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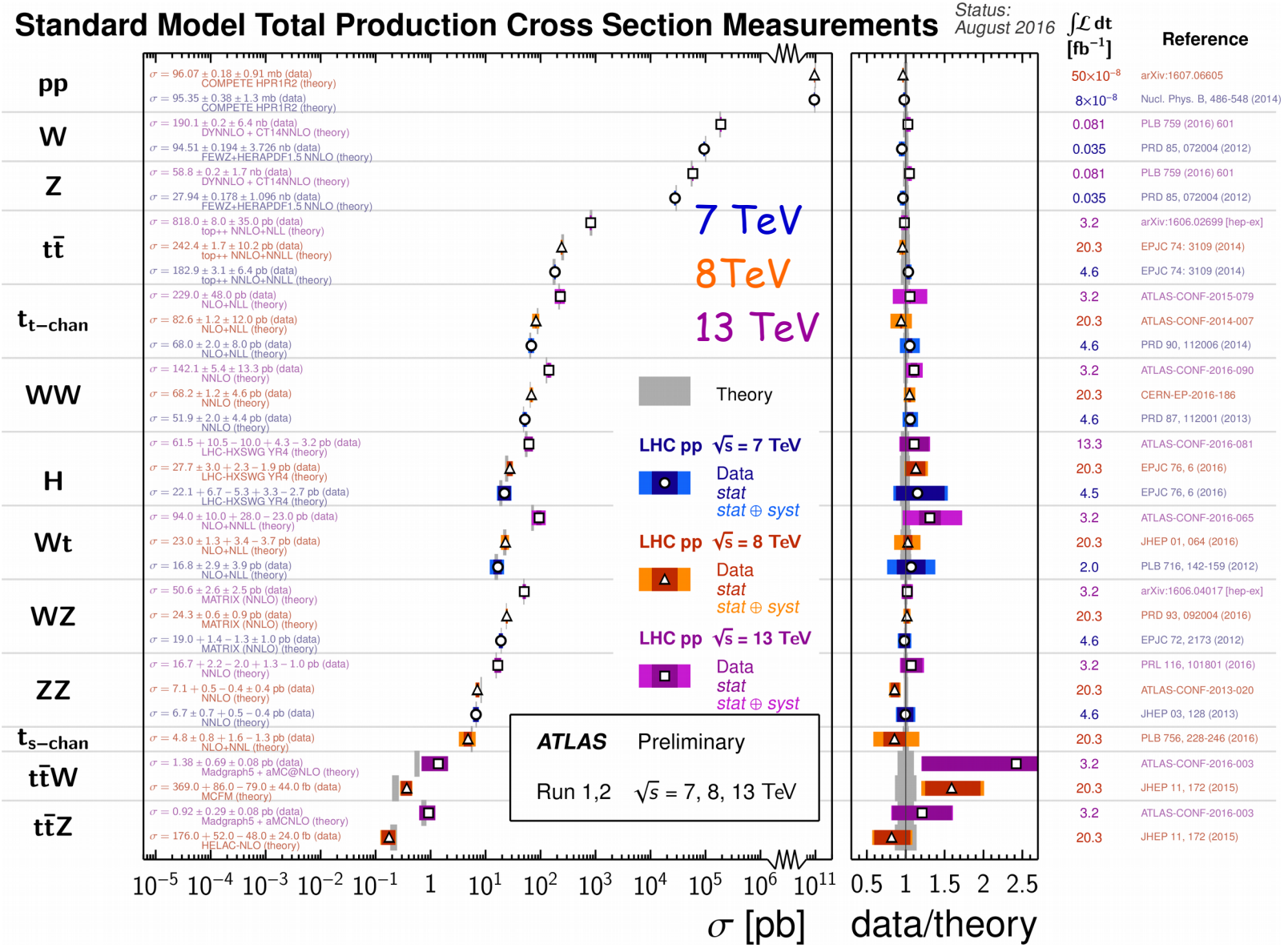
W and Z/γ* inclusive and differential cross sections in ATLAS

Misha Lisovyi on behalf of the ATLAS Collaboration

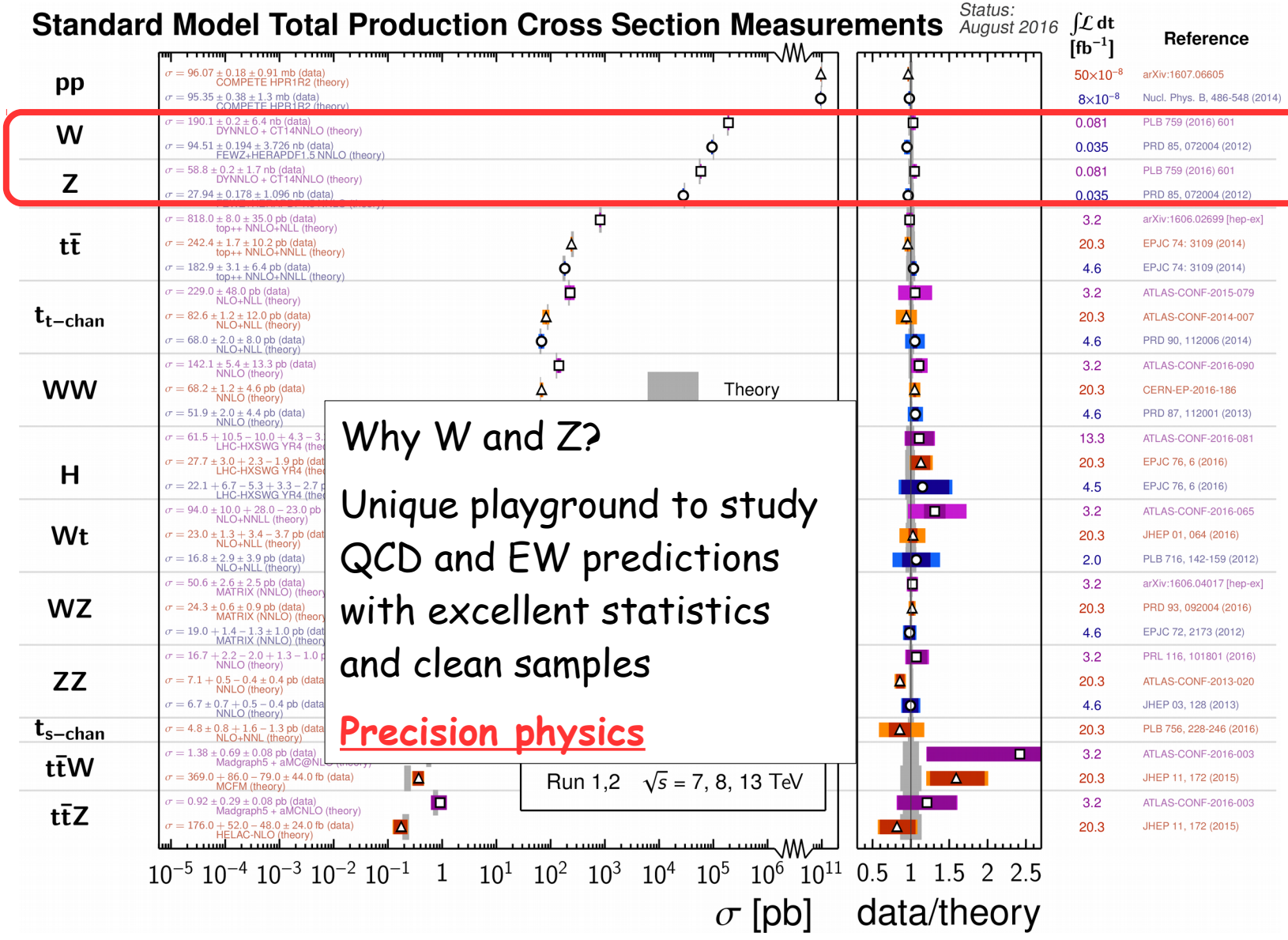
ICHEP

5.08.2016

SM success


Standard Model Total Production Cross Section Measurements
Status: August 2016
$\int \mathcal{L}\,dt$ [fb^{-1}]
Reference
pp
W
Z
$t\bar{t}$
t_{t-chan}
WW
H
Wt
WZ
ZZ
t_{s-chan}
$t\bar{t}W$
$t\bar{t}Z$
7 TeV
8TeV
13 TeV
Theory
LHC pp $\sqrt{s}$ = 7 TeV
Data
stat
stat ⊕ syst
LHC pp $\sqrt{s}$ = 8 TeV
Data
stat
stat ⊕ syst
LHC pp $\sqrt{s}$ = 13 TeV
Data
stat
stat ⊕ syst
ATLAS Preliminary
Run 1,2 $\sqrt{s}$ = 7, 8, 13 TeV
10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 1 10^{1} 10^{2} 10^{3} 10^{4} 10^{5} 10^{6} 10^{11}
σ [pb]
0.5 1 1.5 2 2.5
data/theory

SM success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Reference
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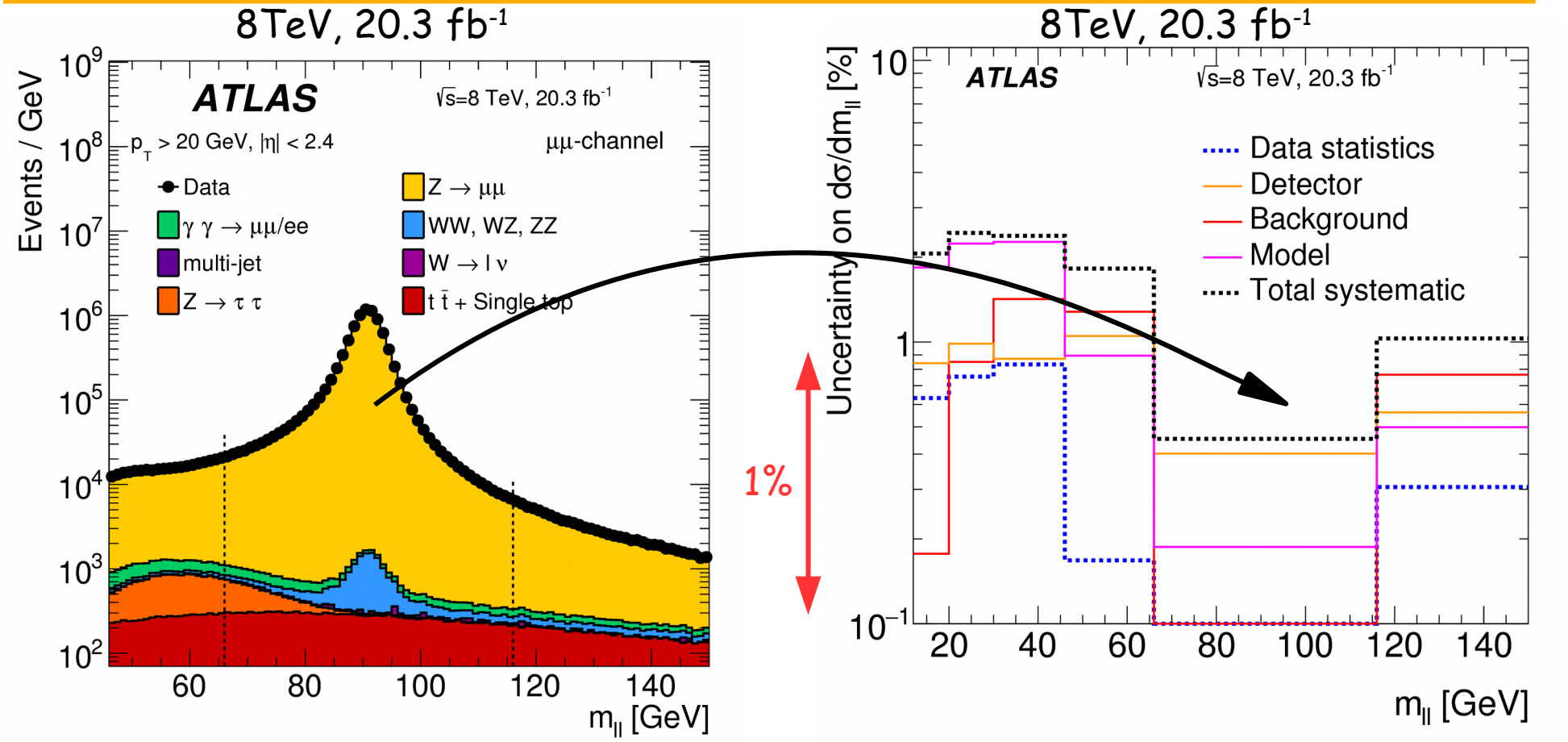
$t\bar{t}$
t_{t-chan}
WW
H
Wt
WZ
ZZ
t_{s-chan}
$t\bar{t}W$
$t\bar{t}Z$
Theory
Why W and Z?
Unique playground to study QCD and EW predictions with excellent statistics and clean samples
Precision physics
Run 1,2 $\sqrt{s}$ = 7, 8, 13 TeV
σ [pb]
data/theory

Precision with W & Z



- O(10M) di-lepton pairs at Z peak --> huge statistics.
- Most systematic sources are constrained by the data --> syst ~ stat.
- Total uncertainties at **permille** level.
- Test QCD and EW corrections at sub-percent level and constrain PDFs.

Outline

- Integrated fiducial W and Z cross sections and ratios @ 13 TeV (PLB 759 (2016) 601)
- High-mass differential Drell-Yan cross sections @ 8 TeV (arXiv:1606.0173, subm. to JHEP)
- Differential Z p_T and φ^*_η cross sections @ 8TeV (EPJC 76 (2016) 291)
- Angular coefficients of leptons from Z decay @ 8 TeV (arXiv:1606.00689, subm. to JHEP)

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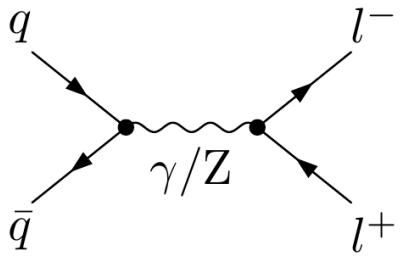
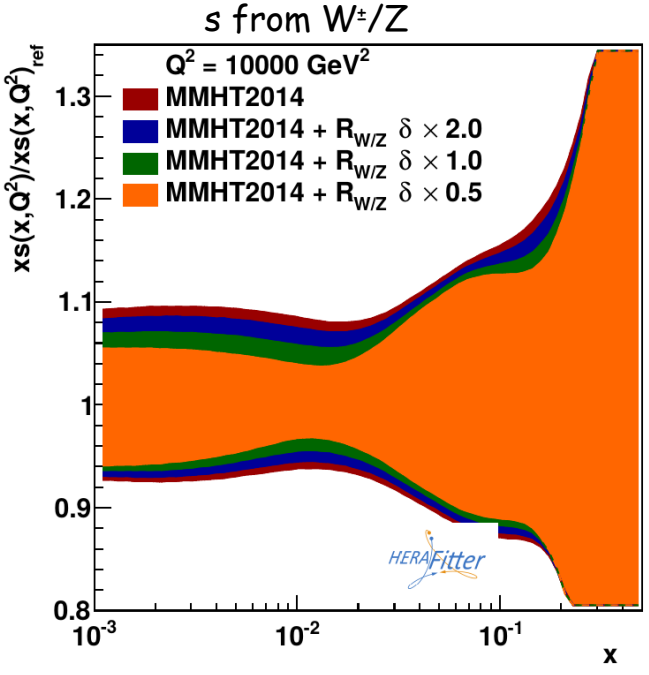
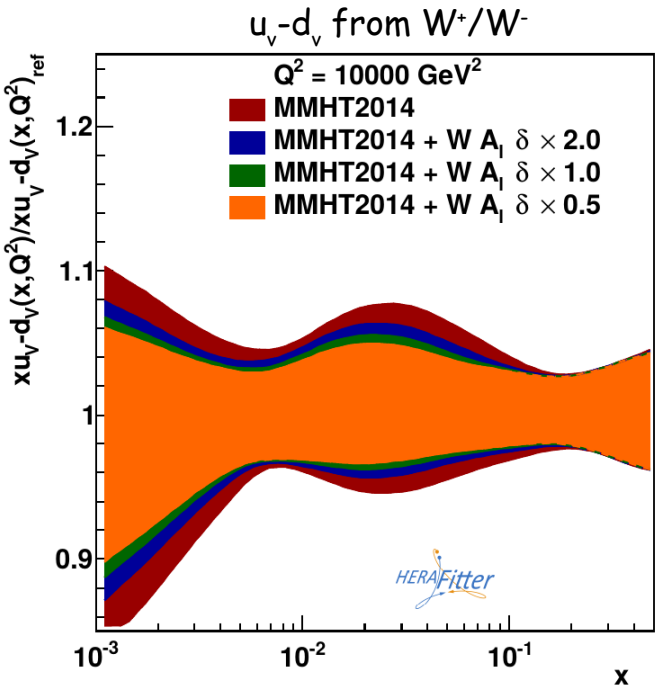
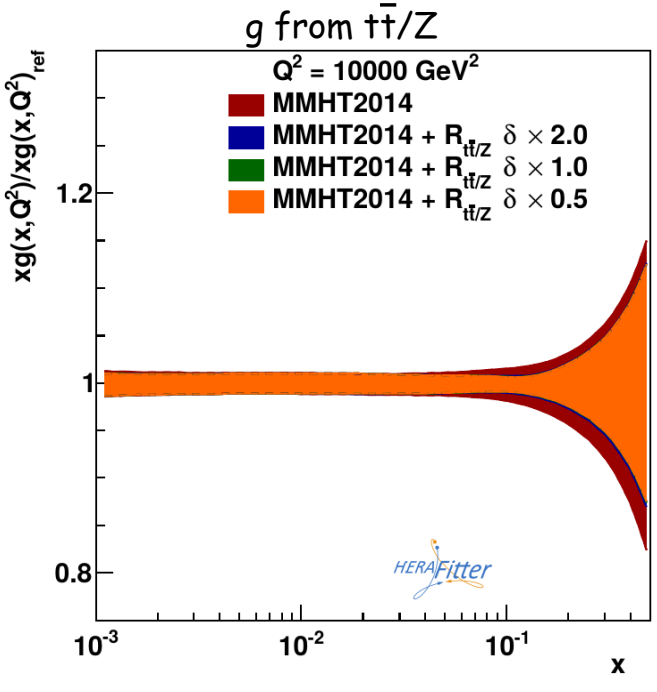
W,Z @ 13 TeV: motivation

- Rediscover standard candles in the new kinematic regime!
- Measure cross-section ratios: fully cancel lumi uncertainties and partially systematics.
- W/Z: 2% exp. precision adds constraint on strange PDF
- W^+/W^-: 2% contrains u_v-d_v PDF.
- $t\bar{t}/Z$: 2-4% adds constraint on the high-x gluon PDF.









J. Rojo et al., J.Phys.G 42 (2015) 103103

Analysis overview

W±:

- $p_T^l > 25$ GeV
- $|\eta^l| < 2.5$
- $p_T^\nu > 25$ GeV
- $m_T > 50$ GeV

Z:

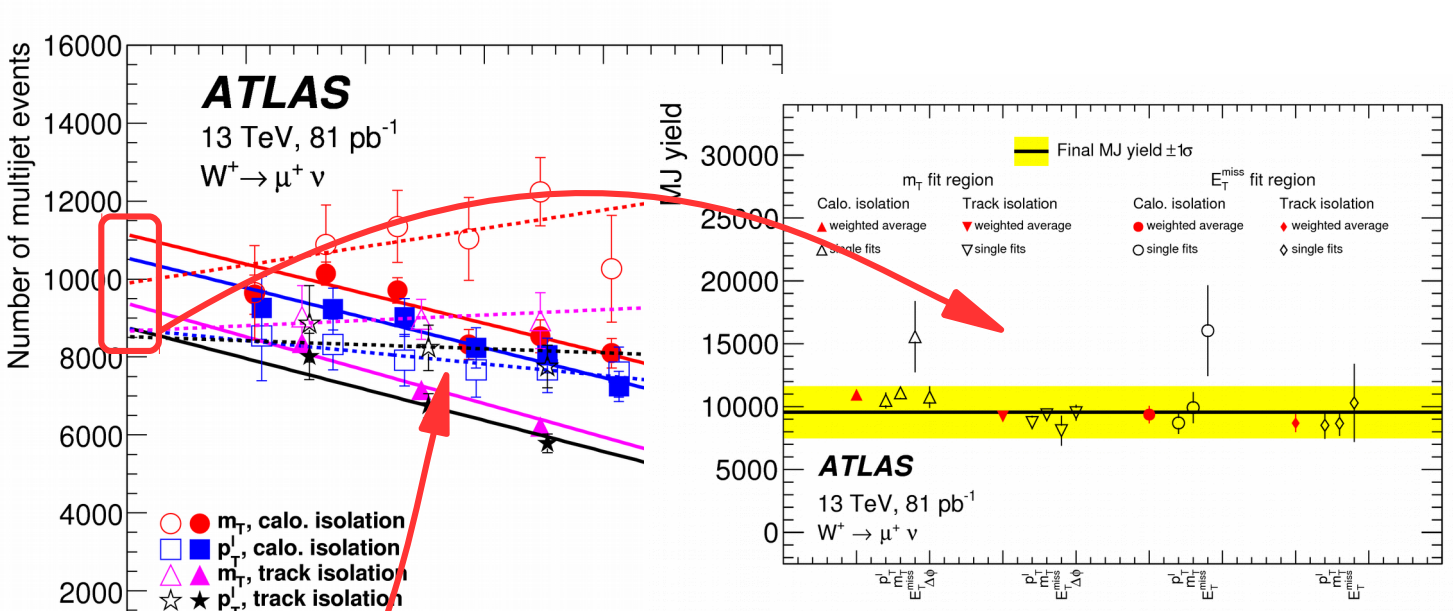
- $p_T^l > 25$ GeV
- $|\eta^l| < 2.5$
- $66 < M < 116$ GeV

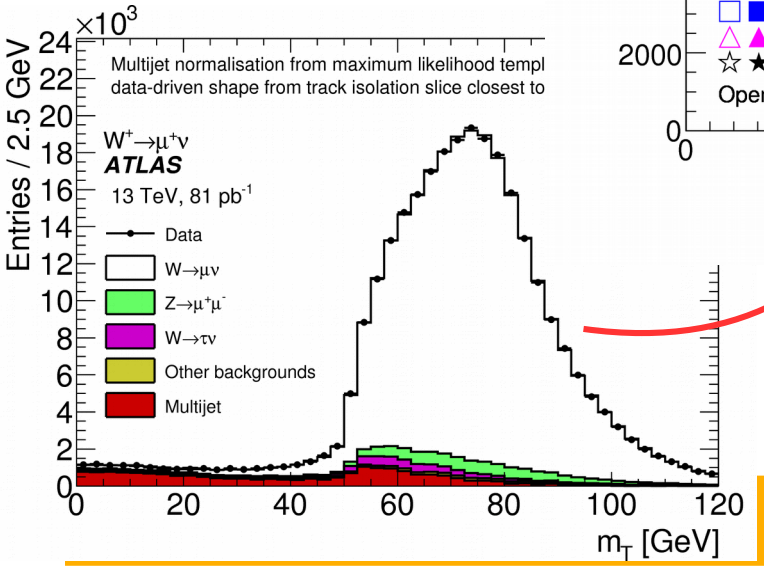
$$\sigma^{fid}_{W,Z} \times BR(W,Z \to l\nu, ll) = \sigma^{tot}_{W,Z} \times BR(W,Z \to l\nu, ll) \cdot A_{W,Z} = \frac{N - B}{C_{W,Z}\,\mathcal{L}_{W,Z}}$$

- N: di-lepton signal candidates W±~O(1M), Z~O(100k)
- B: estimated background candidates: EW+top from MC and data-driven multijet
- $C_{W,Z}$: corrections factor (1-bin unfolding)
- L: luminosity, 81 pb^{-1} ± 2.1%
- Combine ee and μμ cross sections using HERAverager (χ^2 minimisation treating correlated systematics as nuisance parameters)

Multijet background

- Key: <u>isolated leptons from W and non-isolated from QCD</u>.
- Template fit in either of m_T, E_T^{miss}, p_T^l, $\Delta\varphi$ removing either m_T or E_T^{miss} cut for slices of calo- or track-based isolation. Extrapolated to the signal-like isolation topology.
- W -> ev: 9% ± 3%
- W -> μv: 4% ± 0.8%





Measurement precision

- Already systematics-limited!
- Dominating uncertainties:
- Z: lepton reconstruction;
- W: multijet and JES+JER

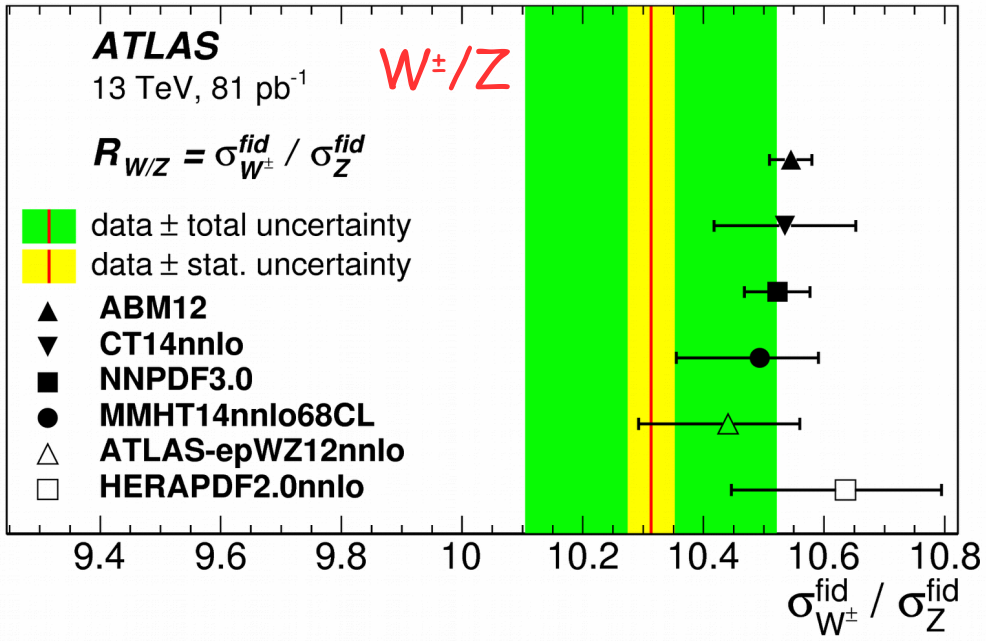
Z: ~1% (+2.1% lumi)

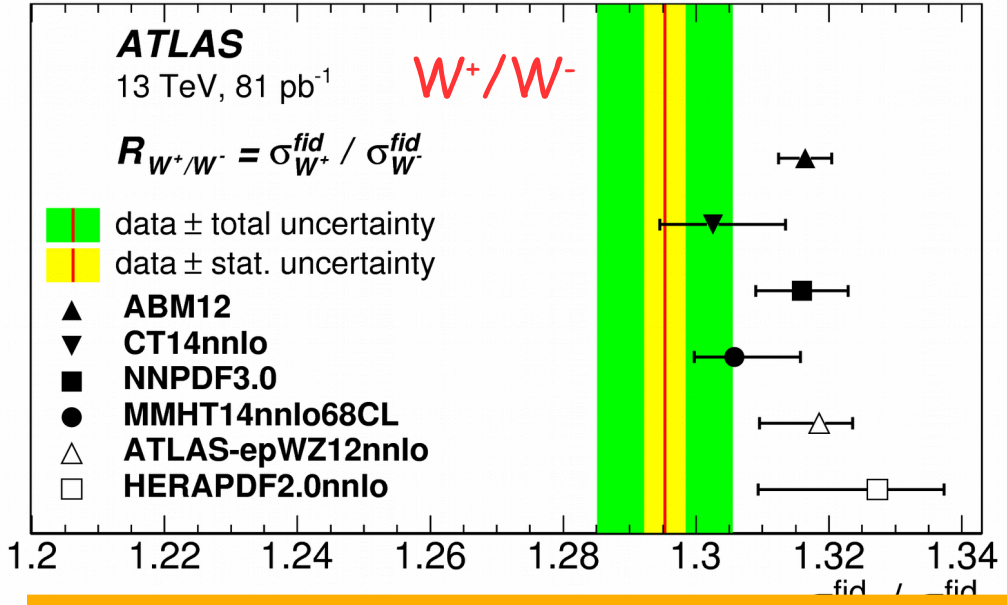
W: ~2% (+2.1% lumi)

$\delta C/C$ [%]	$Z \to e^+e^-$	$W^+ \to e^+\nu$	$W^- \to e^-\bar{\nu}$	$Z \to \mu^+\mu^-$	$W^+ \to \mu^+\nu$	$W^- \to \mu^-\bar{\nu}$
Lepton trigger	0.1	0.3	0.3	0.2	0.6	0.6
Lepton reconstruction, identification	0.9	0.5	0.6	0.9	0.4	0.4
Lepton isolation	0.3	0.1	0.1	0.5	0.3	0.3
Lepton scale and resolution	0.2	0.4	0.4	0.1	0.1	0.1
Charge identification	0.1	0.1	0.1	–	–	–
JES and JER	–	1.7	1.7	–	1.6	1.7
$E_{\mathrm{T}}^{\mathrm{miss}}$	–	0.1	0.1	–	0.1	0.1
Pile-up modelling	< 0.1	0.4	0.3	< 0.1	0.2	0.2
PDF	0.1	0.1	0.1	< 0.1	0.1	0.1
Total	1.0	1.9	1.9	1.1	1.8	1.8
MJ	-	~3	~3	-	~1	~1
Statistical	0.5	~0.25	~0.25	0.5	~0.25	~0.25

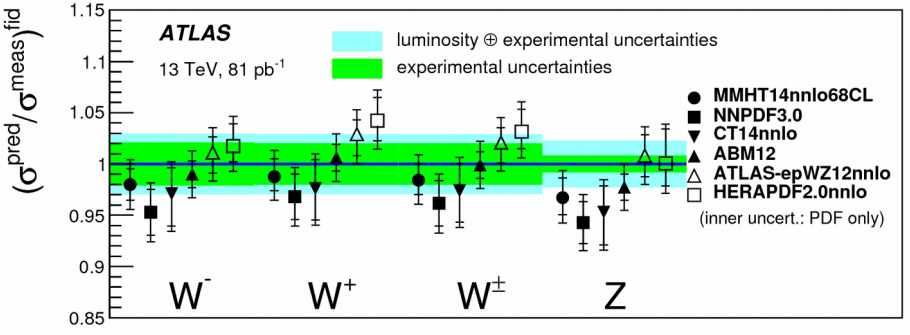
Results

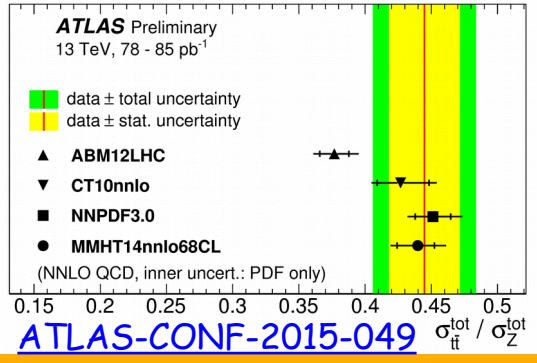
PLB 759 (2016) 601





- Cross sections will constrain PDFs!
- W/Z: Enhanced strangeness observed in 7 TeV ATLAS data (ATLAS-epWZ12nnlo) is confirmed with the 13 TeV data.
- W^+/W^-: u_v-d_v PDF.
- $t\bar{t}/Z$: statistics limited. Need more data!





ATLAS-CONF-2015-049

- Integrated fiducial W and Z cross sections and ratios @ 13 TeV (PLB 759 (2016) 601)
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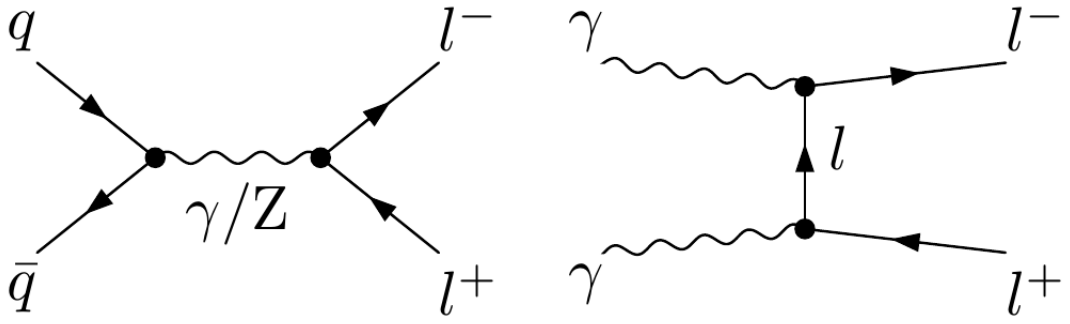
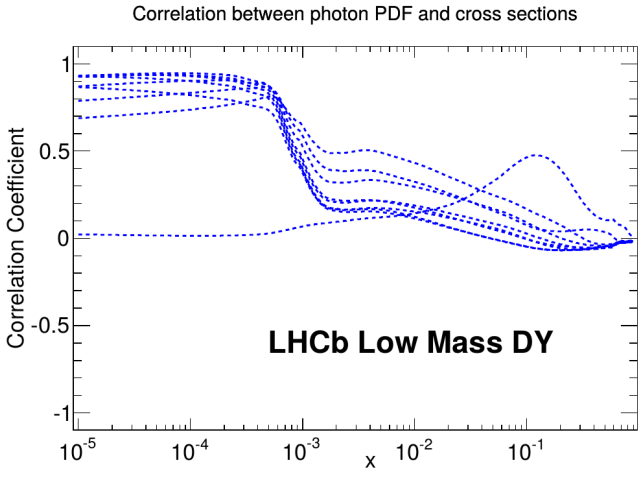
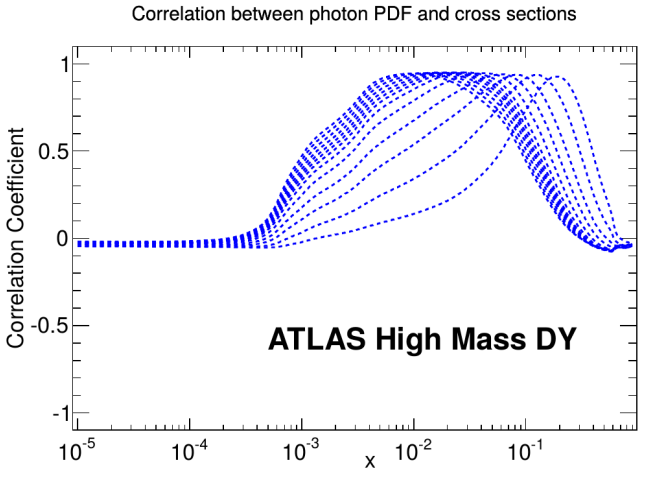
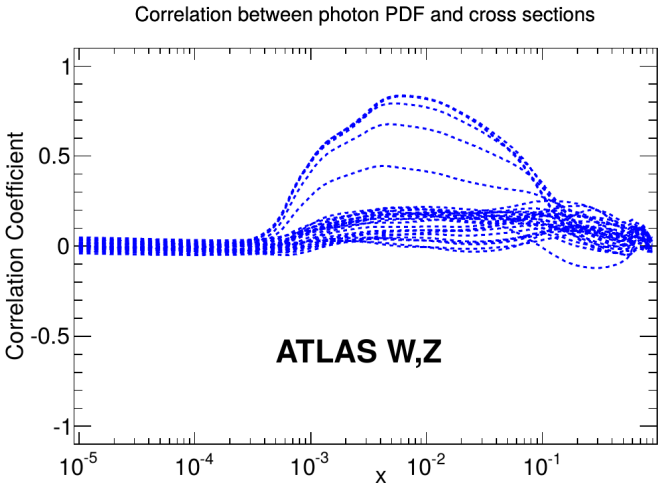
High-mass DY: motivation



- Sensitivity to EW and QCD corrections.
- Constraints on PDFs (in particular on γ): earlier 7 TeV data were used in NNPDF2.3_qed (NPB 877 (2013) 290).



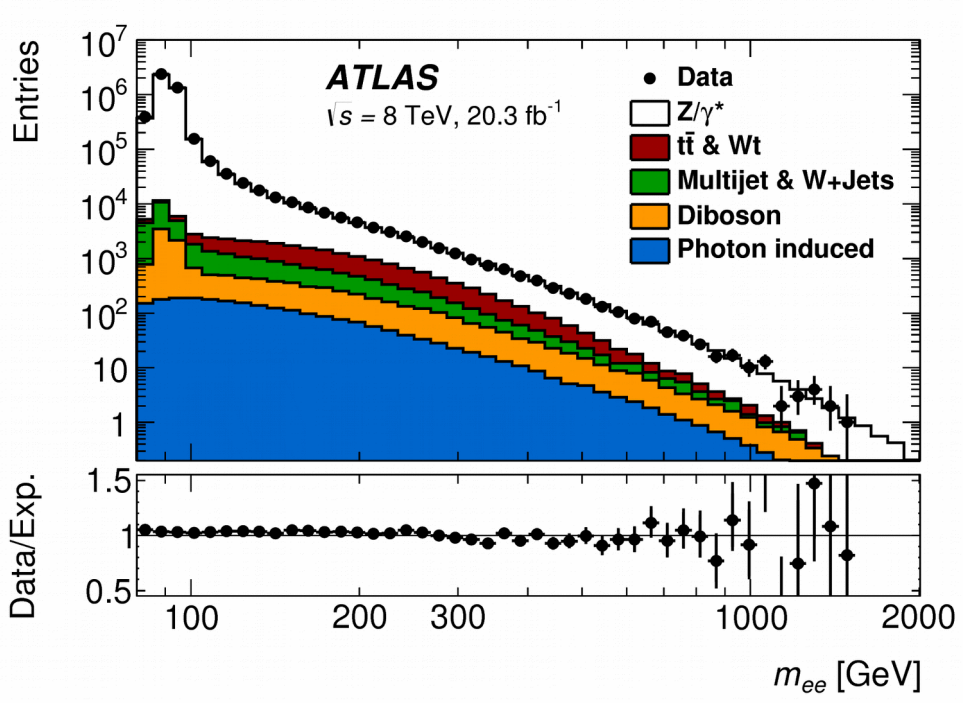




R. Ball et al., NPB 877 (2013) 290

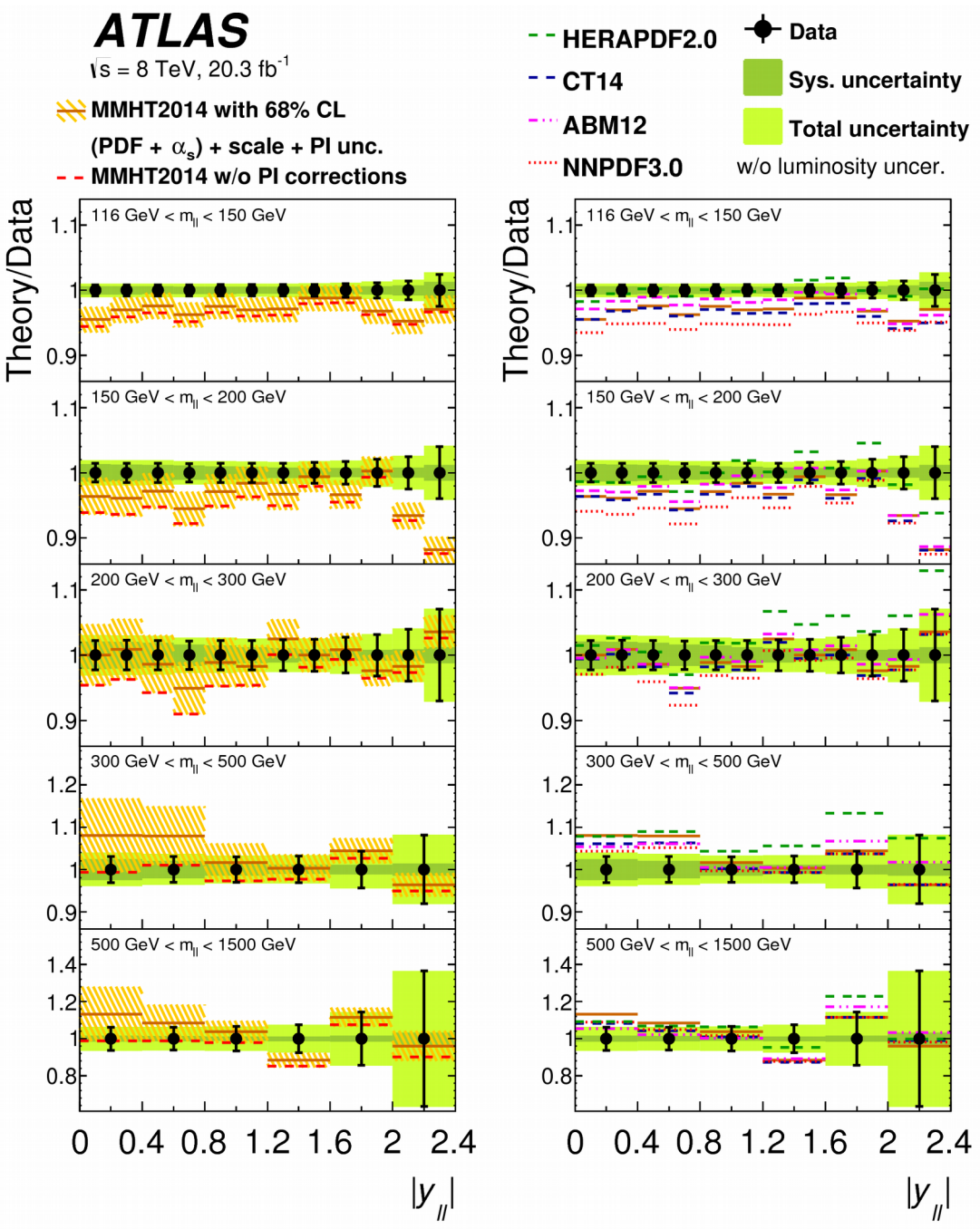
Analysis overview

- p_T^l > 40(30) GeV
- $|\eta^l|$ < 2.5
- 116 < M < 1500 GeV

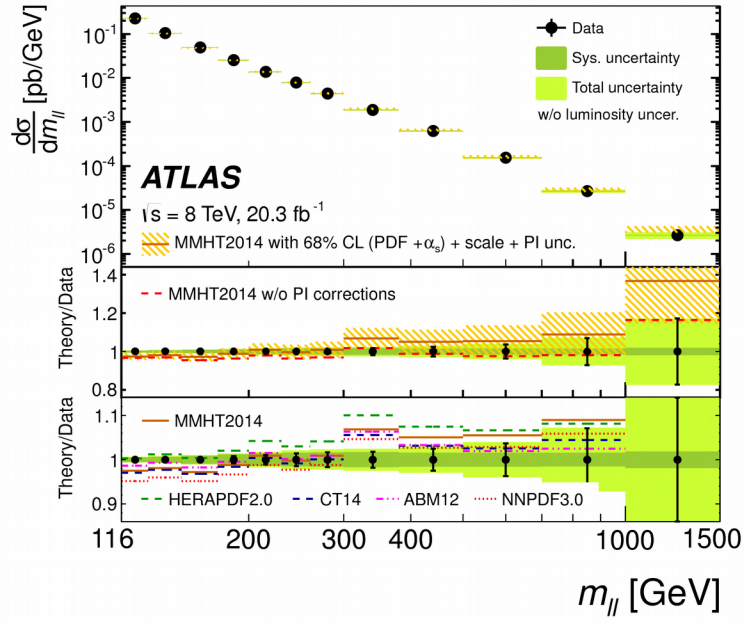


- Full 2012 sample: 20.3 fb^{-1}. --> Double-differential cross sections: $d\sigma/dM$, $d^2\sigma/dM/d|y_{ll}|$, $d^2\sigma/dM/d|\Delta\eta_{ll}|$
- Backgrounds: EW+top from MC and multijet data-driven.
- Bin-by-bin unfolding.
- Combine ee and μμ cross sections using HERAverager.

Comparison to predictions



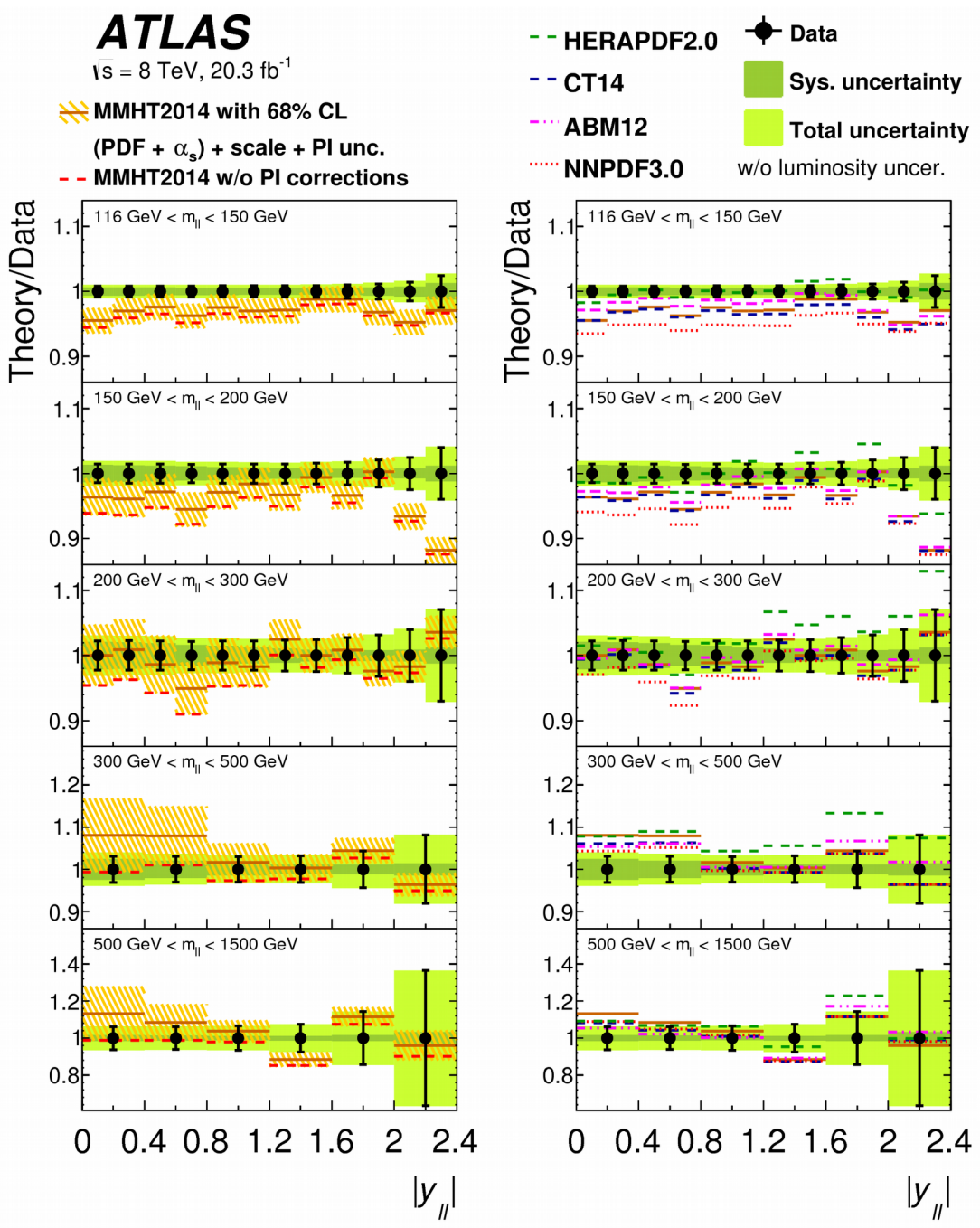
arXiv:1606.0173



χ^2/ndof

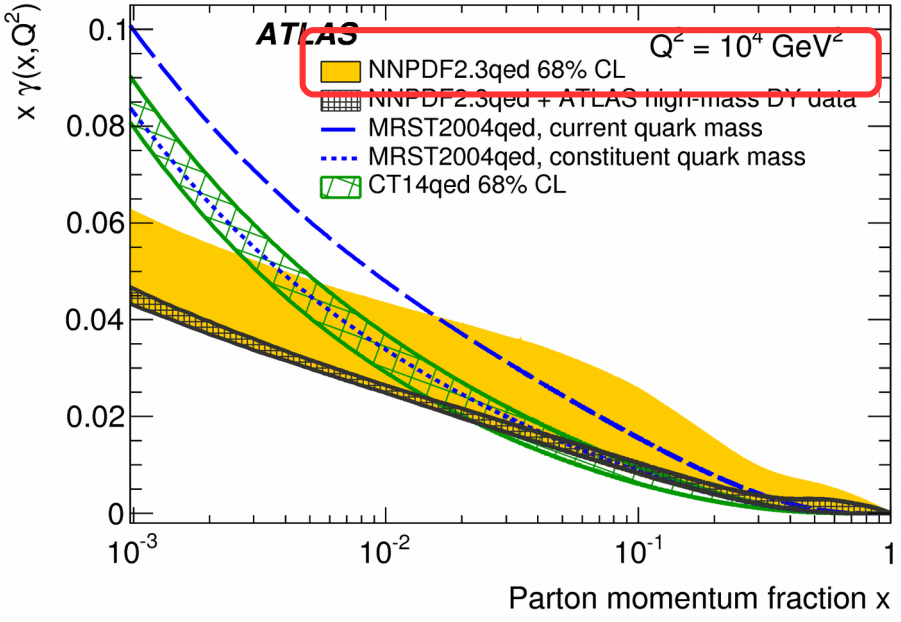
	$m_{\ell\ell}$	$\lvert y_{\ell\ell}\rvert$	$\lvert\Delta\eta_{\ell\ell}\rvert$
MMHT2014	18.2/12	59.3/48	62.8/47
CT14	16.0/12	51.0/48	61.3/47
NNPDF3.0	20.0/12	57.6/48	62.1/47
HERAPDF2.0	15.1/12	55.5/48	60.8/47
ABM12	14.1/12	57.9/48	53.5/47

Photon PDF in proton



arXiv:1606.0173

- Bayesian reweighting of $q\bar{q}$ and $\gamma\gamma$ predictions based on NNPDF2.3qed to illustrate constraining power of the data.
- Significant sensitivity to the photon PDF.



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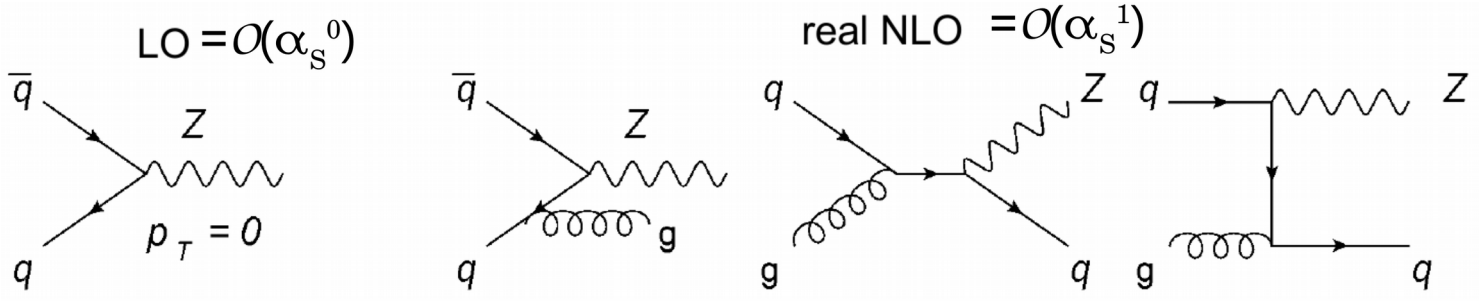
Z p_T: motivation



- Measure p_T and φ^*_η distributions in Z-boson production:
  - Low p_T (multiple soft-gluon emissions): resummation up to NNLL (RESBOS), parton shower (PS) techniques, ME+PS with ME $O(\alpha_s)$.
  - High p_T (hard-gluon emission): fixed-order calculations up to $O(\alpha_s^2)$ (DYNNLO) and beyond...

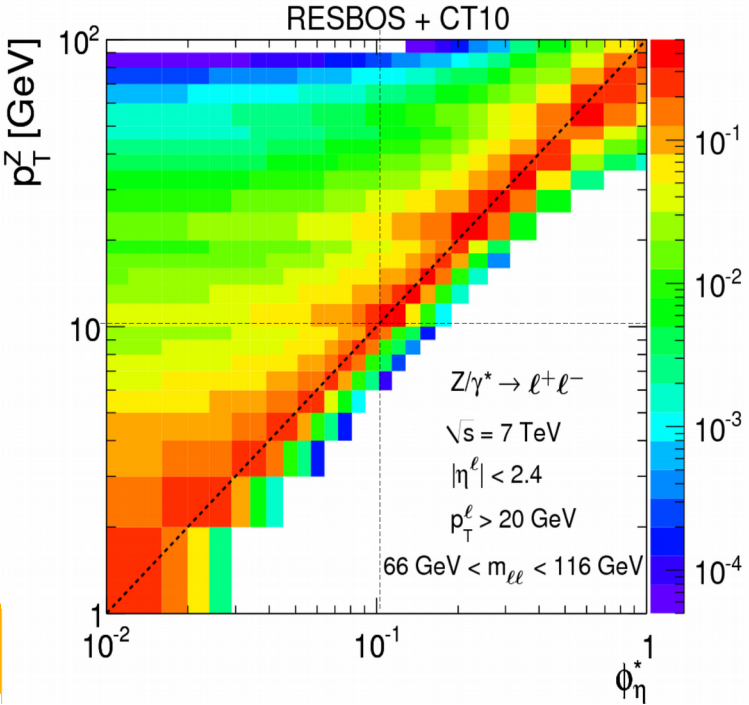
- At <u>low p_T measurements are limited by experimental resolution and uncertainties on momentum scale</u> --> Use φ^*_η, which depends on angular lepton measurements

$$\phi^*_\eta = \tan(\phi_{acop}/2) \times \sin(\theta^*_\eta)$$

$$\phi_{acop} = \pi - \Delta\phi(\ell,\ell)$$

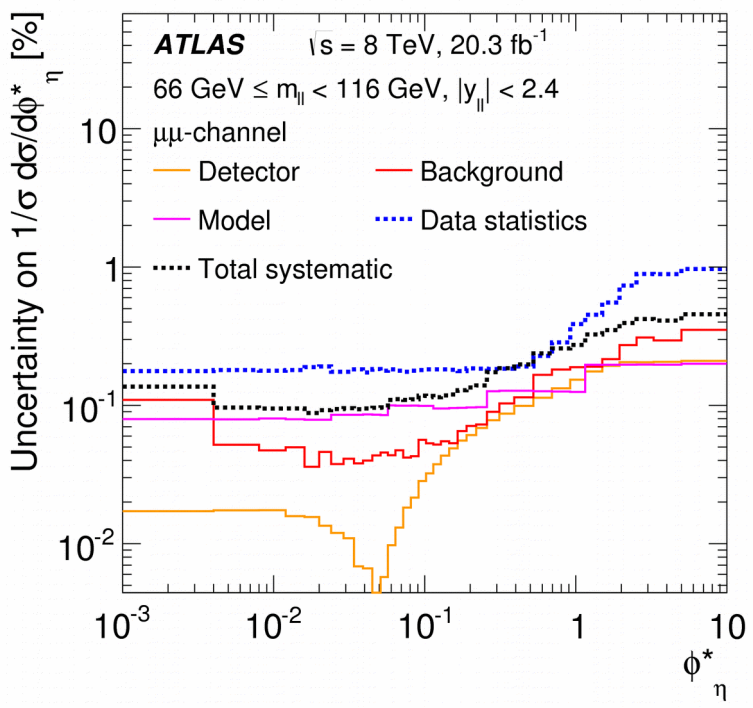
$$\cos(\theta^*_\eta) = \tanh[(\eta^- - \eta^+)/2]$$

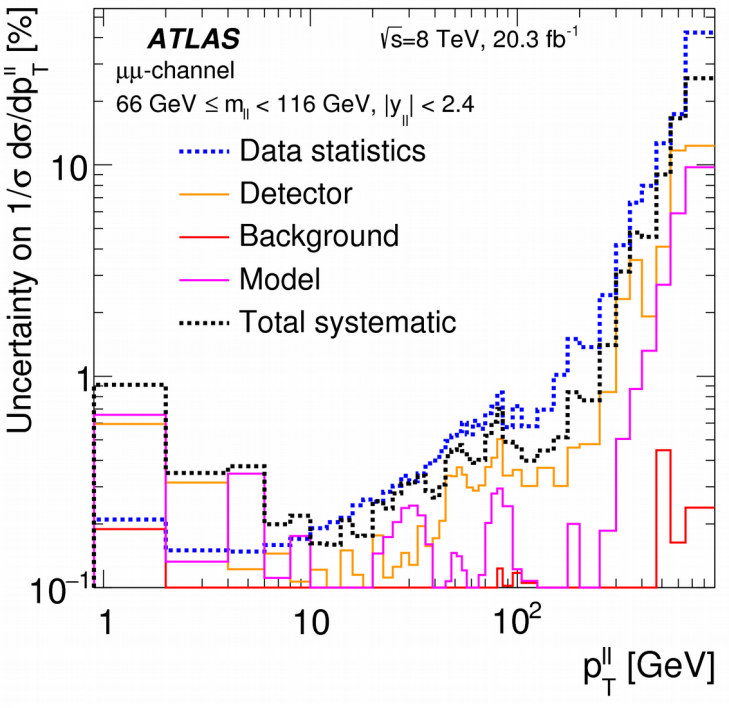
$\Phi^* \sim p_T/M_{ll}$



Analysis overview

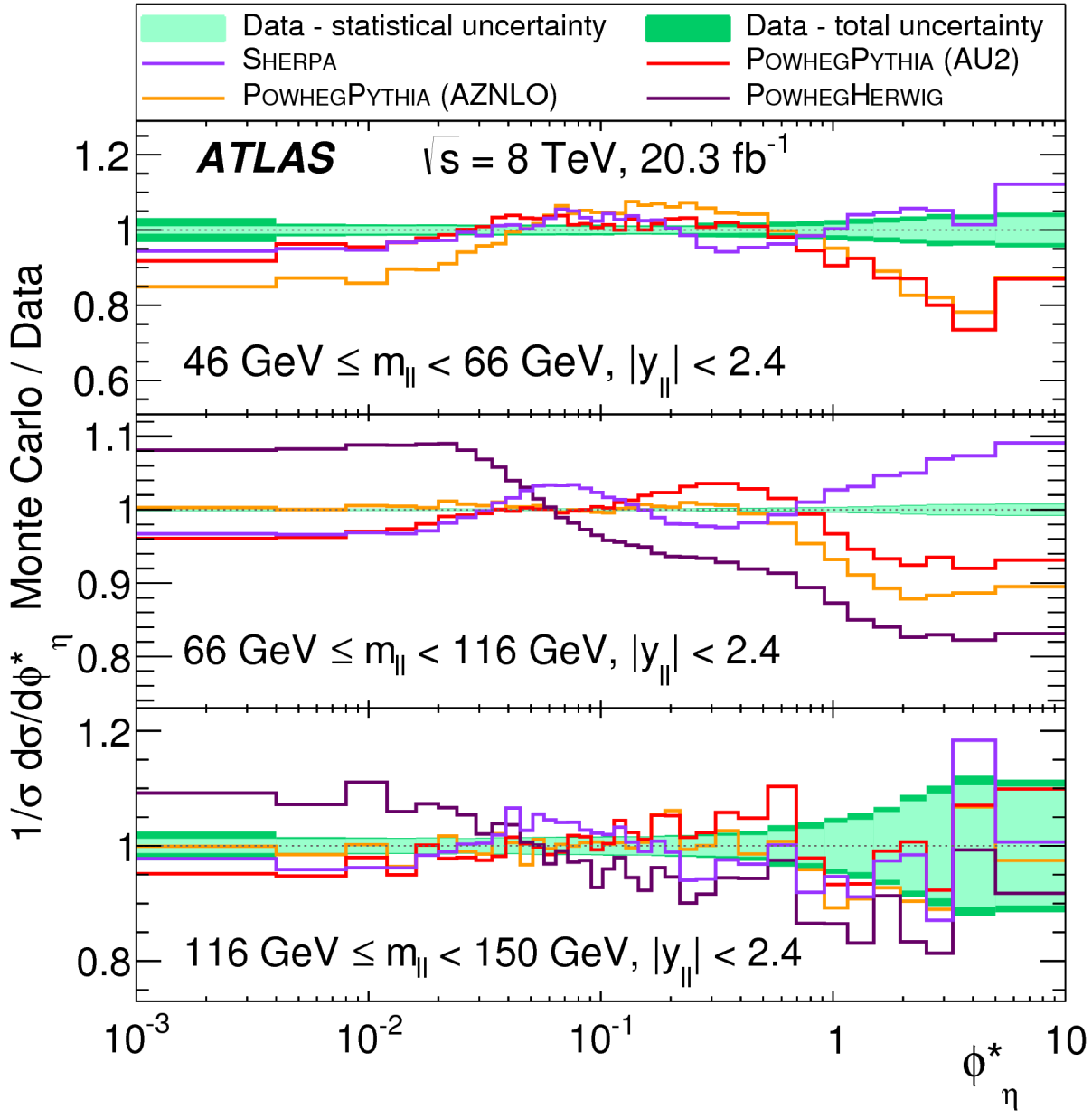
- $p_T^l > 20$ GeV
- $|\eta^l| < 2.4$
- $|y_{ll}| < 2.4$
- $12 < M < 150$ GeV





- Measure normalised cross sections (but also absolute as a function of p_T and integrated fiducial as a function of M) in M and y_{ll} slices.
- φ^*_η : concentrate on the low-p_T and medium-p_T regions.
- p_T: concentrate on the high-p_T region.
- Combine ee and μμ cross sections using HERAverager.

Comparison to MC



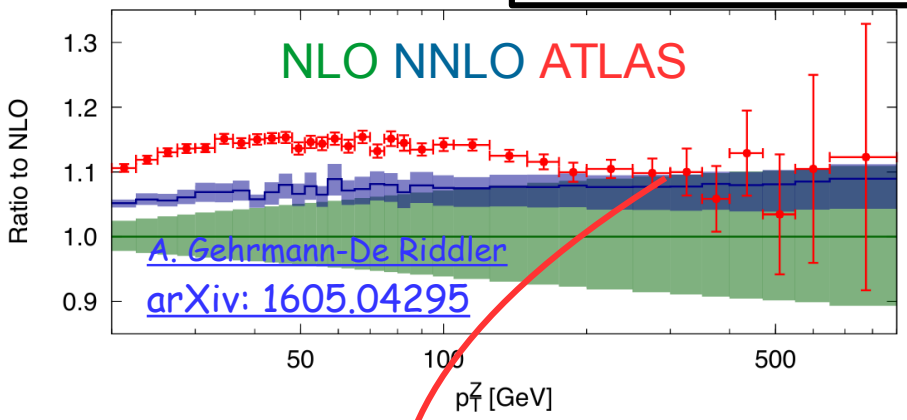
EPJC 76 (2016) 291

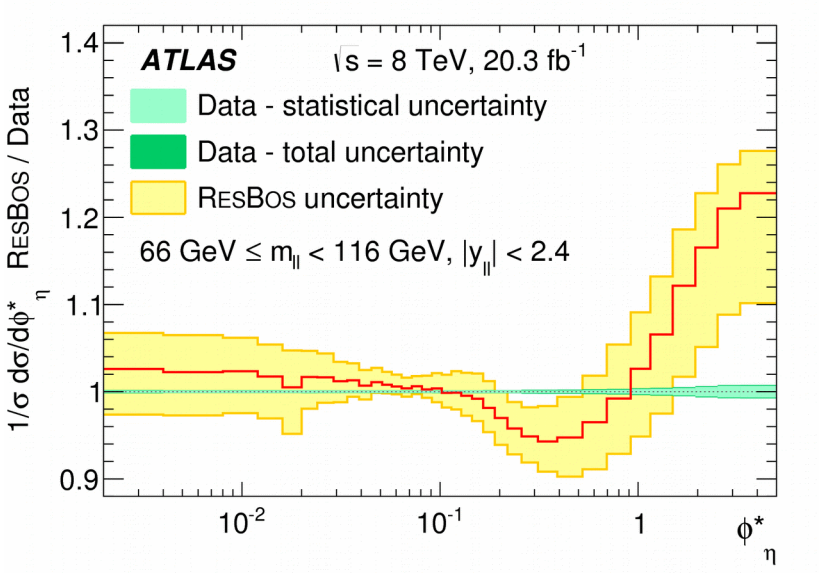
- The data have large constraining potential!
- Powheg+Pythia AZNLO was tuned to earlier 7 TeV Z p_T data (JHEP 09 (2014) 145). Good description in the phase space of the tune (66<M<116 GeV and pT<100 GeV), but fails at low masses.
- High mass is reasonably described by all but Powheg+Herwig.

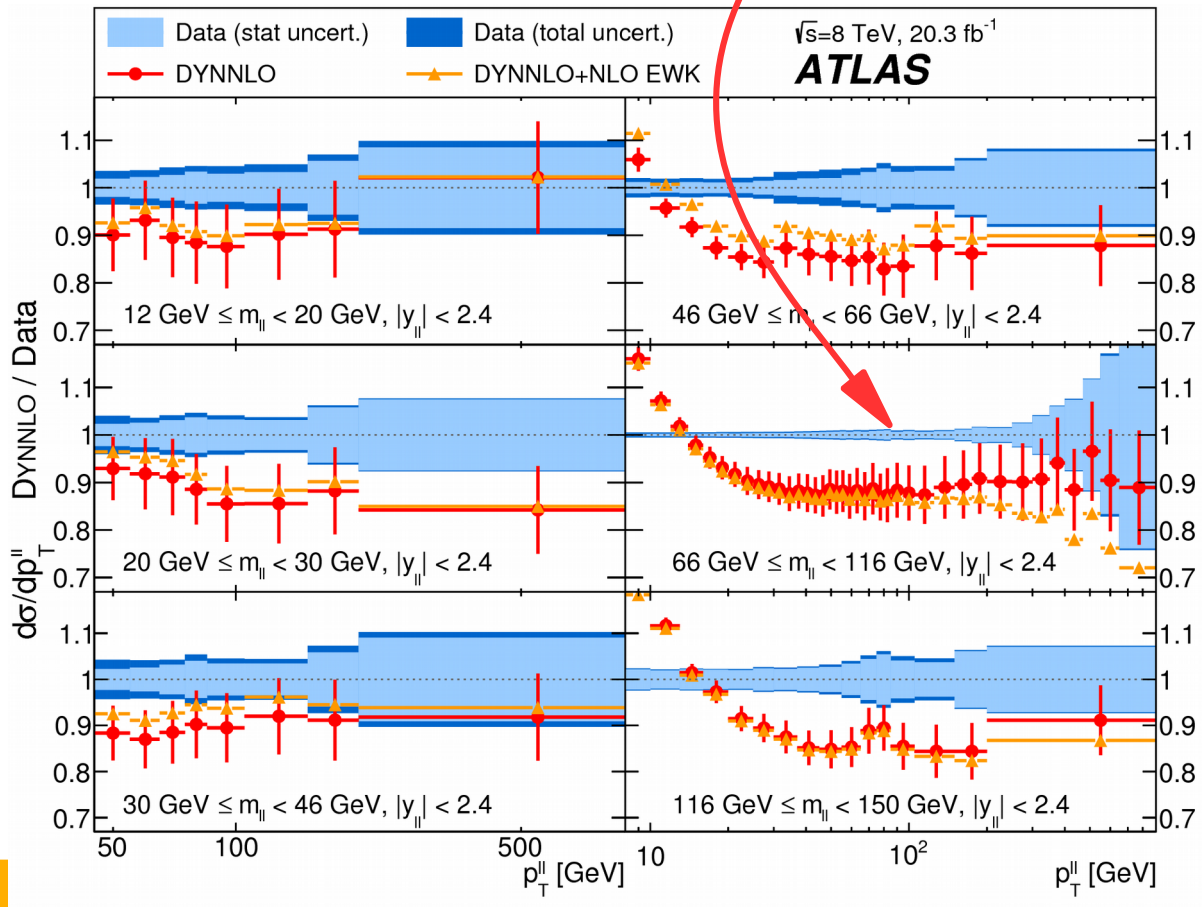
Comparison to theory

EPJC 76 (2016) 291

- High-pT region is sensivite to higher-order QCD (and EW) corrections.
- Recent $O(a_s^3)$ corrections bring predictions closer to the data.
- The measurement has potential to be used for a_s extraction.







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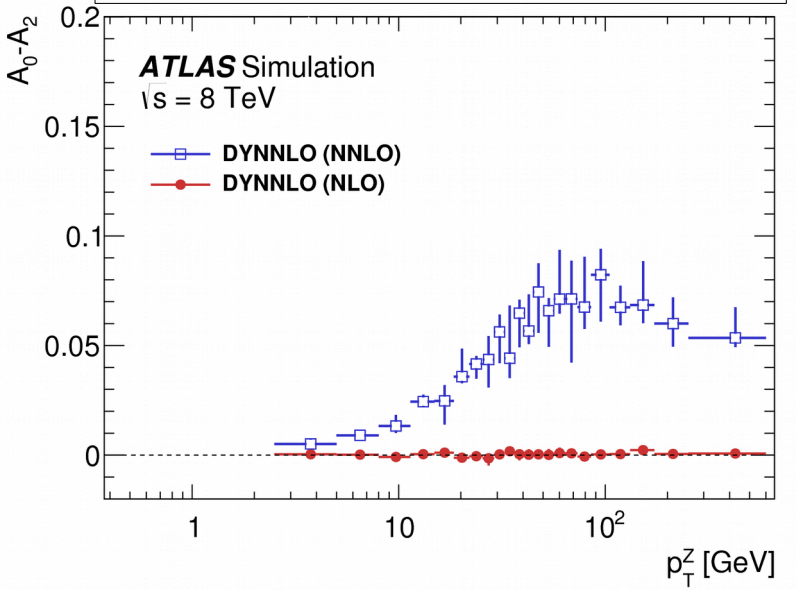
Angular coefficients

- Measure angular distributions of leptons from Z decays --> Access production dynamics and polarisation.
- Decomposition of cross section in QCD hold to all orders. Higher-order effects absorbed in Ai coeffcients.
- Goal: Measure all eight $A_i(p_T^Z)$.
- Implications:
  - Stringent test of pQCD calculations and MC.
  - Sensitivity to EW parameters (in particular $\sin\theta_W$)

- Lam-Tung relation: $A_0=A_2$ @ $O(\alpha_s)$.
- $A_{FB} \sim 3/8 * A_4$
- A_3 and A_4 are sensitive to $\sin\theta_W$.
- A_5, A_6, A_7 are very small

$$\frac{d\sigma}{dp_T^Z\, dy^Z\, dm^Z\, d\cos\theta\, d\phi} = \frac{3}{16\pi}\frac{d\sigma^{U+L}}{dp_T^Z\, dy^Z\, dm^Z}\Big\{(1+\cos^2\theta) + \frac{1}{2}A_0(1-3\cos^2\theta) + A_1\sin 2\theta\cos\phi + \frac{1}{2}A_2\sin^2\theta\cos 2\phi + A_3\sin\theta\cos\phi + A_4\cos\theta + A_5\sin^2\theta\sin 2\phi + A_6\sin 2\theta\sin\phi + A_7\sin\theta\sin\phi\Big\}$$



Analysis overview

- Use ee (central-central (CC) and central-forward (CF) topologies) and μμ (CC).
- Log-likelihood template fit to the data in $\cos\theta_{CS}$ φ_{CS} in p_T bins:

$$\mathcal{L}(A_{ij},\mu_j|N) = \prod_{events}^{N}\left\{\sum_{j=1}^{23}\mu_j\left[T_{8,j}+\sum_{i=0}^{7}A_{ij}\times T_{ij}\right]+\sum_{B}^{bkgs}T_B+T_{Fakes}\right\}$$

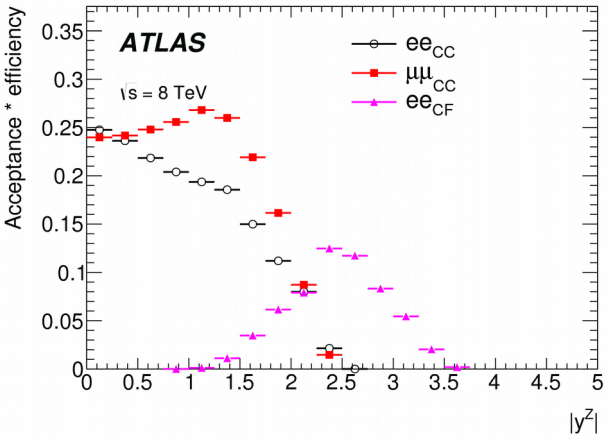
Fakes

Sum over p_T bins

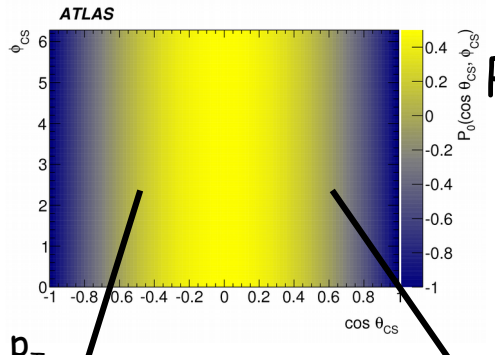
Backgrounds

Floating normalisation to the data in each bin

Signal folded templates corresponding to the original polynomials



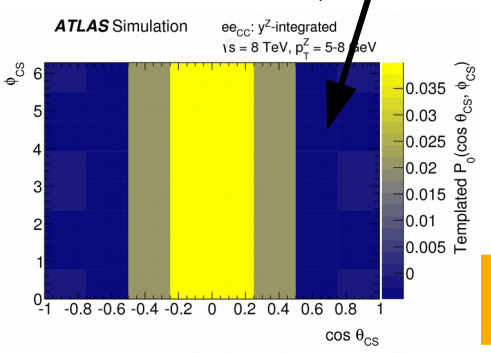
- Original decomposition is valid in the full phase space --> additional folding to fiducial effects and detector effects
- Folded templates are extracted from MC un-weighted to flat distributions, removing any direct dependence on the physics modelling in the generator.

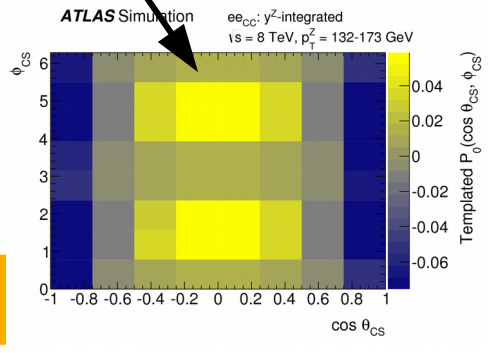


$P_0(\theta,\varphi)$

low p_T

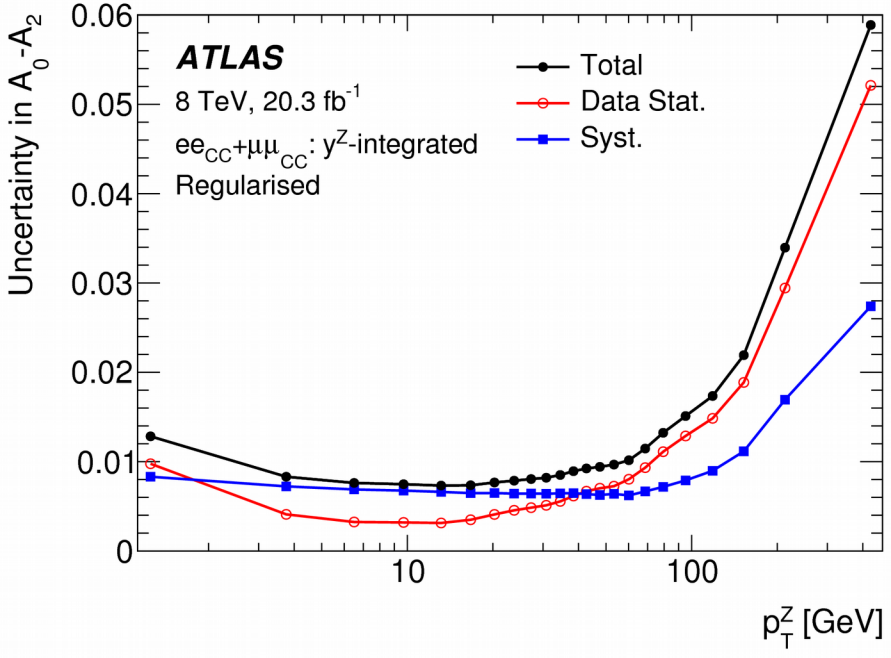
high p_T

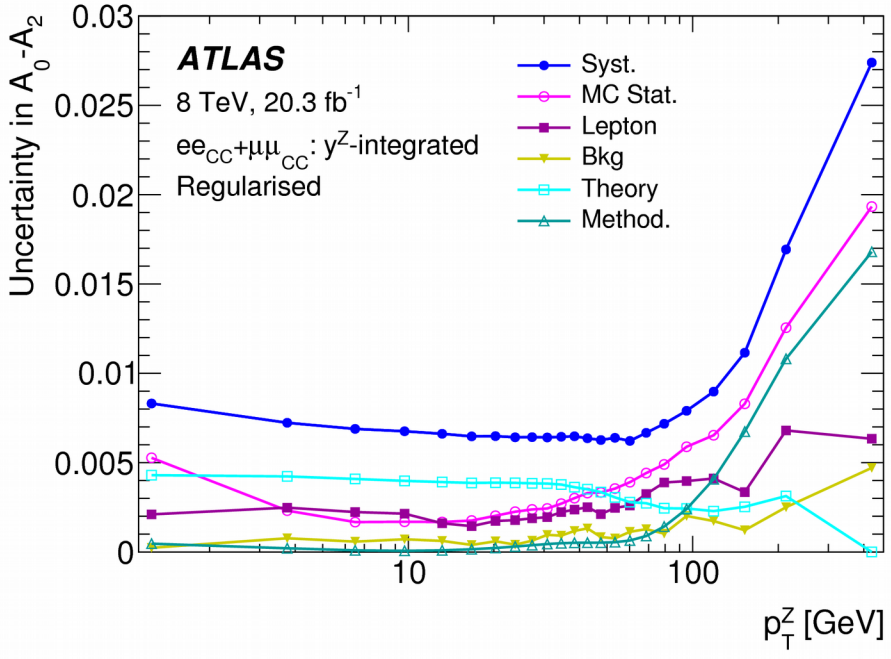




Measurement precision

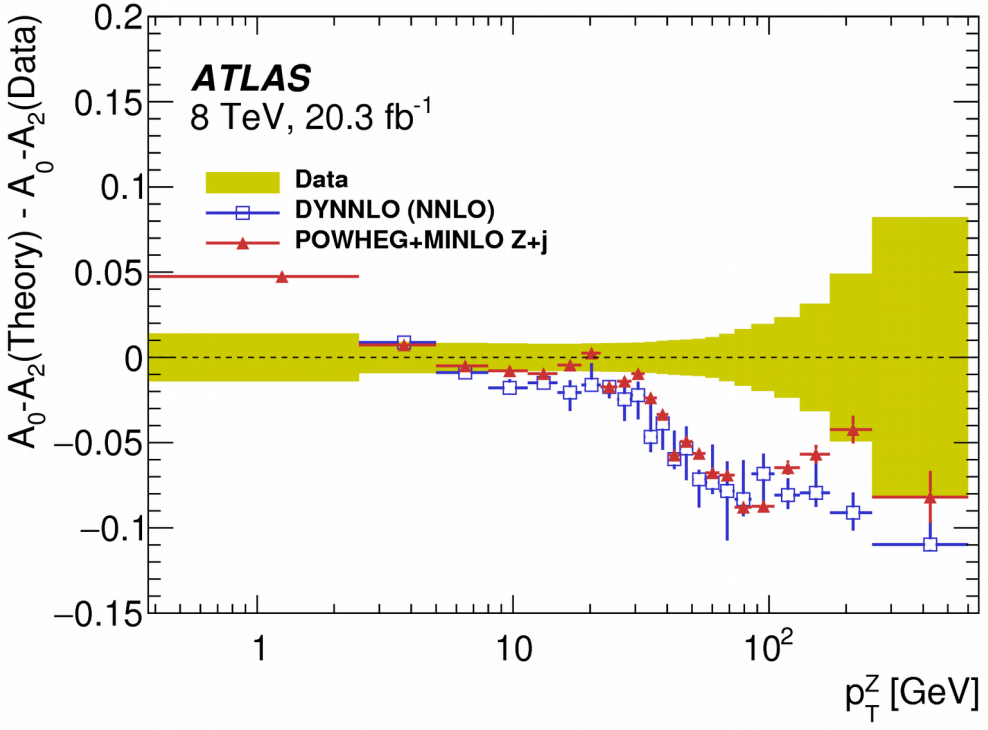
- Use regularisation criterion to smoothen measured coefficients --> significant statistical correlations between bins.
- Experimental systematics: MC stats, lepton efficiency, scale and resolution, background normalisation, methodology.
- Theoretical systematics: PDFs, QCD scale, parton shower.
- Systematic uncertainties are typically small.
- The first observation of non-zero A_5,A_6,A_7 @ 3σ.

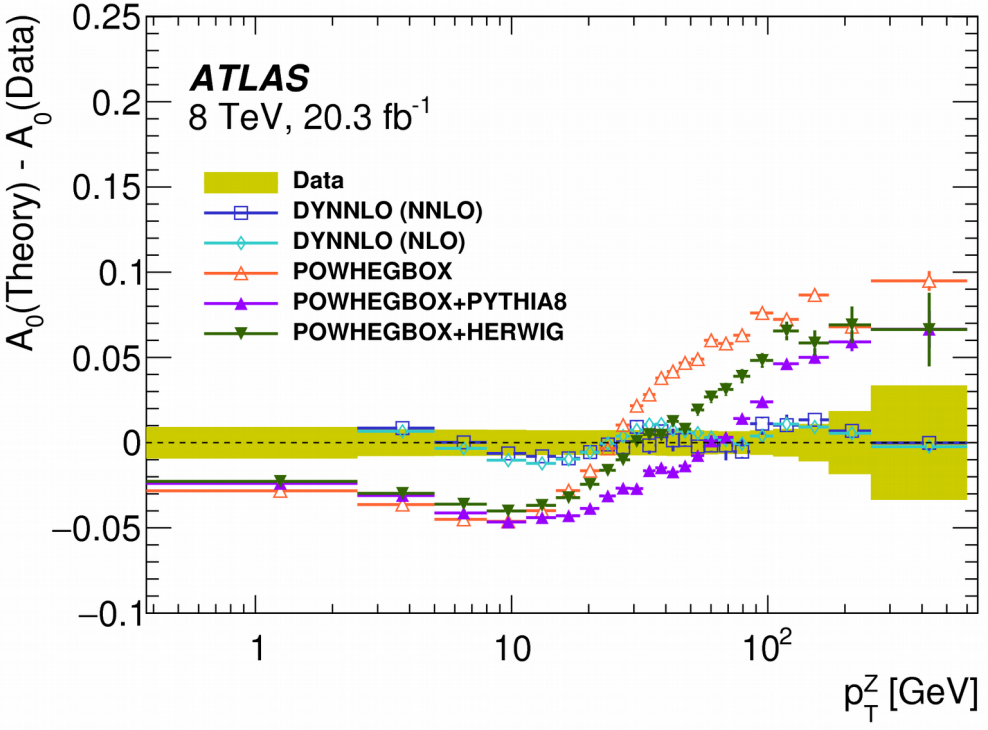




Comparison to theory&MC

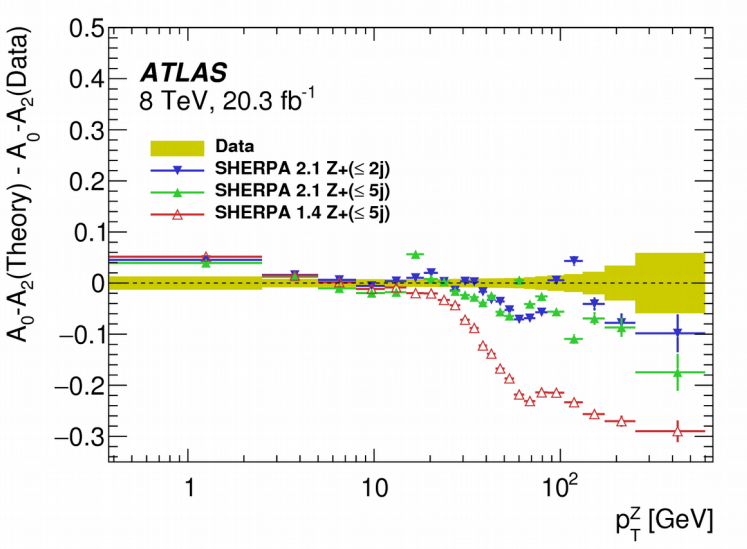
- $O(\alpha_s^2)$ predictions fail to describe the A_0-A_2 difference. Interesting to see effect of $O(\alpha_s^3)$ corrections from arXiv:1605.04295!
- PowhegBox (v1/r2129) fails to describe A_0 (related to the implementation of Sudakov form factor). Fixed in PowhegBox v2.1.

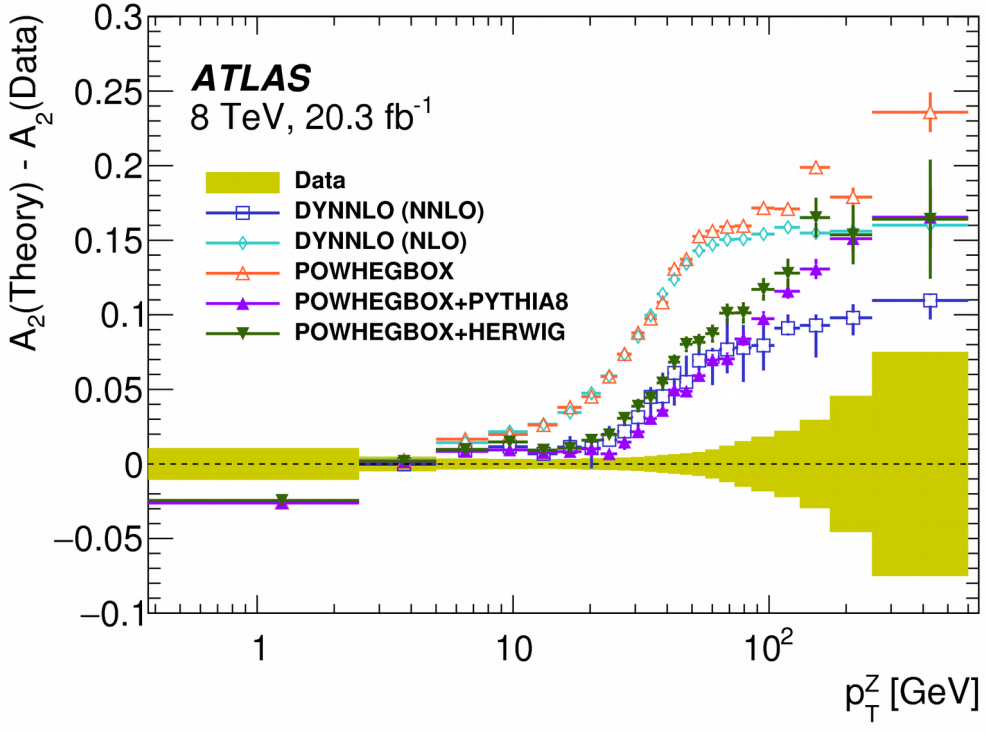


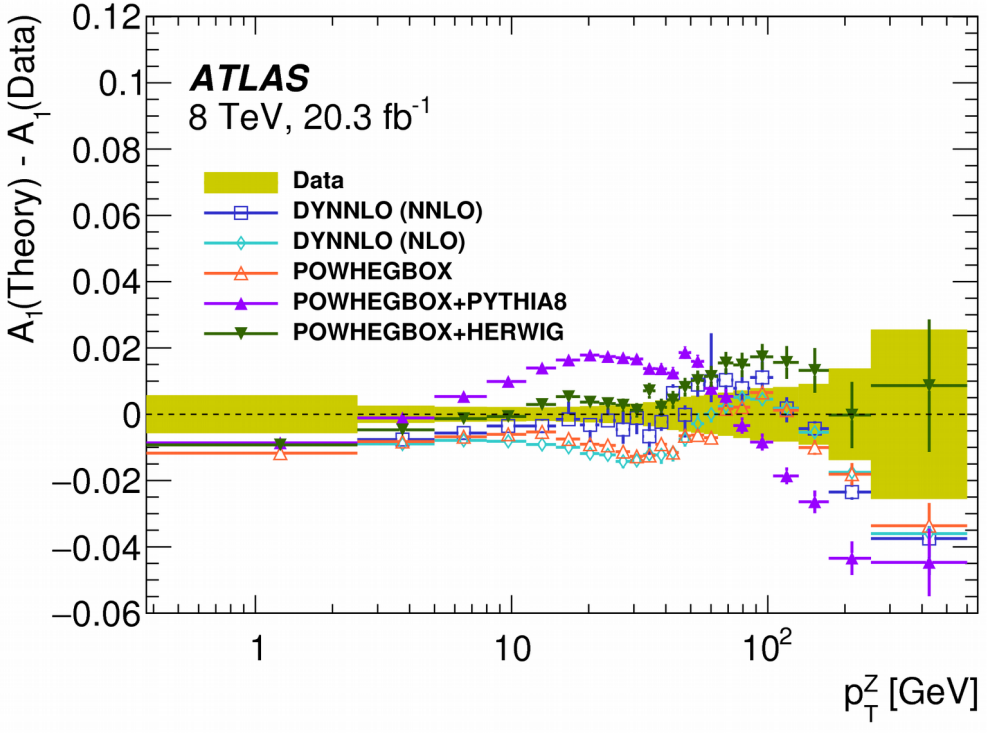


Comparison to MC

- A_1 and A_2 are sensitive to parton shower.
- Sherpa v1.4 and v2.1 do not describe A_0-A_2 well.
- Significant higher-order polinomial contribution in Sherpa version before v2.1.

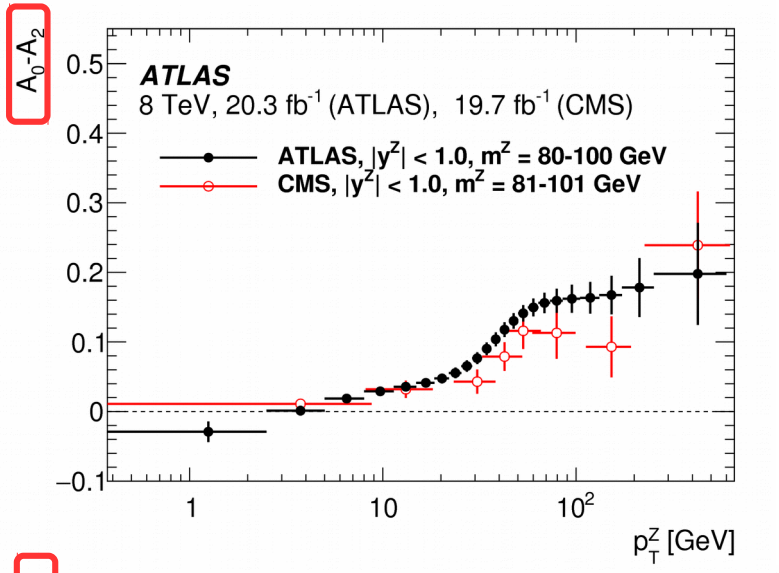


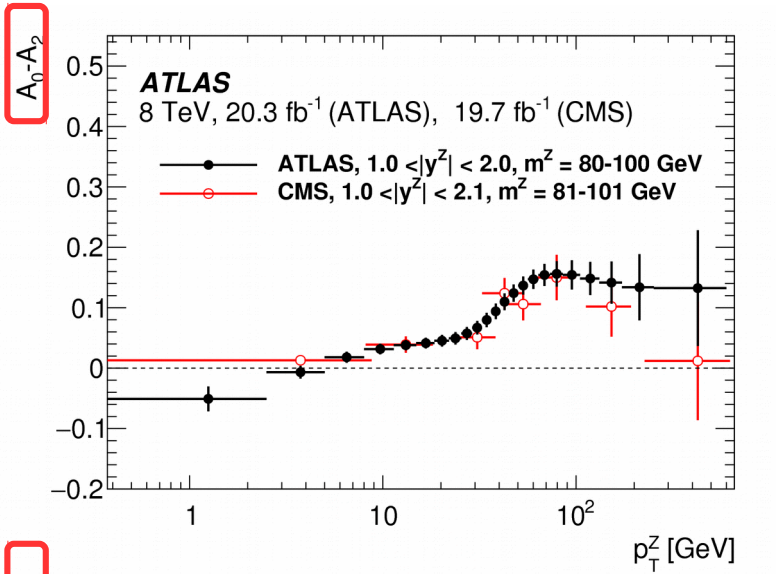


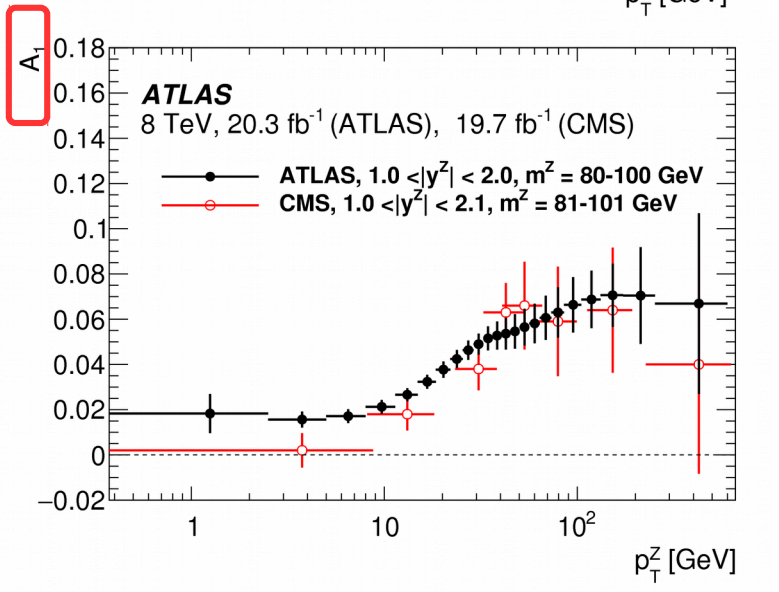


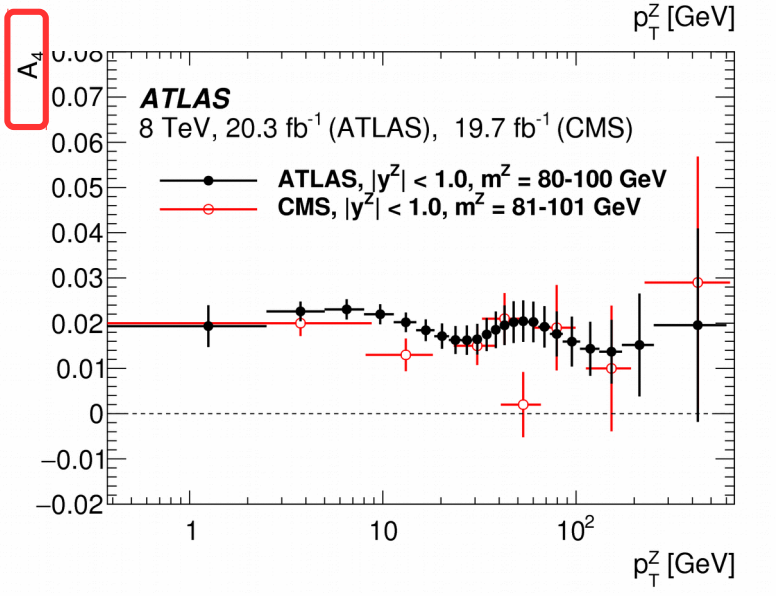
Comparison to CMS

- Good agreement with CMS (PLB 750 (2015) 154)









Summary

- Integrated W,Z cross sections @ 13 TeV: constraints on PDF with early 2015 data
- Differential in M and y or Δη high-mass Drell-Yan cross sections @ 8 TeV: tests of QCD and EW corrections, constraints on photon PDF in the proton.
- Differential in p_T Z cross sections @ 8 TeV: test of QCD and potential for MC tuning.
- Differential in pT measurement of Z angular coefficients @ 8 TeV: stringent test of pQCD and MC generators, sensitivity to WMA.
- W and Z/γ^* measurements provide rich information about QCD and EW theories.

Backup

Even more fun slides...

Multijet background