allows investigation of special topologies
- Real W emission from radiation collinear to a very high-p_T quark

STDM-2015-16



- Studied using angular separation between jet and closest μ from W
- Good description of normalization (NNLO, Sherpa) and shape (also by ALPGEN)
- For more information: *[dedicated poster by W. Miles]*



Z or W plus HF-quarks Analysis in Run I

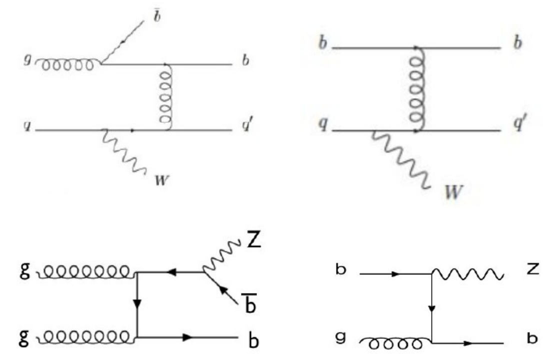
High interest in measuring Z or W boson production in association with HF jets:

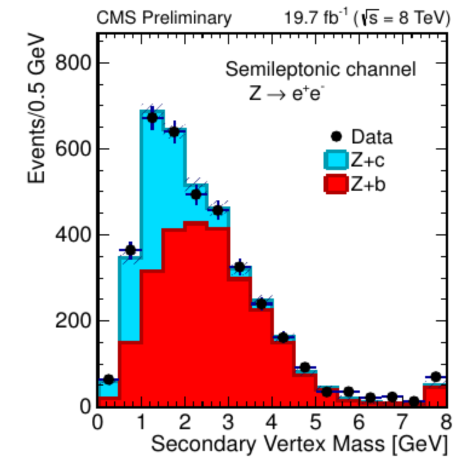
- Theoretical uncertainties due to model of close-by b-quark production and mass
- Sensitivity to b-flavor content of the PDFs: → 4-flavor vs 5-flavor scheme
- Presence of intrinsic charm in the proton
- Main background for BSM and Higgs searches

***Very challenging experimental analysis*:**

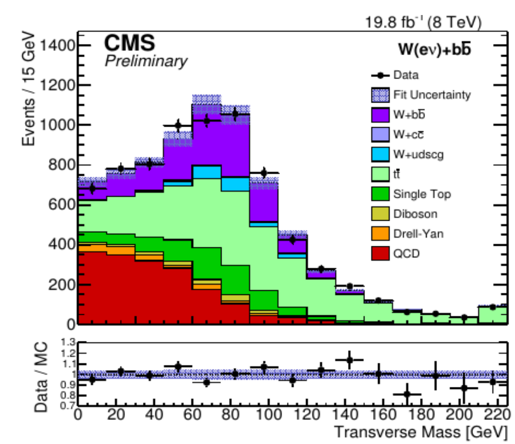
- Small signal cross-section ~ O(10) pb → orders of magnitude lower than inclusive case!
- Fake b-jets reconstruction gives an additional source of reducible backgrounds
- Signal extraction using b-jet-sensitive variable
- Irreducible backgrounds comparable to signal yield in Z + HF channels
- Even worse situation for W channels (bkg > sig)
- Analyses both stat. and syst. limited

4F diagrams: 5F diagrams:





Example Z+c/b jet extraction fit using sec.vertex mass

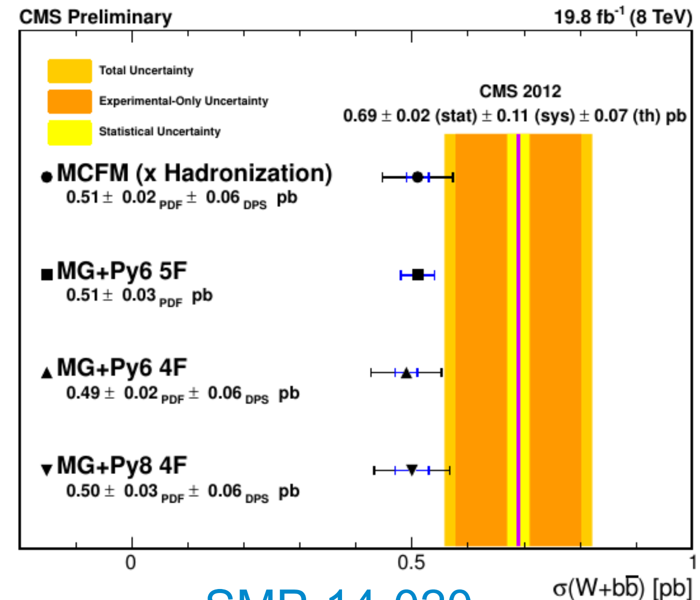


W+bb candidate events composition example

V+b(b) in Run I

Nice set of W and Z recent preliminary measurements from CMS:

- SMP-14-010: Z+1b (inclusive in b-jets) and Z+2b fiducial cross section and cross section ratios
- SMP-14-020: W+bb fiducial cross section



SMP-14-020

$$\sigma_{\text{fiducial}}(Z(1b)) = 3.55 \pm 0.12(\text{stat.}) \pm 0.21(\text{syst.})\ \text{pb}$$

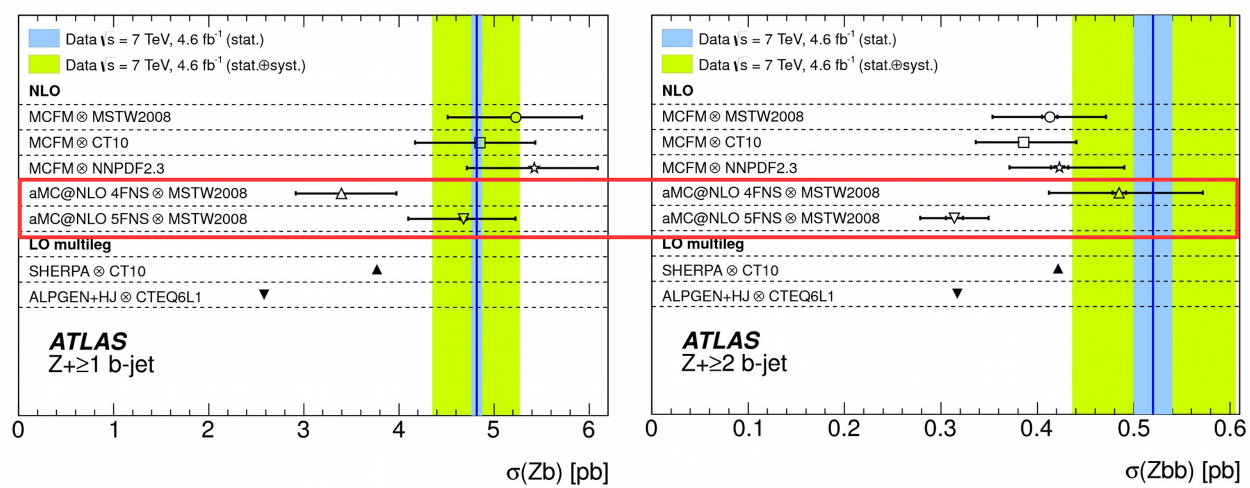
$$\sigma_{\text{fiducial}}(Z(2b)) = 0.331 \pm 0.011(\text{stat.}) \pm 0.035(\text{syst.})\ \text{pb}$$

$$\frac{\sigma_{\text{fiducial}}(Z(2b))}{\sigma_{\text{fiducial}}(Z(1b))} = (9.3 \pm 0.4(\text{stat.}) \pm 0.7(\text{syst.})) \times 10^{-2}$$

- Comparison with predictions using different flavor schemes

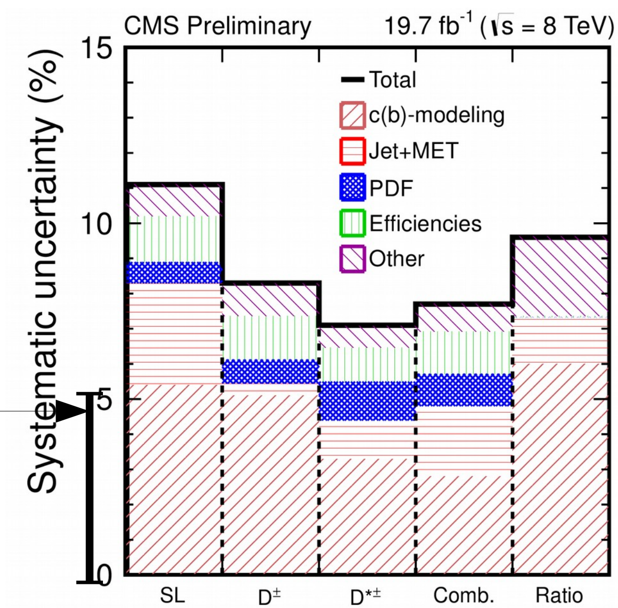
Also interesting to compare with ATLAS Z+b 7 TeV measurements:
JHEP10(2014)141

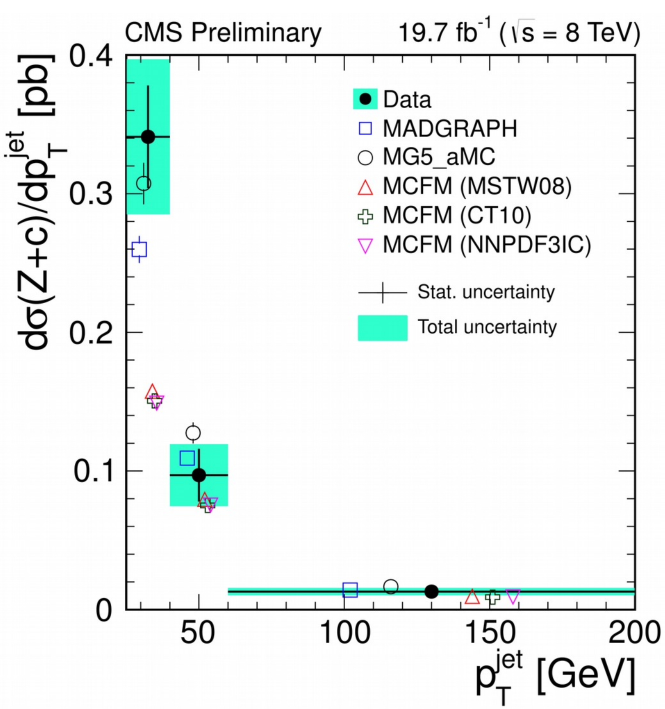
- Large scale uncertainty at NLO
- Better data agreement for NLO than LO ME+PS
- Z+1b data favors NLO 5F
- Z+2b data favors NLO 4F

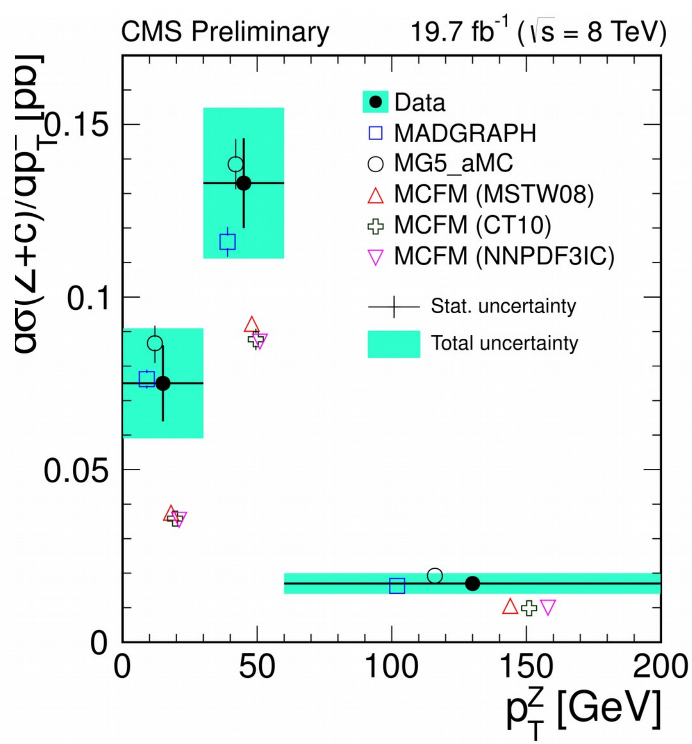


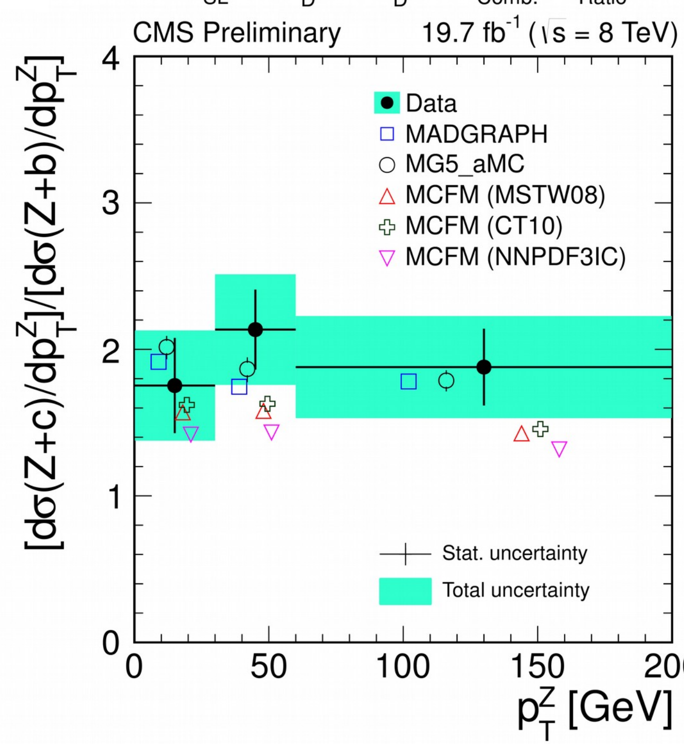
Z + charm Production at 8 TeV

- Measurement (SMP-15-009) of Z+c and Z+b by searching jets (p_T>25 GeV) for secondary decay vertices and semileptonic decay of hadrons
- Z+c measurement in two additional channels using D-meson decays
- Main uncertainty related to c-hadron simulation
- Differential measurement of HF-jet p_T, Z p_T and c/b ratios compared to several predictions









Conclusions and Summary

Measurement of jet production in association with W or Z boson:

- Improves understanding of perturbative QCD
- Will improve MC modeling of kinematic observables which are important in many other analyses and searches

ATLAS and CMS are providing:

- First precise results using LHC Run II data at 13 TeV!
- Vast set of precise results based on Run 1 data which are probing special topologies, as W-collinear emission, or challenging final states, as V + HF jets!

Many fiducial cross sections and differential unfolded measurements are compared to a variety of predictions and generators:

- *While remarkable agreement observed for some distribution, no prediction is perfect (yet)*


Thanks for your attention!
Questions?

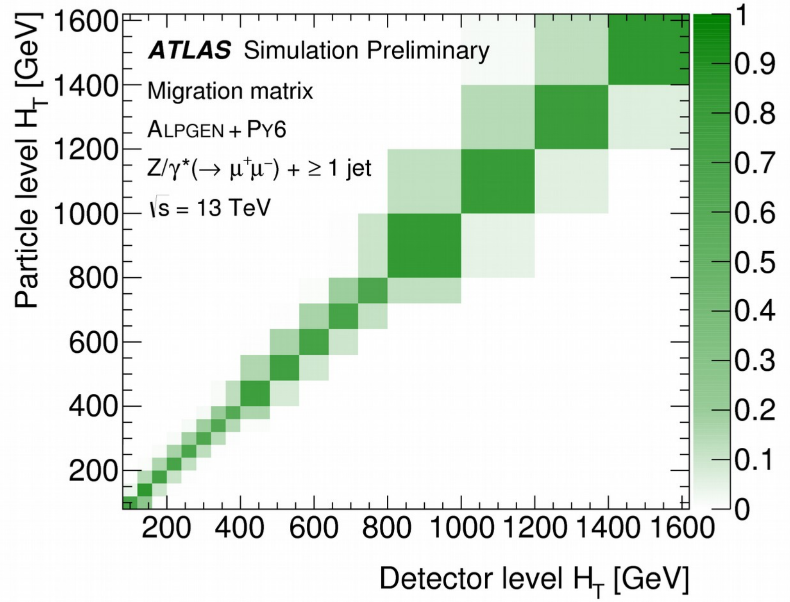
Backup

Bayesian Iterative Unfolding

Response matrix accounts for migrations using MC simulation:

$$M_{ij} = M(R_i|T_j)$$

Conditional probability that the effect R_i is produced by the cause T_j



How to extract *"prediction-unbiased"* probability using iterative Bayesian unfolding:

- Bayes theorem:

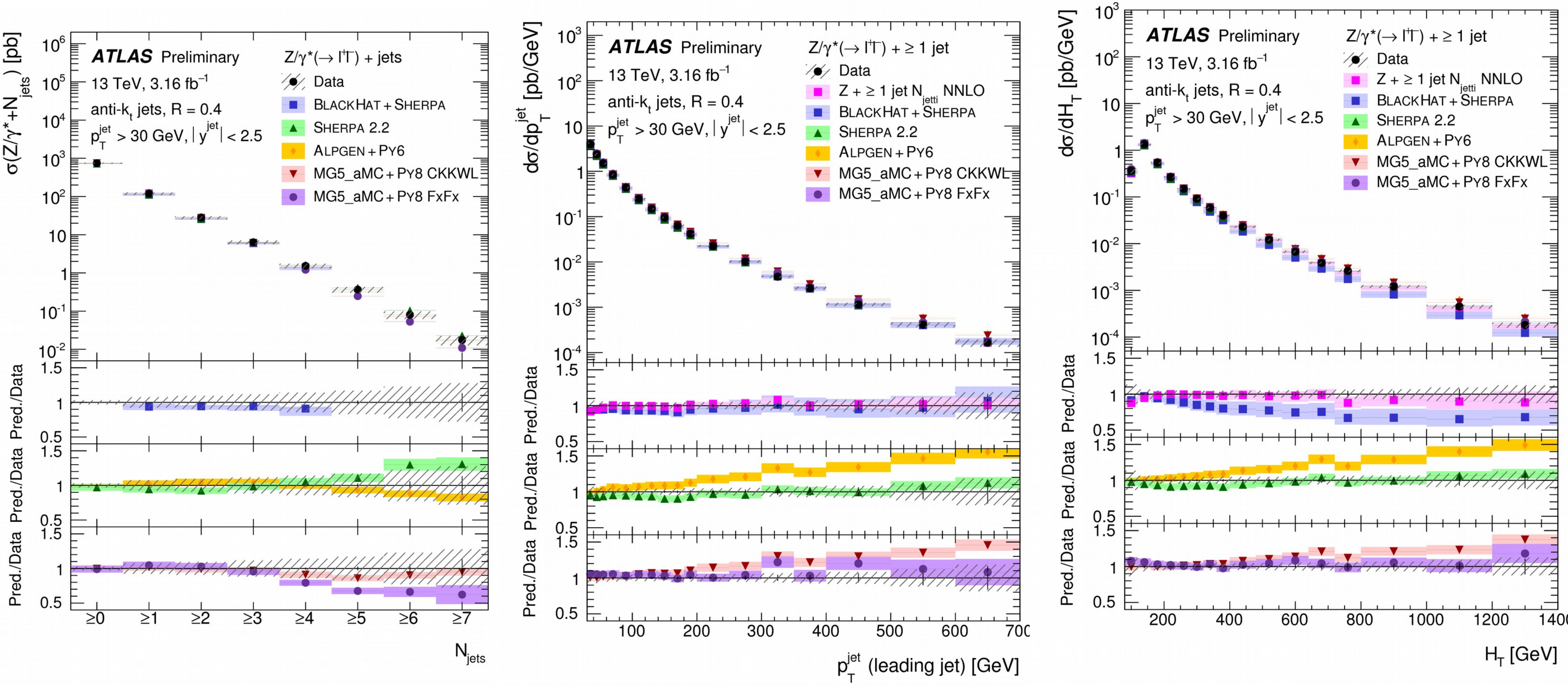
$$M(T_i|R_j) = M(R_i|T_j)\, P_0(T_j) \,/\, \text{Sum}_l\ M(R_i|T_l)\, P_0(T_l)$$

- Particle level MC used as initial prior, $P_0(T_j)$, to determine a first estimate of the unfolded data distribution:

$$T_j = \text{Sum}_i\ M(T_j \mid R_i)\, R_i$$

- In each further iteration the estimator of the unfolded distribution from previous iteration is used as a new prior

Z+jets Including Sherpa 2.2 Predictions



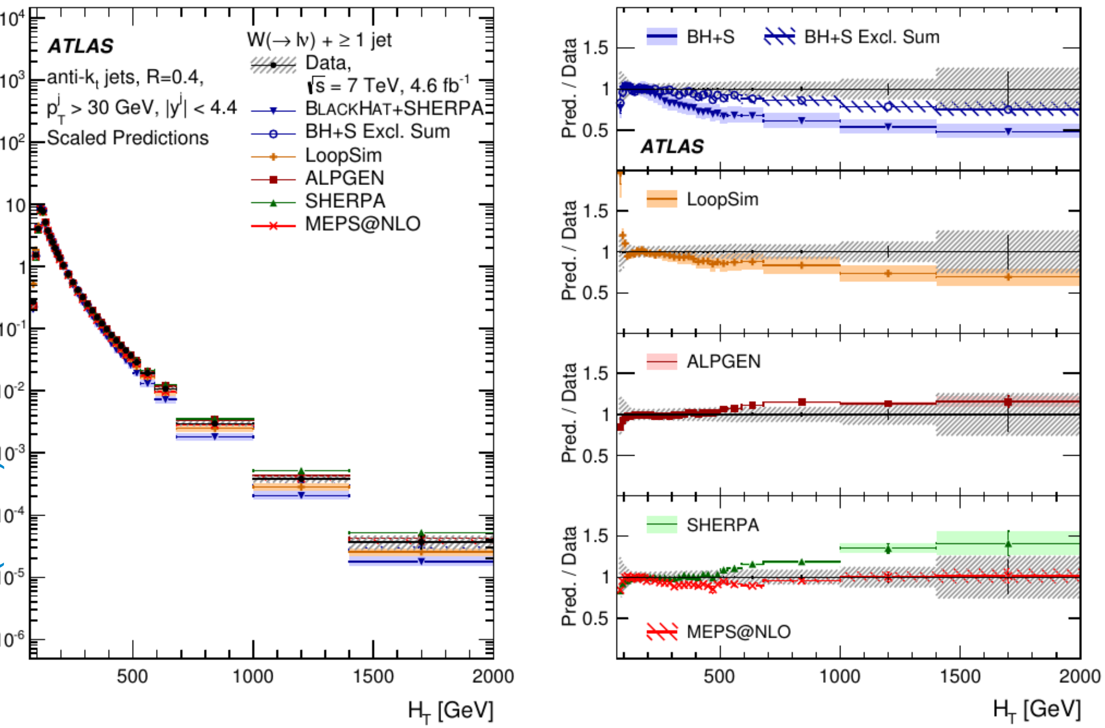
- Sherpa 2.2 predictions were produced with simplified scale setting in multi-parton ME to improve event generation speed
- A theory-based reweighting of the jet multiplicity distribution is applied at event level, derived from event generation with the strict scale prescription
- No relevant differences appear between Sherpa 2.1 predictions and Sherpa 2.2 ones in the considered phase space
- Good agreement with data is observed for Sherpa 2.2 predictions

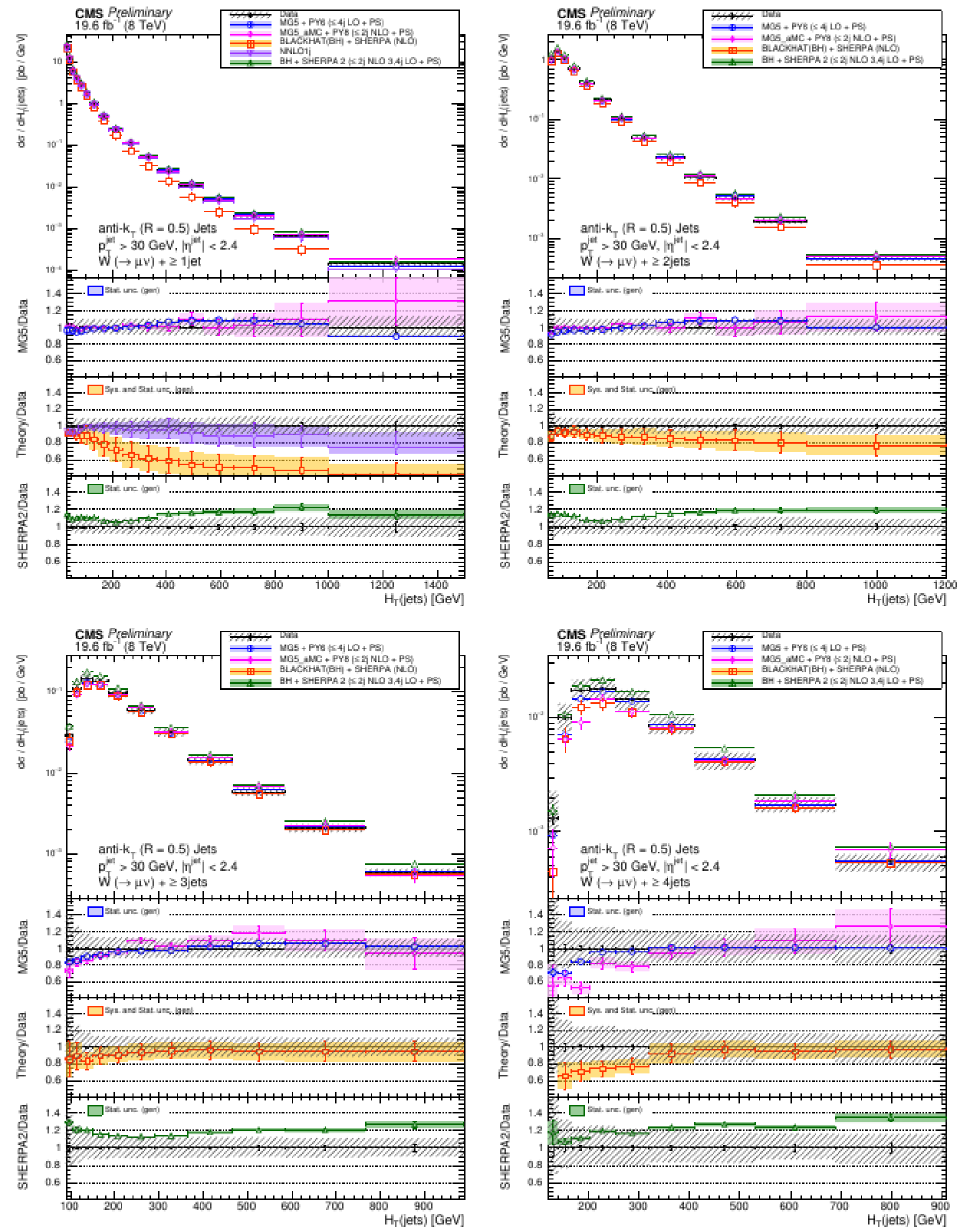
W+jets in Run I: H_T

$$H_T = \Sigma_{l,\nu,jets} \; |p_T|$$

SMP-14-023

EPJC(2015) 75:82





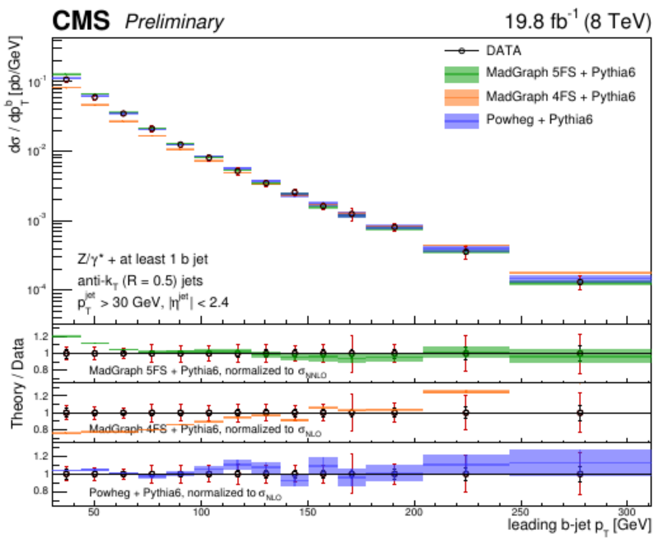
- Fixed order calculations do not describe data at high H_T (as expected)
- Improvement in MEPS@NLO (≡ Sherpa2) compared to Sherpa1
- Degradation for jet multiplicities dominated by many hard-partons in the final state

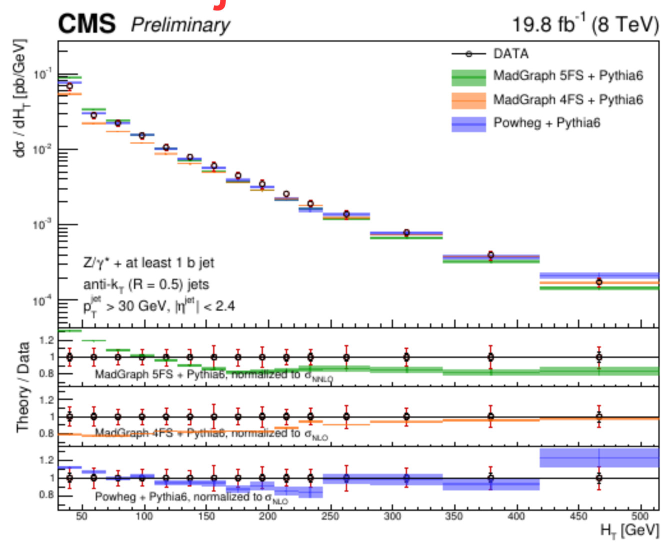
Z+b(b) Kinematics in Run I

Unfolded differential distributions and ratio of distributions with respect to generic jets!

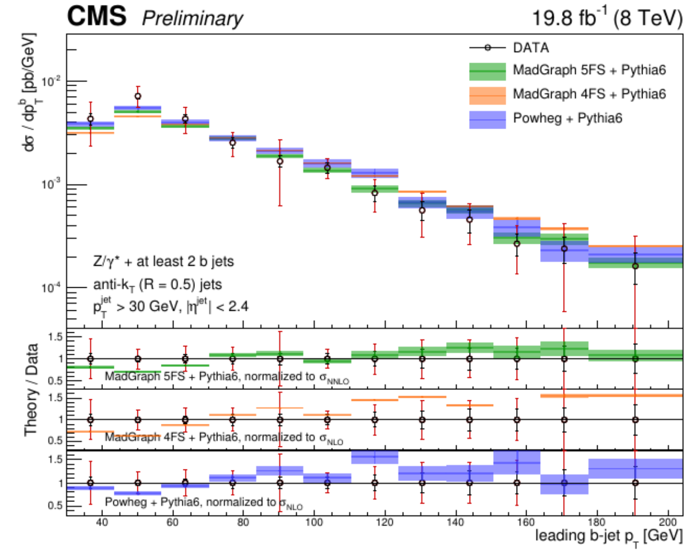
SMP-14-010

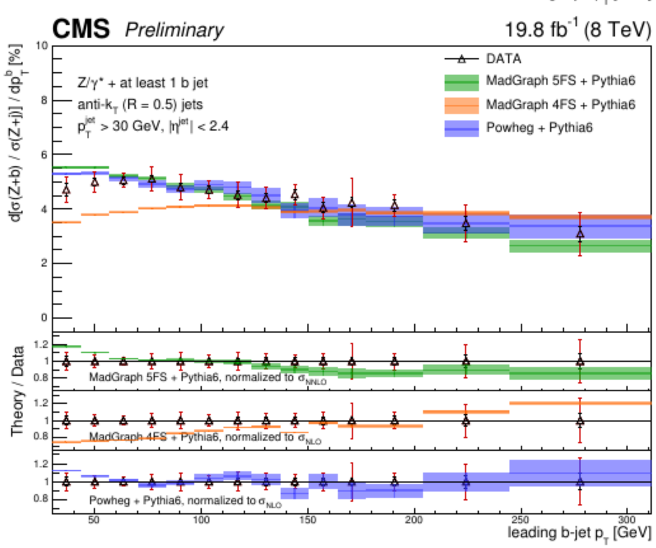
Z+b and Z+b/Z+jets

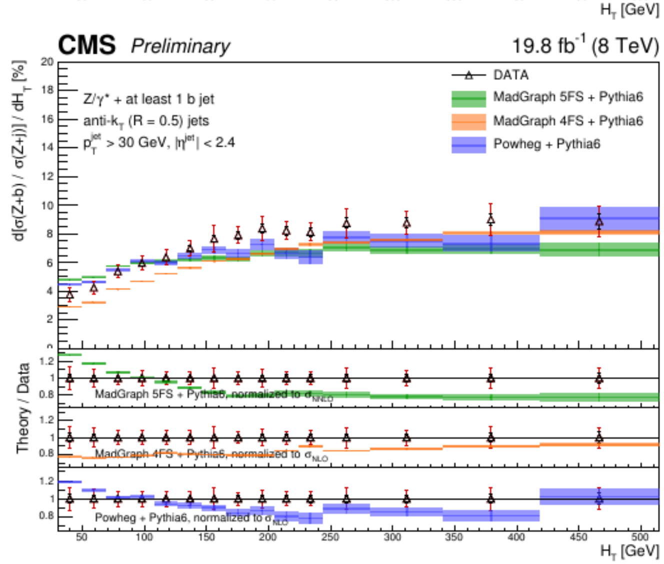


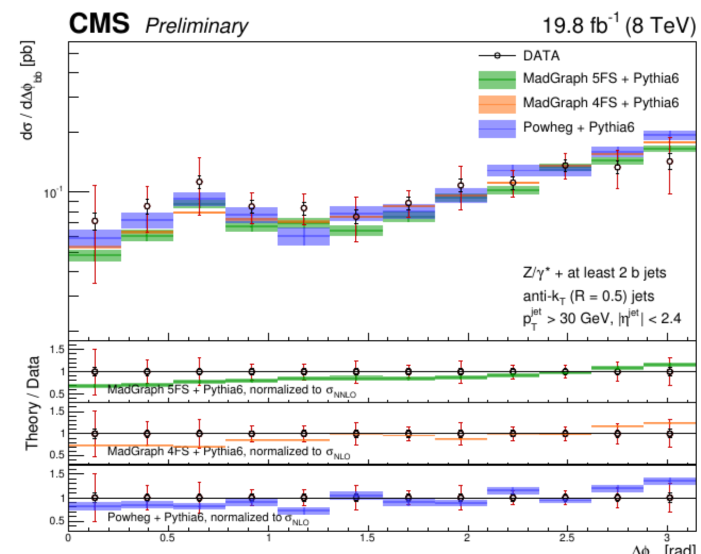


Z+bb









- Different flavor scheme predictions can predict correctly only part of the distributions