W & Z boson production (LHC)

Aristotelis Kyriakis

NCSR 'Demokritos', Athens, Greece

On behalf of the ATLAS and CMS Collaborations

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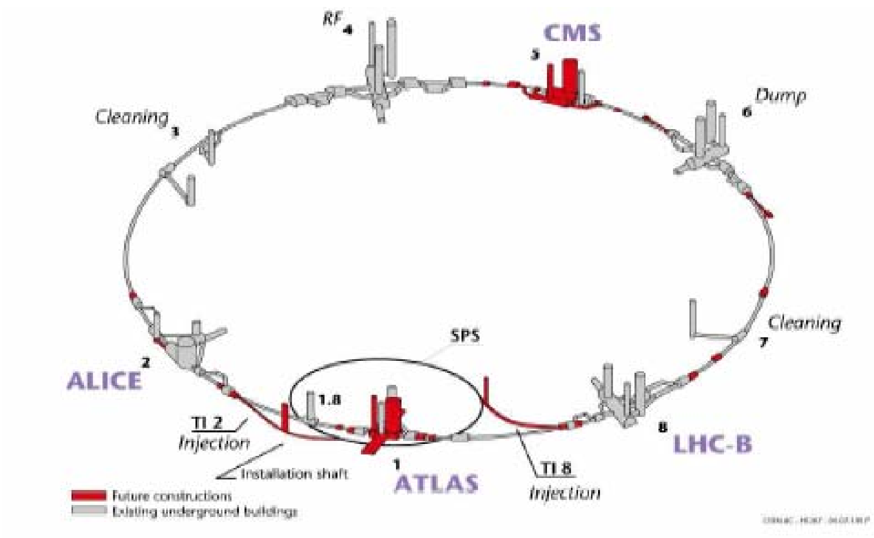
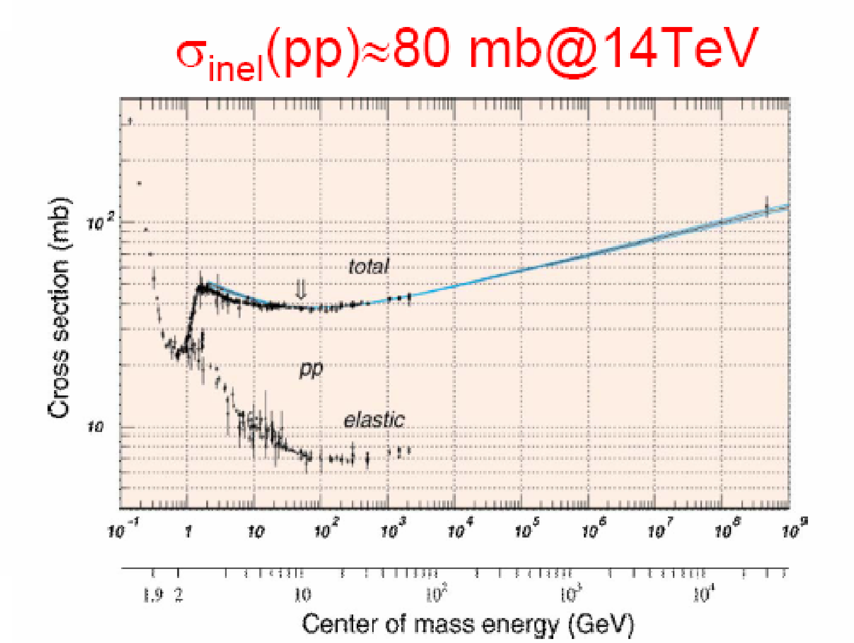
Outline

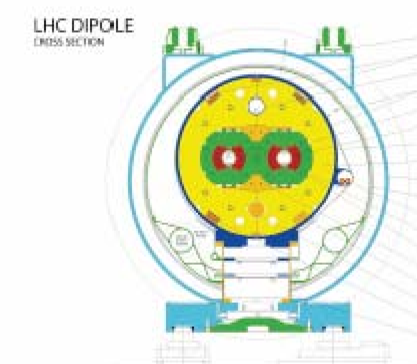
- LHC machine
- ATLAS and CMS detectors
- Inclusive production of Z/ W → leptons
- Data Driven Techniques
- W/Z + Jets
- W charge asymmetry
- Z FB asymmetry
- Summary

LHC machine





LHC Circumference	~27 km
Designed E_{cm}	14 TeV
Designed Luminosity	10^{34} $cm^{-2}s^{-1}$
bunch crossing rate	40 MHz (t_{bc}=25 ns)
protons/*bunch*	~10^{11}



SC dipoles:

Number: 1232

Temp: 1.9K

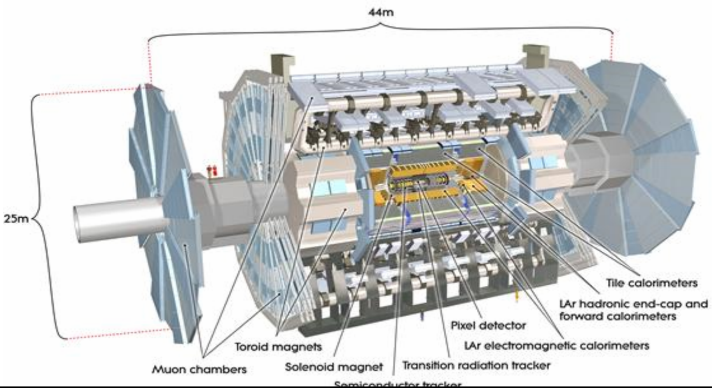
Length: 15m

Weight:34tons

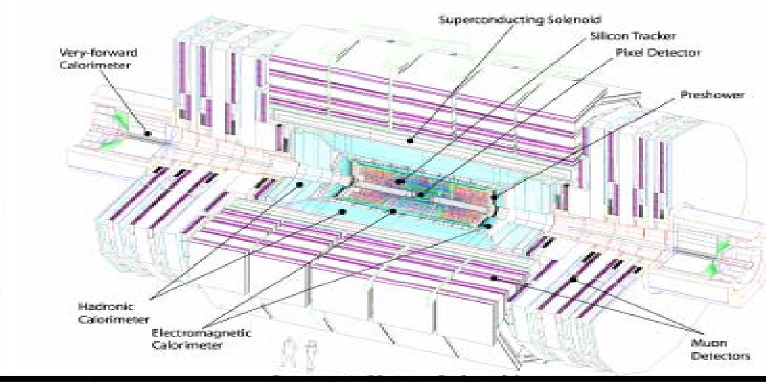
Mag. Field: 8.3Tesla

The ATLAS and CMS Detectors

ATLAS



CMS



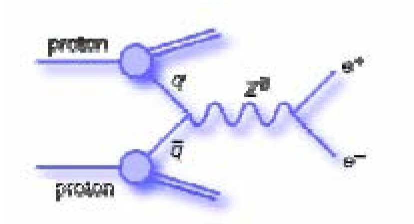
General	**L: 44 m, D: 25 m,** **W: 7000 tones, B: 2T(sol.) + 0.5T&1T(toroid)**	**L: 21 m, D: 15 m** **W: 12500 tones, B: 4Tesla**
Tracker	**Pixel, Silicon, TRT, |η| < 2.5** $\Delta P_t / P_t = 0.05\% P_t \oplus 1\%$ **(P_t in GeV)**	**Pixel, Silicon μStrip, |η| < 2.5** **$\Delta P_t/P_t \sim 0.01\% P_t$ (P_t in GeV)**
E/M Calorimeter	**Pb-LAr, |η| < 3.2** $\sigma / E \approx 10\% / \sqrt{E(GeV)} \oplus 0.7\%$	**$PbWO_4$ Crystals, |η| < 3.0** $\sigma / E \approx (2-5)\% / \sqrt{E(GeV)} \oplus 0.5\%$
Hadron Calorimeter	**Steel/Scint, Cu-LAr,W-LAr |η| < 4.9** $\sigma / E = 60\% / \sqrt{E(GeV)} \oplus 3\% \rightarrow Barrel, Endcaps$ $\sigma / E = 100\% / \sqrt{E(GeV) \oplus 10\%} \rightarrow Forward$	**Brass/Scint., Fe/Quartz Fibers, |η| < 5.0** $\sigma / E = 127\% / \sqrt{E(GeV)}$
Muon System	**MDT,RPC,CSC,TGC, |η| < 2.7** **Pt Resolution:** **~10% , pT ≈1TeV/*c*** **< 3 %, pT < 250 GeV/*c***	**DT, RPC,CSC, |η| < 2.4** **Pt Resolution(Muon+Tracker):** **~7% , pT ≈1TeV/*c*** **< 3 %, pT < 250 GeV/*c***

Inclusive Z/W production

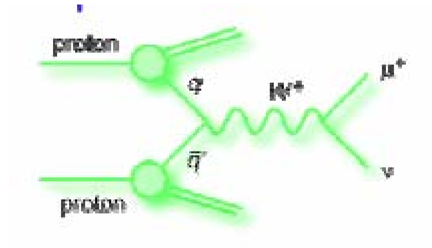
- W,Z properties are well known
- SM rediscovery studying W,Z production at LHC is fundamental

  - Very clean signal through their leptonic decays, large cross section
  - Provide strong constraints on the detector performance-calibration
  - Sufficient statistics for $d\sigma/dpt$ and $d\sigma/d\eta$ measurements
  - $d\sigma/dpt$ spectrum provides constraints on QCD while $d\sigma/d\eta$ is a direct probe of the PDFs
  - Building blocks of new physics scenarios e.i. Z', W', Little Higgs T->tZ …

Total Z/W x-sec measurements



~ 2 nb at 14TeV



~ 20 nb at 14TeV

MAIN FORMULA: $$\sigma \times Br(Z/W \rightarrow leptons) = \frac{N-B}{L \times A \times \varepsilon}$$

Overall Uncertainty:

$$\frac{\delta\sigma}{\sigma} = \frac{\delta N \oplus \delta B}{N-B} \oplus \frac{\delta L}{L} \oplus \frac{\delta A}{A} \oplus \frac{\delta\varepsilon}{\varepsilon}$$

Where:

$$\delta N / N \approx 1/\sqrt{L}$$

N → # of observed events

B → # of background events

L → Integrated Luminosity

A → Acceptance

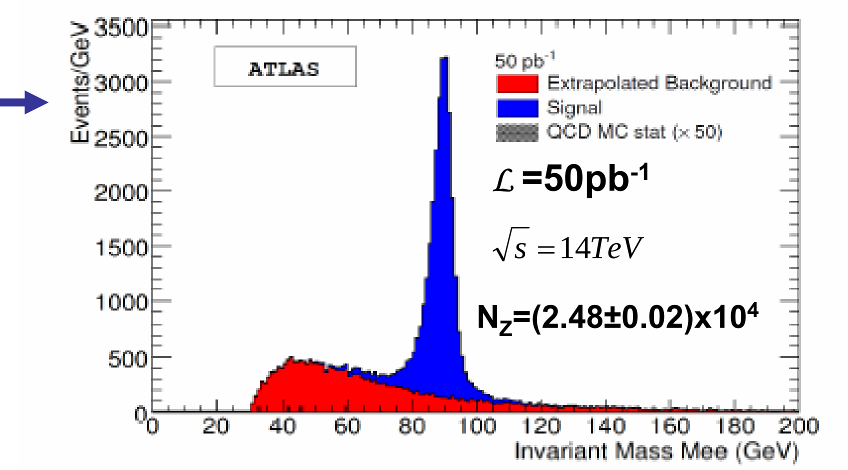
ε → efficiency within Acceptance

$$\varepsilon_{total}^{W\rightarrow l\nu} = \varepsilon_{trigger} \times \varepsilon_{offline}, \varepsilon_{total}^{Z\rightarrow ll} = \varepsilon_{offline}^{2} \times (1-(1-\varepsilon_{trigger})^{2})$$

ATLAS Inclusive Z

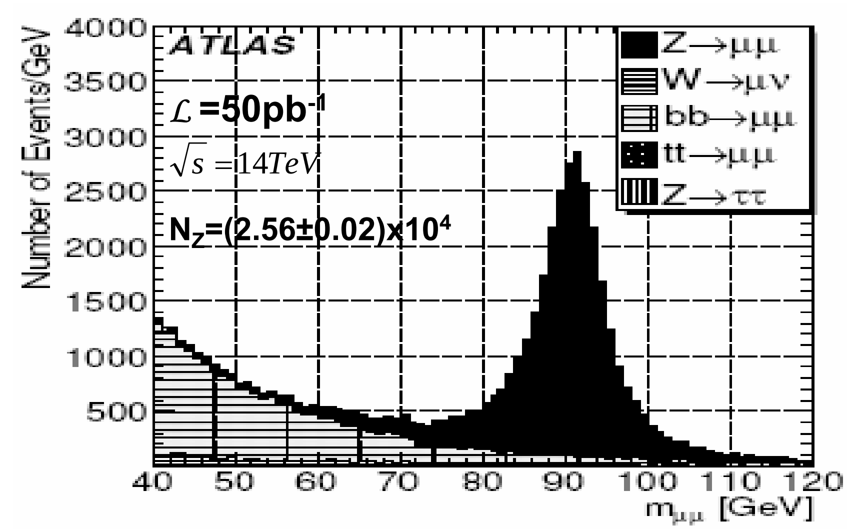
Z->e$^+$e$^-$

- **Single Electron Trigger with P_t>10GeV/c**
- **Two E/M clusters with E_t > 15GeV, |η|<1.37 or 1.52<|η|<2.4, 80GeV/c^2 < $M_{cl,cl}$ < 100 GeV/c^2**
- **Electron ID: using tracker information, Hadronic/EM Energy ratio and EM Shower Shapes**
- **Isolation $\Sigma E_t/E_t^{el}$ < 0.2(in cone ΔR<0.45)**



Z->μ$^+$μ$^-$

- **Single Muon Trigger with P_t>10GeV/c**
- **Two OS muon tracks with P_t > 20GeV, |η|<2.5, | $M_{\mu\mu}$ – 91.2| < 20 GeV/c^2**
- **Muon Isolation from tracker, both number of tracks and ΣP_t of the tracks (in cone 0.05< ΔR <0.5)**

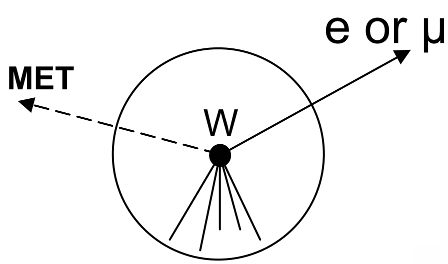


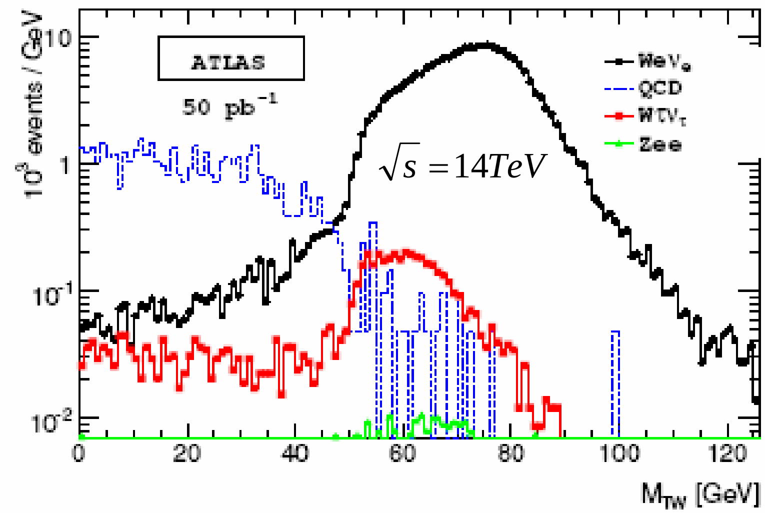
ATLAS Inclusive W

$$M_{WT} = \sqrt{2 \not{E}_T \, p_T^l (1 - \cos \Delta\phi)}$$

W->ev

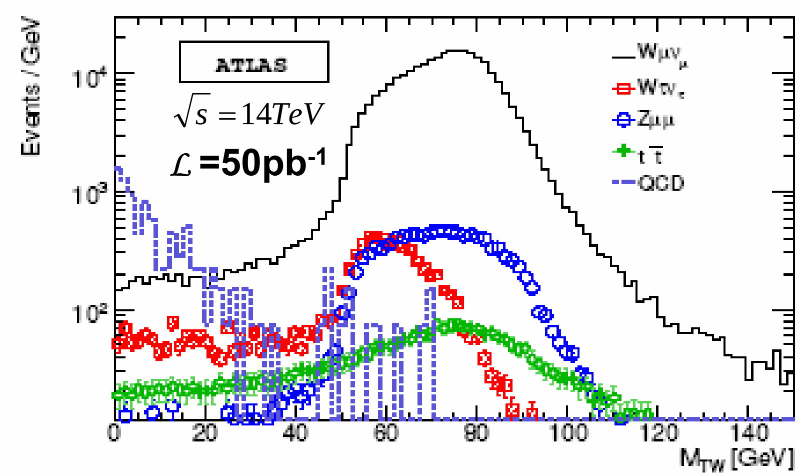
- Single Electron Trigger with P_t>20GeV/c
- Exactly one E/M clusters (matched with a track) with E_t > 25GeV, |η|<1.37 or 1.52<|η|<2.4
- Electron ID
- Missing E_T > 25GeV
- M_{WT} >40GeV/c²





W->μv

- Single Muon Trigger with P_t>20GeV/c
- Exactly one muon with p_t > 25GeV, |η|<2.5
- Muon Isolation from Calorimeters
- Missing E_T > 25GeV
- M_{WT} >40GeV/c²

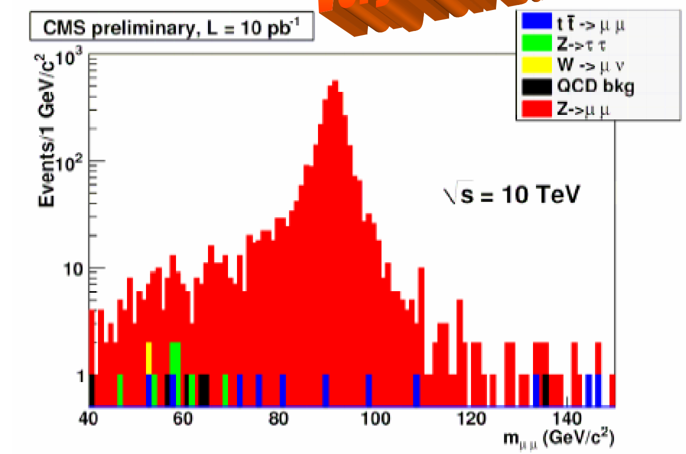


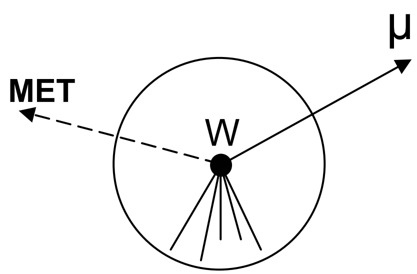
CMS Inclusive Z/W(I)

Z->$\mu^+\mu^-$

- At least one of the Muons fired the trigger
- Two OS muons (hits from Tracker + Muon Chambers) with P_t > 20GeV, $M_{\mu\mu}$ > 20 GeV/c^2
- Muon Isolation from tracker, ΣP_t of the tracks < 3GeV/c (in cone ΔR <0.3)

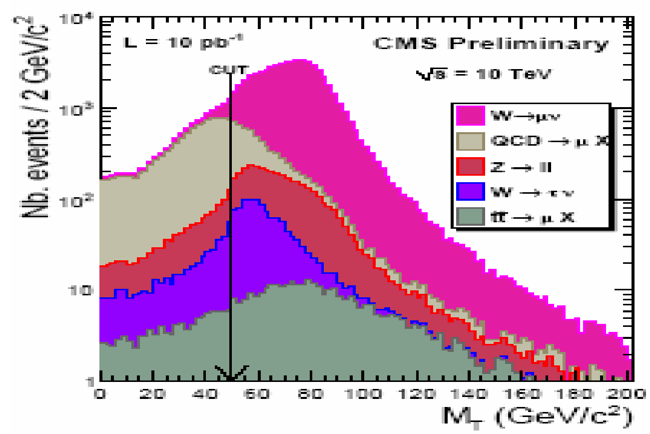
Very Low Background





W->$\mu\nu$

- Muon fired the trigger
- One muon (hits from Tracker + Muon Chambers) with P_t > 25GeV, $|\eta|$ < 2
- Muon Isolation from tracker, ΣP_t of the tracks/Muon Pt < 0.09 (in cone ΔR <0.3)
- MET stands for a measurement of the escaped ν
- M_T > 50 GeV/c^2



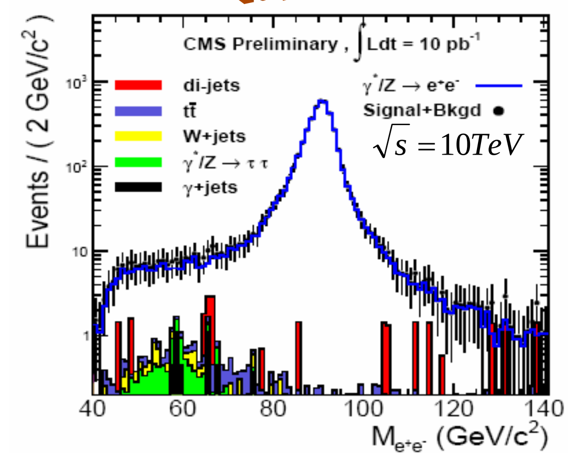
$$M_T = \sqrt{2 E\!\!\!/_T \, p_T^l (1 - \cos\Delta\phi)}$$

CMS Inclusive Z/W(II)

$Z \to e^+e^-$

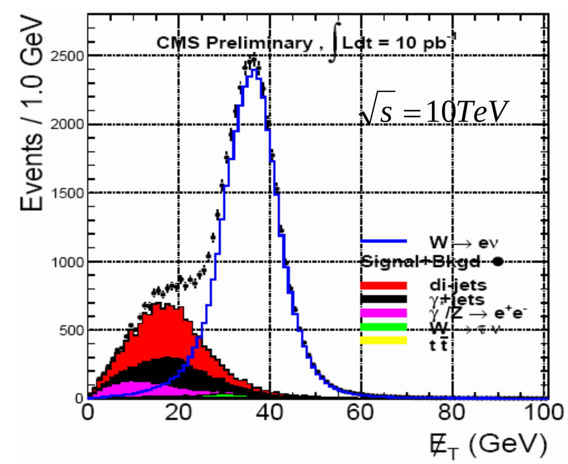
Very Low Background

- At least one of the Electrons should fired the trigger
- Two electrons with E_t > 20GeV, $|\eta|$ < 2.5
- Electron Isolation from tracker, ECAL and HCAL (in cone 0.02<ΔR <0.4)
- Electron Id using shower shape variable(cluster width in η direction) and E/M cluster – track matching
- $70GeV/c^2 < M_{ee} < 110\ GeV/c^2$



W→ev

- Electron fired the trigger
- One electron with E_t > 30GeV, $|\eta|$ < 2.5
- Veto in second electron with Et > 20GeV
- Electron Isolation from tracker, ECAL and HCAL
- Same variables as in Z→e+e- case but tighter cuts



Total Z/W inclusive x-sec

ATLAS RESULTS

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

$\sqrt{s} = 14 TeV$

Process	$N(\times 10^4)$	$B(\times 10^4)$	$A \times \varepsilon$	$\delta A/A$	$\delta\varepsilon/\varepsilon$	σ (pb)
$W \to e\nu$	22.67 ± 0.04	0.61 ± 0.92	0.215	0.023	0.02	$20520 \pm 40 \pm 1060$
$W \to \mu\nu$	30.04 ± 0.05	2.01 ± 0.12	0.273	0.023	0.02	$20530 \pm 40 \pm 630$
$Z \to ee$	2.71 ± 0.02	0.23 ± 0.04	0.246	0.023	0.03	$2016 \pm 16 \pm 83$
$Z \to \mu\mu$	2.57 ± 0.02	0.010 ± 0.002	0.254	0.023	0.03	$2016 \pm 16 \pm 76$

CMS RESULTS

$\mathcal{L}$ = 10 pb^{-1}

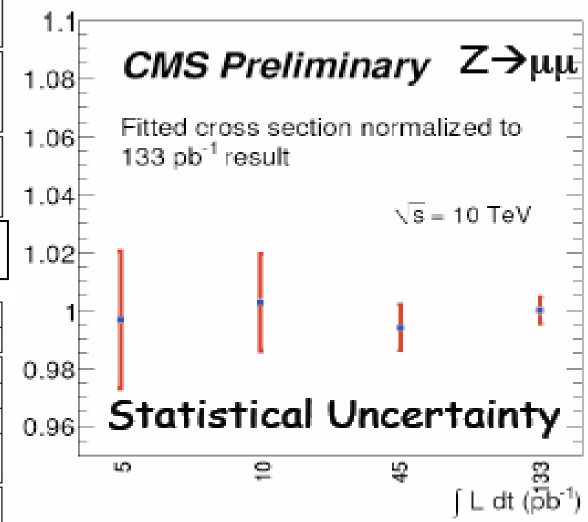
$\sqrt{s} = 10 TeV$

$N_{selected} - N_{bkgd}$	37500 ± 453
Tag&Probe $\varepsilon_{offline}$	74.4 ± 0.6 %
Tag&Probe $\varepsilon_{trigger}$	97.2 ± 0.3 %
Tag&Probe $\varepsilon_{offline \times trigger}$	72.3 ± 0.6 %
Acceptance	36.6 ± 0.1 %
Int. Luminosity	$10\ pb^{-1}$
$\sigma_W \times BR(W \to e\nu)$	14200 ± 200 pb
$\sigma_W \times BR(W \to e\nu)$ (MCtruth)	13865 pb

$\Delta\sigma/\sigma$(sys) = 4%

$N_{selected}$	4273 ± 65
N_{bkgd}	assumed 0.0
Tag&Probe $\varepsilon_{offline}$	90.4 ± 0.3 %
Tag&Probe $\varepsilon_{trigger}$	99.88 ± 0.02 %
Tag&Probe ε_{total}	81.6 ± 0.5 %
Acceptance	40.4 ± 0.2 %
Int. Luminosity	$10\ pb^{-1}$
$\sigma_{Z/\gamma^*} \times BR(Z/\gamma^* \to e^+e^-)$	1300 ± 20 pb
$\sigma_{Z/\gamma^*} \times BR(Z/\gamma^* \to e^+e^-)$ (MCtruth)	1296 pb

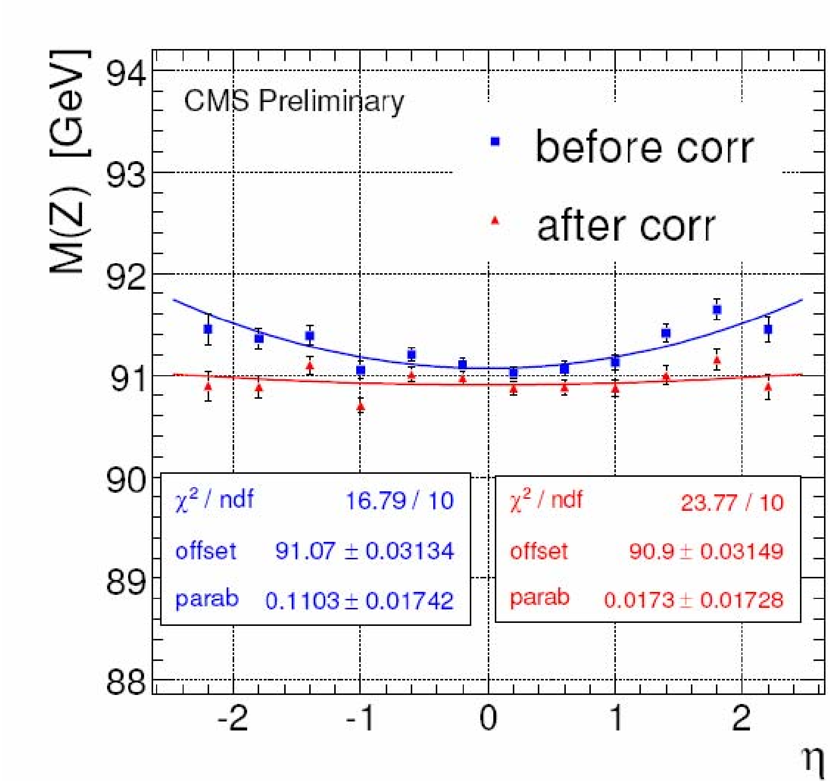
$\Delta\sigma/\sigma$(sys) = 2.4%

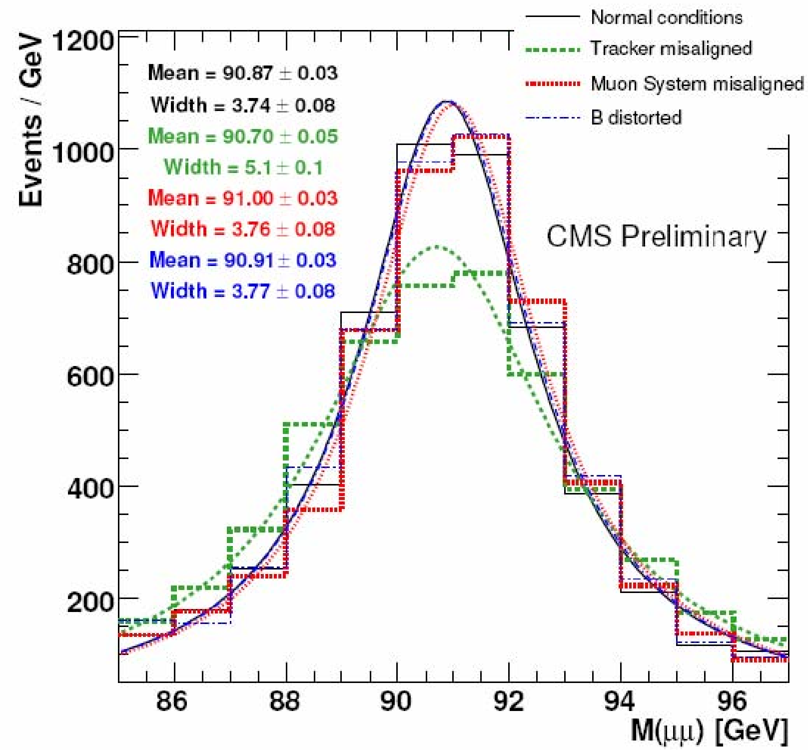


Extra Uncertainty form Luminosity 10%

Muon Momentum scale Correction in $Z \rightarrow \mu^+ \mu^-$

Misalignment and uncertainties on the magnetic field have an impact on the reconstructed Z boson mass due to the muon momentum scale corrections of the order of 2.7%



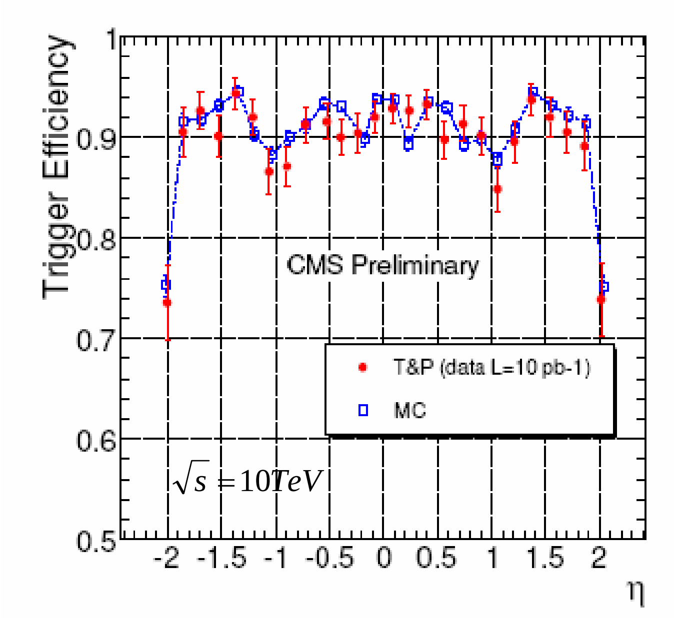


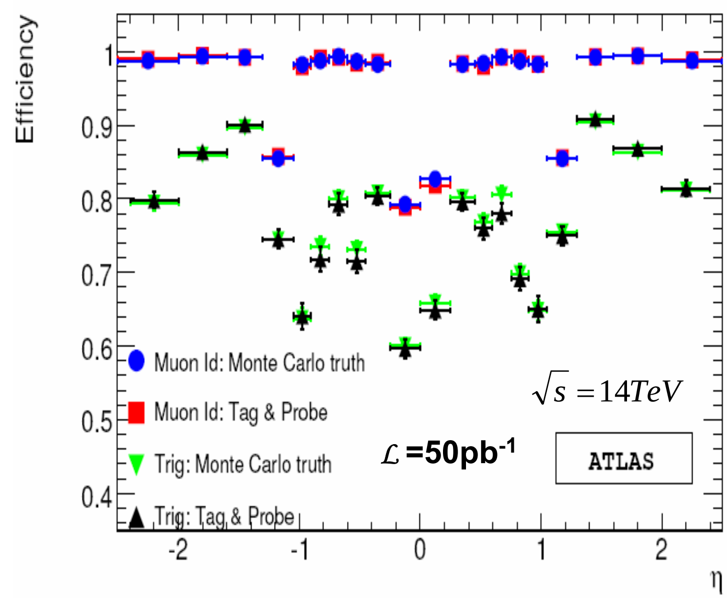
Data Driven Techniques (I)

Tag&Probe Method: Used to measure efficiencies from data

1. **Tag Lepton(μ,e): pass stringent Muon or electron Identification criteria**
2. **Probe(μ,e) : pass a set of id criteria depending on the efficiency under study**
3. **$M_{lepton\text{-}Tag,lepton\text{-}Probe}$ in a window around M_Z**

Both 1,3 are sufficient to ensure high lepton (μ,e) purity

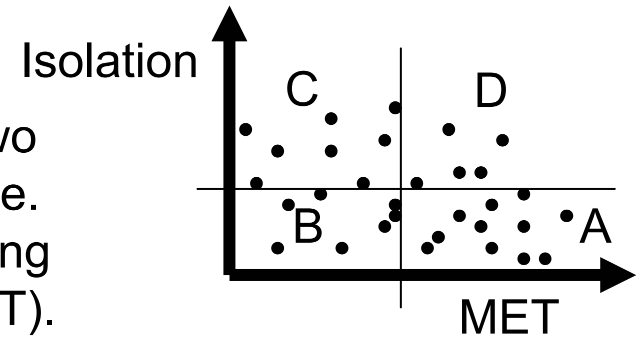




Data Driven Techniques (II)

Matrix or ABCD method:
Used to estimate the QCD background in W leptonic decays from data

Make a scatter plot of two uncorrelated variables i.e. lepton Isolation vs Missing Transverse Energy (MET).

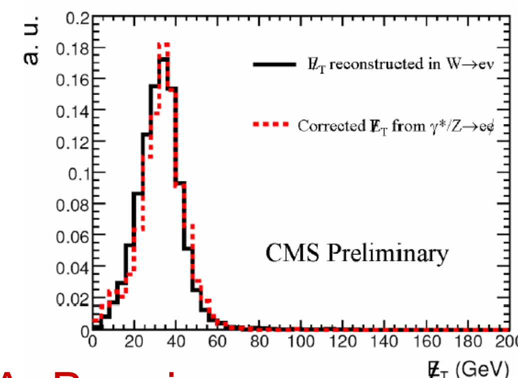


Assume:

$F_{QCD} = QCD_A/QCD_B = QCD_D/QCD_C = F'_{QCD}$

where $QCD_X = N_X - EWK_X - S_X$ and N_X, EWK_X, S_X are the total number of events, the EWK events (small number estimated from MC simulation) and the W→lν events in region X(=A,B,C,D) respectively.

- Then $F_Z = S_A/S_B$, $F_Z' = S_D/S_C$ can be estimated from the γ*/Z→ee Ersatz (substitute) MET.
  So emulate the neutrino by calculating the MET of the Zee sample but exclude one of the electrons and take into account the different kinematics → Provides a reasonable MET representation in W→eν events

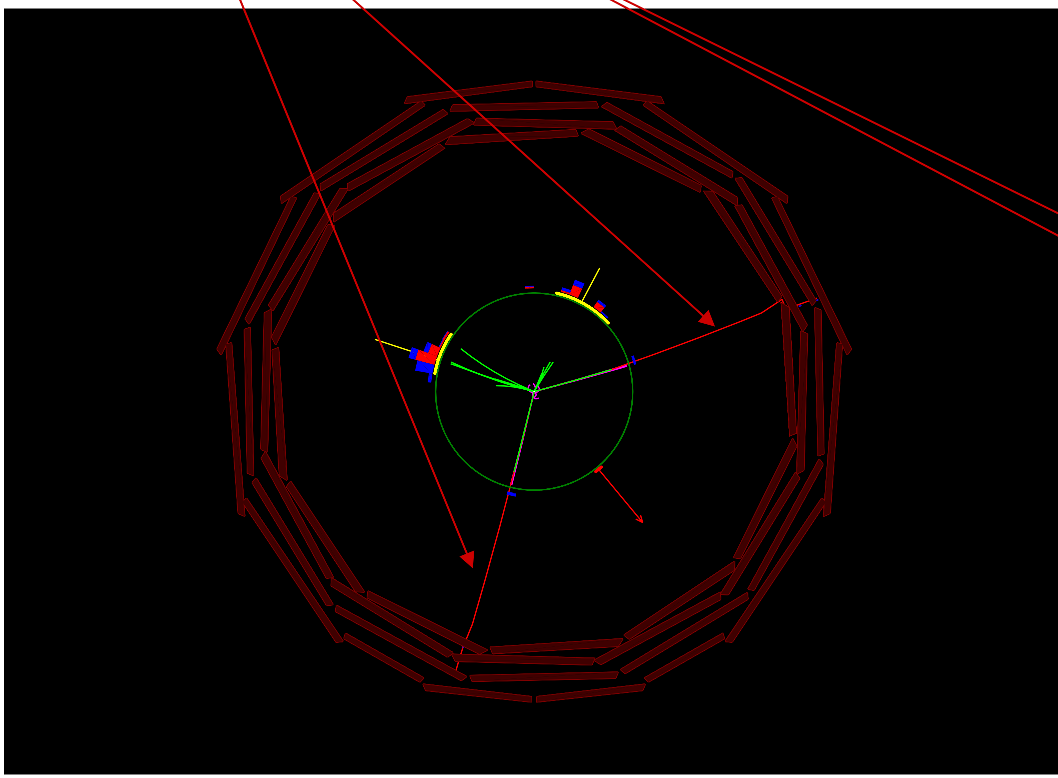


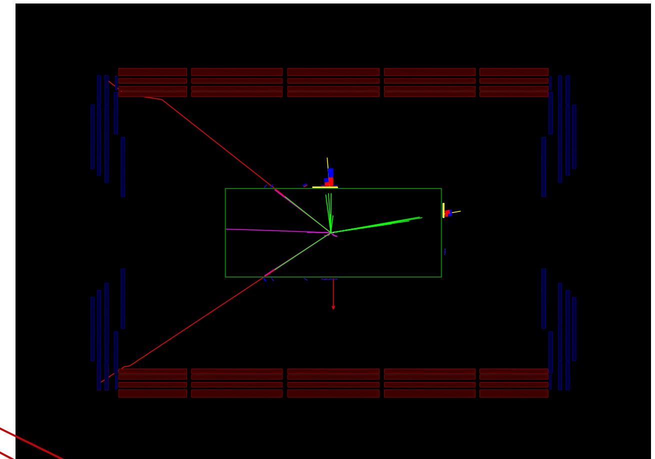
- Also define $I = S_{A+B}/S_{A+B+C+D}$: the efficiency of the Track Isolation cut for the Ws and can be estimated from the T&P method.

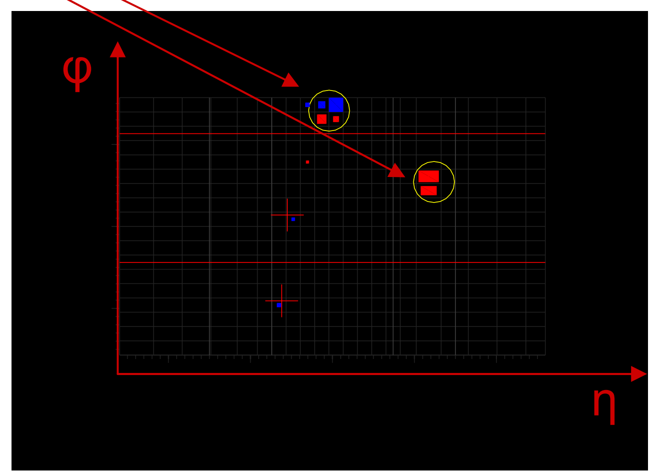
✓ Finally simple algebra gives the Signal (W) in the A+B regions

Z+Jets Cross Sections (I)

$Z(\rightarrow \mu^+\mu^-)$ + 2Jets event





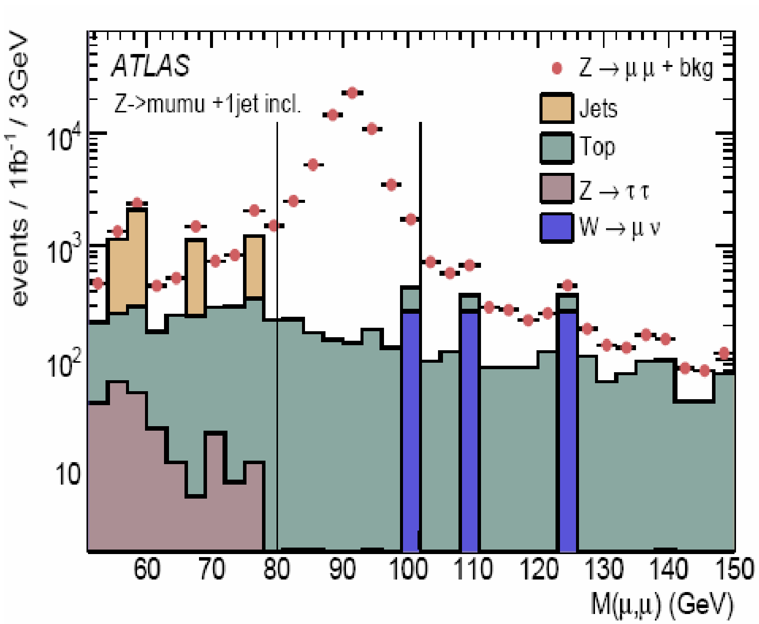


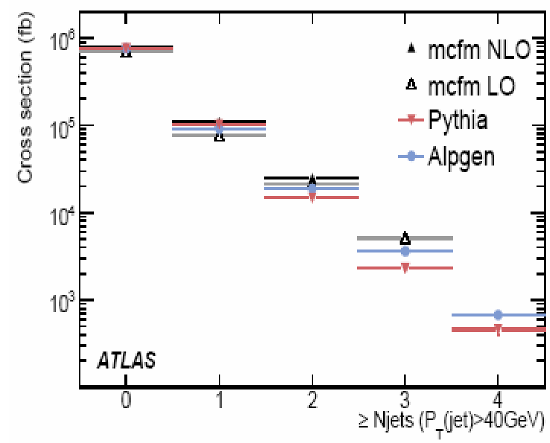
Z+Jets Cross-Sections (II)

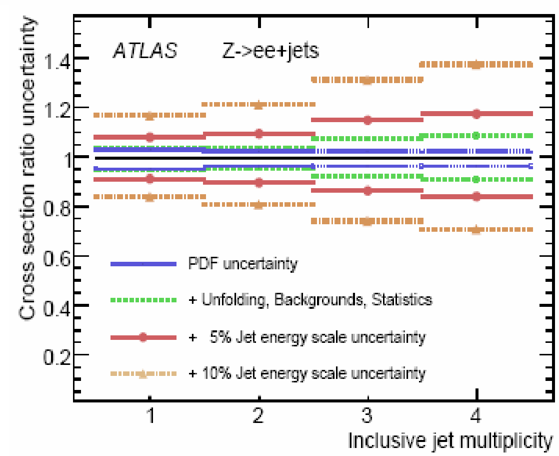
$\sigma(Z + (n+1)\ \mathrm{Jets})/\sigma(Z + n\ \mathrm{Jets}) \sim \alpha_s$

Z+Jets production is important:

- Test of perturbative QCD
- Important backgrounds for SM and BSM physics
- Test of performance of MC event generators

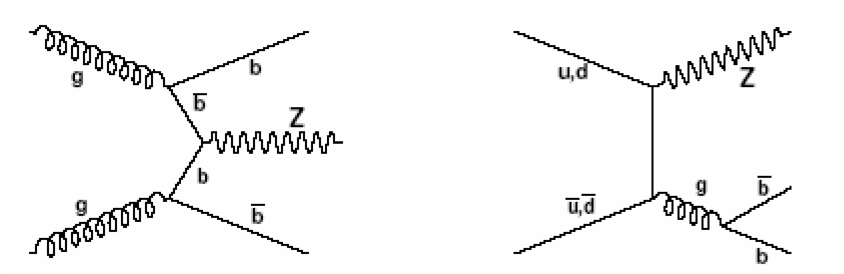




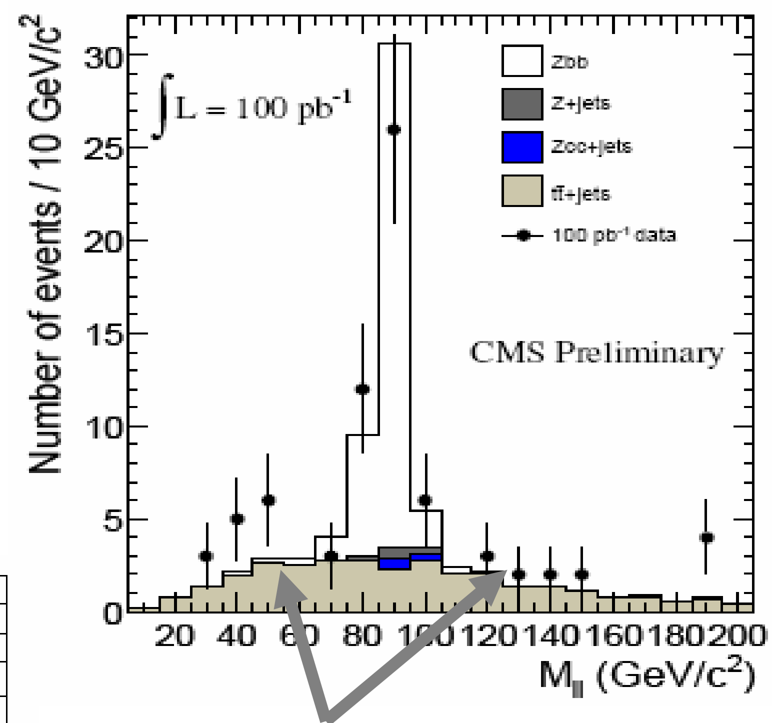


Z+Jets Cross-Sections (III)

$Zb\bar{b}, Z \to \ell\ell$ at 100pb^{-1} and 14TeV



Source of uncertainty	value used (%)	$\delta(\sigma(Zbb))$ (%)
jet energy scale (JES)	7	7.6
Type 1 missing E_T scale	10 (unclustered E_T^{miss}) + 7 (JES)	7.4
MC p_T^{jet}, η^{jet} dependence	-10,+0	-10,+0
b-tagging of b-jets ($\delta\varepsilon_b$)	8	16
mistagging of c-jets ($\delta\varepsilon_c$)	8	0.5
mistagging of light jets ($\delta\varepsilon_\ell$)	7.6	0.5
$N_Z^{after\ b-tag}$ due to $t\bar{t}$ background subtraction	4	4.6
R	5	0.4
lepton selections	0.5	0.5
luminosity	10	10



Side – bands used to estimate the top background from data

$$\delta\sigma = \pm 15\%(stat) \pm^{21\%}_{25\%} (sys)$$

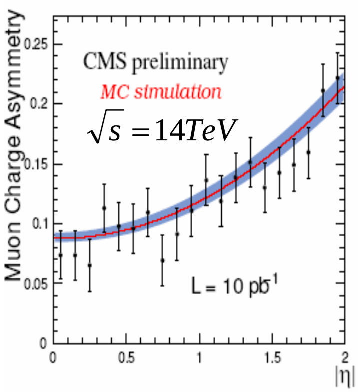
pp→W(μν)+X charge asymmetry

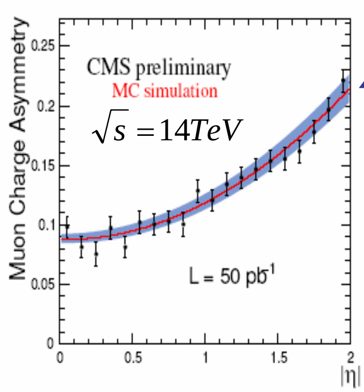
The current PDFs predict an excess of W^+ over W^- production with average charge ratio of 1.5 because protons have two u-type valence quarks

- ➢ A(η) is rather insensitive to systematics
- ➢ Can be used to distinguish between different PDFs

$$A(\eta)=\frac{\frac{d\sigma}{d\eta}(W^+\rightarrow\mu^+\nu)-\frac{d\sigma}{d\eta}(W^-\rightarrow\mu^-\nu)}{\frac{d\sigma}{d\eta}(W^+\rightarrow\mu^+\nu)+\frac{d\sigma}{d\eta}(W^-\rightarrow\mu^-\nu)}$$

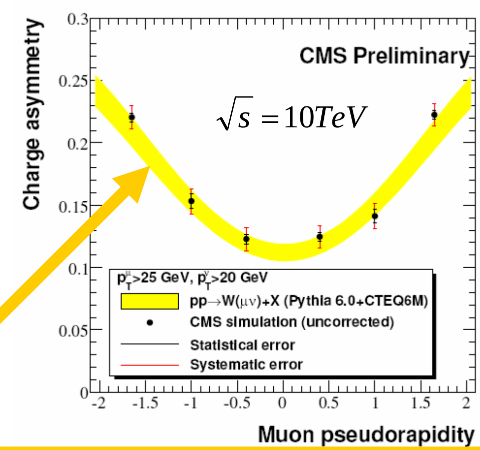
❑ Selection criteria the same as for the W→μν cross section measurement





Blue Band PDF uncertainties from CTEQ6

Statistical uncertainties only



► Promising since can constrain current PDF sets already with 50pb^{-1} at 14TeV

Recent Result : A(η) can constrain current PDF sets already with 100pb^{-1} at 10TeV

Z Boson FB asymmetry (A_{FB})

- In pp collisions, e^+e^- pairs are predominantly produced via $q\bar{q}$ annihilation
- In SM there is an asymmetry (A_{FB}) in the polar emission angle (θ) of the electron relative to the quark momentum vector in the e^+e^- rest frame

A_{FB} measurement is important:

- **improve the knowledge of SM parameters (weak mixing angle - $\sin^2\theta_{eff}^{lept}$). Expect linear dependence between A_{FB} and $\sin 2\theta_{eff}^{lept}$ around Z pole**
- **test the physics BSM (if performed in higher mass)**

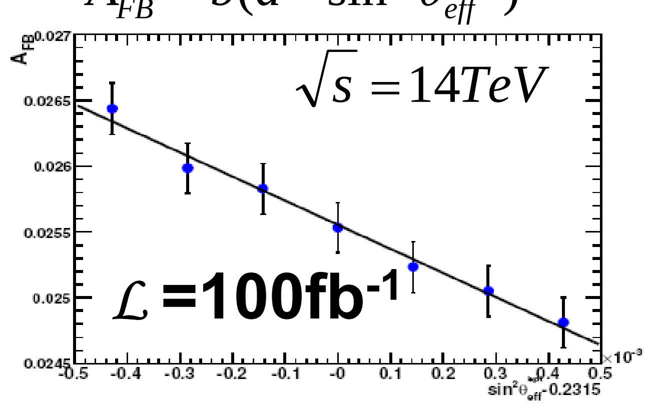
$$A_{FB} = \frac{N_F - N_B}{N_F + N_B}$$

N_F: Forward produced events (cosθ>0)

N_B: Backward produced events (cosθ<0)

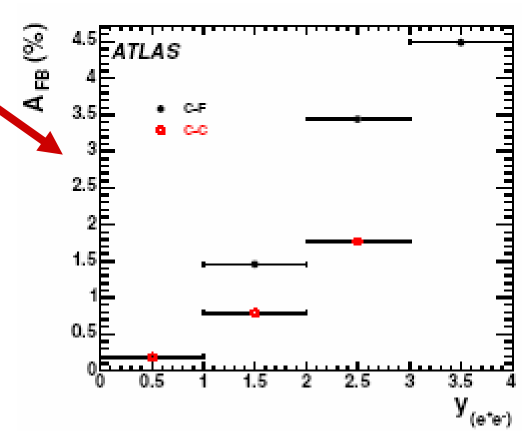
A_{FB} measurement done around Z mass using either both electrons to be in the central region (C-C) or one in the central and the other in the Forward Calorimeters (2.5<|η|<4.9) (C-F)

$$A_{FB} = b(a - \sin^2\theta_{eff}^{lept})$$



$$\delta \sin^2\theta_{eff}^{lept} = (1.5(\text{stat}) \pm 0.3(\text{exp}) \pm 2.4(\text{PDF})) \times 10^{-4}$$

Electron ID efficiency in the Forward Region 80% with < 3% QCD background using multivariate analysis



A_{FB} very sensitive to the electron acceptance

Summary

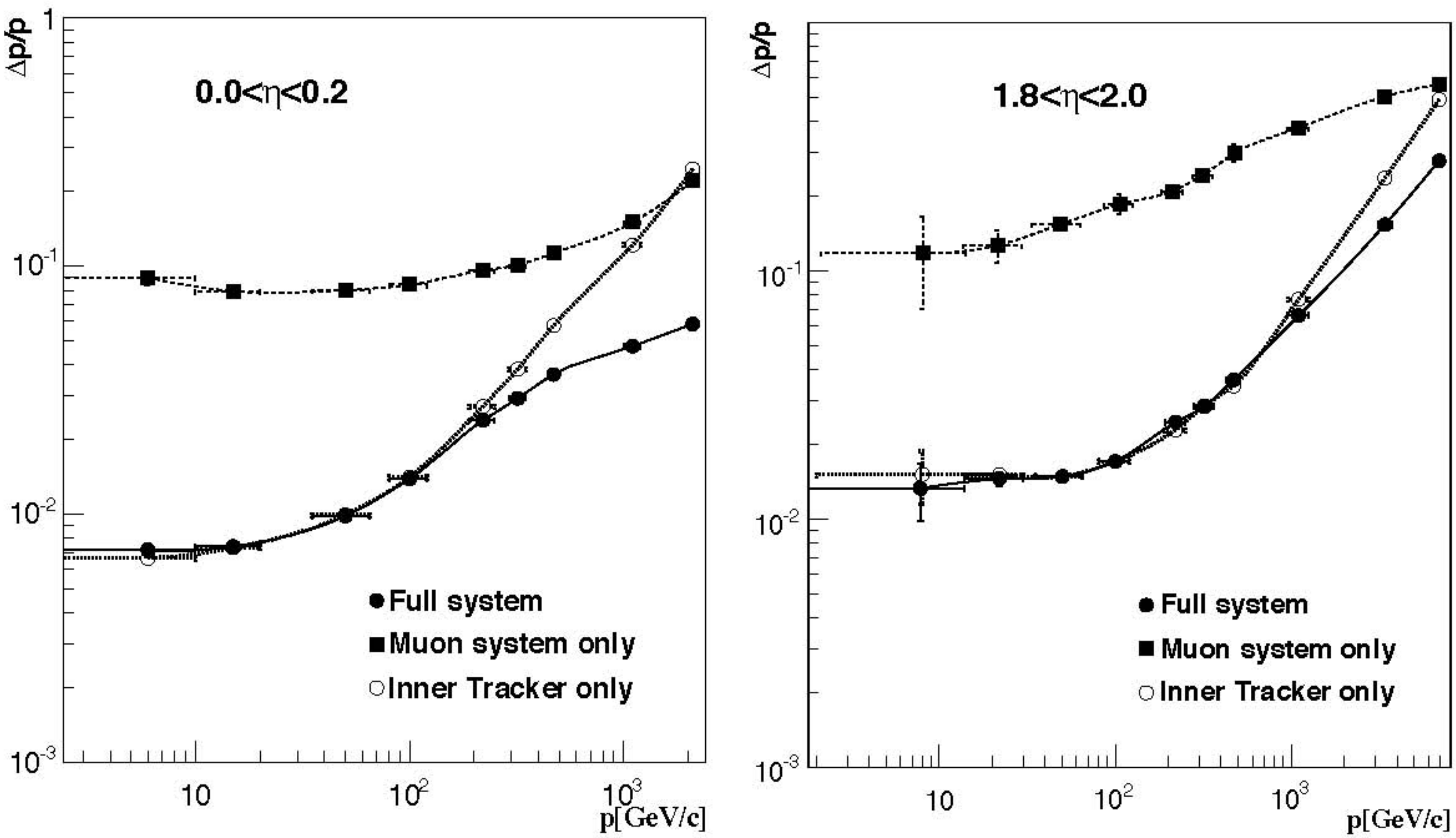
- Inclusive Z/W cross section measurements studies performed in both ATLAS and CMS LHC experiments
- Data Driven methods tested for extracting the efficiencies and QCD background
- Together with Z/W+Jets and W charge asymmetry studies present a robust start-up program
- The control of the SM EWK processes gives a significant confidence for New Physics studies

References

- For CMS: https://twiki.cern.ch/twiki/bin/view/CMS/PhysicsResults
- For ATLAS: http://cdsweb.cern.ch/record/1125884/files/CERN-OPEN-2008-020.pdf?version=5

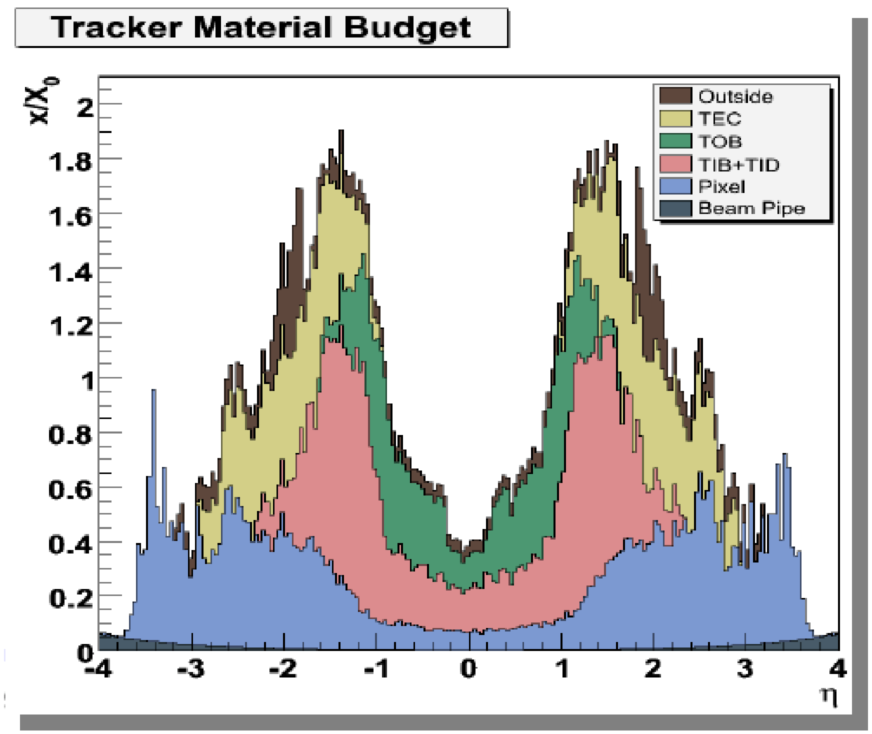
BACK-UP SLIDES

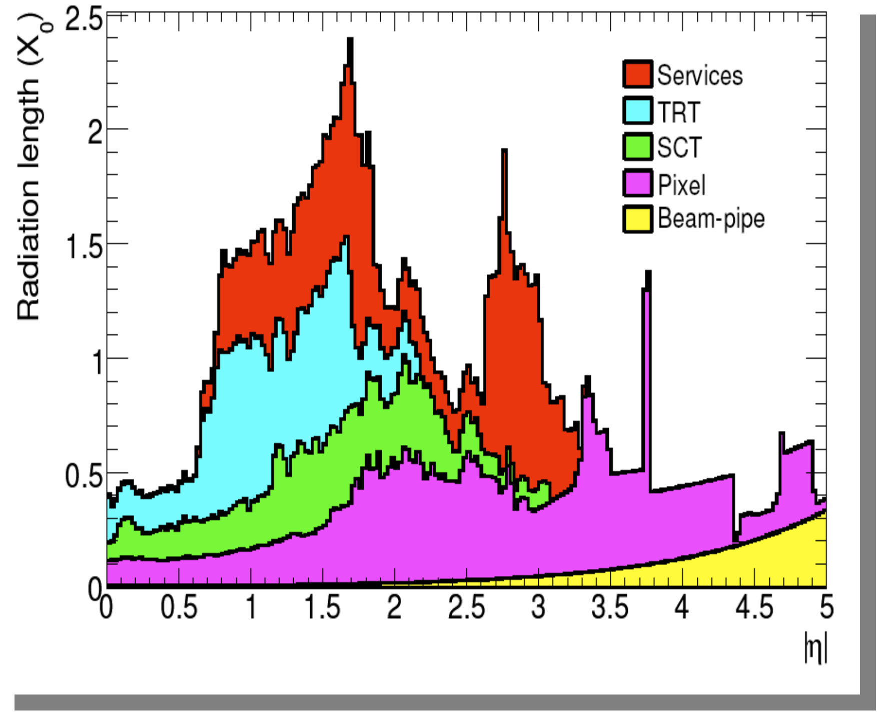
CMS Muon System P_t resolution



- ➢Muon system resolution dominated by multiple scattering in iron for Pt<200 GeV
  - ➢Tracker alone gives best result, except at high Pt

Material Budget





CMS material budget vs η

ATLAS material budget vs η

ATLAS Required Performance

Detector component	Required resolution	η coverage	
		Measurement	Trigger
Tracking	$\sigma_{p_T}/p_T = 0.05\%\ p_T \oplus 1\%$	± 2.5	
EM calorimetry	$\sigma_E/E = 10\%/\sqrt{E} \oplus 0.7\%$	± 3.2	± 2.5
Hadronic calorimetry (jets)			
barrel and end-cap	$\sigma_E/E = 50\%/\sqrt{E} \oplus 3\%$	± 3.2	± 3.2
forward	$\sigma_E/E = 100\%/\sqrt{E} \oplus 10\%$	$3.1 < \lvert\eta\rvert < 4.9$	$3.1 < \lvert\eta\rvert < 4.9$
Muon spectrometer	σ_{p_T}/p_T=10% at p_T = 1 TeV	± 2.7	± 2.4

Table 1. General performance goals of the ATLAS detector. Note that, for high-p_T muons, the muon-spectrometer performance is independent of the inner-detector system. The units for E and p_T are in GeV.

Z→e$^+$e$^-$ inclusive x-sec at CMS

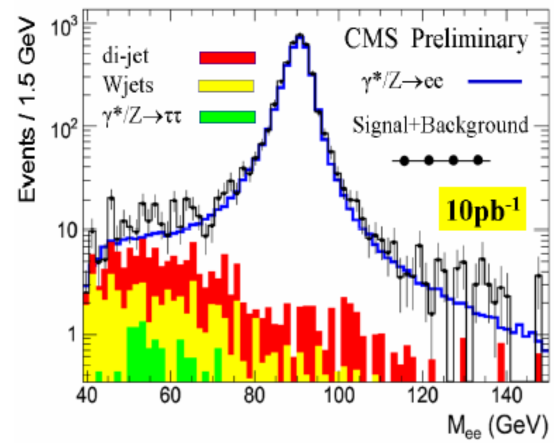
Z→e$^+$e$^-$

- At least one of the Electrons should fired the trigger
- Two electrons with P_t > 20GeV, $|\eta|$ < 2.5
- Electron Isolation from tracker, (ΣP_t of the tracks/P_t^e)^2 < 0.02 (in cone 0.02<ΔR <0.6)

Definition of "robust" electron identification criteria.

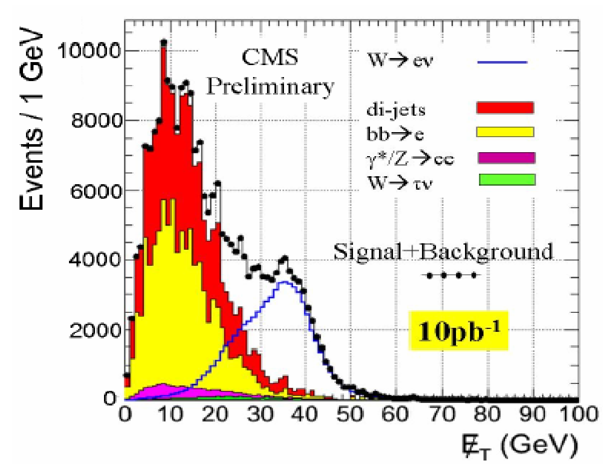
	H/E	$\sigma_{\eta\eta}$	$\Delta\phi_{in}$	$\Delta\eta_{in}$
Barrel	0.115	0.0140	0.090	0.0090
Endcap	0.150	0.0275	0.092	0.0105

$$\sqrt{s} = 14TeV$$



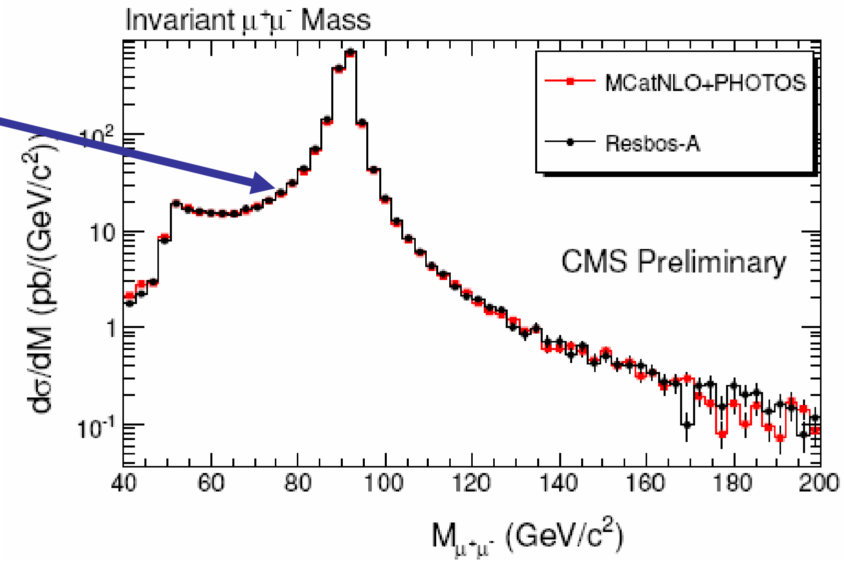
W→eν

- Electron fired the trigger
- One electron with P_t > 20GeV, $|\eta|$ < 2.5
- Electron Isolation from tracker as in the Z →e$^+$e$^-$ case

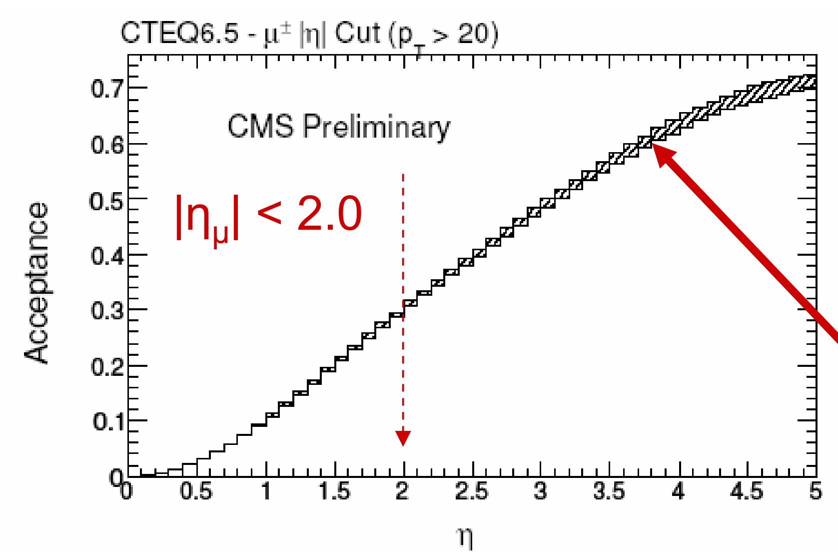


Theoretical Uncertainties

Comparison between MC@NLO+PHOTOS and ResBos-A that includes final state NLO QED corrections to Z/W production and NNLO logarithmic re-summation of soft and collinear QCD radiation



MC@NLO+PHOTOS Generator guaranties an overall theoretical uncertainty on the experimentally measured acceptance at the percent level



$Z/\gamma^* \rightarrow \mu+\mu-$ acceptance vs $|\eta|$ cut

Theoretical uncertainty band due to the limited precision of the used PDF

ABCD Mathematics (I)

$$I = S_{A+B}/S_{A+B+C+D} \quad \rightarrow \quad I/(1.0 - I) = S_{A+B}/S_{C+D} \qquad (1)$$

$$S_{A+B} = (F_Z + 1.0)S_B \qquad (2)$$

$$S_{C+D} = (F'_Z + 1.0)S_C \qquad (3)$$

Each N has three components: W events, QCD and electroweak (EWK) background events.

Assuming that $F'_{QCD} = F_{QCD}$ we get:

$$F_{QCD} = F'_{QCD} = \frac{N_D - EWK_D - S_D}{N_C - EWK_C - S_C} = \frac{N_D - EWK_D - F'_Z S_C}{N_C - EWK_C - S_C} = (1),(3) =$$

$$\frac{(F'_Z + 1.0)I(N_D - EWK_D) - F'_Z(1.0 - I)S_{A+B}}{(F'_Z + 1.0)I(N_C - EWK_C) - (1.0 - I)S_{A+B}} \qquad (4)$$

ABCD Mathematics (II)

In a similar manner:

$$F_{QCD} = \frac{N_A - EWK_A - S_A}{N_B - EWK_B - S_B} = \frac{N_A - EWK_A - F_Z S_B}{N_B - EWK_B - S_B} = (2) = \frac{N_A - EWK_A - F_Z(S_{A+B}/(F_Z + 1.0))}{N_B - EWK_B - (S_{A+B}/(F_Z + 1.0))} \rightarrow$$

$$S_{A+B} = \frac{1.0 + F_Z}{F_Z - F_{QCD}}[N_A - EWK_A - F_{QCD}(N_B - EWK_B)] \quad (5)$$

Combining (4),(5) leads to an equation of the type: $aS_{A+B}^2 + bS_{A+B} + c = 0.0$

with

$$a = (1.0 - I)(F_Z' - F_Z)$$

$$b = I(F_Z' + 1.0)[Fz(N_C - EWK_C) - (N_D - EWK_D)] + (1 + F_Z)(1 - I)[(N_A - EWK_A) - F_Z'(N_B - EWK_B)]$$

$$c = I(1 + F_Z)(1 + F_Z')[(N_D - EWK_D)(N_B - EWK_B) - (N_A - EWK_A)(N_C - EWK_C)]$$

Then

$$if \quad F_Z' = / = F_Z \quad we\ get \ S_{A+B} = (-b \pm SQRT(b^2 - 4ac))/2a$$

$$if \quad F_Z' = F_Z \quad we\ get \ S_{A+B} = -c/b$$