Inclusive W/Z production at ATLAS

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"Physics at the Terascale"

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Introduction

- high precision measurement of Drell-Yan production cross sections
  $\longrightarrow$ further input to constrain PDFs

- measurements based on data recorded with ATLAS in 2010 [arXiv:1109.5141]
  - electron and muon channels + combination
  - integrated and differential measurements
    - vs $|y_Z|$ and $|\eta_l|$ for W

- comparison to theoretical predictions of perturbative QCD at NNLO

  - in this talk: focus on $Z \rightarrow ee$
    (including high η electrons!)

Motivation Z→ee

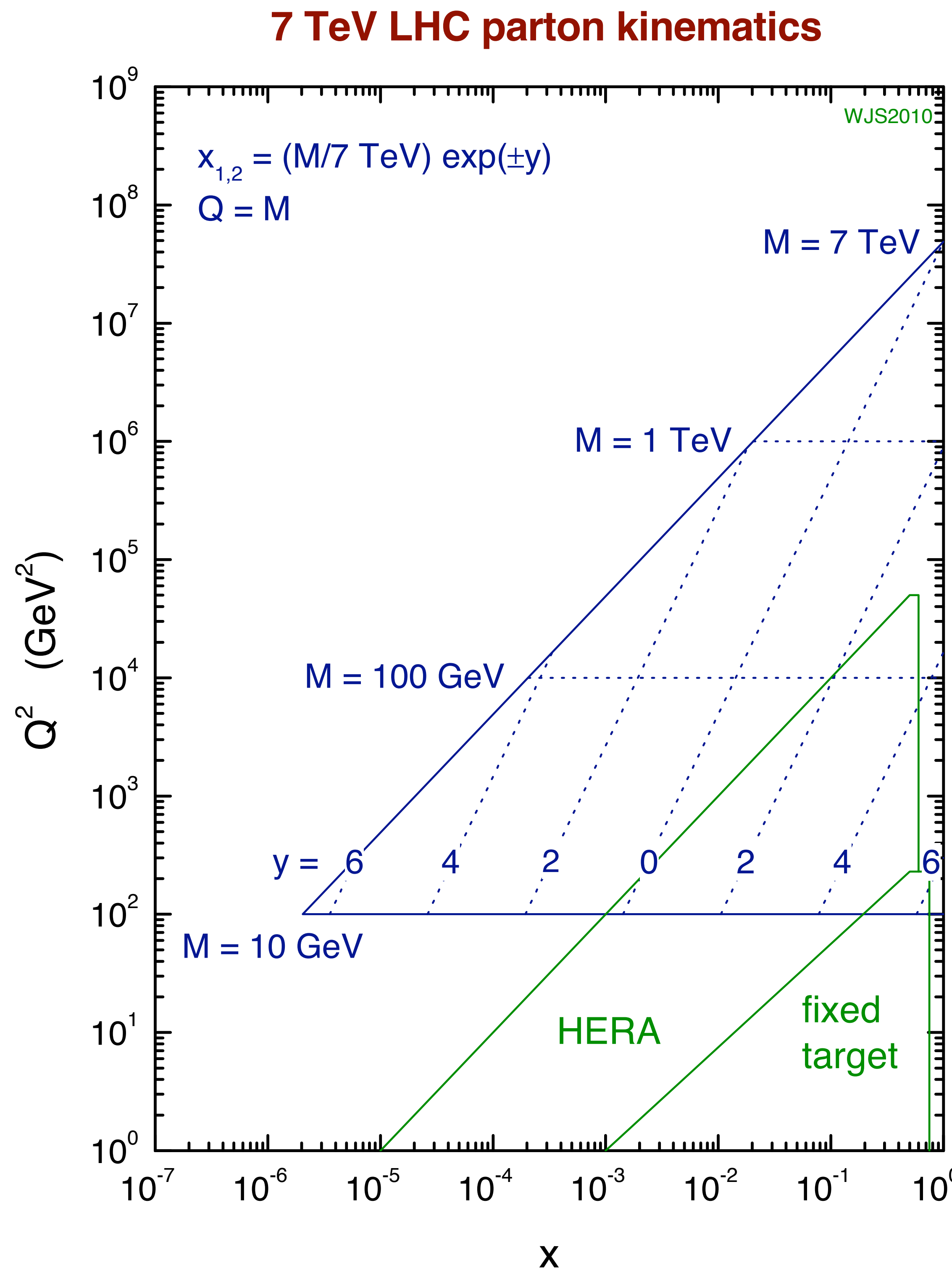
- rapidity (y) distribution of Z sensitive to PDFs of quarks
  - $$x_{1,2} = \frac{M_Z}{\sqrt{s}} e^{\pm y}$$

    $x_{1,2}$ - momentum fraction of parton 1,2 (@LO)

    s - center-of-mass energy squared

    M_Z - invariant mass of di-electron pair

- high rapidities ($|y|>2.4$): $x_1<10^{-3}$, $x_2 \sim 0.1$



LHC:

- additional data to further constrain PDFs
- measurement in new regime

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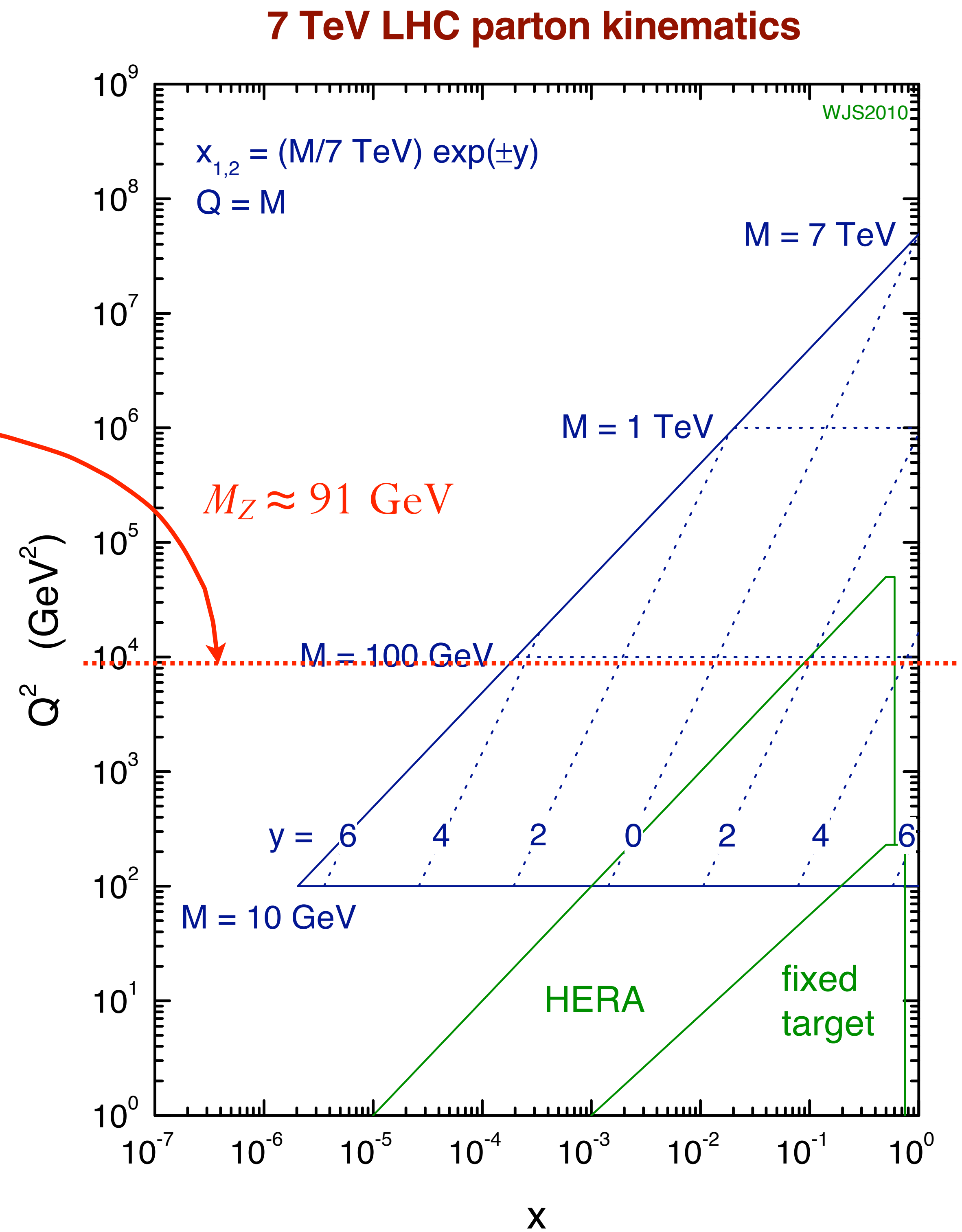

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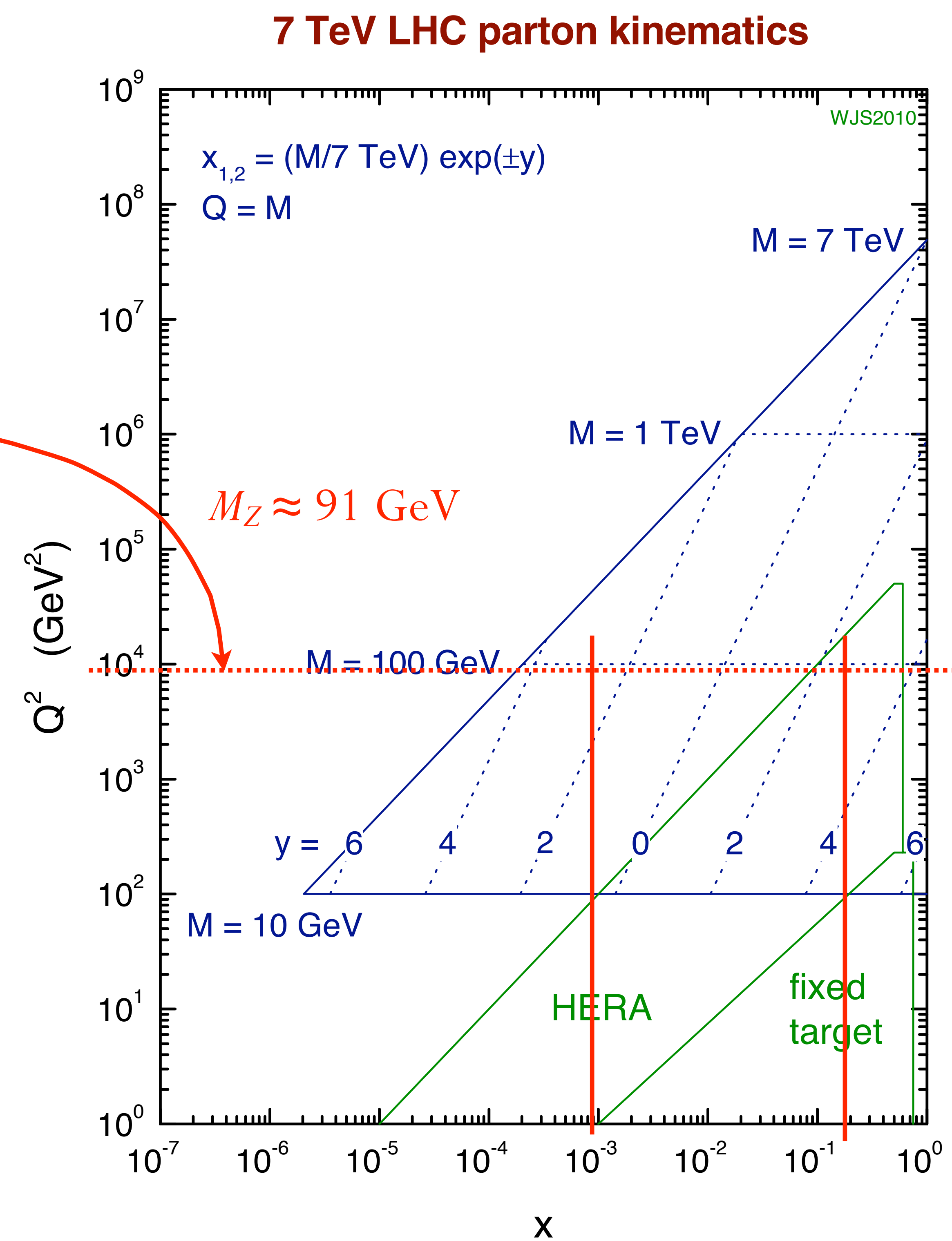

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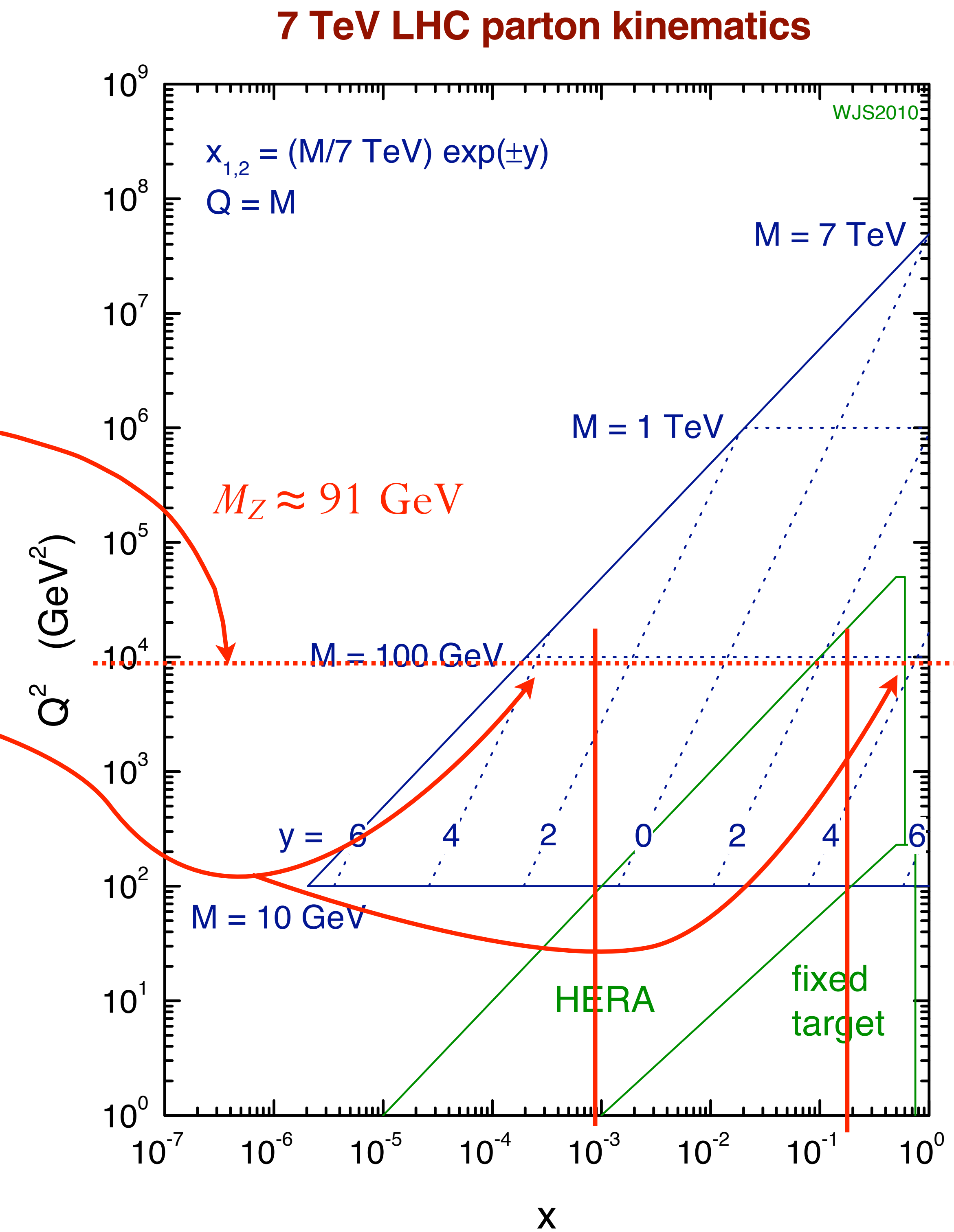

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Motivation Z⟶ee

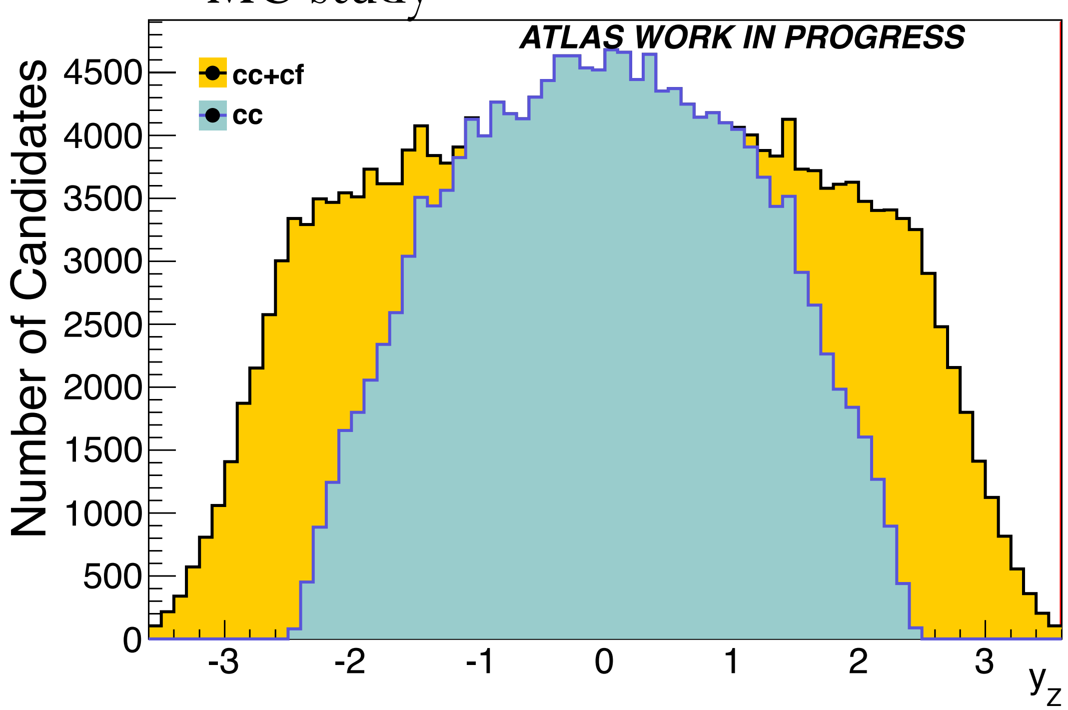
- *Z* rapidity correlated with pseudorapidity η of decay electrons

  ⟶ include "forward electrons"

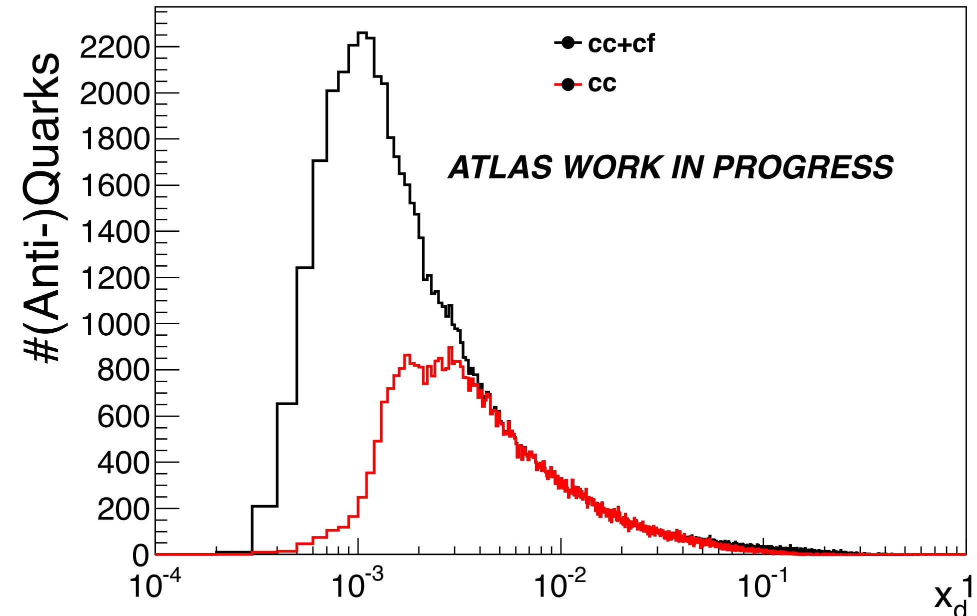
  - central (c): |η| < 2.5
  - forward (f): 2.5 < |η| < 4.9

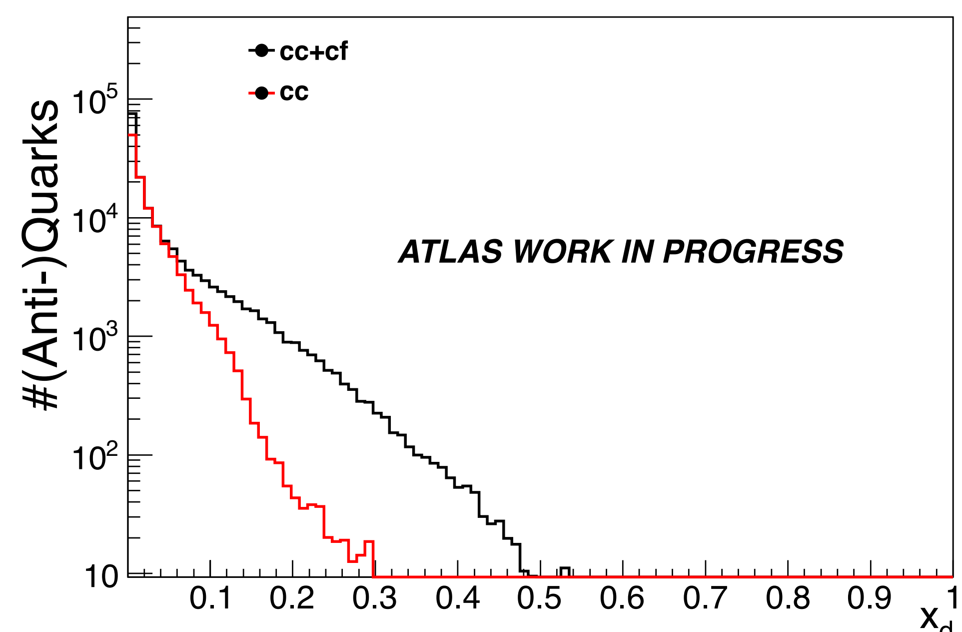
- increase in acceptance due to higher statistics (~40%)

MC study



- x-spectrum for $d/\bar{d}$ quarks (MC study)





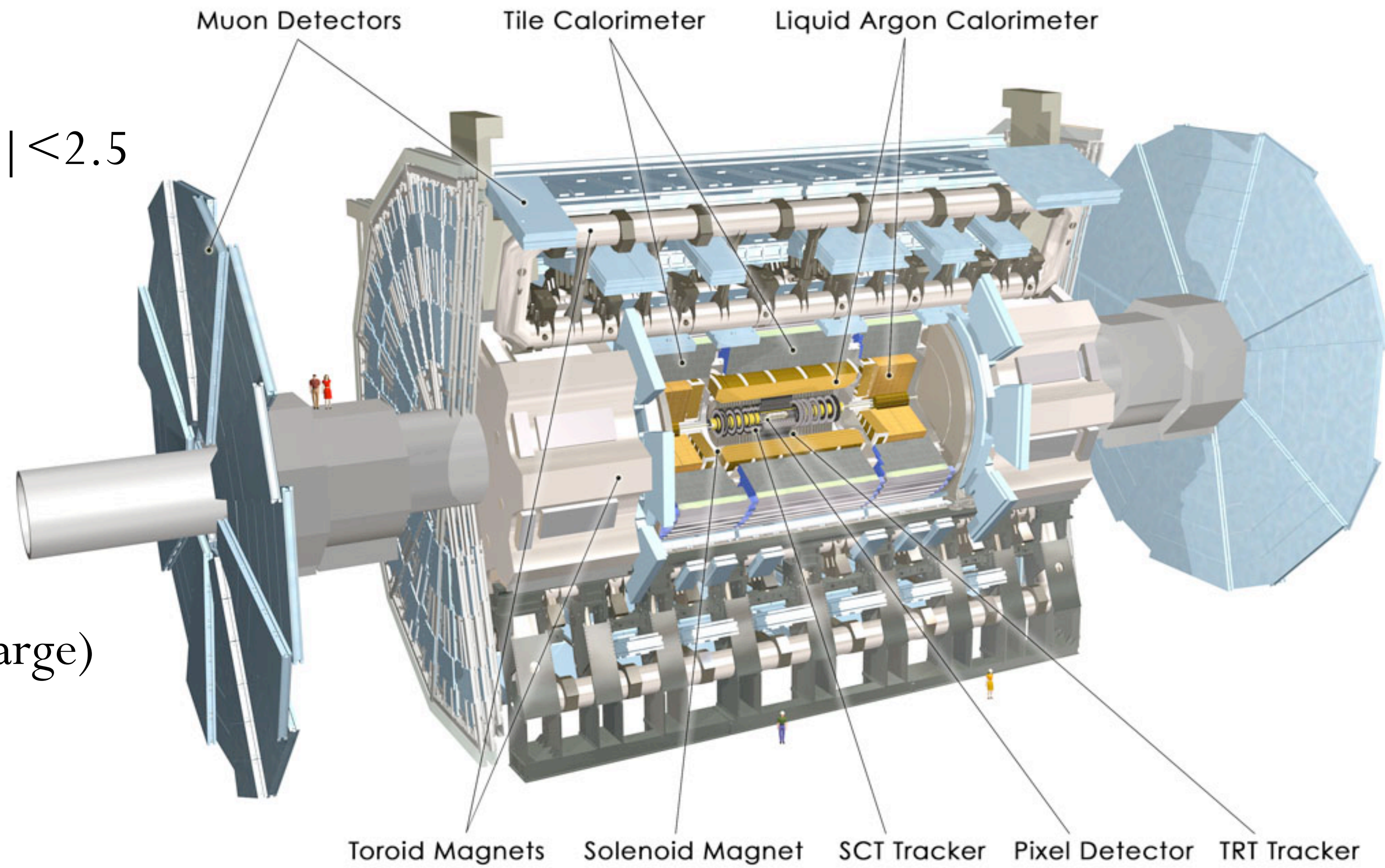
- forward electrons ⟶ extended x-range

ATLAS-Detector

muons
- muon system: $|\eta|<2.7$,
- trigger: $|\eta|<2.4$,
- inner detector tracking: $|\eta|<2.5$

electrons
- tracking system, finely segmented calorimeter: $|\eta|<2.5$ ('central')

- trigger/tracking ($\longrightarrow$ charge) only in this region



- forward electrons ($2.5<|\eta|<4.9$): only calorimeter shower shapes for identification

- @ $1.37 < |\eta| < 1.52$: transition between EM barrel and endcap ("crack")
  - excluded in electron selection ("crack removal")

Analysis Procedure

- $\sigma_{fid} = \dfrac{N - B}{C_{W/Z} L_{int}}$
  - fiducial cross section

- N - number of selected candidates
- B - estimated number of background events
- $C_{W/Z}$ - efficiency correction factor
- L_{int} - integrated luminosity

  36.2pb^{-1} for e, 32.6pb^{-1} for μ

- combination after minimal extrapolation to common phase space
  - central electrons: interpolation over transition region
  - all central leptons: extrapolation to $|\eta| = 2.5$

- $\sigma_{comb} = \dfrac{\sigma_{fid}}{E}$

- total cross section: acceptance correction to full lepton phase space
  - $\sigma_{tot} = \dfrac{\sigma_{fid}}{A}$
  - A - acceptance correction factor

$\longrightarrow$
- additional uncertainty!
  - PS/hadronisation modeling + PDF uncertainties

Event Selection

- data quality requirements (leaving 36.2pb^{-1} for e, 32.6pb^{-1} for μ)
- single lepton trigger
- requirements on primary vertex
- lepton identification criteria
- kinematic and geometric cuts on leptons
  - $p_{T,e/\mu} > 20$ GeV ; $p_{T,\nu} > 25$ GeV
  - central: $|\eta_e| < 2.47$ (without crack)
    $|\eta_\mu| < 2.4$
  - forward: $2.5 < |\eta_e| < 4.9$
- additional track and isolation requirements (especially for μ)
- requirements on lepton pairs
  - Z: $66 < m_{ll} < 116$ GeV ; opposite charge for selection with 2 central leptons
  - W: $m_T > 40$ GeV

$$m_T = \sqrt{2 p_{T,\ell} p_{T,\nu} \cdot (1 - \cos\Delta\phi_{\ell,\nu})}$$

→
- $W^{\pm}$: 130 741 candidates (e), 139 748 (μ)
- Z : 9725 candidates (e) (+ 3376 including forward electrons),
  11709 (μ)

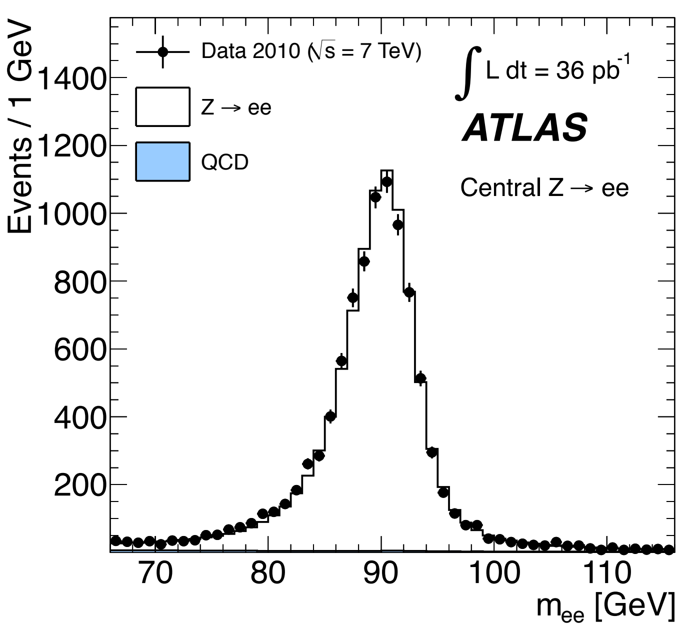
Background

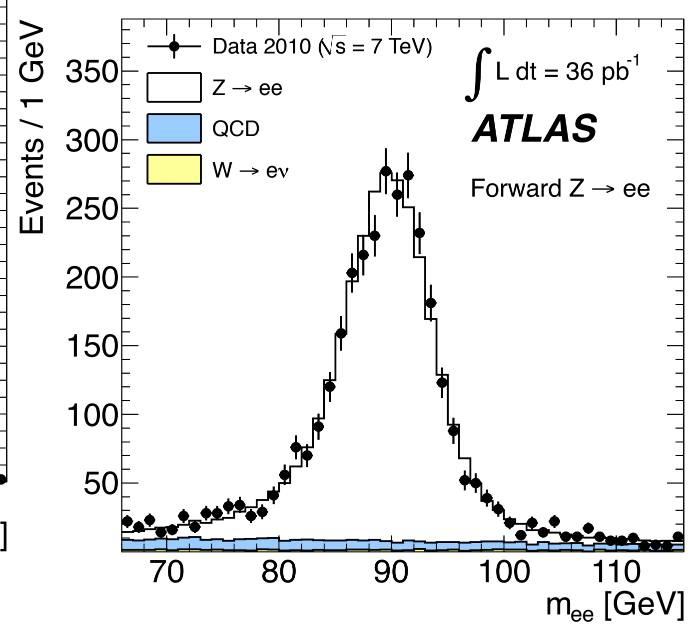
- $t\bar{t}$
- several electroweak (EW) backgrounds (leptons from real vector boson decays)
  - e.g. $W\rightarrow\tau\nu$, $Z\rightarrow\tau\tau$, Diboson

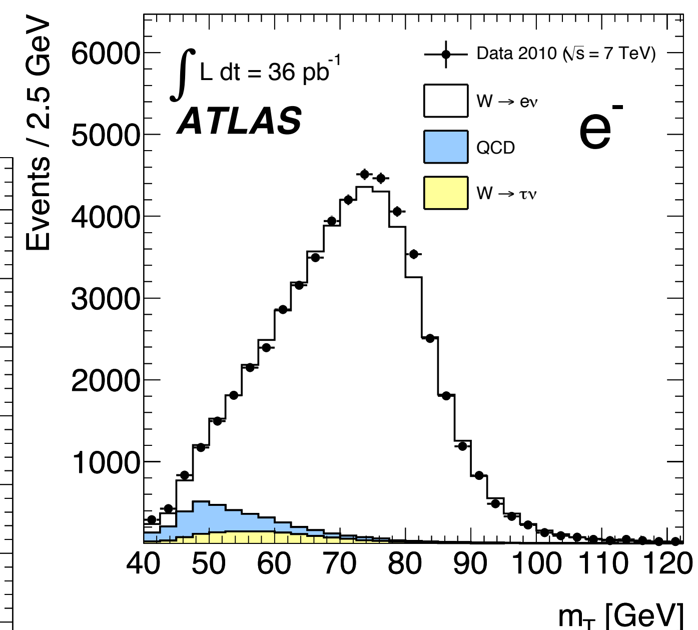
estimated from MC

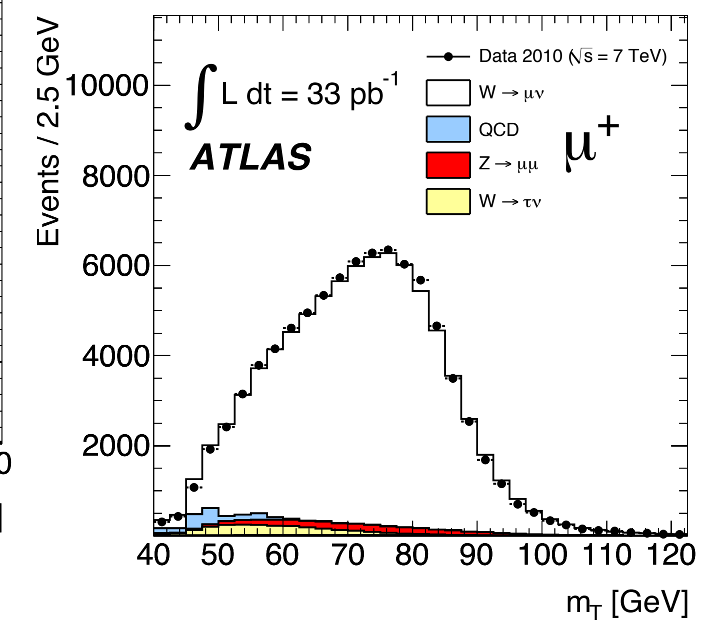
- QCD
  - jets faking electrons
  - muons from heavy quark decays
  - pion, kaon in-flight decays

estimated from data





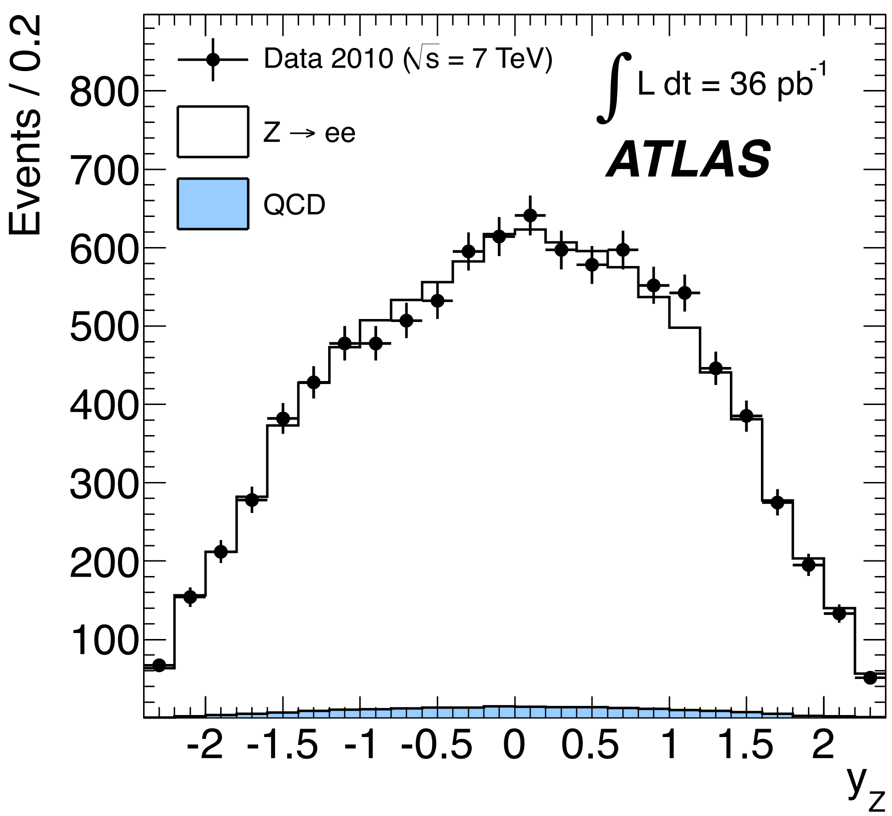




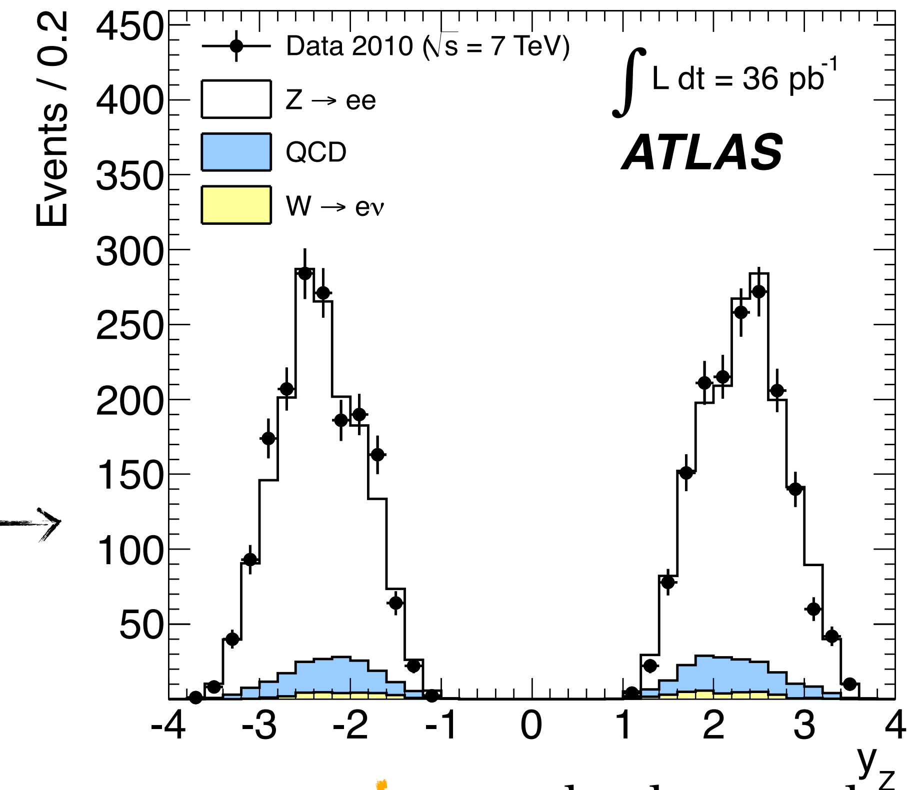
- $Z\rightarrow ee$: all contributions <2%, except for selection with 1 forward electron (QCD ~10%)
- $Z\rightarrow\mu\mu$: all below 1%
- $W\rightarrow e\nu$: each source ~3-5%
- $W\rightarrow\mu\nu$: QCD ~2-3%, EW 6-8%

→ overall good agreement between data and simulation

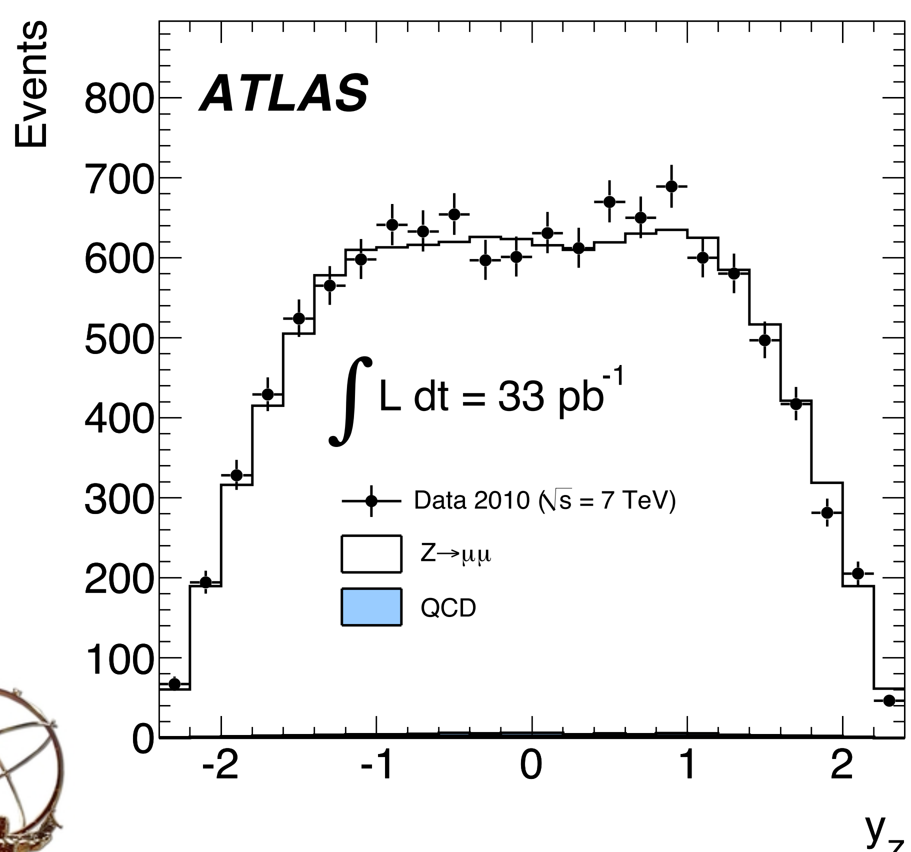
Control Plots Z-Rapidity



extension in y_Z when including forward electrons



- more background in forward region



- very low background level

- good agreement between data and simulation

Efficiency Correction

- estimated from simulation

$$C_{W/Z} = \frac{N_{sel}}{N_{fid}}$$

reconstructed events after full selection

generated events after fiducial cuts

- electrons: $C_W \approx 0.70$, $C_Z \approx 0.62$
- muons: $C_W \approx 0.78$, $C_Z \approx 0.78$

- corrects for reconstruction, trigger, identification inefficiencies…
  - adjustment to data via scale factors

$$sf = \frac{\varepsilon_{data}}{\varepsilon_{simulated}}$$

'tag-and-probe'

'counting'

- measurement involving forward electrons:
  identification efficiency estimation dominant source of uncertainty
  - driven by background estimation in tag&probe

Acceptance

$$A = \frac{N_{fid}}{N_{gen}}$$

generated events after fiducial cuts

generated events (with mass cut for Z)

- MC@NLO with CTEQ6.6

	A	$\delta A^{\text{pdf}}_{\text{err}}$	$\delta A^{\text{pdf}}_{\text{sets}}$	δA_{hs}	δA_{ps}	δA_{tot}
Electron channels						
W^+	0.478	1.0	0.7	0.9	0.8	1.7
W^-	0.452	1.5	1.1	0.2	0.8	2.0
$W^\pm$	0.467	1.0	0.5	0.6	0.8	1.5
Z	0.447	1.7	0.6	0.2	0.7	2.0
Muon channels						
W^+	0.495	1.0	0.8	0.6	0.8	1.6
W^-	0.470	1.5	1.1	0.3	0.8	2.1
$W^\pm$	0.485	1.0	0.5	0.4	0.8	1.5
Z	0.487	1.8	0.6	0.2	0.7	2.0

- eigenvector error set
- different PDF sets
- modeling of hard scattering process
- parton shower/hadronisation description

- total uncertainties ~1.5-2.1% → same order as experimental uncertainties!

Systematic Uncertainties

- electron analysis

	$\delta\sigma_{W^\pm}$	$\delta\sigma_{W^+}$	$\delta\sigma_{W^-}$	$\delta\sigma_Z$
Trigger	0.4	0.4	0.4	<0.1
Electron reconstruction	0.8	0.8	0.8	1.6
Electron identification	0.9	0.8	1.1	1.8
Electron isolation	0.3	0.3	0.3	—
Electron energy scale and resolution	0.5	0.5	0.5	0.2
Non-operational LAr channels	0.4	0.4	0.4	0.8
Charge misidentification	0.0	0.1	0.1	0.6
QCD background	0.4	0.4	0.4	0.7
Electroweak+$t\bar{t}$ background	0.2	0.2	0.2	<0.1
E_T^{miss} scale and resolution	0.8	0.7	1.0	—
Pile-up modeling	0.3	0.3	0.3	0.3
Vertex position	0.1	0.1	0.1	0.1
$C_{W/Z}$ theoretical uncertainty	0.6	0.6	0.6	0.3
Total experimental uncertainty	1.8	1.8	2.0	2.7
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Total excluding luminosity	2.3	2.4	2.8	3.3
Luminosity		3.4		

- many effects checked thoroughly
  - largest contributions:
    - electron identification/reconstruction
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(same for muons)

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- compatible results from e and μ analysis ⟶ combination taking correlations into account

⟶ total cross sections (+ stat + syst + lumi + acc) in nb:

Z : $\sigma_{tot} = 0.937 \pm 0.006 \pm 0.009 \pm 0.032 \pm 0.016$

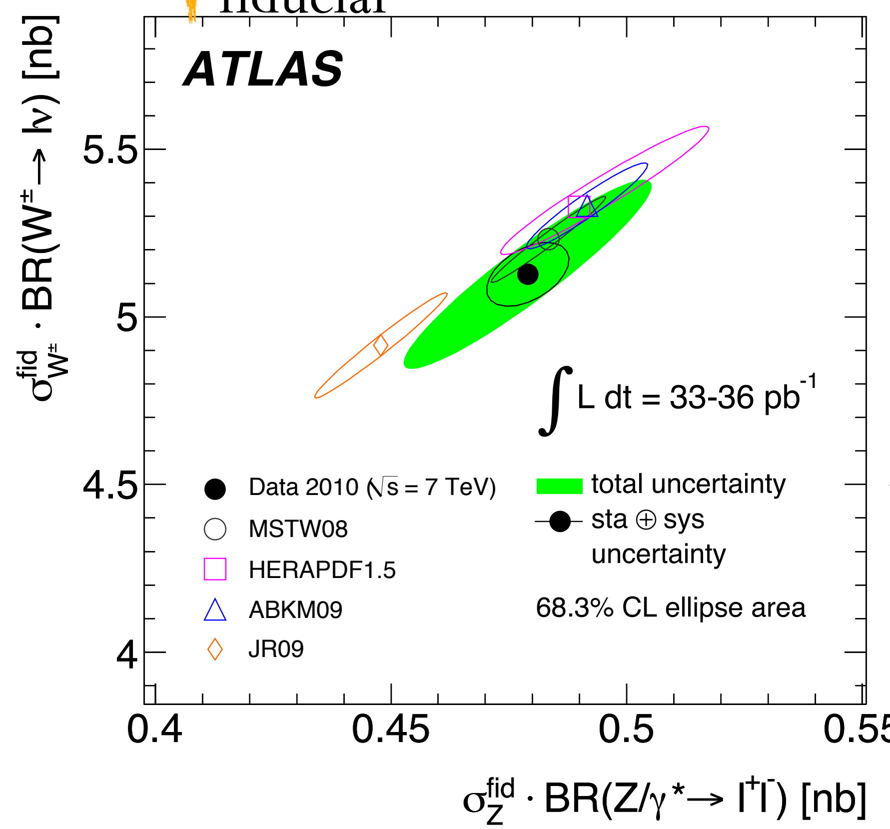
W^+ : $\sigma_{tot} = 6.048 \pm 0.016 \pm 0.072 \pm 0.206 \pm 0.096$

W^- : $\sigma_{tot} = 4.160 \pm 0.014 \pm 0.057 \pm 0.141 \pm 0.083$

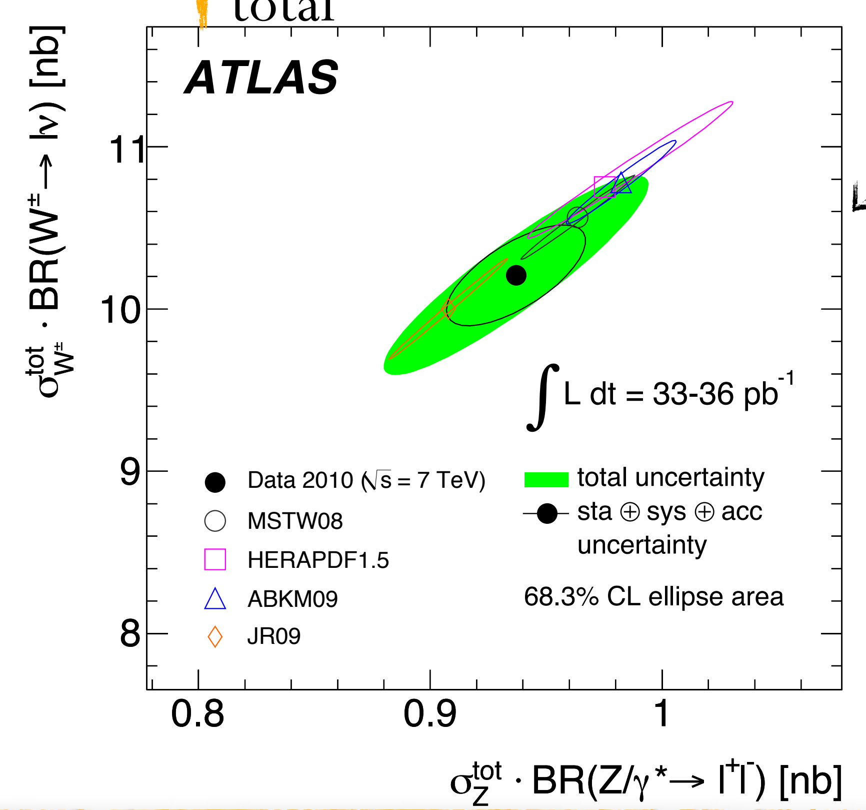
Integrated Cross Sections

- combined cross sections
- comparison with different NNLO PDFs
  - MSTW08
  - HERAPDF1.5
  - ABKM09
    - agreement among these
  - JR09
  - → disfavored

fiducial



total



- total uncertainty dominated by luminosity
- sensitivity ‘polluted’ by acceptance uncertainty

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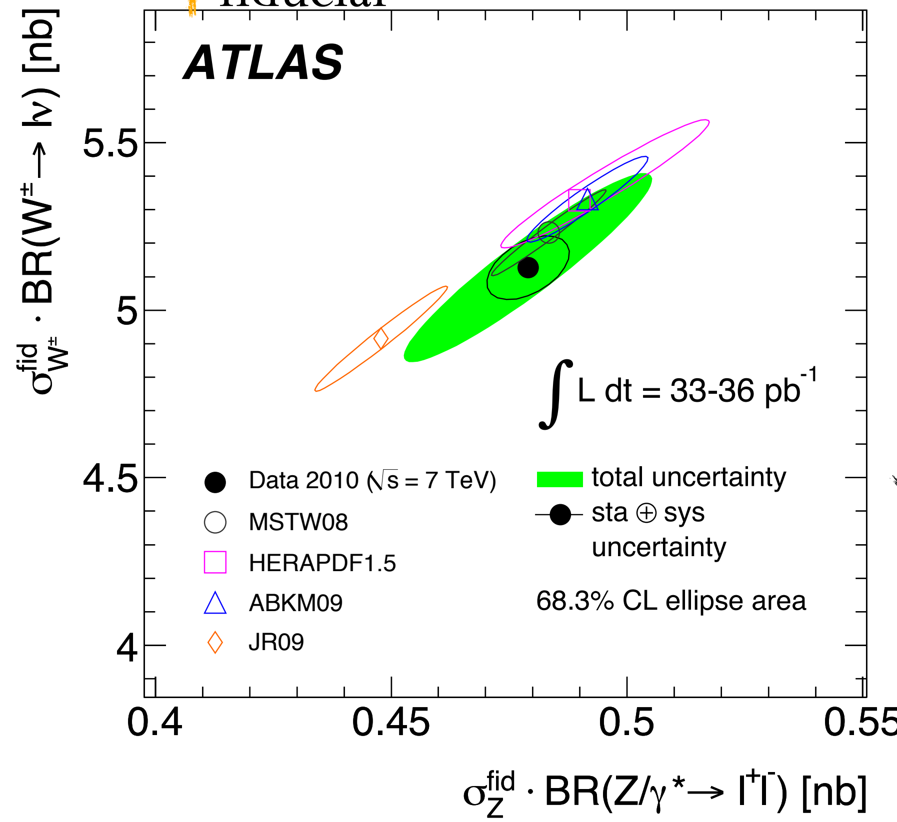
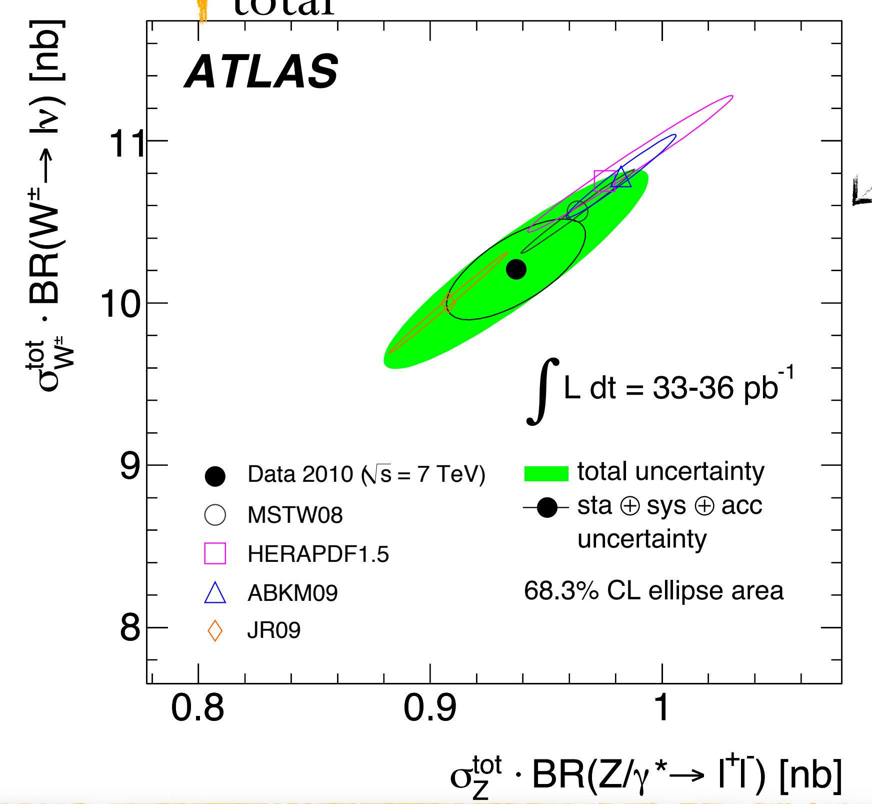
look at fiducial cross sections to study PDF differences

- fiducial



- total uncertainty dominated by luminosity

- total

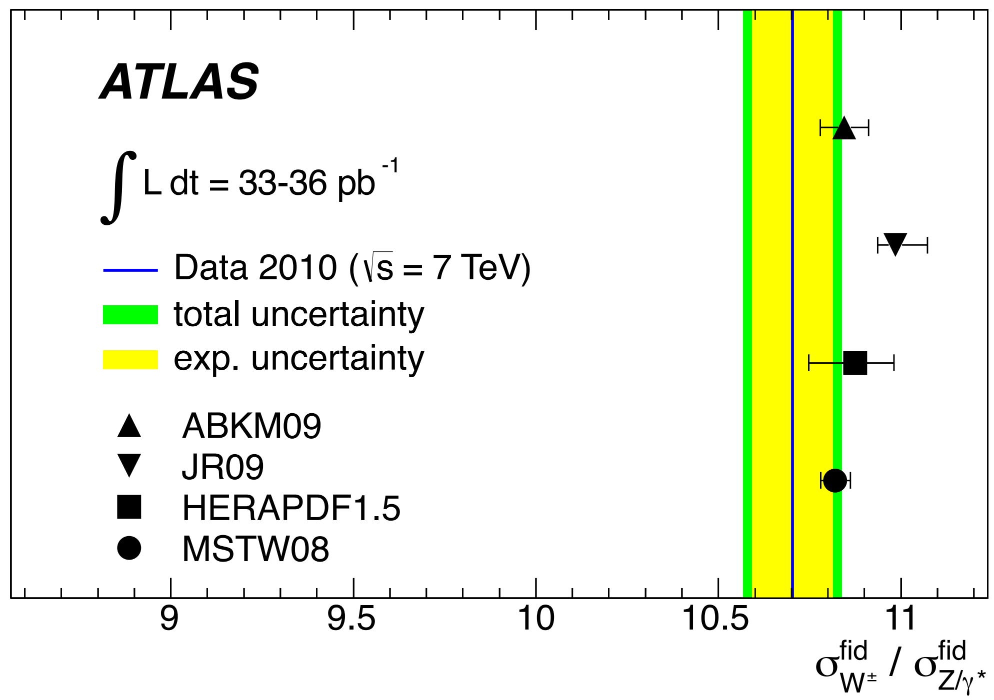


- sensitivity 'polluted' by acceptance uncertainty

Cross Section Ratios

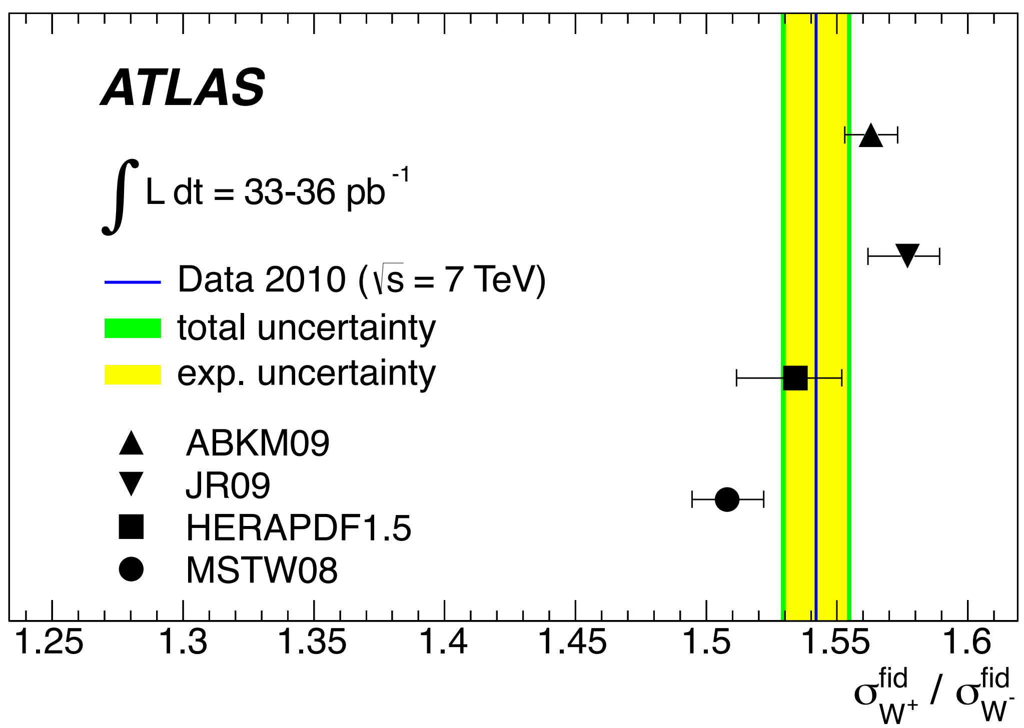
- cancellation of uncertainties (luminosity!)
  - uncertainties reduced to 1.3% ($W^{\pm}/Z$) and 0.9% (W^{+}/W^{-}) (for fiducial measurement)

$W^{\pm}/Z$



- $W^{\pm}/Z$ rather insensitive to PDF differences
- JR09 disfavored

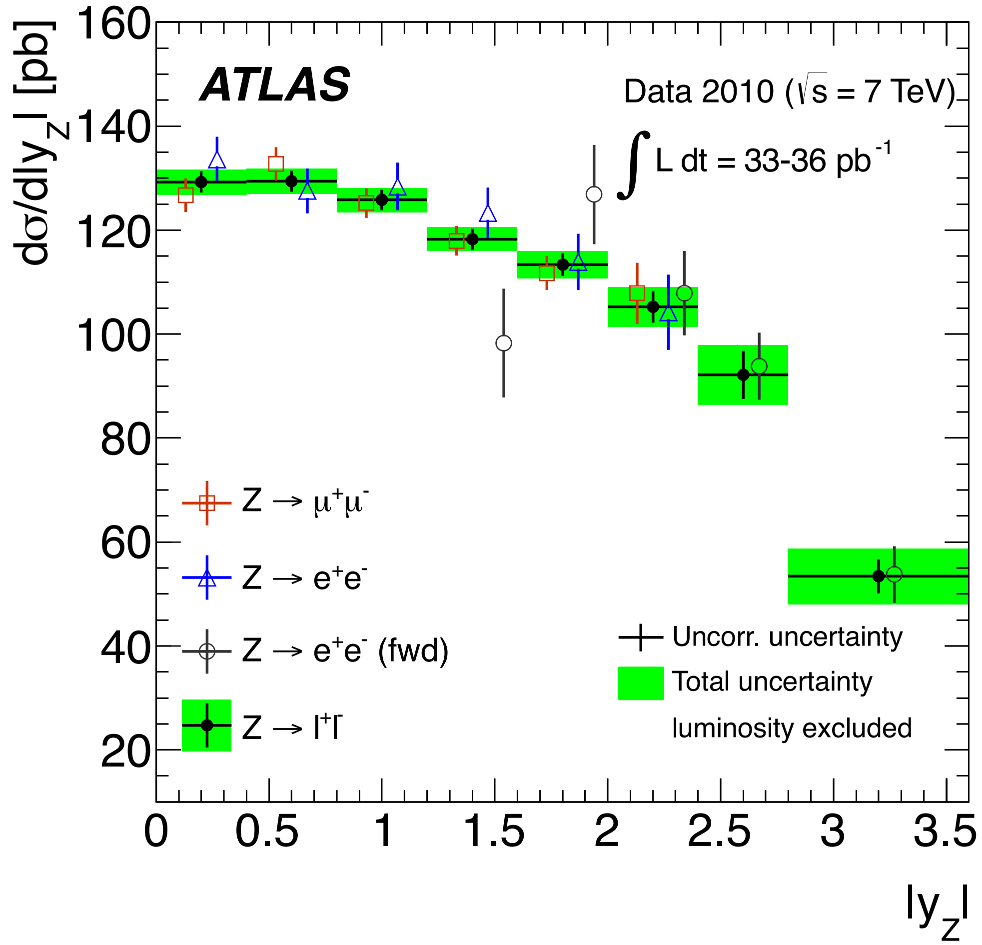
W^{+}/W^{-}



- W^{+}/W^{-} more sensitive to differences in PDF
- for more detailed information: differential measurement

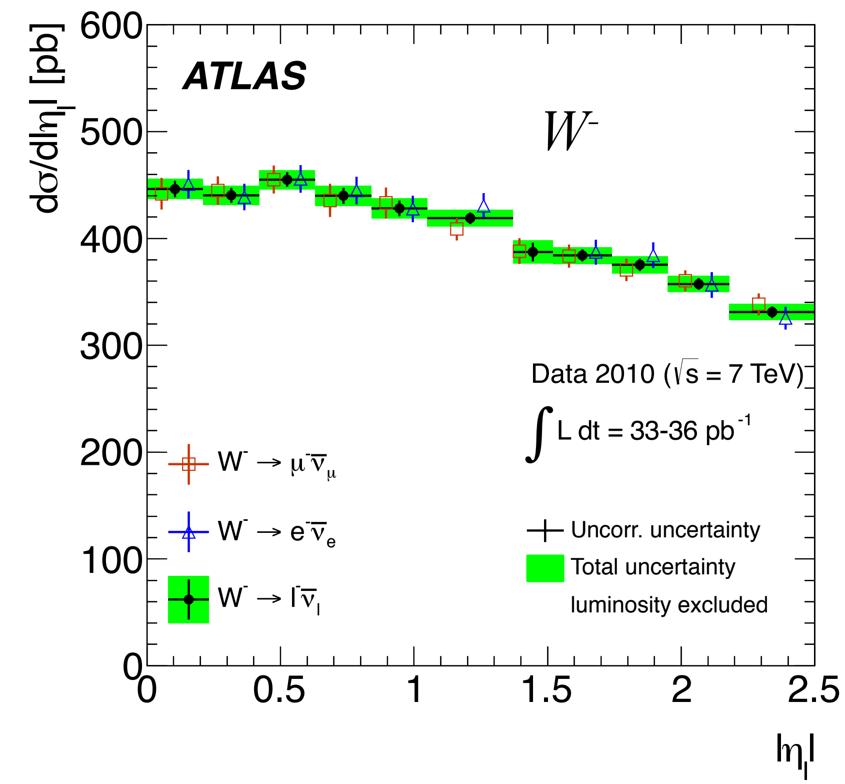
Differential Cross Sections

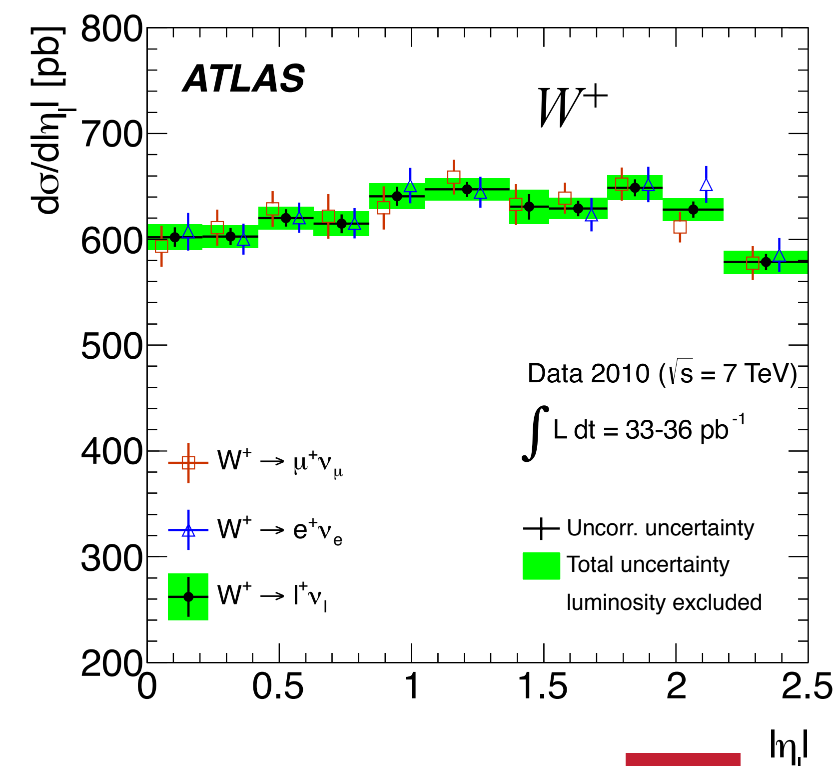
- cross sections determined in bins of $|y_Z|$ and $|\eta_l|$ for W
- Z analysis includes for the first time 'forward' electrons
  - extension of sensitive region to larger $|y|$



- channels in agreement within uncertainties (luminosity not included)

- W results

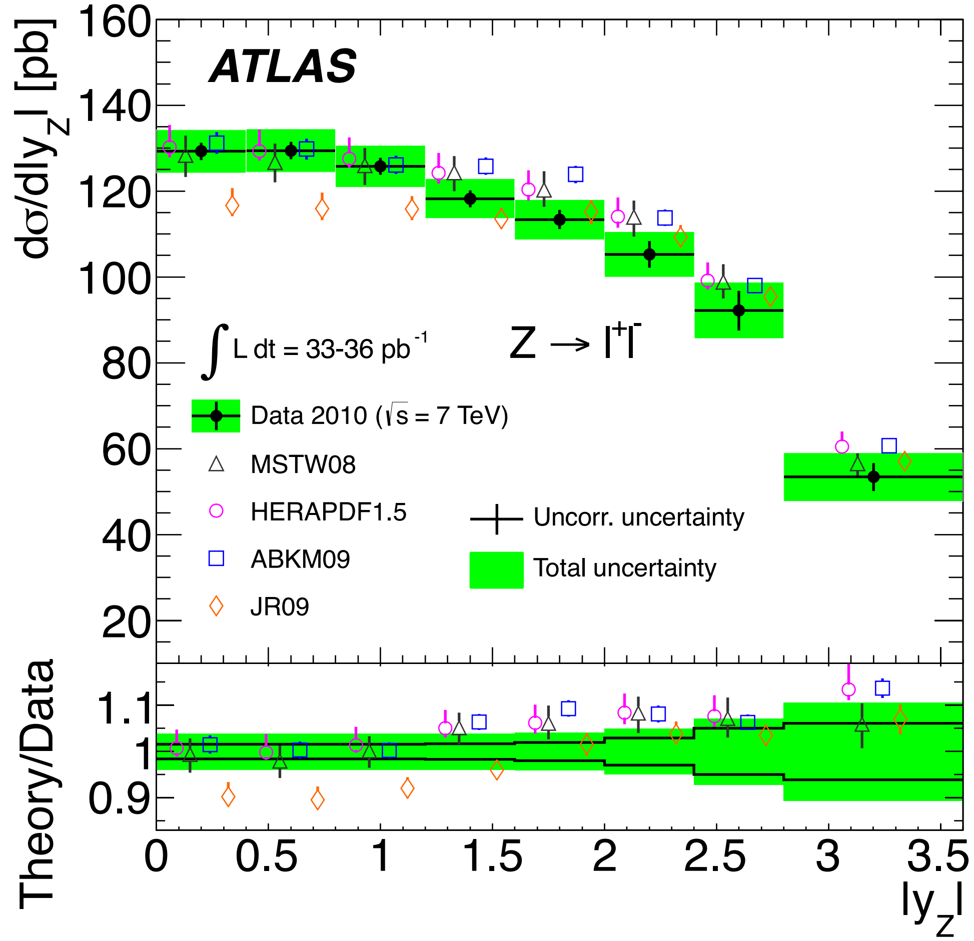


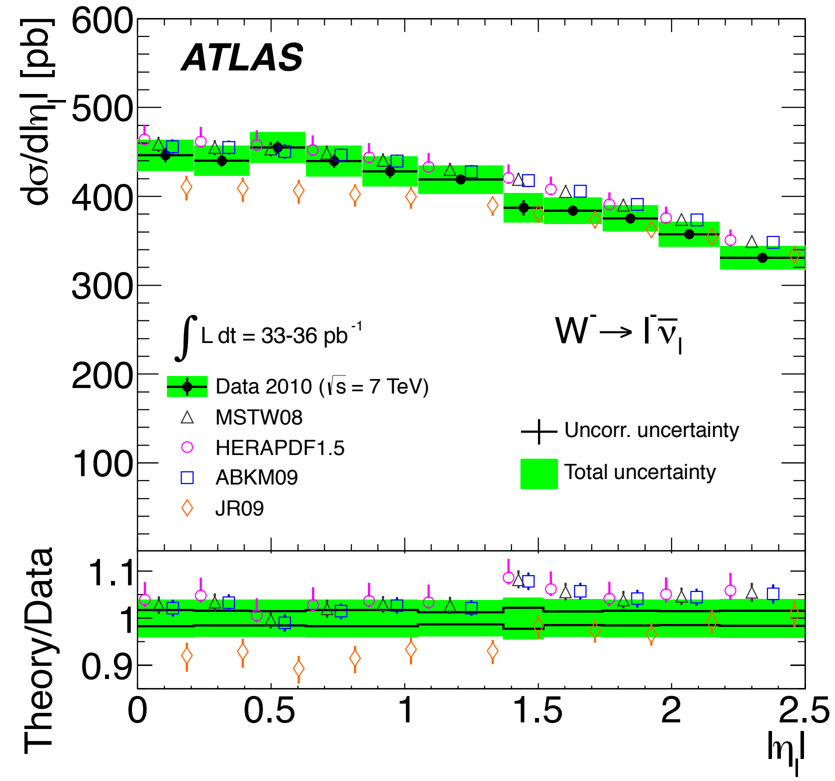


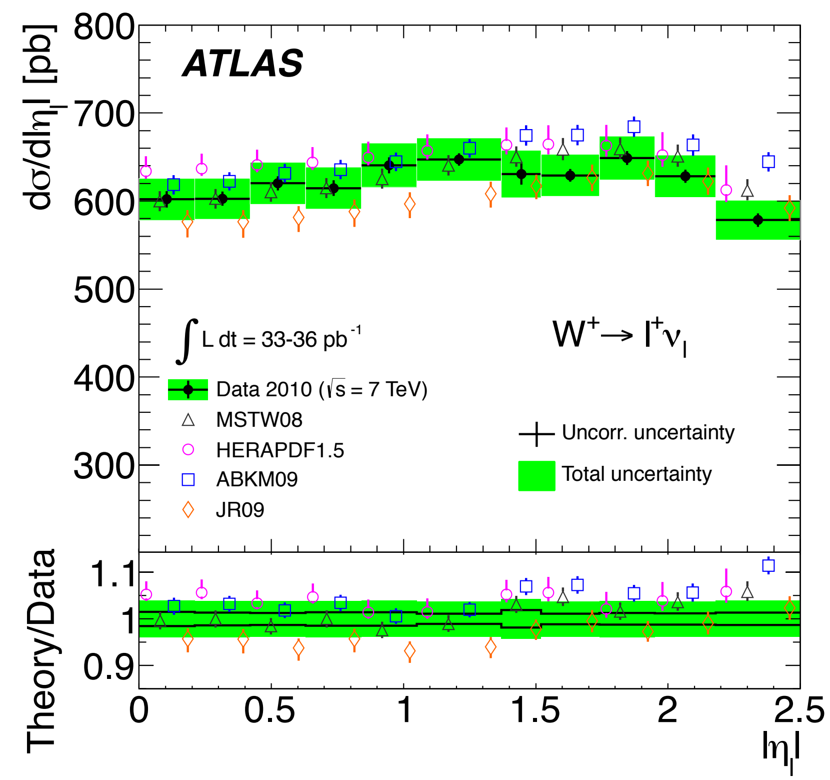
→ combination for comparison with theory predictions

Combination Differential

- comparison with different NNLO PDFs







- overall data described by theory predictions

sensitive to differences in PDFs

Summary

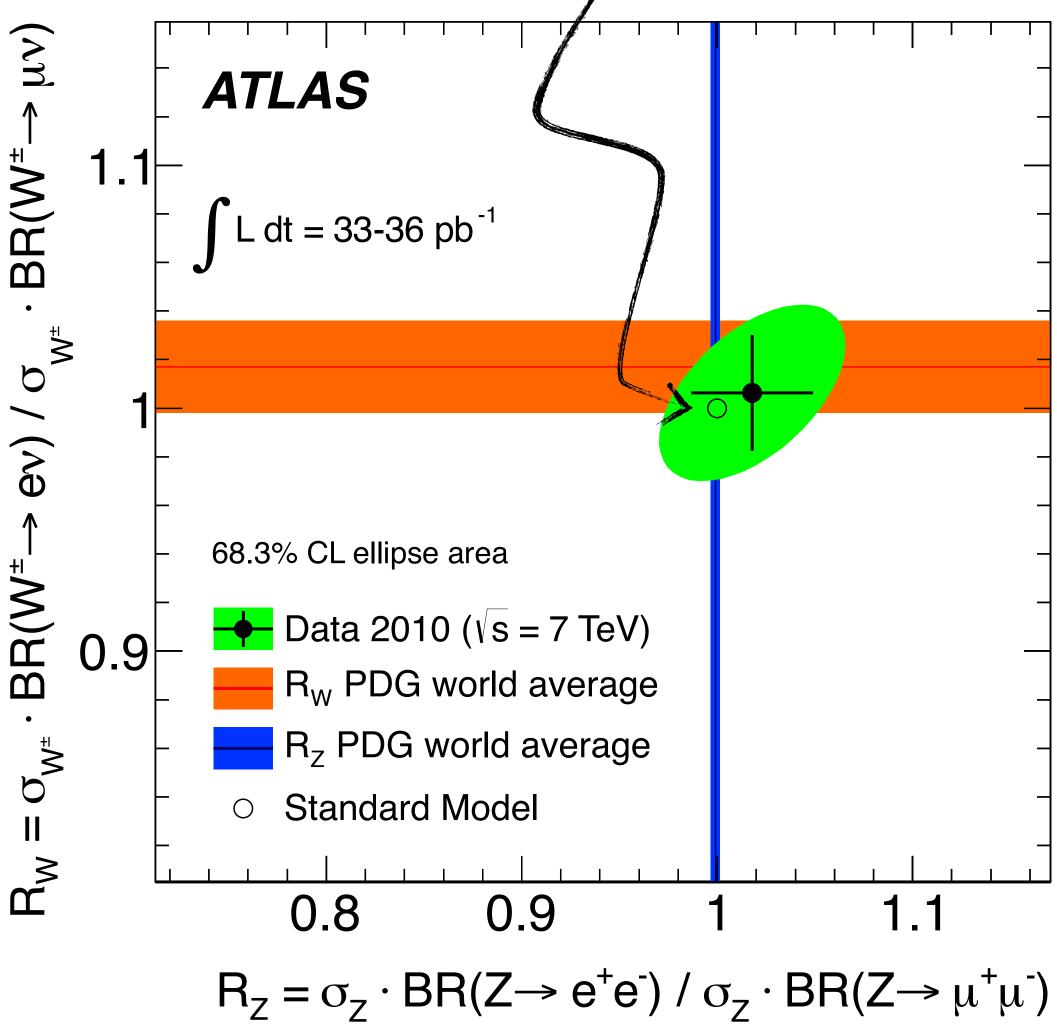
- inclusive DY cross sections for $W^{\pm}$ and Z (full 2010 dataset at ATLAS) arXiv:1109.5141
- extended rapidity range ('forward' electrons)
- experimental precision O(few%)
  - luminosity uncertainty dominating (3.4%)
- further input for PDF restriction
- additional differential measurements in p_T for W and Z arXiv:1107.2381v1 arXiv:1108.6308v1
  - higher order QCD corrections, non-perturbative effects

  - 2011 data set provides ~150 times more data

BACKUP

Lepton Universality

- Standard Model predicts lepton universality



- cancellation of uncertainties
- green ellipse:
  68% CL area for correlated measurement
- error bars:
  one dimensional unc. for single ratios
- both measurements
  compatible with theory

almost sensitive to R_W

Boson p_T Differential Results

- p_T rather independent of PDFs

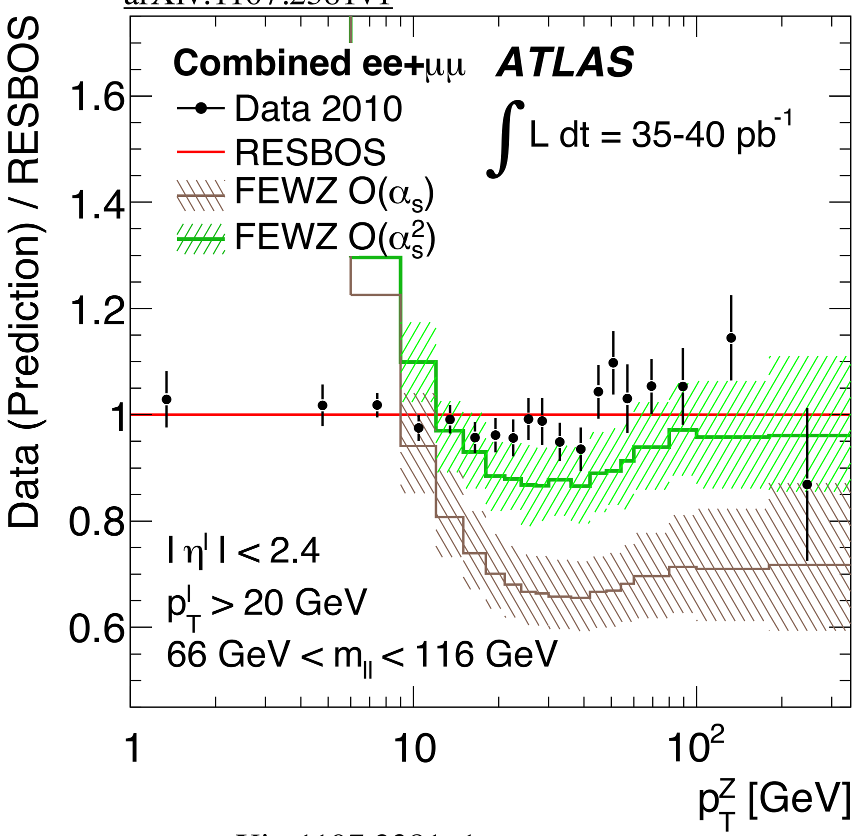
- different descriptions are expected to work better in different regimes of p_T
  - high p_T : hard-jet emission, tests pQCD ;
    low p_T : soft-gluon emission, tests models for logarithmic resummations

- measurements based on 2010 data set: arXiv:1107.2381v1 arXiv:1108.6308v1
  - combination of e and μ channel

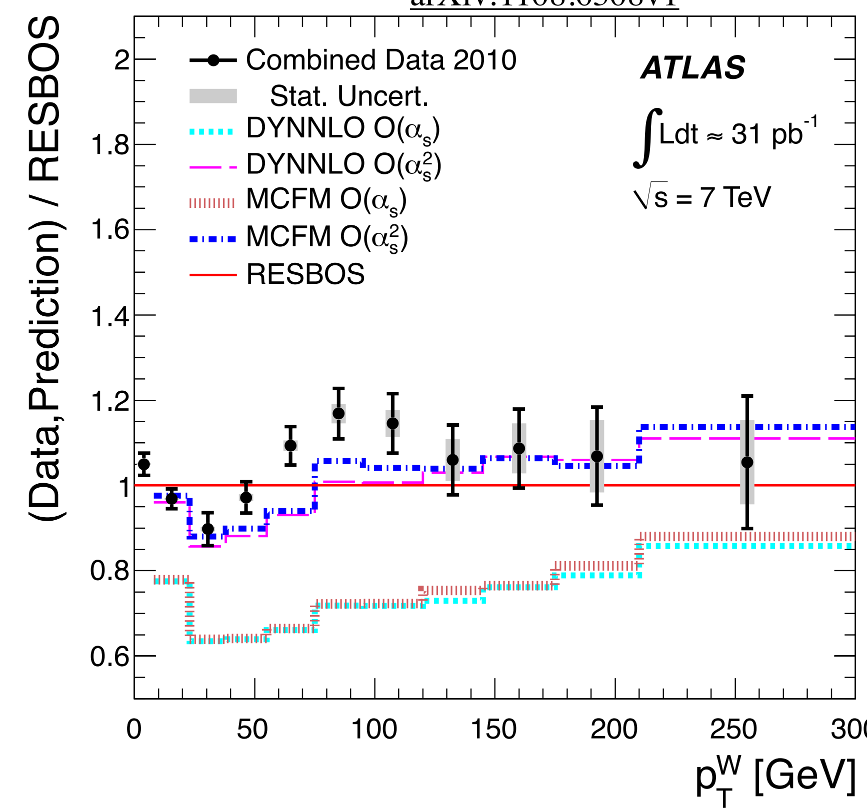
- all measurements and predictions normalised to RESBOS

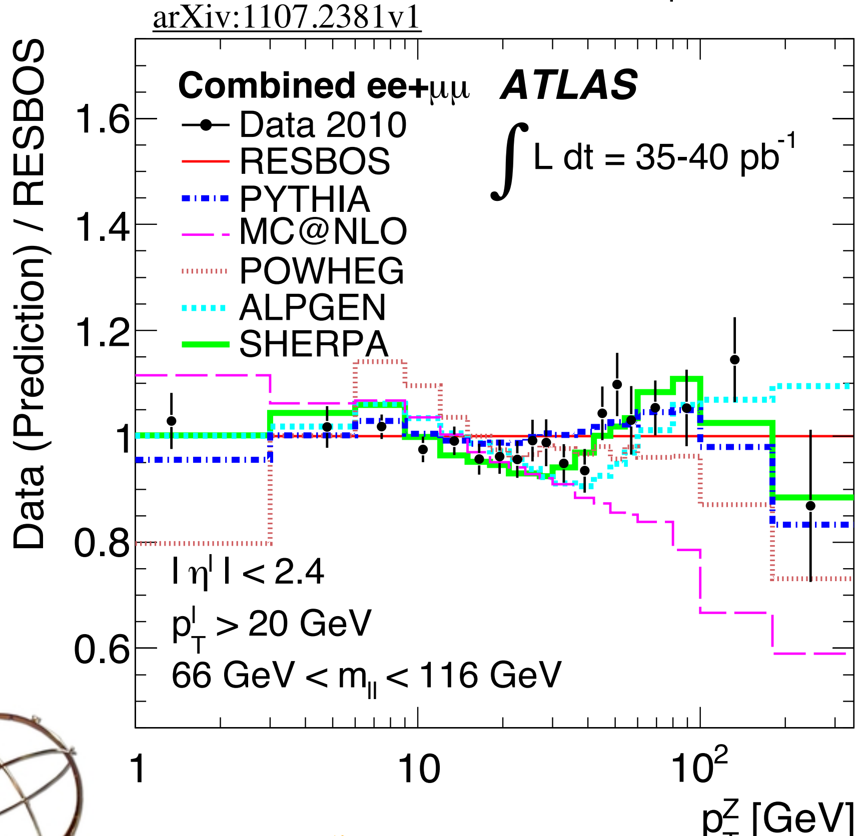
- comparison with different generators and fixed order calculations

Boson p_T Differential Results

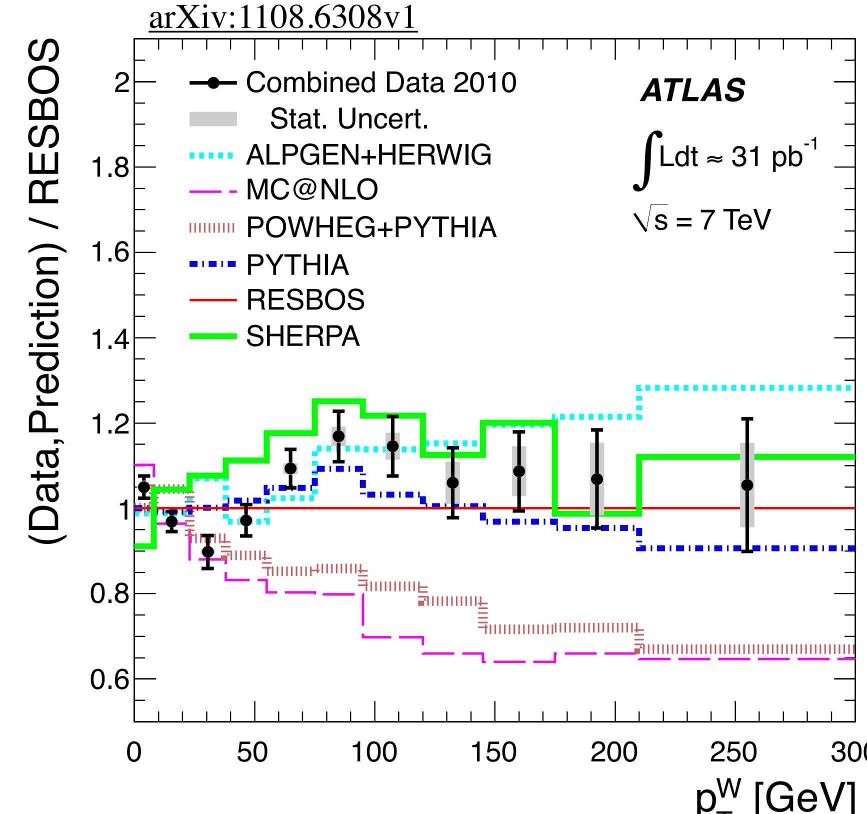


- agreement between different calculations of same order
- NNLO predictions describe data better
- agreement ~10-15% at high p_T





- for NLO generators agreement only in region ~10-40 GeV
- best description: Pythia and generators with multi-parton emissions



- $Z \to \ell\ell$
- $W \to \ell\nu$

Simulation

Physics process	Generator	$\sigma \cdot$ BR [nb]	
$W^+ \to \ell^+\nu$ ($\ell = e, \mu$)	MC@NLO	6.16±0.31	NNLO
$W^- \to \ell^-\bar{\nu}$ ($\ell = e, \mu$)	MC@NLO	4.30±0.21	NNLO
$Z/\gamma^* \to \ell\ell$ ($m_{\ell\ell} > 60$ GeV, $\ell = e, \mu$)	MC@NLO	0.99±0.05	NNLO
$W \to \tau\nu$	PYTHIA	10.46±0.52	NNLO
$Z/\gamma^* \to \tau\tau$ ($m_{\tau\tau} > 60$ GeV)	PYTHIA	0.99±0.05	NNLO
$t\bar{t}$	MC@NLO	$0.165^{+0.011}_{-0.016}$	≈NNLO
WW	HERWIG	0.045±0.003	NLO
WZ	HERWIG	0.0185±0.0009	NLO
ZZ	HERWIG	0.0060±0.0003	NLO
Dijet (e channel, $\hat{p}_T > 15$ GeV)	PYTHIA	1.2×10^6	LO
Dijet (μ channel, $\hat{p}_T > 8$ GeV)	PYTHIA	10.6×10^6	LO
$b\bar{b}$ (μ channel, $\hat{p}_T > 18$ GeV, $p_T(\mu) > 15$ GeV)	PYTHIA	73.9	LO
$c\bar{c}$ (μ channel, $\hat{p}_T > 18$ GeV, $p_T(\mu) > 15$ GeV)	PYTHIA	28.4	LO

- MC@NLO, PowHeg: CTEQ6.6
- Pythia, Herwig: MRSTLO*
- all interfaced to PHOTOS (QED FSR)

- p_T reweighting to data
- pile-up reweighting to data
- corrections for reconstruction, identification, energy scale/resolution
- theoretical predictions for W/Z from FEWZ

Luminosity

- $\mathcal{L} = \frac{n_b f_r n_1 n_2}{2\pi\Sigma_x\Sigma_y}$
  - n_b - number of bunches
  - f_r - machine revolution frequency
  - n_1, n_2 - protons per bunch for beam 1,2
    - $n_1\, n_2$ - ‘bunch charge product’
  - Σ_x, Σ_y - transverse profiles of colliding beams
    - measured in ‘van-der-Meer’ scans
      - beams separated stepwise in x and y direction

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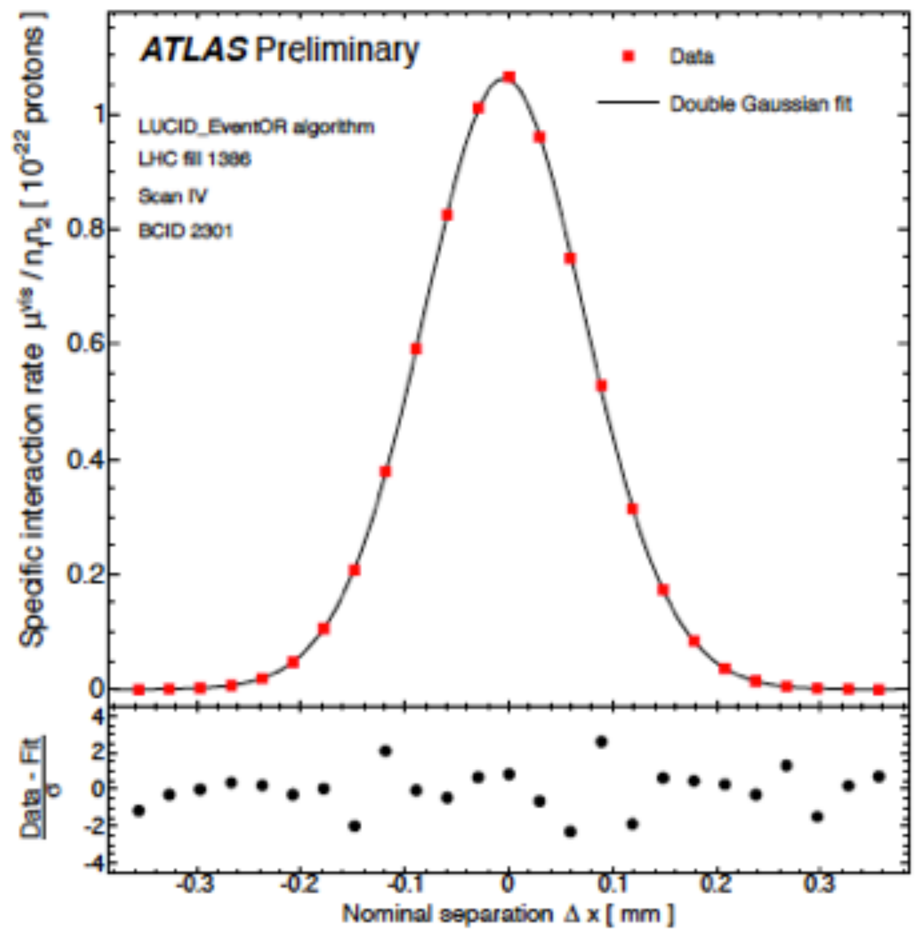


- dominant source of uncertainty:

  measurement of the bunch charge product: 3.1%

  (subleading contribution: transverse correlations 0.9%)

Muon Channel

- systematic uncertainties

	$\delta\sigma_{W^\pm}$	$\delta\sigma_{W^+}$	$\delta\sigma_{W^-}$	$\delta\sigma_Z$
Trigger	0.5	0.5	0.5	0.1
Muon reconstruction	0.3	0.3	0.3	0.6
Muon isolation	0.2	0.2	0.2	0.3
Muon p_T resolution	0.04	0.03	0.05	0.02
Muon p_T scale	0.4	0.6	0.6	0.2
QCD background	0.6	0.5	0.8	0.3
Electroweak+$t\bar{t}$ background	0.4	0.3	0.4	0.02
E_T^{miss} resolution and scale	0.5	0.4	0.6	-
Pile-up modeling	0.3	0.3	0.3	0.3
Vertex position	0.1	0.1	0.1	0.1
$C_{W/Z}$ theoretical uncertainty	0.8	0.8	0.7	0.3
Total experimental uncertainty	1.6	1.7	1.7	0.9
$A_{W/Z}$ theoretical uncertainty	1.5	1.6	2.1	2.0
Total excluding luminosity	2.1	2.3	2.6	2.2
Luminosity	3.4			

Cross Sections

electrons

$\sigma_W^{\text{fid}} \cdot$ BR($W \to e\nu$) [nb]			
	sta	sys	lum
W^+	2.898 ± 0.011	± 0.052	± 0.099
W^-	1.893 ± 0.009	± 0.038	± 0.064
$W^\pm$	4.791 ± 0.014	± 0.089	± 0.163

$\sigma_W^{\text{tot}} \cdot$ BR($W \to e\nu$) [nb]				
	sta	sys	lum	acc
W^+	6.063 ± 0.023	± 0.108	± 0.206	± 0.104
W^-	4.191 ± 0.020	± 0.085	± 0.142	± 0.084
$W^\pm$	10.255 ± 0.031	± 0.190	± 0.349	± 0.156

$\sigma_{Z/\gamma^*}^{\text{fid}} \cdot$ BR($Z/\gamma^* \to ee$) [nb]			
	sta	sys	lum
Z/γ^*	0.426 ± 0.004	± 0.012	± 0.014

$\sigma_{Z/\gamma^*}^{\text{tot}} \cdot$ BR($Z/\gamma^* \to ee$) [nb]				
	sta	sys	lum	acc
Z/γ^*	0.952 ± 0.010	± 0.026	± 0.032	± 0.019

muons

$\sigma_W^{\text{fid}} \cdot$ BR($W \to \mu\nu$) [nb]			
	sta	sys	lum
W^+	3.002 ± 0.011	± 0.050	± 0.102
W^-	1.948 ± 0.009	± 0.034	± 0.066
$W^\pm$	4.949 ± 0.015	± 0.081	± 0.168

$\sigma_W^{\text{tot}} \cdot$ BR($W \to \mu\nu$) [nb]				
	sta	sys	lum	acc
W^+	6.062 ± 0.023	± 0.101	± 0.206	± 0.099
W^-	4.145 ± 0.020	± 0.072	± 0.141	± 0.086
$W^\pm$	10.210 ± 0.030	± 0.166	± 0.347	± 0.153

$\sigma_{Z/\gamma^*}^{\text{fid}} \cdot$ BR($Z/\gamma^* \to \mu\mu$) [nb]			
	sta	sys	lum
Z/γ^*	0.456 ± 0.004	± 0.004	± 0.015

$\sigma_{Z/\gamma^*}^{\text{tot}} \cdot$ BR($Z/\gamma^* \to \mu\mu$) [nb]				
	sta	sys	lum	acc
Z/γ^*	0.935 ± 0.009	± 0.009	± 0.032	± 0.019

Combination Procedure

- averaging procedure, minimising a χ^2-function
  - distinguishing different sources of systematic uncertainties
    - treated fully correlated between e and μ :
      - hadronic recoil uncertainty in MET, EW bkgs, pile-up, vertex position, theoretical uncertainty of acceptance/extrapolation
    - treated fully correlated bin-to-bin and across data sets:
      - extrapolation in non-covered phase space, normalisation of EW bkg, lepton energy/momentum scale and resolution, systematic effects on reconstruction efficiency
    - QCD bkg syst. bin-to-bin correlated but independent for e and μ
    - stat. unc. of lepton identification bin-to-bin uncorrelated but correlated for Z and W
    - stat. unc. of bkgs and electron isolation fully uncorrelated
    - fully anti-correlated between W^+ and W^- : charge misidentification, PDF unc. on C_W
    - luminosity not used since common for all data points

Combination Results

- fiducial cross sections

$\sigma_W^{\text{fid}} \cdot \text{BR}(W \to \ell\nu)$ [nb] $\lvert\eta_\ell\rvert < 2.5$, $p_{T,\ell} > 20$ GeV, $p_{T,\nu} > 25$ GeV and $m_T > 40$ GeV					
		sta	sys	lum	acc
W^+	3.110	± 0.008	± 0.036	± 0.106	± 0.004
W^-	2.017	± 0.007	± 0.028	± 0.069	± 0.002
$W^\pm$	5.127	± 0.011	± 0.061	± 0.174	± 0.005
$\sigma_{Z/\gamma^*}^{\text{fid}} \cdot \text{BR}(Z/\gamma^* \to \ell\ell)$ [nb] $\lvert\eta_\ell\rvert < 2.5$, $p_{T,\ell} > 20$ GeV and $66 < m_{\ell\ell} < 116$ GeV					
		sta	sys	lum	acc
Z/γ^*	0.479	± 0.003	± 0.005	± 0.016	± 0.001

- total cross sections

$\sigma_W^{\text{tot}} \cdot \text{BR}(W \to \ell\nu)$ [nb]					
		sta	sys	lum	acc
W^+	6.048	± 0.016	± 0.072	± 0.206	± 0.096
W^-	4.160	± 0.014	± 0.057	± 0.141	± 0.083
$W^\pm$	10.207	± 0.021	± 0.121	± 0.347	± 0.164
$\sigma_{Z/\gamma^*}^{\text{tot}} \cdot \text{BR}(Z/\gamma^* \to \ell\ell)$ [nb] $66 < m_{\ell\ell} < 116$ GeV					
		sta	sys	lum	acc
Z/γ^*	0.937	± 0.006	± 0.009	± 0.032	± 0.016

- uncertainties significantly reduced

- uncertainty correlation coefficients

left: full uncertainty, right: without luminosity

	Z	W^+	W^-
Z	1.00	0.94	0.93
W^+	0.94	1.00	0.97
W^-	0.93	0.97	1.00

	Z	W^+	W^-
Z	1.00	0.48	0.44
W^+	0.48	1.00	0.79
W^-	0.44	0.79	1.00

	Z	W^+	W^-
Z	1.00	0.91	0.91
W^+	0.91	1.00	0.91
W^-	0.91	0.91	1.00

	Z	W^+	W^-
Z	1.00	0.67	0.71
W^+	0.67	1.00	0.70
W^-	0.71	0.70	1.00

Differential Cross Sections

- cross sections determined in bins of $|y_Z|$ and $|\eta_l|$ for W
- for the first time with ATLAS

- almost same procedure as for the integrated measurement
  - for differential measurement only extrapolation to common phase space
    - in order to be more sensitive to details in the different PDF sets

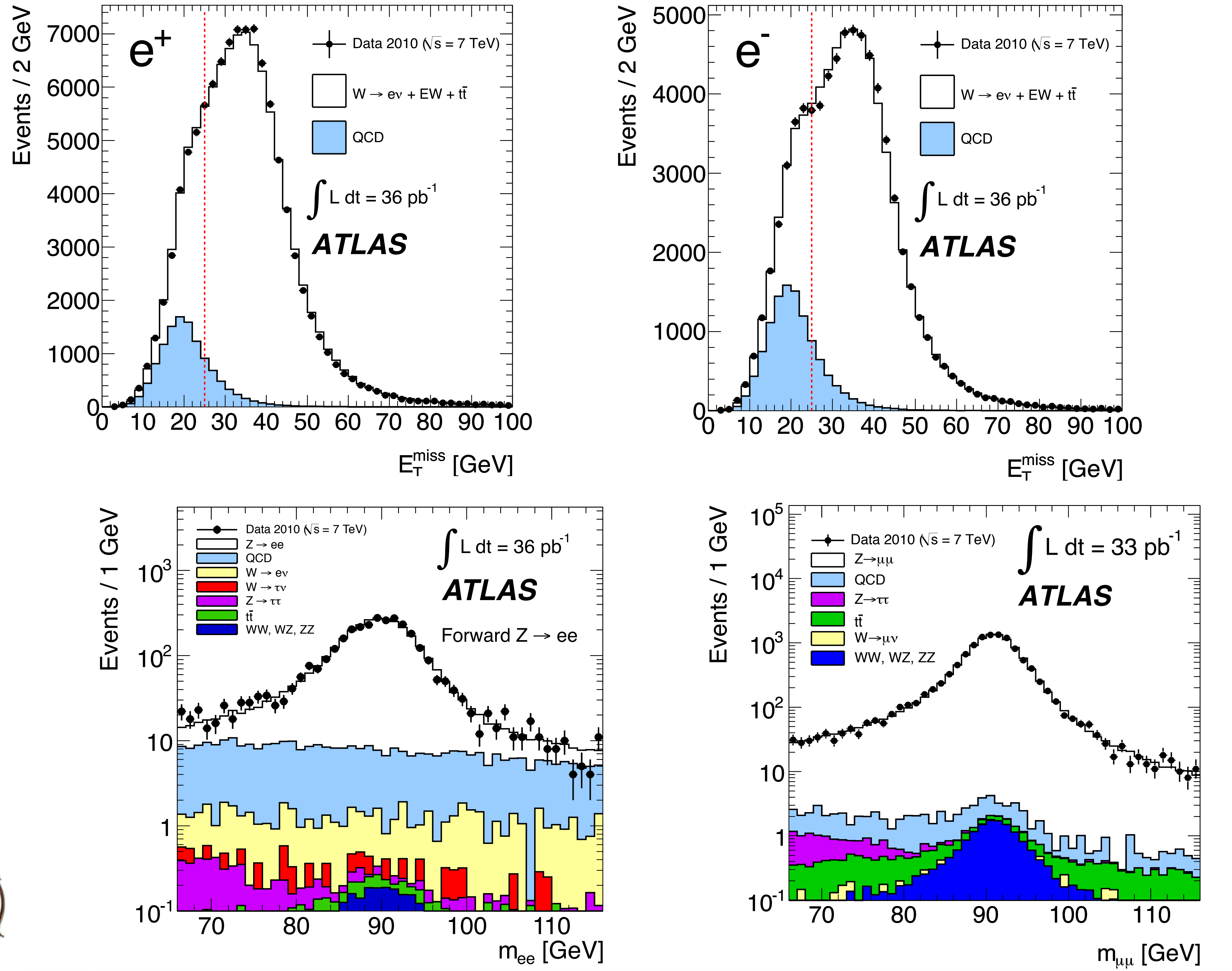
- extrapolation factors with PDF uncertainties for Z channel

y_Z^{min}	y_Z^{max}	$Z \to \mu\mu$	Central $Z \to ee$	Forward $Z \to ee$
0.0	0.4	1.000(0)	0.954(1)	-
0.4	0.8	1.000(0)	0.903(1)	-
0.8	1.2	0.984(1)	0.855(2)	-
1.2	1.6	0.849(2)	0.746(3)	0.103(1)
1.6	2.0	0.578(5)	0.512(4)	0.327(3)
2.0	2.4	0.207(5)	0.273(5)	0.590(7)
2.4	2.8	-	-	0.797(1)
2.8	3.6	-	-	0.404(4)

- for W channel effective only in highest $|\eta_l|$ bins;
  30% for muons, 9% for electrons

- more detailed information on PDFs (and their uncertainties)

Control Plots



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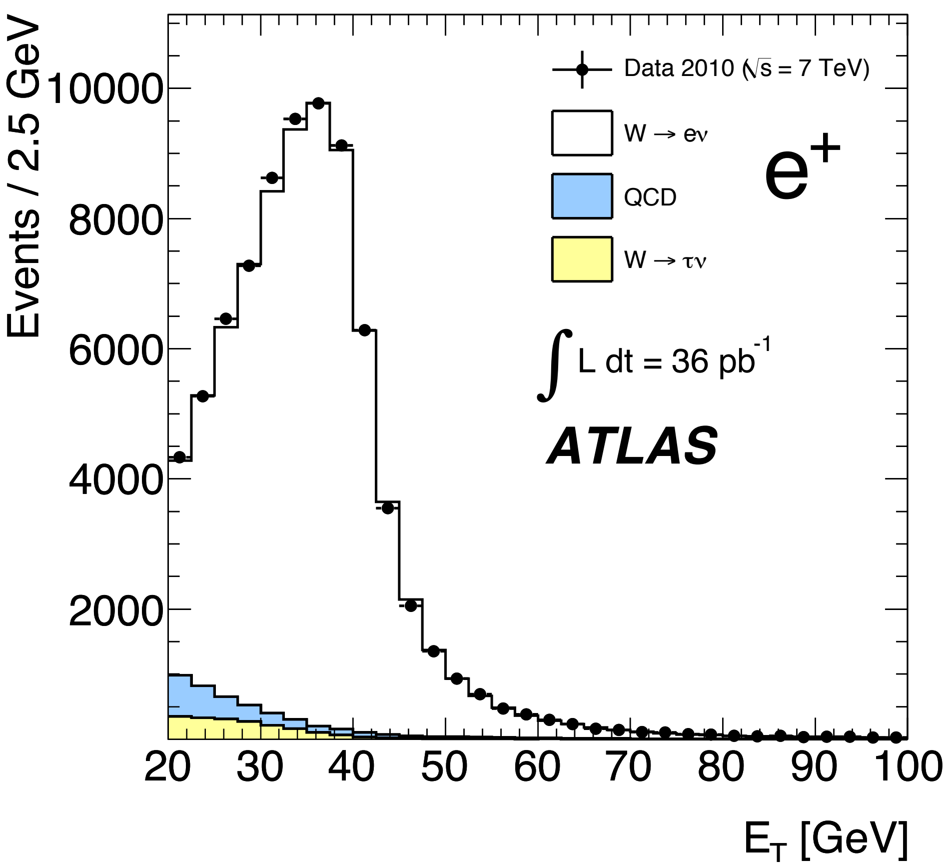

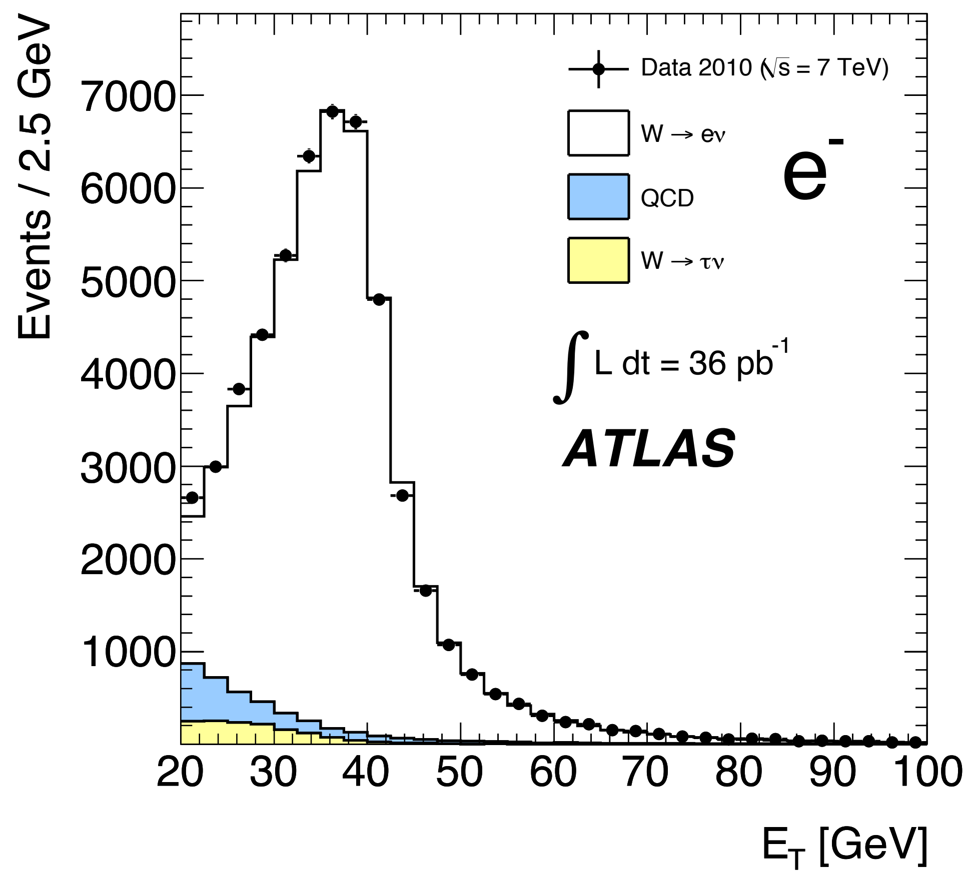

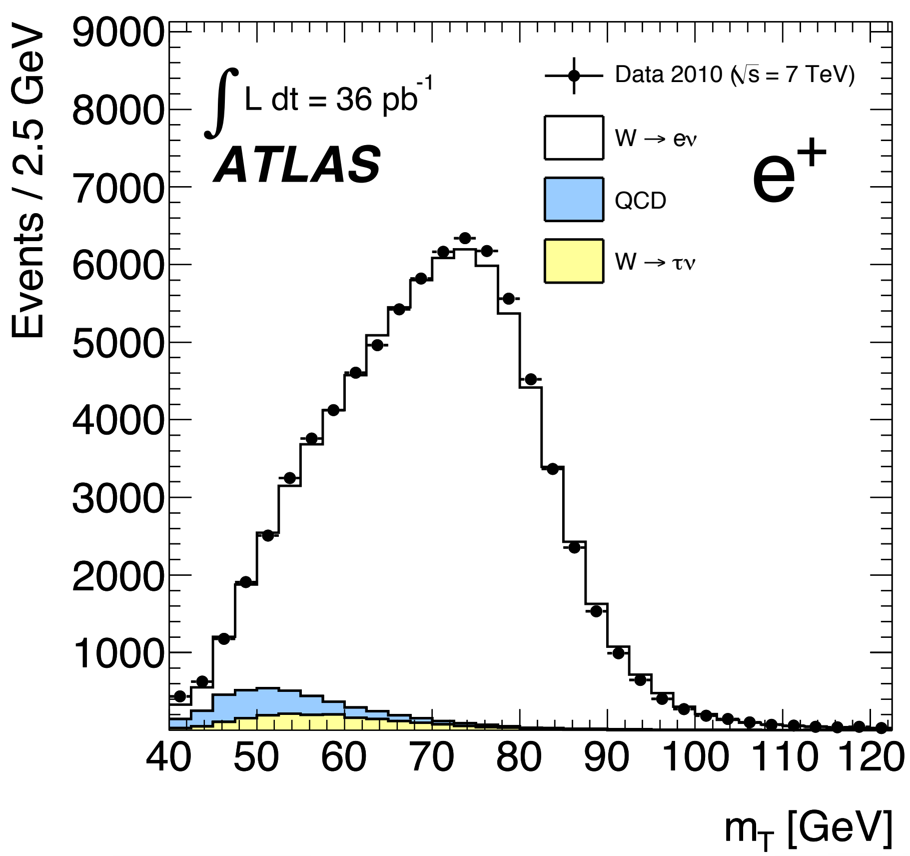

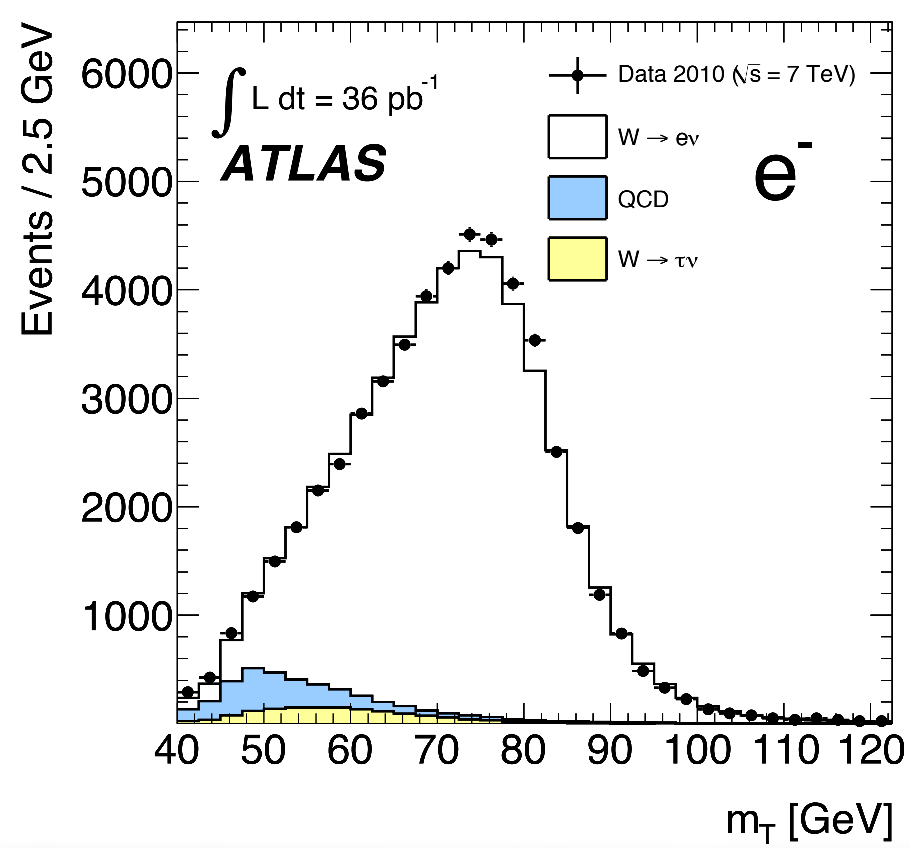

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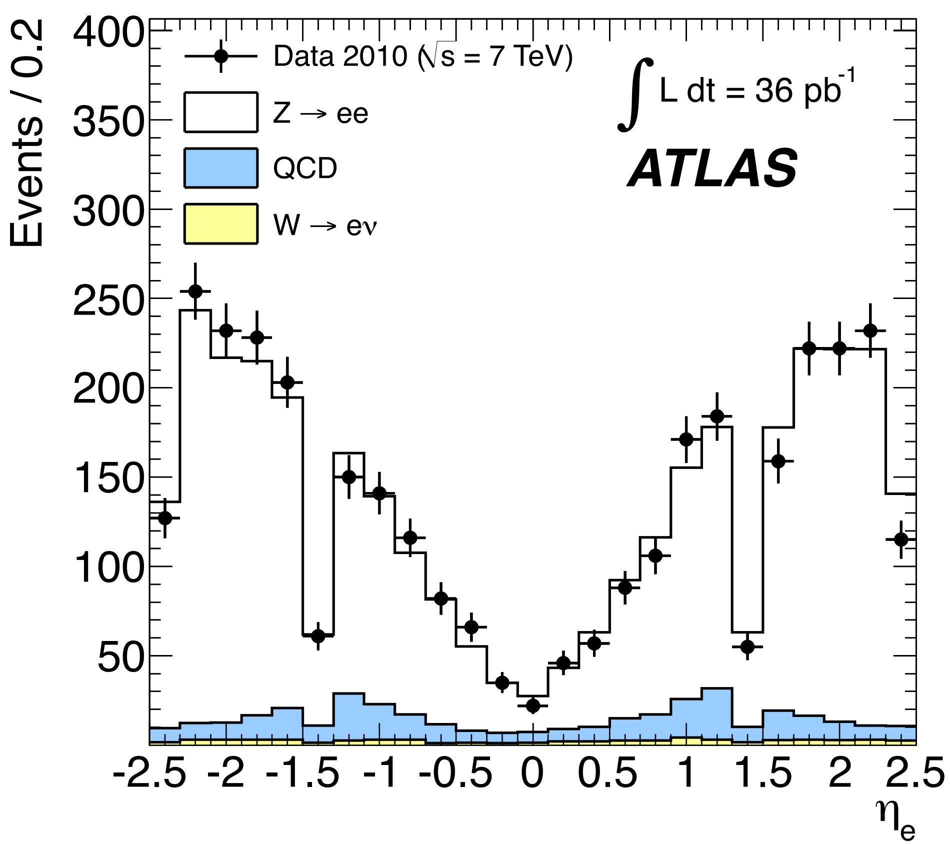

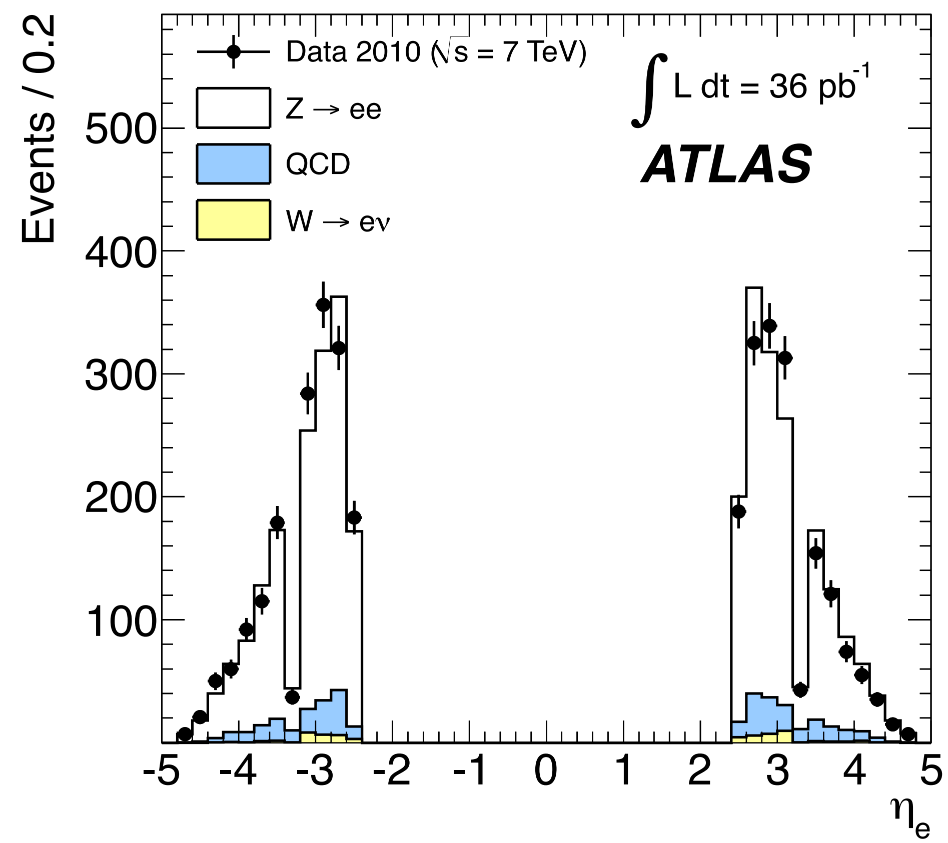

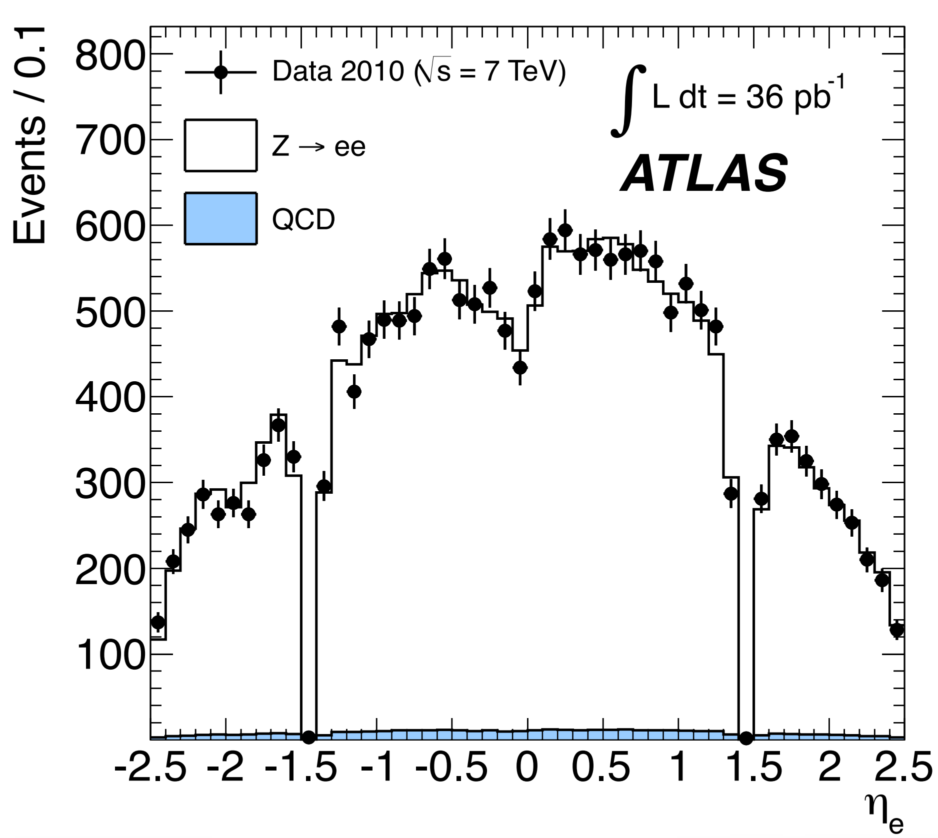

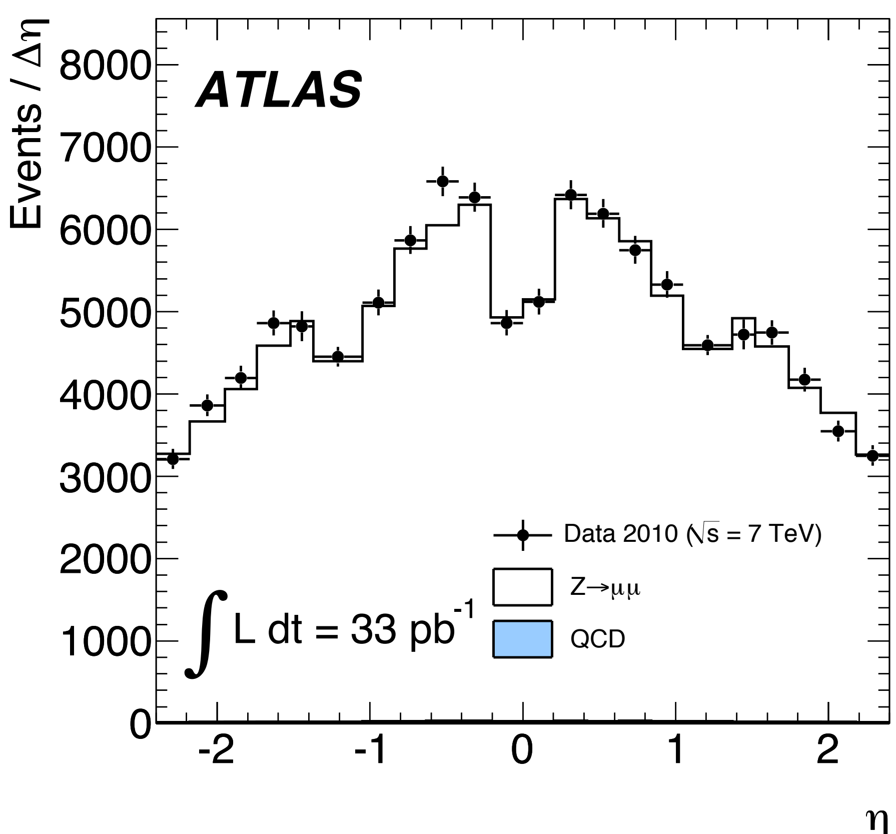

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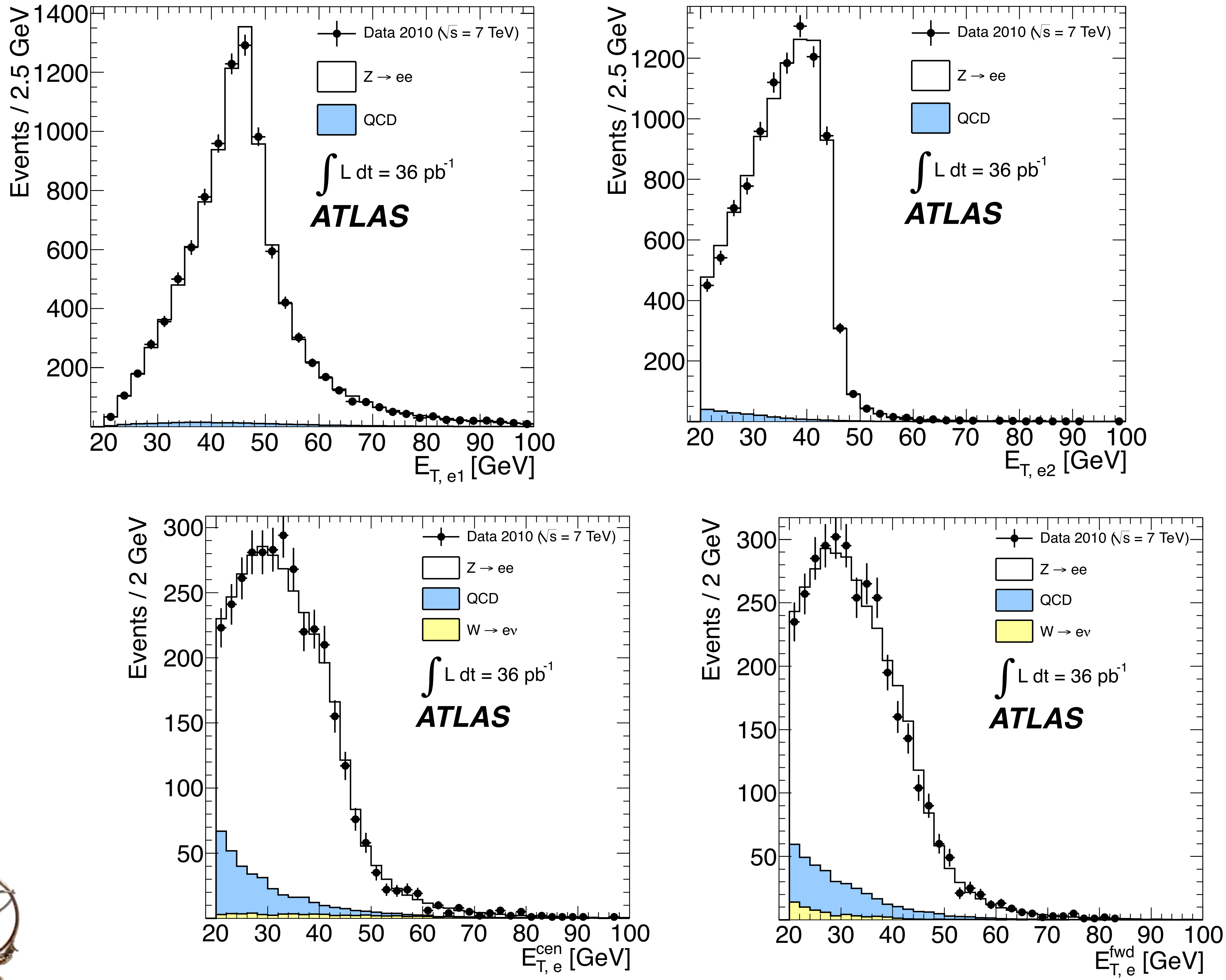

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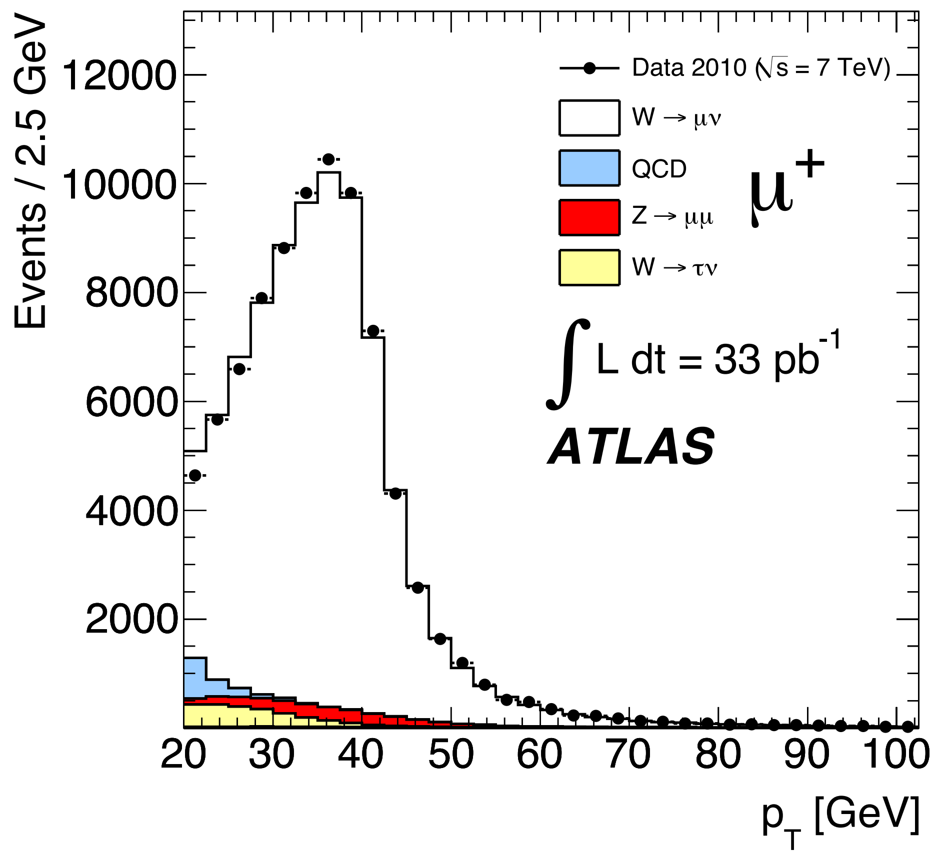

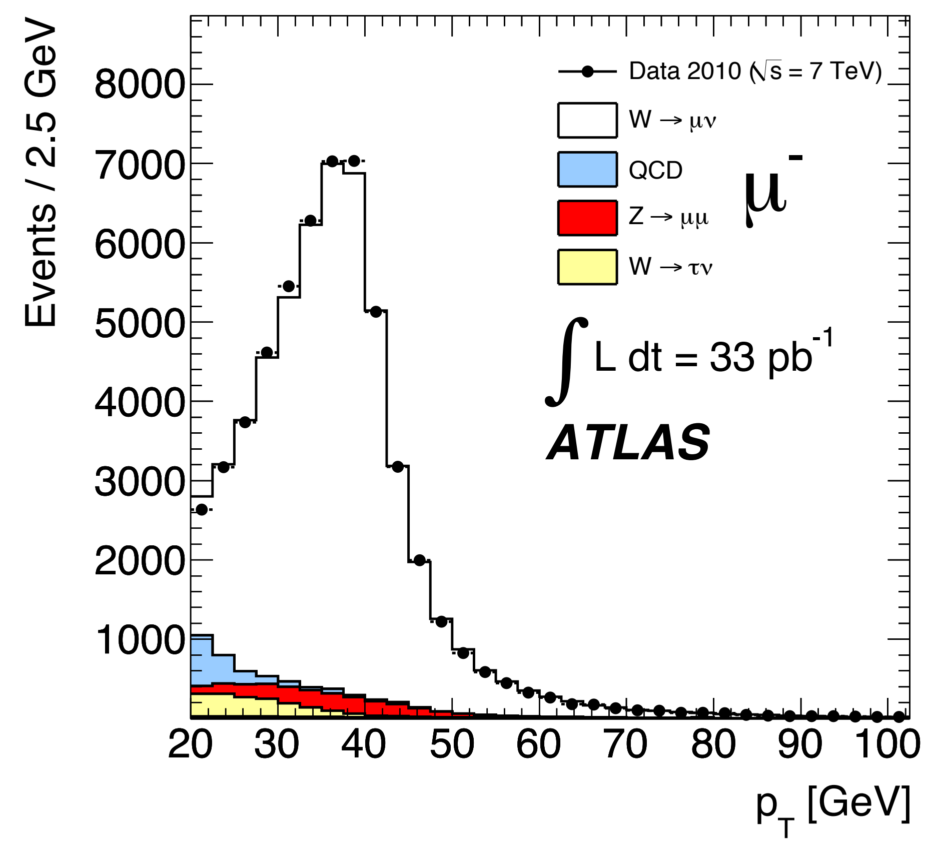

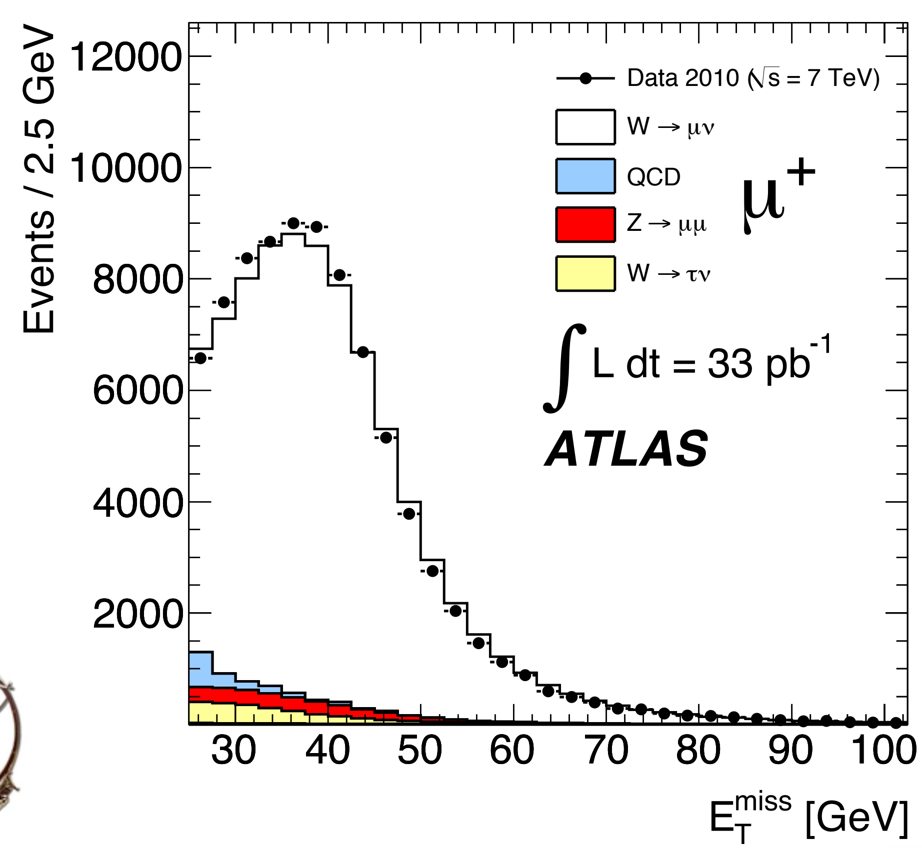

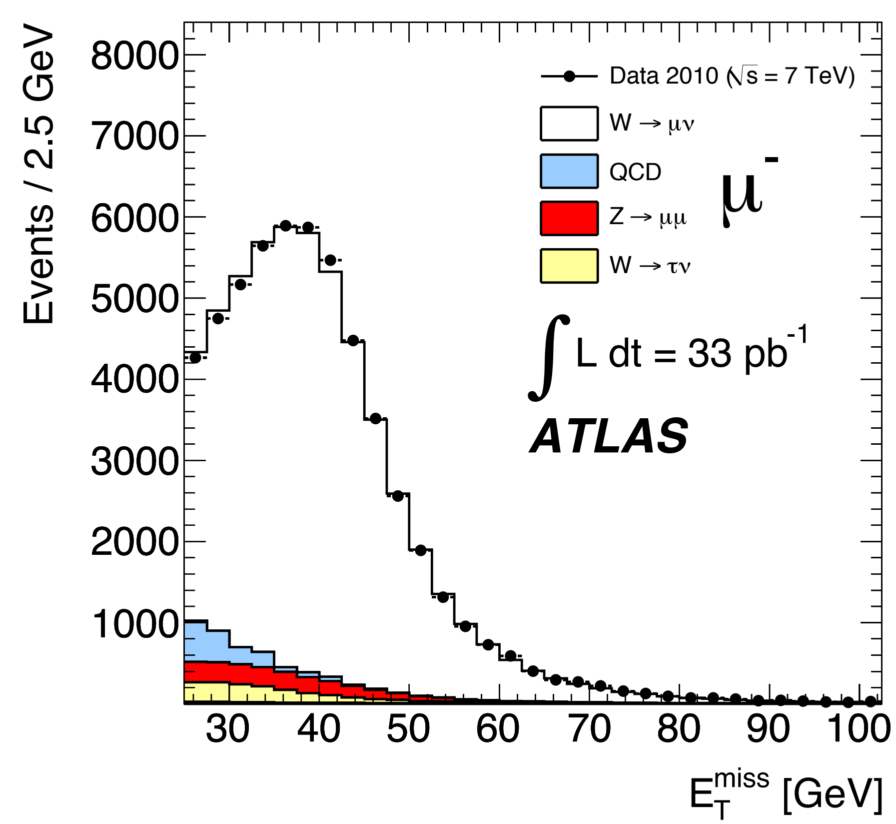

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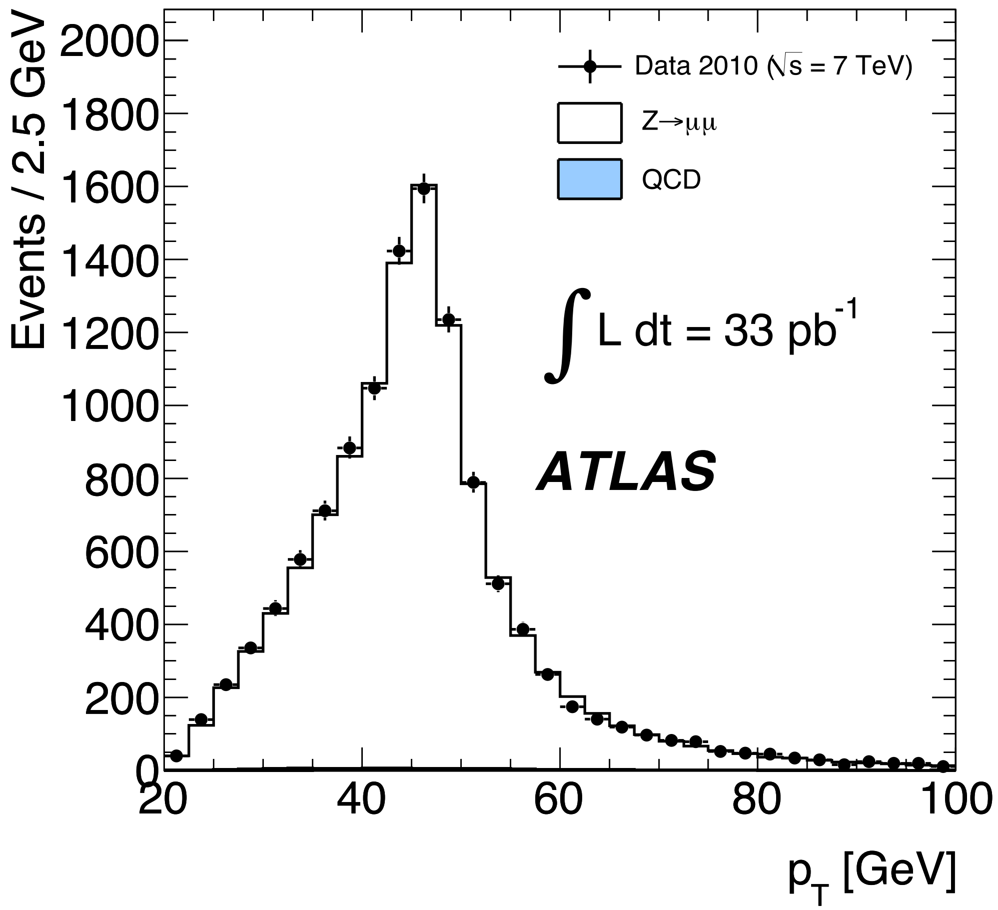

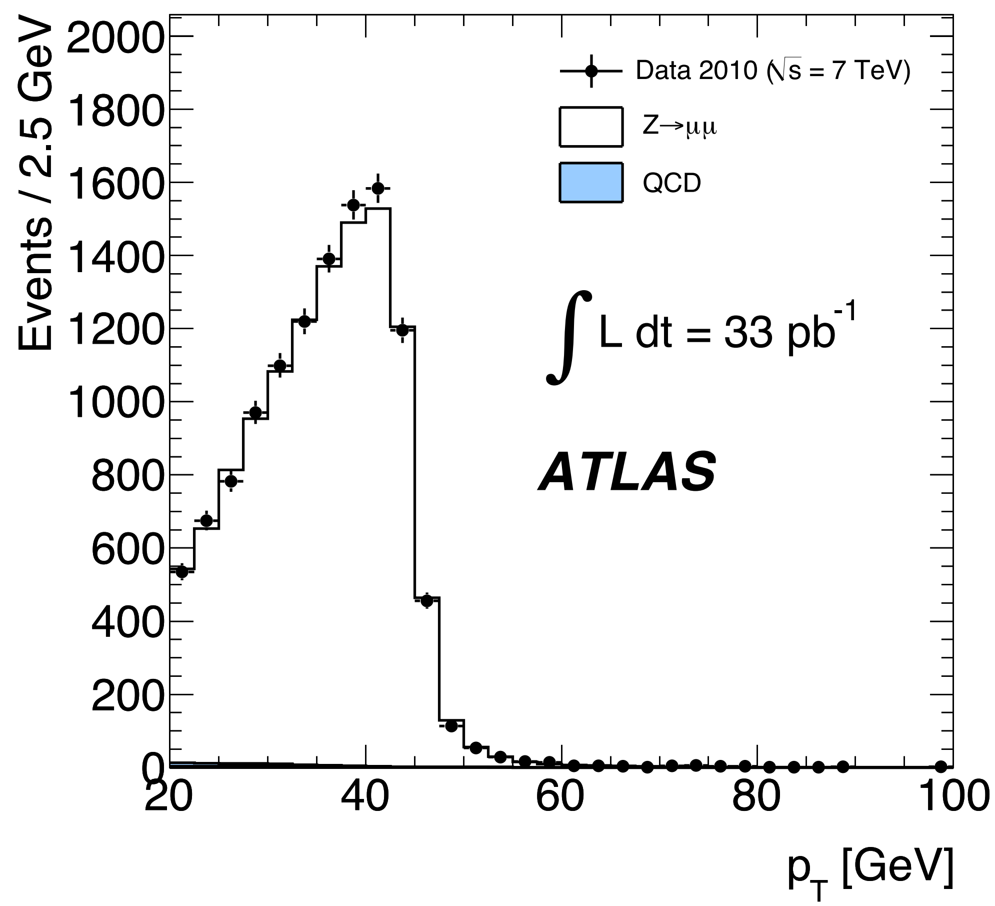

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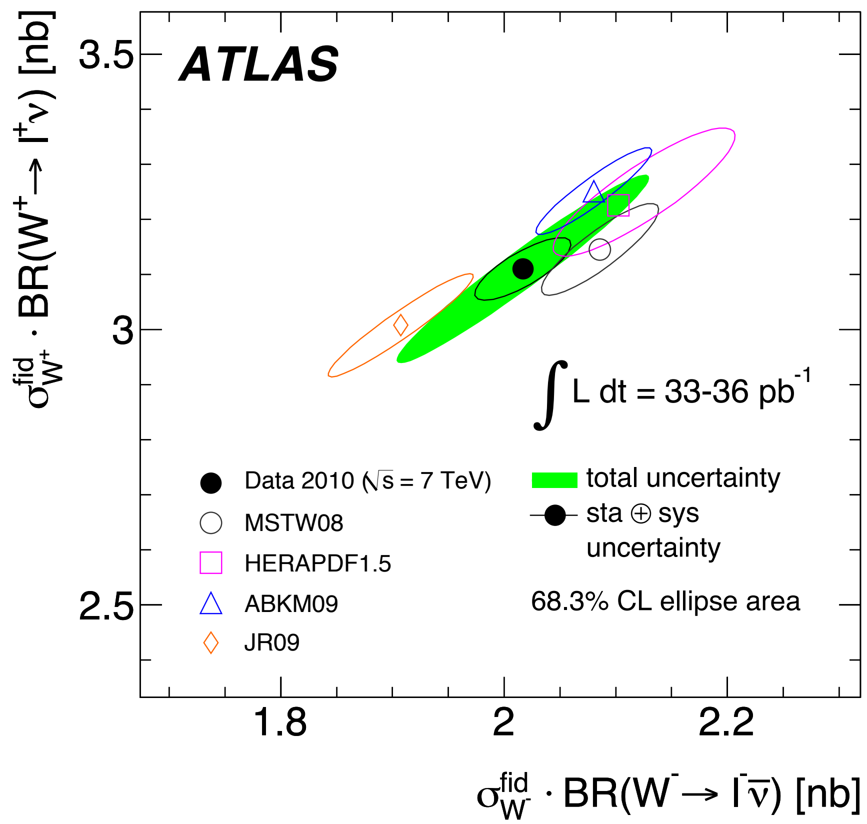
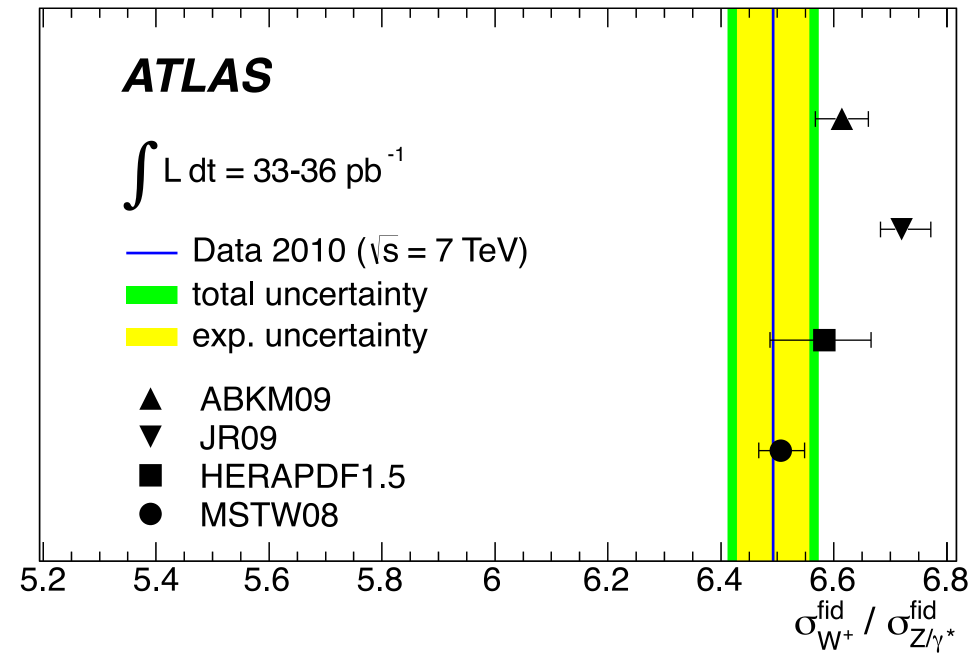
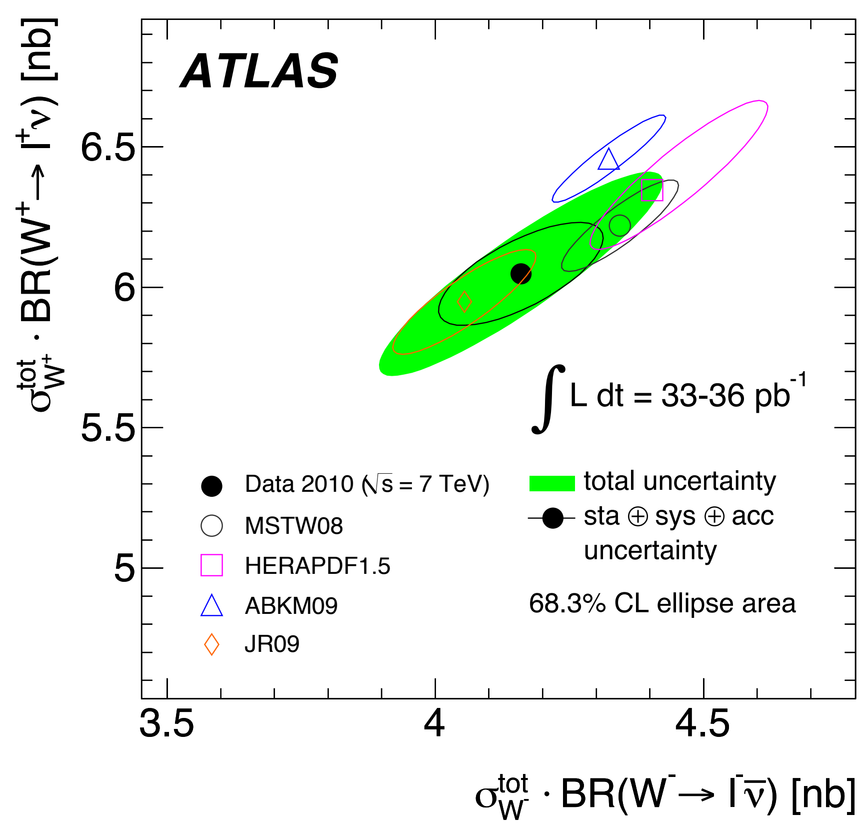
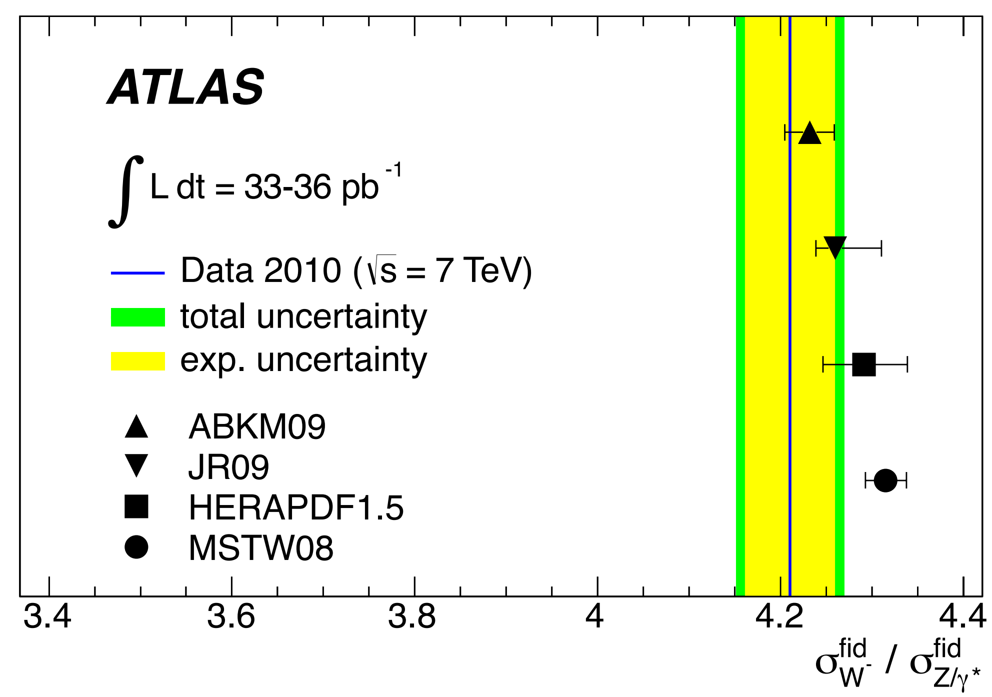








Forward Electrons in ATLAS

- electrons reconstructed from electromagnetic clusters
  - topological clustering algorithm (TopoCluster)
  - cluster moments used for electron identification

$$\langle x^n \rangle = \frac{1}{E_{norm}} \sum_i E_i x_i^n$$

- cluster moment of degree n of variable x

$$E_{norm} = \sum_i E_i$$

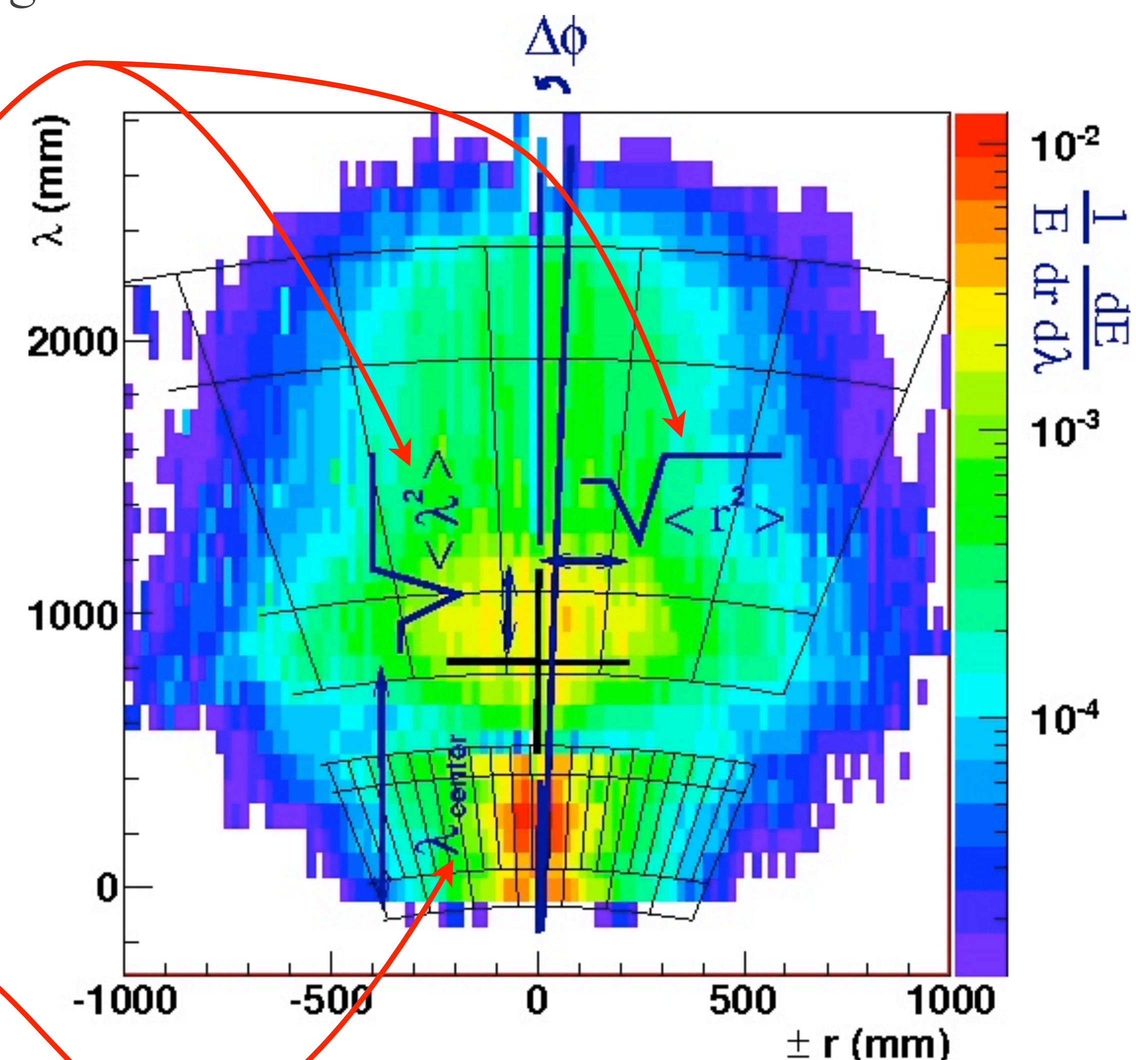
$\vec{s}$ - direction along shower axis

$\vec{c}$ - position of shower center

lateral dimension: $r_i = |(\vec{x}_i - \vec{c}) \times \vec{s}\,|$

longitudinal dimension: $\lambda_i = (\vec{x}_i - \vec{c}) \cdot \vec{s}$

- (normalised) second moments of these
  - distance of center from calo front face
  - energy fraction in most energectic cell



- 2 sets of cuts optimized on data defining "loose" and "tight" ID