Precision Electroweak Measurements at LHC

Stilianos Kesisoglou
Institute of Nuclear Physics
National Center for Scientific Research "Demokritos", Greece

on behalf of the CMS Collaboration

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Why Precision Measurements?

- Electroweak (EWK) Standard Model (SM) is characterized by three independent input parameters:
  - Mass of the W (M_W)
  - Mass of the Z (M_Z)
  - Fine-structure constant (α_s)
- A cornerstone of the Electroweak Standard Model is the functional relation of those input parameters with Fermi coupling constant (G_F)
  - G_F is experimentally well measured (precision ~1 x 10^{-5})
  - G_F radiative corrections depend on Higgs mass.
- If Higgs boson is not found, alternative models of electroweak symmetry breaking will be tested.
- Precise measurement of the above parameters will be a key issue in this case, if we want to impose stringent constrains on the models.

Experimental Point of View

- Observables that are really Electroweak (EWK)
  - Mass (M_W) and width (Γ_W) of the W boson
  - Forward-Backward Asymmetries
  - $d\sigma/dM$ from Drell-Yan
  - Triple gauge couplings

- Observables that use EWK bosons to probe the structure of the hard interactions
  - Inclusive cross-section of W and Z
  - Charge and Polarization Asymmetries
  - Ratios of W/Z, W^+/W^-
  - Ratios of V+jets (V=W,Z)

- Solid foundations on all these SM processes are essential for future searches for New Physics.
  - Precision measurements play a key role.

Disclaimer

- Obviously we didn’t manage to perform all the measurements of the relevant quantities yet.
- I will focus on what we have measured up to now and explain the limitations of these measurements.
- More measurements will become available as the volume of the collected data increases.

Inclusive cross-sections of W and Z

- Motivation
  - Experimental
    - One of the first EWK processes studied at LHC
    - First attempt on reconstruction and identification for high p_T electrons/muons
    - LHC luminosity estimator
  - Theoretical
    - Precision test of the perturbative QCD predictions at NNLO (α_s)
    - Sensitive on the proton Parton Distribution Functions (PDF's)
- Physics Measurements
  - Inclusive W and Z production cross-section
  - Ratios of W+/W- and W/Z production cross sections
  - Cross-section in restricted Acceptance Region
- http://arxiv.org/abs/1012.2466

Signals and Backgrounds Overview

- Z Signal
  - Two high-p_T leptons (isolated) with M_{ll} in a window around M_Z
- Z Background
  - Negligible
- W Signal
  - High-p_T lepton (isolated) with significant missing E_T (MET)
- W Background
  - QCD multi-jets
  - γ + jets (for electrons)
  - Drell-Yan
  - $W \rightarrow \tau + \nu$, $Z \rightarrow \tau + \tau$
  - ttbar , di-bosons (WW, WZ, ZZ)

Ingredients of the Measurement

- High-transverse momentum leptons from W and Z decays have a very distinctive signature at hadron colliders

- Allows for a clear measurement of their production rates

$$\sigma \times BR = \frac{N^{pass} - N^{bkgr}}{A \times \varepsilon \times \int L dt}$$

  - N^{pass} : total number of events passing the selection
  - N^{bkgr} : total number of expected background events
  - A : acceptance (determined from MC - POWHEG)
  - ε : selection efficiency (for signal falling within the acceptance)
  - $\int L dt$: total integrated luminosity

Analysis Uncertainties

- In this analysis the uncertainties have been grouped as follows:
  - Luminosity uncertainty
    - Improves by applying better experimental techniques
    - Improves by using well understood and well measured final states
  - Statistical uncertainties
    - Refers only to the signal yield
    - Improves by collecting more data/refining the analysis
  - Systematic uncertainties
    - Experimental component
      - Improved by using data control samples (eliminating hypotheses based on MC)
      - For those having a statistical component improves by additional statistics
    - Theoretical component
      - Improved theoretical models/calculations implemented in MC generators.

Analysis Uncertainties

- Signal (background-subtracted yield of selected events)
- Statistical component (due to finite sample size)
- Systematic component (biases in the background subtraction and signal modeling)

$$\sigma \times BR = \frac{N^{pass} - N^{bkgr}}{A \times \varepsilon \times \int L dt}$$

- Luminosity (integrated)
- Experimental in origin

- Acceptance (fraction of events passing kinematic and geometrical cuts)
- Systematic
- Imperfect signal model (theory)
- Detector smearing

- Efficiency (selection efficiency)
- Statistical component (due to finite control sample size). Propagated as systematic uncertainty to the final result.
- Systematic component (biases in the background subtraction & signal modeling)

Luminosity

- Luminosity is been determined in CMS using:
  - Forward Hadronic Calorimeter signals (instantaneous)
  - Van der Meer scans (provides absolute normalization)
    - Limited by the beam current
    - For the moment 11% , expected 5% - 6%
- Above method has minimum reliance on simulations
- Another way to estimate luminosity:
  - Using a physics process with a well-known/measured cross-section
  - For example $e^+e^- \rightarrow e^+e^-$ at LEP.

W Signals

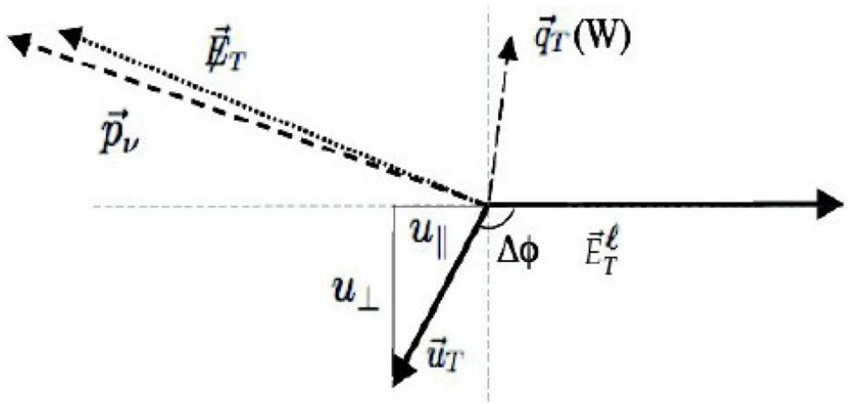
- W event selection
  - Apply identification, isolation and trigger criteria
    - Electrons: $N_{W+} = 7193 \pm 89$, $N_{W-} = 4728 \pm 73$
    - Muons: $N_{W+} = 7445 \pm 87$, $N_{W-} = 4812 \pm 67$
- W signal extraction
  - Fit to the MET (electron) or M_T (muons) distribution
  - Signal shape obtained from MC and corrected using data
    - Main unknown the W recoil. Corrections obtained from Z data.
    - Electrons 1.8 % , Muons 0.4%
  - Background shape (QCD) obtained from data
    - Anti-selection criteria applied to remove signal (templates for MET/M_T)
    - Modeled by a parametric function (Rayleigh form for MET)
    - Electrons 1.3% , Muons 2.0%
  - Simultaneous fit to the individual MET / M_T distributions in order to extract signal and background yields
- Other experimental systematic uncertainties
  - Lepton energy scale and resolution: Electrons 2.0%, Muons 0.3%

W signal modeling

- Some discrepancies observed between MC and real data, due to:
    - Lepton energy scale & resolution
    - Response/Resolution of hadronic recoil
- After the corrections, agreement with data is quite good
- Recoil (u) defined as MET after subtracting off the lepton(s)

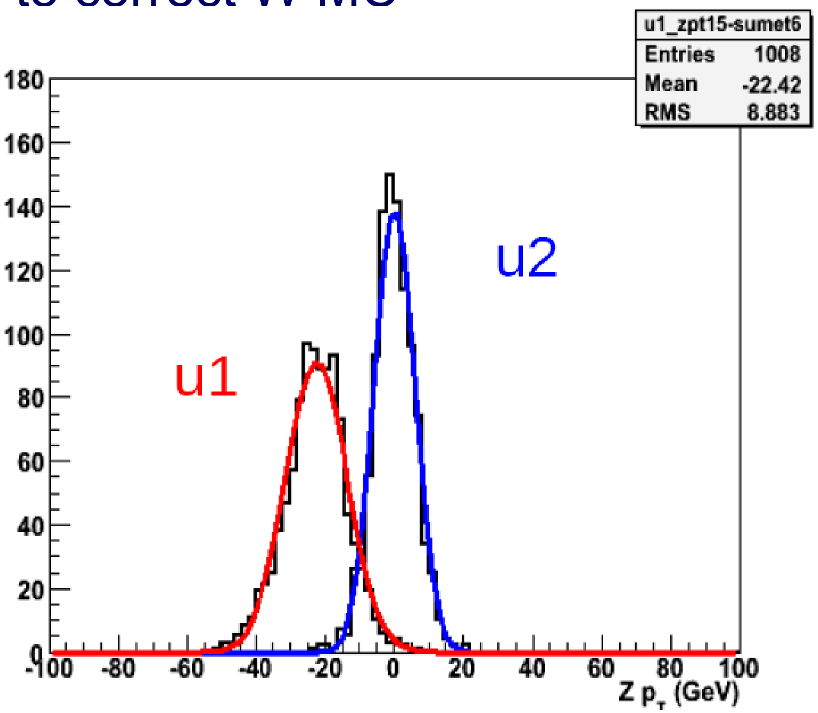
$$\vec{u} = \overrightarrow{\not{E}_T} - \overrightarrow{E_T^l}$$

- Recoil components u|| , u⊥ parallel/perpendicular to bozon qT axis.

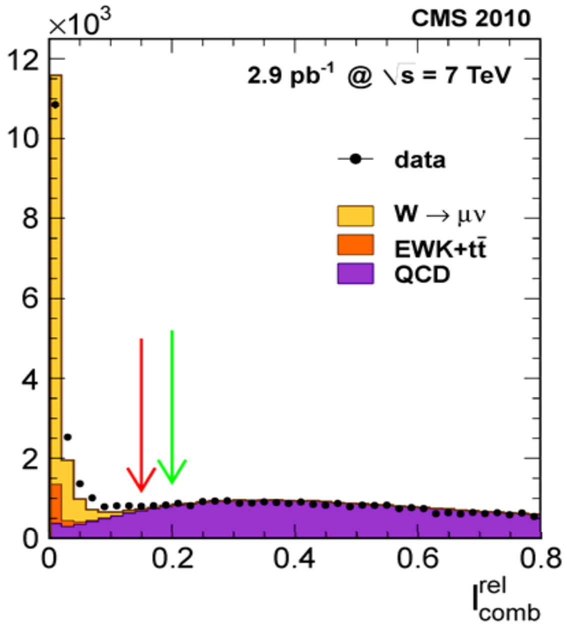


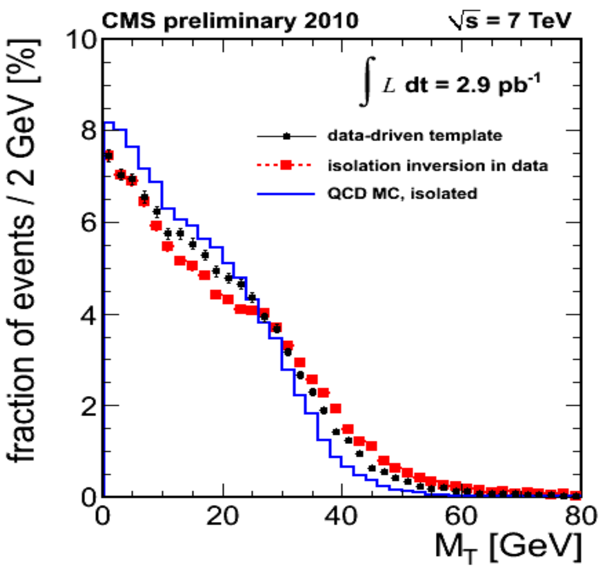
W signal modeling

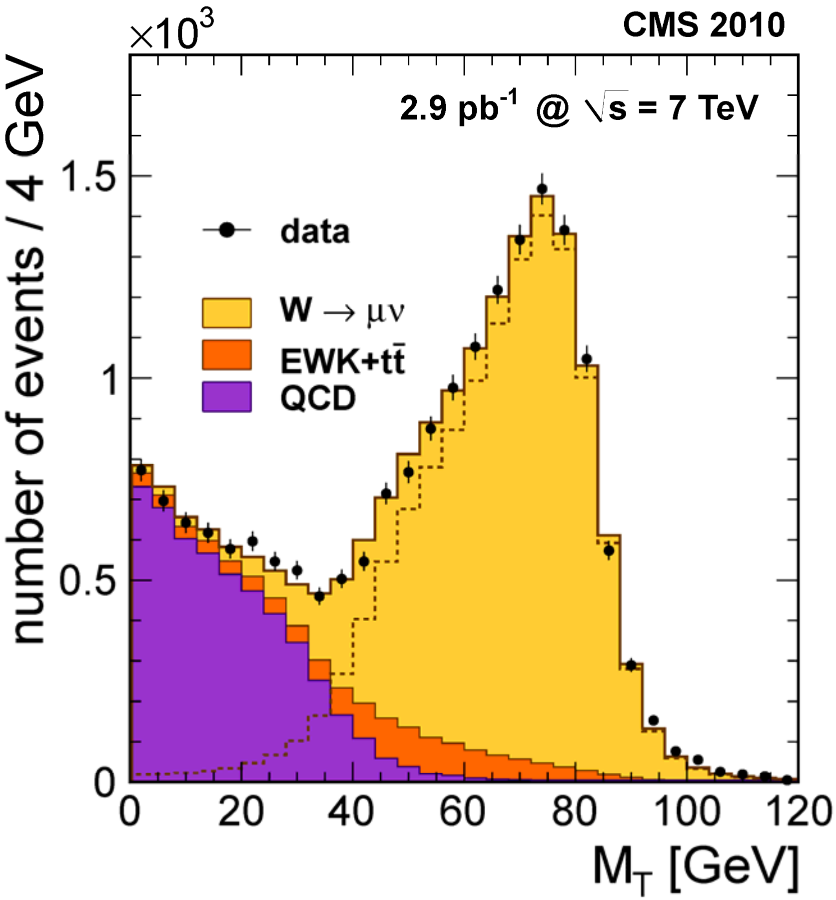
- Calculate u|| , u⊥ for Z data, Z MC and W MC.
- Model components with Gaussians in qT
- Determine Z data / MC scale factors to correct W MC response/resolution
- Recalculate MET for each MC event



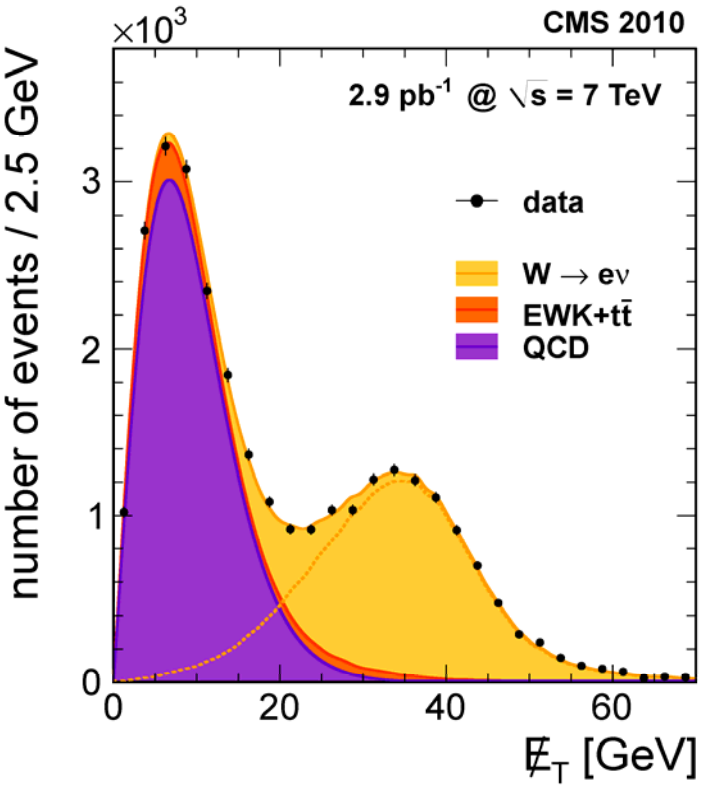
$W \rightarrow \mu + \nu$

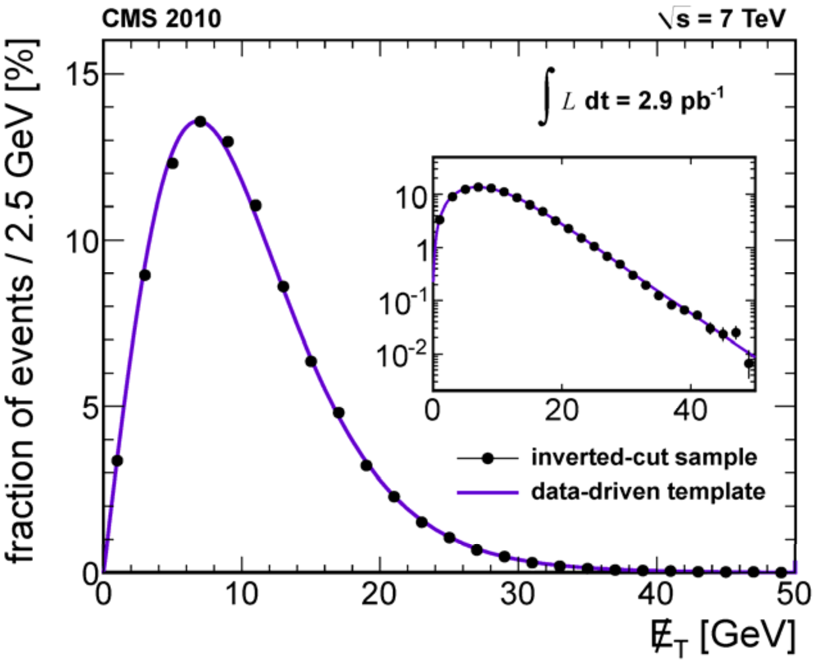






$W \rightarrow e + \nu$

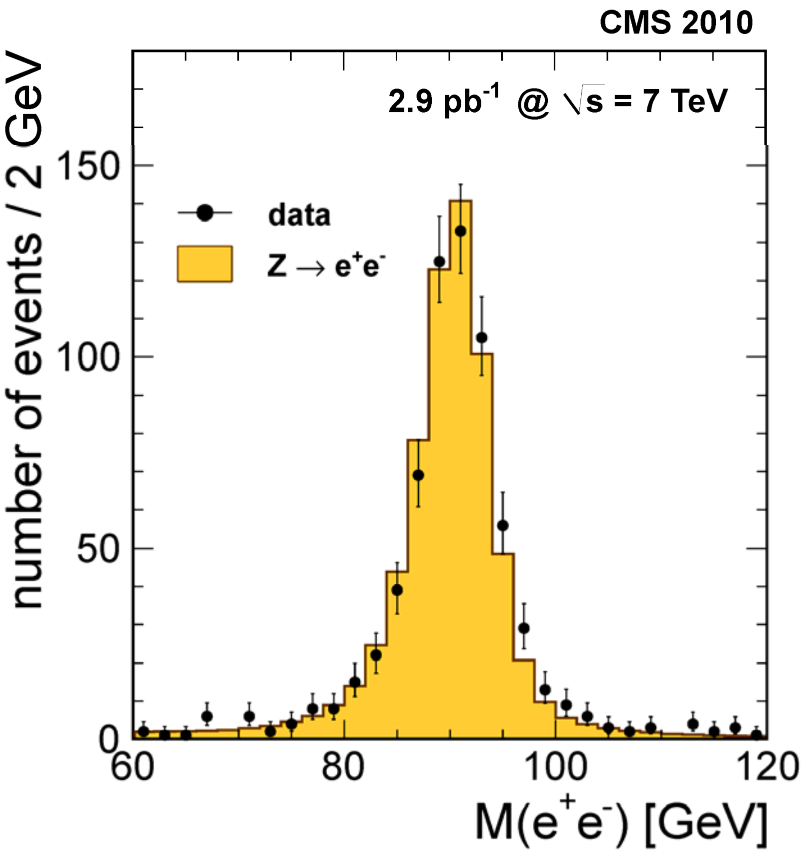




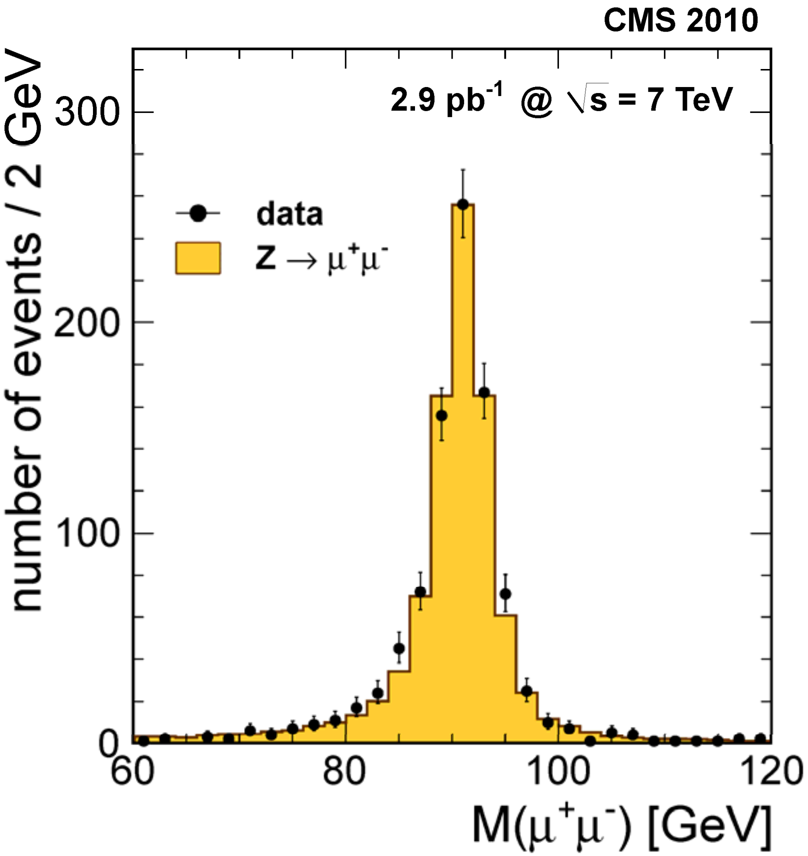
Z Signals

- Z event selection
  - Require a pair of indentified leptons
    - Restrict di-lepton invariant mass within a window around M_Z
    - Electrons: $N_Z = 677$
    - Muons: $N_Z = 913$
- Z signal extraction
  - Very small backgrounds
    - Electrons: 0.1%
    - Muons: 0.2%
  - Electron yields
    - Counting selected events
  - Muon yields
    - Extracted from simultaneous fit of signal yield and signal efficiency

Z Signals



CMS 2010
2.9 pb^{-1} @ $\sqrt{s}$ = 7 TeV
data
Z → e$^+$e$^-$
number of events / 2 GeV
0
50
100
150
60
80
100
120
M(e$^+$e$^-$) [GeV]



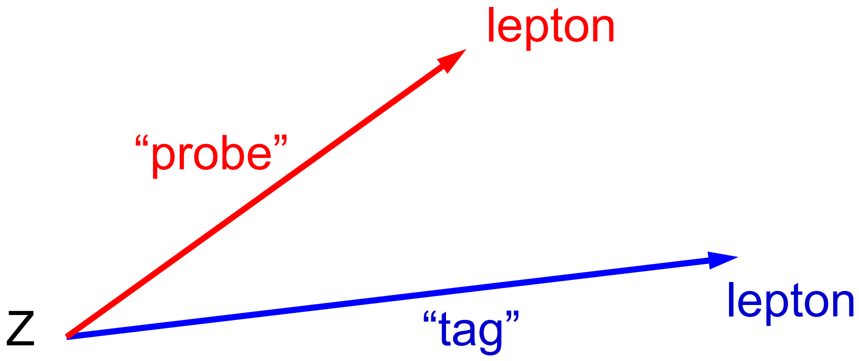
CMS 2010
2.9 pb^{-1} @ $\sqrt{s}$ = 7 TeV
data
Z → μ$^+$μ$^-$
number of events / 2 GeV
0
100
200
300
60
80
100
120
M(μ$^+$μ$^-$) [GeV]

Signal Efficiencies

- Signal efficiency determined from MC and corrected with data

- "Tag and Probe" Methodology
  - ➢ High-purity lepton sample taken from Z decays
  - ➢ One lepton ("tag") passes stringent lepton ID criteria
  - ➢ Second lepton ("probe") satisfies a sub-set of lepton ID criteria
    - ❖ Sub-set depends upon the efficiency under study
  - ➢ "Tag and Probe" invariant mass (M_{TP}) falls within a window around M_Z

- Systematic uncertainties
  - ➢ 3.9% for $W \rightarrow e\,\nu$
  - ➢ 1.5% for $W \rightarrow \mu\,\nu$
  - ➢ 5.9% for $Z \rightarrow e^+ e^-$
  - ➢ 0.5% for $W \rightarrow \mu^+ \mu^-$



Cross-section in the Restricted Acceptance

- Based on the above determined results the cross-section in the restricted acceptance can be determined:
  - ➢ Independent from theoretical models.
  - ➢ Can be used for model comparisons.

$$\sigma \times BR \times A = \frac{N^{pass} - N^{bkgr}}{\varepsilon \times \int Ldt}$$

Channel	$\sigma \times \mathcal{B}$ in acceptance A (nb)	A	
$W \to e\nu_e$	$6.04 \pm 0.06\,(\text{stat.}) \pm 0.31\,(\text{syst.}) \pm 0.66\,(\text{lumi.})$	0.601 ± 0.005	$p_T > 20$ GeV, $\lvert\eta\rvert < 2.5$
$W^+ \to e^+\nu_e$	$3.69 \pm 0.05\,(\text{stat.}) \pm 0.22\,(\text{syst.}) \pm 0.41\,(\text{lumi.})$	0.622 ± 0.006	
$W^- \to e^-\overline{\nu}_e$	$2.36 \pm 0.04\,(\text{stat.}) \pm 0.14\,(\text{syst.}) \pm 0.26\,(\text{lumi.})$	0.571 ± 0.009	
$Z \to e^+e^-$	$0.460 \pm 0.018\,(\text{stat.}) \pm 0.028\,(\text{syst.}) \pm 0.051\,(\text{lumi.})$	0.479 ± 0.005	
$W \to \mu\nu_\mu$	$5.21 \pm 0.05\,(\text{stat.}) \pm 0.15\,(\text{syst.}) \pm 0.57\,(\text{lumi.})$	0.525 ± 0.006	$p_T > 20$ GeV, $\lvert\eta\rvert < 2.1$
$W^+ \to \mu^+\nu_\mu$	$3.16 \pm 0.04\,(\text{stat.}) \pm 0.10\,(\text{syst.}) \pm 0.35\,(\text{lumi.})$	0.541 ± 0.006	
$W^- \to \mu^-\overline{\nu}_\mu$	$2.05 \pm 0.03\,(\text{stat.}) \pm 0.06\,(\text{syst.}) \pm 0.22\,(\text{lumi.})$	0.502 ± 0.006	
$Z \to \mu^+\mu^-$	$0.368 \pm 0.012\,(\text{stat.}) \pm 0.007\,(\text{syst.}) \pm 0.040\,(\text{lumi.})$	0.398 ± 0.005	

Monte Carlo and Acceptances

- Theoretical uncertainties in the cross section affect the estimation of the acceptance.

- Monte Carlo estimates are based on simulations using:
  - POWHEG generator with NLO and CTEQ6.6 PDF's
    - Used as baseline for quoting uncertainties
    - Has a good agreement with ResBos (excellent results at Tevatron)

- PDF systematics were calculated for both electrons and muons
  - On the acceptance (for W, W^+, W^-, Z,)
  - On the acceptance corrections (for W/Z and , W^+/ W^-)

- PDF set's used: CTEQ6.6 , MSTW08NLO , NNPDF2.0

Monte Carlo and Acceptances

- For each set the 68% CL positive and negative variations was obtained
- Assigned systematic equals to half of the maximum difference between positive and negative variations for any combination of PDF sets
- Observed variations in the acceptance are less than 1.2%
- Remaining theoretical uncertainties amount to ~ 1.5 %
  - Initial State Radiation
  - Final-State QED radiation
  - Missing Electroweak effects
  - Renormalization and Factorization scale assumptions

Monte Carlo and Acceptances

- Higher Order systematics (not accounted in the baseline MC)
  - Soft non-perturbative effects
  - Hard high order effects
  - Initial State Radiation (ISR)
    - Baseline MC / ResBos at NNLO comparison

- Systematics were calculated:
  - On the acceptance (for W, W^+, W^-, Z,)
    - Of the order of 1.3% for W, 1.4% for Z
  - On the acceptance corrections (for W/Z and , W^+/ W^-)
    - Of the order of 1.23% for W^+/ W^-, 1.19% for W/Z

Results / Cross sections

FEWZ + MSTW08

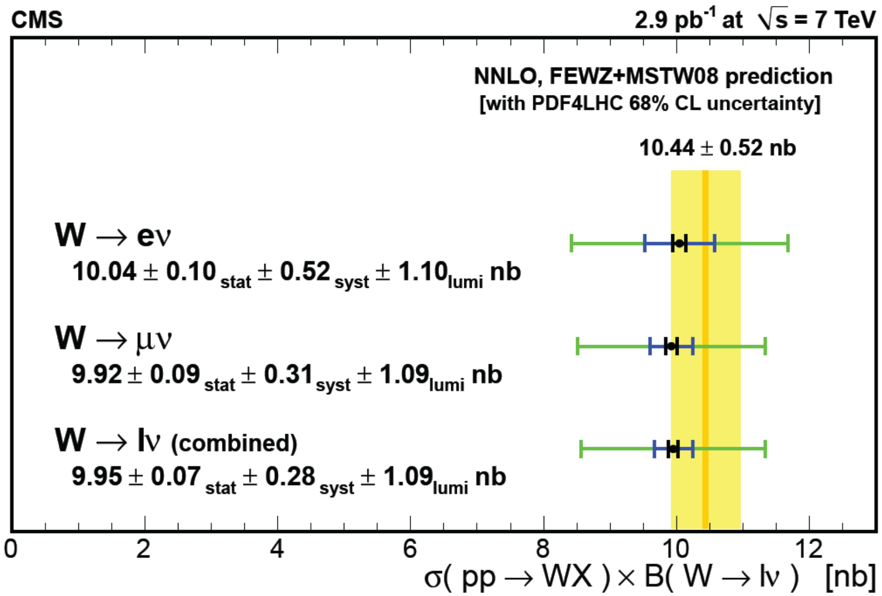
Channel		$\sigma \times \mathcal{B}$ (nb)	NNLO (nb)
W	$e\nu$	10.04 ± 0.10 (stat.) ± 0.52 (syst.) ± 1.10 (lumi.)	10.44 ± 0.52
	$\mu\nu$	9.92 ± 0.09 (stat.) ± 0.31 (syst.) ± 1.09 (lumi.)	
	$\ell\nu$	9.95 ± 0.07 (stat.) ± 0.28 (syst.) ± 1.09 (lumi.)	
W^+	$e^+\nu$	5.93 ± 0.07 (stat.) ± 0.36 (syst.) ± 0.65 (lumi.)	6.15 ± 0.29
	$\mu^+\nu$	5.84 ± 0.07 (stat.) ± 0.18 (syst.) ± 0.64 (lumi.)	
	$\ell^+\nu$	5.86 ± 0.06 (stat.) ± 0.17 (syst.) ± 0.64 (lumi.)	
W^-	$e^-\bar{\nu}$	4.14 ± 0.06 (stat.) ± 0.25 (syst.) ± 0.45 (lumi.)	4.29 ± 0.23
	$\mu^-\bar{\nu}$	4.08 ± 0.06 (stat.) ± 0.15 (syst.) ± 0.45 (lumi.)	
	$\ell^-\bar{\nu}$	4.09 ± 0.05 (stat.) ± 0.14 (syst.) ± 0.45 (lumi.)	
Z	e^+e^-	0.960 ± 0.037 (stat.) ± 0.059 (syst.) ± 0.106 (lumi.)	0.972 ± 0.042
	$\mu^+\mu^-$	0.924 ± 0.031 (stat.) ± 0.022 (syst.) ± 0.102 (lumi.)	
	$\ell^+\ell^-$	0.931 ± 0.026 (stat.) ± 0.023 (syst.) ± 0.102 (lumi.)	

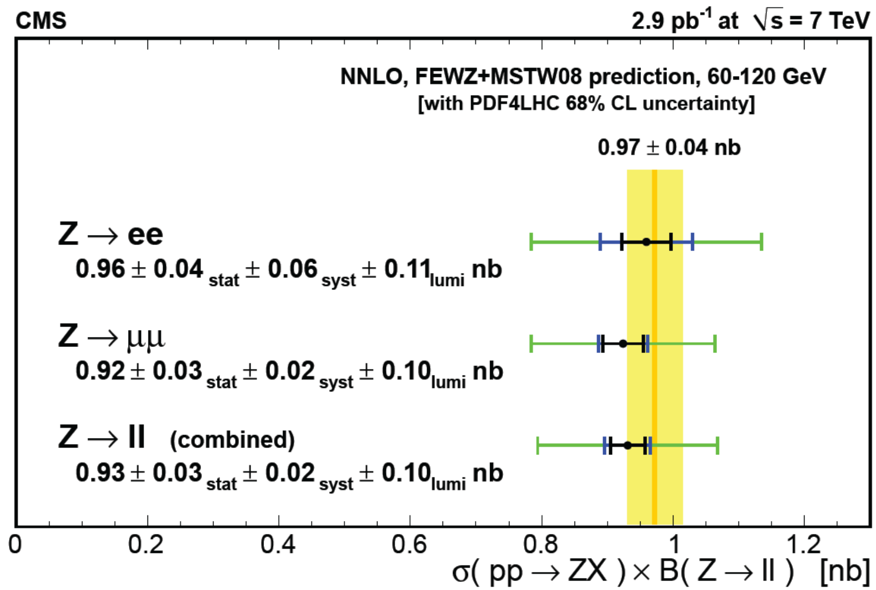
Results / Ratios

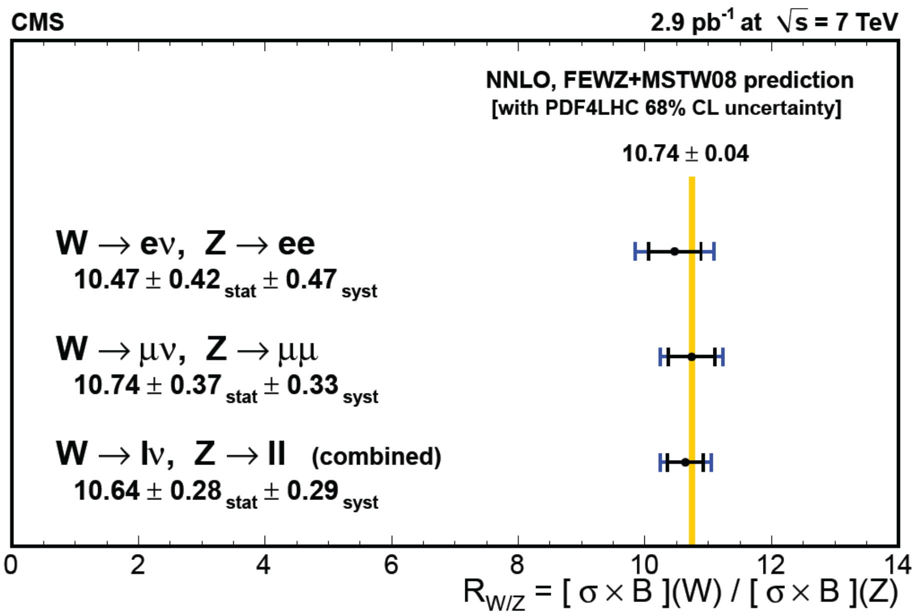
FEWZ + MSTW08

Quantity		Ratio	NNLO
$R_{W/Z}$	e	$10.47 \pm 0.42\,(\text{stat.}) \pm 0.47\,(\text{syst.})$	10.74 ± 0.04
	μ	$10.74 \pm 0.37\,(\text{stat.}) \pm 0.33\,(\text{syst.})$	
	ℓ	$10.64 \pm 0.28\,(\text{stat.}) \pm 0.29\,(\text{syst.})$	
$R_{+/-}$	e	$1.434 \pm 0.028\,(\text{stat.}) \pm 0.082\,(\text{syst.})$	1.435 ± 0.044
	μ	$1.433 \pm 0.026\,(\text{stat.}) \pm 0.054\,(\text{syst.})$	
	ℓ	$1.433 \pm 0.020\,(\text{stat.}) \pm 0.050\,(\text{syst.})$	

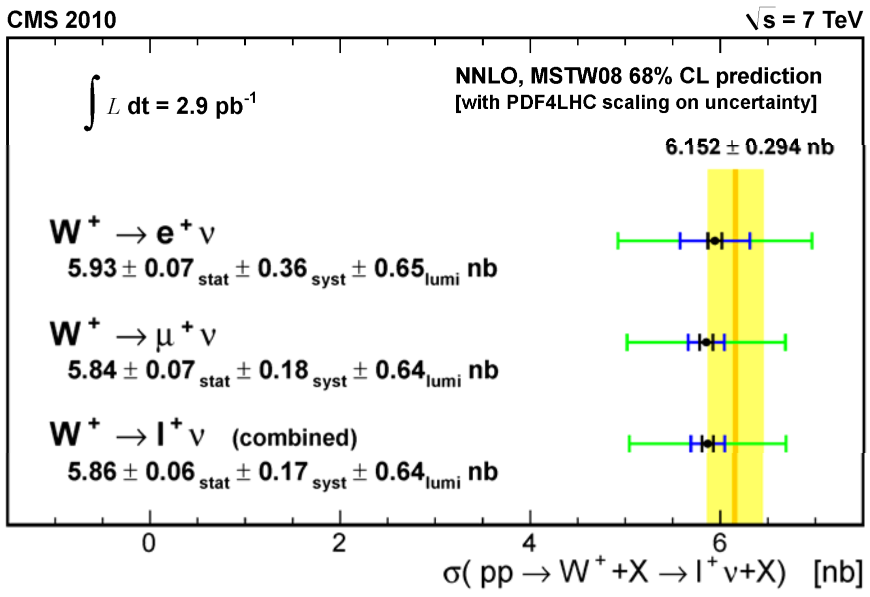
W , Z and ratio W/Z

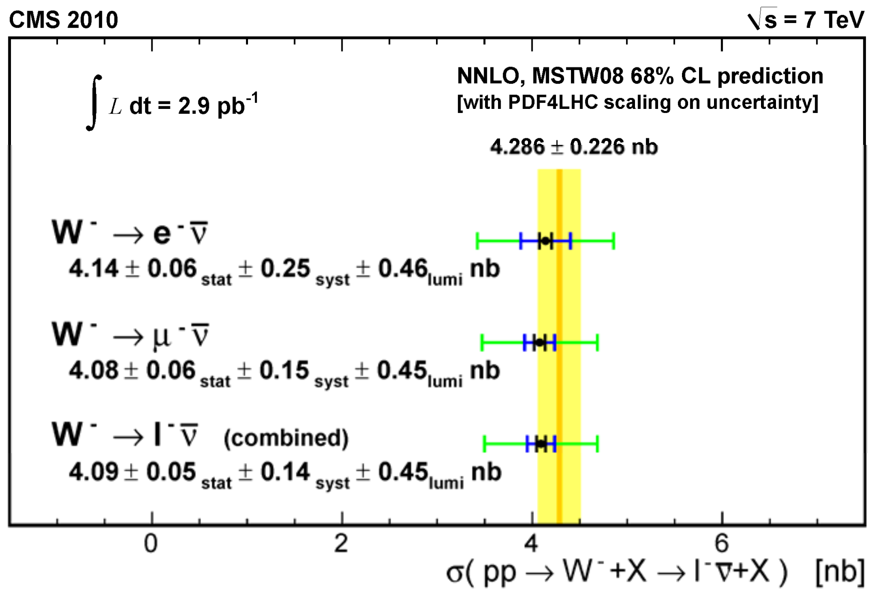


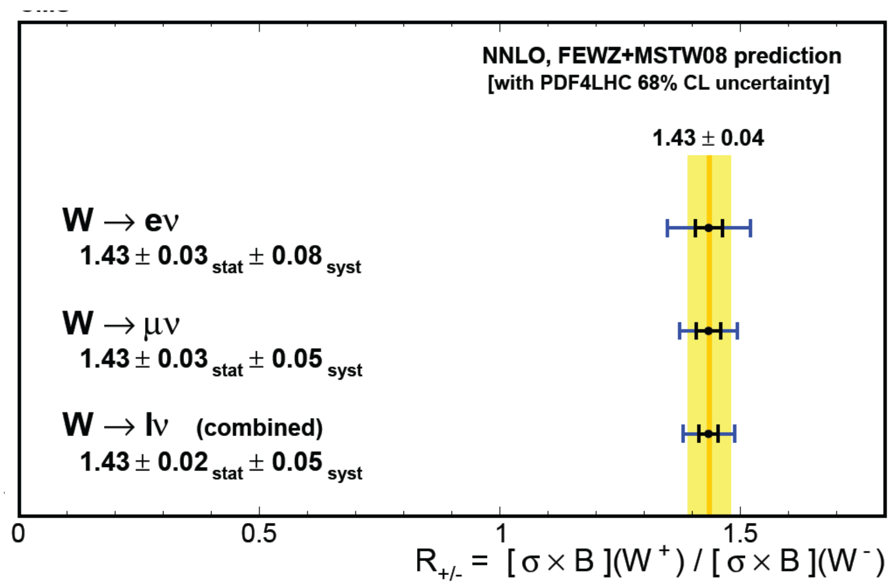




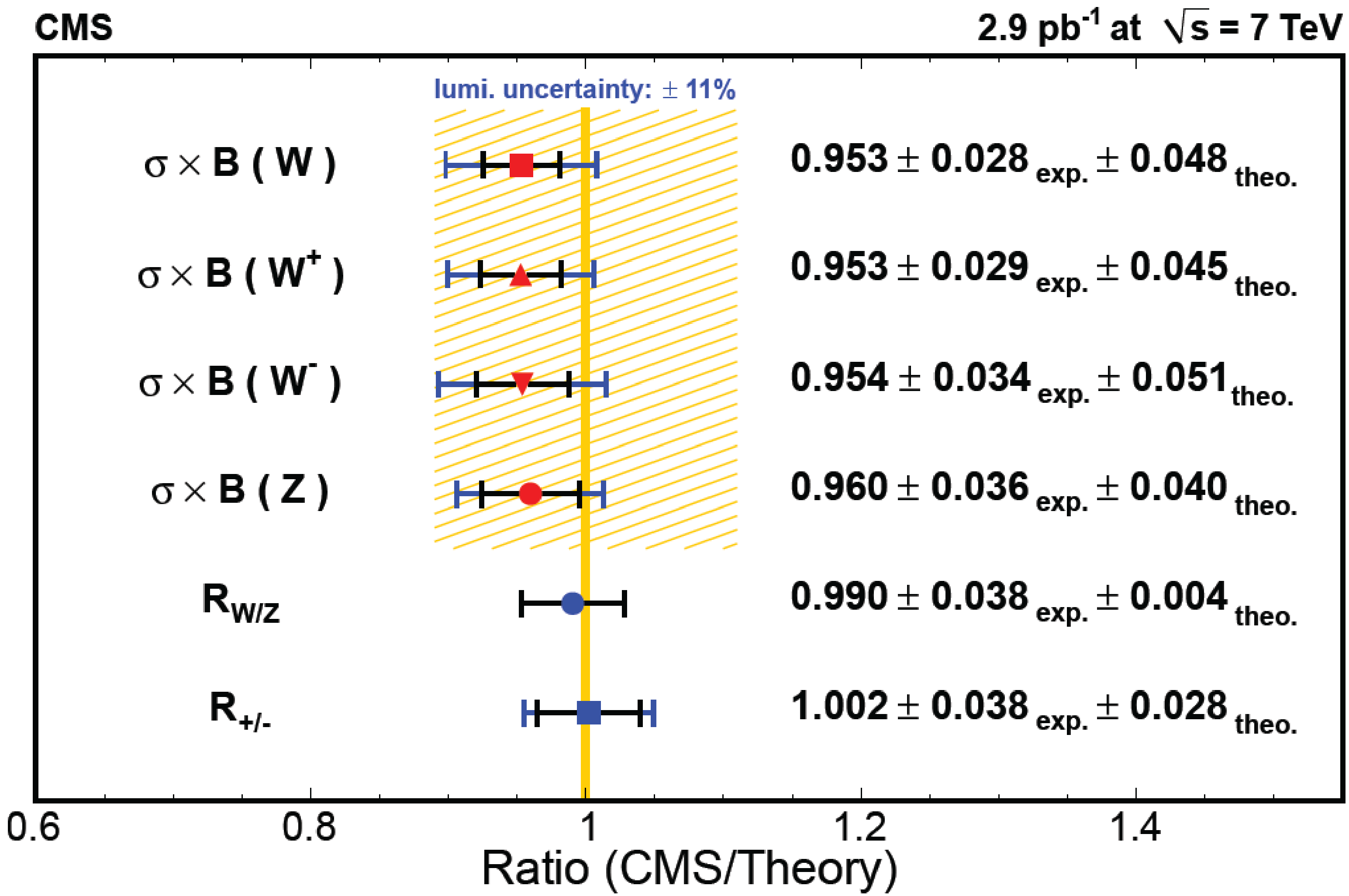
W^+ , W^- and ratio W^+/W^-



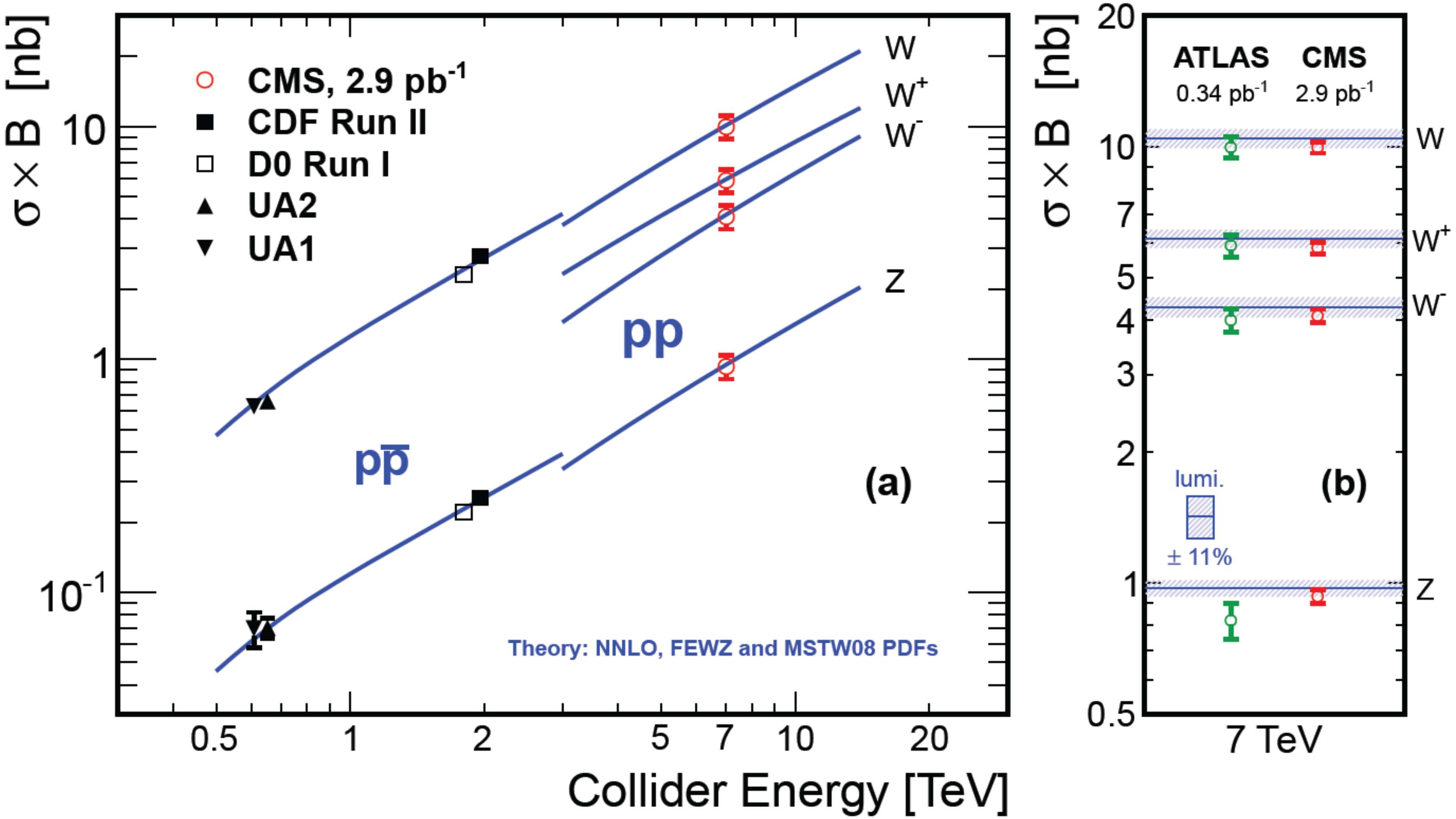




Ratio (Experiment / Theory)



Inclusive cross sections



Conclusions

- Measurements of inclusive W and Z boson production cross sections in pp collisions at $\sqrt{s} = 7$ TeV using $(2.88 \pm 0.32)\ pb^{-1}$ of data have been performed.

- Theoretical predictions for cross sections and ratios agree with our measurements.

- Aside from the luminosity uncertainty, canceled in the ratios, the systematic uncertainties are comparable to the statistical ones in our measurement.
  - Part of the systematic uncertainties will decrease with larger data samples due to their statistical nature.

- Experimental uncertainties are smaller than those on the theoretical predictions.