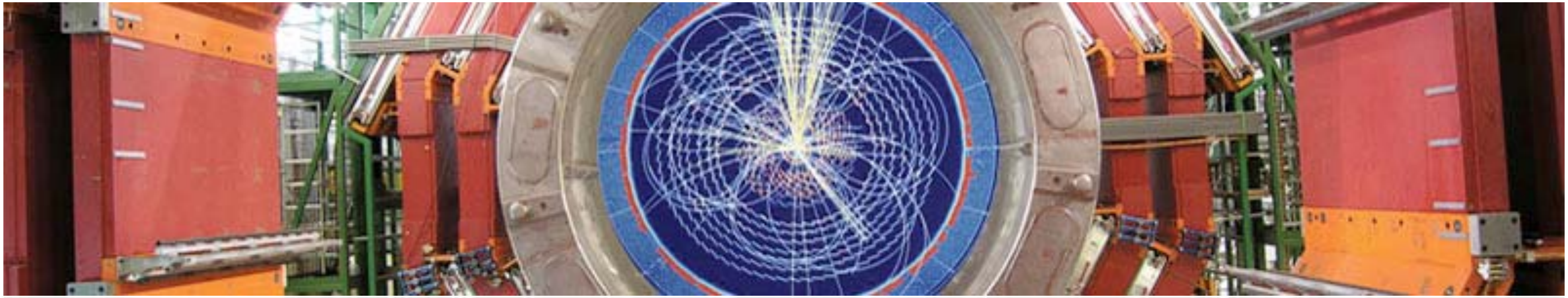


Electroweak Physics at CMS

David Futyan

On behalf of the CMS collaboration

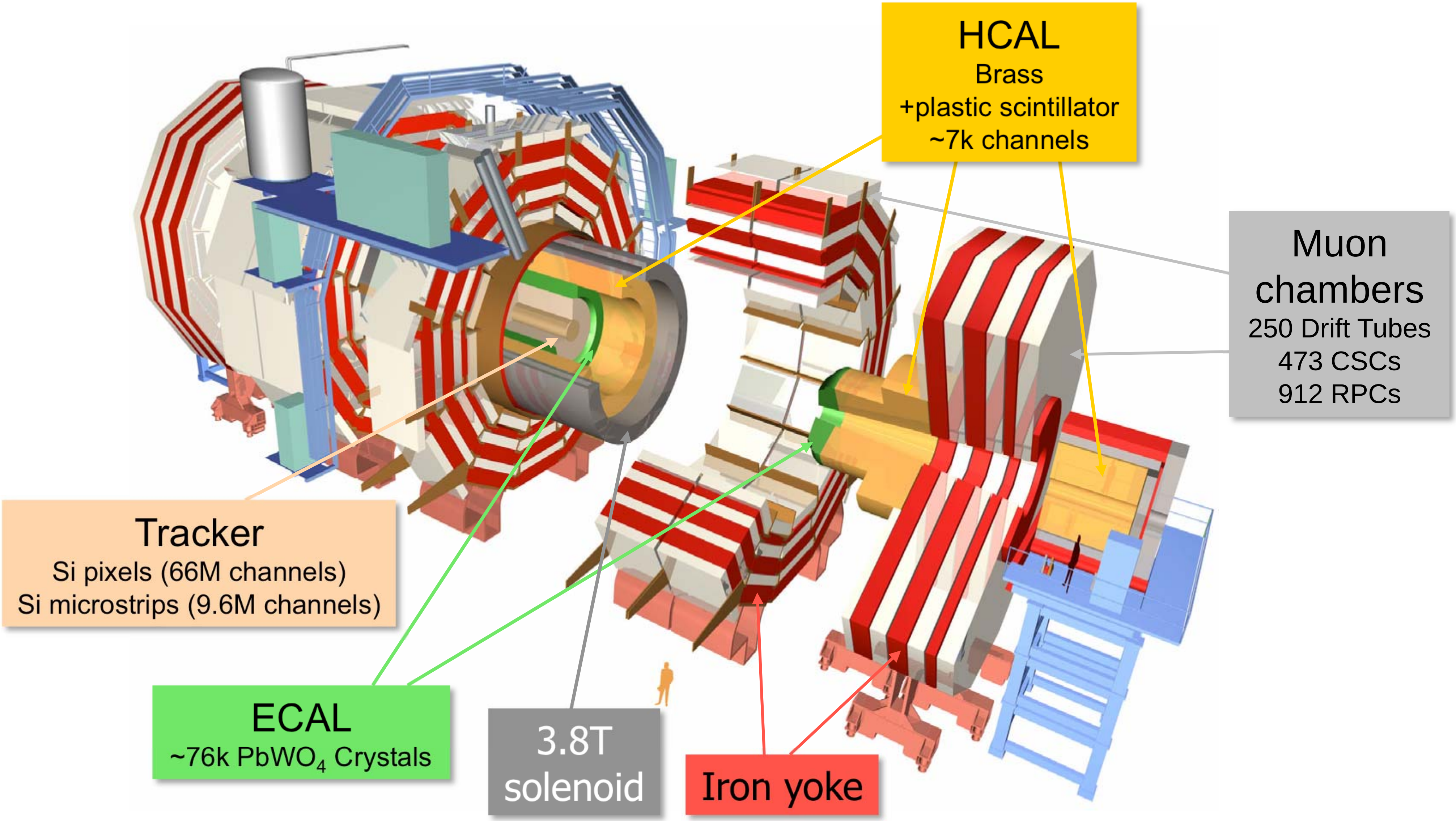
Imperial College London

ASPEN 2011

Outline

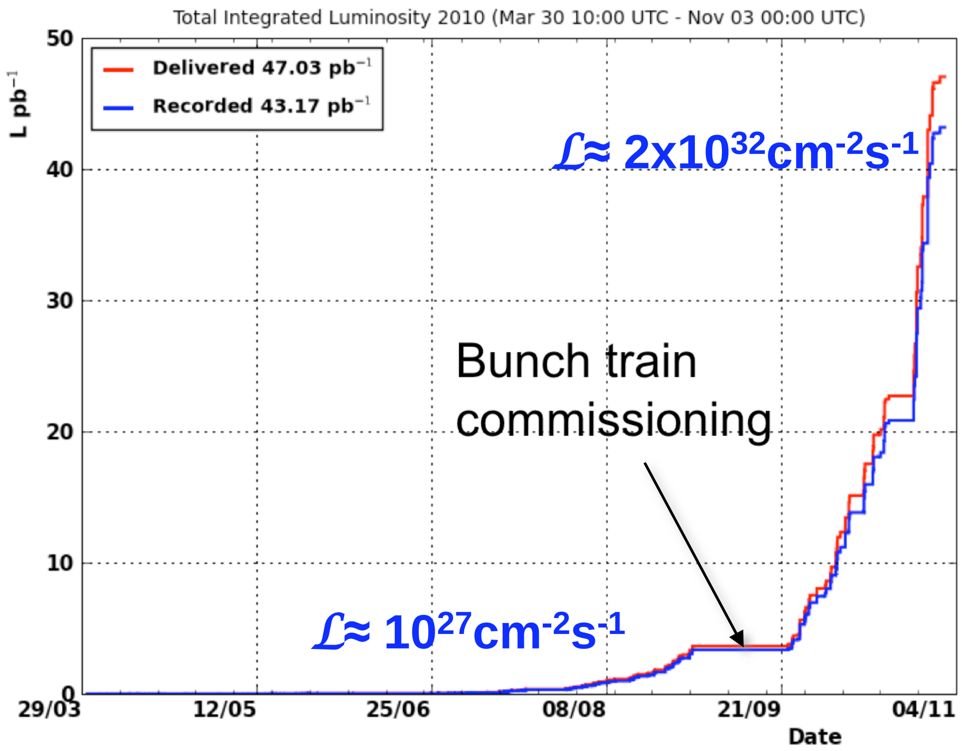
- Introduction: CMS in 2010
- W and Z boson signal extraction and cross-section measurement with $2.9 pb^{-1}$
  - Preview of results for $36 pb^{-1}$
- WW cross-section measurement ($36 pb^{-1}$)
- Preview of analyses in progress
- Summary and outlook

The CMS Detector



CMS Operation in 2010

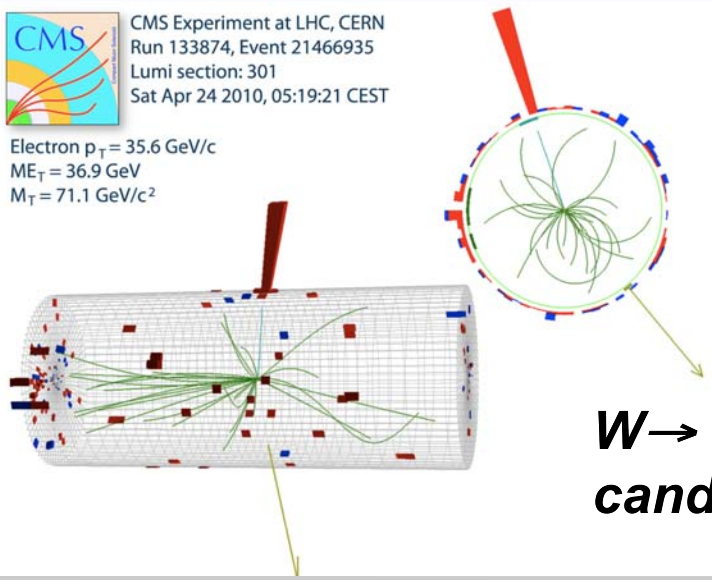
- $47 pb^{-1}$ delivered by LHC and $43 pb^{-1}$ of data collected by CMS
  - Overall data taking efficiency ~92%.
  - ~84% of recorded data good quality for physics analysis → ~$36 pb^{-1}$
- Excellent performance in coping with more than 5 order of magnitude increase in instantaneous luminosity



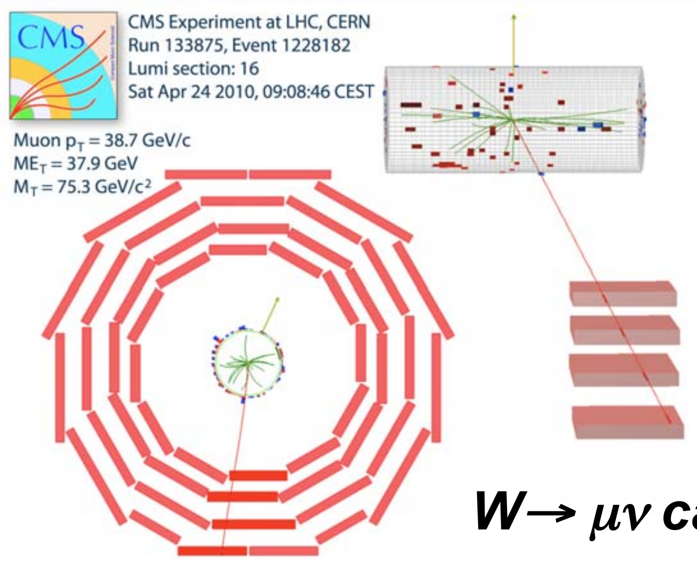
Motivations for Electroweak Physics at CMS

- Although Electroweak processes are well understood from earlier experiments, precise measurements at LHC are important for many reasons:
- Detector and physics object commissioning:
  - W, Z: predominant source of isolated high p_T leptons
    - Benchmark for lepton reconstruction and identification (understand efficiency, resolution)
- Test of perturbative QCD, constrain proton PDFs
- Understand backgrounds for many new physics searches
- Deviations from standard model predictions can be a sign of new physics, e.g. anomalous TGCs in WW production
- Estimators of LHC Luminosity

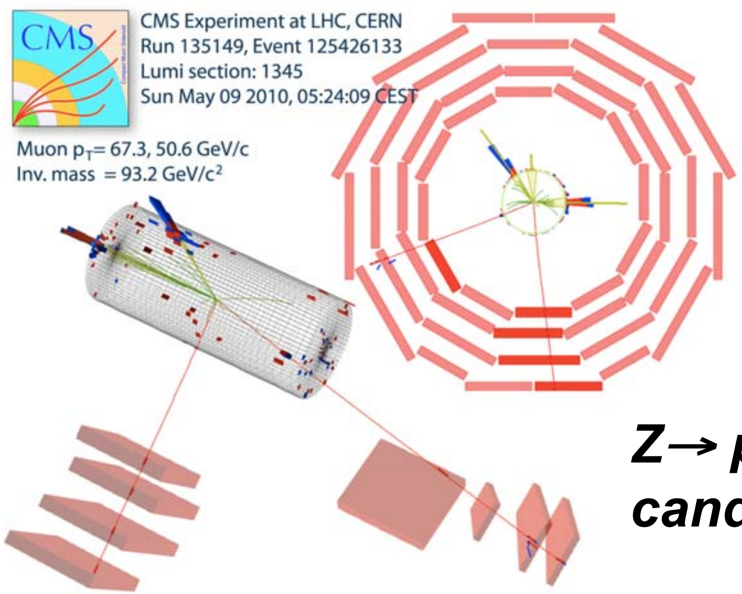
W and Z candidates: Event Displays



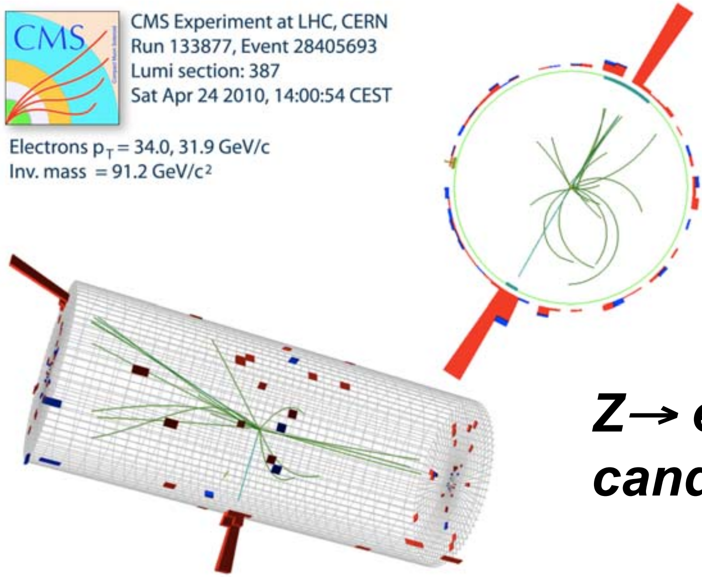
W→ eν candidate



W→ μν candidate



Z→ μμ candidate



Z→ ee candidate

W and Z: Signal and Background characteristics

- $W \rightarrow l\nu$ Signal:
  - Single high p_T isolated lepton with significant missing transverse energy
- $Z \rightarrow ll$ Signal:
  - Two high p_T isolated leptons with di-lepton invariant mass close to M_Z

- $W \rightarrow l\nu$ Backgrounds:
  - QCD di-jets and γ+jets (for electrons)
    - Fake leptons, leptons from heavy flavour decays, photon conversions (for electrons)
  - Drell-Yan including $Z \rightarrow ll$
  - $W \rightarrow \tau\nu$
  - Small contributions from $Z \rightarrow \tau\tau$, di-bosons (WW, WZ, ZZ) and ttbar
- $Z \rightarrow ll$ Backgrounds:
  - Very low: Small contributions from $Z \rightarrow \tau\tau$, di-bosons (WW, WZ, ZZ) and ttbar

W and Z: Event Selection

- One (W) or two (Z) isolated electrons or muons with p_T>20 GeV, passing ID and quality requirements
  - Explicit rejection of converted photons (for electron case)
  - Explicit rejection of cosmic muons (for muon case)
- No cut on missing E_T
- For Z require $60<M_{ll}<120$ GeV/c^2

W and Z Cross-section Measurement

Signal yield extracted from fits to distributions of:

- missing transverse energy (MET) or transverse mass (M_T) for W
- di-lepton invariant mass for Z

Integrated luminosity:

- largest source of systematic uncertainty in the measurement (11%)

$$\sigma \times BR = \frac{N_{Signal}}{A \times \varepsilon \times \int L dt}$$

Fiducial and kinematic acceptance:

- determined from simulation (POWHEG NLO with CTEQ6.6 PDFs)

Selection efficiency for signal falling within the acceptance :

- obtained using simulation
- corrected using efficiencies measured in data and MC with tag and probe:

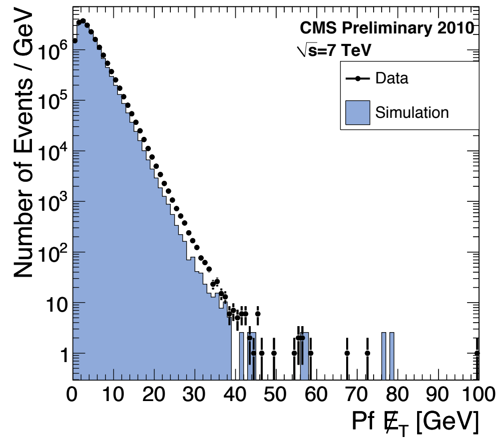
$$\varepsilon = \varepsilon_{MC} \times (\varepsilon^{TP}_{DATA} / \varepsilon^{TP}_{MC})$$

W Signal Extraction

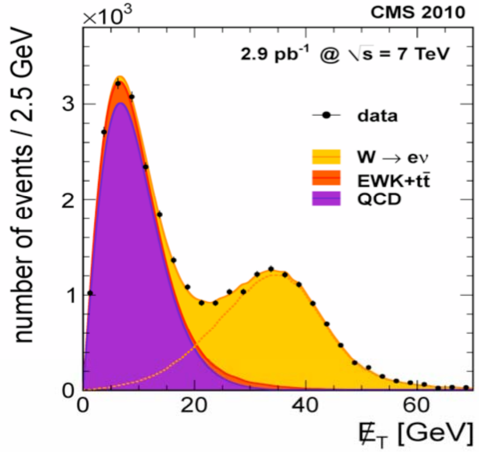
- Maximum likelihood fit to missing transverse energy (MET) distribution (electrons) or transverse mass (M_T) distribution (muons)

$$M_T = \sqrt{2P_T(\mu)MET(1-\cos\theta_{\mu-MET})}$$

- Missing transverse energy calculated using the Particle Flow algorithm
  - $-\Sigma p_T$ for all particles reconstructed in the event
  - Well reproduced by simulation



- Signal shape from simulation with corrections from data to account for electron energy scale and resolution and response/resolution of hadronic recoil
  - event-by-event correction in bins of W p_T, determined from hadronic recoil distributions of Z events in data
- Electroweak background shape and normalization w.r.t. signal fixed from simulation/theory

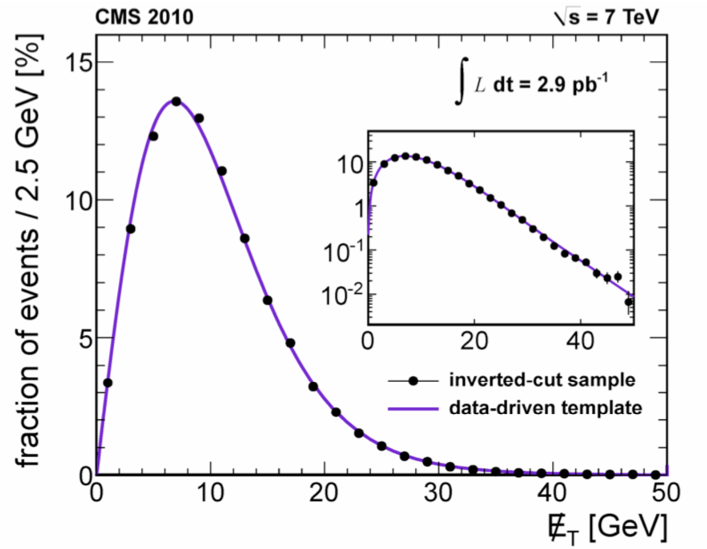


QCD template

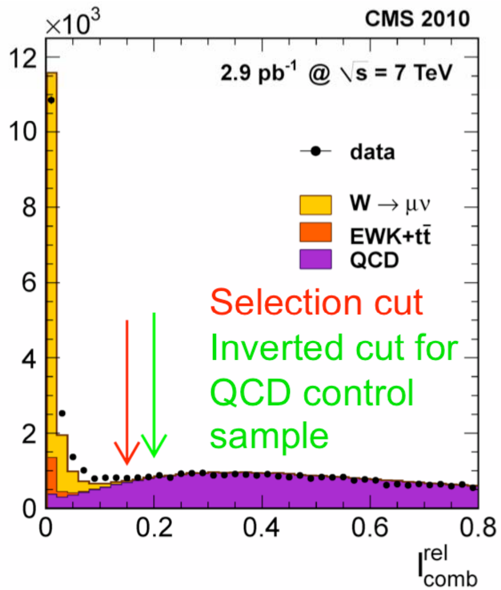
- Electrons: MET shape parameterized using a modified Rayleigh function

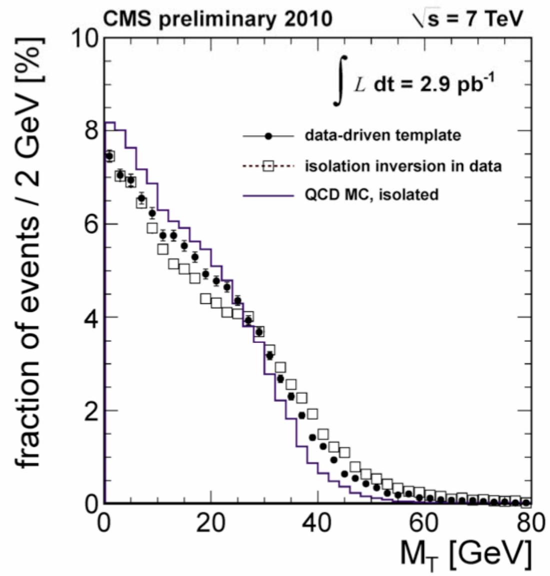
$$f(\not{E}_T) = \not{E}_T \times \exp\left(-\frac{\not{E}_T^2}{2(\sigma_0 + \sigma_1 \not{E}_T)^2}\right)$$

- Shape parameters σ_0, σ_1 and normalization allowed to float in the fit



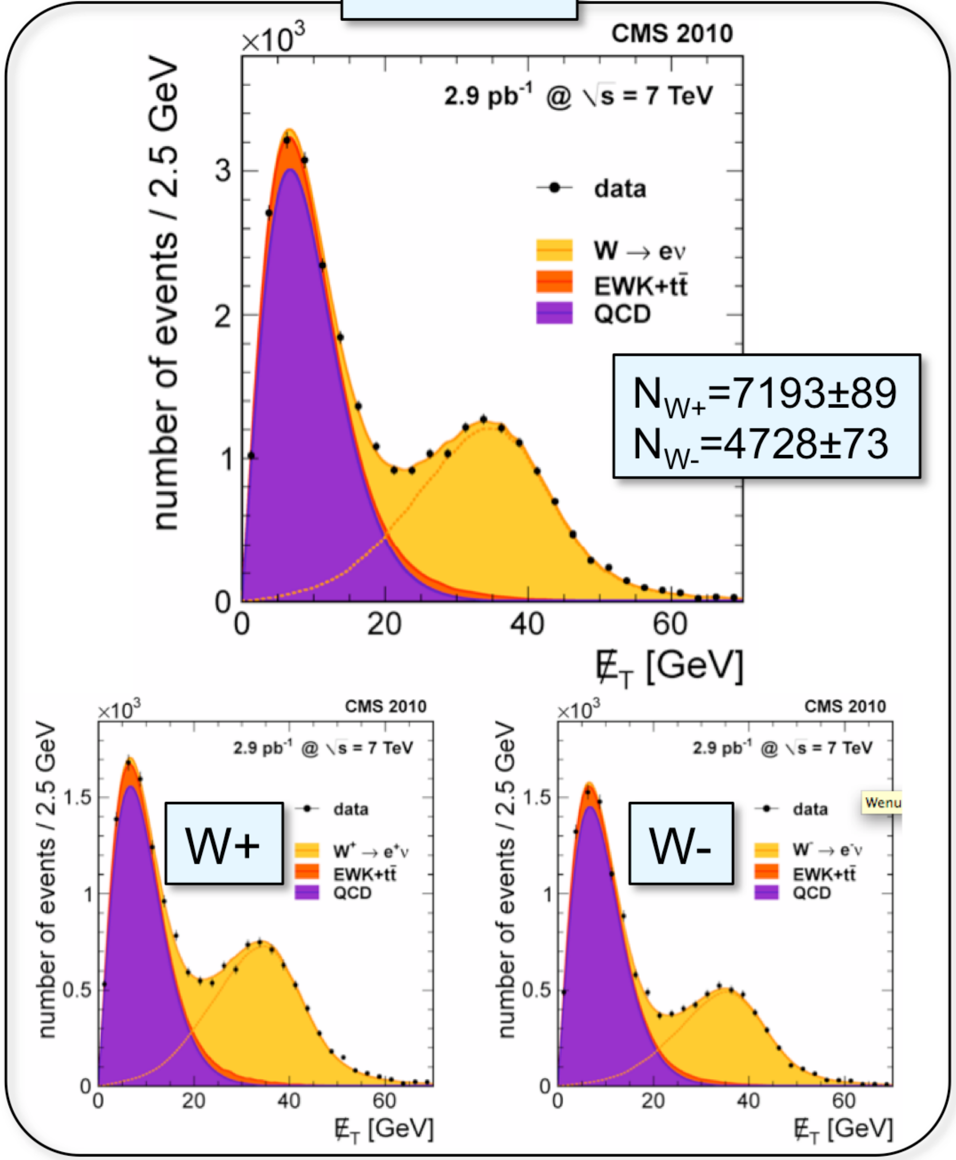
- Muons: M_T shape constructed from control sample obtained by inverting the isolation cut
- Corrections applied to account for shape bias due to a correlation between isolation and M_T





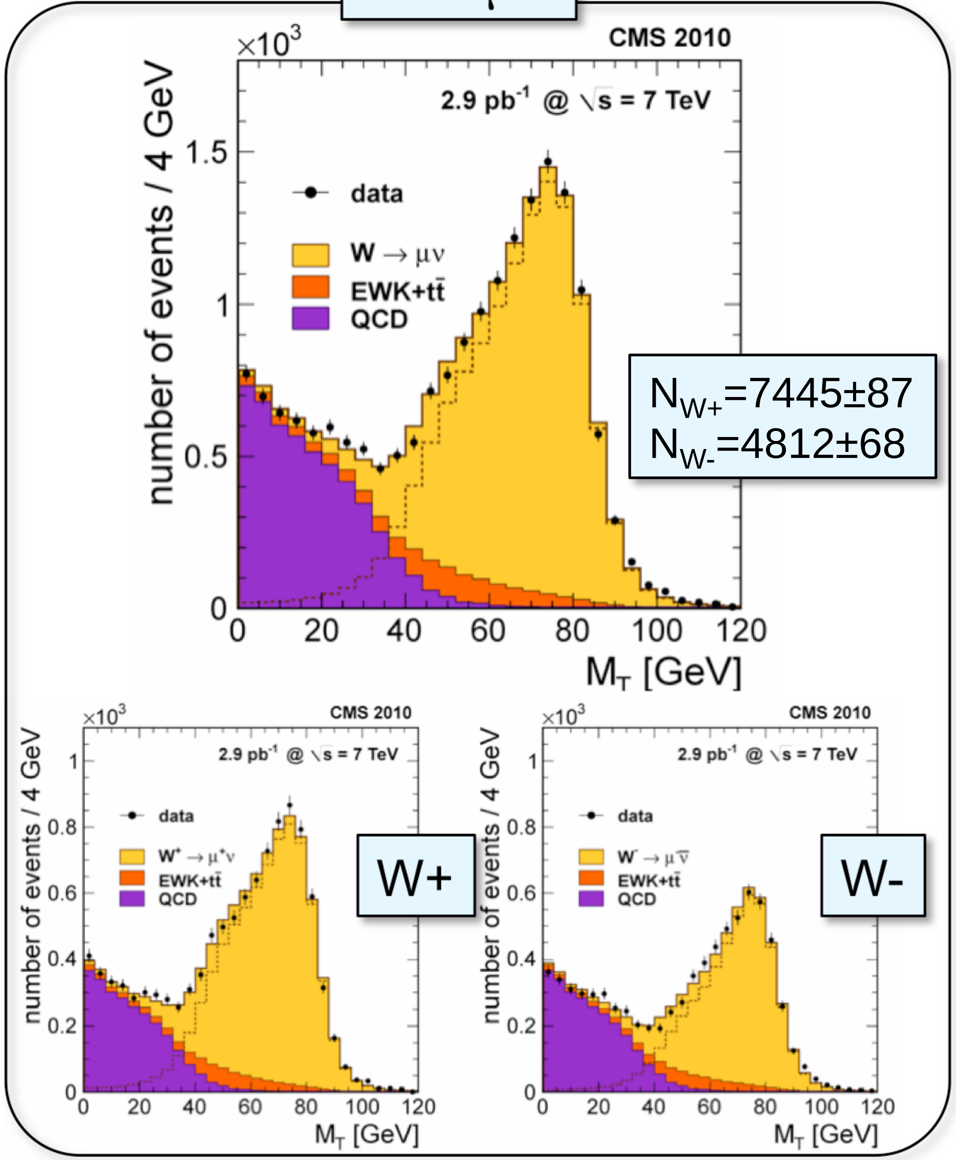
Fit Results

W→eν



N_{W+}=7193±89
N_{W-}=4728±73

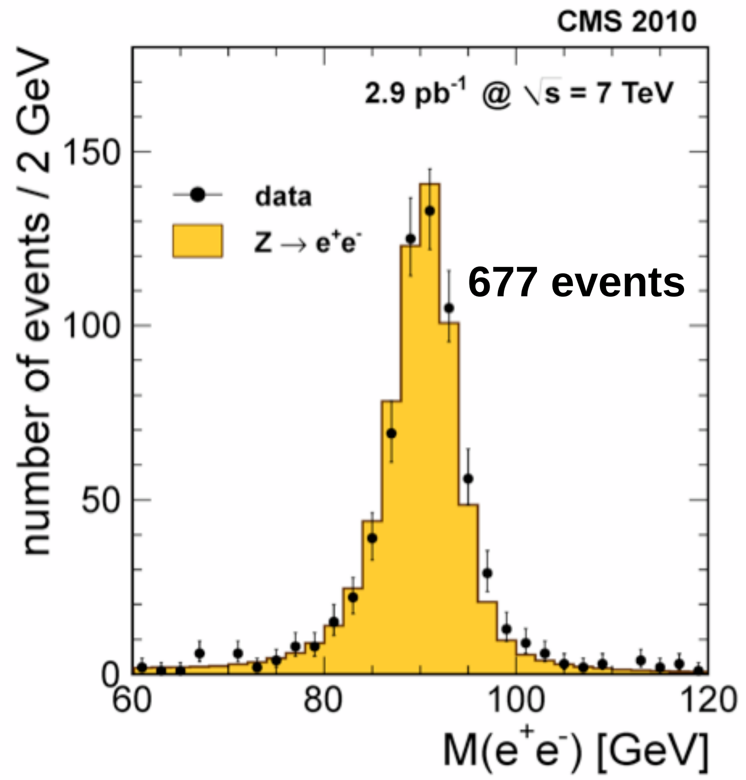
W→μν



N_{W+}=7445±87
N_{W-}=4812±68

Z→ee Signal Extraction

- Cut and count di-lepton events within invariant mass window $60 < M_{e+e-} < 120$ GeV/c^2

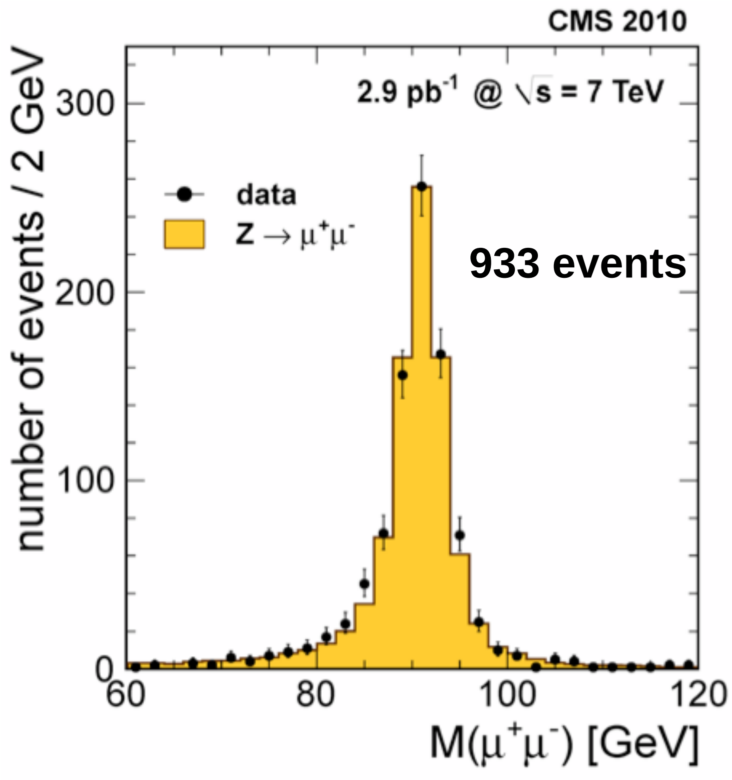


- Correction factors derived for ECAL super-cluster energy scale:

Barrel	1.015 +- 0.002
Endcaps	1.033 +- 0.005

- Subtract background:
  - QCD: 0.04±0.04, from data driven estimates
  - EWK (Z→ττ, ttbar, di-boson) = 2.8±0.4, from MC

$Z \rightarrow \mu\mu$ Signal Extraction



No scale corrections required

- A simultaneous fit is used to extract signal yield and selection efficiency
  - Efficiency corrected yield from fits is N_Z/ε_Z = 1050 ± 35 events

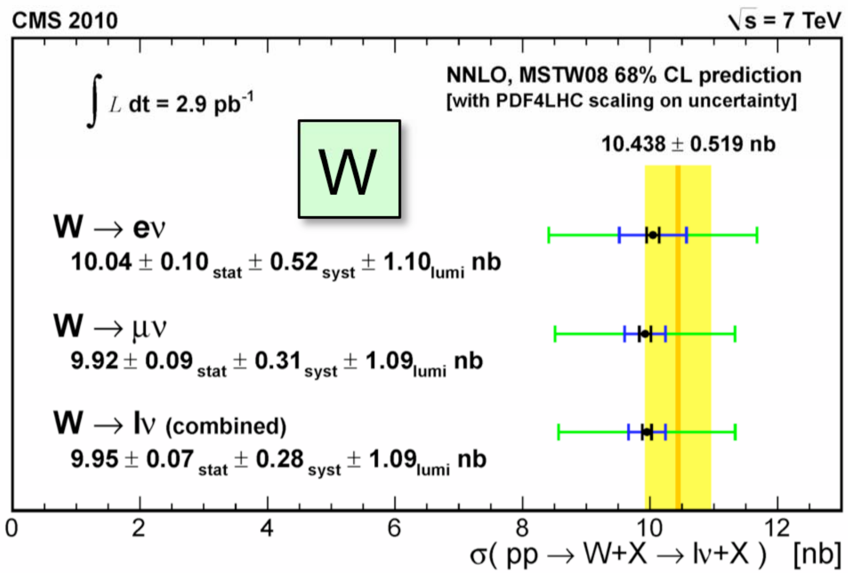
Systematic Uncertainties

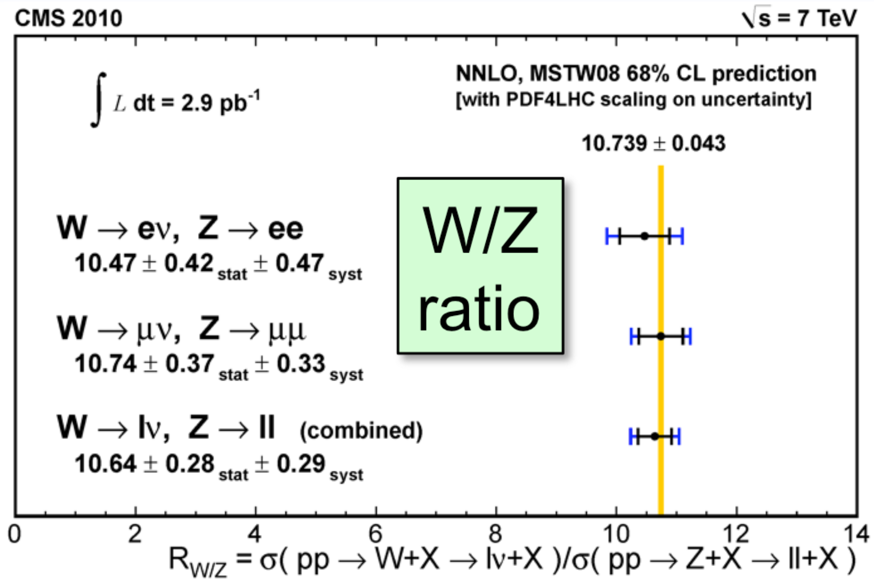
- Breakdown of systematic uncertainties (%)
- Data driven methods used to derive all experimental uncertainties

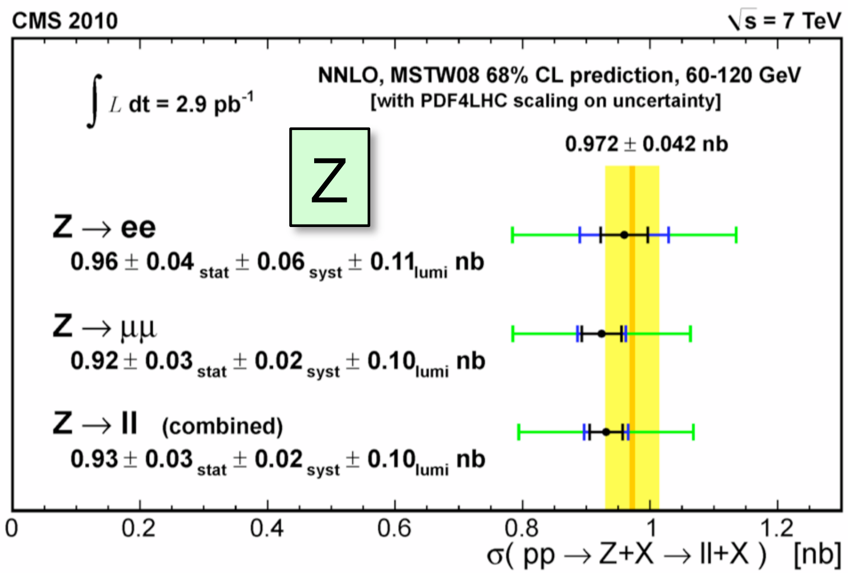
Source	W(eν)	W(μν)	Z(ee)	Z(μμ)
Lepton Reco&ID	3.9	1.5	5.9	0.5
Momentun scale & resolution	2.0	0.3	0.6	0.2
MET scale & resolution	1.8	0.4	n/a	n/a
BKG subtraction	1.3	2.0	0.1	1.0
PDF uncertainty for acceptance	0.8	1.1	1.1	1.2
Other theoretical uncertainties	1.3	1.4	1.3	1.6
TOTAL	**5.1**	**3.1**	**6.2**	**2.3**

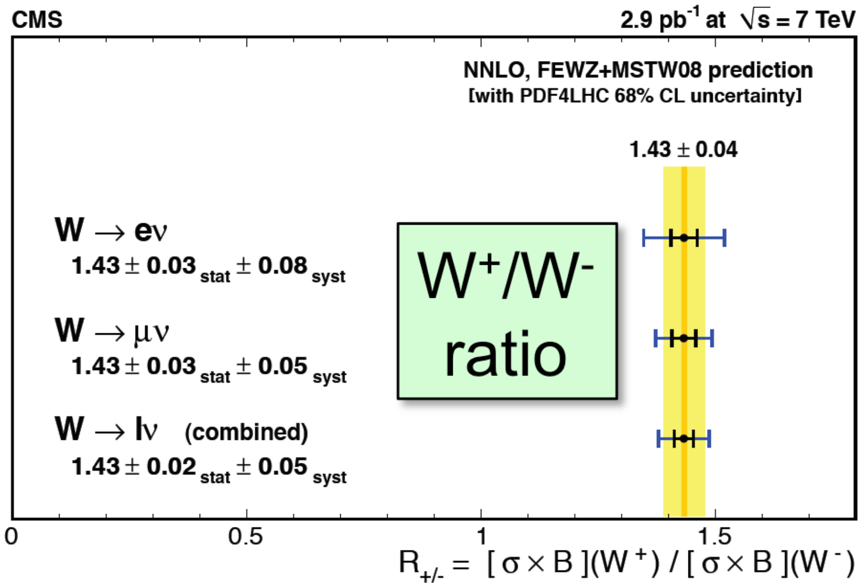
- Uncertainty from integrated luminosity: **11%** (expected to decrease soon)

W and Z Cross-section Results

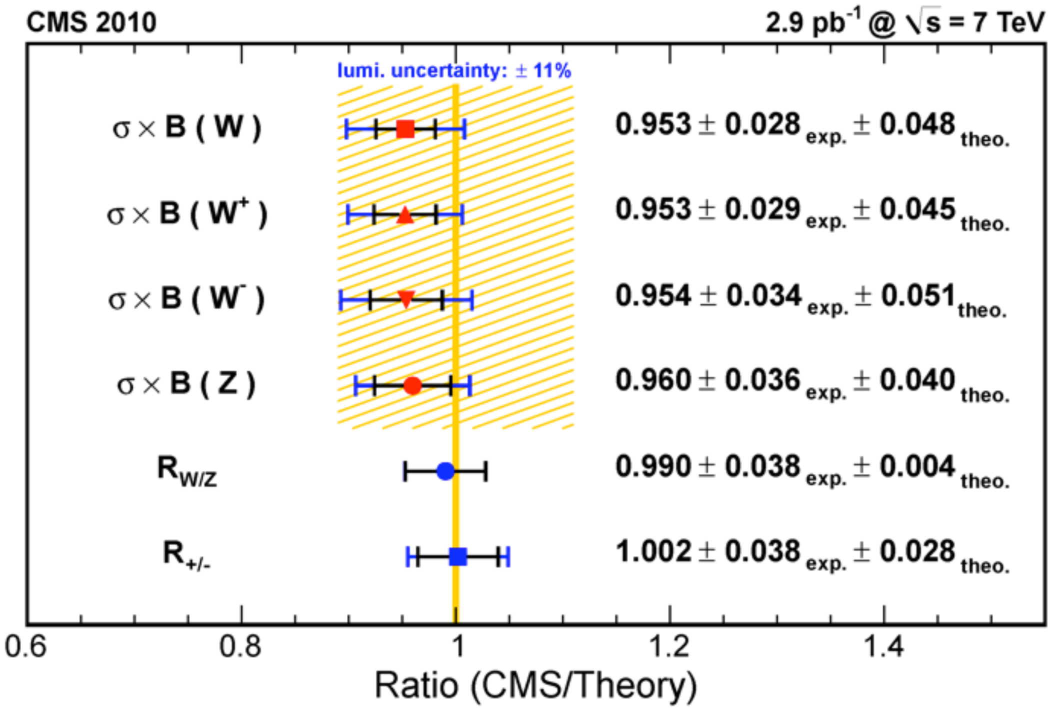


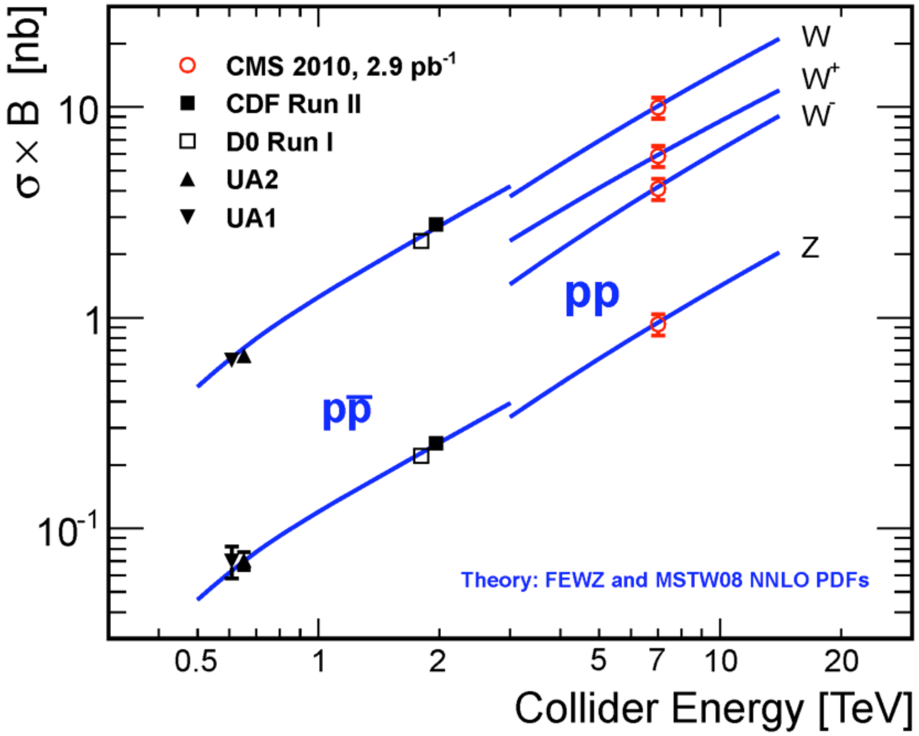




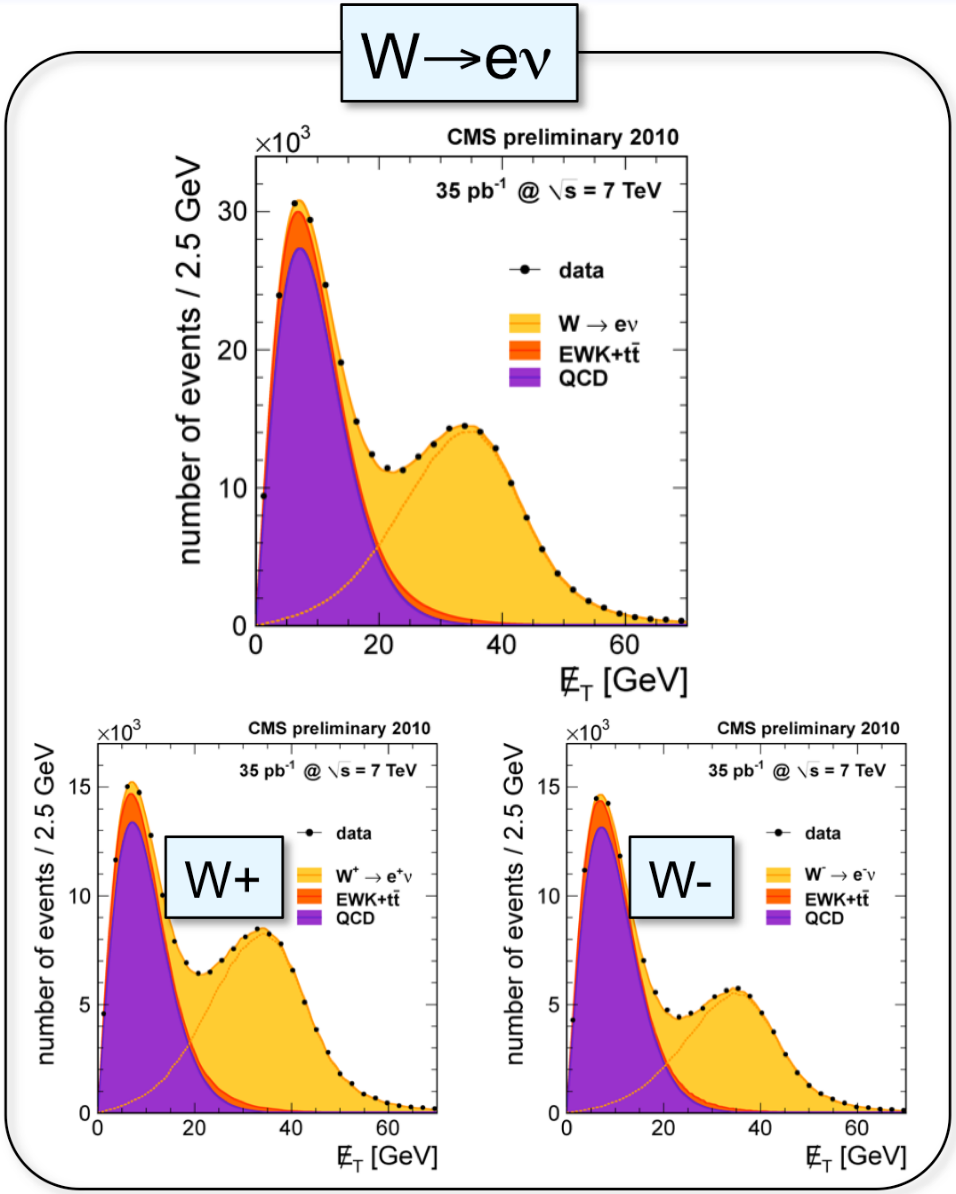


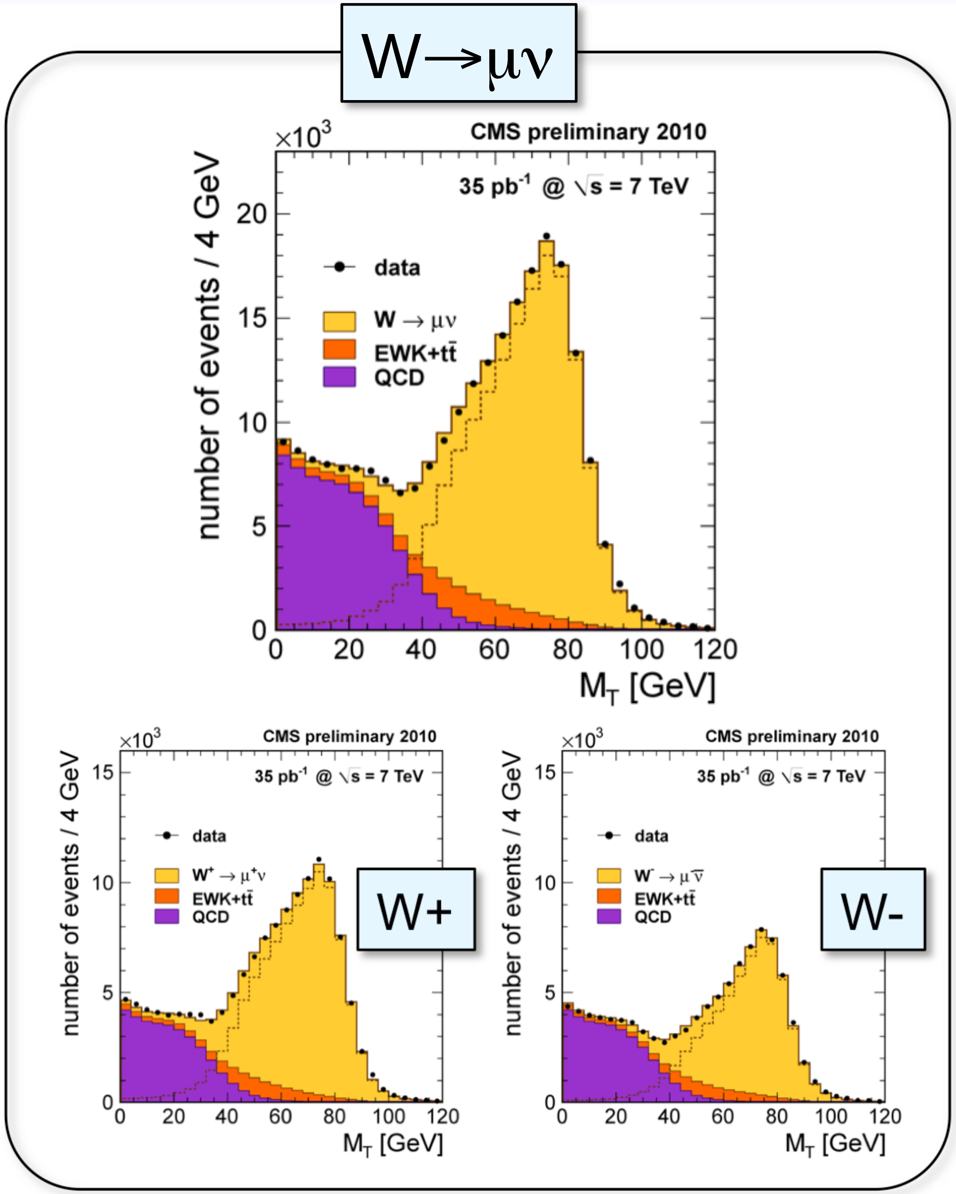
Comparison with Theory





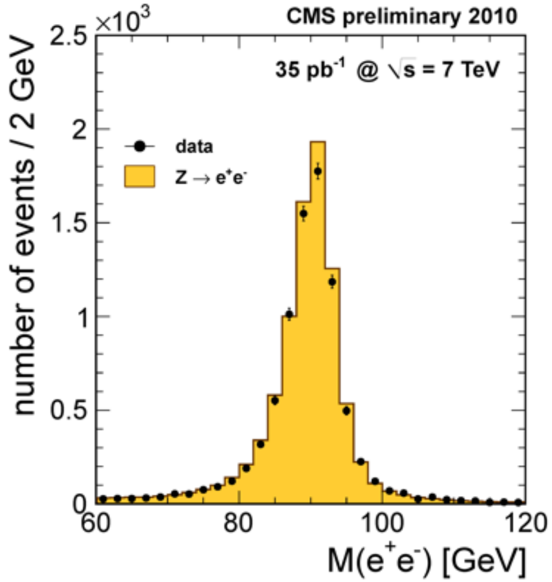
Preview: W→lν with 35pb^{-1}

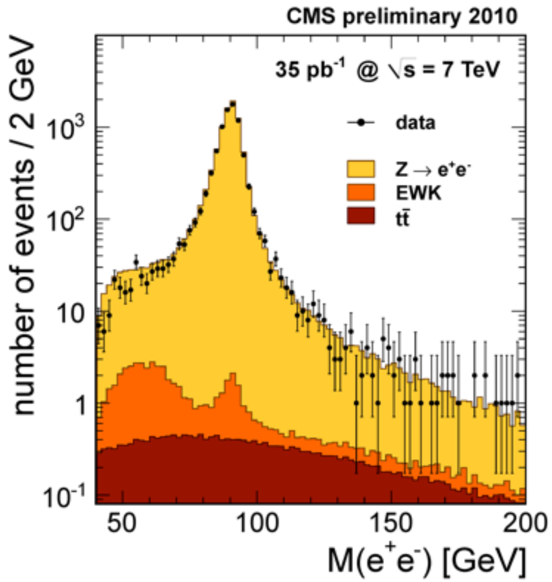




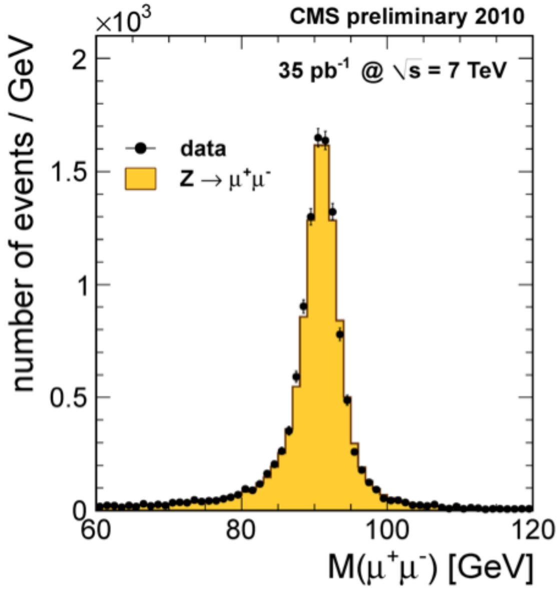
Preview: Z→ll with 35pb^{-1}

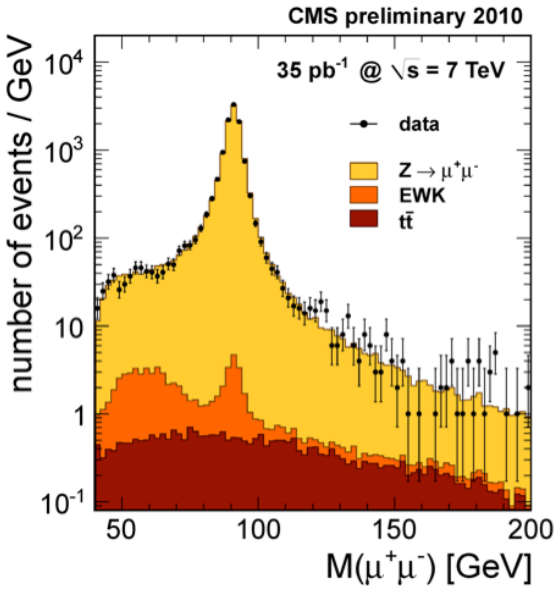
Z→ee



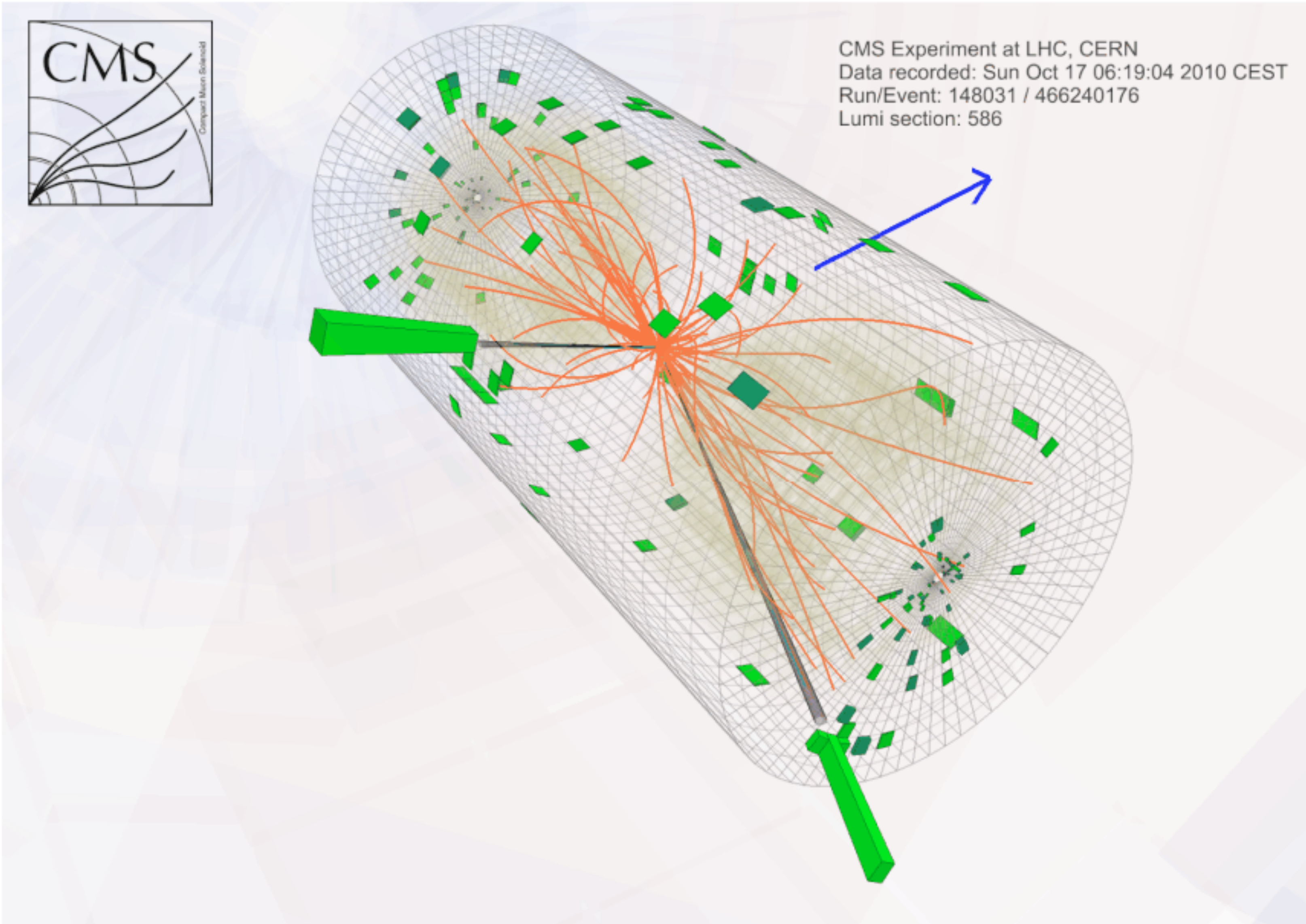


Z→μμ



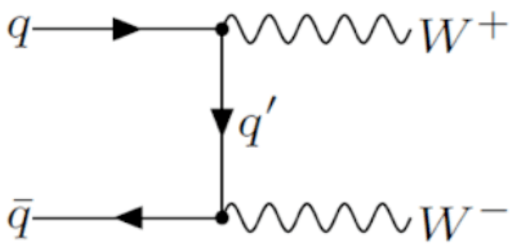


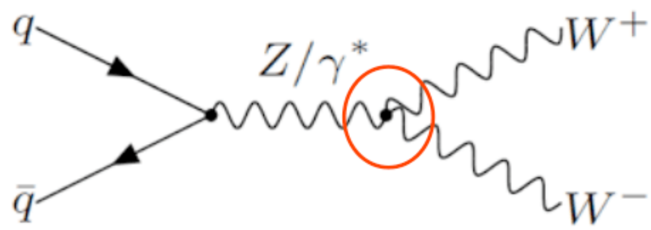
WW Cross-Section Measurement



WW Cross-Section Measurement

- First measurement of the WW cross-section at 7 TeV
- Provides a benchmark for Higgs and new physics searches
  - Standard Model WW production is the dominant background for the Higgs → WW search
  - New physics inducing anomalous WWγ and WWZ triple-gauge-boson couplings (aTGC) enhances the WW production cross section at high p_T





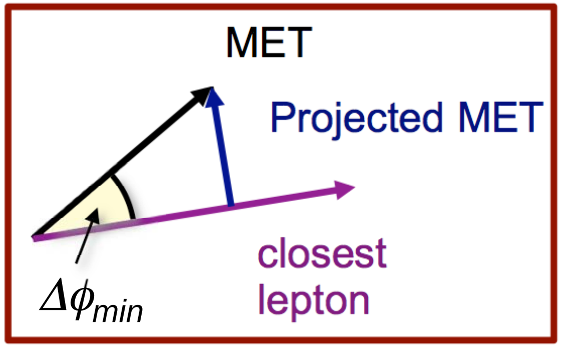
WW Event Selection

- Simple cut and count method
- Fully leptonic decay channels only (ee, $\mu\mu$, eμ)
- Signal: two oppositely charged isolated high p_T leptons with significant missing transverse energy
- Backgrounds:
  - W+jets and QCD (jet faking a lepton)
    - Jet veto: reject events containing jets with p_T>25 GeV/c and $|\eta|$<5.0
  - Drell-Yan $Z\rightarrow ll$
    - reject events with M_{ll} within 15GeV of Z mass or M_{ll}<12 GeV
  - tW, ttbar
    - Top vetos based on soft-muon and *b*-jet tagging
  - Diboson: Wγ, WZ, ZZ
    - Reject events with a 3rd lepton with p_T>10 GeV/c

Projected MET

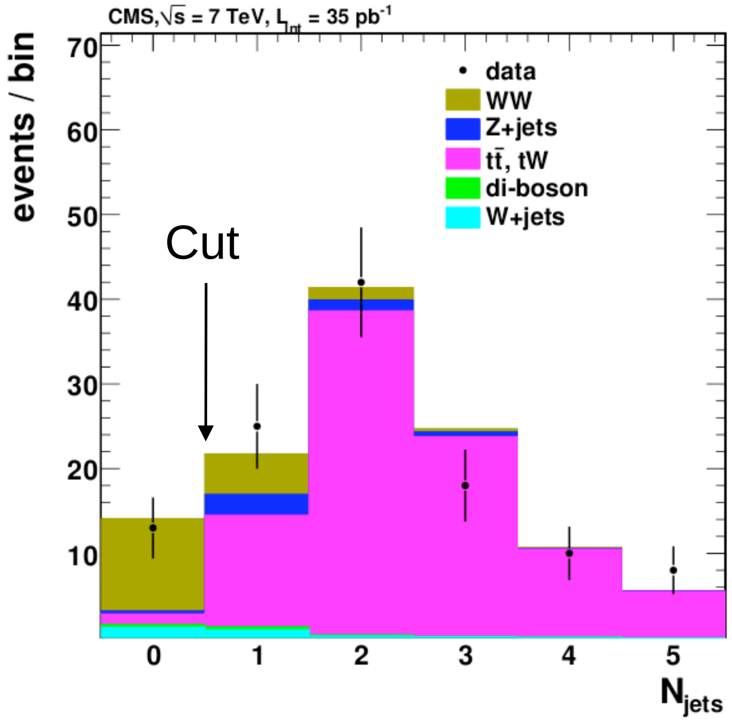
- MET calculated using the track corrected MET algorithm:
  - MET measured from calorimeters with corrections for jet energy scale and corrections from individual tracks to correct calorimeter response
- To improve rejection of $Z\rightarrow\tau\tau$ and $Z\rightarrow ll$ events with fake MET due to lepton mis-measurement, use "projected MET":

$$Projected\ MET = \begin{cases} E_{\mathrm{T}}^{\mathrm{miss}} & \text{if } \Delta\phi_{min} > \frac{\pi}{2}, \\ E_{\mathrm{T}}^{\mathrm{miss}} \sin(\Delta\phi_{min}) & \text{if } \Delta\phi_{min} < \frac{\pi}{2} \end{cases}$$

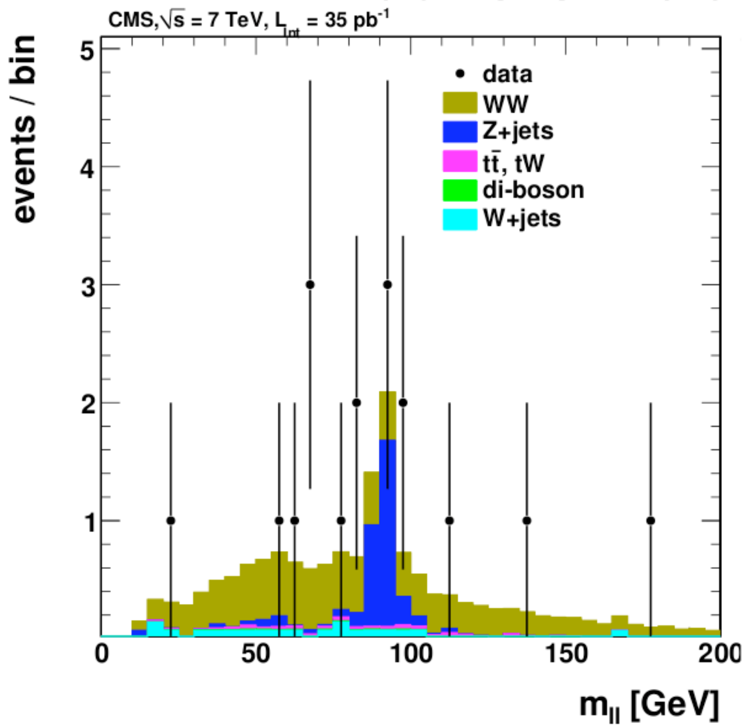


projected MET>35 GeV for ee, $\mu\mu$
projected MET>20 GeV for $e\mu$

Event Yields



Jet multiplicity distribution after all cuts except jet and top vetos



Di-lepton mass distribution after all cuts except di-lepton mass cut

Channel	Event Yield
ee	1
μμ	2
eμ	10
Total	**13**

Background Estimation

Process	Events
W+jets + QCD	$1.7 \pm 0.4 \pm 0.7$
$tt + tW$	$0.77 \pm 0.05 \pm 0.77$
$W\gamma$	$0.31 \pm 0.04 \pm 0.05$
$Z + WZ + ZZ \to e^+e^- / \mu^+\mu^-$	$0.2 \pm 0.2 \pm 0.3$
$WZ + ZZ$, not from Z	$0.22 \pm 0.01 \pm 0.04$
$Z \to \tau^+\tau^-$	$0.09 \pm 0.05 \pm 0.09$
Total	$3.29 \pm 0.45 \pm 1.09$

Data driven

From MC with cross-check from data

From MC

WW Cross-section Results

$$\sigma = \frac{N_{data} - N_{bkg}}{\epsilon \mathcal{L} BR(W \to \ell\nu)^2}$$

$$\Delta\sigma = \frac{\sqrt{N_{data}}}{\epsilon \mathcal{L}} \oplus \frac{\Delta N_{bkg}}{\epsilon \mathcal{L}} \oplus \frac{\Delta\epsilon}{\epsilon}\sigma \oplus \frac{\Delta\mathcal{L}}{\mathcal{L}}\sigma$$

variable	value	uncertainty
N_{data}	13	—
N_{bkg}	3.29	1.18
ϵ (%)	6.34	0.46
$\mathcal{L}$ (pb)	35.5	3.9
$BR(W \to l\nu)$	0.1080	0.0009

- Signal efficiency is derived from simulation. Data/MC efficiency scale factors extracted using Tag and Probe (Z→ll) are used to correct efficiency and to provide systematic uncertainties: $\varepsilon = \varepsilon_{MC} \times (\varepsilon_{DATA}^{TP} / \varepsilon_{MC}^{TP})$

$$\sigma_{WW} = 41.1 \pm 15.3(stat.) \pm 5.8(syst.) \pm 4.5(lumi.)\, pb$$

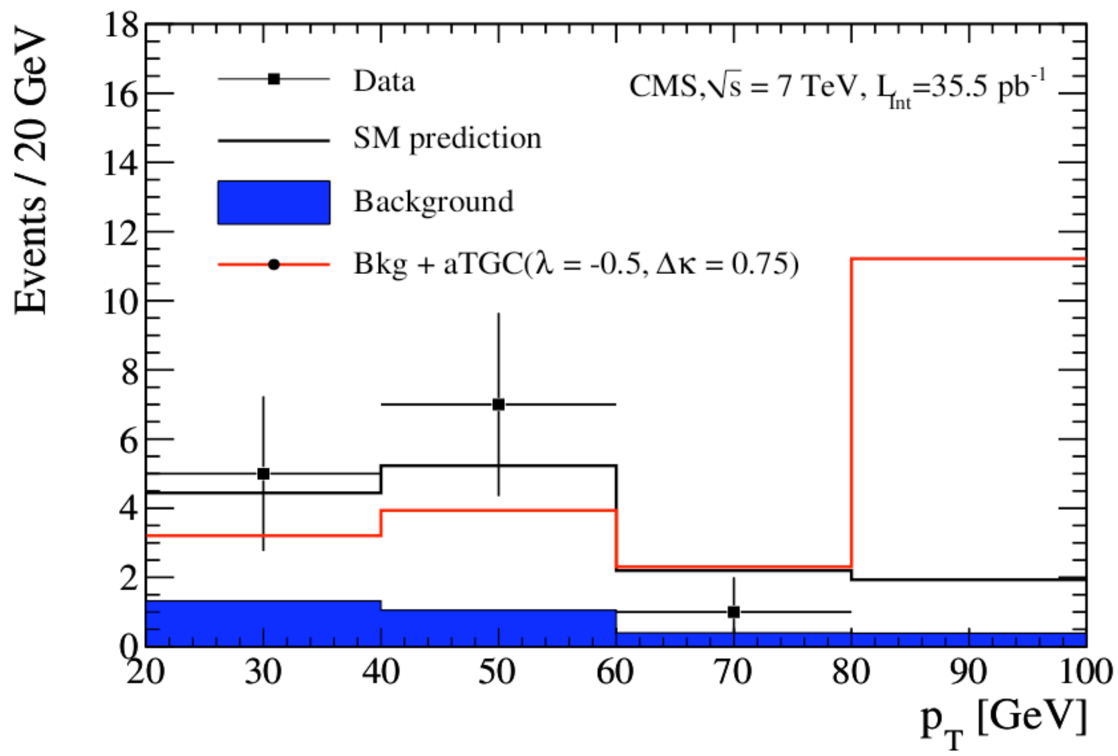
NLO prediction: 43.0 ± 2.0 pb

$$\frac{\sigma_{WW}}{\sigma_W} = (4.46 \pm 1.66 \pm 0.64) \cdot 10^{-4}$$

NLO prediction: $(4.45 \pm 0.30).10^{-4}$

Limits on Anomalous Triple Gauge Couplings

- Non-zero anomalous coupling gives enhancement of WW cross section at large p_T
  - Derive limits on aTGC parameters by fitting to leading lepton p_T distribution and inclusive cross section

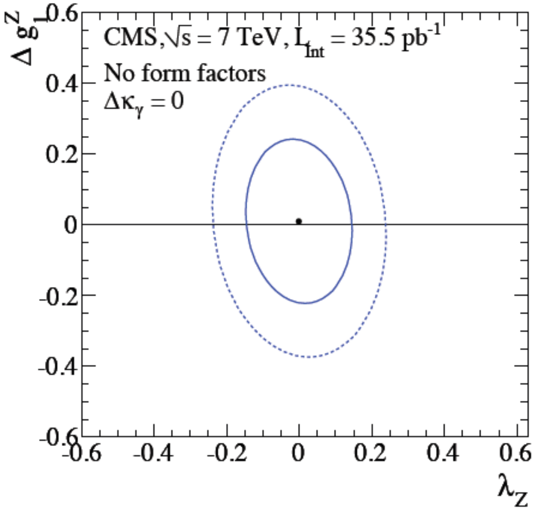


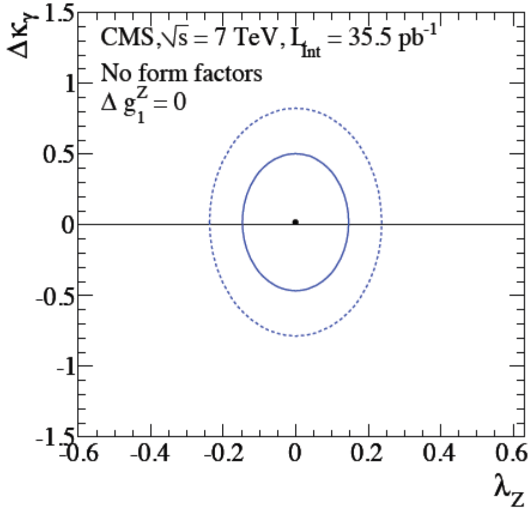
Limits on Anomalous Triple Gauge Couplings

- HISZ parametrization: 3 free parameters: λ, Δg_1^Z, $\Delta\kappa_\gamma$
- 95% CL limits on single parameter, fixing other 2 parameters to SM value:

	λ	Δg_1^Z	$\Delta\kappa_\gamma$
Unbinned fit	[-0.19, 0.19]	[-0.29, 0.31]	[-0.61, 0.65]
Binned fit	[-0.23, 0.23]	[-0.33, 0.40]	[-0.75, 0.72]

- 68% and 95% CL limits on two parameters, fixing 3rd parameter to zero (SM):





- Limits are consistent with SM and are comparable with current Tevatron results

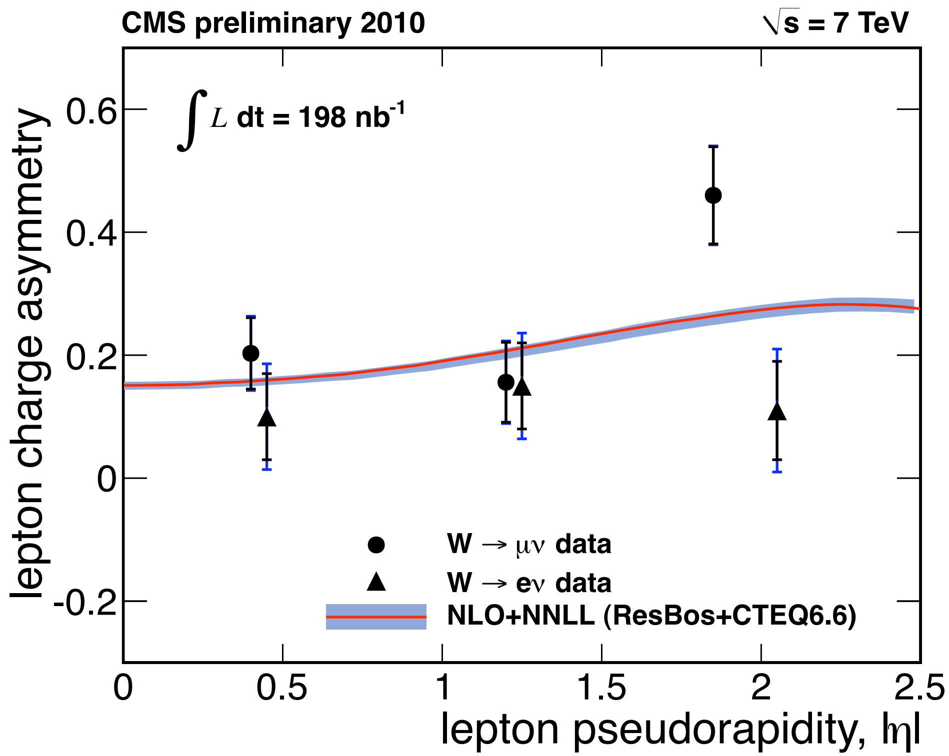
Additional results with 198nb^{-1}

(analyses for full 2010 dataset in progress)

W Charge Asymmetry

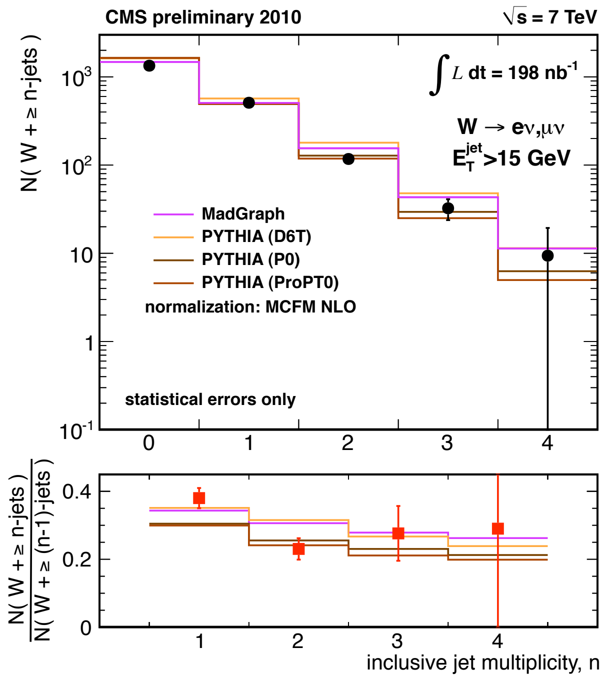
- W+ produced in greater numbers than W- at LHC due to prevalence of *u* quarks w.r.t. *d* quarks in protons
- Measurement of asymmetry can provide important constraints on proton PDFs
  - Particularly sensitive to *d(x)/u(x)* ratio
- Analysis with $35 pb^{-1}$ performed using 6 η bins
  - Comparison with predictions using different PDFs
  - Nearing completion

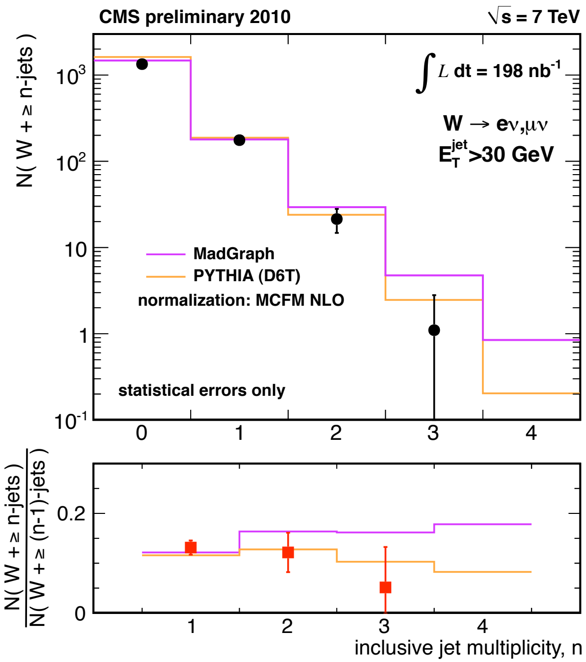
$$A_{exp}(\eta) = \frac{\frac{dN}{d\eta}(\ell^+) - \frac{dN}{d\eta}(\ell^-)}{\frac{dN}{d\eta}(\ell^+) + \frac{dN}{d\eta}(\ell^-)}$$

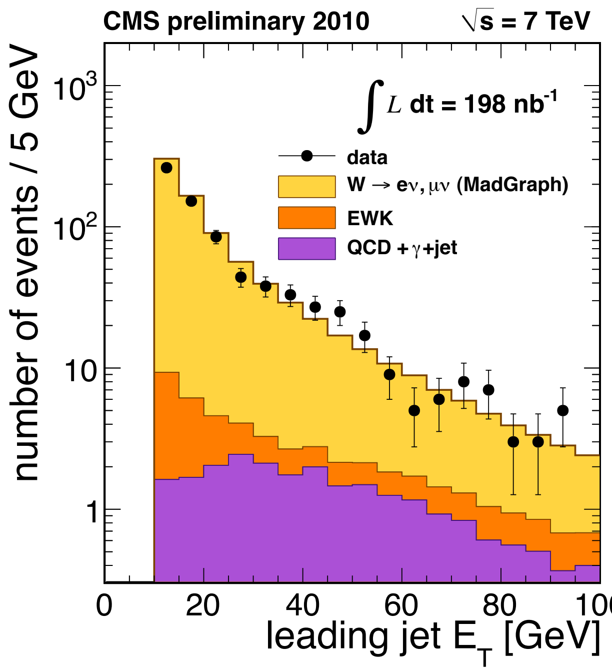


Associated QCD production: W+Jets

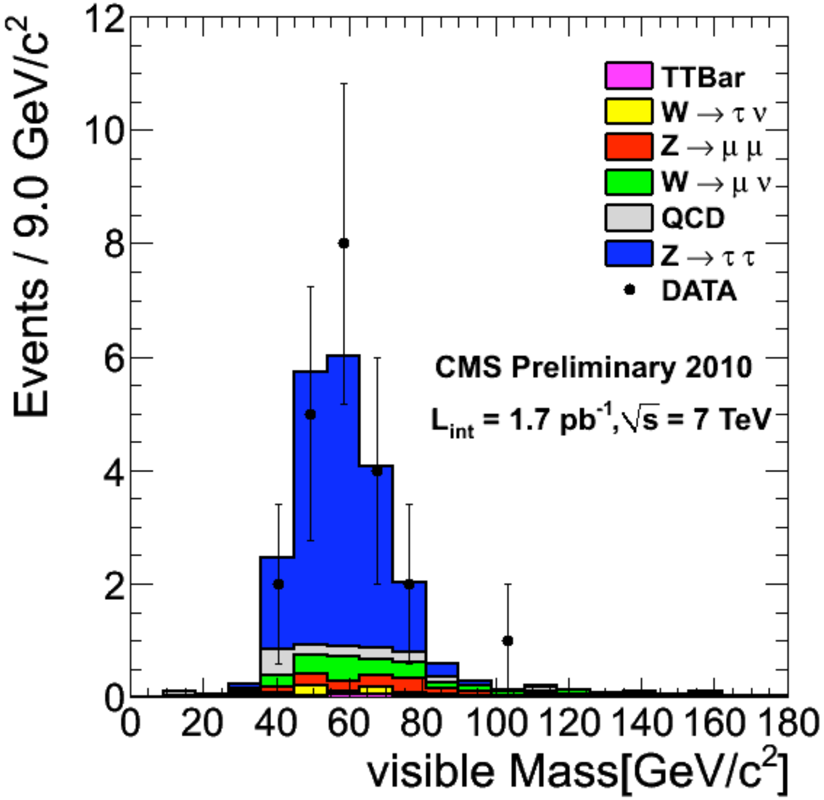
- High p_T lepton + jets is an important final state for many new physics searches

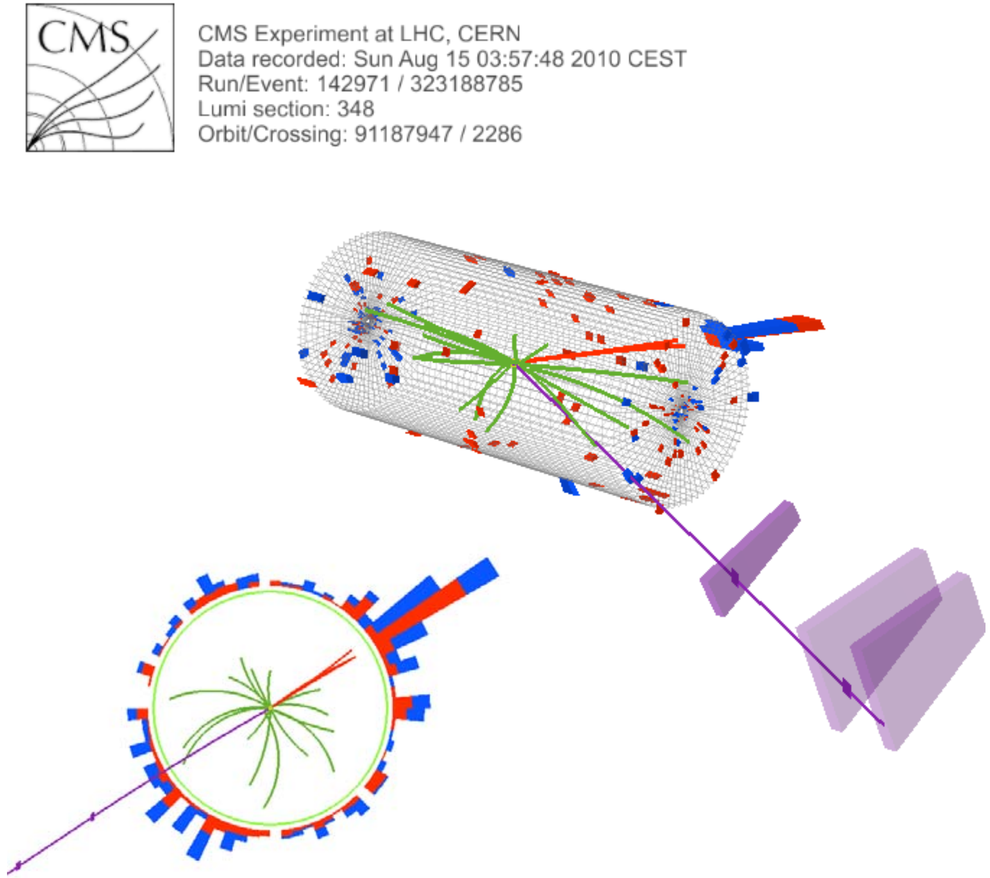






$Z \rightarrow \tau\tau$ Observation





- Measurement of $Z \rightarrow \tau\tau$ cross-section being performed with $36pb^{-1}$
  - comparing to e and μ channels gives a measurement of tau ID efficiency

Summary and Outlook

- CMS has performed remarkably well during 2010, allowing precision measurements of the W and Z cross-sections at 7 TeV with only $3pb^{-1}$ of data
- WW cross-section constitutes first Electroweak measurement using the full 2010 dataset ($36pb^{-1}$)
- Measured cross-sections and ratios are consistent with Standard Model at Next to Leading Order
- Many new Electroweak results will be published within the coming weeks using the full 2010 dataset:

W and Z cross-sections	Drell-Yan ($d\sigma/dM$)
W charge asymmetry	Z Differential cross-sections ($d\sigma/dq_T$, $d\sigma/dY$)
W polarization	Di-lepton A_{FB} and $\sin^2\theta_W$
W,Z + γ	W,Z + jets
$\sigma(Z\rightarrow\tau\tau)$	Z+bb

Backup

Event Selection

- Electrons:
  - ECAL super-cluster in fiducial region ($|\eta|<1.44$, $1.57<|\eta|<2.5$), with $E_T>20$GeV
  - Electron identification requirements (track-cluster matching in η and ϕ coordinates, narrow shower shape in η, low HCAL/ECAL energy ratio)
  - Conversion rejection (no missing hits in pixel layers, no second track consistent with being a conversion partner)
  - Veto on presence of 2nd electron with $E_T>20$GeV for W selection
- Muons:
  - $p_T>20$GeV/c, $|\eta|<2.1$
  - Muon candidate reconstructed with good fit quality by both of two algorithms, one starting in the inner tracker, the other starting in the muon chambers
  - Cosmic ray rejection: impact parameter on transverse plane <2mm
- QCD background rejected using relative isolation:
  - Electrons: I_{ECAL}/p_T^{ele}, I_{HCAL}/p_T^{ele}, I_{trk}/p_T^{ele}
  - Muons: $I_{comb}^{rel} = \sum(I_{HCAL} + I_{ECAL} + I_{trk})/P_T^{muon}$

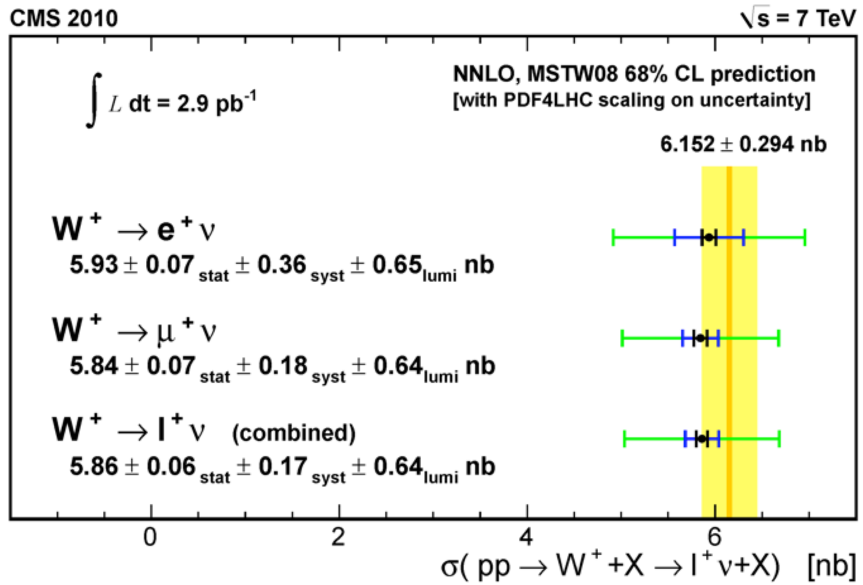
$$I_{ECAL} = \sum E_T(ECAL)$$

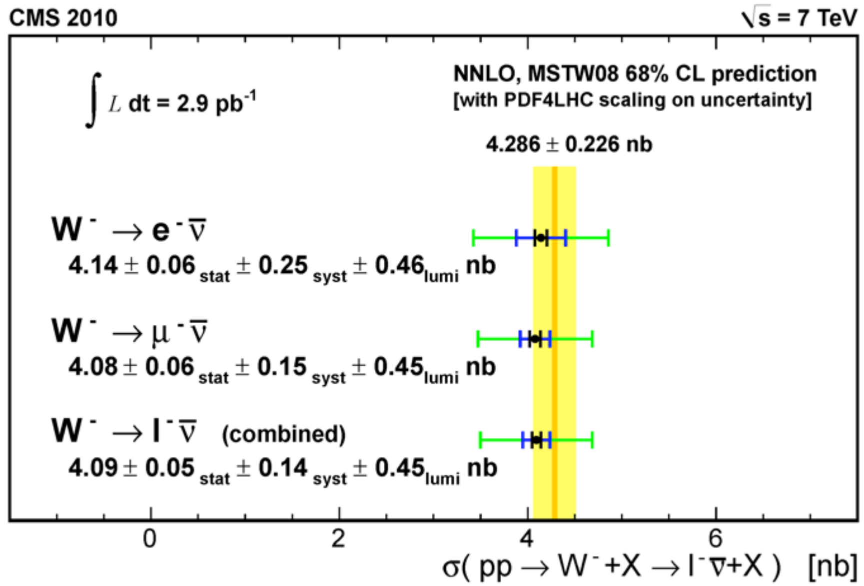
$$I_{HCAL} = \sum E_T(HCAL)$$

$$I_{TRK} = \sum p_T(tracks)$$

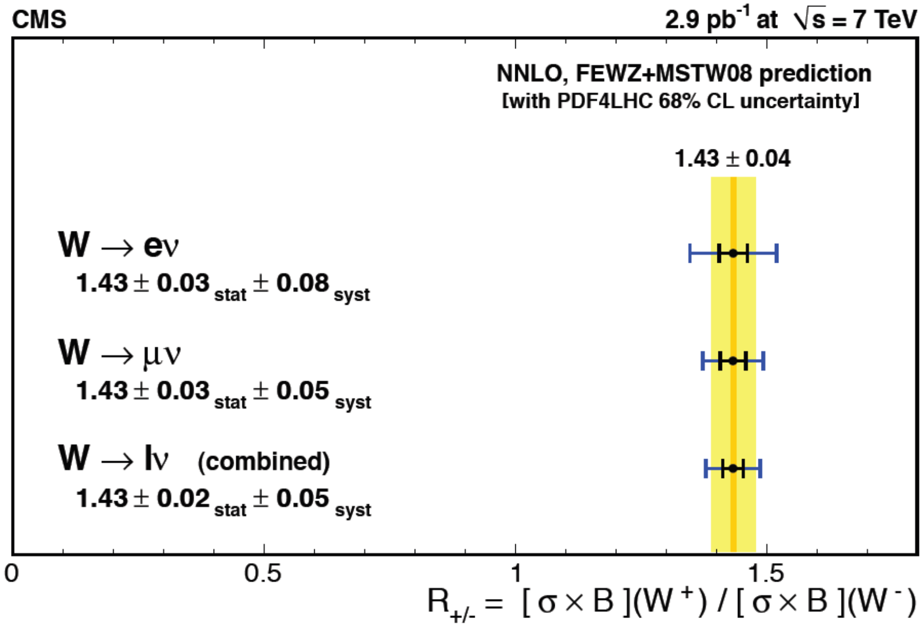
Cone: $\Delta R<0.3$

W Charge Ratio



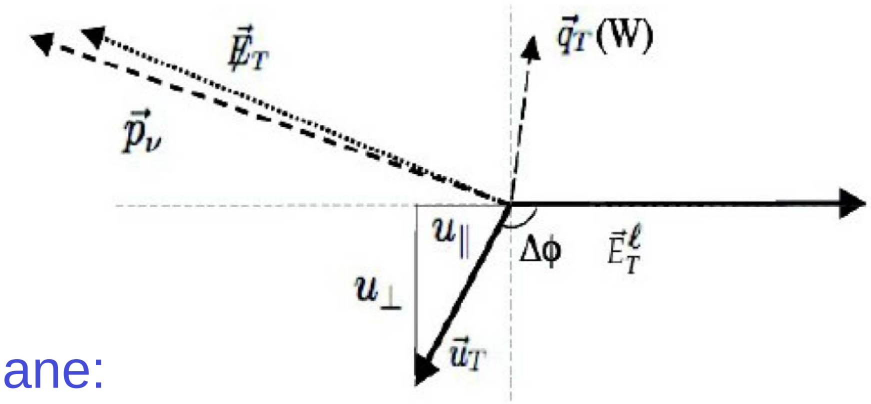


W^+/W^- Ratio



W Signal Modeling

- Signal templates are derived from simulation, separately for W+ and W−
- Event-by-event correction in order to account for imperfect modeling of:
  - electron energy scale & resolution
  - response/resolution of hadronic recoil



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

- Conservation of momentum in transverse plane:
  - Calculate recoil components $u_{||}$, $u_{\perp}$ parallel/perpendicular to boson qT axis for Z data, Z MC and W MC.
- Determine Z data/MC scale factors in bins of W p_T and apply to W MC

Background Estimation

Data driven

From MC with cross-check from data

From MC

Process	Events
W+jets + QCD	$1.7 \pm 0.4 \pm 0.7$
$t\bar{t} + tW$	$0.77 \pm 0.05 \pm 0.77$
$W\gamma$	$0.31 \pm 0.04 \pm 0.05$
$Z + WZ + ZZ \rightarrow e^+e^-/\mu^+\mu^-$	$0.2 \pm 0.2 \pm 0.3$
$WZ + ZZ$, not from Z	$0.22 \pm 0.01 \pm 0.04$
$Z \rightarrow \tau^+\tau^-$	$0.09 \pm 0.05 \pm 0.09$
Total	$3.29 \pm 0.45 \pm 1.09$

- W+jets and QCD: Extrapolate lepton fake rate from loose to tight lepton ID
  - Measure fake rate in background enriched data samples
  - Apply fake rate to samples passing tight+loose & loose+loose selections to predict W+Jets & QCD background respectively
- Z→ll (including WZ, ZZ): Ratio of yield inside to outside Z mass window from MC used to extrapolate Z/γ* yield in data to outside the Z mass window
  - Non Z/γ* events within Z mass window subtracted estimated using eμ events, corrected for lepton efficiencies