Study of W and Z Production in the LHC

María Cepeda (CIEMAT)

On behalf of the

CMS & ATLAS Collaborations

Outline

- Introduction
- Standard Model Physics @ LHC
  - Cross-Section Measurement for first data
  - W and Z Selection in ATLAS and CMS
- Weak Vector Bosons Production and PDFs
  - Expected uncertainties
  - Constraints: Rapidity Distribution (ATLAS) and W Asymmetry measurement (CMS)
- Conclusions

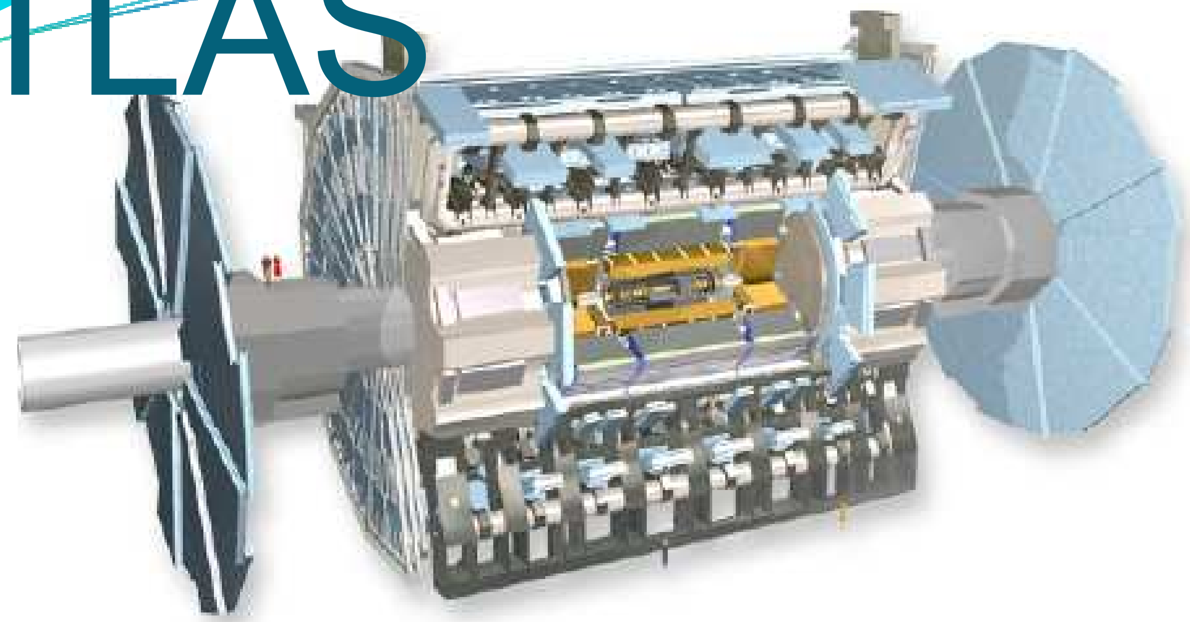
See talks by E. Klinkby on "Prospects for Precise ElectroWeak Physics" and by J. Nielsen on "W/Z+jets crossection measurements" for more on W and Z physics at the LHC

Introduction: LHC Start-Up

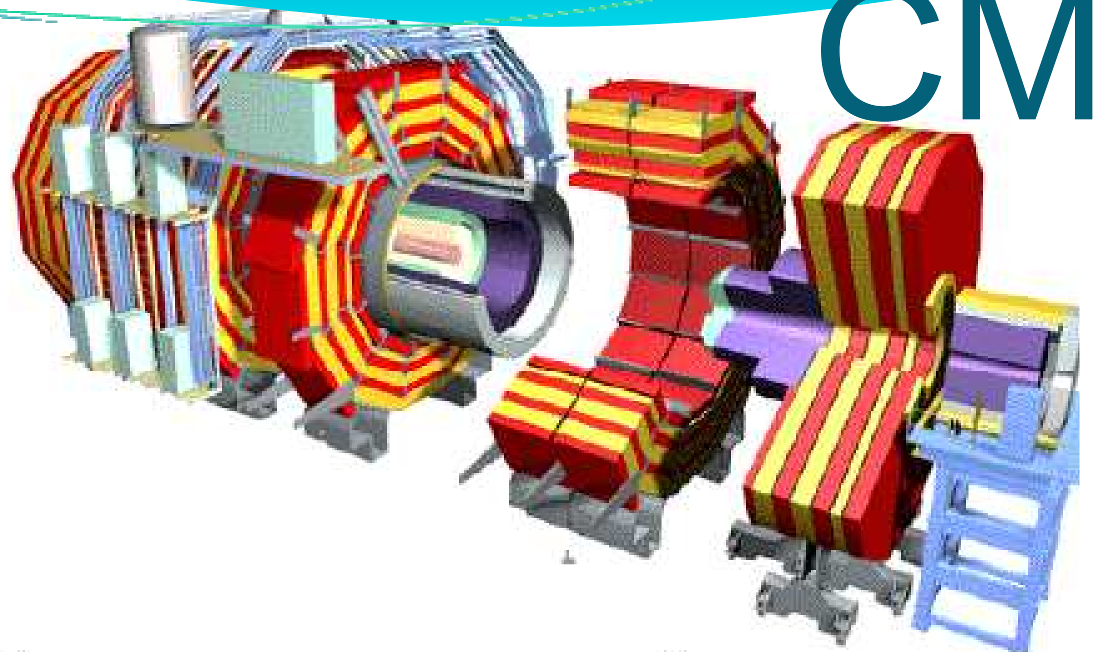
- Start-Up: E_{CM} =10 TeV
- First data from Run 2009-2010 → Expected **$\mathcal{L}$=200 pb^{-1}**

First collisions expected for late Autumn 2009

ATLAS



CMS



Magnetic Field		2.4 T Solenoid + 4T Toroid	4 T Solenoid
Inner Tracker	$\sigma(p_T)/p_T$ (100 GeV)	3.8%	1.5%
	$\lvert\eta\rvert$ coverage	2.5	2.5
EM Calorimeter	$\sigma(E)/E$	$10\%/\sqrt{E}+0.007$	$2\text{-}5\%/\sqrt{E}+0.005$
	$\lvert\eta\rvert$ coverage	3.2	3.0
HAD Calorimeter	$\sigma(E)/E$	$50\%/\sqrt{E}+0.03$	$100\%/\sqrt{E}+0.05$
	$\lvert\eta\rvert$ coverage	4.9	5.2
Muon Performance	$\sigma(p_T)/p_T$ (1 TeV)	7%	5%
	$\lvert\eta\rvert$ coverage	2.7	2.4

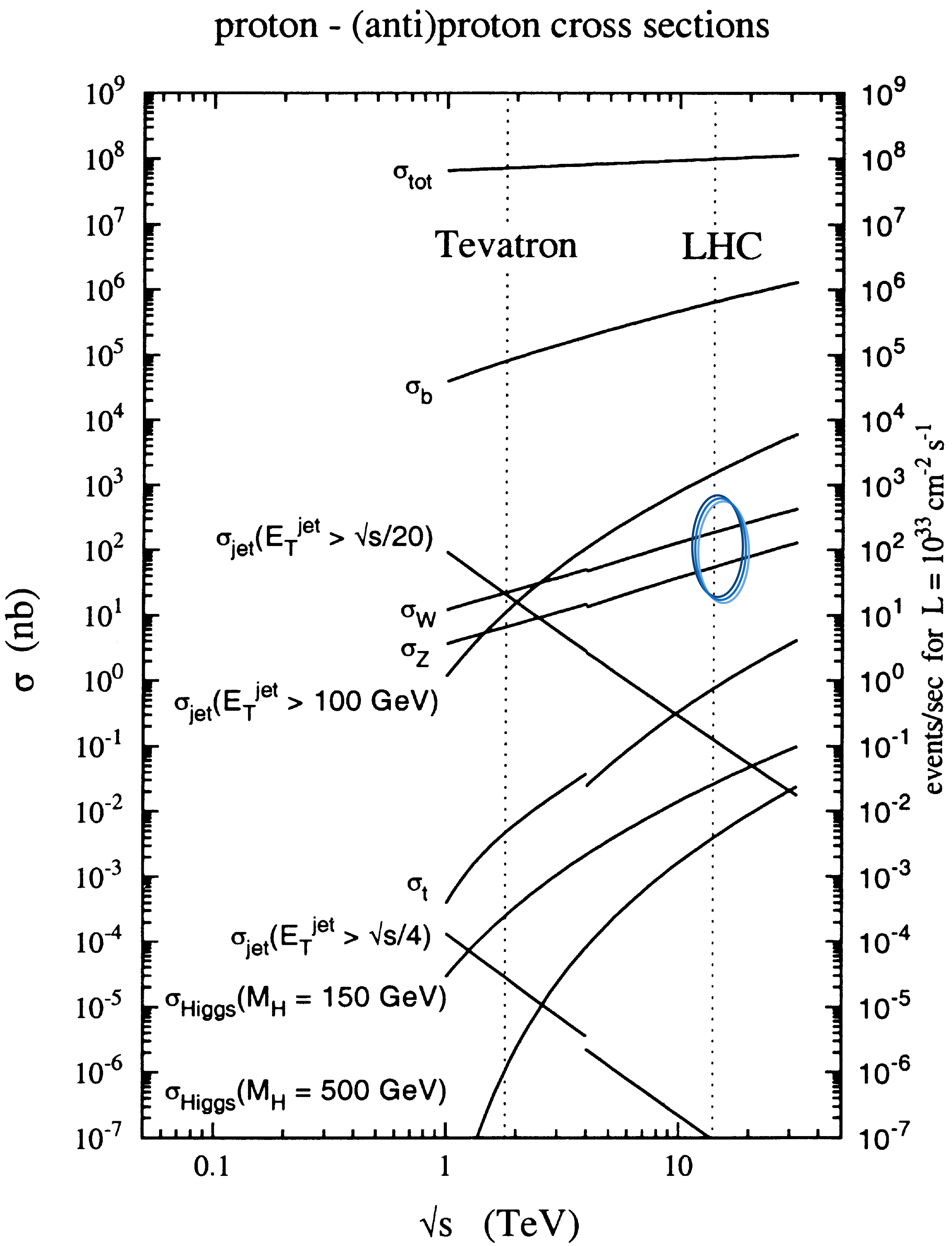
Standard Model Measurements

- The LHC is a discovery machine, but before any new physics is found the Standard Model has to be re-discovered.

Vector Boson production

→ benchmark process for the LHC

- **Large production cross-sections**
- **Well understood theoretically**
- **Clean and simple** experimental signatures
- **W, Z Standard Candles** for detector calibration
- **Background for many searches**



- W and Z measurements provide unique tools for testing the SM in a new energetic regime (10 TeV)

Standard Candles

- LHC is a W, Z factory!

  ~10^5 W, ~10^4 Z events for 10 pb^{-1}

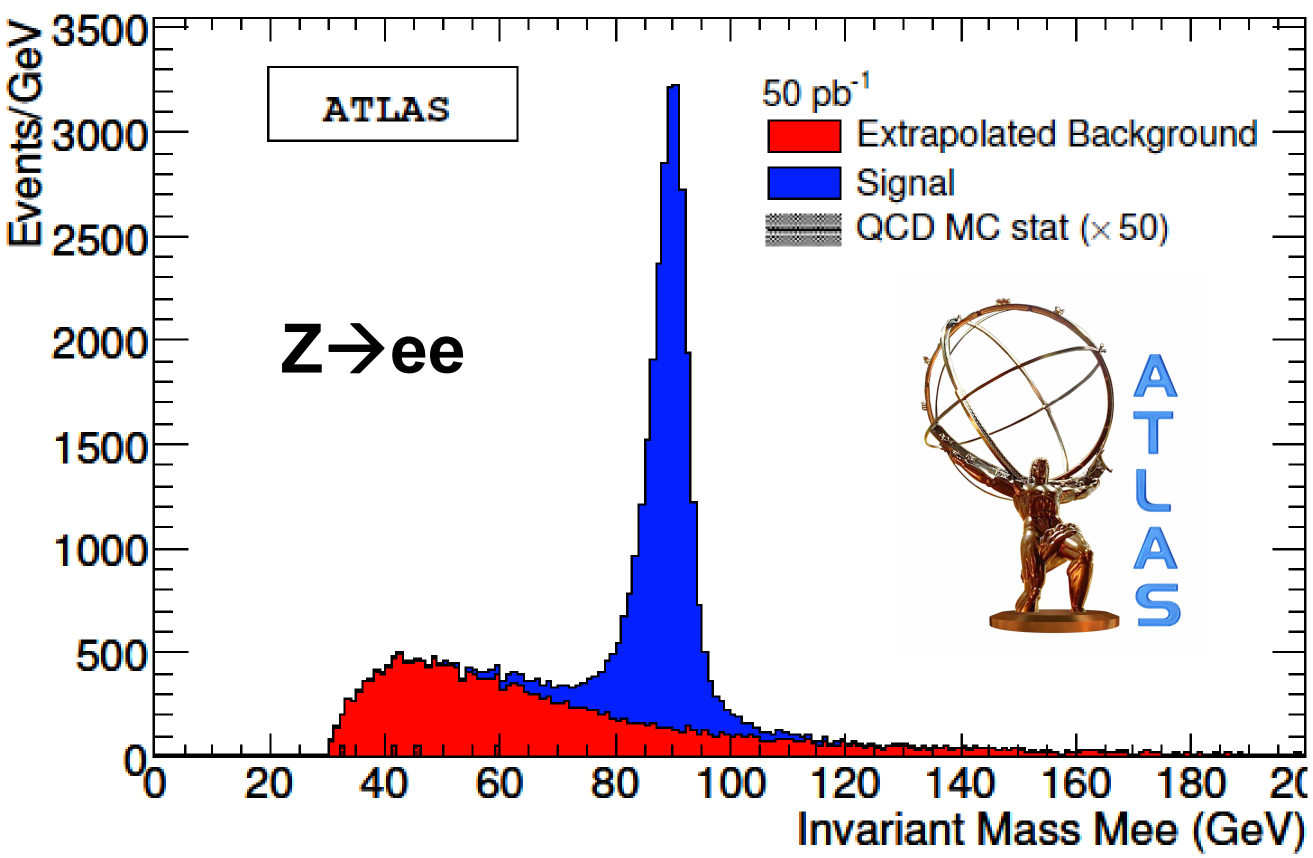
  (cross-sections 4, 6 times larger than Tevatron)
- Well known theoretically ($\Delta\sigma/\sigma<5\%$)
- Selection criteria keep robust for first data analysis
- Data Driven methods are essential!

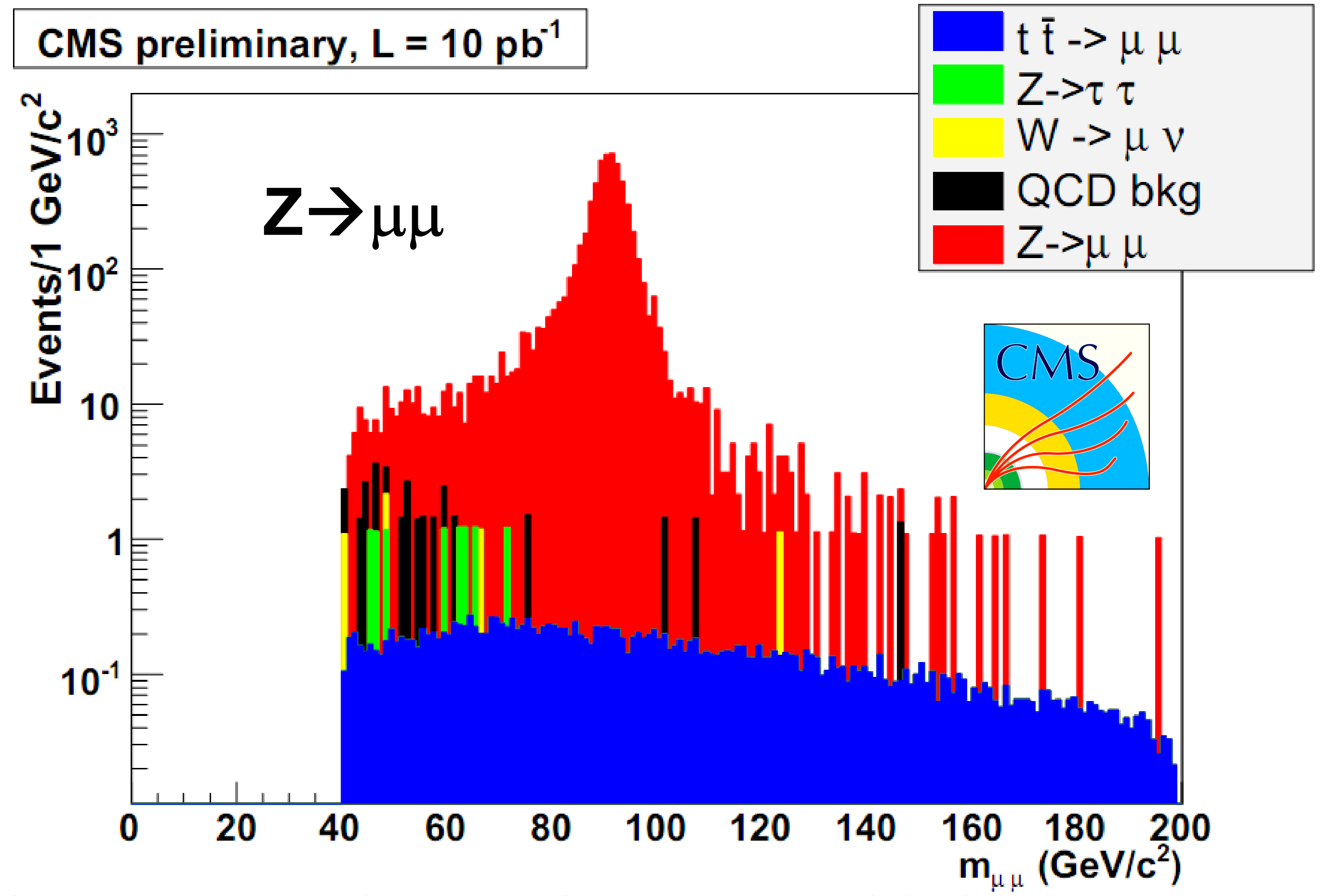
σ(pb) LO	$\sqrt{s}$ 10 TeV	$\sqrt{s}$ 14 TeV
$Z\rightarrow ll$	1200	1800
$W\rightarrow l\nu$	11800	17200

l=e,μ,τ

Detector Tuning	EWK&QCD Measurements
•Luminosity measurement •Momentum Scale and Resolution •Misalignment calibration •Lepton Efficiencies	•Inclusive and differential σ •W, Z + jets σ and ratios •M_W, Γ_W •Di-Boson production •Asymmetries •PDF constraints

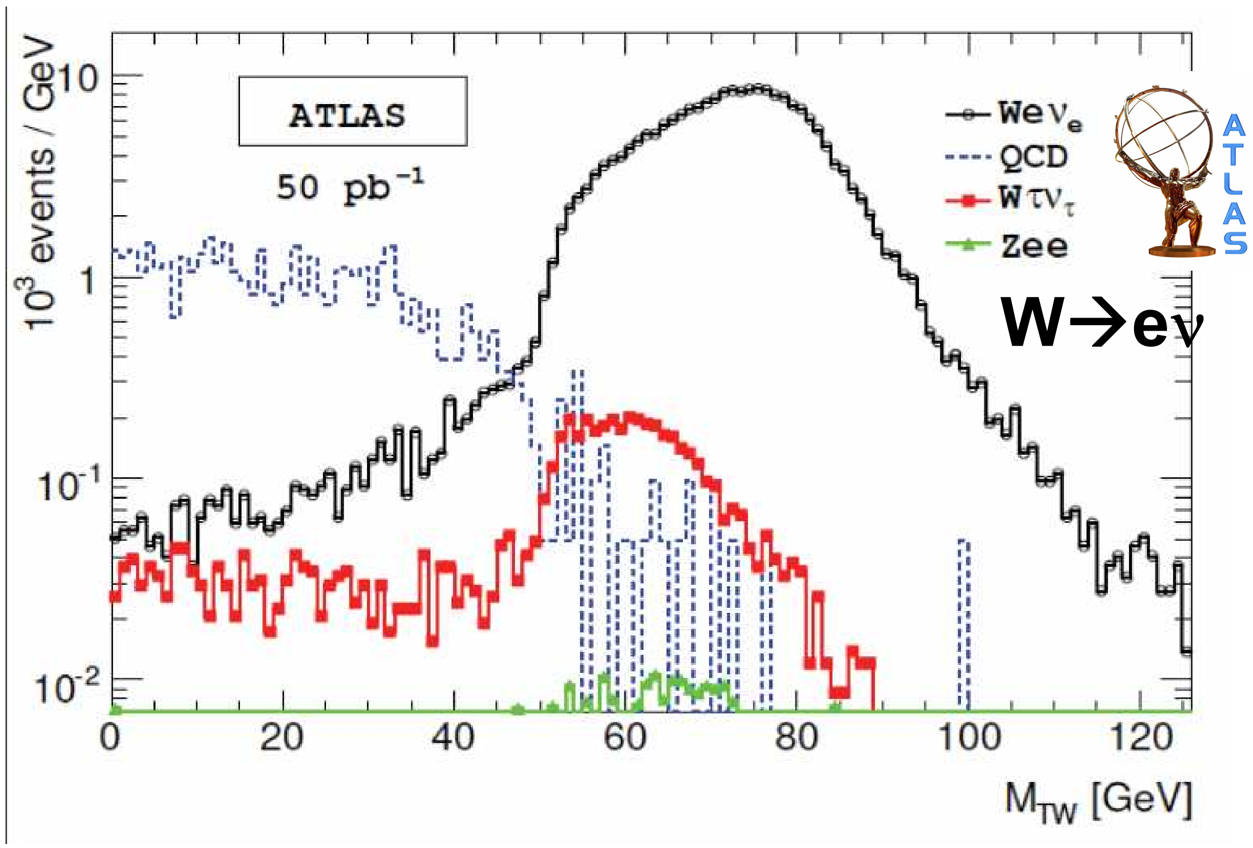
Z→l+l- Selection

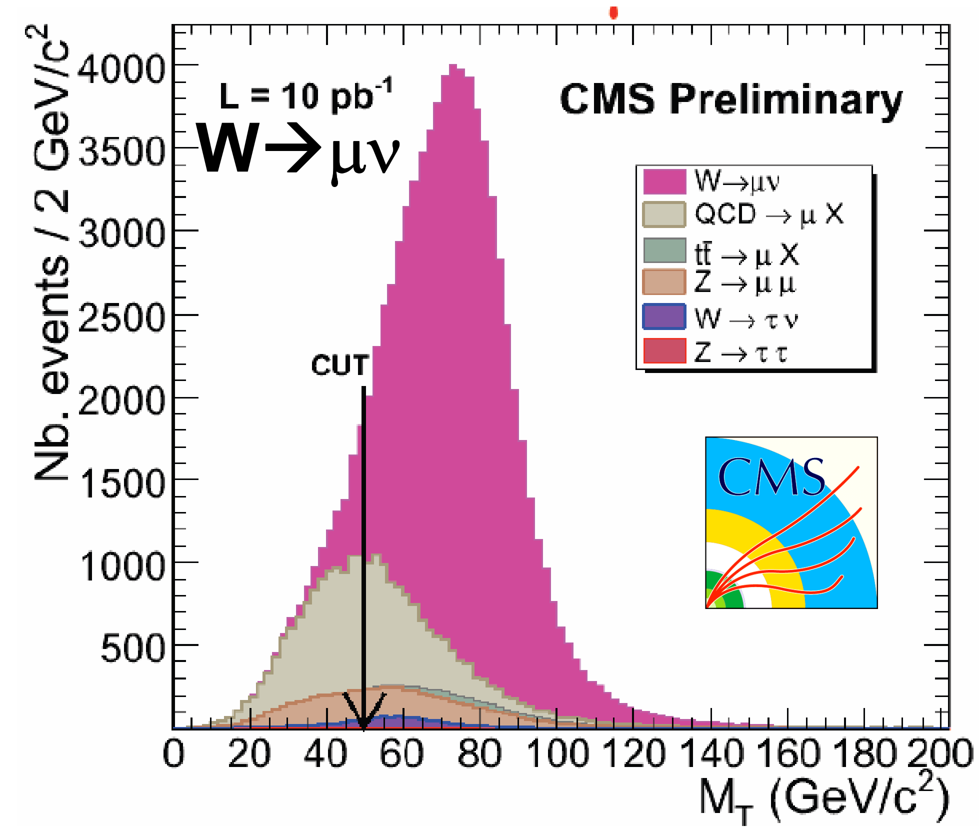




- **Experimental Signature**: Two isolated, opposite charge, leptons of high momentum; $M(\ell\ell) \sim M_Z$
- **Minimal background contamination (<1%):** Z→ττ, ttbar, QCD,W+jets
  - Estimated from sidebands, charge correlation and/or fits to the whole mass range
- **Calibration tool:** Momentum Scale and Resolution of leptons,
  Misalignement monitor
- **Efficiency Calculation:** estimated from Tag and Probe methods and/or simultaneous fits to signal and background

W→lν Selection





- **Experimental Signature**: Isolated high p_t lepton, high $\not{E}_T$, high M_T
- **Main Backgrounds:**
  - **ElectroWeak:** Z→ll, W→τν (estimated from Monte Carlo)
  - **QCD:** Estimated from data (Matrix and Template methods)

- Z→ll information used for modeling M_T(W) shape and for lepton efficiency calculations

Vector Boson Cross-sections

$$\sigma_{W(Z)} \times Br(W(Z) \to ll) = \frac{N_{W(Z)}^{obs} - N_{W(Z)}^{bckg}}{A_{W(Z)} \cdot \varepsilon_{W(Z)} \cdot \int L dt}$$

Uncertainty at Start-Up:

- Statistical: ~1% at $\mathcal{L}$=10 pb^{-1} → Measurement dominated by systematics!
- **A_W:** Detector Acceptance (QED and QCD corrections, PDF uncertainties) → ~2%
- **ε_W :** Selection efficiency (trigger,reconstruction, identification) evaluated from data → <3%
- **N^{obs}- N^{bckg}:** Background Estimation (from MC or from data) → <5%
- **Luminosity:** ~10% (later on expected to be ~ 3-7%)

e decays

$\Delta\sigma/\sigma(Z \to ee)$ = 0.8 (stat) ± 4.1 (syst) %

$\Delta\sigma/\sigma(W \to e\nu)$ = 0.2 (stat) ± 5.2 (syst) %

μ decays

$\Delta\sigma/\sigma(Z \to \mu\mu)$ = 0.8 (stat) ± 3.8 (syst) %

$\Delta\sigma/\sigma(W \to \mu\nu)$ = 0.2 (stat) ± 3.1 (syst) %

ATLAS

$\mathcal{L}$= 50 pb^{-1}

V Production & PDFs

$$\sigma_{pp\to VX} = \sum_{a,b=q,\bar{q},g} \int_0^1 dx_1 dx_2 f_a\left(x_1,Q^2\right) f_b\left(x_2,Q^2\right) \sigma_{ab\to VX}\left(x_a,x_b,Q^2\right)$$

- **PDFs $f_a(x, Q^2)$: parametrization of the partonic content of the proton**
  - → **obtained from global fits to the existing data (HERA, ZEUS, CDF, DO, fixed target DIS)**

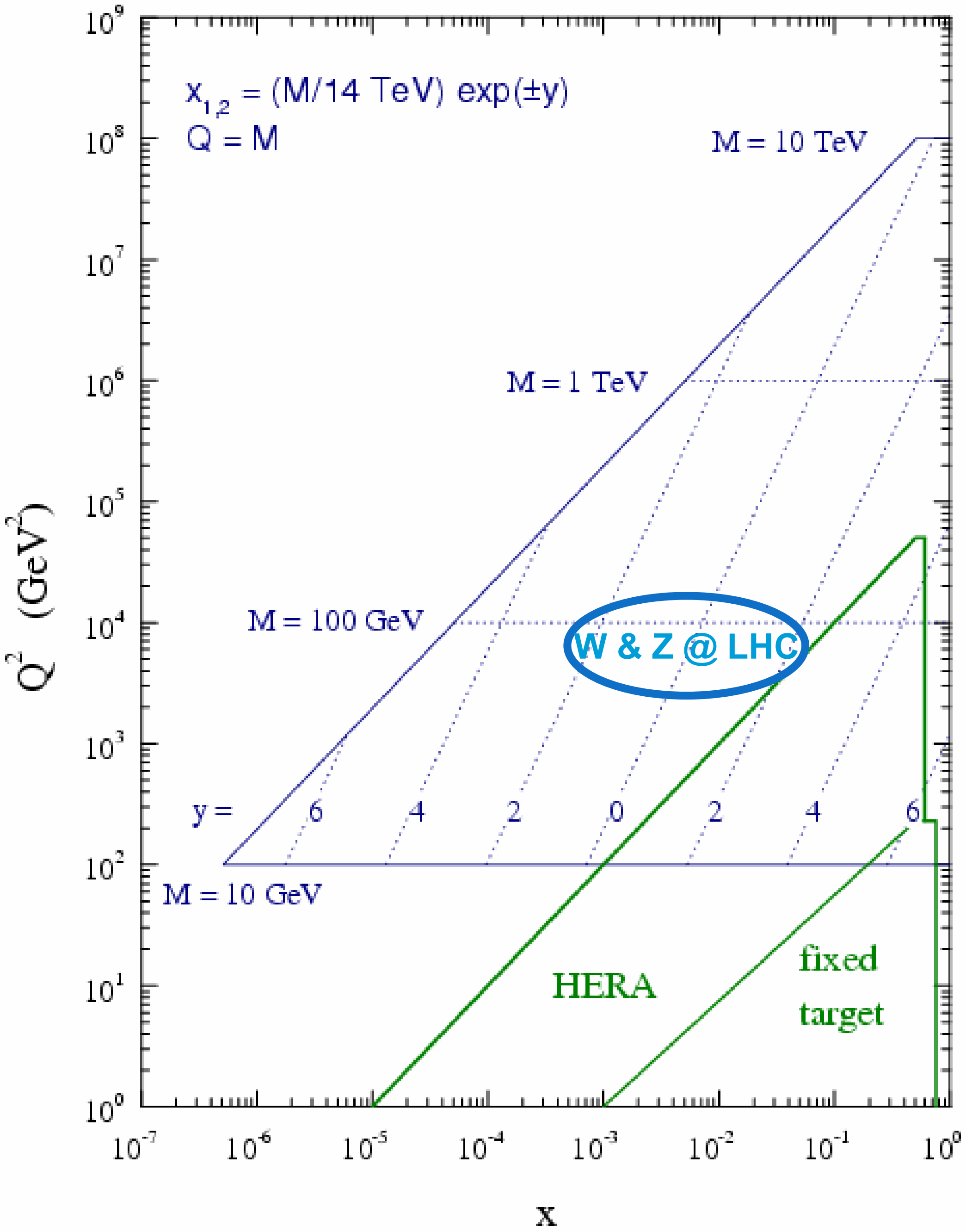
→ **In pp collisions W and Z are produced by Valence-Sea and Sea-Sea interactions**

→ **At LHC W and Z will be produced at low x for central rapidities (not in the valence region)**

14 TeV: $6\cdot10^{-4}<x<6\cdot10^{-2}$

10 TeV: $8.5\cdot10^{-4}<x<8.5\cdot10^{-2}$

LHC parton kinematics



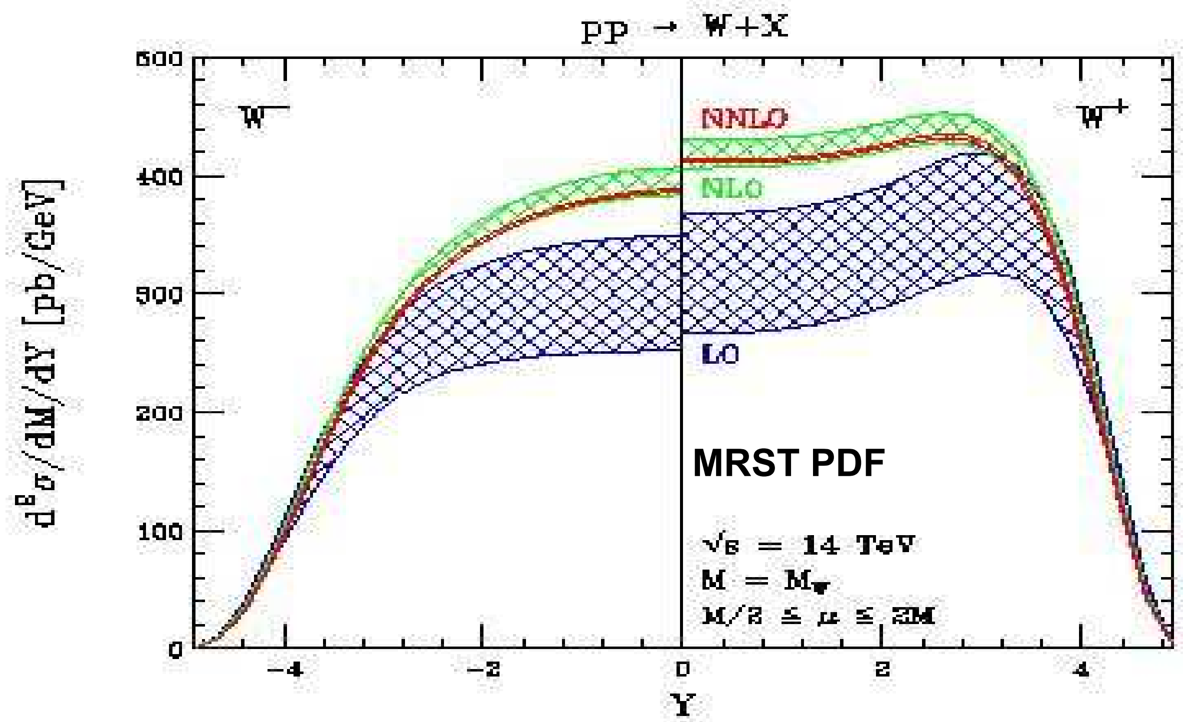
V Production & PDFs

Different sets of PDFs

→ Uncertainties < 4 %

- **Theoretical**: perturbative calculations, non-perturbative parametrizations
- **Experimental:** statistical and systematic

→Differences between central values from different PDF sets can differ more than the uncertainty estimates



Predictions for the total cross-sections for 10 TeV

PDF set (10 TeV)	$\sigma_{W+} B_{W\to l\nu}$ (nb)	$\sigma_{W-} B_{W\to l\nu}$ (nb)	$\sigma_{Z} B_{Z\to ll}$ (nb)
MSTW08	8.62 ± 0.16	6.30 ± 0.12	1.39 ± 0.025
CTEQ66	8.77 ± 0.18	6.22 ± 0.14	1.40 ± 0.027
HERAPDF	8.64 ± 0.10	6.27 ± 0.11	1.38 ± 0.02
CTEQ61	8.29 ± 0.22	5.90 ± 0.17	1.32 ± 0.030
ZEUS-2005	8.51 ± 0.30	6.08 ± 0.20	1.36 ± 0.04

A. Cooper-Sarkar, March 2009

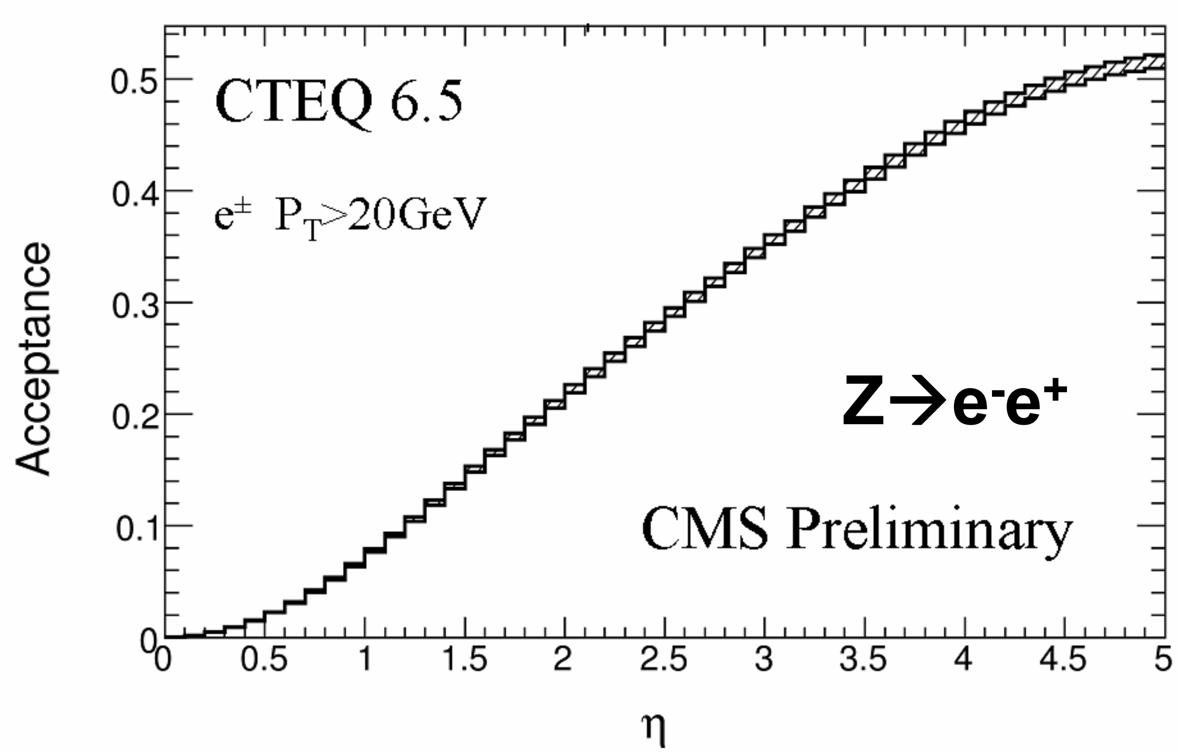
PDF uncertainties @ LHC

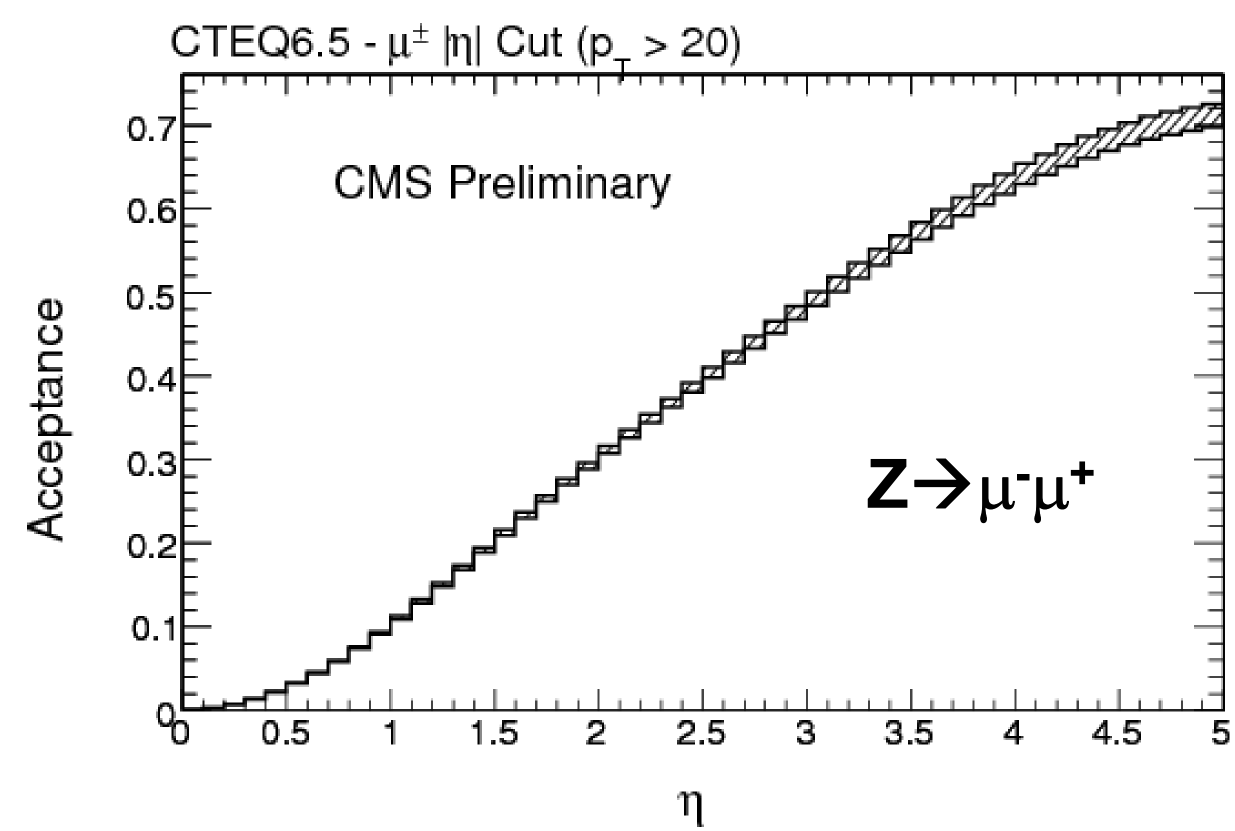
- **Rate uncertainty (CTEQ6.5) → ~4%**
  → Related to a global normalization factor
  → Reduced in relative measurements (ratios, distribution shapes)
  → If PDF uncertainties <5% → luminosity measurement at LHC better than 5% using W, Z cross-sections

14 TeV

CTEQ 6.5	ΔRate	ΔAcceptance
$Z \to ll$ $M_{ll}>40$, $p_t>20$, $\lvert\eta\rvert<2$	3.79%	1.32%
$W^+ \to l^+\nu$ $\not{E}_T>20$, $p_t>25$, $\lvert\eta\rvert<1$	4.01%	2.28%
$W^- \to l^-\nu$ $\not{E}_T>20$, $p_t>25$, $\lvert\eta\rvert<1$	3.31%	2.22%

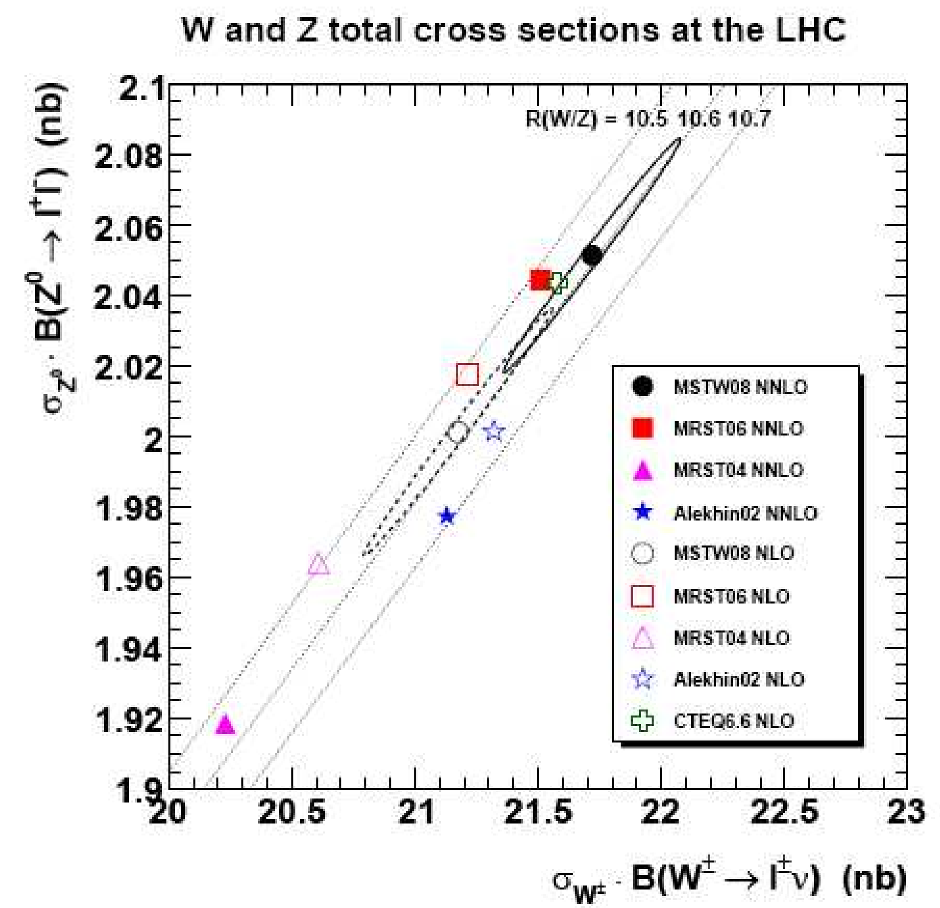
- **Acceptance uncertainty → ~2%** (affects experimental σ uncertainty)





PDF Constraints

hep-ph/0901.0002v2



W and Z measurements will improve our knowledge of PDFs

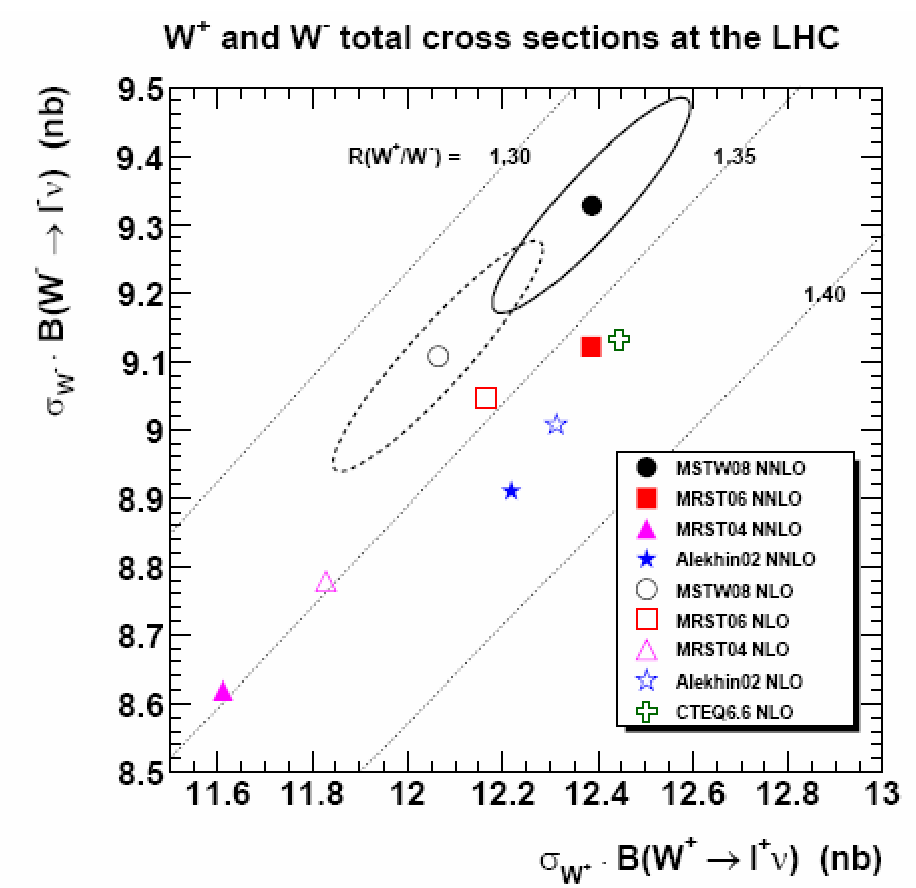
→ Looking at **lepton decay spectra (ATLAS)**

W^+: $u\bar{d}$	W^-: $\bar{u}d$

→ Looking at observables less sensitive to systematics→ **Ratios (CMS)**

$$A_{ZW} = \frac{Z}{W^+ + W^-}$$

$$A_W = \frac{W^+ - W^-}{W^+ + W^-} \qquad A_l = \frac{l^+ - l^-}{l^+ + l^-}$$



Rapidity distribution

→ If **systematics at ~5% order**, improvement of pdfs expected, especially in the description of the **gluon PDF at low X**

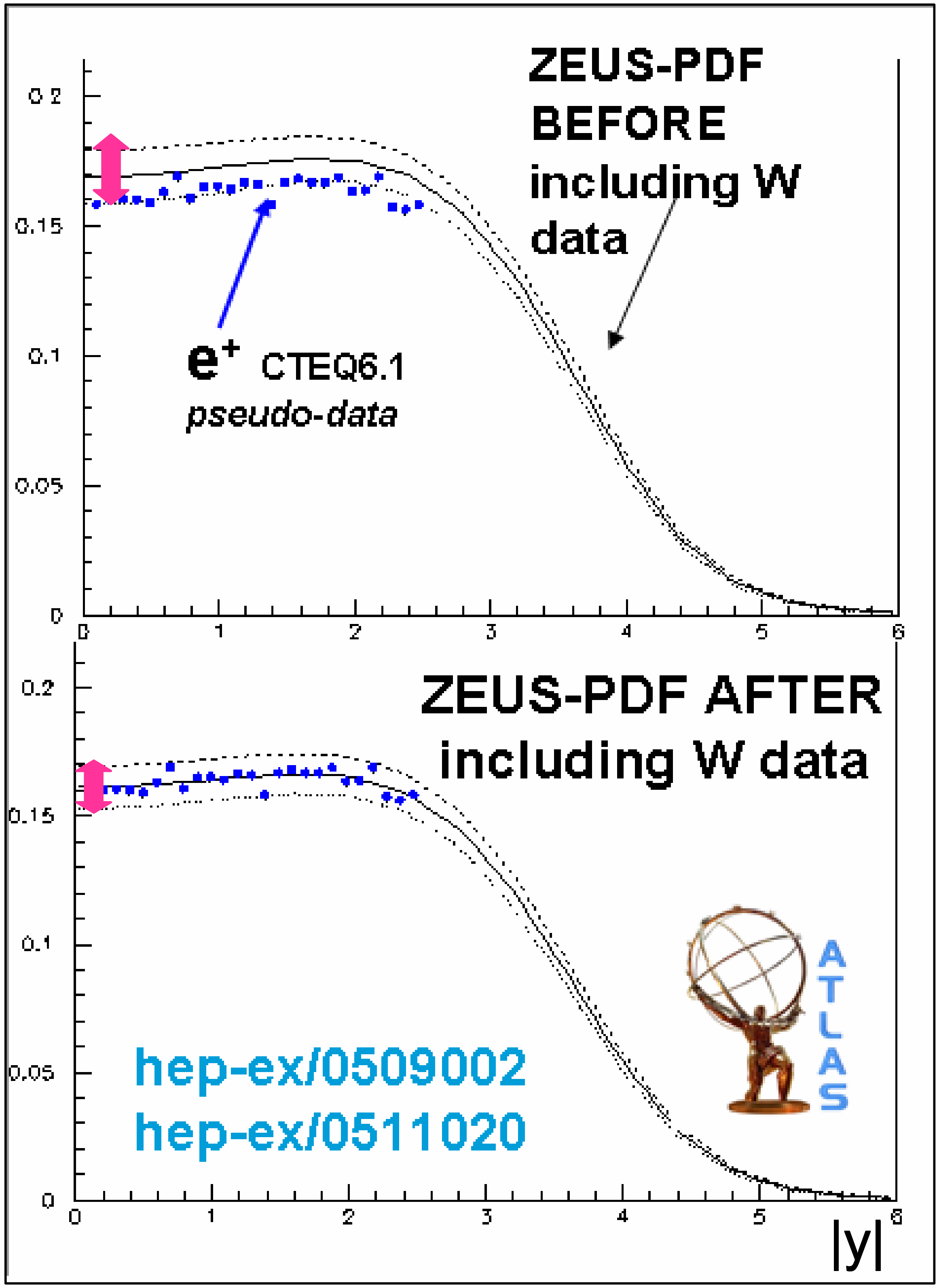
- **ATLFAST approach**
  - 150 pb^{-1} of W→eNu at 14 TeV
  - Generated with CTEQ6.1M
  - 4% of systematic error from detector simulation introduced (statistical error negligible)
  - Introduce data in the global ZEUS PDF fits →Re-Do fit

Reduction of the error band (6%→4.5%)

$$xg(x) \sim x^{-\lambda}$$

λ = -0.199 ± 0.046 ➡ λ = -0.186 ± 0.027

→ **Improvement of 41% in Δλ**



W Asymmetry

- More $u\bar{d}$ than $d\bar{u}$ in pp collisions → Charge Asymmetry in W production

$$A(\eta) = \frac{\frac{d\sigma}{d\eta}(W^+ \to \mu^+\bar{\nu}_\mu) - \frac{d\sigma}{d\eta}(W^- \to \mu^-\nu_\mu)}{\frac{d\sigma}{d\eta}(W^+ \to \mu^+\bar{\nu}_\mu) + \frac{d\sigma}{d\eta}(W^- \to \mu^-\nu_\mu)}$$

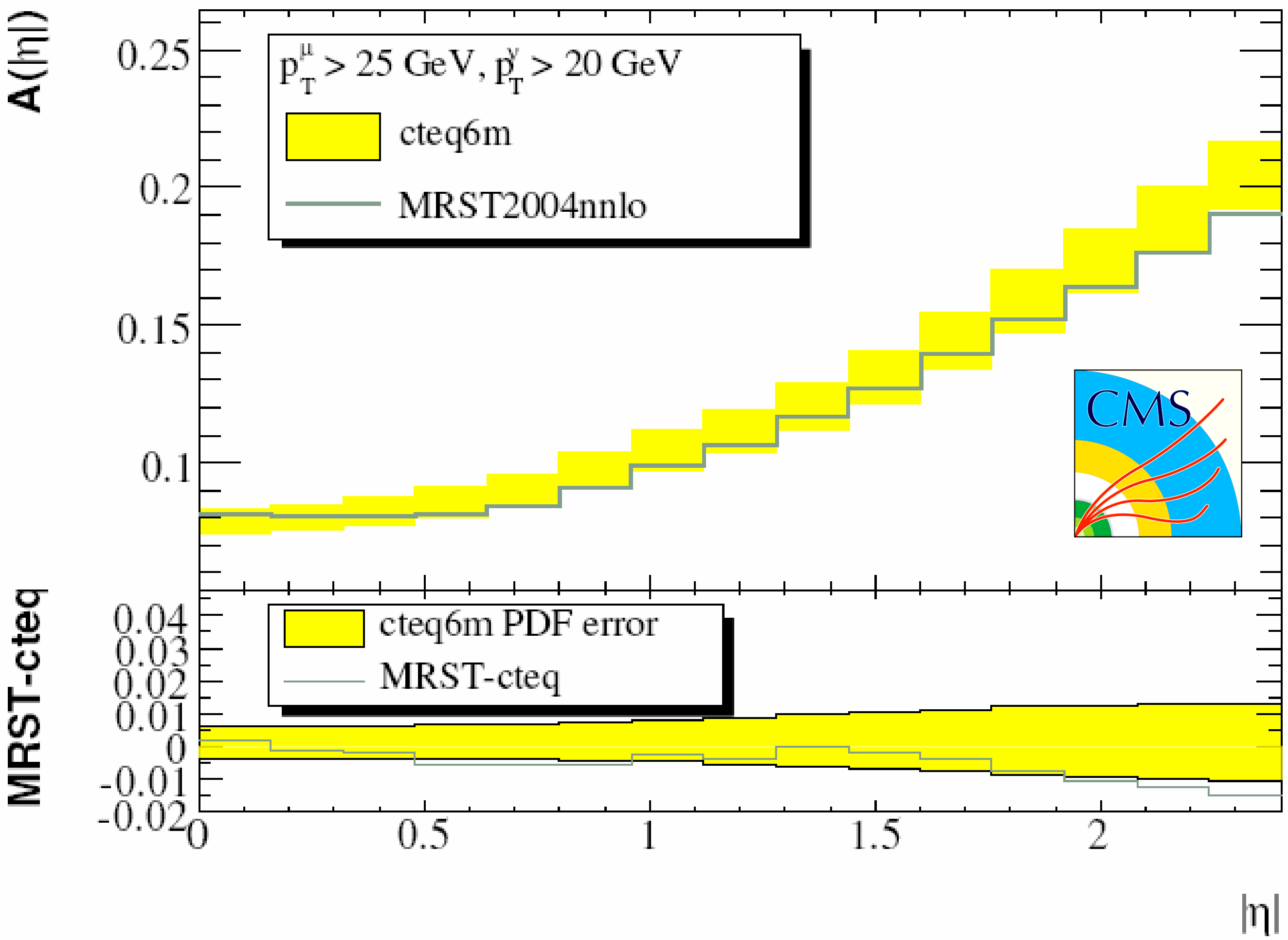
$$A_W \approx \frac{u\bar{d} - \bar{u}d}{u\bar{d} + \bar{u}d} \approx \frac{u_{val} - d_{val}}{u_{val} + d_{val} + 2\bar{q}}$$

Variation with η
→ d/u asymmetry
& V-A asymmetric decay of W

- Different predictions from PDF sets→ predictions for **valence** distributions at small-x are different

- A_W varies from +10% to +20% (predicted with 1-2% error)

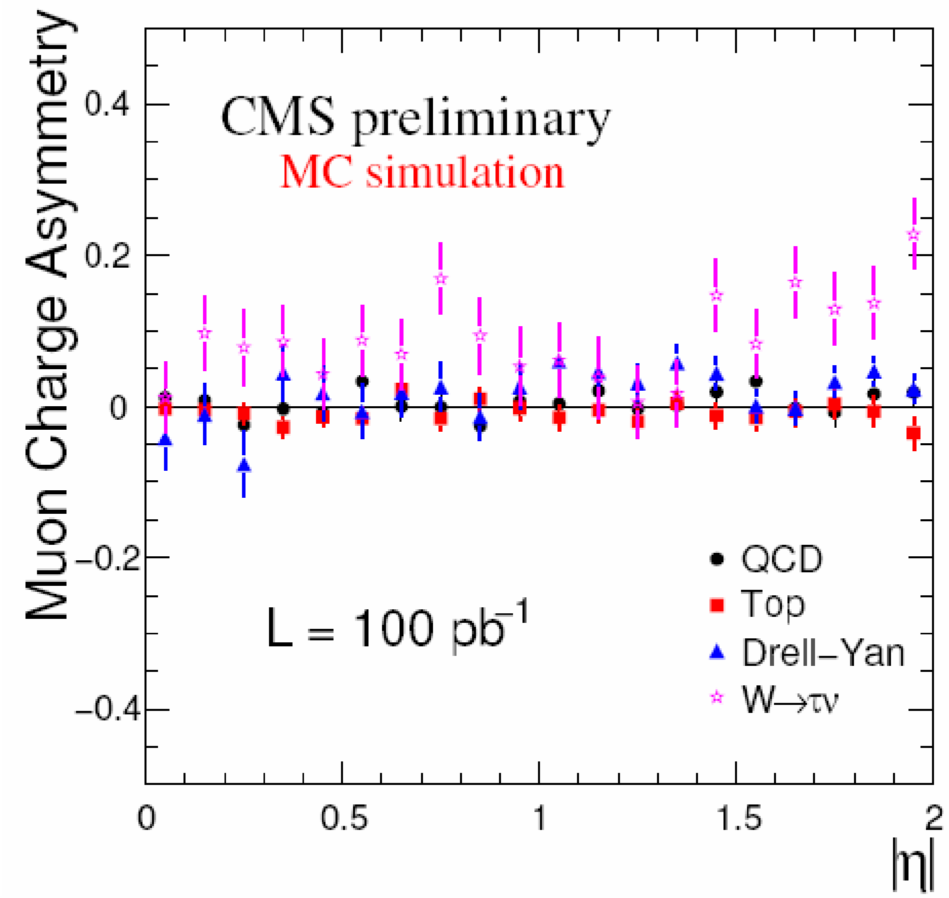
- Precision at 1% or less, sampled in several rapidity bins → constrains PDFs within a same SET (ie CTEQ)

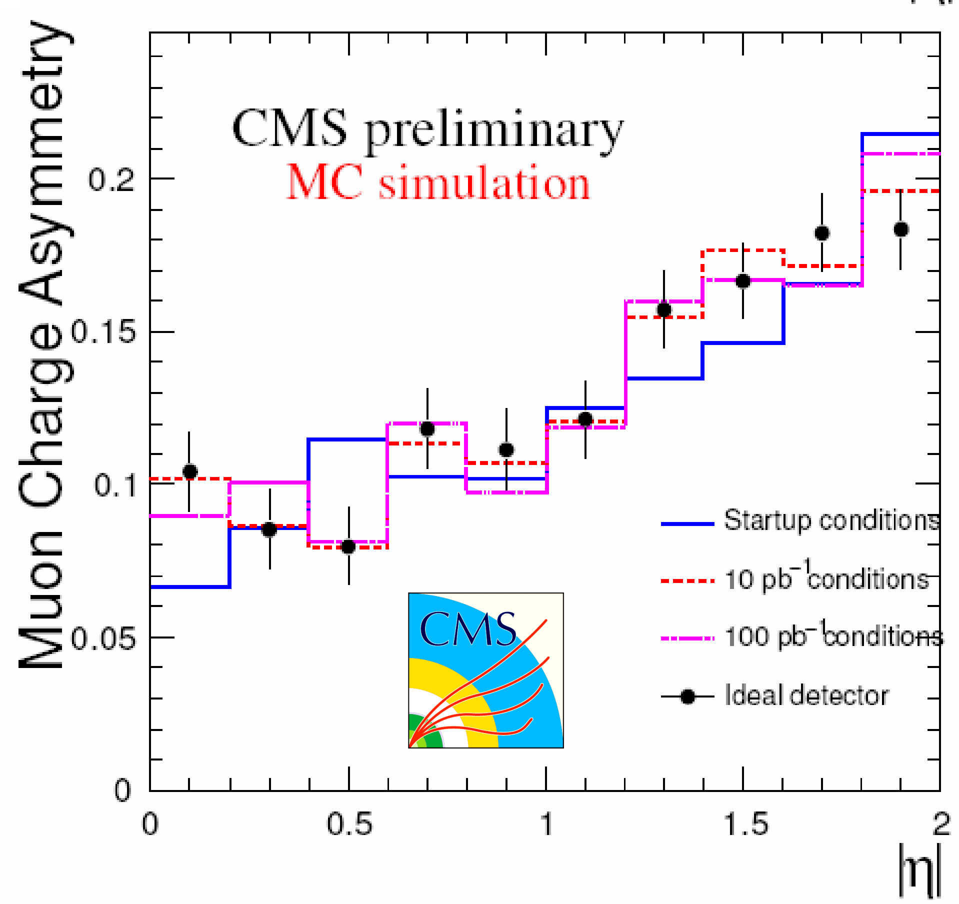


W Asymmetry

CMS Measurement of A_l

- **Full data-driven analysis performed with CTEQ6.5**
- Generated 100 pb^{-1} of $W \rightarrow \mu\nu$
- W Selection like in inclusive σ measurement
- Backgrounds:
  - QCD (10%), top
  - DY (5%), $W \rightarrow \tau\nu$
  - → Overall dilution of the asymmetry ~20 %
- Experimental systematical effects
  - Muon triggering, reconstruction & ID <1%,
  - Detector misaligned, miscalibration <1%

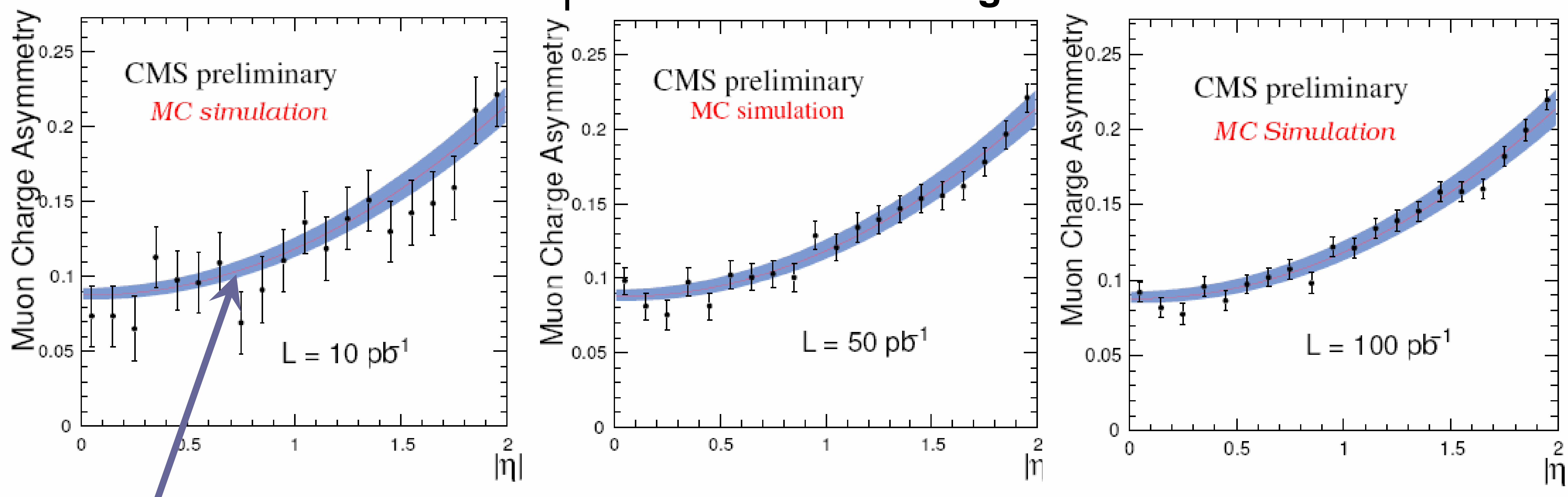




W Asymmetry

- At low integrated luminosities (10 pb^{-1}) the experimental measurement is a sensitive check of the validity of PDF assumptions at the LHC.
- At larger integrated luminosities (> 100 pb^{-1}) the measurement becomes a clean way to improve our PDF knowledge.

Measured A_l corrected from background dilution



Uncertainty band from CTEQ6.5 PDF predictions

Improved accuracy and change of shape of valence quark PDFs from $\mathcal{L}$ = 100 pb^{-1}

Conclusion

- LHC Start-Up will bring Particle Physics to a new energy regime
  - ATLAS and CMS are ready for collisions
  - First data will help to understand and tune the detectors for new physics
  - Luminosity and cross-sections much higher than previous experiments

- Rediscovery of the Standard Model: **W and Z benchmark proccesses**
  - Tools for calibration of the detector (Momentum Scale, Tag&Probe)
  - First tests of our knowledge of the SM
  - First data→ **First Measurement of the W&Z cross-sections @ 10 TeV**

- Knowledge of **PDFs**:
  - Main theoretical contribution to uncertainties
  - **W Lepton Rapidity Distribution** & **W Asymmetry** will improve our knowledge of PDFs at 100 pb^{-1} (if systematics <5%)

Acknowledgements

- Thanks to the ElectroWeak groups in ATLAS & CMS for their help and comments ☺

Main references

- ATLAS & CMS Physics TDR
- PDF constraints from ATLAS: A. Tricoli et al, **hep-ex/0509002**
- CMS W&Z crossection measurements with first data (e & μ)
  CMS PAS EWK-07-02, EWK-08-005, EWK-09-001
- Muon Charge Asymmetry in CMS: **CMS PAS EWK-08-002**
- Parton Distributions for the LHC, A.Martin et al: hep-ph/0901.0002
- Evaluation of Theoretical Uncertainty of Z→ll (W→lν) crossections at the LHC, N. Adam et al: **hep-ph/0802.3251 (hep-ph/0808.0758)**
- Proceedings from HCP 08 (K. Mazumdar)
- Proceedings from DIS 08 & 07 (A. Cooper-Sarkar, S. Bolognesi, S. Goy)
- Talk on ATLAS PDF issues at " Standard Model Discoveries with early LHC data", March 2009, by A. Cooper-Sarkar

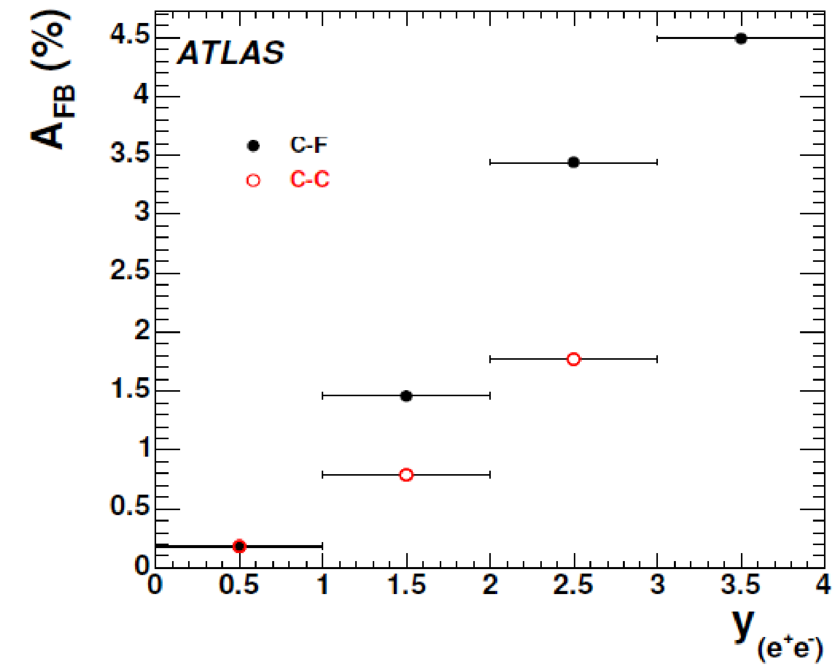
Back-Up

Forward-Backward Z Asymmetry

- Asymmetry in the polar emission angle of the electron in the rest frame of the e^-e^+ pair in pp $\rightarrow Z \rightarrow ee$ events

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta} = \frac{3}{8}N_C\left[1+\frac{4}{3}A_{FB}\cos\theta+\cos\theta^2\right]$$

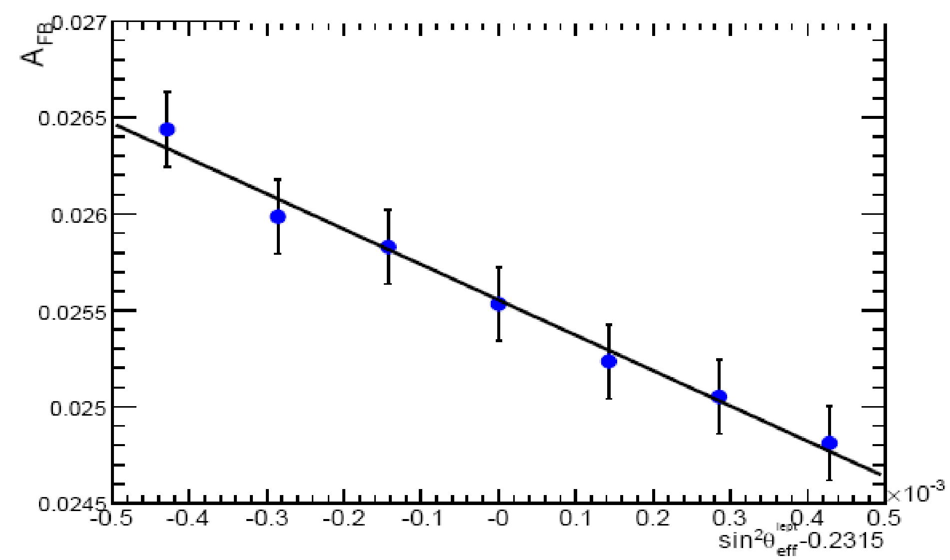
Counting problem: $A_{FB} = \dfrac{N_F - N_B}{N_F + N_B}$



- Determination of Standard Model Parameter $\sin^2\theta_{eff}$:

$$A_{FB} = b(a - \sin\theta^{lept}{}_{eff})$$

pdf dependent



ATLAS: Measurement of $\sin^2\theta_{eff}$ for 100 fb^{-1}

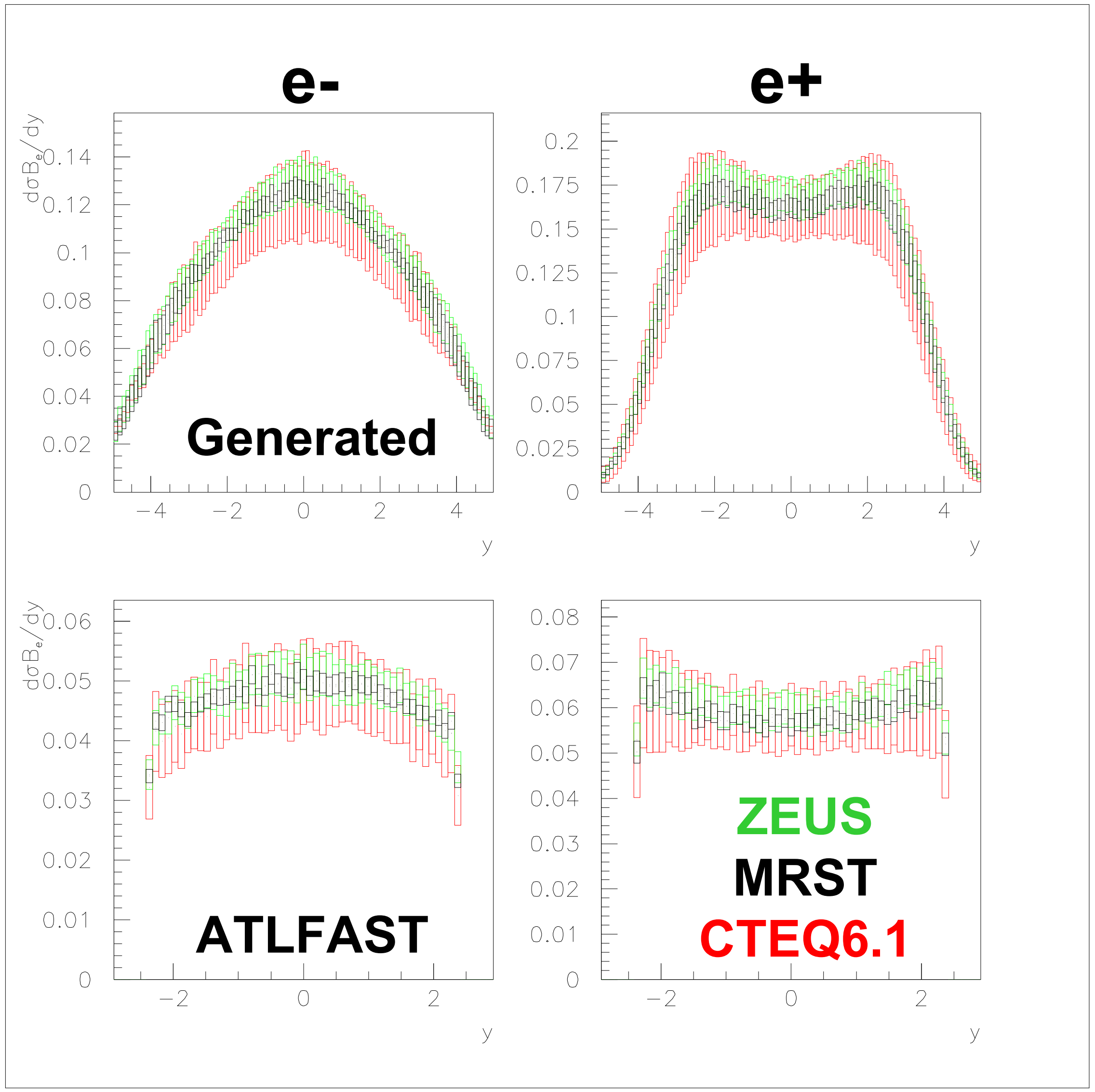
$\delta \sin^2\theta_{eff}$ **=(1.5(stat)±0.3(exp)±2.4(PDF)) ×10⁻⁴**

→Possible constraint on PDFs?

More on E. Klinkby's talk (Precise ElectroWeak Physics)

Rapidity distribution

- Measuring the decay lepton spectra in ATLAS & CMS we can improve our knowledge of PDFs



W+: $u\bar{d}$ W-: $\bar{u}d$

ATLAS: Comparison of different PDF sets

Generate pseudodata at 14TeV corresponding to 100pb^{-1} using **CTEQ6.1M** **ZEUS_S** **MRST2001** PDFs → Simulate Detector & Selection Cuts with ATLFAST

At y=0 the total uncertainty is

~ ±6% from ZEUS

~ ±4% from MRST01E

~ ±8% from CTEQ6.1

hep-ex/0509002
hep-ex/0511020

PDF Predictions for σ

14 TeV

PDF set	$\sigma_{W+} B_{W\to l\nu}$ (nb)	$\sigma_{W-} B_{W\to l\nu}$ (nb)	$\sigma_{Z} B_{Z\to ll}$ (nb)
ZEUS-2005	11.87±0.45	8.74±0.31	1.97±0.06
MSTW08	11.97±0.22	9.04±0.16	1.98±0.035
CTEQ66	12.34±0.34	9.06±0.22	2.02±0.04
HERAPDF	12.13±0.13	9.13±0.15	2.01±0.025
CTEQ61	11.61±0.34	8.54±0.26	1.89±0.055
NNPDF1.0	11.83±0.26	8.41±0.20	1.95±0.04

Re-Done for 10 TeV

PDF set	$\sigma_{W+} B_{W\to l\nu}$ (nb)	$\sigma_{W-} B_{W\to l\nu}$ (nb)	$\sigma_{Z} B_{Z\to ll}$ (nb)
ZEUS-2005	8.51±0.30	6.08±0.20	1.36±0.04
MSTW08	8.55±0.15	6.25±0.12	1.38±0.025
CTEQ66	8.77±0.18	6.22±0.14	1.40±0.027
HERAPDF	8.64±0.10	6.27±0.11	1.38±0.02
CTEQ61	8.29±0.22	5.90±0.17	1.32±0.030

Talk on ATLAS PDF issues at " Standard Model Discoveries with early LHC data", March 2009.

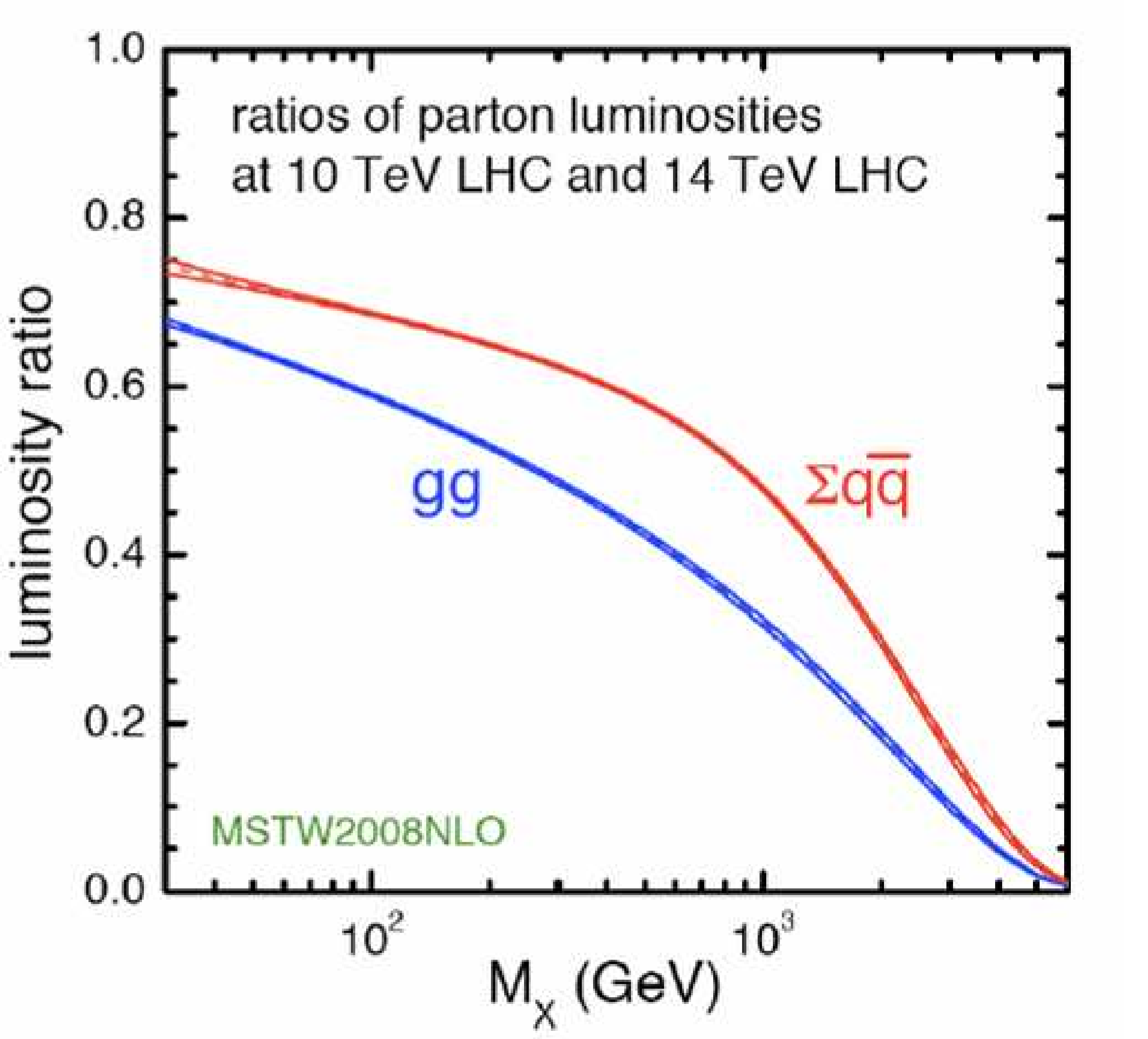
by A. Cooper-Sarkar

E_{CM} = 10 TeV

First run of LHC will be at **E_{CM}=10 TeV**

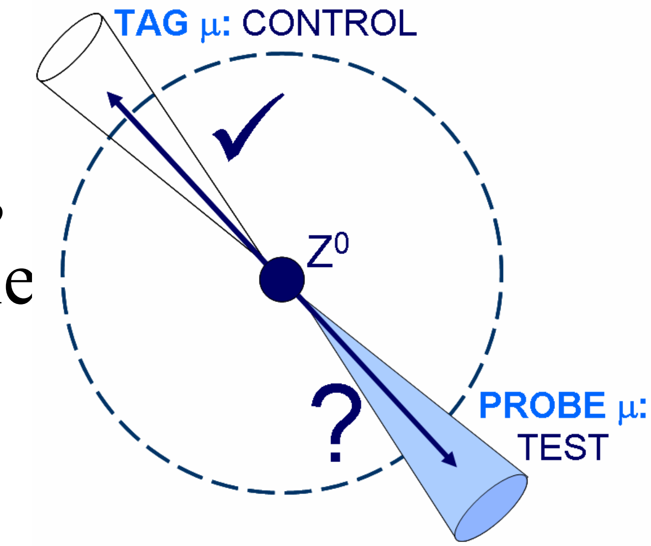
→All the results shown in the talk (W asym & W rapidity) correspond to 14 TeV analysis

→Results being updated currently to prepare for the new center of mass energy

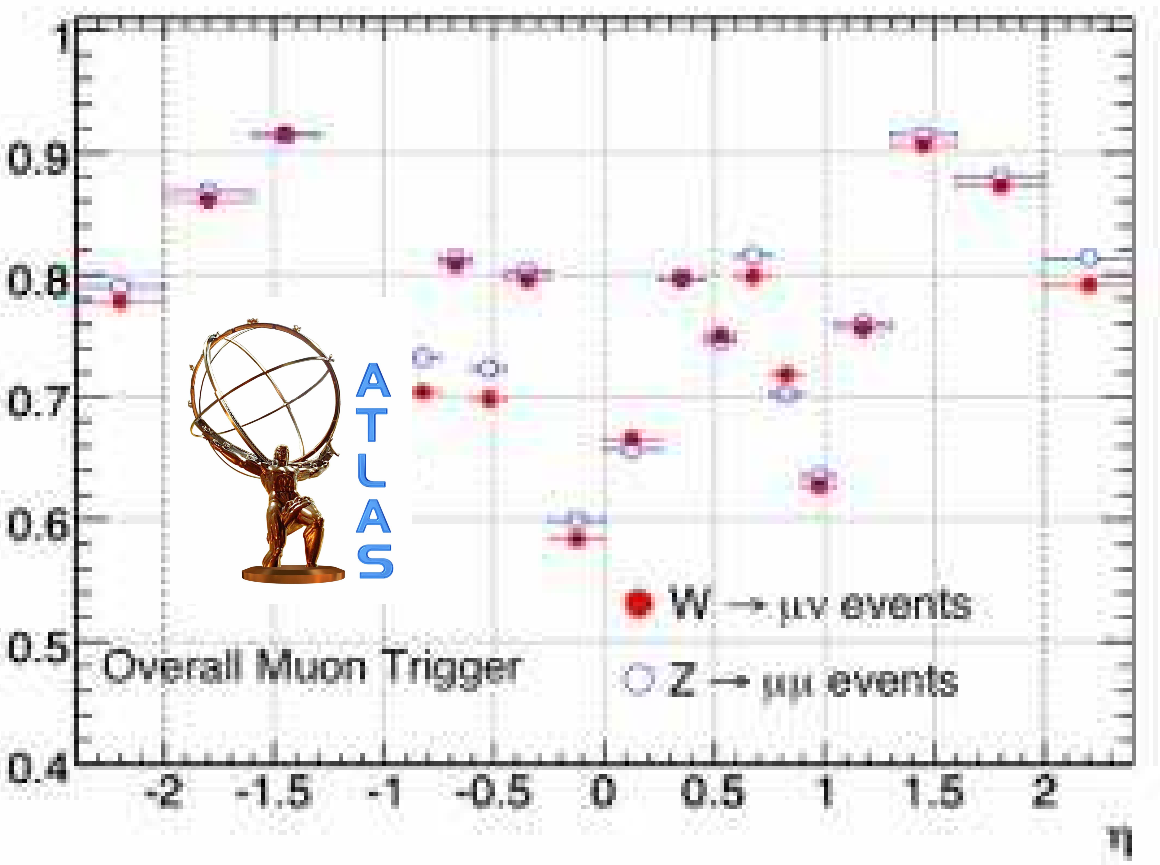


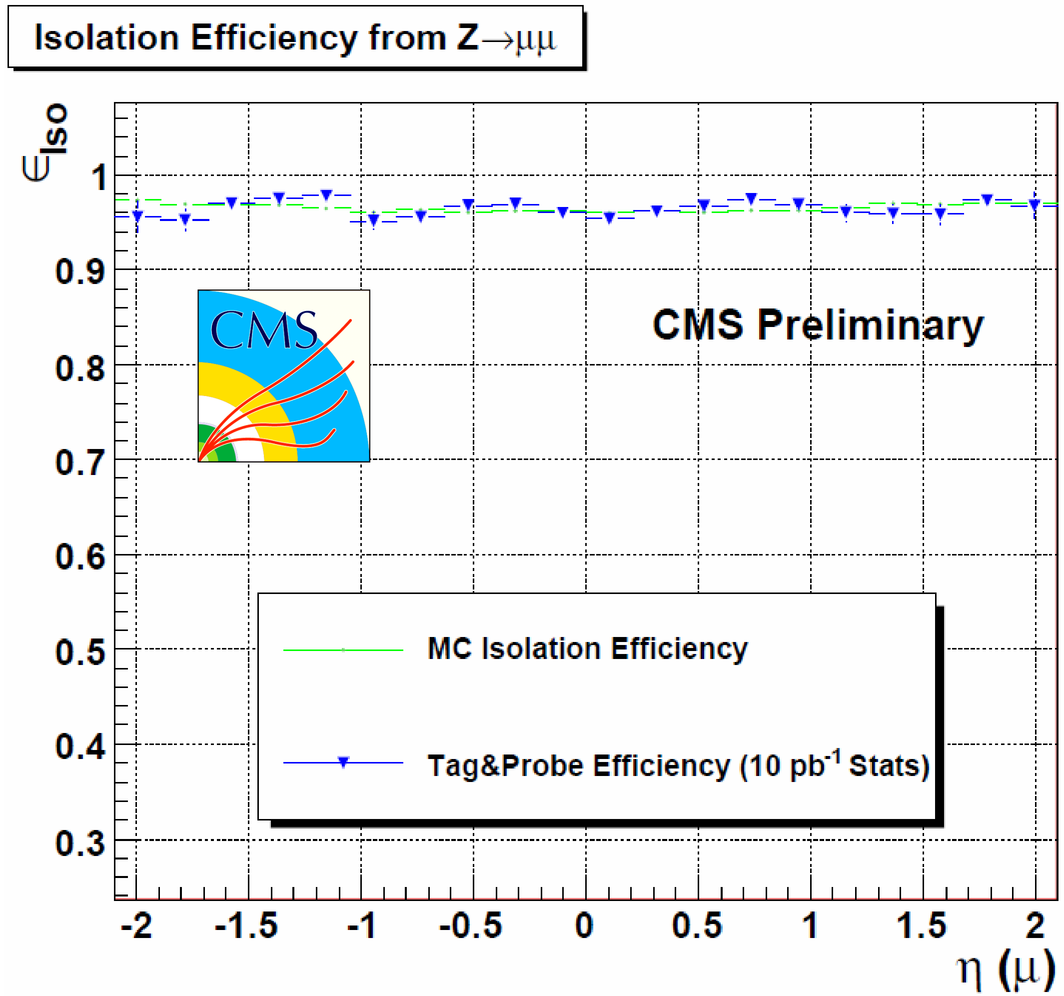
Efficiency: Tag&Probe

- All the online (trigger) and offline (reconstruction, identification, isolation) efficiencies for leptons are computed from the Z sample with tag&probe method:
  - Tabulate efficiency in p_t, η bins to incorporate to analysis
  - Beware of possible correlations
  - Method validated with Monte Carlo samples
- Example: Trigger efficiency



$$\varepsilon_\mu = \varepsilon_{rec}\varepsilon_{iso}\varepsilon_{trig}$$



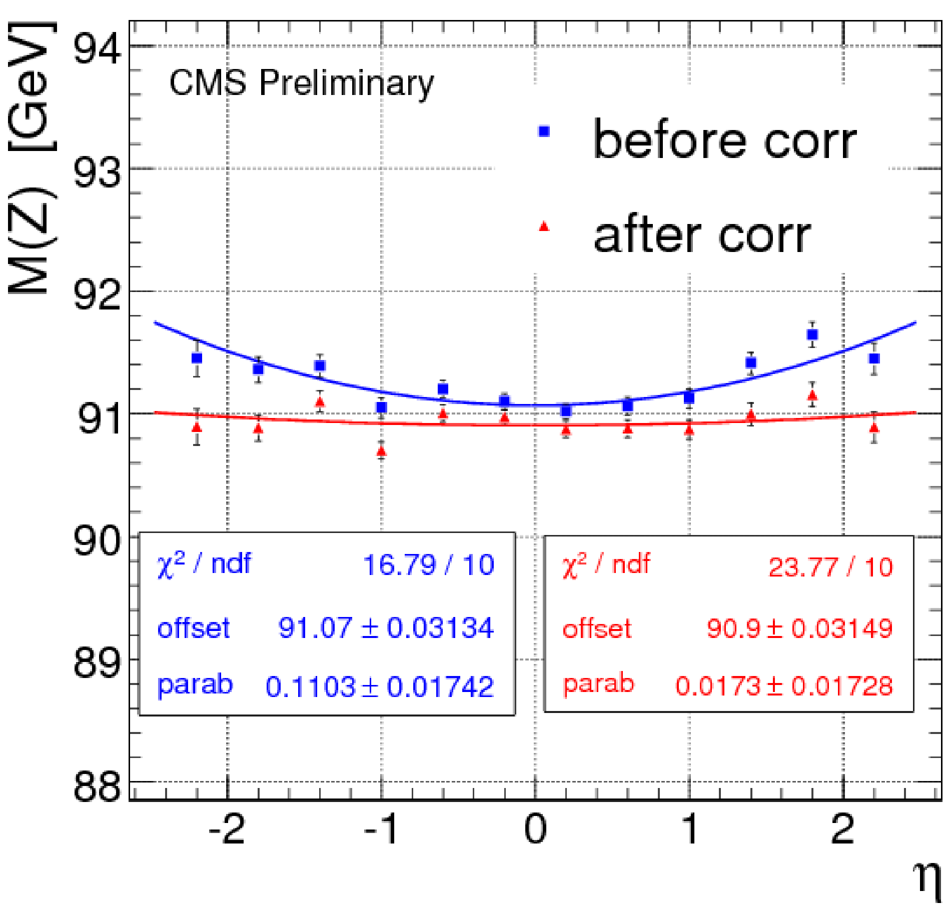


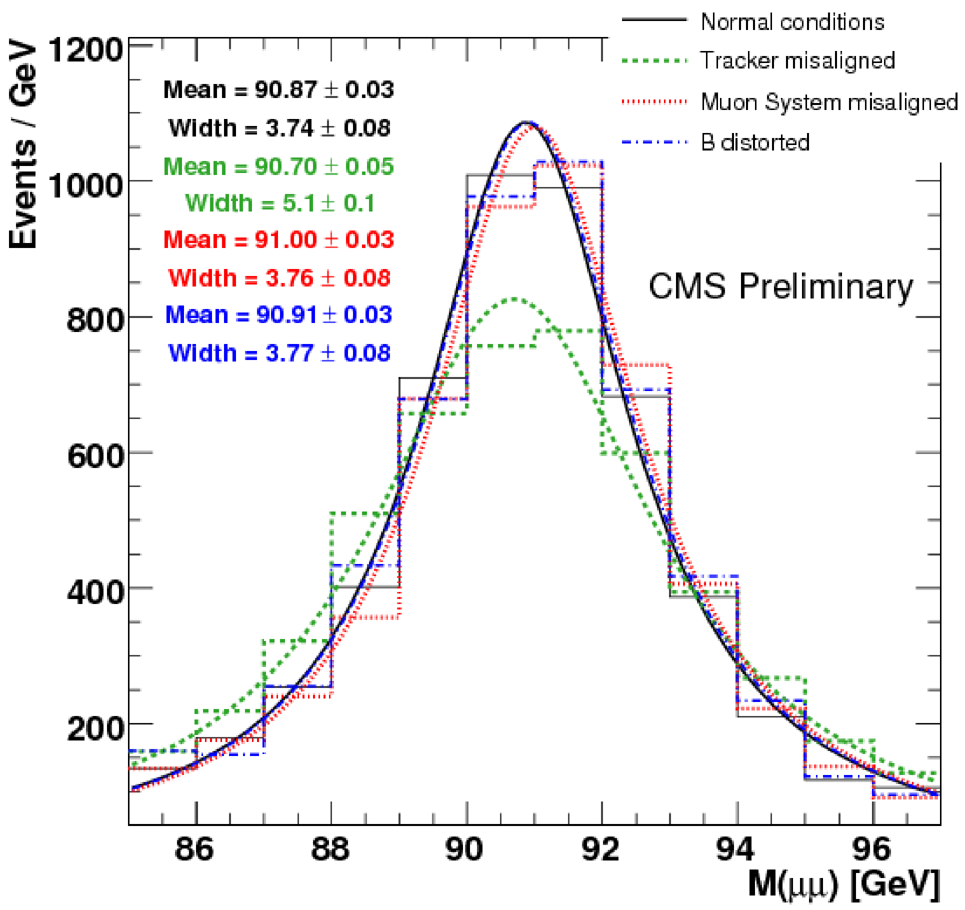
Lepton Momentum Scale

Di-lepton resonances will be used in ATLAS&CMS to measure momentum scale and resolution

Example from **CMS** using Z→$\mu\mu$ data:

→ likelihood technique to compute correction (as a function of muon kinematics) forcing the Z peak in the right position





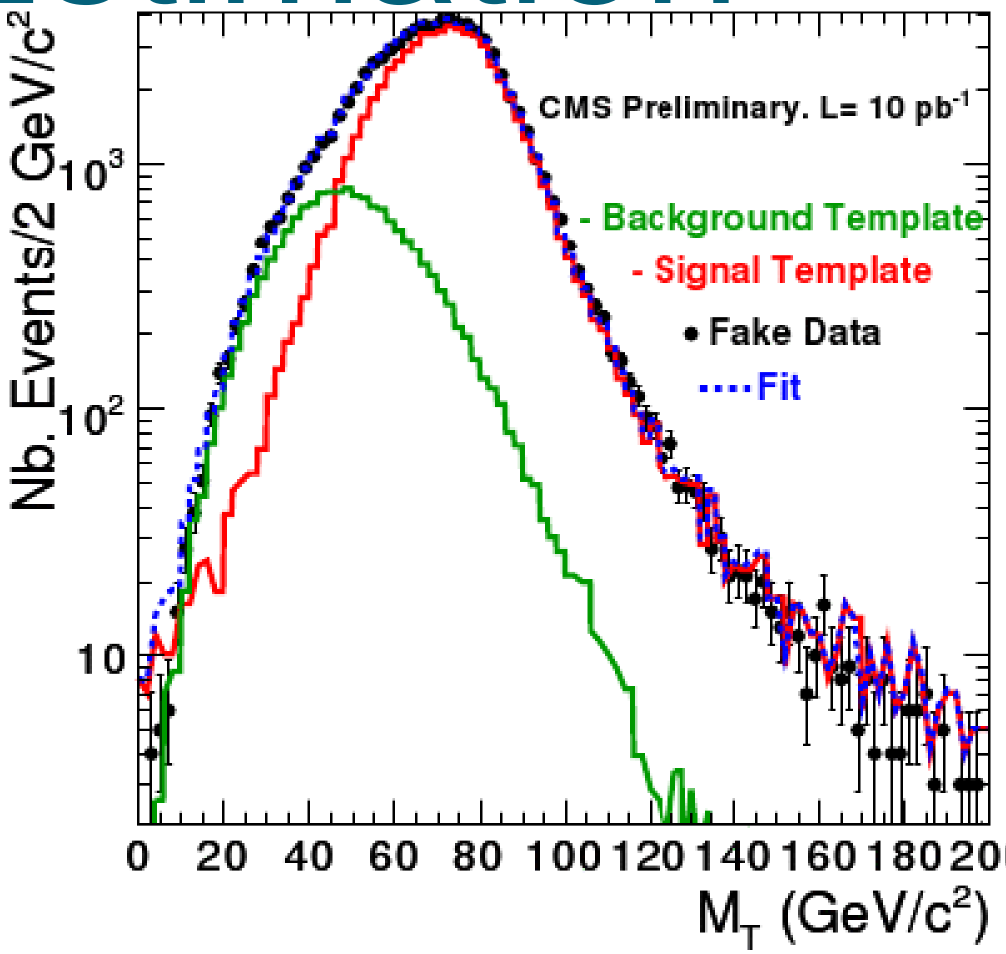
W→lν Background Estimation

- Template method:

Obtain bckg shape template reversing one of the cuts (ie, isolation)

Obtain signal template from Z→ll

Fit data to signal & bckg templates



- Matrix method:

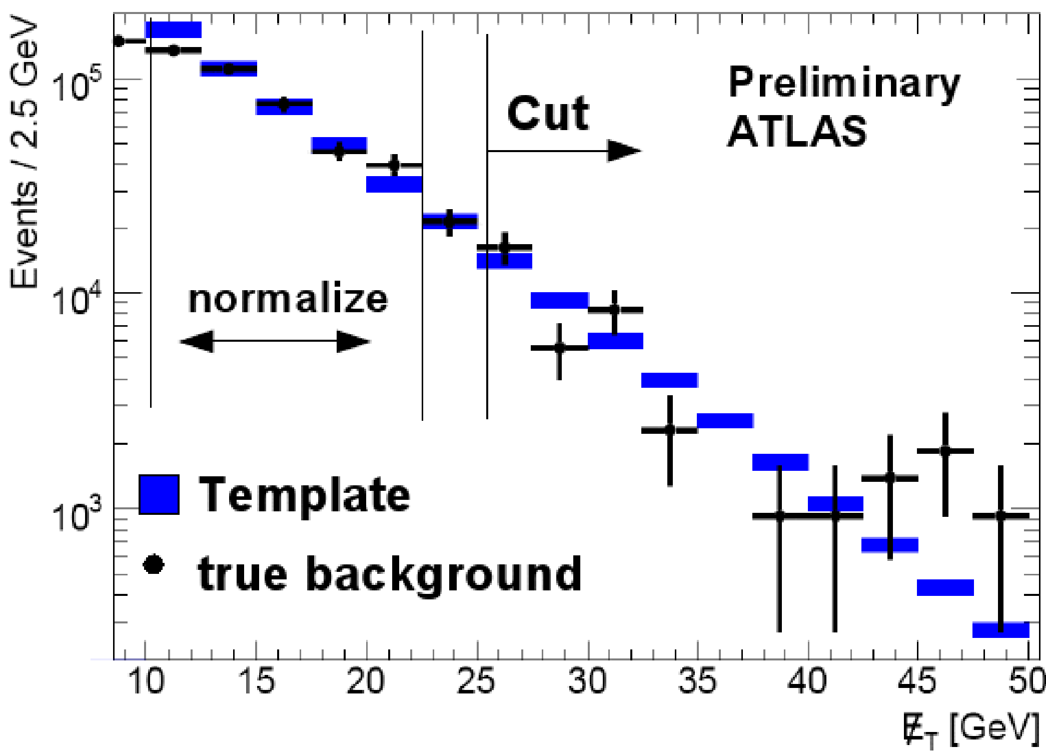
Select two uncorrelated variables

Divide phase space into 1 signal-like region (A) and 3 background-like region (B,C,D)

Obtain Background contamination in A from B, C, D →

QCD(A) ~ QCD(B)xQCD(C)/QCD(D)

Correct for signal contamination in bckg regions (using signal template)



W Mass

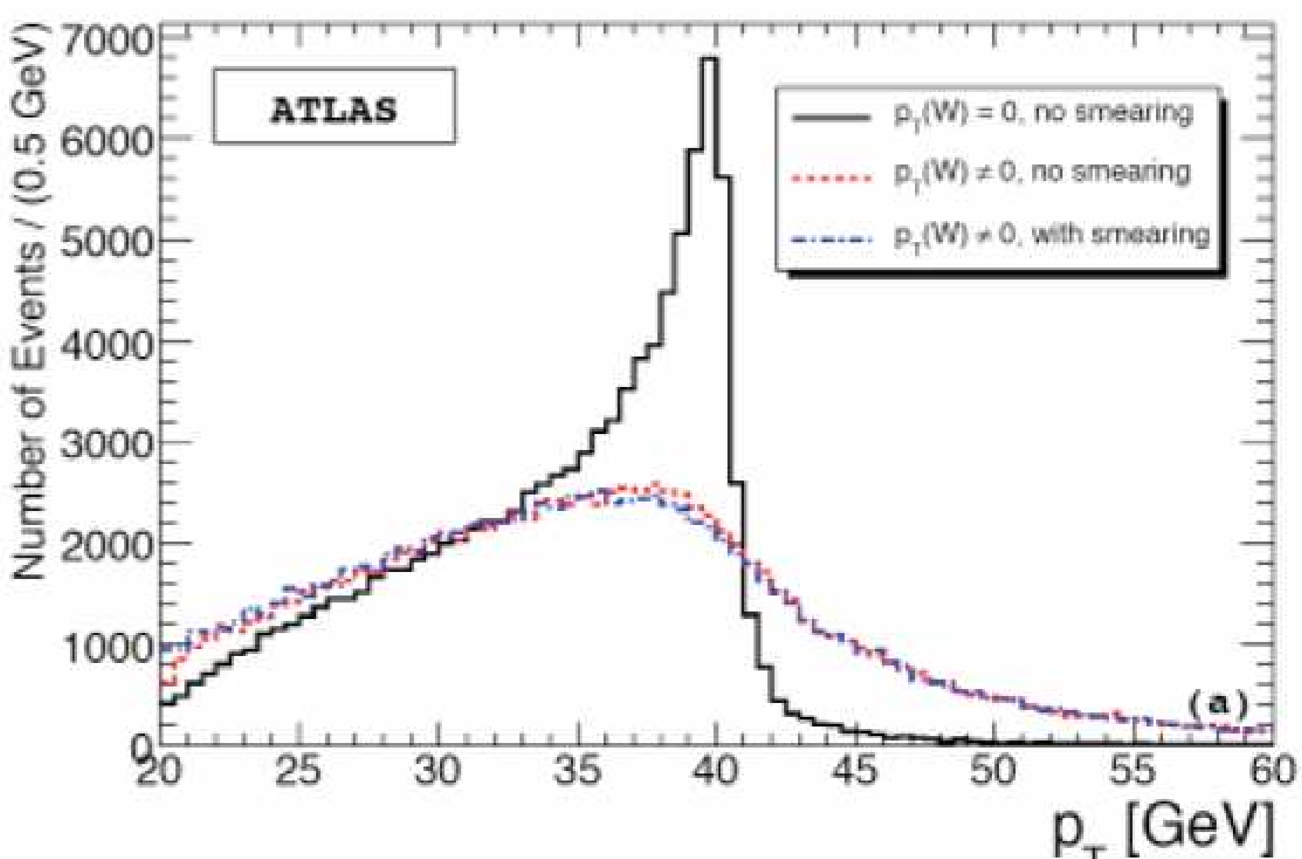
- Fundamental parameter of the Standard Model
  (M$_W$ & M$_{top}$ → constraints on the Higgs Mass)

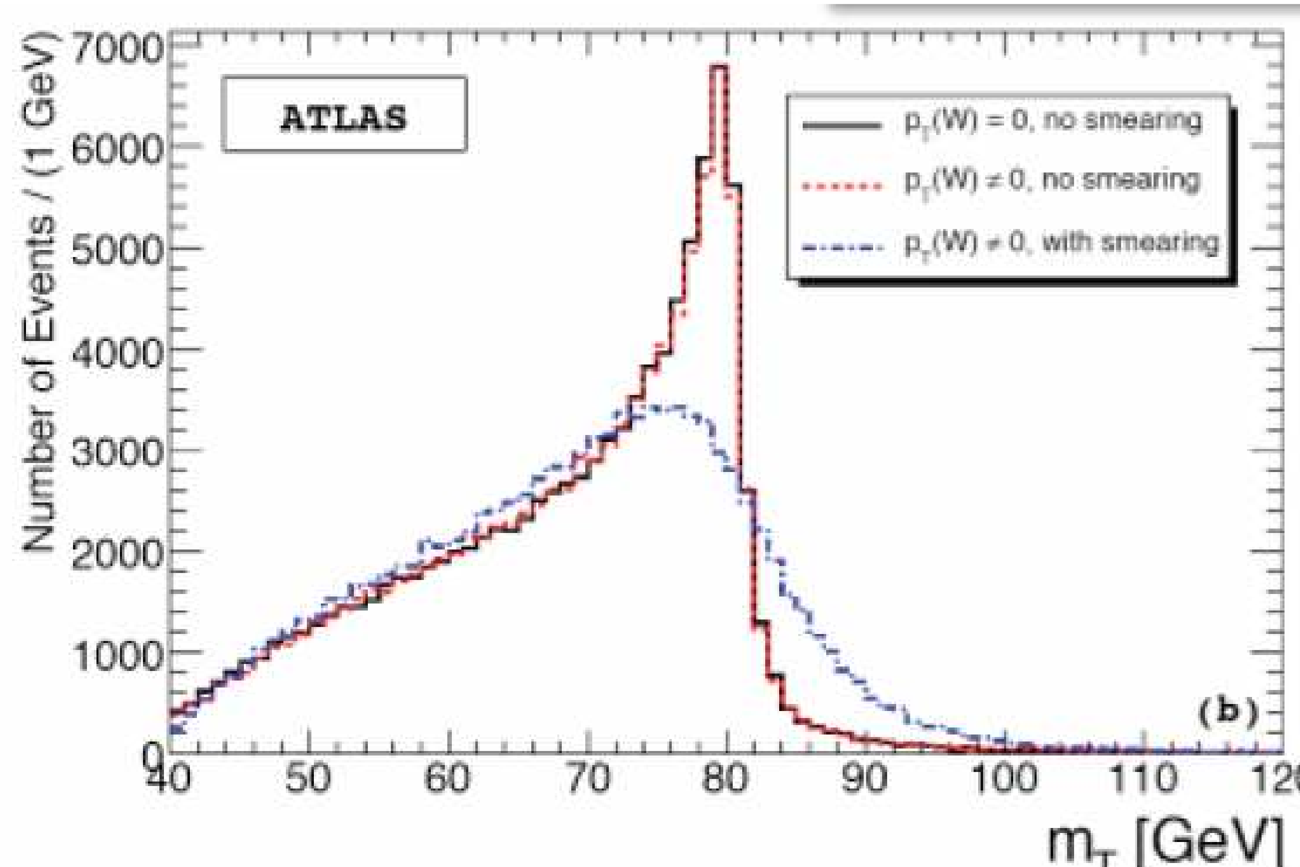
- M$_W$ obtained from M$_T$ and from p$_t$:
  - Z events used to build template for W
  - Fit the templates to the data → m$_W$

$$m_T^W = \sqrt{2 p_T^l p_T^\nu (1 - \cos\Delta\phi)}$$

$$p_T^\nu \equiv p_T^{missing}$$

- Z events are crucial: template & lepton energy scale and energy resolution, as well as to control systematics





W Mass

See Esben Klinkby's talk on Precise ElectroWeak Physics

Low luminosity measurement

ATLAS 15 pb^{-1}	pT(e)	pT(μ)	MT(e)	MT(μ)
Stat	120	106	61	57
Exp	114	114	230	230
Theo	25	25	25	25
TOT	167	158	239	238

Not competitive with current error.
Sets the experimental method

High luminosity measurement

CMS	E_T (e)		M_T (μ)	
	1 fb	10 fb	1 fb	10 fb
Stat	40	15	40	<15
Exp	40	<20	64	<30
Theo	20	<10	20	<10
TOT	60	26	78	35

Improvement in the W mass caculation!
Precision expected ~10 MeV
(combining both channels for 10 fb^{-1})