Measurements of the Vector boson production with the ATLAS Detector

Kostas KORDAS

Aristotle University of Thessaloniki

ARISTOTLE UNIVERSITY OF THESSALONIKI

ATLAS EXPERIMENT

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http://indico.cern.ch/event/icnfp2017

Outline

- The electroweak sector of the Standard Model can be tested by precision measurements of fundamental parameters, such as the W boson mass (**m_W**) and the electroweak mixing angle (**$\sin^2\theta_W$**)
- Precise cross section measurements of W and Z production also constrain the PDFs and are sensitive probes of higher order QCD

In this talk:

- **W mass** : arXiv : 1701.07240 (submitted to EPJC)
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/STDM-2014-18/
- **$W^{+/-}$ and Z cross sections** : Eur. Phys. J. C77 (2017) 367
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/STDM-2012-20/
- **Z + jets** : Eur. Phys. J. C77 (2017) 361
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/STDM-2016-01/
- **kt splitting scales in Z events** : arXiv:1704.01530 (submitted to JHEP)
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/STDM-2015-14/
- **Z/γ* triple differential cross section**: to be submitted soon

1. W mass measurement

"Measurement of the W-boson mass in pp collisions at $\sqrt{s}$ = 7 TeV with the ATLAS detector"

arXiv : 1701.07240 (submitted to EPJC)

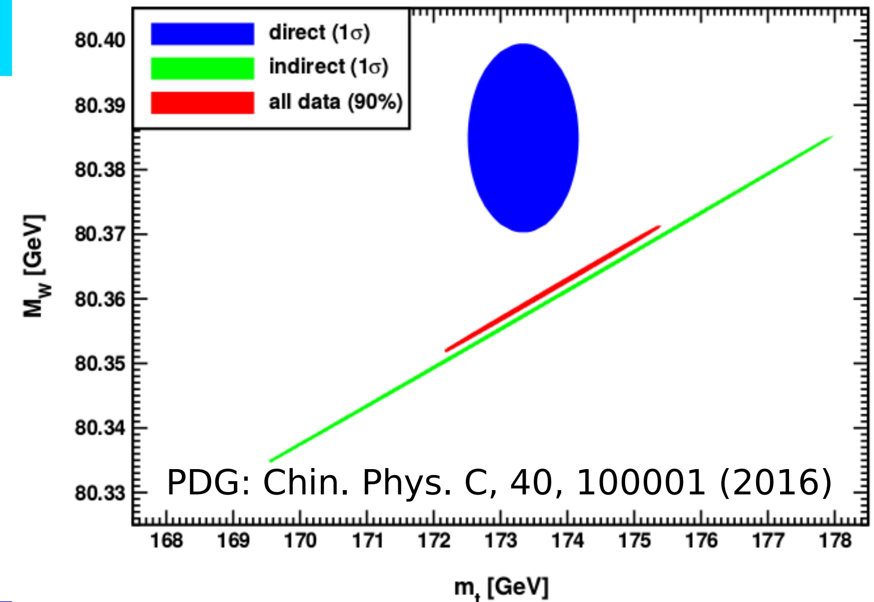
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/STDM-2014-18/

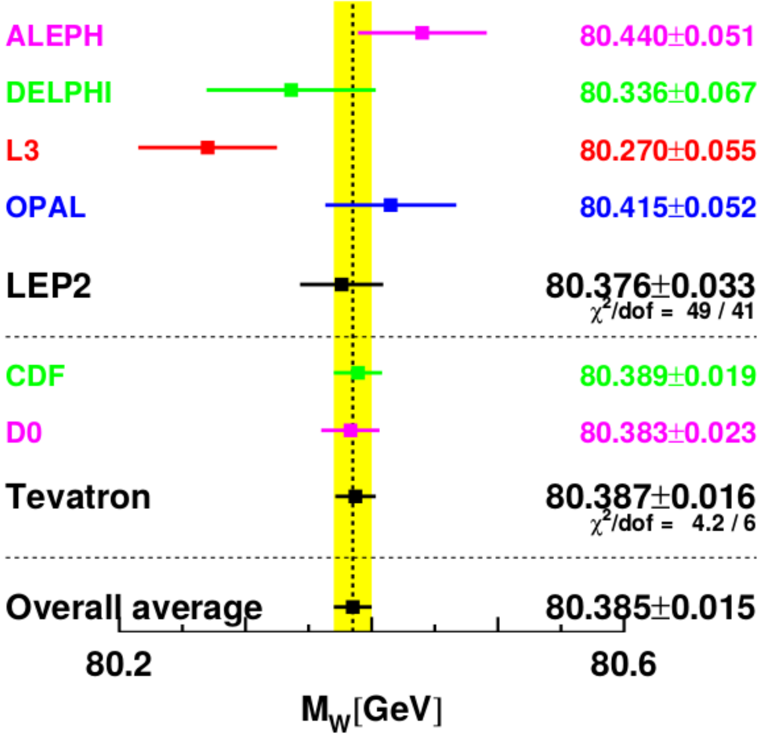
W mass: precision needed

- W mass, top mass and Higgs mass linked via radiative corrections

$$m_W^2\left(1-\frac{m_W^2}{m_Z^2}\right)=\frac{\pi\alpha}{\sqrt{2}G_\mu}(1+\Delta r)$$

Δr receives contributions from additional particles and interactions





PDG: Chin. Phys. C, 40, 100001 (2016)

Given the precisely measured values of α, G_μ and m_Z , and taking recent top & Higgs mass measurements, the SM prediction is

m_W = 80362 ± 8 MeV

(HEPfit group, JHEP 12 (2016) 135, arXiv:1608.01509 [hep-ph])

Measurement world average:
m_W = 80385 ± 15 MeV
at +1.5σ from
SM prediction : **80362 ± 8 MeV**

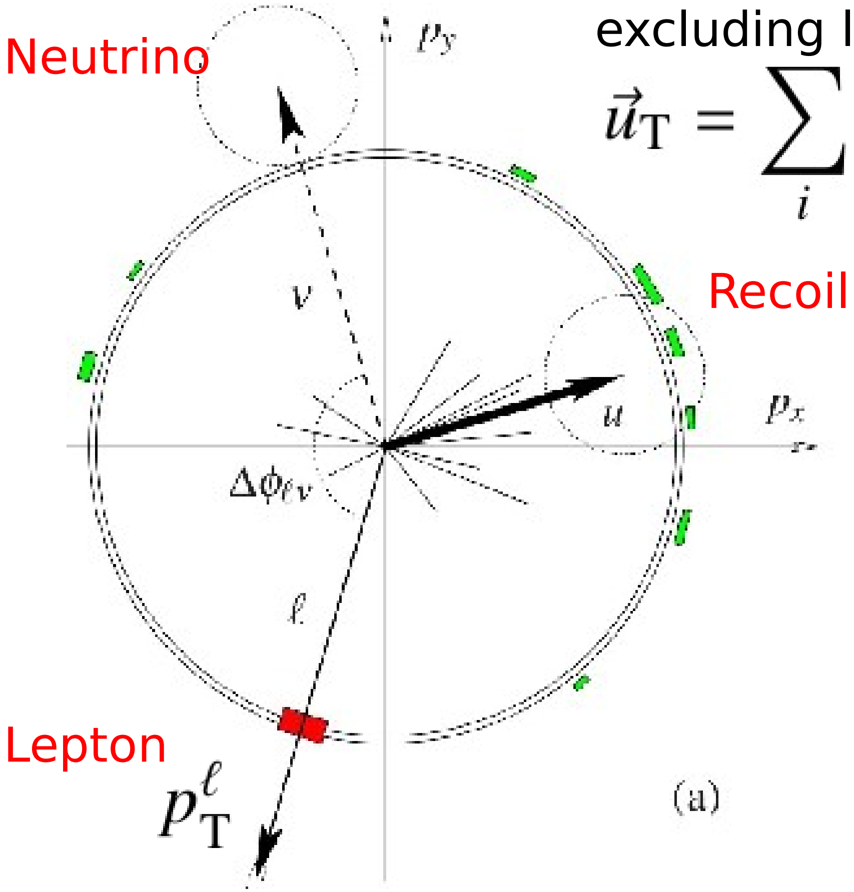
8 MeV is target for m_W measurements

W mass : topology & method

$$\vec{p}_{\mathrm{T}}^{\mathrm{miss}} = -\left(\vec{p}_{\mathrm{T}}^{\ell} + \vec{u}_{\mathrm{T}}\right)$$

(Sum of calorimeter energy deposits excluding leptons)

$$\vec{u}_{\mathrm{T}} = \sum_i \vec{E}_{\mathrm{T},i}$$



$$m_{\mathrm{T}} = \sqrt{2 p_{\mathrm{T}}^{\ell} p_{\mathrm{T}}^{\mathrm{miss}} (1 - \cos\Delta\phi)}$$

(transverse mass)

W mass : from fits to lepton p_T & m_T distributions

Template distributions for various m_W values (with bkg included) → comparison to observed distributions yields m_W based on χ^2 test.

Templates affected by bkg and also:

- Physics modelling (recoil description, W p_T, fraction of W helicity states, PDFs)
- Detector response (energy & momentum calibration, lepton identification & reconstruction efficiencies)

Use $Z \rightarrow l^+ l^-$ to calibrate detector, control physics modelling and validate the mass extraction method

Extract m_W with various selections, cross-check and combine

W mass: Physics Modelling

- Powheg+Pythia 8 for inclusive W and Z samples
- Reweight each event to study effect of systematics:
  - effects of higher-order QCD and electroweak (EW) corrections
  - results of fits to measured distributions (which improve the agreement of simulated kinematic distributions with data)

Based on the factorization of fully differential cross-section in 4 terms:

$$\frac{d\sigma}{dp_1\,dp_2} = \left[\frac{d\sigma(m)}{dm}\right]\left[\frac{d\sigma(y)}{dy}\right]\left[\frac{d\sigma(p_T,y)}{dp_T\,dy}\left(\frac{d\sigma(y)}{dy}\right)^{-1}\right]\left[(1+\cos^2\theta)+\sum_{i=0}^{7}A_i(p_T,y)P_i(\cos\theta,\phi)\right]$$

Breit Wigner

Boson p_T at fixed y:
Pythia8 AZ tune
for parton shower

Boson rapidity & Polarization coefficients A_i:
fixed-order NNLO pQCD prediction

Model tested with Drell-Yan measurements, Z-mass fits, control plots, and m_W estimation from various event categories

Physics modelling: uncertainties on m_W

- QED/EW effects: FSR photons (Photos & Sanc), EW (Winhac)

Decay channel	$W \to e\nu$		$W \to \mu\nu$	
Kinematic distribution	p_T^ℓ	m_T	p_T^ℓ	m_T
δm_W [MeV]				
FSR (real) Final State Radiation	< 0.1	< 0.1	< 0.1	< 0.1
Pure weak and IFI corrections	3.3	2.5	3.5	2.5
FSR (pair production)	3.6	0.8	4.4	0.8
Total	4.9	2.6	5.6	2.6

(FSR: Final State Radiation)
(IFI: Interference Initial-Final State Rad)

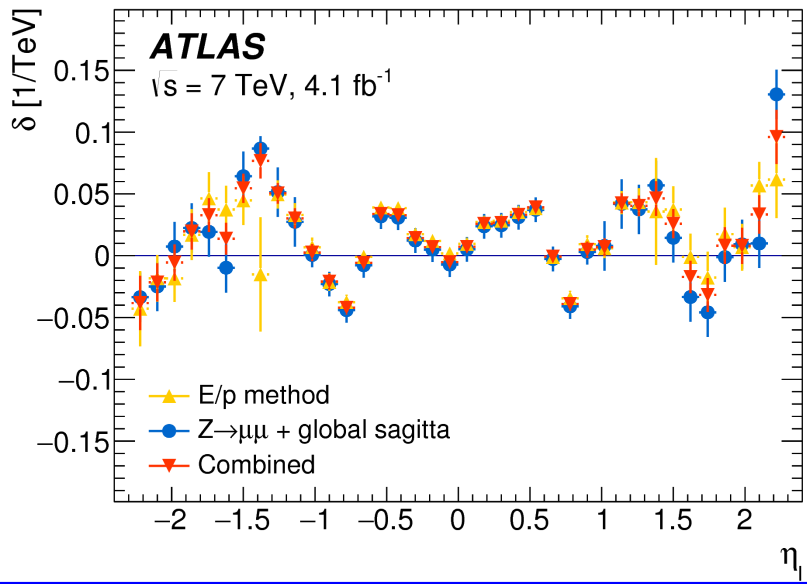
- QCD modelling: PDF dominate

	W-boson charge	W^+		W^-		Combined	
	Kinematic distribution	p_T^ℓ	m_T	p_T^ℓ	m_T	p_T^ℓ	m_T
	δm_W [MeV]						
*	Fixed-order PDF uncertainty	13.1	14.9	12.0	14.2	8.0	8.7
	AZ tune	3.0	3.4	3.0	3.4	3.0	3.4
	Charm-quark mass	1.2	1.5	1.2	1.5	1.2	1.5
*	Parton shower μ_F with heavy-flavour decorrelation	5.0	6.9	5.0	6.9	5.0	6.9
	Parton shower PDF uncertainty	3.6	4.0	2.6	2.4	1.0	1.6
*	Angular coefficients	5.8	5.3	5.8	5.3	5.8	5.3
	Total	15.9	18.1	14.8	17.2	11.6	12.9

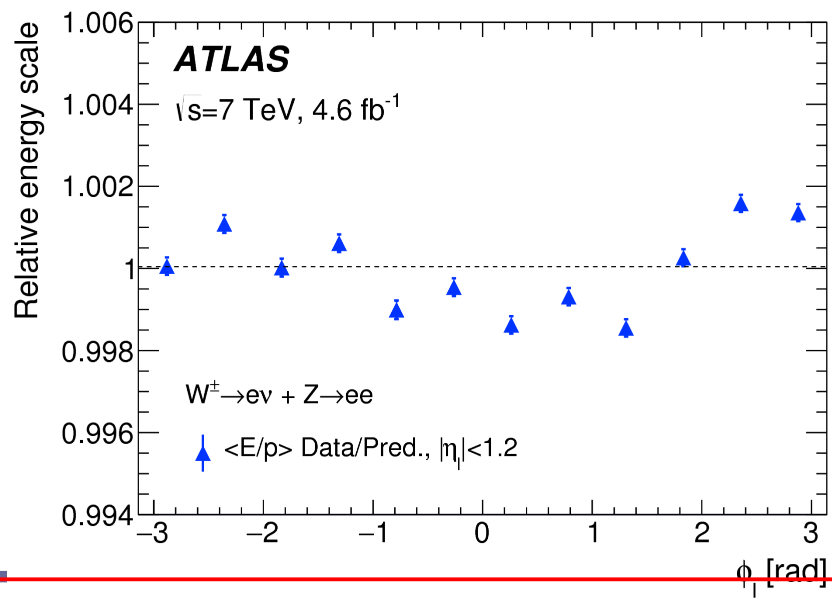
  - PDF uncertainty improves in the combination of W^+ & W^-
  - p_T W uncertainty (mostly from from heavy-flavour production) : similar for W^+ & W^- ; similar for p_T lepton & m_T methods

Experimental: lepton calibration

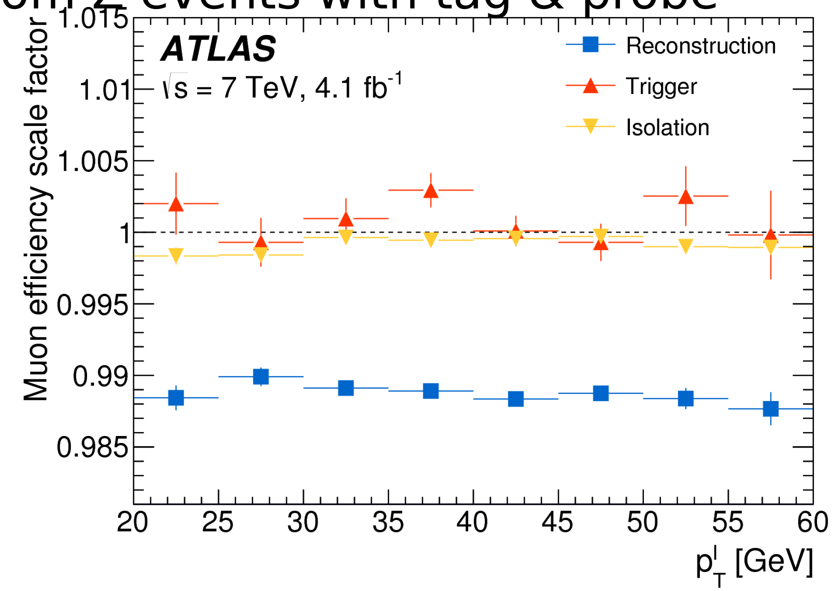
- Charge dependent corrections
- Scale and resolution corrections derived from Z, extrapolated to W using p_T lepton spectra.
- "Sagitta bias" (detector displacements or twists) from Z events and also from E/p in $W \rightarrow e\nu$



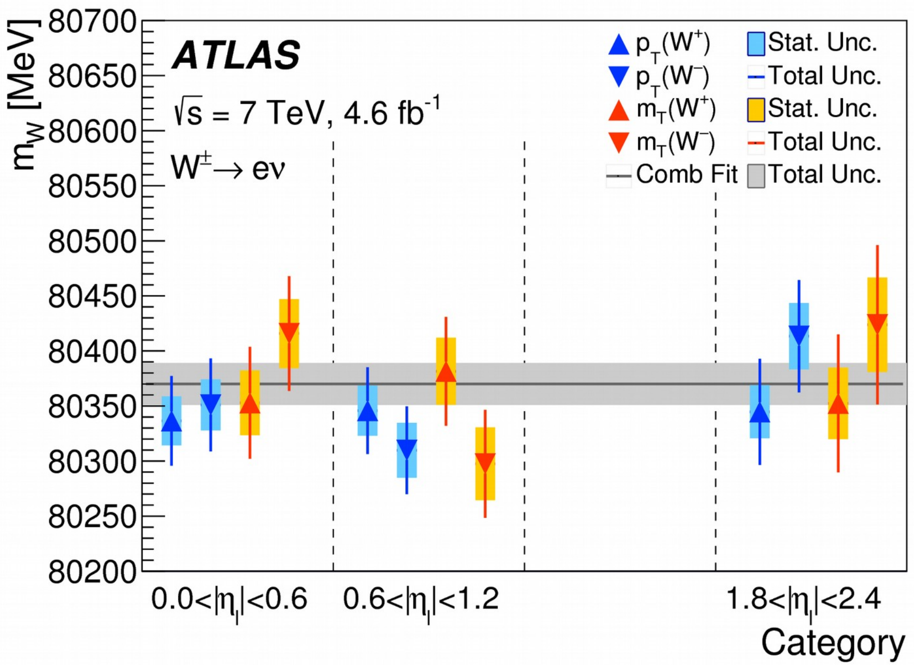
- Electron φ modulation due to mechanical deformation under gravity corrected with W & Z events

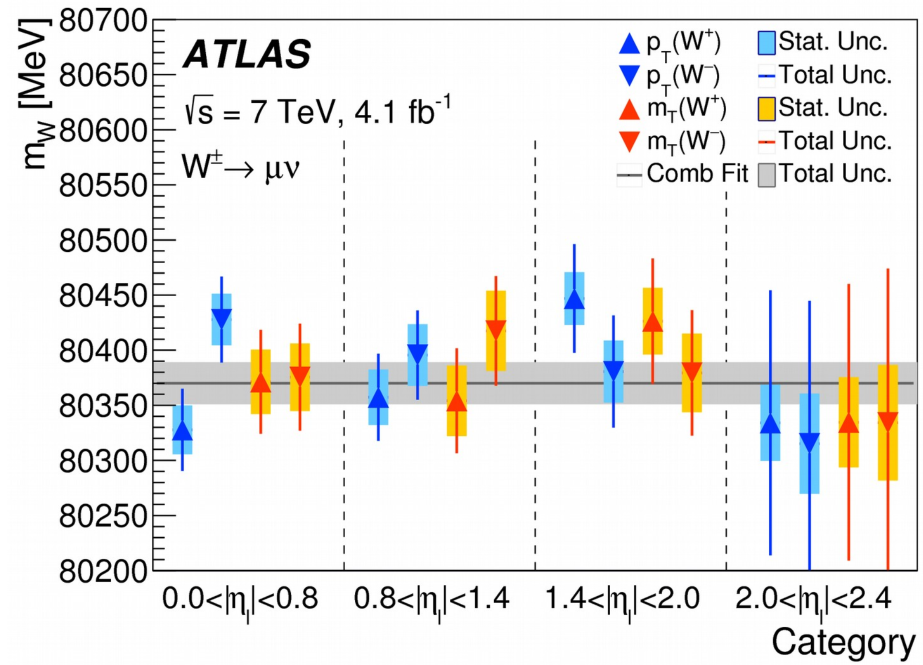


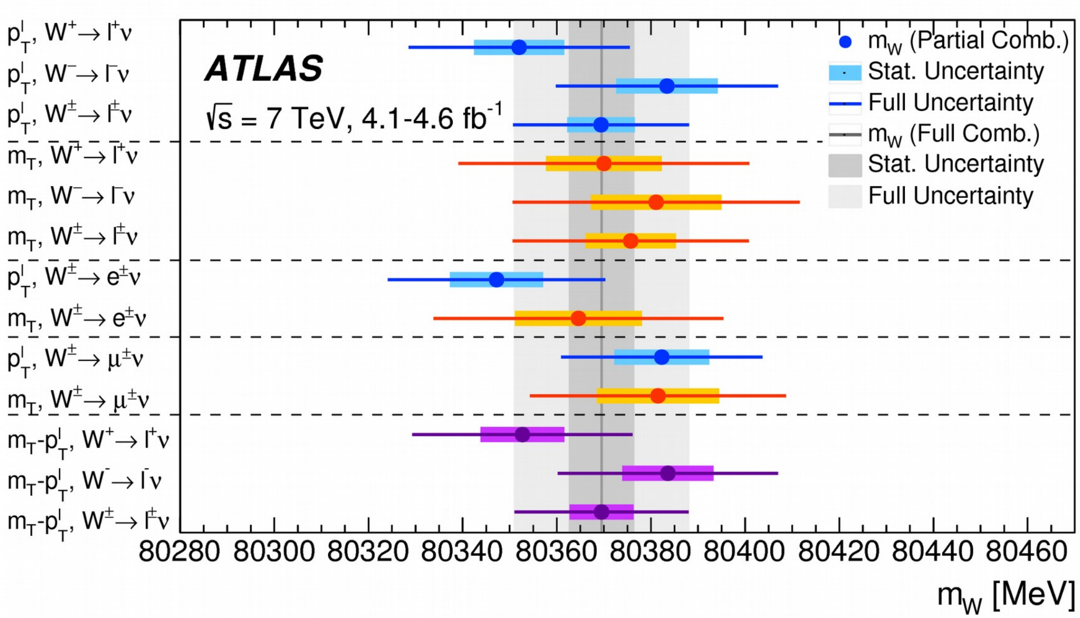
Scale factors for identification, reconstruction & trigger efficiencies from Z events with tag & probe



m_W from pT lepton, mT ; e, μ, W^+, W^-, η categories







All categories give consistent result: validation of physics modelling and detector calibration. So, combine:

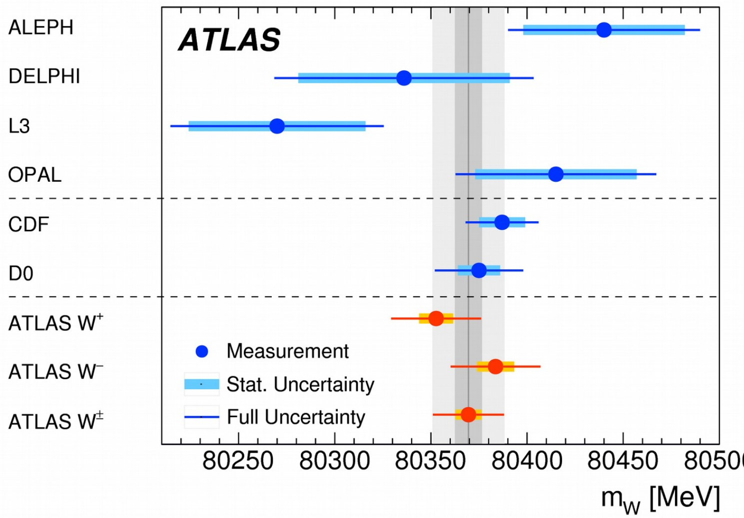
Combination	Weight
Electrons	0.427
Muons	0.573
m_T	0.144
p_T^ℓ	0.856
W^+	0.519
W^-	0.481

ATLAS m_W measurement

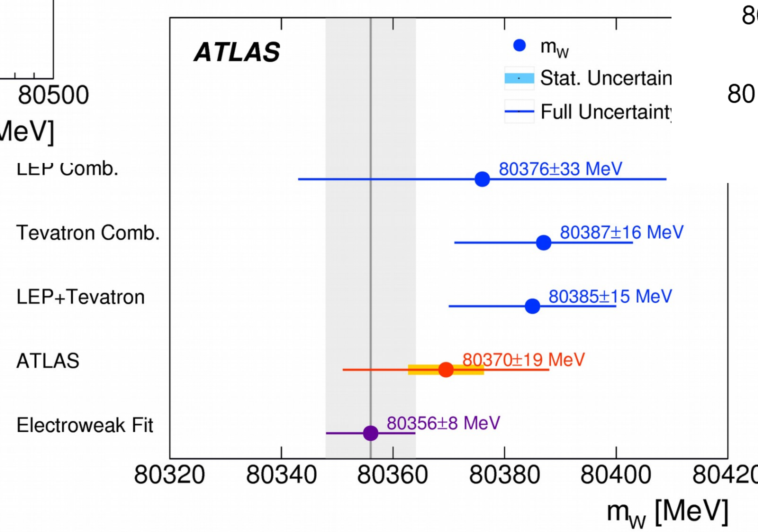
$$m_W = 80370 \pm 7\,(\text{stat.}) \pm 11\,(\text{exp. syst.}) \pm 14\,(\text{mod. syst.})\ \text{MeV}$$

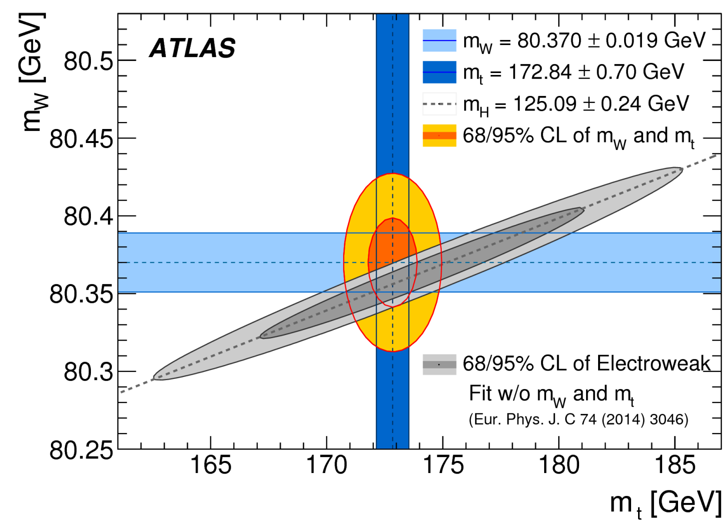
m_W = 80370 ± 19 MeV , $m_{W+} - m_{W-} = -29 \pm 28$ MeV

Combined categories	Value [MeV]	Stat. Unc.	Muon Unc.	Elec. Unc.	Recoil Unc.	Bckg. Unc.	QCD Unc.	EW Unc.	PDF Unc.	Total Unc.	χ^2/dof of Comb.
m_T-p_T^ℓ, $W^\pm$, e-μ	80369.5	6.8	6.6	6.4	2.9	4.5	8.3	5.5	9.2	18.5	29/27
		(stat)	(experimental)				(physics modelling)				



As precise as previous single-best measurement from CDF





Reduced tension with SM ElectroWeak fit

2. W and Z cross sections

“Precision measurement and interpretation of inclusive W+, W− and Z/γ∗ production cross sections with the ATLAS detector”

Eur. Phys. J. C77 (2017) 367

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/STDM-2012-20/

pp @ 7 TeV

W, Z cross sections in e/μ channels $W^{+/-} \to l^{+/-} \nu$, $Z \to l^+ l^-$

- "Fiducial cross sections" reported: a fraction of the total, corresponding to the reduced phase-space and the decay channels of the actual measurements (so it includes the branching fractions)

$$\sigma^{fid}(pp \to V + X, V \to leptons) = \frac{N-B}{L*C}$$

N-B: Observed events – bkg estimate
C: detector efficiency , L: integrated luminosity

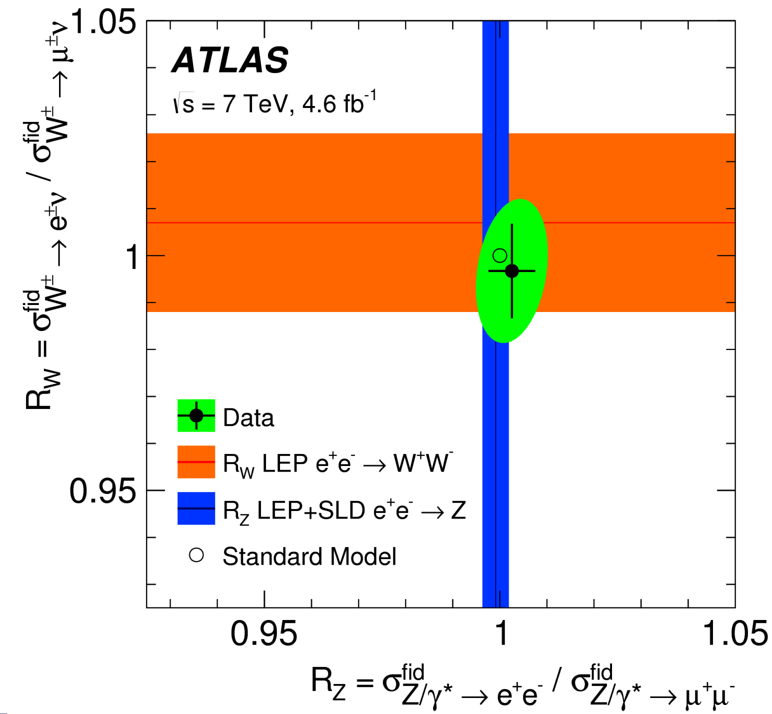
$$\text{Central } Z/\gamma^* \to \ell\ell : \quad p_{T,\ell} > 20 \text{ GeV}, \ |\eta_\ell| < 2.5, \ 46 < m_{\ell\ell} < 150 \text{ GeV}$$

$$\text{Forward } Z/\gamma^* \to \ell\ell : \quad p_{T,\ell} > 20 \text{ GeV}, \ \text{one lepton } |\eta_\ell| < 2.5, \ \text{other lepton } 2.5 < |\eta_\ell| < 4.9, \ 66 < m_{\ell\ell} < 150 \text{ GeV}$$

$$W^\pm \to \ell\nu : \quad p_{T,\ell} > 25 \text{ GeV}, \ |\eta_\ell| < 2.5, \ p_{T,\nu} > 25 \text{ GeV}, \ m_T > 40 \text{ GeV}.$$

- Differential distributions in rapidity sensitive to PDFs

- Cross section ratios
sensitive to
Lepton universality and
valence & s-quark distributions



W, Z : fiducial cross sections & their ratios

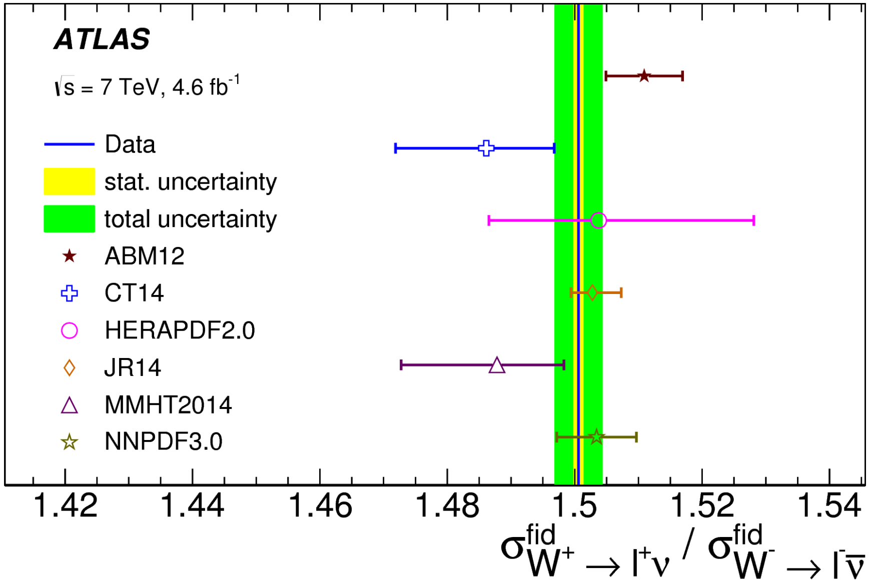
- Fiducial cross sections

W :

	$\sigma^{\text{fid}}_{W\to\ell\nu}$ [pb]
$W^+ \to e^+\nu$	$2939 \pm 1\,(\text{stat}) \pm 28\,(\text{syst}) \pm 53\,(\text{lumi})$
$W^+ \to \mu^+\nu$	$2948 \pm 1\,(\text{stat}) \pm 21\,(\text{syst}) \pm 53\,(\text{lumi})$
$W^+ \to \ell^+\nu$	$2947 \pm 1\,(\text{stat}) \pm 15\,(\text{syst}) \pm 53\,(\text{lumi})$
$W^- \to e^-\bar{\nu}$	$1957 \pm 1\,(\text{stat}) \pm 21\,(\text{syst}) \pm 35\,(\text{lumi})$
$W^- \to \mu^-\bar{\nu}$	$1964 \pm 1\,(\text{stat}) \pm 13\,(\text{syst}) \pm 35\,(\text{lumi})$
$W^- \to \ell^-\bar{\nu}$	$1964 \pm 1\,(\text{stat}) \pm 11\,(\text{syst}) \pm 35\,(\text{lumi})$
$W \to e\nu$	$4896 \pm 2\,(\text{stat}) \pm 49\,(\text{syst}) \pm 88\,(\text{lumi})$
$W \to \mu\nu$	$4912 \pm 1\,(\text{stat}) \pm 32\,(\text{syst}) \pm 88\,(\text{lumi})$
$W \to \ell\nu$	$4911 \pm 1\,(\text{stat}) \pm 26\,(\text{syst}) \pm 88\,(\text{lumi})$

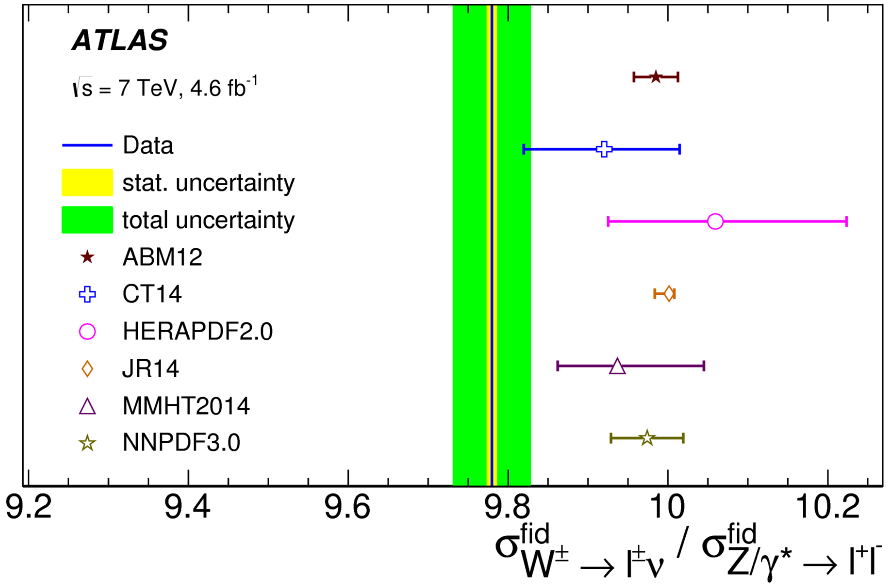
Z : m_{ll} : 66 – 116 GeV

	$\sigma^{\text{fid}}_{Z/\gamma^*\to\ell\ell}$ [pb]
$Z/\gamma^* \to e^+e^-$	$502.7 \pm 0.5\,(\text{stat}) \pm 2.0\,(\text{syst}) \pm 9.0\,(\text{lumi})$
$Z/\gamma^* \to \mu^+\mu^-$	$501.4 \pm 0.4\,(\text{stat}) \pm 2.3\,(\text{syst}) \pm 9.0\,(\text{lumi})$
$Z/\gamma^* \to \ell\ell$	$502.2 \pm 0.3\,(\text{stat}) \pm 1.7\,(\text{syst}) \pm 9.0\,(\text{lumi})$



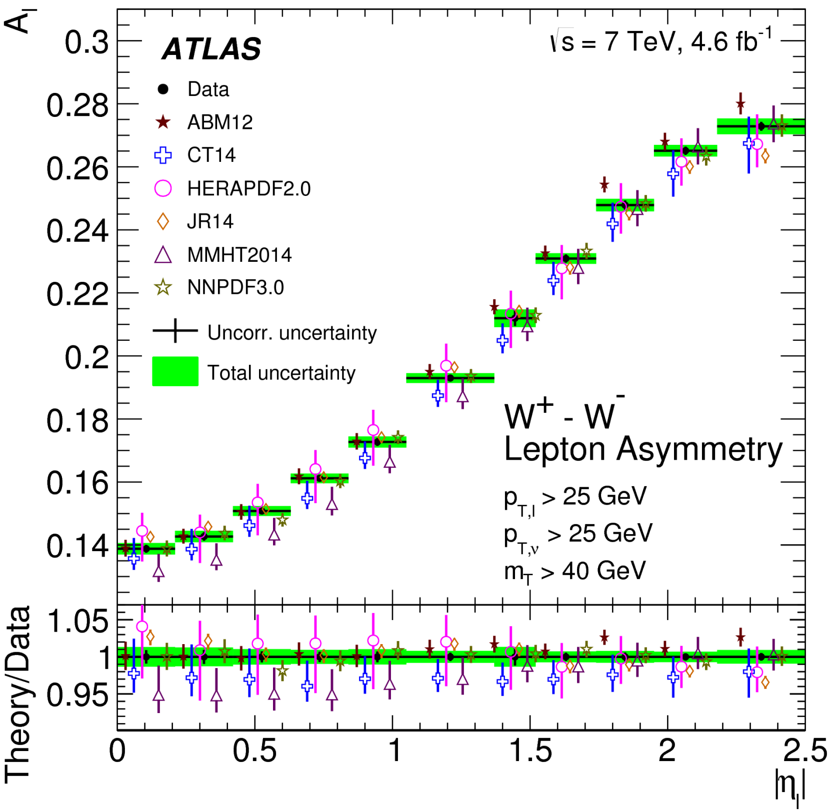
- Cancellation of luminosity uncertainty in the ratios

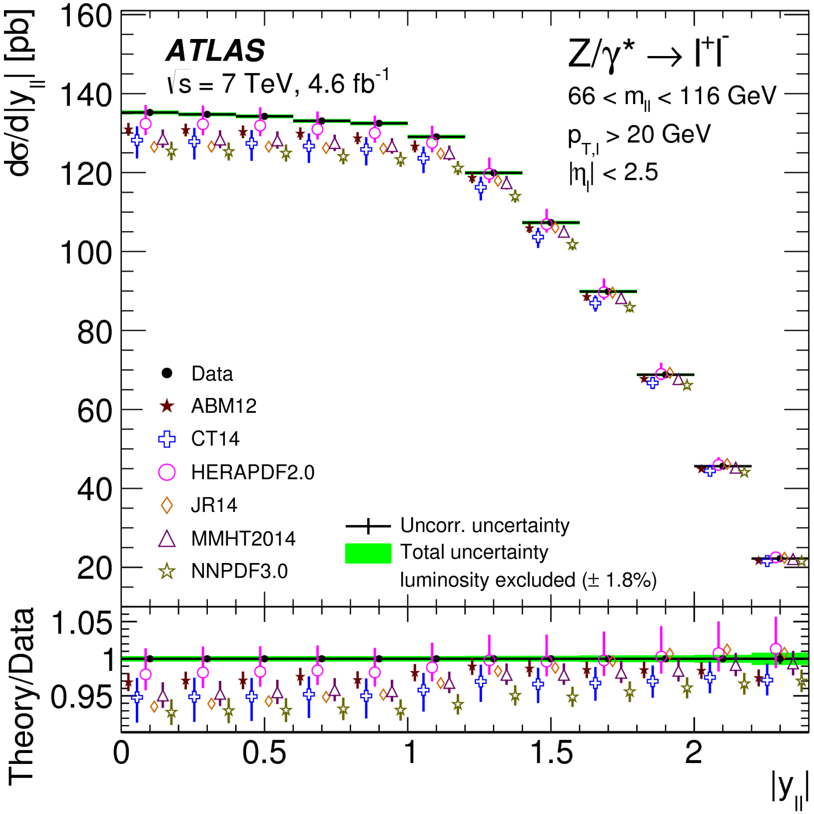
- Data precision → constraining for theory predictions (uncertainties of the theoretical calculations correspond to PDF only)



- Predictions for $W^\pm/Z$ are systematically higher than measured in data

Differential cross sections: W charge asymmetry & Z vs. rapidity





W^+ / W^- Lepton Asymmetry:
Difference over Sum of cross sections

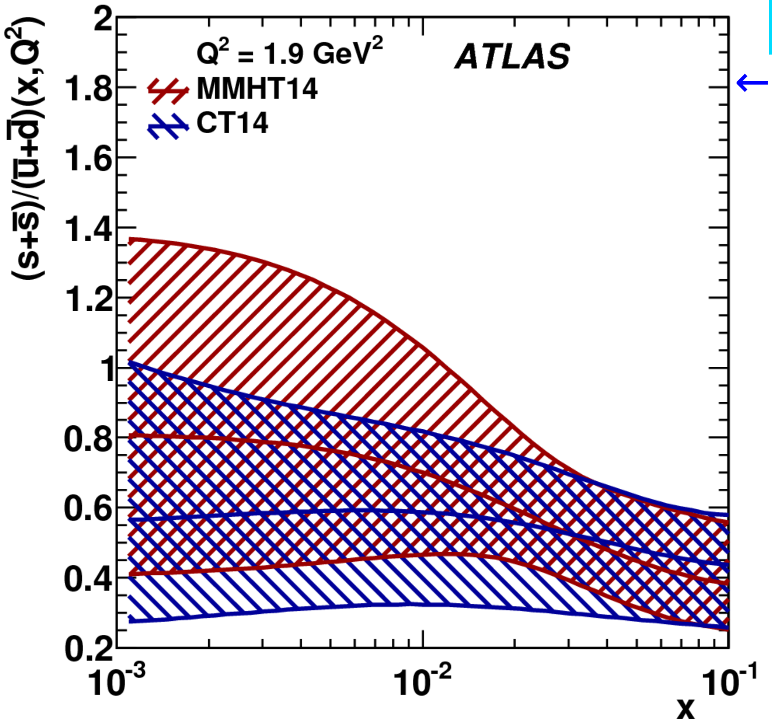
Experimental accuracy at the <1% level
Good agreement with theory

Z rapidity:

Most predictions lower than data in |y|<1
Potential problem in description of s-quark vs. sea d-quarks ?

(Predictions computed at NNLO QCD with NLO EW corrections)

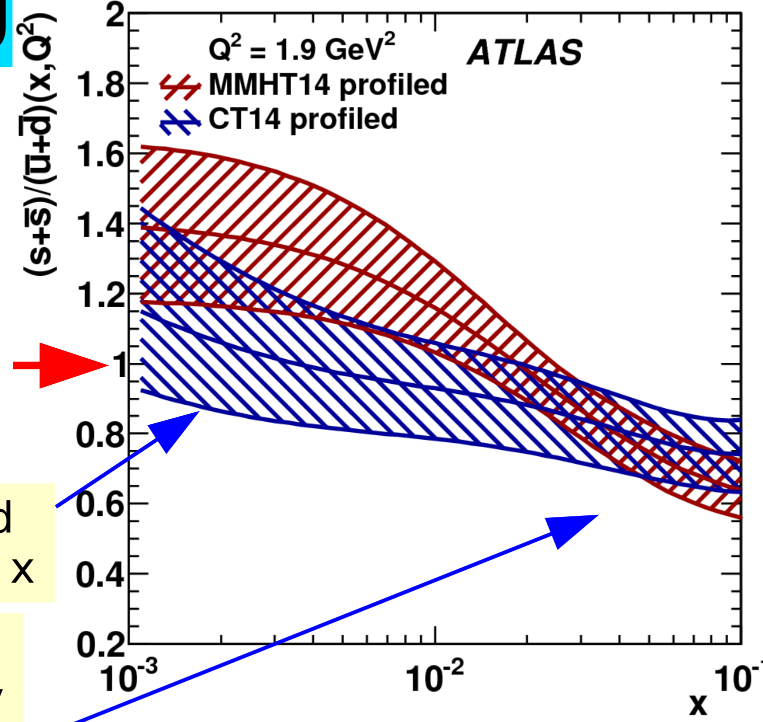
PDF profiling



← Original PDFs

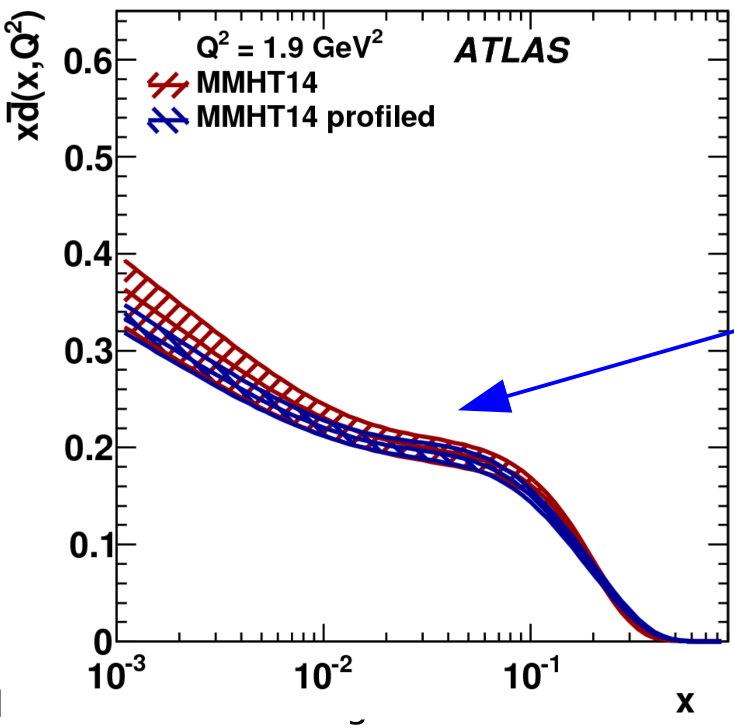
$$R_s(x)=\frac{s(x)+\bar{s}(x)}{\bar{u}(x)+\bar{d}(x)}$$

After "profiled" with new W & Z differential cross section data

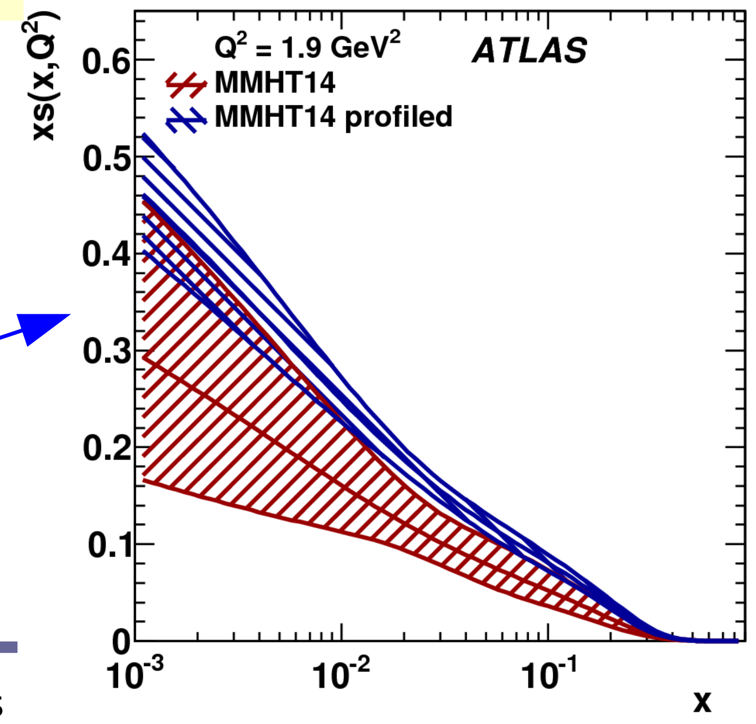


s-quarks not suppressed w.r.t valence u, d at low x

Uncertainty reduces significantly, especially at x~0.023

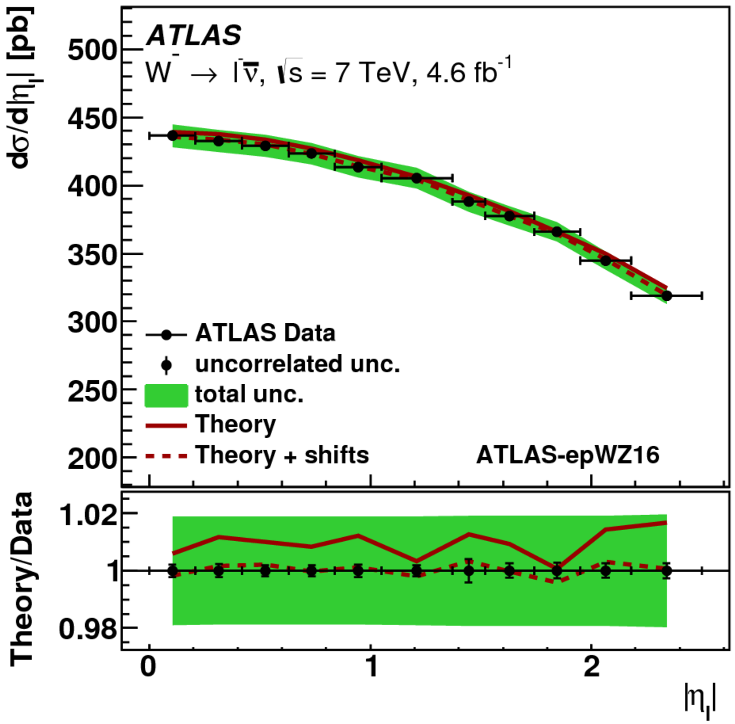


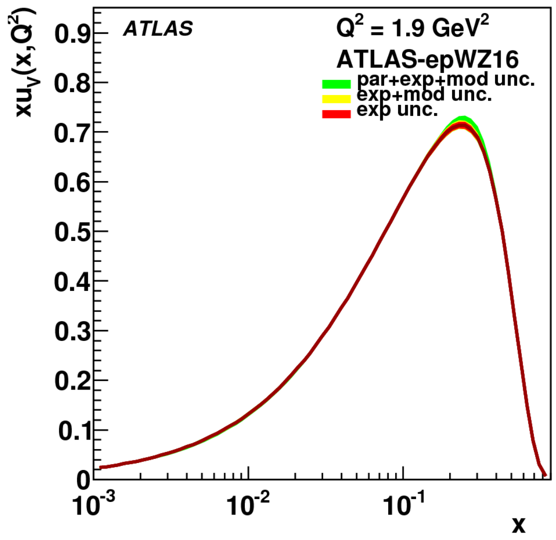
After "profiling": Valence u and d reduced, s-quark enhanced

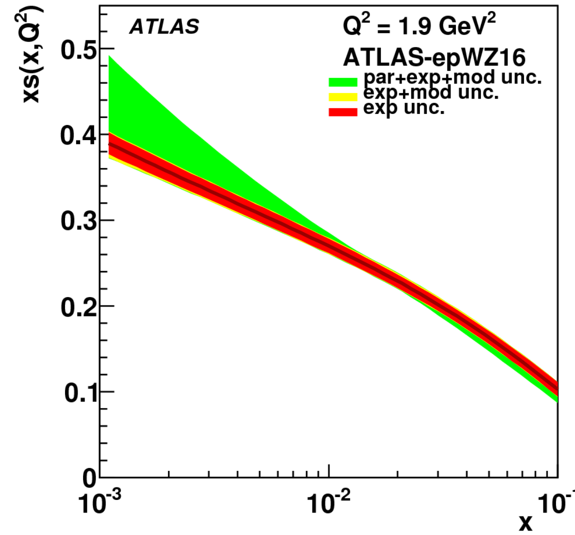


Full QCD fit

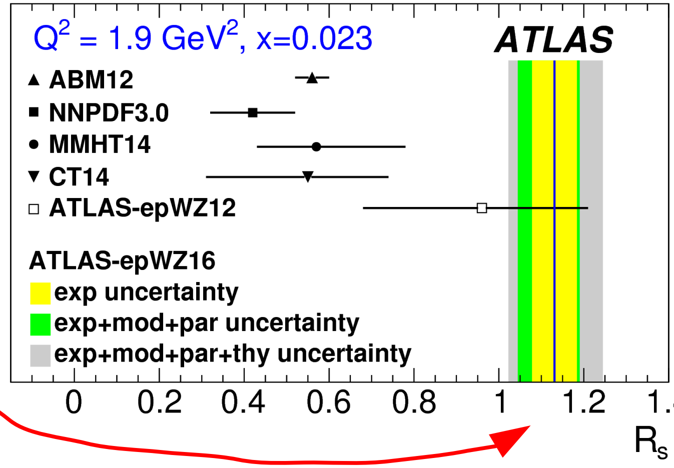
QCD fit to data → PDF set: ATLAS-epWZ16







- QCD fit is performed using DIS HERA I+II and ATLAS DY data
- Data are described well by fit
- Fit determines a new set of PDFs: **ATLAS-epWZ16** smaller uncertainties than previous ATLAS-epWZ12 set
- Measured R_S confirms **unsuppressed strangenes** at low x~0.023 and low Q^2 = 1.9 GeV^2



3. Z + jets cross sections

(jets with with p_T > 30 GeV, |y|<2.5)

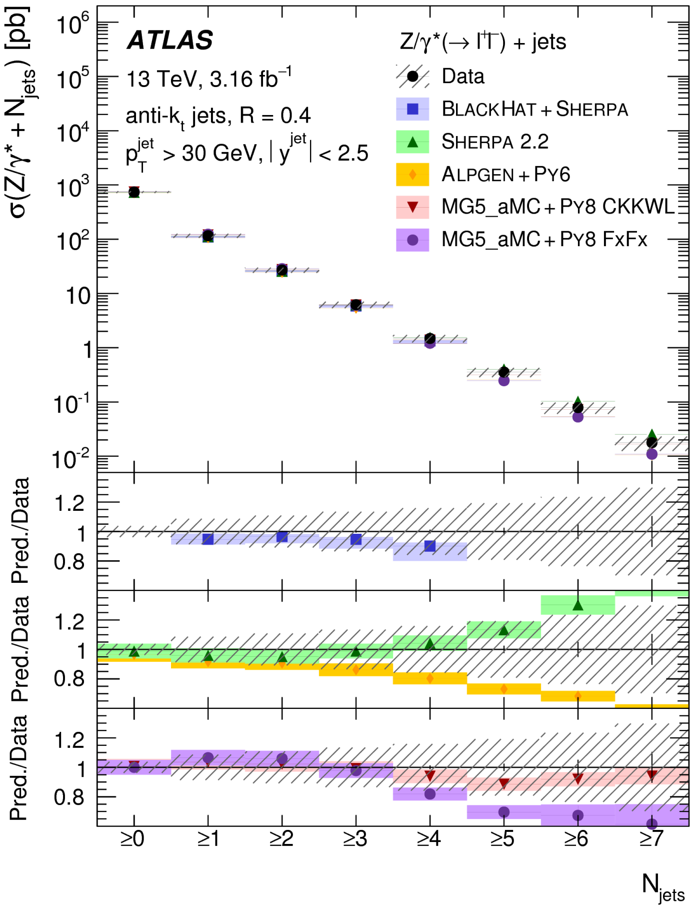
"Measurements of the production cross section of a Z boson in association with jets in pp collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector"

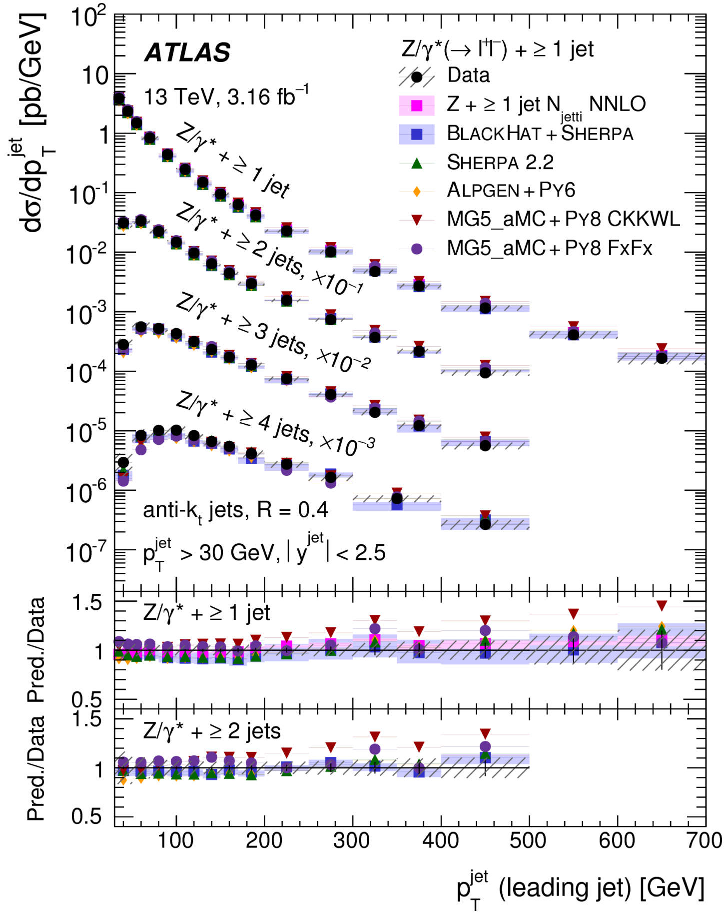
Eur. Phys. J. C77 (2017) 361

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/STDM-2016-01/

Jet production
in association with a leptonically decaying heavy gauge boson (W, Z)
allows effects of the strong interaction to be studied
in a relatively clean environment

Z + jets – jet multiplicity & pT





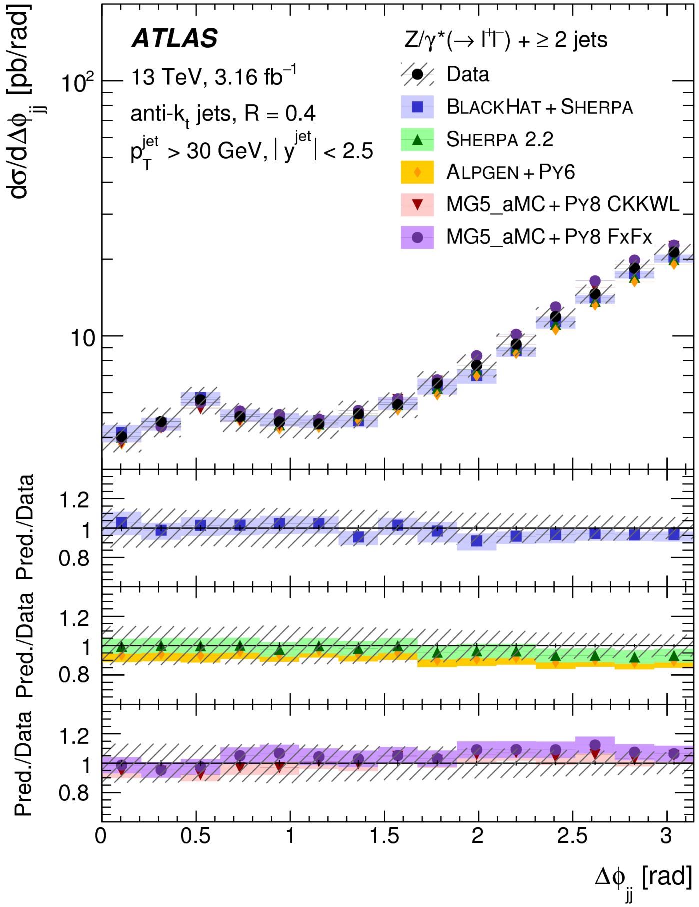
NLO Sherpa 2.2, Alpgen+Py6 and MG5_aMC+Py8 FxFx not OK for high jet multiplicity, where a non-negligible fraction of the jets are from parton shower

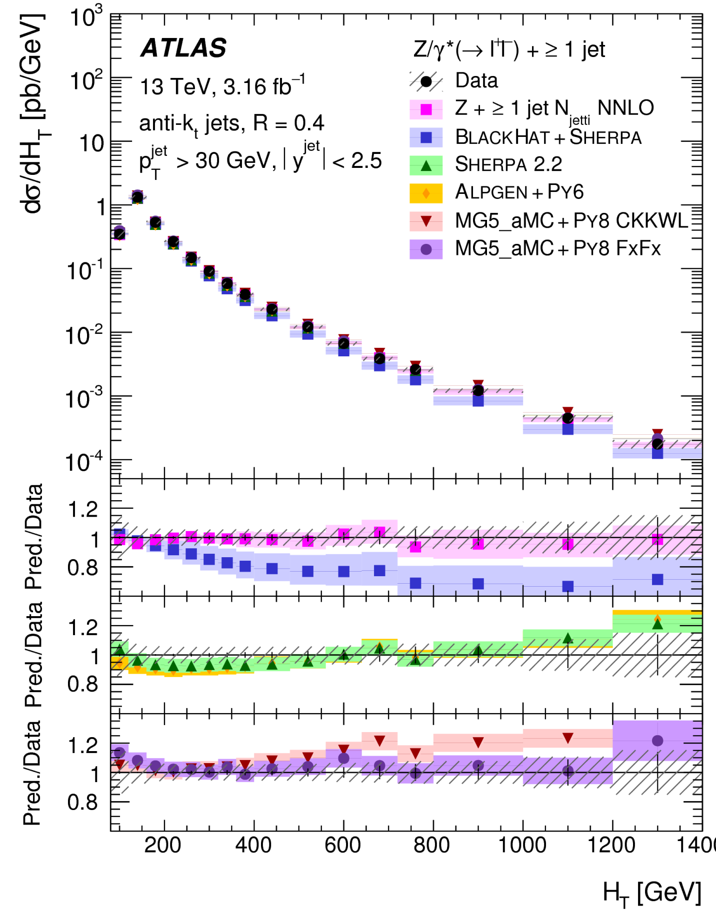
- LO generator MG5_aMC+Py8 CKKWL seems OK for jet multiplicity

NLO BlackHat+Sherpa, Sherpa 2.2,and MG5_aMC+Py8 FxFx, OK for jet pT

- MG5_aMC+Py8 CKKWL predicts a too-hard jet pT spectrum at high pT
  - indication that the dynamic μF & μR scale used in the generation is not appropriate for the full jet pT range

Z + jets – jet Δφ & event kinematics





- Relative jet topology (mostly back-to-back) modelled by all
- MG5_aMC+Py8 CKKWL - overestimates contribution at large H_T (hard jets)
- BlackHat+Sherpa (fixed order NLO) underestimates at HT > 300 GeV due to missing contribution from higher parton multiplicities (higher orders in pQCD) → solved with Njetti NNLO

$$H_T = \sum_{\ell,jets} |p_T|$$

4. kt splitting scales in Z events

"Measurement of the kt splitting scales in $Z \rightarrow \ell\ell$ events in pp collisions at $\sqrt{s}$=8 TeV with the ATLAS detector"

arXiv:1704.01530 (submitted to JHEP)

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/STDM-2015-14/

Studying of jet production rates at different resolution scales instead of jet properties like jet pT we saw just before

K_t splitting scales d_k

For a given iteration the number of input momenta drops from k+1 → k, and a "splitting scale" is defined:

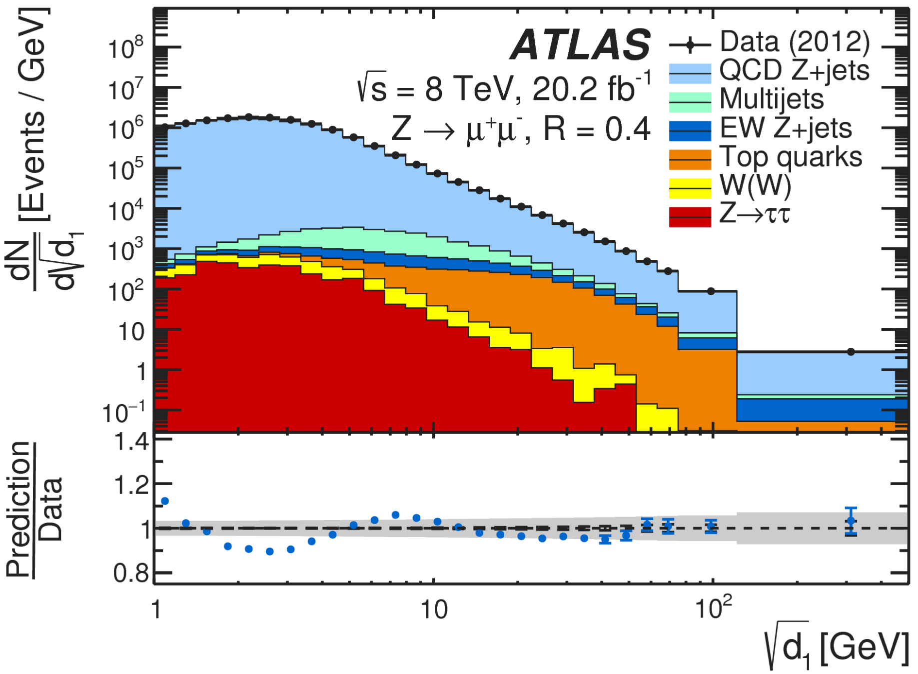
$$d_k = \min_{i,j}(d_{ij}, d_{ib})$$

* if min is d_{ij} → combine i,j
* if min is d_{ib} → remove i from list and call it a jet

The index k defines the "order of the splitting scale",
k= 0 : last iteration step before algorithm terminates
$\sqrt{d_0}$ = "zeroth-order splitting scale" = **leading jet p_T**

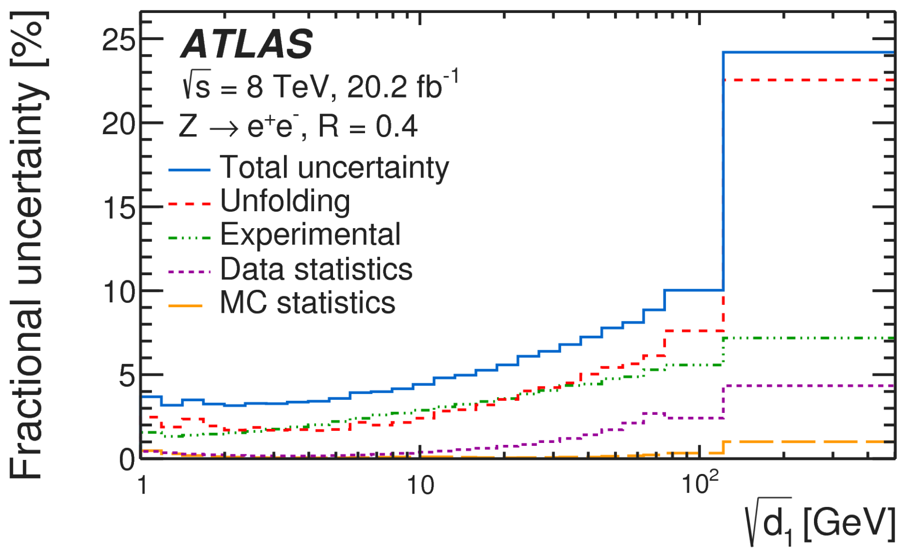
N^{th} splitting scale, d_N : distance measure at which an N-jet event is resolved as an (N+1)-jet event

Differential event counting as function of $\sqrt{d_1}$

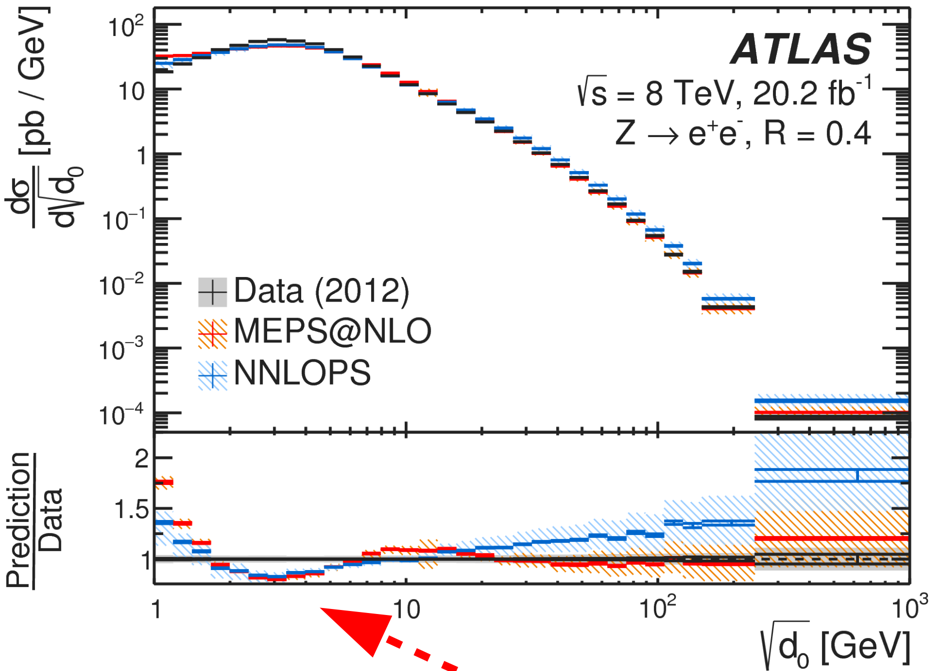


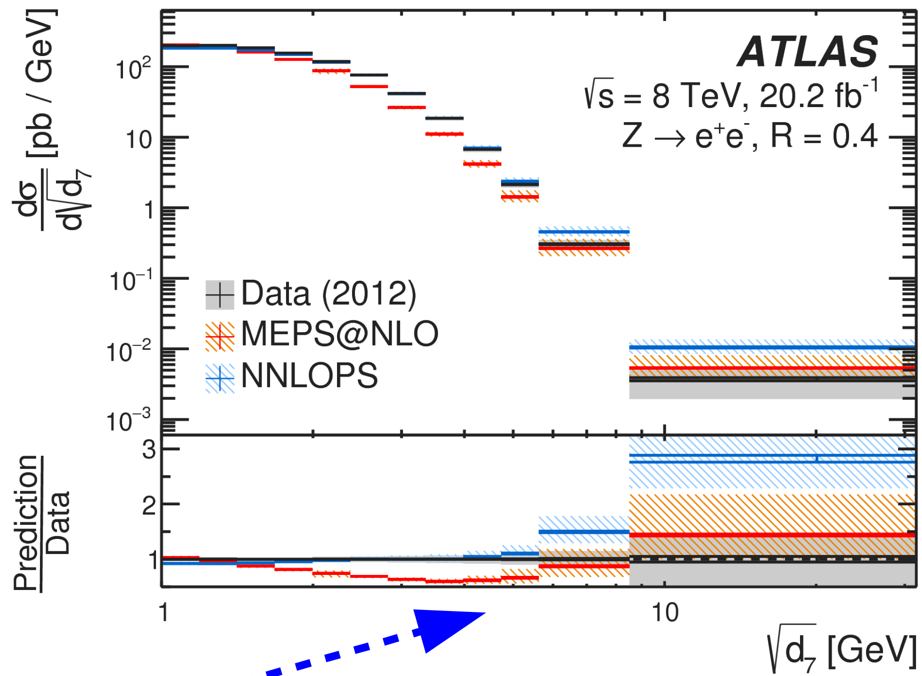
Soft region ← activity → Hard region

Make differential cross sections as function of these scales with reasonable uncertainties (luminosity: 1.9%)



Differential cross sections for various splitting scales





Low order splitting scales: Both predictions underestimate the cross section in the peak region (~3 GeV) by ~10–20 %. Consistent with the data at 10 GeV. Both overshoot the data significantly in the region close to 1 GeV.

High order splitting scales: MEPS@NLO prediction agrees well with the data at hard region, where NNLOPS prediction overestimates the cross section
The level of agreement of the NNLOPS predictions in the soft region is improved significantly for the higher-order splitting scales.

→ Discrepancies indicate that data can provide new input for the tuning of the Monte Carlo event generators

5. $Z/\gamma^* \rightarrow l^+ l^-$ triple differential cross section

TO BE SUBMITTED FOR PUBLICATION SOON

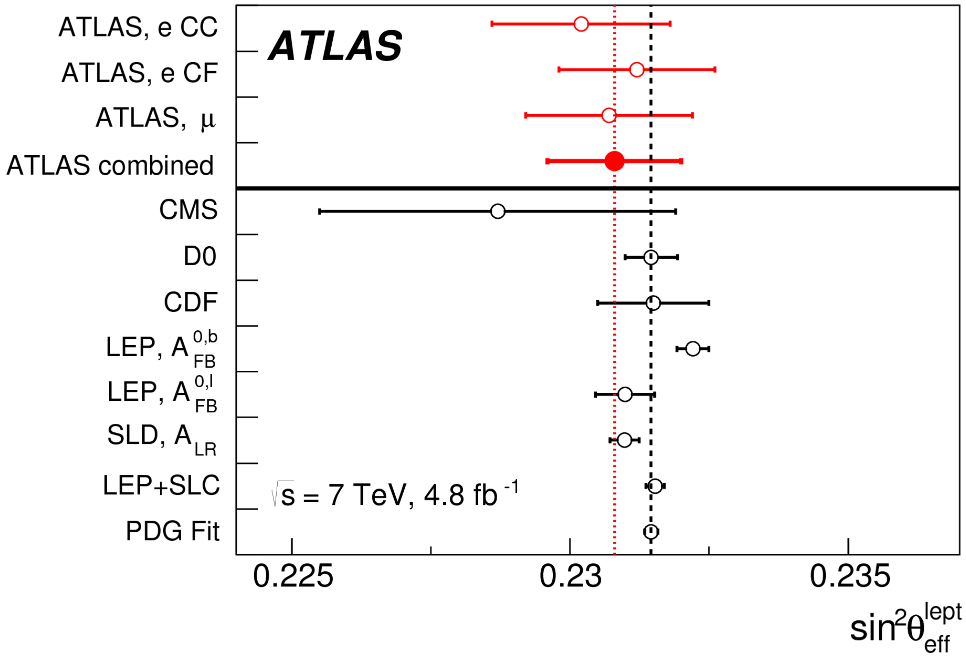
Z/γ* → l⁺ l⁻ triple differential cross section

TO BE SUBMITTED FOR PUBLICATION SOON

Triple differential cross-section measurement
(cosθ* in Collins-Soper frame)

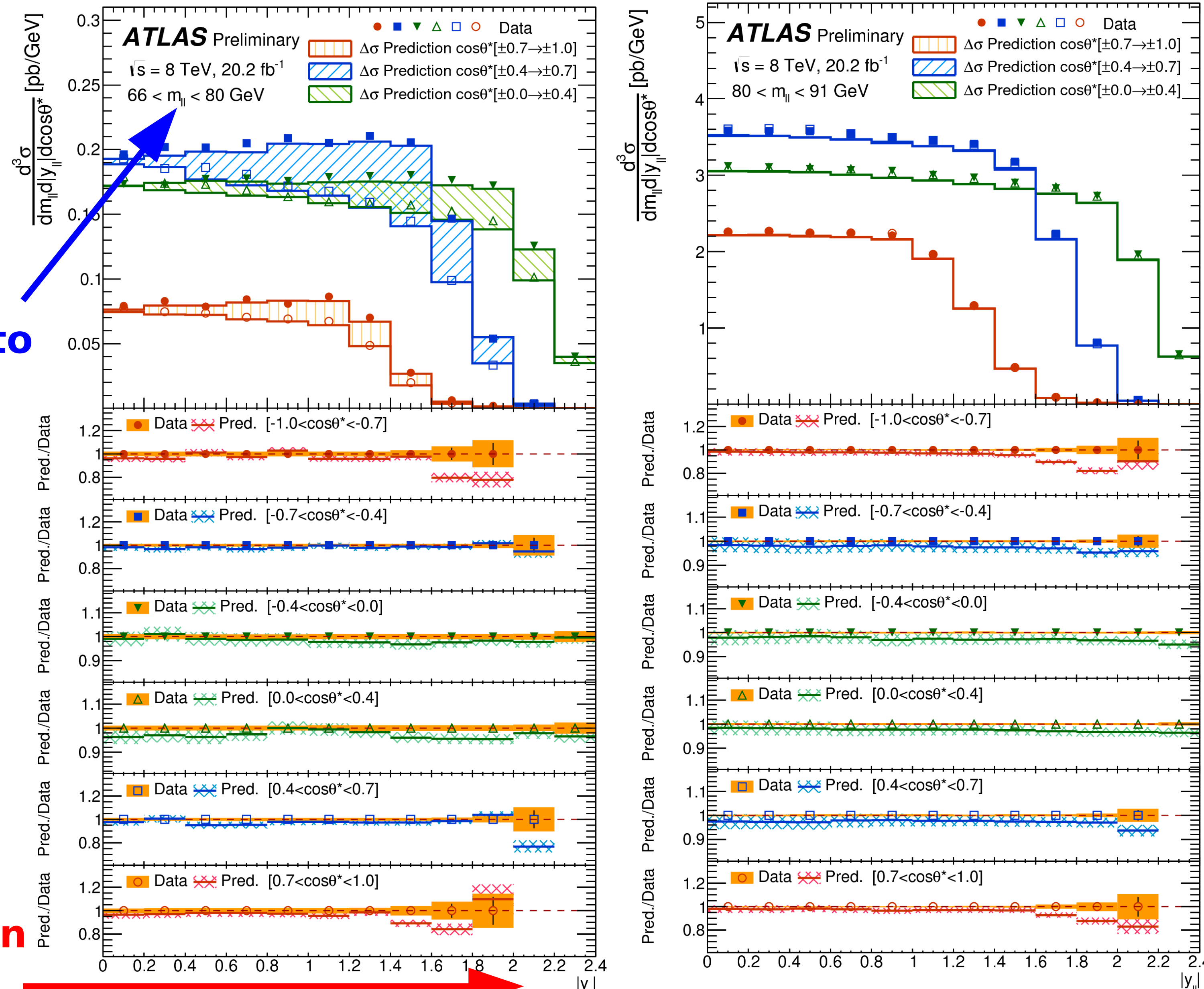
$$\frac{d^3\sigma}{dm_{\ell\ell}dy_{\ell\ell}d\cos\theta^*_{CS}}$$

- Sensitivity to the PDFs and the Z forward-backward asymmetry, AFB
- Builds foundation for a possible future extraction of the weak-mixing angle.
  - Previous result at 7 TeV, 4.6 /fb [JHEP09(2015)049] limited by PDF uncertaitnies



Z/γ* → l⁺ l⁻ triple differential cross section

TO BE SUBMITTED FOR PUBLICATION SOON



1. Each plot refers to an m_{ll} bin

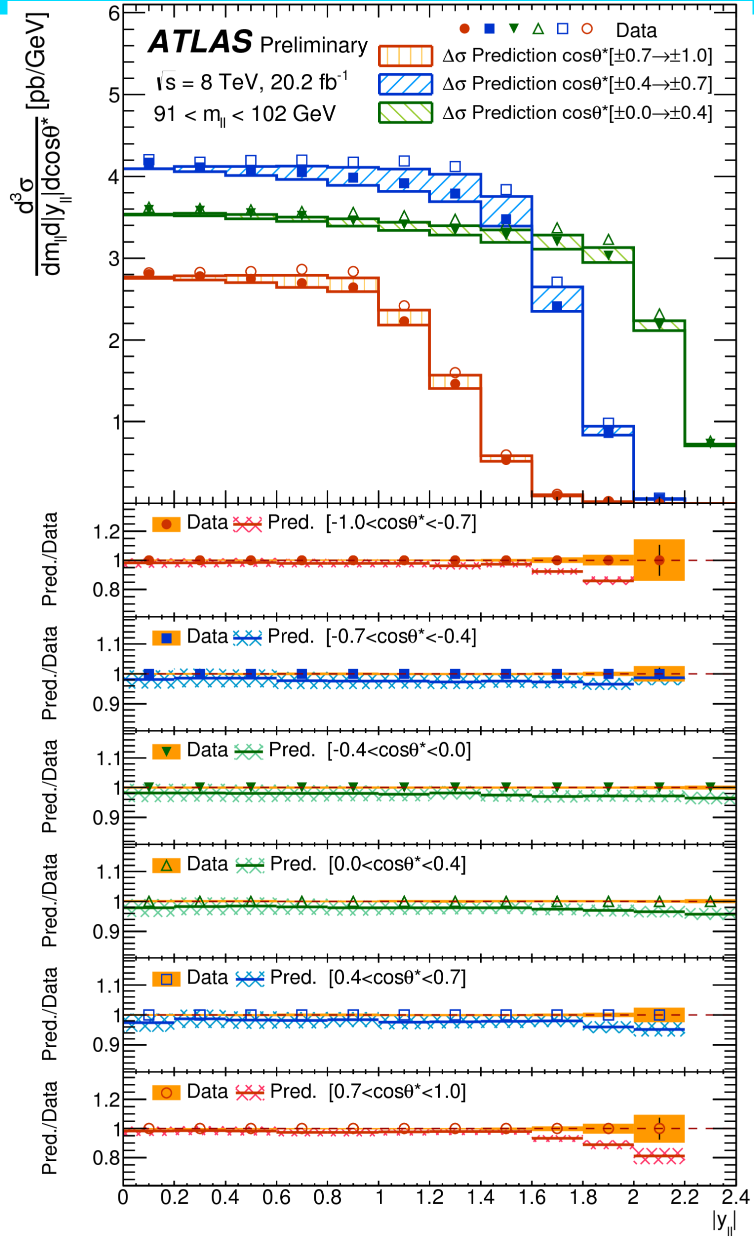
2. Function of y_{ll}

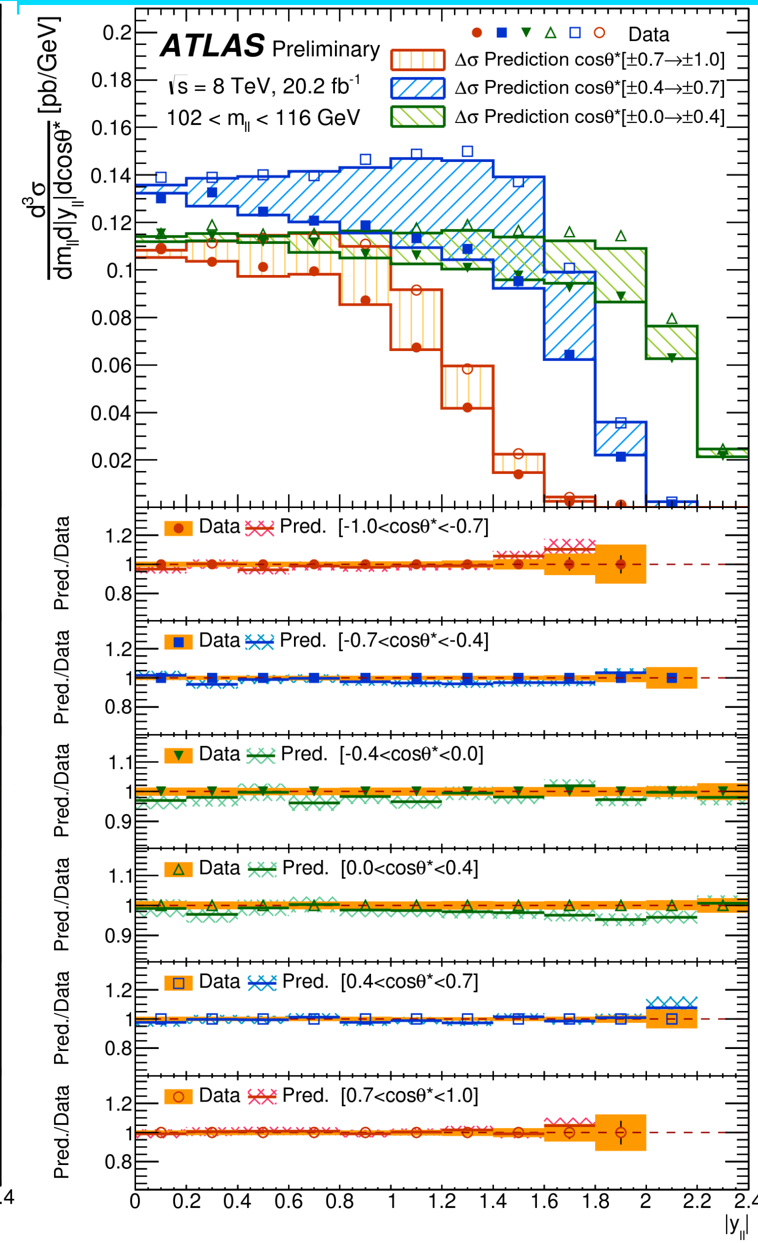
3. Compares >0 & <0 symmetric cosθ* bins

Negative FB-asymmetry below the Z-peak, vanishing at the peak, and…

Z/γ* → l⁺ l⁻ triple differential cross section

TO BE SUBMITTED FOR PUBLICATION SOON



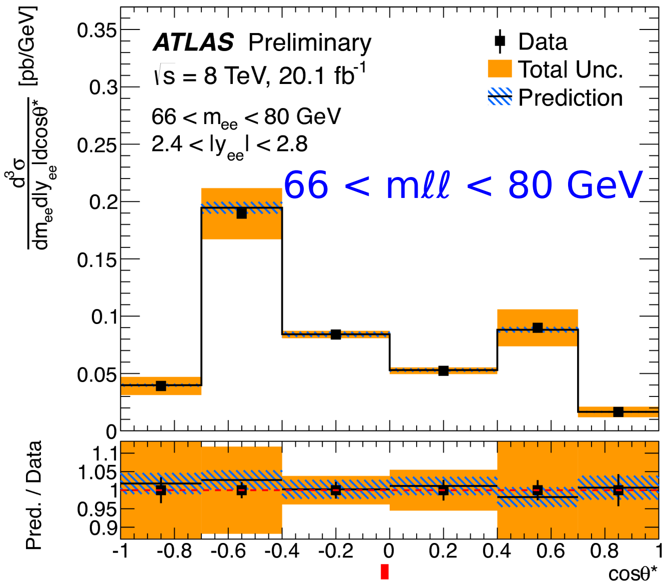


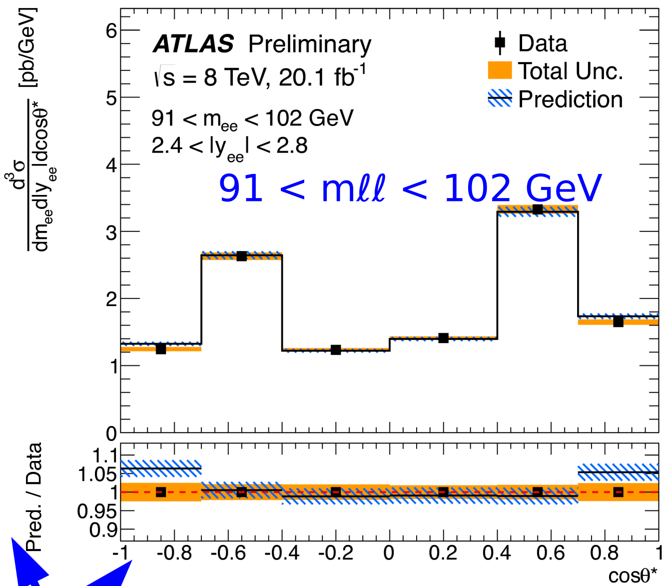
...FB-asymmetry flips sign at Z-peak

* The data accuracy is better than 0.5% in the Z-peak region for $|y_{\ell\ell}| < 1.4$
* Overall good agreement between data and Powheg-based predictions.

$Z/\gamma^* \rightarrow l^+ l^-$: $\cos\theta^*$ for various mass bins & A_{FB}

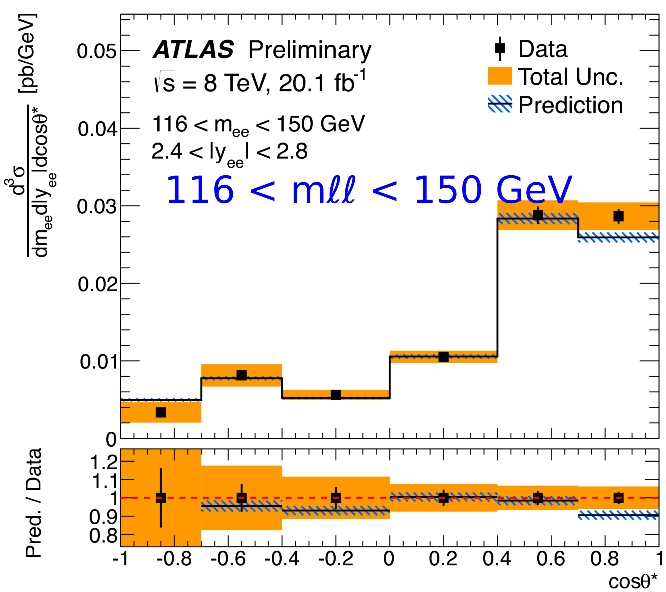
TO BE SUBMITTED FOR PUBLICATION SOON





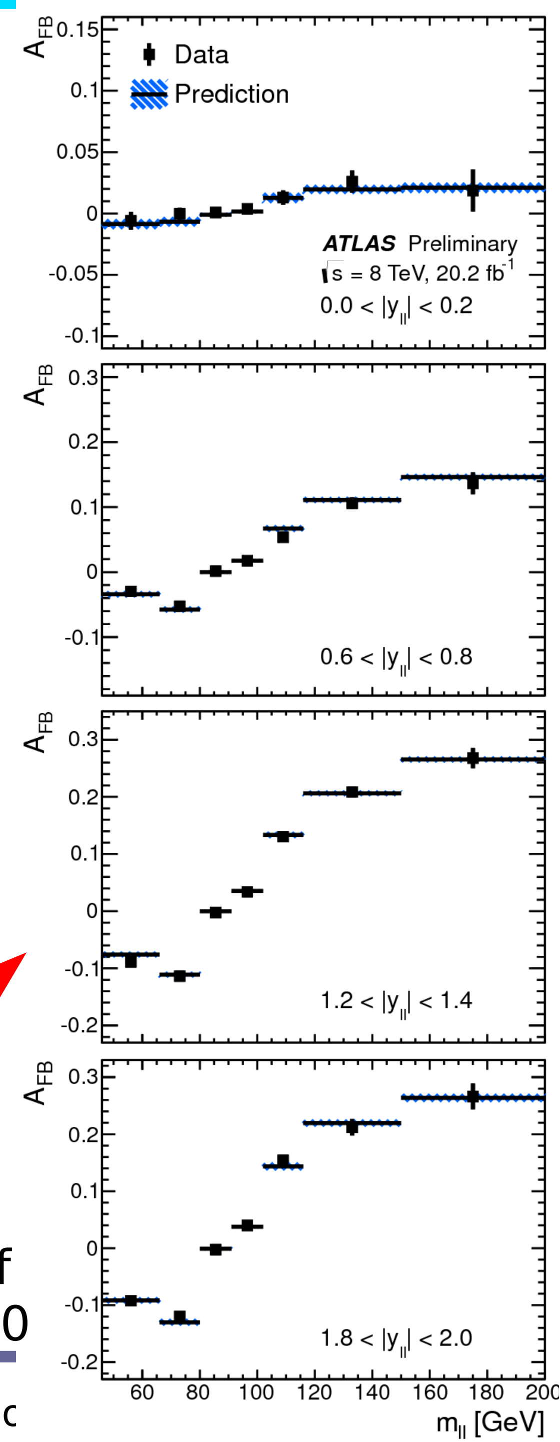
$\cos\theta^* < 0$ | $\cos\theta^* > 0$

$2.4 < y_{\ell\ell} < 2.8$



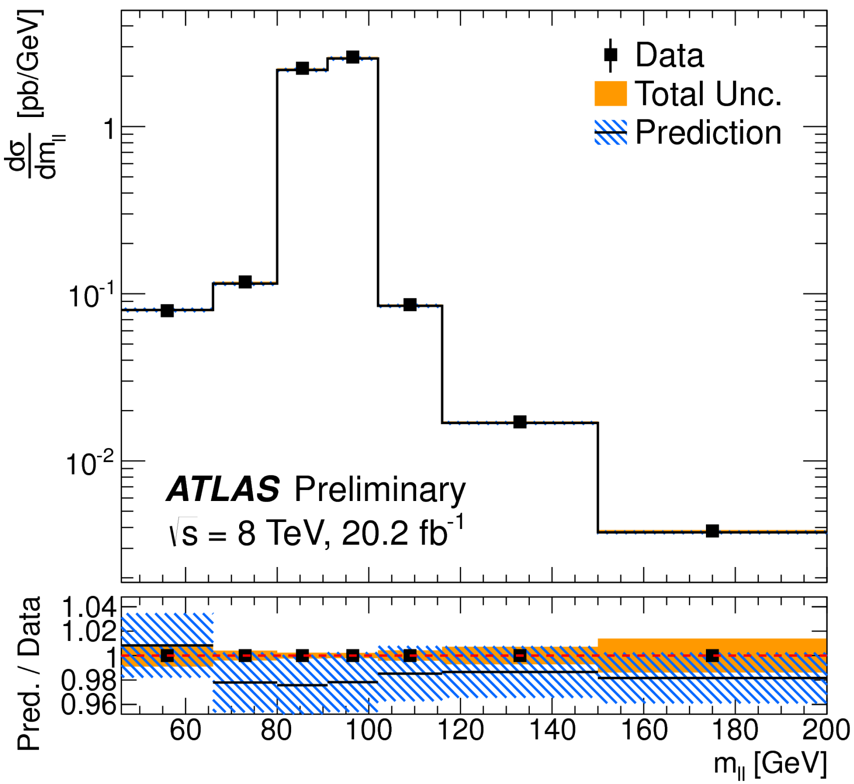
- Large forward-backward Asymmetry develops above Z pole mass;
  Asymmetry flips sign from <0 below Z pole mass to >0 above Z pole

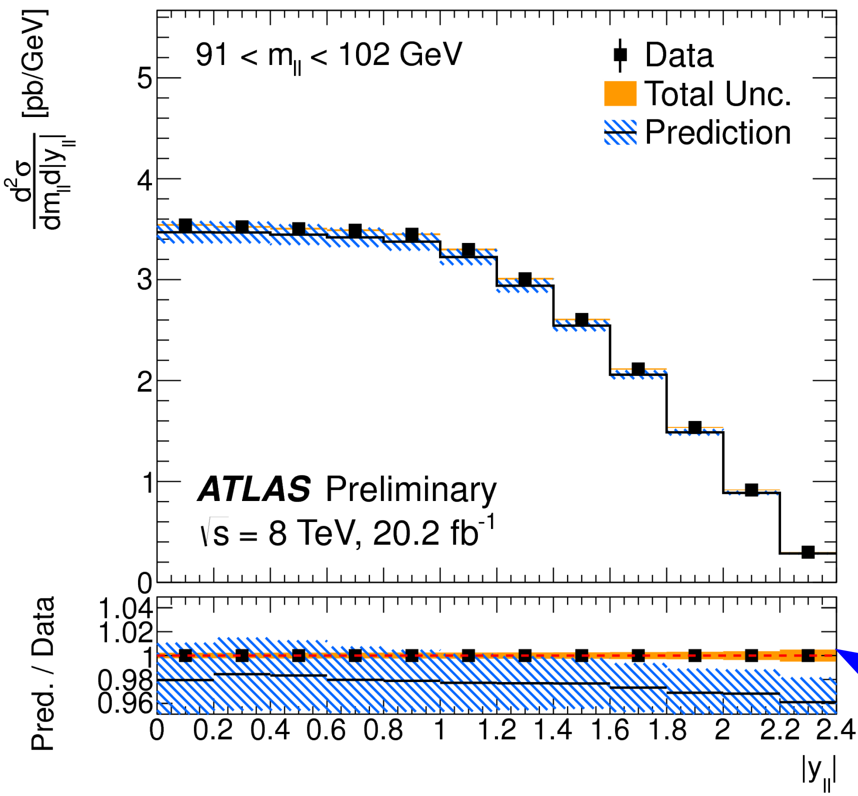
A_{FB} vs. $m_{\ell\ell}$
for rapidity bins
difference over sum of $\cos\theta^* > 0$ and $\cos\theta^* < 0$



TO BE SUBMITTED FOR PUBLICATION SOON

$Z/\gamma^* \rightarrow l^+ l^-$: 1D and 2D





Drell-Yan signal MC uses Powheg with CT10 PDF set, with mass-dependent NNLO/NLO k-factor and pT(ℓℓ)-dependent polarisation coefficients correction computed using DYNNLO

<u>1D (mass) on left:</u> Powheg-based prediction in good agreement with data overall;

<u>2D on right:</u> Notice the great precision of the data compared to the prediction (blue theory band includes the theoretical PDF uncertainty) → potential to constrain PDFs

Summary & Conclusions

- **W mass:**
  - first ATLAS measurement: **m_W = 80370 ± 19 MeV** (same precision as CDF), better agreement of measurements with electroweak fits
- **W and Z cross sections:**
  - precision at sub-percent level, **discriminating predictions**
  - **powerful tools for PDFs** : new PDF set ATLAS-epWZ16 ; valence & s-quark distributions; s-quark ratio to light sea-quarks at low x ~ 1
- **Jets activity in Z events:**
  - **input for further optimisation of MC generators** of Z+jet production
  - powerful **test of pQCD** for processes with high number of partons in the final state
- **Kt splitting scales in Z events:**
  - **sensitive to the hard perturbative modelling and soft hadronic activity**: complementary input to standard jet measurements, in particular in the transition region.
  - With their specific identification of QCD jet evolution they **provide means to constrain and potentially tune Monte Carlo event generators**
- **Triple differential Z/γ cross section**
  - **Mass, rapidity and cosθ*. A_{FB}, on the road the weak-mixing angle**

Thank you

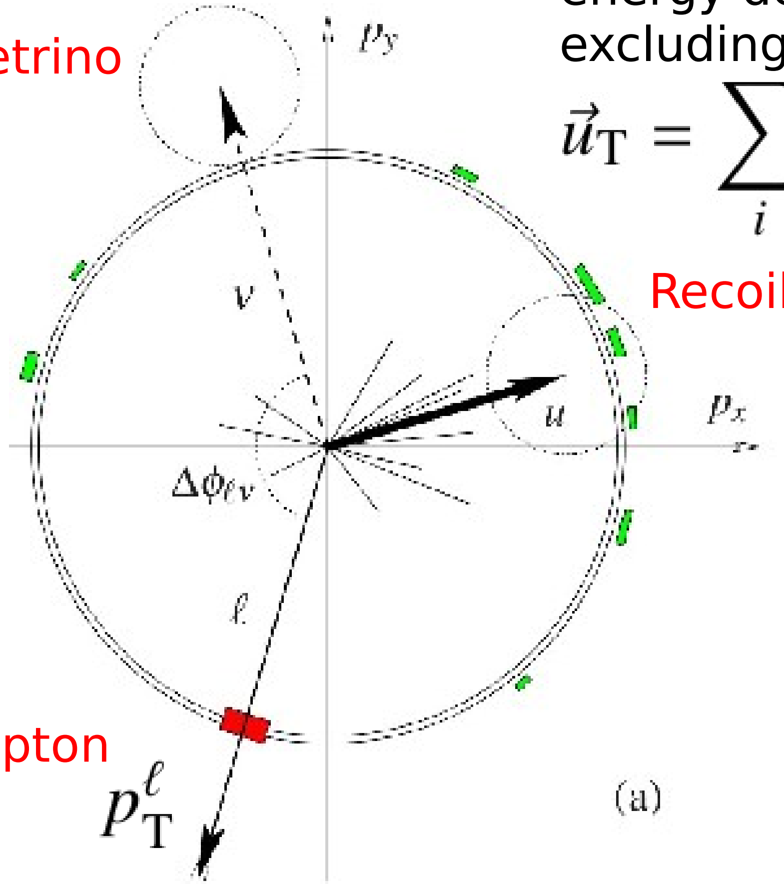
Extra

W mass : topology & method

$$\vec{p}_{\mathrm{T}}^{\mathrm{miss}} = -\left(\vec{p}_{\mathrm{T}}^{\ell} + \vec{u}_{\mathrm{T}}\right)$$

(Sum of calorimeter energy deposits excluding leptons)

$$\vec{u}_{\mathrm{T}} = \sum_i \vec{E}_{\mathrm{T},i}$$



$$m_{\mathrm{T}} = \sqrt{2 p_{\mathrm{T}}^{\ell} p_{\mathrm{T}}^{\mathrm{miss}} (1 - \cos \Delta\phi)}$$

(transverse mass)

- W mass : from fits to lepton p_T and transverse mass distributions
  - Lepton $p_T > 30$ GeV
  - Recoil $u_T < 30$ GeV
  - missing $p_T > 30$ GeV
  - $m_T > 60$ GeV
- Template distributions for various m_W values (with bkg included) → comparison to observed distributions yields m_W based on χ^2 test.

W mass : topology & method

$$\vec{p}_{\mathrm{T}}^{\,\mathrm{miss}} = -\left(\vec{p}_{\mathrm{T}}^{\,\ell} + \vec{u}_{\mathrm{T}}\right)$$

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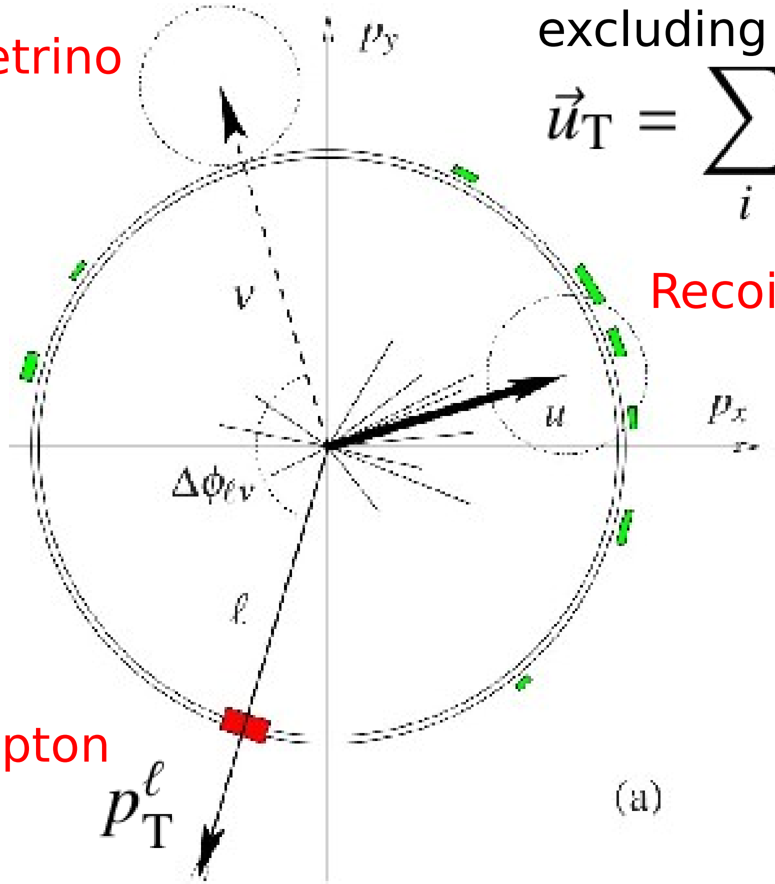

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W mass : from fits to lepton p_T & m_T distributions

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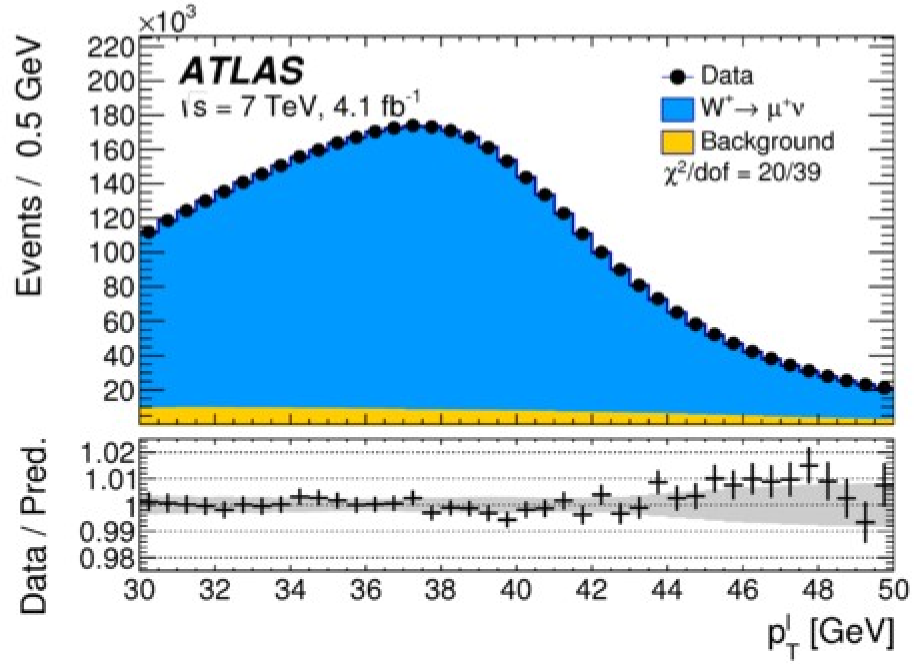
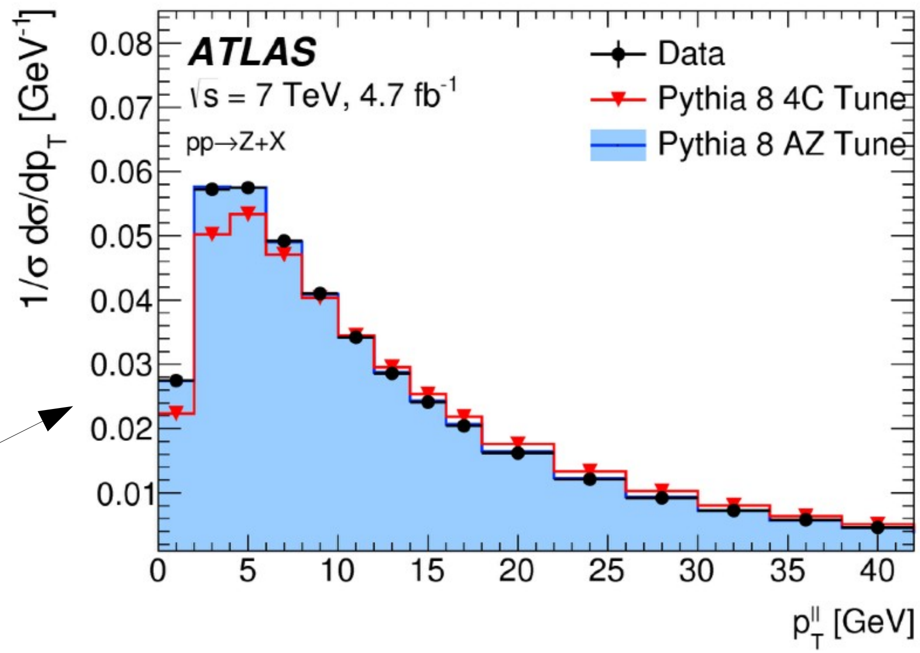


Example lepton p_T ($W^+ \to \mu^+ \nu$)

(<u>for W at rest</u>: lepton p_T has Jacobian edge at m_W / 2 , while m_T has an end-point at m_W)

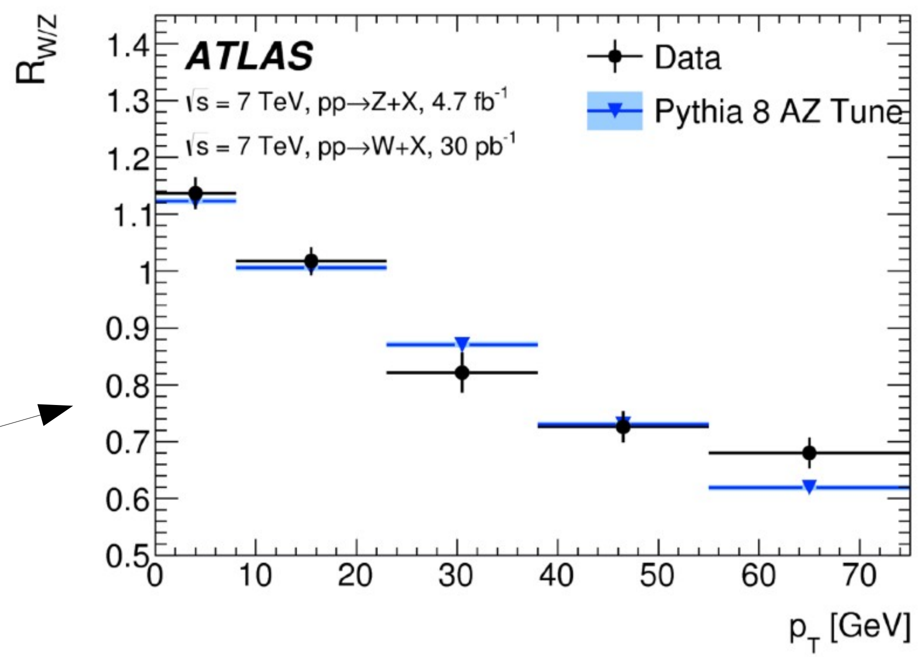
W mass: Physics modelling p_T W

- Pythia8 p_T-ordered parton shower used as model for the p_T W
  - AZ tune: parameters of the model fit to the pT Z measurement at 7 TeV [JHEP 09 (2014) 145]
  - The Pythia8 AZ tune describe the p_T Z data within 2% inclusively and in rapidity bins



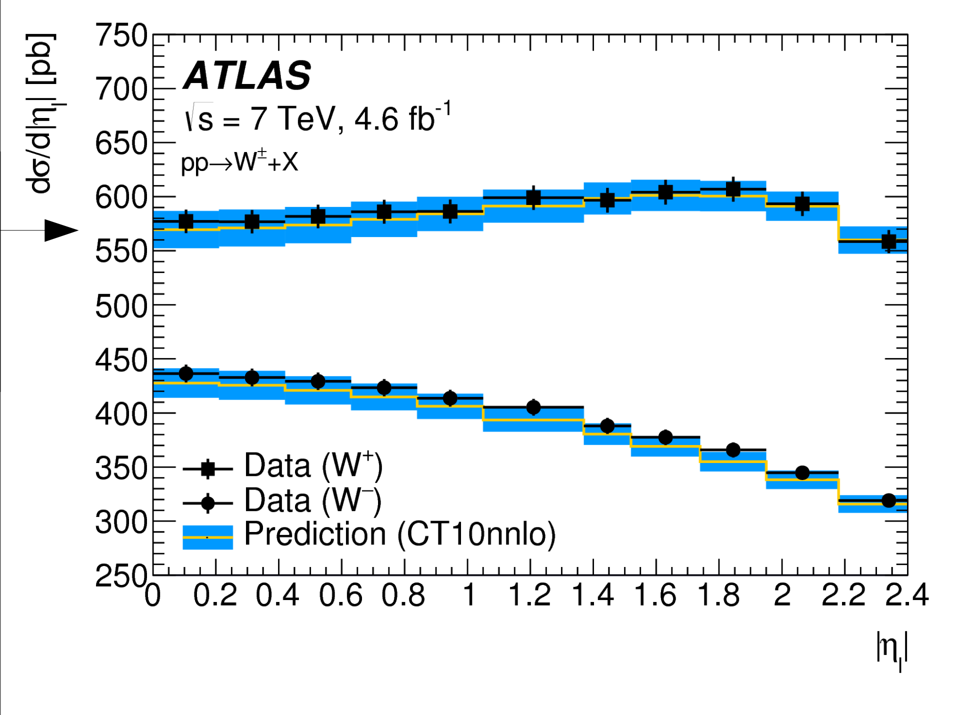
- Pythia8 is used to transfer from the pT Z to the pT W distribution and to evaluate theory uncertainties on the W/Z pT ratio

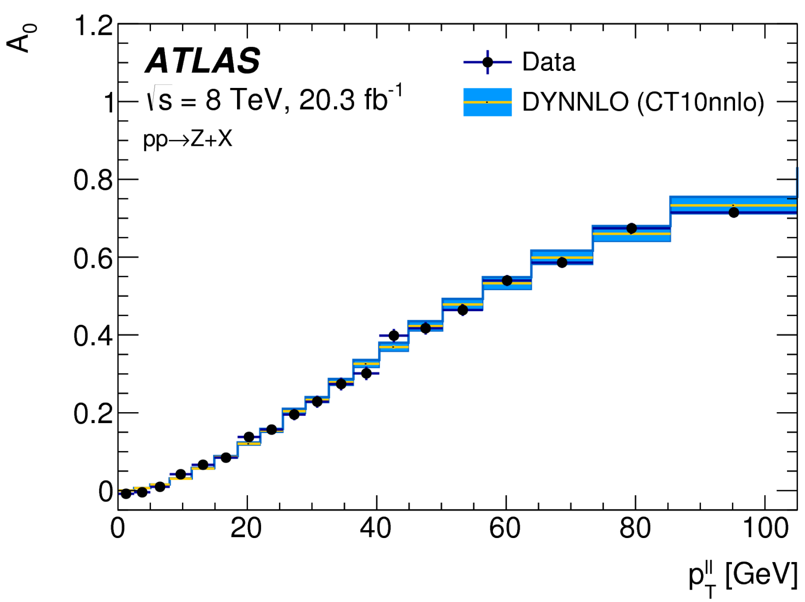
$R_{W/Z}$: ratio of pT shapes

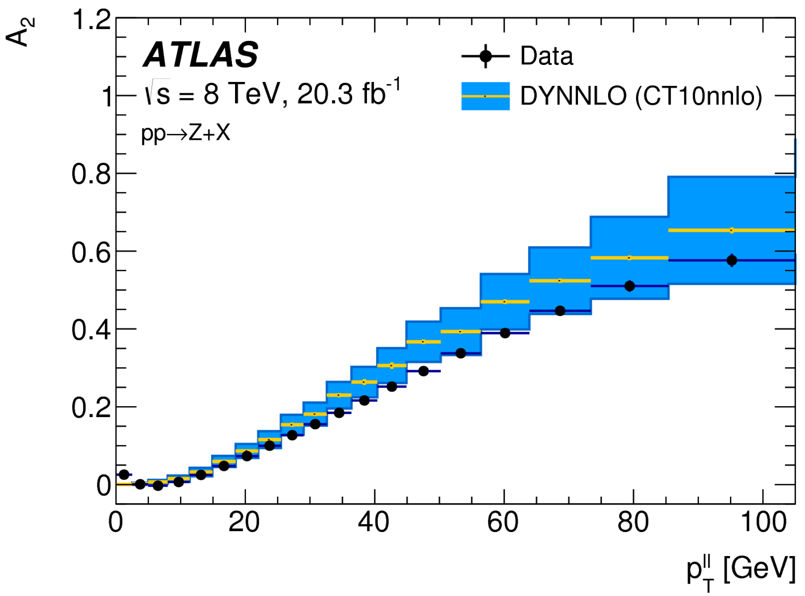


W mass: W rapidity & polarization

- **Use DYNNLO (fixed order NNLO) with CT10nnlo PDF set**
- Validated in W and Z cross section measurements [arXiv:1612.03016, submitted to EPJC]
- ATLAS Z polarization measurement validates fixed-order prediction [JHEP08(2016)159]
  - Uncertainties assigned and propagated from Z to W

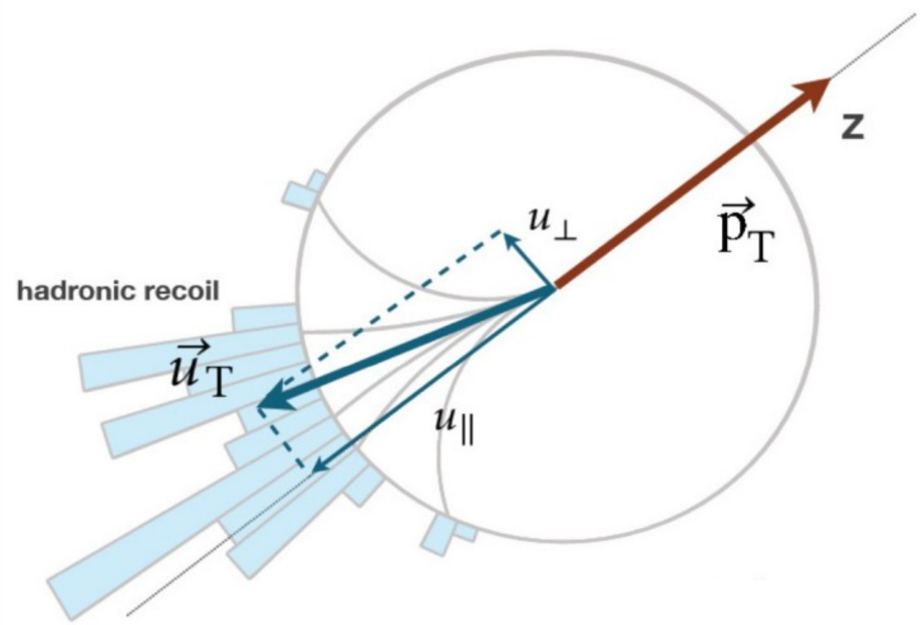


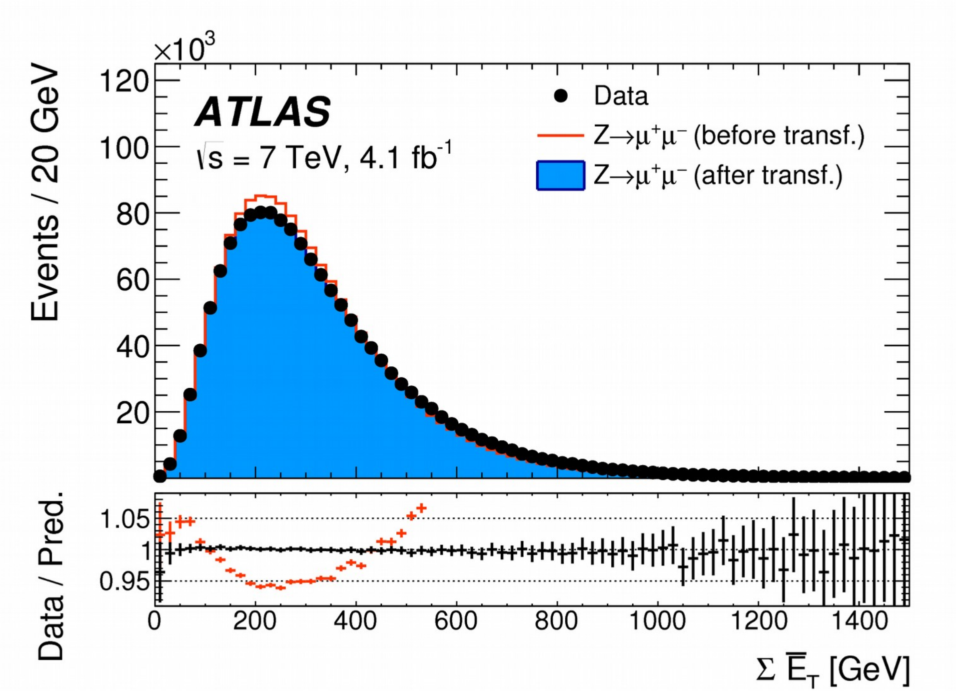


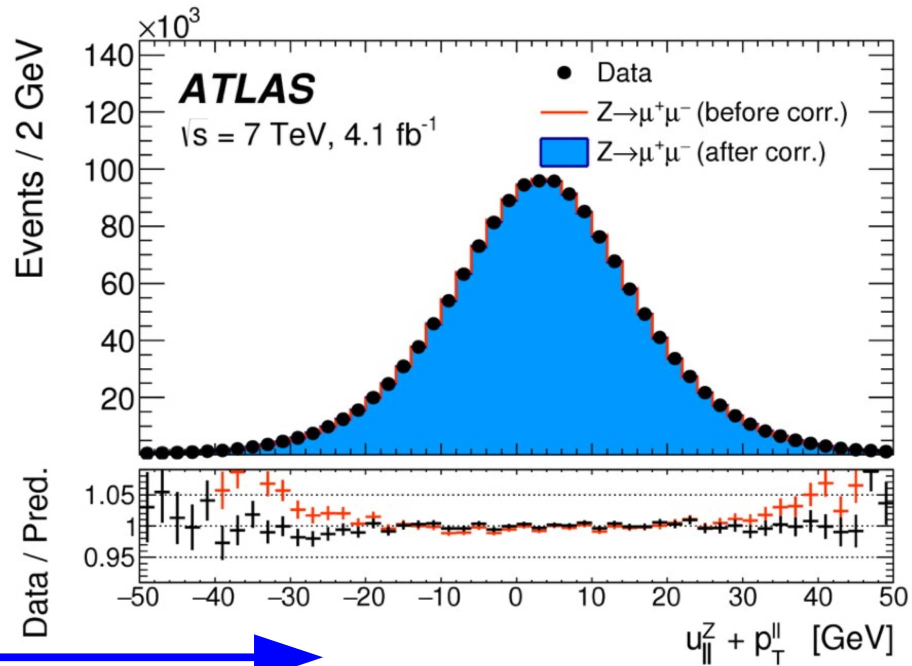


Experimental: Hadronic recoil calibration

- Correct pile-up multiplicity in MC to match the data
- Correct for residual differences in the ΣE_T distribution







- Derive scale and resolution corrections from the p_T balance in Z events

W mass: Hadronic recoil calibration

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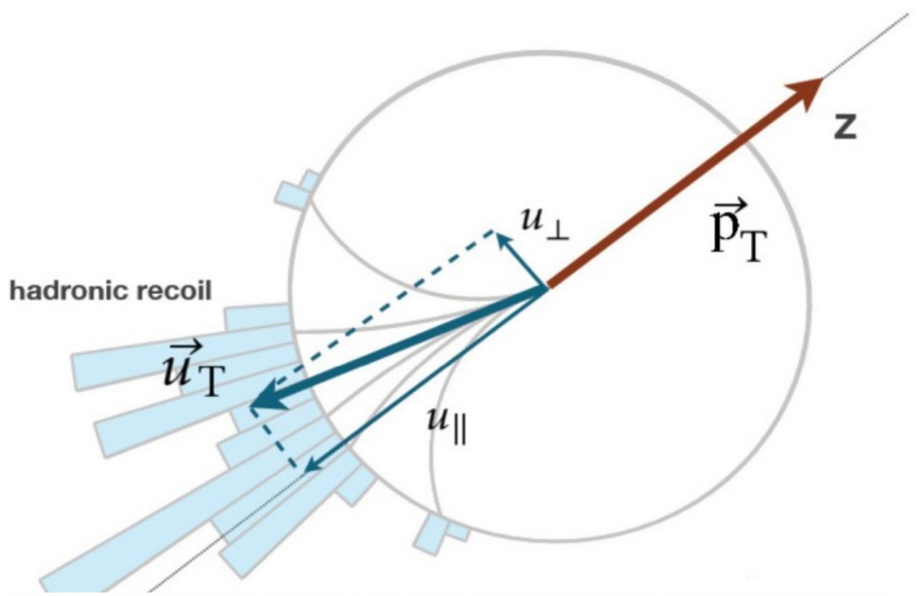
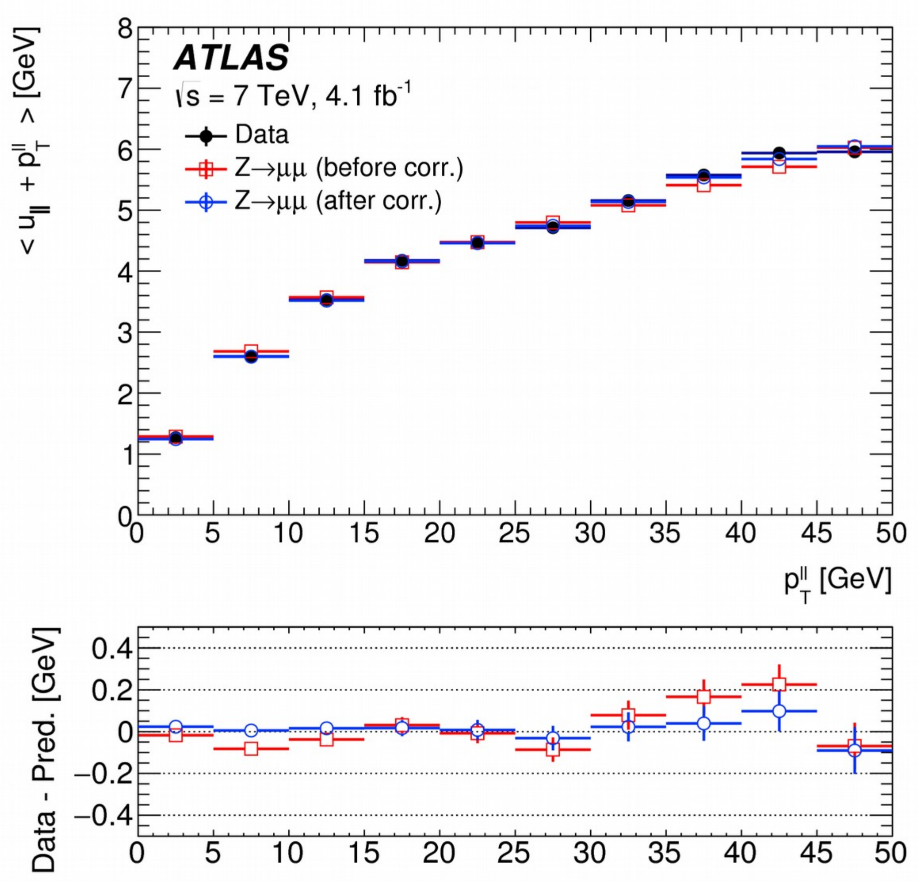
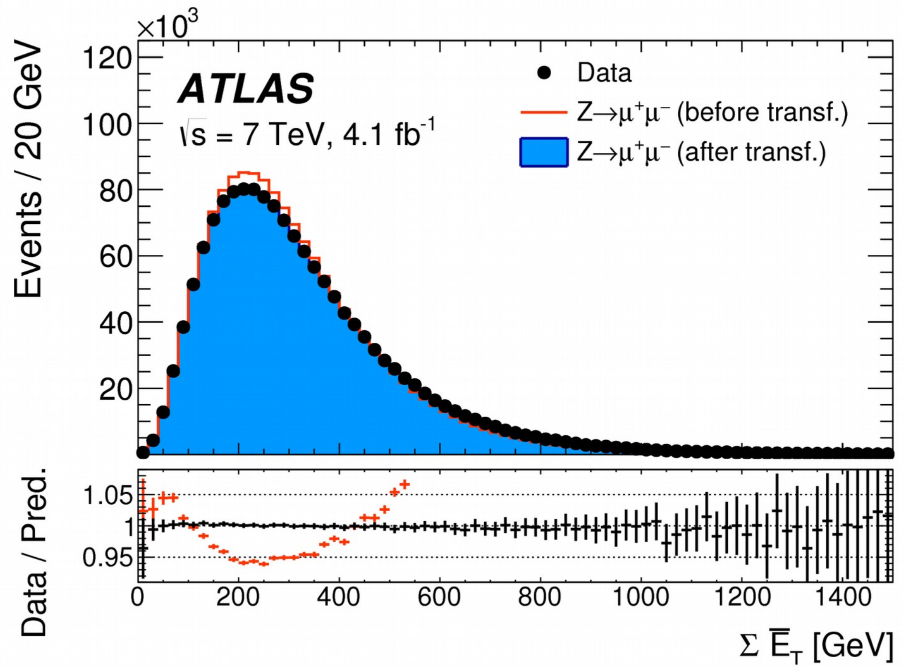


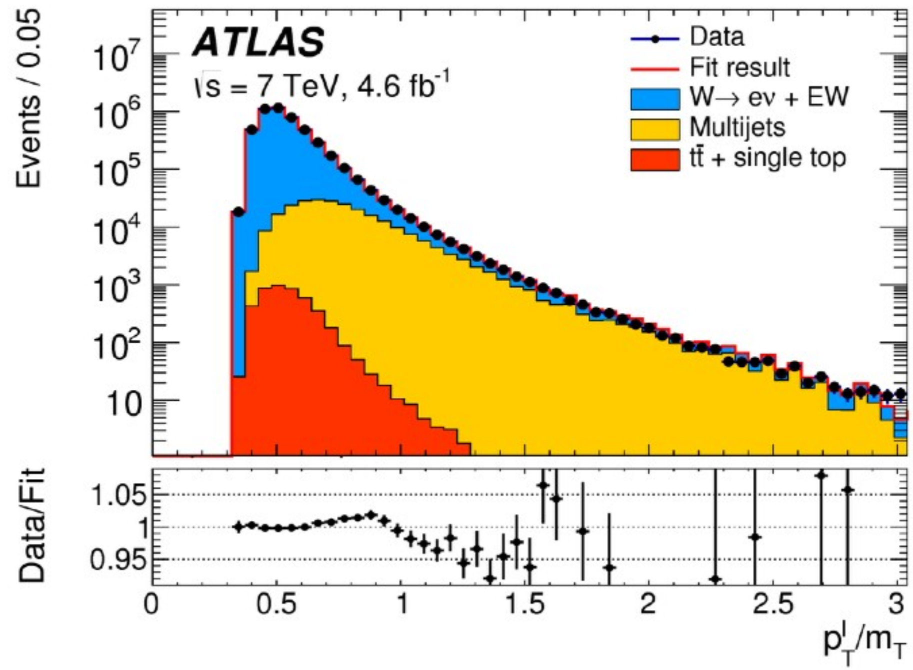


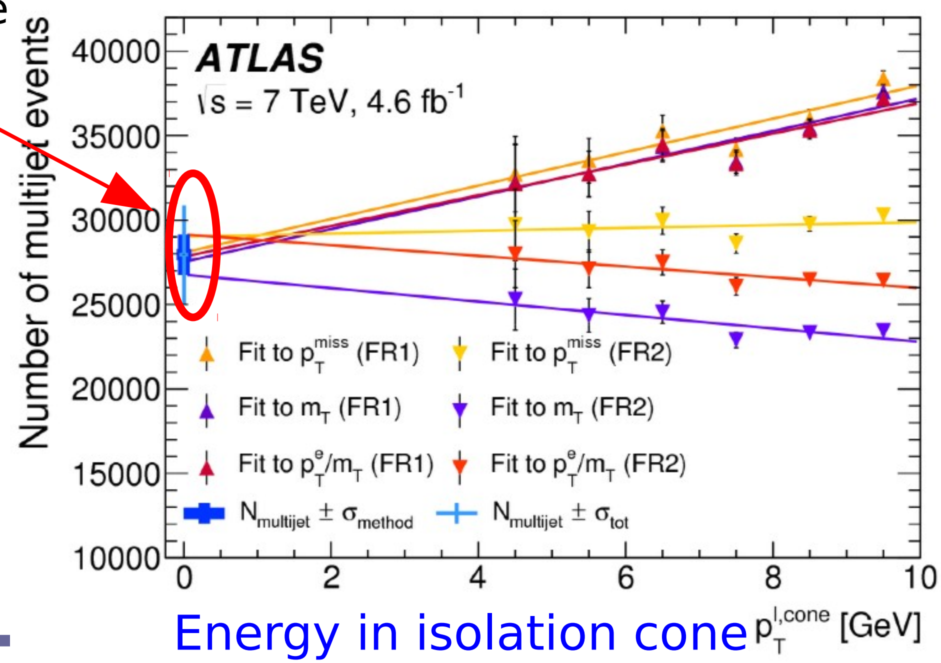


W mass: background

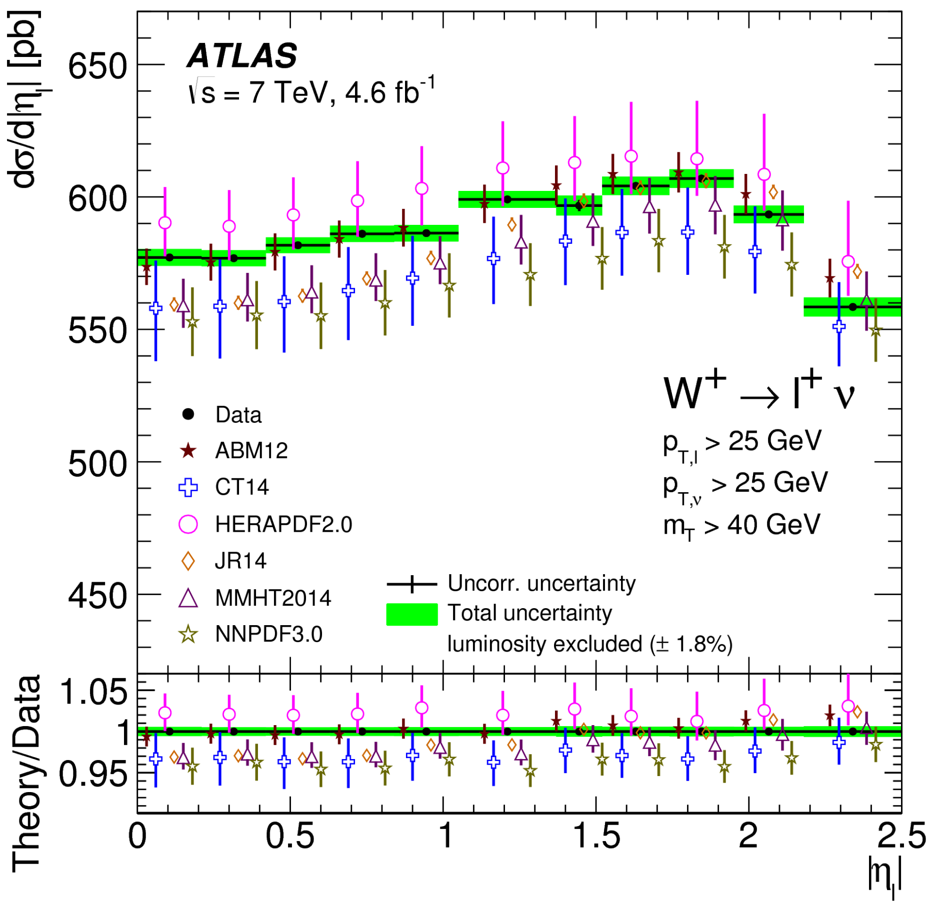
- Estimated number of multijet-background events as a function of the lower bound of the isolation-variable range used to define the control regions.
- The estimation is performed for the two regions FR1 and FR2 with different bkg fraction and three distributions pTmiss, mT, and pTℓ/mT.
- The linear extrapolations are indicated by the solid lines. The thick crosses show the results of the linear extrapolation of the background estimate to the **signal region**, including uncertainties from the extrapolation only. The thin crosses also include the uncertainty induced by the contamination of the control regions by EW and top-quark processes.

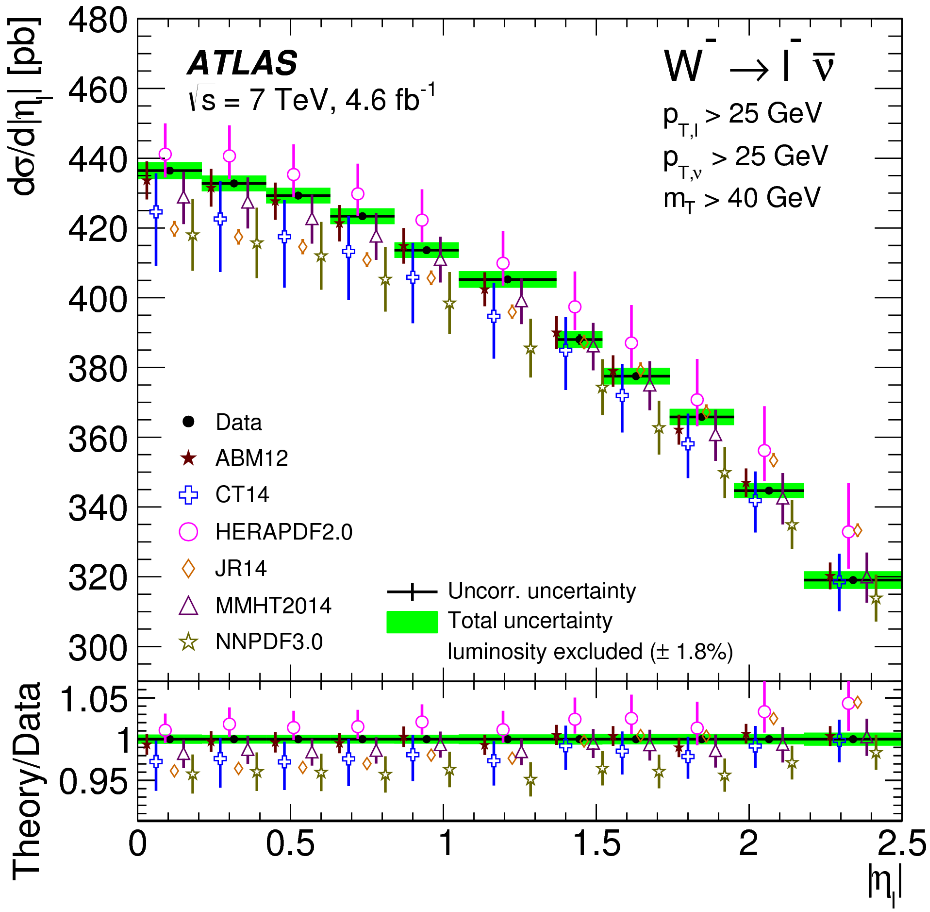
Kinematic distribution	p_T^ℓ				m_T			
Decay channel	$W \to e\nu$		$W \to \mu\nu$		$W \to e\nu$		$W \to \mu\nu$	
W-boson charge	W^+	W^-	W^+	W^-	W^+	W^-	W^+	W^-
δm_W [MeV]								
$W \to \tau\nu$ (fraction, shape)	0.1	0.1	0.1	0.2	0.1	0.2	0.1	0.3
$Z \to ee$ (fraction, shape)	3.3	4.8	–	–	4.3	6.4	–	–
$Z \to \mu\mu$ (fraction, shape)	–	–	3.5	4.5	–	–	4.3	5.2
$Z \to \tau\tau$ (fraction, shape)	0.1	0.1	0.1	0.2	0.1	0.2	0.1	0.3
WW, WZ, ZZ (fraction)	0.1	0.1	0.1	0.1	0.4	0.4	0.3	0.4
Top (fraction)	0.1	0.1	0.1	0.1	0.3	0.3	0.3	0.3
Multijet (fraction)	3.2	3.6	1.8	2.4	8.1	8.6	3.7	4.6
Multijet (shape)	3.8	3.1	1.6	1.5	8.6	8.0	2.5	2.4
Total	6.0	6.8	4.3	5.3	12.6	13.4	6.2	7.4





W^+ and W^- differential cross sections



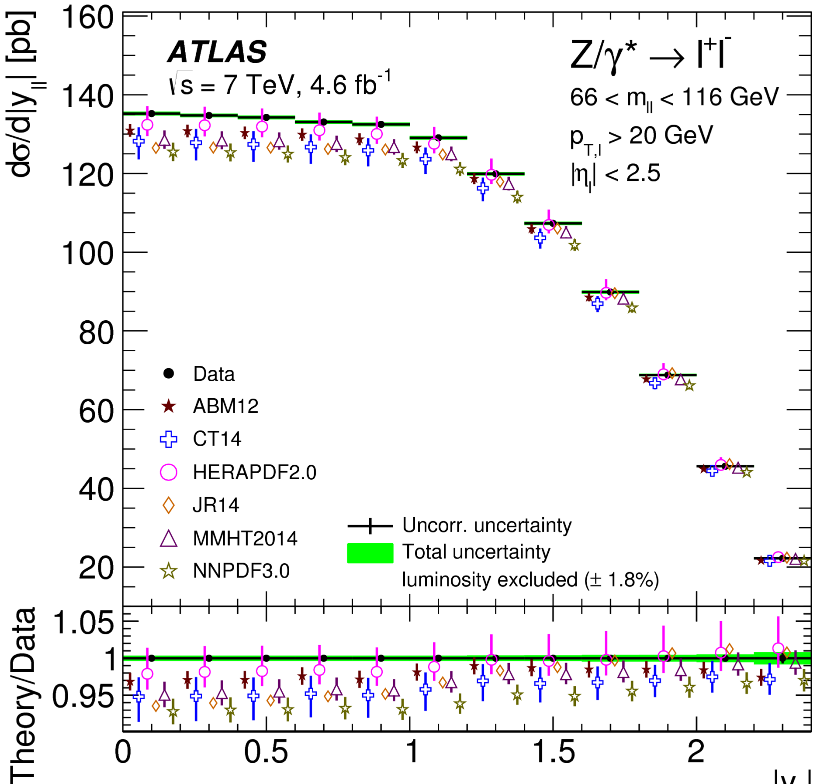


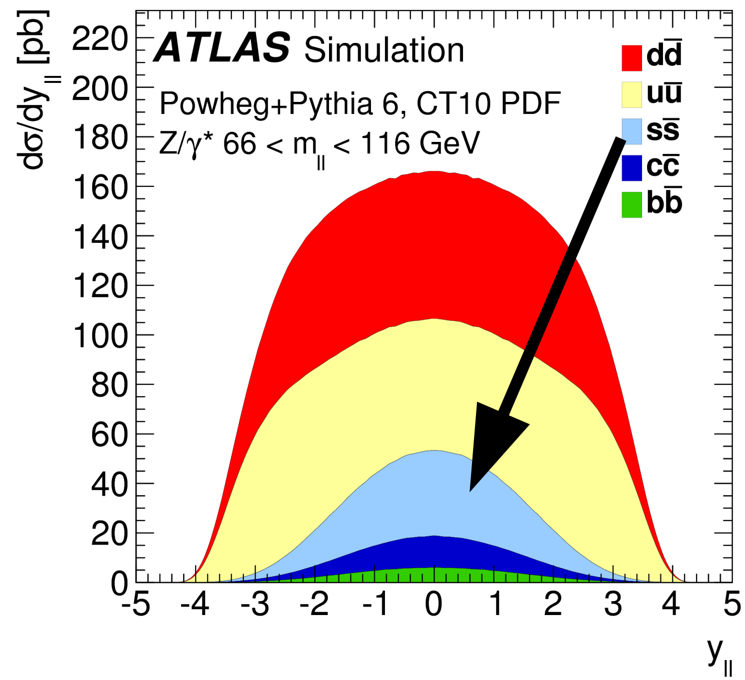
Uncertainty on measured shape is ~0.1 - 0.2% per bin : large constraining power

All predictions besides HERAPDF2.0 lower than measurements, and all with large PDF uncertainties

(Predictions computed at NNLO QCD with NLO EW corrections)

Z differential cross sections and s-quarks

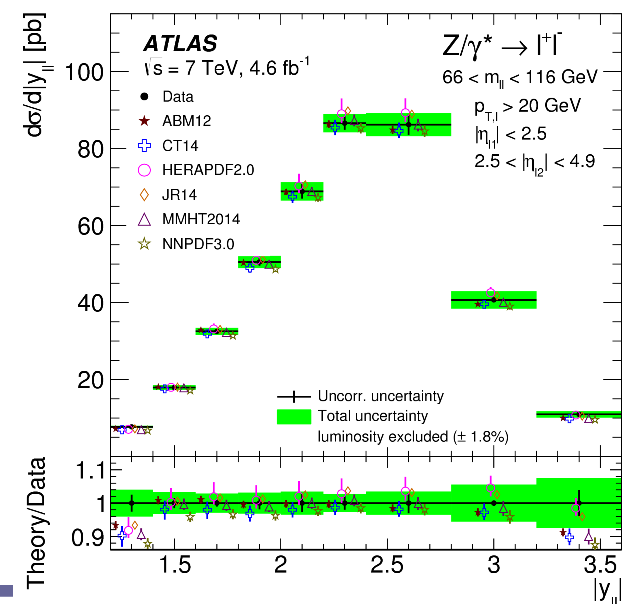




Prediction from Powheg+Pythia with CT10 PDF
No event selection beyond dilepton mass window

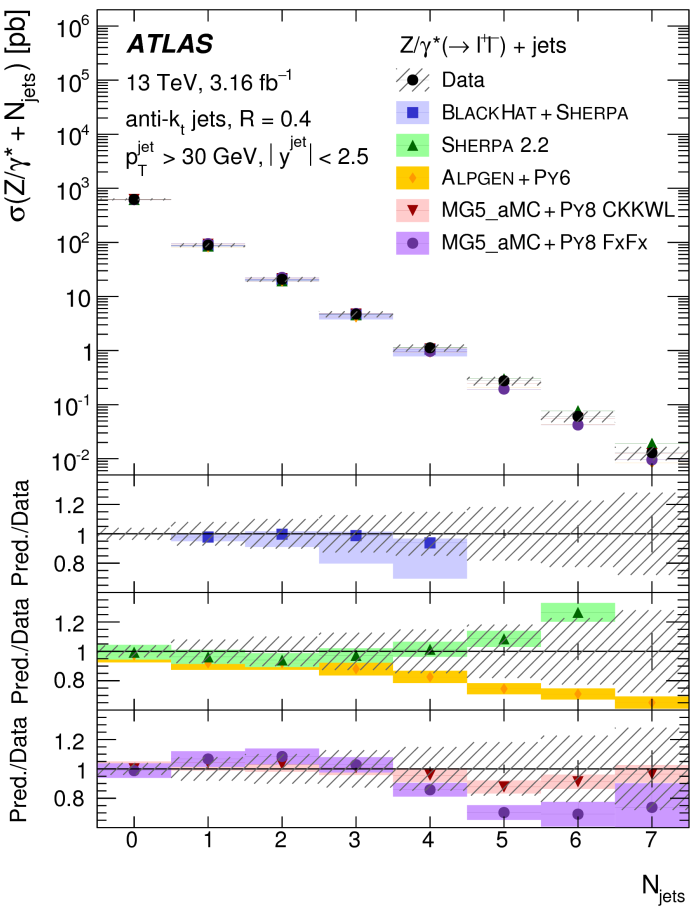
Z rapidity:

Most predictions lower than data in |y|<1
Potential problem in description of s-quark vs. sea d-quarks ?

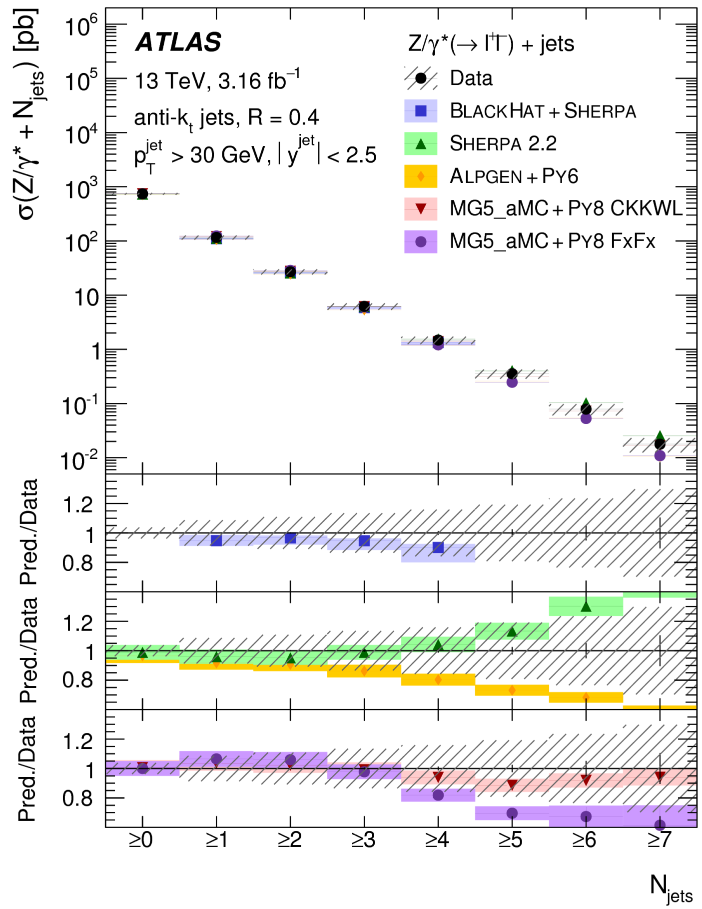


Z rapidity: OK for Z rapidity 1.1 < |y| < 3.5

Z + jets – jet multiplicity



Exclusive jet multiplicity



Inclusive jet multiplicity

- Sherpa 2.2, Alpgen+Py6, MG5_aMC+Py8 FxFx do not describe data for high jet multiplicity, where large fraction of jets produced by PS.
  - MG5_aMC+Py8 CKKWL seems OK for jet multiplicity

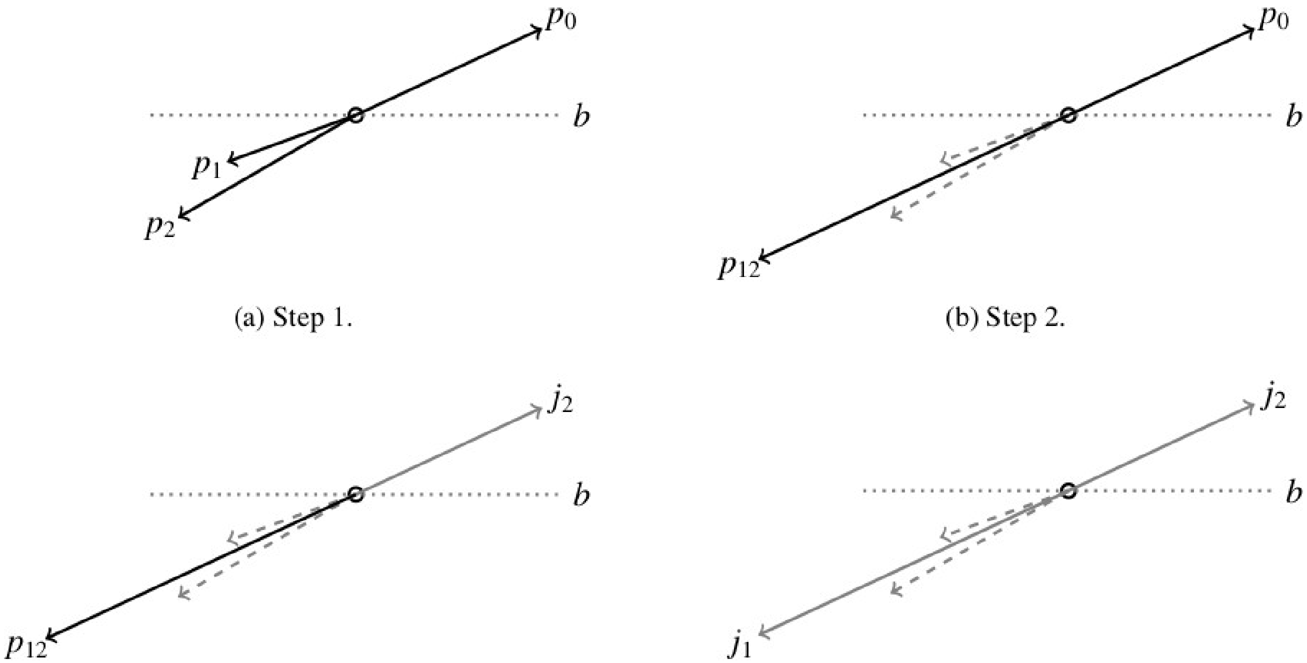
Jet clustering by k_t algorithm

- Splitting scales of jets constructed with the "k_t clustering algorithm": infrared-safe, based on sequential combination of objects in a list till exhausting the list.

Combinations based on two distances:

1) $$d_{ij} = \min\left(p_{T,i}^2, p_{T,j}^2\right) \times \frac{\Delta R_{ij}^2}{R^2}, \qquad \left(\Delta R_{ij}\right)^2 = \left(y_i - y_j\right)^2 + \left(\phi_i - \phi_j\right)^2$$

2) $$d_{ib} = p_{T,i}^2,$$ ← each item compared to the beam axis



(a) Step 1. (b) Step 2. (c) Step 3. (d) Step 4.

For a given iteration the number of input momenta drops from k+1 → k, and a "splitting scale" is defined:

$$d_k = \min_{i,j}(d_{ij}, d_{ib})$$

* if min is d_{ij} → combine i,j
* if min is d_{ib} → remove i from list and call it a jet

$Z/\gamma \to l^+ l^-$ triple differential cross section

TO BE SUBMITTED FOR PUBLICATION SOON

Triple differential cross-section measurement
CS: Collins-Soper frame.

$$\frac{d^3\sigma}{dm_{\ell\ell}\,dy_{\ell\ell}\,d\cos\theta^*_{CS}}$$

- Sensitivity to the PDFs and the Z forward-backward asymmetry, AFB
  - Difference in Z / γ couplings allows for PDF decomposition
  - Terms proportional to Z and γ contribute differently at different $m_{\ell\ell}$
  - Interference term generates cosθ* asymmetry which changes sign at m_Z. The asymmetry vanishes at $y_{\ell\ell} = 0$, and increases with $y_{\ell\ell}$, due to larger difference in q and ¯q contributions.
- Builds foundation for a possible future extraction of the weak-mixing angle.
  - Previous result at 7 TeV, 4.6 /fb [JHEP09(2015)049] limited by PDF uncertaitnies