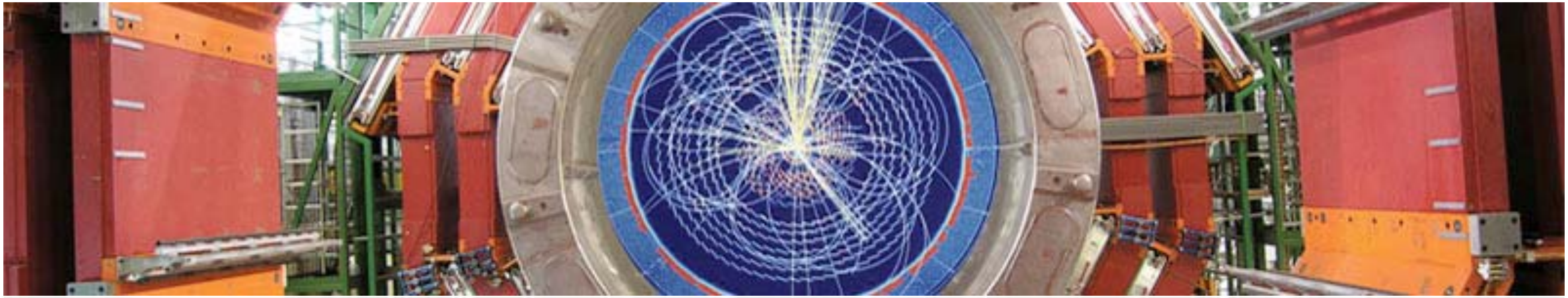
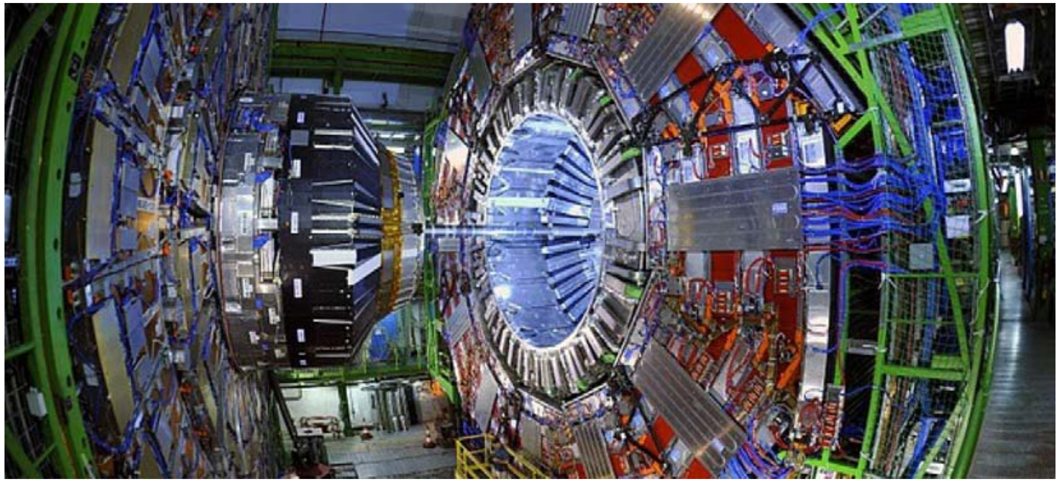


Electroweak Physics at CMS

David Futyan

Imperial College London

$W^{\pm}$

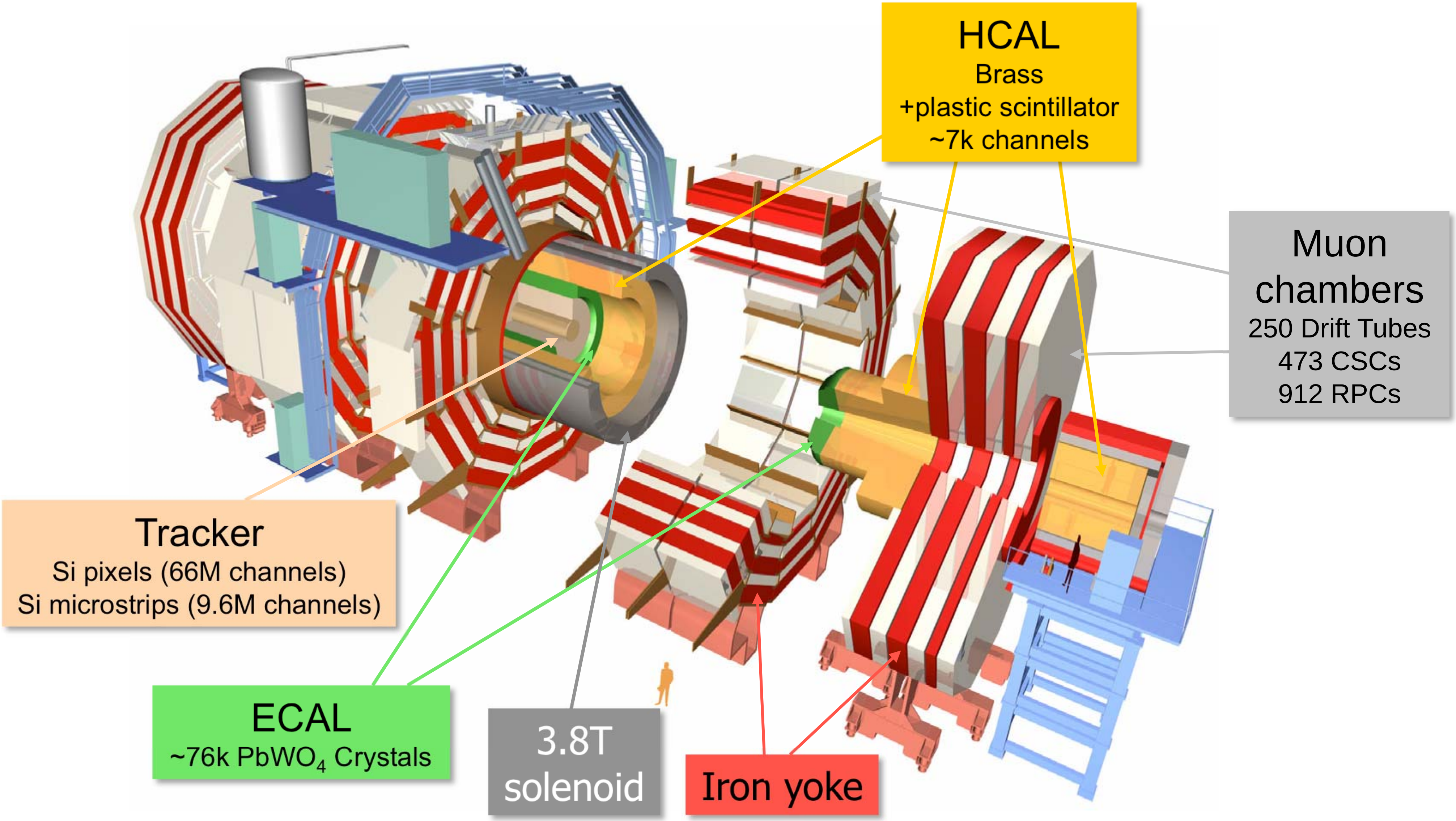


Z^{0}

Outline

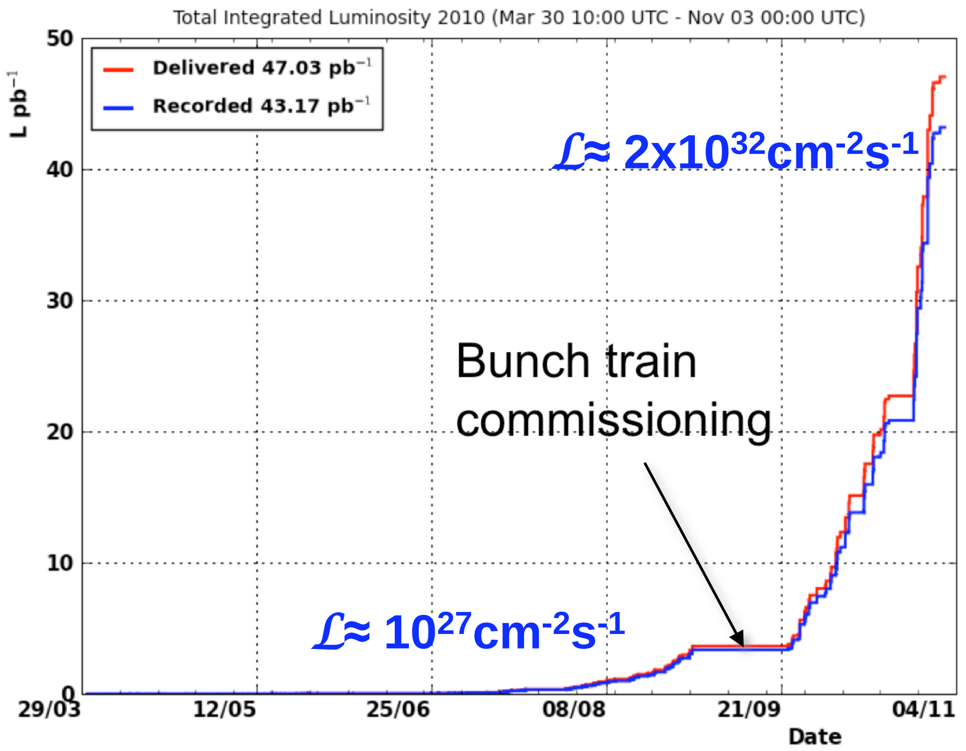
- Introduction
- **Inclusive W and Z production cross-section**
- W charge asymmetry
- W polarization
- Additional selected results:
  - WW cross-section
  - $Z \rightarrow \tau\tau$ cross-section
  - W,Z + jets
  - Drell-Yan $d\sigma/dM$
  - Z differential cross-sections: $d\sigma/dy$, $d\sigma/dq_T$
  - AFB and $\sin^2\theta_W$

The CMS Detector



CMS Operation in 2010

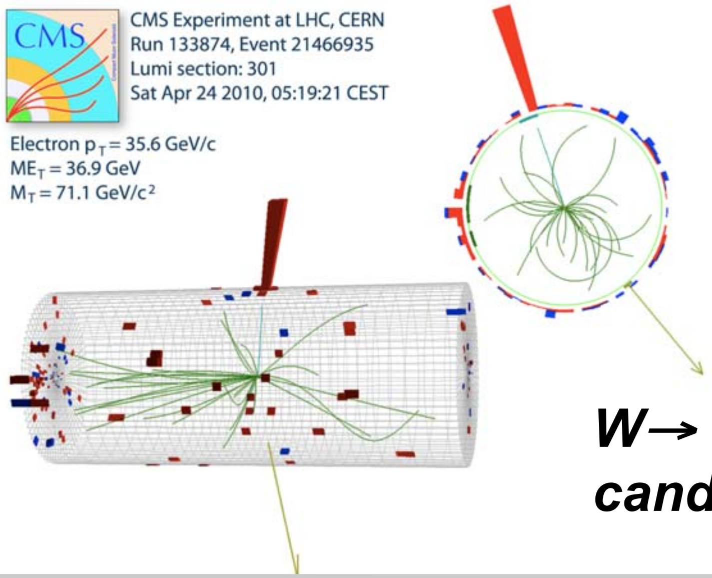
- 47pb^{-1} delivered by LHC and 43pb^{-1} of data collected by CMS
  - Overall data taking efficiency ~92%.
  - ~84% of recorded data good quality for physics analysis → ~36pb^{-1}
- Excellent performance in coping with more than 5 order of magnitude increase in instantaneous luminosity



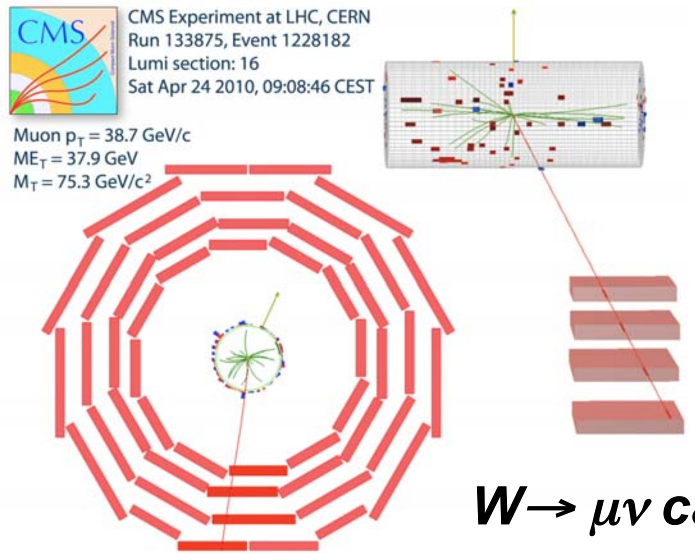
Motivations for Electroweak Physics at CMS

- 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 di-boson production
- Estimators of LHC Luminosity

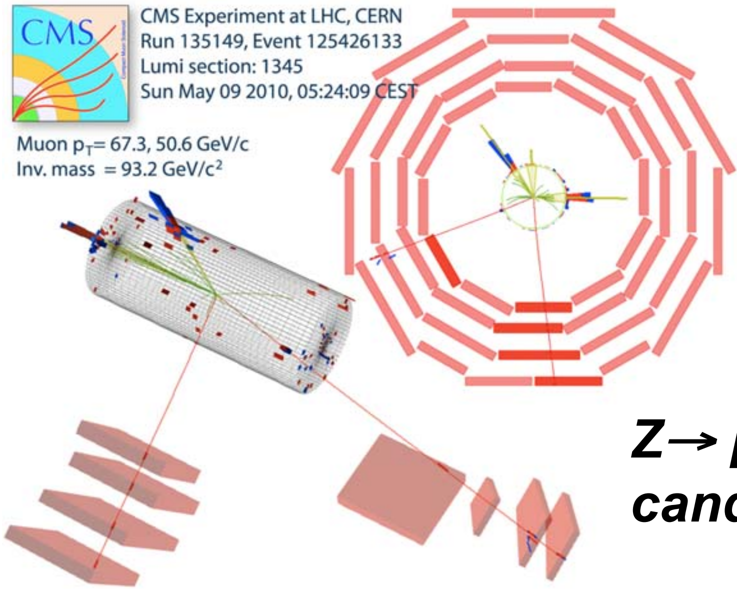
W and Z candidates: Event Displays



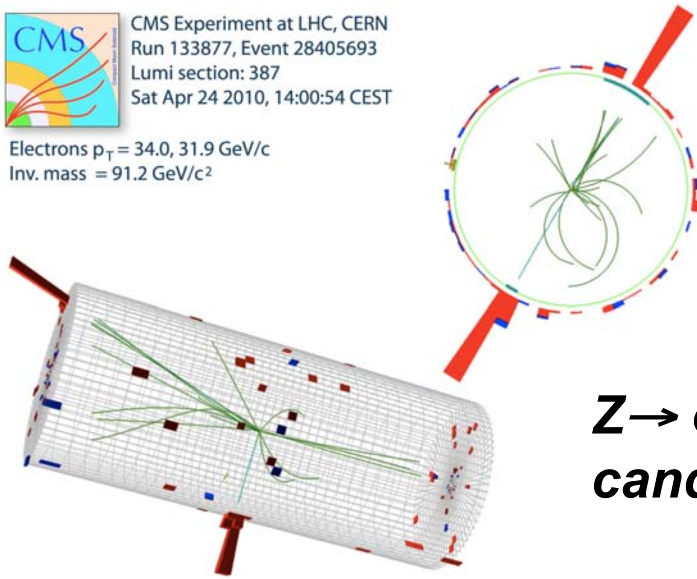
W→ eν candidate



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>25 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 or transverse mass for W selection
- 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 for W
- di-lepton invariant mass for Z

Integrated luminosity:

- largest source of systematic uncertainty in the measurement (4%)

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

Fiducial and kinematic acceptance:

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

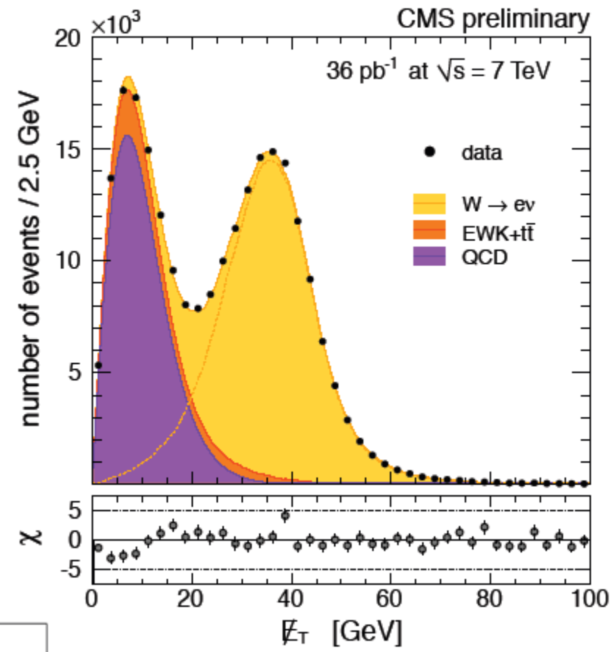
Selection efficiency for signal falling within the acceptance :

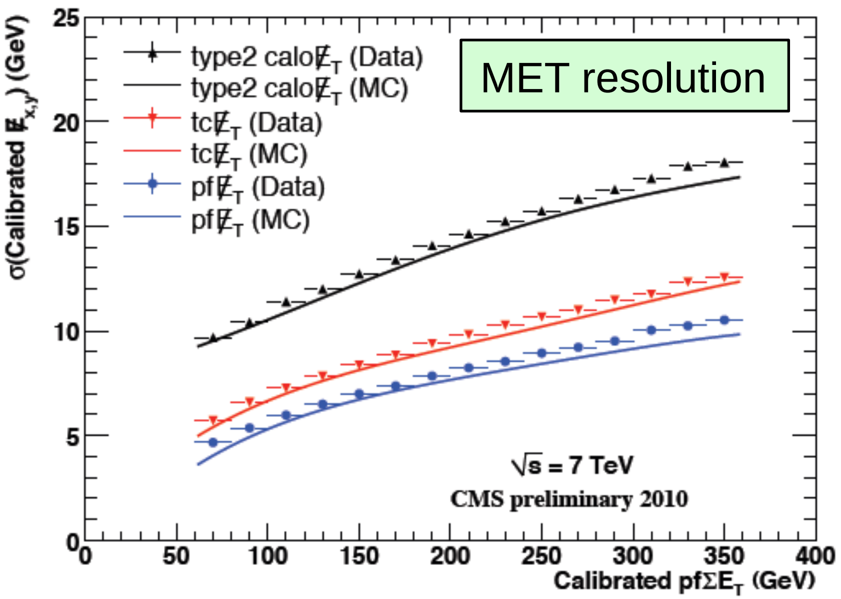
- obtained using simulation
- corrected using efficiencies measured in data and MC with tag and probe:

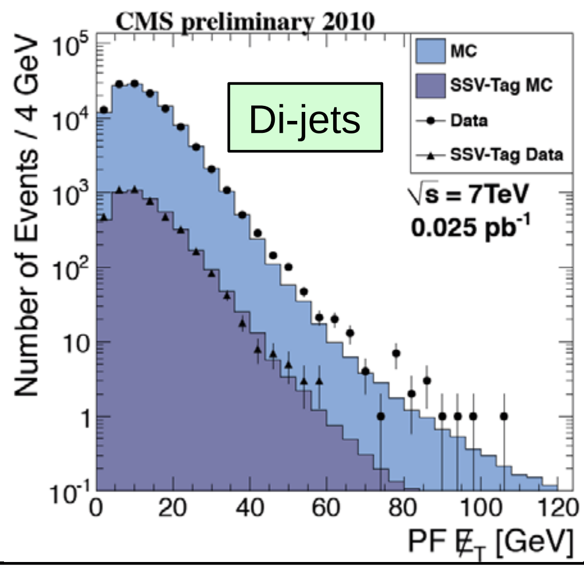
$$\varepsilon = \varepsilon_{MC} \times (\varepsilon^{TP}_{DATA} / \varepsilon^{TP}_{MC})$$

W Signal Extraction

- Signal extraction performed via a maximum likelihood fit to missing transverse energy distribution
- Missing transverse energy calculated using the Particle Flow algorithm
  - $-\Sigma p_T$ for all particles reconstructed in the event
  - Well reproduced by simulation

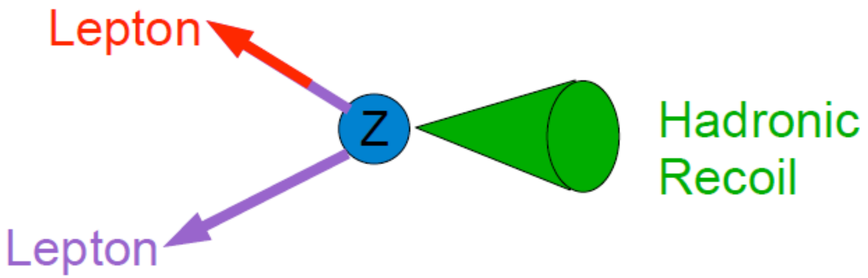






Signal shape modeling

- Accurate modeling of MET distribution difficult due imperfect simulation of low level physics and detector effects
- $Z \rightarrow ll$ events in data are used to derive corrections for:
  - Lepton energy scale and resolution:
    - Apply a range of energy scale and resolution (smearing) factors to $Z \rightarrow ll$ MC and minimize negative log likelihood of invariant mass distribution compared to data
  - Response and resolution of hadronic recoil:



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

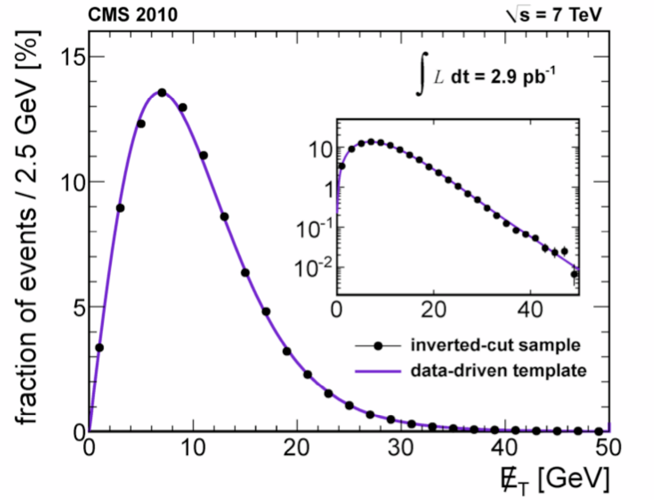
    - Measure components of recoil $u_{||}$, $u_{\perp}$ parallel/perpendicular to boson p_T axis in $Z \rightarrow ll$ data and MC events
      - derive data/MC correction factors for means and widths of $u_{||}$, $u_{\perp}$ distributions as functions of boson p_T – apply corrections to W MC

QCD background modeling: W→eν

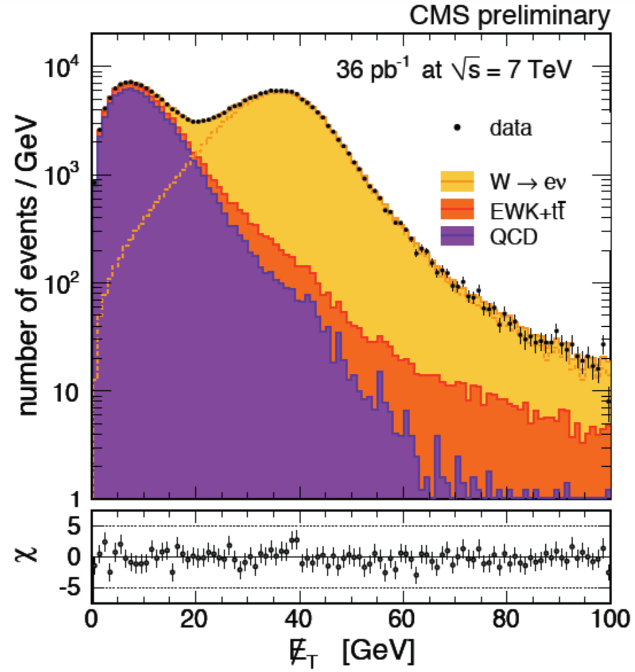
- Electrons: MET shape parameterized using a modified Rayleigh function

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

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



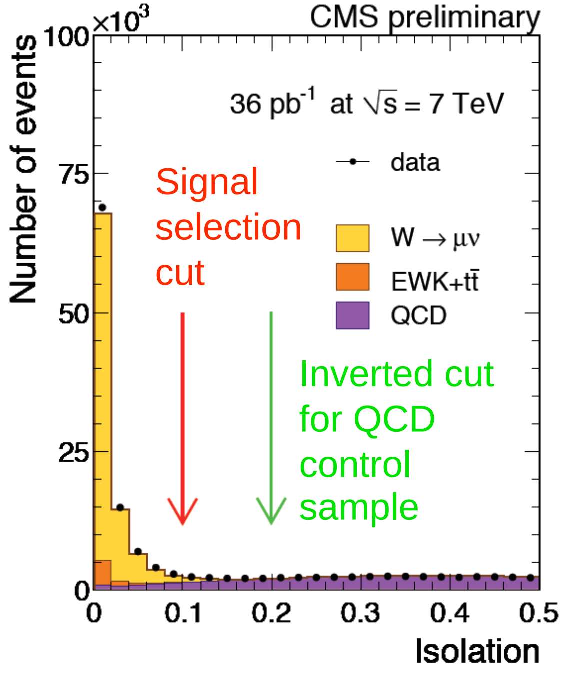
- Alternative method extracts MET shape from data using a control sample obtained by inverting one of the electron ID cuts (~uncorrelated with MET)
  - Signal contamination in the control sample (~1%) is estimated using the tag and probe technique with Z→ee events. Signal yield is corrected accordingly



- Yields from the two approaches agree to within 0.3%

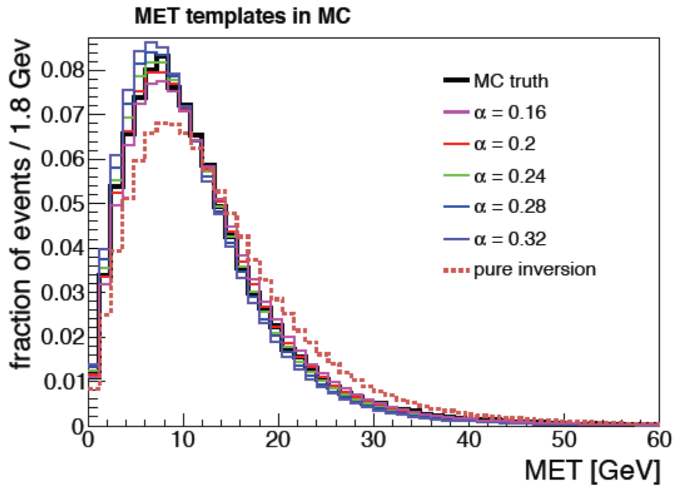
QCD background modeling: $W \rightarrow \mu\nu$

- MET shape constructed from control sample obtained by inverting isolation cut



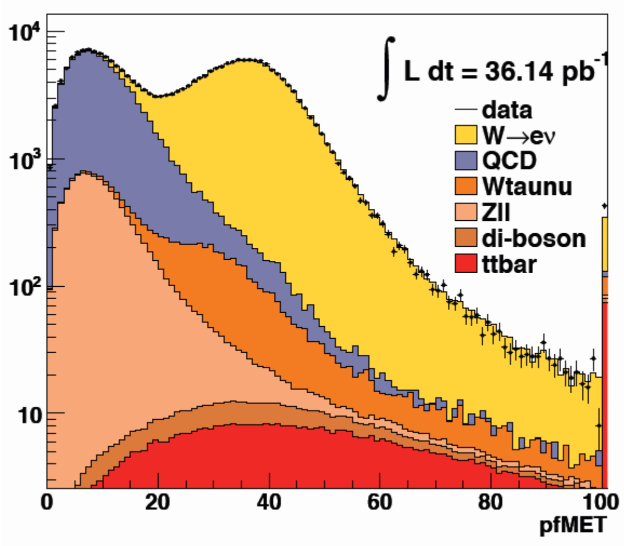
- Control sample has high purity (negligible signal contamination) but MET shape suffers a bias due to a correlation between isolation and MET
  - Mean value of MET positively correlated with isolation
  - Correction derived by fitting the observed correlation in data:

$$\not{E}'_T = \not{E}_T / (1 + \alpha\, I^{rel}_{comb})$$



Electroweak Background

- Electroweak background composed of:
  - $Z \to ee + Z \to \tau\tau$
  - $W \to \tau\nu$
  - Di-boson: WW, WZ, ZZ
  - ttbar

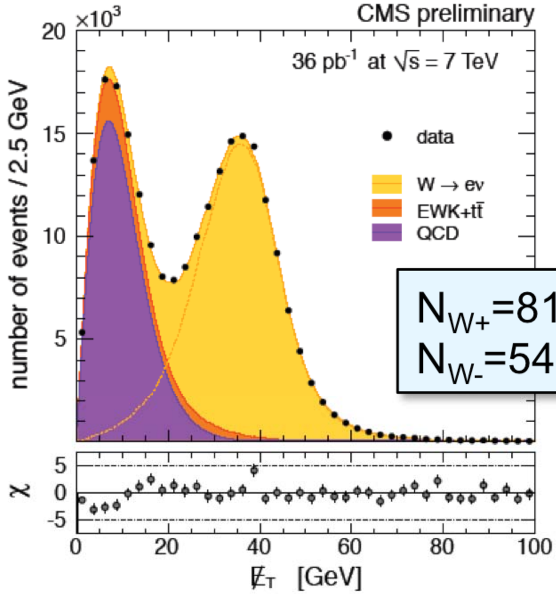


- Shapes for $Z \to ll$ and $W \to \tau\nu$ taken from MC with corrections as for signal
- Shapes for di-boson and ttbar directly from MC
- Normalization of each component w.r.t. signal fixed using theoretical cross -section ratios
  - Signal+EWK treated as a single fixed shape template in the fit

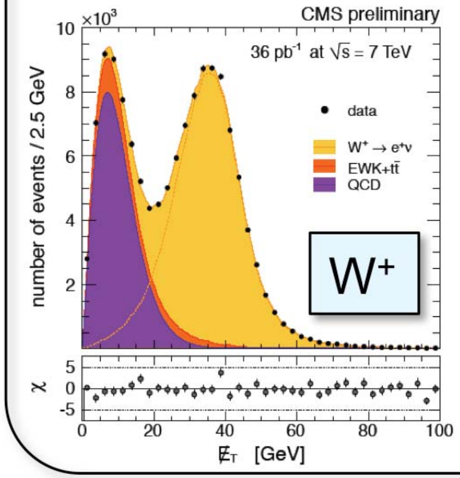
  → combined normalization as the only free parameter

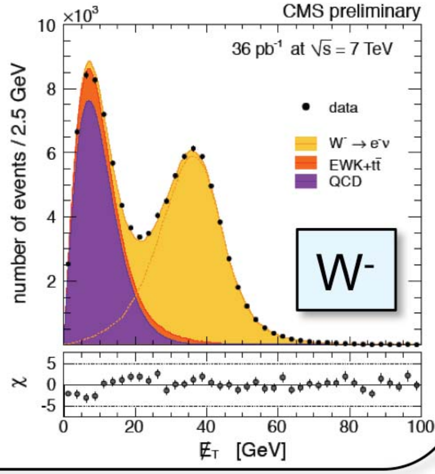
Fit Results

W→eν

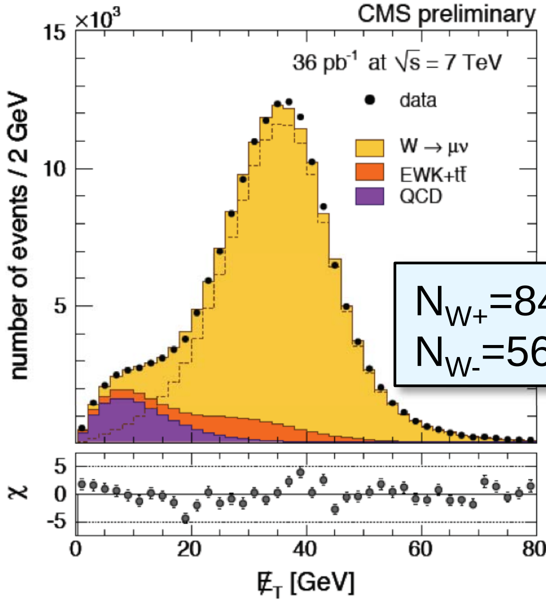


N_{W+}=81568 ±297
N_{W-}=54760 ±246

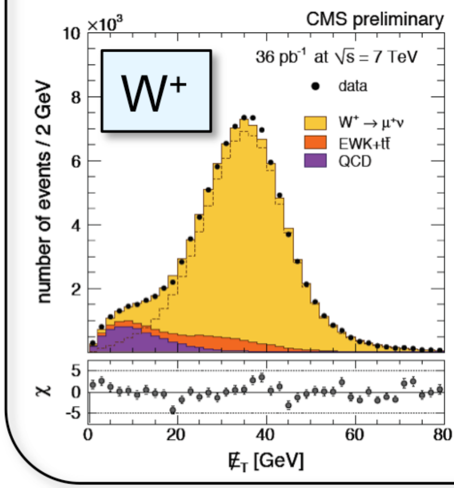


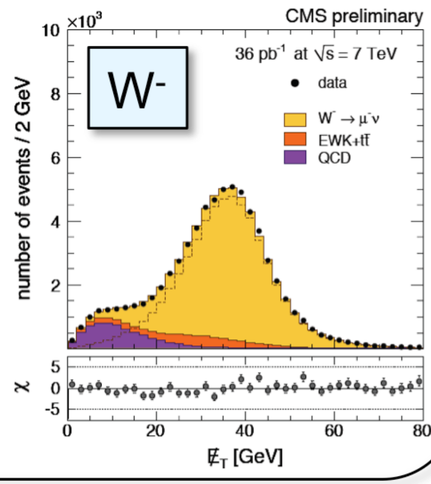


W→μν



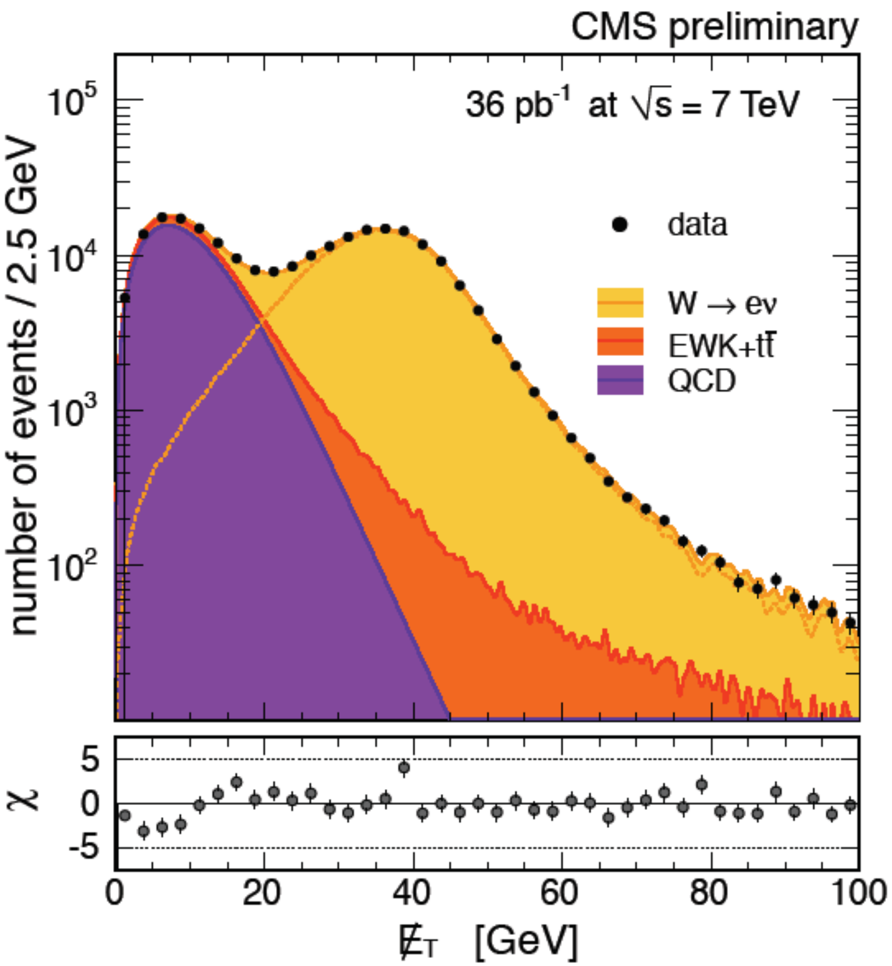
N_{W+}=84292 ±292
N_{W-}=56818 ±240



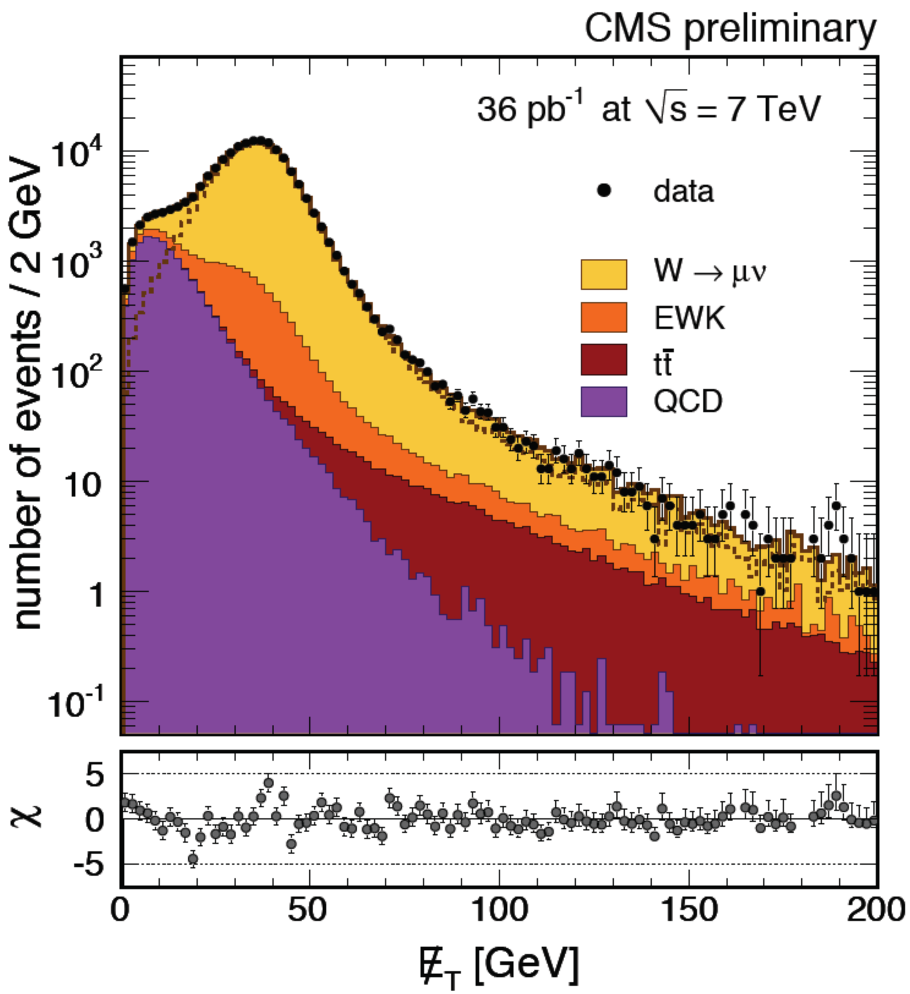


Fit Results

W→eν

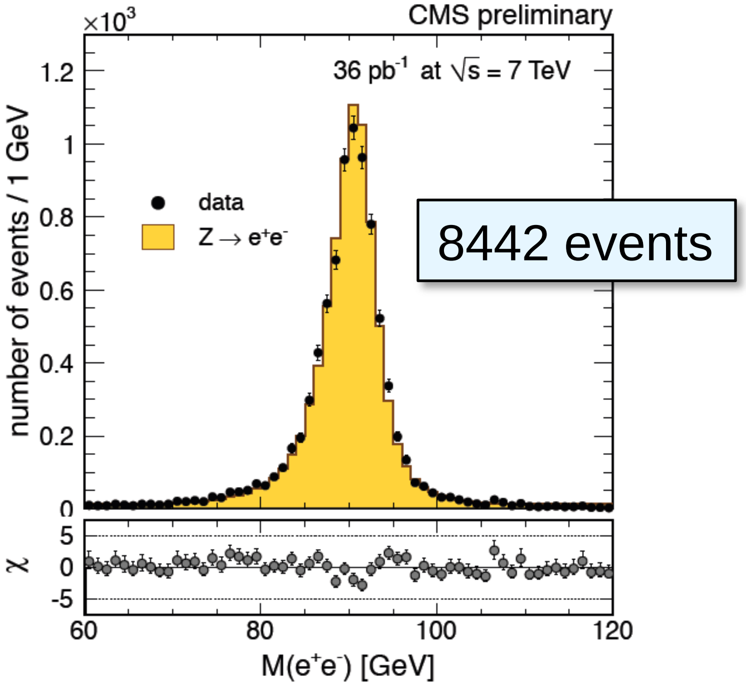


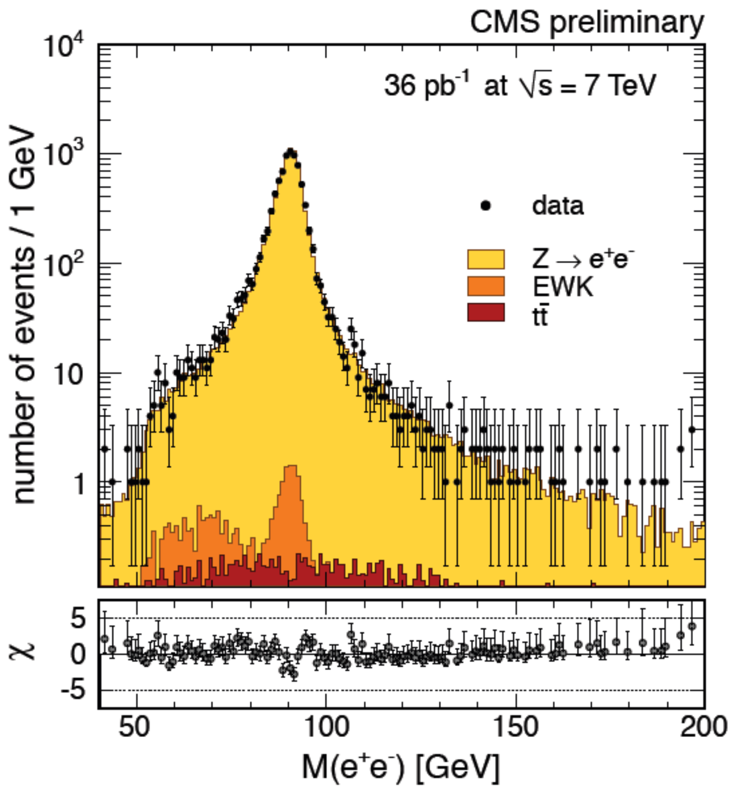
W→μν



Z→ee Signal Extraction

- Cut and count di-lepton events within invariant mass window $60<M_{e+e-}<120$ GeV/c^2
- Corrections applied for energy scale (data) and resolution (MC)

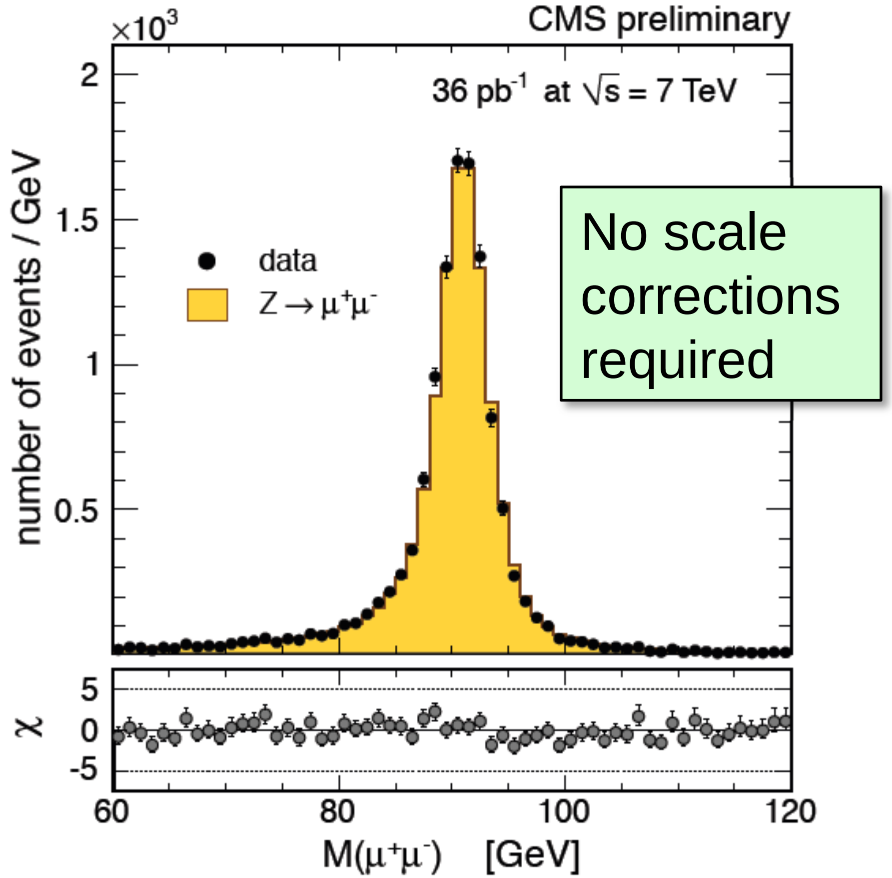


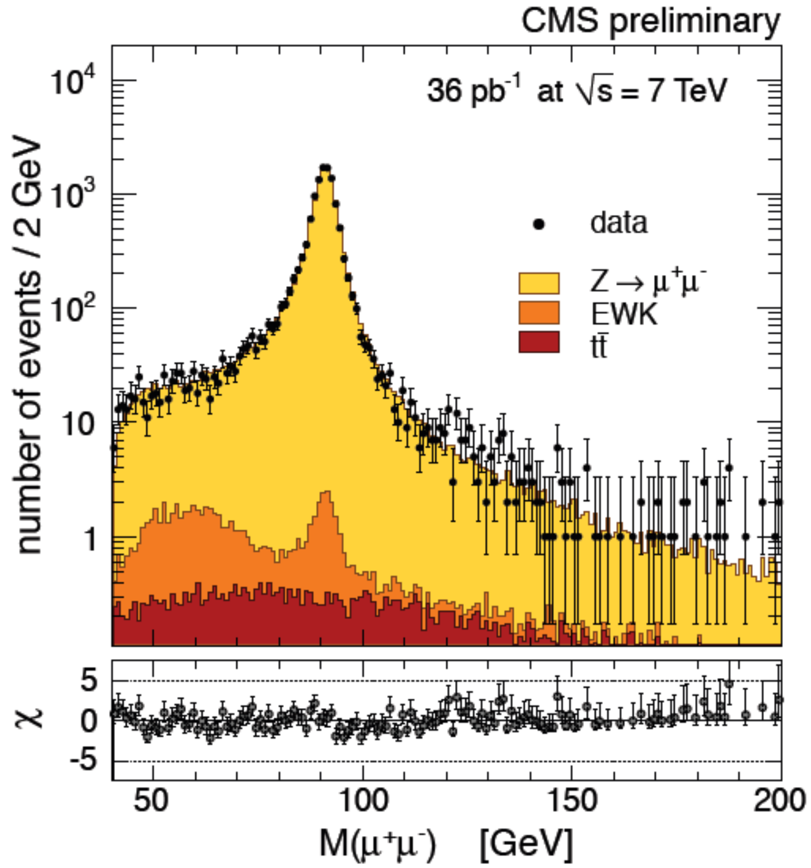


- Subtract background:
  - EWK (Z→ττ, ttbar, di-boson) = 30.8 ± 0.4, from MC using NNLO cross-sections
  - QCD negligible (consistent with 0 events from data driven estimates)

Z→μμ Signal Extraction

- A simultaneous fit is used to extract signal yield and selection efficiency
  - Efficiency corrected yield from fits is N_Z/ε_Z = 13728 ± 121 events





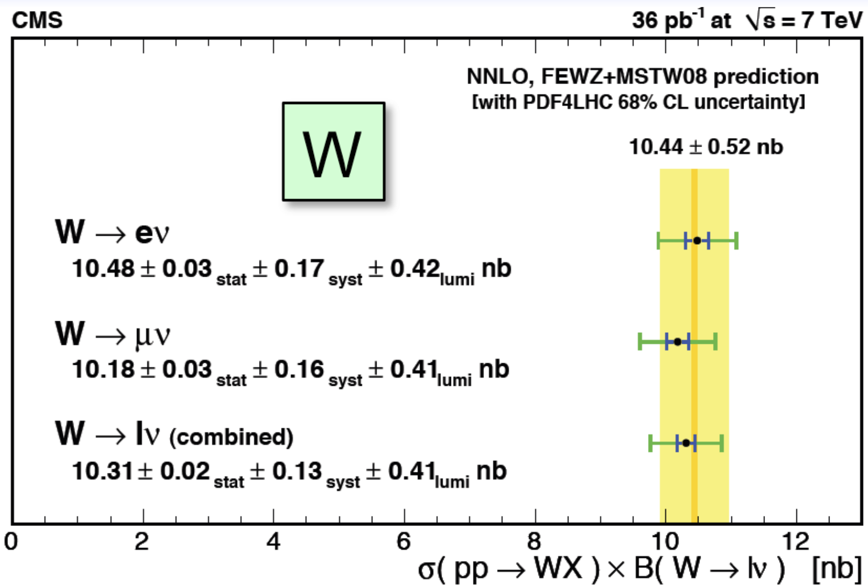
Systematic Uncertainties

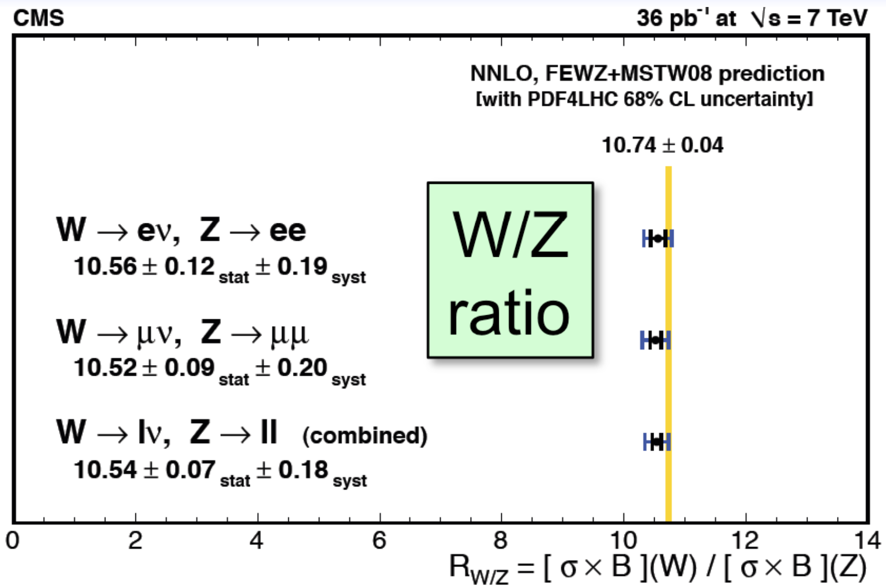
- Breakdown of systematic uncertainties (%)
- Data driven methods used to derive all experimental uncertainties

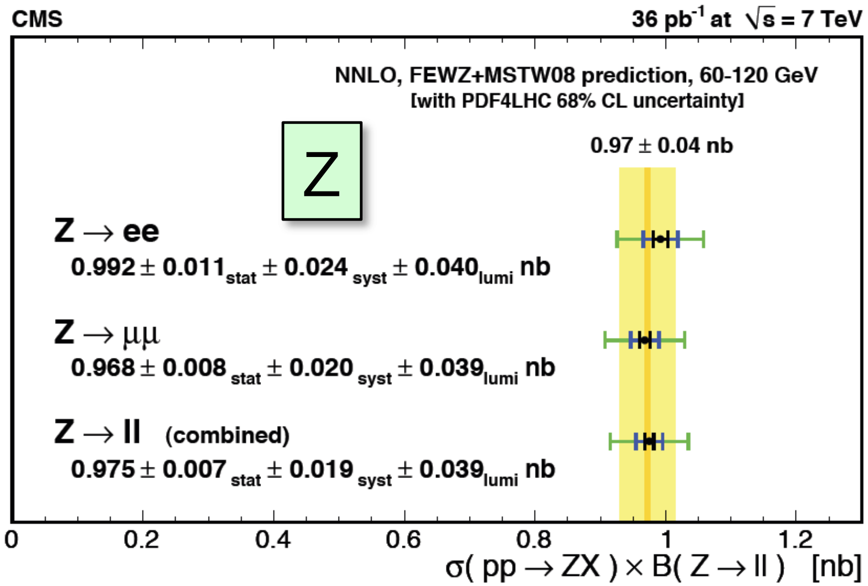
Source	$W\to e\nu$	$W\to\mu\nu$	$Z\to ee$	$Z\to\mu\mu$
Lepton Reco & ID	1.3	0.9	1.8	-
Momentum scale & resolution	0.5	0.22	0.12	0.35
MET scale & resolution	0.3	0.2	-	-
BKG subtraction	0.35	0.4	0.14	0.28
Total experimental	**1.5**	**1.1**	**1.8**	**0.7**
PDF uncertainty for acceptance	0.6	0.7	0.9	1.2
Other theoretical uncertainties	0.7	0.8	1.4	1.6
Total theoretical	**0.9**	**1.1**	**1.7**	**2.0**
TOTAL	**1.7**	**1.6**	**2.5**	**2.1**

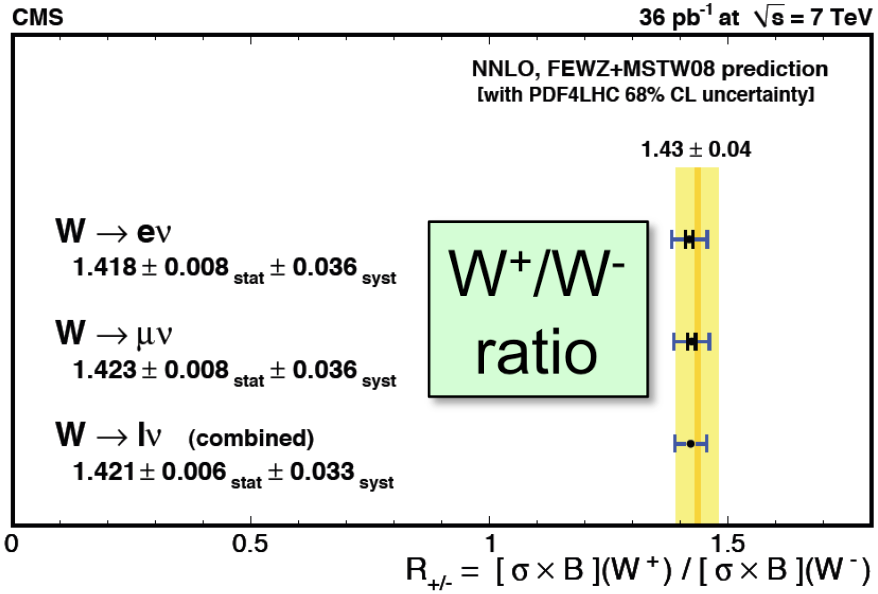
- Uncertainty from integrated luminosity: **4%**

W and Z Cross-section Results

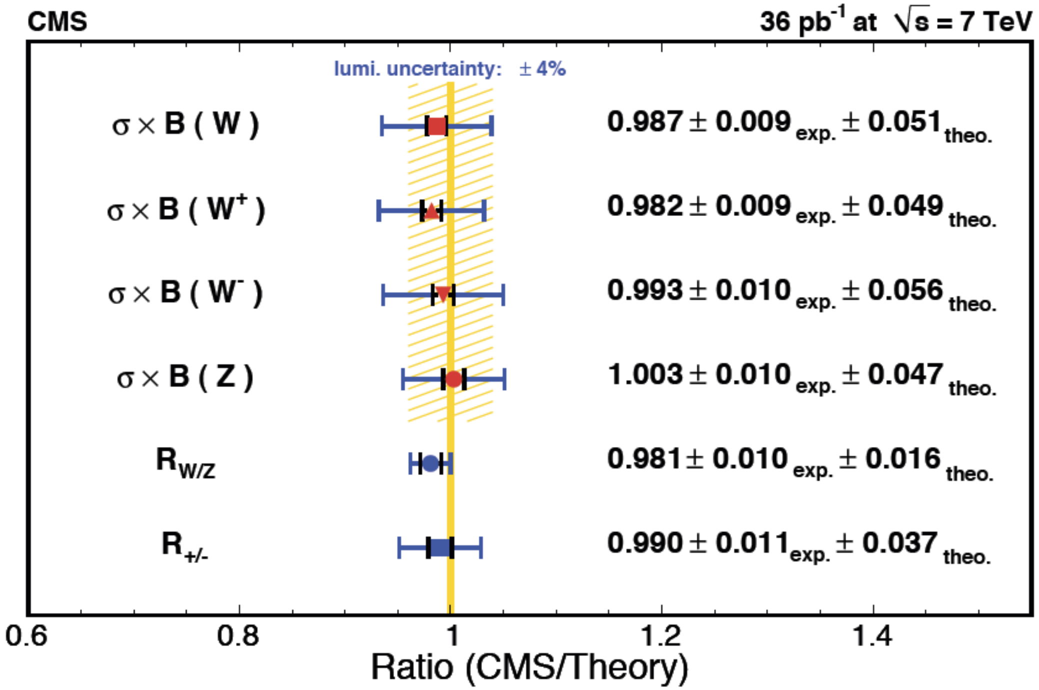


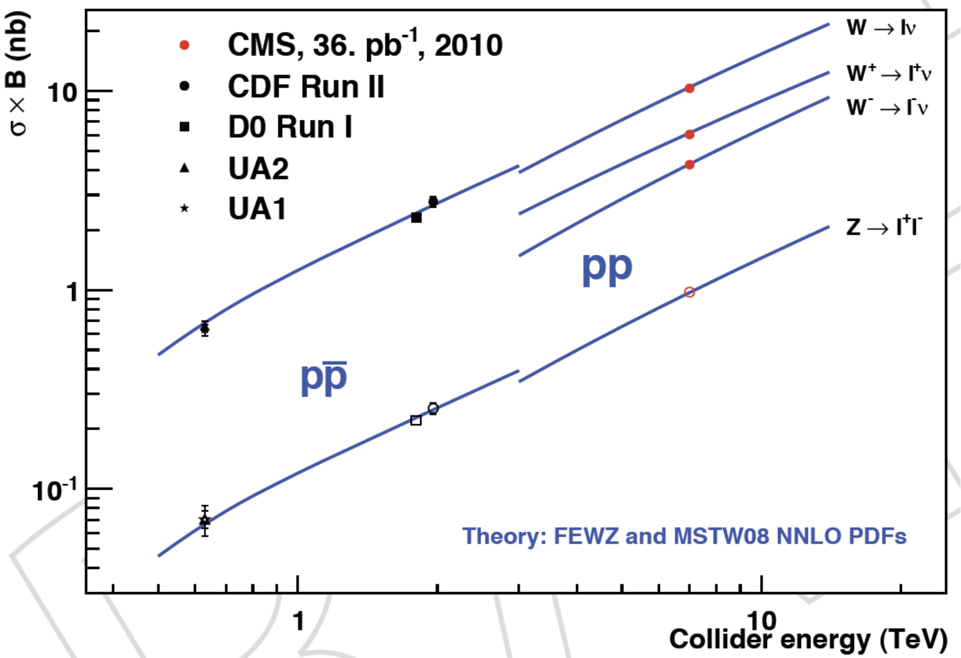






Comparison with Theory





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
- Experimentally accessible observable is the charge asymmetry as a function of lepton pseudorapidity:

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

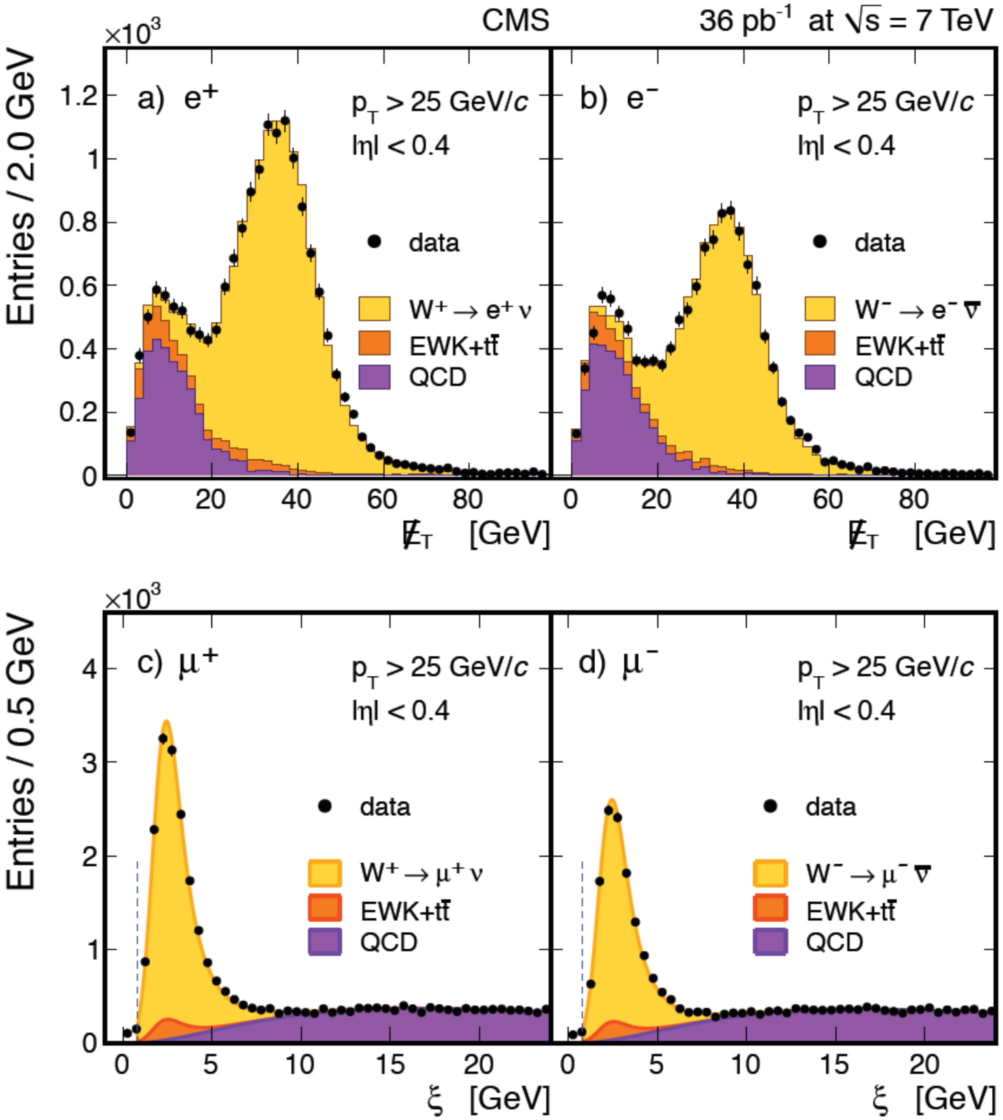
- Analysis performed for both e and μ channels using 6 η bins

W charge asymmetry: Signal Extraction

- W→eν signal extraction as for inclusive measurement using a fit to **particle flow missing E_T**
- W→μν signal extraction with fit to **modified isolation variable**:

$$\xi = \sum_{\Delta R<0.3} [p_T(tracks) + E_T(em) + E_T(had)]$$

  - Signal+EWK shape: convolution of Gaussian with Landau, with parameters fixed using Z→μμ
  - QCD shape: empirical parameterization: $\xi^{\alpha} e^{-\beta\sqrt{\xi}}$
    - α fixed from control sample
    - β allowed to float in the fit
  - EWK normalized to signal using theoretical cross-section ratios

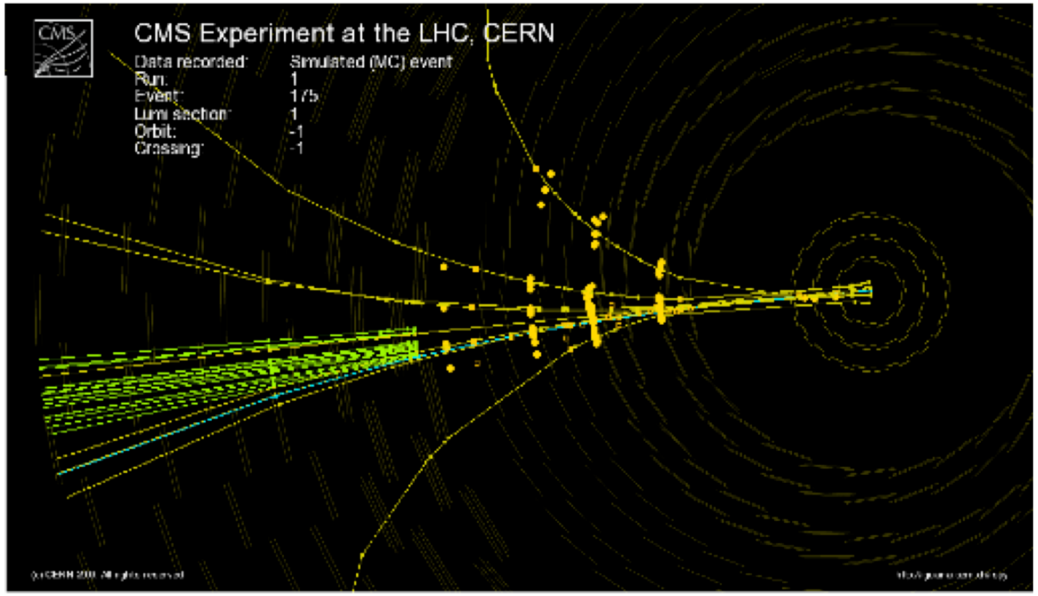


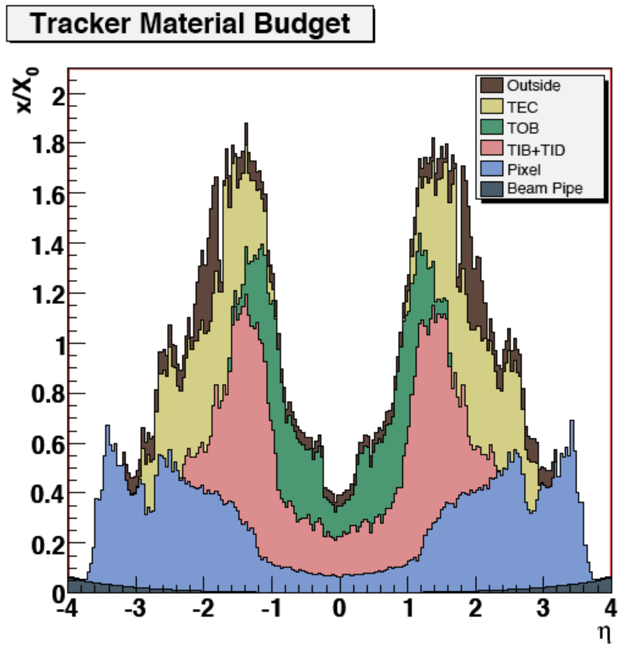
Charge Identification

- For muons, curvature in Silicon Tracker unambiguous in this momentum range
  - Charge mis-ID $<10^{-5}$ in MC, $<10^{-4}$ from cosmic data (track splitting method)

- Electron charge-ID challenging due to bremsstrahlung and conversions

Single MC electron, p_T=35 GeV

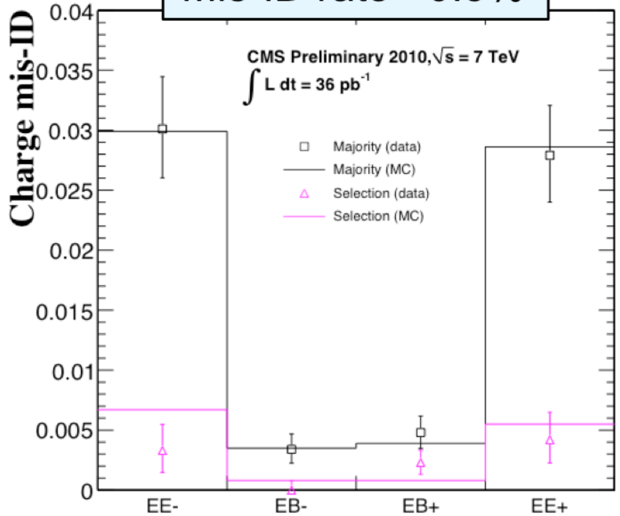


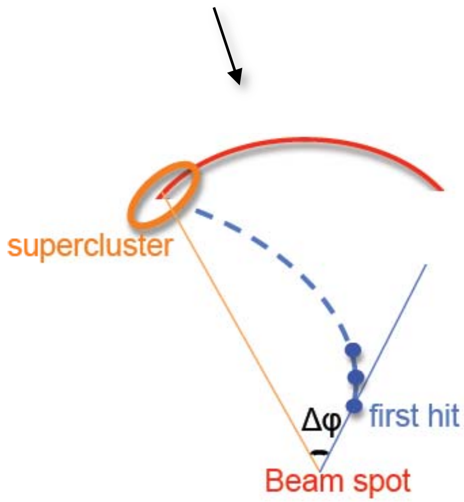


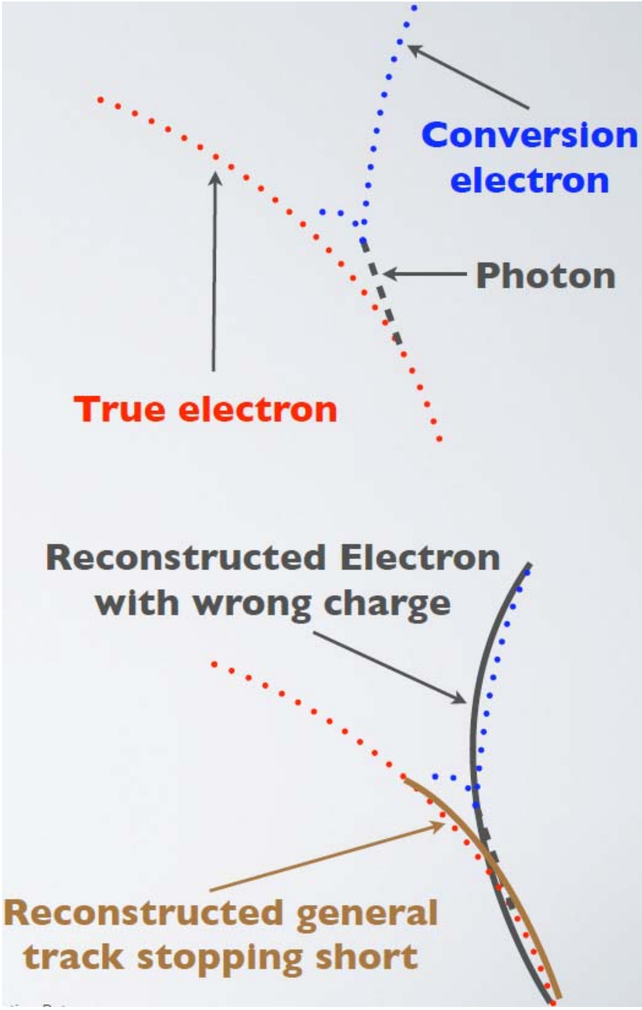
Charge identification

- Minimize charge mis-ID probability by requiring 3 charge assignment measurements to agree
  - Q(CKF track) = q(GSF track) = q(Δϕ)

Mis-ID rate <0.5%

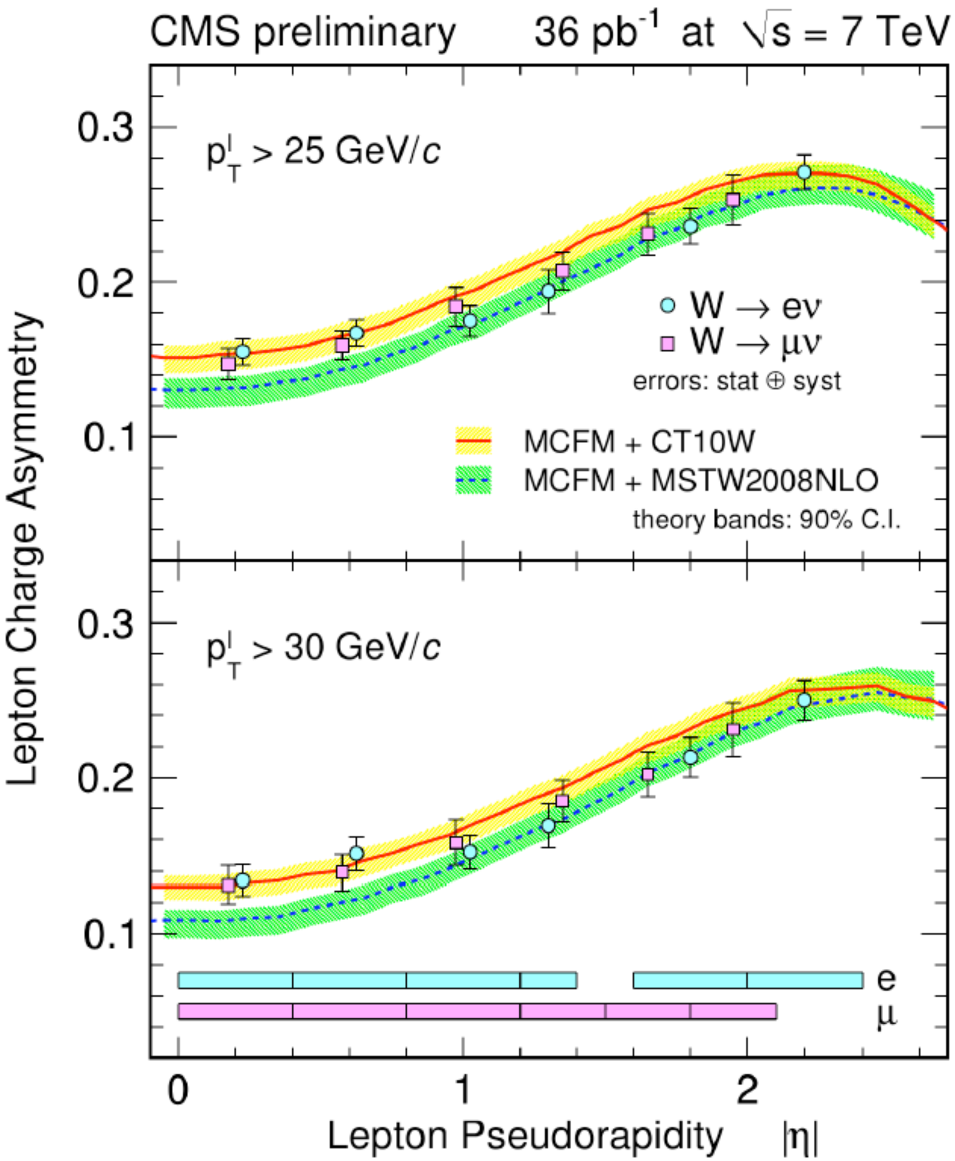






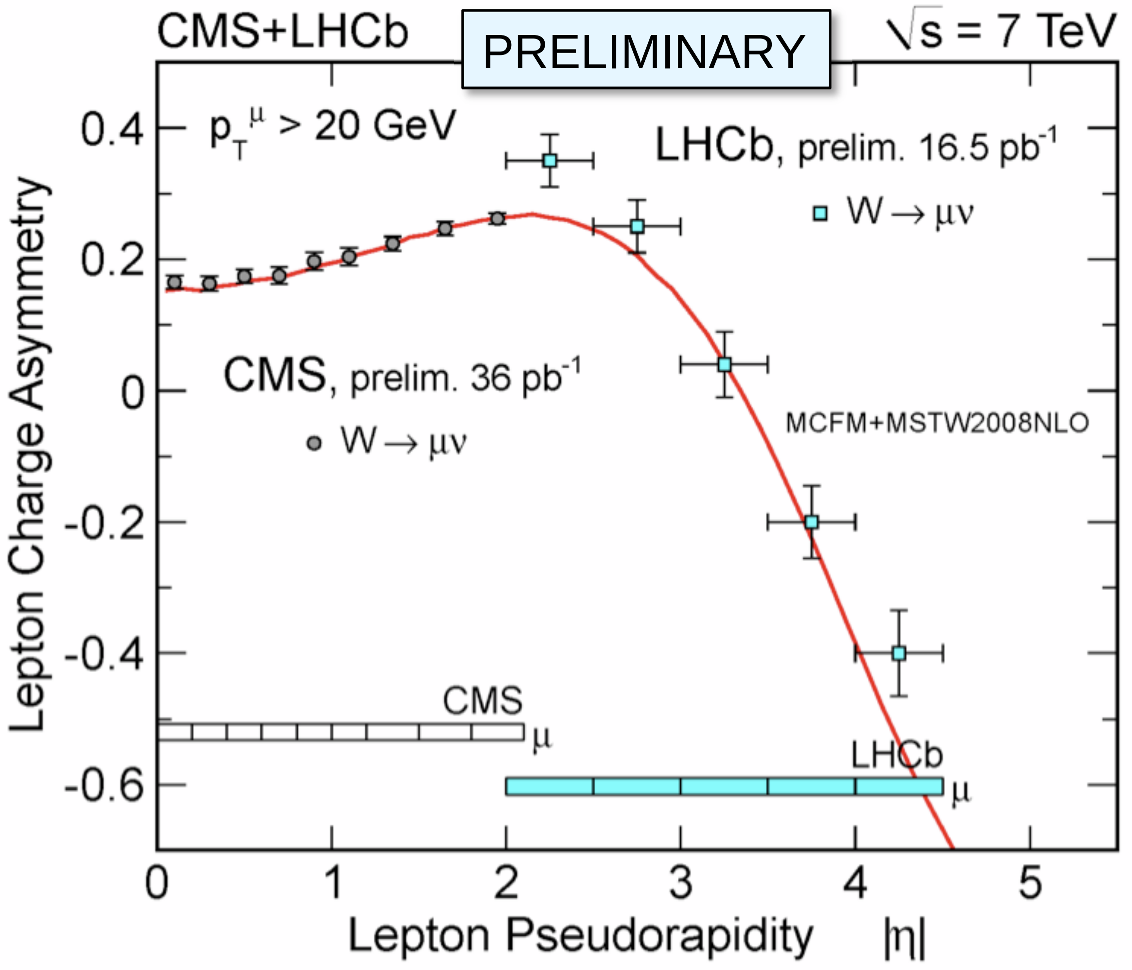
- Asymmetry corrected for measured charge mis-ID
- Uncertainty on correction taken as a systematic

W charge asymmetry: Results



- Results quoted within two well defined regions of phase space:
  - $p_T > 25=30$ GeV, no cut on pT
- Good agreement between electron and muon results
- First constraints on PDF's from LHC

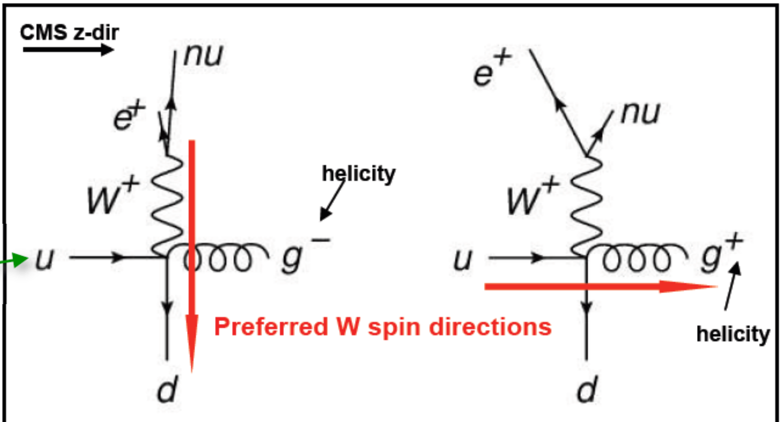
W charge asymmetry: Combination with LHCb



W Polarization

- Dominant production mechanism for high p_T W-bosons (>50 GeV) at the LHC is valence quark - gluon
  - Favours production of **right handed W bosons**, regardless of whether valence quark is u or d – i.e. **true for both W+ and W-**

Replacing u with d changes charge but not helicity



W+1jet dominant production mechanism at LHC (not a Feynman diagram)

First time this has been measured at a proton collider

  - Expect strong polarization effects in the transverse plane → left-right polarization asymmetry expected

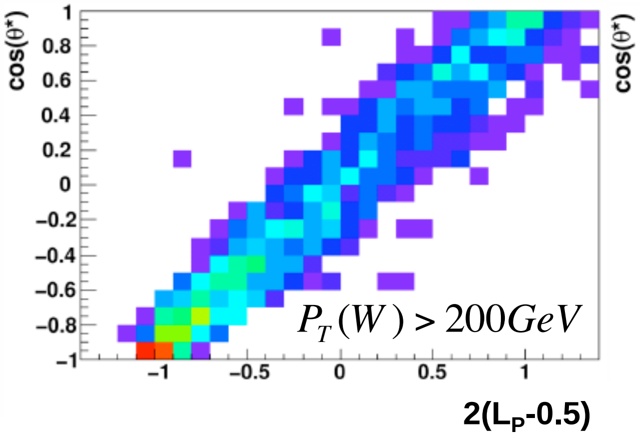
- Differs from ppbar collisions at the Tevatron where antiquark-gluon processes contribute equally, canceling the effect

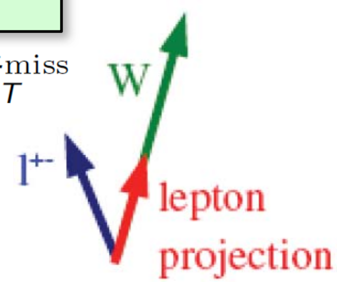
W Polarization: Lepton projection variable

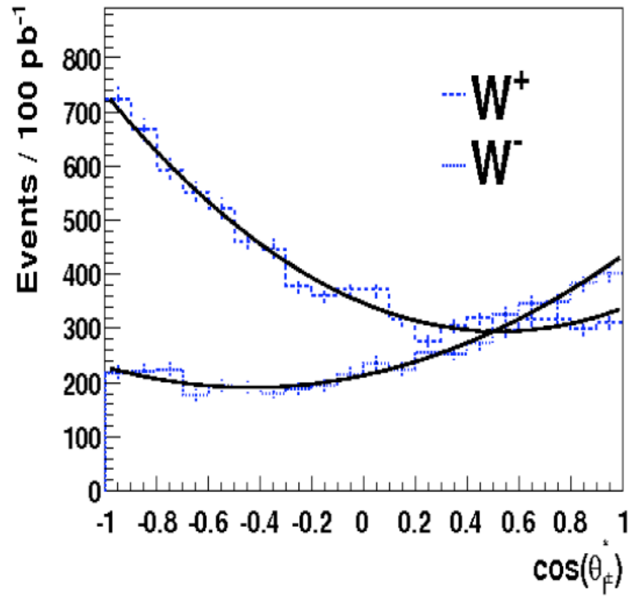
- Polarization characterized by cos(θ*)
  - θ* is the polar angle of the charged lepton in the W rest frame w.r.t. the boson direction in the lab frame
- Cannot measure cos(θ*) directly because longitudinal component of neutrino momentum (and hence the boson momentum) is unknown
- Need a detector level quantity which is highly correlated with cos(θ*) → **Lepton projection variable**:

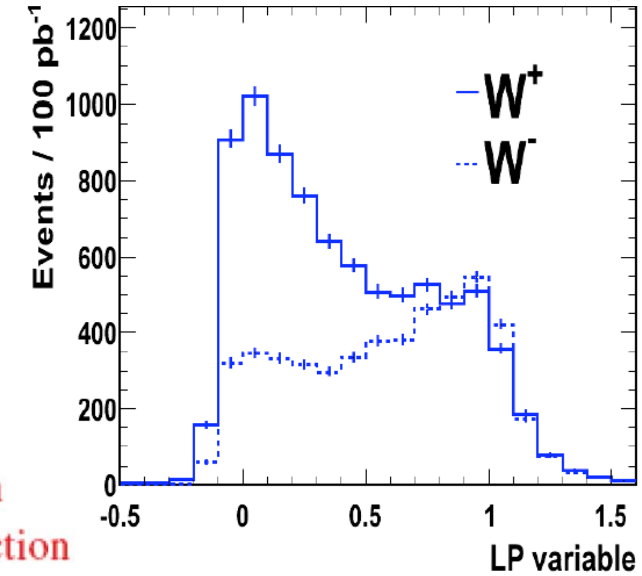
$$L_P = \frac{\vec{P}_T(\ell)\cdot\vec{P}_T(W)}{\left|\vec{P}_T(W)\right|^2}$$

$$\vec{P}_T(W) = \vec{P}_T(\ell) + \vec{E}_T^{\rm miss}$$



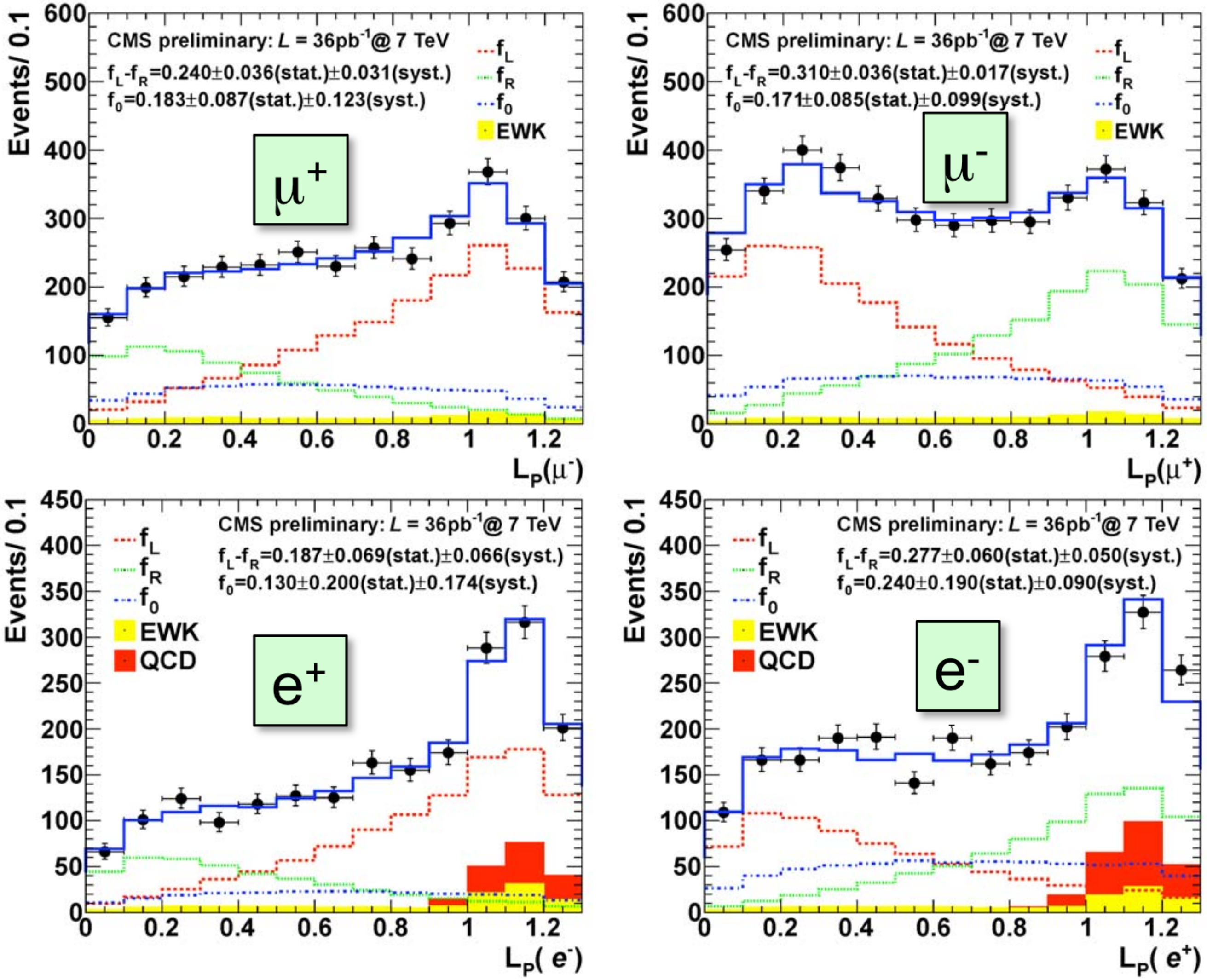






W Polarization: Fit results

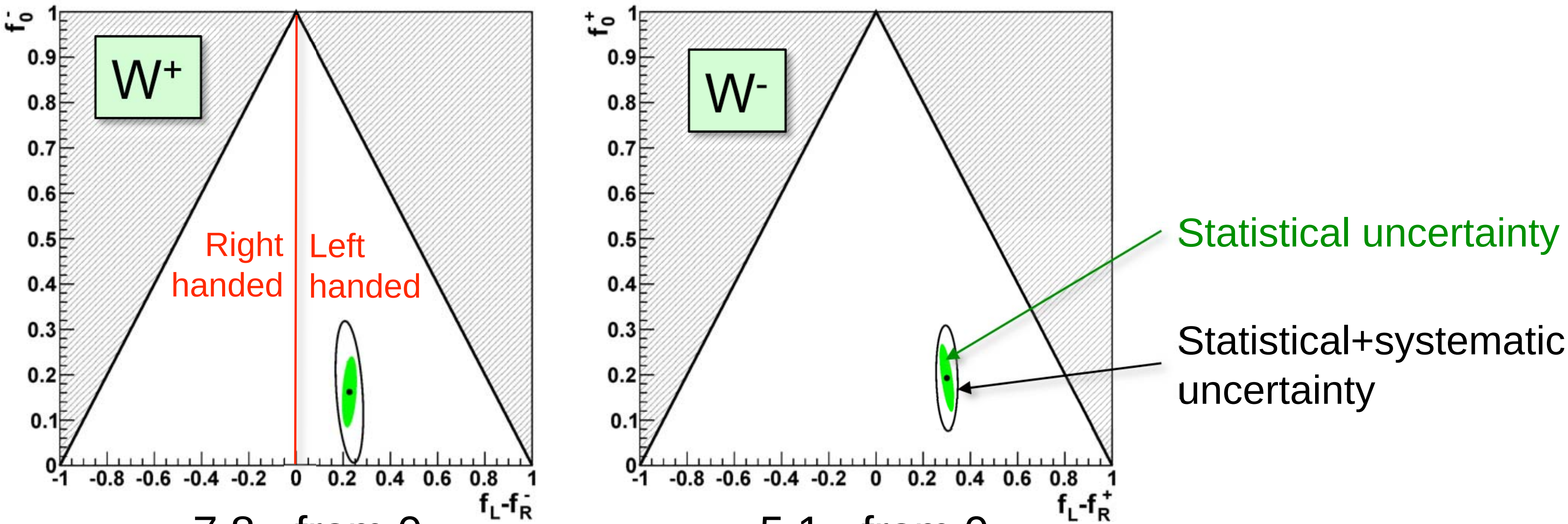
- Fit templates from MC corresponding to each helicity state to the L_P distribution:
  - f_L = left handed
  - f_R = right handed
  - f_0 = longitudinal



- For electron case, QCD background is non-negligible
  - Template shape derived from data (inverted electron ID)
  - Normalization allowed to float in fit

W Polarization: Simultaneous fit

- Perform simultaneous fit for electron and muon channels

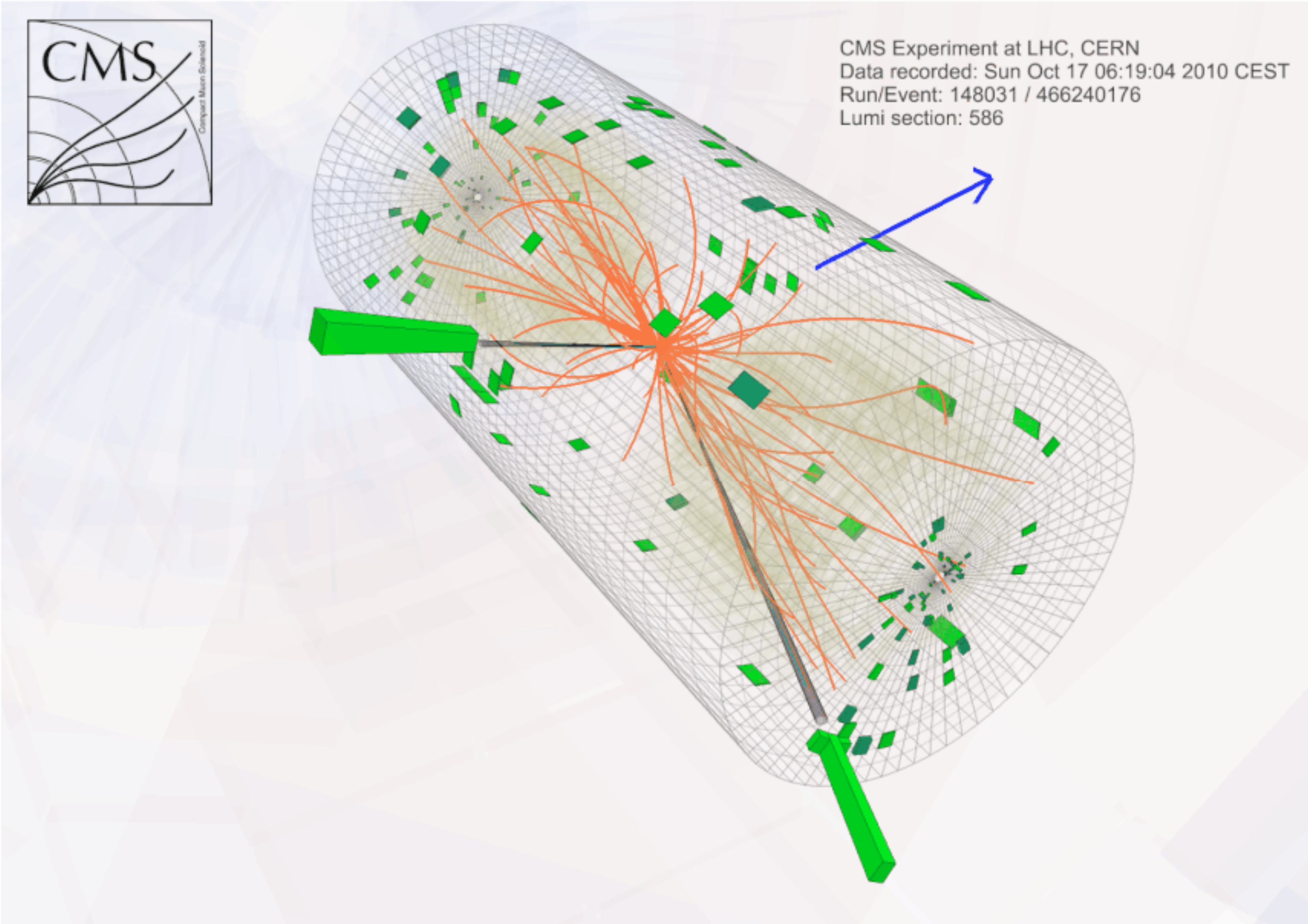


7.8σ from 0

5.1σ from 0

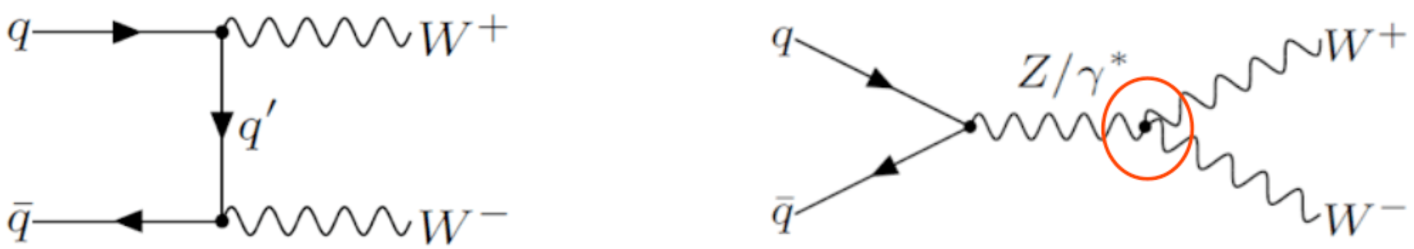
(fL-fR)-	0.226 ± 0.031 (stat) ± 0.050 (syst)
f0-	0.162 ± 0.078 (stat) ± 0.136 (syst)
(fL-fR)+	0.300 ± 0.031 (stat) ± 0.034 (syst)
f0+	0.192 ± 0.075 (stat) ± 0.089 (syst)

WW Cross-Section Measurement



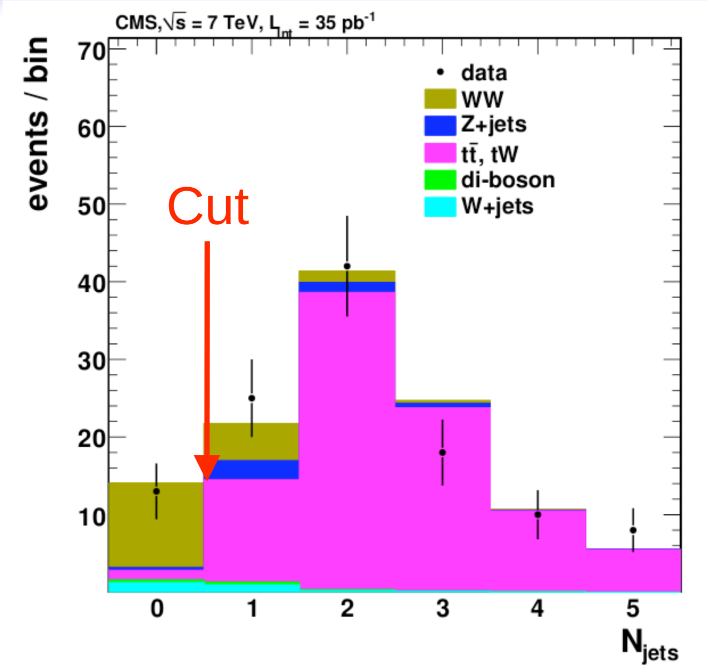
WW Cross-Section Measurement

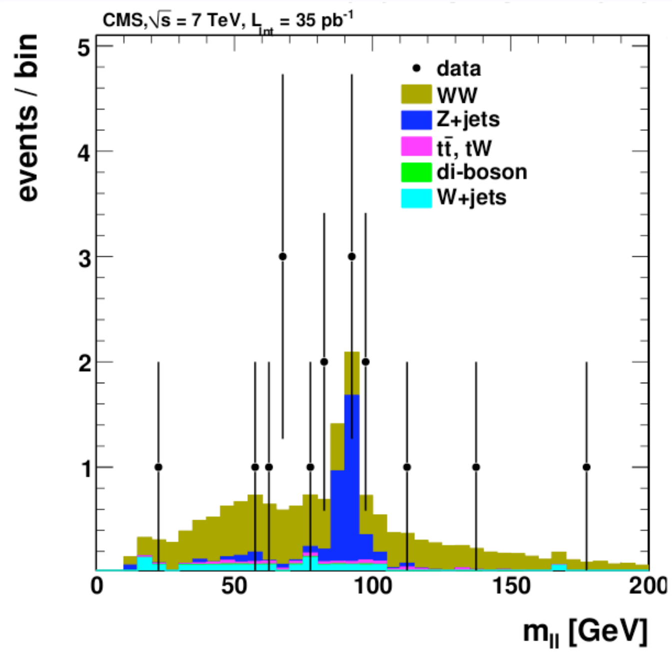
- Provides a benchmark for Higgs and new physics searches
  - Standard Model WW production is the dominant background for the Higgs → WW search
  - New physics inducing anomalous WWγ and WWZ triple-gauge-boson couplings (aTGC) enhances the WW production cross section at high p_T



- Simple cut and count method
- Fully leptonic decay channels only (ee, μμ, eμ)
- Select events with two oppositely charged isolated high p_T leptons with significant missing transverse energy
  - Explicit Drell-Yan and top vetos

WW cross-section: Results





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

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

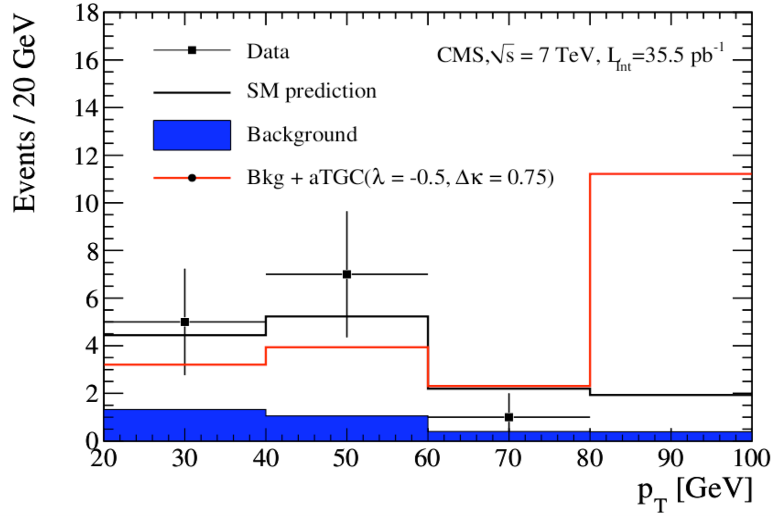
NLO prediction: 43.0 ± 2.0 pb

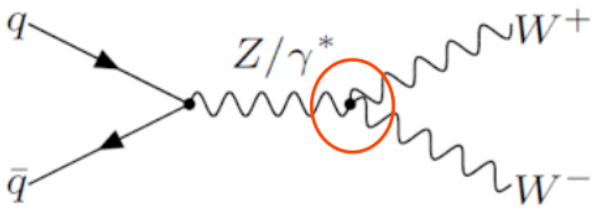
$$\frac{\sigma_{WW}}{\sigma_W} = (4.46 \pm 1.66 \pm 0.64) \cdot 10^{-4}$$

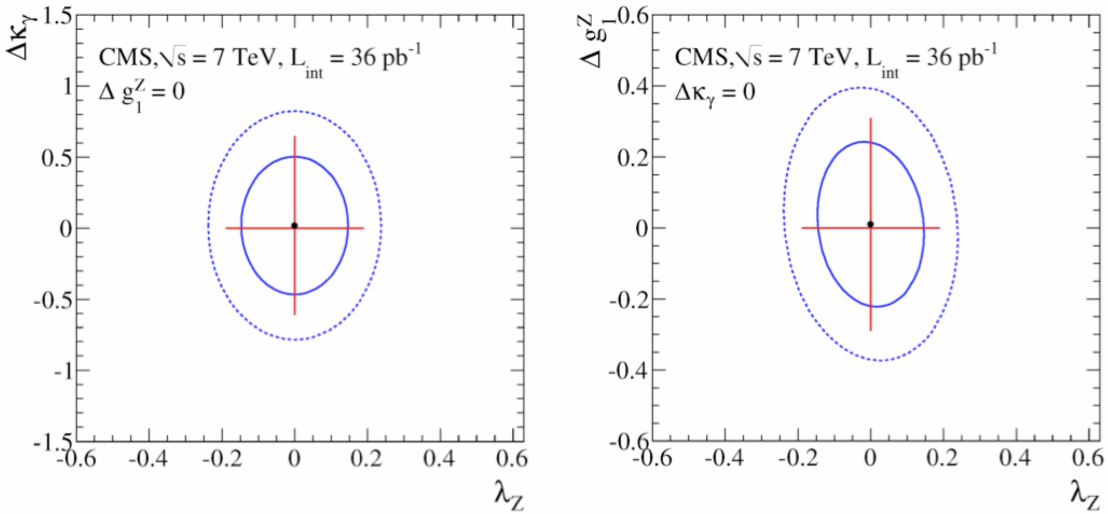
NLO prediction: $(4.45 \pm 0.30).10^{-4}$

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

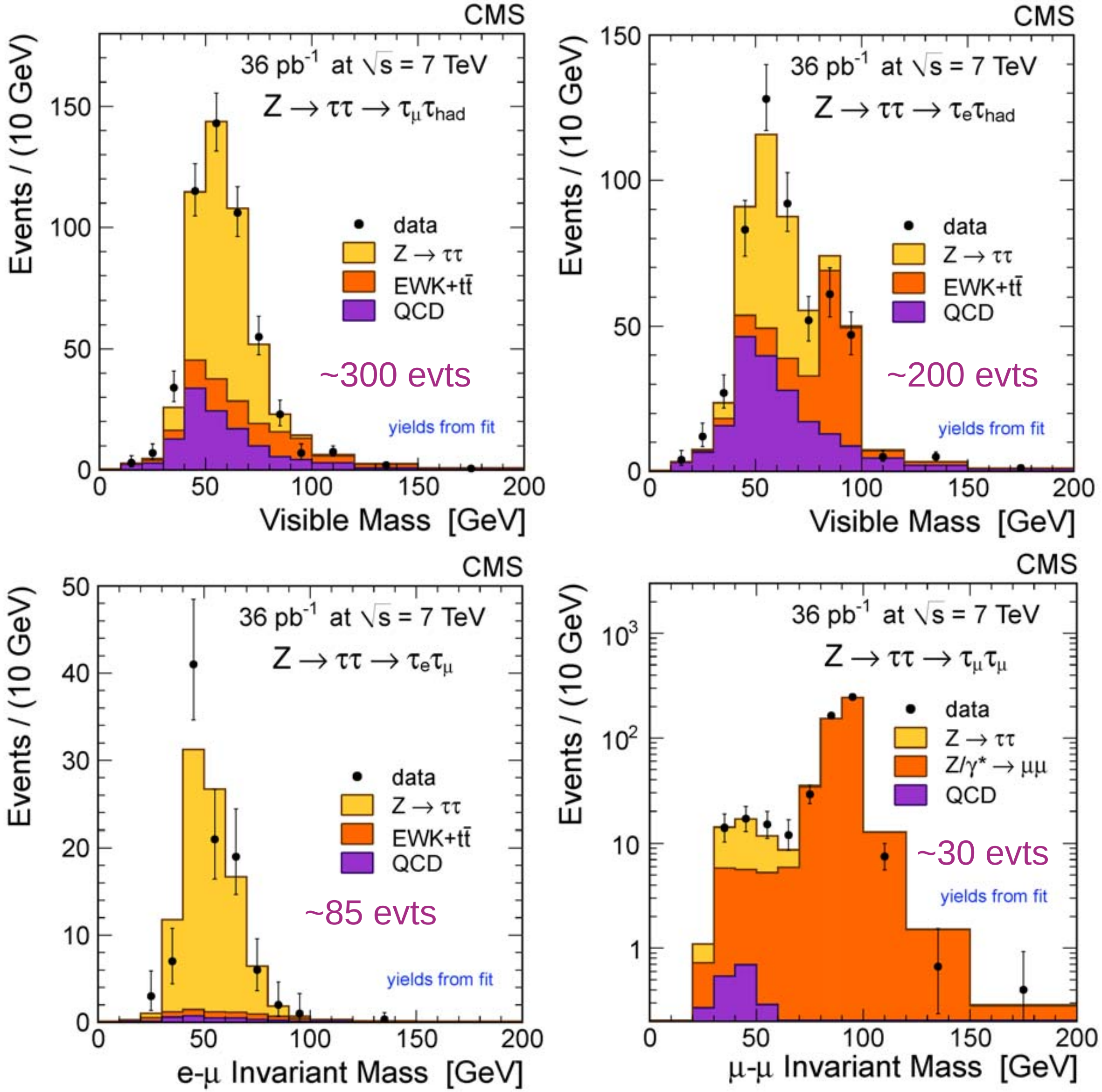


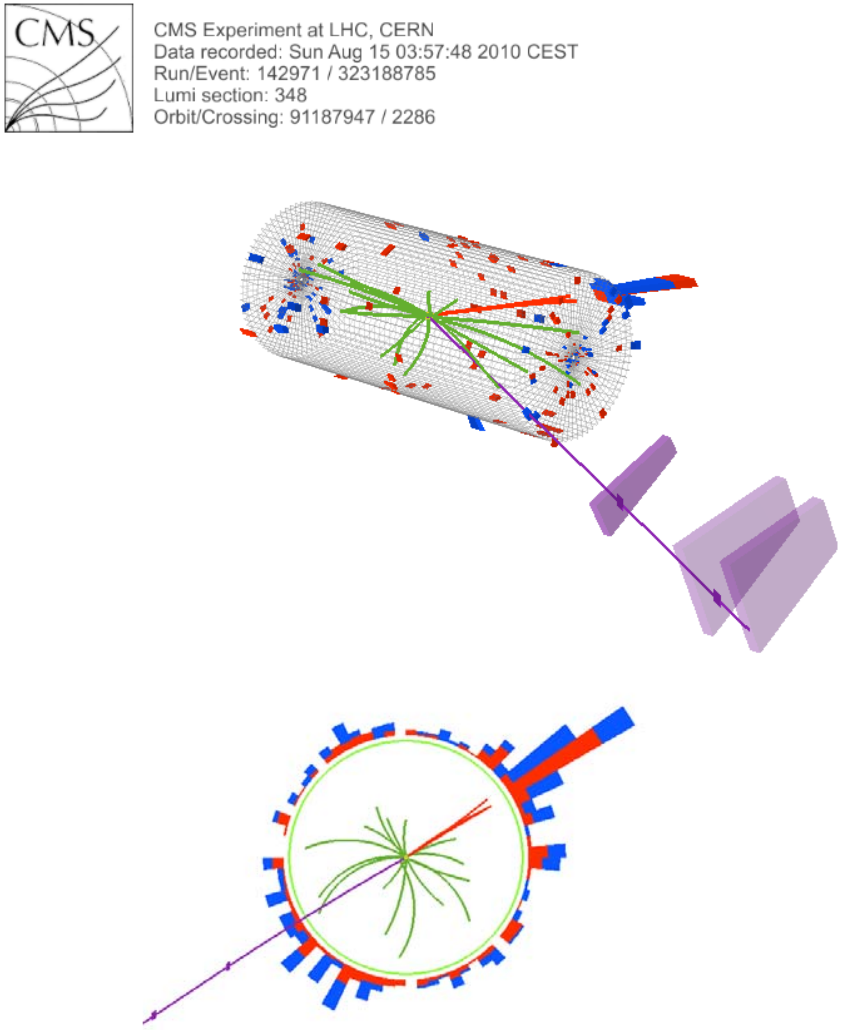




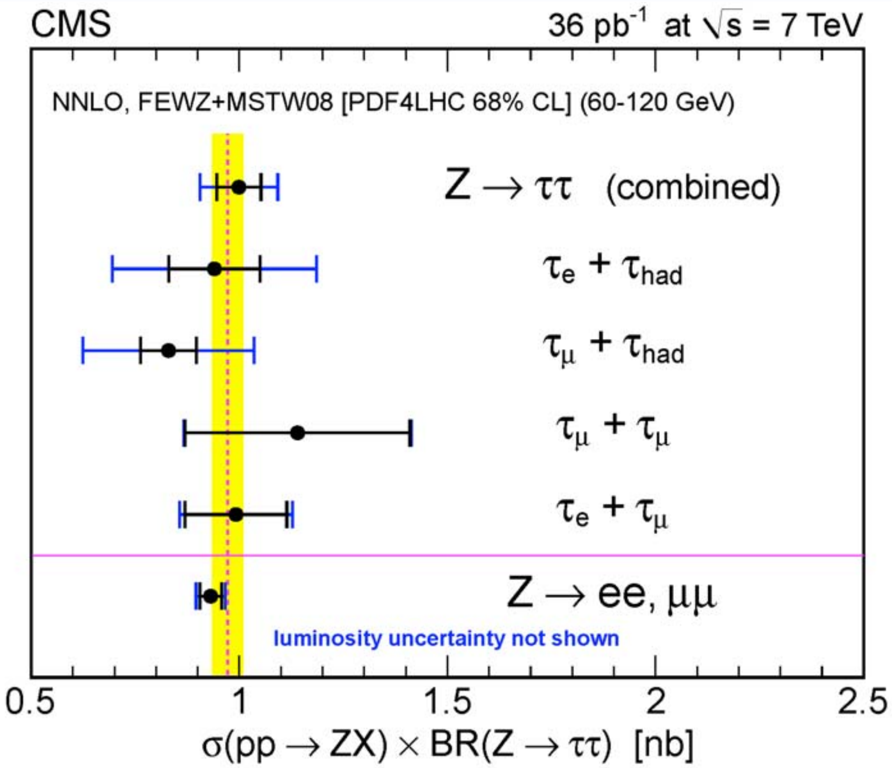
- Limits are consistent with SM and are comparable with current Tevatron results

Z→ττ Cross-section Measurement

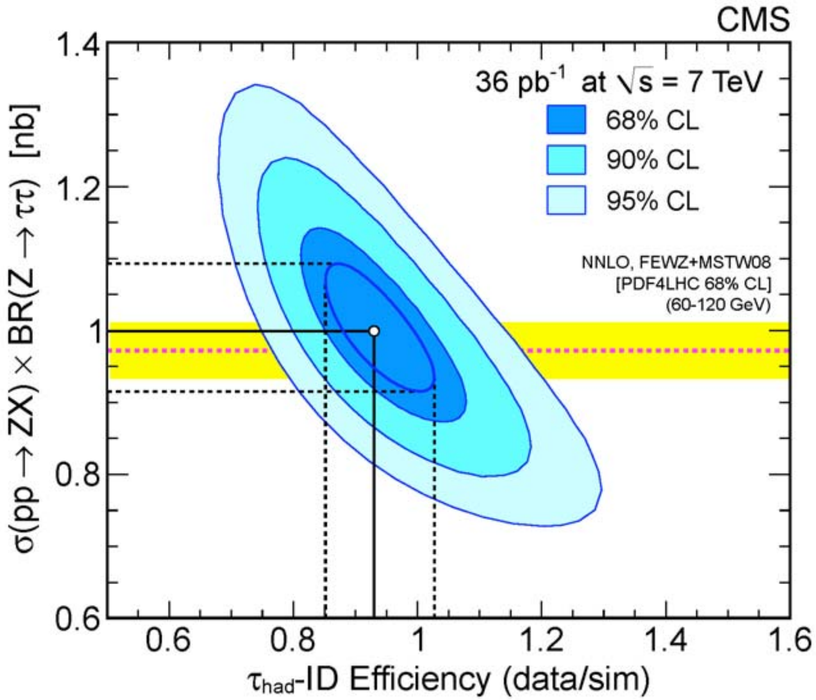




$Z \rightarrow \tau\tau$ Cross-section Measurement

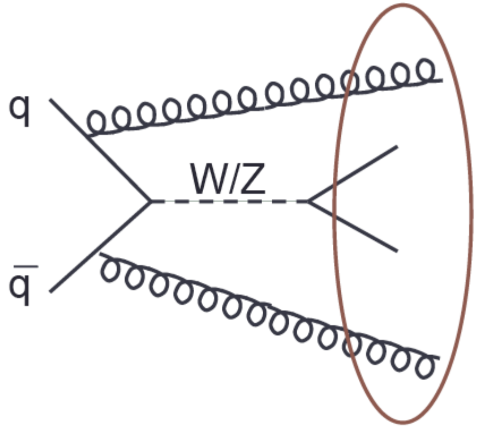


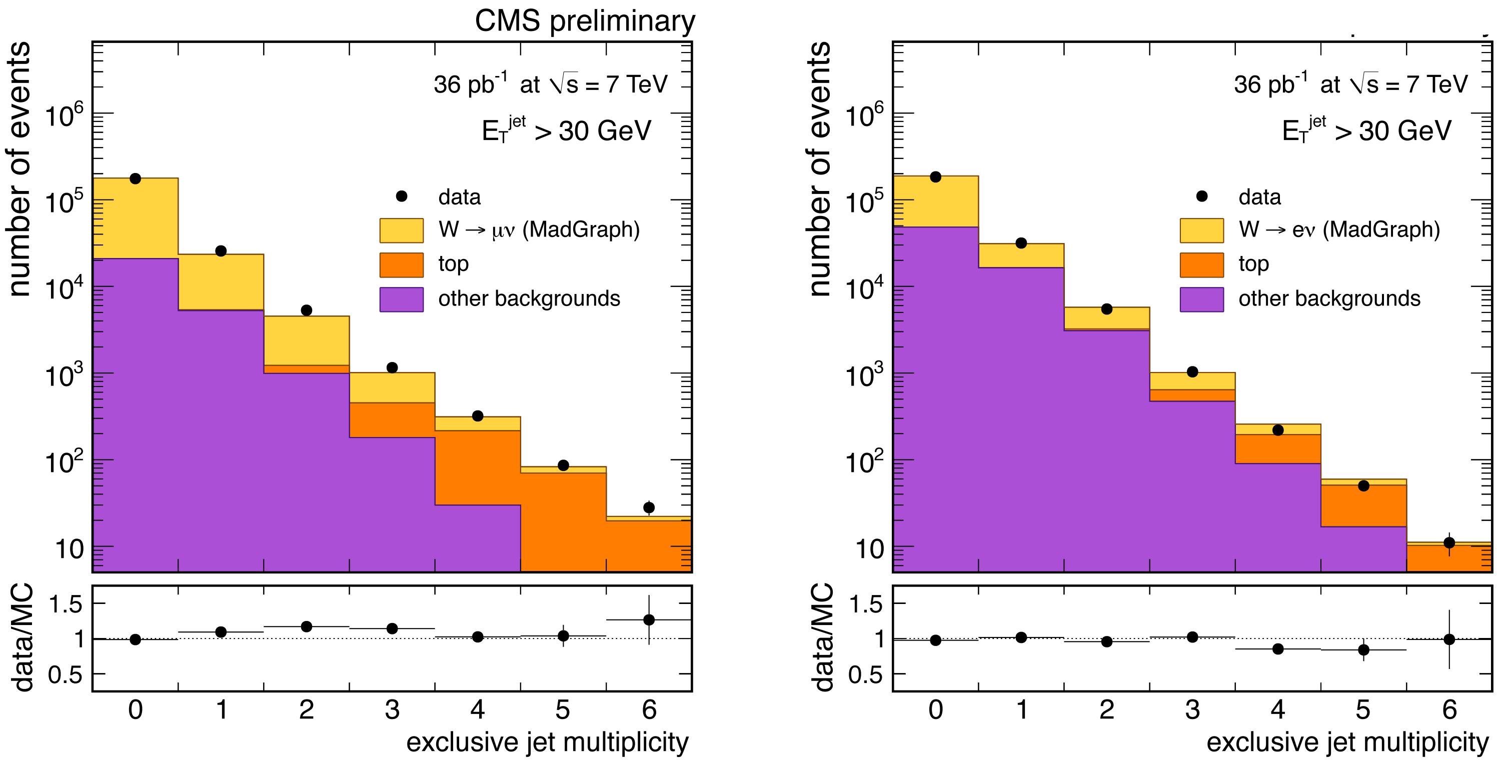
- Global fit of the $\tau_\mu\tau_{had}$ and $\tau_e\tau_{had}$ channels with the cross-section fixed to the value measured for $Z \rightarrow ee,\mu\mu$ provides a 7% constraint on the hadronic tau reconstruction efficiency



W and Z +Jets

- High p_T lepton + jets is an important final state for many new physics searches
- Cross-sections difficult to calculate, especially for high nJets



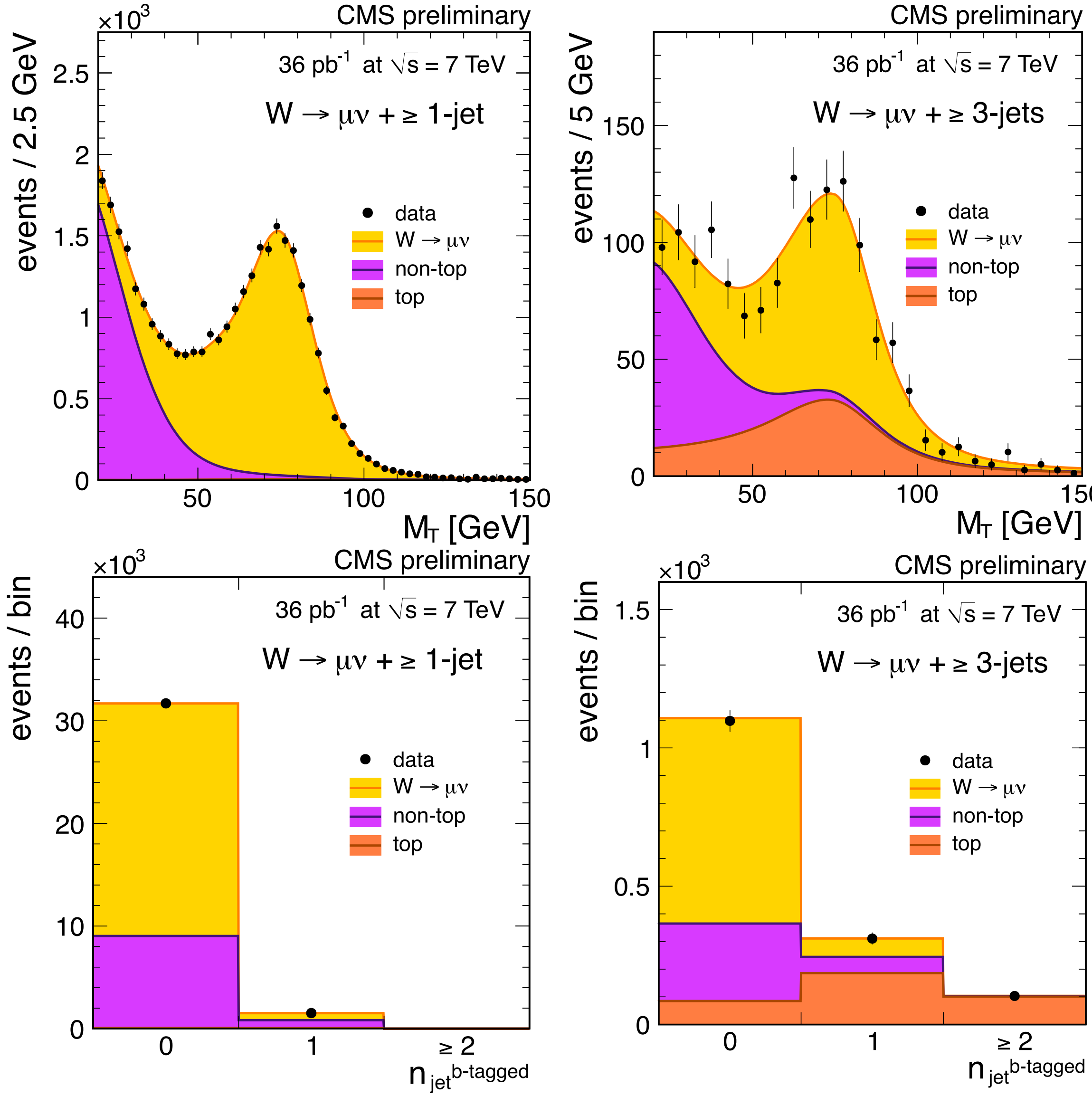


W +Jets signal extraction

- For each njet multiplicity bin fit the 2D distribution of M_T vs $n_{jets}^{btagged}$

QCD normalization

Top normalization

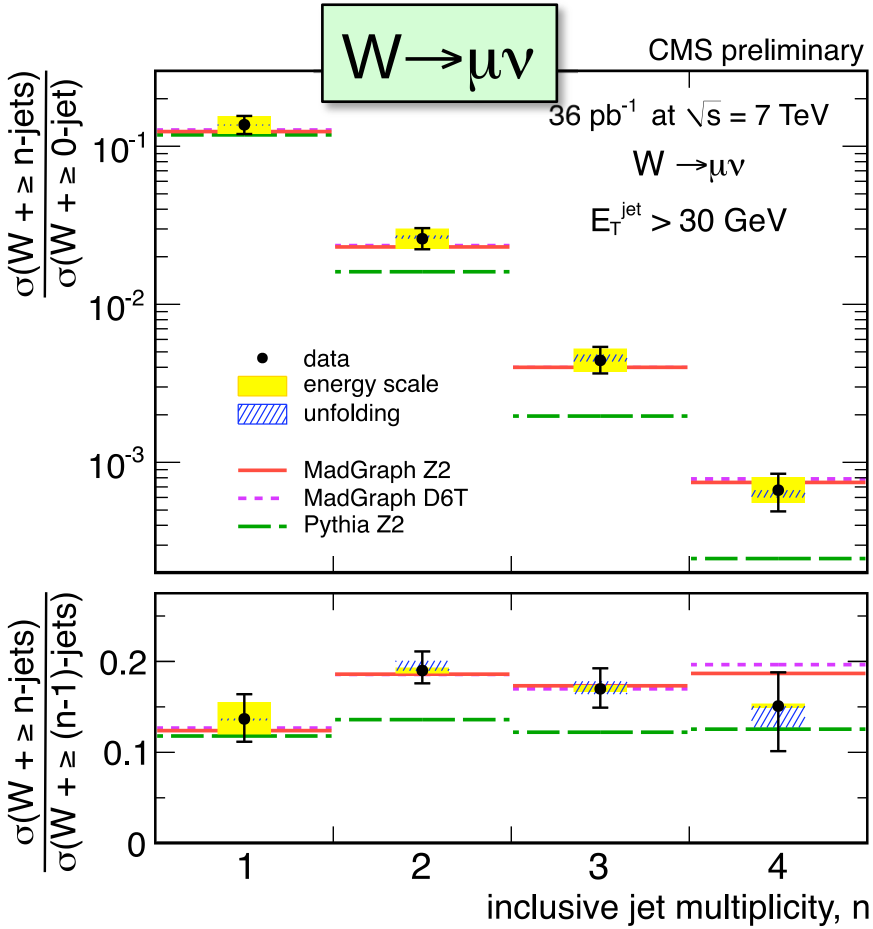


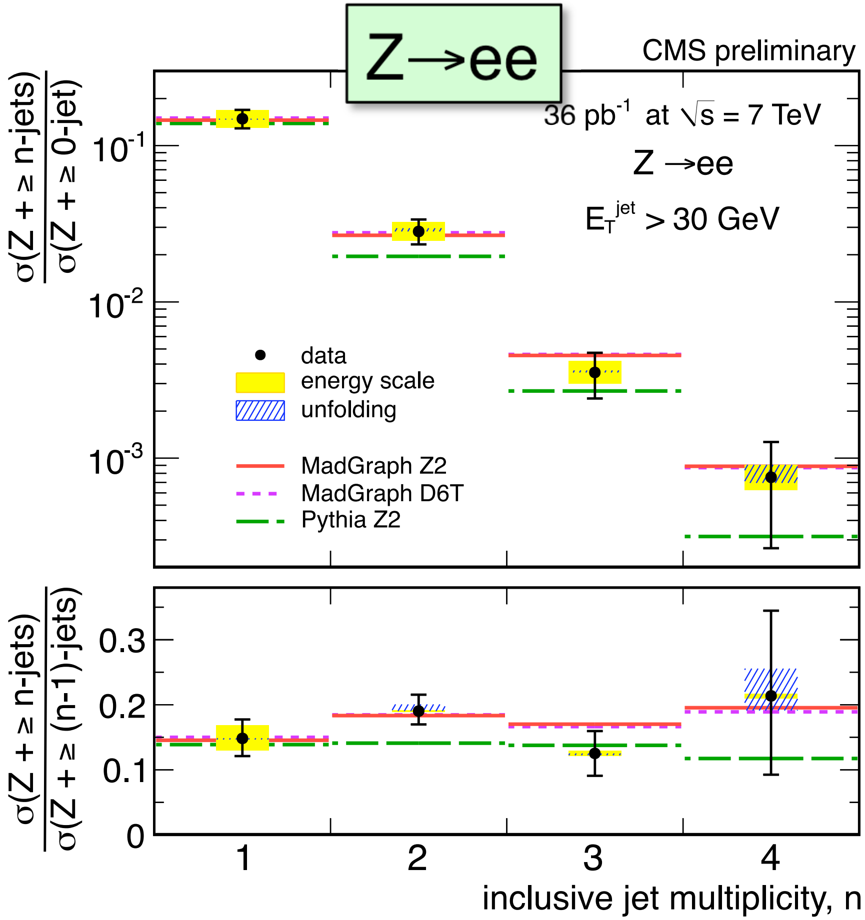
W and Z + Jets cross-sections

- Measure cross-section ratios:

$$\sigma(V + njets)/\sigma(V_{tot})$$

$$\sigma(V + njets)/\sigma(V + (n-1)jets)$$

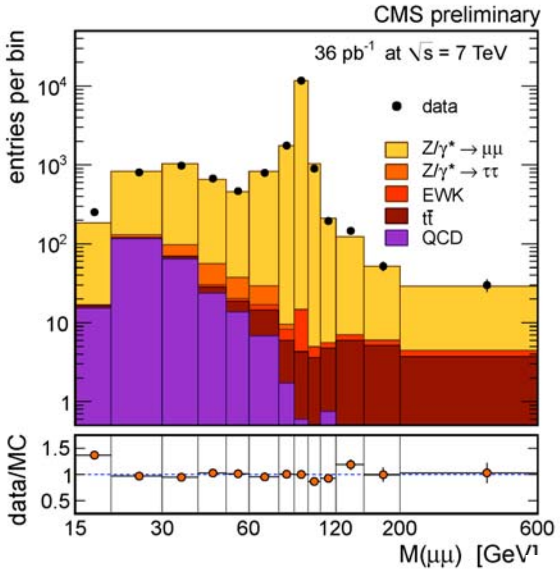


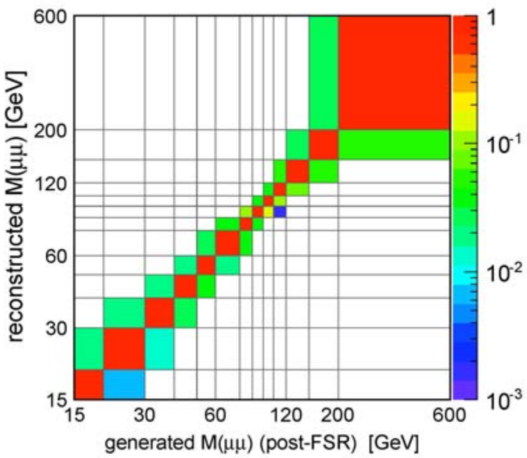


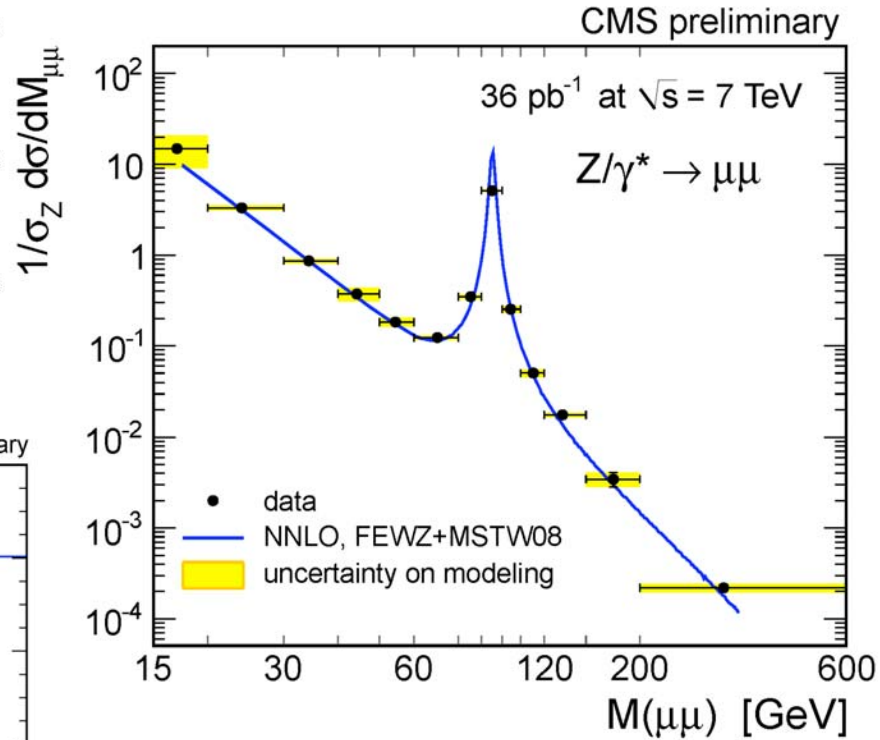
Drell-Yan differential cross-section: dσ/dM

- Correct for resolution effects using MC response matrix ("unfolding")

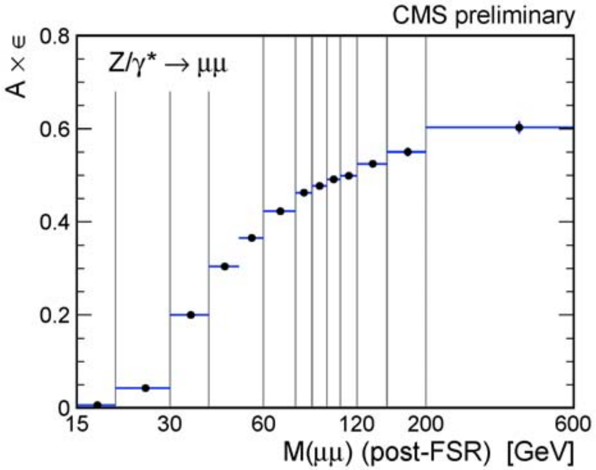
$$N_i^{obs} = \sum_k T_{ik} N_k^{true}$$





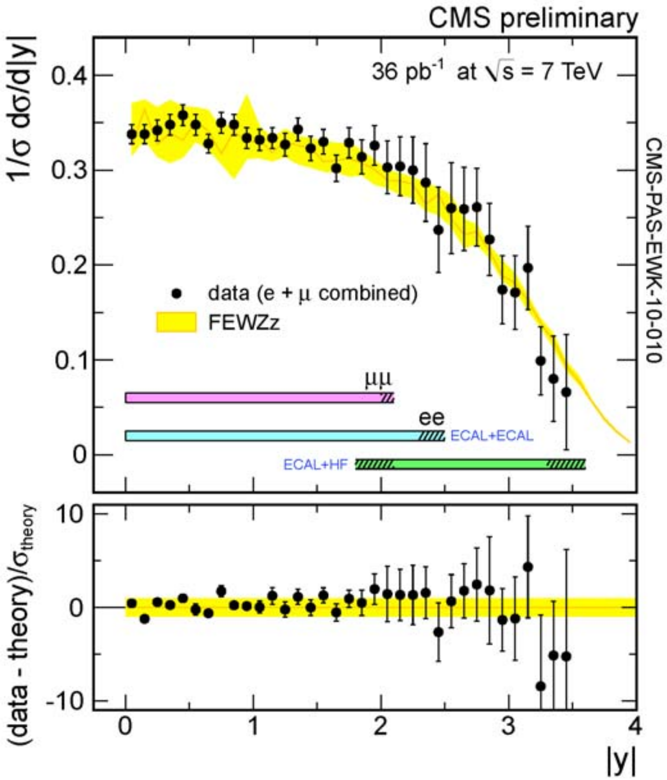


- A×ε from MC with corrections to efficiency from data (tag and probe)

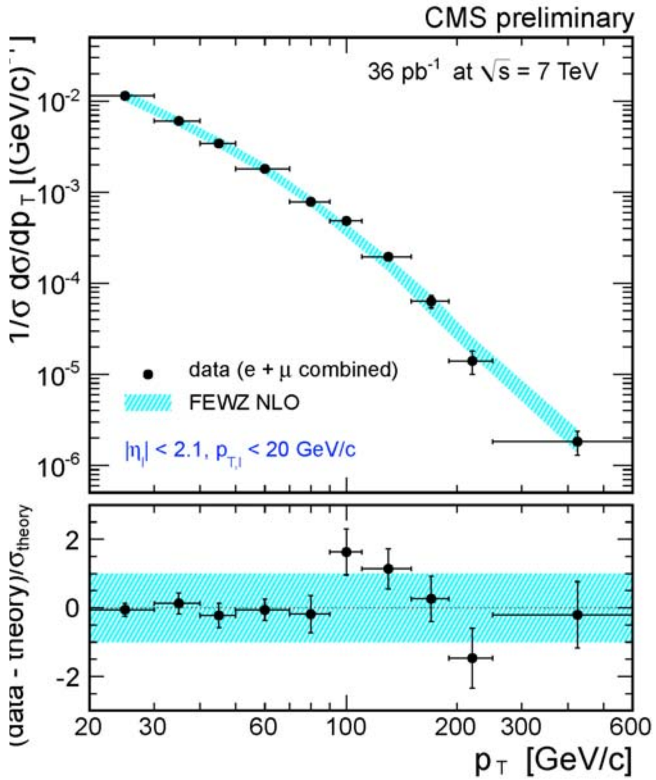


Z Differential cross-sections: $d\sigma/dy$, $d\sigma/dp_T$

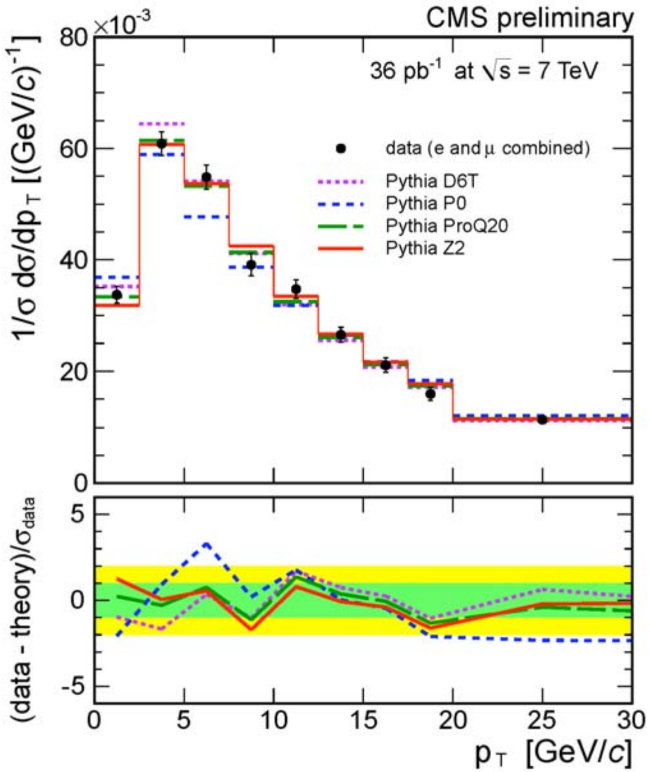
$d\sigma/dy$



$d\sigma/dp_T$ (p_T>20 GeV/c)



$d\sigma/dp_T$ (p_T<30 GeV/c)

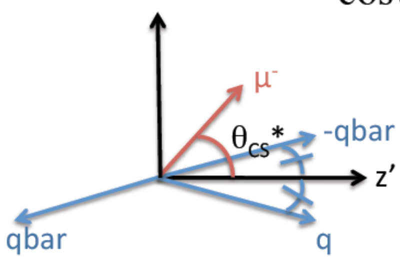


Z Forward-Backward Asymmetry

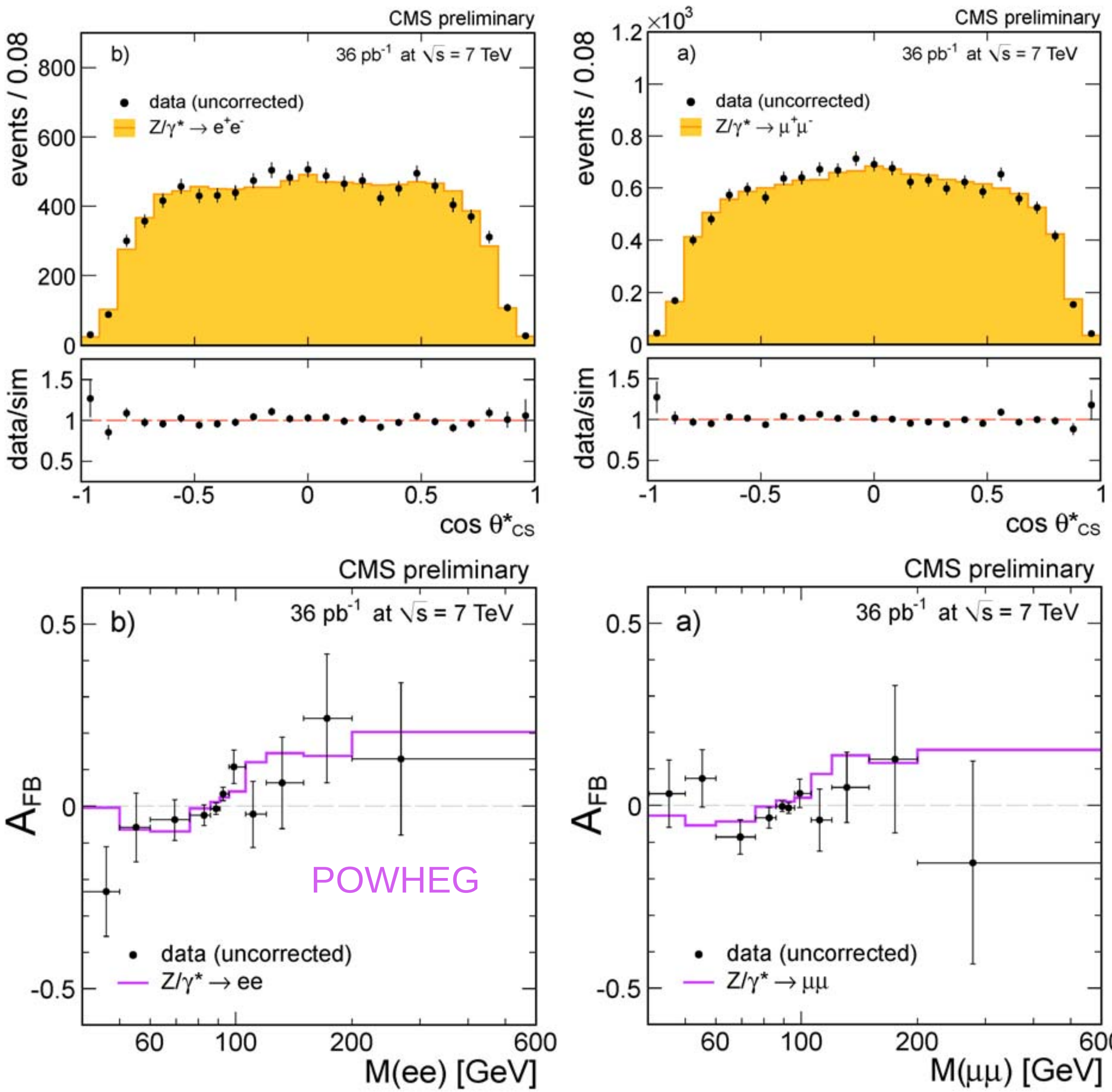
$$A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}$$

- Forward/backward defined in terms of polar angle of lepton on Collins-Soper frame

Collins-Soper frame



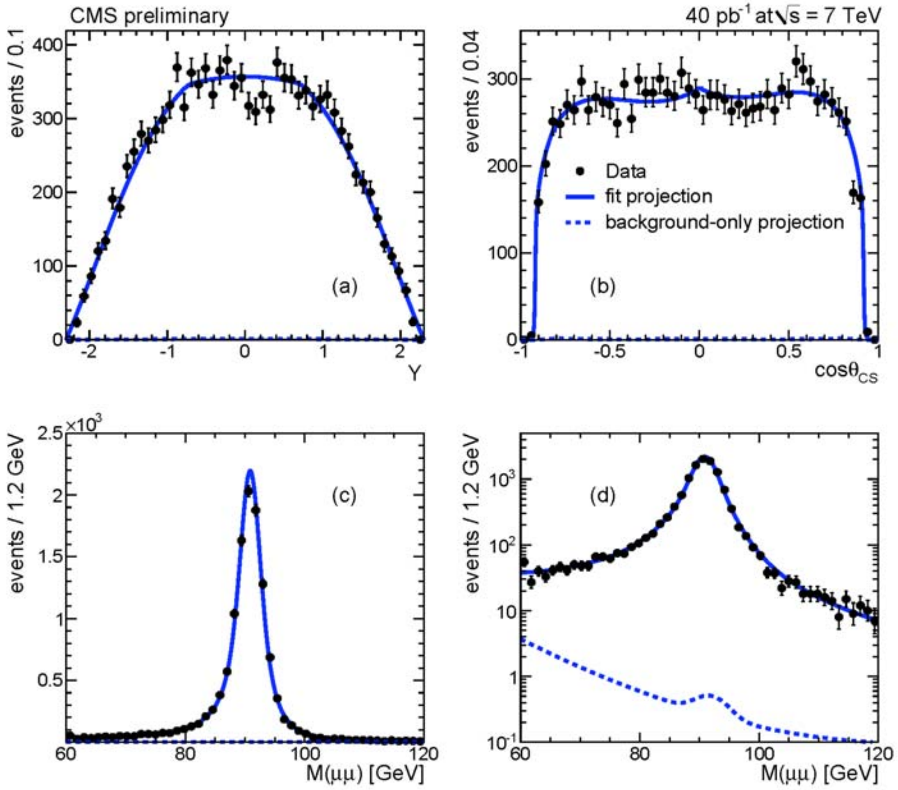
$$\cos\theta^*_{CS} = \frac{2\left(P_1^+P_2^- - P_1^-P_2^+\right)}{\sqrt{Q^2\left(Q^2 + Q_T^2\right)}}$$



- A_{FB} diluted due to:
  - Detector resolution and QED FSR
  - Acceptance
  - Unknown quark/antiquark directions.

Measurement of Weak Mixing Angle $\sin\theta_W$

- Unbinned maximum likelihood fit based on 3 variables:
  - di-lepton rapidity
  - $\cos\theta_{CS}$
  - di-lepton Invariant mass
- Probability density functions from theory with corrections for detector and acceptance effects

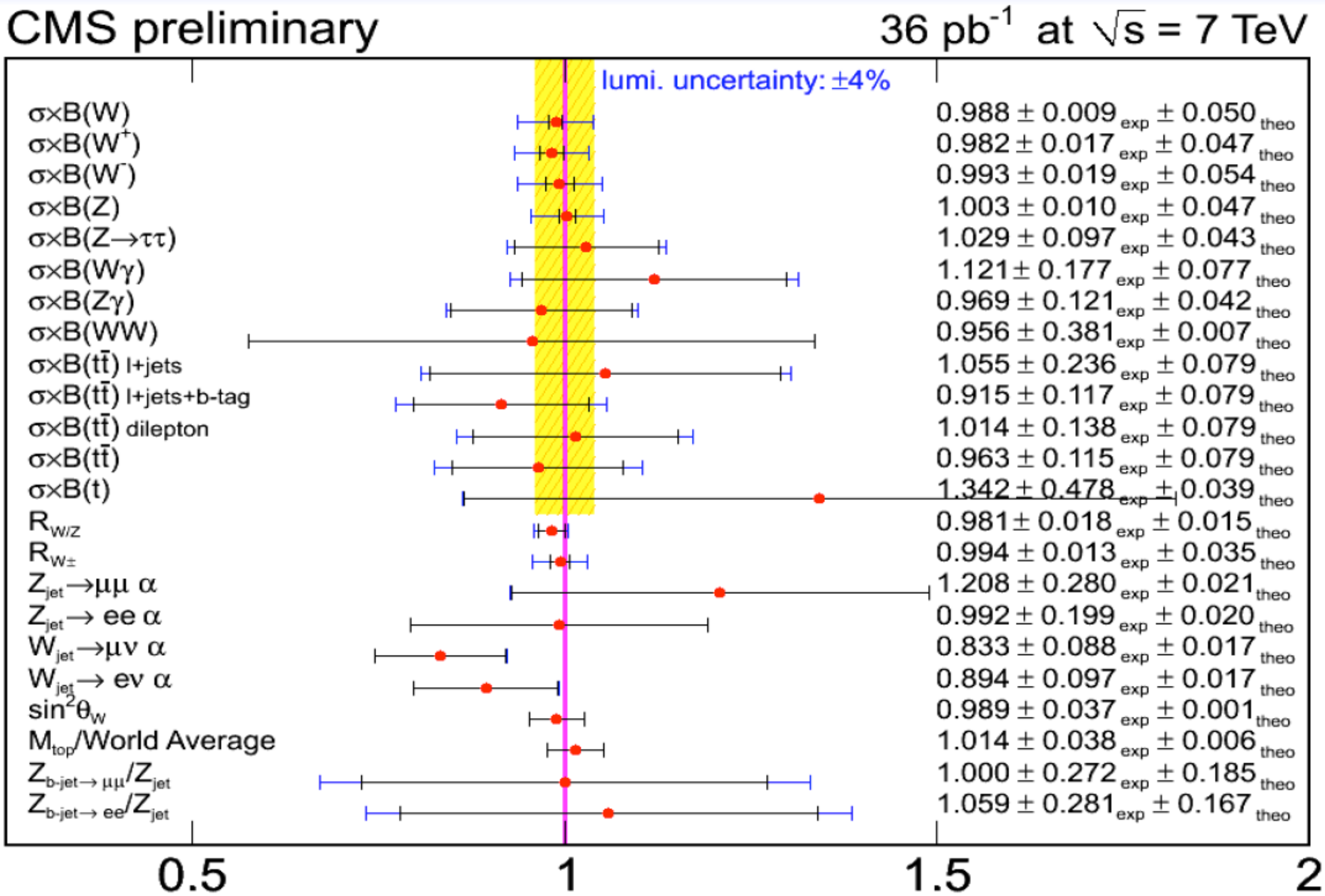


$\sin^2\theta_{eff} = 0.229 \pm 0.008(\text{stat}) \pm 0.004(\text{syst})$

PDG value: 0.23116(13)

Tevatron: 0.232 ± 0.002

Summary of Results



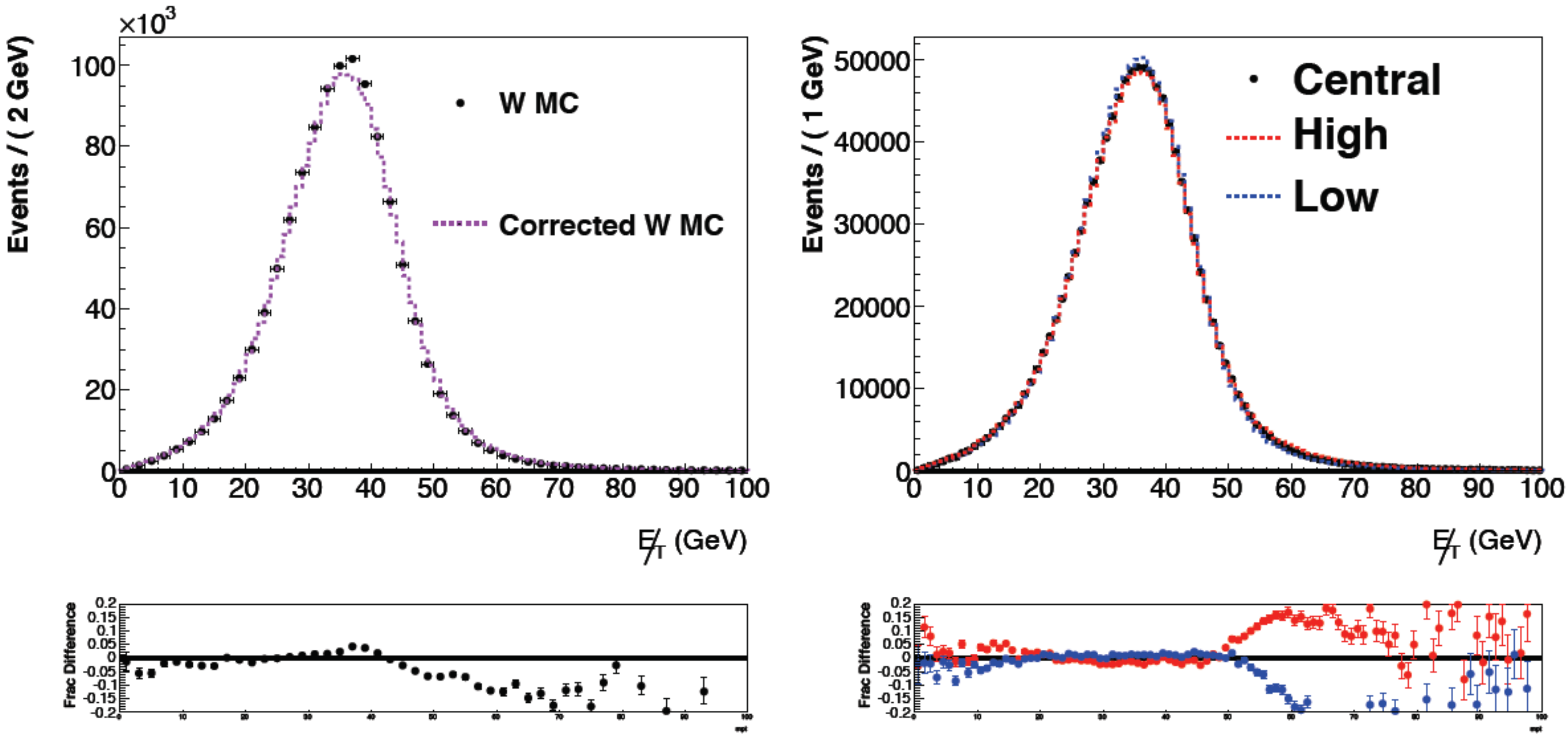
Summary

- The first year of data from CMS has allowed a large number of Standard Model measurements at a new energy scale
- Several to very high precision
  - W and Z cross-section measurement limited by theoretical uncertainties
- W polarization measured for the first time at a proton collider
- We are starting to put new constraints on:
  - PDF uncertainties
  - Standard Model Couplings
  - NNLO differential calculations
  - Associated jet production
- These results form the reference baseline for this year's data taking
- Experience from making these measurements has given us a high level of understanding of our detector and of the backgrounds for searches
  - Ready for new physics!

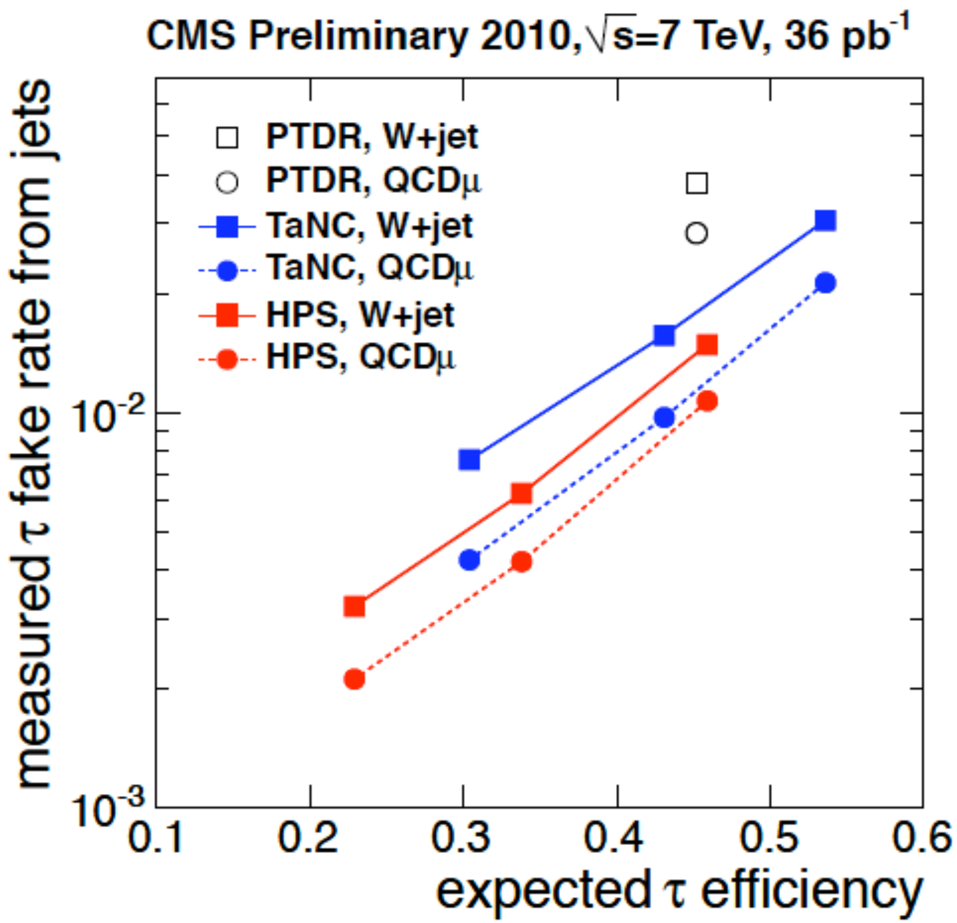
Backup

Signal shape modeling (contd)

- Effect of hadronic recoil correction:



Tau ID efficiency vs fake rate



V + Jets: Berends-Giele scaling