W and Z boson production at CMS at $\sqrt{s}$ = 7 TeV

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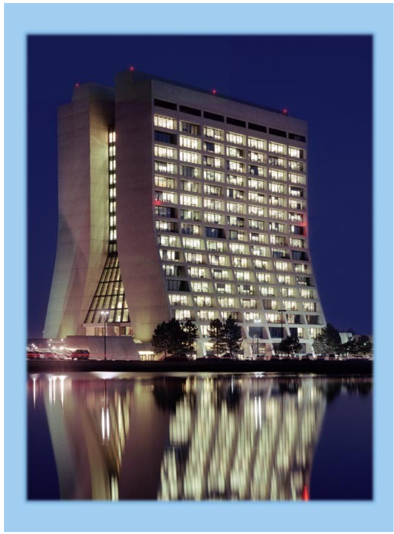
On behalf of the CMS Collaboration

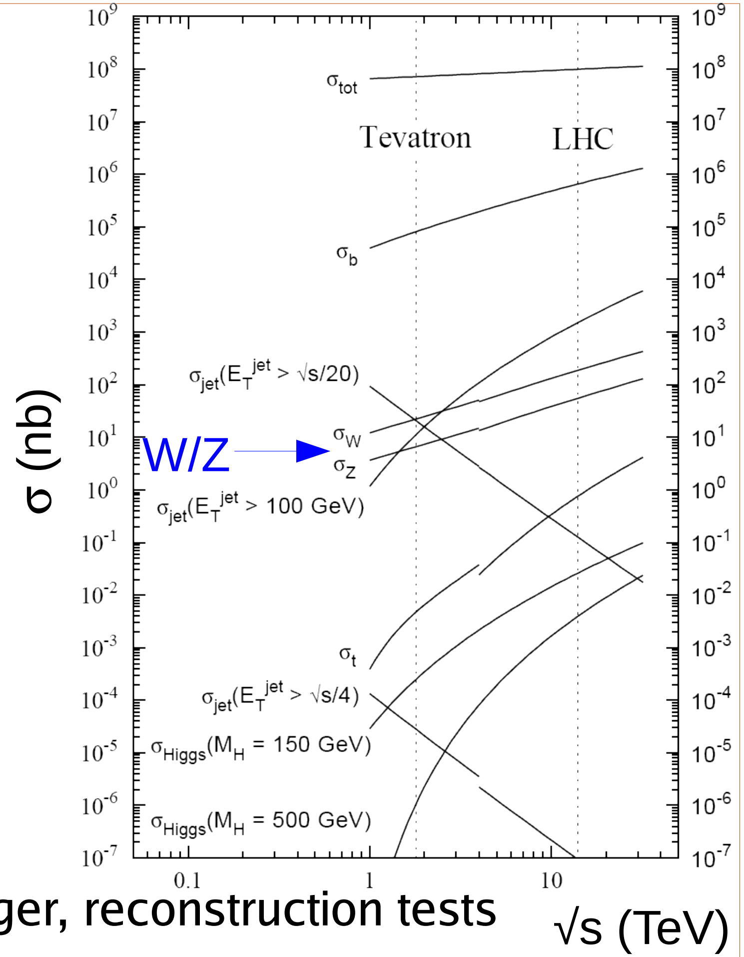


Outline

- Introduction
- Data and MC simulation
- Leptons and MET
- W and Z signal extraction
- Systematic uncertainties
- Cross-section results
- Updates
- W/Z + jets

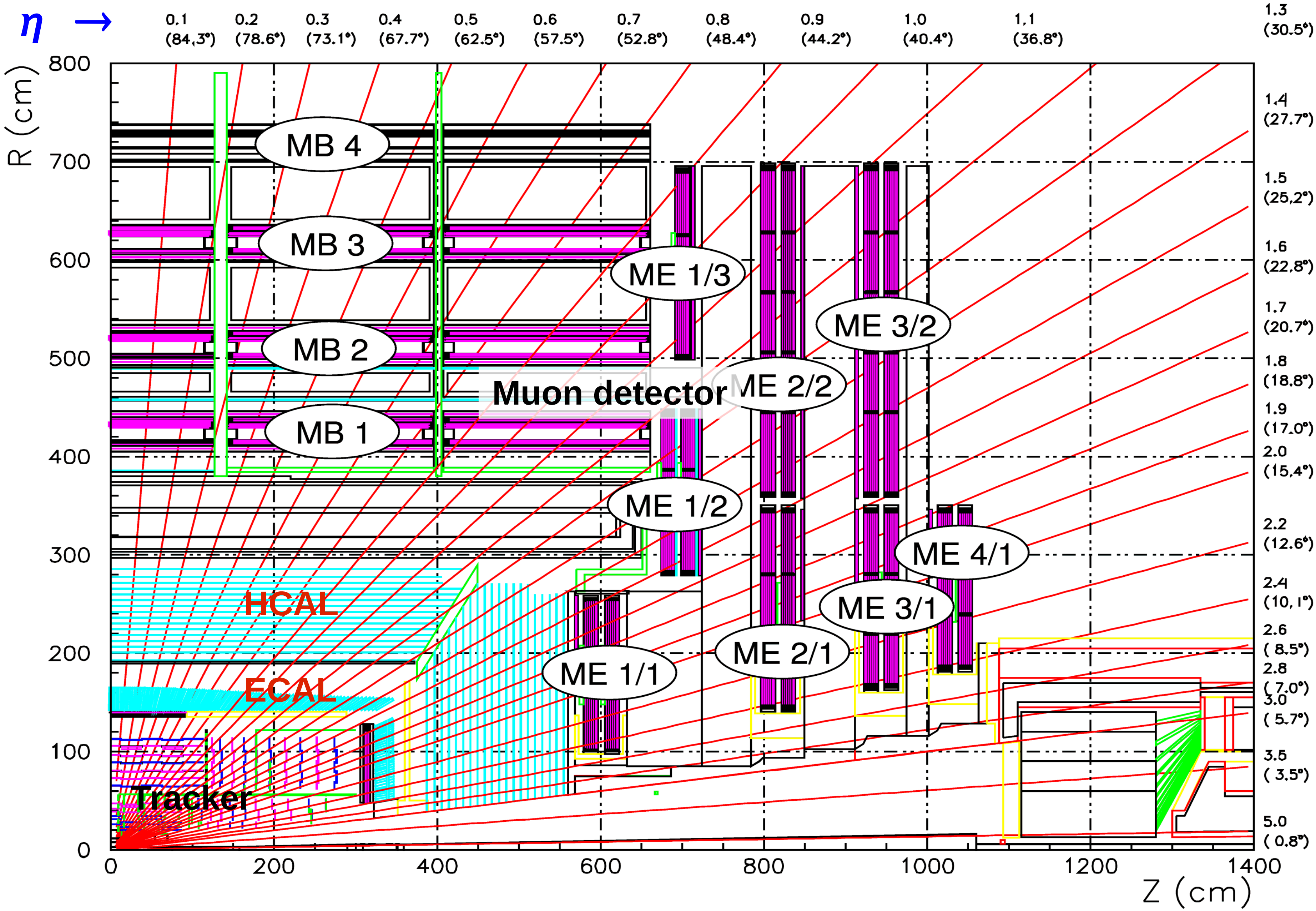
W and Z bosons

- Experimental point of view
  - inclusive cross-sections and properties well established
  - differential cross-sections also measured
  - associated jet production and asymmetries are of interest
  - now we need to have the experimental results for higher center-of-mass energy as well
- Theoretical view
  - compare predictions extrapolated to higher energies
  - extract PDF constraints
  - test higher order QCD corrections
  - tune model parameters
- Perspective view
  - established reference point for calibration, alignment, trigger, reconstruction tests
  - establishes the standard for analyses
  - apparent starting point for BSM searches (in particular higher masses and p_T)
  - luminosity measurements



Presented here: W and Z measurements at CMS in the electron and the muon decay channels

CMS detector



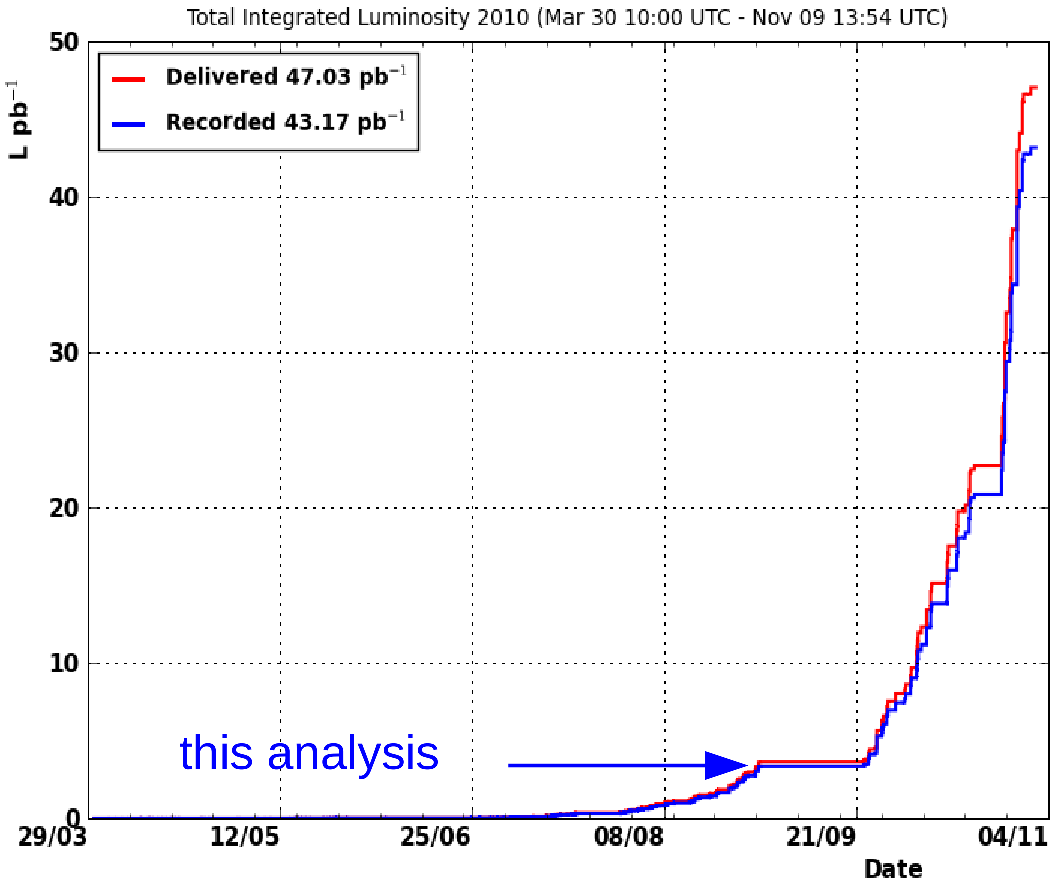
Data

- Collision data from May through September 2010
  - $\int L = 2.88 \pm 0.32 \ pb^{-1}$ (analyzed)
  - more data are being analyzed (updated plots presented here)

- Each detector is certified for quality (in terms of luminosity sections)

- The analyzed data is the certified fraction of the recorded data for a given period of time

Integrated luminosity



Monte Carlo Simulation and Tools

- Large samples for signal and background processes
  - Z and W production – POWHEG (PDF from CTEQ66) interfaced with PYTHIA6 (for jet analyses –MADGRAPH samples)
  - QCD and ttbar - PYTHIA6

- Processed with GEANT4 detector simulation

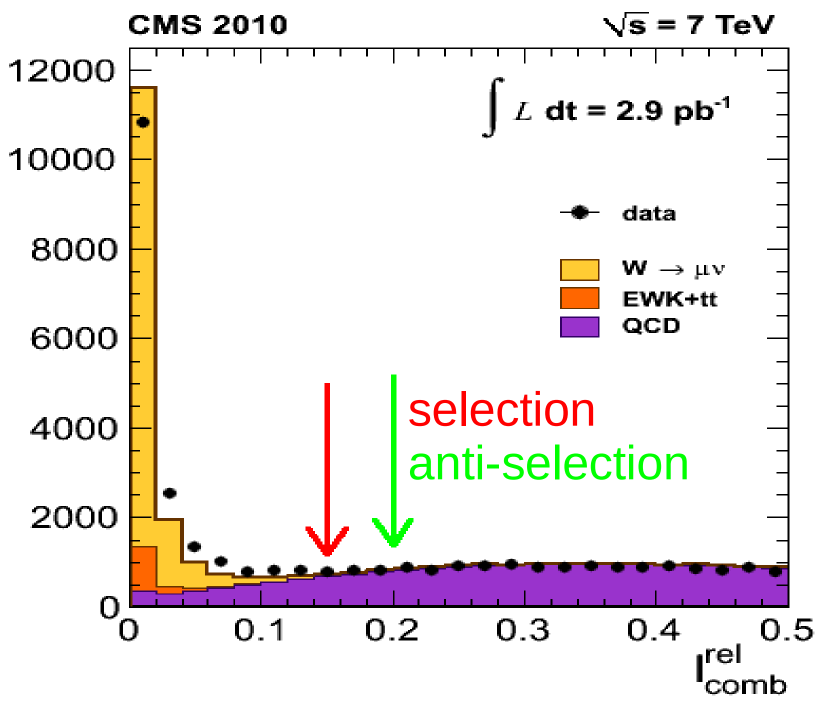
- CMS trigger emulation and event reconstruction

- Theoretical predictions and uncertainties
  - PDFs: CTEQ66, MSTW2008NLO, NNPDF2.0; PDF4LHC recommendations
  - Higher order QCD corrections and initial/final state radiation (ISR/FSR)
    - FEWZ (factorization/renormalization scale)
    - HORACE (EWK and FSR)
  - ResBos (NNLO compared to POWHEG+PYTHIA)

Muon Selection

- On-line : High Level Trigger 9 GeV muon
- Off-line
  - p_T>20 GeV , $|\eta|$<2.1
  - good quality
    - hits in the tracker (pixels and strips) and the muon system
    - χ^2/ndf < 10
  - penetration depth
    - at least two muon stations with hits
  - cosmic veto by the transverse impact parameter
    - $|d_{xy}|$<2 mm
  - isolation
    - relative isolation I_{rel} in a cone of $\Delta R=[(\Delta\varphi)^2+(\Delta\eta)^2]^{1/2} < 0.3$

Relative isolation



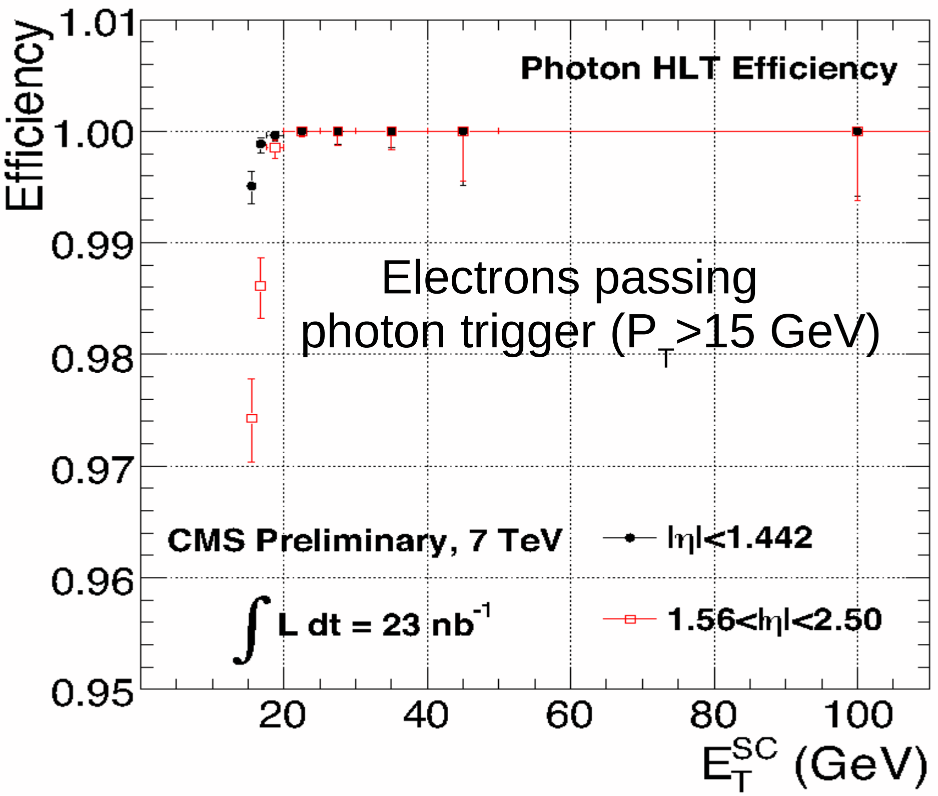
$$I_{rel}=\frac{\sum p_T(tracks)+E_T(ECAL)+E_T(HCAL)}{p_T(\mu)}<0.15$$

- The off-line selection efficiency is approximately 93% for data

Electron Selection

- On-line : High Level Trigger 15 GeV electron or photon (run dependent)

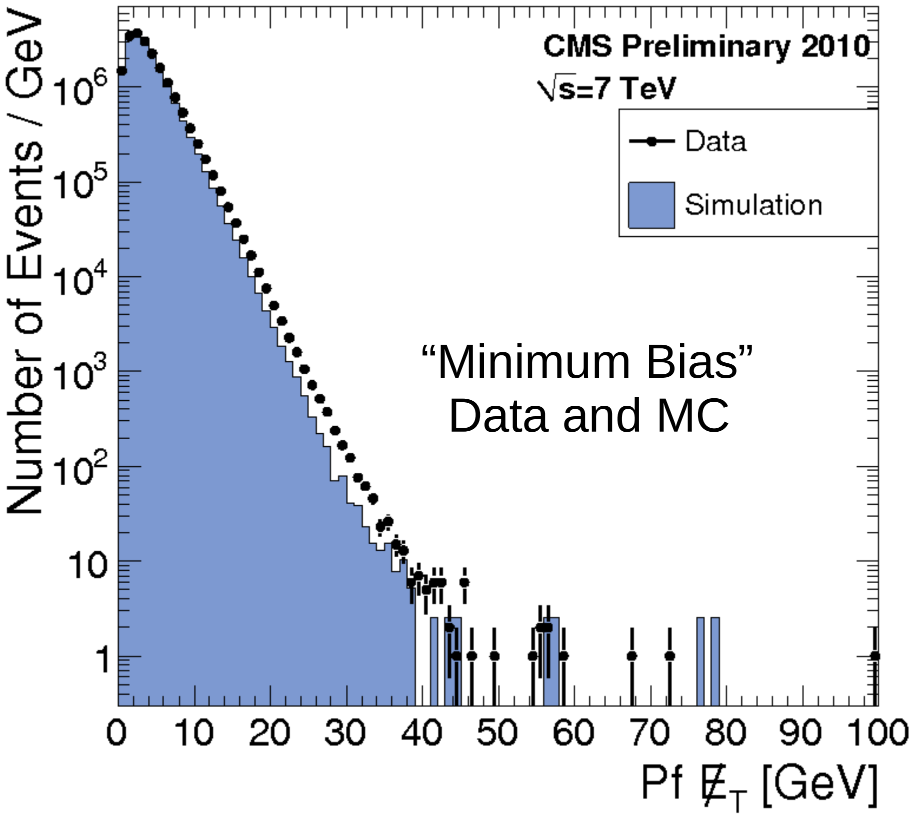
- Off-line
  - E_T>20 GeV
    $|\eta|<1.44$ (barrel) OR $1.57<|\eta|<2.50$ (endcap)
  - ECAL and tracker information
    - ECAL cluster shape requirement
    - track with no inner missing hits or a partner track
    - track to cluster matching
  - HCAL information
    - low hadron activity behind the ECAL cluster
  - isolation
    - separate relative isolation requirements in the tracker, ECAL and HCAL



- The off-line selection efficiency is approximately 75% for data

Missing Transverse Energy (MET)

- It uses "Particle flow" (PF) - fully reconstructed particles in the event
- Computed by the vector sum of all the PF objects (particles)
- Due to the optimal use of information from all the detectors MET from PF is less sensitive to calorimeter calibrations
- Distributions are well reproduced by the simulation
- Better performance compared to calorimeter only or track corrected MET
- Pile up has negligible effect on the W yield measurement (presented here)
  - in less than 40% there is more than one primary vertex
  - In these cases there is ~10% broadening of the MET distribution
  - no significant effect on the results is found



$W\rightarrow\mu\nu$ and $W\rightarrow e\nu$ Signal Extraction*

- $W\rightarrow\mu\nu$: Binned maximum likelihood fit to the transverse mass (M_T)** distribution
- $W\rightarrow e\nu$: Unbinned maximum likelihood fit to the MET distribution
- Yields are corrected for acceptance and efficiencies

No cut on MET/M_T

- Three different contributions to the observed fitted shape:
  - Signal –obtained from MC corrected by Zll modeling the hadronic recoil
  - QCD background – $W\rightarrow\mu\nu$: obtained from a cut inversion technique correcting MC
    $W\rightarrow e\nu$: obtained by a parametric function
    (Rayleigh distribution: magnitude of vector with independent Gaussian components)

$$f(x=MET)=Cx\exp\left[\frac{-x^2}{2(\sigma_0+\sigma_1 x)^2}\right]$$

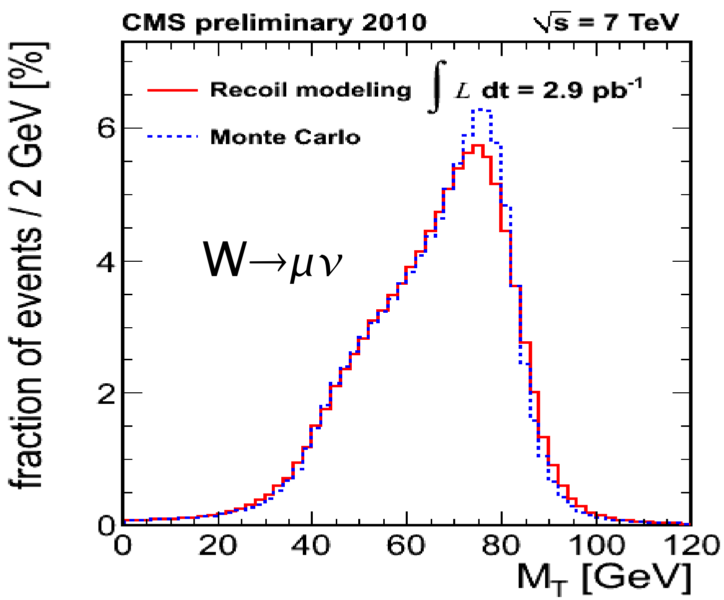
  - Electroweak + ttbar background –obtained from MC

- $W\rightarrow\mu\nu$: The fit returns the normalizations of the signal and the QCD background
- $W\rightarrow e\nu$: The fit returns the normalizations of the signal and the QCD background together with the background shape parameters $\sigma_{0,1}$

* Events with a second muon (electron) with pT>10 (20) GeV and looser selection requirements are vetoed

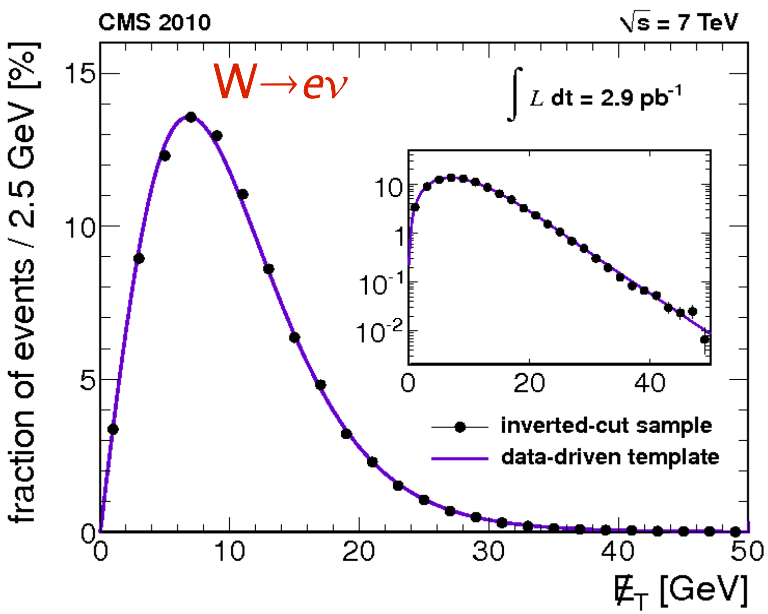
** $M_T = \sqrt{2p_T(\mu)\not{E}_T*(1-\cos(\Delta\phi_{\mu,\not{E}_T}))}$

Signal and Background parametrization



Signal shape is derived from MC and hadronic recoil modeling of Z→ll events in data

Event-by-event correction in bins of P_T (W)



$$f(x=MET)=Cx\exp\left[\frac{-x^2}{2(\sigma_0+\sigma_1 x+\sigma_2 x^2)^2}\right]$$

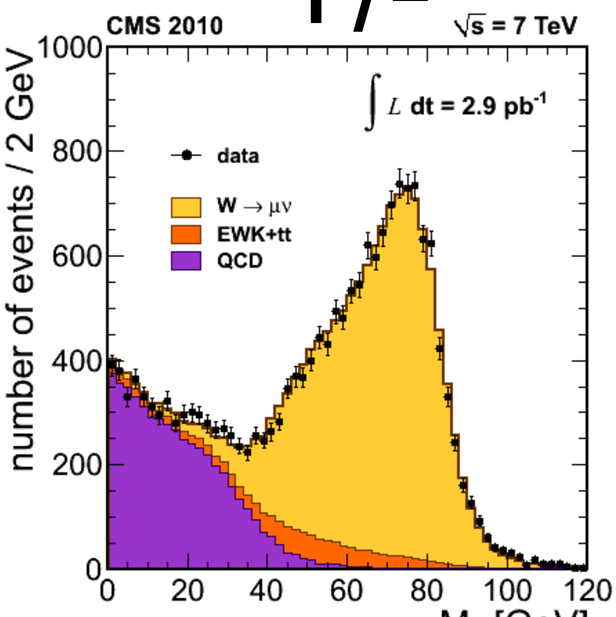
Tale parametrization

Additional shape parameter for systematics studies <u>only</u>

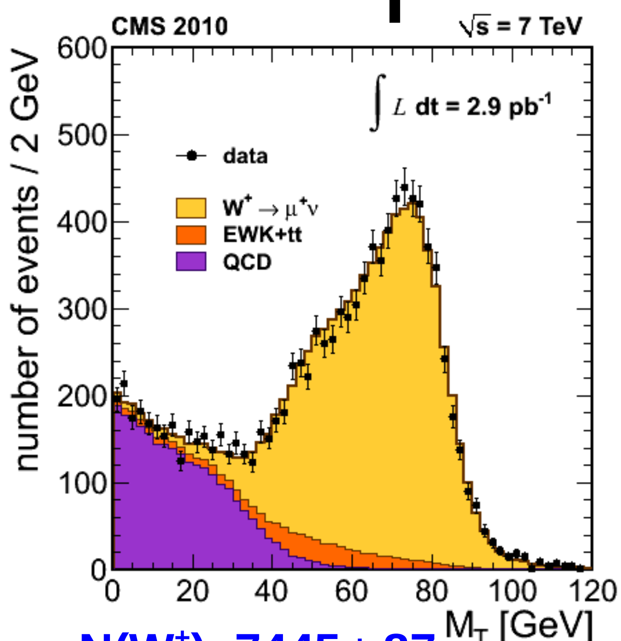
Describes well the QCD background shapes in MC as well as "signal-free" samples in data (obtained by inverting the isolation requirement)

$W \to \mu\nu$ and $W \to e\nu$ Signal Extraction (2)

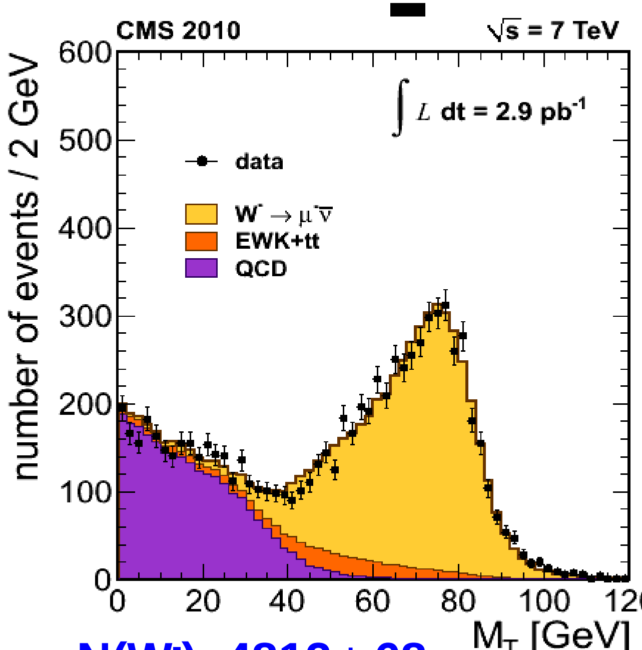
+/-   +   -



N(W)=12257±111

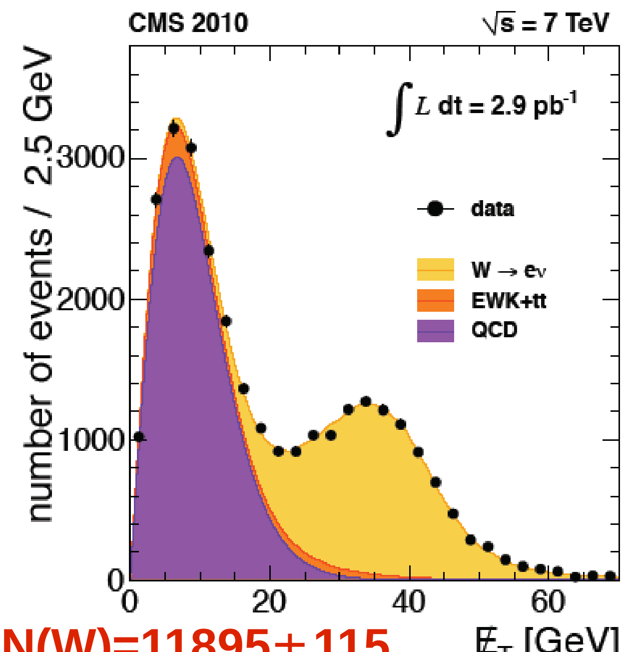


N(W+)=7445±87

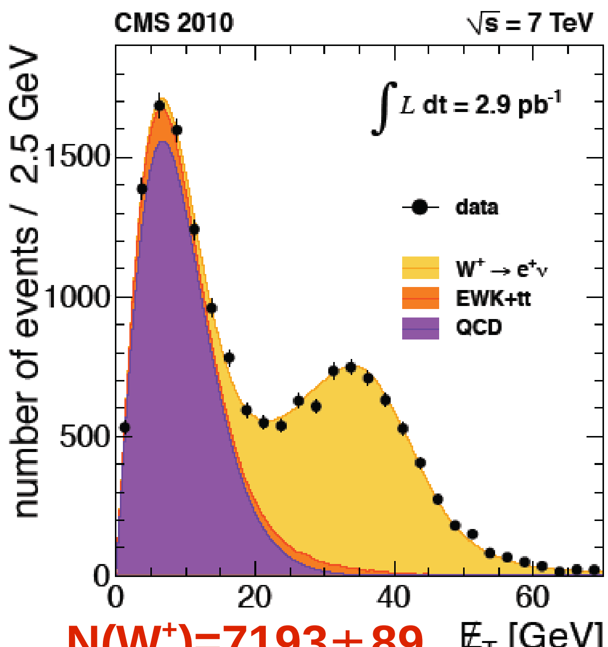


N(W-)=4812±68

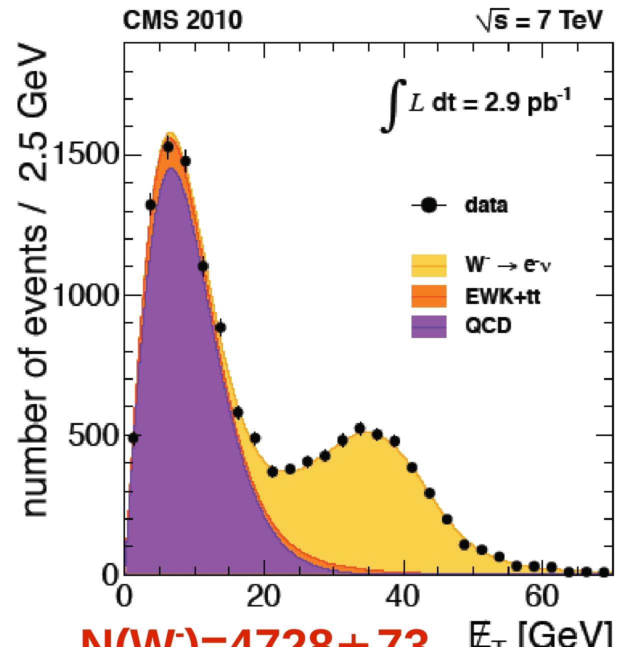
μ



N(W)=11895±115



N(W+)=7193±89



N(W-)=4728±73

e

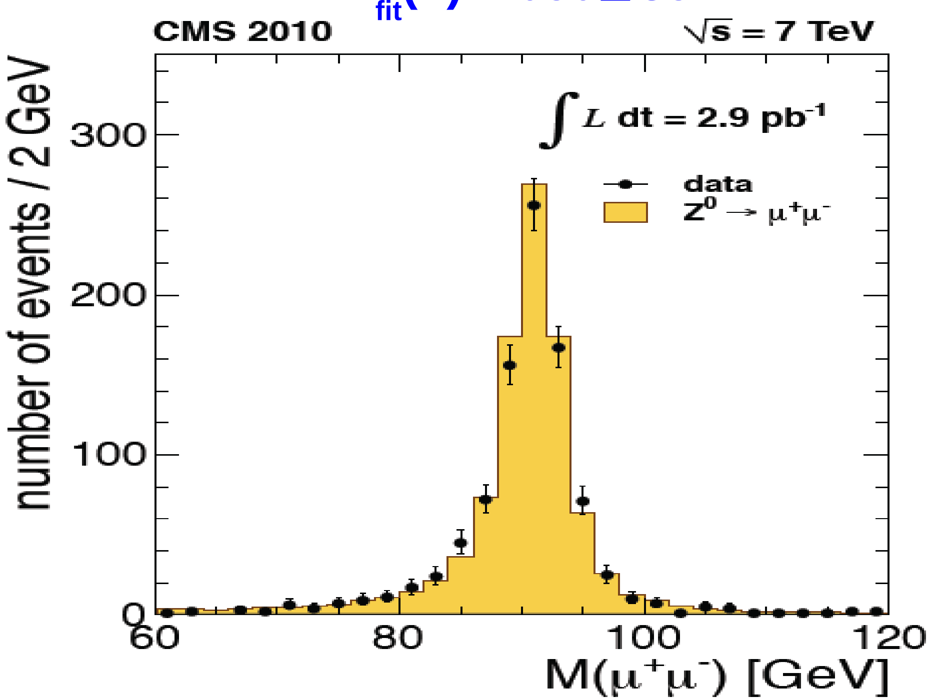
$Z\to\mu\mu$ and $Z\to ee$ Signal Extraction

- $Z\to\mu\mu$: Simultaneous fit to extract the yield and all the efficiency factors
- $Z\to ee$: Counting method
- Yields are corrected for acceptance (and background and efficiencies for $Z\to ee$)

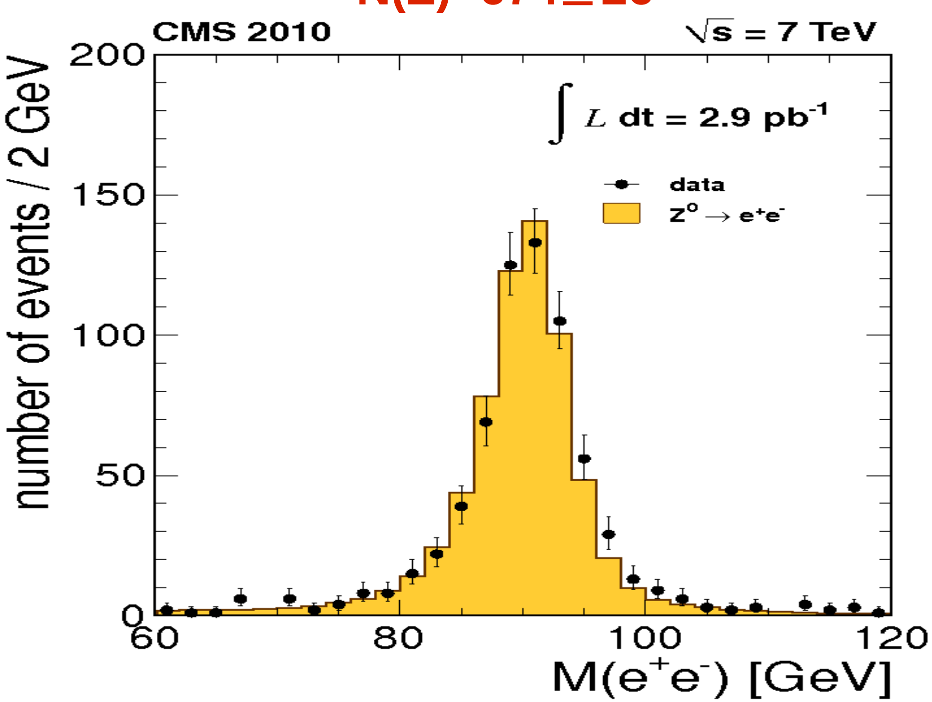
- Two selected leptons with 60 GeV $< M_{ll} <$ 120 GeV
  - Opposite charges for the muons

- Backgrounds are small (QCD background is estimated from data, the rest - from MC)

$N_{fit}(Z)=1050\pm35$



$N(Z)=674\pm26$



Simultaneous fit

- Explores mutually exclusive categories of di-lepton events
  - one of them is the “standard” signal category
  - the rest represent trigger or muon ID/reconstruction “failures”
  - all are related by efficiency factors

- Parametrize the signal and background as functions of the invariant mass
  - signal shape from the signal category and/or MC (+ resolution correction)
  - background shapes modeled as products of exponential and polynomial functions

- Proper handling of correlations between efficiencies
  - careful choice of the lepton selection to minimize correlation effects
  - extensive studies of residual effects

- A Poisson likelihood ratio* fit returns the yield and the efficiency factors

* For large statistics it follows a χ^2 distribution

Systematic Uncertainties

- Efficiencies
  - Measured in MC (tag-and-probe) with data-driven corrections
  - Their statistical uncertainties are propagated as a systematic error
  - In $Z \to \mu\mu$ these uncertainties are absorbed in the statistical error from the fit

- Momentum (energy) scale and resolution
  - From the shape and shift of the Z mass peak; impact on the fits
  - From hadronic recoil response (using $Z \to ll$ events for calibration)

- MET scale (exploring differences between data driven and MC techniques)

- Background modeling
  - Introducing a quadratic dependence on MET in the parametric function ($W \to e\nu$)
  - QCD-enriched vs MC M_T shapes, correcting M_T instead of MET, ... ($W \to \mu\nu$)
  - "Fake rate" methods, opposite/same sign di-lepton candidates, template methods ($Z \to ll$)

Systematic Uncertainties (2)

- Acceptance (PDF uncertainty) : ~ 1-2 %*
  - uncertainties estimated by the variations between acceptances obtained by CTEQ66, MSTW2008NLO and NNPDF2.0 predictions following PDF4LHC recommendations (re-weighting of events using the modified PDFs)
  - Δ_{CTEQ66}, $\Delta_{MSTW2008NLO}$, $\Delta_{NNPDF2.0}$: 68% CF uncertainties within each set
  - Δ_{sets} : half of max. difference between the central values of any pair of sets
  - syst: $\Delta_{CTEQ66} \oplus \Delta_{MSTW2008NLO} \oplus \Delta_{NNPDF2.0} \oplus \Delta_{sets} \oplus$ (remaining $\alpha_S \sim 0.1\%$)

- Theory (typical uncertainty : ~ 1-1.5 %)
  - POWHEG is in good agreement with ResBos
  - Scale dependence of NNLO calculations (by FEWZ) introduces systematics
  - ISR, FSR, virtual and real EWK corrections (HORACE compared to PYTHIA)

* Correlations between experimental acceptance corrections and PDF corrections are not of practical concern as they are at ~10% level

Systematic Uncertainties (in %)

Source	$W\to\mu\nu$	$W\to e\nu$	$Z\to\mu\mu$	$Z\to ee$
Lepton ID efficiencies	1.4	3.9	n/a	5.9
pre-triggering	0.5	n/a	0.5	n/a
Momentum/energy scale & resolution	0.3	2.0	0.2	0.6
MET scale & resolution	0.4	1.8	n/a	n/a
Background subtraction	2.0	1.3	1.0	0.1
PDF uncertainty (acceptance)	1.1	0.8	1.2	1.1
Theoretical	1.4	1.3	1.6	1.3
TOTAL	**3.1**	**5.1**	**2.3**	**6.2**

In addition: the luminosity uncertainty is 11%.

Systematic Uncertainties (in %)

Source	$W^+(\mu)$	$W^-(\mu)$	$W^+/W^-(\mu)$	$W/Z(\mu)$
Lepton ID efficiencies	1.5	1.5	2.8	0.9
Momentum/energy scale & resolution	0.3	0.3	0.3	0.1
MET scale & resolution	0.4	0.4	0.0	0.4
Background subtraction	1.7	2.3	0.7	2.2
PDF uncertainty (acceptance)	1.3	1.9	2.1	1.1
Theoretical	1.4	1.3	1.2	1.4
TOTAL	**3.0**	**3.6**	**3.8**	**3.0**

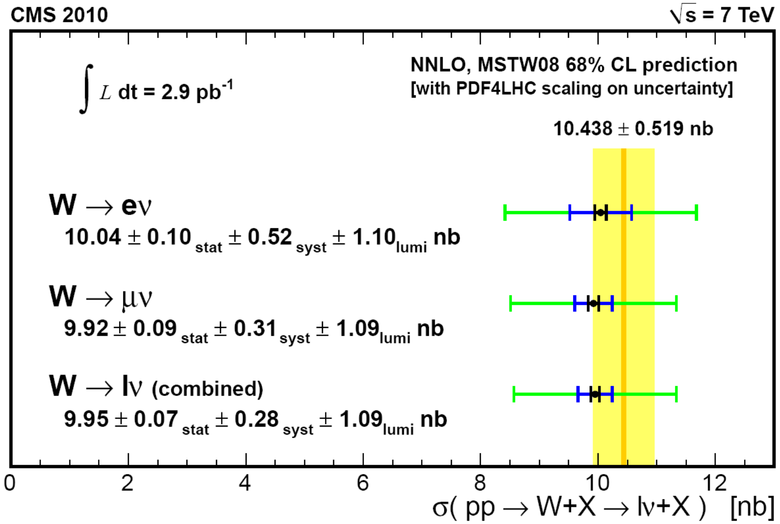
μ

Source	$W^+(e)$	$W^-(e)$	$W^+/W^-(e)$	$W/Z(e)$
Lepton ID efficiencies	5.1	5.1	5.2	3.0
Momentum/energy scale & resolution	2.2	1.8	0.4	2.0
MET scale & resolution	1.6	1.9	0.4	1.8
Background subtraction	1.1	1.5	0.7	1.3
PDF uncertainty (acceptance)	0.9	1.5	1.7	0.9
Theoretical	1.3	0.9	1.3	1.0
TOTAL	**6.1**	**6.2**	**5.7**	**4.4**

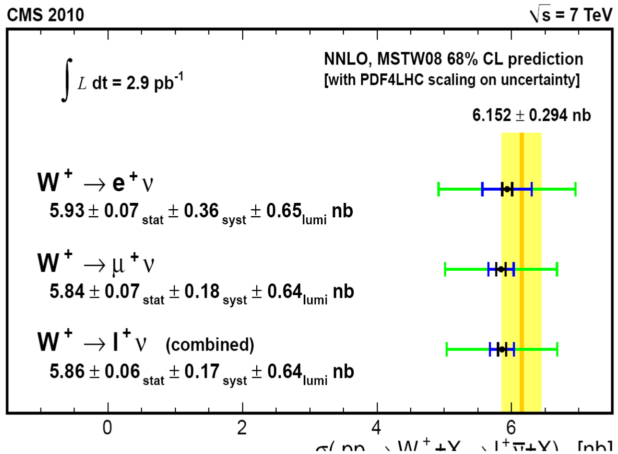
e

Cross-section results

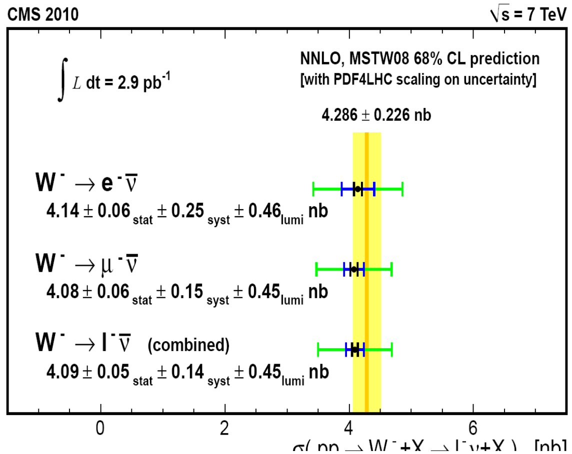
W



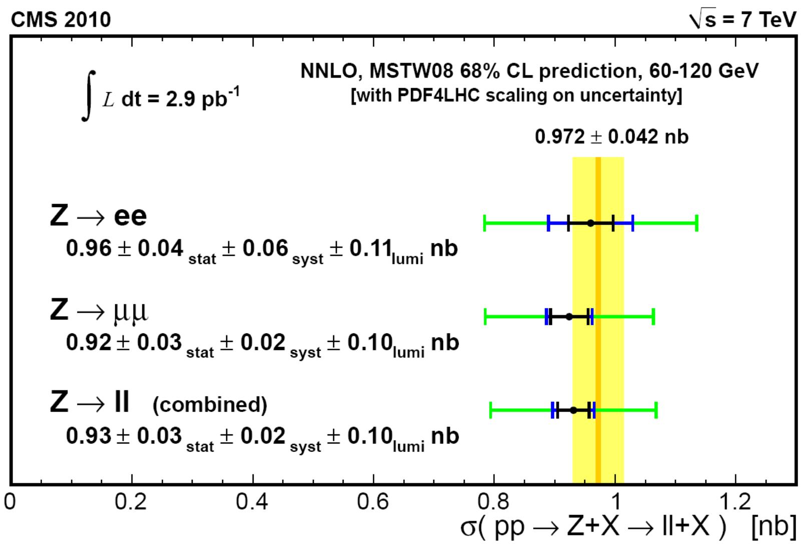
W+

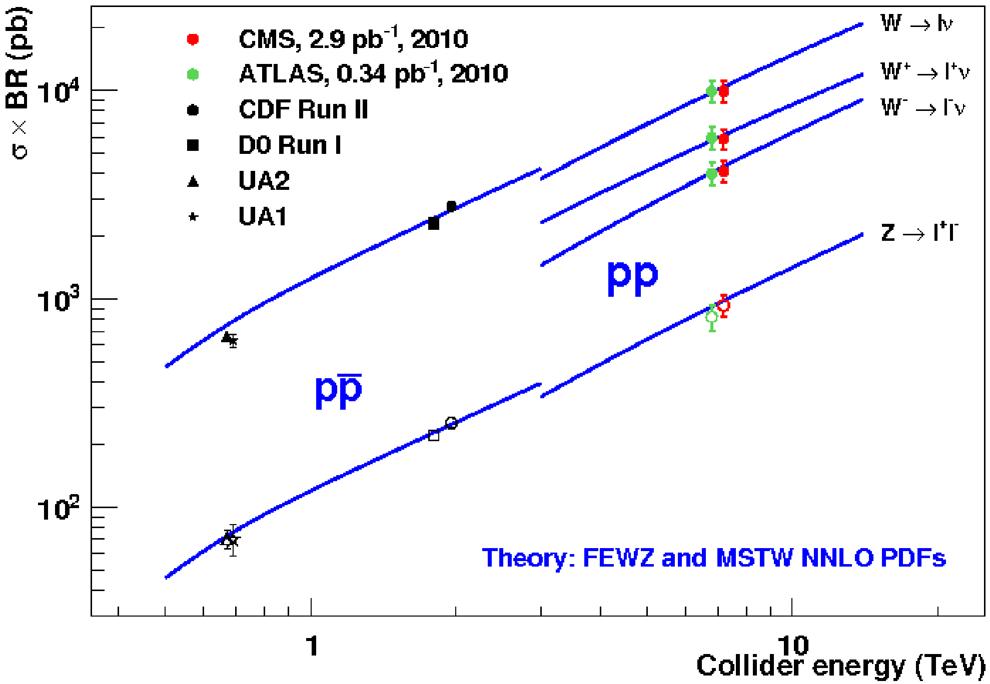


W-



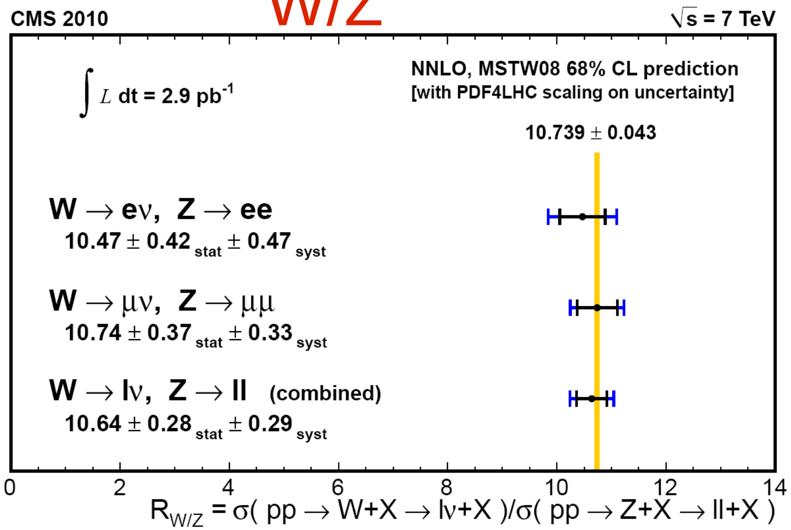
Z



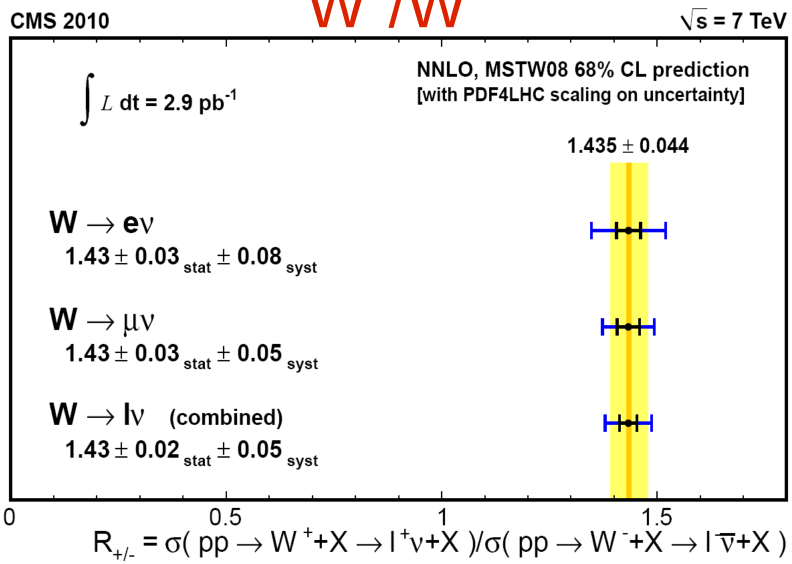


Cross-section ratios

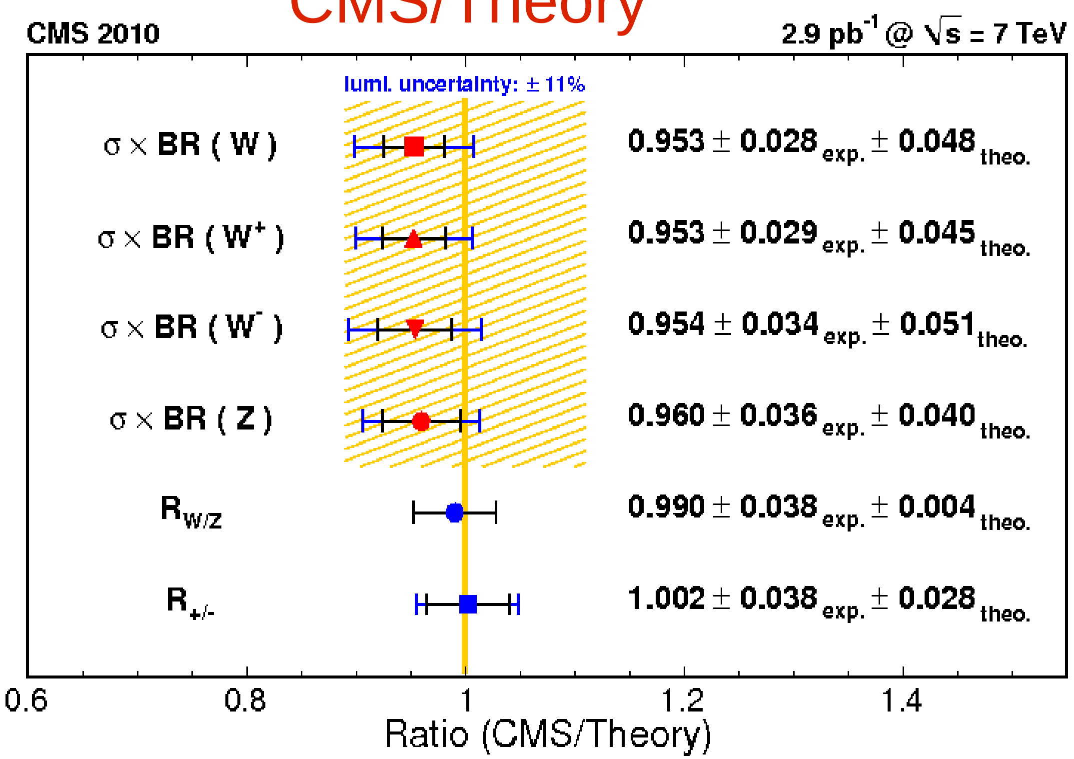
W/Z



W^+/W^-



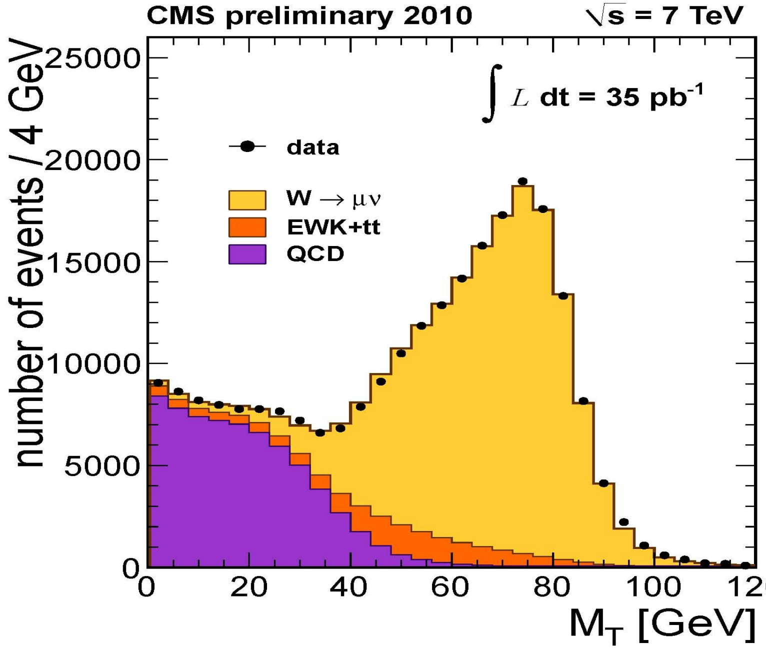
CMS/Theory



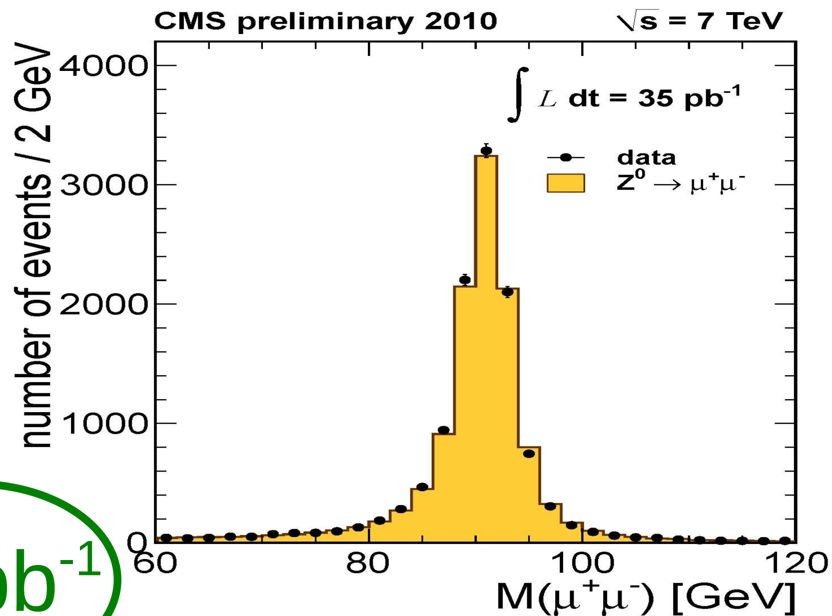
Excellent agreement with theory.
Cross-sections are overall lower by 4-5% (still within the luminosity uncertainty which is likely the source of this underestimation).

Updated distributions

W

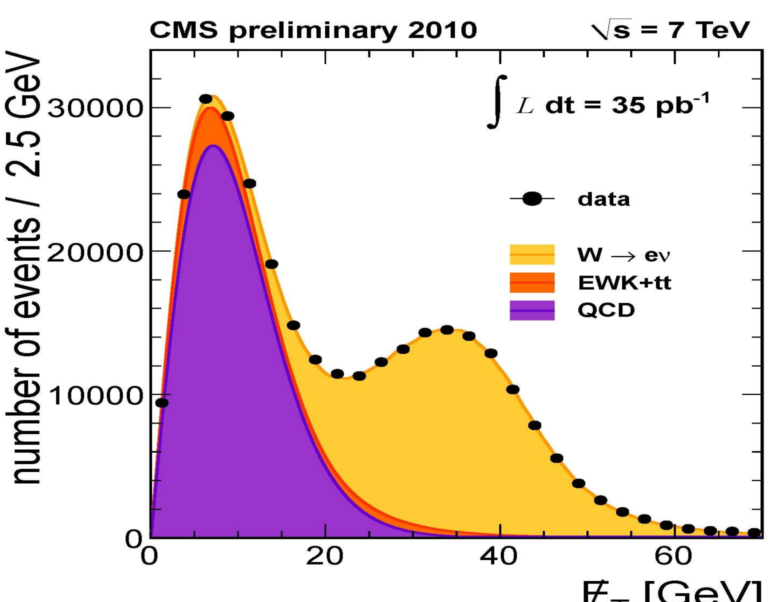


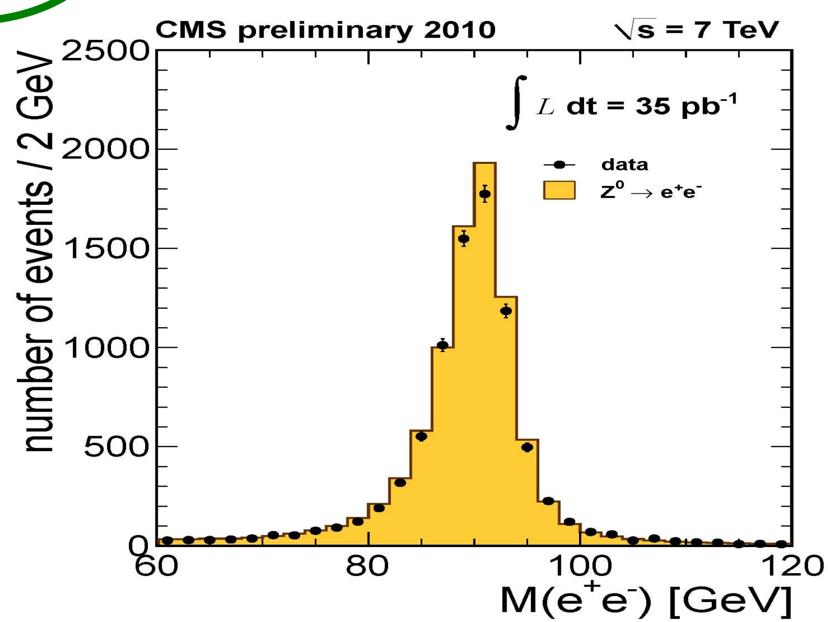
Z



μ

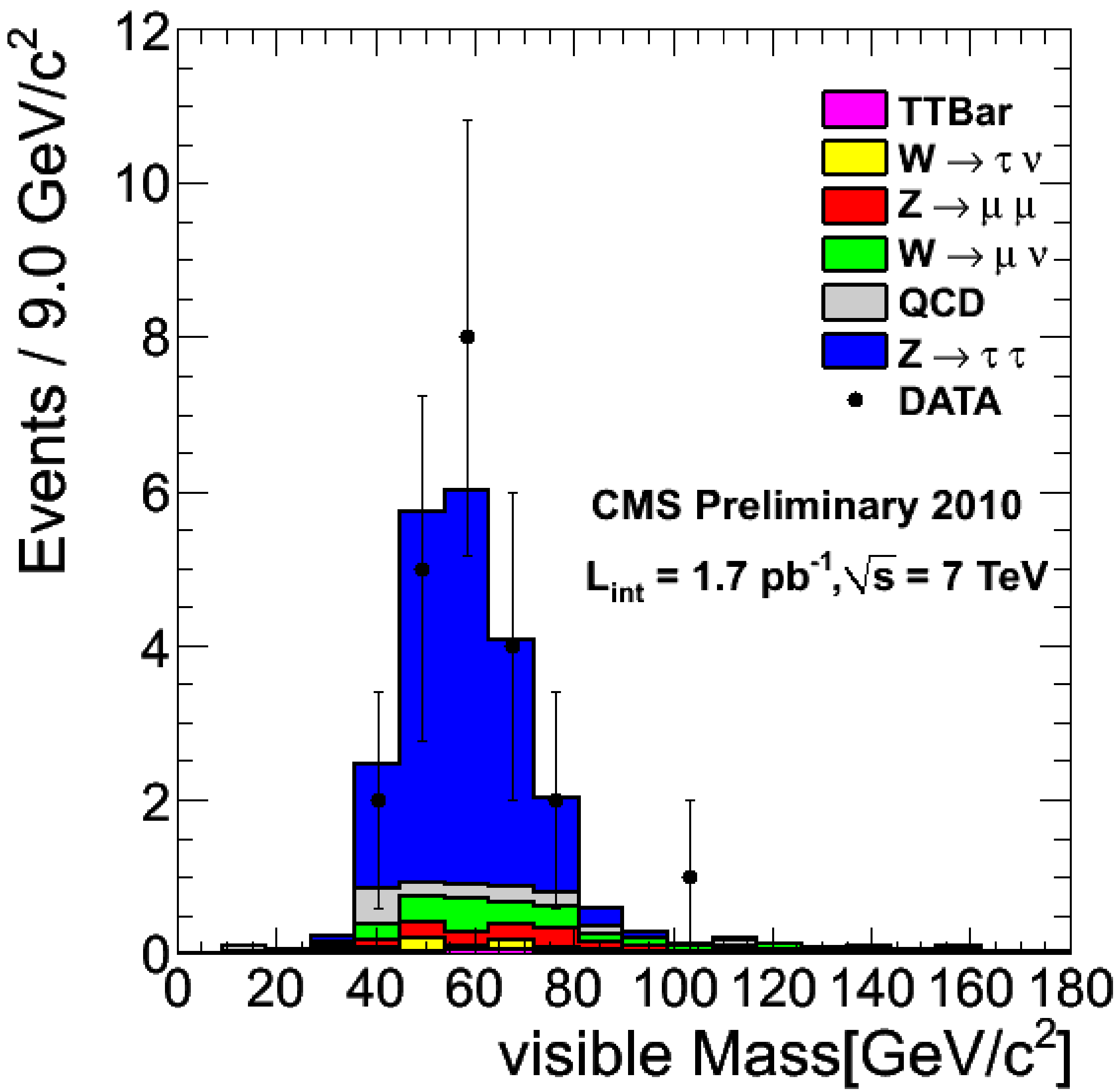
35 pb^{-1}





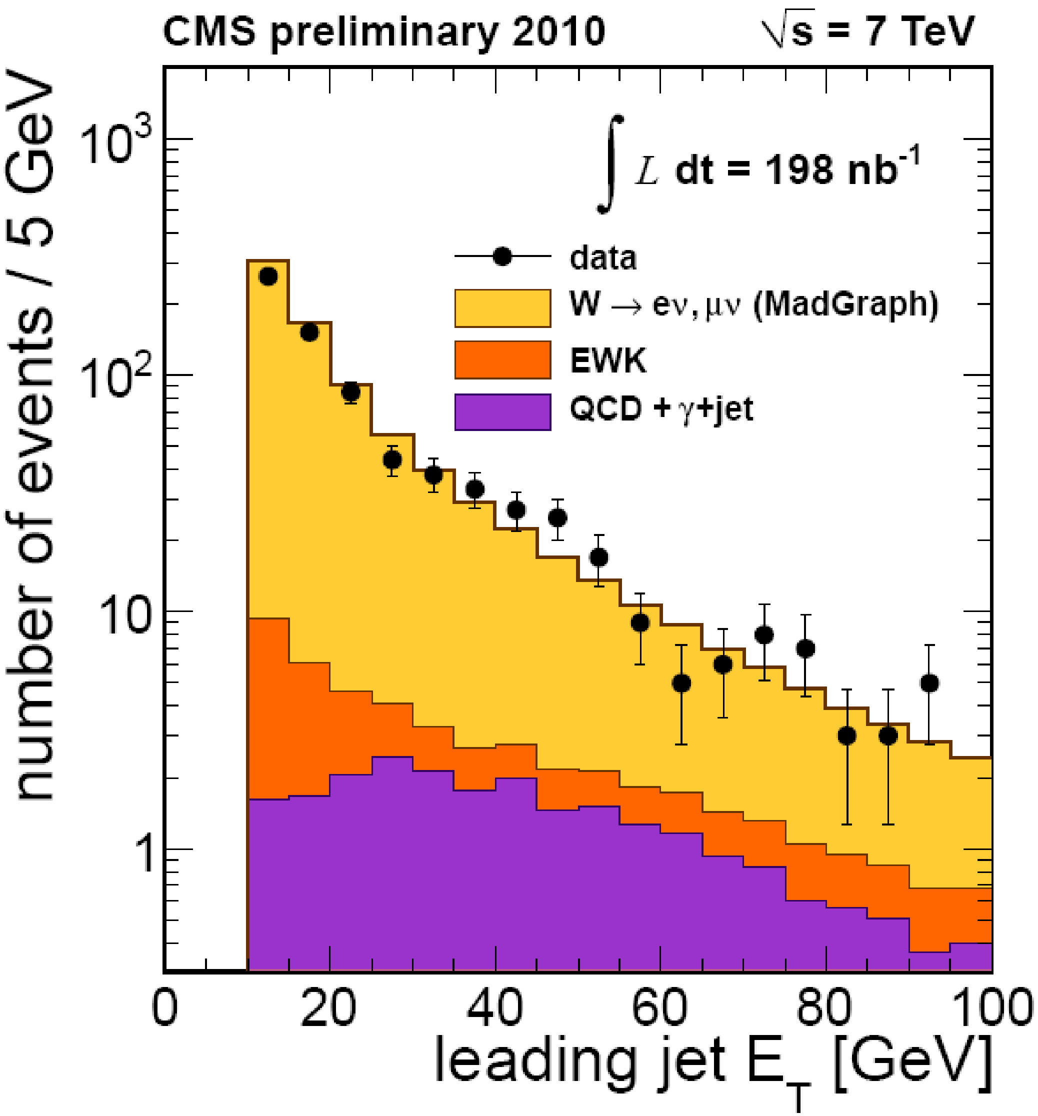
e

$Z \to \tau\tau$



- Muon P_T > 15 GeV
- Relative Combined "Particle Flow" isolation < 0.1
- Tau P_T > 20 GeV
- The tau ID algorithm uses the multiplicities and the invariant mass of the hadrons within a narrow cone

W+jets associated production

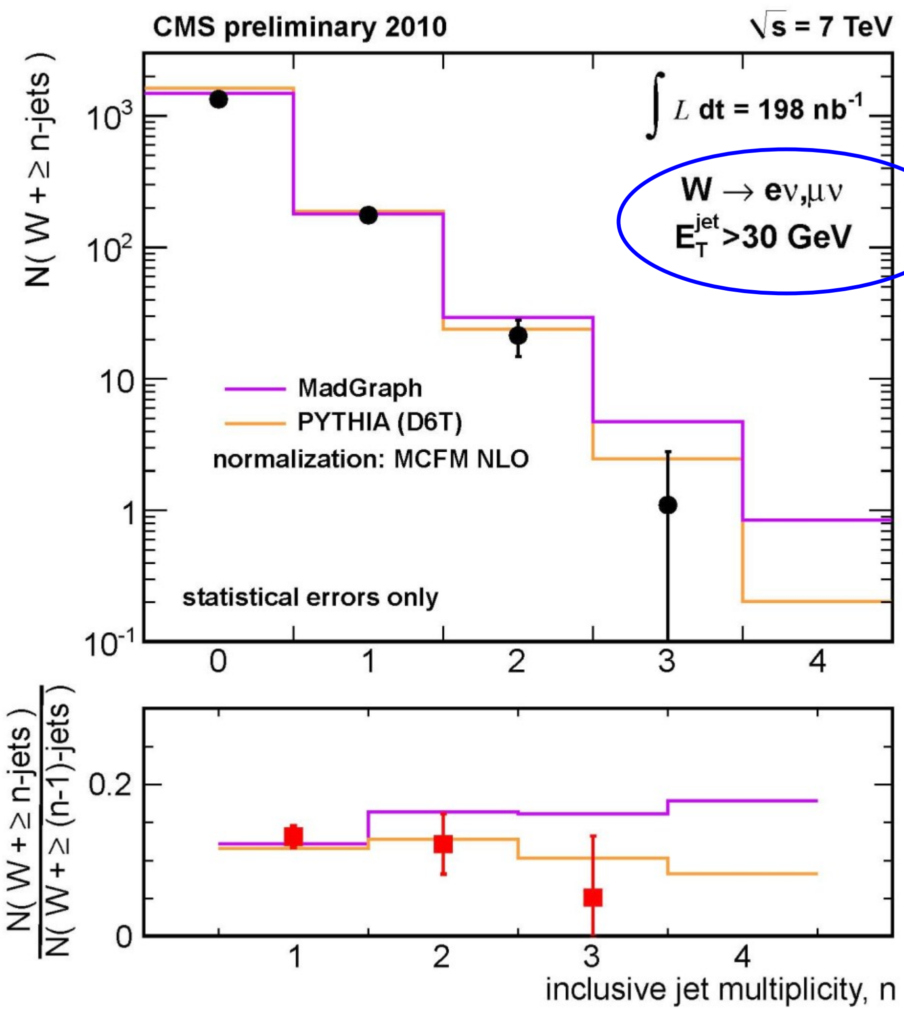


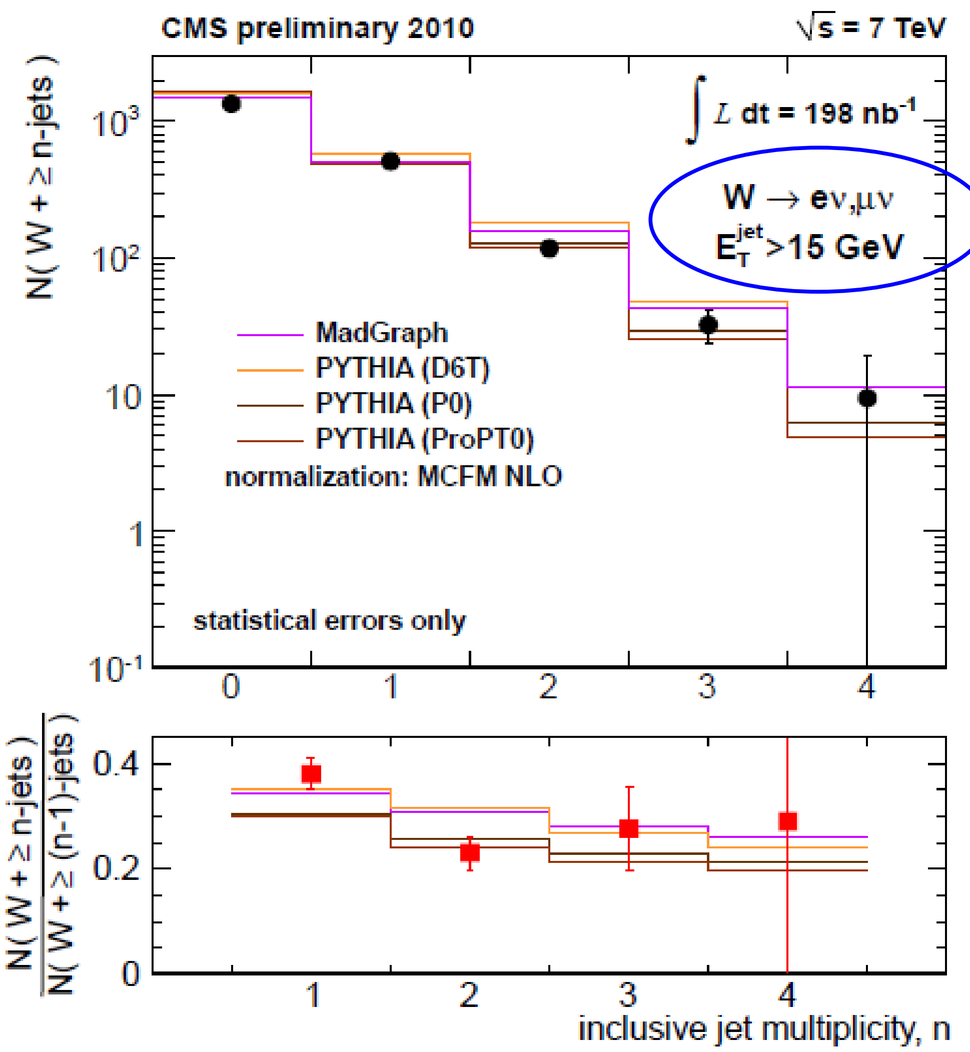
- Jet reconstruction performed with Particle Flow and Anti-Kt algorithm (ΔR=0.5)
- Lepton-jet separation ΔR>0.5
- $|\eta(\text{jet})|<2.5$

Statistical errors only shown.

Main systematics:
jet energy scale (10-20%)

W+jets associated production (2)





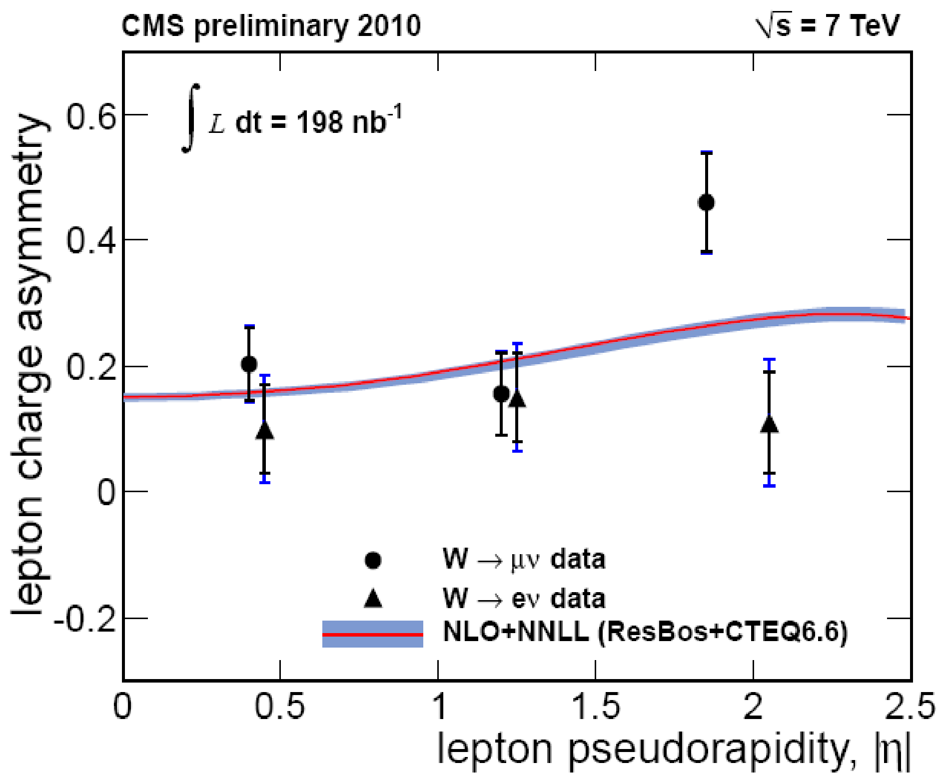
Updates are underway.

Summary and Outlook

- W and Z cross-section results agree very well with theory
- The uncertainty on the W^+/W^- cross-section ratio is becoming comparable to the theoretical uncertainty
- Data-driven techniques employed to understand and minimize the systematic effects
- Differential measurements to be performed with the full 2010 data
- W/Z + jets, W/Z + γ and more EWK updates and measurements also forthcoming

Back up

W^+ and W^- charge asymmetry as a function of the lepton η provides a constraint on PDFs

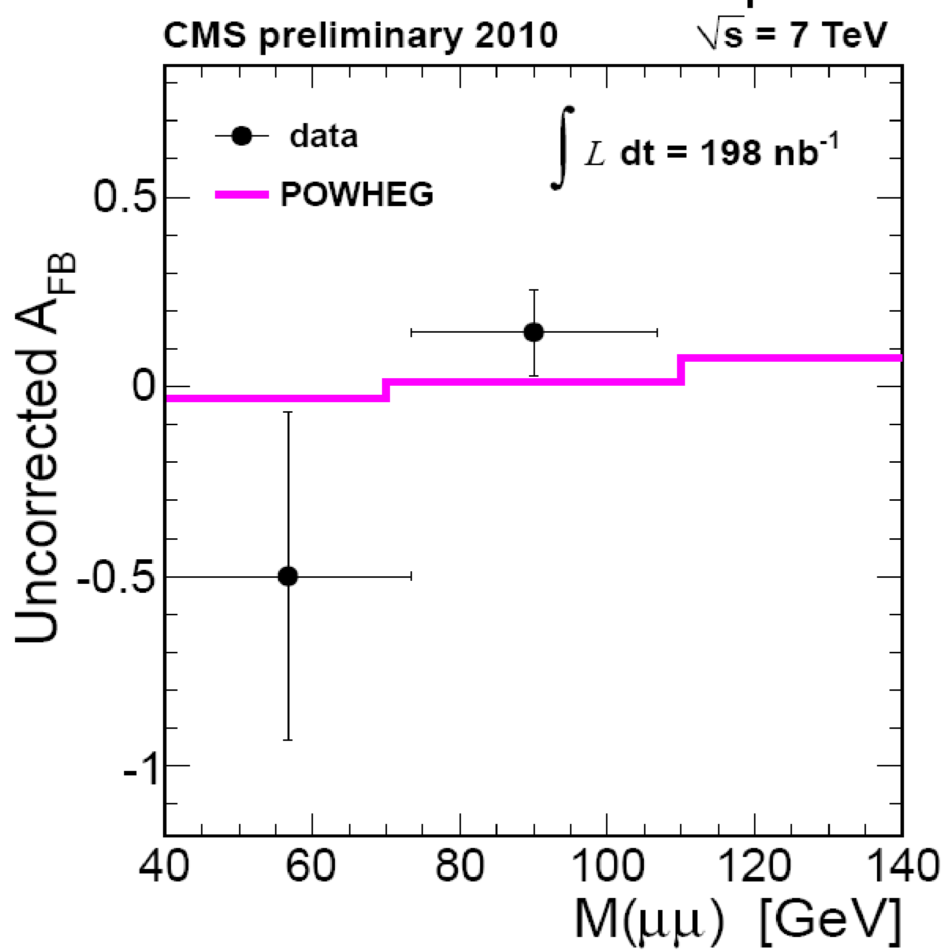


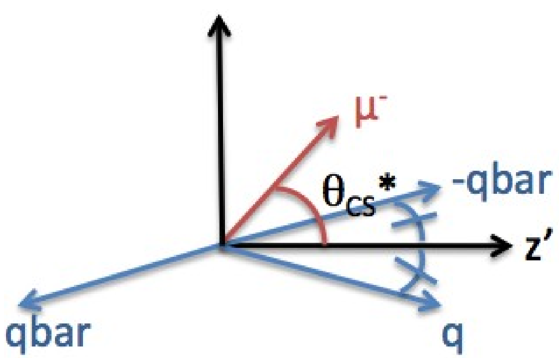
$$A(\eta) = \frac{d\sigma^{(+)}/d\eta_\ell - d\sigma^{(-)}/d\eta_\ell}{d\sigma^{(+)}/d\eta_\ell + d\sigma^{(-)}/d\eta_\ell}$$

Ratio of positive to negative reconstruction efficiencies compatible with unity within 5% (9%) for muons (electrons)

Back up

- Di-lepton forward-backward asymmetry depends on the di-lepton invariant mass, being small near the Z mass and sizable around 70 and 110 GeV
- Deviations from SM value may indicate the presence of a new neutral gauge boson
- A_{FB} has been measured for $Z \rightarrow \mu\mu$ in the Collins-Soper frame[*], for a single mass bin around the Z mass





[*] CS frame: Z rest frame in which the z axis bisects p_1, $-p_2$, p_1 and p_2 being the incoming quark and anti-quark momenta

Back up

NNLO: FEWZ & MSTW08

NNLO: 10.44 ± 0.52 nb

$$\sigma(pp \to WX) \times \mathrm{BF}(W \to e\nu) = 10.045 \pm 0.097\,(\mathrm{stat.}) \pm 0.517\,(\mathrm{syst.}) \pm 1.105\,(\mathrm{lumi.})\,\mathrm{nb},$$
$$\sigma(pp \to WX) \times \mathrm{BF}(W \to \mu\nu) = 9.922 \pm 0.090\,(\mathrm{stat.}) \pm 0.307\,(\mathrm{syst.}) \pm 1.091\,(\mathrm{lumi.})\,\mathrm{nb},$$
$$\sigma(pp \to WX) \times \mathrm{BF}(W \to \ell\nu) = 9.951 \pm 0.073\,(\mathrm{stat.}) \pm 0.280\,(\mathrm{syst.}) \pm 1.095\,(\mathrm{lumi.})\,\mathrm{nb}.$$

NNLO: 6.15 ± 0.29 nb

$$\sigma(pp \to W^+X) \times \mathrm{BF}(W^+ \to e^+\bar{\nu}) = 5.935 \pm 0.074\,(\mathrm{stat.}) \pm 0.359\,(\mathrm{syst.}) \pm 0.653\,(\mathrm{lumi.})\,\mathrm{nb},$$
$$\sigma(pp \to W^+X) \times \mathrm{BF}(W^+ \to \mu^+\nu) = 5.844 \pm 0.069\,(\mathrm{stat.}) \pm 0.176\,(\mathrm{syst.}) \pm 0.643\,(\mathrm{lumi.})\,\mathrm{nb},$$
$$\sigma(pp \to W^+X) \times \mathrm{BF}(W^+ \to \ell^+\nu) = 5.859 \pm 0.059\,(\mathrm{stat.}) \pm 0.168\,(\mathrm{syst.}) \pm 0.645\,(\mathrm{lumi.})\,\mathrm{nb};$$

NNLO: 4.29 ± 0.23 nb

$$\sigma(pp \to W^-X) \times \mathrm{BF}(W^- \to e^-\nu) = 4.140 \pm 0.064\,(\mathrm{stat.}) \pm 0.254\,(\mathrm{syst.}) \pm 0.455\,(\mathrm{lumi.})\,\mathrm{nb},$$
$$\sigma(pp \to W^-X) \times \mathrm{BF}(W^- \to \mu^-\bar{\nu}) = 4.078 \pm 0.057\,(\mathrm{stat.}) \pm 0.147\,(\mathrm{syst.}) \pm 0.449\,(\mathrm{lumi.})\,\mathrm{nb},$$
$$\sigma(pp \to W^-X) \times \mathrm{BF}(W^- \to \ell^-\bar{\nu}) = 4.092 \pm 0.046\,(\mathrm{stat.}) \pm 0.136\,(\mathrm{syst.}) \pm 0.450\,(\mathrm{lumi.})\,\mathrm{nb}.$$

NNLO: 0.97 ± 0.04 nb

$$\sigma(pp \to ZX) \times \mathrm{BF}(Z \to e^+e^-) = 0.960 \pm 0.037\,(\mathrm{stat.}) \pm 0.059\,(\mathrm{syst.}) \pm 0.106\,(\mathrm{lumi.})\,\mathrm{nb},$$
$$\sigma(pp \to ZX) \times \mathrm{BF}(Z \to \mu^+\mu^-) = 0.924 \pm 0.031\,(\mathrm{stat.}) \pm 0.022\,(\mathrm{syst.}) \pm 0.102\,(\mathrm{lumi.})\,\mathrm{nb},$$
$$\sigma(pp \to ZX) \times \mathrm{BF}(Z \to \ell^+\ell^-) = 0.931 \pm 0.026\,(\mathrm{stat.}) \pm 0.023\,(\mathrm{syst.}) \pm 0.102\,(\mathrm{lumi.})\,\mathrm{nb}.$$

Back up

NNLO: FEWZ & MSTW08

NNLO: 10.74 ± 0.04 nb

$$\frac{\sigma(pp \to WX) \times \mathrm{BF}(W \to e\nu)}{\sigma(pp \to ZX) \times \mathrm{BF}(Z \to e^+e^-)} = 10.468 \pm 0.416\,(\mathrm{stat.}) \pm 0.468\,(\mathrm{syst.}),$$

$$\frac{\sigma(pp \to WX) \times \mathrm{BF}(W \to \mu\nu)}{\sigma(pp \to ZX) \times \mathrm{BF}(Z \to \mu^+\mu^-)} = 10.738 \pm 0.368\,(\mathrm{stat.}) \pm 0.326\,(\mathrm{syst.}),$$

$$\frac{\sigma(pp \to WX) \times \mathrm{BF}(W \to \ell\nu)}{\sigma(pp \to ZX) \times \mathrm{BF}(Z \to \ell^+\ell^-)} = 10.638 \pm 0.278\,(\mathrm{stat.}) \pm 0.291\,(\mathrm{syst.}).$$

NNLO: 1.43 ± 0.04 nb

$$\frac{\sigma(pp \to W^+X) \times \mathrm{BF}(W^+ \to e^+\nu)}{\sigma(pp \to W^-X) \times \mathrm{BF}(W^- \to e^-\bar{\nu})} = 1.434 \pm 0.028\,(\mathrm{stat.}) \pm 0.082\,(\mathrm{syst.}),$$

$$\frac{\sigma(pp \to W^+X) \times \mathrm{BF}(W^+ \to \mu^+\nu)}{\sigma(pp \to W^-X) \times \mathrm{BF}(W^- \to \mu^-\bar{\nu})} = 1.433 \pm 0.026\,(\mathrm{stat.}) \pm 0.054\,(\mathrm{syst.}),$$

$$\frac{\sigma(pp \to W^+X) \times \mathrm{BF}(W^+ \to \ell^+\nu)}{\sigma(pp \to W^-X) \times \mathrm{BF}(W^- \to \ell^-\bar{\nu})} = 1.433 \pm 0.020\,(\mathrm{stat.}) \pm 0.050\,(\mathrm{syst.}).$$

Back up

- Cross sections as measured within the experimental acceptance (eliminating PDF uncertainties from the experimental measurements).

- These cross sections cannot be combined, because electrons & muons have different acceptances (**Electrons**: P_T>20.0GeV & $|\eta_{Gen}|$<2.5 , **Muons**: P_T>20.0 & $|\eta_{Gen}|$<2.1).

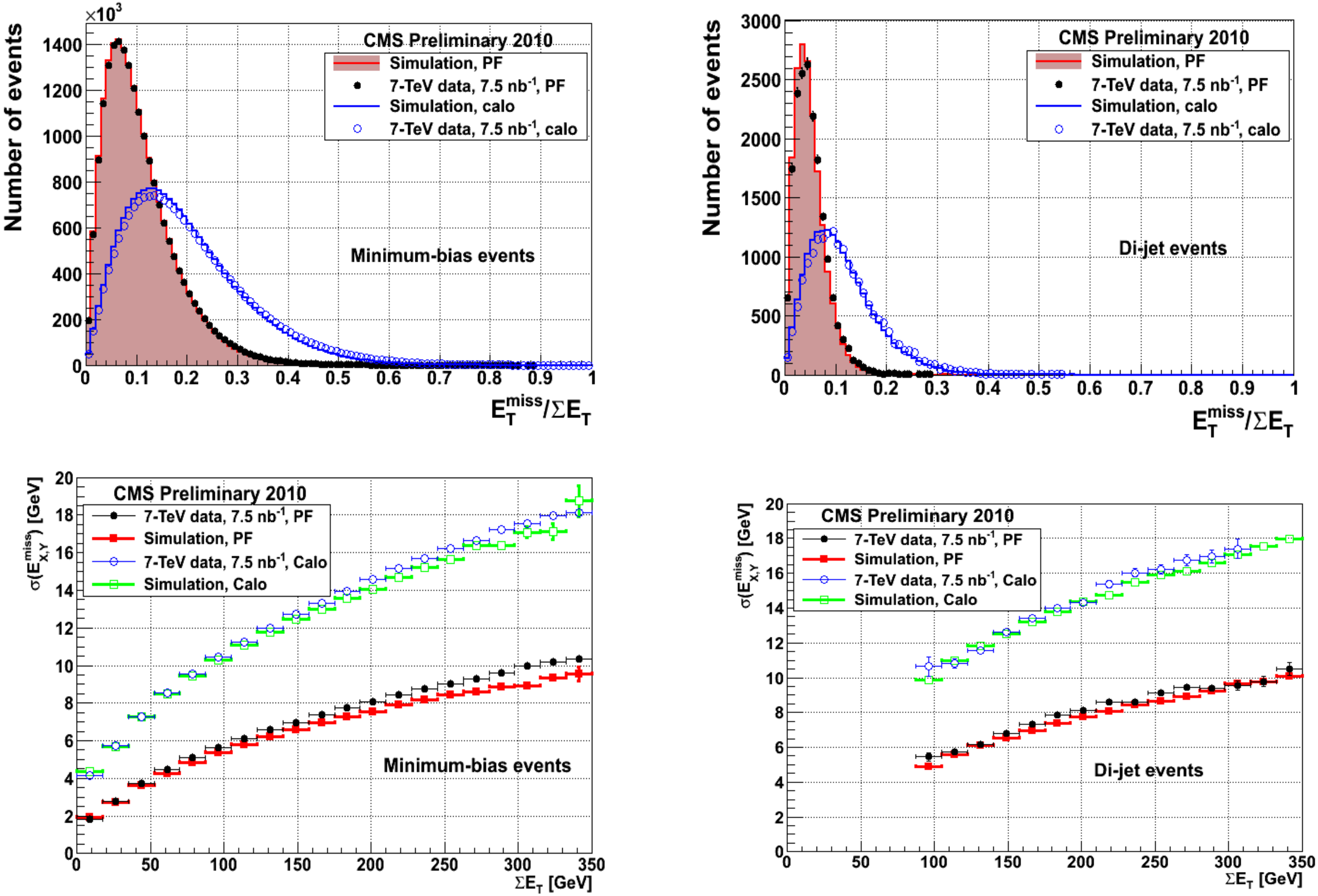
$$\sigma_{restricted} = \sigma \times A, \quad A \equiv \text{ generator level acceptance}$$

The restricted cross sections measurements are:

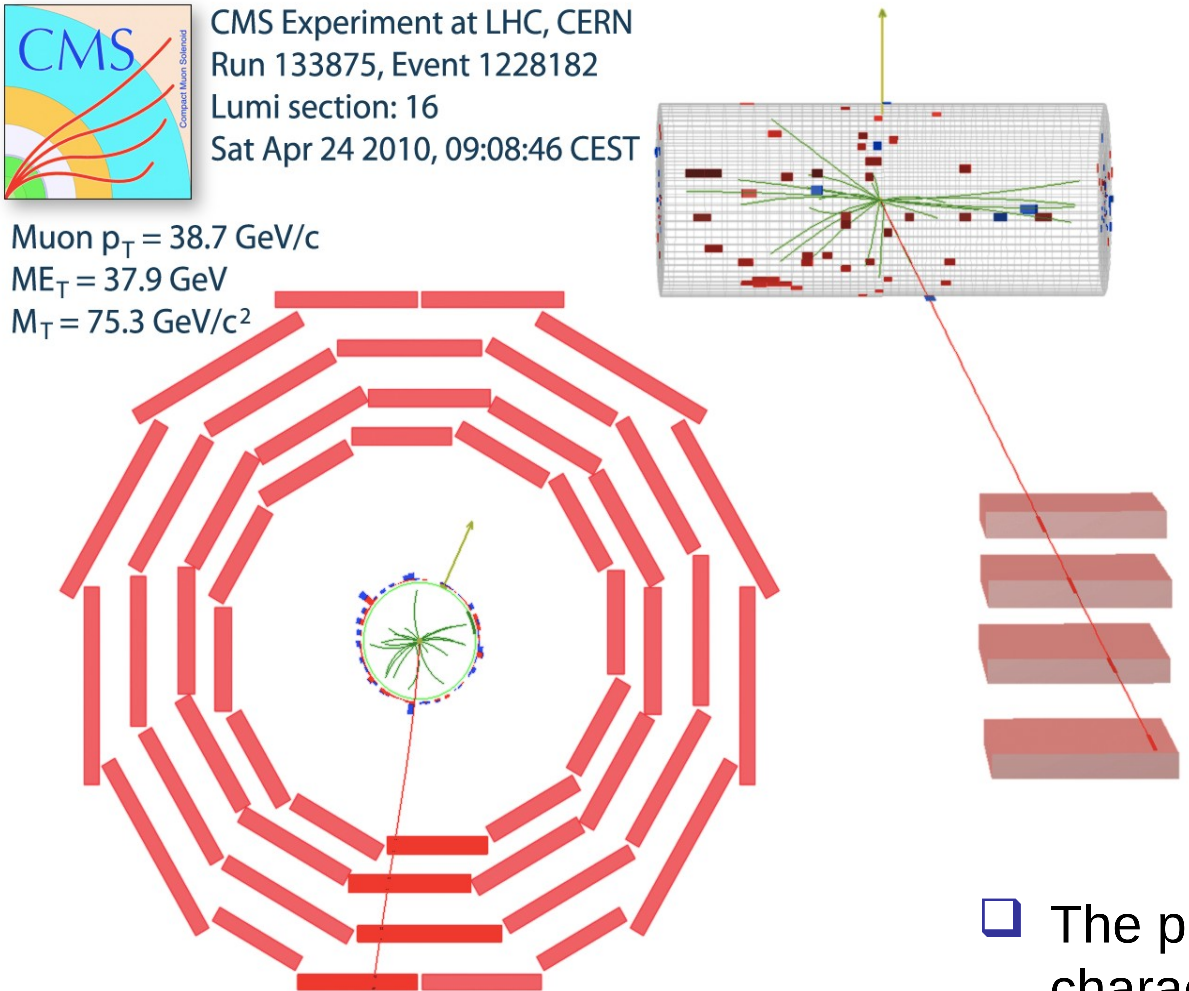
$$\begin{aligned}
\sigma\,(pp \to WX) \times \mathrm{BF}\,(W \to e\nu) &= 6.037 \pm 0.058\,(\mathrm{stat.}) \pm 0.307\,(\mathrm{syst.}) \pm 0.664\,(\mathrm{lumi.})\,\mathrm{nb}, \\
\sigma\,(pp \to WX) \times \mathrm{BF}\,(W \to \mu\nu) &= 5.212 \pm 0.047\,(\mathrm{stat.}) \pm 0.150\,(\mathrm{syst.}) \pm 0.573\,(\mathrm{lumi.})\,\mathrm{nb}, \\
\sigma\,(pp \to W^+X) \times \mathrm{BF}\,(W^+ \to e^+\nu) &= 3.688 \pm 0.046\,(\mathrm{stat.}) \pm 0.220\,(\mathrm{syst.}) \pm 0.406\,(\mathrm{lumi.})\,\mathrm{nb}, \\
\sigma\,(pp \to W^+X) \times \mathrm{BF}\,(W^+ \to \mu^+\nu) &= 3.163 \pm 0.037\,(\mathrm{stat.}) \pm 0.099\,(\mathrm{syst.}) \pm 0.348\,(\mathrm{lumi.})\,\mathrm{nb}, \\
\sigma\,(pp \to W^-X) \times \mathrm{BF}\,(W^- \to e^-\bar{\nu}) &= 2.363 \pm 0.036\,(\mathrm{stat.}) \pm 0.140\,(\mathrm{syst.}) \pm 0.260\,(\mathrm{lumi.})\,\mathrm{nb}, \\
\sigma\,(pp \to W^-X) \times \mathrm{BF}\,(W^- \to \mu^-\bar{\nu}) &= 2.048 \pm 0.029\,(\mathrm{stat.}) \pm 0.063\,(\mathrm{syst.}) \pm 0.225\,(\mathrm{lumi.})\,\mathrm{nb}, \\
\sigma\,(pp \to ZX) \times \mathrm{BF}\,(Z \to e^+e^-) &= 0.460 \pm 0.018\,(\mathrm{stat.}) \pm 0.028\,(\mathrm{syst.}) \pm 0.051\,(\mathrm{lumi.})\,\mathrm{nb}, \\
\sigma\,(pp \to ZX) \times \mathrm{BF}\,(Z \to \mu^+\mu^-) &= 0.368 \pm 0.012\,(\mathrm{stat.}) \pm 0.007\,(\mathrm{syst.}) \pm 0.040\,(\mathrm{lumi.})\,\mathrm{nb}.
\end{aligned}$$

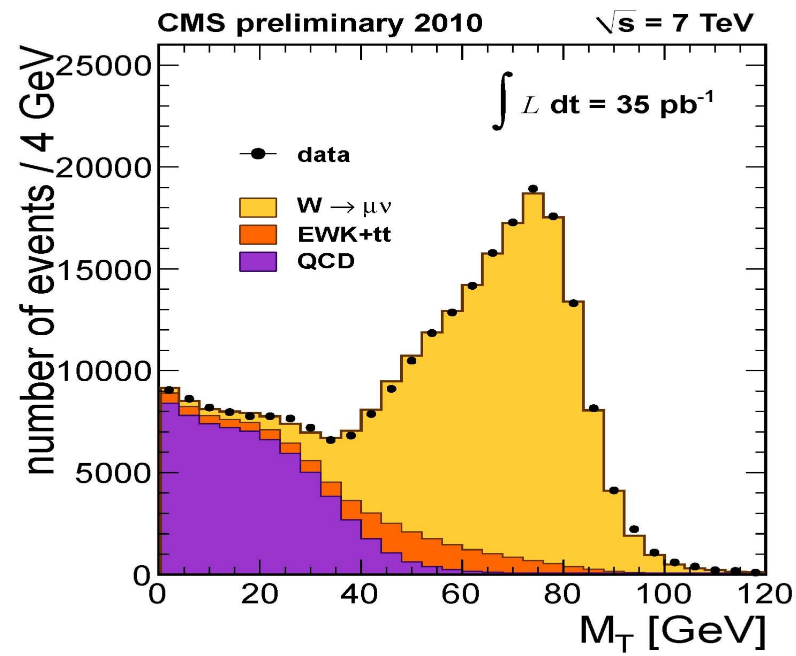
Back up

Particle flow (PF) performance with jets



Back up

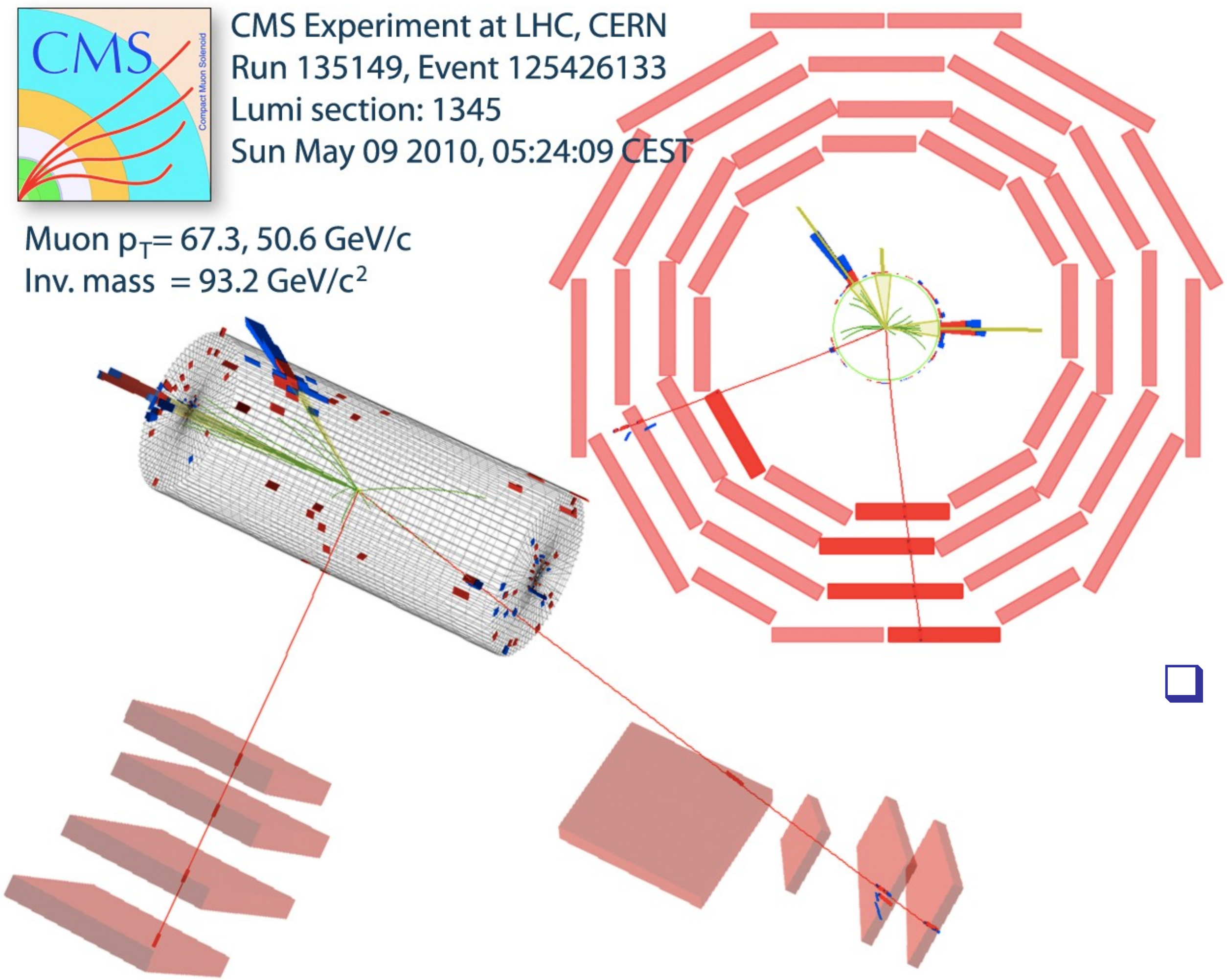


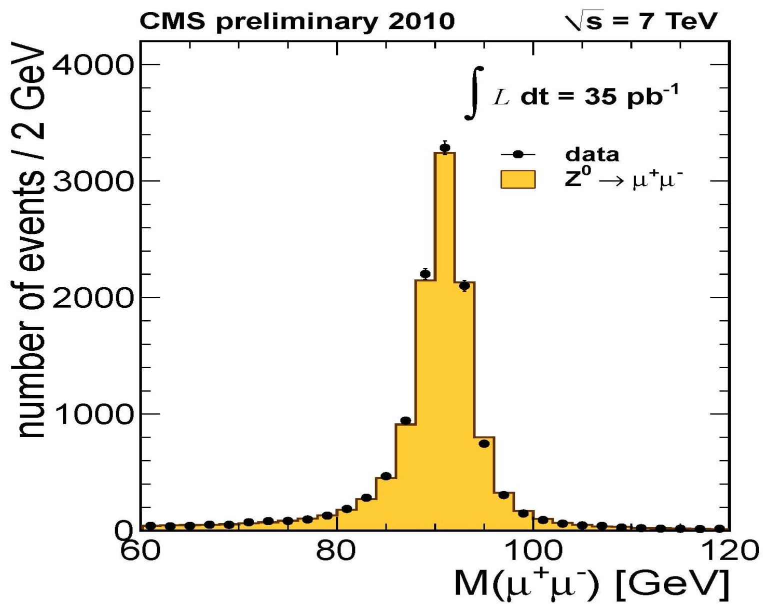


$$M_T = \sqrt{2p_T(\mu)\not{E}_T * (1 - \cos(\Delta\phi_{\mu,\not{E}_T}))}$$

- The process W to leptons is characterized by high transverse charge lepton momentum (P_T), the lepton is “isolated” and there is high missing transverse energy (ME_T) and characteristic mass distribution (M_T)

Back up





- The process Z to leptons is characterized by two high P_T “isolated” muons with invariant mass spectrum peaking at the Z pole

Data-driven techniques validate the reconstructed objects, measure their efficiencies, resolutions, etc.