W and Z Physics at CMS

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Fermilab

On behalf of the CMS Collaboration

Conference on LHC First Data

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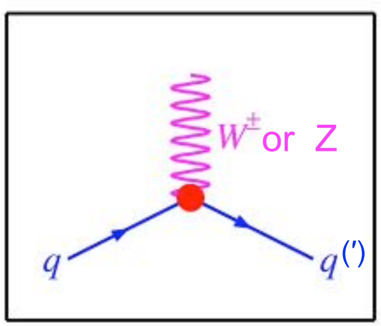
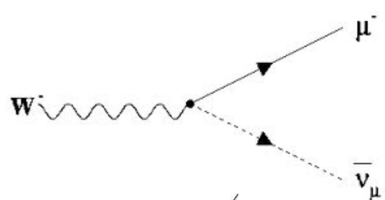
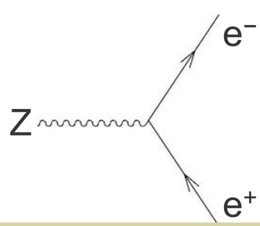
Observables and motivation

Motivation

- W and Z production are the first EWK processes studied at LHC
- First benchmark for high-p_T electron and muon reconstruction and identification
- Precision test of perturbative QCD and proton PDFs
- Estimator of LHC luminosity







Measurements

✦Inclusive W and Z production cross sections
- separately for electrons and muons, and combined
- for direct comparison with Standard Model NNLO predictions
- precision limited by LHC luminosity uncertainties (11%)

✦Ratio of W^+/W^- and W/Z production cross sections
- insensitive to luminosity and other sources of uncertainties (4% precision)

✦Cross sections in restricted acceptance
- to minimize theoretical dependencies

W and Z production at the LHC

✦Occurs through admixture of valence quark/sea quark annihilation and sea quark/sea quark annihilation

-at HERA-like low parton x (10^{-5} to 10^{-2})

✦4X higher cross sections than Tevatron, with stronger sea-sea component (lower x)

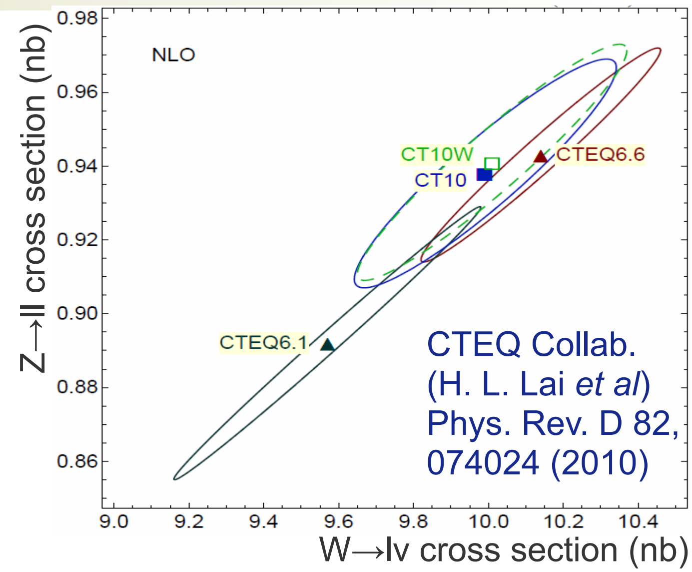
-W σxBR(W→lν) ~10 nb per channel

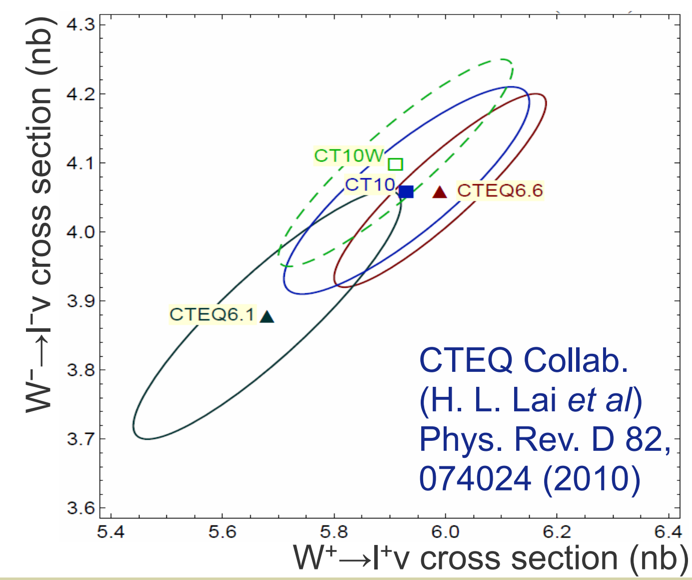
-Z σxBR(Z→ll) ~1 nb per channel

✦W production in pp collisions is globally charge asymmetric:

- pp has 2X more u$\bar{d}$ than d$\bar{u}$ collisions due to uud valence quark content of p
- -sea quark-sea quark charge symmetric production dilutes W^+/W^- ratio from 2 to ~1.4

✦Theory uncertainties at few percent level





CMS data samples

✦For this analysis use collision data from March through September 2010

- $\int L$ = 2.88 ± 0.32 pb^{-1} (analyzed)

✦10X larger data sample on tape

-about 47 pb^{-1} delivered by LHC, 43 pb^{-1} of data collected by CMS

-these data are being analyzed

-I will show updated plots at the end

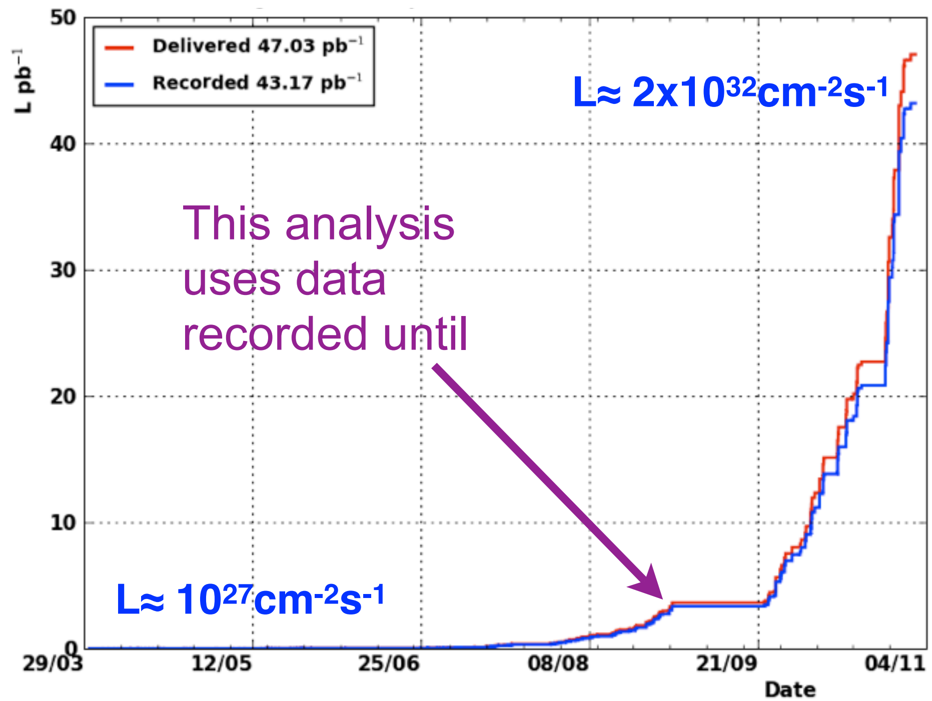
✦1 fb^{-1} Geant4 simulations of electroweak backgrounds:

-POWHEG NLO generator

•interfaced to PYTHIA FSR

•CTEQ66 PDF

-higher order effects small, estimated separately



How many events we expect for each signal?

Assuming Acceptance: 55% for W, 40% for Z

Efficiency: 80% each lepton

We can expect to get in each lepton channel:

N_W = 10 nb * 2880 nb^{-1} * 0.8 * 0.55 **~12000**

N_Z = 1 nb * 2880 nb^{-1} * 0.8*0.8 * 0.4 **~700**

Target: 1% stat. precision for W, 4% for Z

Brief history of vector bosons at CMS

March: 7 TeV pp collisions begin

April: First candidates observed with first nb^{-1}

May: Significant W excess observed with first few nb^{-1}; first Z candidates observed

June: 37 nb^{-1} samples confirm SM-like signals in all channels

July 14: 78 nb^{-1} analysis approved; ~10% non-lumi precision achieved

July 20: Analysis updated to 198 nb^{-1} , presented at ICHEP 2010 July 22
http://cdsweb.cern.ch/record/1279615

August-September: 3 pb^{-1} accumulated, 1000 Z, 10000 W per channel measured
October-November: 3 pb^{-1} result finalized and readied for publication

November 16: Result approved for the public. Submitted to JHEP (CERN-PH-EP-2010-050). CMS members can consult EWK-10-002 journal draft for more detail.

This winter: 35 pb^{-1} analysis in progress.

W, Z cross section measurement

Signal W: Prompt, energetic, isolated lepton and significant MET
Background W: QCD multi-jets, γ+jets (electrons), Drell-Yan, $W \rightarrow \tau\nu$, $Z \rightarrow \tau\tau$, $t\bar{t}$, diboson
Signal & background yields: by fitting M_T (muons) or MET (electrons) distributions.

Signal Z: Two energetic, isolated leptons with M_{ll} around M_Z
Background Z: Negligible QCD bkgd, EWK and top bkgd known precisely @NLO
Signal yields: Cut & count (electrons), Simultaneous fit for yield & efficiencies (muons)

$$\sigma \cdot \mathrm{Br} = \frac{N_{\mathrm{candidates}} - N_{\mathrm{background}}}{\mathrm{Acceptance} \cdot \mathrm{Efficiency} \cdot L}$$

Acceptance: From MC (POWHEG)

Efficiency:

$$\epsilon_{\mathrm{X}} = \epsilon_{\mathrm{MC\text{-}X}} \times \rho_{\mathrm{eff\text{-}X}},$$

$$\rho_{\mathrm{eff\text{-}X}} = \frac{\epsilon_{\mathrm{TNP\text{-}X}}(\mathrm{data})}{\epsilon_{\mathrm{TNP\text{-}X}}(\mathrm{MC})}$$

L: External input 11% uncert.

W/Z analysis ingredients: Electrons

✦Kinematics

- -p_T > 20 GeV
- -|η|<1.44 (i.e., ECAL Barrel) OR 1.57<|η|<2.5 (i.e., ECAL Endcaps)
- -Trigger: Single e/γ E_T > 15 GeV, Level-1: 5 GeV (>99% efficient)

✦Electron reconstruction & ID

- -Seeded from >5 GeV ECAL super-cluster
- -Specialized track reconstruction, incorporates bremsstrahlung
- -Cuts on ID variables:
  - •track/cluster matching
  - •shower shape, H/E
- -Conversion rejection:
  - •require no missing hits in inner pixel layers
  - •reject electrons having conversion partner track

✦Isolation

- -Both W & Z: separate, relative isolations
- -in tracker, ECAL, and HCAL

-Overall efficiency for this selection: ~75% per electron
-Overall acceptance:
W: ~57%, Z: 43.5%

Electron efficiency determination: tag & probe

Tag one leg of the Z and probe the other leg using invariant mass constraint

Tag Selection

Reconstructed electron with
- Super cluster within $|\eta|$ acceptance
- $E_T > 20$ GeV
- Passing isolation and Id cuts
- Matched to the trigger electron candidate

Probe Selection

Super cluster with
- $E_T > 20$ GeV, $|\eta|$ in acceptance
- Fit the tag-probe invariant mass to get the number of signal events.

Obtain factorized efficiencies for passing probes:

SuperCluster → electron →Id, isolation, selection → HLT

offline reconstruction efficiency with respect to acceptance

trigger efficiency w.r.t. offline selection

Estimated efficiencies:

ε_{RECO} : SuperCluster → electron

ε_{Id} : electron → offline selection

ε_{TRG} : offline selection → trigger criteria

Methodology to apply data-driven efficiency

✦Efficiencies are determined from MC and corrected with data

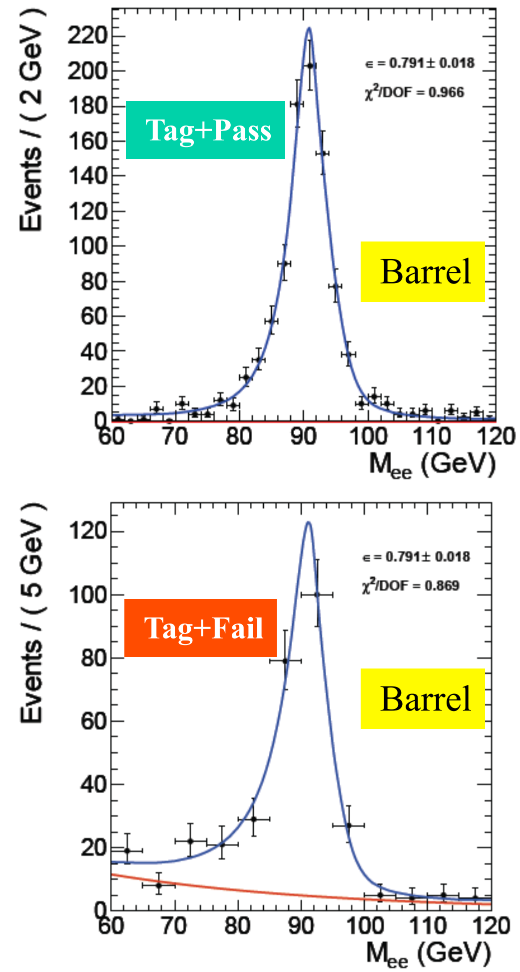
$$\epsilon_X = \epsilon_{\text{MC-X}} \times \rho_{\text{eff-X}}, \quad \rho_{\text{eff-X}} = \frac{\epsilon_{\text{TNP-X}}(\text{data})}{\epsilon_{\text{TNP-X}}(\text{MC})}$$

separately in ECAL Barrel & Endcaps, for e^+ and e^-.

✦Data/MC correction factors (ρ) estimated w/ Tag&Probe
- primarily because electrons in a given analysis have different kinematic distribution than in the calibration sample (i.e., Z→ee)
- kinematics are well-modeled in Monte Carlo, therefore data/MC ratio is unbiased.

✦Simultaneous unbinned likelihood fit of M_{ee} in Tag+Pass and Tag+Fail categories:
- signal shape templates: (NLO lineshape ⊗ resolution smearing) - exponential or polynomial model for bkgd

simultaneous fit for electron selection eff.



Electron efficiencies and acceptance

EB ≡ ECAL Barrel, EE ≡ ECAL Endcaps

	Topology	Monte-Carlo		Data				Data/Monte-Carlo
		ϵ	$\Delta\epsilon$	ϵ	$\Delta\epsilon$ (stat)	$\Delta\epsilon$ (syst)	$\Delta\epsilon$ (total)	
SC→Reco	EB	0.9851	0.0002	0.986	0.005	0.012	0.013	1.001 ± 0.013
	EE	0.9629	0.0004	0.962	0.008	0.012	0.015	0.999 ± 0.016
Reco→Id	EB	0.8547	0.0004	0.791	0.018	0.020	0.027	0.925 ± 0.032
	EE	0.7488	0.0006	0.692	0.020	0.020	0.028	0.924 ± 0.037
Id→Trig	EB	0.997	0.0001	0.989	0.003	0.001	0.0032	0.992 ± 0.003
	EE	0.988	0.0003	0.992	0.005	0.001	0.0051	1.004 ± 0.005

Reference MC
NLO MC generator POWHEG + CTEQ66 PDF´s

Channel	Corrected efficiency	Acceptance
W^+	(71.4 ± 3.6) %	58.95 %
W^-	(73.0 ± 3.7) %	54.31 %
$W^\pm$	(72.1 ± 2.8) %	57.07 %
Z	(56.2 ± 3.3) %	43.45 % ($60<M_{ee}<120$ GeV)

↑ sys+stat

↑ negligible stat error
will discuss syst error later

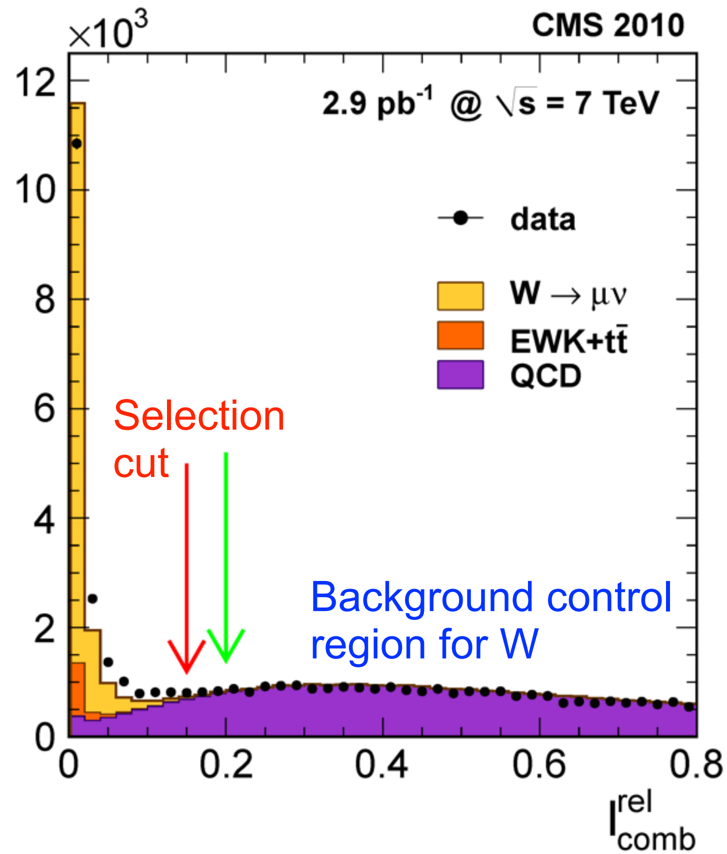
W/Z analysis ingredients: Muons

✦Kinematics

- p_T > 20 GeV, |η| < 2.1
- Trigger: Single muon p_T>9 GeV

✦Quality Requirements

- ≥10 tracker hits, ≥1 pixel hits
- ≥1 good muon chamber hit
- Both inside-out & outside-in reconstruction
- Track matching with ≥2 segments in the muon stations
- χ2/ndf < 10 global fit
- Cosmic veto: impact parameter $|d_{xy}|$<2 mm (w.r.t. the beam spot)



✦Isolation

- Combined relative isolation (R=0.3)

$$I^{rel}_{comb} = \left\{ \sum (p_T(tracks) + E_T(em) + E_T(had)) \right\} / p_T(\mu) \quad < 0.15$$

Muon Efficiencies and acceptance for W & Z

Derived from $Z \to \mu\mu$ sample using Tag & Probe technique
(analogous to the electron case)

	Efficiency	Data	Simulation	Data/Simulation (ρ_{eff})
track→μ efficiency	ϵ_{SA}	$(96.4 \pm 0.5)\%$	97.2%	0.992 ± 0.005
tracker eff	ϵ_{TRK}	$(99.1 \pm 0.4)\%$	99.3%	0.998 ± 0.003
eff for χ^2, $\|d_{xy}\|$,..	ϵ_{SEL}	$(99.7 \pm 0.3)\%$	99.7%	1.000 ± 0.003
isolation eff	ϵ_{ISO}	$(98.5 \pm 0.4)\%$	99.1%	0.994 ± 0.004
trigger eff	ϵ_{TRG}	$(88.3 \pm 0.8)\%$	93.2%	0.947 ± 0.009
	Net	$(82.8 \pm 1.0)\%$	88.7%	0.933 ± 0.012

Reference MC
NLO MC generator POWHEG + CTEQ66 PDF´s

Acceptance:

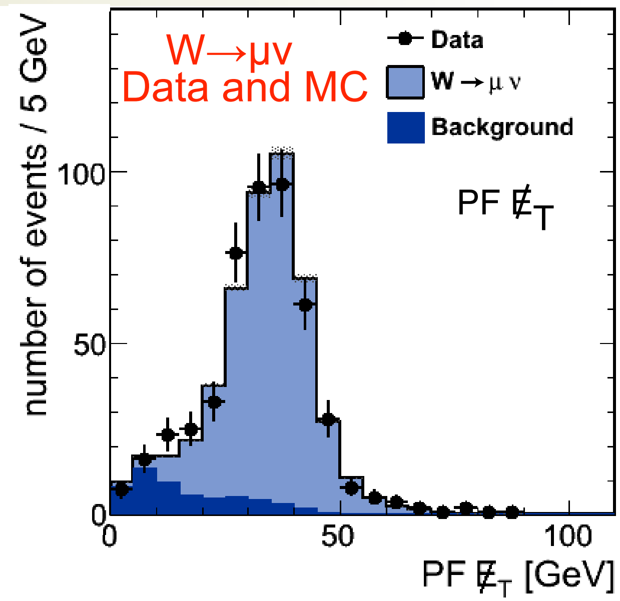
$W \to \mu\nu$	A
W^+	0.5413 ± 0.0060
W^-	0.5023 ± 0.0055
$W^\pm$	0.5253 ± 0.0058

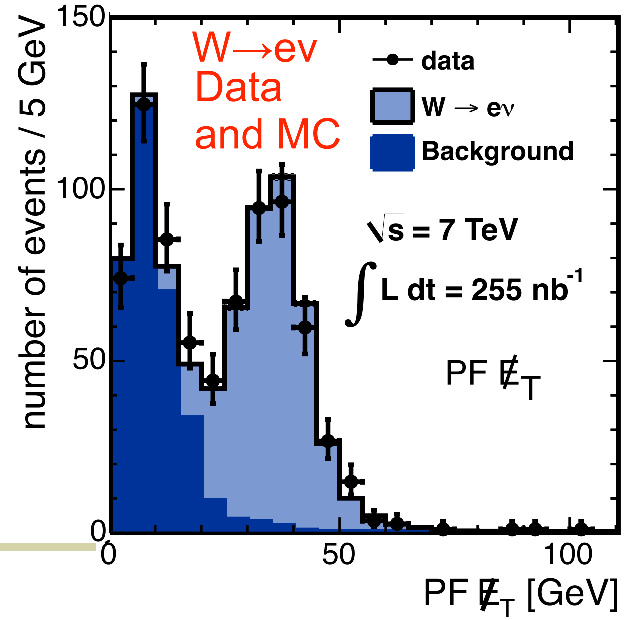
A	$Z \to \mu^+\mu^-$
Z	0.3977 ± 0.0048

($60 < M_{\mu\mu} < 120$ GeV)

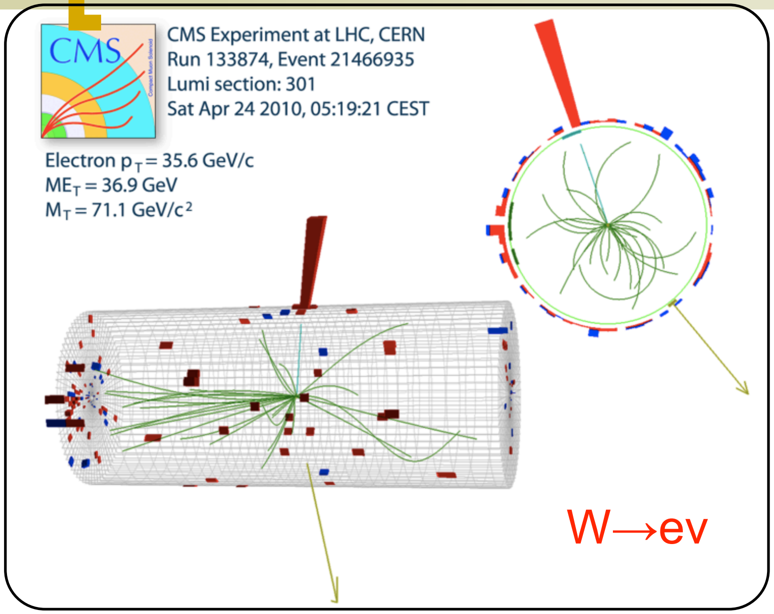
W/Z analysis ingredients: missing E_T

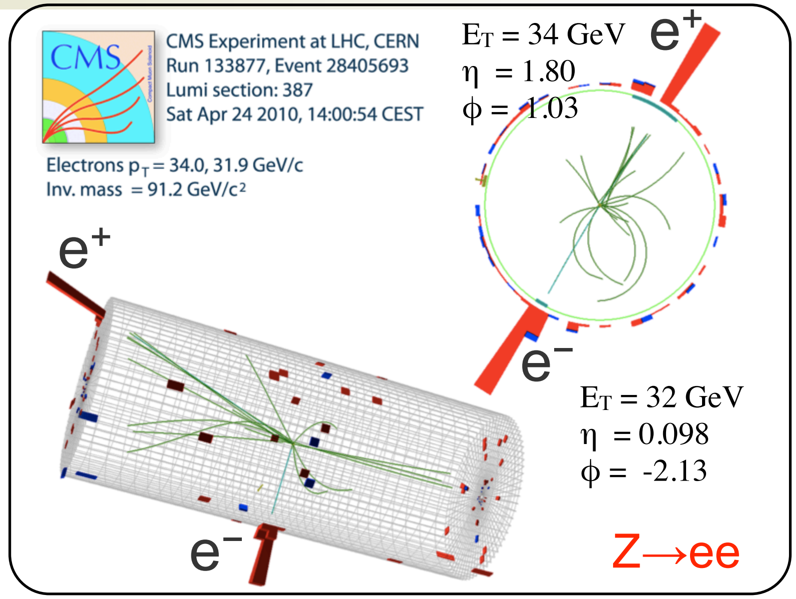
- ✦Compute missing E_T in from full "Particle flow", *i.e.*, using vector sum of all reconstructed particles the event
  - -better resolution than simple calorimetric MET
  - -less sensitive to calorimeter calibrations
  - -well reproduced by simulation
- ✦For W signal events derive MET shape using data-driven technique
  - -from momentum balance in transverse plane in events containing a Z boson and hadronic recoil
  - -detail on a later slide
- ✦Pileup has negligible effect on W yield
  - -Less than 40% events have >1 primary vertex
  - -in these cases there is ~10% broadening of MET distribution
  - -no significant effect on the results
  - -to the first order correct for it in recoil p_T balance

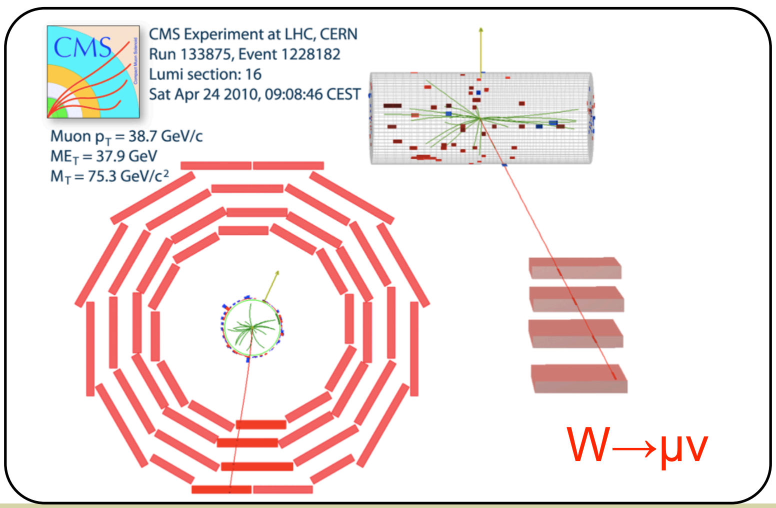


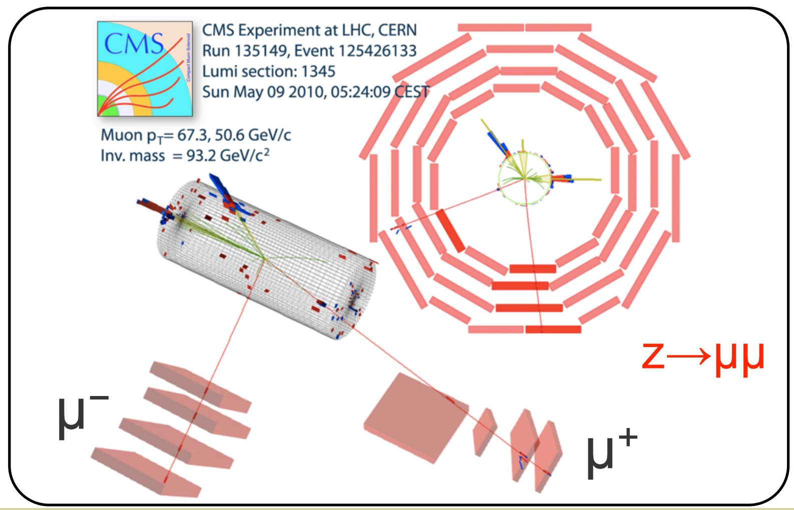


W and Z signal extraction









$W \rightarrow e\nu$ signal extraction strategy

- A well-reconstructed electron
  - passing selection & trigger criteria listed earlier
- $Z \rightarrow ee$ events are vetoed by removing events with a second electron
  - passing a looser selection cut
- Use missing E_T as discriminating variable:
  - no explicit cut, but fit to get signal yield
- Main backgrounds:

source	N_{bkg}/N_W	how estimated
QCD multi-jet + γ-jet	~ 1.3	from UML fit
$Z \rightarrow e^+e^- + Z \rightarrow \tau^+\tau^-$	8.3%	MC
$W \rightarrow \tau\nu$	4.5%	MC
di-boson production	0.13%	MC
$t\bar{t}$	0.4%	MC
EWK	13.3%	MC

W→eν signal extraction: signal shape

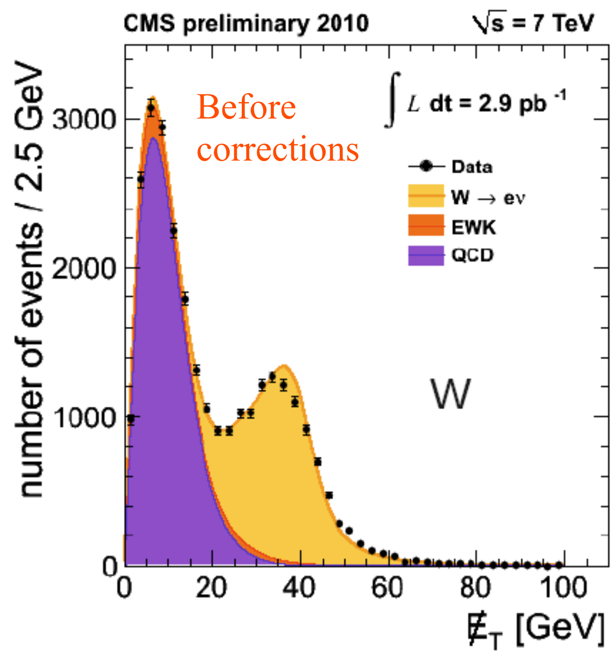
W→eν signal MET shape:

- POWHEG MC shows poor agreement with data

  Should be corrected for :

  -electron energy scale & resolution

  -response/resolution of hadronic recoil

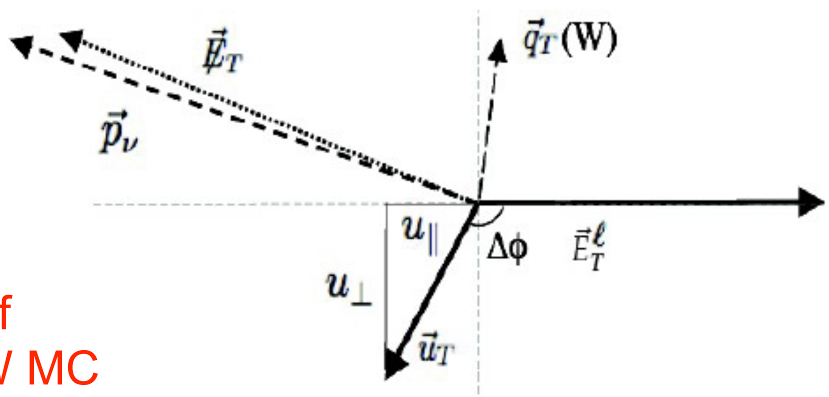


- After corrections, agreement with data is good.
- Hadronic recoil (u) in the event is defined via conservation of momentum in transverse plane:

$$\vec{q}_T + \vec{u}_T + \vec{\not{E}}_T = 0$$

-recoil has components $u_{||}$, $u_{\perp}$ parallel/ perpendicular to boson q_T axis.

-calculate $u_{||}$, $u_{\perp}$ for Z data, Z MC and W MC.



Determine Z data/MC scale factors in bins of boson p_T to correct response/resolution in W MC

W→eν signal extraction: background shape

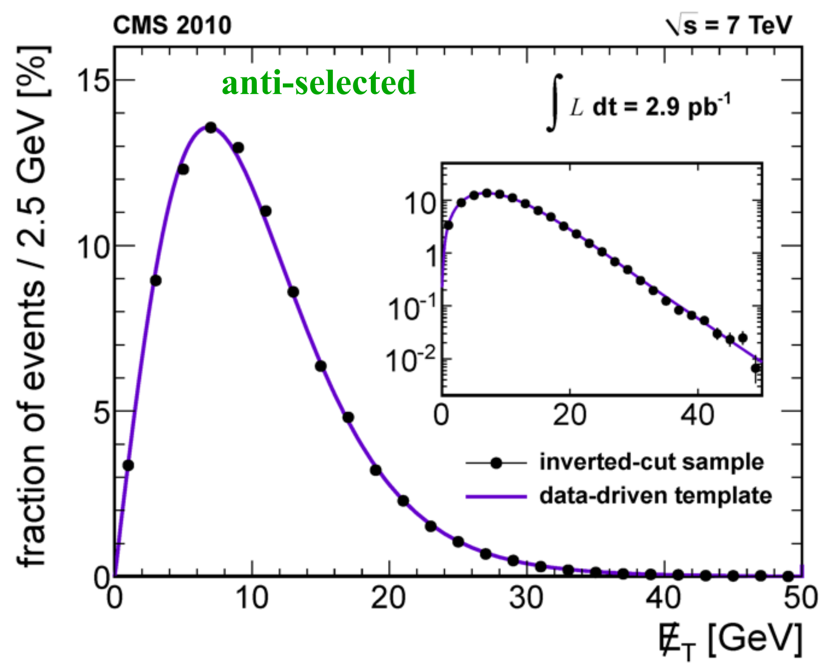
QCD background MET shape:

- Rayleigh distribution: magnitude of MET vector with independent Gaussian components

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

- Tail parameter σ_1 for ΣE_T dependence
- Both σ_0 & σ_1 are free parameters in the fit

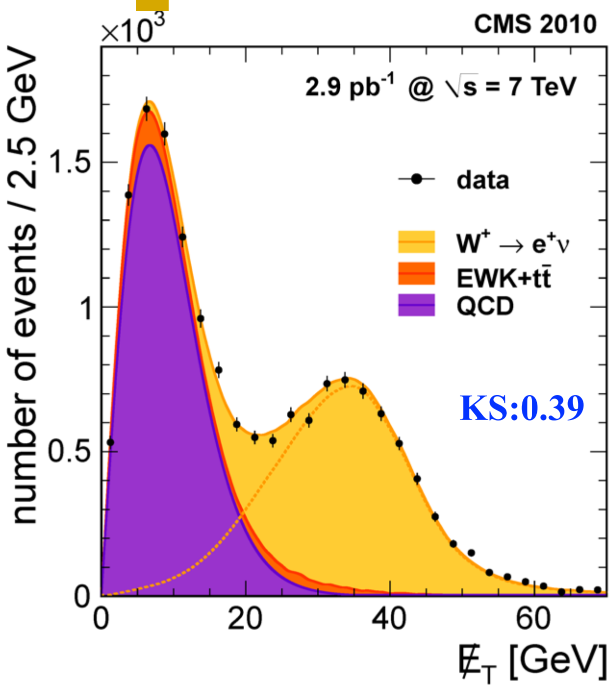
- A simultaneous fit with separate W^+ and W^- components is performed, constraining the bkgd shape parameters to be identical for both charges.

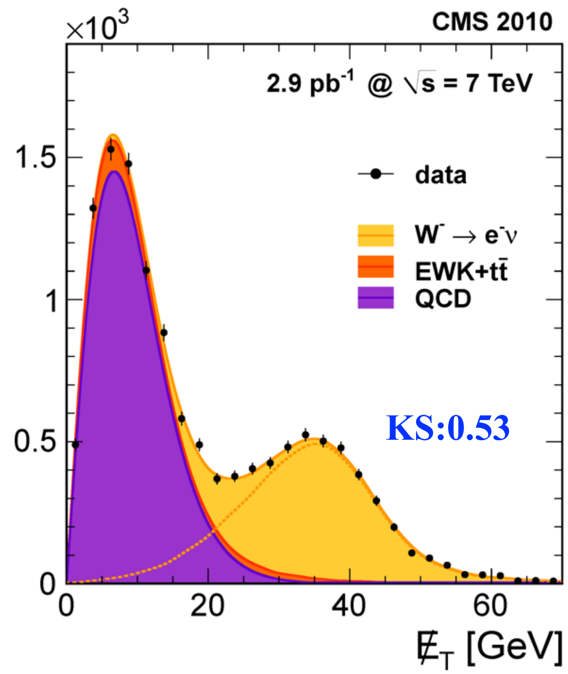


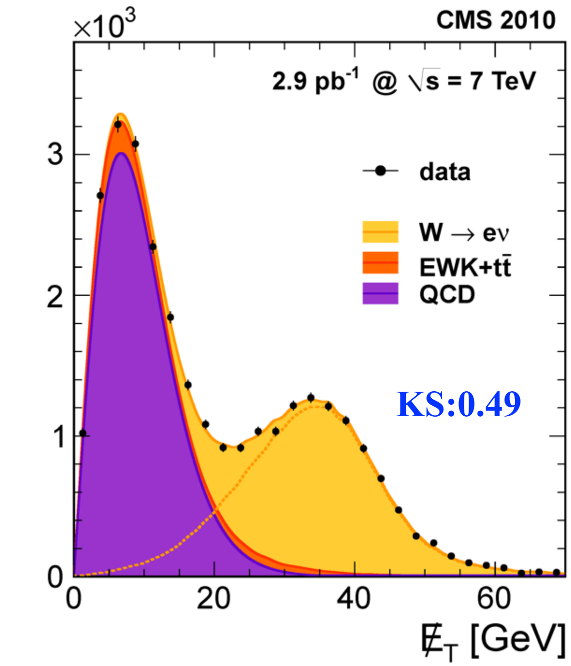
EWK background MET shapes:

Normalized w.r.t. acceptance and NLO cross sections

W→eν signal yield & cross section measurement







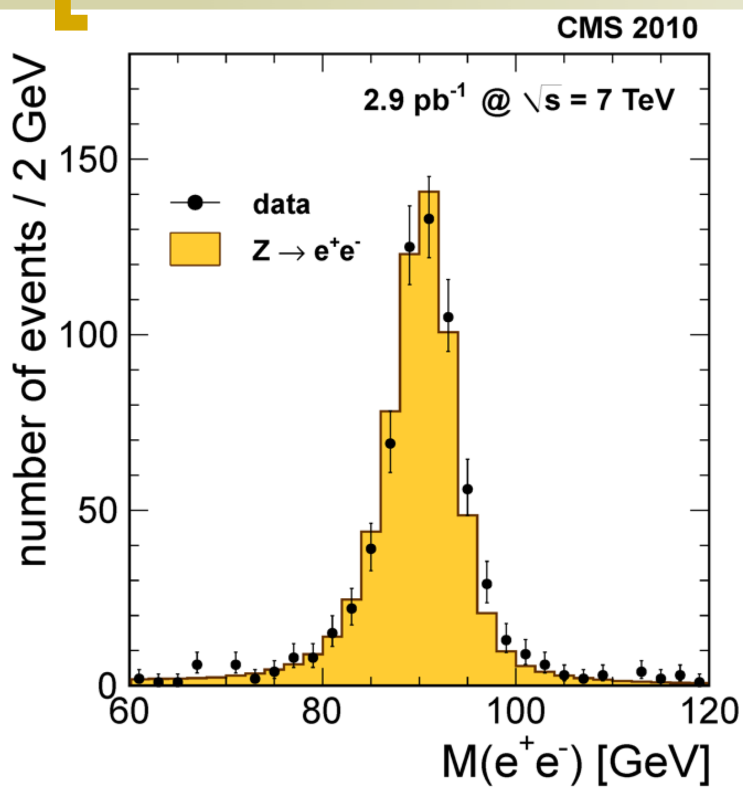
W+ Sel. Cand.: 15859
Signal Yield : 7193 ± 89
Acceptance : 0.5895
Corrected eff. : (71.4 ± 3.6)%
x-section (nb) : 5.935 ± 0.074_{stat}
NNLO (nb) : 6.15

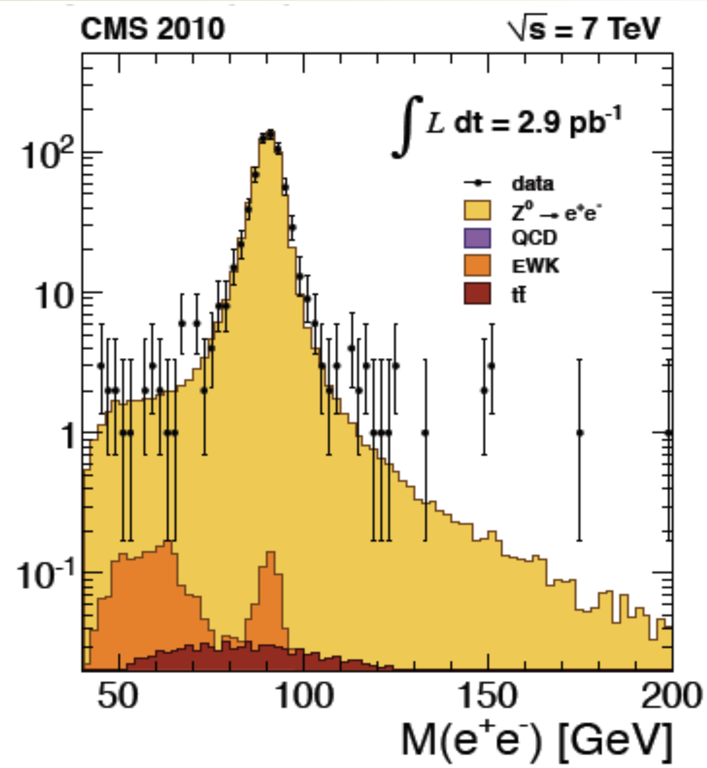
W- Sel. Cand.: 12742
Signal Yield : 4728 ± 73
Acceptance : 0.5431
Corrected eff.: (73.0 ± 3.7)%
x-section (nb): 4.140 ± 0.064_{stat}
NNLO (nb) : 4.29

W Sel. Cand. : 28601
Signal Yield : 11895 ± 115
Acceptance : 0.5707
Corrected eff. : (72.1 ± 2.8)%
x-section (nb) : 10.045 ± 0.097_{stat}
NNLO (nb) : 10.44

W^+/W^- cross section ratio = 1.434 ± 0.028_{stat}

Z→ee mass distribution, cross section





No opposite charge requirement

Simple "cut & count" method

Z Sel. Cand. : 677

Signal Yield : 674 ± 26

Acceptance : 0.4345

Corrected eff. : (56.2 ± 3.3)%

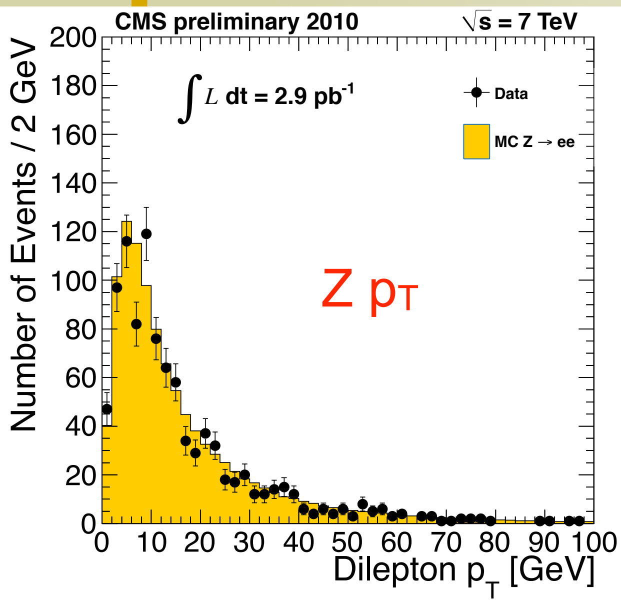
x-section (nb) : $0.960 \pm 0.037_{stat}$

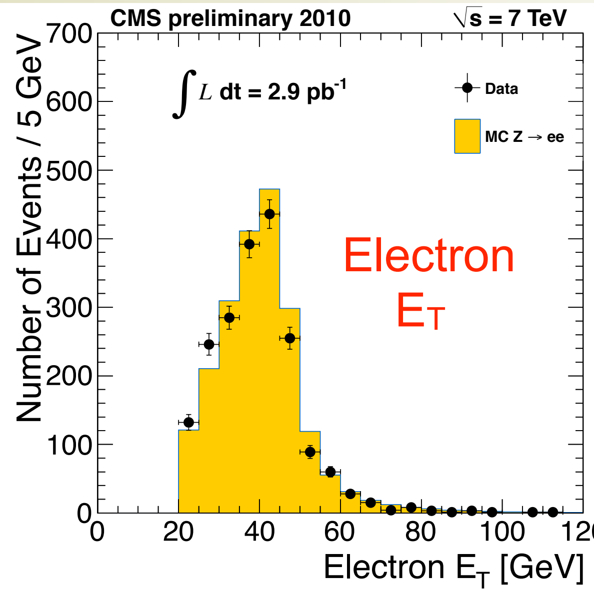
NNLO (nb) : 0.97

Expected background from MC

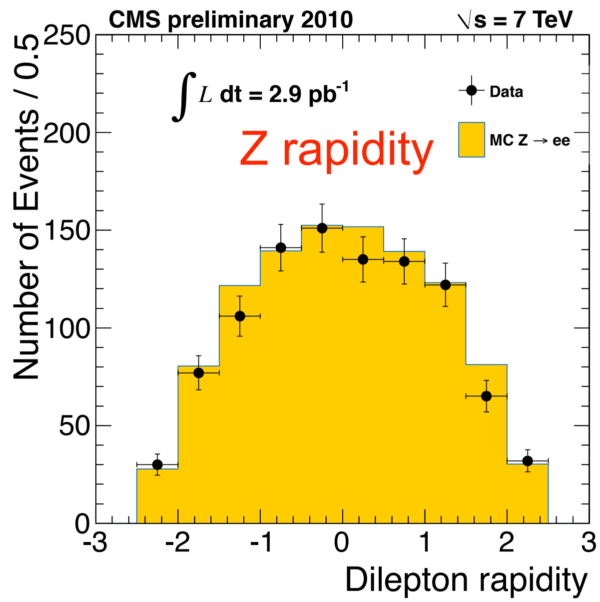
source	fraction	N_{est}
QCD multi-jet	0.06%	0.4 ± 0.4
$Z \rightarrow \tau^+\tau^-$ (MC)	0.11%	0.77
di-boson production (MC)	0.12%	0.76
$t\bar{t}$ (MC)	0.11%	0.83
EWK (MC)	0.35%	2.36
total	0.41%	2.8 ± 0.4

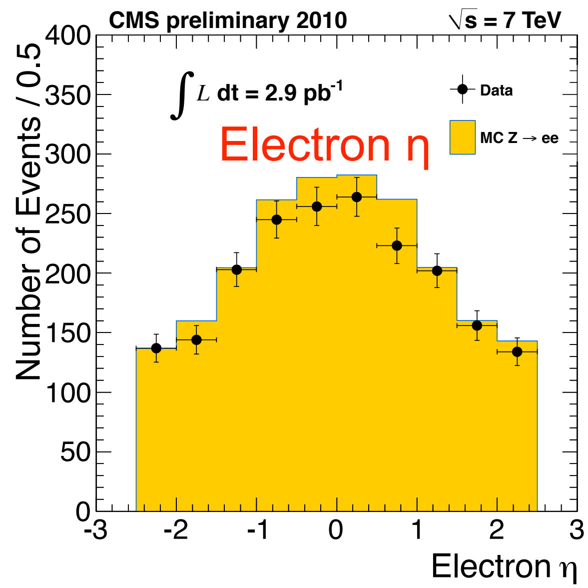
Z→ee differential distributions





- ✦MC normalized to lumi
- ✦Data not yet corrected for energy scale, effi.
- ✦Energy under-estimated by ~1% in barrel, ~3% in endcap
- ✦E_T resolution in data a little worse than MC





Can provide powerful checks on boson production/decay:

- p_T : low-x resummation, perturbative predictions
- Rapidity: low-x gluon PDFs

W→μν signal extraction strategy

- ✦A well-reconstructed muon passing selection & trigger criteria listed earlier
- ✦$Z \to \mu\mu$ events are vetoed by removing events with a 2nd muon of p_T>10 GeV
- ✦Number of candidate events:
  - -total W : 18571, W^+ : 10682, W^- : 7889
  - -with MT>50 GeV W : 11011, W^+ : 6495, W^- : 4516

✦Use M_T as discriminating variable: no explicit cut, fit to get signal yield

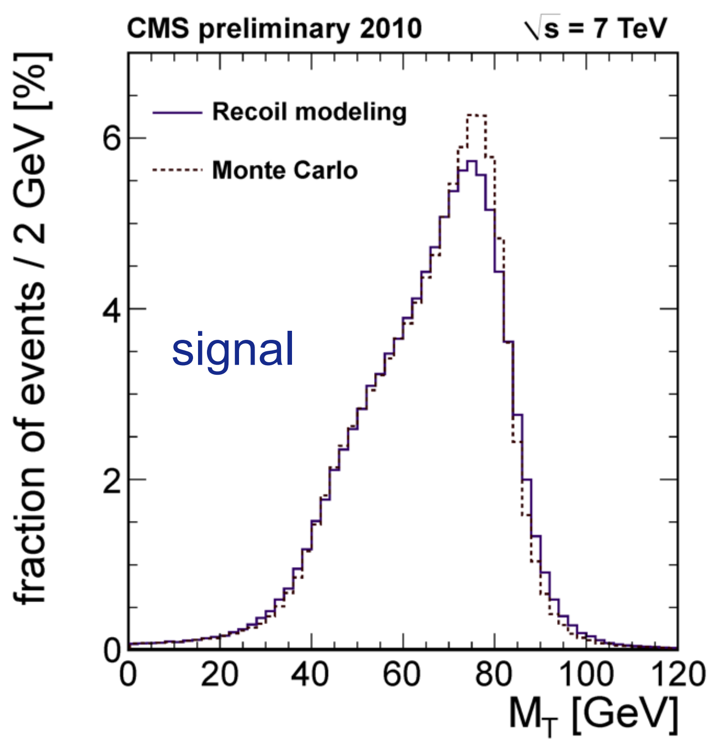
✦ Main backgrounds:

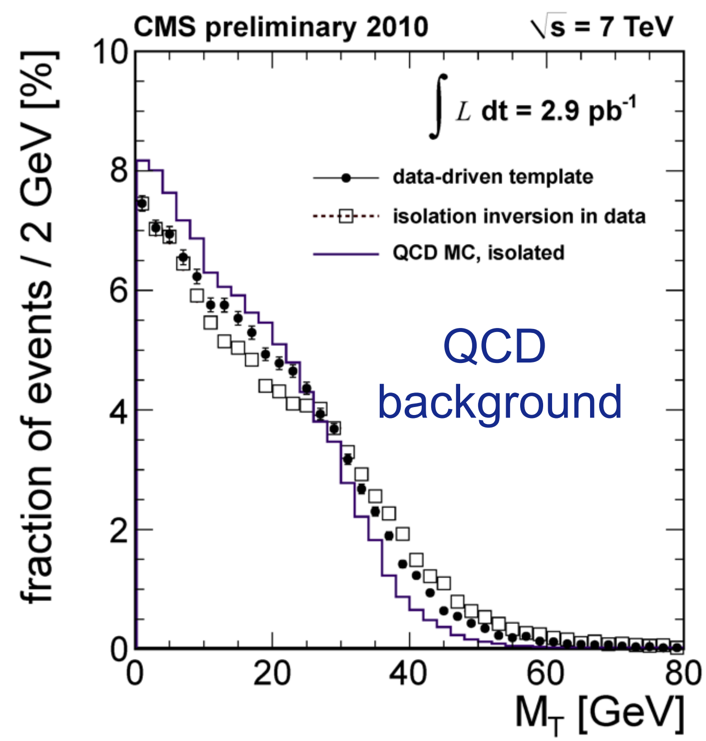
source	$N_{bg}/(N_W + N_{bg})$	N_{bg} in 2.88 pb^{-1}
QCD multi-jet	19.7%	3688
$Z \to \mu^+\mu^-$	3.5%	647
$W \to \tau\nu$	2.5%	474
$Z \to \tau^+\tau^-$	0.6%	112
WW+WZ+ZZ	0.1%	17
$t\bar{t}$	0.3%	53
EWK + $t\bar{t}$	6.9%	1303
total	26.7%	4991
$W \to \mu\nu$ signal	73.3%	13720

W→μν signal extraction: signal & bkgd shape

For signal shape use the same method as for electrons. Applied to M_T.

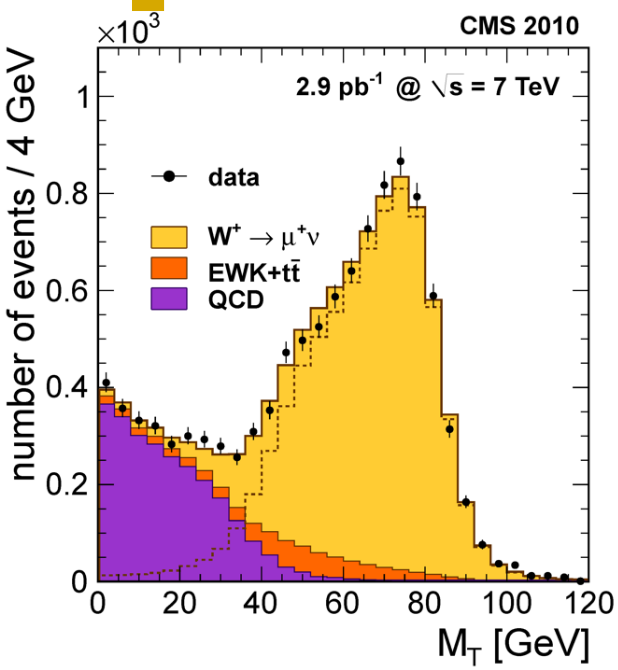
Assign full difference with respect to MC template (0.4%) as systematic uncertainty.

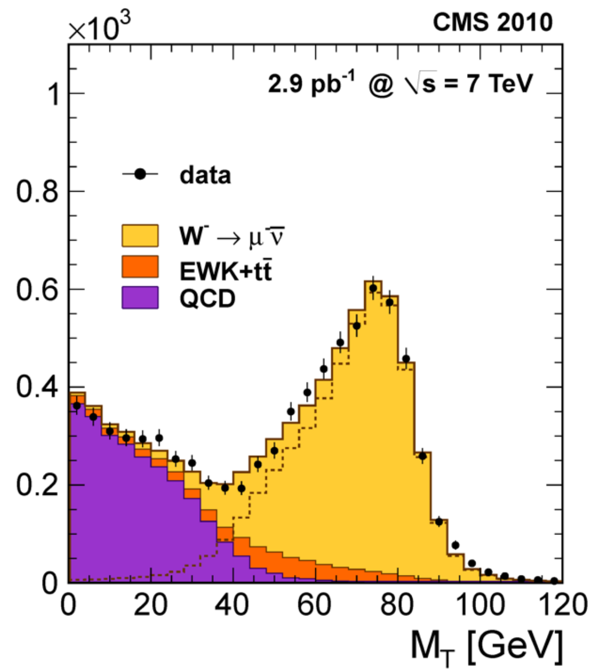


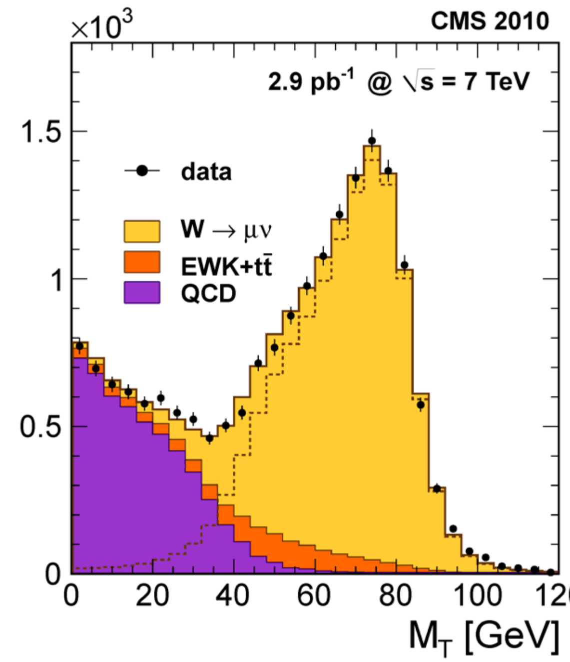


Background shape: use bkgd control sample by inverting the isolation cut. Account for small correlation between M_T and isolation. Assign full difference w.r.t. the MC template/simple data inversion template (2%) as a systematic uncertainty.

W→μν signal yield & cross section measurement







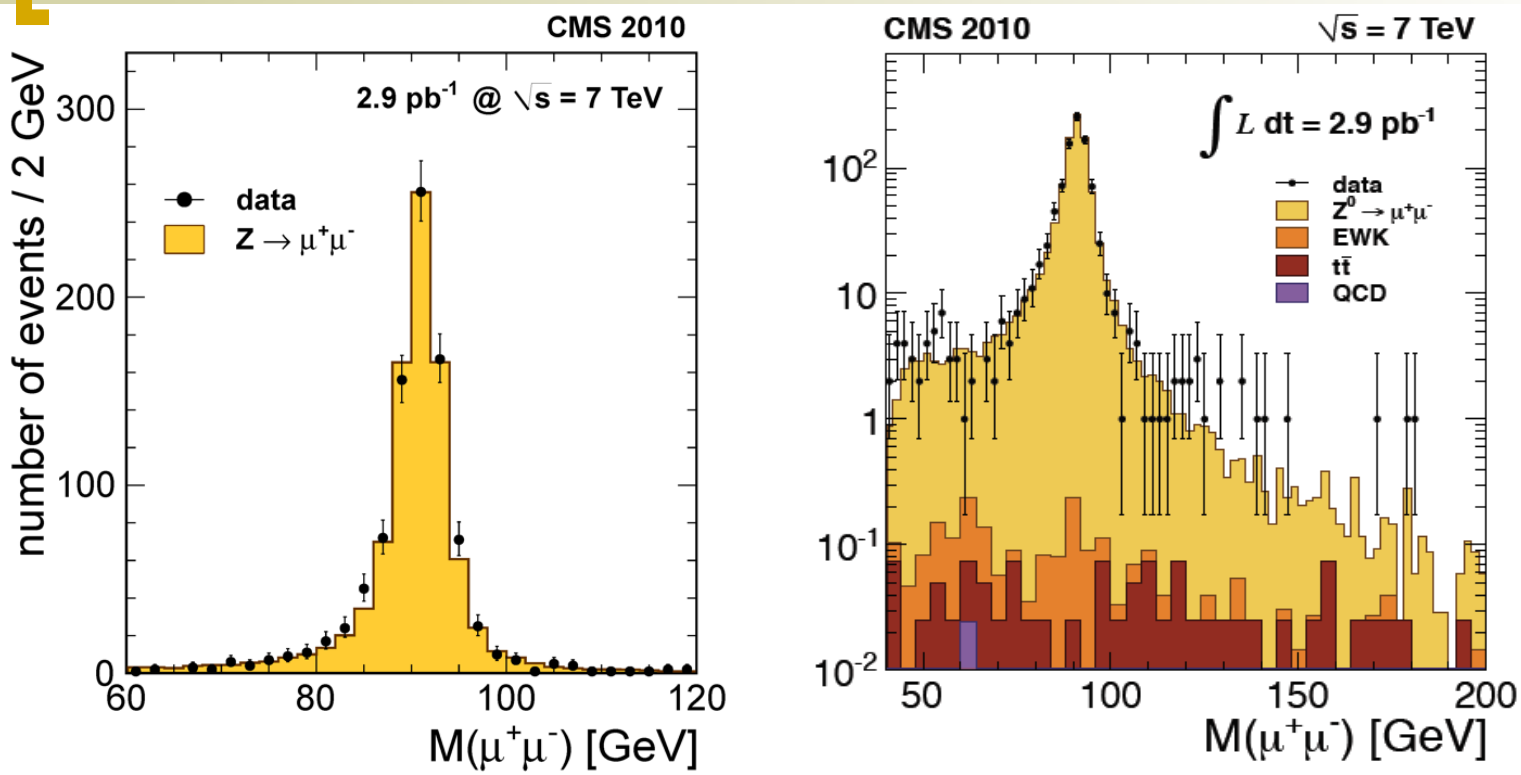
W+ Sel. Cand.: 10682
Signal Yield : 7445 ± 87
Acceptance : 0.5413
Corrected eff. : (81.72 ± 1.13)%
x-section (nb) : 5.844 ± 0.069$_{stat}$
NNLO (nb) : 6.15

W- Sel. Cand.: 7889
Signal Yield : 4812 ± 68
Acceptance : 0.5023
Corrected eff.: (81.56 ± 1.13)%
x-section (nb): 4.078 ± 0.057$_{stat}$
NNLO (nb) : 4.29

W Sel. Cand. : 18571
Signal Yield : 12257 ± 111
Acceptance : 0.5253
Corrected eff. : (81.61 ± 1.13)%
x-section (nb) : 9.922 ± 0.090$_{stat}$
NNLO (nb) : 10.44

W^+/W^- cross section ratio = 1.433 ± 0.026 $_{stat}$

Z→μμ mass distribution, cross section



Simultaneous determination of Z signal yield and muon efficiency

Fitted yield (corrected for efficiency):

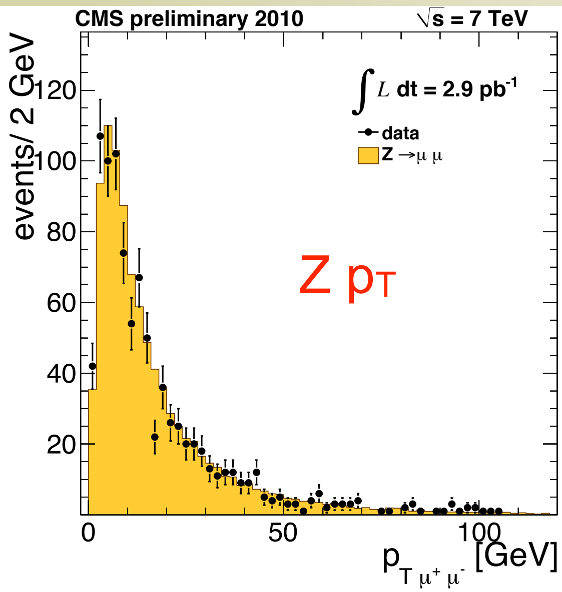
$N_{Z\rightarrow\mu\mu} = 1050 \pm 35$, Bkgd = 3.5 ± 0.2

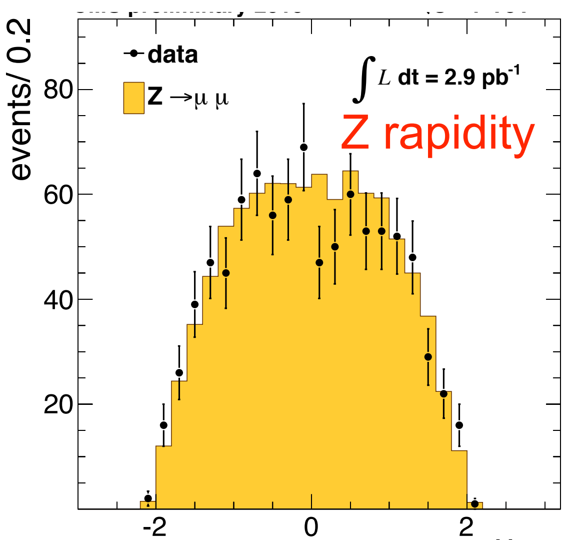
$\sigma\ (pp \rightarrow ZX \rightarrow \mu^+\mu^-\ X) = 0.924 \pm 0.031$ nb

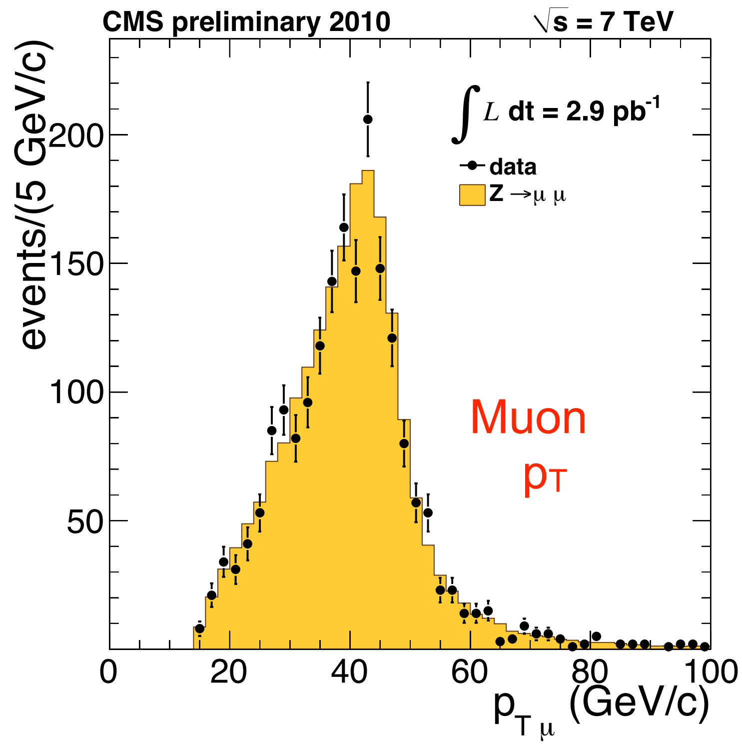
Systematic uncertainty:

- Bkgd parameterization for eff.: **1%**
- Bkgd subtraction in high purity sample: **0.2%**

Z→μμ differential distributions







- ✦Distributions are in agreement with NLO predictions.
- ✦Not efficiency-corrected

Systematic uncertainties (%)

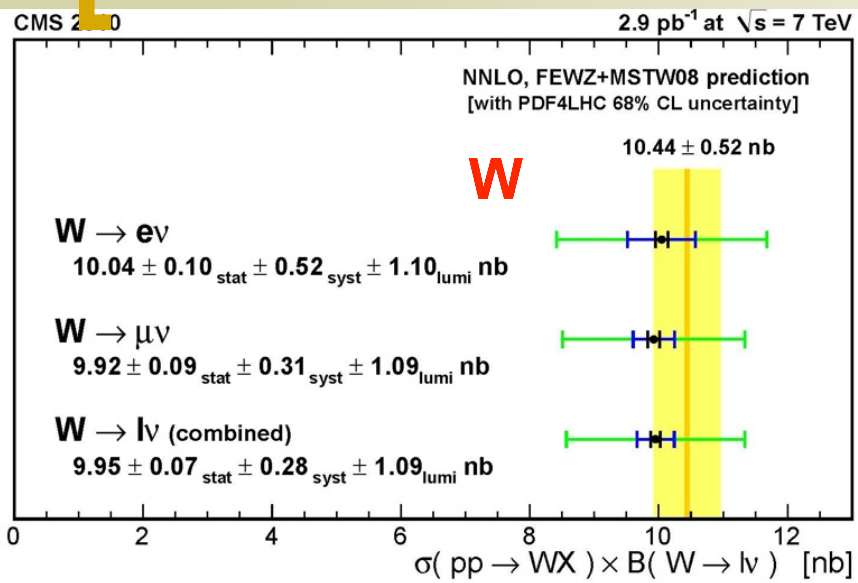
Source	$W \to e\nu$	$W \to \mu\nu$	$Z \to e^+e^-$	$Z \to \mu^+\mu^-$
Lepton reconstruction & identification	3.9	1.4	5.9	n/a
Pre-triggering	n/a	0.5	n/a	0.5
Momentum scale & resolution	2.0	0.3	0.6	0.2
$\not{E}_T$ scale & resolution	1.8	0.4	n/a	n/a
Background subtraction / modeling	1.3	2.0	0.1	1.0
PDF uncertainty 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

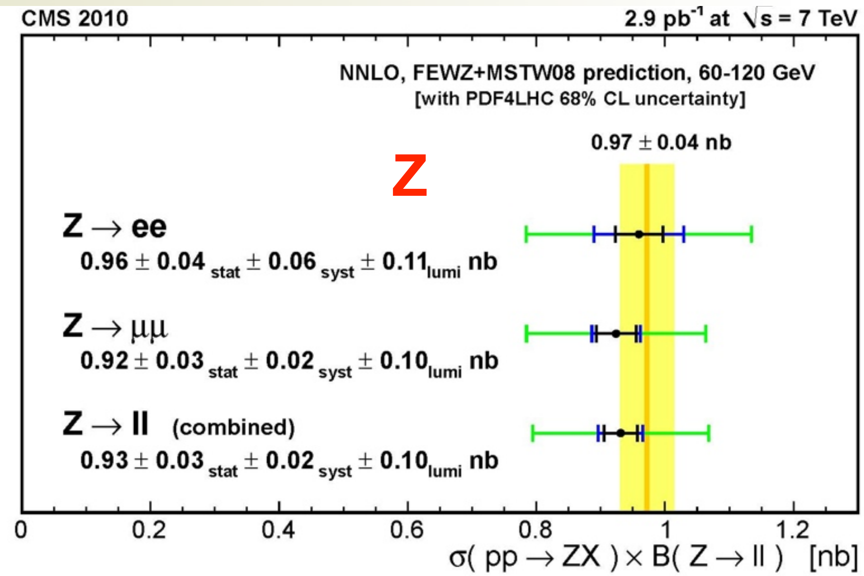
Source	W^+ (μ)	W^- (μ)	W^+/W^- (μ)	W/Z (μ)
Lepton reconstruction & identification	1.5	1.5	2.8	0.9
Momentum scale & resolution	0.3	0.3	0.3	0.1
$\not{E}_T$ scale & resolution	0.4	0.4	0	0.4
Background subtraction / modeling	1.7	2.3	0.7	2.2
PDF uncertainty for acceptance	1.3	1.9	2.1	1.1
Other theoretical uncertainties	1.4	1.3	1.2	1.4
Total	3.0	3.6	3.8	3.0

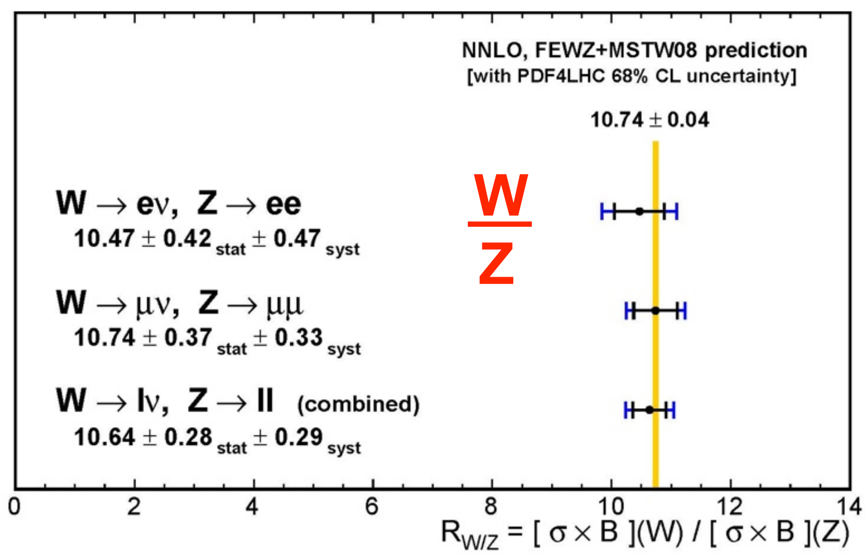
Source	W^+ (e)	W^- (e)	W^+/W^- (e)	W/Z (e)
Lepton reconstruction & identification	5.1	5.1	5.2	3.0
Momentum scale & resolution	2.2	1.8	0.4	2.0
$\not{E}_T$ scale & resolution	1.6	1.9	0.4	1.8
Background subtraction / modeling	1.1	1.5	0.7	1.3
PDF uncertainty for acceptance	0.9	1.5	1.7	0.9
Other theoretical uncertainties	1.3	0.9	1.3	1.0
Total	6.1	6.2	5.7	4.4

- W^+/W^- ratio limited by knowledge of l^-/l^+ efficiency ratio (determined empirically from statistics limited Z samples)
- W/Z ratio limited by W background/ signal model and lepton efficiency estimation
- Only correlated systematics are luminosity and acceptance.

Cross Section Results: Graphical



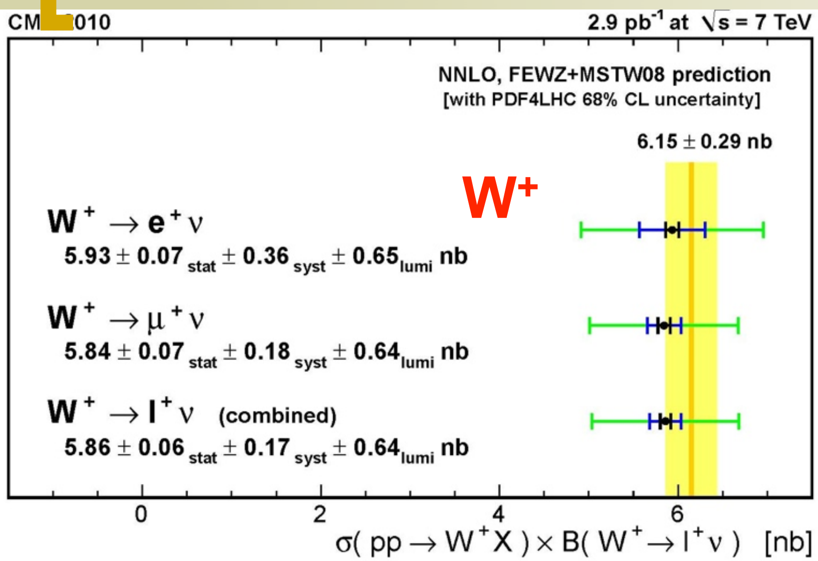


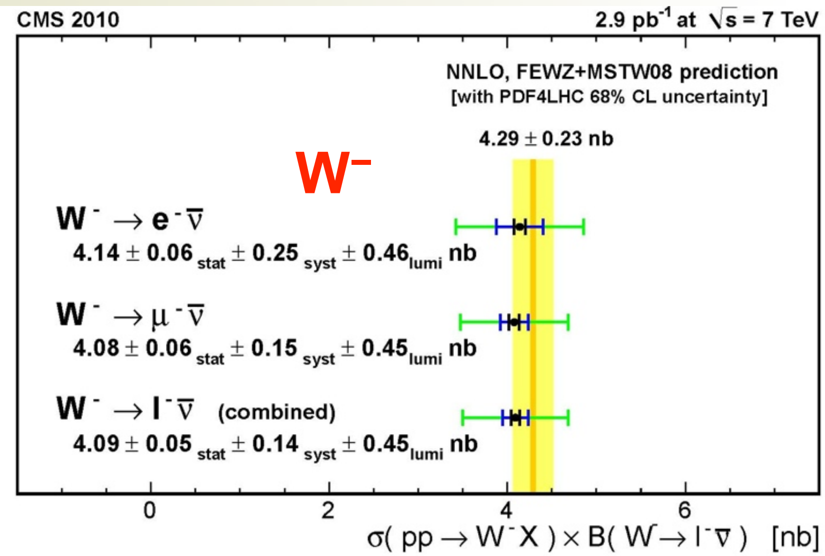


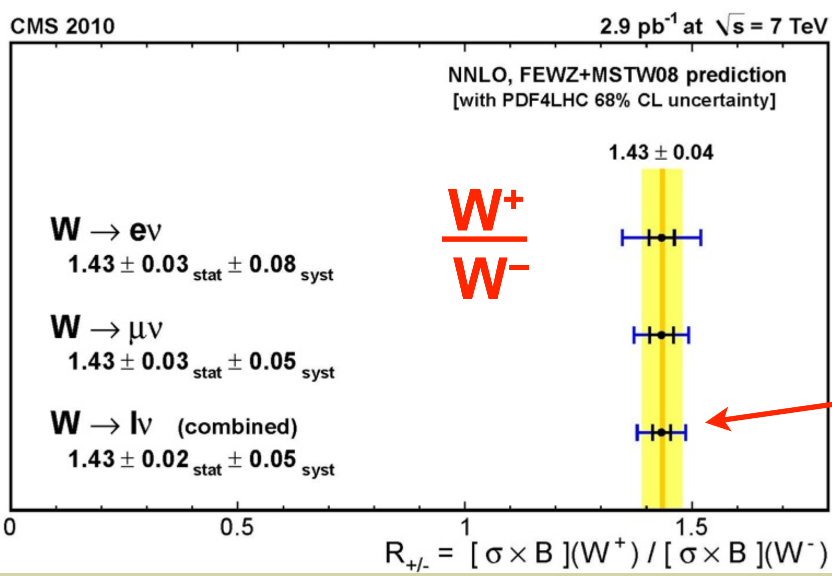
- Uncertainty in theory prediction
- Statistical uncertainty
- Systematic uncertainty
- Luminosity uncertainty

- W cross section non-lumi error 2.9%
- Z cross section non-lumi error 3.9%
- W/Z ratio total error 3.8%
- Internally consistent across channels
- Everywhere close to systematics limited

Cross Section Results: Graphical







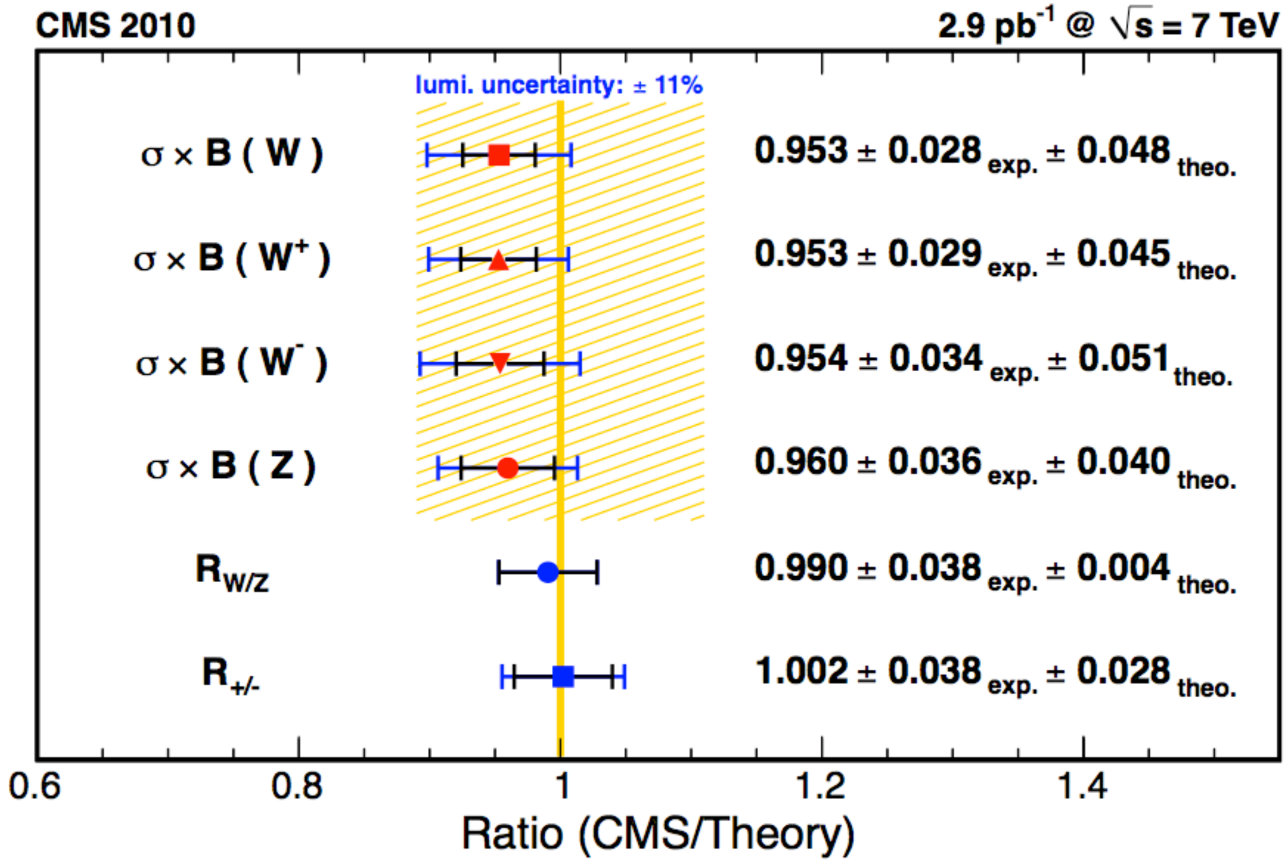
Uncertainty in theory prediction
Statistical uncertainty
Systematic uncertainty
Luminosity uncertainty

- W^+ and W^- consistent with PDF expectations
- Close to challenging global PDF precision!
- Limited primarily by +/- efficiency ratio (Z statistics)

Ratio of CMS measurements to NNLO predictions

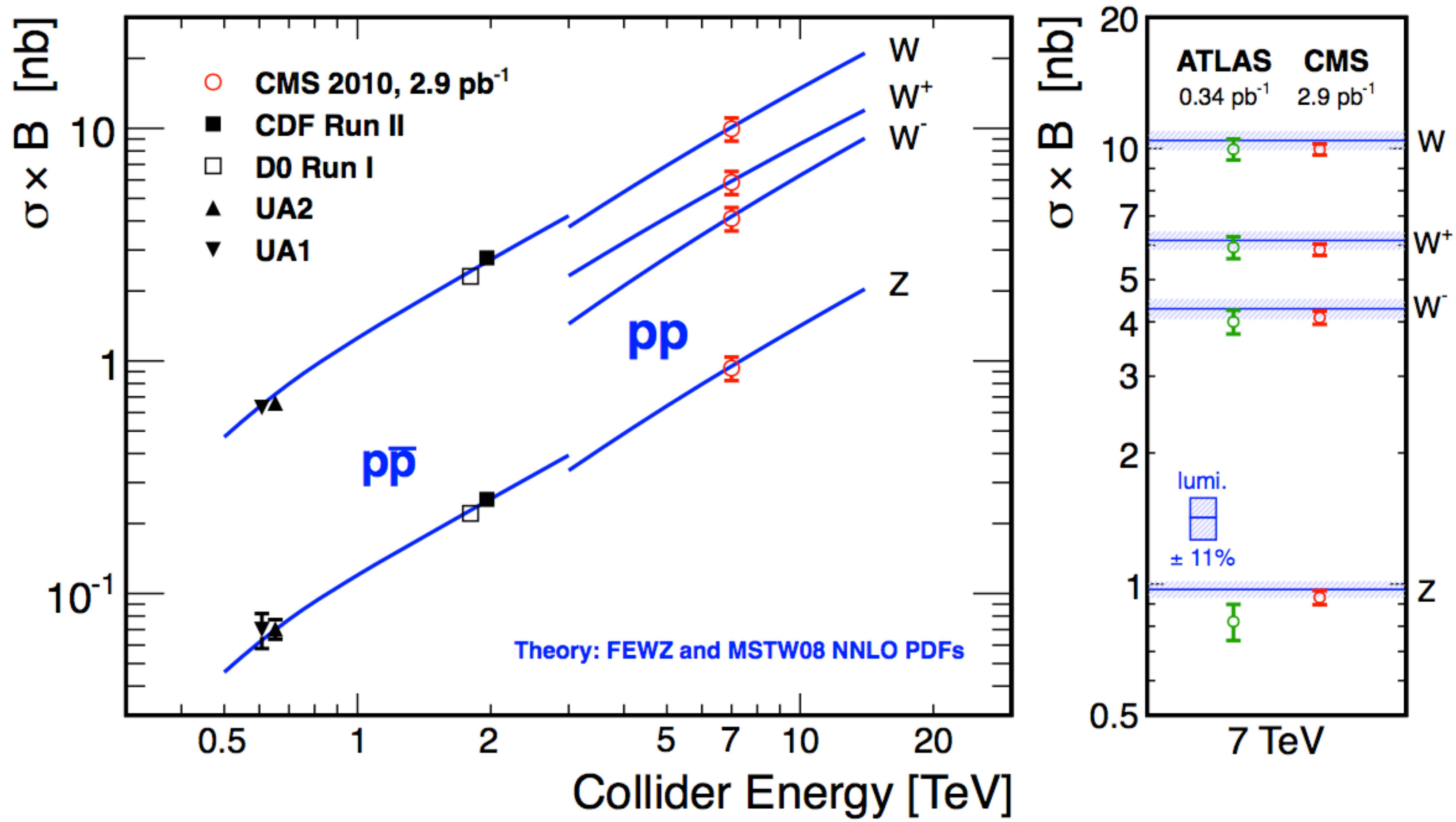
✦W and Z cross sections are consistently 4-5% below nominal predictions. Ratios exhibit excellent agreement.

✦This is consistent with a systematic bias from LHC luminosity estimation, well contained by present uncertainties.



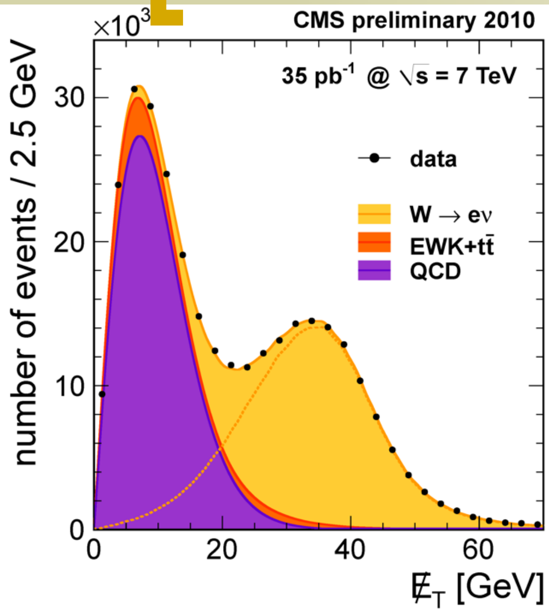
New upcoming luminosity measurements are expected to cut the luminosity uncertainty in half, which should confirm or refute this interpretation.

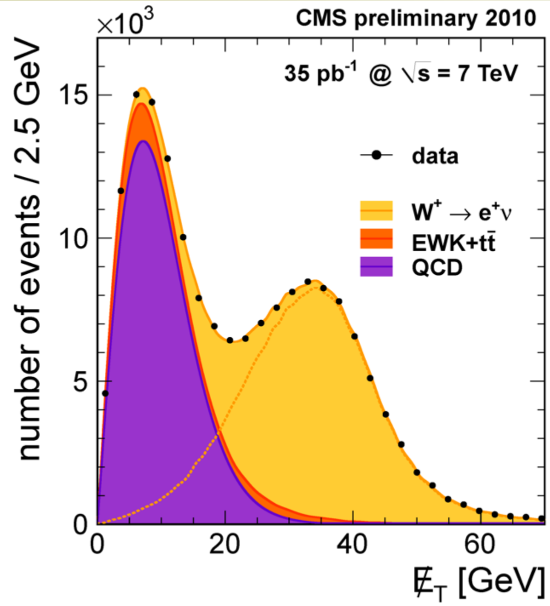
Inclusive W, Z cross section vs collider energy

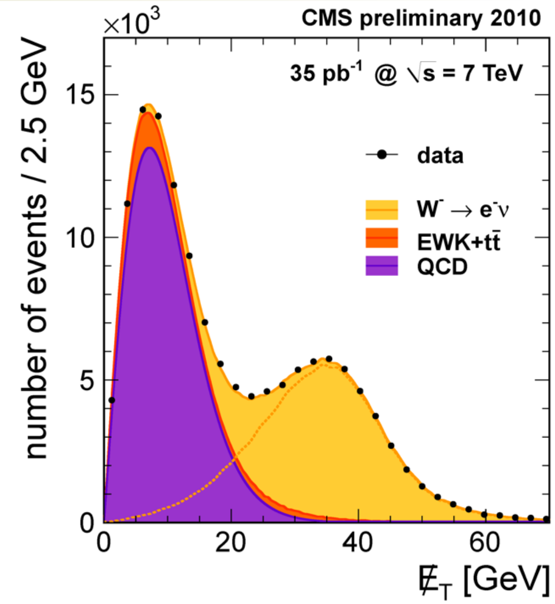


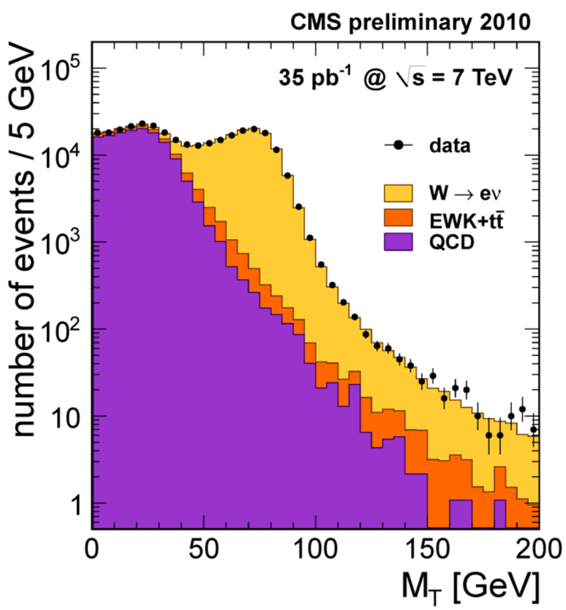
A first look at 35 pb^{-1} data (entire 2010 Run)

W→eν with 35 pb^{-1}







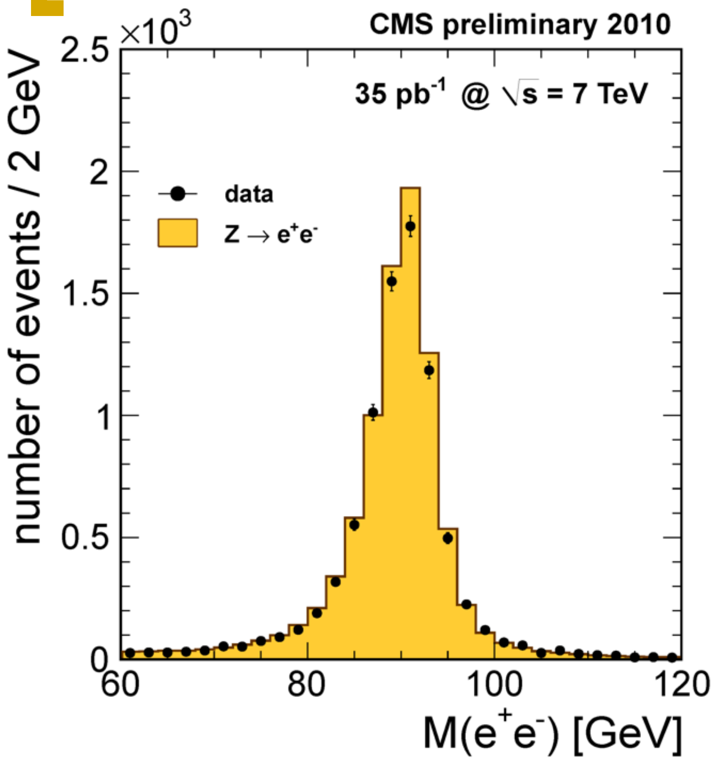


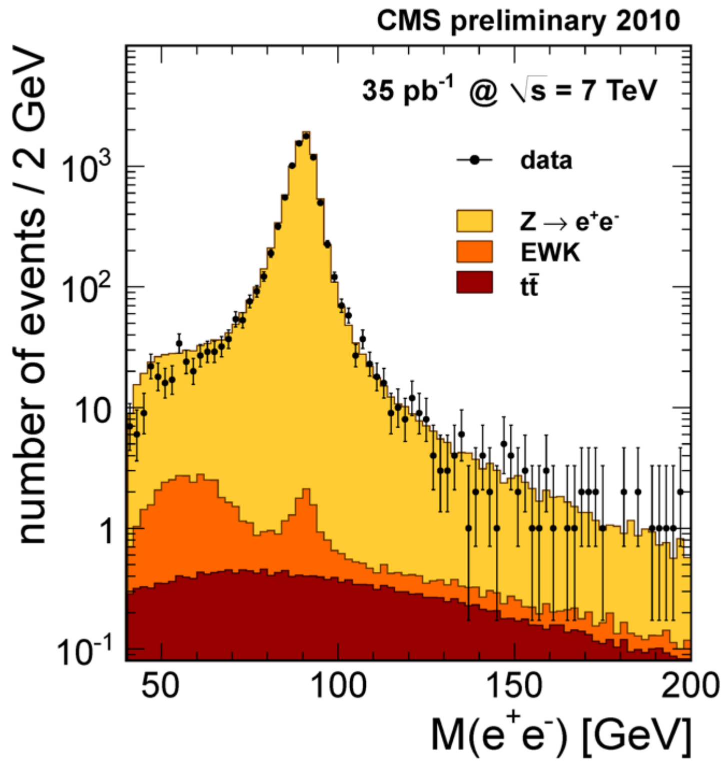
Total number of candidates: 306408

W± yield : 144486
W+ yield : 87884
W- yield : 56912

✦Observed candidates agree with expectations (within old systematics).
✦Updated recoil corrections to W signal, electron energy scale continue to give an excellent description of data.

Z→ee with 35 pb^{-1}



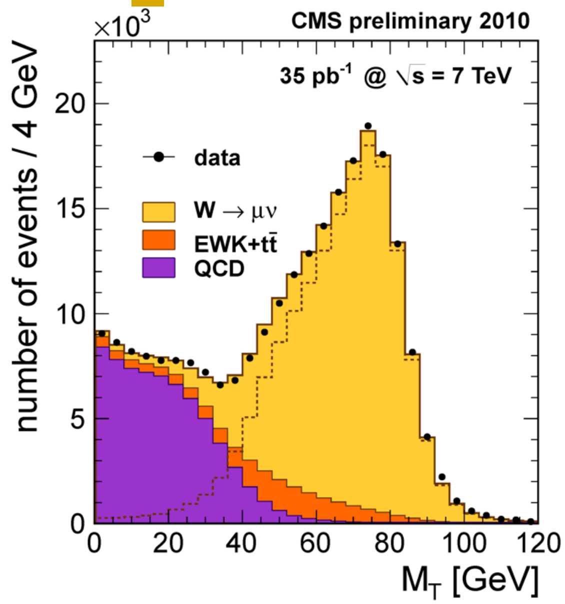


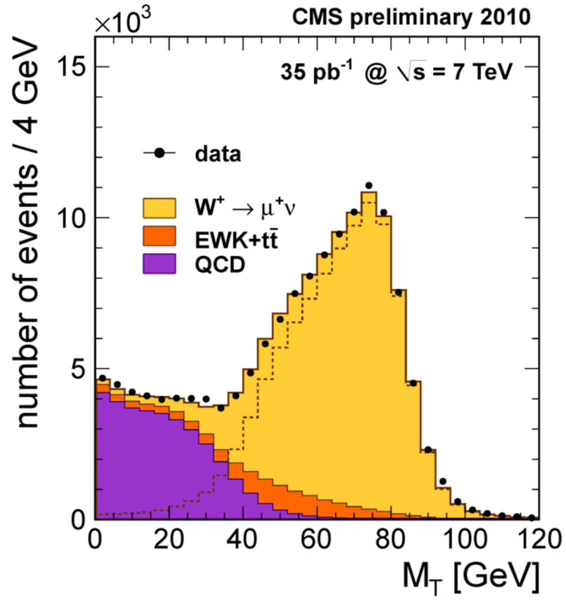
Total yield: 8253
Barrel-Barrel = 4816
Barrel-Endcaps = 2671
Endcaps-Endcaps = 766

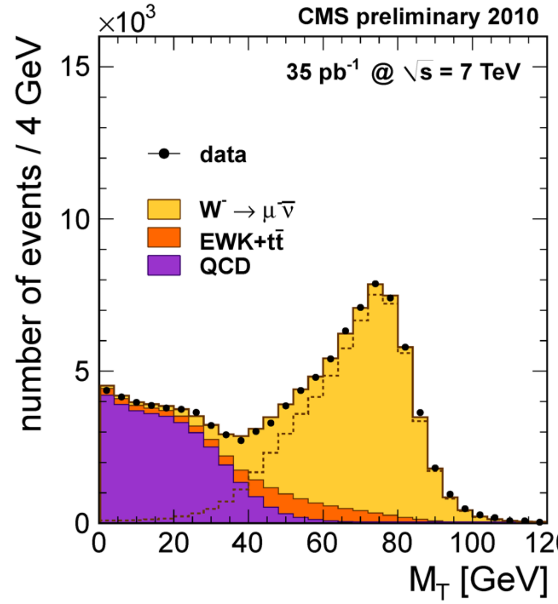
✦The Monte Carlo is normalized to integrated luminosity times overall data/MC efficiency ratio.

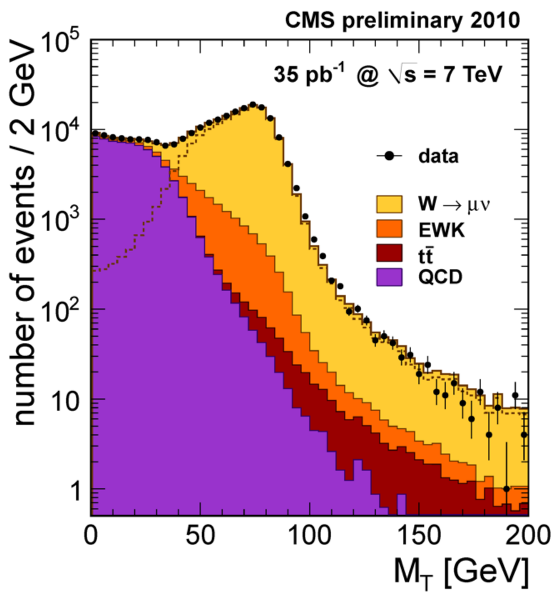
✦Observed candidates agree with expectations (within old systematics).

$W \to \mu\nu$ with 35 pb^{-1}







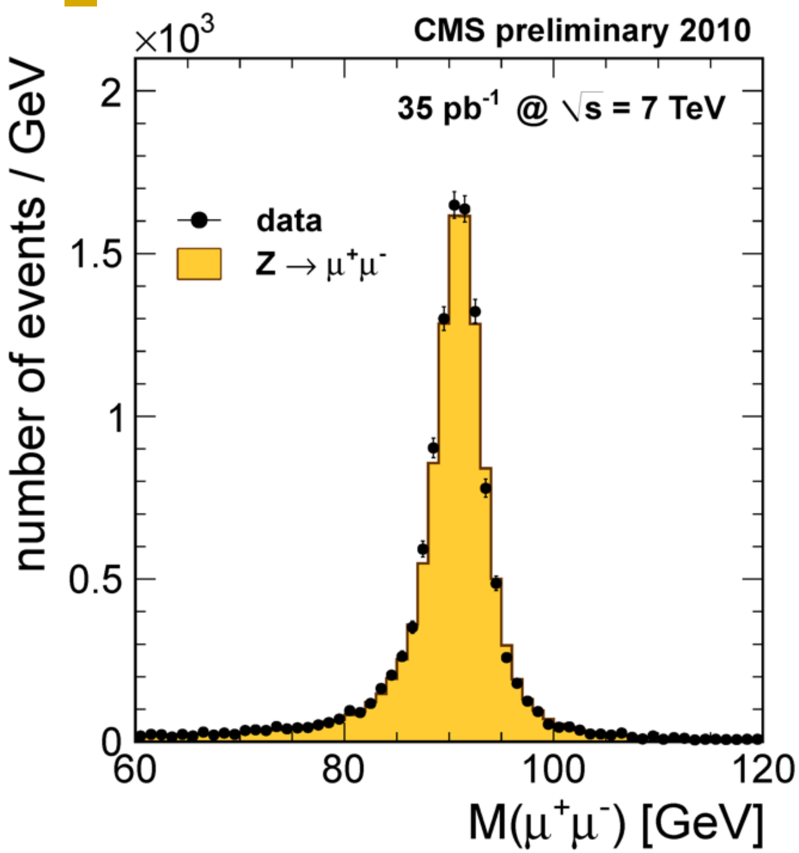


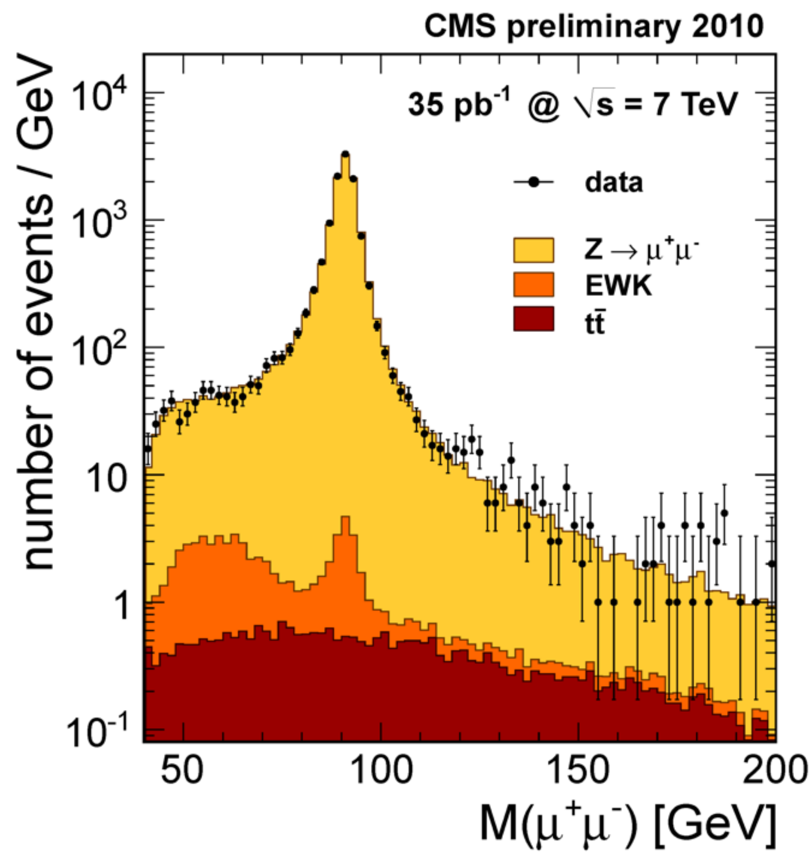
W± Candidates : 244516
W+ Candidates : 141138
W- Candidates : 103378

W± yield : 160870
W+ yield : 98156
W- yield : 62714

Observed candidates agree with expectations (within old systematics)

Z→μμ with 35 pb^{-1}





Total yield: 11697

Observed candidates agree with expectations (within old systematics)

The path to higher precision with 35 pb^{-1}

✦Target non-lumi, non-theory experimental precision of 2% (2X improvement)
- -Then limiting systematic is theory uncertainties in acceptance (~2%)

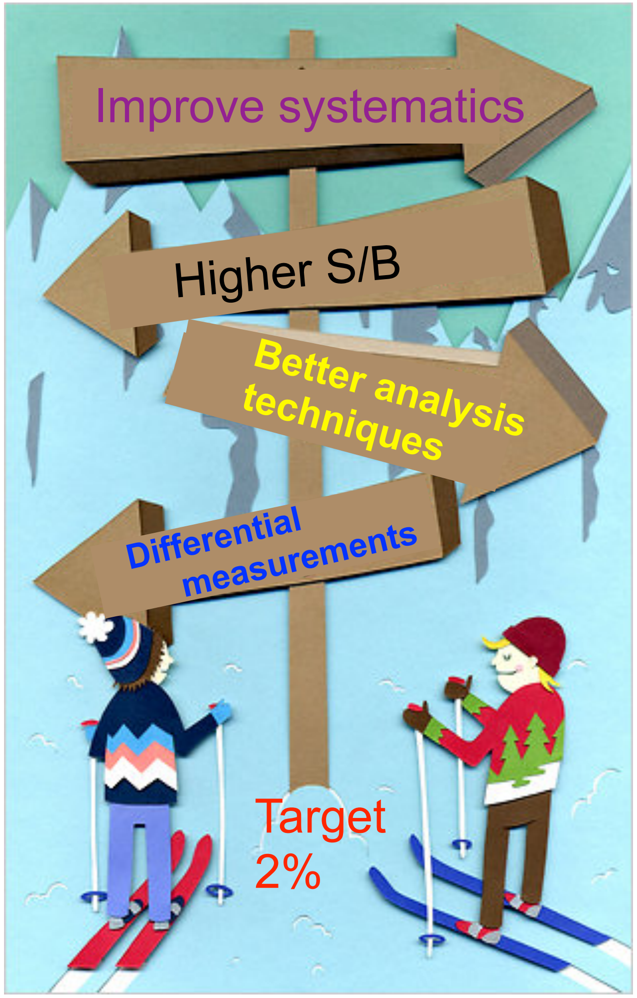
✦Statistical errors will naturally improve by 3X

✦Key systematics which need to improve by ~2X:
- -Signal/background shape for $Z \rightarrow ll$ efficiency fits
- -Background shape model for $W \rightarrow l\nu$
- -Electron energy scale
- -Higher S/B lepton operating point would improve all of these

✦More finely-binned model of efficiency and recoil corrections will be required

✦Simultaneous fit technique for Z extended to more bins, include electron channel

✦At this stage, differential measurements (W asymmetry vs. eta, Z rapidity) are more valuable precision tests of QCD/PDFs



Conclusions

✦Only eight months into its first 7 TeV collision run, CMS has achieved 4% precision tests of electroweak physics.

- electrons, muons, and missing energy are well-calibrated detector objects ready for precision analysis.
- uncertainty on the W^+/W^- cross-section ratio is becoming comparable to the theoretical uncertainty
- W and Z production rates are already superior estimators of integrated luminosity and real time detector performance.

✦Coming months should provide sufficient data for more precision EWK measurements to constrain pdf and probe new physics.

✦Extraordinary performance by detector operations, computing, detector simulation, and physics objects groups made this possible.

BACKUP SLIDES

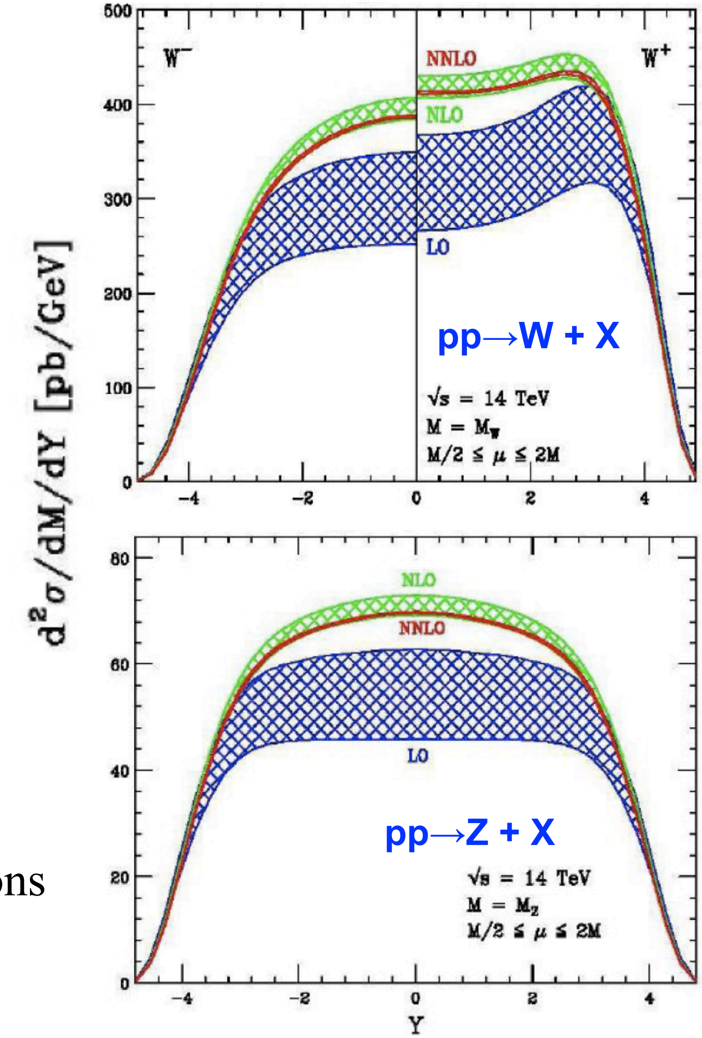
Simulation

Large Monte Carlo samples for Electroweak processes for both electrons & muons.

✦Used for the estimation of:
- Acceptances for Signal & EWK backgrounds
- Selections Efficiencies & comparisons with data driven methods (Tag & Probe)
- W-signal and background shape templates
- Z di-lepton mass shapes

✦Baseline EWK MC generation:
- POWHEG NLO with CTEQ 6.6 (NLO)
- $W \to \tau\nu$ & $Z \to \tau\tau$ from PYTHIA

✦Theory systematic uncertainties:
- ResBos: ISR and missing NNLO corrections
- FEWZ: factorization/renormalization scale, complete NNLO calculations
- HORACE: full 1-loop Electroweak & FSR corrections
- PHOTOS: final-state QED showering



Electron energy scale & resolution

Use Z→ee events to evaluate energy scale corrections & resolutions.

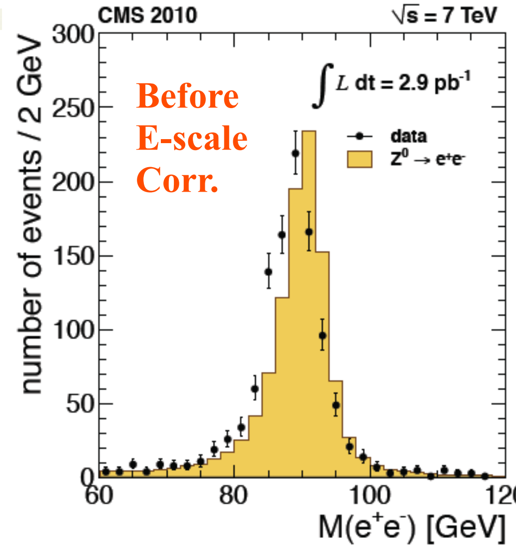
- Apply a floating scale correction and a floating smearing factor (resolution) to MC Z→ee electrons and perform a likelihood maximization of the Z mass distribution in 2 dimensions.

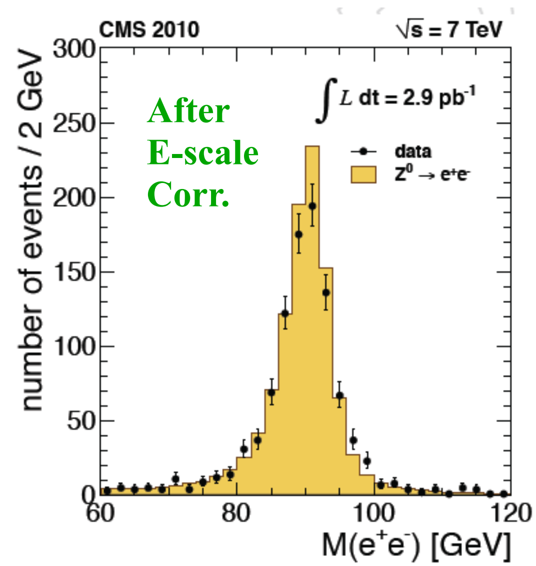
- EB scale factor & resolution derived from Barrel-Barrel electrons.
- EE scale factor & resolution derived from Barrel-Endcap electrons by fixing the EB scale factor & resolution.

- Inverted energy scale factors applied to data.
  Resolution (smearing) applied to MC.

Measured	scale factors for data	&	resolution for MC:
EB:	1.015 ± 0.002	,	0.82 ± 0.16 GeV
EE	1.033 ± 0.005	,	0.67 ± 0.35 GeV

Scale factors and resolutions are propagated in W & Z analyses





Electron efficiency systematics

- Signal Shape
  - Extend Mee window to include more of the low mass tail, 50-120 GeV
  - Construct data-driven signal shapes by tightening selection on Tag+Fail
    - Fit with these templates, difference w.r.t nominal fit is the systematic
- Background Model
  - Consider power-law ($1/M^{\alpha}$) as alternative model to exponential
  - Fix α to value found from fit to dijet data and generate pseudo-experiments
  - Fit each trial with exponential, measure bias
- Energy Scale /Resolution
  - Apply corrections ± uncertainties to the MC, measure difference in yield

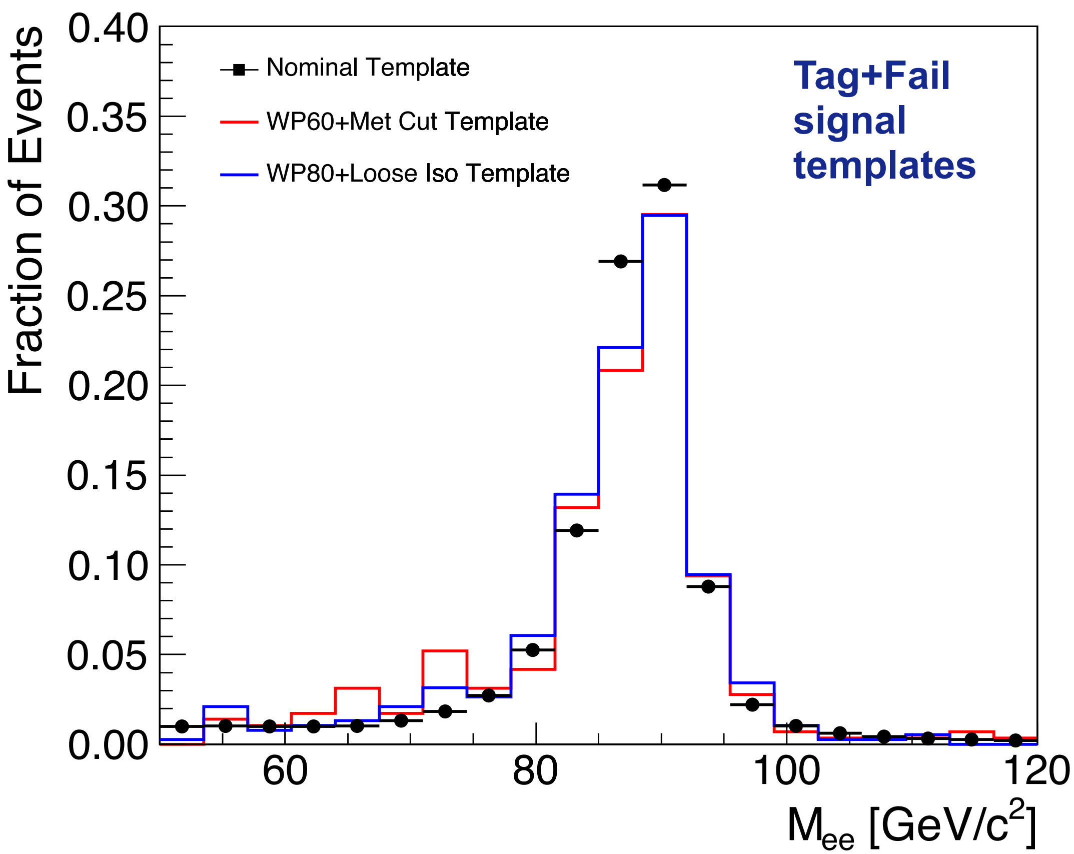
Source	% ε_{reco}	% $\varepsilon_{reco\text{-}WP95}$	% $\varepsilon_{reco\text{-}WP80}$	% $\varepsilon_{WP80\text{-}HLT}$	% $\varepsilon_{WP80\text{-}HLT}$
Background Model	0.06	0.25	0.24	0.01	< 0.00
Energy Scale	0.1	0.1	0.2	< 0.00	0.1
Signal Shape	1.2	1.0	2.0	-	-

I will focus on this in the next slide

Main source of efficiency systematic uncertainty

What was done in inclusive W,Z analysis ?

Take signal template for Tag+FailingProbe events from MC. Use data-driven template to validate the technique, and compute systematic uncertainty.



- Data driven shapes have large uncertainty,
  - •due to extrapolations involved,
  - •unknown escale & resolution for failing electrons,
  - •imprecise knowledge of the material model
  - •and of farction of showering electrons etc.

-Overall good agreement between data and MC signal templates.

-Currently try all these templates

⇒ syst.= largest deviation in eff

Acceptances for W→eν & Z→ee

Acceptance for W→eν (A^{ECAL}):

fraction of generated W events with a SuperCluster passing kinematic selection

$|\eta_{SC}|<1.44$ or $1.57 < |\eta_{SC}| < 2.5$

SuperCluster $E_T > 20$ GeV

A^{ECAL}	W^+	W^-	$W^\pm$
EB	0.3618 ± 0.0006	0.3532 ± 0.0007	0.3583 ± 0.0005
EE	0.2277 ± 0.0005	0.1899 ± 0.0006	0.2124 ± 0.0004
EB+EE	0.5895 ± 0.0006	0.5431 ± 0.0008	0.5707 ± 0.0005

Generator Level Acceptance for W→eν (A):

fraction of generated W events with a generated electron passing kinematic selection

$|\eta_{GEN}| < 2.5$

Gen. electron $E_T > 20$ GeV (after FSR)

$W \to e\nu$	A
W^+	0.6215 ± 0.0056
W^-	0.5708 ± 0.0086
$W^\pm$	0.6010 ± 0.0048

→ PDF & renorm. scale uncertainties.

Acceptance for Z→ee (A^{ECAL}):

fraction of generated Z events with two SuperClusters passing kinematic selections

$|\eta_{SC}|<1.44$ or $1.57 < |\eta_{SC}| < 2.5$

Both SuperClusters $E_T > 20$ GeV

$60 < M_{SC,SC} < 120$ GeV

A^{ECAL}	$Z \to e^+e^-$
EB+EB	0.2257 ± 0.0004
EB+EE	0.1612 ± 0.0003
EE+EE	0.0476 ± 0.0002
all	0.4345 ± 0.0005

Genarator Level Accept. for Z→ee (A):

fraction of generated Z events with two gen. electrons passing kinematic selection

$|\eta_{GEN}|<2.5$

Both Gen. electrons $E_T > 20$ GeV (after FSR)

$60 < Mee < 120$ GeV

A	$Z \to e^+e^-$
Z	0.4794 ± 0.0049

Theoretical uncertainties in electron acceptance

- Follow PDF4LHC recommendations
- Δ_{CTEQ66}, $\Delta_{MSTW2008NLO}$, $\Delta_{NNPDF2.0}$: 68% CL uncertainties within each set
- Δsets : 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 α_s uncert. ~0.1% for acceptances)

PDF uncertainties at the order of 1-2 %

Quantity	Δ_{CTEQ} (%)	Δ_{MSTW} (%)	Δ_{NNPDF} (%)	Δ_{sets} (%)	Syst. (%)
W^+ acceptance (e)	± 0.5	± 0.2	± 0.3	0.4 (NNPDF-CTEQ)	0.9
W^- acceptance (e)	± 0.9	± 0.5	± 0.8	0.8 (NNPDF-MSTW)	1.5
W acceptance (e)	± 0.5	± 0.3	± 0.4	0.3 (MSTW-CTEQ)	0.8
Z acceptance (e)	± 0.8	± 0.5	± 0.7	0.4 (MSTW-CTEQ)	1.1
W^+/W^- correction (e)	± 1.0	± 0.5	± 0.7	1.1 (NNPDF-MSTW)	1.7
W/Z correction (e)	± 0.6	± 0.3	± 0.4	0.6 (NNPDF-MSTW)	0.9

Other uncertainties studied with dedicated programs

QCD-HO and ISR: ResBos@NNLO vs POWHEG+CTEQ66
QCD-α_s: scale dependence of NNLO calculations, FEWZ
EWK corrections and FSR: HORACE vs PYTHIA

Reference MC
NLO MC generator POWHEG
+ CTEQ66 PDF´s

Source	$W^+ \to e\nu$	$W^- \to e\nu$	$Z \to e^+e^-$	W^+/W^- (e)	Z/W (e)
QCD-HO and ISR	-1.30%$\pm$0.09	-0.78%$\pm$0.10	$\pm$0.6%	0.56%$\pm$0.13	0.47%$\pm$0.17
QCD-α_s scaling	0.23%$\pm$0.22	0.37%$\pm$0.32	$\pm$1.1%	1.13%$\pm$0.63	0.57%$\pm$0.52
FSR	0.08%$\pm$0.17	0.07%$\pm$0.19	-0.03%$\pm$0.21	0.15%$\pm$0.27	-0.10%$\pm$0.30
EWK	0.07%$\pm$0.13	0.21%$\pm$0.19	-0.51%$\pm$0.22	0.00%$\pm$0.27	-0.70%$\pm$0.29
Total	1.33%	0.90%	1.34%	1.27%	1.03%

Muon Acceptances

Generator Level Acceptance for $W \to \mu\nu$:

fraction of generated W events with a generated muon passing kinematic selection

$|\eta_{GEN}| < 2.1$

Gen. muon $P_T > 20$ GeV (after FSR)

$W \to \mu\nu$	A
W^+	0.5413 ± 0.0060
W^-	0.5023 ± 0.0055
$W^\pm$	0.5253 ± 0.0058

Generator Level Accept. for $Z \to \mu\mu$:

fraction of generated Z events with two gen. muons passing kinematic selection

$|\eta_{GEN}| < 2.1$

Both Gen. muons $P_T > 20$ GeV (after FSR)

$60 < M_{\mu\mu} < 120$ GeV

A	$Z \to \mu^+\mu^-$
Z	0.3977 ± 0.0048

Generator-level acceptances from the POWHEG

Muon momentum scale & resolution

Different methods and p_T regions studied:

- Low mass di-muon resonances
- Tracker track vs stand alone muon residuals
- Cosmics momentum end-point
- Z mass distribution
- W p_T spectrum

Effects in muon scale, larger than 0.4% can be excluded

Maximal effect on Z and W acceptance amounts to 0.2% and 0.4% respectively

Muon efficiencies

Correction factors for positive-negative muons.

Table 6: Correction factors for subsets of muons.

Subset	Data/Simulation (Net ρ_{eff})
positive muons	0.935 ± 0.018
negative muons	0.931 ± 0.019
barrel ($\lvert\eta\rvert < 0.9$)	0.955 ± 0.024
transition ($0.9 < \lvert\eta\rvert < 1.2$)	0.89 ± 0.04
endcap ($1.2 < \lvert\eta\rvert < 2.1$)	0.92 ± 0.03

Pre-Triggering

No negligible probability of firing an event at wrong bunch crossing.
T&P cannot account for such inefficiencies.

Probability of pre-triggering per muon :
(1.1 ± 0.5)% in barrel , ~0.1% in the endcap & barrel-endcap transition region

Effect on the measured cross sections:
(1.0 ± 0.5)% for $Z\to\mu\mu$ & (0.5 ± 0.5)% for $W\to\mu\nu$

Measurements are corrected for the pre-triggering effects and uncertainties are added to the systematic uncertainties of the trigger efficiency.

Theoretical uncertainties in muon acceptance

PDF uncertainties at the order of 1-2 %

- Follow PDF4LHC recommendations
- Δ_{CTEQ66}, $\Delta_{MSTW2008NLO}$, $\Delta_{NNPDF2.0}$: 68% CL uncertainties within each set
- Δsets : 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 α_s uncert. ~0.1% for acceptances)

Quantity	Δ_{CTEQ} (%)	Δ_{MSTW} (%)	Δ_{NNPDF} (%)	Δ_{sets} (%)	Syst. (%)
W^+ acceptance (μ)	±0.7	±0.4	±0.5	0.6 (NNPDF-CTEQ)	1.3
W^- acceptance (μ)	±1.1	±0.7	±1.1	0.9 (NNPDF-MSTW)	1.9
W acceptance (μ)	±0.7	±0.4	±0.6	0.4 (MSTW-CTEQ)	1.1
Z acceptance (μ)	±0.9	±0.5	±0.8	0.4 (MSTW-CTEQ)	1.2
W^+/W^- correction (μ)	±1.1	±0.6	±0.9	1.3 (NNPDF-MSTW)	2.1
W/Z correction (μ)	±0.6	±0.4	±0.5	0.6 (NNPDF-MSTW)	1.1

Other uncertainties studied with dedicated programs

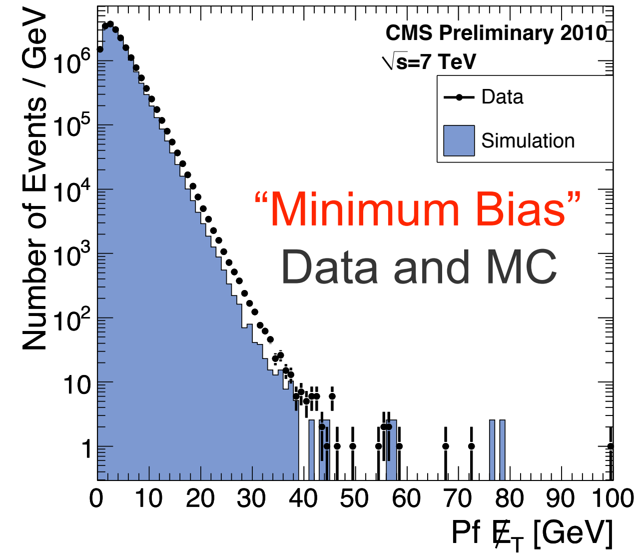
QCD-HO and ISR: ResBos@NNLO vs POWHEG+CTEQ66
QCD-α_s: scale dependence of NNLO calculations, FEWZ
EWK corrections and FSR: HORACE vs PYTHIA

Reference MC
NLO MC generator POWHEG
+ CTEQ66 PDF´s

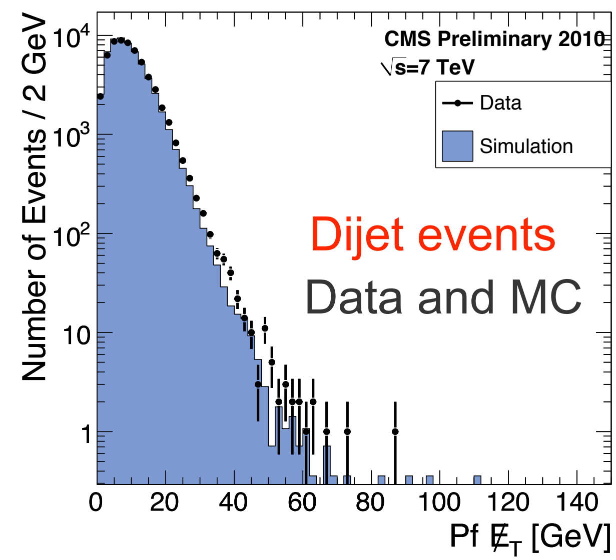
Source	$W^+ \to \mu\nu$	$W^- \to \mu\nu$	$Z \to \mu^+\mu^-$	W^+/W^- (μ)	Z/W (μ)
QCD-HO and ISR	-1.39%±0.09	-1.17%±0.14	±0.6%	0.22%±0.17	0.70%±0.18
QCD-α_s scaling	0.23%±0.22	0.37%±0.32	±1.1%	1.13%±0.63	0.57%±0.52
FSR	0.11%±0.12	0.01%±0.17	0.38%±0.24	-0.08%±0.19	0.15%±0.27
EWK	-0.02%±0.12	0.26%±0.17	-1.02%±0.24	0.28%±0.19	-0.98%±0.24
Total	1.42%	1.26%	1.58%	1.19%	1.35%

W/Z analysis ingredients: missing E_T

- "Particle flow" – using fully reconstructed particles
  - -better resolution than simple calorimetric MET
  - -computed from the vector sum of all particles in the event
  - -less sensitive to calorimeter calibrations
  - -well reproduced by simulation

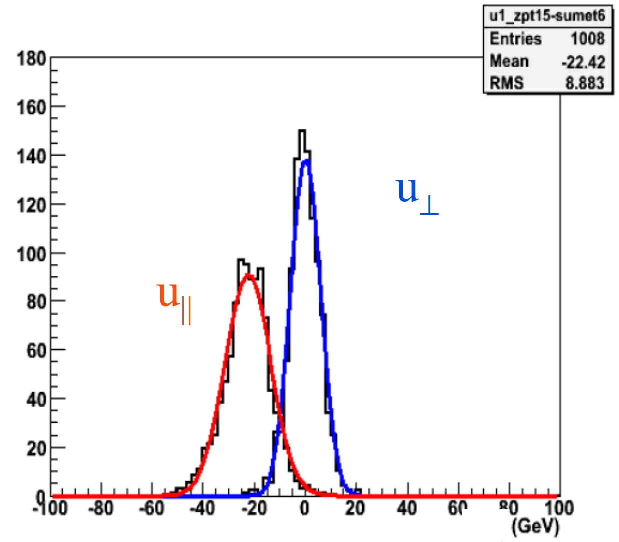


- Pileup has negligible effect on W yield
  - -Less than 40% events have >1 primary vertex
  - -in these cases there is ~10% broadening of MET distribution
  - -no significant effect on the results

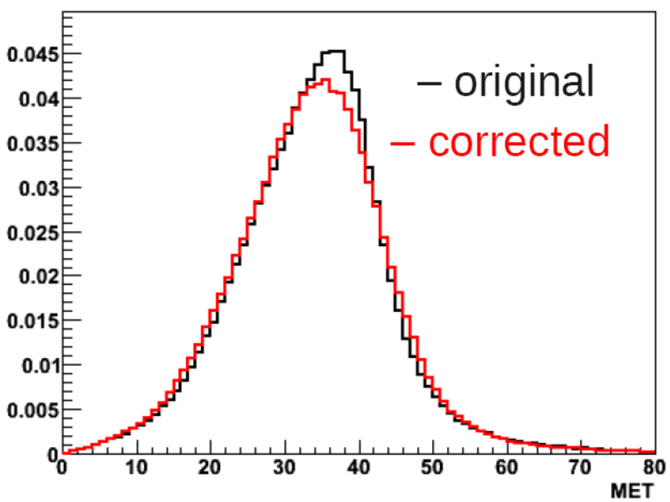


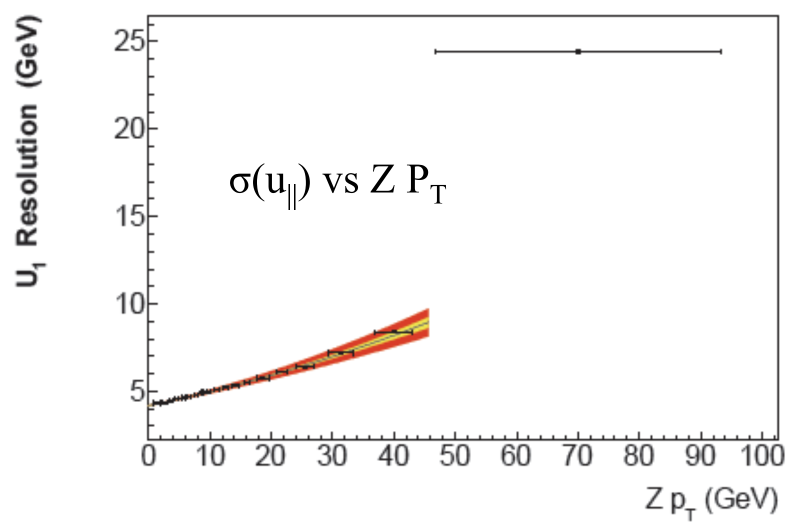
W signal extraction: signal shape

- Model components with Gaussians in qT
  - Fit response (mean) and resolution (width) in qT with 2nd order polynomials
  - Determine Z data/MC scale factors to correct W MC response/resolution



- Recalculate MET for each W MC event
  - Again, subtract off the electron electron
  - Sample $u_\parallel/u_\perp$ distributions, parameters from scaled W MC curves
  - Add the (energy scaled) electron back to obtain corrected MET

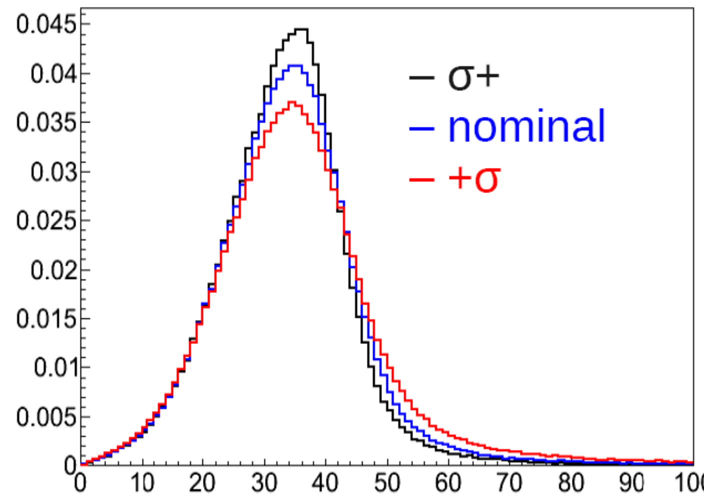




W→eν Signal Extraction Systematics

MET shape uncertainties (~ 1.8%)

- Recoil: modeling uncertainties give fluctuated MET shapes w.r.t. the best-fit, corrected MC template.



Generate pseudo-experiments using fluctuated Shapes, then fit w/ nominal.

Energy Scale/Resolution uncertainties (~ 2.0%)

- Uncertainties transferred to Signal MET shape via the recoil method
- Impact on selection

- Background modeling (~ 1.3%)
  - Consider our Rayleigh distribution with an extra power in the tail ($\sigma_2 x^2$)
    - Fit anti-selected data & MC, selected MC w/ the 3-parameter Rayleigh
    - Largest σ_2 found is 0.001 from anti-selected MC
  - Generate pseudo-experiments with 3-parameter model, fit with nominal
    - Difference in yield is the systematic

Z→ee signal extraction strategy

- Two well-reconstructed electrons passing selection and trigger criteria described earlier
- No opposite sign requirement
- Count events in $60 < M_{ee} < 120$ GeV mass bin

Selected events: 677

Expected MC background:

0.0 QCD, 2.36±0.04 EWK ($Z \to \tau\tau$, TTbar, di-bosons)

source	fraction	N_{est}
QCD multi-jet	0.06%	0.4 ± 0.4
$Z \to \tau^+\tau^-$ (MC)	0.11%	0.77
di-boson production (MC)	0.12%	0.76
$t\bar{t}$ (MC)	0.11%	0.83
EWK (MC)	0.35%	2.36
total	0.41%	2.8 ± 0.4

Data-Driven methods to cross check the Z→ee background

Fake rate method based on a large sample of jets faking electrons: $N_{QCD+EWK} = 2.8 \pm 0.4$ (sys+stat)

SS/OS method based on counting the signs of the track charges: $N_{QCD+EWK} = 0.0 \pm 7.5$ (sys+stat)

Template method based on the relative track isolation shape : $N_{QCD+EWK} = 4.5 \pm 4.6$ (sys+stat)

Summary of electron results

Source	$W \to e\nu$	$Z \to e^+e^-$	W^+ (e)	W^- (e)	W^+/W^- (e)	W/Z (e)
Lepton reconstruction & identification	3.9	5.9	5.1	5.1	5.2	3.0
Momentum scale & resolution	2.0	0.6	2.2	1.8	0.4	2.0
$\not{E}_T$ scale & resolution	1.8	n/a	1.6	1.9	0.4	1.8
Background subtraction / modeling	1.3	0.1	1.1	1.5	0.7	1.3
PDF uncertainty for acceptance	0.8	1.1	0.9	1.5	1.7	0.9
Other theoretical uncertainties	1.3	1.3	1.3	0.9	1.3	1.0
Total	5.1	6.2	6.1	6.2	5.7	4.4

$$\sigma(pp \to WX) \times \mathrm{BF}(W \to e\nu) = 10.045 \pm 0.097\,(\mathrm{stat.}) \pm 0.517\,(\mathrm{syst.}) \pm 1.105\,(\mathrm{lumi.})\ \mathrm{nb},$$

$$\sigma(pp \to W^+X) \times \mathrm{BF}(W^+ \to e^+\bar{\nu}) = 5.935 \pm 0.074\,(\mathrm{stat.}) \pm 0.359\,(\mathrm{syst.}) \pm 0.653\,(\mathrm{lumi.})\ \mathrm{nb},$$

$$\sigma(pp \to W^-X) \times \mathrm{BF}(W^- \to e^-\nu) = 4.140 \pm 0.064\,(\mathrm{stat.}) \pm 0.254\,(\mathrm{syst.}) \pm 0.455\,(\mathrm{lumi.})\ \mathrm{nb},$$

$$\sigma(pp \to ZX) \times \mathrm{BF}(Z \to e^+e^-) = 0.960 \pm 0.037\,(\mathrm{stat.}) \pm 0.059\,(\mathrm{syst.}) \pm 0.106\,(\mathrm{lumi.})\ \mathrm{nb},$$

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

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

$W\rightarrow\mu\nu$ signal extraction strategy

W Signal yield extracted through a Binned Log Likelihood fit to the M_T distribution.

Shape from from MC corrected by modeling of the hadronic recoil from $Z\rightarrow\mu\mu$ data.

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

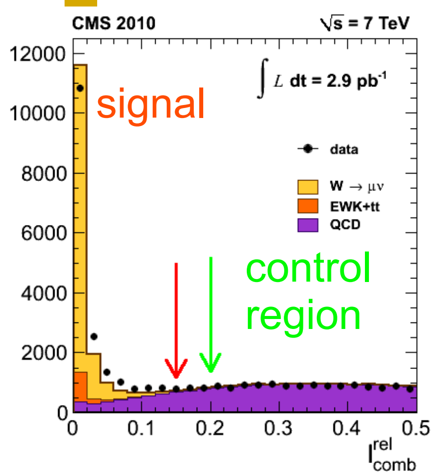
$\Delta\phi_{\mu,\not{E}_T}$ Angle between the muon and MET

Main backgrounds arise from:

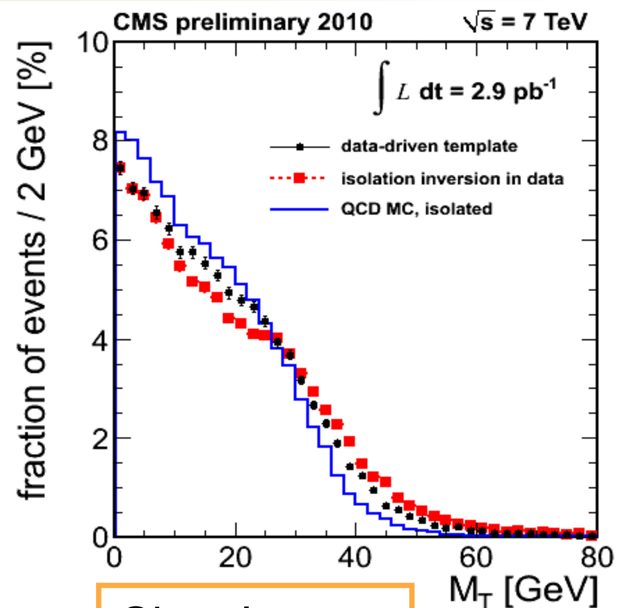
- QCD (b decays mainly, plus decays in flight), at low M_T. Shape derived from a cut inversion technique correcting MC with help from data.
- Electroweak processes: $Z\rightarrow\mu\mu$, $Z\rightarrow\tau\tau$, $W\rightarrow\tau\nu$, tt-bar, Dibosons (WW, WZ, ZZ). Normalized to the signal contribution. Shape derived from MC.

$$N(M_T) = \{\sigma_W \times [\underbrace{\mathcal{A}_W(M_T)}_{W} + \underbrace{K \times \mathcal{A}_{EWK}(M_T)}_{EWK}] + \underbrace{\mathcal{F}_{QCD}\mathcal{T}(M_T)}_{QCD}\} \times \mathcal{L}_{int}$$

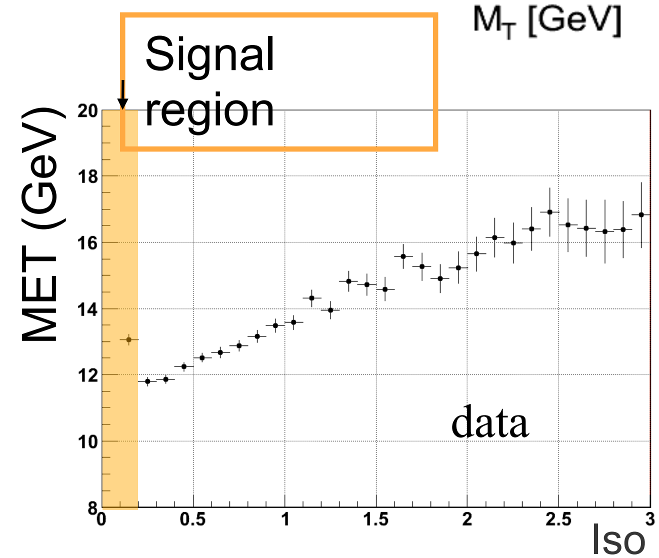
W→μν signal extraction: QCD template



M_T shape of QCD background extracted from the not isolated region (I^{rel}_{comb} >0.2)

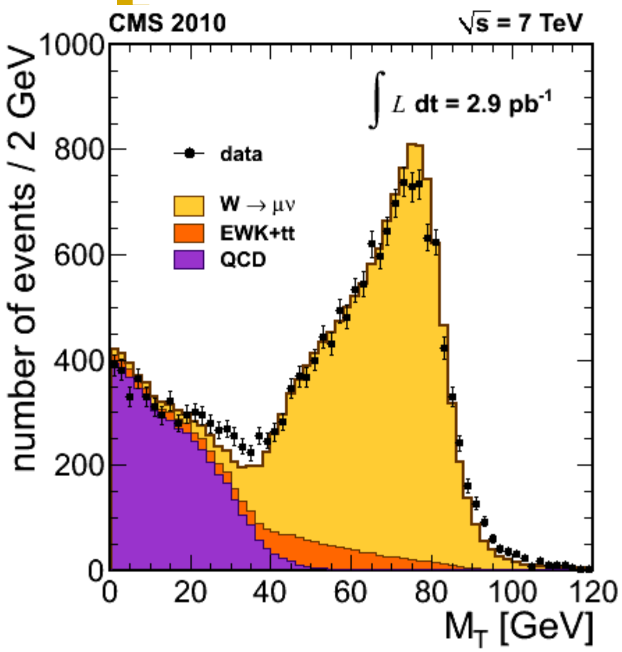


The increase or decrease of hadronic activity induces a correlation between MET (and M_T) and the isolation Variable.



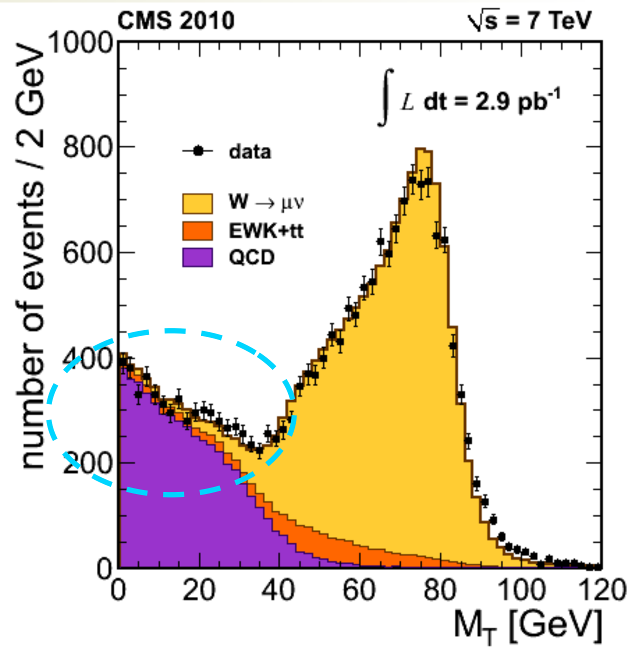
Apply a correction (estimated from data) of the kind
MET → MET /(1+α×I^{rel}_{comb}) (α~0.2)
to the isolation inversion control sample.

W→μν background shape



MC QCD template & MC W signal template

Clear improvement in the low MT region



Data-driven QCD template & MC W signal template

Assign the full difference with respect to the MC template/plain inversion template (**2%**) as a systematic error.

Summary of muon results

Source	$W \to \mu\nu$	$Z \to \mu^+\mu^-$	$W^+ (\mu)$	$W^- (\mu)$	$W^+/W^- (\mu)$	$W/Z (\mu)$
Lepton reconstruction & identification	1.4	n/a	1.5	1.5	2.8	0.9
Pre-triggering	0.5	0.5	0.5	0.5	0.5	0.5
Momentum scale & resolution	0.3	0.2	0.3	0.3	0.3	0.1
$\not{E}_T$ scale & resolution	0.4	n/a	0.4	0.4	0	0.4
Background subtraction / modeling	2.0	1.0	1.7	2.3	0.7	2.2
PDF uncertainty for acceptance	1.1	1.2	1.3	1.9	2.1	1.1
Other theoretical uncertainties	1.4	1.6	1.4	1.3	1.2	1.4
Total	3.1	2.3	3.0	3.6	3.8	3.0

$$\sigma(pp \to WX) \times \mathrm{BF}(W \to \mu\nu) = 9.922 \pm 0.090\,(\mathrm{stat.}) \pm 0.307\,(\mathrm{syst.}) \pm 1.091\,(\mathrm{lumi.})\,\mathrm{nb},$$

$$\sigma(pp \to W^+X) \times \mathrm{BF}(W^+ \to \mu^+\nu) = 5.844 \pm 0.069\,(\mathrm{stat.}) \pm 0.176\,(\mathrm{syst.}) \pm 0.643\,(\mathrm{lumi.})\,\mathrm{nb},$$

$$\sigma(pp \to W^-X) \times \mathrm{BF}(W^- \to \mu^-\bar{\nu}) = 4.078 \pm 0.057\,(\mathrm{stat.}) \pm 0.147\,(\mathrm{syst.}) \pm 0.449\,(\mathrm{lumi.})\,\mathrm{nb},$$

$$\sigma(pp \to ZX) \times \mathrm{BF}(Z \to \mu^+\mu^-) = 0.924 \pm 0.031\,(\mathrm{stat.}) \pm 0.022\,(\mathrm{syst.}) \pm 0.102\,(\mathrm{lumi.})\,\mathrm{nb},$$

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

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

$Z \rightarrow \mu\mu$ event selection

- Both muons pass the muon selection
- They must have opposite charge
- The di-muon mass must satisfy $60 < M_{\mu\mu} < 120$ GeV
- At least one muon must match to a trigger muon (HLT_Mu9)

Selected events: **913**

Expected for 2.88 ± 0.32 pb-1 : 950 signal events , 3.48 ± 0.18 background

source	fraction	N_{est}	how estimated
QCD multi-jet	negl.	0.048 ± 0.002	
$W \rightarrow \mu\nu$	negl.	0.03 ± 0.03	MC
$t\bar{t}$	$(0.12 \pm 0.01)\%$	1.19 ± 0.10	MC
$Z \rightarrow \tau^+\tau^-$	$(0.05 \pm 0.01)\%$	0.52 ± 0.07	MC
WZ	$(0.08 \pm 0.01)\%$	0.82 ± 0.09	MC
WW	$(0.03 \pm 0.01)\%$	0.31 ± 0.05	MC
ZZ	$(0.06 \pm 0.01)\%$	0.55 ± 0.12	MC
total	$(0.37 \pm 0.02)\%$	3.48 ± 0.18	

Table 21: Estimates of backgrounds in the $Z \rightarrow \mu^+\mu^-$ channel

$Z \to \mu\mu$ simultaneous fit : event categories

Establish several event categories, mutually exclusive, hence statistically independent

One of the muons passes ALL selection criteria and the other is required to be pass All−1 condition, to extract the efficiency for that condition

$Z\mu\mu^{2HLT}$: Two good muons, both HLT matched
$Z\mu\mu^{1HLT}$: Two good muons, one HLT matched } ε_HLT

$Z\mu s$: Good muon + stand alone muon → ε_TK

$Z\mu t$: Good muon + (generic) track → ε_SA

$Z\mu\mu^{non\ iso}$: Two good muons, one not isolated → ε_Iso

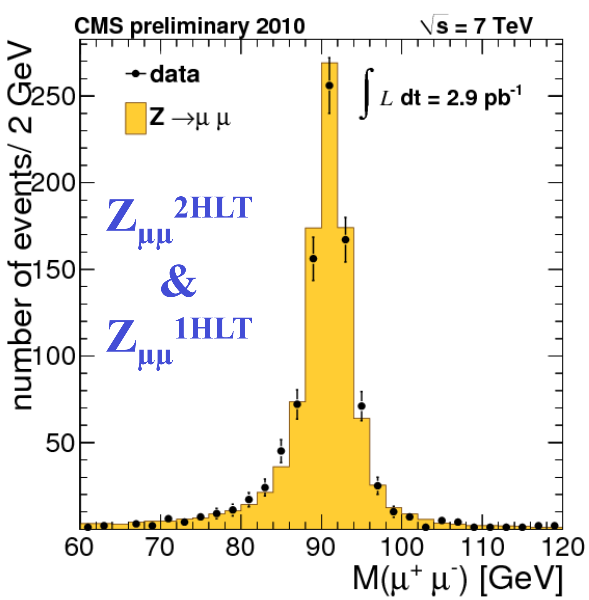
$Z\mu\mu^{qual}$: Two good muons → ε_Sel

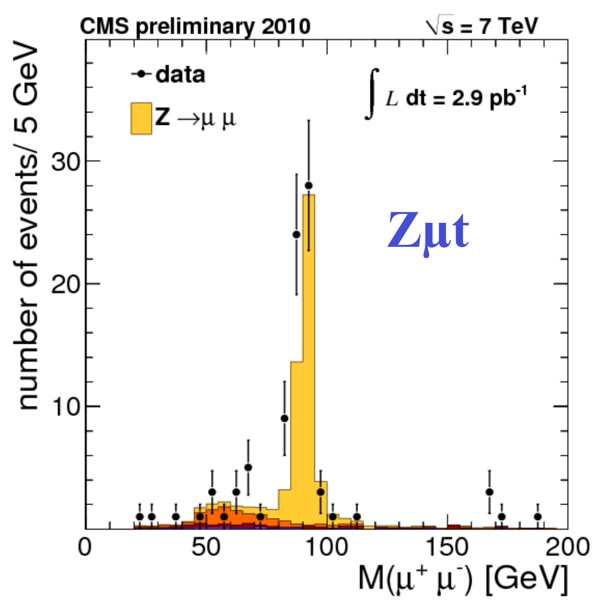
(Efficiencies can be factorized if correlations can be neglected)

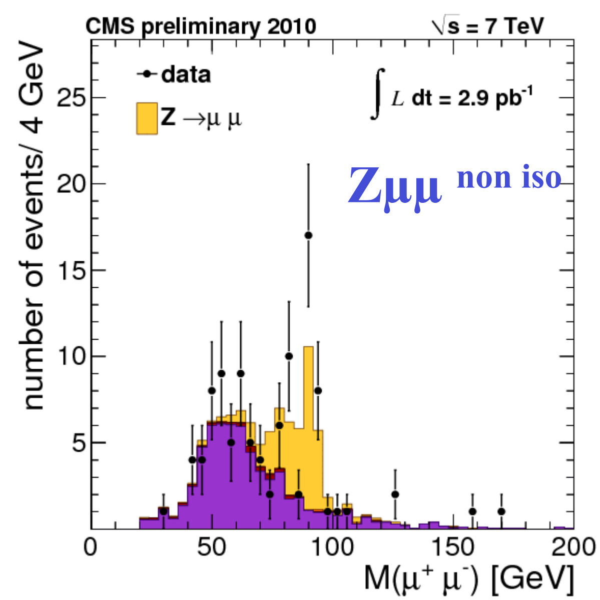
Z→μμ simultaneous fit: categories distributions

Golden categories ($Z_{\mu\mu}^{2HLT}$ and $Z_{\mu\mu}^{1HLT}$):
Assume that this category is background free.

Not the case for the other categories. Background subtraction applied.







Z→μμ simultaneous fit: the fit

Joint fit to all mass spectra to subtract the background and extract yield and efficiencies

Signal modeling:

– $f_{\text{peak}}(m)$: taken from $Z_{\mu\mu} = Z_{\mu\mu}^{2HLT} + Z_{\mu\mu}^{1HLT}$ mass spectra

Background modeling:

– Polynomial times exponential functions

Binned Maximum Log Likelihood fit: minimize a global χ^2

$$\chi^2 = \frac{(N_{\mu\mu}^{2\mathrm{HLT}} - N_{Z\to\mu^+\mu^-}\epsilon_{\mathrm{HLT}}^2\epsilon_{\mathrm{iso}}^2\epsilon_{trk}^2\epsilon_{sa}^2)^2}{N_{\mu\mu}^{2\mathrm{HLT}}} + \frac{(N_{\mu\mu}^{1\mathrm{HLT}} - 2N_{Z\to\mu^+\mu^-}\epsilon_{\mathrm{HLT}}(1-\epsilon_{\mathrm{HLT}})\epsilon_{\mathrm{iso}}^2\epsilon_{trk}^2\epsilon_{sa}^2)^2}{N_{\mu\mu}^{1\mathrm{HLT}}} + \chi_{\mu s}^2 + \chi_{\mu t}^2 + \chi_{\mu\mu}^{\text{non iso }2}$$

Fitted yield (corrected for efficiency):

$N_{Z\to\mu\mu} = 1050 \pm 35$, Bkgd = 3.5 ± 0.2

$\sigma\,(pp \to ZX \to \mu^+\mu^- X) = 0.924 \pm 0.031$ nb

Cross section results

W NNLO: 10.44 ± 0.52 nb

NNLO: FEWZ & MSTW08

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

W+ NNLO: 6.15 ± 0.29 nb

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

W− NNLO: 4.29 ± 0.23 nb

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

Z NNLO: 0.97 ± 0.04 nb

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

Cross section ratios: W/Z and W^+/W^-

$$\frac{\sigma_W}{\sigma_Z} = \frac{N_W}{N_Z}\frac{\epsilon_Z}{\epsilon_W}\frac{A_Z}{A_W}$$

NNLO: 10.74 ± 0.04 nb

NNLO: FEWZ & MSTW08

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

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

Combination via Likelihood

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

$$\frac{\sigma_{W^+}}{\sigma_{W^-}} = \frac{N_{W^+}}{N_{W^-}}\frac{\epsilon_{W^-}}{\epsilon_{W^+}}\frac{A_{W^-}}{A_{W^+}}.$$

NNLO: 1.43 ± 0.04 nb

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

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

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

Cross Sections in Restricted Acceptance

- 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:

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