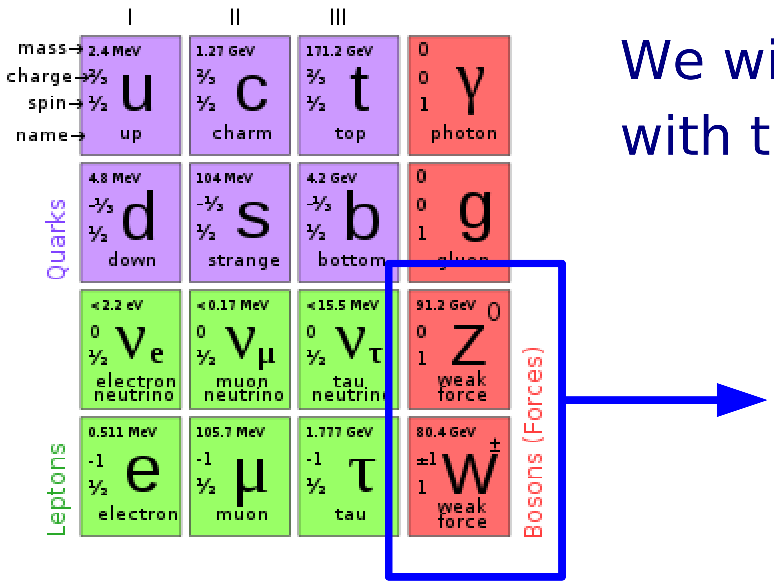
Hamburg

Measurements of Electroweak Physics at the LHC

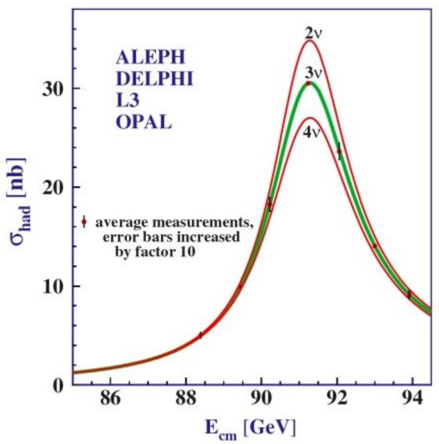
Roger Wolf

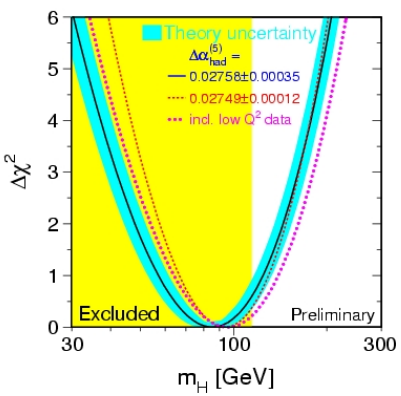
Triumphs of EWK Physics...



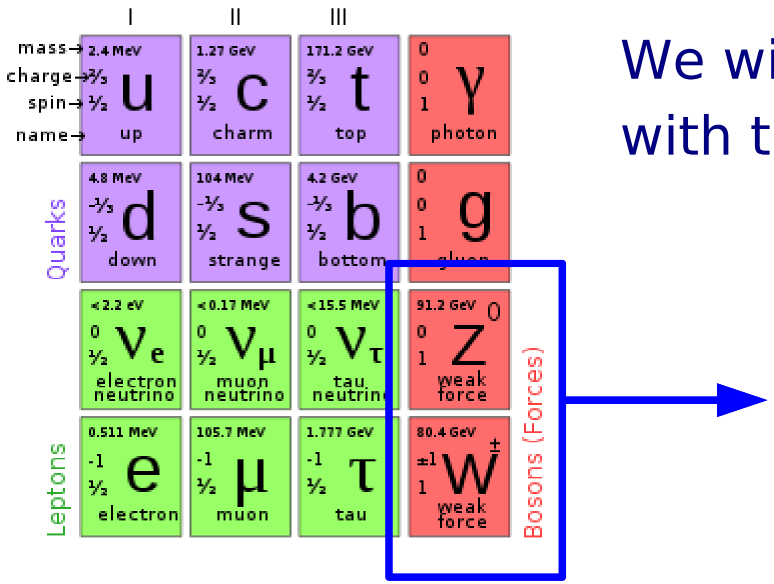
We will call everything electroweak, which has to do with the exchange of a W/Z boson:

- W/Z bosons were first discovered first at CERN
  - UA1/UA2 Collaboration (Phys. Lett. B122 1983) [W→eν]
  - UA1 Collaboration (Phys. Lett. B126 1983) [Z→ee]
  - UA2 Collaboration (Phys. Lett. B129 1983) [Z→ee]
- And then measured with tremendous precision!
  - M(Z)=91.1876±0.0023 GeV (PDG 2008)
  - M(W)=80.399 ±0.023 GeV (Tevatron cmb 2010)
  - $\cos(\theta_W)=0.89$ (corresponding to $\theta_W \sim 27°$)
- Still today LEP holds the record in the precision of the Z mass and many important measurements!





... in Precision Measurements



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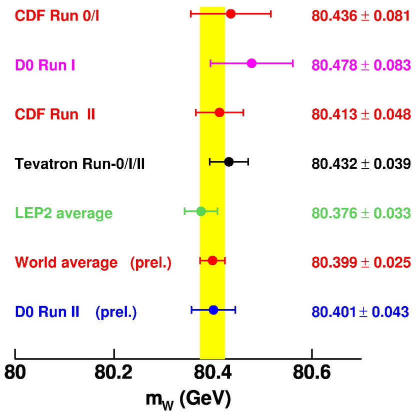
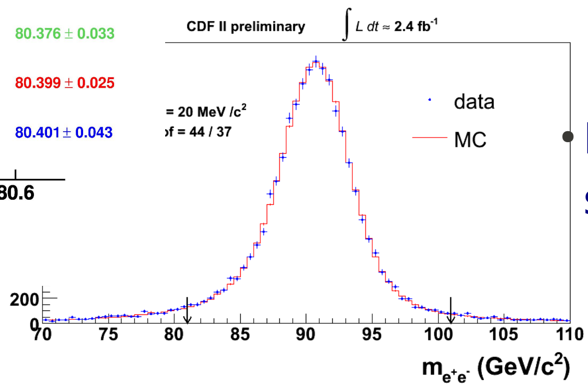
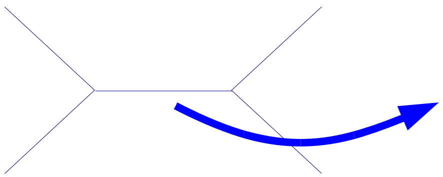




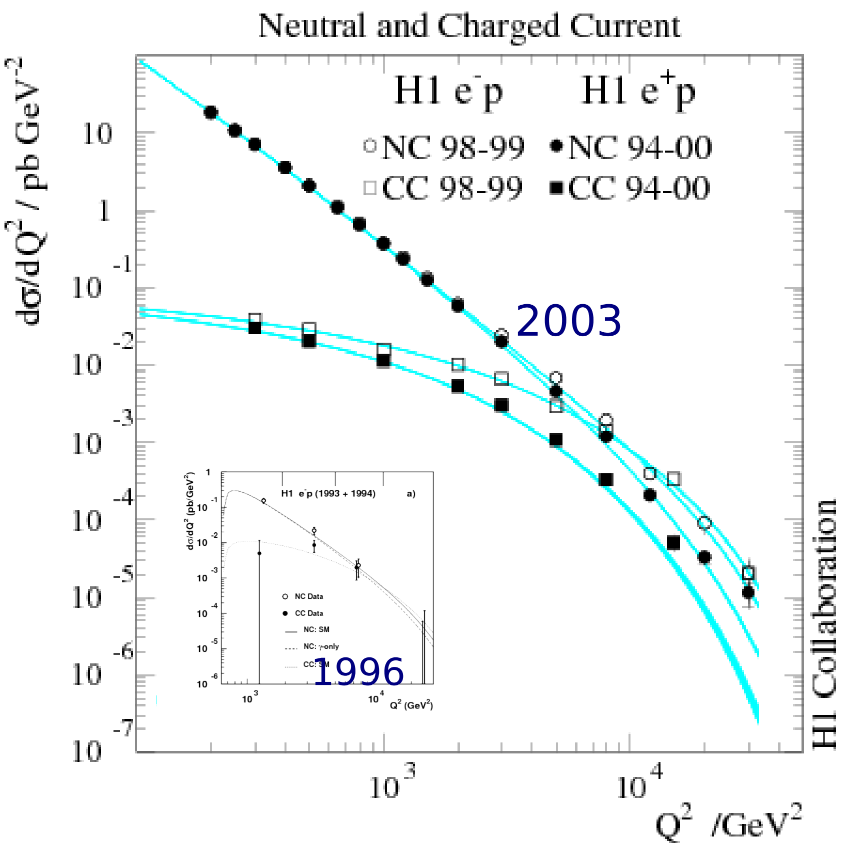
- But Tevatron took over for the W mass (precision measurement at a hadron collider)!

… and in Fundamental Structures

Propagator structure of the coupling:

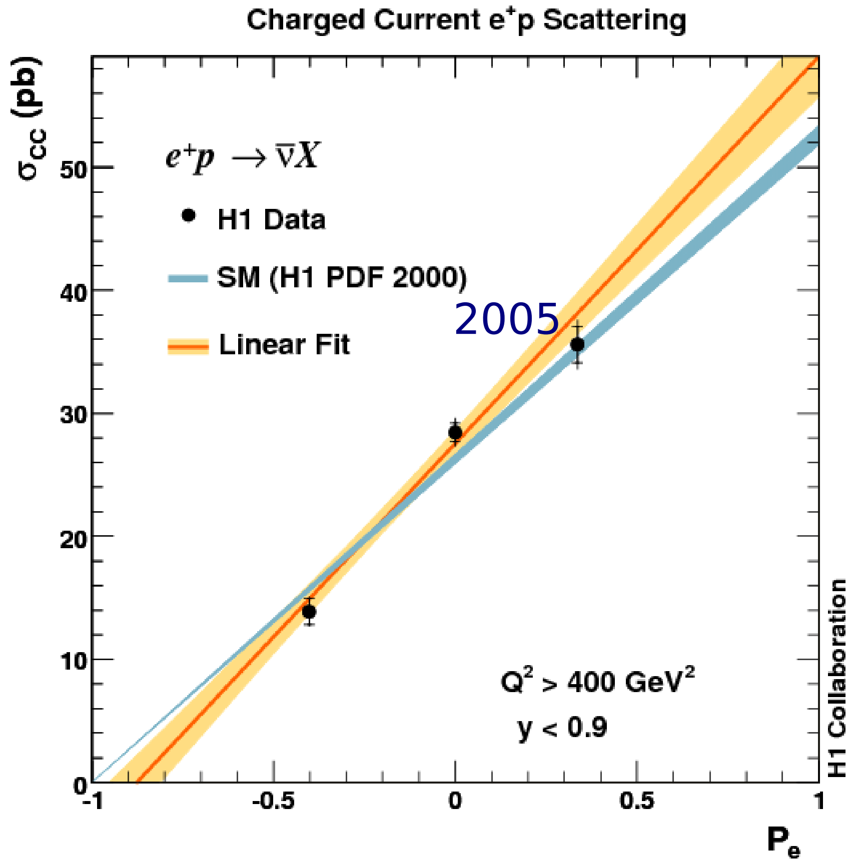


$$\frac{1}{Q^2+M_W{}^2}$$



V-A coupling:

- $W^{+/-}$ couples ONLY left handed (anti-)leptons



EWK Physics at the LHC

EWK measurements are a strong pillar of the SM!

Should we still do EWK measurements at the LHC (still anything to learn)?

Final judge on the fate of the SM:

- Masses of the W/Z lead to the need of electroweak symmetry breaking!
- Three heaviest objects of the SM set the scale and rule the mechanisms of EWK symmetry breaking (→ W, Z, Top).
- Even if we don't find a Higgs elastic WW scattering will open the door towards NP.

Standard candle/Master Tool:

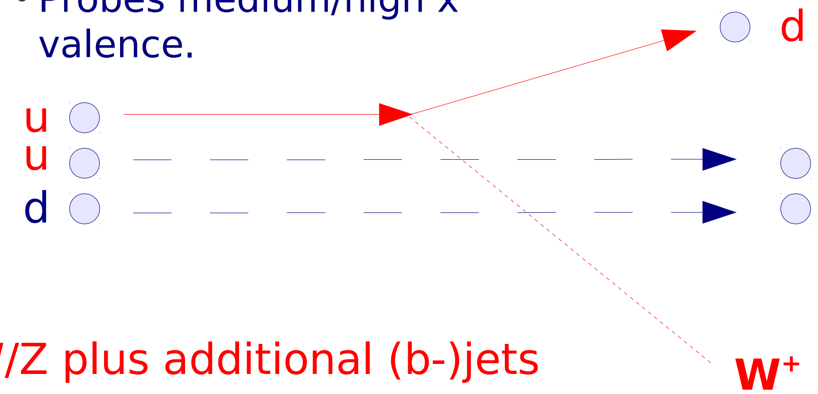
- Theoretically well known/predictable.
- Important background.
- Measurements relative to Z cross section.
- Input to PDFs and luminosity estimates.
- Valuable tool $Z \rightarrow l^+ l^-$.

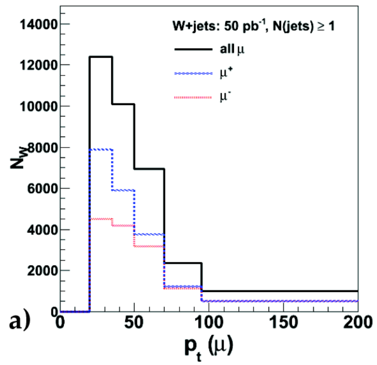
This will be and remain an important physics sector at the LHC!

Most Obvious Measurements

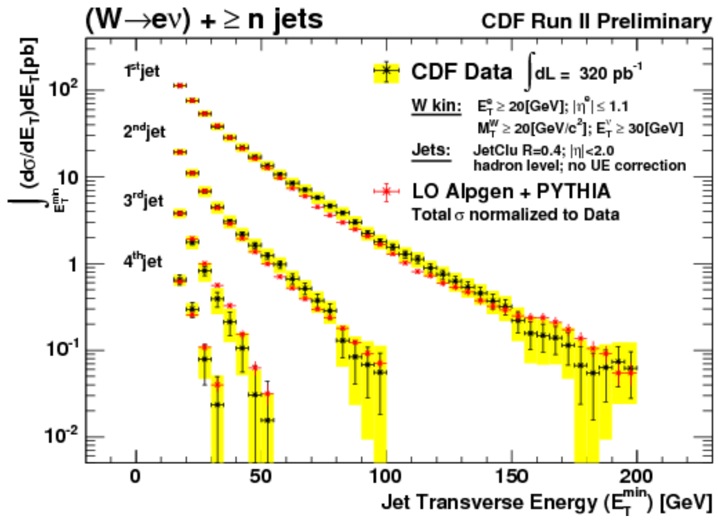
What will be the most obvious EWK measurements at the LHC?

- Inclusive production cross section (in a so far unrevealed kinematic regime).
- Charge asymmetry (key to PDF measurements)
  - More u over d in pp collisions.
  - Probes medium/high x valence.





- W/Z plus additional (b-)jets
  - Z+Jet for calorimeter calibration (combines calorimeter with tracker information).
  - Important background for top!
- WW/WZ/ZZ production
  - Important background for Higgs!



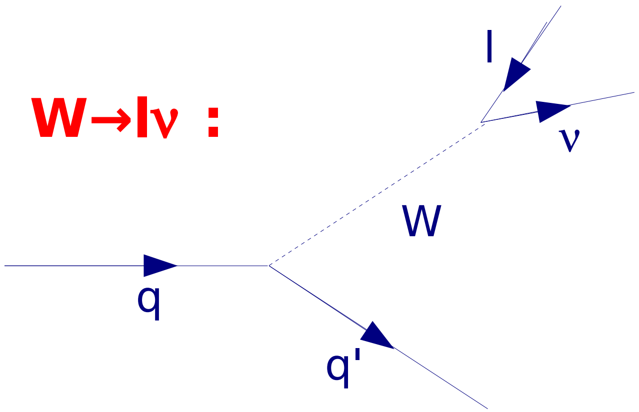
Outline

We will discuss in the following:

- Inclusive production cross section (in a so far unrevealed kinematic regime).
  - *CMS PAS EWK-10-002 (200nb^{-1})*
  - *ATLAS CONF 2010-051 (17nb^{-1})*
- Discuss both $Z \rightarrow ll$ and $W \rightarrow l\nu$.
- Mostly concentrate on CMS when discussing the μ and on ATLAS when discussing the e channel.
- Hadronic channel or τ are not discussed.
- Small review of the objects used the event selection.
- Signal extraction methods and background estimation.
- Systematics and results.

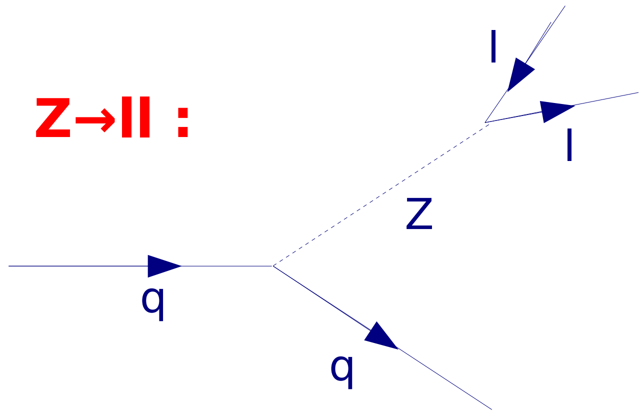
Event Signature and Backgrounds

W→lν :



- Well isolated lepton (red flag).
- Missing transverse energy (MET).

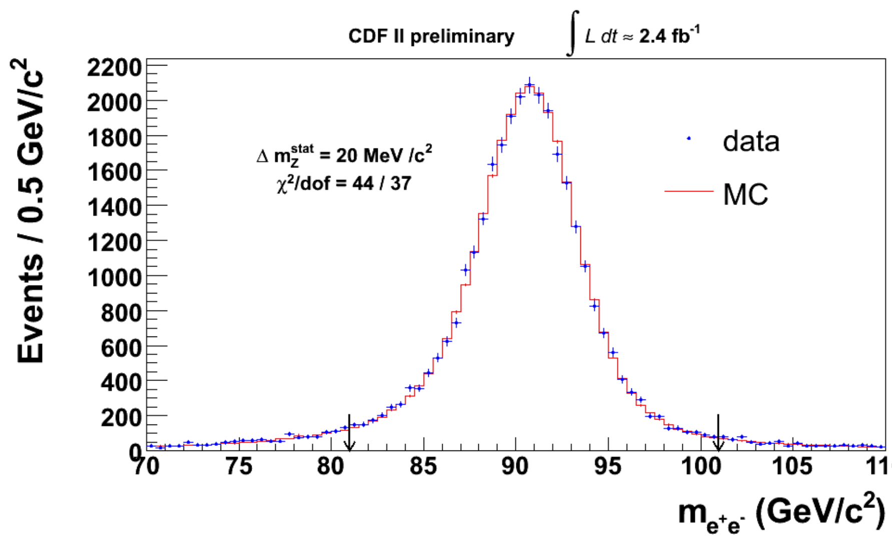
Z→ll :



- Two well isolated leptons!
- Opposite charge, same flavor.
- No missing transverse energy (MET).

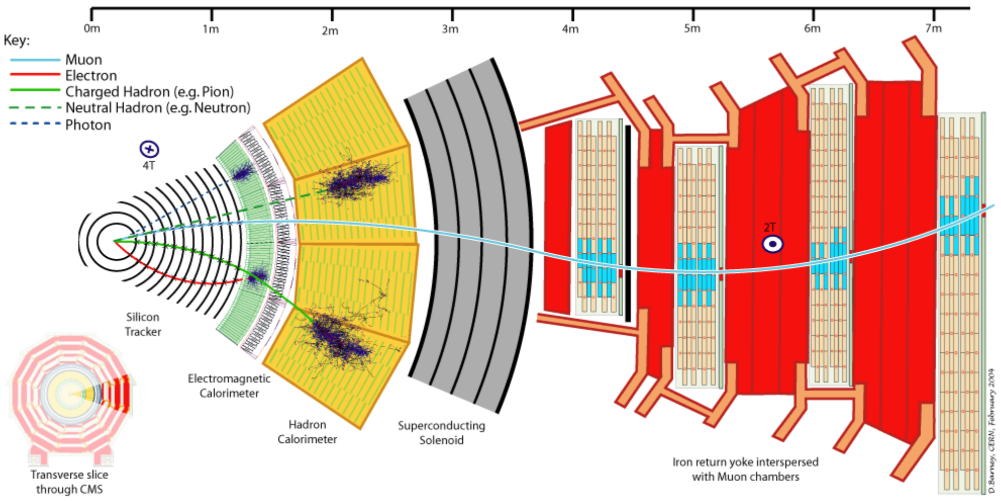
Major Backgrounds:

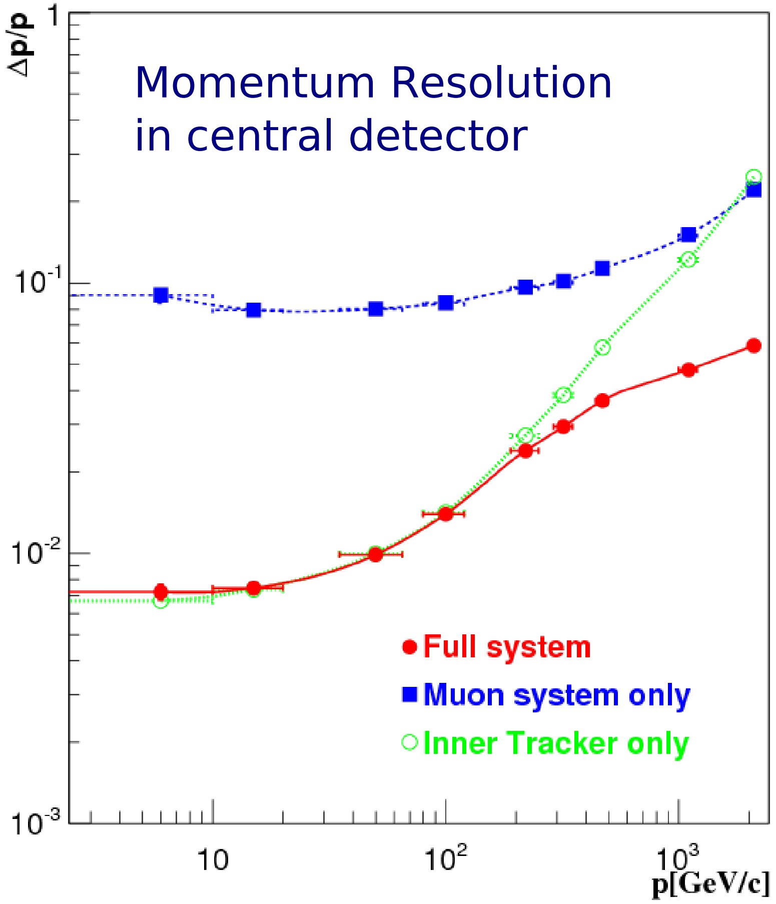
- QCD (Q-decays, mis-tagged hadrons, conversions).
- Drell-Yan (for Z→ll).
- Z→l(l) (one lepton out of acceptance for W→lν).
- Z→ττ.



Object Reconstruction: Muons

Example CMS:





- Tracker only:

  Si tracks + MIP signature in calorimeters + a hit in the first muon chamber (inner→out).

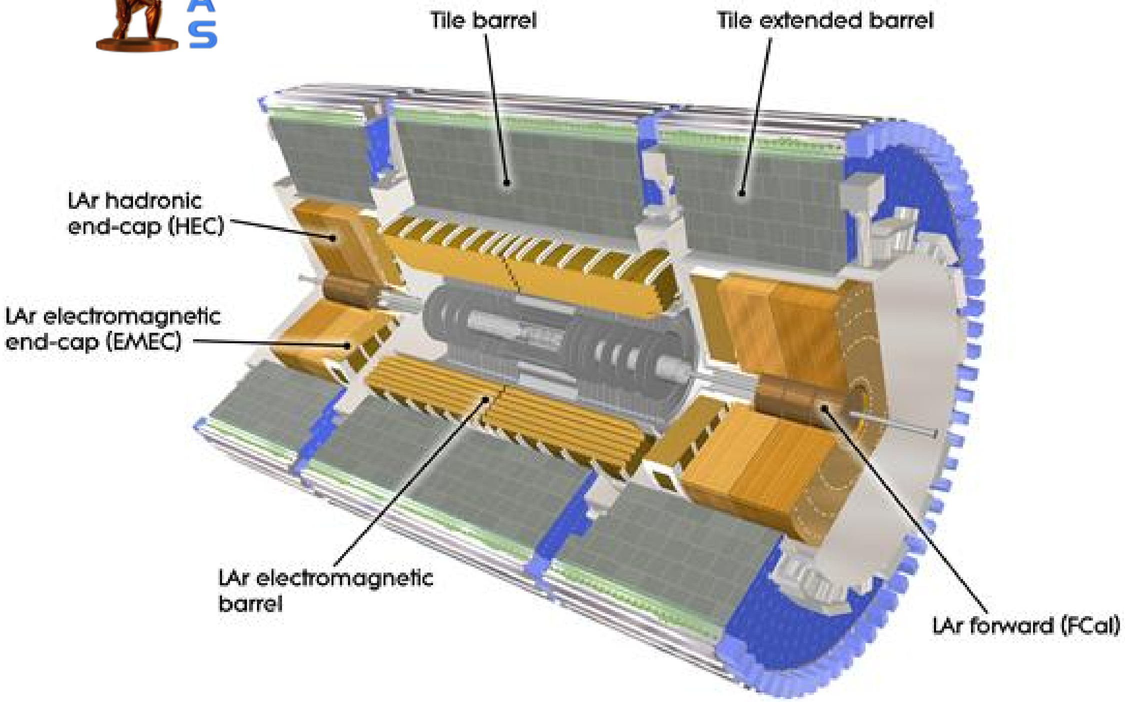
- Muon System only:

  Reconstructed track segments in muon chambers.

- Combined Tracker & Muon System: Separate reconstruction and re-fit (outer→inner).

Object Reconstruction: Electrons

Example ATLAS:



LAr(EM):

- Three layers of lead in LAr.
- 173k cells.
- $|\eta|<3.9$ (including LAr fwd).

Reconstruction:

- Seeded by cluster with $E_T>2.5$ GeV (in second layer of LAr, sliding window).
- Linked to closest tracks with $p_T>0.5$ GeV.
- Total E_T is taken from calorimeter.

Electron Categories (barrel):

- Loose: shower shapes, leakage in HCAL. ($\varepsilon\sim94\%$, $E_T(e)>20$ GeV – Rej 1100).
- Medium: more shower shapes, track quality, ($\varepsilon\sim90\%$, $E_T(e)>20$ GeV – Rej 6800).
- Tight: e/p, signal in TRT, conversion supp. ($\varepsilon\sim70\%$, $E_T(e)>20$ GeV – Rej 9200).

Missing Transverse Energy Reconstruction

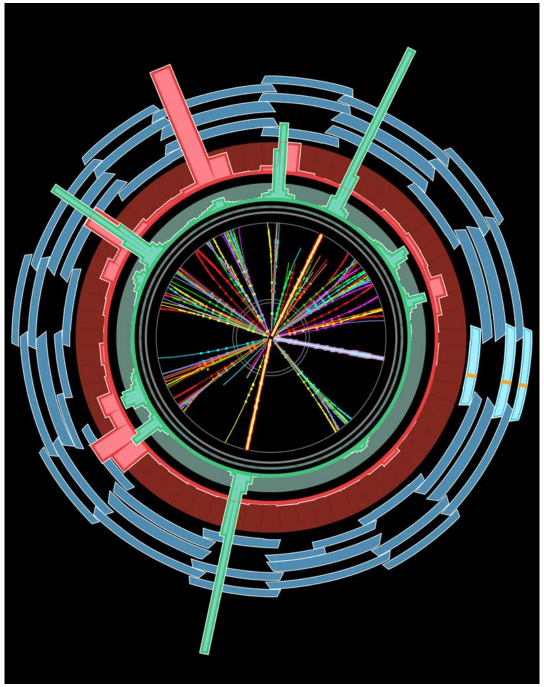
What is missing transverse energy?

Theory

The undetected energy that leaves with ν or other weakly interacting particles.

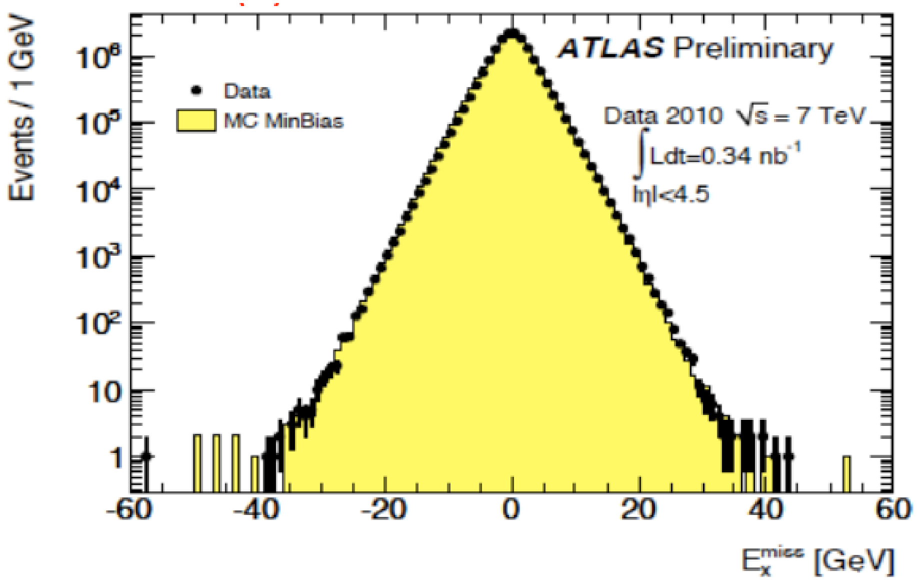
Praxis

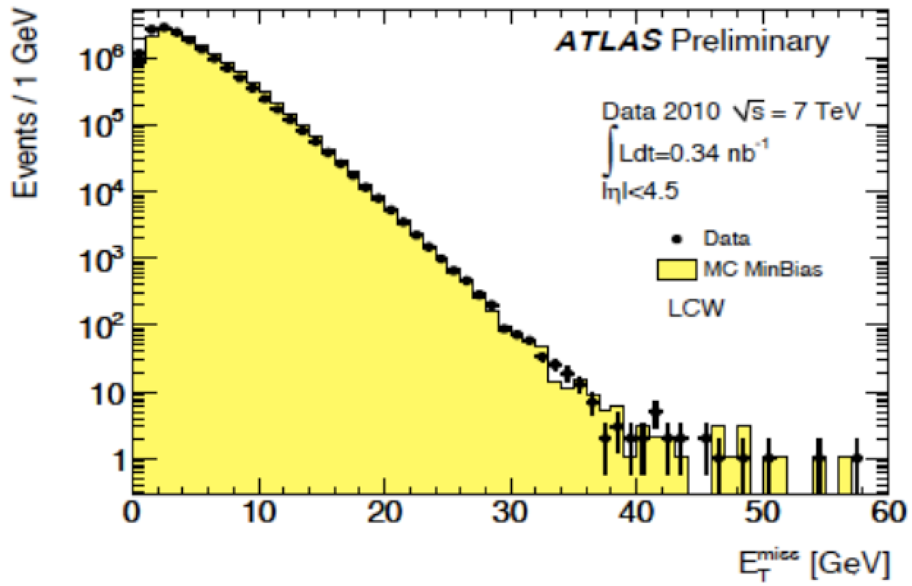
The negative vectorial sum of all energy measured in the detector.



- Need full 4π coverage (ATLAS $|\eta|<4$, CMS $|\eta|<5$).
- Good energy resolution in calorimeter.
- Good energy calibration of the calorimeters.
- Easily affected by instrumental noise.
- High p_T muons leave only MIP signature in calorimeters.
- Some times H_T is used instead of MET (only energy in jets is summed).

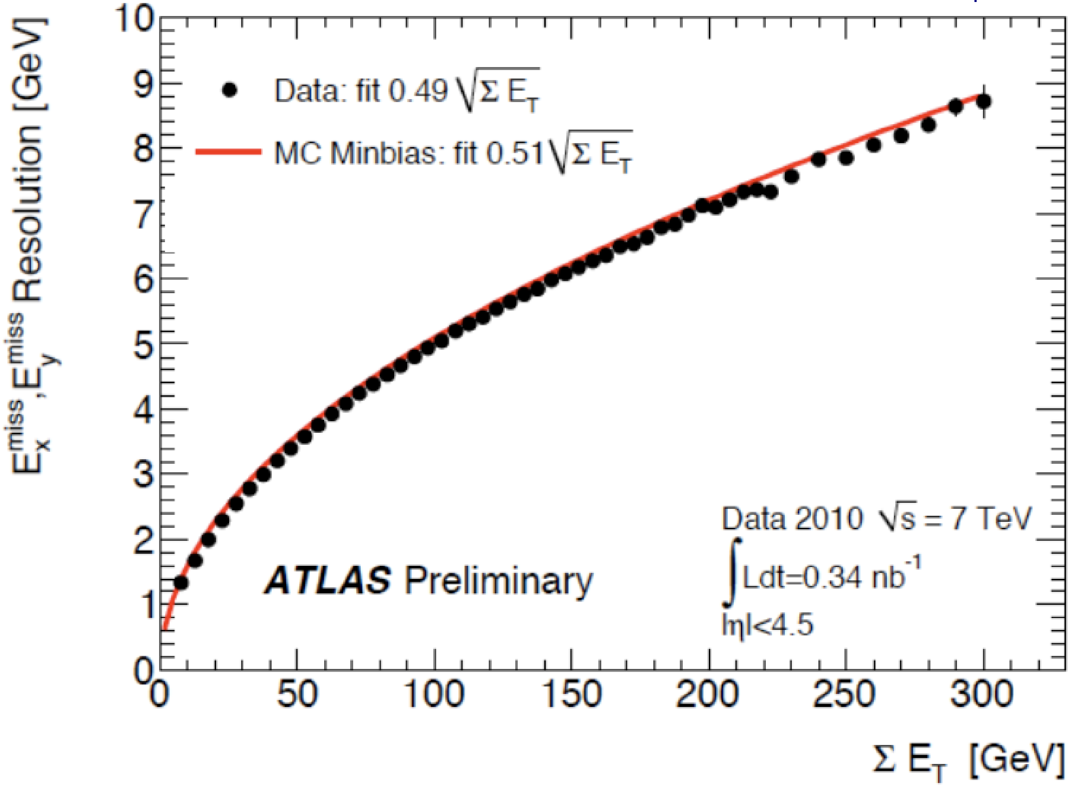
Missing Transverse Momentum Performance





Example ATLAS:

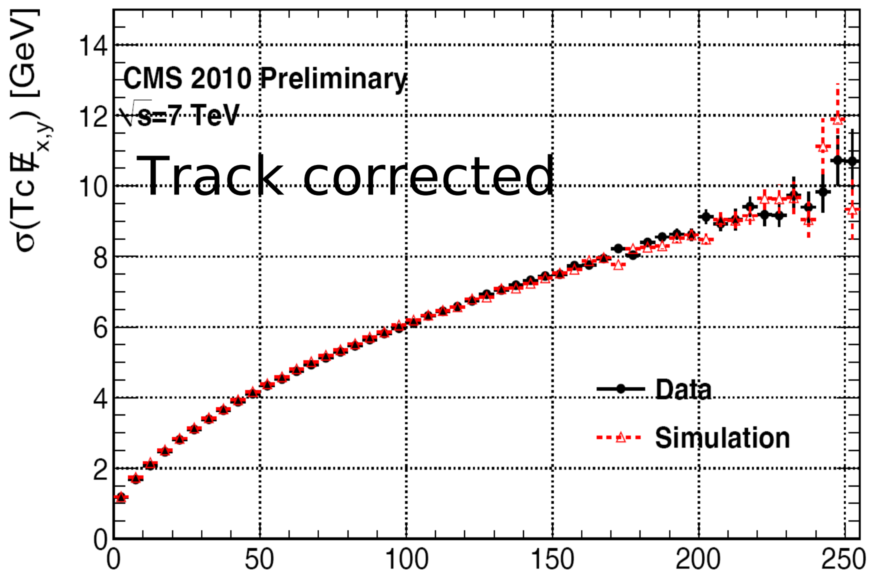
Expect that MET resolution scales with $\sqrt{\Sigma E_T}$

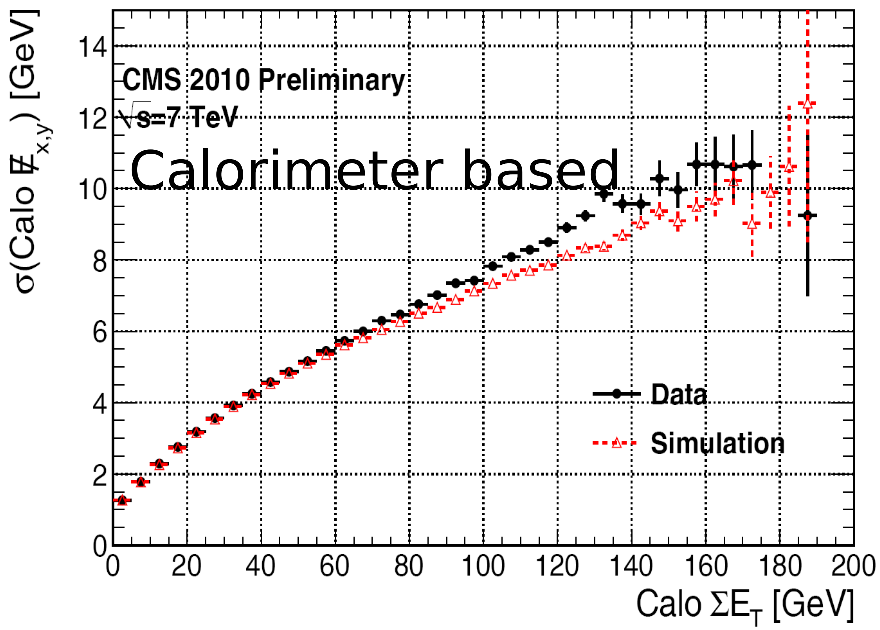


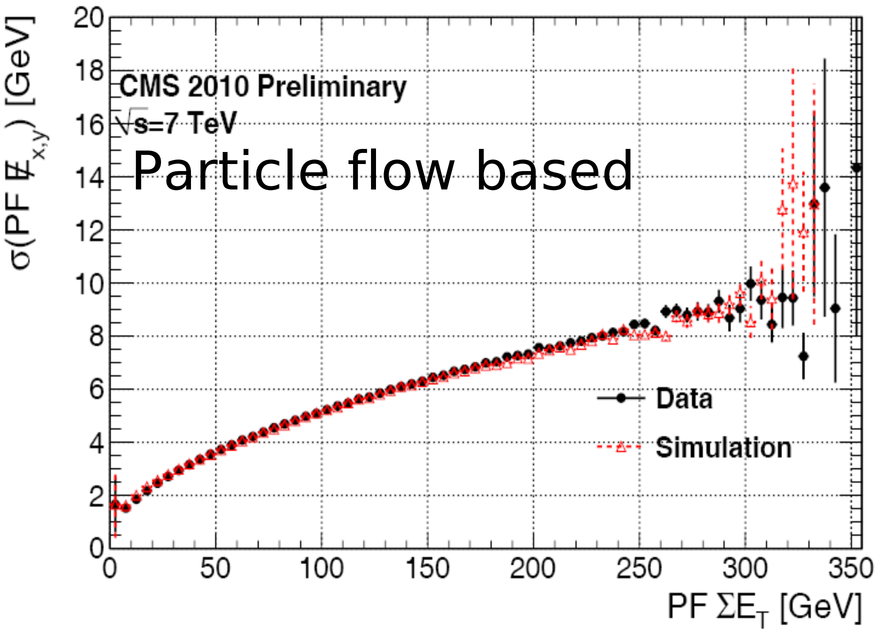
Missing Transverse Momentum Performance

Example CMS:

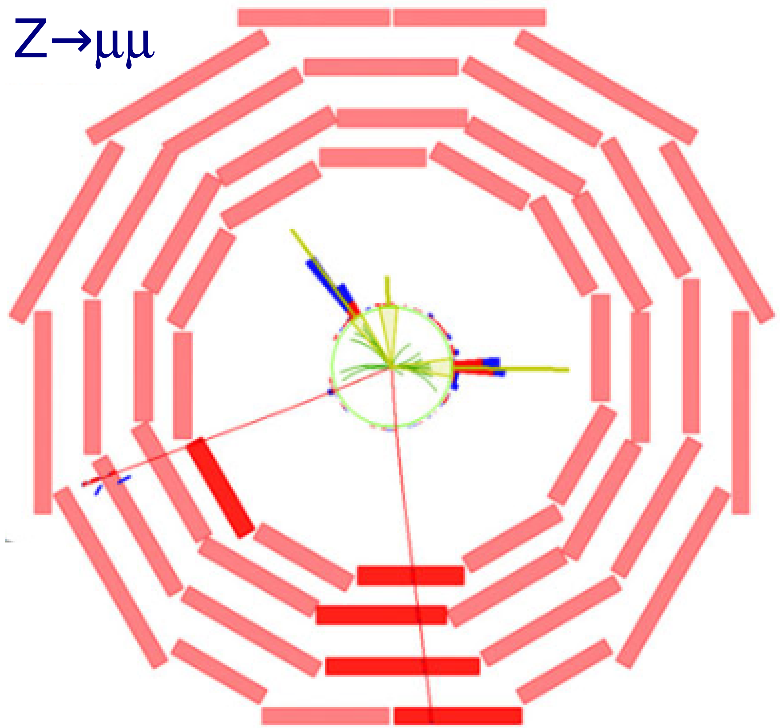
- Three types of MET (calo, track corrected & based on particle flow candidates)
- MET corrected for jet energy calibration and muons.

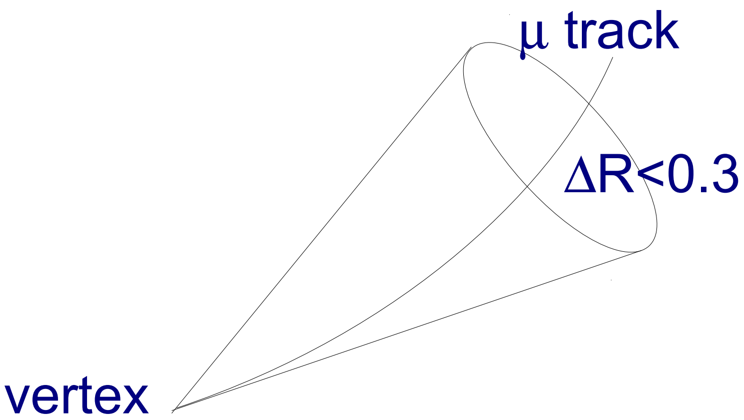






Event Selection ($Z \to \mu\mu$)





Muon Quality:

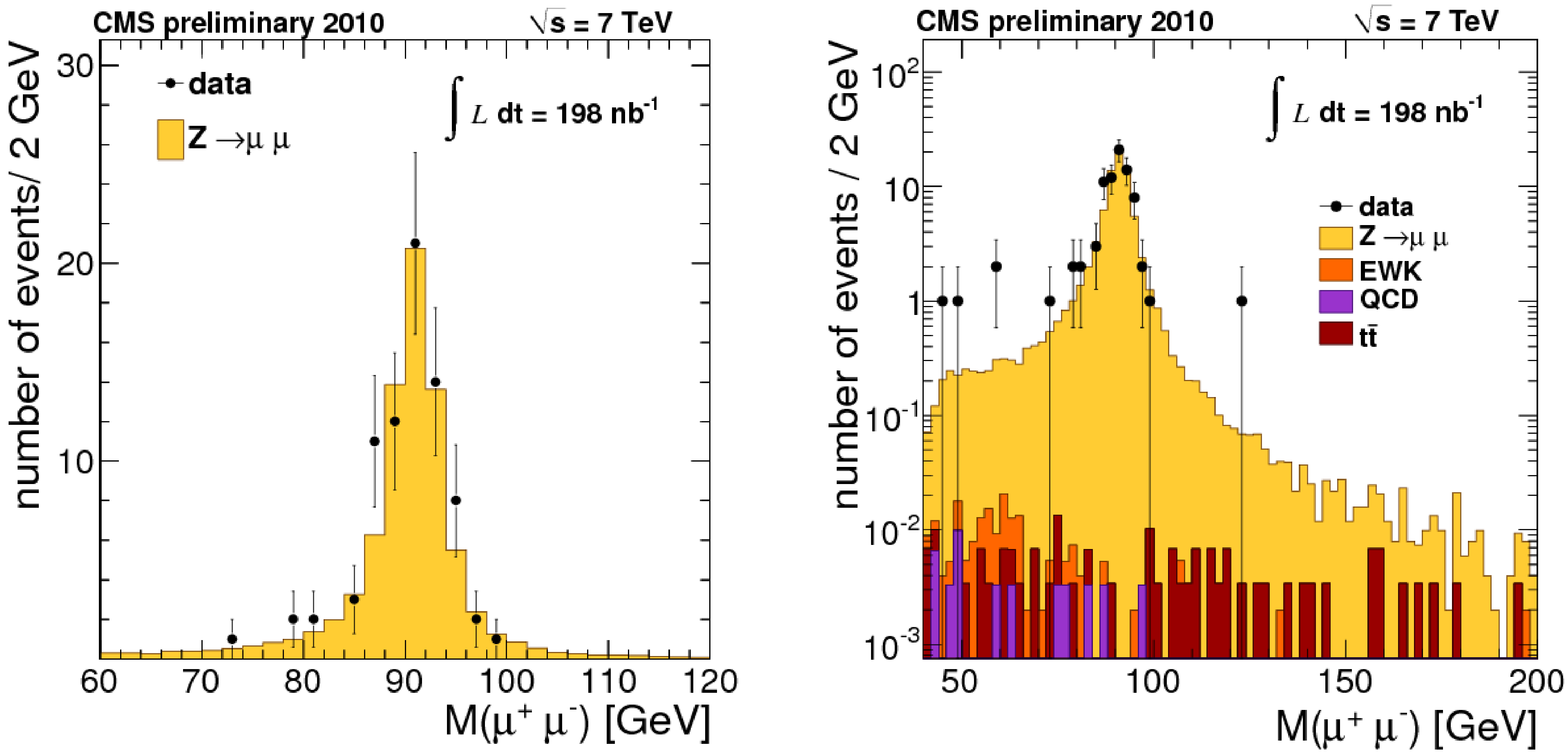
- Trigger: HLT μ p_T>9 GeV $|\eta|$<2.1 (prescales 1).
- Combined muon with χ^2<10.
- N_{Hits}>10 in Si tracker (incl. Pixel) and muon system (>1 station).
- Transverse impact parameter wrt beamspot d_0<2mm.

Muon Selection:

- 2μ (opposite charge, one with slightly looser quality)
- $p_T(\mu)$>20 GeV, $|\eta|$<2.1, 60 GeV<$m_{\mu\mu}$<120 GeV
- $I=\Sigma p_T$(track)<3 GeV

- This results in a basically background free sample.
- Counting experiment (Cut & Count).

Z→μμ Peak



- 77 events in 200 nb^{-1} (ε_{MC}=47.6±0.2(stat.)%, ε(trigger)=92±3%).
- Expected background fraction: 0.3% (QCD, ttbar, Z→ττ).

Signal efficiency

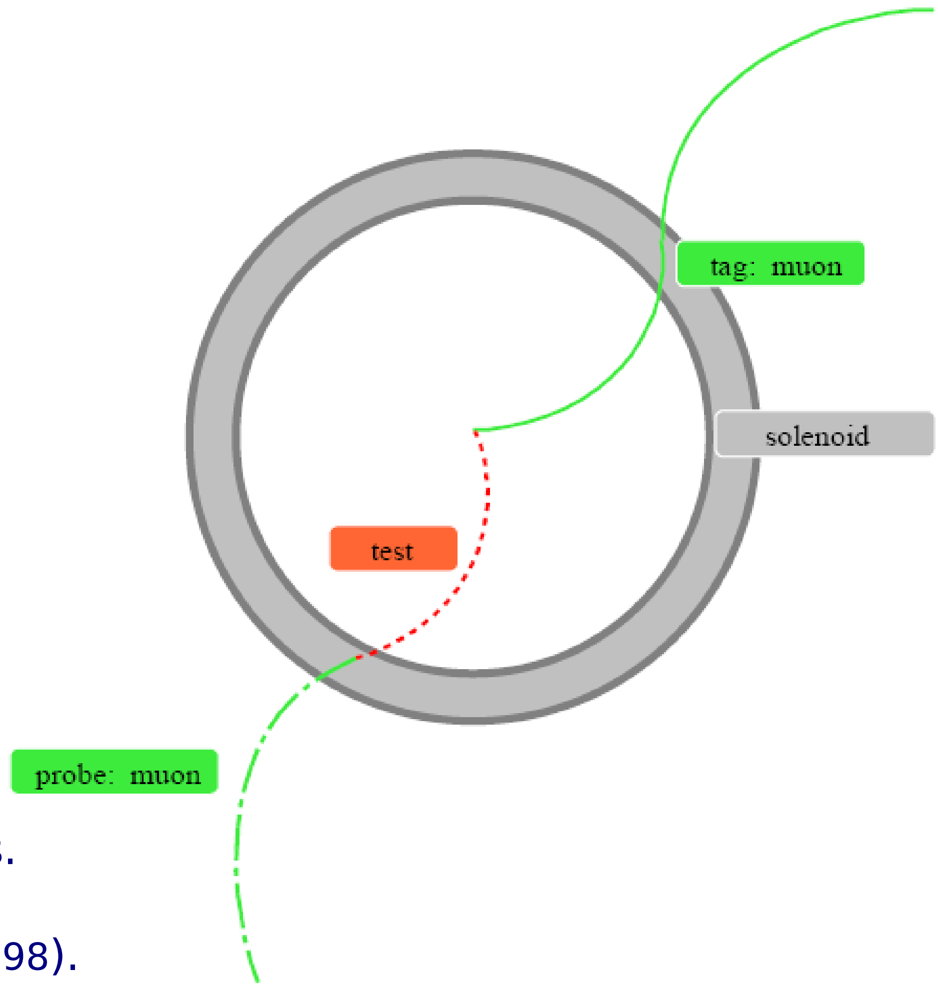
- Determined from the events themselves (Tag and Probe methods cf. Tutorials).
- On relaxed selection due to statistics.

Probe:

μ with some loose quality criteria.

Tag:

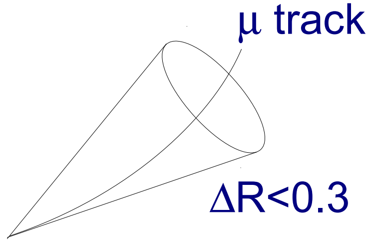
Strictly selected μ that forms M_Z with the probe.



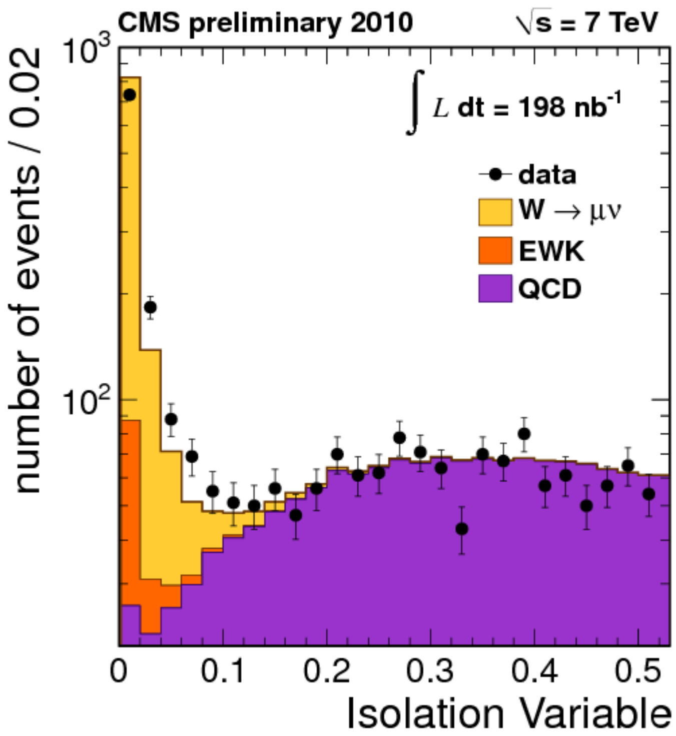
- How often does probe fulfill a test requirement?
- Apply efficiency from MC if consistent within stats.
- Apply correction factor in case of deviations (C=0.98).
- These efficiencies can also be applied to $W \to \mu\nu$!

Event Selection ($W \to \mu\nu$)

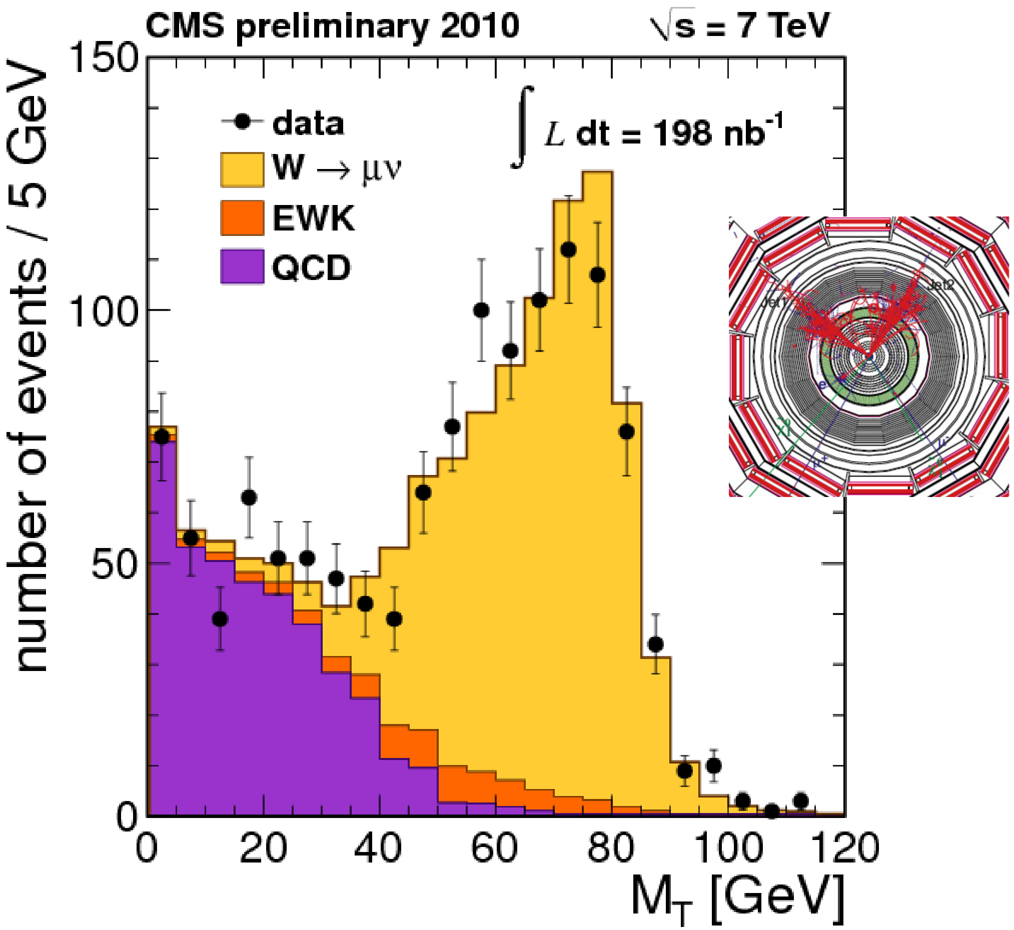
Muon Selection:



- 1 isolated μ
- $I_{rel} = (\Sigma p_T(\text{track}) + E_T(\text{em}) + E_T(\text{had}))/p_T(\mu) < 0.15$



$M_T = \sqrt{p_T(\mu)^*MET(1-\cos(\Delta\phi_{\mu MET}))}$:

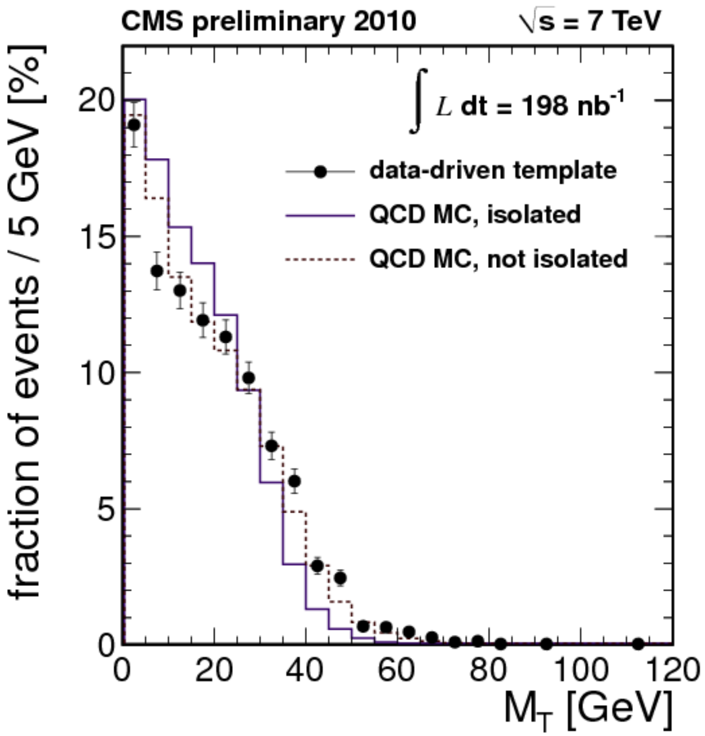


- $N_W = 818 \pm 12$ ($\varepsilon_{sig} = 64.1 \pm 0.2$(stat.)%).
- Estimate from binned LL fit.

Data driven QCD BG Estimate ($W \rightarrow \mu\nu$)

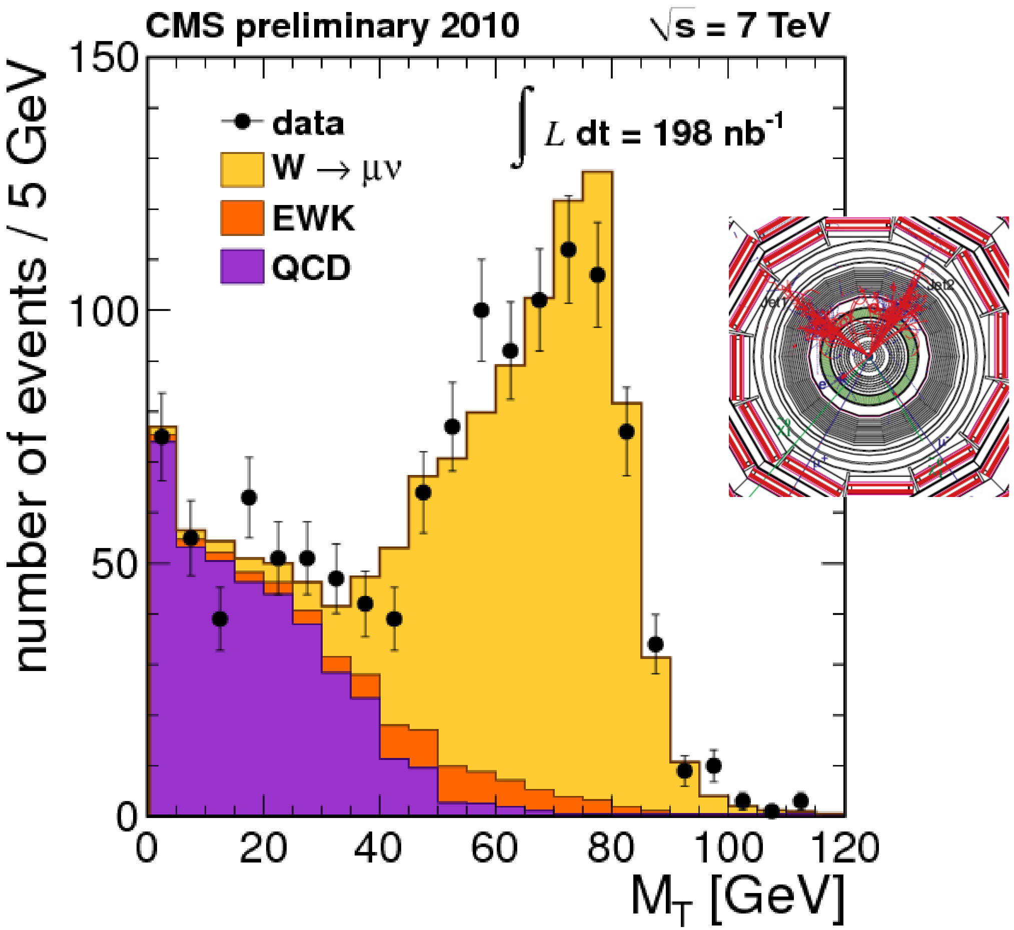
Background Composition:

- $Z \rightarrow \mu\mu$ (3%) $W \rightarrow \tau\nu$, $Z \rightarrow \tau\tau$ (2%)
- QCD (Q-decays) → data driven:
- $I_{rel} > 0.20$.



- Use full difference of MC for uncertainty estimate.

$M_T = \sqrt{p_T(\mu)*MET(1-\cos(\Delta\phi_{\mu MET}))}$:

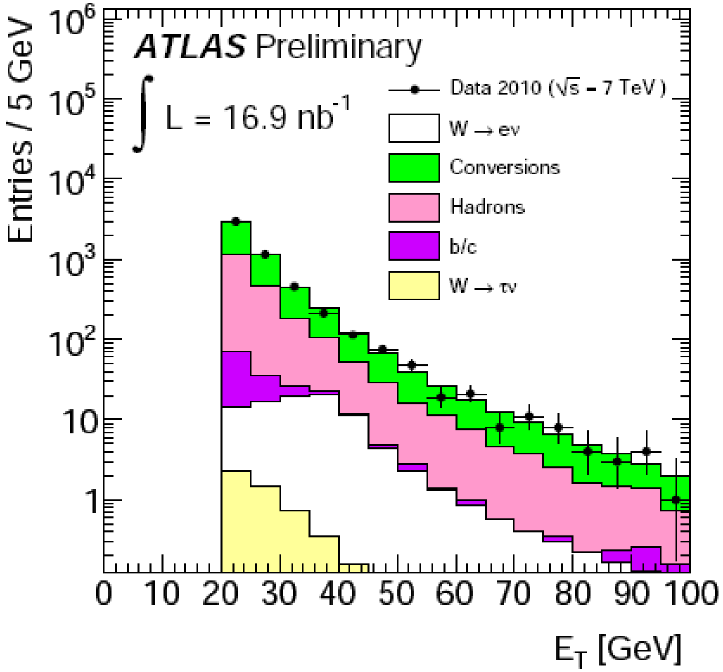


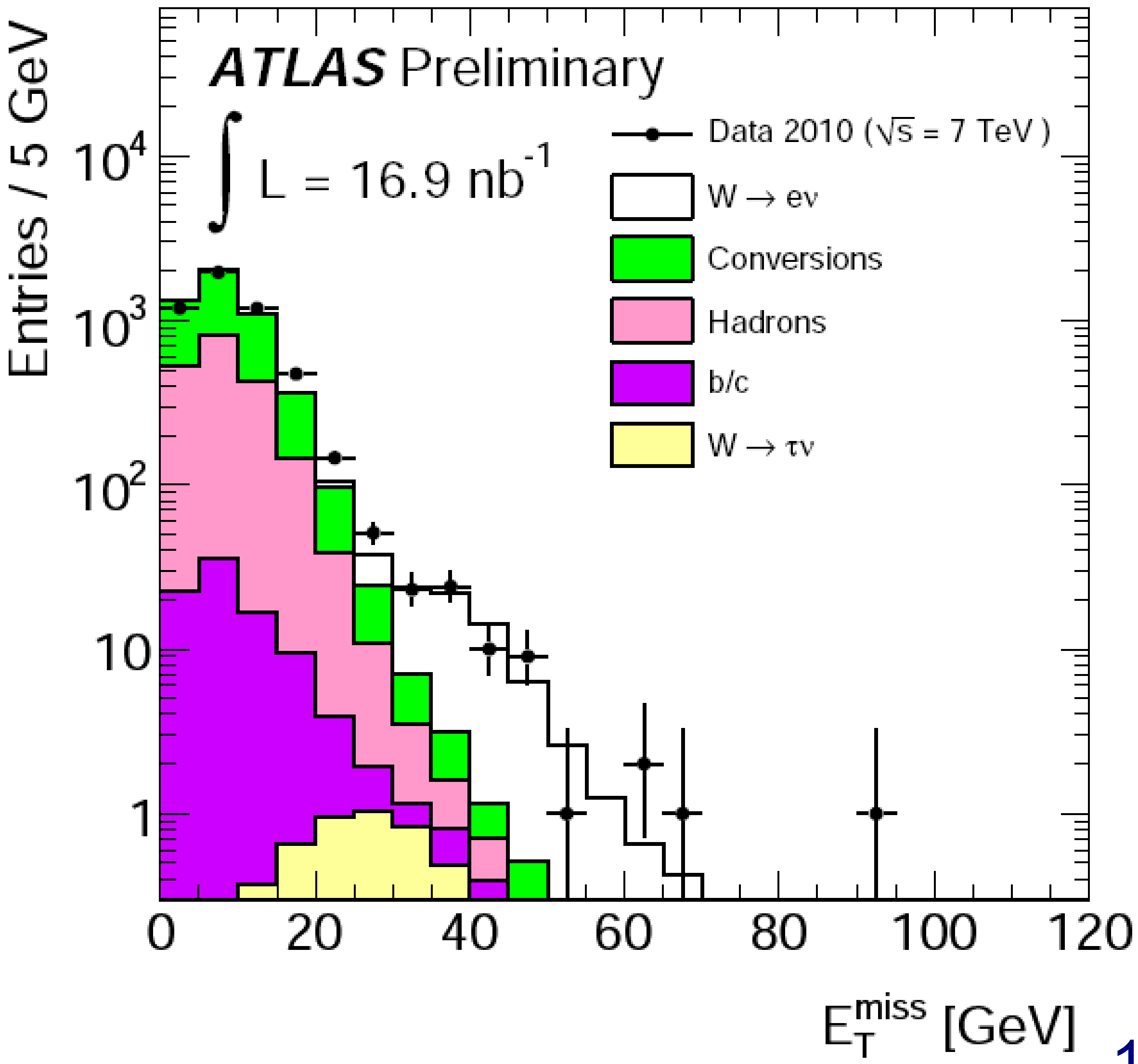
- $N_W = 818 \pm 12$ ($\varepsilon_{sig} = 64.1 \pm 0.2$(stat.)%).
- Estimate from binned LL fit.

Event Selection ($W \rightarrow e\nu$)

Preselection:

- Trigger: e/γ $|\eta|<2.5$, $E_T>5$ GeV.
- Restriction to fiducial volume.
- Electron category 'loose' ($\varepsilon \sim 94\%$):
- $E_T(e)>20$ GeV, $|\eta|<2.47$.

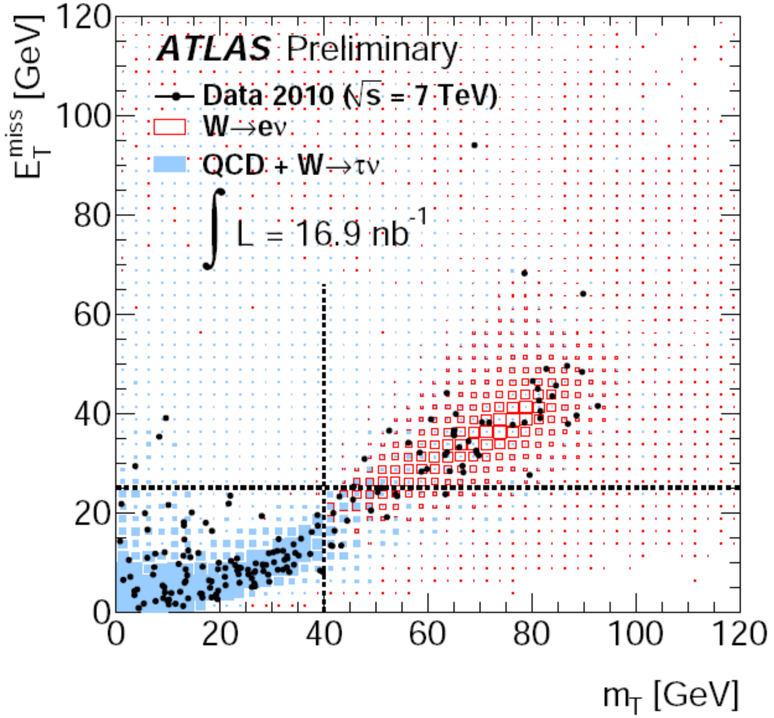


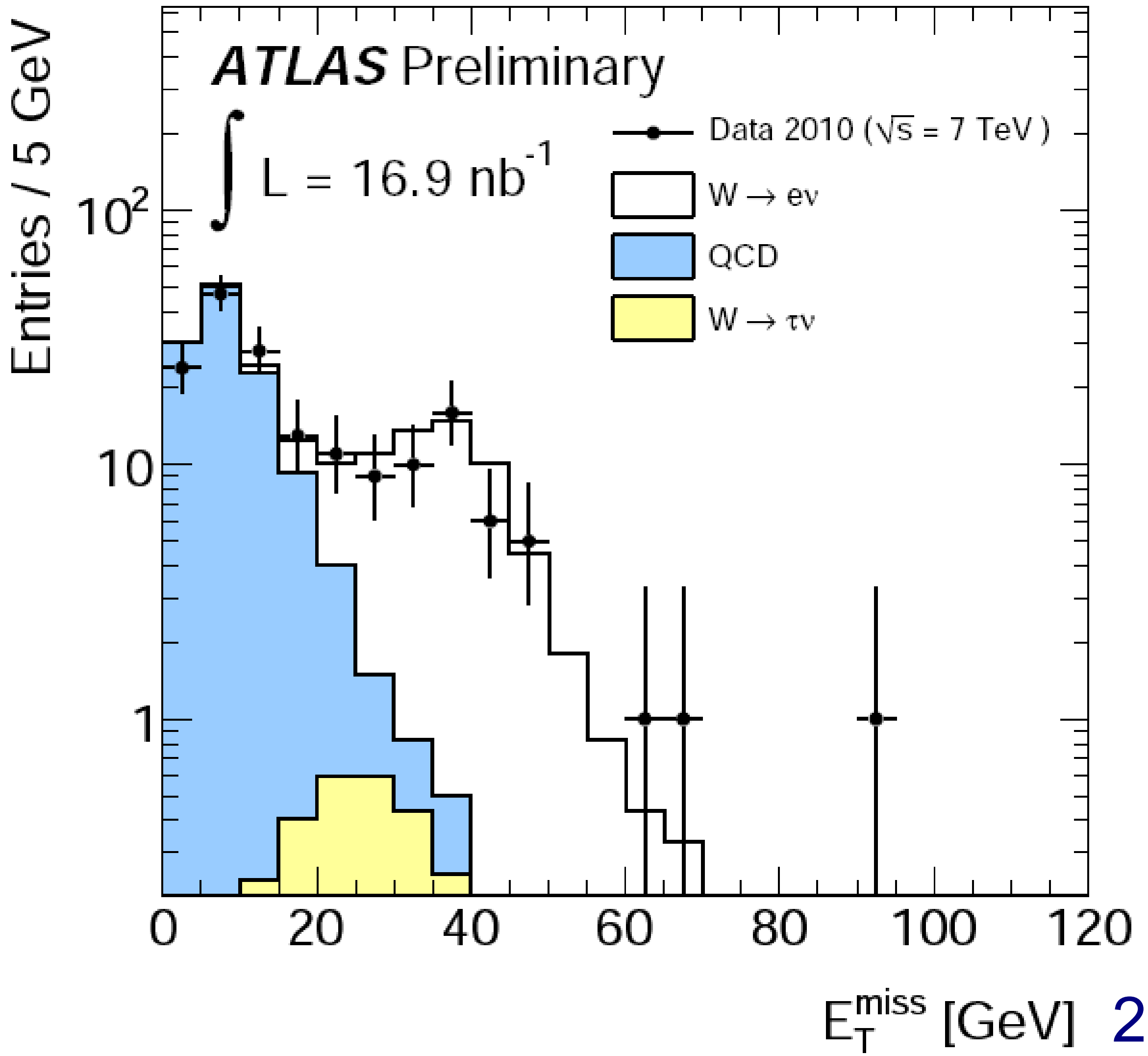


Event Selection (W→eν)

Final Selection:

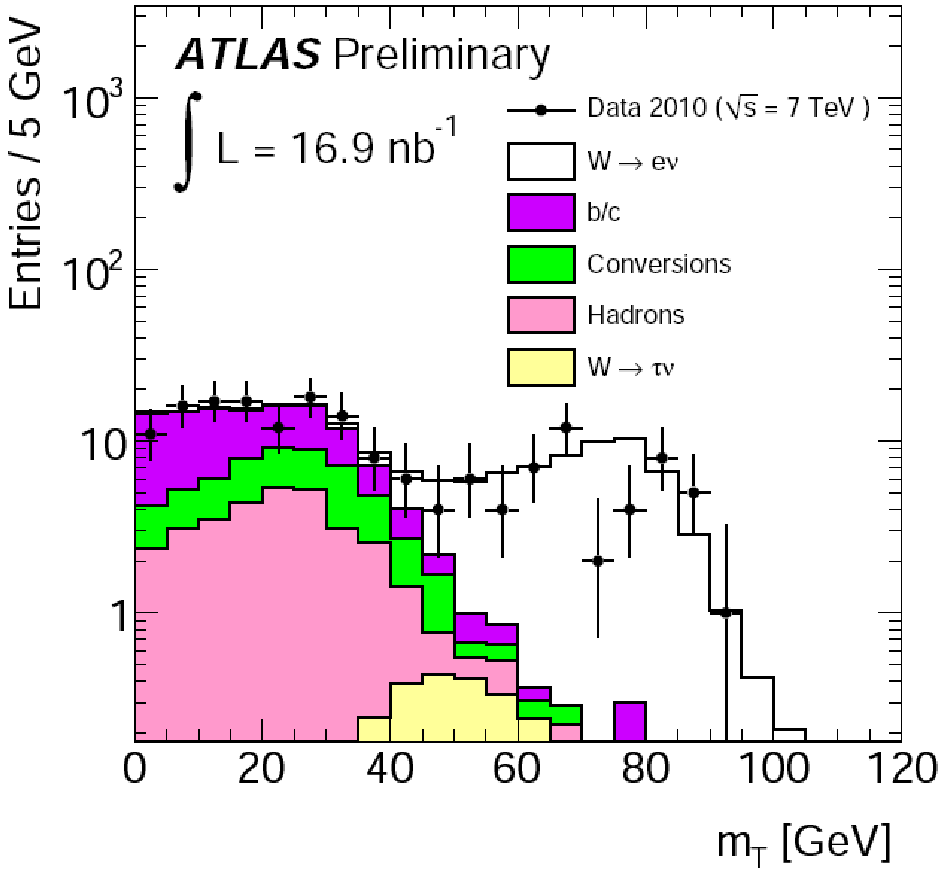
- Electron category 'tight' (ε~70%):
- No further isolation requirement (as used for BG estimate).
- MET>25 GeV & M_T>40 GeV



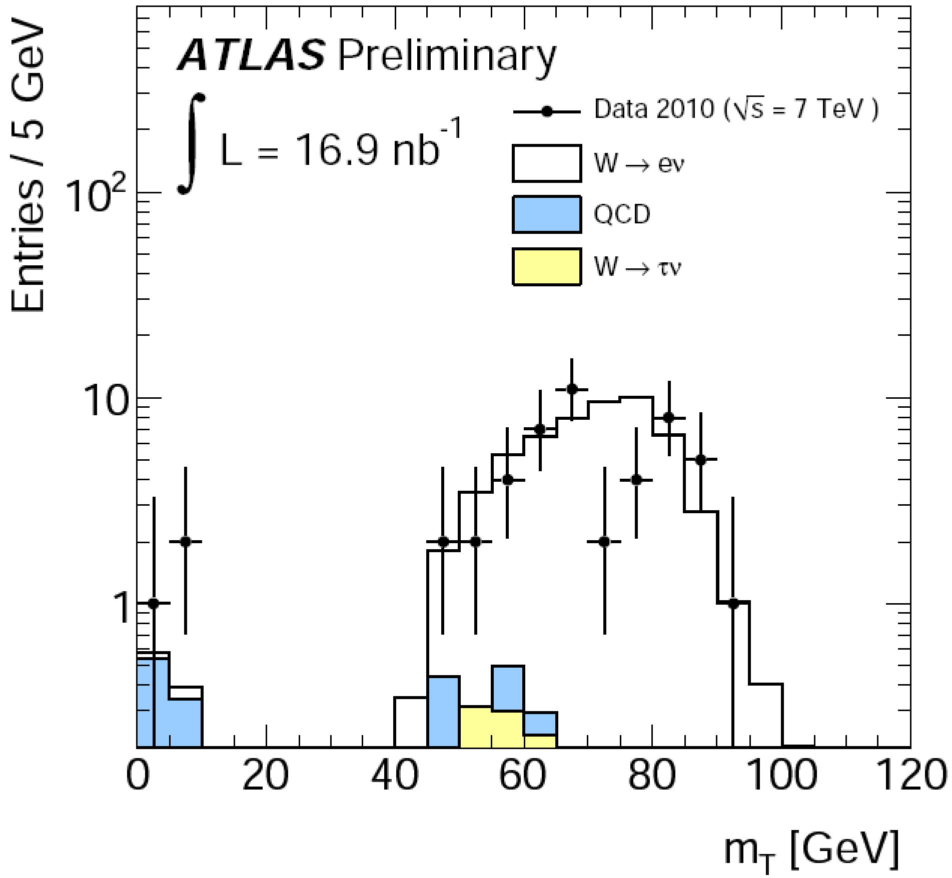


Signal Extraction (W→eν)

M_T (before MET>25 GeV):



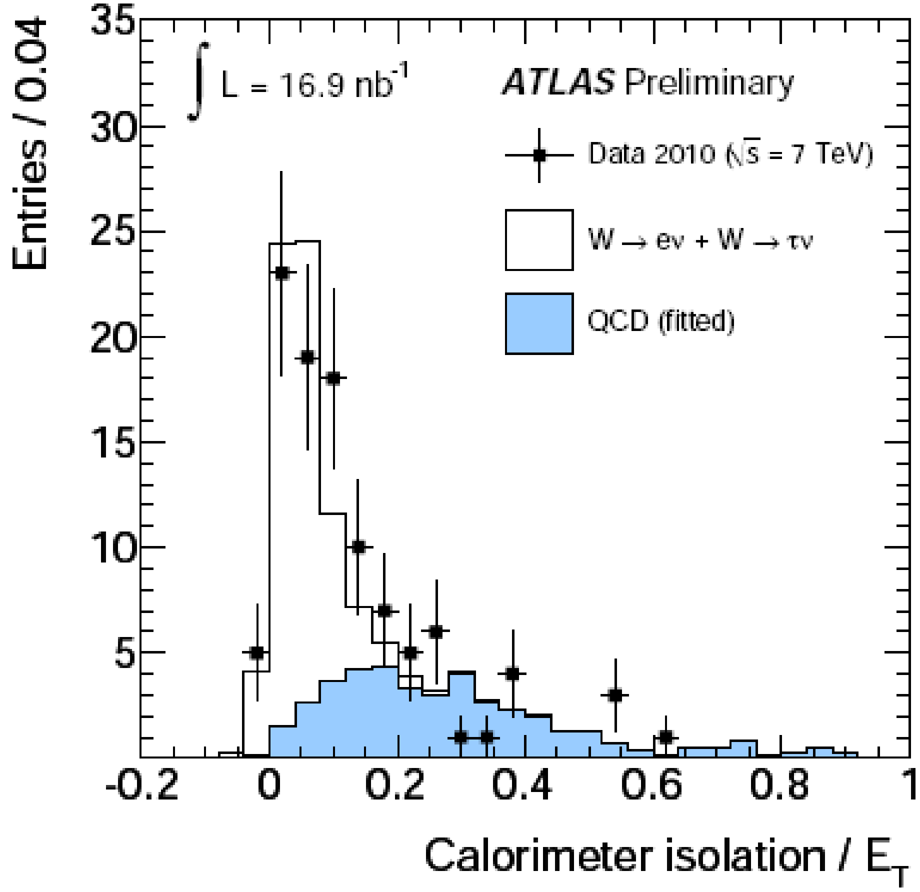
M_T (after MET>25 GeV):



Signal extraction as counting experiment after MT>40 GeV (N_W=46; ε_{MC}=0.78±5(sys.)%)

Semi-data driven QCD BG Estimate ($W \rightarrow e\nu$)

- Use calorimeter based isolation: $I_{rel} = \Sigma E_T(\Delta R < 0.3) / E_T(e)$
- Apply all requirements but electron category 'tight' (for statistics reasons).
- Binned LL fit (shapes taken from MC).
- Extrapolate to electron category 'tight'.
- N_{QCD}(est)=1, in the signal region.



Cross Section Determination

Number of background events

Number of signal events

$$\sigma_{tot} = \frac{N_{sig} - N_{BG}}{A_{Geo}\ \varepsilon_{rec}\ L_{int}}$$

Integrated Luminosity

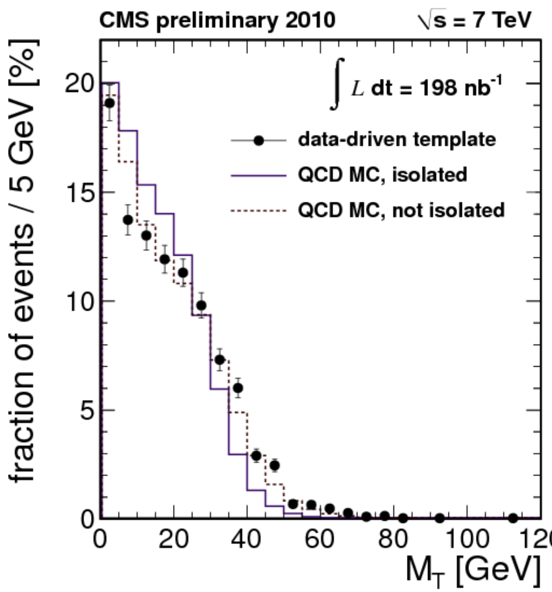
Geometrical acceptance
taken from simulation

Reconstruction efficiency
taken from MC, checked &
corrected from data.

Systematic Uncertainties

Are taken from:

- Known limitations (e.g. luminosity, BR's).
- Comparisons of data with the simulation.
- Limited knowledge/modeling (hadronization).

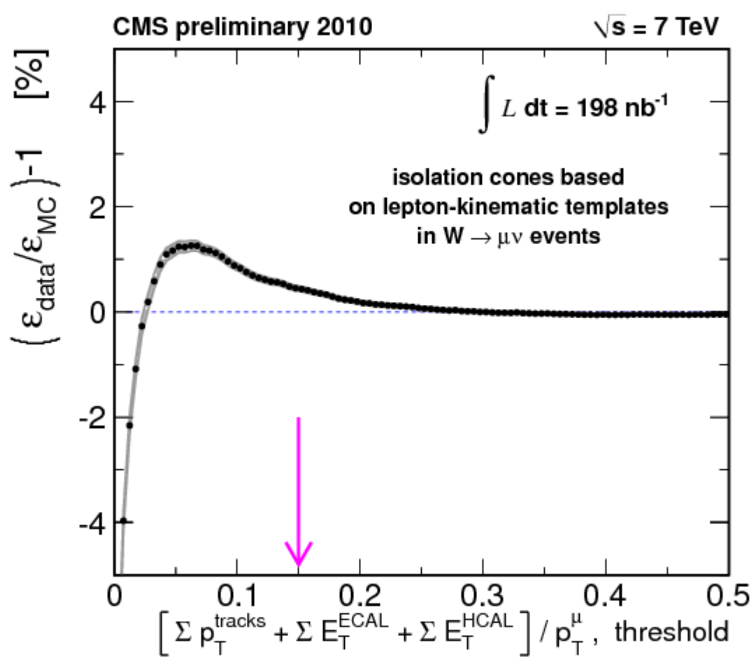


Art of measurement:

Define measurements, which are not sensitive to the most prominent systematics (e.g. ratios, clever phasespace definition, new methods!)

Implementation:

- Apply as numbers, propagate uncertainty.
- Vary of shift (shapes or parameters) & redo the analysis to check sensitivity.
- Change model and check sensitivity.



Example:

Top mass from lifetime meas.

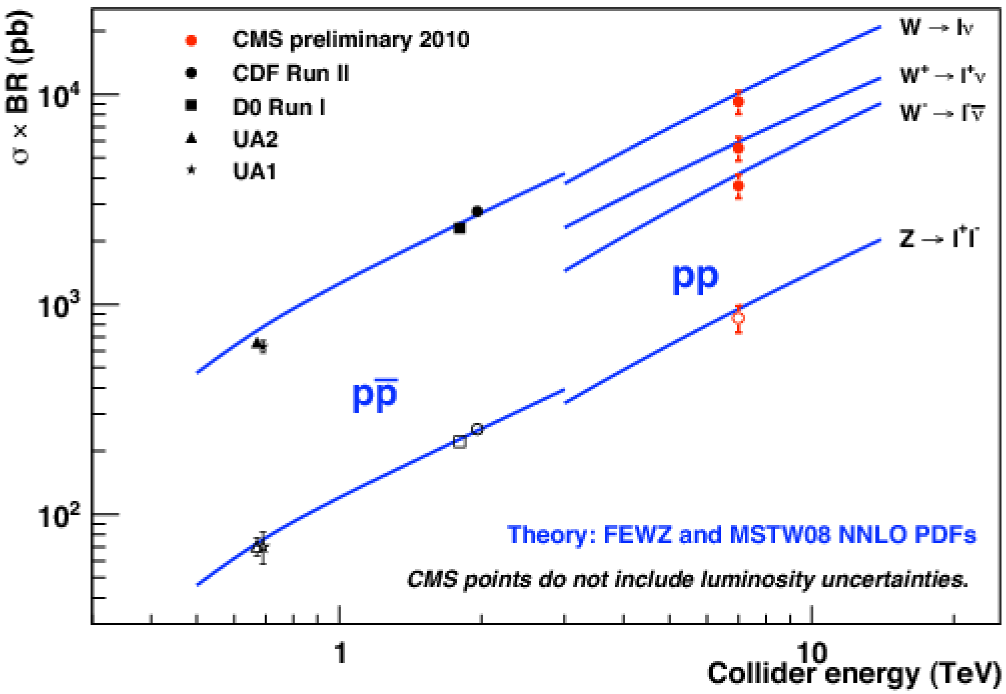
Systematic Uncertainties

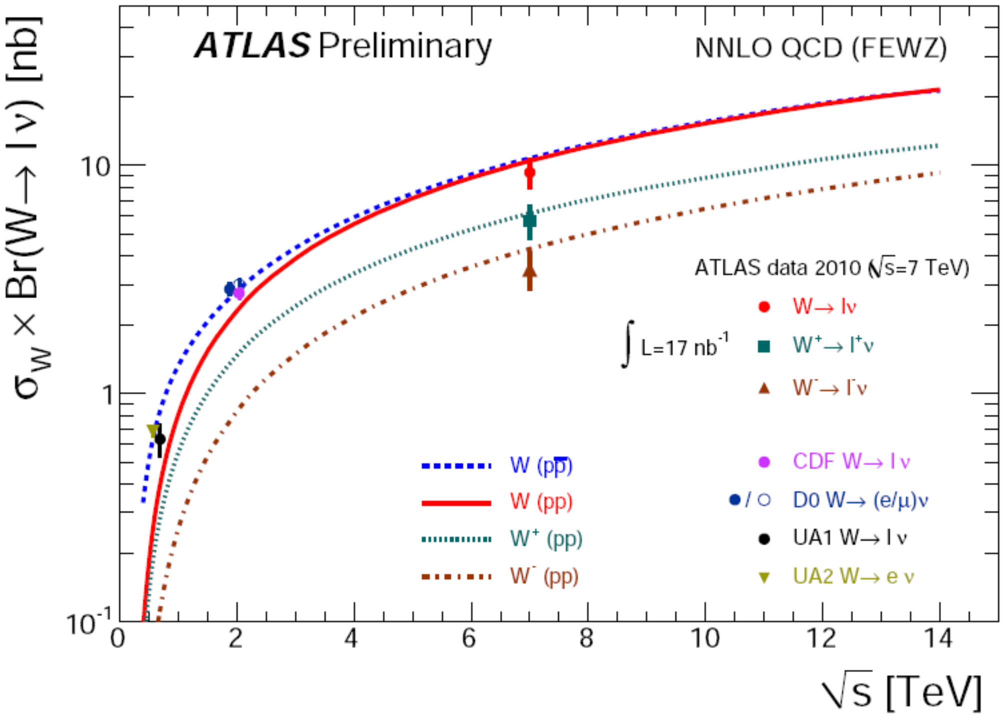
For the muon example:

Source	W channel (%)	Z channel (%)
Muon reconstruction/identification	3.0	2.5
Trigger efficiency	3.2	0.7
Isolation efficiency	0.5	1.0
Muon momentum scale/resolution	1.0	0.5
$\not{E}_T$ scale/resolution	1.0	-
Background subtraction	3.5	-
PDF uncertainty in acceptance	2.0	2.0
Other theoretical uncertainties	1.4	1.6
TOTAL (without luminosity uncertainty)	6.3	3.8
Luminosity	11.0	11.0

Statistical uncertainty: ~4% ($W \rightarrow \mu\nu$) ; ~12% ($Z \rightarrow \mu\mu$)

Inclusive Cross Section



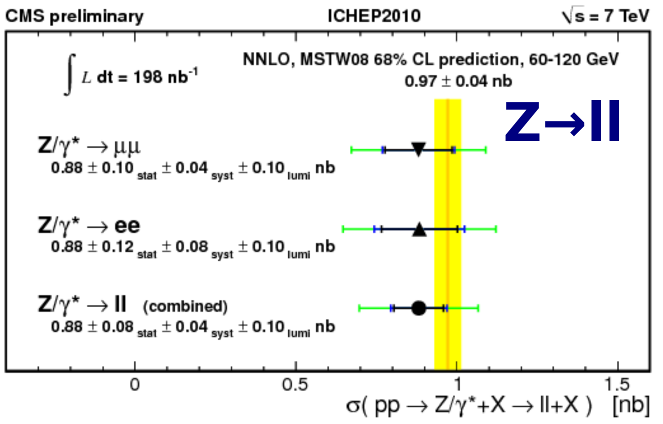


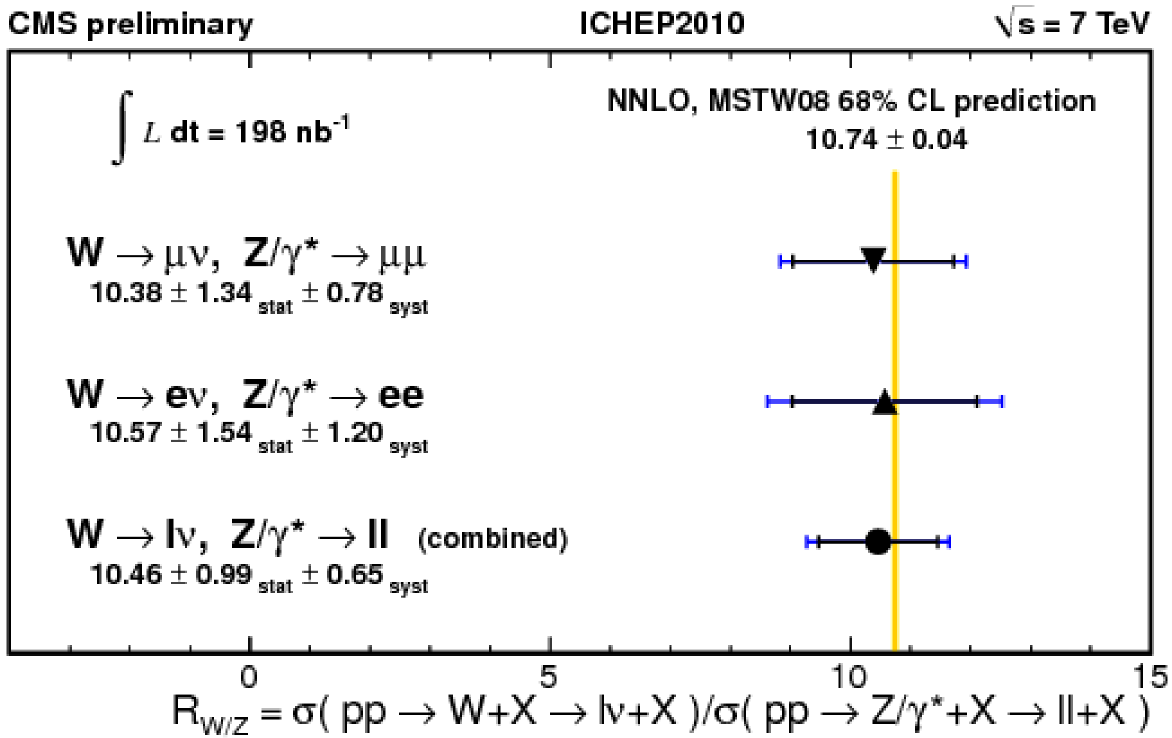
$\sigma_{tot}(Z\to\mu\mu) = 0.9 \pm 0.1(stat) \pm 0.04(syst) \pm 0.1(lumi)$ nb

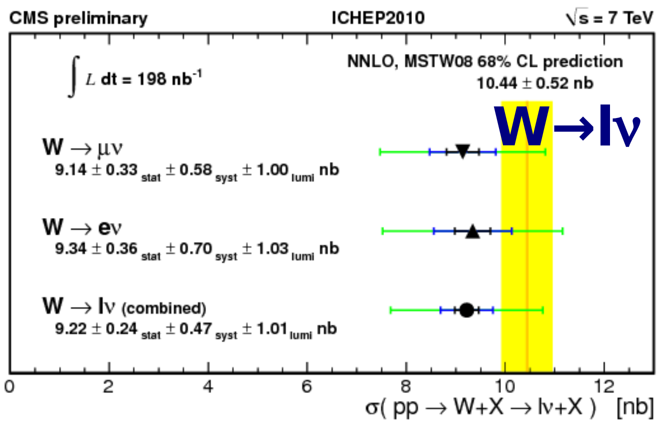
$\sigma_{tot}(W\to\mu\nu) = 9.14 \pm 0.33(stat) \pm 0.58(syst) \pm 1.00(lumi)$ nb

$\sigma_{tot}(W\to e\nu) = 8.5 \pm 1.3(stat) \pm 0.7(syst) \pm 0.9(lumi)$ nb

Cross Section Ratio

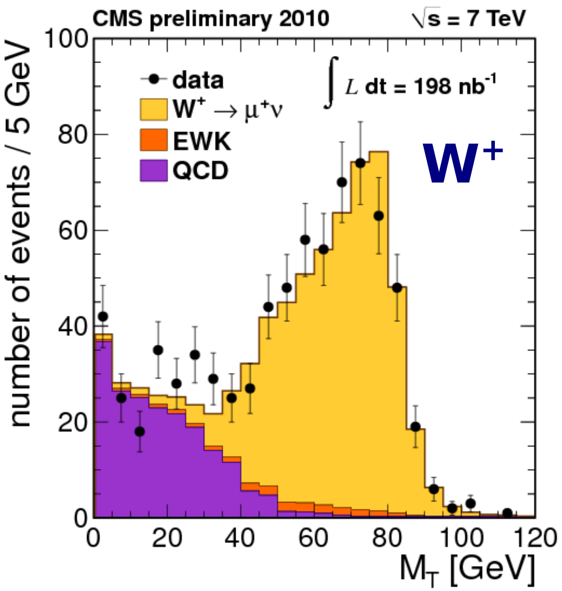


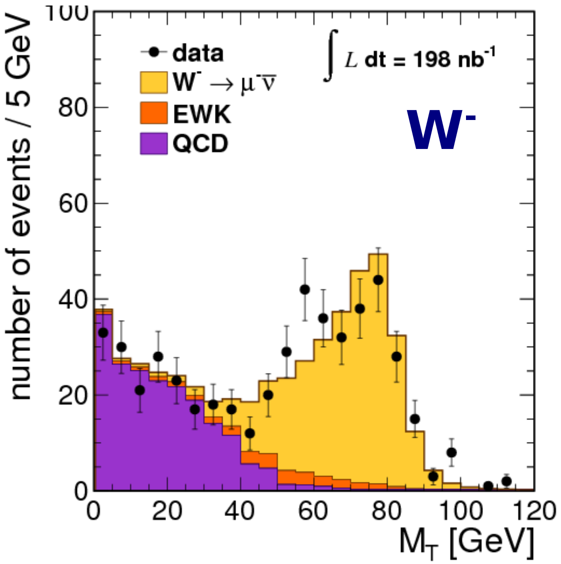


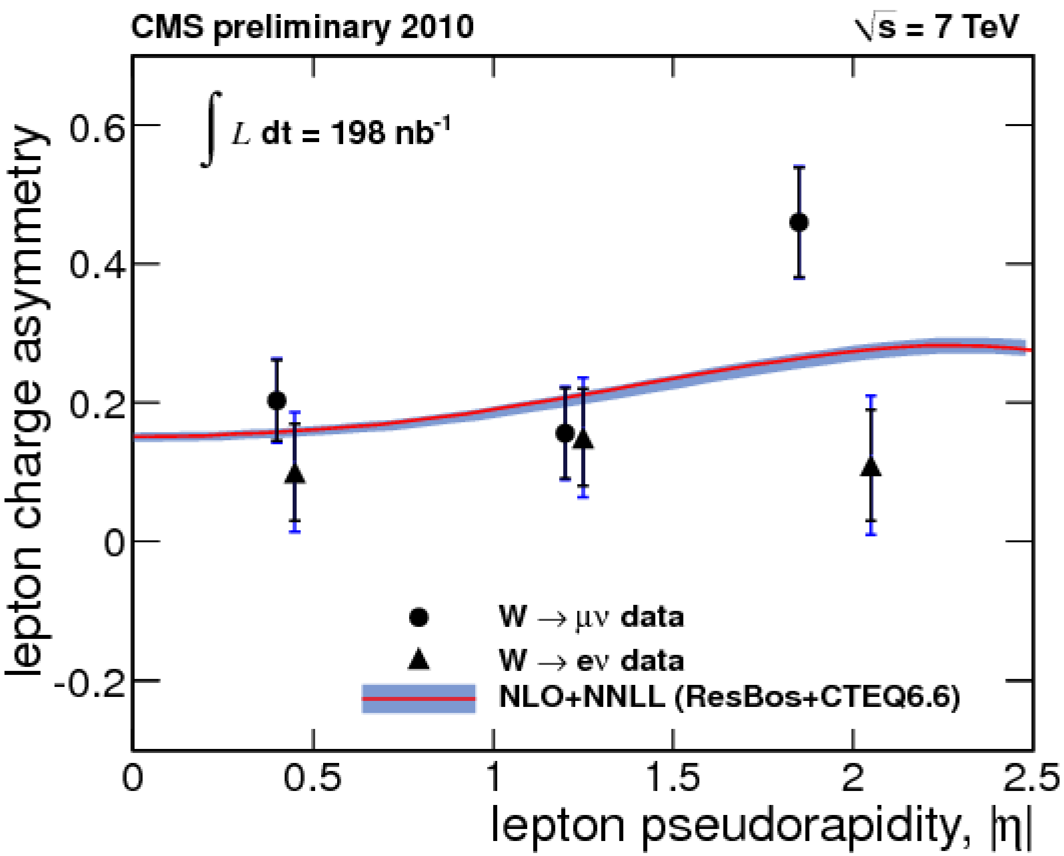


R(Z/W)= 10.4± 1.2(stat)±0.7(syst)

Charge Asymmetry

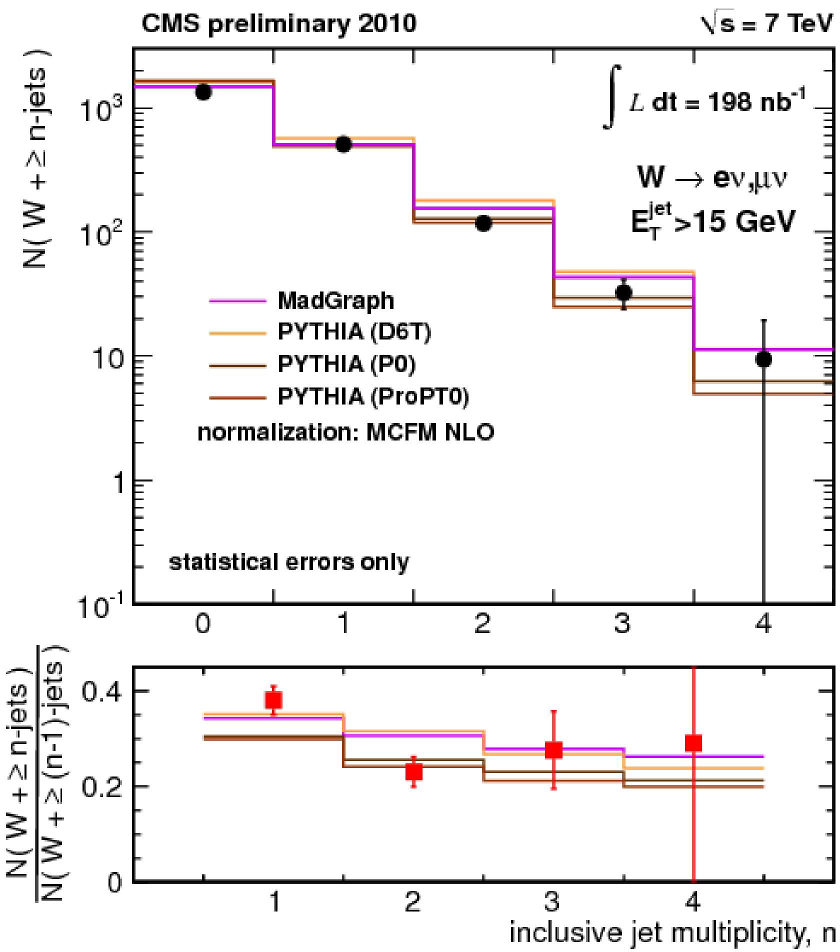




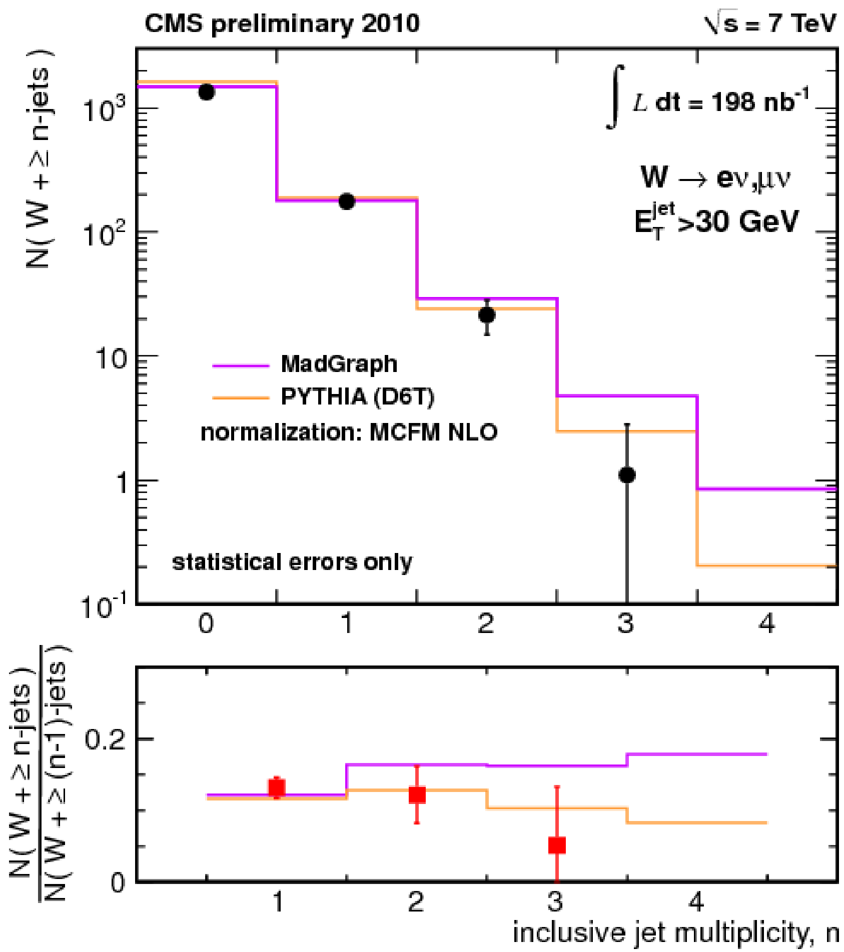


W+Jets

AK5(Pflow)>15GeV



AK5(Pflow)>30GeV



Conclusions and Outlook

- First nice Z/W measurements already with $O(100nb^{-1})$ → typical runwise lumi now!
- We can watch W bosons being reconstructed in our online DQM GUIs
- W(Z) can be used to constrain LHC PDFs
- Z is a phantastic tool for detector understanding (only touched slightly)
- W/Z give very good real life(!) examples how to make measurements at the LHC.

Many thanx for your attention. After some discussion enjoy

your lunch break...