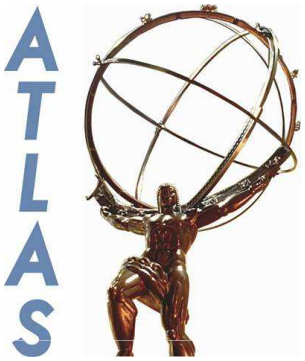
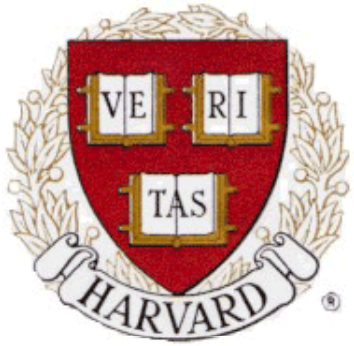
# First measurement of the $W \to \mu\nu$ and $Z \to \mu\mu$ cross-sections on ATLAS

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**Harvard University**

**on behalf of the ATLAS Collaboration**

*US LHC Users Meeting, Fermilab*

October 29, 2010

# *Outline*

- Motivations for *W*, *Z* cross-section measurement
- Dataset
- Event pre-selection
- *W* boson selection and backgrounds
- *Z* boson selection and backgrounds
- Efficiencies and acceptance
- Measured cross-sections and *W/Z* cross-section ratio
  - comparison to theory
- Conclusion & outlook

# *Motivations for measuring W, Z cross-sections*

With first dataset: Validation of theory predictions:

- QCD corrections significantly modify *W*, *Z* cross-sections
- Perturbative calculations available up to NNLO
- Test predictions by comparison with measured cross-sections

With entire 2010 dataset: *W*, *Z* production as benchmark processes

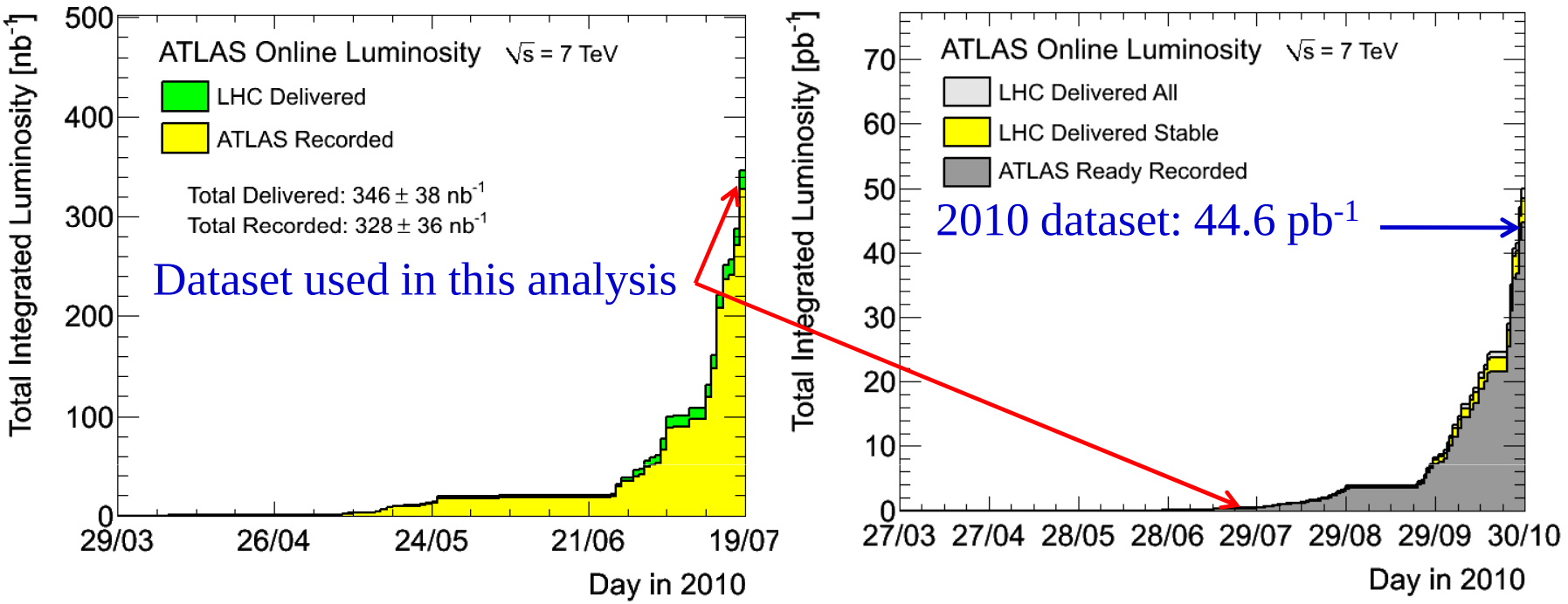
- *W*, *Z* decay products allow measurement of:

  - reconstruction and trigger efficiencies
  - lepton energy scales and detector resolution
  - missing $E_T$ resolution

With larger datasets: *W*, *Z* production as a luminosity monitor

- Given well-measured cross-sections, can count *W*, *Z* to estimate integrated luminosity on a run-by-run basis

# *Data sample*




- Measurement using 310 $nb^{-1}$ for *W*, 331 $nb^{-1}$ for *Z* channel
- Monte Carlo (fully simulated) datasets:
  - heavy flavor, *W*, *Z* channels using Pythia
  - *ttbar* using Powheg

# *Event pre-selection criteria*

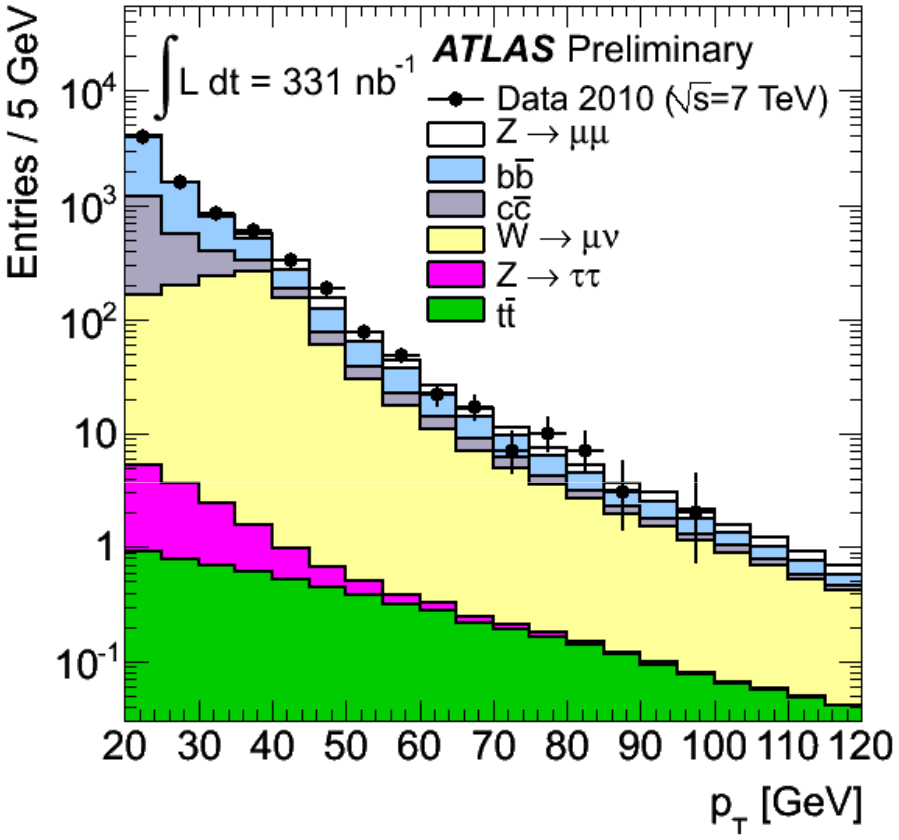
- Beam halo and beam-gas event rejection: event must correspond to passage of proton bunches that collide in ATLAS
- Cosmic rejection:

  - at least one primary vertex in event with >=3 assoc. tracks
  - $|z_0^{\mu} - z^{vtx}| < 1$ cm
- Level-1 single muon trigger with 6 GeV $P_T$ threshold
- At least one combined muon, formed by matching muon spectrometer (MS) track with inner detector (ID) track

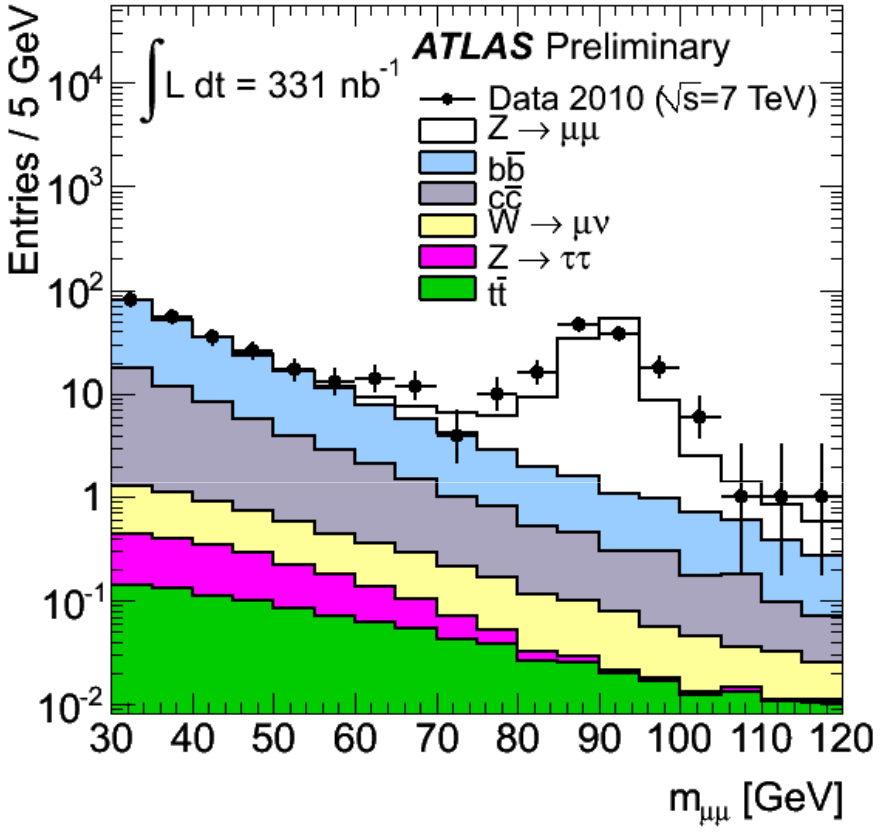
  - $P_T(comb) > 15$ GeV
  - $|\eta| < 2.4$ <– dictated by muon trigger coverage
  - $P_T(MS) > 10$ GeV
  - $|P_T(MS) - P_T(ID)| < 15$ GeV

Muon quality cuts, rejects badly matched tracks, decays-in-flight

# *Kinematics of pre-selected events*




Muon transverse momentum



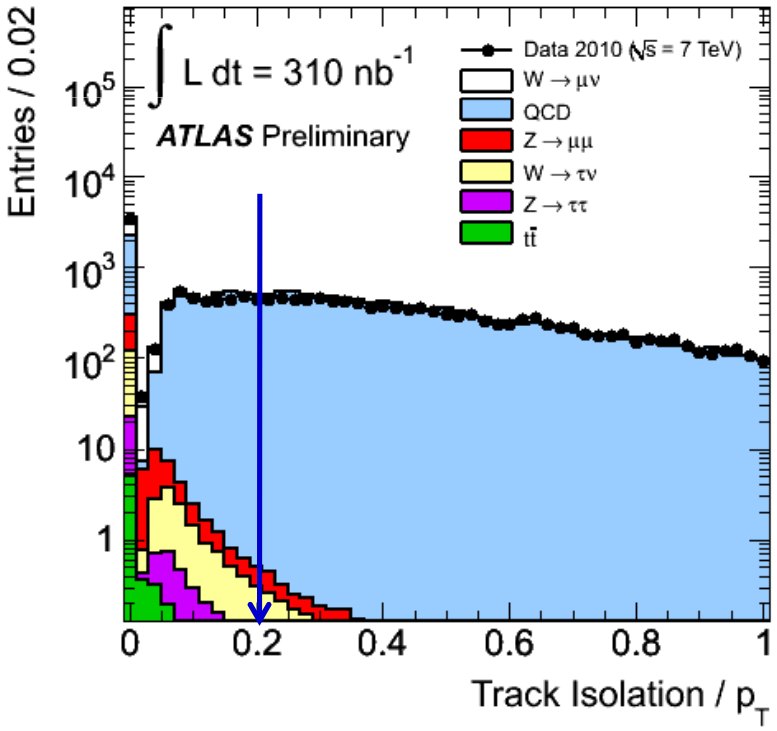

Dimuon invariant mass

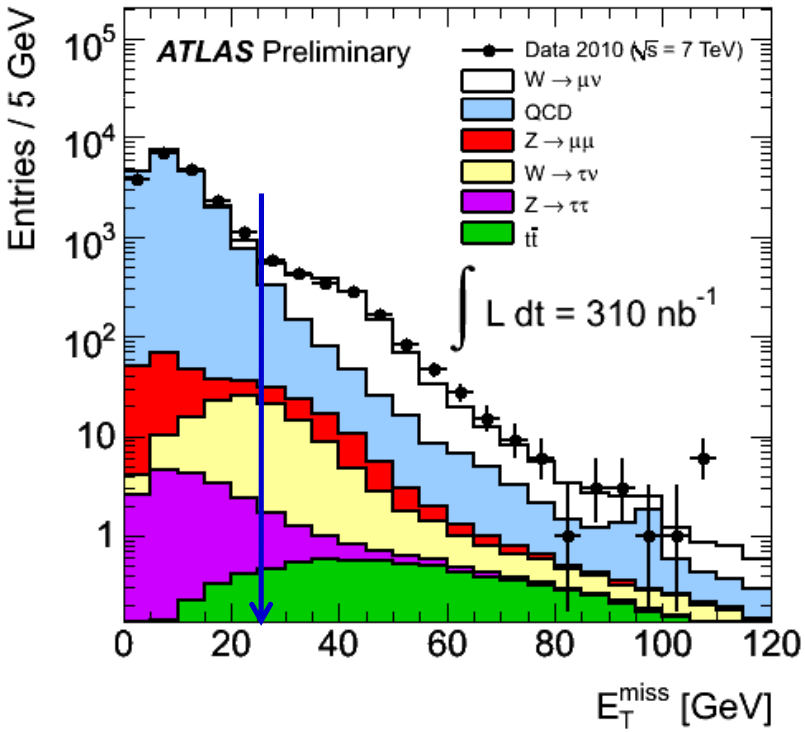
Note: Monte Carlo is normalized to the number of data events

# *W event selection - I*

- Combined muon $P_T > 20$ GeV, $|\eta| < 2.4$
- Track isolation ratio $r_{iso} < 0.2$

  - $r_{iso}$: sum $P_T$ of ID tracks in cone of size 0.4 around muon track divided by muon $P_T$
- Missing transverse energy $E_T^{miss} > 25$ GeV

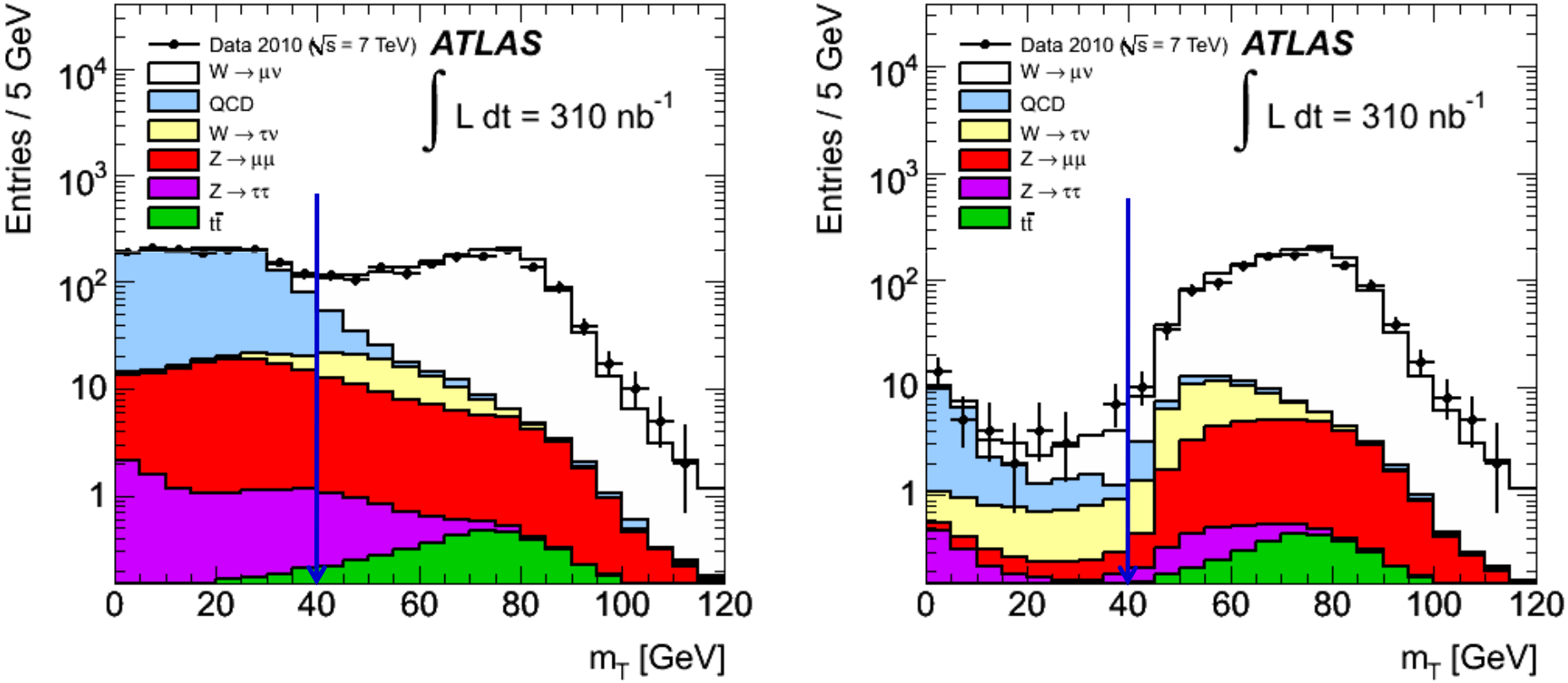


# *W event selection - II*

- Transverse mass $m_T > 40$ GeV

1181 $W \rightarrow \mu\nu$ events after all cuts




*W* transverse mass distribution before (*left*) and after (*right*) missing $E_T$ cut.

# *W backgrounds: electroweak and cosmics*

- Electroweak backgrounds: $Z \rightarrow \mu\mu$, $W \rightarrow \tau\nu$, $t\bar{t}$, $Z \rightarrow \tau\tau$

  - estimated using Monte Carlo samples

  - total predicted EW background: $77.6 \pm 0.3(\text{stat}) \pm 5.4(\text{sys})$

- Out-of-time cosmics: rejected by primary vertex cut

  - residual contamination checked using non-colliding proton bunches

  - negligibly small

- In-time cosmics: measured using non-colliding bunches without trigger and vertex requirements

  - probability of cosmic muon passing trigger in time with colliding bunches: $3.3*10^{-5}$

  - probability of cosmic muon passing *W* selection: $0.34*10^{-5}$

  - expected cosmic contamination: $1.7 \pm 0.7(\text{stat}) \pm 0.4(\text{sys})$

# *W backgrounds: QCD*

- Estimated using a matrix method

➢ Define two event samples, one with all *W* selection cuts, other with all cuts except isolation

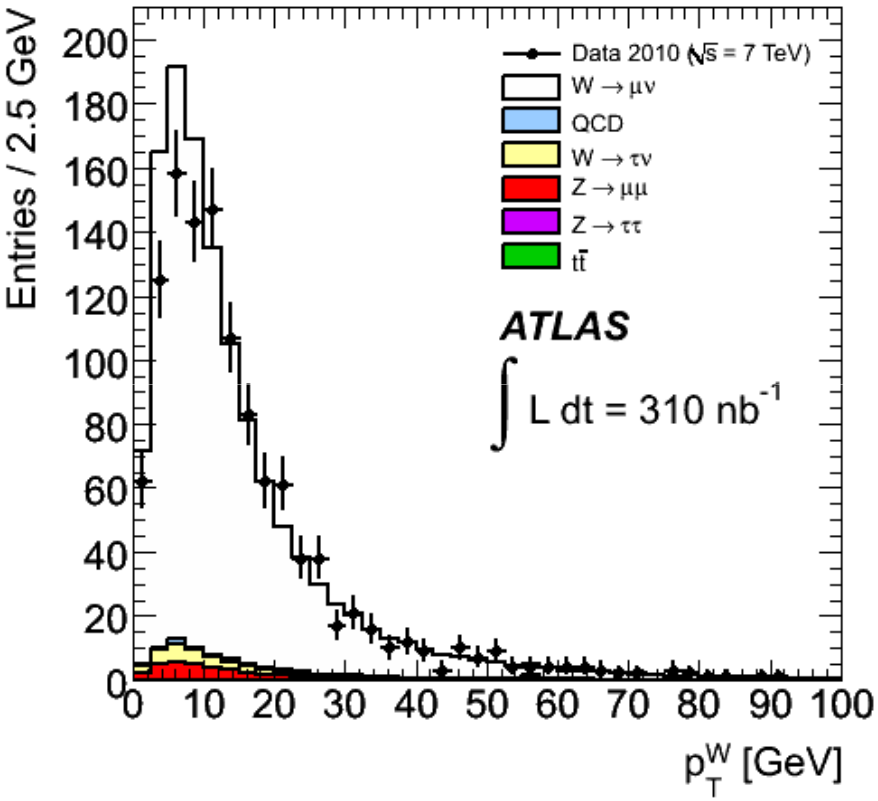
➢ If isolation cut efficiency is $\varepsilon_{QCD}$ and $\varepsilon_{non\text{-}QCD}$ resp for QCD and non-QCD muons,

$$N_{non\text{-}isol} = N_{QCD} + N_{non\text{-}QCD}$$
$$N_{isol} = \varepsilon_{QCD} N_{QCD} + \varepsilon_{non\text{-}QCD} N_{non\text{-}QCD}$$
$$\Longrightarrow N_{QCD} = \frac{N_{non\text{-}isol}\varepsilon_{non\text{-}QCD} - N_{isol}}{\varepsilon_{non\text{-}QCD} - \varepsilon_{QCD}}$$

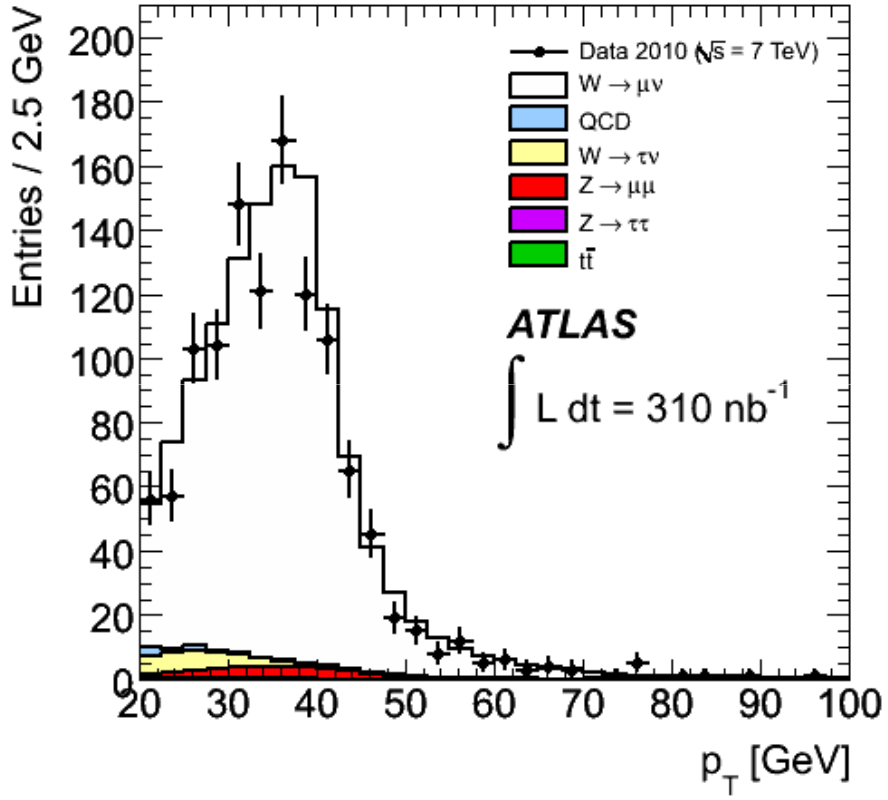
- Estimate $\varepsilon_{QCD}$ using pre-selected muons with 15 GeV < $P_T$ < 20 GeV, extrapolated to $P_T$ > 20 GeV using MC–> $\varepsilon_{QCD} = 22.6 \pm 0.6\%$
- Estimate $\varepsilon_{non\text{-}QCD}$ from tag-probe method using $Z$ –> μμ events
  –> $\varepsilon_{non\text{-}QCD} = 98.4 \pm 1.0\%$
- QCD background : $\varepsilon_{QCD} N_{QCD} = 21.1 \pm 4.5(stat) \pm 8.7(sys)$

Total expected background events: 100.4 ± 4.6(stat) ± 14.5(sys)

$W \rightarrow \mu\nu$ events after background subtraction: 1080.4 ± 34.4(stat) ± 11.2(sys)




$P_T$ spectrum of $W$ candidates




$P_T$ spectrum of $W$ decay muons

Note: Monte Carlo is normalized to the integrated luminosity

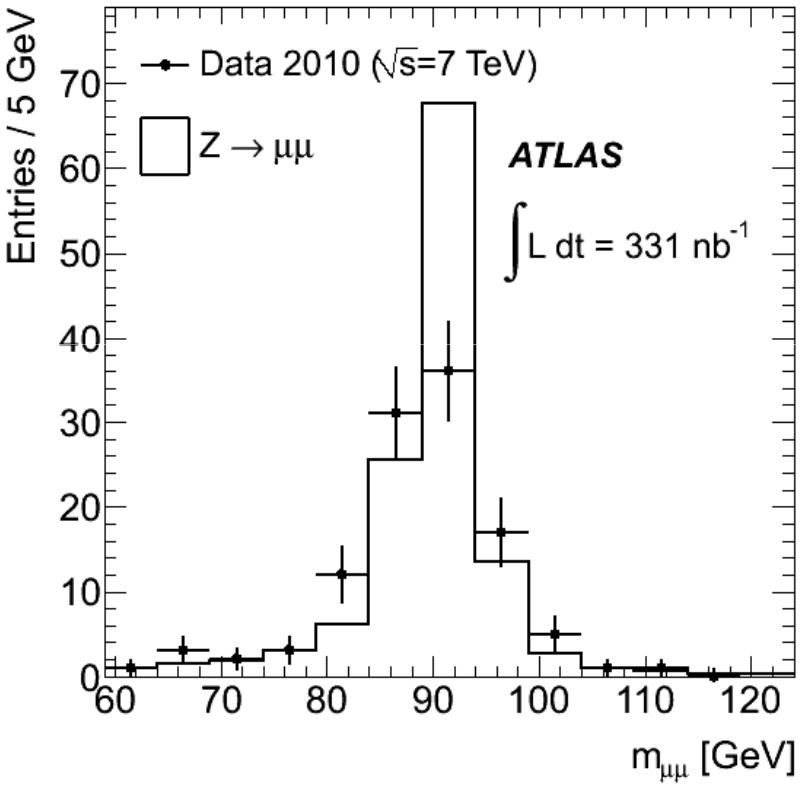
# *Z event selection and backgrounds*

- At least two combined muons in event, each with
  - $P_T > 20$ GeV
  - $|\eta| < 2.4$
  - quality cuts as for the pre-selection
- Track isolation ratio $r_{iso} < 0.2$ for both muons
- Opposite charge
- Dimuon invariant mass window: $66 \text{ GeV} < M_{\mu\mu} < 116 \text{ GeV}$
- Electroweak and QCD backgrounds estimated from Monte Carlo:
  - EW: $0.21 \pm 0.01(\text{stat}) \pm 0.01(\text{sys})$
  - QCD: $0.04 \pm 0.01(\text{stat}) \pm 0.04(\text{sys})$
- Cosmics: estimated using unpaired bunches as for *W* channel
  - negligibly small

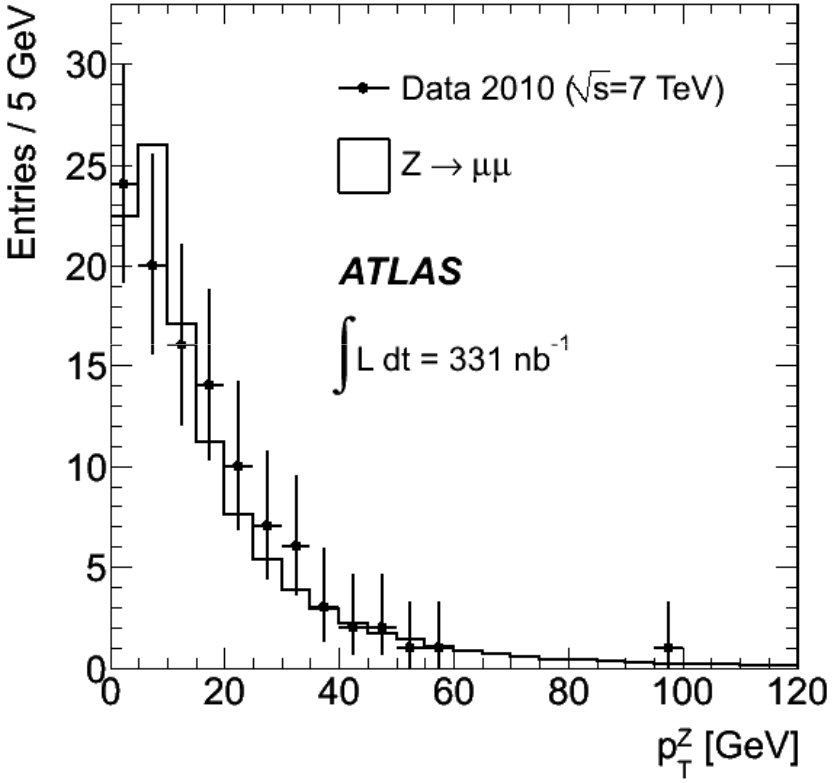
109 $Z \rightarrow \mu\mu$ events after all cuts

Total expected background events: 0.25 $\pm$ 0.01(stat) $\pm$ 0.05(sys)

$Z \rightarrow \mu\mu$ events after background subtraction: 108.8 $\pm$ 10.4(stat) $\pm$ 0.0(sys)




Dimuon invariant mass distribution

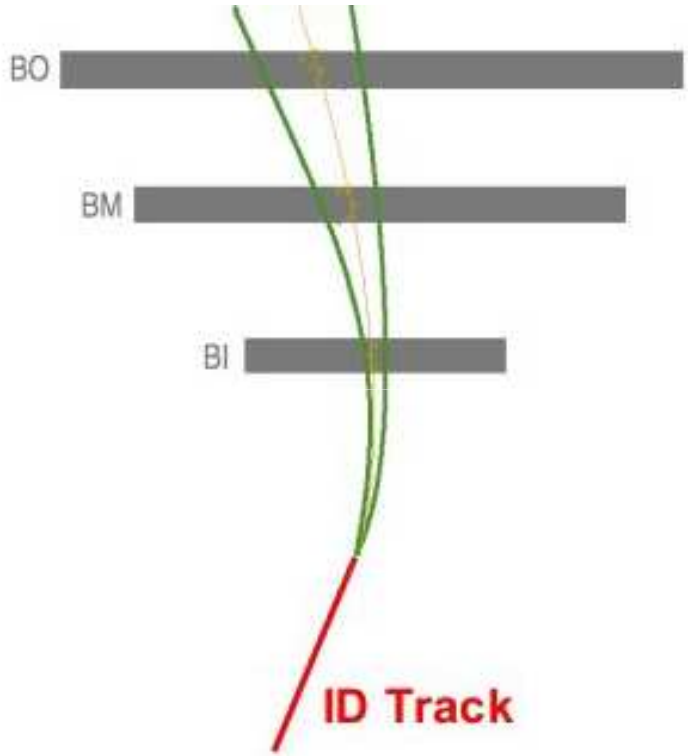



$P_T$ spectrum of $Z$ candidates

Note: Monte Carlo is normalized to the integrated luminosity

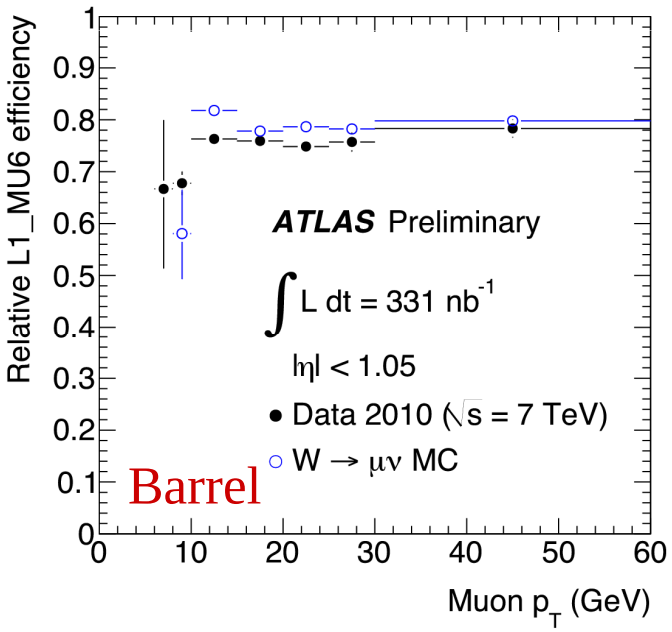
# *Muon reconstruction efficiency: MS hit method*

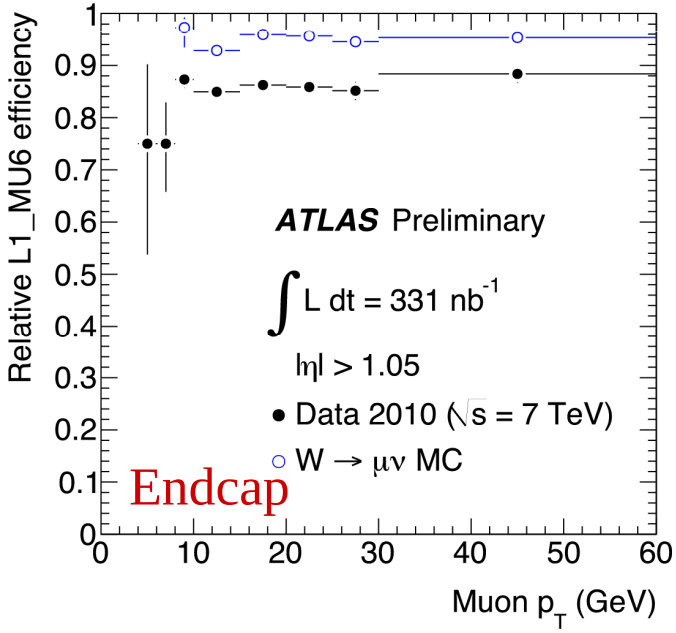
- Tag an ID track as a muon by associating it with hits in the MS
- Look for a combined muon track within $\Delta R = 0.4$ of tagged track
- Contamination from $\pi/K$ decay muons: correction factor derived using templates from Monte Carlo
- Major systematic from correction for non-prompt muons
- Data efficiency: $0.994 \pm 0.006(\text{stat}) \pm 0.024(\text{sys})$
- MC efficiency: 0.986



# *Trigger efficiency: orthogonal trigger method*

- Estimate efficiency of 6 GeV muon trigger using events passing jet trigger with 15 GeV $E_T$ threshold
- Select events and combined muon tracks with pre-selection criteria used in cross-section analysis
- For selected combined muons, look for *region of interest* (RoI) defined by Level-1 muon trigger




Note: 'efficiency' in these plots folds in acceptance

# *Trigger efficiency (cont'd)*

- Major systematics from:

o $P_T$ cut used in muon selection: estimated by varying cut by $\pm$ 5 GeV

o difference in efficiency results using muons reconstructed with two different algorithms

| | Barrel trigger efficiency | Endcap trigger efficiency |
|---|---|---|
| Data | 0.760 $\pm$ 0.009(stat) $\pm$ 0.020(sys) | 0.863 $\pm$ 0.008(stat) $\pm$ 0.018(sys) |
| MC | 0.792 $\pm$ 0.003(stat) | 0.951$\pm$ 0.002(stat) |
| Data/MC scale factor (*W*) | 0.929 $\pm$ 0.010(stat) $\pm$ 0.015(sys) | |
| Data/MC scale factor (*Z*) | 0.981 $\pm$ 0.003(stat) $\pm$ 0.006(sys) | |

- Correct event acceptance from Monte Carlo with data/MC scale factor for trigger efficiency

# *Acceptances*

$$\sigma_{W,Z} = \frac{N_{Sig} - N_{BG}}{A_{W,Z} C_{W,Z} L_{\text{int}}}$$

$A_{W,Z}$: kinematic acceptance
$C_{W,Z}$: event detection efficiency

- $A_{W,Z}$: measured at truth-level in Pythia Monte Carlo
- Systematics derived using PDF error sets, different PDF sets and different generators
- $A_W$: 0.480 $\pm$ 0.014, $A_Z$: 0.486 $\pm$ 0.019
- $C_{W,Z}$: ratio of events passing all reco-level cuts to those passing truth-level kinematic cuts
  - Corrected by trigger efficiency scale factor
  - Error in reconstruction efficiency in data is assigned as systematic
  - All experimental systematics included, added in quadrature
- $C_W$: 0.758 $\pm$ 0.030, $C_Z$: 0.773 $\pm$ 0.043

# *W–>μν* and *Z–>μμ cross-sections*

$$\sigma_W \times BR(W \to \mu\nu) : 9.58 \pm 0.30(\text{stat}) \pm 0.50(\text{sys}) \pm 1.05(\text{lum})\ \text{nb}$$

$$\sigma_{Z/\gamma^*} \times BR(Z/\gamma^* \to \mu\mu) : 0.87 \pm 0.08(\text{stat}) \pm 0.05(\text{sys}) \pm 0.10(\text{lum})\ \text{nb}$$

- Luminosity uncertainty of 11% dominates the measurement errors

➢ Theoretical predictions:

- Calculated with FEWZ to NNLO accuracy
- Errors derived from PDF error set, variations of scale and $\alpha_S$

$$\sigma^{NNLO}_{W \to \mu\nu} : 10.46 \pm 0.52\ \text{nb}$$

$$\sigma^{NNLO}_{Z/\gamma^* \to \mu\mu} : 0.96 \pm 0.05\ \text{nb, for } 66\ \text{GeV} < M_{\mu\mu} < 116\ \text{GeV}$$

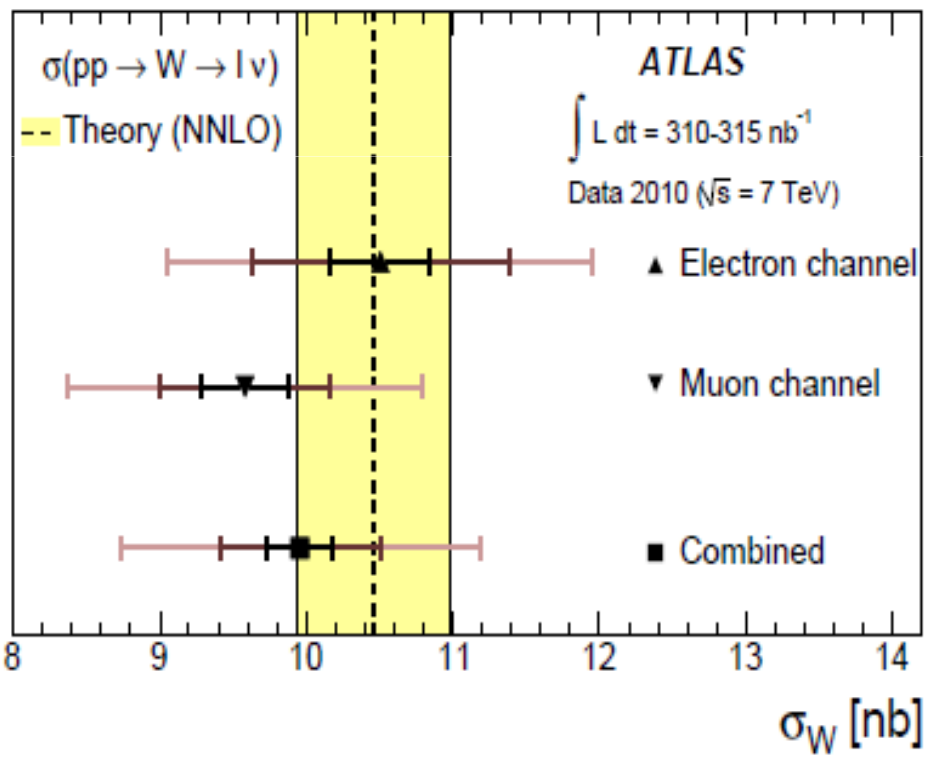
Both measurements agree with predictions!

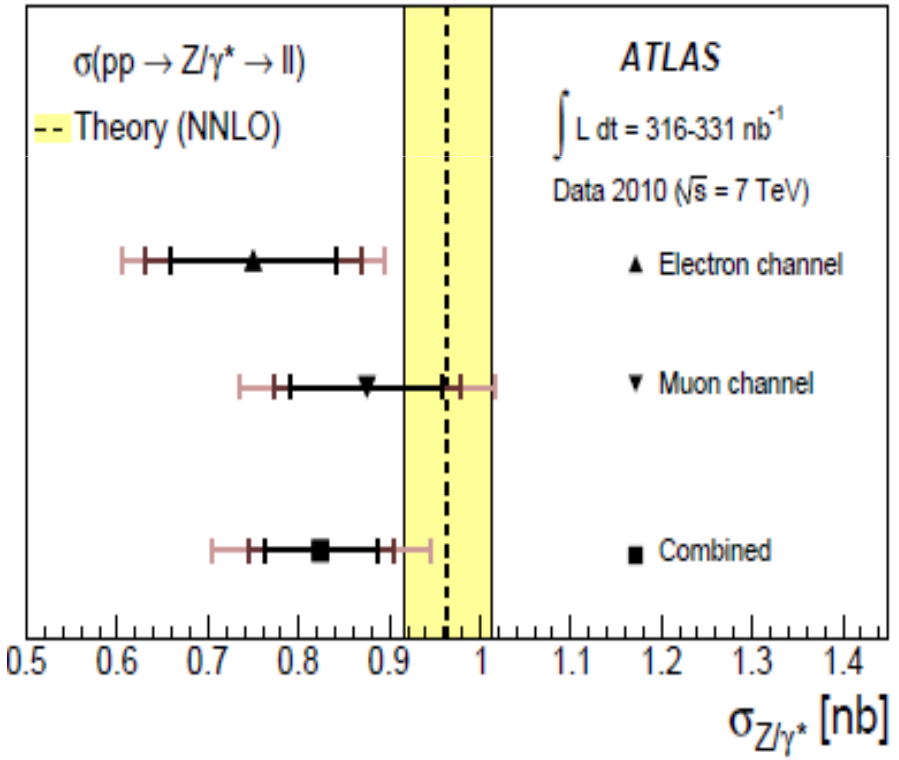
# $W \to e\nu$ and $Z \to ee$ cross-section measurements

$$\sigma_W \times BR(W \to e\nu) : 10.51 \pm 0.34(\text{stat}) \pm 0.81(\text{sys}) \pm 1.16(\text{lum})\ \text{nb}$$

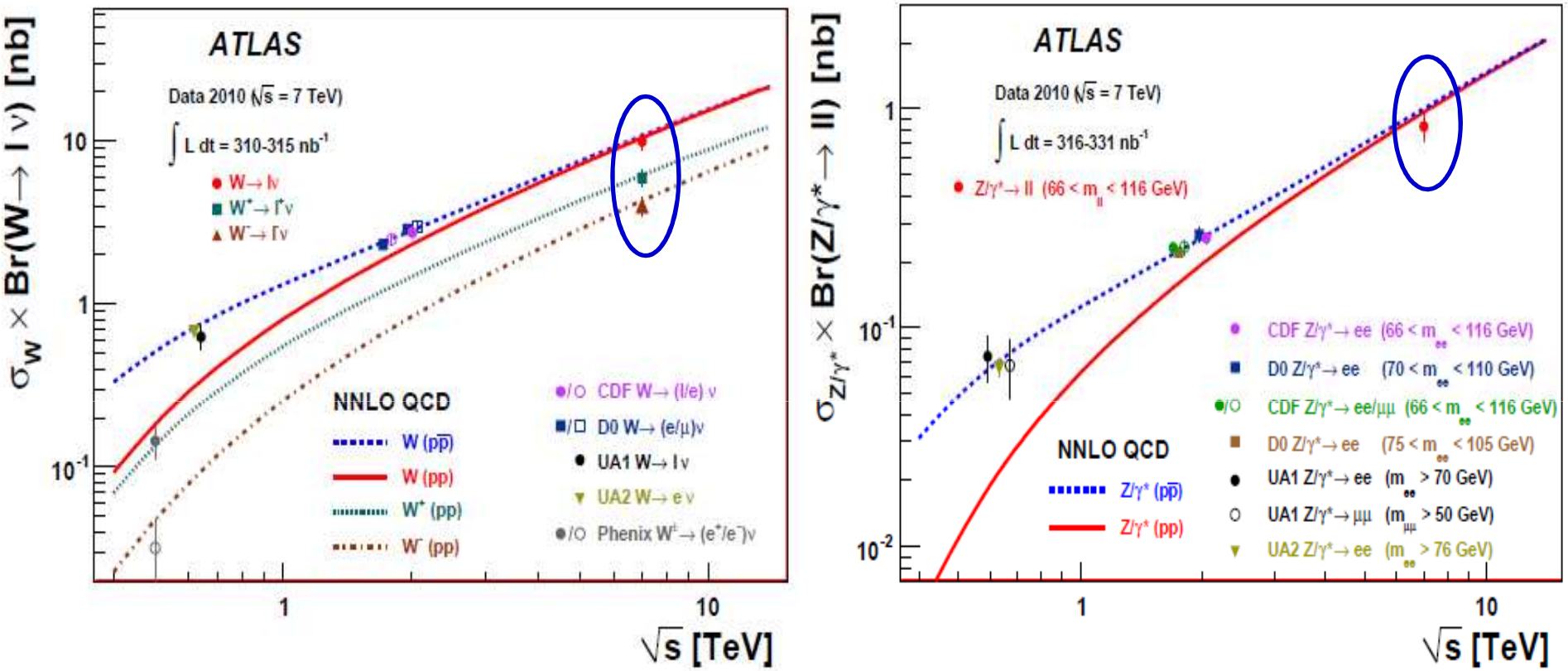
$$\sigma_{Z/\gamma^*} \times BR(Z/\gamma^* \to ee) : 0.75 \pm 0.09(\text{stat}) \pm 0.08(\text{sys}) \pm 0.08(\text{lum})\ \text{nb}$$

Also in agreement with predictions



# *Measurements in historical context*




*W –> lν* and *Z –> ll (l = μ, e)* cross-section measurements on ATLAS at 7 TeV compared with theory predictions and with measurements by other experiments.

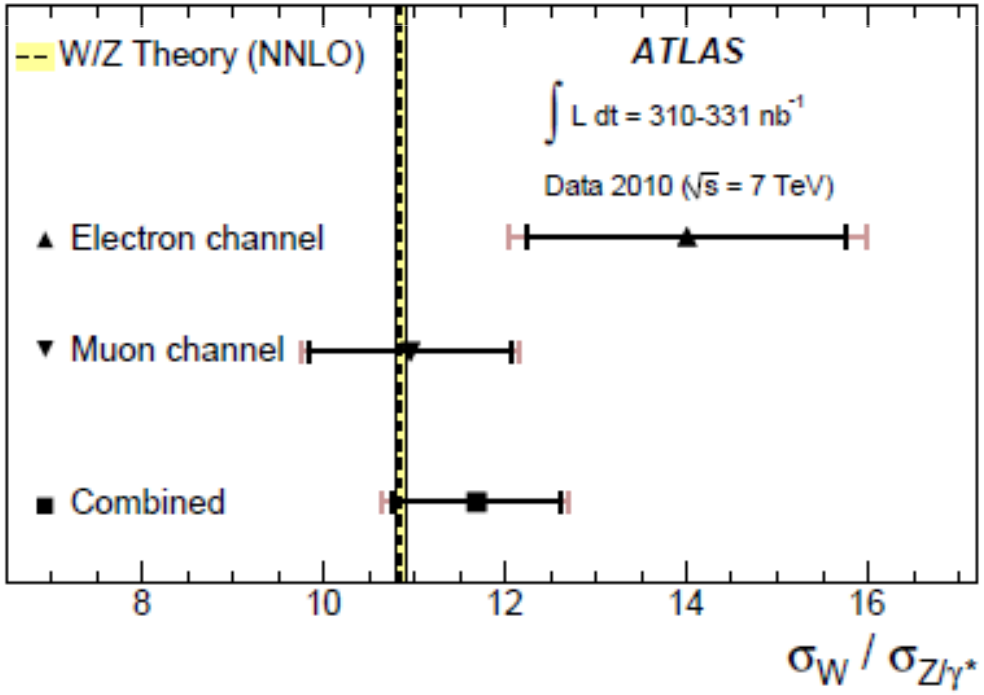
# *W/Z* cross-section ratio

- Luminosity uncertainty cancels in ratio of cross-sections

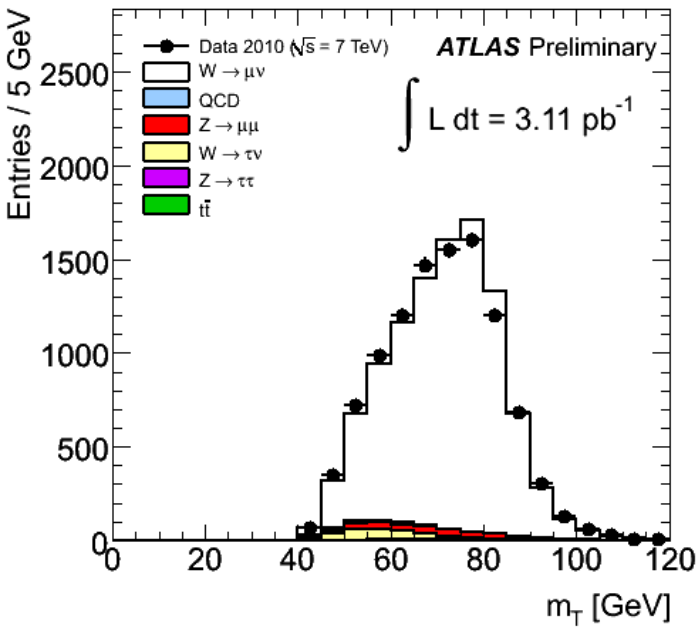
$$R^{\mu}_{W/Z} : 11.0 \pm 1.1(\text{stat}) \pm 0.5(\text{sys})$$

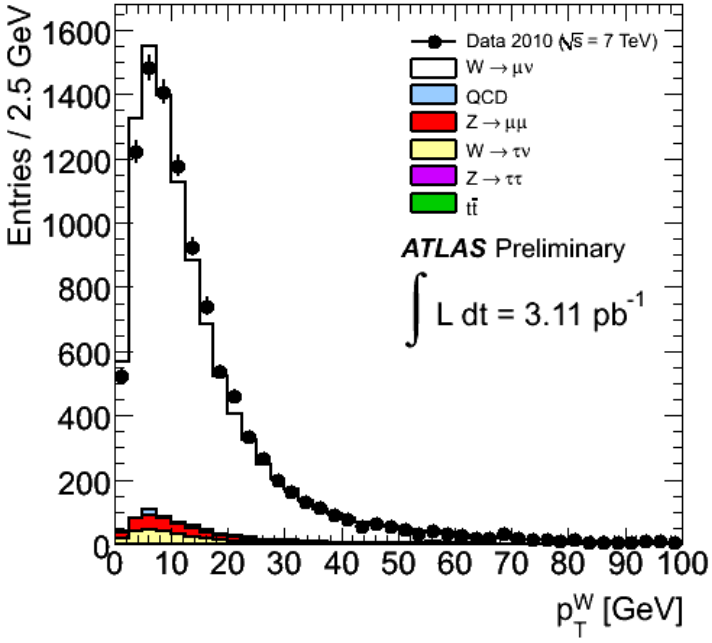
$$R^{e}_{W/Z} : 14.0 \pm 1.8(\text{stat}) \pm 0.9(\text{sys})$$

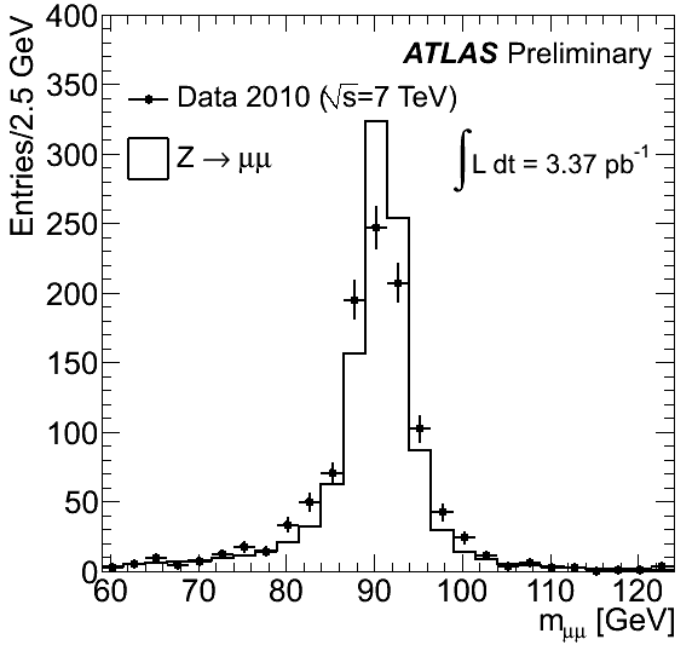
$$R^{l}_{W/Z} : 11.7 \pm 0.9(\text{stat}) \pm 0.4(\text{sys})$$ ⟸ *e, μ* channels combined

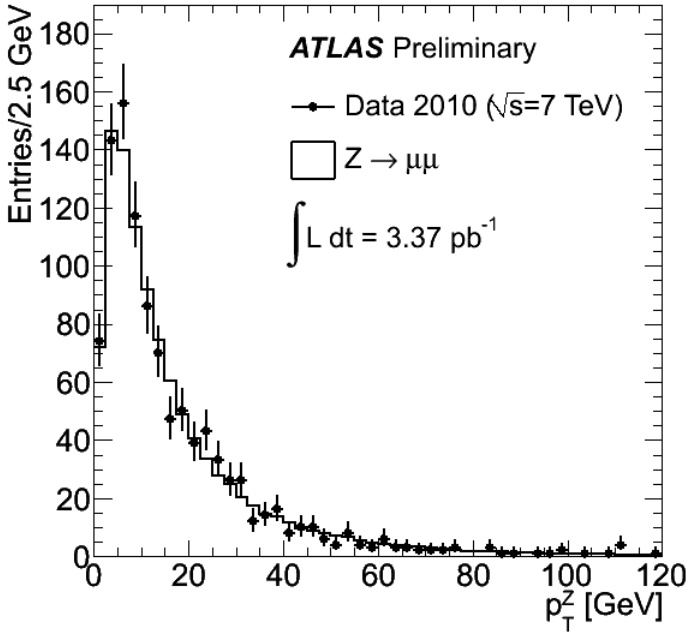


# *With more data…*



# *Conclusion & outlook*

- The first $W \rightarrow \mu\nu$ and $Z \rightarrow \mu\mu$ cross-sections and their ratios have been measured by ATLAS with ~300 $nb^{-1}$ of data

  - paper submitted to *JHEP* (arXiv:1010.2130v1 [hep-ex])

- Measurements in agreement with prediction
- ~45 $pb^{-1}$ of data from the 2010 proton run
- ~200k *W*, 20k *Z* events after full selection, leading to accurate measurements of:

  - muon reconstruction, trigger efficiencies using tag-probe method
  - muon $P_T$ scale, resolution from *Z* lineshape fit
  - data-driven QCD background estimation for all channels

- Differential measurements: boson $P_T$, $\eta$ distributions

  –> PDF constraints, sensitive to new physics

# Backup

# *Muon reconstruction efficiency: tag-probe method*

- Select $Z \rightarrow \mu\mu$ events:

  - a high-$P_T$ isolated combined muon (tag)

  - a high-$P_T$ isolated ID track (probe) such that $76 < M_{tag\text{-}probe} < 106$ GeV

- Compute fraction events that have a combined muon within $\Delta R = 0.01$ of probe

- Contamination from events with 2 non-prompt muons: correction factor derived using Monte Carlo

- Major systematics:

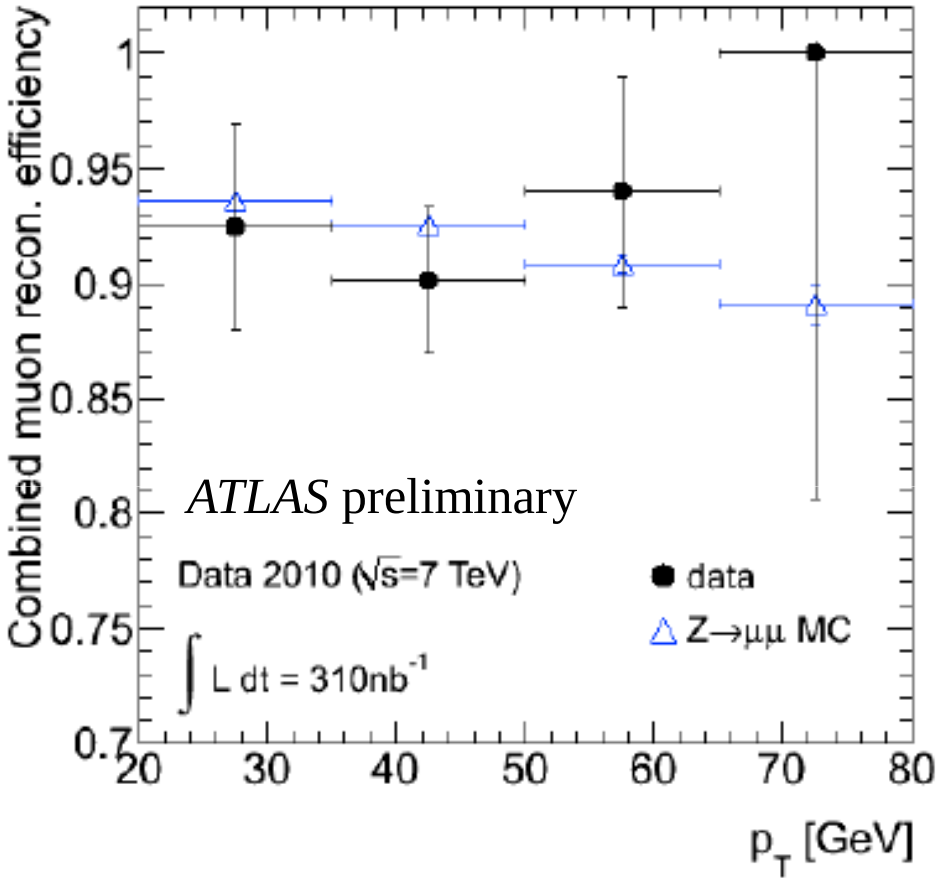
  - non-prompt muon correction

  - stability of muon isolation and ID track selection cuts

- Data efficiency: $0.933 \pm 0.022(\text{stat}) \pm 0.013(\text{sys})$

- MC efficiency: 0.924

# *Muon reconstruction efficiency vs muon* $P_T$




Reconstruction efficiency from the tag-probe method *vs* probe muon $P_T$

# *Muon $P_T$ scale and resolution*

- Determined from fit to *Z* lineshape
- Smear $P_T$ scale and resolution by formula:

$$(1/p_T)_s = 1/C_1 \times (1/p_T)_{MC} \times (1 + x \times C_2)$$

where $C_1$, $C_2$ are resp scale and resolution parameters

- Construct invariant mass distribution in MC as parameters are varied
- Extract *Z* mass peak position and width for each variation
- Determine parameter values which reproduce peak position and width in data:

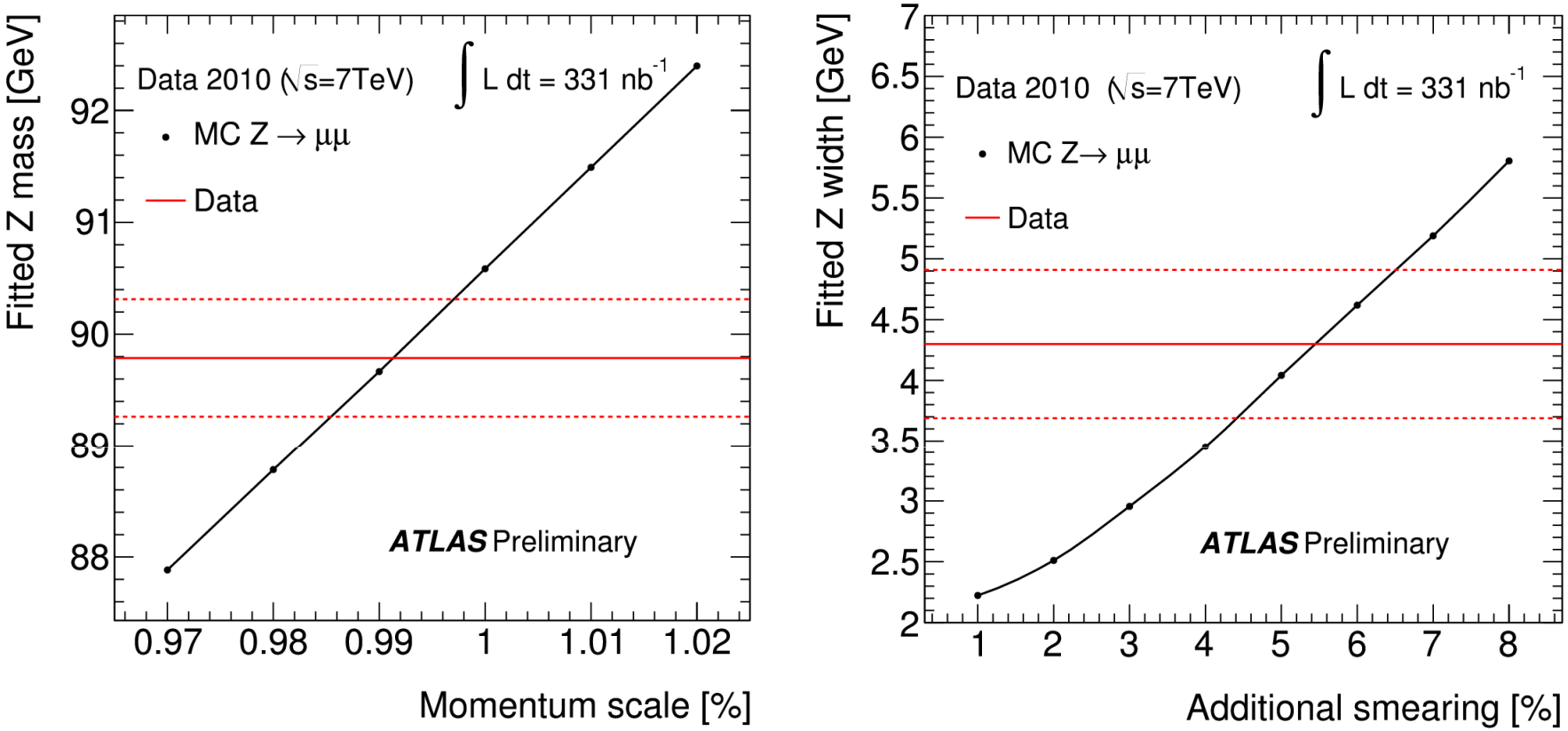
$C_1 = 0.991 \pm 0.005$, $C_2 = 0.055 \pm 0.012$

- Now find effect of varying scale and resolution by these amounts on *W*, *Z* acceptance:

Scale : $\delta C_W = 1.15\%$, $\delta C_Z = 0.45\%$

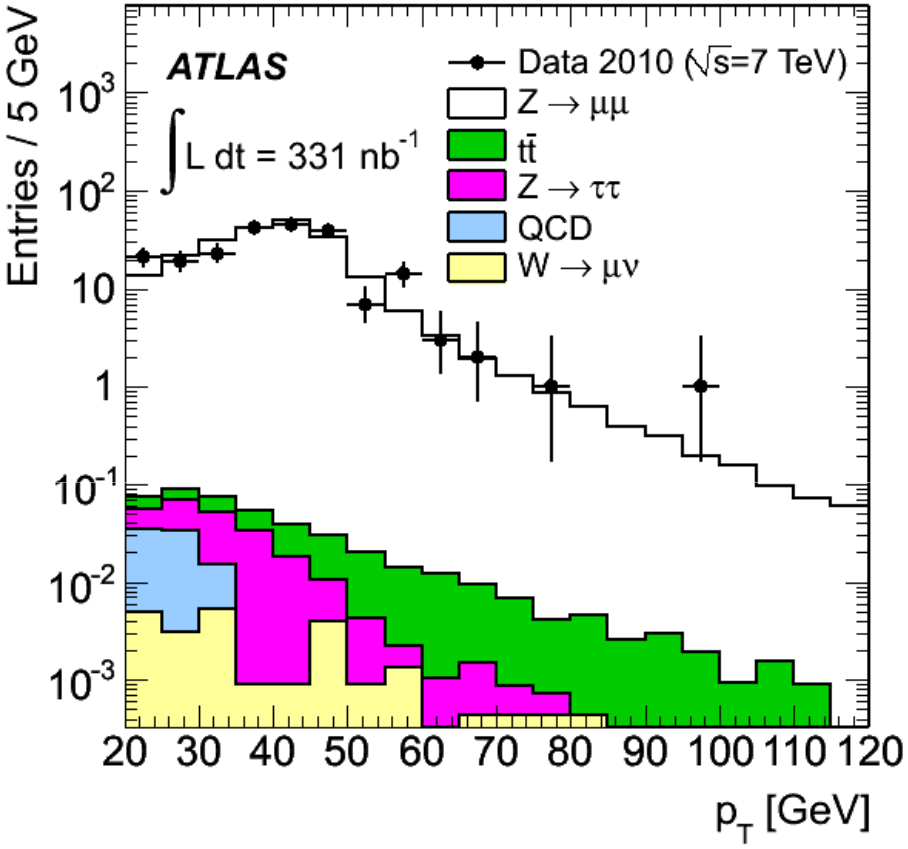
Resolution: $\delta C_W = 0.24\%$, $\delta C_Z = 0.48\%$

# *Determination of $P_T$ scale and resolution*

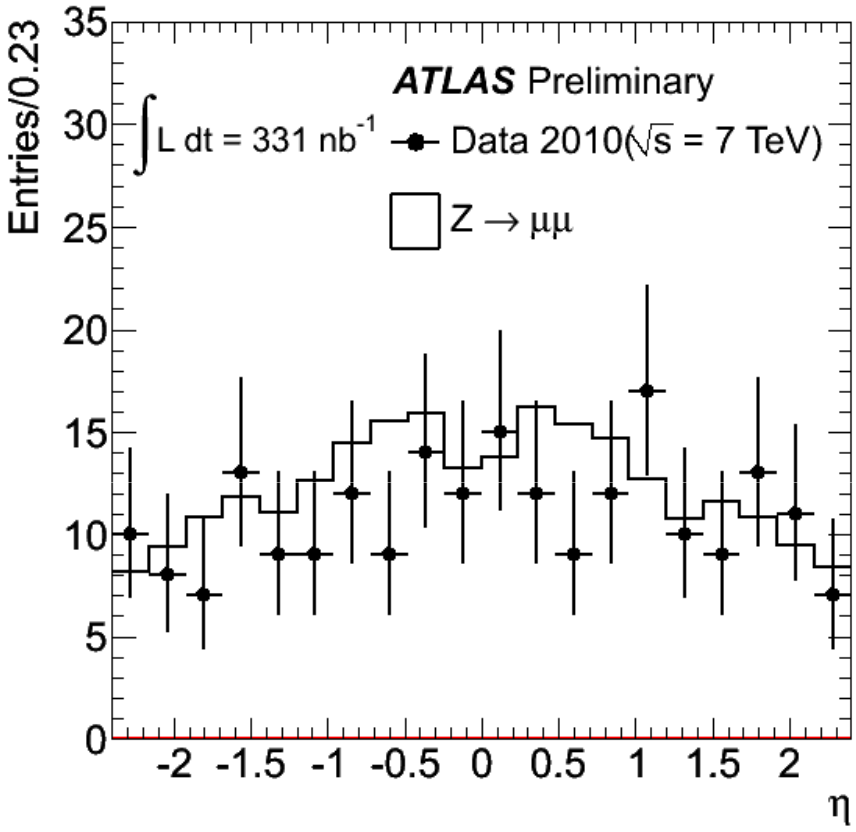



Red lines: peak position and width of *Z* mass spectrum from data, with uncertainty band. Black points: peak position and width of *Z* mass spectrum from Monte Carlo as scale and resolution parameters are varied.

# *Kinematics of Z decay muons*




$P_T$ spectrum of *Z* decay muons




η spectrum of *Z* decay muons

Note: Monte Carlo is normalized to the integrated luminosity