Z, DY, and W Differential Measurements at the LHC
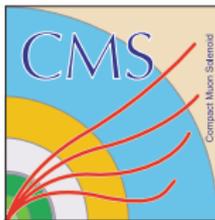
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on behalf of the ATLAS, CMS, and LHCb Collaborations

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April 21, 2015

# SM@LHC

Overview

- measure the inclusive
  production of vector bosons
  via leptonic final states
  $(\ell = e, \mu)$
  - 6 ATLAS analyses, 6 CMS
    analyses, 5 LHCb analyses
- clean experimental signature
  - understand detector
    efficiencies
  - calibrate luminosity
- precision tests of the SM
  - low systematic uncertainties
  - high statistics
- important constraints on PDFs

LHC 8 TeV Kinematics

from S. Farry
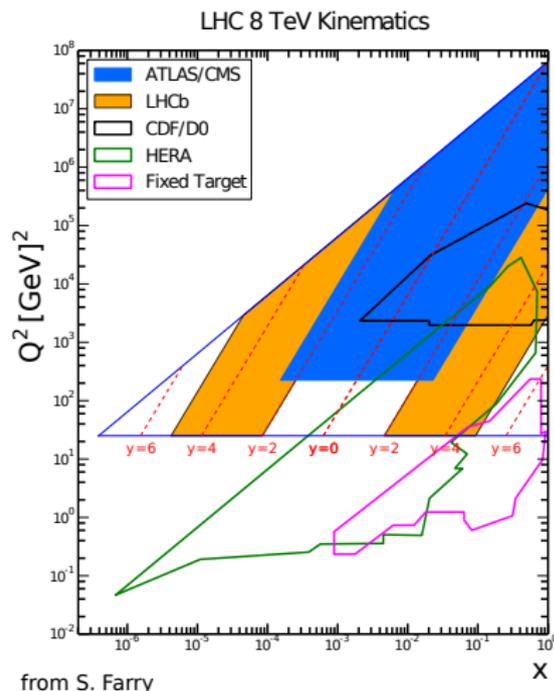
$$Q^2(x) = e^{\pm 2y} x^2 s$$

Observables

- Z: $\gamma^*/Z \to \ell\ell$ about the Z-pole
  - $66 < m(Z) < 116$ GeV for ATLAS
  - $60 < m(Z) < 120$ GeV for CMS and LHCb
- DY (Drell-Yan): $\gamma^*/Z \to \ell\ell$ away from the Z-pole
  - both low and high mass
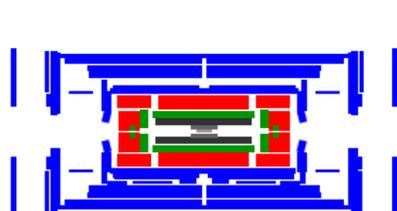- W: $W \to \ell\nu$ with no mass constraint
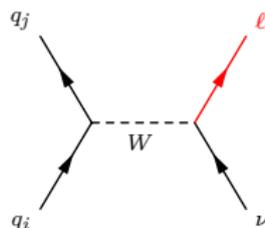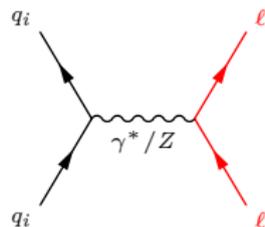
- differential cross-sections: $\frac{1}{\sigma}\frac{\mathrm{d}\sigma}{\mathrm{d}X}$, $\frac{\mathrm{d}\sigma}{\mathrm{d}X}$, $\frac{\mathrm{d}^2\sigma}{\mathrm{d}X\mathrm{d}Y}$
- lepton charge asymmetry (W only): $\mathcal{A}(X) \equiv \frac{(\mathrm{d}\sigma_{W^+}/\mathrm{d}X) - (\mathrm{d}\sigma_{W^-}/\mathrm{d}X)}{(\mathrm{d}\sigma_{W^+}/\mathrm{d}X) + (\mathrm{d}\sigma_{W^-}/\mathrm{d}X)}$
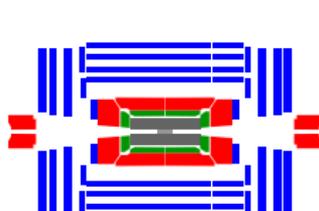
Differential Variables

- lepton four-vectors
  - bare: no QED FSR correction
  - dressed: summed with photons from cone of $\Delta R(\ell, \gamma) \lesssim 0.1$
  - Born-level: corrected using QED FSR from theory
  - *all results shown are corrected to Born-level*

- $p_T(Z)$: $\sqrt{p_x^2 + p_y^2}$ of di-lepton four-vector
- $\phi^*(Z)$: $\frac{\tan(\phi_{\text{acop}}/2)}{\cosh(\Delta\eta(\ell^+,\ell^-)/2)}$ where $\phi_{\text{acop}} = \pi - \Delta\phi(\ell^+, \ell^-)$
  - approximately proportional to $p_T(Z)/m(Z)$
  - angular resolution typically better than momentum
- $m(Z/\text{DY})$: $\sqrt{E^2 - p^2}$ from di-lepton four-vector
- $y(Z/\text{DY})$: $\frac{1}{2}\ln\left(\frac{E+p_z}{E-p_z}\right)$ from di-lepton four-vector
- $p_T(W)$: unfolded $p_T(\ell) + \not{E}_T$
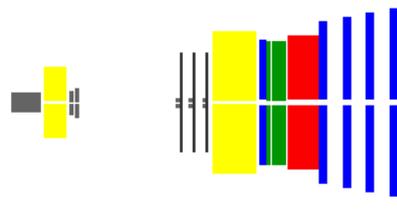- $\eta(\ell)$: $\ln\left[\tan(\theta(\ell)/2)\right]$ where ℓ from a W

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
$\|\eta(\mu)\| < 2.4$	$\|\eta(\mu)\| < 2.4$	$2.0 < \eta(\mu) < 4.5$
$\|\eta(e)\| < 1.37$ $1.52 < \|\eta(e)\| < 2.47$	$\|\eta(e)\| < 1.44$ $1.57 < \|\eta(e)\| < 2.5$ $3.1 < \|\eta(e)\| < 4.6$	$2.0 < \eta(e) < 4.5$
$\delta_{\mathcal{L}} = 1.8\%$	$\delta_{\mathcal{L}} = 2.6\%$	$\delta_{\mathcal{L}} =$ $1.71\%(7\,\mathrm{TeV}), 1.16\%(8\,\mathrm{TeV}),$ (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	$4.7~\mathrm{fb}^{-1}$	7	ATLAS	JHEP **1409** (2014) 145
	e, μ	$36~\mathrm{pb}^{-1}$	7	CMS	Phys. Rev. D **85** (2012) 032002
	μ	$19.7~\mathrm{fb}^{-1}$	8	CMS	arXiv:1504.03511
	μ	$1~\mathrm{fb}^{-1}$	7	LHCb	LHCb-PAPER-2015-001
$\frac{\mathrm{d}\sigma_Z}{\mathrm{d}\phi^*(Z)}$	e, μ	$4.6~\mathrm{fb}^{-1}$	7	ATLAS	Phys. Lett. B **720** (2013) 32
	μ	$1~\mathrm{fb}^{-1}$	7	LHCb	LHCb-PAPER-2015-001
	e	$1~\mathrm{fb}^{-1}$	7	LHCb	JHEP **1302** (2013) 106
	e	$2~\mathrm{fb}^{-1}$	8	LHCb	arXiv:1503.00963
$\frac{\mathrm{d}\sigma_Z}{\mathrm{d}y(Z)}$	e, μ	$35~\mathrm{pb}^{-1}$	7	ATLAS	Phys. Rev. D **85** (2012) 072004
	e, μ	$36~\mathrm{pb}^{-1}$	7	CMS	Phys. Rev. D **85** (2012) 032002
	μ	$19.7~\mathrm{fb}^{-1}$	8	CMS	arXiv:1504.03511
	μ	$1~\mathrm{fb}^{-1}$	7	LHCb	LHCb-PAPER-2015-001
	e	$1~\mathrm{fb}^{-1}$	7	LHCb	JHEP **1302** (2013) 106
	e	$2~\mathrm{fb}^{-1}$	8	LHCb	arXiv:1503.00963
$\frac{\mathrm{d}^2\sigma_Z}{\mathrm{d}y(Z)\mathrm{d}p_{\mathrm{T}}(Z)}$	e, μ	$4.7~\mathrm{fb}^{-1}$	7	ATLAS	JHEP **1409** (2014) 145
	μ	$19.7~\mathrm{fb}^{-1}$	8	CMS	arXiv:1504.03511
$\frac{\mathrm{d}^2\sigma_Z}{\mathrm{d}y(Z)\mathrm{d}\phi^*(Z)}$	e, μ	$4.6~\mathrm{fb}^{-1}$	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 $\|\eta(\ell)\| < 2.4$ $\left(\text{not for } \frac{\mathrm{d}\sigma_Z}{\mathrm{d}y(Z)}\right)$
CMS	$60 < m(Z) < 120$ GeV (7 TeV)	$\|p_\mathrm{T}(\ell)\| > 20$ GeV $\left(\text{only for } \frac{\mathrm{d}\sigma_Z}{\mathrm{d}p_\mathrm{T}(Z)}\right)$ $\|\eta(\ell)\| < 2.1$
	$81 < m(Z) < 101$ GeV (8 TeV) $\|y(Z)\| < 2$ $\left(\text{only for } \frac{\mathrm{d}\sigma_Z}{\mathrm{d}p_\mathrm{T}(Z)}\right)$	$p_\mathrm{T}(\ell) > 25(10)$ GeV $\|\eta(\ell)\| < 2.1(2.4)$
LHCb	$60 < m(Z) < 120$ GeV	$p_\mathrm{T}(\ell) > 20$ $2.0 < \eta(\ell) < 4.5$

$\frac{\mathrm{d}\sigma_Z}{\mathrm{d}p_T(Z)}$ (LHCb 7 TeV)

- comparison with nNLO p_T resummation (ResBos) and showered NLO (Powheg/Herwig)

- PDF uncertainty from CT10
- similar predictions
- slight overestimate for $p_T < 10$ GeV
- slight underestimate for $p_T > 10$ GeV
- systematic uncertainties $\approx 2\%$
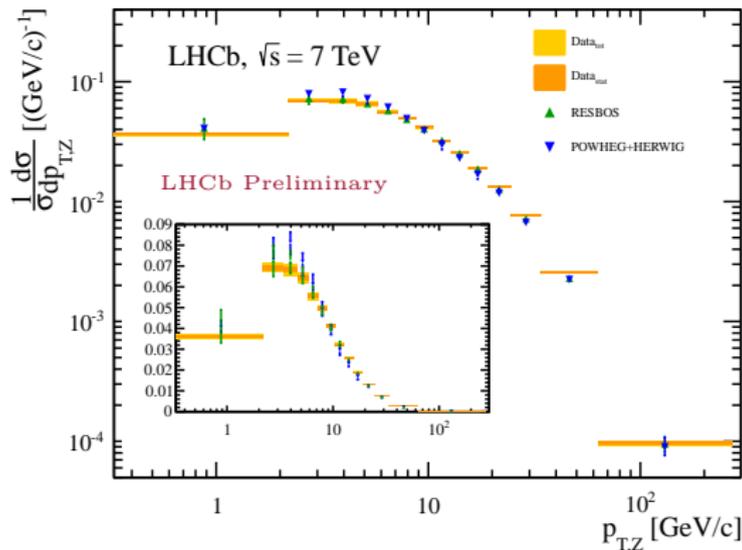
$\frac{\mathrm{d}\sigma_Z}{\mathrm{d}p_{\mathrm{T}}(Z)}$ (CMS 8 TeV)

- comparison with Pythia showered LO MadGraph and NLO Powheg

- $0 - 4$ jets produced with MadGraph

- CTEQ6L1 (MadGraph) and CT10 (Powheg)

- k_{T}-MLM matching

- MadGraph spectra is too hard while Powheg is too soft

- systematic uncertainties $\approx 3\%$
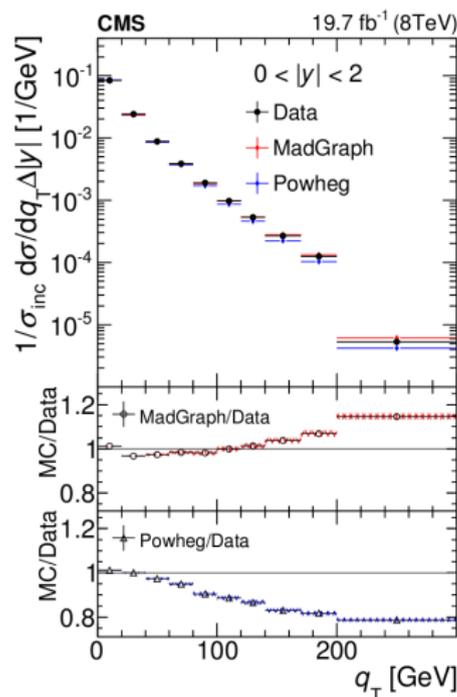
$\dfrac{\mathrm{d}^2\sigma_Z}{\mathrm{d}y(Z)\mathrm{d}p_{\mathrm{T}}(Z)}$ (CMS 8 TeV)

- comparison with fixed-order NNLO FEWZ
- PDF uncertainty from NNPDF23 and CT10 envelope
- $p_{\mathrm{T}} > 20$ GeV primarily from Z+jet
  - effectively NLO Z+jet
  - scale uncertainty increases
- $p_{\mathrm{T}} < 20$ GeV missing soft emissions
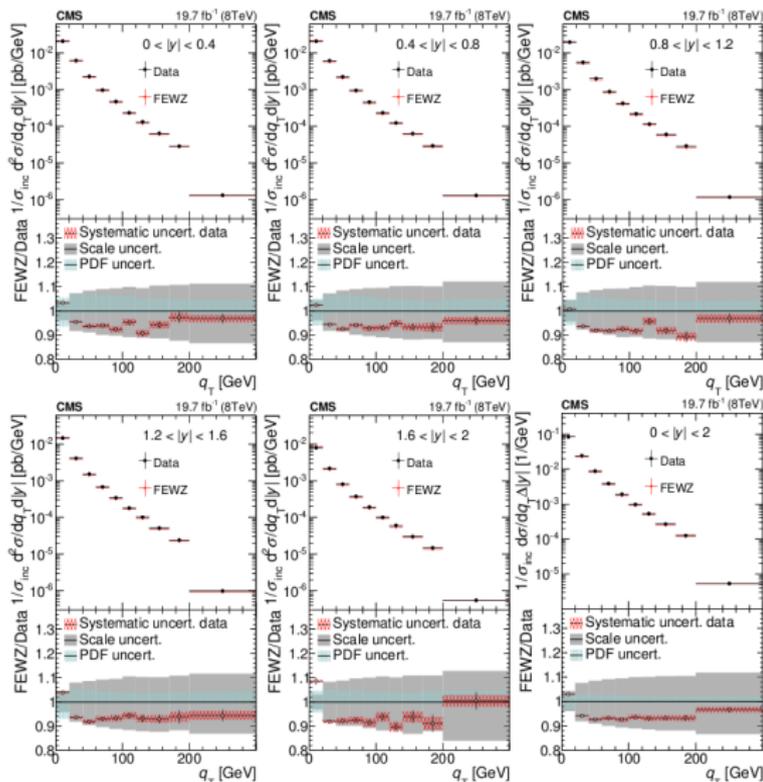
DY → $\ell\ell$ Measurements

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	$m(\text{DY}) < 66$: $\quad |\eta(\ell)| < 2.4$ $\quad\quad\quad\quad\quad\quad p_\text{T}(\ell) > 15(12)$ GeV $m(\text{DY}) > 116$: $|\eta(\ell)| < 2.5$ $\quad\quad\quad\quad\quad\quad p_\text{T}(\ell) > 25$ 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

$\frac{\mathrm{d}\sigma_{\mathrm{DY}}}{\mathrm{d}m(\mathrm{DY})}$ (ATLAS 7 TeV)

- fixed-order NLO at low mass not sufficient
- both fixed-order NNLO and showered NLO agree well
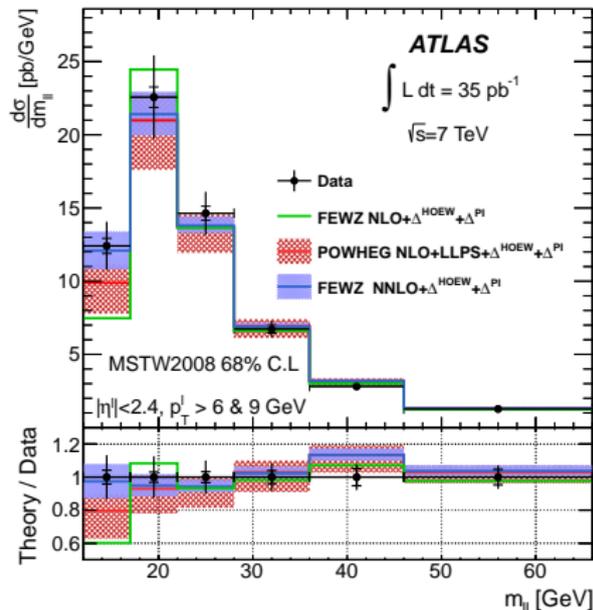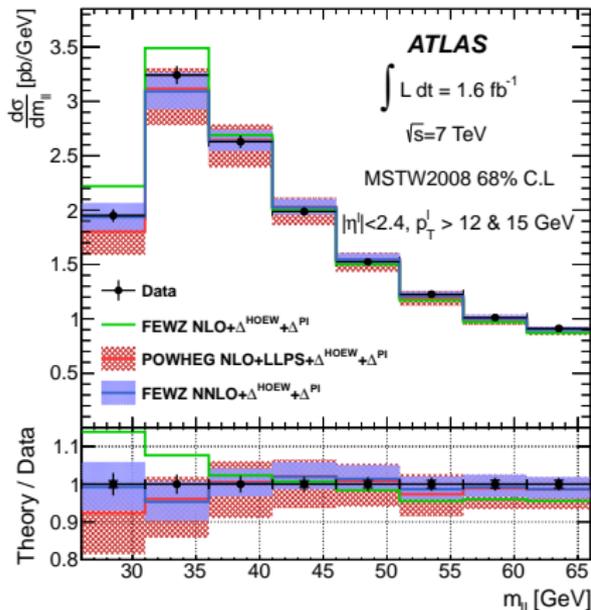
$\frac{\mathrm{d}\sigma_{\mathrm{DY}}}{\mathrm{d}m(\mathrm{DY})}$ (CMS 8/7 TeV)

$$R \equiv \frac{\frac{1}{\sigma_Z}\frac{\mathrm{d}^2\sigma_{\mathrm{DY}}}{\mathrm{d}m(\mathrm{DY})\mathrm{d}y(\mathrm{DY})} \text{ (8 TeV)}}{\frac{1}{\sigma_Z}\frac{\mathrm{d}^2\sigma_{\mathrm{DY}}}{\mathrm{d}m(\mathrm{DY})\mathrm{d}y(\mathrm{DY})} \text{ (7 TeV)}}$$

- at $m(\mathrm{DY}) \approx m(Z)$ the ratio is 1 by definition
- below $m(\mathrm{DY}) < 200$ GeV linear in $\log(m(\mathrm{DY}))$
  - produced primarily via low x partons
- above 200 GeV requires high x partons, limited by $\sqrt{s}$
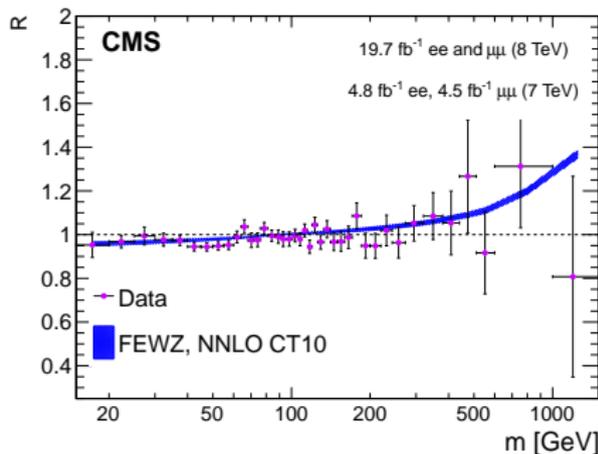
$\frac{\mathrm{d}^2\sigma_{\mathrm{DY}}}{\mathrm{d}m(\mathrm{DY})\mathrm{d}y(\mathrm{DY})}$ (CMS 8/7 TeV)

$$R_{\mathrm{det}} \equiv \frac{\frac{1}{\sigma_Z}\frac{\mathrm{d}^2\sigma_{\mathrm{DY}}}{\mathrm{d}m(\mathrm{DY})\mathrm{d}y(\mathrm{DY})} \; (8 \text{ TeV}, p_{\mathrm{T}}(\ell) > 20(10) \text{ GeV})}{\frac{1}{\sigma_Z}\frac{\mathrm{d}^2\sigma_{\mathrm{DY}}}{\mathrm{d}m(\mathrm{DY})\mathrm{d}y(\mathrm{DY})} \; (7 \text{ TeV}, p_{\mathrm{T}}(\ell) > 14(9) \text{ GeV})}$$
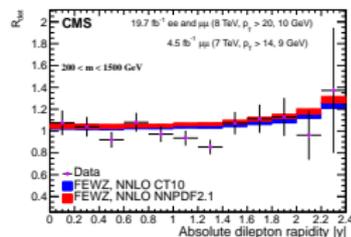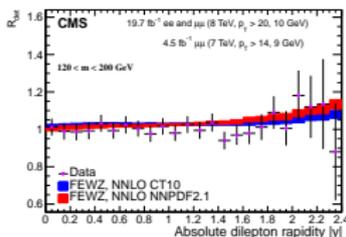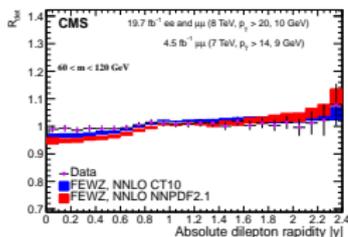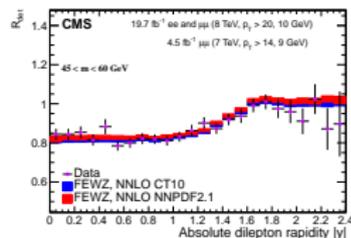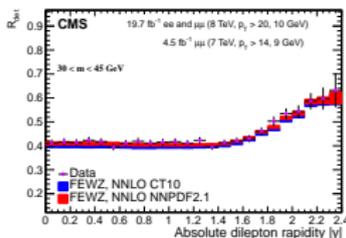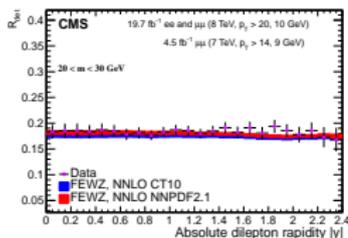
$W \to \ell\nu$ Measurements

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	LHCb-PAPER-2015-001
$\mathcal{A}(\eta(\ell))$	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	LHCb-PAPER-2015-001

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	$p_{\mathrm{T}}(\ell) > 20$ $2.0 < \eta(\ell) < 4.5$

$\frac{\sigma_W}{\sigma_Z}$ (LHCb 7 TeV)

- many uncertainties cancel in ratios, precisions of $\approx 0.8\%$
- very sensitive to PDFs, including s content and symmetry
- see Phys. Rev. Lett. **109** (2012) 012001 or Phys. Rev. D **90** (2014) 032004 for interpretations
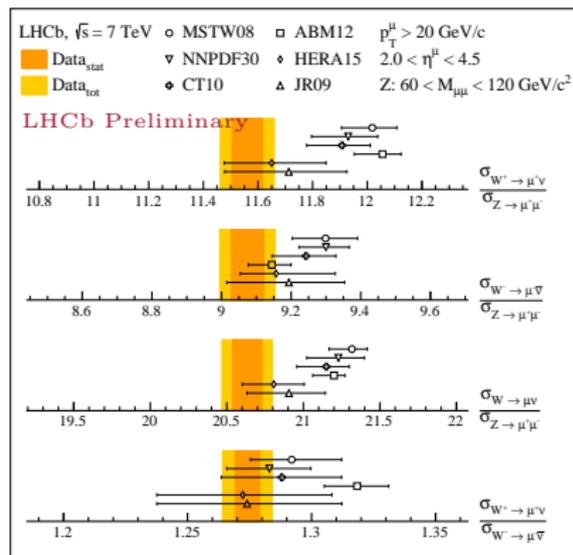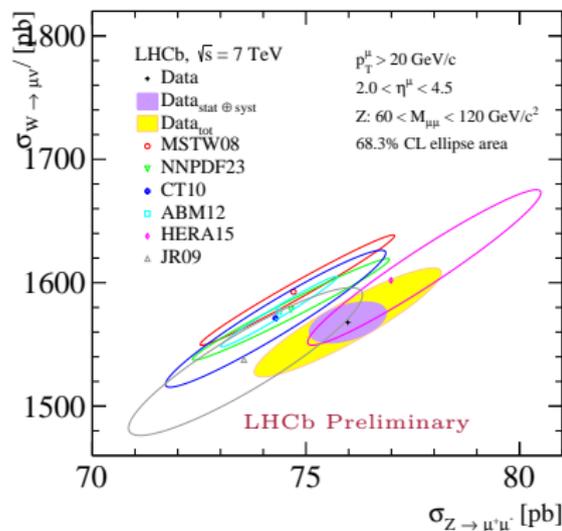
Comparisons
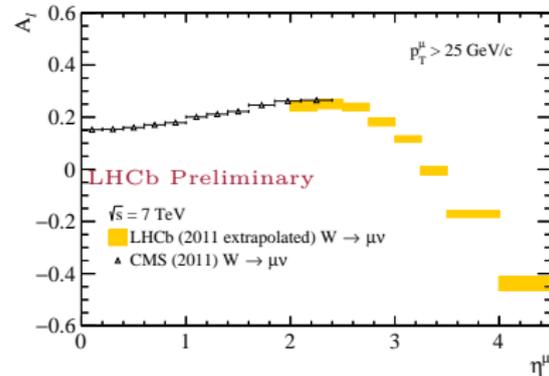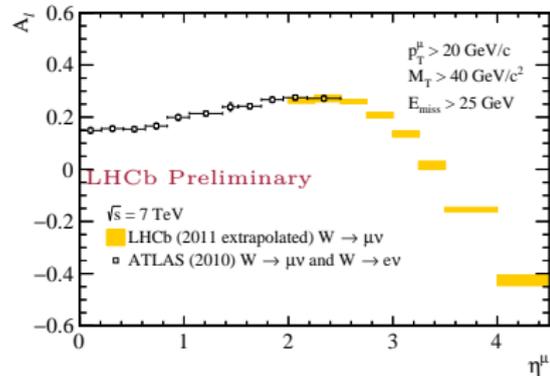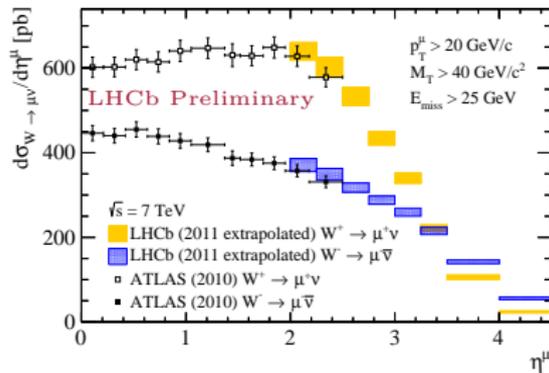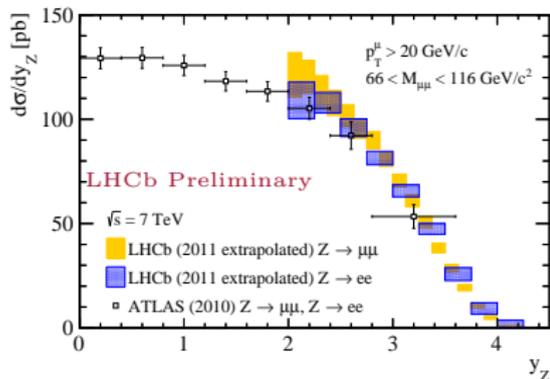
Conclusions

Summary and Outlook

- large number of results available
  - not yet a complete set, but hopefully soon
  - missing 8 TeV results from ATLAS and LHCb
- results between the three experiments appear consistent
- 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
- thanks to ATLAS, CMS, and LHCb for all the hard work!

$Z \rightarrow \ell\ell$ Measurements

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

ATLAS	CMS	LHCb
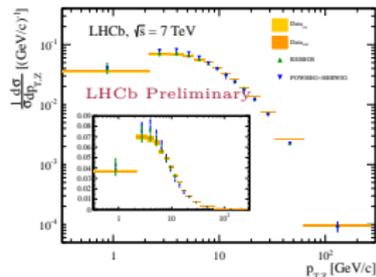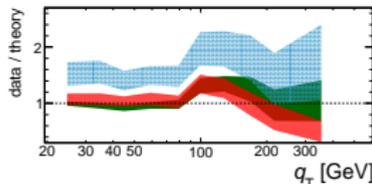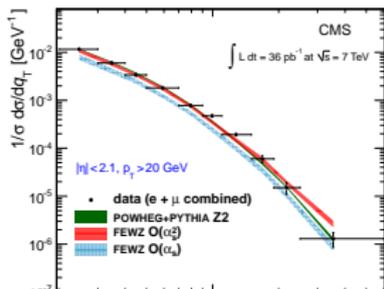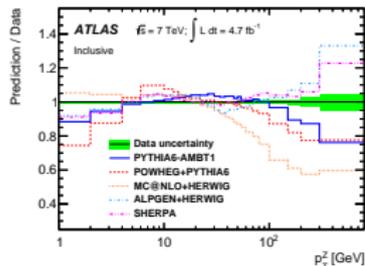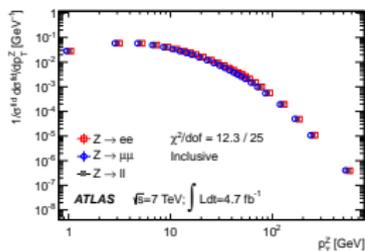
δ_{total}:	$0.6 - 4.9\%$	
δ_{sys}:	$0.5 - 2.4\%$	
efficiency/energy scale		

δ_{total}:	$4 - 34\%$	
δ_{sys}:	$2 - 5\%$	
alignment/energy scale		

δ_{total}:	$3 - 4\%$	
δ_{sys}:	$2 - 3\%$	
tracking efficiency		

$\dfrac{\mathrm{d}\sigma_Z}{\mathrm{d}p_{\mathrm{T}}(Z)}$ (8 TeV)

ATLAS	CMS	LHCb
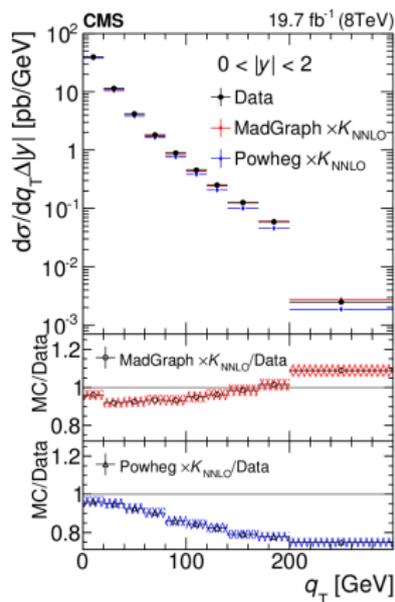
$$\delta_{\text{total}}: \quad 3 - 4\%$$
$$\delta_{\text{sys}}: \quad 3 - 4\%$$
$$\text{efficiency}$$

$\dfrac{\mathrm{d}\sigma_Z}{\mathrm{d}\phi^*(Z)}$ (7 TeV)

ATLAS	CMS	LHCb
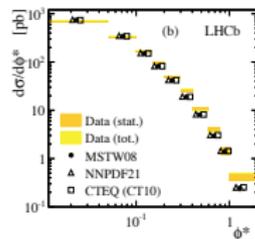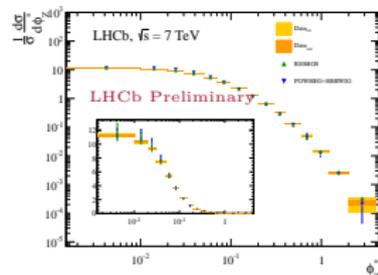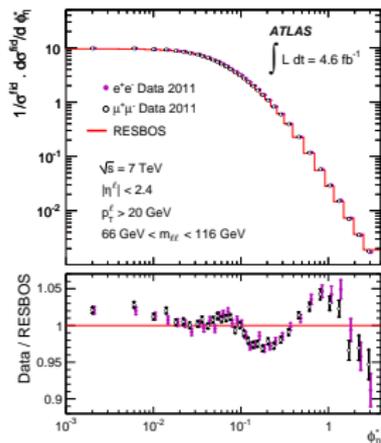
δ_{total}:	$0.4 - 1.7\%$	δ_{total}:	$2 - 41, 3 - 17\%$
δ_{sys}:	$0.2 - 0.6\%$	δ_{sys}:	$1 - 37, 3 - 8\%$
	efficiency		tracking efficiency

$\dfrac{\mathrm{d}\sigma_Z}{\mathrm{d}\phi^*(Z)}$ (8 TeV)

ATLAS	CMS	LHCb
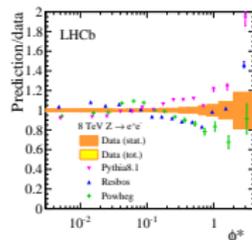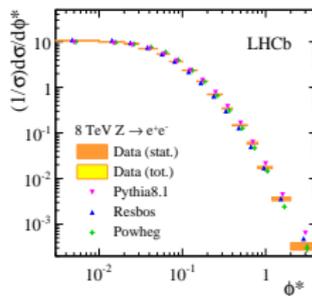
δ_{total}: $\quad 2 - 21\%$
δ_{sys}: $\quad 2 - 7\%$
tracking efficiency

$\dfrac{\mathrm{d}\sigma_Z}{\mathrm{d}y(Z)}$ (7 TeV)
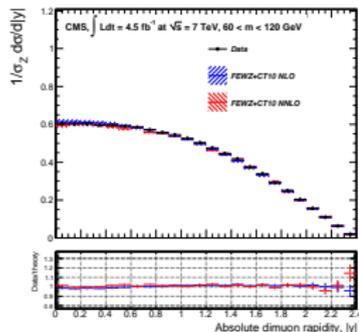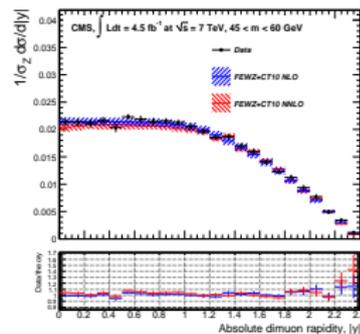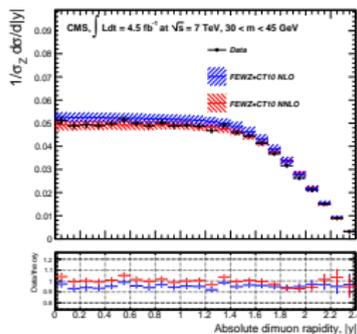
ATLAS	CMS	LHCb

muon

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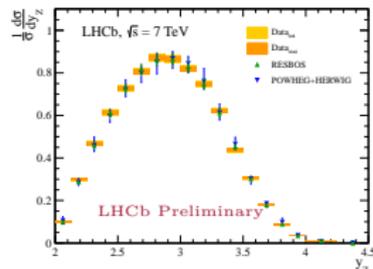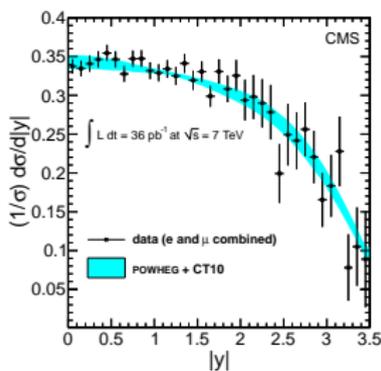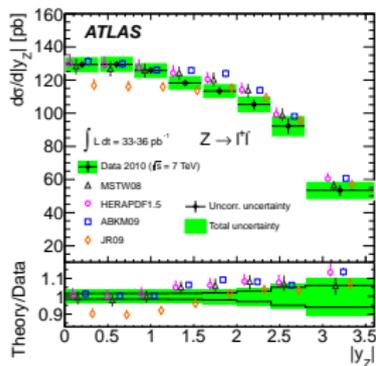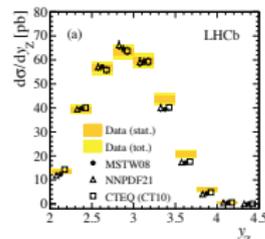
δ_{total}:	$2 - 10\%$	δ_{total}:	$3 - 70\%$	δ_{total}:	$5 - 12, 6 - 50\%$
δ_{sys}:	$1 - 9\%$	δ_{sys}:	$4 - 7\%$	δ_{sys}:	$3 - 5, 4 - 6\%$
reconstruction efficiency		background/efficiency		tracking efficiency	

$\frac{d\sigma_Z}{dy(Z)}$ (8 TeV)

ATLAS	CMS	LHCb
	δ_{total}: $3 - 4\%$ δ_{sys}: $3 - 4\%$ efficiency	δ_{total}: $4 - 20\%$ δ_{sys}: $3 - 9\%$ tracking efficiency

$\dfrac{\mathrm{d}^2\sigma_Z}{\mathrm{d}y(Z)\mathrm{d}p_{\mathrm{T}}(Z)}$ (ATLAS 7 TeV)
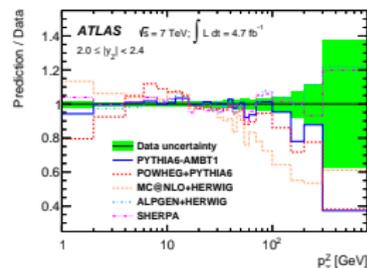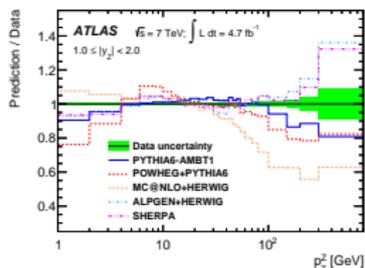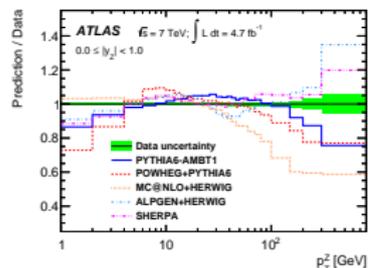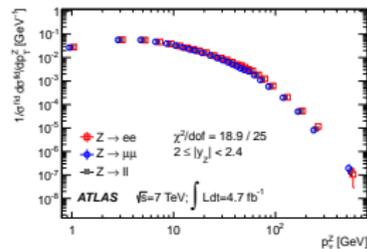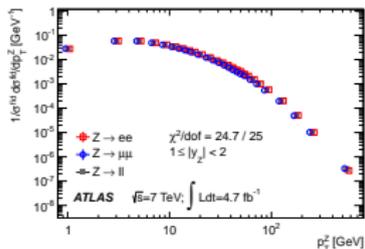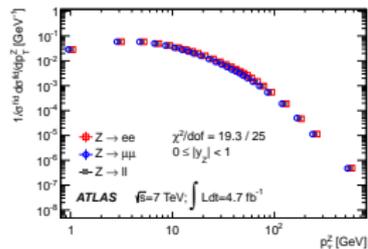
$\dfrac{\mathrm{d}^2\sigma_Z}{\mathrm{d}y(Z)\mathrm{d}p_\mathrm{T}(Z)}$ (CMS 8 TeV)
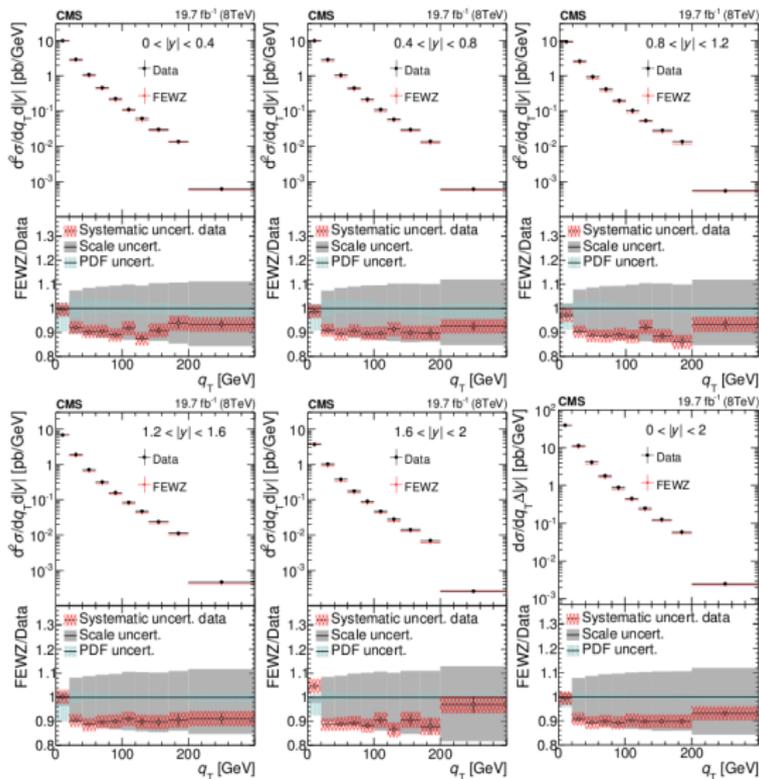
DY → $\ell\ell$ Measurements

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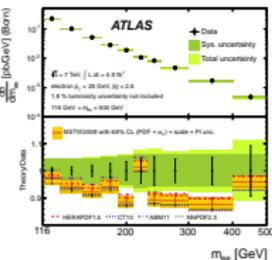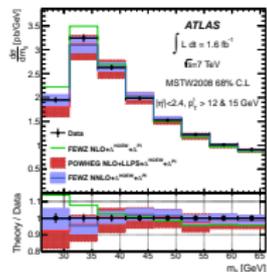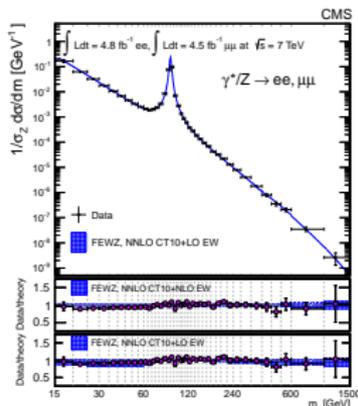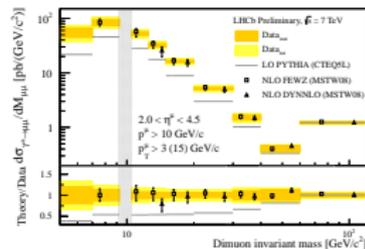
ATLAS	CMS	LHCb
		LHCb Preliminary
δ_{total}: $\quad 4-2, 4-51\%$ δ_{sys}: $\quad 4-2, 4-10\%$ background	δ_{total}: $\quad 8-51\%$ δ_{sys}: $\quad 2-15\%$ efficiency	δ_{total}: $\quad 33-6\%$ δ_{sys}: $\quad 26-5\%$ tracking efficiency

$\frac{\mathrm{d}\sigma_{\mathrm{DY}}}{\mathrm{d}m(\mathrm{DY})}$ (8 TeV)
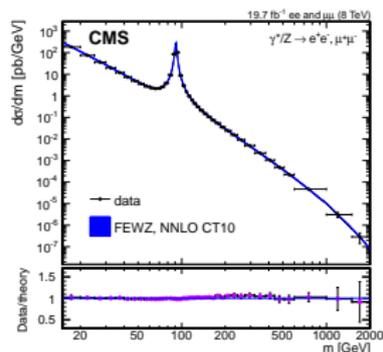
ATLAS	CMS	LHCb
	δ_{total}: $\quad 4-14\%$ δ_{sys}: $\quad 4-14\%$ efficiency	

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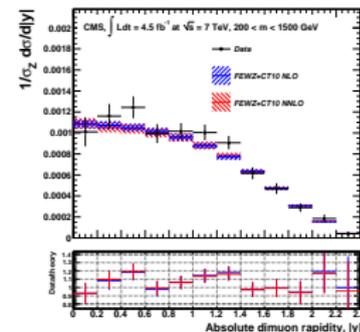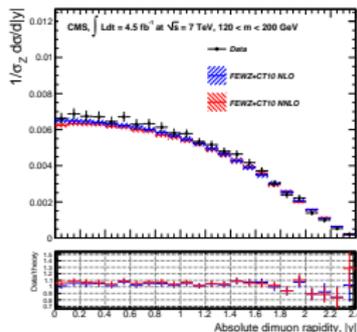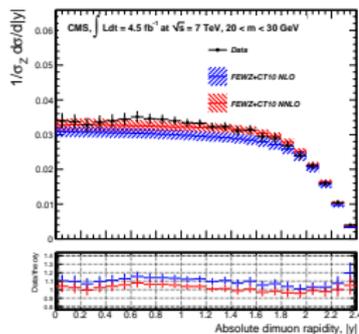
$\dfrac{\mathrm{d}^2\sigma_{\mathrm{DY}}}{\mathrm{d}m(\mathrm{DY})\mathrm{d}y(\mathrm{DY})}$ (CMS 8 TeV)
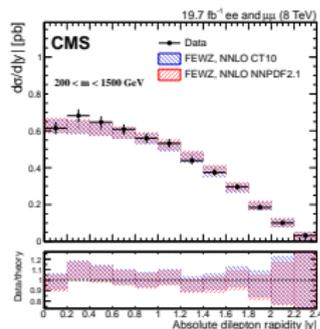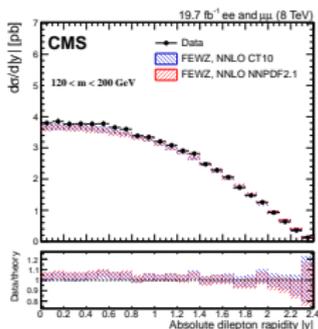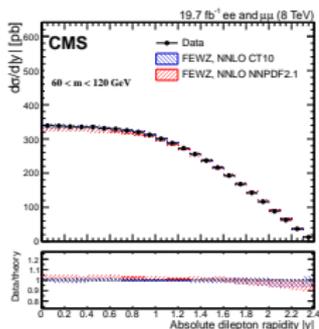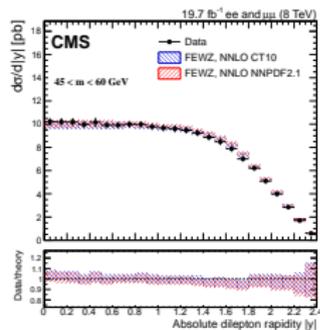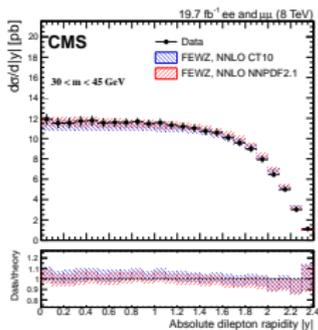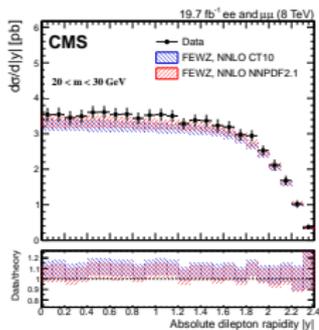
$\dfrac{\mathrm{d}^2\sigma_{\mathrm{DY}}}{\mathrm{d}m(\mathrm{DY})\mathrm{d}y(\mathrm{DY})}$ (LHCb 7 TeV)

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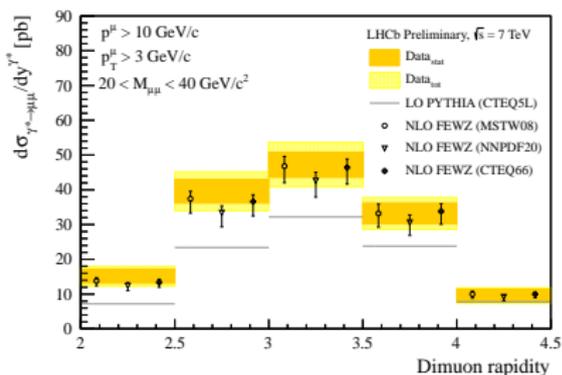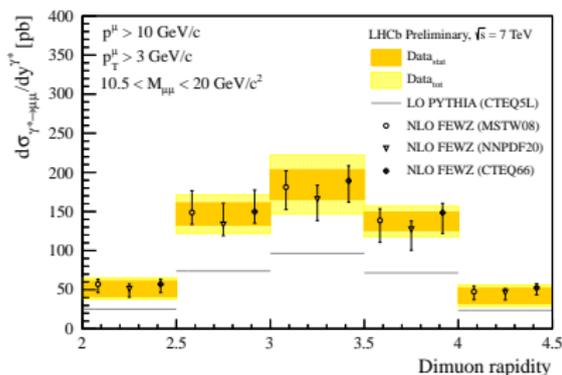
$W \rightarrow \ell\nu$ Measurements

$\dfrac{\mathrm{d}\sigma_W}{\mathrm{d}p_{\mathrm{T}}(W)}$ (7/8 TeV)

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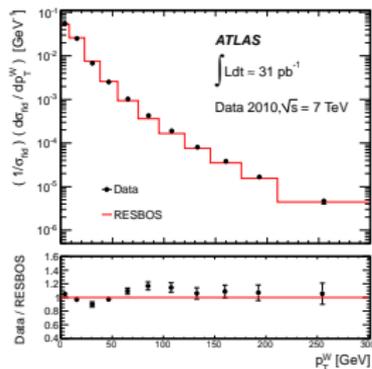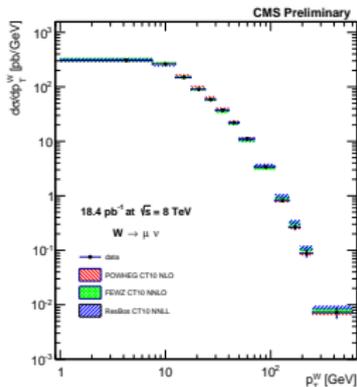
δ_{total}: $\quad 3 - 14\%$	δ_{total}: $\quad 4 - 43\%$	
δ_{sys}: $\quad 2 - 9\%$	δ_{sys}: $\quad 4 - 10\%$	
backgrounds/unfolding	backgrounds/unfolding	

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

ATLAS	CMS	LHCb
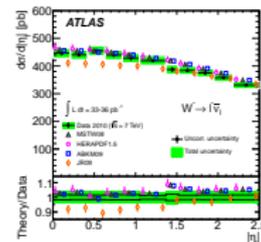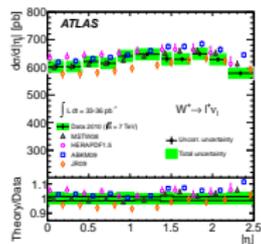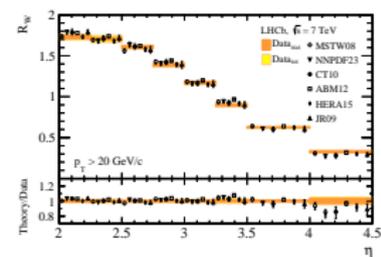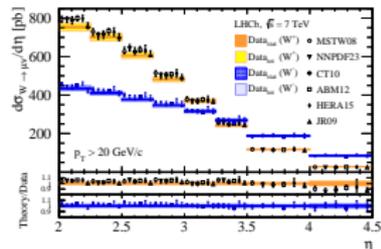
δ_{total}: $2 - 2, 2 - 2\%$

δ_{sys}: $2 - 2, 2 - 2\%$

e identification

δ_{total}: $2 - 4\%$

δ_{sys}: $2 - 3\%$

efficiency

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

ATLAS	CMS	LHCb

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