Inclusive W and Z: Precision LHC Measurements

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on behalf of the ATLAS, CMS, and LHCb Collaborations

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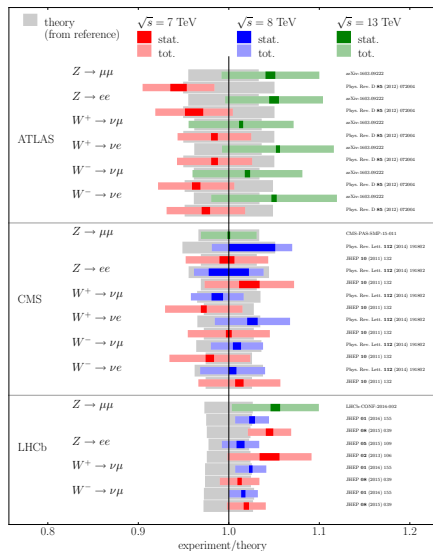
May 3, 2016

SM@LHC

Overview

- comprehensive W and Z results from ATLAS, CMS, and LHCb
  - recent results today, full summary in appendix
- LHC not just for discovery
  - tests of the SM with sub-percent uncertainty
  - important constraints on PDFs

- 13 TeV cross-sections
- new 7/8 TeV results
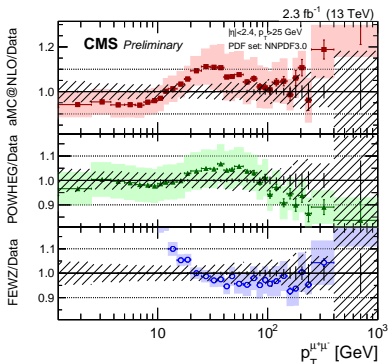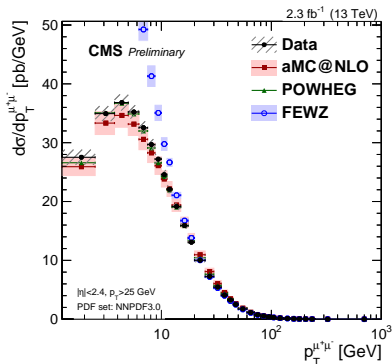- A_{FB} and $\sin^2 \theta_{\mathrm{W}}^{\mathrm{eff}}$

13 TeV Results

CMS: Differential Z Cross-Sections [CMS-PAS-SMP-15-011]

- measurement of $Z \to \mu\mu$ cross-section
  - $\sqrt{s} = 13$ TeV, 2.3 fb^{-1} dataset
  - $60 < m(\mu\mu) < 120$ GeV, $|\eta(\mu)| < 2.4$, $p_T(\mu) > 25$ GeV
  - differential in $y(\mu\mu)$, $p_T(\mu\mu)$, and $\phi^*(\mu\mu)$
- compared to three theory predictions
  - NNPDF3.0 used as nominal PDF set
  - AMC@NLO + PYTHIA 8
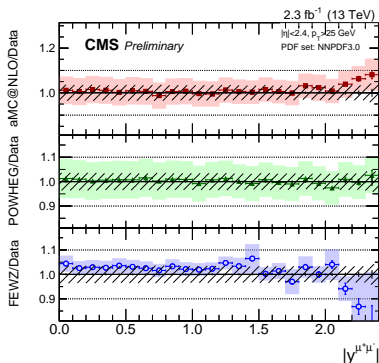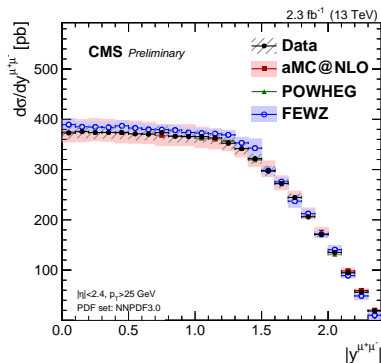 - POWHEGBOX + PYTHIA 8
  - fixed order FEWZ
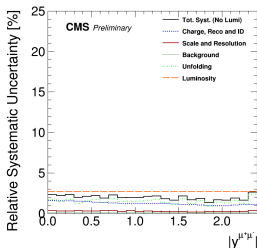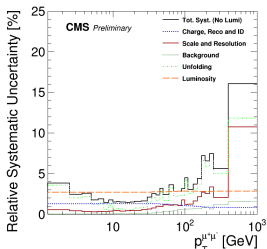
CMS: Differential Z Cross-Sections [CMS-PAS-SMP-15-011]

- showered predictions handle low $p_T(\mu\mu)$ well
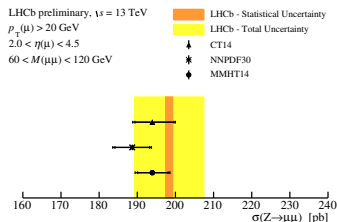- fixed order flat between $20 < p_T(\mu\mu) < 200$ GeV

CMS: Differential Z Cross-Sections [CMS-PAS-SMP-15-011]

- PowhegBox flat across complete $y(\mu\mu)$ range
- small deviations (within uncertainty) in $y(\mu\mu)$ tails for aMC@Nlo and Fewz

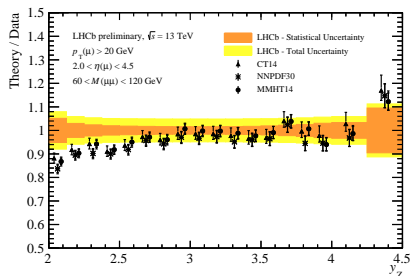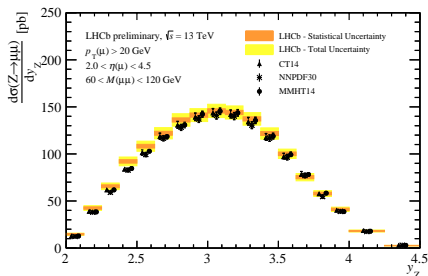# LHCb: Differential Z Cross-Sections [LHCb-CONF-2016-002]

- measurement of $Z \to \mu\mu$ cross-section
  - $\sqrt{s} = 13$ TeV, 300 pb^{-1} dataset
  - $60 < m(\mu\mu) < 120$ GeV, $2.0 < \eta(\mu) < 4.5$, $p_{\mathrm{T}}(\mu) > 20$ GeV
  - differential in $y(\mu\mu)$, $p_{\mathrm{T}}(\mu\mu)$, and $\phi^*(\mu\mu)$

Source	$\Delta\,\sigma_{Z \to \mu\mu}$ [%]
Statistical	0.5
Reconstruction efficiencies	2.4
Purity	0.2
FSR	0.1
Total systematic (excl. lumi.)	2.4
Luminosity	3.9
Total uncertainty	4.6

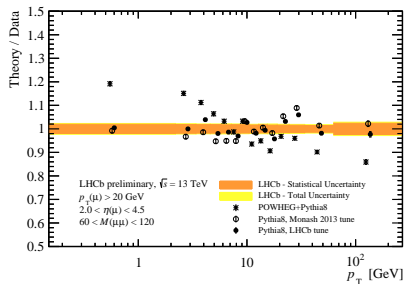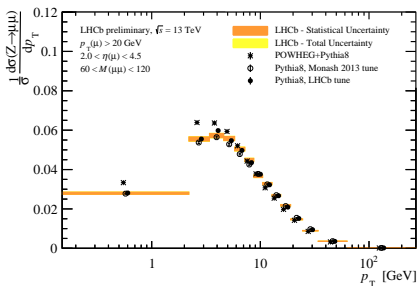# LHCb: Differential Z Cross-Sections [LHCb-CONF-2016-002]

- comparison to fixed order FEWZ predictions with three PDF sets
- slight tension for $y(\mu\mu) < 2.5$

LHCb: Differential Z Cross-Sections [LHCb-CONF-2016-002]

- comparison to NLO PowhegBox with Pythia 8 shower and LO Pythia 8 with different tunes
- LO Pythia 8 describe the data better, both at low and high $p_{\mathrm{T}}(\mu\mu)$
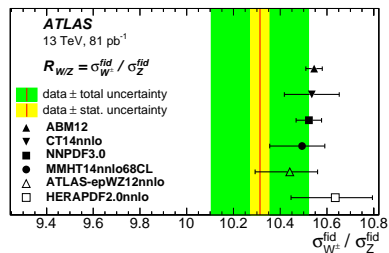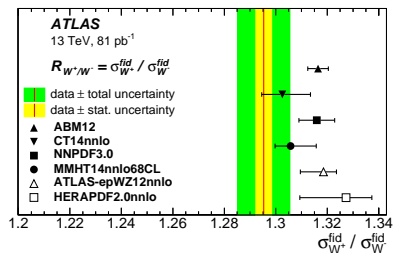
ATLAS: Total W and Z Cross-Sections [arXiv:1603.09222]

- measurement of $Z \to \mu\mu, ee$ and $W \to \nu\mu, \nu e$ cross-sections
  - $\sqrt{s} = 13$ TeV, 81 pb^{-1} dataset
  - W: $p_{\mathrm{T}}(\nu, \ell) > 25$ GeV, $|\eta(\ell)| < 2.5$, $m_{\mathrm{T}}(\nu\ell) > 50$ GeV
  - Z: $p_{\mathrm{T}}(\ell) > 25$ GeV, $|\eta(\ell)| < 2.5$, $66 < m(\ell\ell) < 116$ GeV
- $\delta\sigma(Z) \approx 1\%$, $\delta\sigma(W) \approx 2\%$, $\delta\mathcal{L} \approx 5\%$
- test of lepton universality and comparison to PDF set predictions
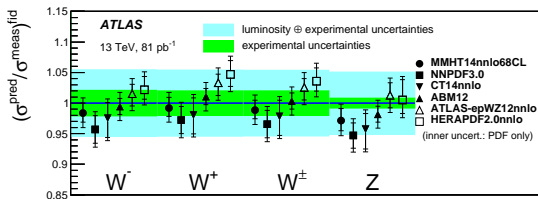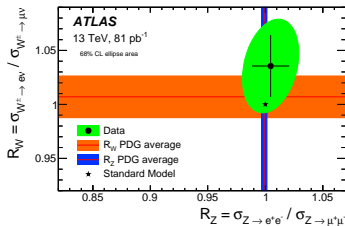
ATLAS: Total W and Z Cross-Sections [arXiv:1603.09222]

- ratios of $\sigma(W^+)/\sigma(W^-)$ and $\sigma(W^\pm)/\sigma(Z)$ also measured
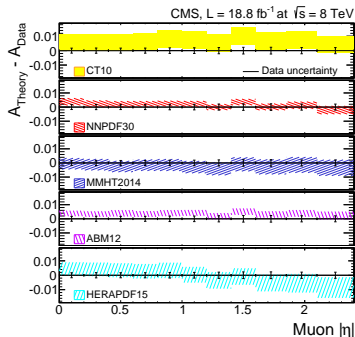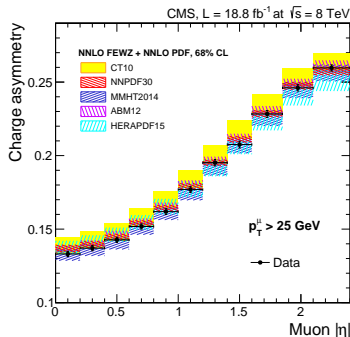- total uncertainty $\approx 0.8\%$

7/8 TeV Cross-Sections

CMS: Differential W Asymmetry [arXiv:1603.01803]
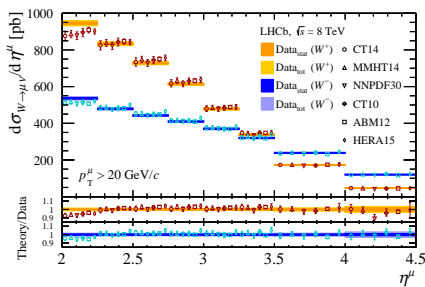
- differential $W \to \nu\mu$ charge asymmetry measurement
  - $\sqrt{s} = 8$ TeV, 18.8 fb^{-1} dataset
  - $p_{\mathrm{T}}(\mu) > 25$ GeV, $|\eta(\mu)| < 2.4$

$$\mathcal{A} \equiv \frac{\sigma(W^+) - \sigma(W^-)}{\sigma(W^+) + \sigma(W^-)}$$

- comparison to FEWZ predictions with 5 PDF sets

# LHCb: Differential W,Z Cross-Sections [JHEP **01** (2016) 155]

- differential $W \to \nu\mu$ and $Z \to \mu\mu$ cross-section measurements
  - $\sqrt{s} = 8$ TeV, 2 fb^{-1} dataset
  - $p_T(\mu) > 20$ GeV, $2.0 < \eta(\mu) < 4.5$, $60 < m(\mu\mu) < 120$ GeV
- comparison to FEWZ predictions with 6 PDF sets
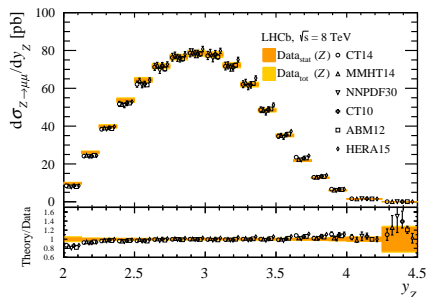
LHCb: Differential W,Z Cross-Sections [JHEP **01** (2016) 155]

- precise ratios between $\sqrt{s} = 7$ and 8 TeV total cross-sections ...
- even more precise double ratios (sub-percent)
- compared to five different PDF sets
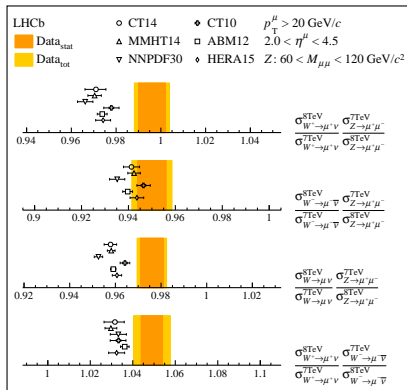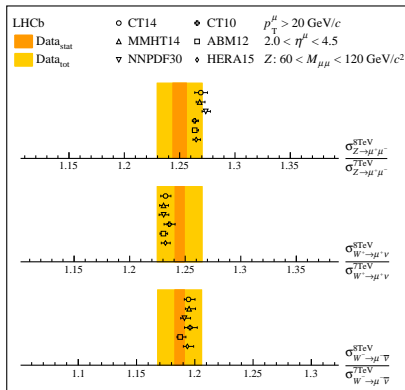
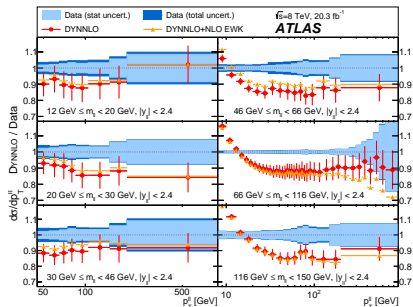# ATLAS: Differential DY Cross-Sections [arXiv:1512.02192]

- differential Drell-Yan cross-section in $p_{\mathrm{T}}(\ell\ell)$, $\phi^*(\ell\ell)$, $y(\ell\ell)$, and $m(\ell\ell)$
  - $\sqrt{s} = 8$ TeV, 20.3 fb^{-1} dataset
  - $p_{\mathrm{T}}(\ell) > 20$ GeV, $|\eta(\mu)| < 2.5$
- comparison to fixed order and showered predictions
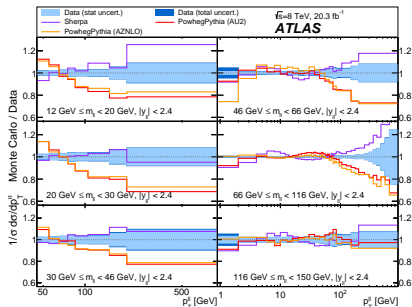
ATLAS: High Mass DY Cross-Sections [preliminary]

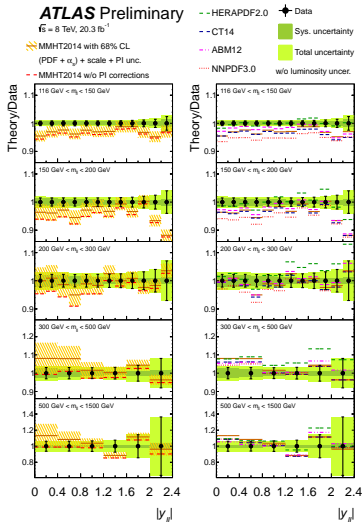- double differential Drell-Yan cross-section in $m(\ell\ell)$ and $y(\ell\ell)$ or $\Delta\eta(\ell\ell)$
  - $\sqrt{s} = 8$ TeV, 20.3 fb^{-1} dataset
  - $p_T(\ell) > 40(3)$ GeV, $|\eta(\ell)| < 2.5$
- comparison to NNLO QCD/NLO EWK predictions
- sensitive to photo-production

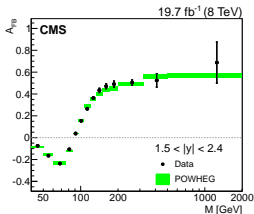$$A_{\mathrm{FB}} \text{ and } \sin^2\theta_{\mathrm{W}}^{\mathrm{eff}}$$

CMS: Double Differential A_{FB} [arXiv:1601.04768]

$$A_{\mathrm{FB}} \equiv \frac{\sigma_{\mathrm{F}} - \sigma_{\mathrm{B}}}{\sigma_{\mathrm{F}} + \sigma_{\mathrm{B}}}$$

- $\mathrm{F} \equiv \cos\theta^* > 0$
  (Collins-Soper Frame)

- $\sqrt{s} = 8$ TeV, 19.7 fb^{-1}
  dataset

- both $Z \to ee$ and
  $Z \to \mu\mu$ final states

- dilution from unknown
  quark direction at low
  $y(\mu\mu)$
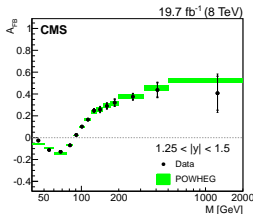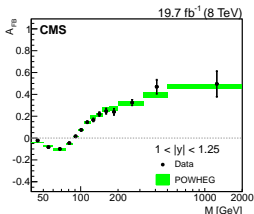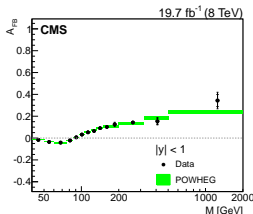
ATLAS: A_{FB} with *ee* and $\mu\mu$ [JHEP **09** (2015) 049]

- both $Z \to ee$ and $Z \to \mu\mu$ final states
- $\sqrt{s} = 7$ TeV, 4.8 fb^{-1} dataset
- electrons extend forward range
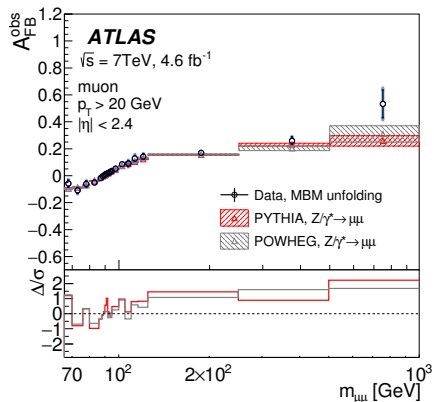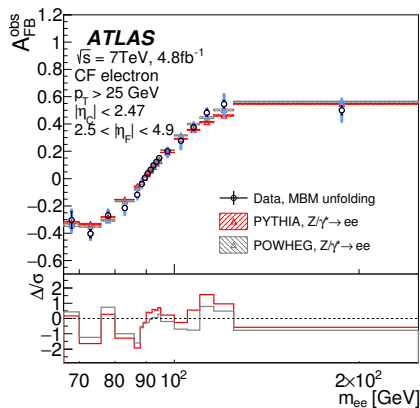
ATLAS: Angular Correlations [preliminary]

$$A_0 = \frac{20}{6}\langle 1 - 3\cos^2\theta\rangle + \frac{2}{3}$$

$$A_2 = 10\langle \sin^2\theta \cos 2\phi\rangle$$
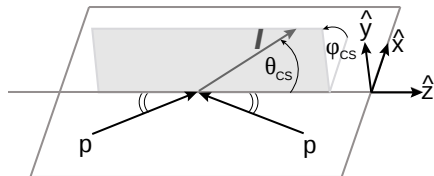
- both $Z \to ee$ and $Z \to \mu\mu$ final states
- $\sqrt{s} = 8$ TeV, 20.3 fb^{-1} dataset
- $p_{\mathrm{T}}(\ell) > 25$ GeV, forward and central electrons
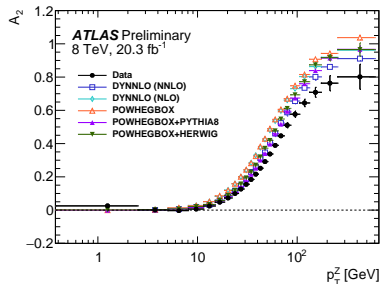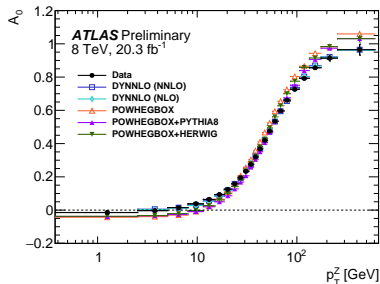
ATLAS: Angular Correlations [preliminary]
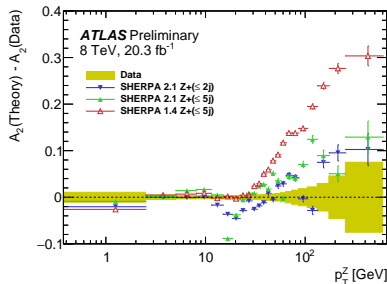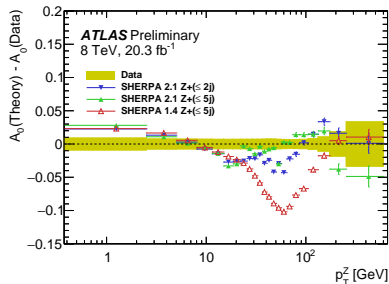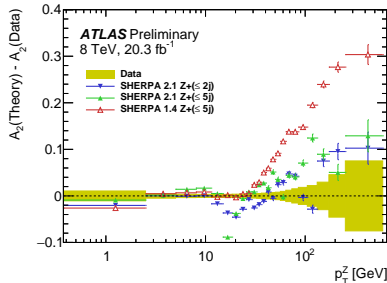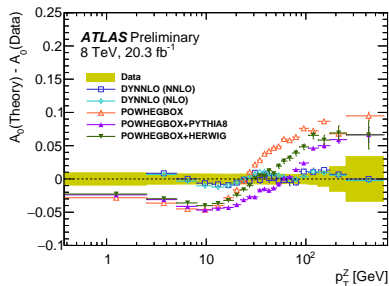
LHCb: Forward A_{FB} [JHEP **11** (2015) 190]

- forward measurement using only $Z \to \mu\mu$ final states
- $\sqrt{s} = 7$ TeV, 1 fb^{-1} dataset, and $\sqrt{s} = 8$ TeV, 2 fb^{-1} dataset
- fit the A_{FB} distribution with different $\sin^2 \theta_W^{eff}$ predictions
  - template uncertainty from PDFs and scale
  - resulting $\sin^2 \theta_W^{eff}$ is model dependent, here POWHEGBOX
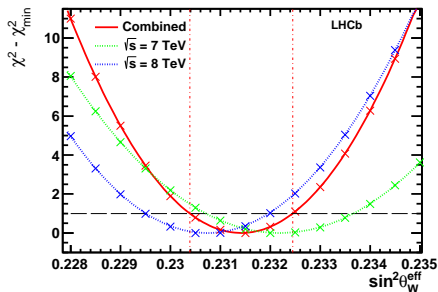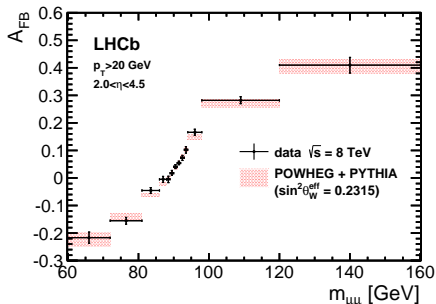
Combined: $\sin^2\theta_{\mathrm{W}}^{\mathrm{eff}}$ Determination [JHEP 11 (2015) 190]

LEP + SLD
Phys. Rept. 427 (2006) 257
0.2315 ± 0.0002

LEP A_{FB}(b)
Phys. Rept. 427 (2006) 257
0.2322 ± 0.0003

SLD A_{LR}
Phys. Rev. Lett. 84 (2000) 5945
0.2310 ± 0.0003

D0
Phys. Rev. Lett. 115 (2015) 041801
0.2315 ± 0.0005

CDF
Phys. Rev. Lett. D89 (2014) 072005
0.2315 ± 0.0010

ATLAS
arXiv:1503:03709
0.2308 ± 0.0012

CMS
Phys. Rev. Lett. D84 (2011) 112002
0.2287 ± 0.0032

LHCb
0.2314 ± 0.0011

LHCb $\sqrt{s}$=7TeV
0.2329 ± 0.0015

LHCb $\sqrt{s}$=8TeV
0.2307 ± 0.0012

0.224 0.226 0.228 0.23 0.232 0.234

$\sin^2\theta_{\mathrm{W}}^{\mathrm{eff}}$

Conclusions

Summary and Outlook

- comprehensive set of results available
  - measurements at $\sqrt{s} = 7$, 8, and 13 TeV
  - more exciting and precise 13 TeV measurements to come!
- differential uncertainties down to as low as 1%
- p_T spectra (W and Z) well measured
  - important for precision W mass measurements
  - useful for tunes, checking fixed order and p_T resummation
- very precise tests with W/Z ratios and COM ratios of ratios
  - strong constraints on PDFs
- $\sin^2 \theta_W^{\text{eff}}$ and A_{FB} measurements with precision comparable to Tevatron results
- thanks to ATLAS, CMS, and LHCb for all the hard work!

Appendix

Detecteurs

Detectors

	pixel		silicon strip		ECAL		Cherenkov
	drift tube		HCAL		muon		
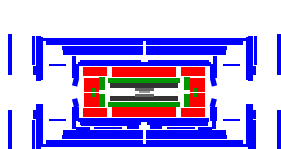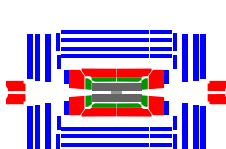
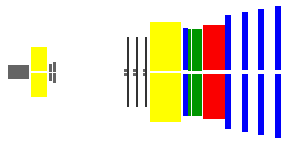| ATLAS	CMS	LHCb
JINST **3** (2008) S08003	JINST **3** (2008) S08004	JINST **3** (2008) S08005
$\|\eta(\mu)\| < 2.4$	$\|\eta(\mu)\| < 2.4$	$2.0 < \eta(\mu) < 4.5$
$\|\eta(e)\| < 1.37$ $1.52 < \|\eta(e)\| < 2.47$	$\|\eta(e)\| < 1.44$ $1.57 < \|\eta(e)\| < 2.5$ $3.1 < \|\eta(e)\| < 4.6$	$2.0 < \eta(e) < 4.5$
$\delta_{\mathcal{L}} = 1.8\%$	$\delta_{\mathcal{L}} = 2.6\%$	$\delta_{\mathcal{L}} =$ $1.71\%(7\ \text{TeV}), 1.16\%(8\ \text{TeV}),$ (3.5%)

$Z \rightarrow \ell\ell$ Measurements

Analyses

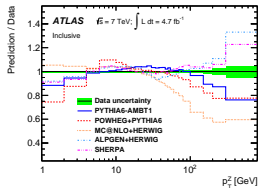| obs.	ℓ	$\mathcal{L}$	$\sqrt{s}$ [TeV]	exp.	reference
$\frac{\mathrm{d}\sigma_Z}{\mathrm{d}p_{\mathrm{T}}(Z)}$	e,μ	4.7 fb^{-1}	7	ATLAS	JHEP **1409** (2014) 145
	e,μ	36 pb^{-1}	7	CMS	Phys. Rev. D **85** (2012) 032002
	μ	19.7 fb^{-1}	8	CMS	arXiv:1504.03511
	μ	1 fb^{-1}	7	LHCb	JHEP **08** (2015) 039
$\frac{\mathrm{d}\sigma_Z}{\mathrm{d}\phi^*(Z)}$	e,μ	4.6 fb^{-1}	7	ATLAS	Phys. Lett. B **720** (2013) 32
	μ	1 fb^{-1}	7	LHCb	JHEP **08** (2015) 039
	e	1 fb^{-1}	7	LHCb	JHEP **1302** (2013) 106
	e	2 fb^{-1}	8	LHCb	arXiv:1503.00963
$\frac{\mathrm{d}\sigma_Z}{\mathrm{d}y(Z)}$	e,μ	35 pb^{-1}	7	ATLAS	Phys. Rev. D **85** (2012) 072004
	e,μ	36 pb^{-1}	7	CMS	Phys. Rev. D **85** (2012) 032002
	μ	19.7 fb^{-1}	8	CMS	arXiv:1504.03511
	μ	1 fb^{-1}	7	LHCb	JHEP **08** (2015) 039
	e	1 fb^{-1}	7	LHCb	JHEP **1302** (2013) 106
	e	2 fb^{-1}	8	LHCb	arXiv:1503.00963
$\frac{\mathrm{d}^2\sigma_Z}{\mathrm{d}y(Z)\mathrm{d}p_{\mathrm{T}}(Z)}$	e,μ	4.7 fb^{-1}	7	ATLAS	JHEP **1409** (2014) 145
	μ	19.7 fb^{-1}	8	CMS	arXiv:1504.03511
$\frac{\mathrm{d}^2\sigma_Z}{\mathrm{d}y(Z)\mathrm{d}\phi^*(Z)}$	e,μ	4.6 fb^{-1}	7	ATLAS	Phys. Lett. B **720** (2013) 32

Fiducial Definitions

exp.	boson	lepton
ATLAS	$66 < m(Z) < 116$ GeV	$p_{\mathrm{T}}(\ell) > 20$ GeV $\quad$ $\|\eta(\ell)\| < 2.4 \left(\text{not for } \frac{\mathrm{d}\sigma_Z}{\mathrm{d}y(Z)}\right)$
CMS	$60 < m(Z) < 120$ GeV (7 TeV)	$\|p_{\mathrm{T}}(\ell)\| > 20$ GeV $\left(\text{only for } \frac{\mathrm{d}\sigma_Z}{\mathrm{d}p_{\mathrm{T}}(Z)}\right)$ $\quad$ $\|\eta(\ell)\| < 2.1$
	$81 < m(Z) < 101$ GeV (8 TeV) $\quad$ $\|y(Z)\| < 2 \left(\text{only for } \frac{\mathrm{d}\sigma_Z}{\mathrm{d}p_{\mathrm{T}}(Z)}\right)$	$p_{\mathrm{T}}(\ell) > 25(10)$ GeV $\quad$ $\|\eta(\ell)\| < 2.1(2.4)$
LHCb	$60 < m(Z) < 120$ GeV	$p_{\mathrm{T}}(\ell) > 20$ $\quad$ $2.0 < \eta(\ell) < 4.5$

$\dfrac{\mathrm{d}\sigma_Z}{\mathrm{d}p_\mathrm{T}(Z)}$ (7 TeV)

ATLAS	CMS	LHCb
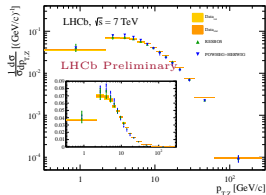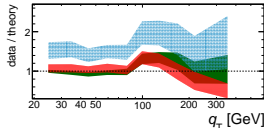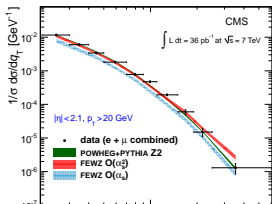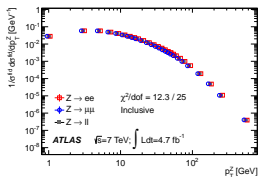
δ_total: $0.6 - 4.9\%$	δ_total: $4 - 34\%$	δ_total: $3 - 4\%$
δ_sys: $0.5 - 2.4\%$	δ_sys: $2 - 5\%$	δ_sys: $2 - 3\%$
efficiency/energy scale	alignment/energy scale	tracking efficiency

$\dfrac{\mathrm{d}\sigma_Z}{\mathrm{d}p_{\mathrm{T}}(Z)}$ (8 TeV)
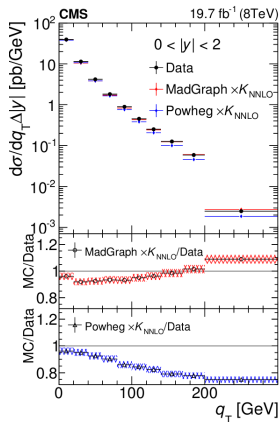
ATLAS	CMS	LHCb
	δ_{total}: $3-4\%$	
	δ_{sys}: $3-4\%$	
	efficiency	

$\dfrac{\mathrm{d}\sigma_Z}{\mathrm{d}\phi^*(Z)}$ (7 TeV)
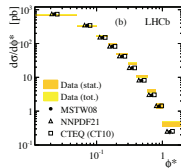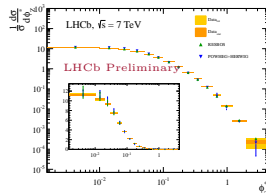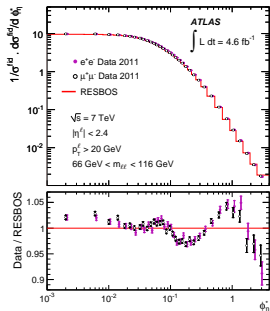
ATLAS	CMS	LHCb
δ_{total}: $\quad 0.4 - 1.7\%$ δ_{sys}: $\quad 0.2 - 0.6\%$ efficiency		δ_{total}: $\quad 2 - 41, 3 - 17\%$ δ_{sys}: $\quad 1 - 37, 3 - 8\%$ tracking efficiency

$\dfrac{\mathrm{d}\sigma_Z}{\mathrm{d}\phi^*(Z)}$ (8 TeV)
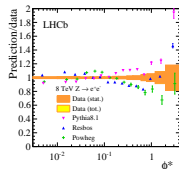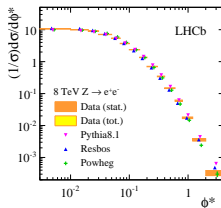
ATLAS	CMS	LHCb
		δ_{total}: $2 - 21\%$ δ_{sys}: $2 - 7\%$ tracking efficiency

$$\frac{\mathrm{d}\sigma_Z}{\mathrm{d}y(Z)} \ (7 \text{ TeV})$$

ATLAS	CMS	LHCb

muon

electron
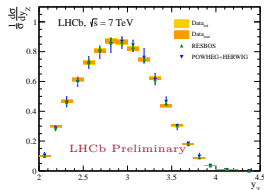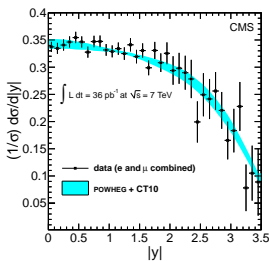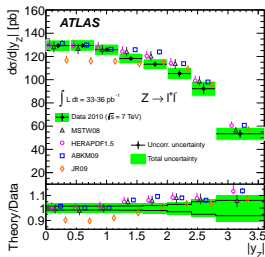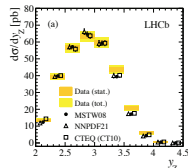
δ_{total}: $\quad 2 - 10\%$	δ_{total}: $\quad 3 - 70\%$	δ_{total}: $\quad 5 - 12, 6 - 50\%$
δ_{sys}: $\quad 1 - 9\%$	δ_{sys}: $\quad 4 - 7\%$	δ_{sys}: $\quad 3 - 5, 4 - 6\%$
reconstruction efficiency	background/efficiency	tracking efficiency

$\frac{\mathrm{d}\sigma_Z}{\mathrm{d}y(Z)}$ (8 TeV)
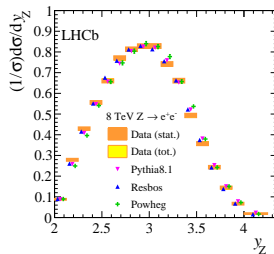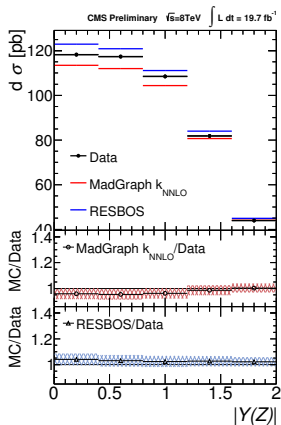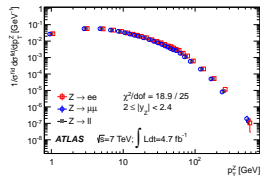
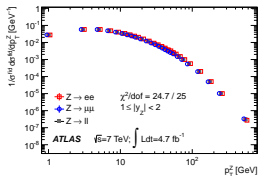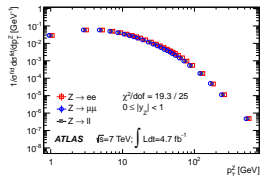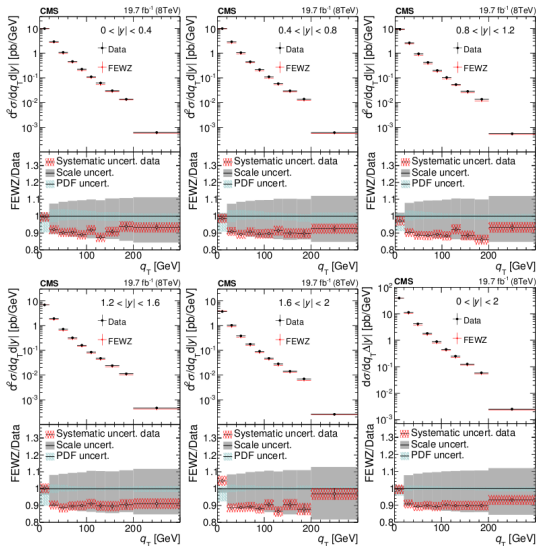| ATLAS	CMS	LHCb
	δ_{total}: $3 - 4\%$ δ_{sys}: $3 - 4\%$ efficiency	δ_{total}: $4 - 20\%$ δ_{sys}: $3 - 9\%$ tracking efficiency

$$\frac{\mathrm{d}^2\sigma_Z}{\mathrm{d}y(Z)\mathrm{d}p_{\mathrm{T}}(Z)} \text{ (ATLAS 7 TeV)}$$
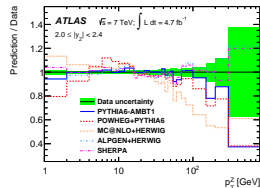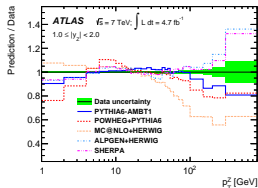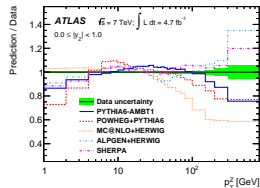
$\dfrac{\mathrm{d}^2\sigma_Z}{\mathrm{d}y(Z)\mathrm{d}p_{\mathrm{T}}(Z)}$ (CMS 8 TeV)

DY → ℓℓ Measurements

Analyses

obs.	ℓ	$\mathcal{L}$	$\sqrt{s}$ [TeV]	exp.	reference
$\frac{\mathrm{d}\sigma_{\mathrm{DY}}}{\mathrm{d}m(\mathrm{DY})}$	e, μ	1.6 fb^{-1}	7	ATLAS	JHEP **1406** (2014) 112
	e	4.9 fb^{-1}	7	ATLAS	Phys. Lett. B **725** (2013) 223
	e, μ	4.8 fb^{-1}	7	CMS	JHEP **1312** (2013) 030
	e, μ	19.7 fb^{-1}	8	CMS	Eur. Phys. J. C 75 (2015) 147
	μ	37 pb^{-1}	7	LHCb	LHCb-CONF-2012-013
$\frac{\mathrm{d}^2\sigma_{\mathrm{DY}}}{\mathrm{d}m(\mathrm{DY})\mathrm{d}y(\mathrm{DY})}$	e, μ	4.8 fb^{-1}	7	CMS	JHEP **1312** (2013) 030
	e, μ	19.7 fb^{-1}	8	CMS	Eur. Phys. J. C 75 (2015) 147
	μ	37 pb^{-1}	7	LHCb	LHCb-CONF-2012-013

Fiducial Definitions

exp.	boson	lepton
ATLAS	full phase-space	$m(\text{DY}) < 66$: $\|\eta(\ell)\| < 2.4$ $p_\text{T}(\ell) > 15(12)$ GeV $m(\text{DY}) > 116$: $\|\eta(\ell)\| < 2.5$ $p_\text{T}(\ell) > 25$ GeV
CMS	full phase-space	full phase-space
LHCb	full phase-space	$2.0 < \eta(\ell) < 4.5$ $p(\ell) > 10$ GeV $m(\text{DY}) \leq 40$ GeV : $p_\text{T}(\ell) > 3$ GeV $m(\text{DY}) > 40$ GeV : $p_\text{T}(\ell) > 15$ GeV

$\frac{\mathrm{d}\sigma_{\mathrm{DY}}}{\mathrm{d}m(\mathrm{DY})}$ (7 TeV)
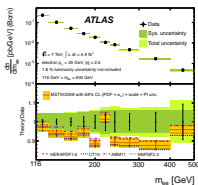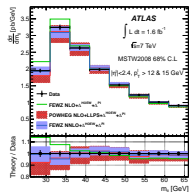
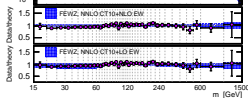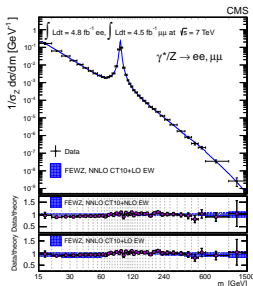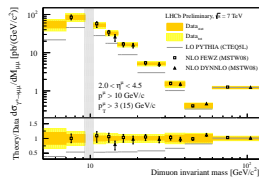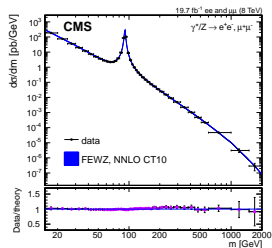| ATLAS	CMS	LHCb
		LHCb Preliminary
δ_{total}: $4 - 2, 4 - 51\%$ δ_{sys}: $4 - 2, 4 - 10\%$ background	δ_{total}: $8 - 51\%$ δ_{sys}: $2 - 15\%$ efficiency	δ_{total}: $33 - 6\%$ δ_{sys}: $26 - 5\%$ tracking efficiency

$\frac{\mathrm{d}\sigma_{\mathrm{DY}}}{\mathrm{d}m(\mathrm{DY})}$ (8 TeV)

ATLAS	CMS	LHCb
	δ_{total}: $4-14\%$	
	δ_{sys}: $4-14\%$	
	efficiency	

$\dfrac{\mathrm{d}^2\sigma_{\mathrm{DY}}}{\mathrm{d}m(\mathrm{DY})\mathrm{d}y(\mathrm{DY})}$ (CMS 7 TeV)
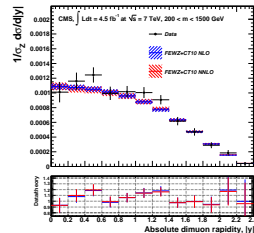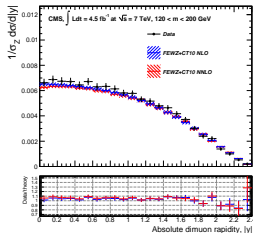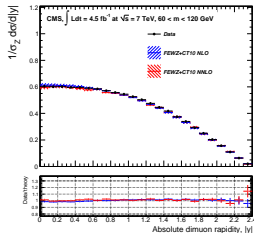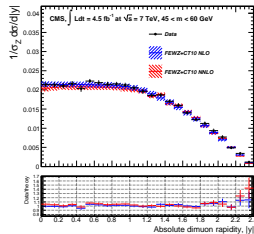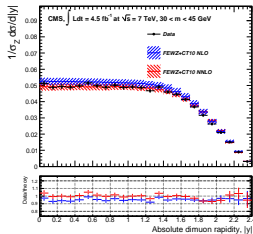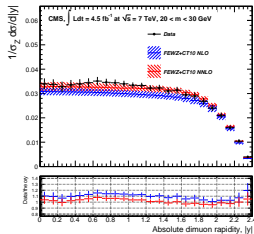
$\dfrac{\mathrm{d}^2\sigma_{\mathrm{DY}}}{\mathrm{d}m(\mathrm{DY})\mathrm{d}y(\mathrm{DY})}$ (CMS 8 TeV)
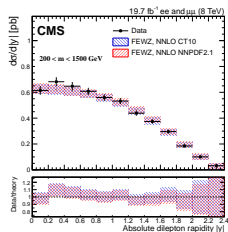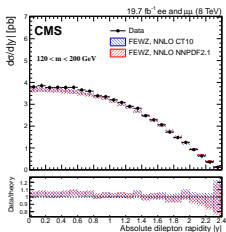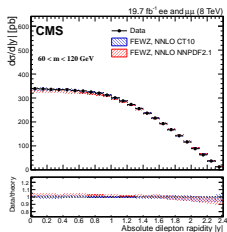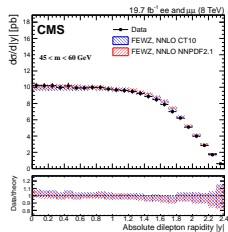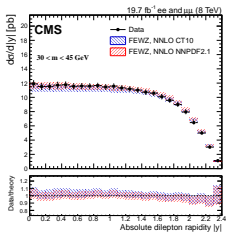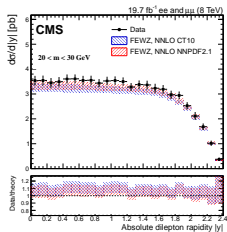
$\dfrac{\mathrm{d}^2\sigma_{\mathrm{DY}}}{\mathrm{d}m(\mathrm{DY})\mathrm{d}y(\mathrm{DY})}$ (LHCb 7 TeV)

LHCb Preliminary
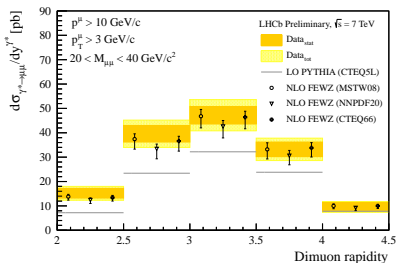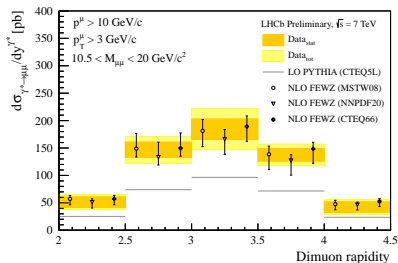
$W \to \ell\nu$ Measurements

Analyses

obs.	ℓ	$\mathcal{L}$	$\sqrt{s}$ [TeV]	exp.	reference
$\frac{\mathrm{d}\sigma_W}{\mathrm{d}p_{\mathrm{T}}(W)}$	e,μ	31 pb^{-1}	7	ATLAS	Phys. Rev. D **85** (2012) 012005
	e,μ	18.4 pb^{-1}	8	CMS	CMS-PAS-SMP-13-006
$\frac{\mathrm{d}\sigma_W}{\mathrm{d}\eta(\ell)}$	e,μ	35 pb^{-1}	7	ATLAS	Phys. Rev. D **85** (2012) 072004
	μ	1 fb^{-1}	7	LHCb	JHEP **1412** (2014) 079
	μ	1 fb^{-1}	7	LHCb	JHEP **08** (2015) 039
$\mathcal{A}(\eta(\ell))$	e,μ	35 pb^{-1}	7	ATLAS	Phys. Rev. D **85** (2012) 072004
	μ	4.7 fb^{-1}	7	CMS	Phys. Rev. D **90** (2014) 032004
	μ	1 fb^{-1}	7	LHCb	JHEP **1412** (2014) 079
	μ	1 fb^{-1}	7	LHCb	JHEP **08** (2015) 039

Fiducial Definitions

exp.	boson	lepton
ATLAS	$m_{\mathrm{T}}(W) > 40$ GeV	$p_{\mathrm{T}}(\ell) > 20$ GeV $p_{\mathrm{T}}(\nu) > 25$ GeV $\|\eta(\ell)\| < 2.4 \left(\text{only for } \frac{\mathrm{d}\sigma_W}{\mathrm{d}p_{\mathrm{T}}(W)}\right)$
CMS	full phase-space (7 TeV)	$p_{\mathrm{T}}(\ell) > 25$ GeV, $p_{\mathrm{T}}(\ell) > 35$ GeV
	full phase-space (8 TeV)	$p_{\mathrm{T}}(\mu) > 20$ GeV, $p_{\mathrm{T}}(e) > 25$ GeV $\|\eta(\mu)\| < 2.1$, $\|\eta(e)\| < 2.5$
LHCb	full phase-space	$p_{\mathrm{T}}(\ell) > 20$ $2.0 < \eta(\ell) < 4.5$

$\dfrac{\mathrm{d}\sigma_W}{\mathrm{d}p_{\mathrm{T}}(W)}$ (7/8 TeV)
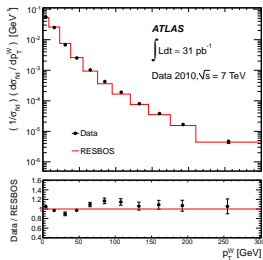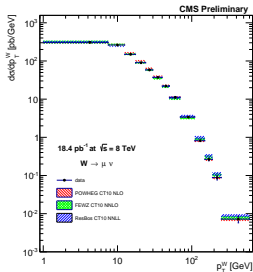
ATLAS	CMS	LHCb
(7 TeV)	(8 TeV)	
δ_{total}: $\quad 3 - 14\%$ δ_{sys}: $\quad 2 - 9\%$ backgrounds/unfolding	δ_{total}: $\quad 4 - 43\%$ δ_{sys}: $\quad 4 - 10\%$ backgrounds/unfolding	

$\frac{\mathrm{d}\sigma_W}{\mathrm{d}\eta(\ell)}$ (7 TeV)

ATLAS	CMS	LHCb
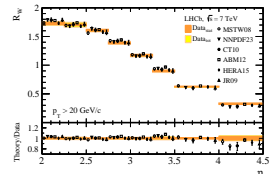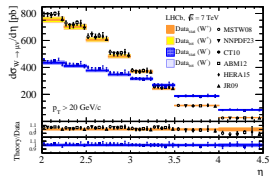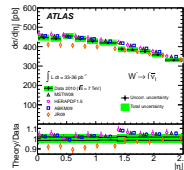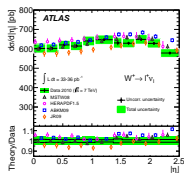
δ_{total}: $\quad 2-2, 2-2\%$		δ_{total}: $\quad 2-4\%$
δ_{sys}: $\quad 2-2, 2-2\%$		δ_{sys}: $\quad 2-3\%$
e identification		efficiency

$\mathcal{A}(\eta(\ell))$ (7 TeV)

ATLAS	CMS	LHCb

	ATLAS		CMS		LHCb
δ_{total}:	$8 - 4\%$	δ_{total}:	$0.2 - 0.4\%$	δ_{total}:	$4 - 4\%$
δ_{sys}:	$6 - 3\%$	δ_{sys}:	$0.2 - 0.4\%$	δ_{sys}:	$3 - 3\%$
	-		efficiency		template shape