Associated Production of Vector Bosons and Jets at LHC

Standard Model @ LHC 2019

23-26 April 2019, Zurich

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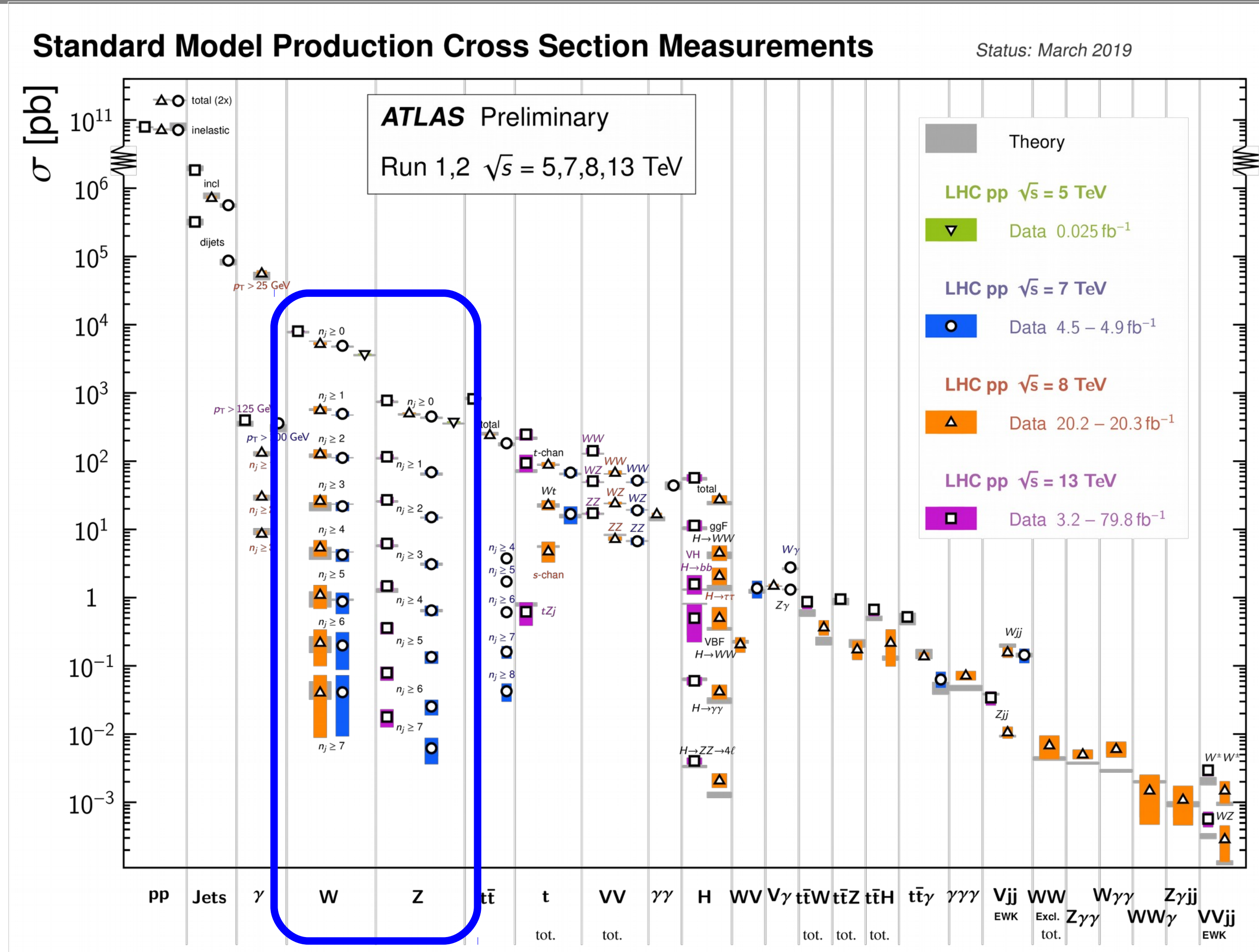
on behalf of ATLAS and CMS Collaborations

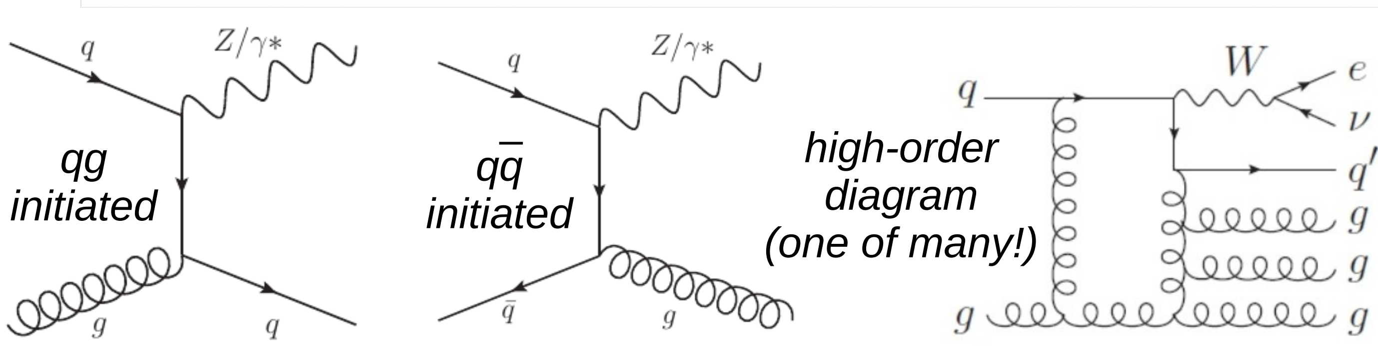
W or Z plus jets at LHC:

- Abundant QCD production spanning several orders of magnitude of cross-section
- Wide range of measurements now available at different energies and conditions thanks to CMS and ATLAS



Measurements are test of:

- *MC modeling* ⇒ key for Higgs, BSM, EWK etc.
- Perturbative QCD (*pQCD*) predictions
- *Proton PDFs* ⇒ Thanks to dominant *qg* interaction



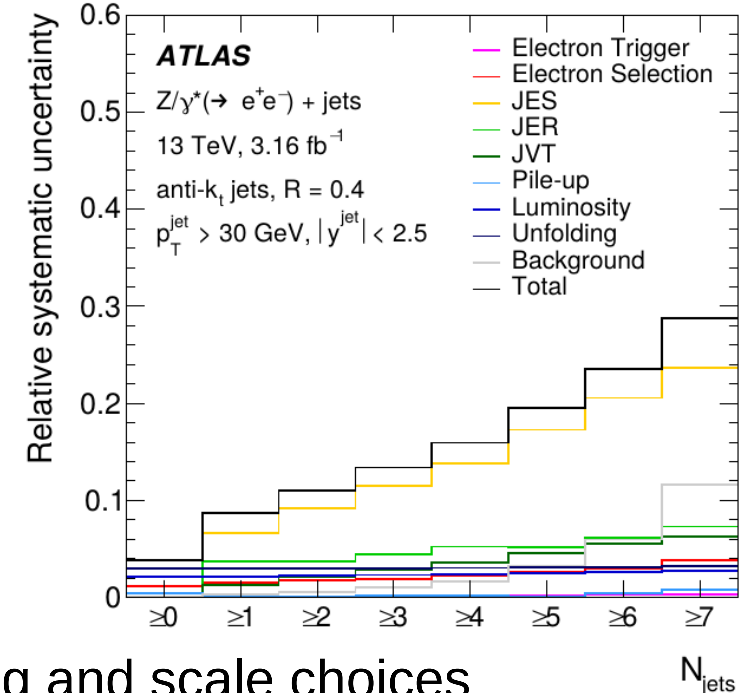
One Slide Overview of V+jets Analyses

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

- *Isolated* leptons (electron or muon) with p_T > 20 or 25 GeV and |η| < 2.4 to 2.5
- **Z:** di-lepton invariant mass around Z peak ⇒ ***pure sample***
- **W:** E_T^{miss} for *ν* reconstruction, l*ν* transverse mass ⇒ ***multi-jet bkg. (data-driven)***

Jet reconstruction and selection in fiducial volume:

- Anti-k_t ΔR = 0.4, p_T > 30 GeV,
- |Y| < 2.5 (ATLAS), |η| < 2.4 CMS
- **NB:** also |Y| < 4.4 in ATLAS Run 1



Extract signal as function a variable "x":

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

Unfold background-subtracted data to *truth*:

- Signal MC used to remove detector effects (efficiencies, resolution, scale, etc.)
- Main experimental uncertainties ⇒ *JES, JER*

Compare to ME+PS or Fixed-Order predictions:

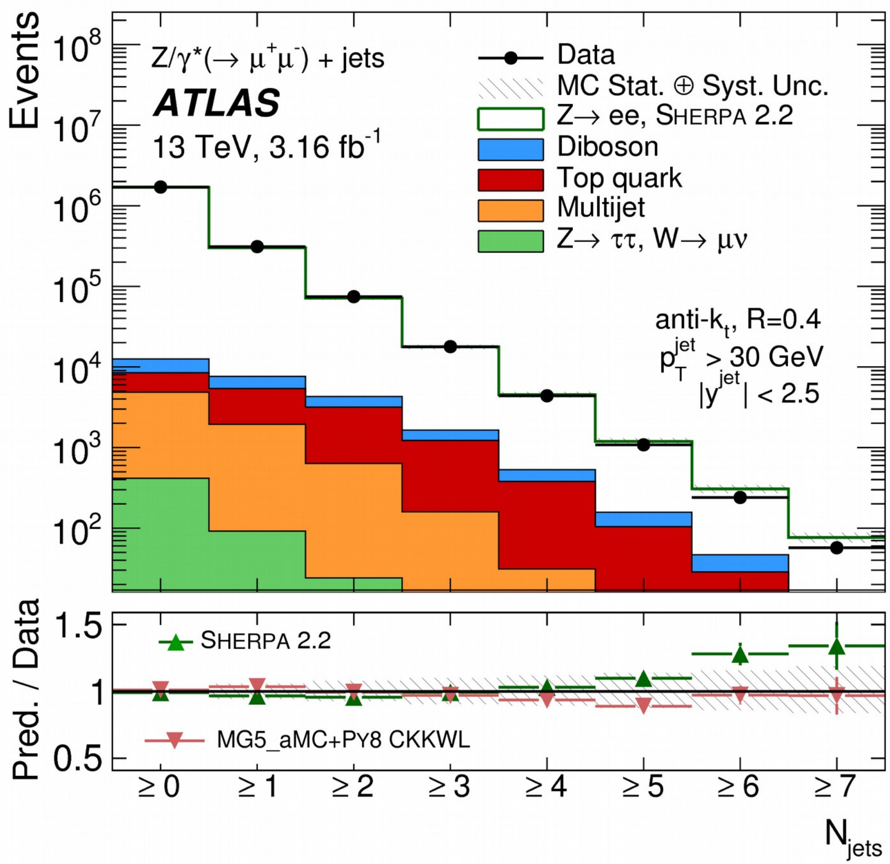
- Multi-parton MC at LO or NLO with different matching and scale choices
- Fixed-order at NLO and NNLO ⇒ **impressive recent progress**!

Z+jets at 13 TeV

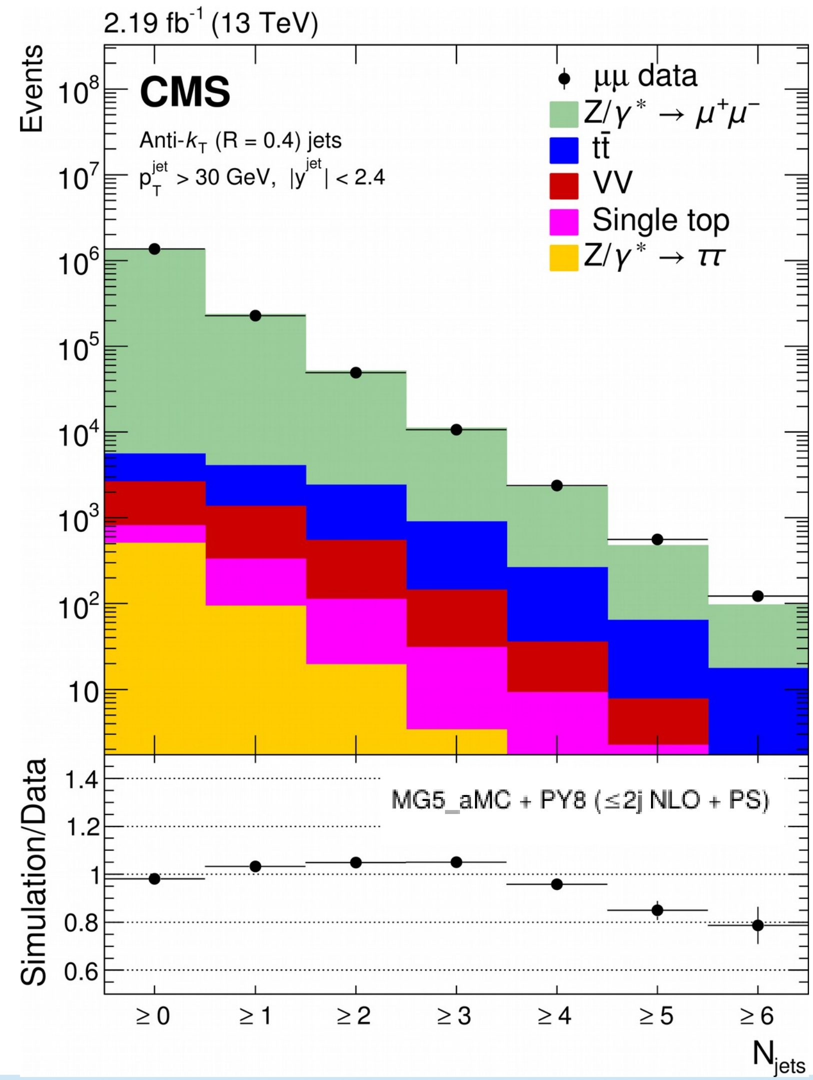
- Run 2 results by ATLAS (2017) and recently published also by CMS (2018)
- Both analyses based on electron and muon data collected in 2015:

  ⇒ 2.2 fb^{-1} (CMS) or 3.2 fb^{-1} (ATLAS), statistical uncertainties already tiny

2017 Result: EPJC77(2017)361



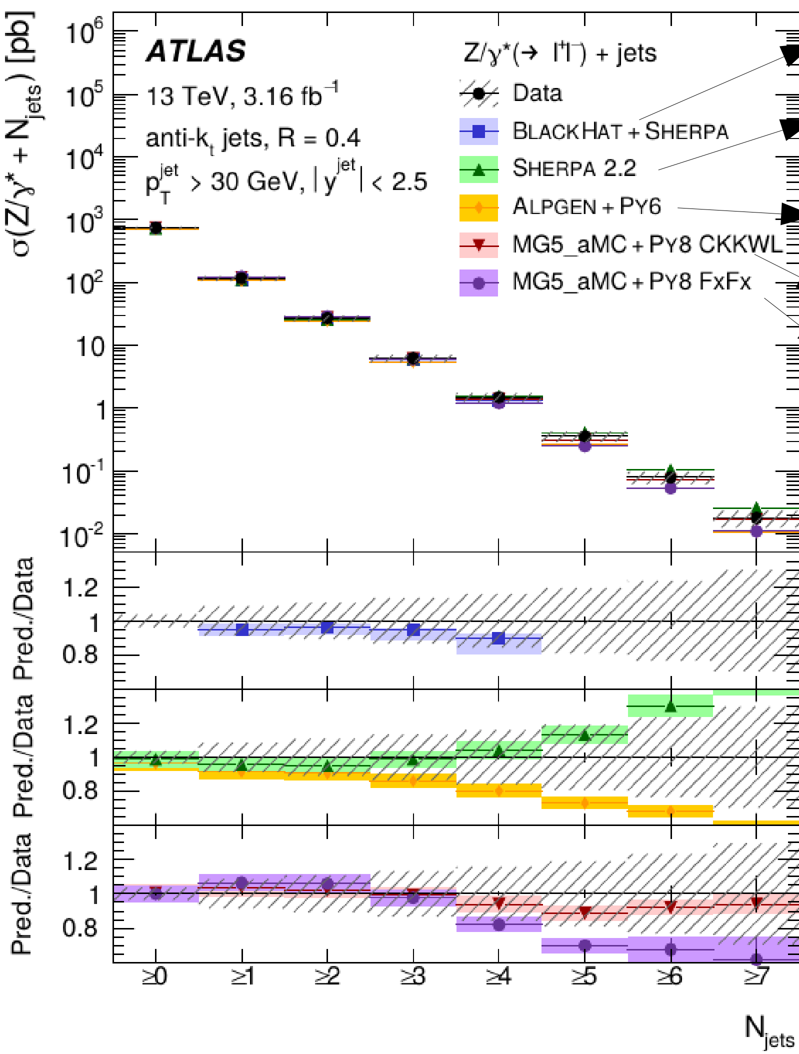
- Similar ground offers maybe interesting comparisons



2018 Result: EPJC78(2018)965

Z + ≥ N-jets at 13 TeV

- One of the main figures of merit for QCD predictions



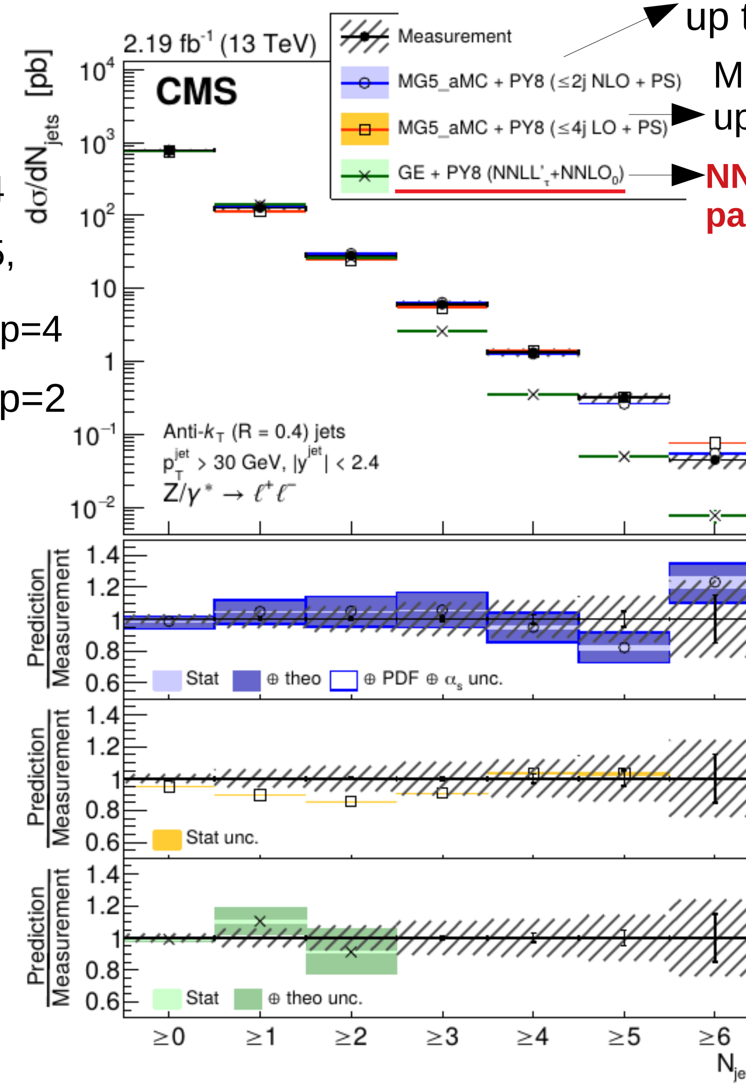
FixedOrder NLO

with PS, NLO up to Np=2, LO up to Np=4

MLM, LO up to Np=5,

CKKW-L LO up to Np=4

FxFx, NLO up to Np=2



FxFx, NLO up to Np=2

MLM, LO up to Np=4

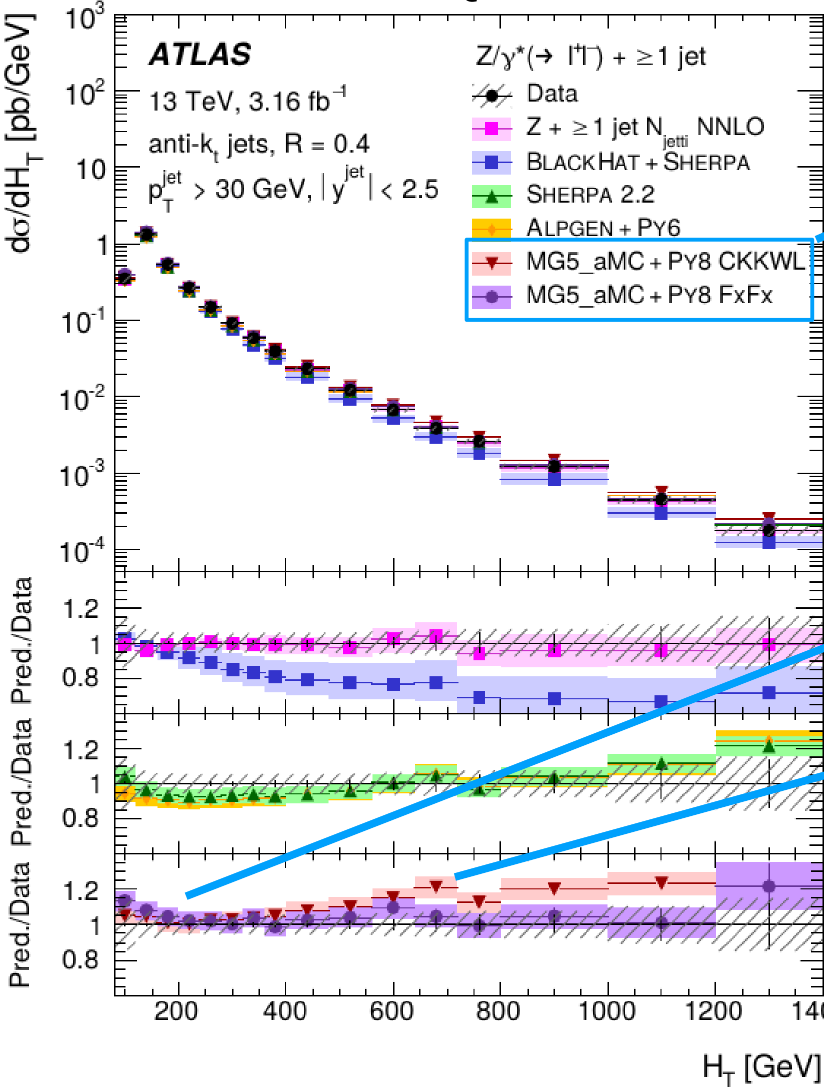
NNLO+ partial N³LL

- CMS systematic errors are a bit smaller (JER in particular), ATLAS extends to 7 jets
- Good agreement up to 4 jets ⇒ deviations in PS-dominated multiplicities where also exp. syst. are sizable (*NB: PS-tuning syst. are not considered in any publication*)

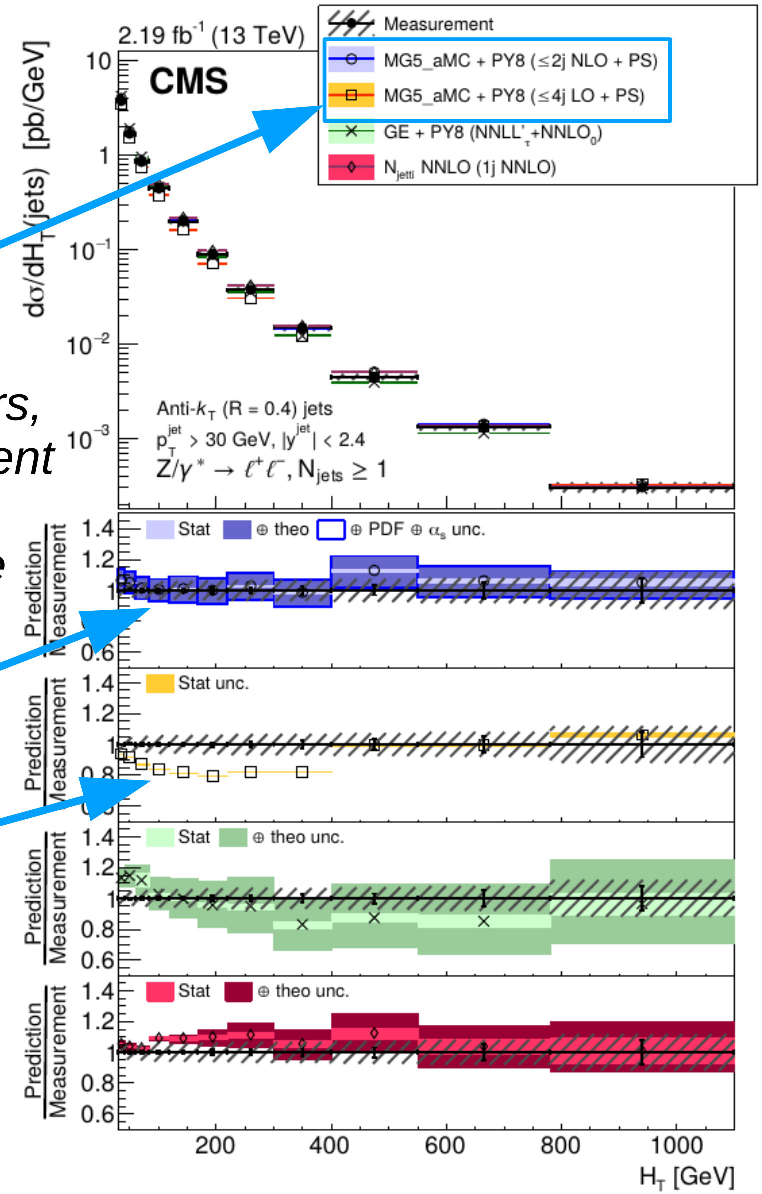
H_T in Z + jets at 13 TeV

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

- Often considered as the QCD scale of the event



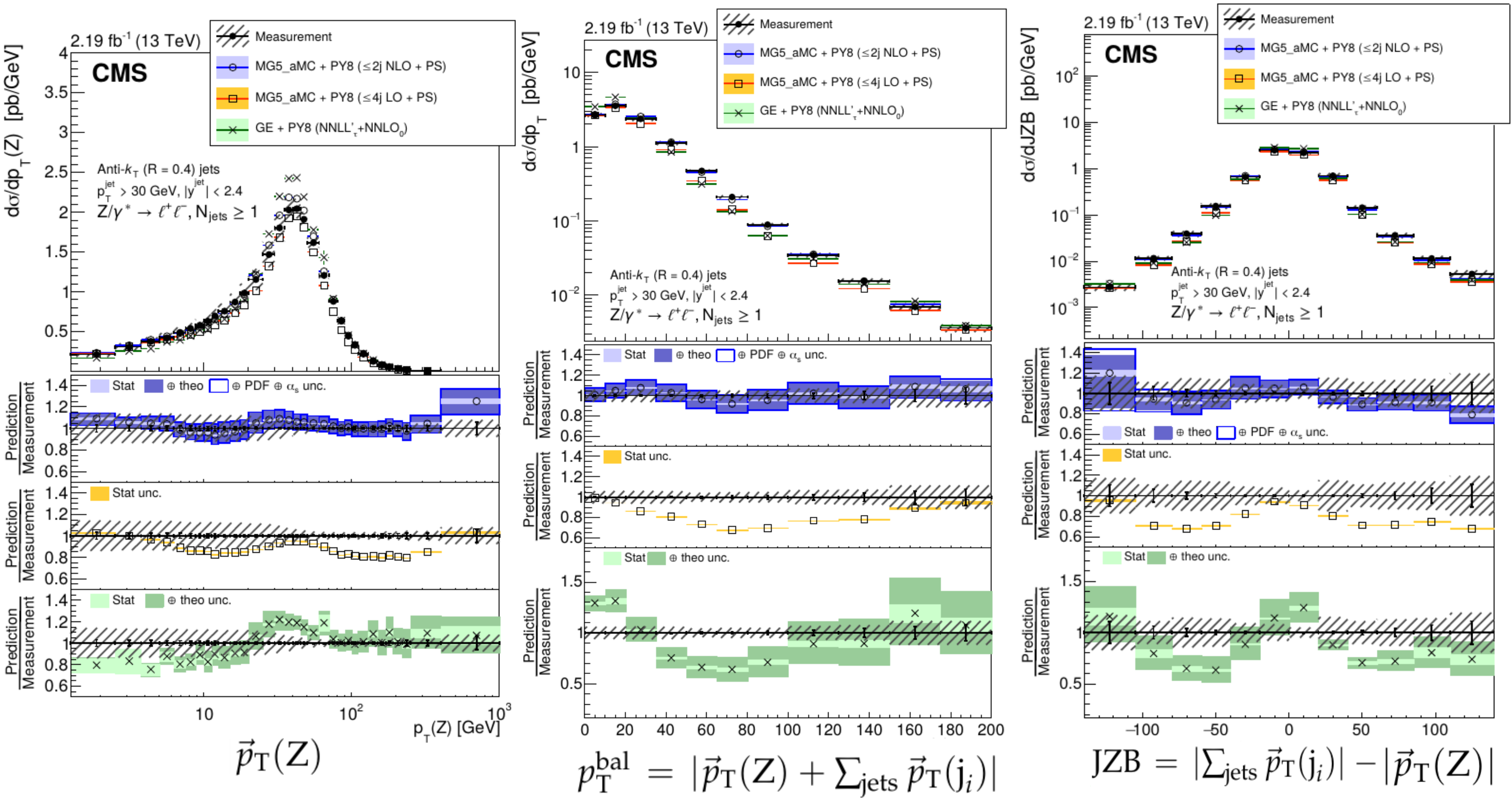
Same generators, but different matching and scale choices



- Noticeable differences in ME+PS ⇒ best for NLO+PS, but also LO can perform well
- *Excellent agreement from NNLO predictions within prescribed uncertainties*

Analysis of Z p_T and Jet-Z-Balance

Test of Z recoil against clustered and unclustered hadronic activity



- MG+PY8 FxFx, with CMS setup, performs very well

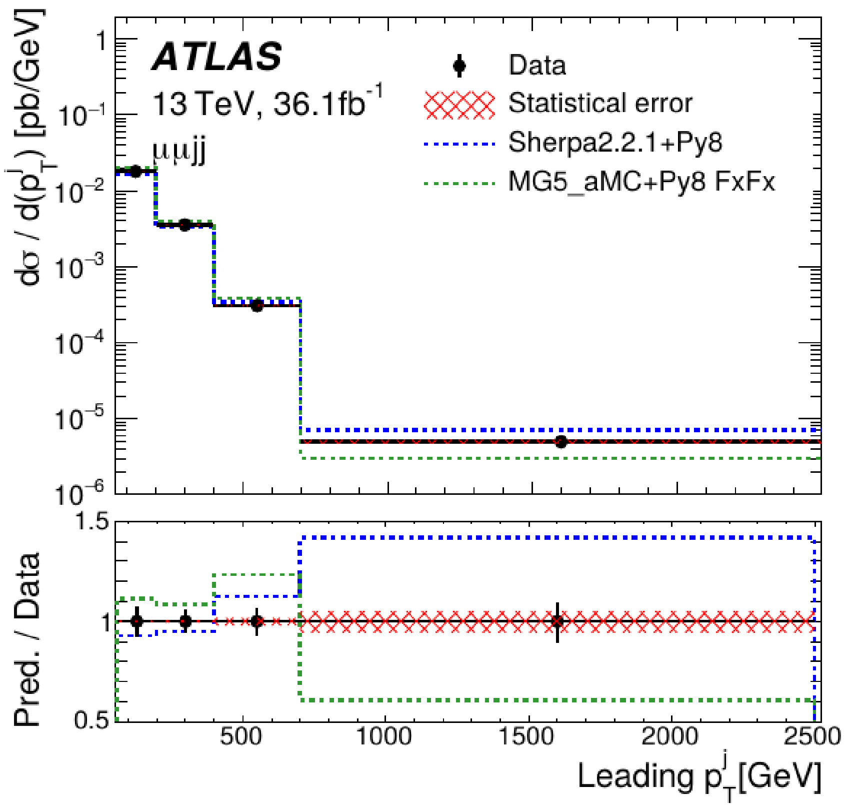
Searches and Unfolding: Z + 2 jets

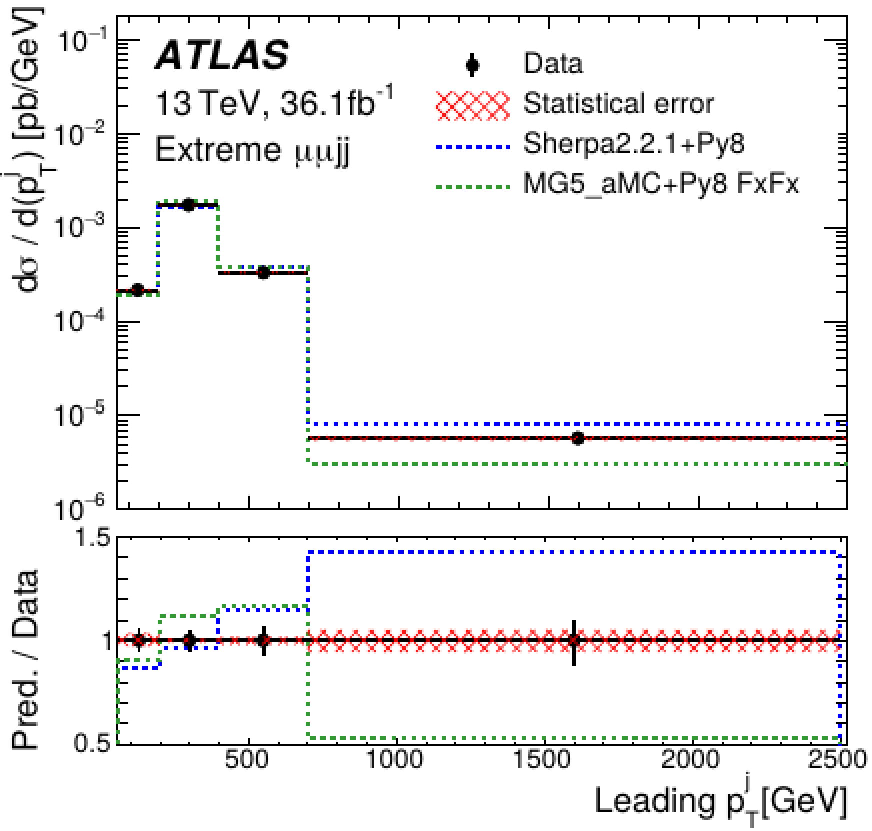
- "Default" MC generators for CMS and ATLAS are NLO+PS (Sherpa 2.2 and MG FxFx)

  Data/MC comparison is remarkably good, although not perfect

- However any residual trend in corners of phase space may mask a BSM signal…
- **Searches (e.g. Z+2jets) now starting to explore *unfolding* of signal-region selections**

Feb. 2019 Result: arXiv:1902.00377



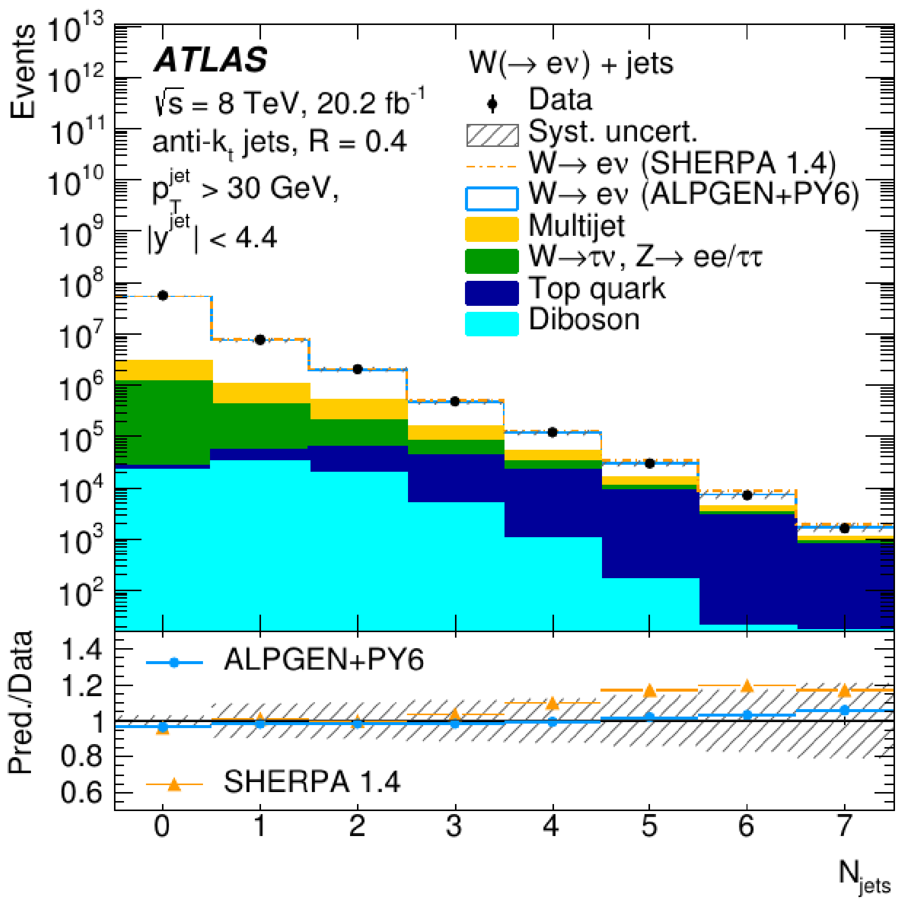


- Model independent test of extreme phase space ⇒ example of S_T>600 GeV selection
- Simple unfolding technique (e.g. bin-by-bin unfolding) but very fast result (*36 fb^{-1}*) !

W+jets Studies at LHC

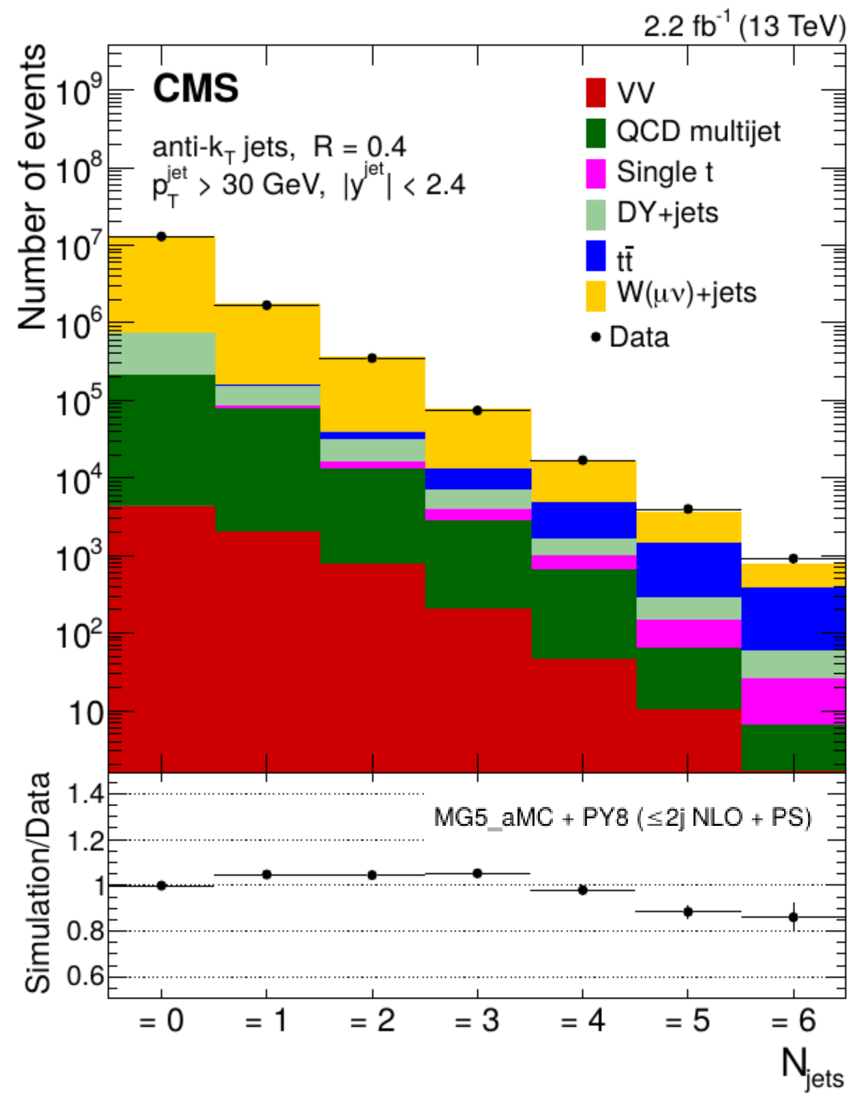
- Analysis is more challenging ⇒ experimental picture more various than Z+jets
- CMS results using 13 TeV 2015 data 2.2 fb^{-1} , jet $|\eta|<2.4$, only muon data
- ATLAS results using 8 TeV 2012 data, 20 fb^{-1}, jet $|Y|<4.4$, only electron data

2018 Result: JHEP05(2018)077



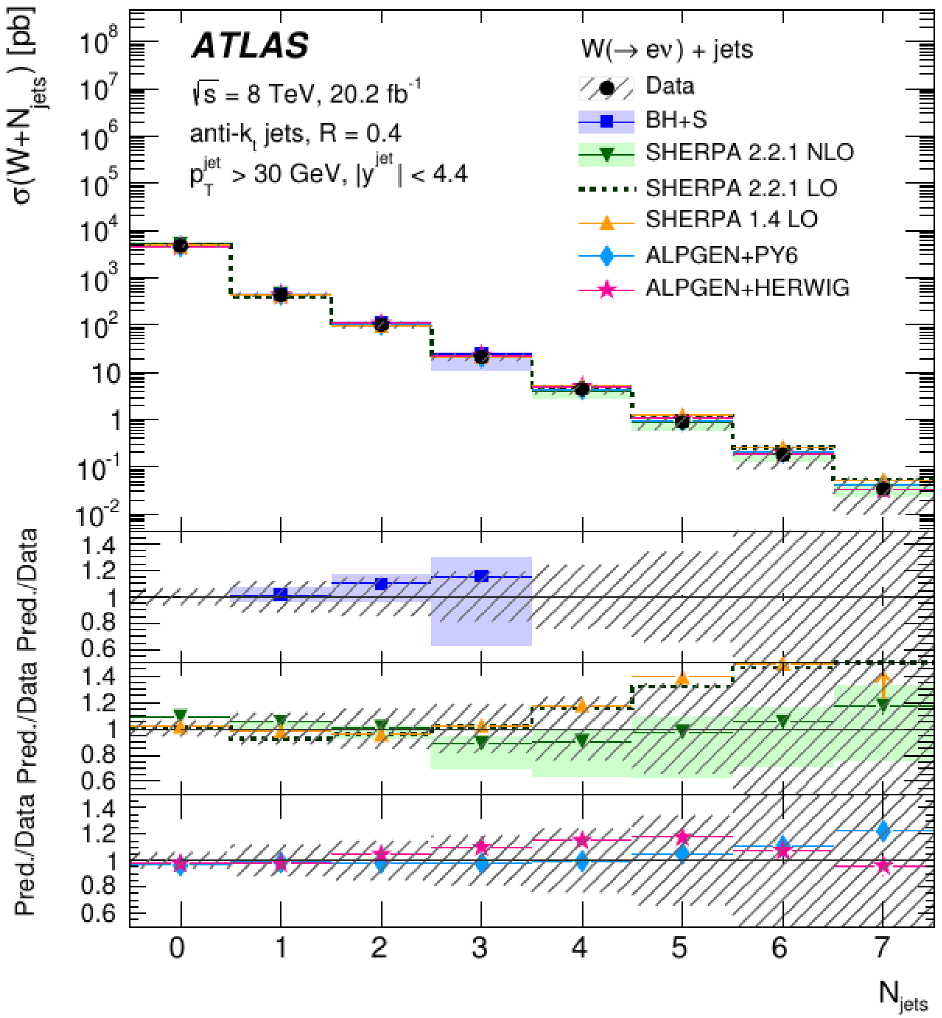
- Nevertheless still similar enough to have a close comparison

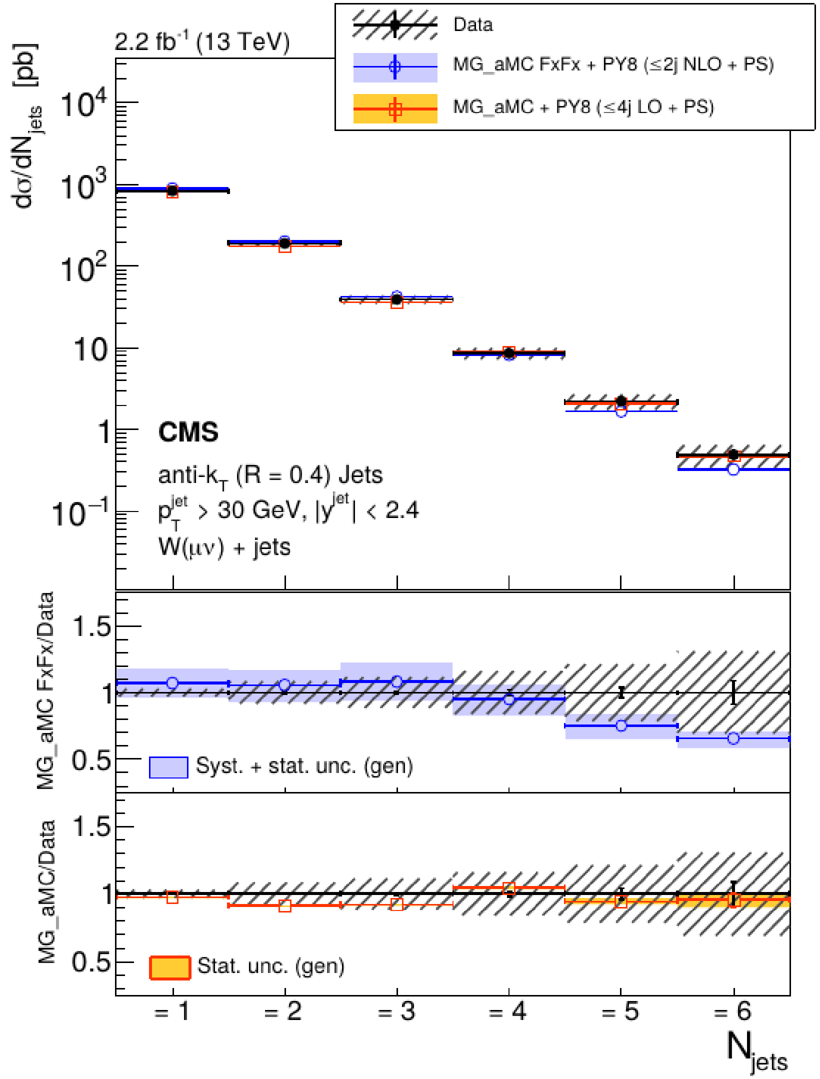
2017 Result: PRD96(2017)072005



W + N-jets Measurements

- Unfolded analysis 40 (ATLAS) 20 (CMS) distributions!



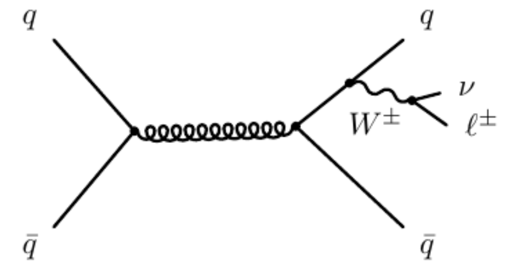


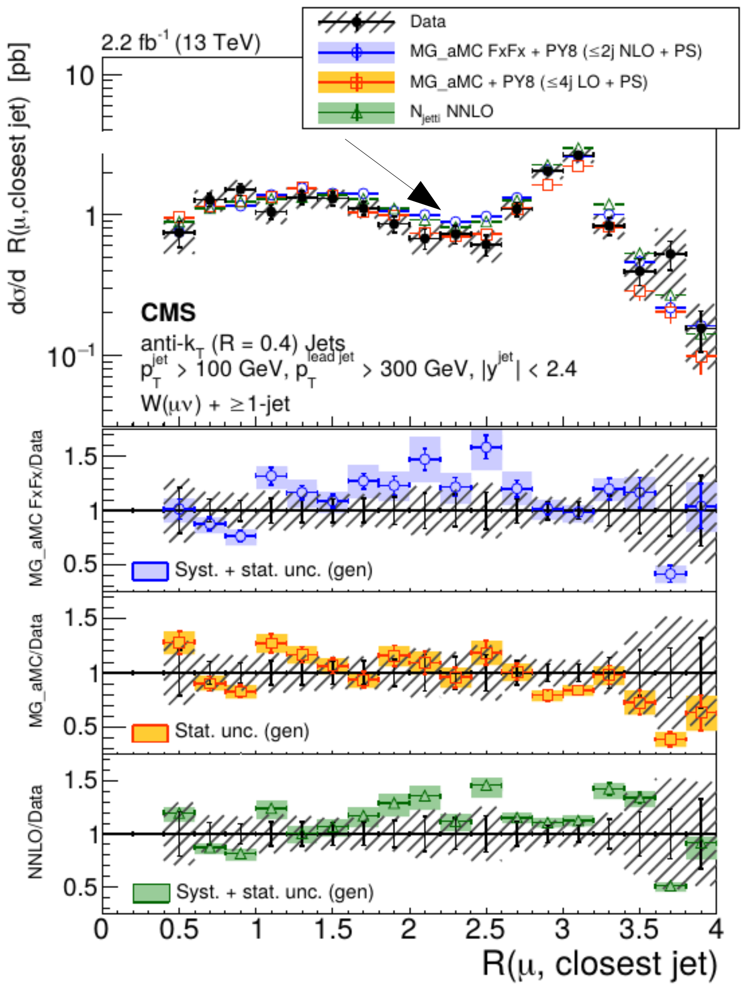
- Also for W, the “exclusive” or “inclusive” jet multiplicities are well reproduced up N~4
- Run 1 JES/JER ATLAS uncertainty larger w.r.t. Run 2, partially from use of |Y|<4.4

Collinear W Emission off high-p_T jets

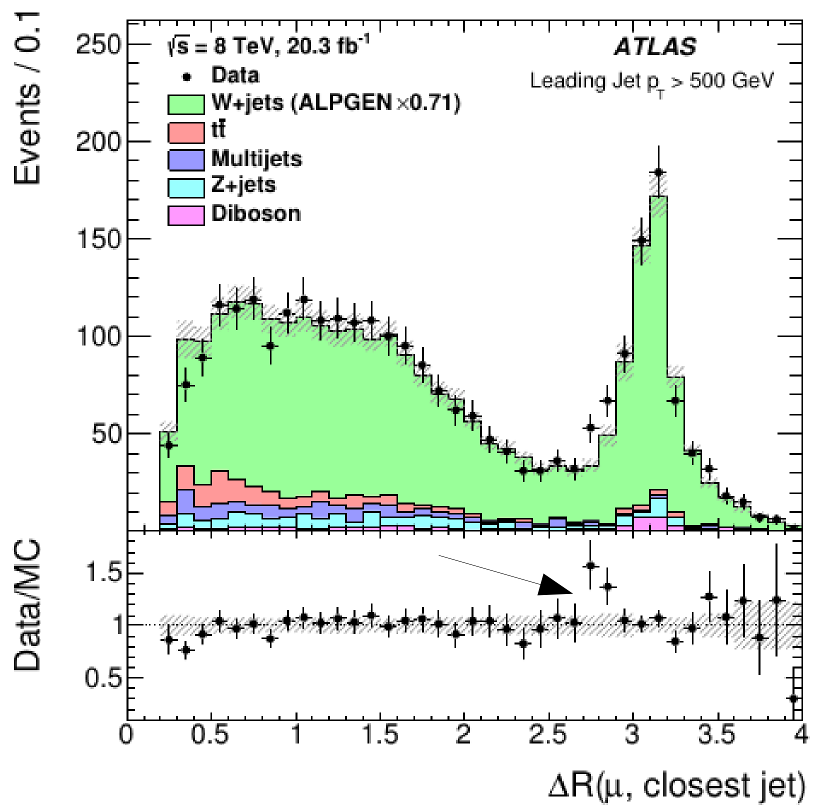
Challenging phase of collinear emission of a W off a jet, accessible thanks to large statistics in W sample

- Requires presence of very high-p_T leading jet (>300-500 GeV)





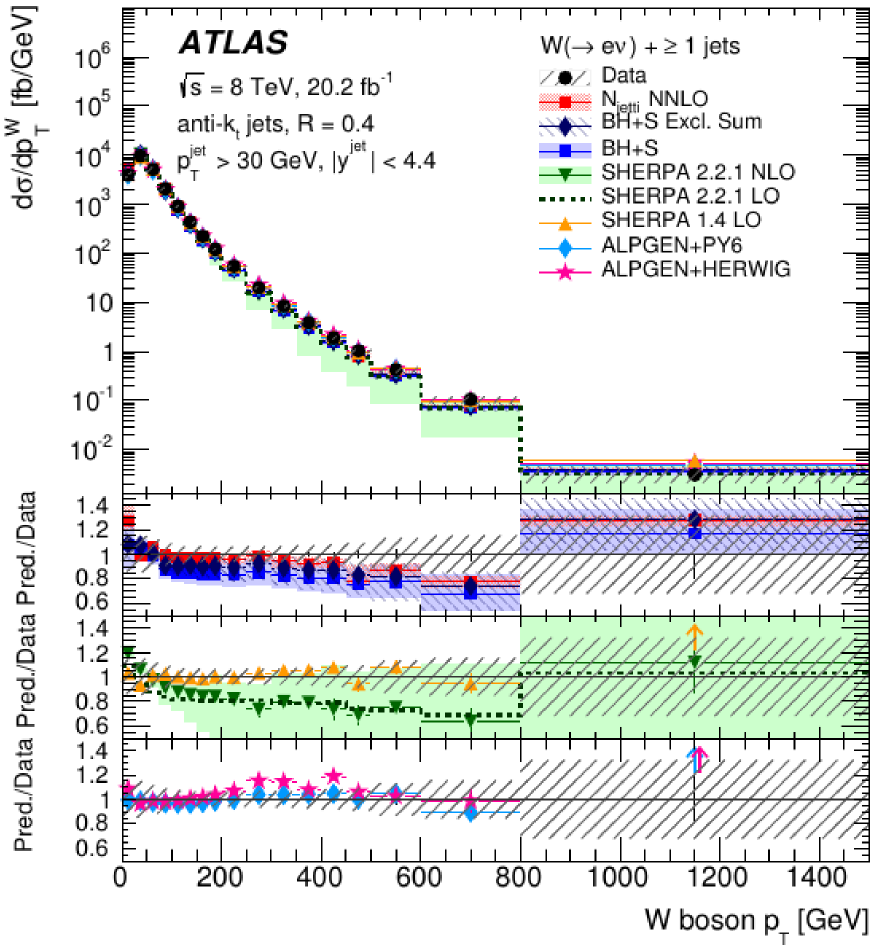
- Dedicated ATLAS Run 1 analysis:

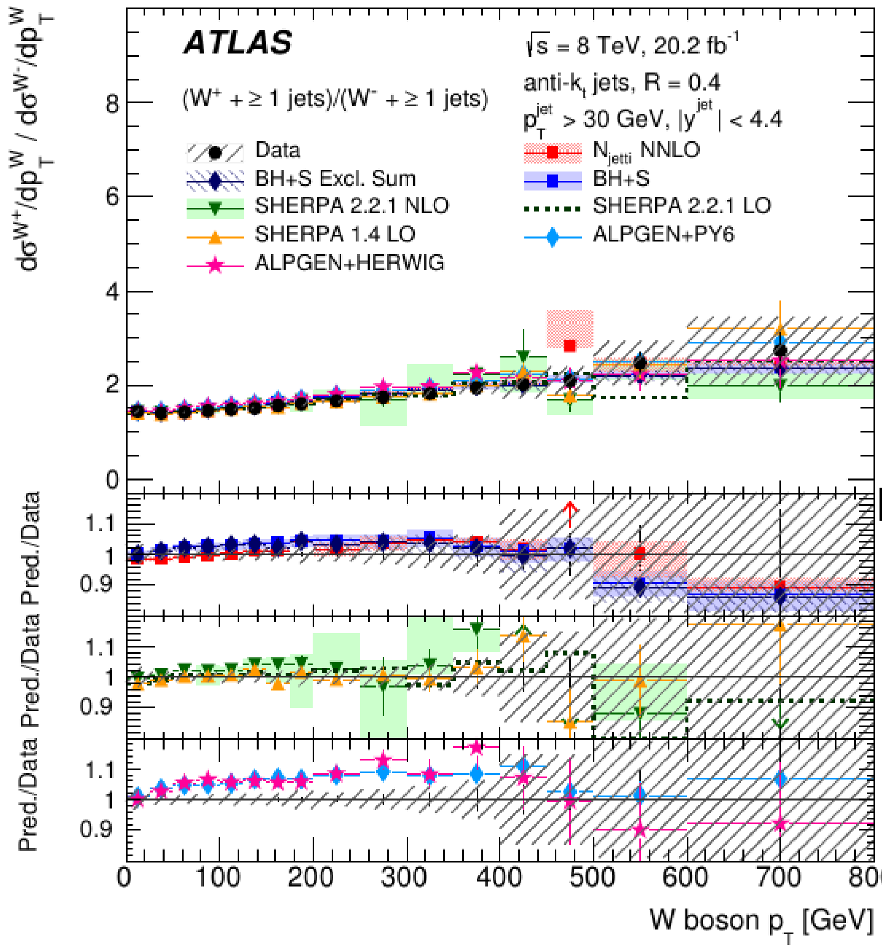


2017 Result: PLB765(2017)132

- Some discrepancy at transition between collinear/standard emission ΔR(μ,j)~2.5
- Origin could be experimental (e.g. angular resolution) or due to MC radiation

W p_T and W^+/W^- Ratio





Different PDFs in ME:

⇒ *NNPDF3.0*

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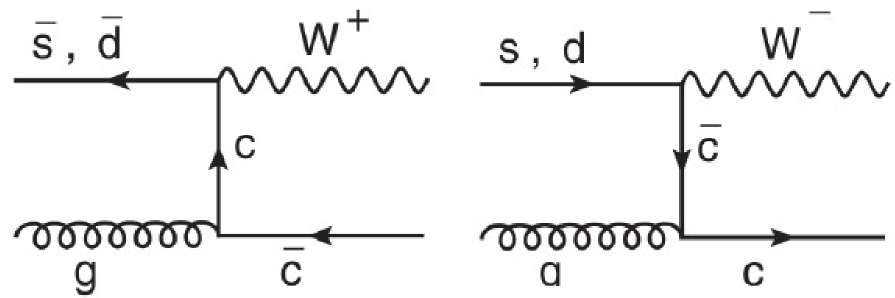
⇒ *CTEQ6L1*

- Challenging to model full spectrum both at low/high W p_T (PS, scale, accuracy, etc.)
- Availability of both W^+ and W^- samples, with their correlations, allows extraction of precise ratio measurements where uncertainties cancel
- Different trends in W^+/W^- ⇒ Hints to sensitivity to different items, e.g. PDF sets

W+Charm Measurement

- W+c-jet can test strange-quark PDF
- Use W vs c-hadron charge correlation
  ⇒ Opposite-Sign (OS) - Same-Sign (SS)
- ***New CMS result with 36 fb^{-1} !***

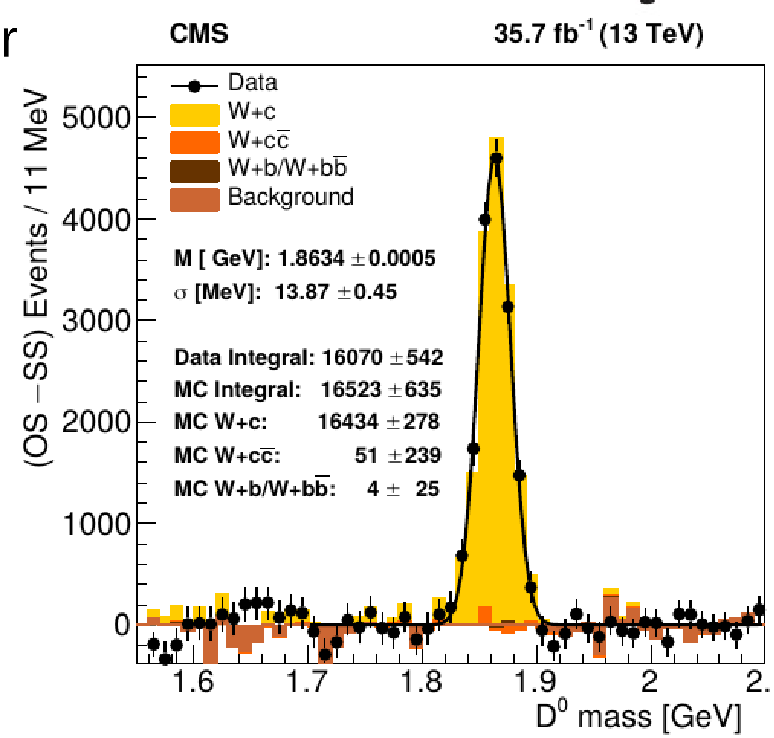
2019 Result: [EPJC79(2019)269]

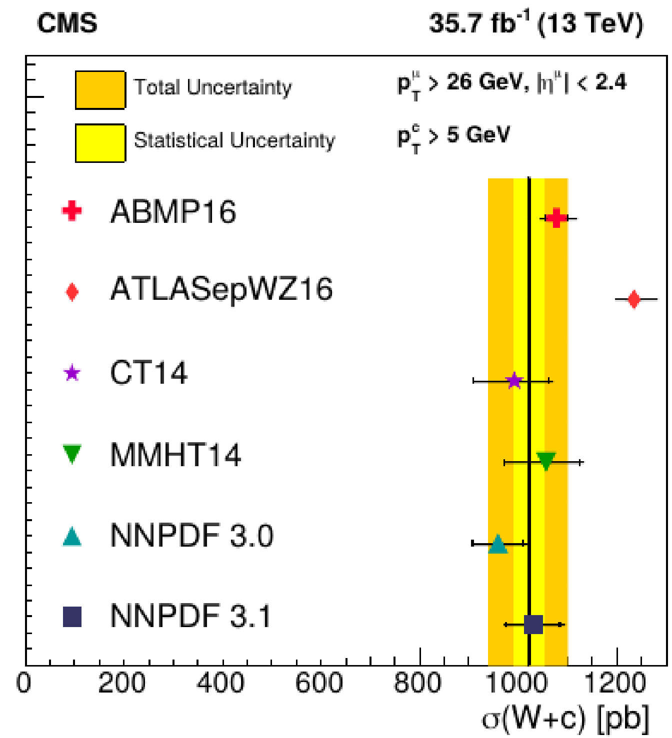


- Uses D-meson decay and mass reconstruction for pure selection

  $D^*(2010)^{\pm} \rightarrow$
  $D^0 + \pi^{\pm}_{slow} \rightarrow$
  $K^{\mp}+\pi^{\pm}+\pi^{\pm}_{slow}$

- Extrapolation factor (~10) between W+D and W+c-quarks production

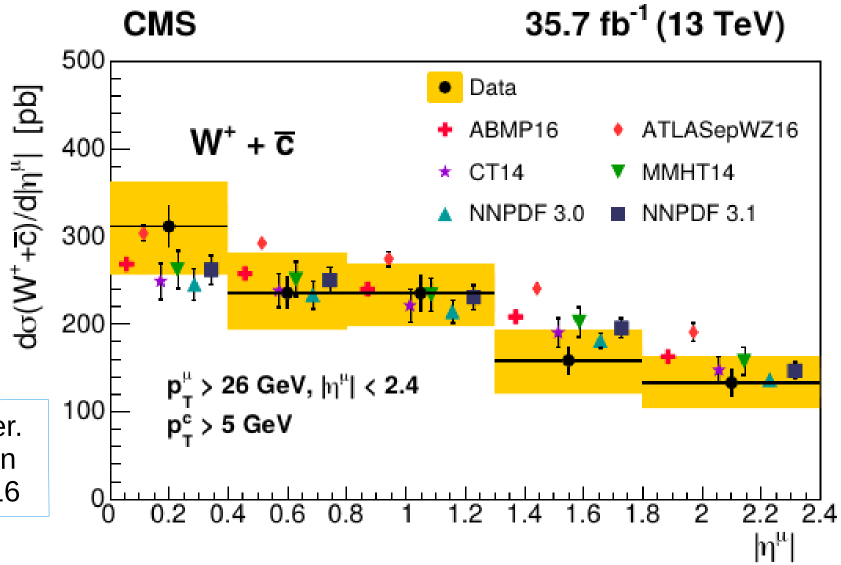




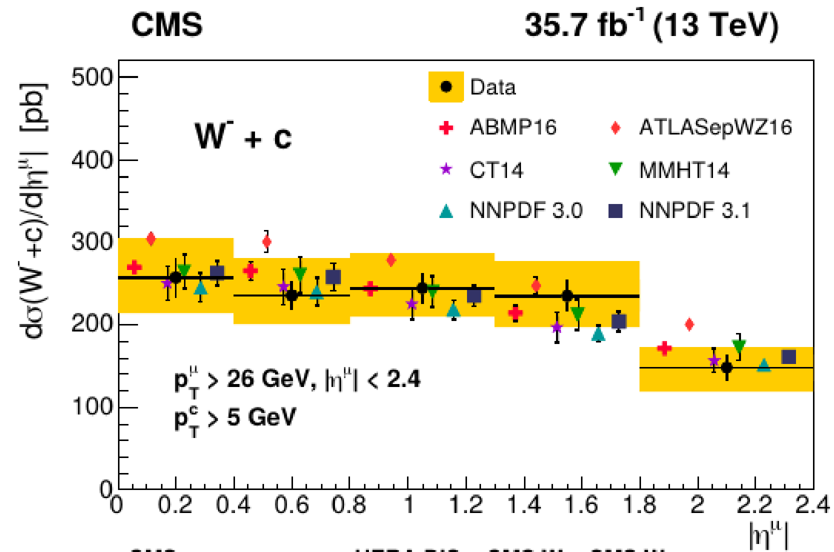
- Data driven W+LF background, other bkgs and extrapolation factors based on MC
- Other results at 7 TeV: CMS [PRD90(2014)032004] ATLAS [JHEP05(2014)068]

W+Charm PDF Analysis

- Bin-by-bin unfolded $|\eta_\mu|$ in agreement with most PDF sets
- Tension with *ATLASepWZ16* PDF set where strange-quark is not suppressed



NB: No parameter. uncertainty shown on ATLASepWZ16

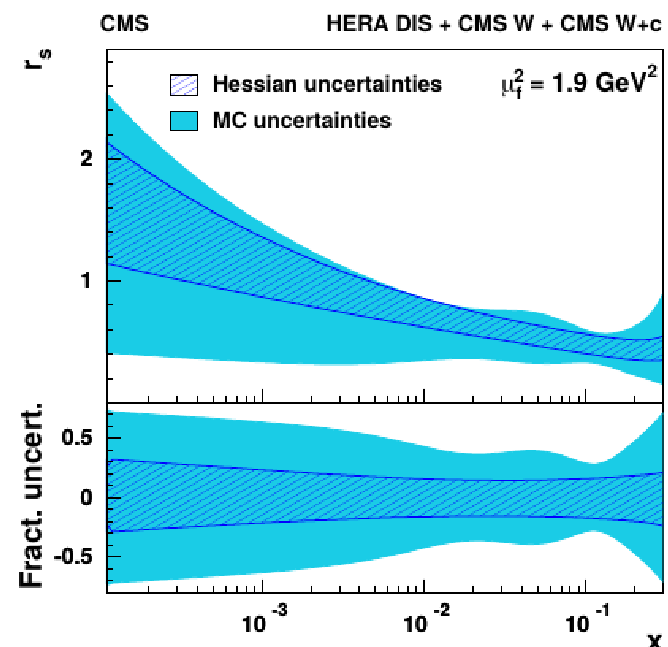


Performed full QCD analysis at NLO:

- HERA DIS, CMS W-asymmetry at 7 TeV and 8 TeV, CMS W+c at 7 TeV, **and 13 TeV**
- Strangeness suppression factor R_s (or r_s):

$$R_s = \frac{s + \bar{s}}{\bar{u} + \bar{d}}$$

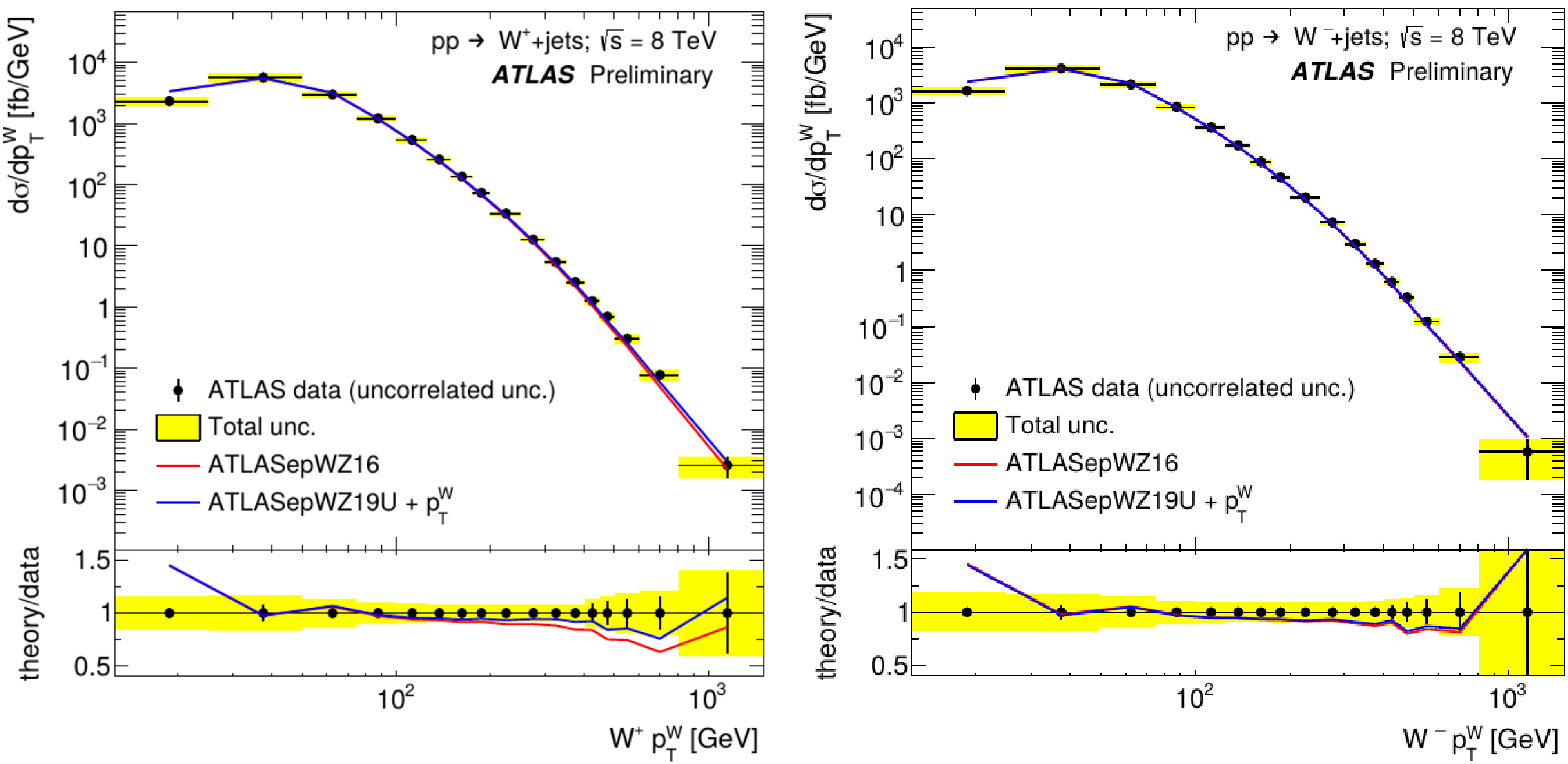
- In agreement with strangeness "suppression" observed in neutrino scattering experiments



Additional PDF Studies with W+jets

- *ATLASepWZ16* PDFs derived using W, Z 7 TeV ATLAS data (EPJC77(2017)367)
  - ⇒ Can W+jets data, and its sensitivity to PDFs, be of help?
- ***New ATLAS QCD analysis hot from the press:*** **ATL-PHYS-PUB-2019-016**
- At **NNLO**, new parameterization, including W,Z 7 TeV, HERA, and *W+jets 8 TeV*

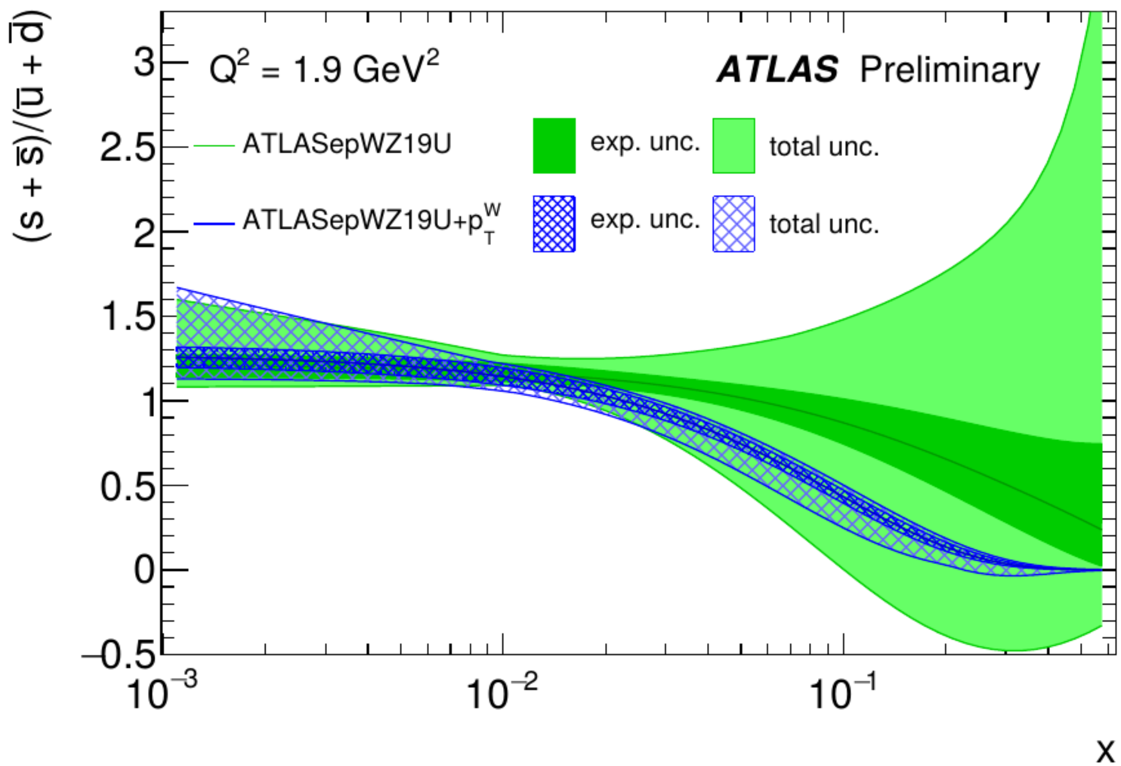
2019 Result: ATL-PHYS-PUB-2019-016

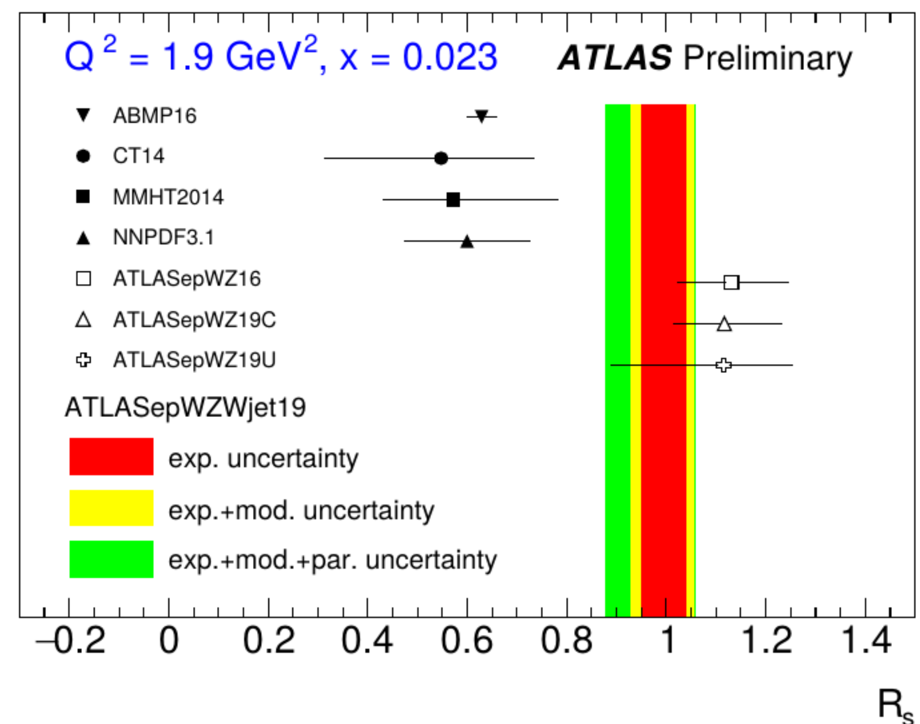


- *W^+ and W^- W-p_T 8 TeV data shows good constraining power on high-x sea-quark*

PDF Interpretation

- New PDF set has been derived and is now public ⇒ ***ATLSepWZWjet19***
- Consistency test using new/old extraction method vs with/without W p_T shows importance W+jet data ⇒ *greatly reduced model uncertainty!*
- R_s reduced at higher x (w.r.t. ATLASep2016) but still enhanced at low x!





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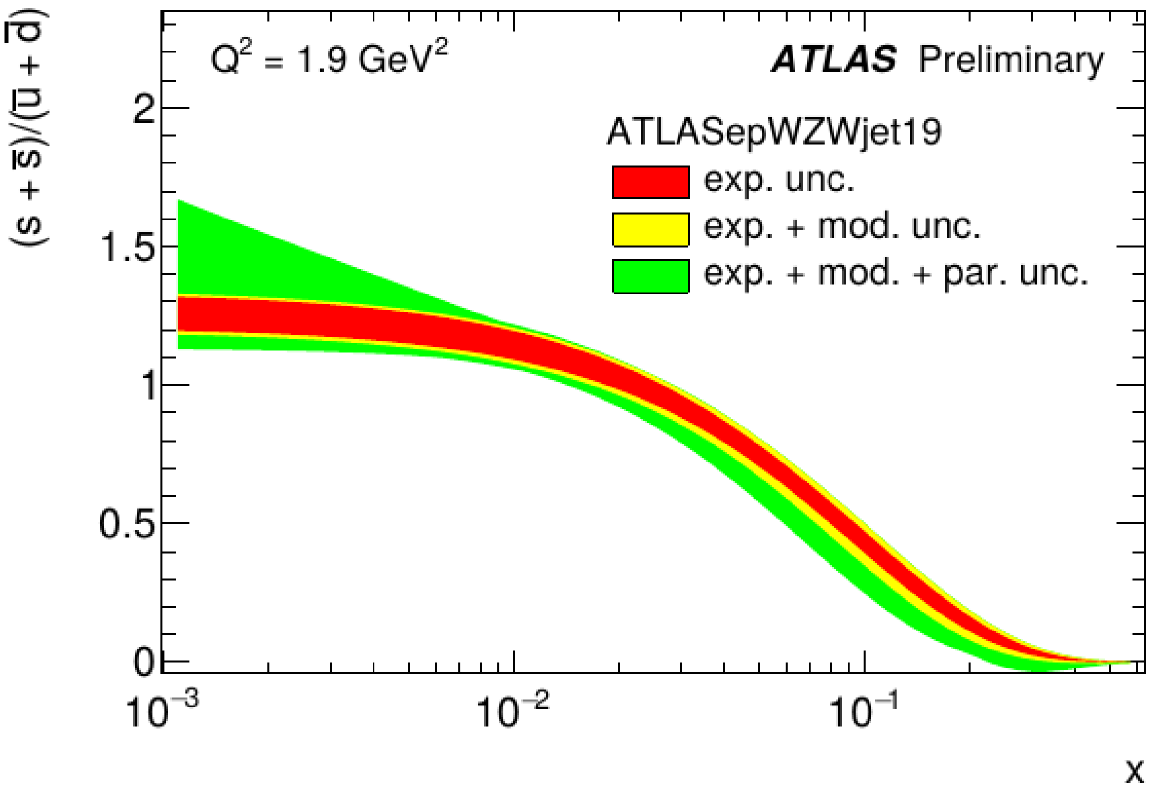
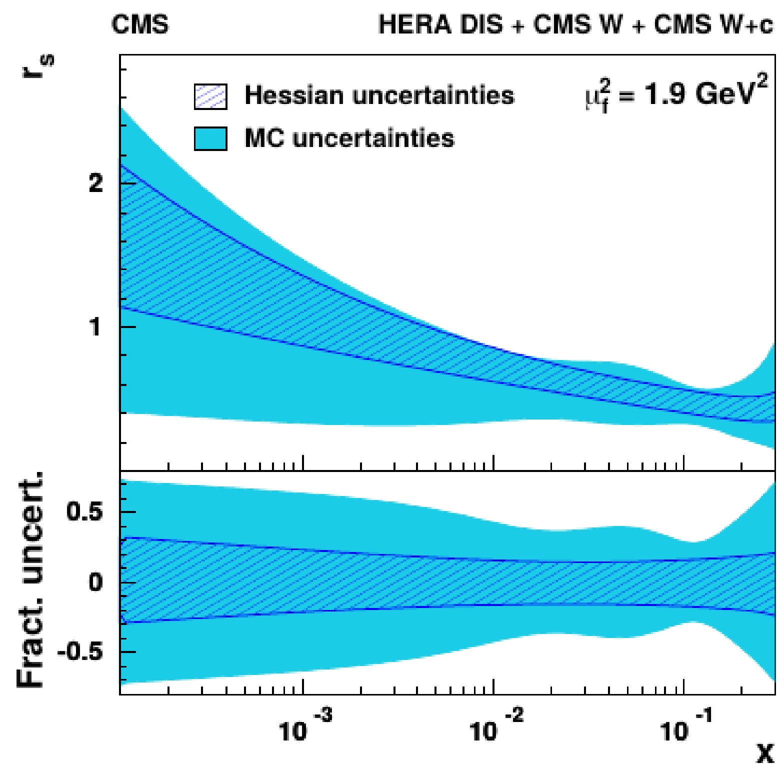
- Comparison against CMS is not trivial (NLO vs NNLO, parameteriz., etc,)





- **Tension is reduced…** ***probably not yet final answer about strangeness!***

Conclusions and Summary

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

- Improve understanding of perturbative QCD
- Test MC modeling for observables used in analyses and searches
- Provide an important handle to constraint proton PDFs

ATLAS and CMS are providing many fiducial cross sections and differential unfolded measurements compared to a variety of predictions and generators:

- *Remarkable agreement for many distribution but none is yet perfect, nevertheless the unprecedented accuracy today available*
- *Some tensions are present between experiments and against predictions ⇒ can be understood thanks to better and more precise measurements*
    - ***Stay tuned for the many more results in preparation!***

A complete set of V+jets (and more) SM measurements is available at:

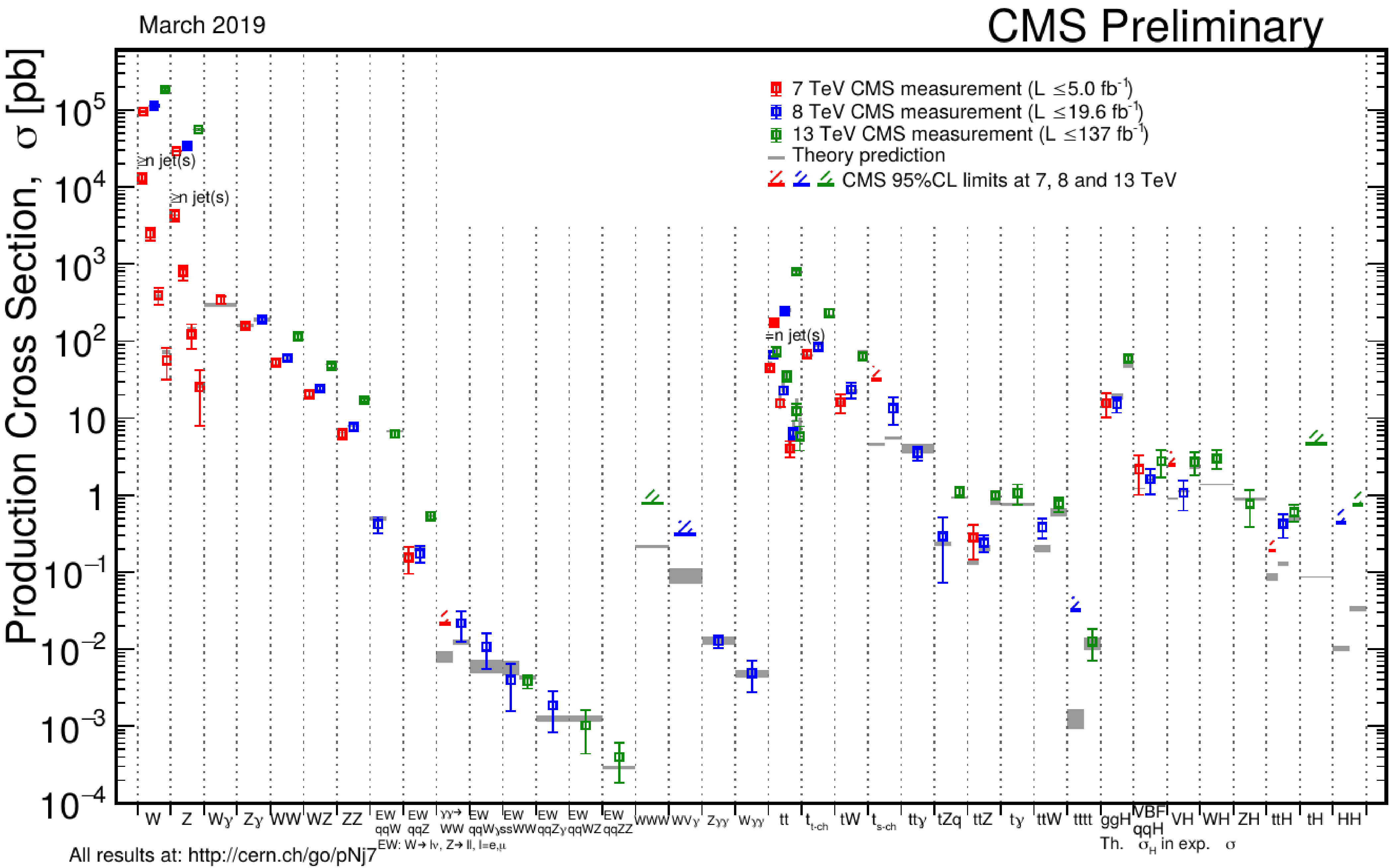
- https://twiki.cern.ch/twiki/bin/view/AtlasPublic/StandardModelPublicResults
- http://cms-results.web.cern.ch/cms-results/public-results/publications/SMP/index.html
- http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/SMP/index.html

Backup

Available V+jets Predictions

Type of Prediction	MCs & Calculations “label”	Usage & Notes
multi-partons (Np) LO ME+PS	**Sherpa 1.X**: LO up to Np = 4	Wide use in ATLAS Run 1
	Madgraph5: up to Np = 4, allows different merging schemes (e.g. CKKW-L or MLM)	Wide use in CMS Run 1
	ALPGEN: up to Np = 5, MLM merging	Run 1 (and Run 2)
multi-parton (Np) NLO and LO ME+PS	**Madgraph5**: aMC@NLO: NLO up to Np = 2, FxFx merging	CMS Run 2 “Standard”
	Sherpa 2.X: NLO up to Np = 2, LO up to Np =4, includes PS merging	ATLAS Run 2 “Standard”
	Powheg: NLO Np = 1	Tested by ATLAS and CMS
Fixed order calculation	**BlackHat+Sherpa**: NLO up to Np = 5)	Tested in Run 1 & 2 (both ATLAS and CMS)
	N-Jettiness: full NNLO QCD	*Tested for fist time in Run 2*
NNLO+PS	**GENEVA**: NNLO+ partial N^3LL + PY8	*Tested for fist time in Run 2*

CMS Result Summary

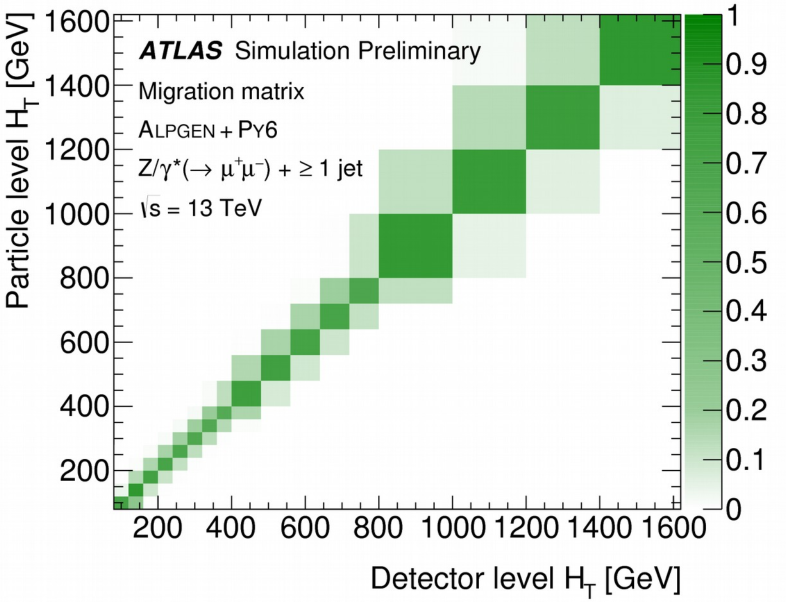


Bayesian Iterative Unfolding

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



Extract *"prediction-unbiased"* probability with iterative Bayesian unfolding:

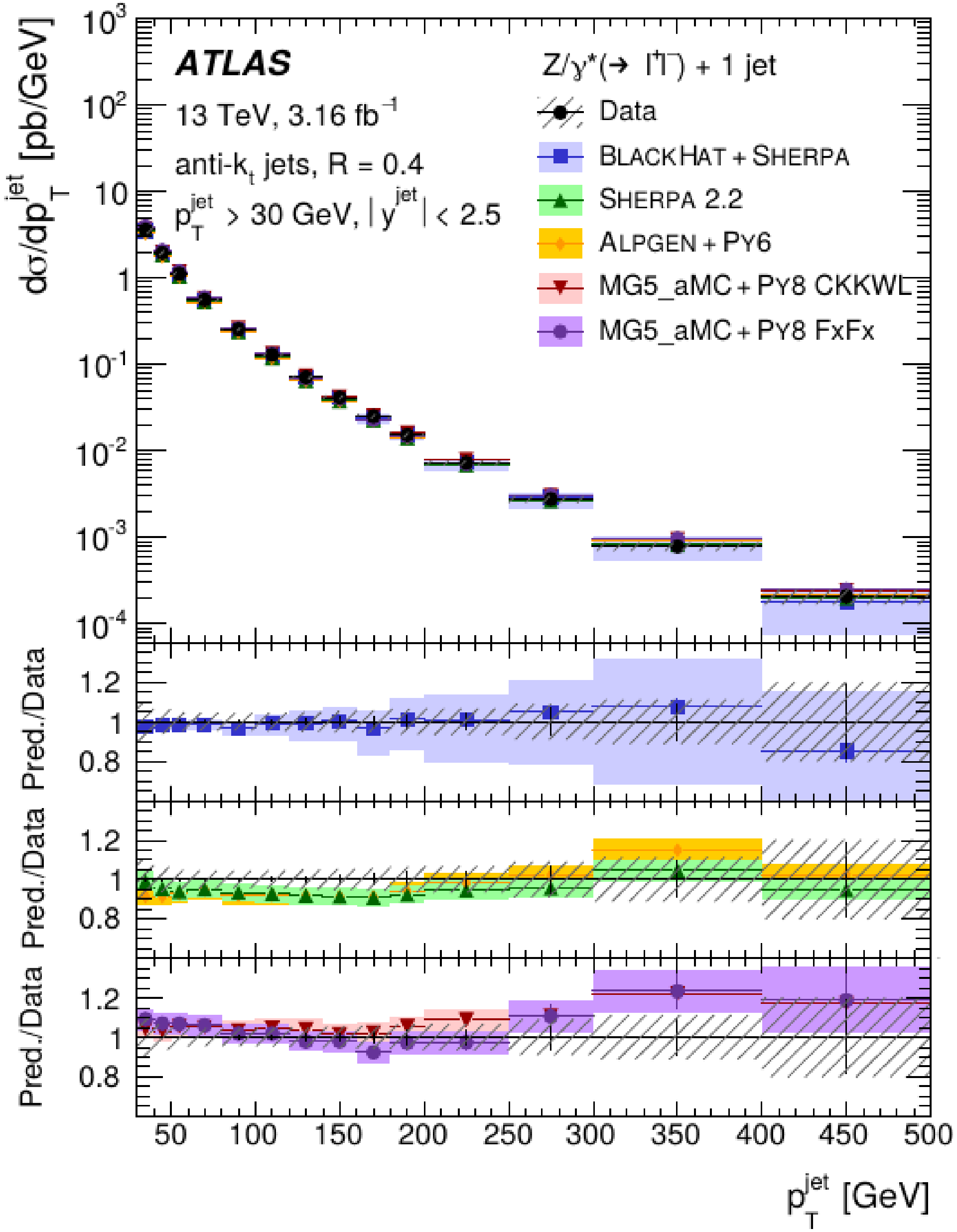
- Bayes theorem:

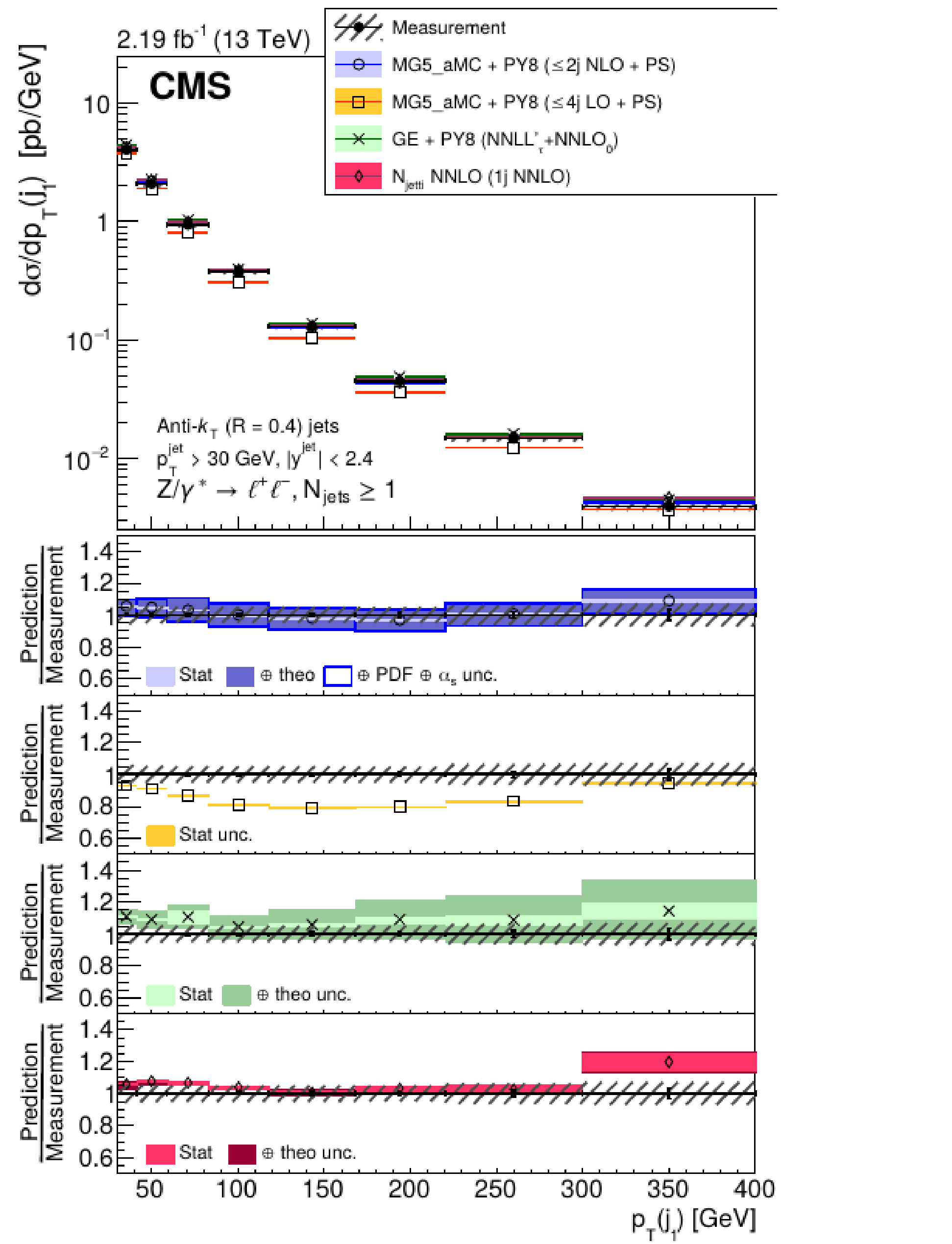
$$M(T_i|R_j) = M(R_i|T_j)\ P_0(T_j)\ /\ \mathrm{Sum}_l\ \ M(R_i|T_l)\ P_0(T_l)$$

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

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

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


ATLAS
13 TeV, 3.16 fb^{-1}
anti-k_t jets, R = 0.4
p_T^{jet} > 30 GeV, $|y^{jet}|$ < 2.5
$Z/\gamma^*(\rightarrow l^+l^-)$ + 1 jet
Data
BLACKHAT + SHERPA
SHERPA 2.2
ALPGEN + PY6
MG5_aMC + PY8 CKKWL
MG5_aMC + PY8 FxFx
$d\sigma/dp_T^{jet}$ [pb/GeV]
Pred./Data
p_T^{jet} [GeV]


2.19 fb^{-1} (13 TeV)
CMS
Measurement
MG5_aMC + PY8 (≤2j NLO + PS)
MG5_aMC + PY8 (≤4j LO + PS)
GE + PY8 (NNLL'$_\tau$+NNLO$_0$)
N$_{jetti}$ NNLO (1j NNLO)
Anti-k_T (R = 0.4) jets
p_T^{jet} > 30 GeV, $|y^{jet}|$ < 2.4
$Z/\gamma^* \rightarrow \ell^+\ell^-$, $N_{jets} \geq 1$
$d\sigma/dp_T(j_1)$ [pb/GeV]
Prediction / Measurement
Stat ⊕ theo ⊕ PDF ⊕ α_s unc.
Stat unc.
Stat ⊕ theo unc.
Stat ⊕ theo unc.
$p_T(j_1)$ [GeV]

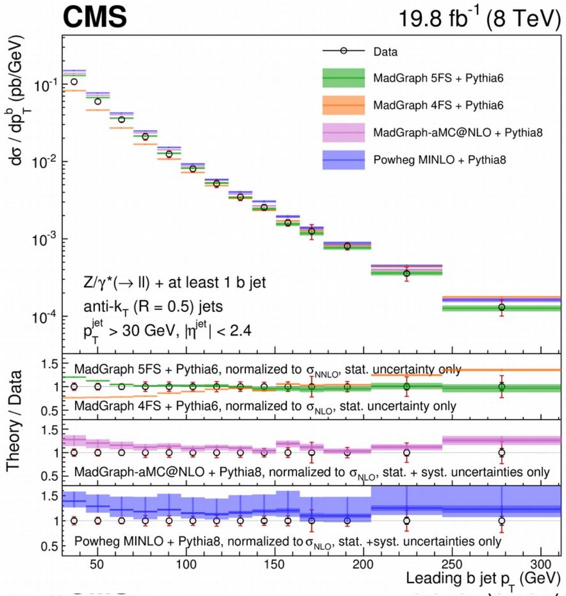
Z+b(b) Kinematics in Run I

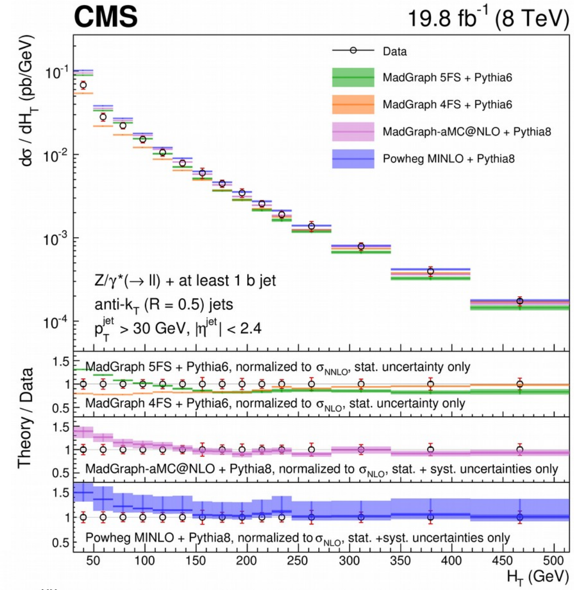
Unfolded differential distributions and ratio of distributions with respect to generic jets!

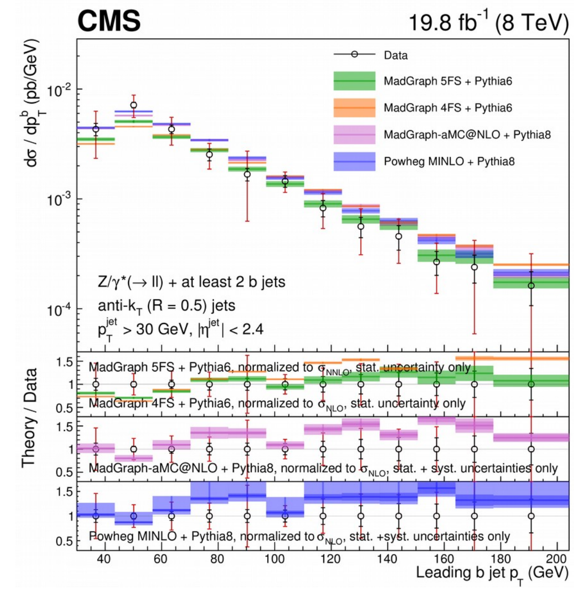
EPJC77(2017)751

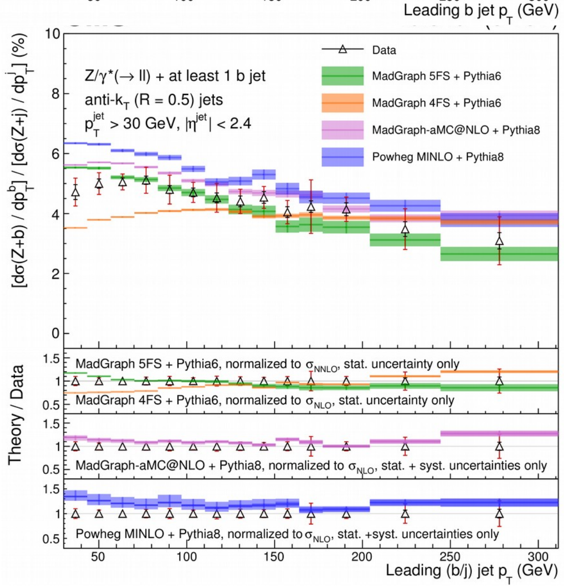
Z+b and Z+b/Z+jets

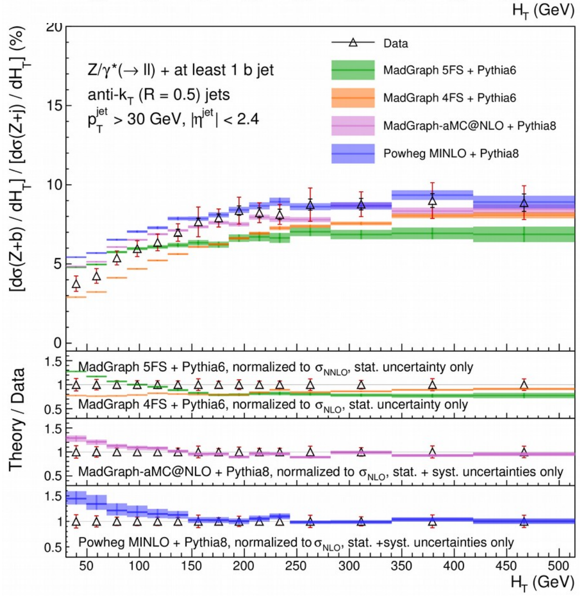
Z+bb

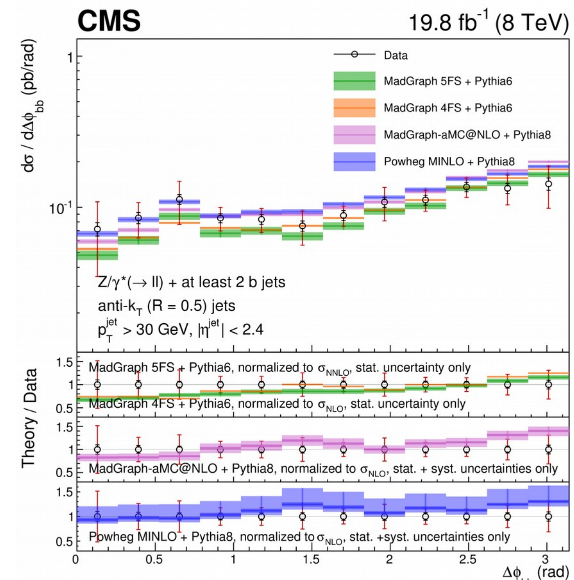








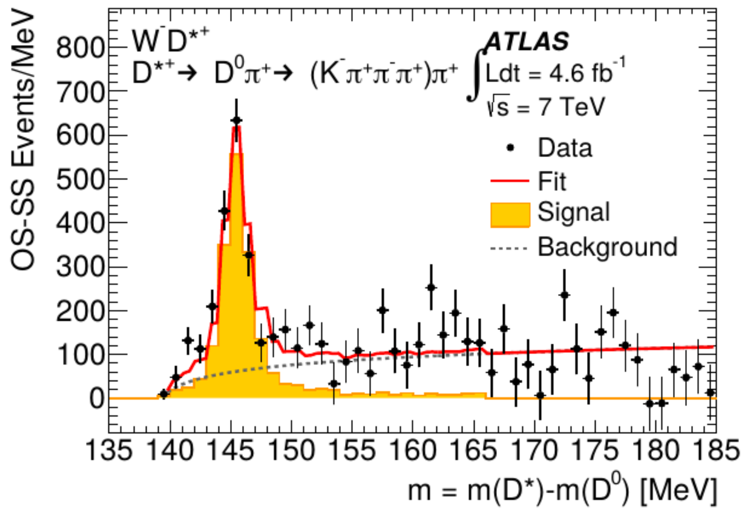




- Different flavor scheme predictions can predict correctly only part of the distributions

W+D* comparison

- Good precision of ATLAS W+D 7 TeV (**JHEP05(2014)068**) but not used in PDF fits



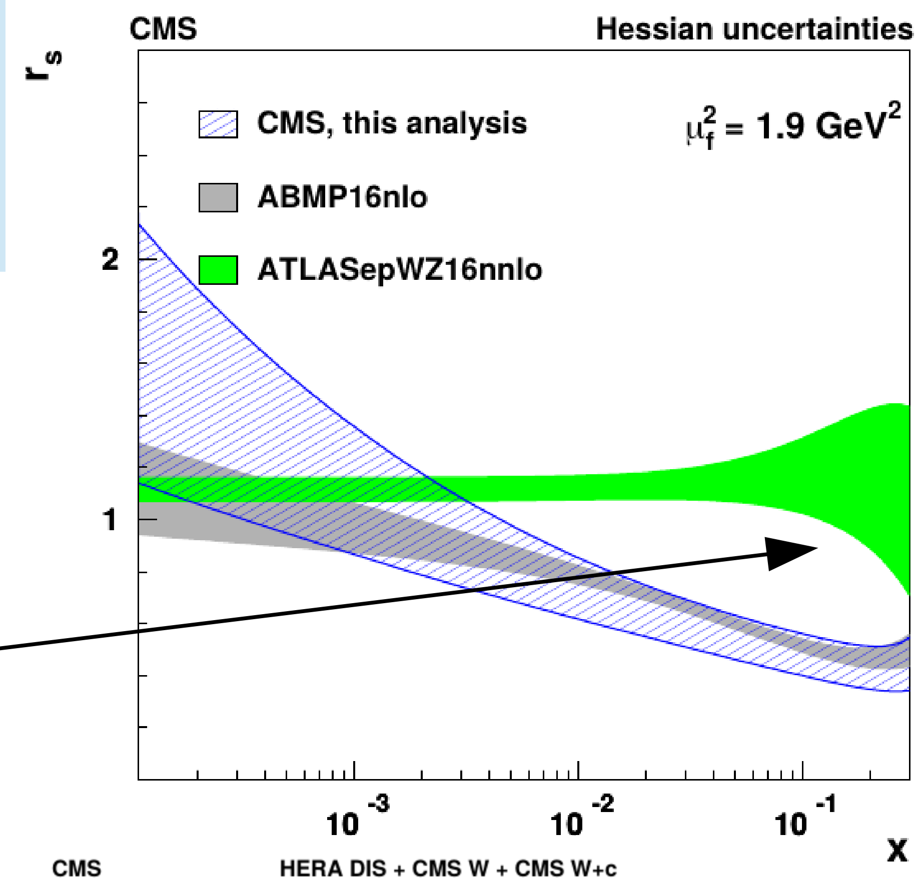
Relative systematic uncertainty in %	WD	WD^*
Lepton trigger and reconstruction*	0.4	0.4
Lepton momentum scale and resolution*	0.2	0.2
Lepton charge misidentification	0.1	0.1
E_T^{miss} reconstruction*	0.4	0.4
W background estimation	1.3	1.3
Background in $WD^{(*)}$ events	0.7	0.6
W efficiency correction	0.6	0.6
Tracking efficiency	2.1	2.2
Secondary vertex reconstruction efficiency	0.4	0.4
D^* isolation efficiency	-	2
Fitting procedure	0.8	0.5
Signal modelling	1.4	1.9
Statistical uncertainty on response	0.2	0.2
Branching ratio	2.1	1.5
Extrapolation to fiducial region	0.8	0.8
Integrated luminosity*	1.8	1.8
Total	4.3	4.8

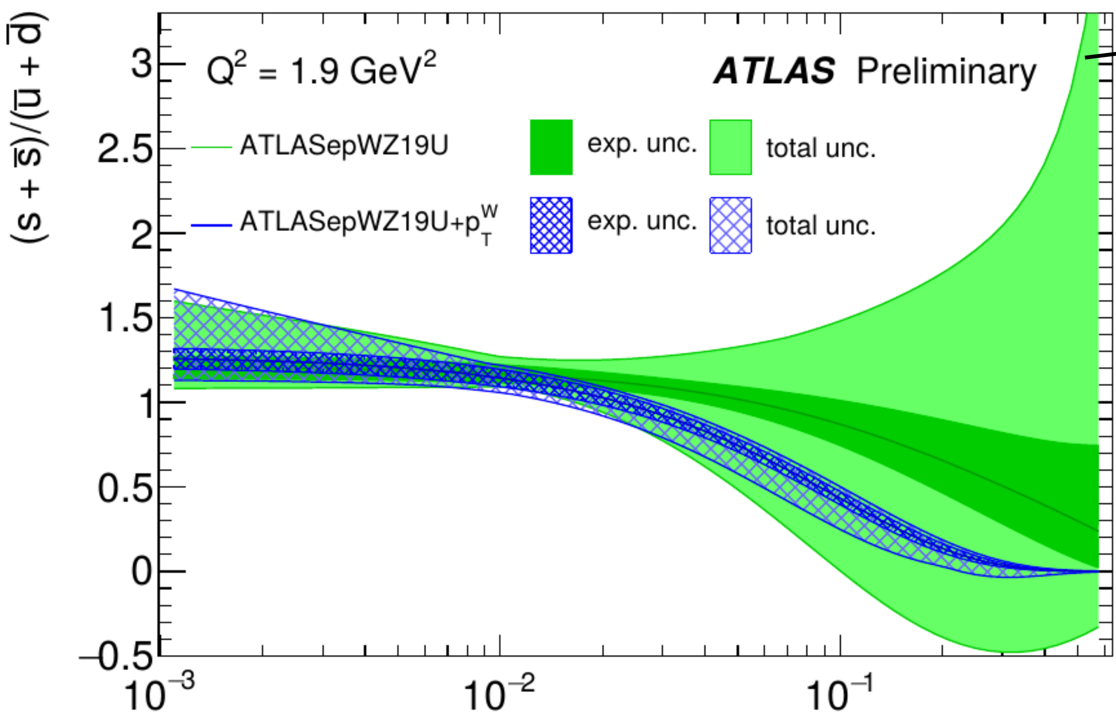
- CMS 13 TeV W+D* systematic uncertainties

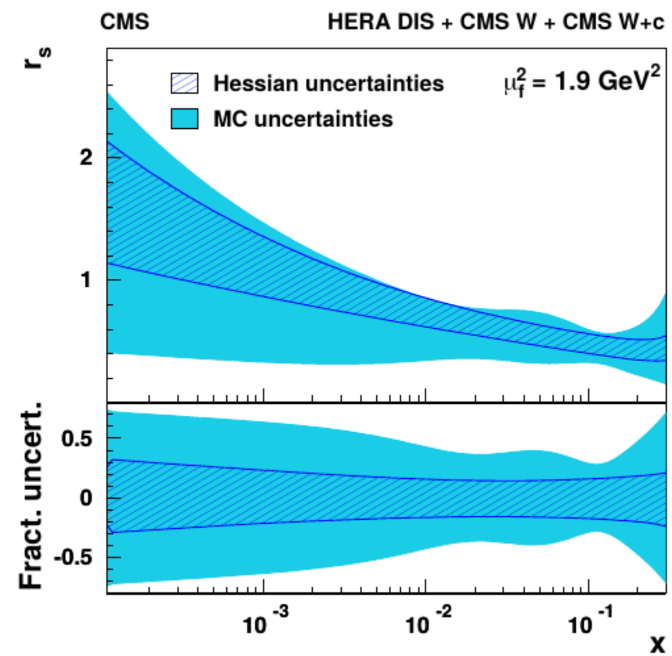
Pseudorapidity $[\|\eta^\mu\|]$	[0, 2.4]	[0, 0.4]	[0.4, 0.8]	[0.8, 1.3]	[1.3, 1.8]	[1.8, 2.4]
Luminosity	±2.5	±2.5	±2.5	±2.5	±2.5	±2.5
Tracking	±2.3	±2.3	±2.3	±2.3	±2.3	±2.3
Branching	±2.4	±2.4	±2.4	±2.4	±2.4	±2.4
Muons	±1.2	±1.2	±1.2	±1.2	±1.2	±1.2
N_{sel} determination	±1.5	±1.5	±1.5	±1.5	±1.5	±1.5
$D^*(2010)^\pm$ kinematics	±0.5	±0.5	±0.5	±0.5	±0.5	±0.5
Background normalization	± 0.5	+0.9/−0.8	+1.9/−0.8	+1.4/−0.5	+0.8/−1.0	0.0/−0.6
$\vec{p}_T^{miss}$	+0.7/−0.9	+0.4/−1.2	+1.3/−0.3	+1.1/−1.0	0.0/−2.6	0.0/+1.5
Pileup	+2.0/−1.9	+0.4/−0.5	+2.9/−3.0	+2.0/−1.9	+4.6/−5.1	+2.7/−2.6
Secondary vertex	−1.1	+1.3	−1.2	−1.5	−2.7	−2.5
PDF	±1.2	±1.3	±0.9	±1.4	±1.5	±1.7
Fragmentation	+3.9/−3.2	+3.4/−1.8	+7.4/−5.2	+3.3/−3.0	+2.2/−1.2	+7.4/−5.7
MC statistics	+3.6/−3.3	+8.8/−7.5	+9.0/−11.9	+7.9/−6.8	+9.8/−14.1	+10.1/−8.5
Total	+7.5/−7.0	+10.7/−9.3	+13.2/−14.2	+10.1/−9.3	+12.7/−16.2	+13.8/−12.1

s-quark Suppression Comparison

- Parameterization uncertainties have large impact on ATLASepWZ16nlo (similar to ATLASepWZ19U)
- Underestimate of ATLASepWZ16nlo uncertainties in CMS comparison

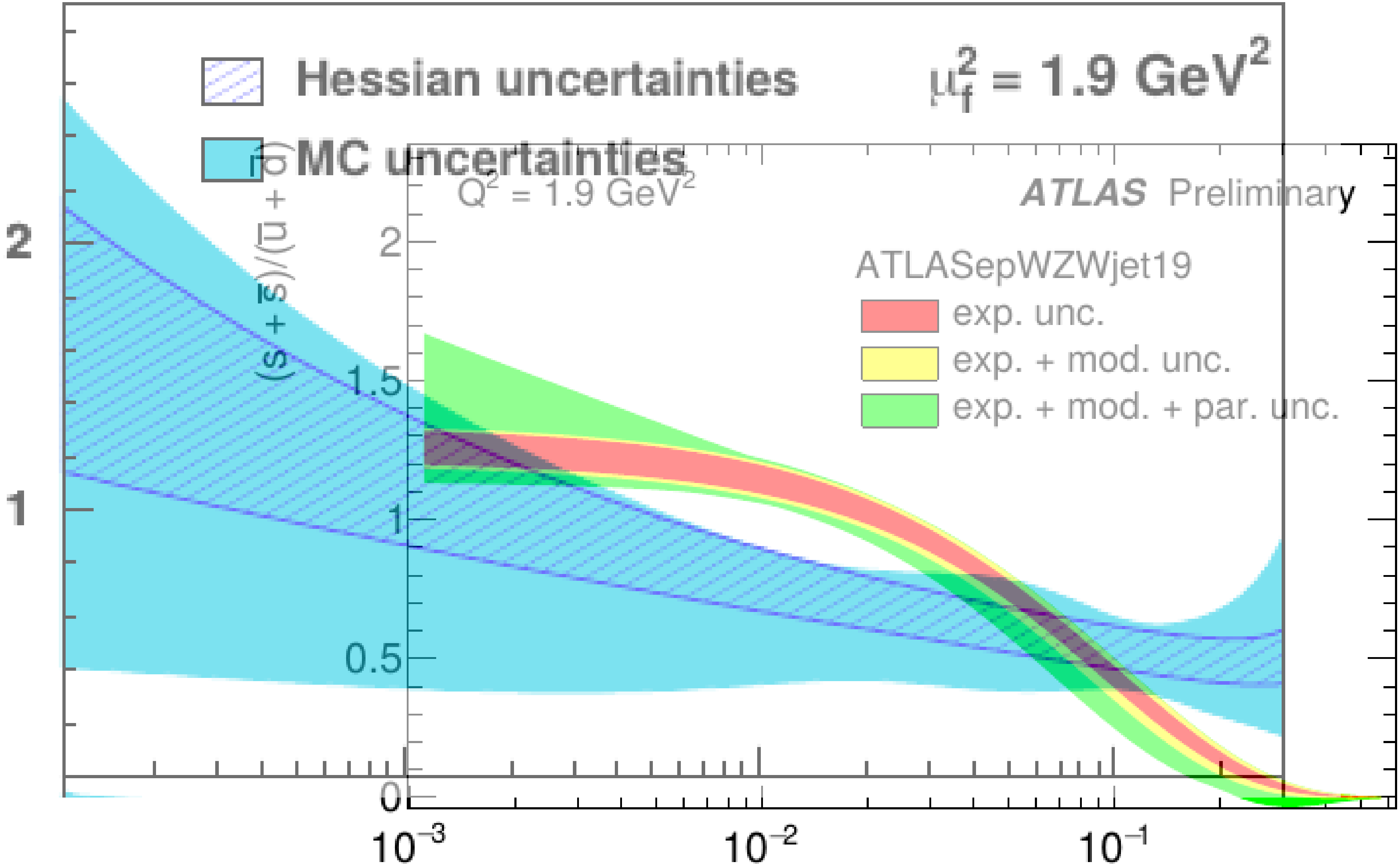






- Important reduction of uncertainties at high-x because of new W-p_T data from ATLAS W+jets

Strangeness Suppression



NB: Many many caveats in this comparison!

Different parameterization, different accuracy in QCD analysis, etc.