# Precision measurements in the EW sector: synopsis

- I don't remember when I last gave a talk including data from my experiment (probably around 1988-1989) when already working almost full time towards LHC

→ a short historical perspective

- W/Z properties at the Tevatron and LHC

→ differential measurements and sensitivity to pdfs

→ W/Z transverse momentum measurements

- Dibosons at the Tevatron and LHC

→ towards differential cross-sections (higher statistics needed!)

→ sensitivity to anomalous couplings

- Precision EW measurements at the Tevatron and LHC:

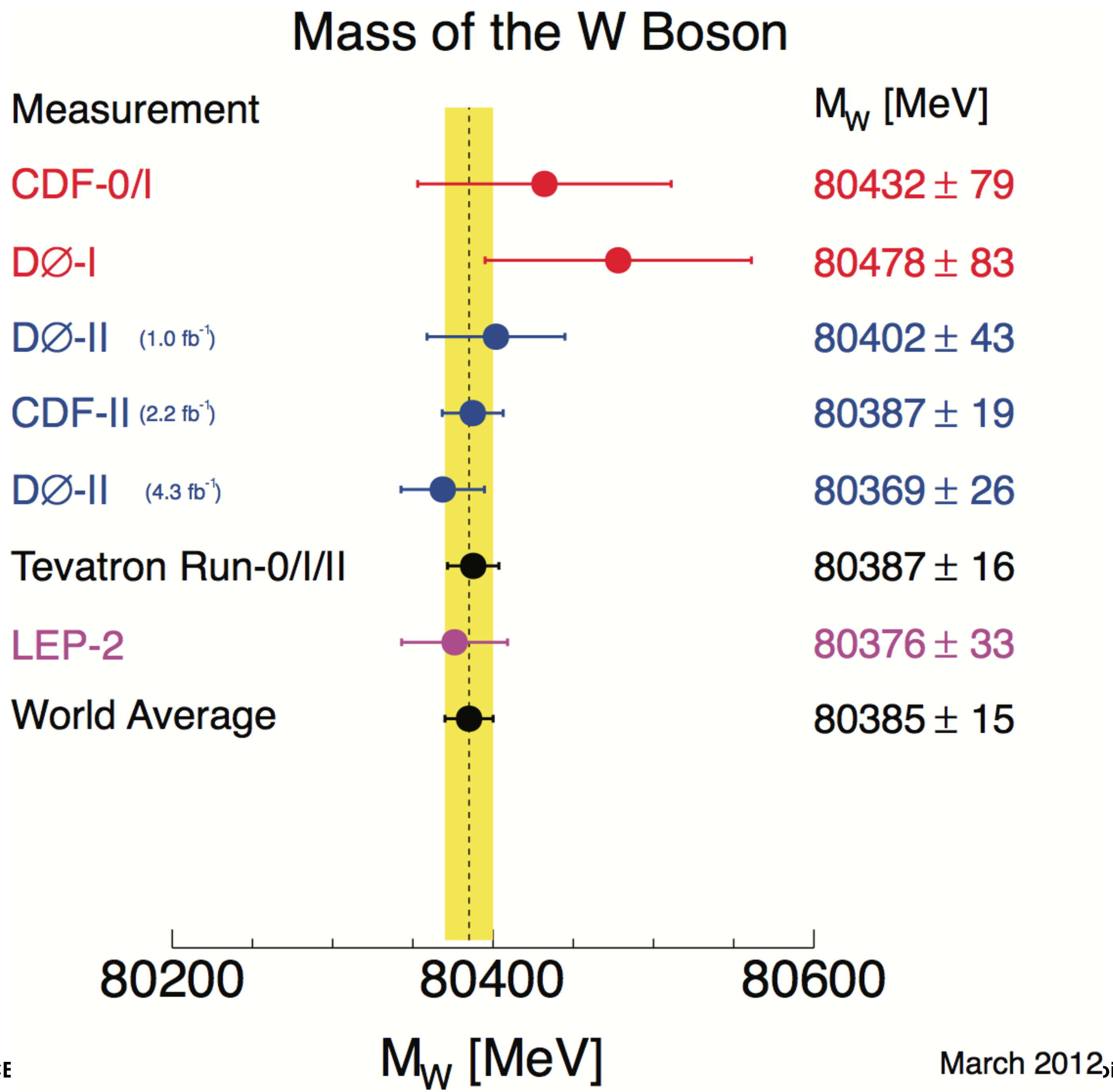
→ recent measurement of $A_{FB}$ and $\sin^2\theta_w$ by D0/CMS

→ recent measurements of $m_W$ by CDF and D0

→ prospects for future precision measurements at the LHC

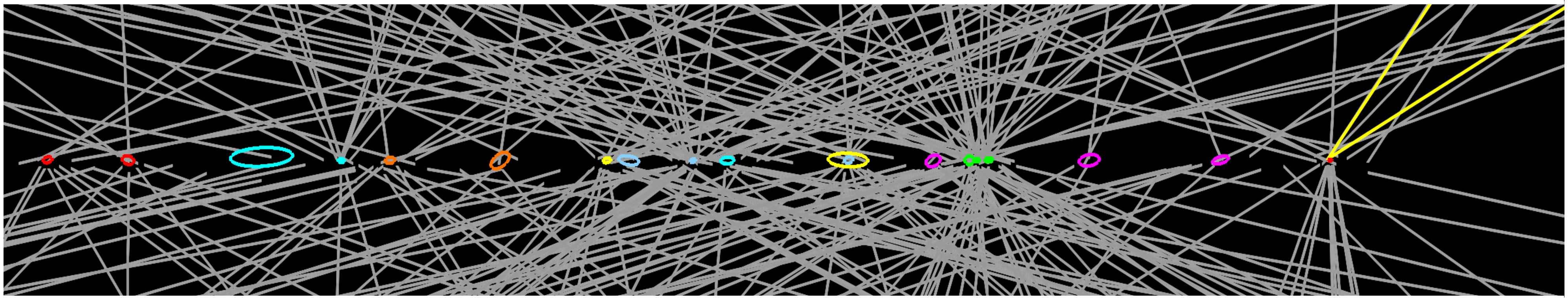
**See talks by M. Pioppi, E. Le Menedeu, M. Cooke and C. Hays in EW parallel session this afternoon, many more results will be shown!**

# Precision measurements in the EW sector: synopsis



# Precision measurements in the EW sector: an overview

- **Will cover recent results from Tevatron and LHC with some historical perspective on hadron colliders**
- **Will discuss future prospects for such measurements at the LHC in the context of a possible discovery of the Higgs boson**
- **2011: achieved $L_{max} \sim 3.4\ 10^{33}$, $L_{tot} \sim 5\ fb^{-1}$ at 7 TeV**
- **2012: already achieved $L_{max} \sim 6.7\ 10^{33}$, $L_{tot} \sim 3.3\ fb^{-1}$ at 8 TeV**
- **Very high average number of interactions excellent for discovery reach, but not so good for precision EW physics!**



**Example of Z → μμ decay in ATLAS with 20 reconstructed vertices. Total scale along z is ~ ± 15 cm, $p_T$ threshold for track reco is 0.4 GeV (ellipses have size of 20σ for visibility).**

**In 2012, reach maximum of ~ 40 interactions per BX at L ~ 6 $10^{33}$!**

# Historical perspective: the 80's in UA1/UA2 at the SppS

## From the beginning, with the observation of two-jet dominance and of 4 W → eν and 8 Z → $e^+e^-$ decays

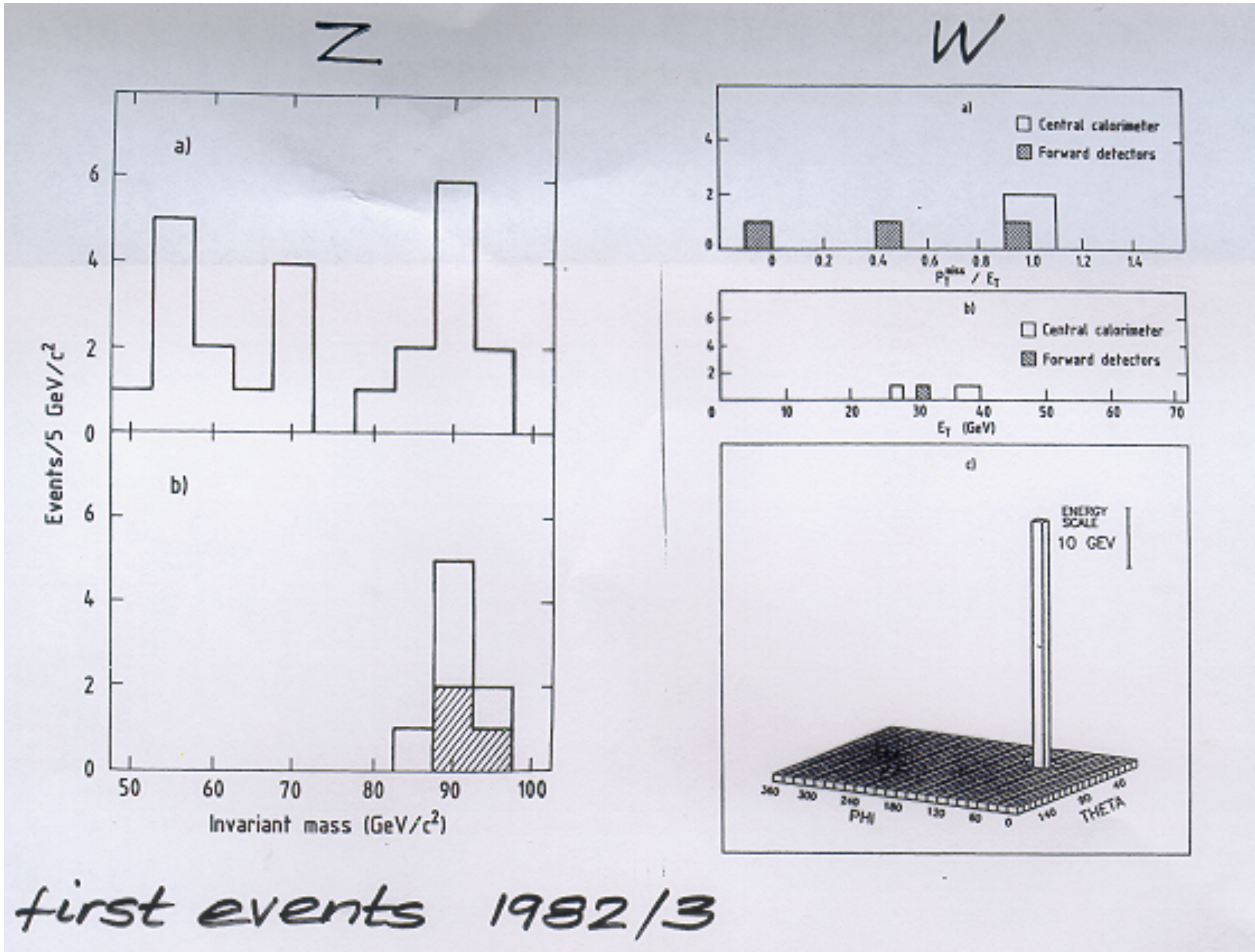
## $\sqrt{s}$ = 546 GeV, L ~ $10^{29}$ $cm^{-2}s^{-1}$

**UA2 was perceived as large at the time:**

- ♥ 10-12 institutes
- ♥ from 50 to 100 authors
- ♥ cost ~ 10 MCHF
- ♥ duration 1980 to 1990

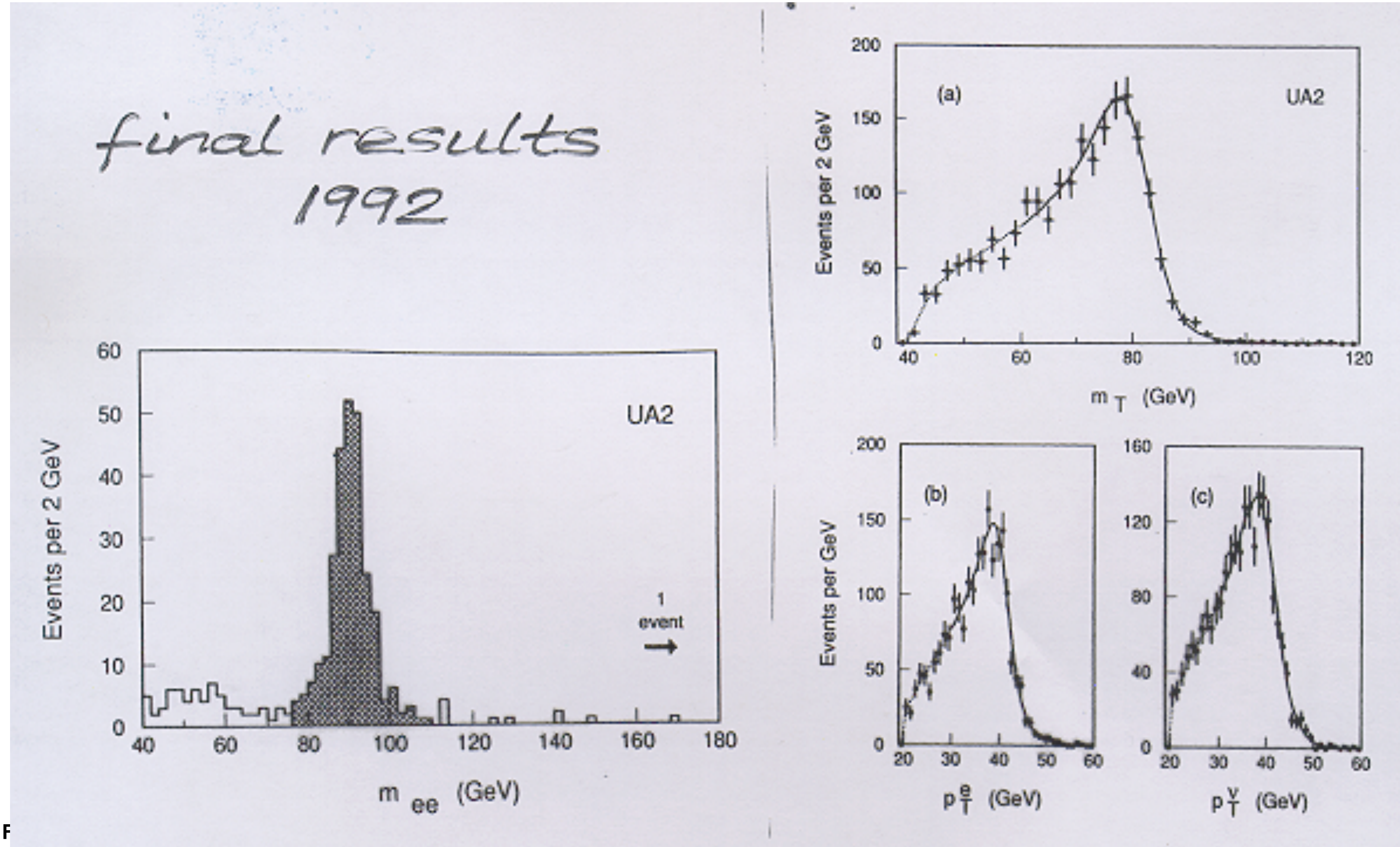
**Physics analysis was organised in two groups:**

1. Electrons → electroweak
2. Jets → QCD

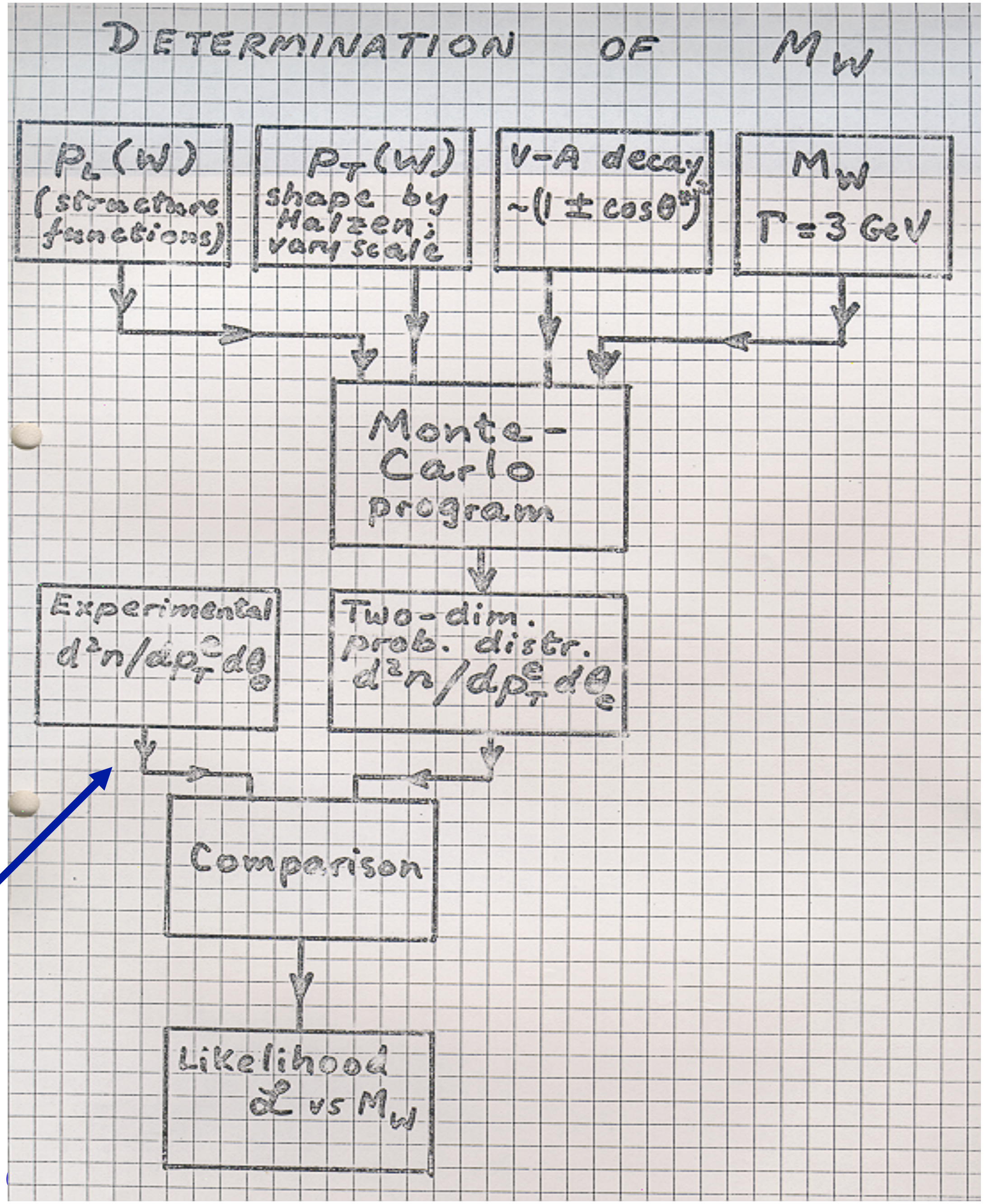


# Historical perspective: the 80's in UA1/UA2 at the SppS

## To the end, with first accurate measurements of the W/Z masses and the search for the top quark and for supersymmetry

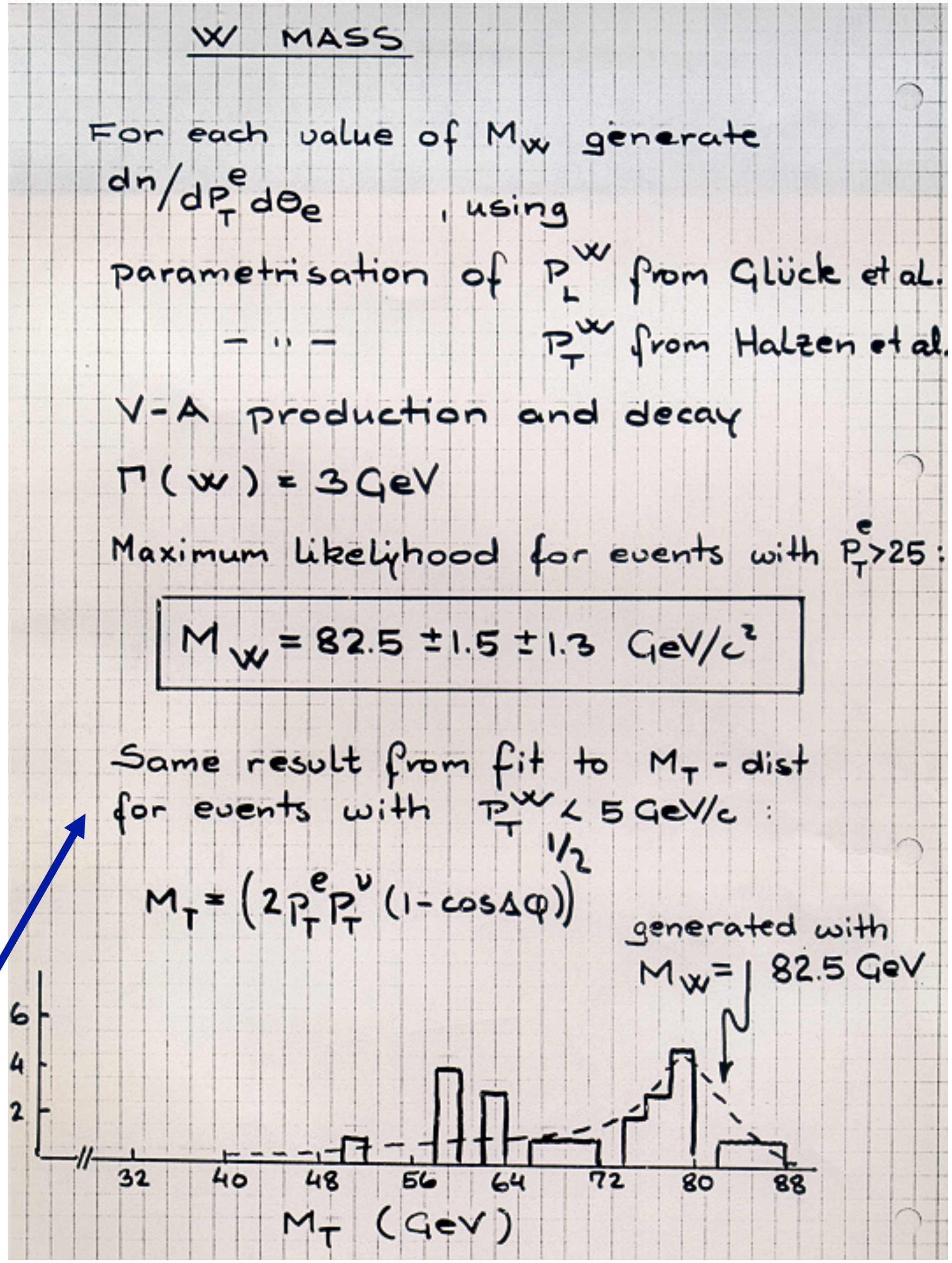


# Historical perspective: the 80's in UA1/UA2 at the SppS




**Software design in UA2**

# Historical perspective: the 80's in UA1/UA2 at the SppS



W MASS

For each value of $M_W$ generate $dn/dP_T^e d\Theta_e$, using

parametrisation of $P_L^W$ from Glück et al.

— " — $P_T^W$ from Halzen et al.

V-A production and decay

$\Gamma(W) = 3$ GeV

Maximum likelihood for events with $P_T^e > 25$:

$$M_W = 82.5 \pm 1.5 \pm 1.3 \text{ GeV}/c^2$$

Same result from fit to $M_T$-dist for events with $P_T^W < 5$ GeV/c:

$$M_T = \left(2 P_T^e P_T^\nu (1 - \cos\Delta\varphi)\right)^{1/2}$$



**Software documentation in UA2**

# Historical perspective: the 80's in UA1/UA2 at the SppS

## 1984-1985 were exciting (and confusing) times!
## Beware false positive signals!!

Over-abundance of Z → eeγ events

Monojets

Dijets with missing $E_T$

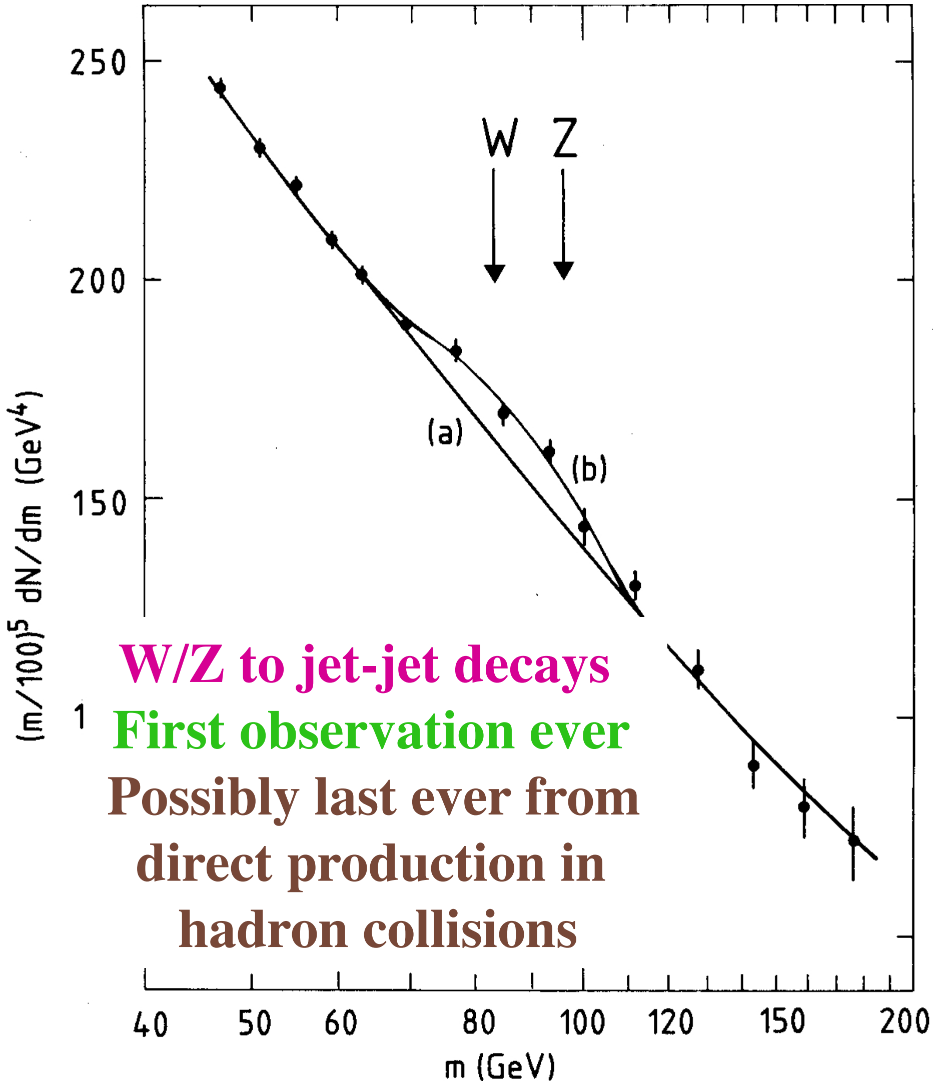
High-$p_T$ electrons with jets and missing $E_T$

Top quark "discovery"

Bumps in distributions
(jet-jet mass in UA2,
W decay electron spectrum in UA1)

# Historical perspective: the 80's in UA1/UA2 at the SppS

We have presented evidence for a signal, at the level of ≃ 3 standard deviations above the copious and steeply falling strong interaction background, in agreement with Standard Model expectations for W and Z bosons decaying into two quark jets. It contains 632 ± 190 events, 1.4 standard deviations above the expectation of 340 ± 80 events. Stronger evidence for the signal and a significant quantitative measurement of the W,Z → $q\bar{q}$ branching fractions will require the collection of a significantly larger data sample [18].

# Historical perspective: the 80's in UA1/UA2 at the SppS

## First ever EW fits in UA2 before LEP turned on

From these events we measure the mass of the $Z^o$ boson to be :

$$M_Z = 91.9 \pm 1.3 \pm 1.4 \text{ GeV/c}^2 \quad (2)$$

where the first error accounts for measurement errors and the second for the uncertainty on the overall energy scale.

The rms of this distribution is 2.6 GeV/c$^2$, consistent with the expected $Z^o$ width[14] and with our experimental resolution of $\sim$ 3%.

Under the hypothesis of Breit-Wigner distribution we can place an upper limit on its full width

$$\Gamma < 11 \text{ GeV/c}^2 \quad (90\% \text{ CL}) \quad (3)$$

corresponding to a maximum of $\sim$ 50 different neutrino types in the universe[15].

The standard SU(2) × U(1) electroweak model makes definite predictions on the $Z^o$ mass. Taking into account radiative corrections to 0 ($\alpha$) one finds[14]

$$M_Z = 77 \rho^{-\frac{1}{2}} (\sin 2\theta_W)^{-1} \text{ GeV/c}^2 \quad (4)$$

where $\theta_W$ is the renormalised weak mixing angle defined by modified minimal subtraction, and $\rho$ is a parameter which is unity in the minimal model.

Assuming $\rho = 1$ we find

$$\sin^2\theta_W = 0.227 \pm 0.009 \quad (5)$$

However, we can also use the preliminary value of the W mass found in this experiment[16]

$$M_W = 81.0 \pm 2.5 \pm 1.3 \text{ GeV/c}^2.$$

Using the formula[14]

$$M_W = 38.5 (\sin \theta_W)^{-1} \text{ GeV/c}^2 \quad (6)$$

we find $\sin^2\theta_W = 0.226 \pm 0.014$, and using also Eq. (4) and our experimental value of $M_Z$ we obtain

$$\rho = 1.004 \pm 0.052 \quad (7)$$

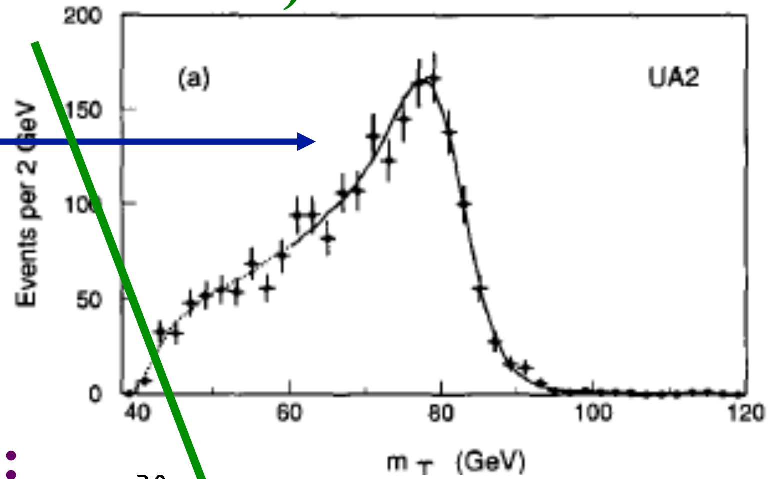
# Historical perspective: the 80's in UA1/UA2 at the SppS

**Most important results from 1987-1990 campaign with UA2:**

**precise measurement of $m_W/m_Z$**

**and direct limit on top-quark mass ($m_{top}$ < 60 GeV)**

**Transverse mass distribution for electron-neutrino pairs**




$$\frac{m_W}{m_Z} = 0.8813 \pm 0.0036 \pm 0.0019$$

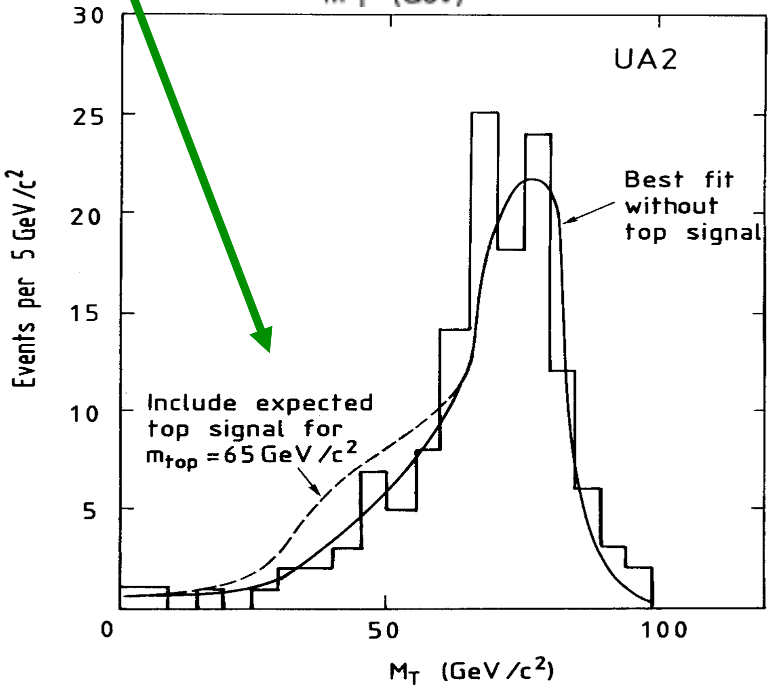
**Using the precise measurement of $m_Z$ (LEP):**

$$m_W = 80.35 \pm 0.33 \pm 0.17 \text{ GeV}$$

**→ Indirect limits on top-quark mass in the context of the Standard Model:**

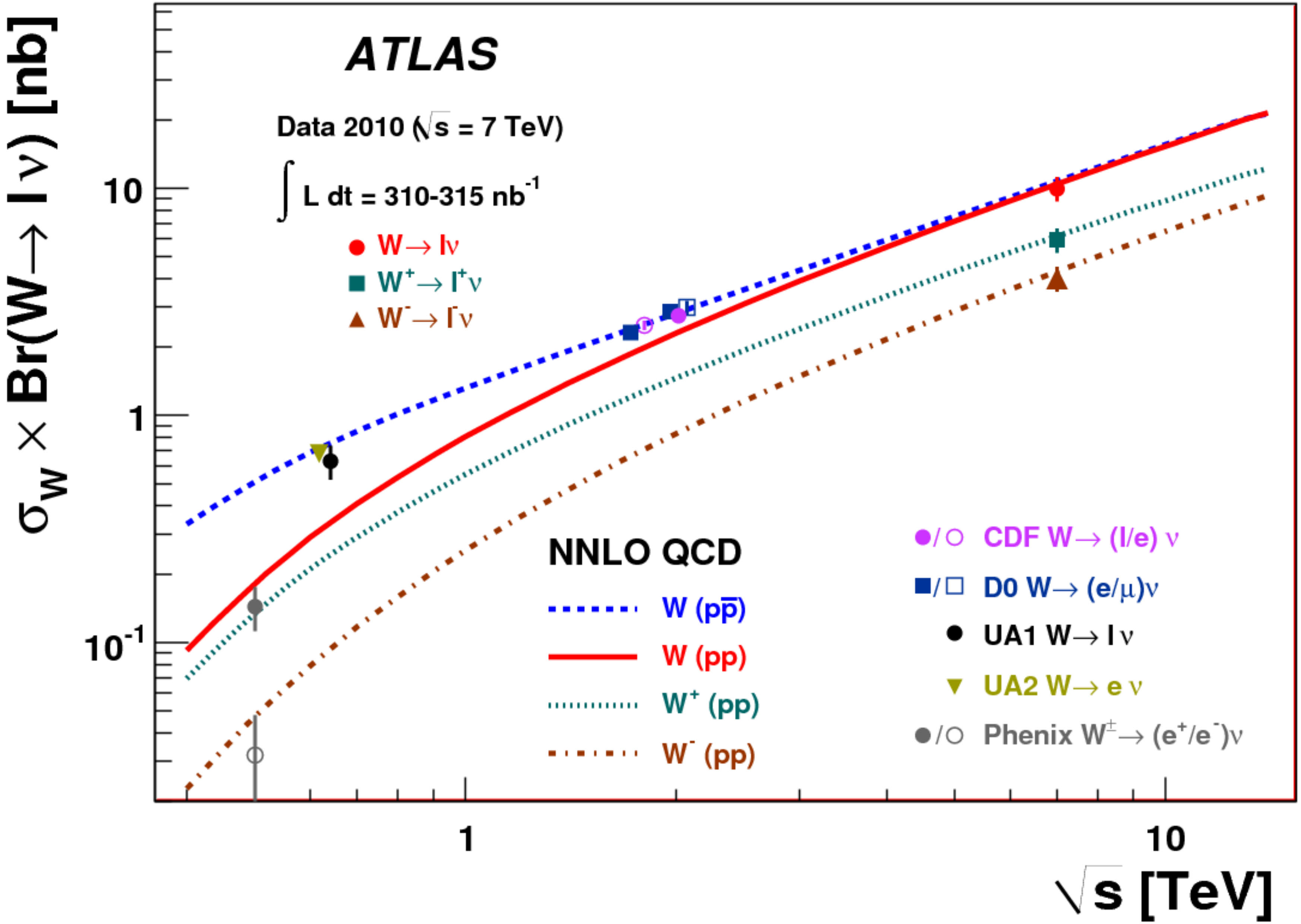
$$m_{top} = 160^{+50}_{-60} \text{ GeV}$$

**(four years before the discovery of the top quark at Fermilab)**



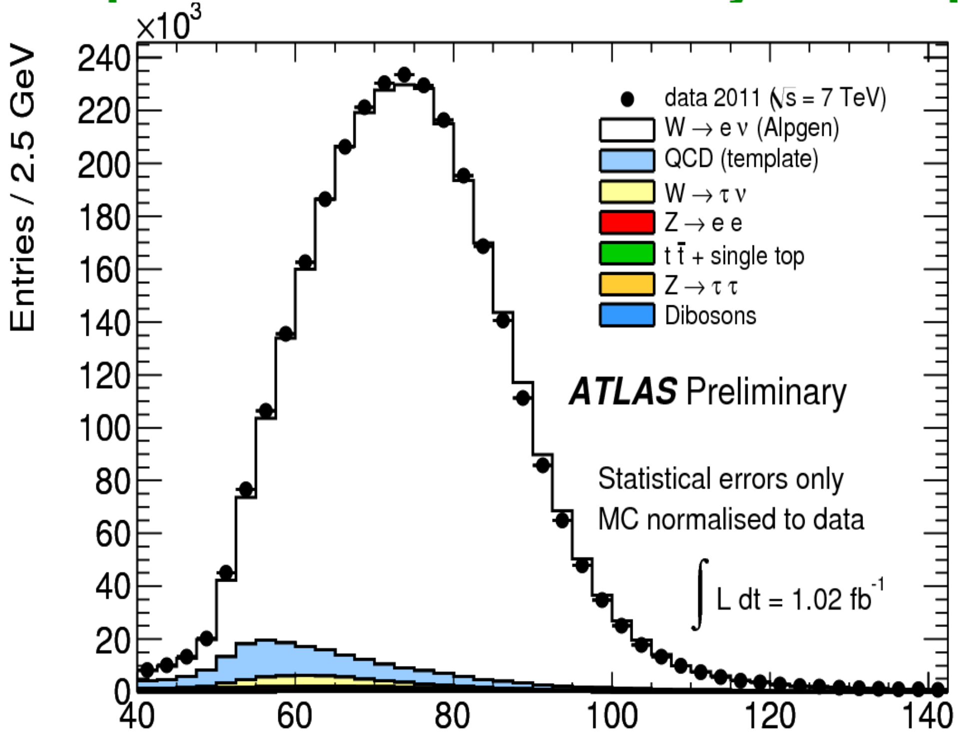
# Historical perspective: first run at 7 TeV in 2010

## First W/Z events seen in April-May 2010 were very exciting!

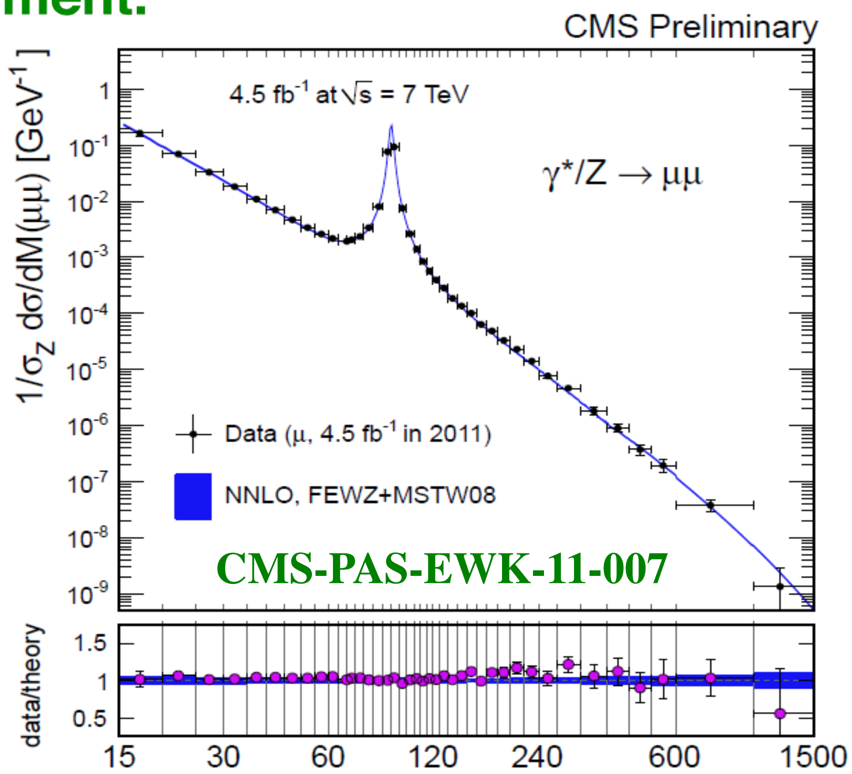


# W/Z differential measurements

- ATLAS and CMS have published 2010 data a while ago: excellent training for 2011 analysis which will be a precision test of theoretical predictions.
- For 5 $fb^{-1}$ at 7 TeV, have ~ 25M W to e/$\mu\nu$ decays, 3M Z to ee/$\mu\mu$ decays, and 0.8M Z to ee decays with one forward electron (2.5 < |$\eta$| < 4.9)
- NNLO tools to predict fiducial cross-sections (FEWZ, DYNNLO) are extremely powerful and provide the means for high-precision comparisons between theory and experiment.




$m_T^{e\nu}$ for W to e$\nu$ in ATLAS (1.0 $fb^{-1}$)




$m_{\mu\mu}$ for Z to $\mu\mu$ in CMS (4.5 $fb^{-1}$)

# W/Z differential measurements

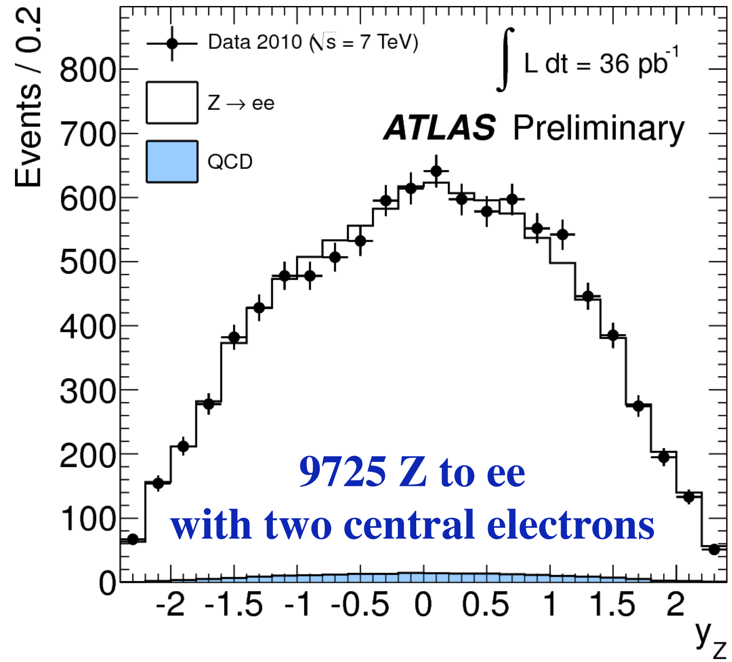
- A certain number of interesting lessons learned already:
  - Full set of differential distributions for $W^+$, $W^-$, and Z will provide strong constraints on theoretical predictions and in particular on pdfs.
    Very promising for 2011/2012 analysis!
  - Measurements will benefit from significant decrease of experimental systematic uncertainties on efficiencies and $E_T^{miss}$ for ratios and also of luminosity for absolute measurements

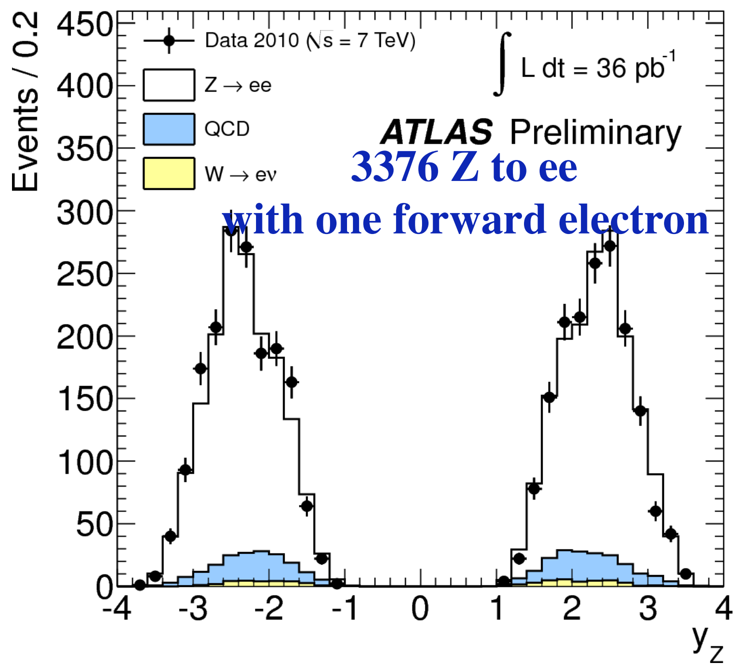
| Uncertainty Source | $\delta\mathcal{L}/\mathcal{L}$ |
|---|---|
| Statistical | $< 0.1\%$ |
| Bunch charge product | 3.1% |
| Beam centering | 0.1% |
| Emittance growth and other non-reproducibility | 0.4% |
| Beam position jitter | 0.2% |
| Length scale calibration | 0.3% |
| Absolute ID length scale | 0.3% |
| Fit model | 0.2% |
| Transverse correlations | 0.9% |
| $\mu$ dependence | 0.6% |
| Long-term consistency | 0.5% |
| Total | 3.4% |

0.35% !!

Experimental systematics are now dominant for luminosity determination

CMS already quote total uncertainty of 2% on luminosity for 2011 results



# W/Z differential measurements

- A certain number of interesting lessons learned already:
  - Full set of differential distributions for $W^+$, $W^-$, and Z will provide strong constraints on theoretical predictions and in particular on pdfs. Very promising for 2011/2012 analysis!

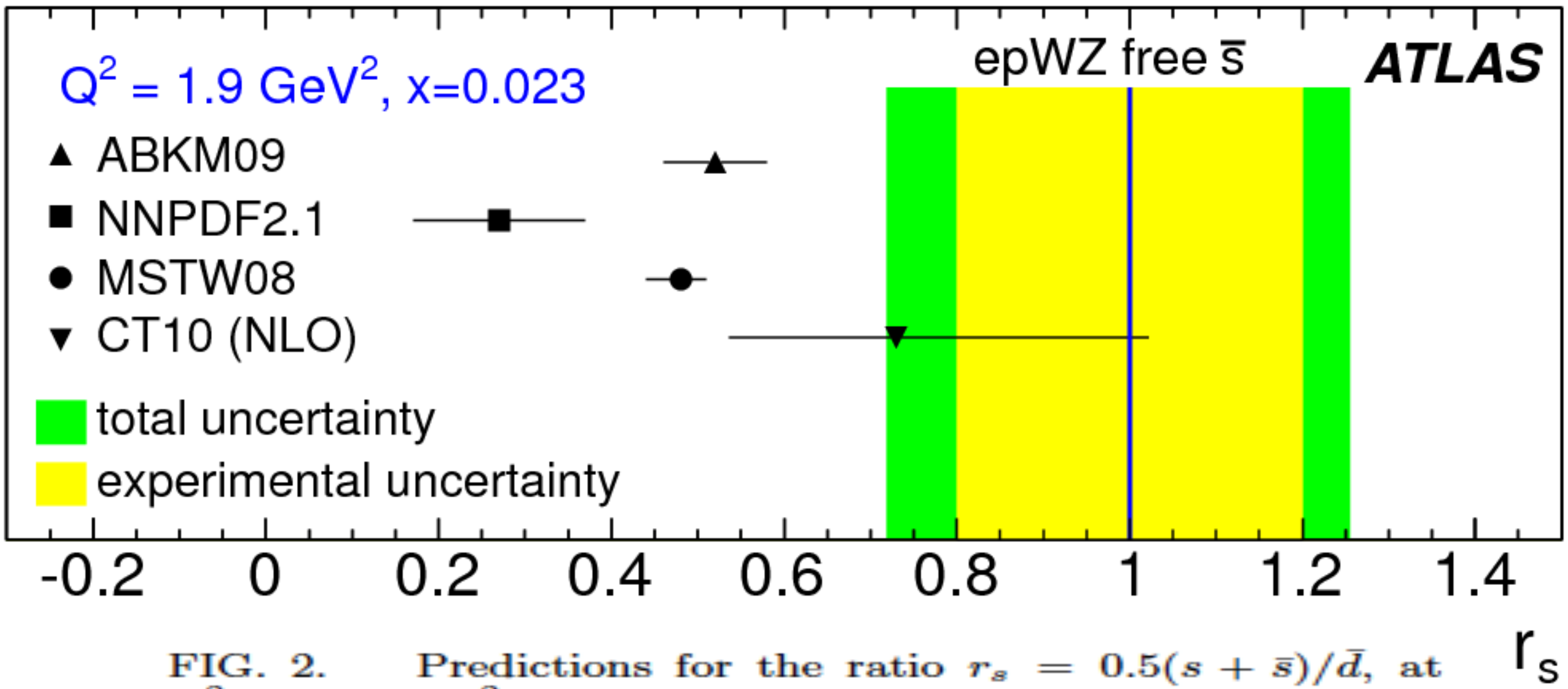



FIG. 2. Predictions for the ratio $r_s = 0.5(s + \bar{s})/\bar{d}$, at $Q^2 = 1.9\,\mathrm{GeV}^2$, $x = 0.023$. Points: global fit results using the PDF uncertainties as quoted; bands: this analysis; inner band, experimental uncertainty; outer band, total uncertainty.

# W/Z differential measurements

- Fiducial measurements provide already now a more precise test of QCD predictions, at least in terms of pdfs, than when they are corrected back to the total cross-sections

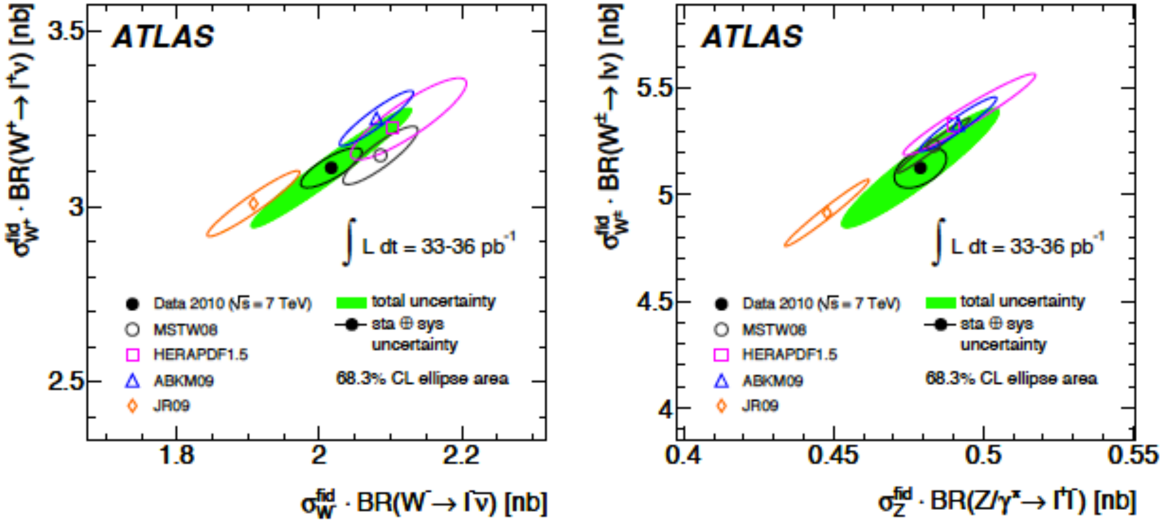



FIG. 15. *Measured and predicted fiducial cross sections times leptonic branching ratios, $\sigma_{W+}$ vs. $\sigma_{W-}$ (left) and ($\sigma_{W+} + \sigma_{W-}$) vs. $\sigma_{Z/\gamma^*}$ (right). The ellipses illustrate the 68 % CL coverage for total uncertainties (full green) and excluding the luminosity uncertainty (open black). The uncertainties of the theoretical predictions are the PDF uncertainties only.*

- Reducing the size of the error bars on the major axes of these ellipses is the challenge ATLAS and CMS are working on now!

Note that the green ellipse is dominated by the uncertainty on the luminosity measurement which will surely shrink substantially.

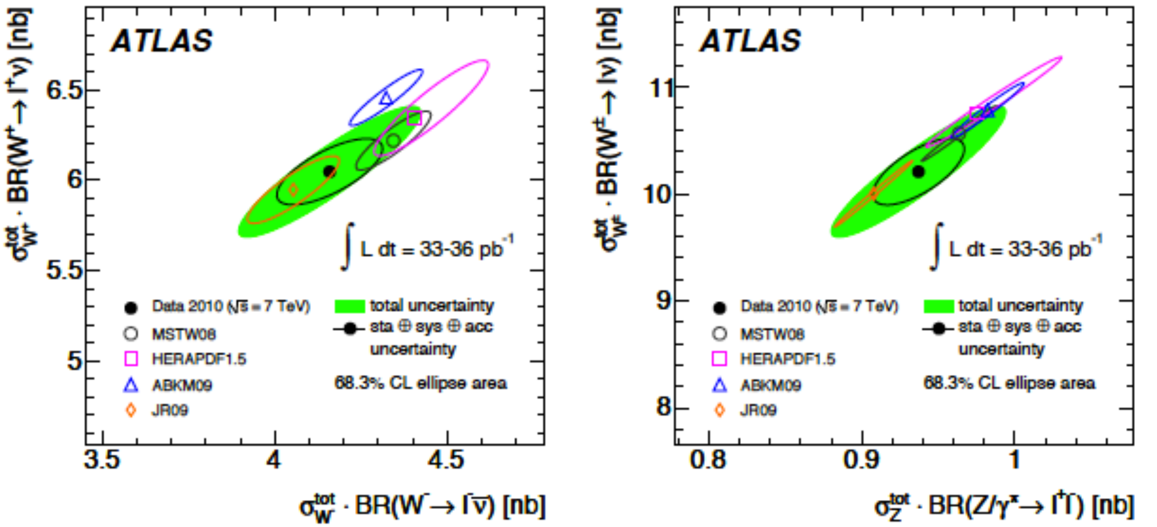



FIG. 16. *Measured and predicted total cross sections times leptonic branching ratios: $\sigma_{W+}$ vs. $\sigma_{W-}$ (left) and ($\sigma_{W+} + \sigma_{W-}$) vs. $\sigma_{Z/\gamma^*}$ (right). The ellipses illustrate the 68 % CL coverage for total uncertainties (full green) and excluding the luminosity uncertainty (open black). The uncertainties of the theoretical predictions are the PDF uncertainties only.*

# W/Z differential measurements

- **Already in 2010, probe lepton universality with high accuracy compared to the PDG world average from LEP and TeVatron for W boson!**

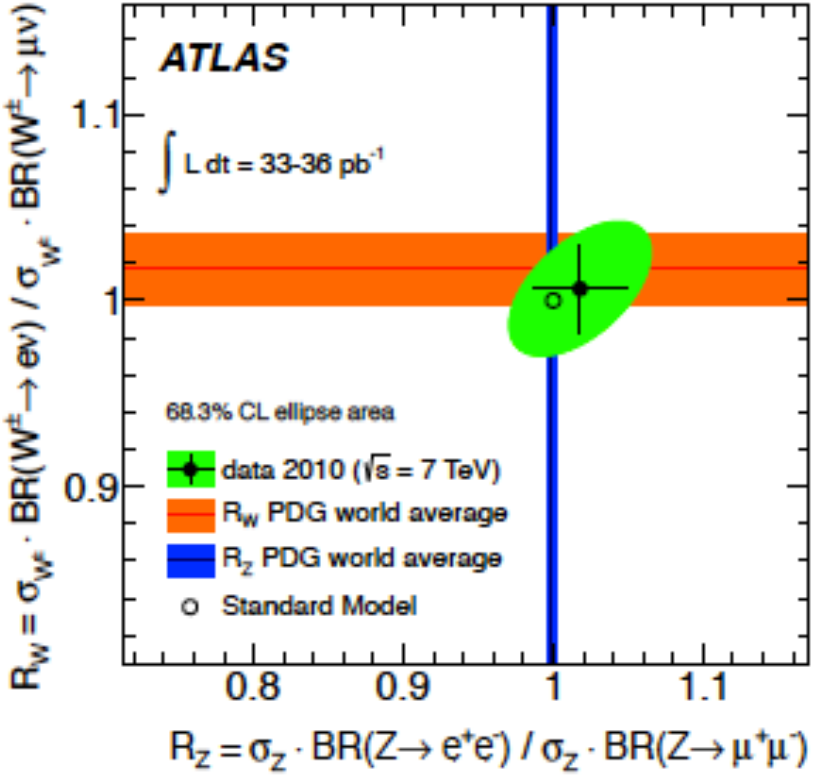



FIG. 17. *The correlated measurement of the electron-to-muon cross section ratios in the W and the Z channels. The cross section ratios represent measurements of the ratios of the branching fractions of the W and the Z in the electron and muon channels. The vertical (horizontal) band represents the uncertainty of the corresponding Z (W) branching fractions based on the current world average data. The green ellipse illustrates the* 68 % *CL for the correlated measurement of* $R_W$ *and* $R_Z$ *.*

# W/Z differential measurements

- **Finally, the ratios of W to Z fiducial cross-sections have perhaps the highest potential for precision measurements in the future**

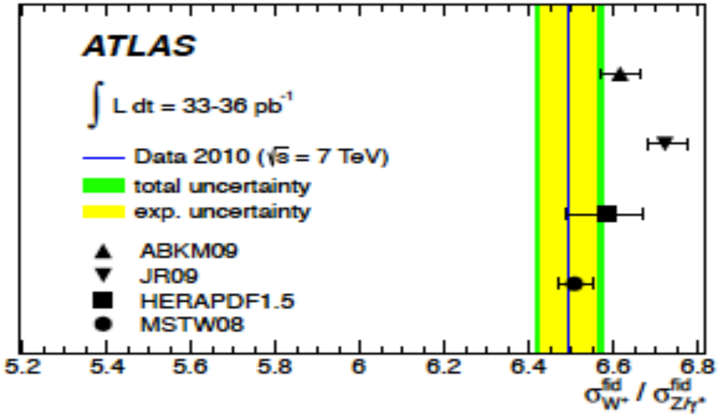
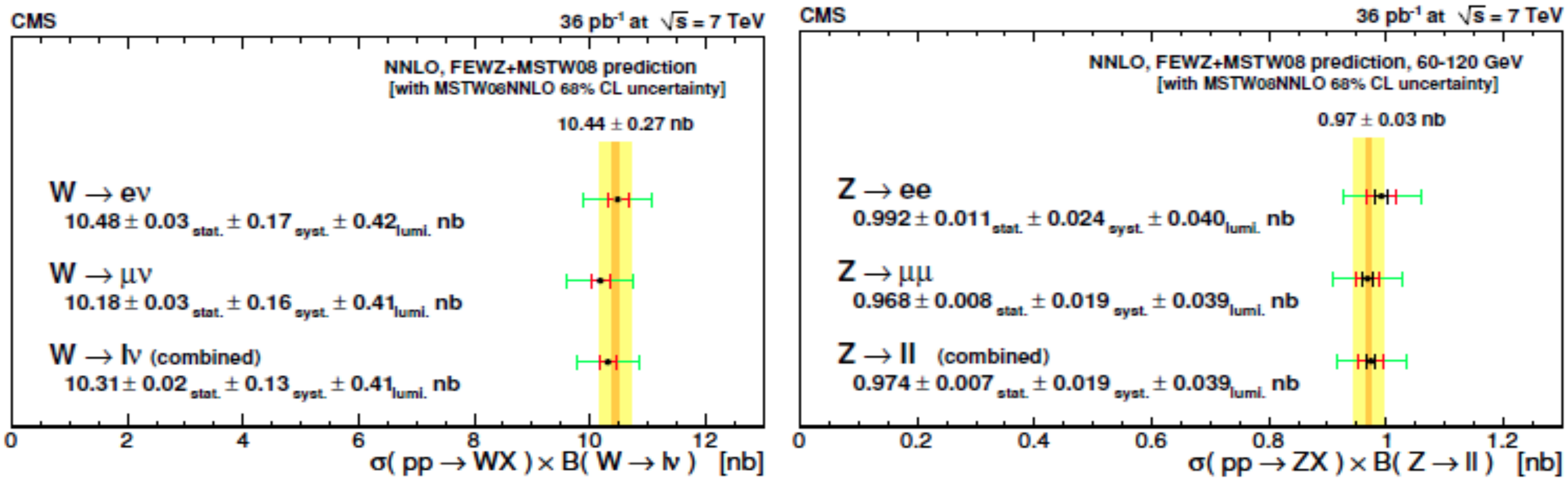
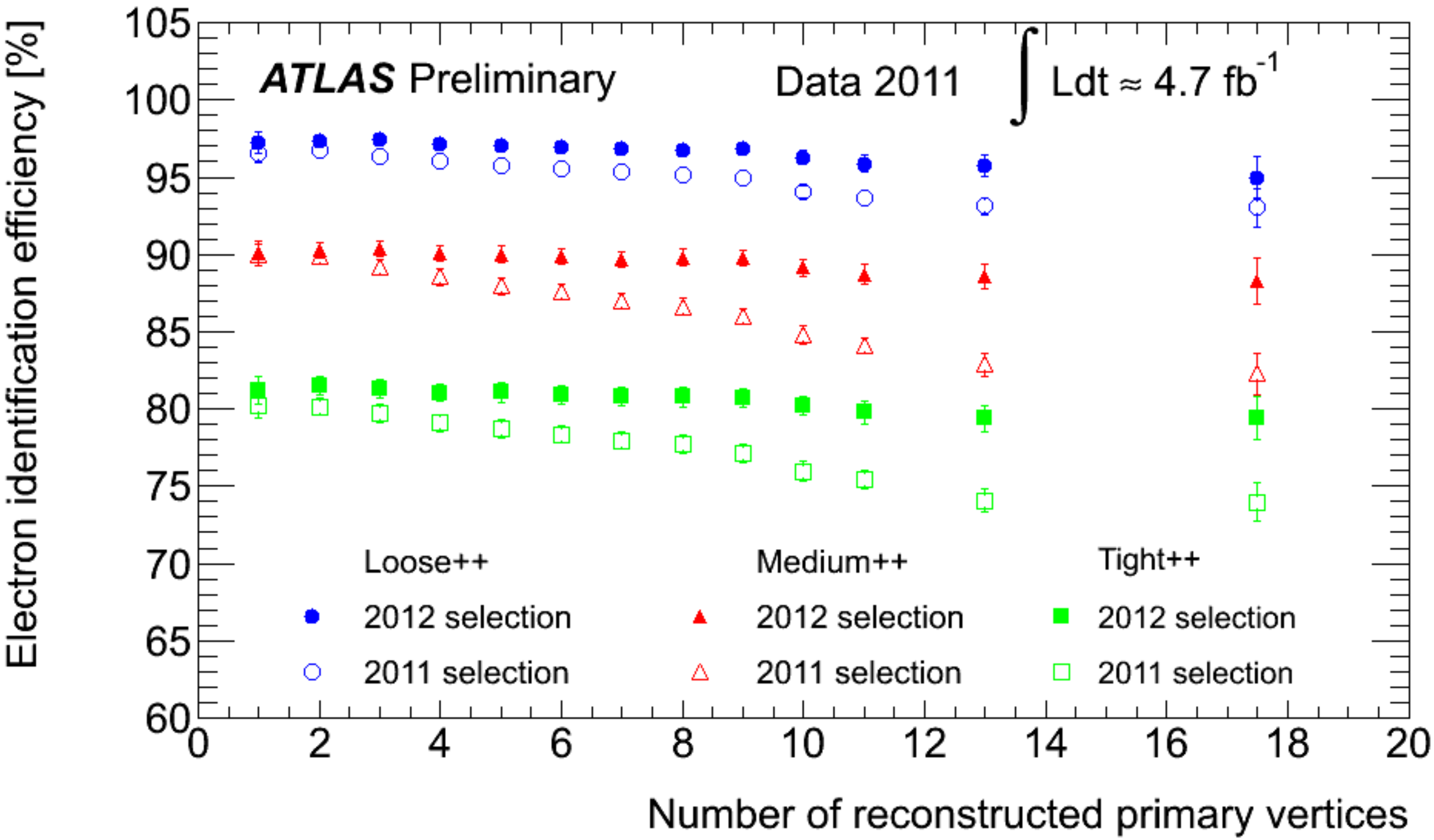



FIG. 19. *Measured and predicted fiducial cross section ratios, $\sigma_{W+}/\sigma_{Z/\gamma^*}$ (left) and $\sigma_{W-}/\sigma_{Z/\gamma^*}$ (right). The experimental uncertainty (inner yellow band) of the measurement includes the experimental systematic errors. The total uncertainty (outer green band) includes the statistical uncertainty and the small contribution from the acceptance correction. The uncertainties of the ABKM, JR and MSTW predictions are given by the PDF uncertainties considered to correspond to 68 % CL and their correlations are derived from the eigenvector sets. The results for HERAPDF comprise all three sources of uncertainty of that set.*



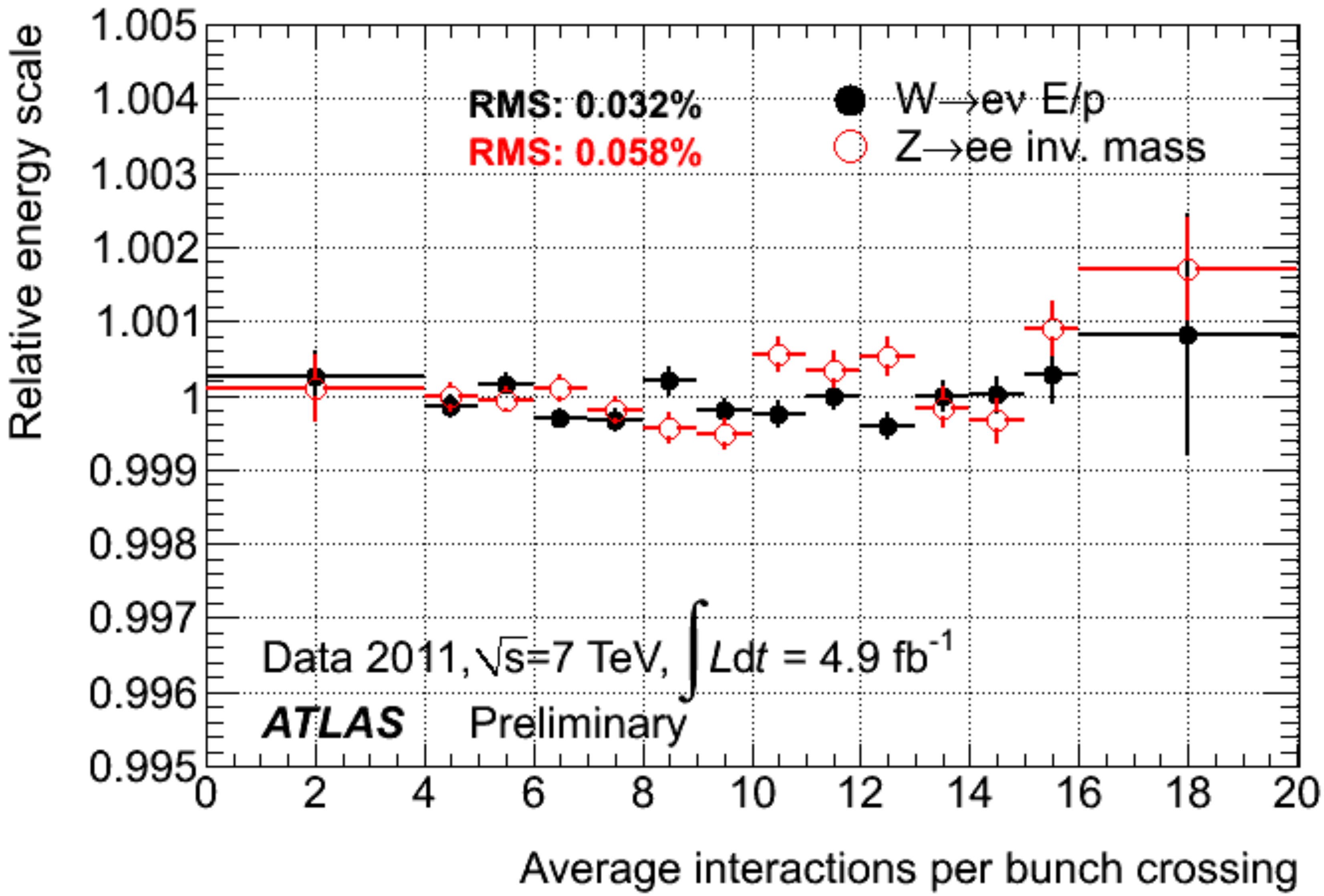
# ATLAS electron identification: preserve performance versus pile-up

## 2011 was difficult year, stability better in 2012



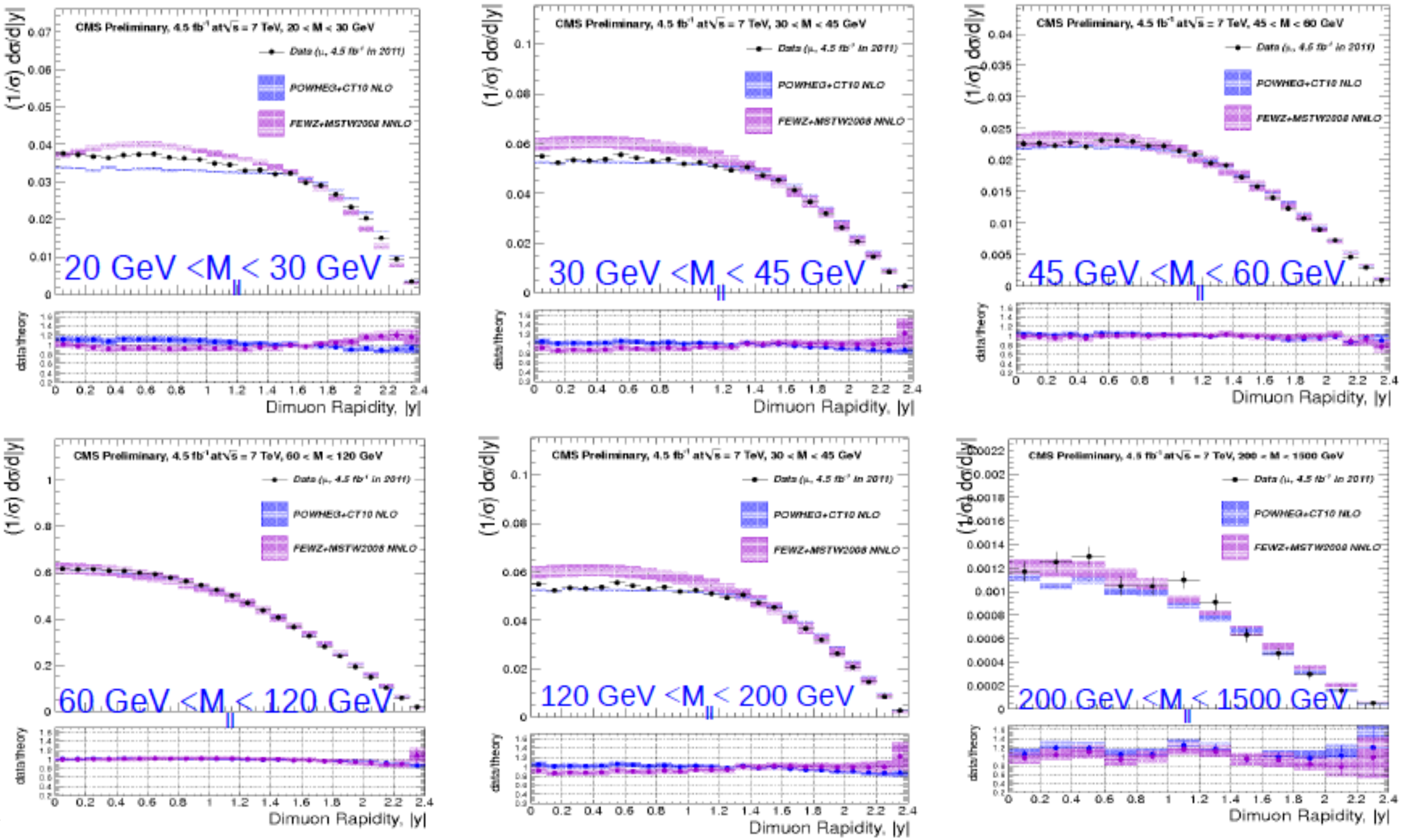
# ATLAS electron/photon energy scale: verify stability versus pile-up!

**Stability in 2011 verified with $m_{ee}$ for Z and E/p for W to better than 0.2%**



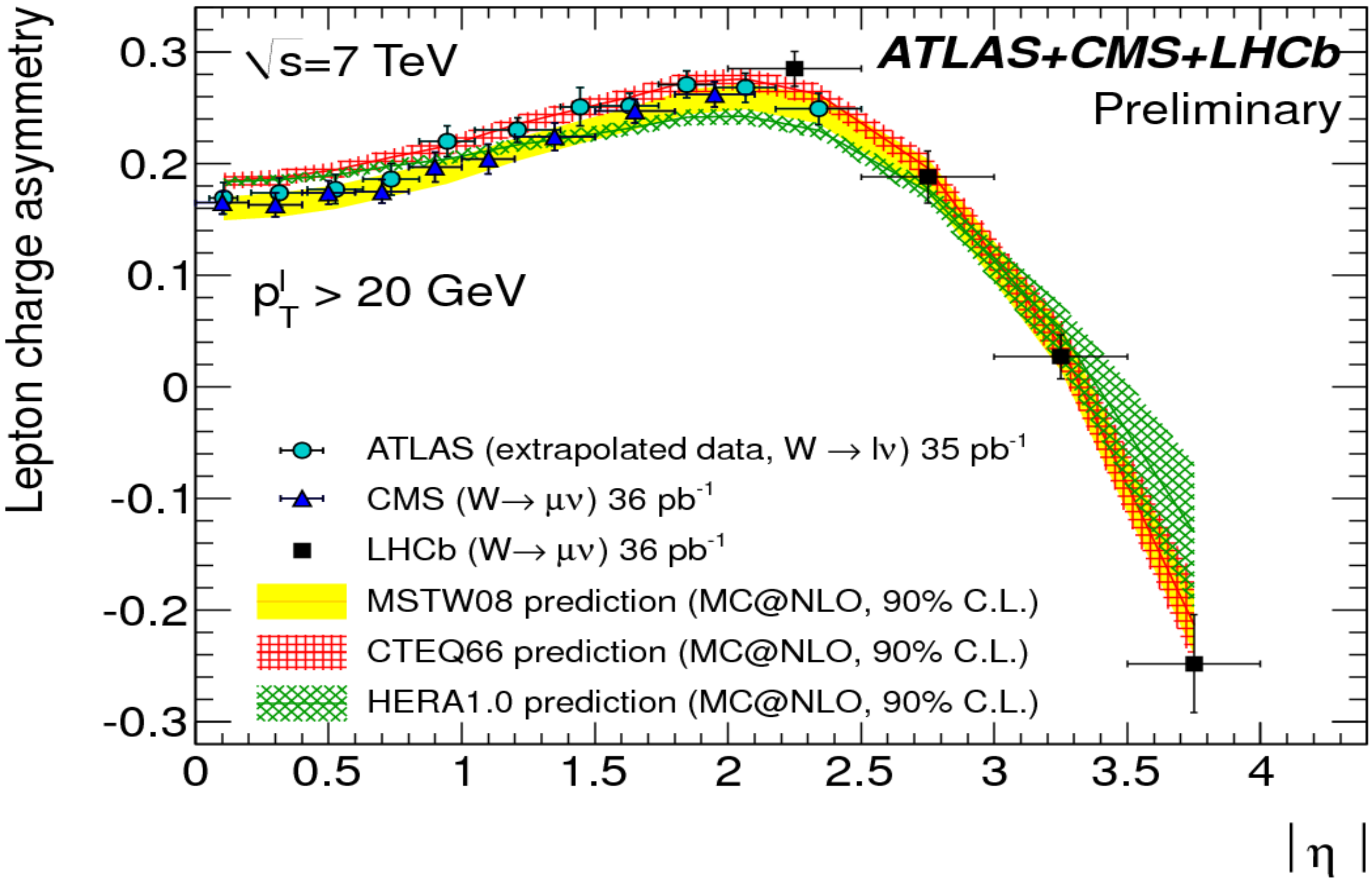
# W/Z differential measurements

- First DY double-differential (in bins of $y_{\mu\mu}$ and $m_{\mu\mu}$) measurements by CMS with full 2011 statistics **CMS-PAS-EWK-11-007**
- Significant differences seen between data, NLO Powheg and FEWZ at low mass but trigger bias ($p_T^{\mu}$ > 20, 10 GeV) might enhance need for higher-order calculations



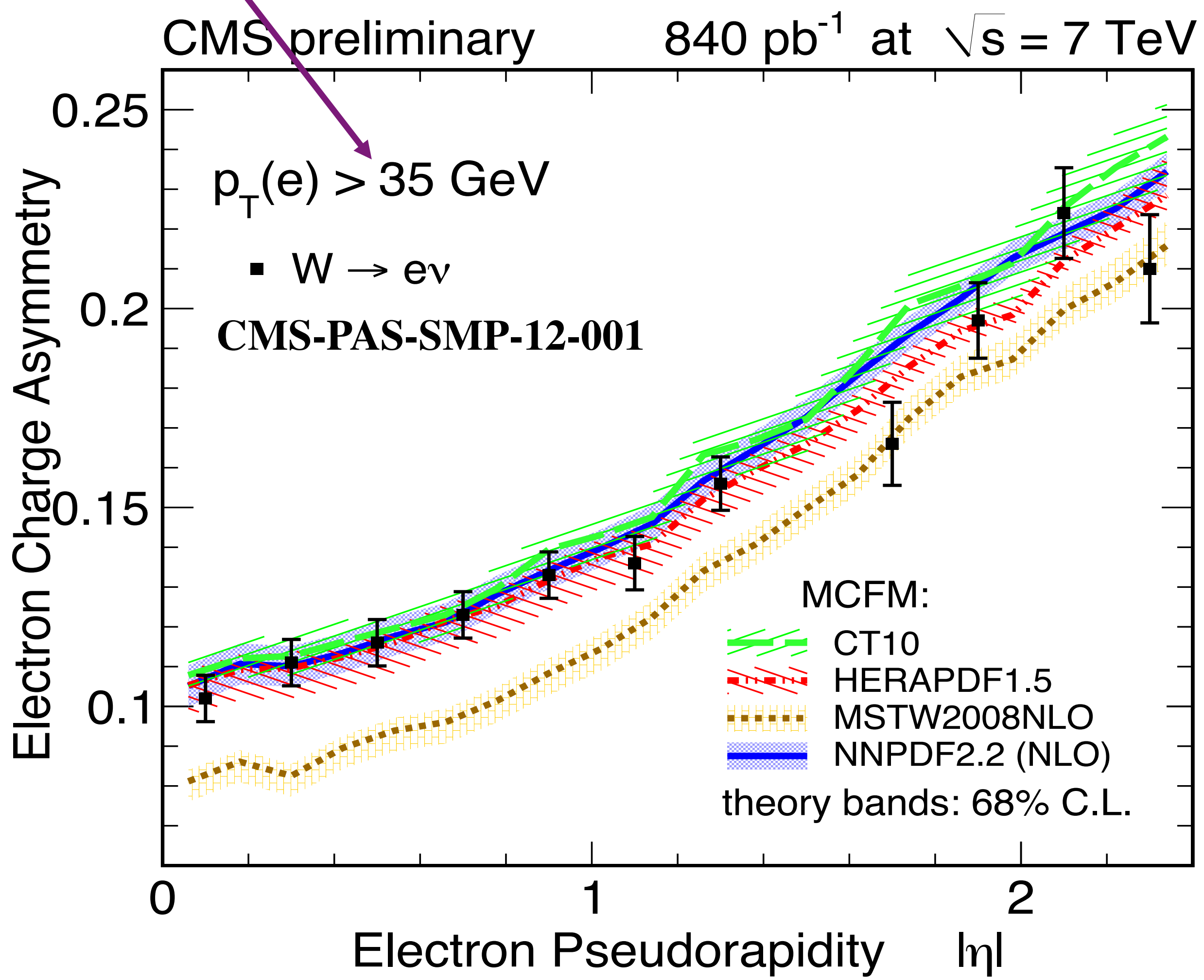
# Measurement of lepton charge asymmetry in W decays

- **Lepton charge asymmetry in the lab is one of the sensitive 1D distributions to PDFs and was the first used to produce LHC combined plot with 2010 data**



# Measurement of lepton charge asymmetry in W decays

- Lepton charge asymmetry in the lab is one of the sensitive 1D distributions to PDFs and was the first used to produce LHC combined plot with 2010 data
- Recent high-statistics results from 2011 data by CMS disfavour certain PDF sets but trigger threshold was very high (thereby diluting the measurement)
- However, recent PDF4LHC workshop at CERN shows that interaction between PDF fitters and LHC experiments is developing rapidly



# Trigger: preserve performance and physics!

## Difficult e.g. to keep inclusive single lepton trigger at ~ 20 GeV in 2011!

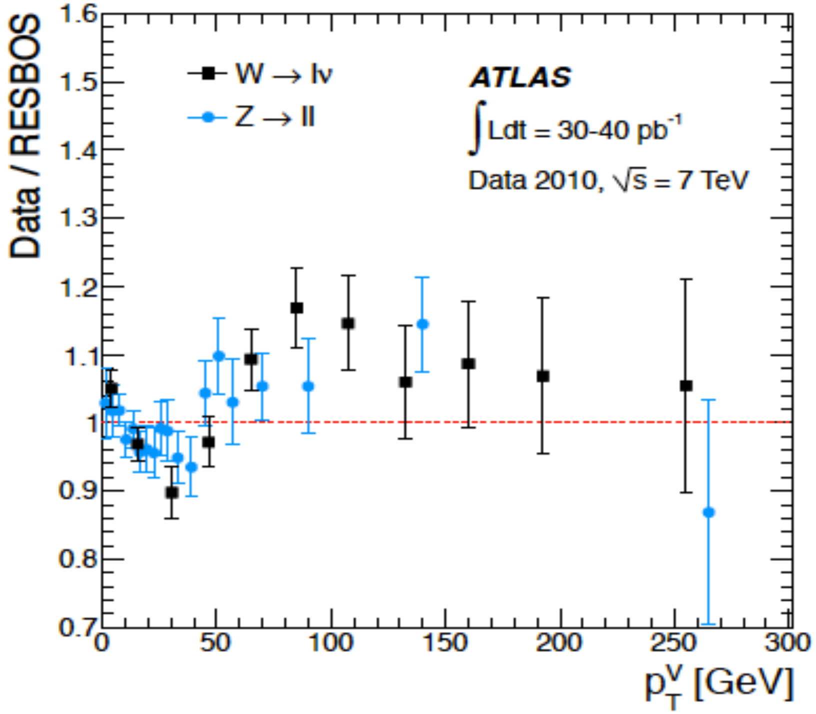
## Electron threshold in 2012 raised to 25 GeV (ATLAS) and lowered to 30 GeV (CMS)

| Trigger objects (ATLAS 2011) | Offline Selection 2011 ($p_T$ thresholds) | Trigger Selection | | L1 Rate (kHz) at 3 $10^{33}$ | EF Rate (Hz) at 3 $10^{33}$ |
|---|---|---|---|---|---|
| | | L1 | EF | | |
| Single leptons | Single muon > 20 GeV | 11 GeV | 18 GeV | 8 | 100 |
| | Single electron > 25 GeV | 16 GeV | 22 GeV | 9 | 55 |
| Two leptons | 2 muons > 4 GeV | 11 GeV | 15,10 GeV | 6 | 5 |
| | 2 electrons, > 15 GeV | 2x10 GeV | 2x12 GeV | 2 | 1.3 |
| | 2 $\tau \rightarrow$ h > 45, 30 GeV | 15,11 GeV | 29,20 GeV | 7.5 | 15 |
| Two photons | 2 photons, > 25 GeV | 2x12 GeV | 2x20 GeV | 3.5 | 5 |
| $E_T^{miss}$ | $E_T^{miss}$ > 170 GeV | 50 GeV | 70 GeV | 0.6 | 5 |
| Multi-jets | 5 jets, > 55 GeV | 5x10 GeV | 5x30 GeV | 0.2 | 9 |
| Single jet plus $E_T^{miss}$ | Jet $p_T$ > 130 GeV & $E_T^{miss}$ > 140 GeV | 50 GeV & 35 GeV | 75 GeV & 55 GeV | 0.8 | 18 |
| Total rate (peak): includes all trigger types, not only those above. | | | | 55 kHz | 550 Hz |

# Measurement of $p_T^Z$ and $p_T^W$

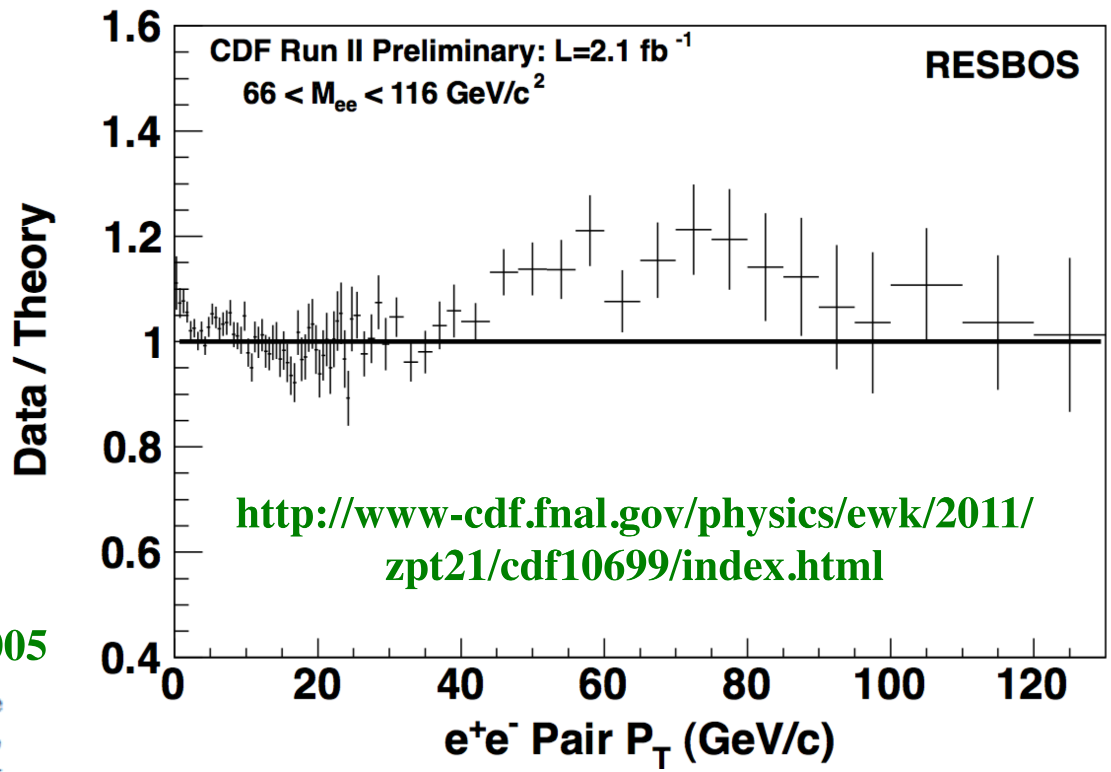
- Fully unfolded fiducial distributions for $p_T^V$ in ATLAS show shape differences wrt certain models (eg ResBos below left)
- As shown on the right below, recent measurement by CDF for Z to ee shows similar shape distortion to that of ATLAS when compared to ResBos
- The region, $40 < p_T^V < 90$ GeV is where the resummed, perturbative and asymptotic cross-sections are matched

(note that ResBos is tuned to TeVatron data but not yet to LHC data)




http://prd.aps.org/abstract/PRD/v85/i1/e012005

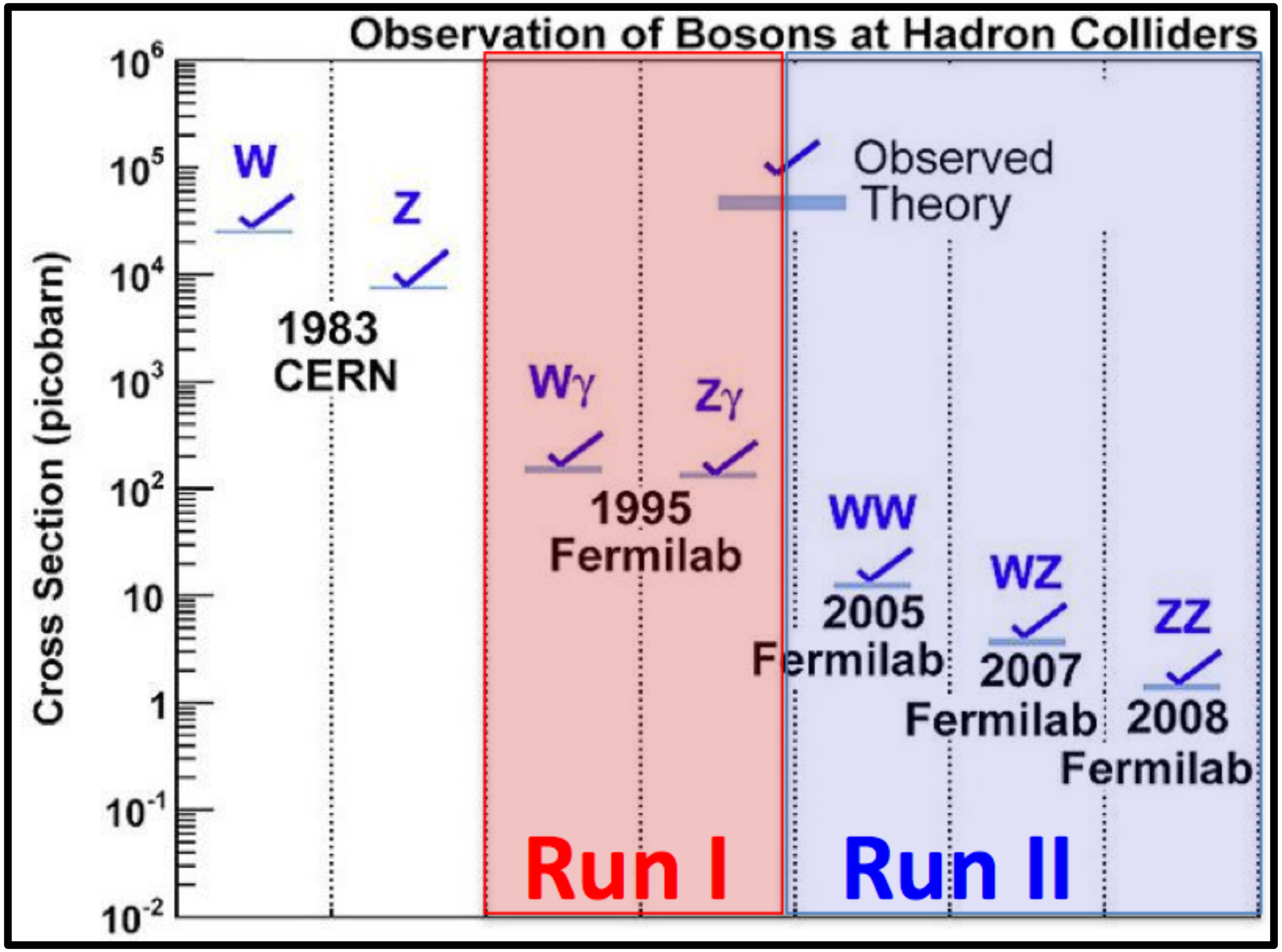
FIG. 8. The ratio of $(1/\sigma_{fid})(d\sigma_{fid}/dp_T^W)$ as measured in the combined electron and muon data to the RESBOS prediction, overlaid with the ratio of $(1/\sigma_{fid})(d\sigma_{fid}/dp_T^Z)$ measured as described in Ref. [2] to the RESBOS prediction.




http://www-cdf.fnal.gov/physics/ewk/2011/zpt21/cdf10699/index.html

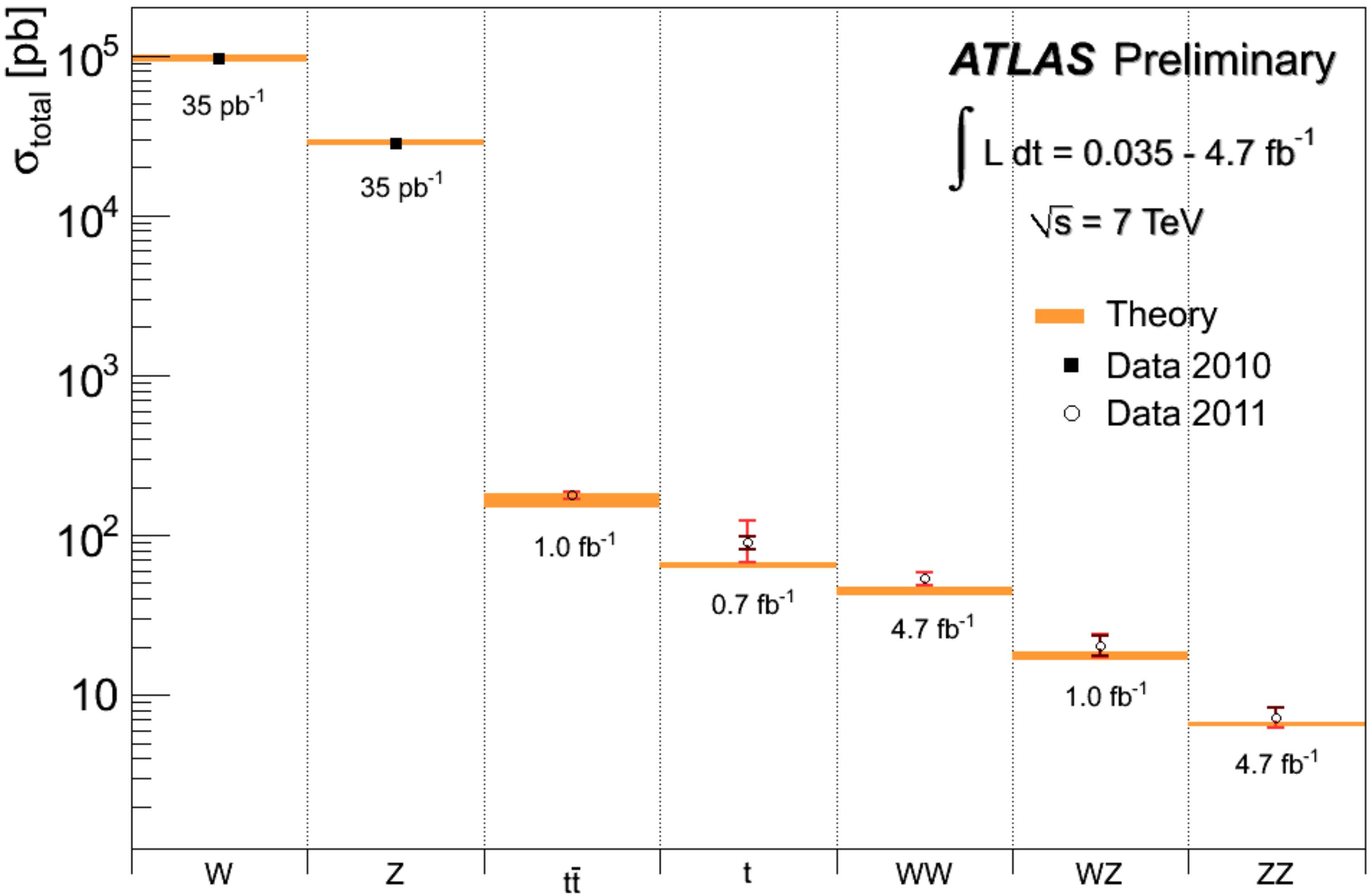
# Diboson measurements: the beginning of the road for LHC

- Small cross-sections, large reducible backgrounds
- Important backgrounds to many Higgs-boson searches
- Sensitive to anomalous triple-gauge boson couplings (aTGCs)
- LEP2 and then Tevatron have paved the way
- Also, dibosons (WW/WZ) with final states to jets, and more importantly to bb pairs, have been first observed at the Tevatron (see talks by A. Juste and M. Cooke)



# Diboson measurements: the beginning of the road for LHC

- Small cross-sections, large reducible backgrounds
- Important backgrounds to many Higgs-boson searches
- Sensitive to anomalous triple-gauge boson couplings (aTGCs)
- LEP2 and then Tevatron have paved the way
- Also, dibosons (WW/WZ) with final states to jets, and more importantly to bb pairs, have been first observed at the Tevatron (see talks by A. Juste and M. Cooke)



# Diboson measurements

- Use only leptonic modes to obtain fairly clean signals (show ATLAS/CMS typical S/B below):

(S/B ~ 50 for ZZ → llll decreasing to S/B ~ 10 for Zγ → llγ, to S/B ~ 5 for WZ → lνll, to S/B ~ 2-3 for Wγ → lng and WW to lνlν, to S/B ~ 1 for ZZ → llνν)

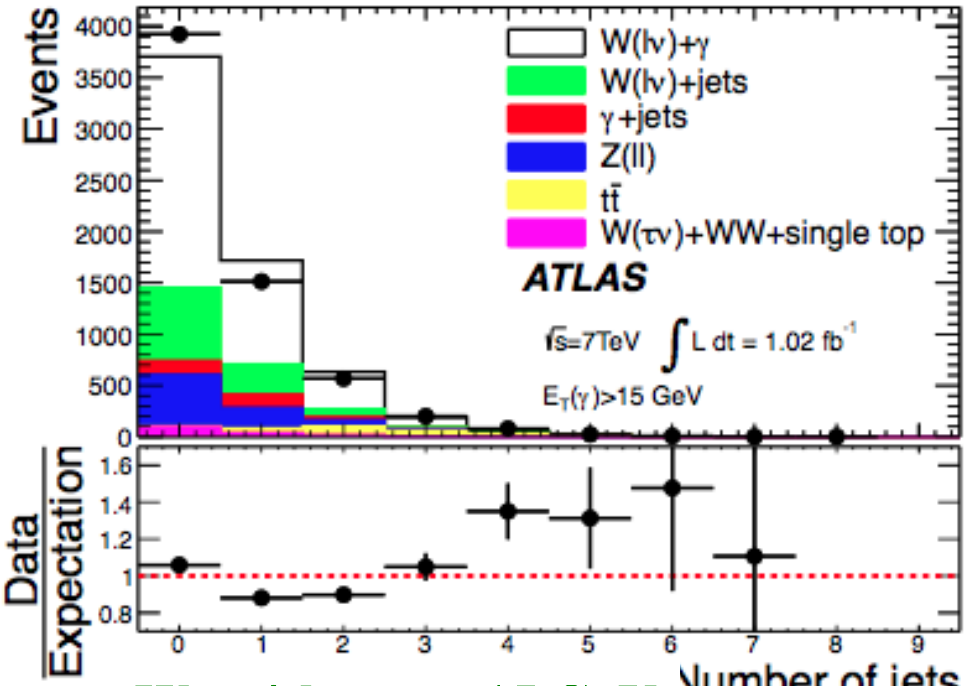
- Example comparison between D0 ($8.6\ fb^{-1}$) and ATLAS ($4.7\ fb^{-1}$) for one of the more difficult channels, namely ZZ → llνν:
  - D0: $N_{signal} = 14$, $N_{bgnd} = 48$, $\sigma_{exp} = 1.6 \pm 0.5$, $\sigma_{theory} = 1.3 \pm 0.1$ pb
    http://arxiv.org/abs/1201.5652
  - ATLAS: $N_{signal} = 37$, $N_{bgnd} = 41$, $\sigma_{exp} = 5.4 \pm 0.7$, $\sigma_{theory} = 6.5 \pm 0.3$ pb
    [ATLAS-CONF-2012-027]

| Channel | ATLAS $\sigma/\sigma_{fid}$ | CMS $\sigma$ | ATLAS aTGC | CMS aTGC |
|---|---|---|---|---|
| W/Z γ → lν/ll γ | $1.0\ fb^{-1}$ | $36\ pb^{-1}$ | $1.0\ fb^{-1}$ | $36\ pb^{-1}$ |
| WW → lνlν | $4.7\ fb^{-1}$ | $4.9\ fb^{-1}$ | $1.0\ fb^{-1}$ | $36\ pb^{-1}$ |
| WZ → lνll | $1.0\ fb^{-1}$ | $1.1\ fb^{-1}$ | $1.0\ fb^{-1}$ | - |
| ZZ → llνν | $4.7\ fb^{-1}$ | - | $1.0\ fb^{-1}$ | - |
| ZZ → llll | $4.7\ fb^{-1}$ | $1.1\ fb^{-1}$ | $1.0\ fb^{-1}$ | - |

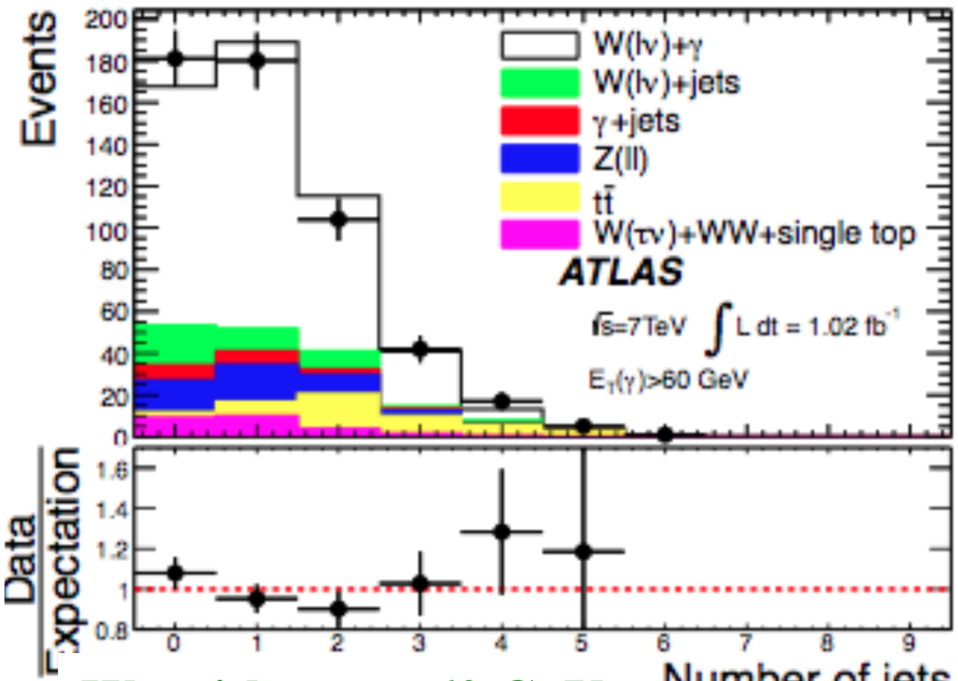
# Diboson measurements: Wγ and Zγ

- Observe that jet multiplicity in data is much higher than expected from NLO event generators
→ use Alpgen with up to 5 partons and Sherpa with up to three partons

- Agreement with MCFM for inclusive events also found to be poor, but improves substantially if one applies jet veto (at parton level for MCFM), i.e. if one selects exclusively events without jets (cannot compare to any NLO calculation reliably in this case however).




Wγ with $p_T\gamma$ > 15 GeV



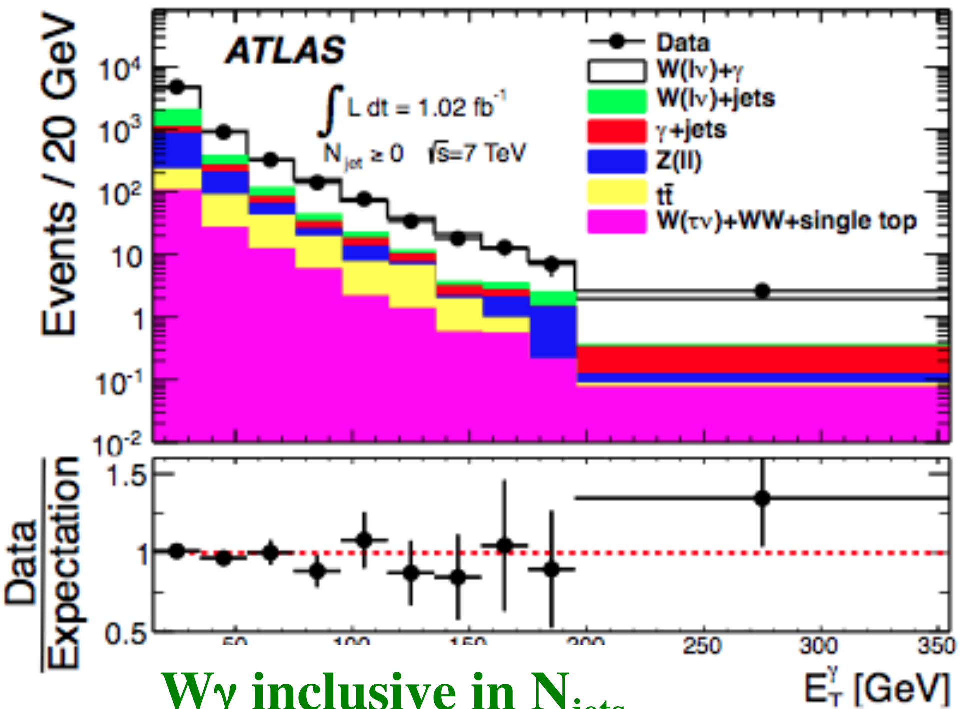

Wγ with $p_T\gamma$ > 60 GeV

# Diboson measurements: Wγ and Zγ

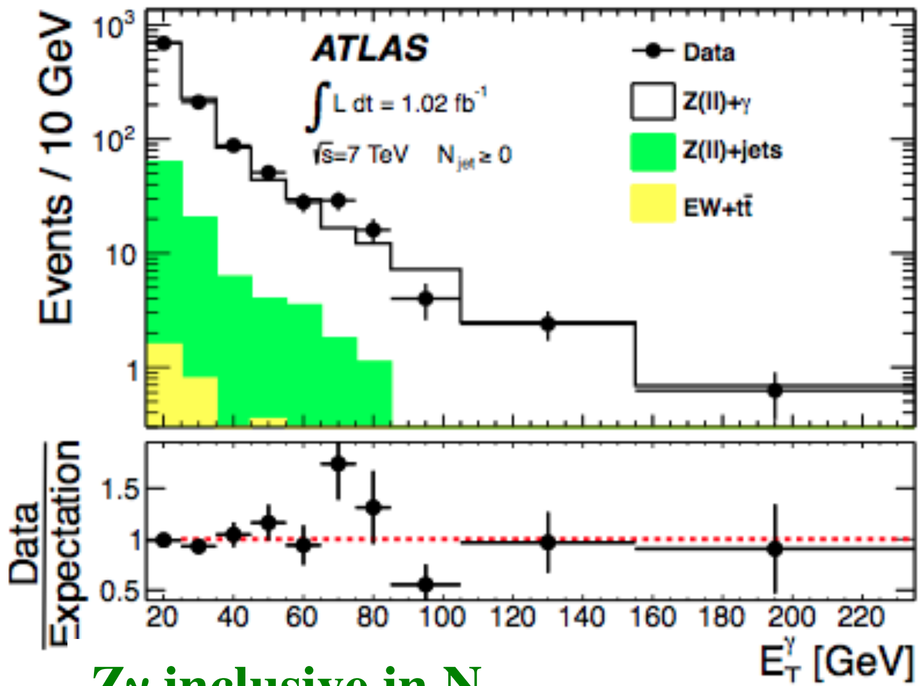
- Compare data to Alpgen/Herwig for Wγ and to Sherpa for Zγ
- Agreement between data and MC quite good

ATLAS: [arxiv:1205.2531]

CMS: [PLB 701 (2011)]



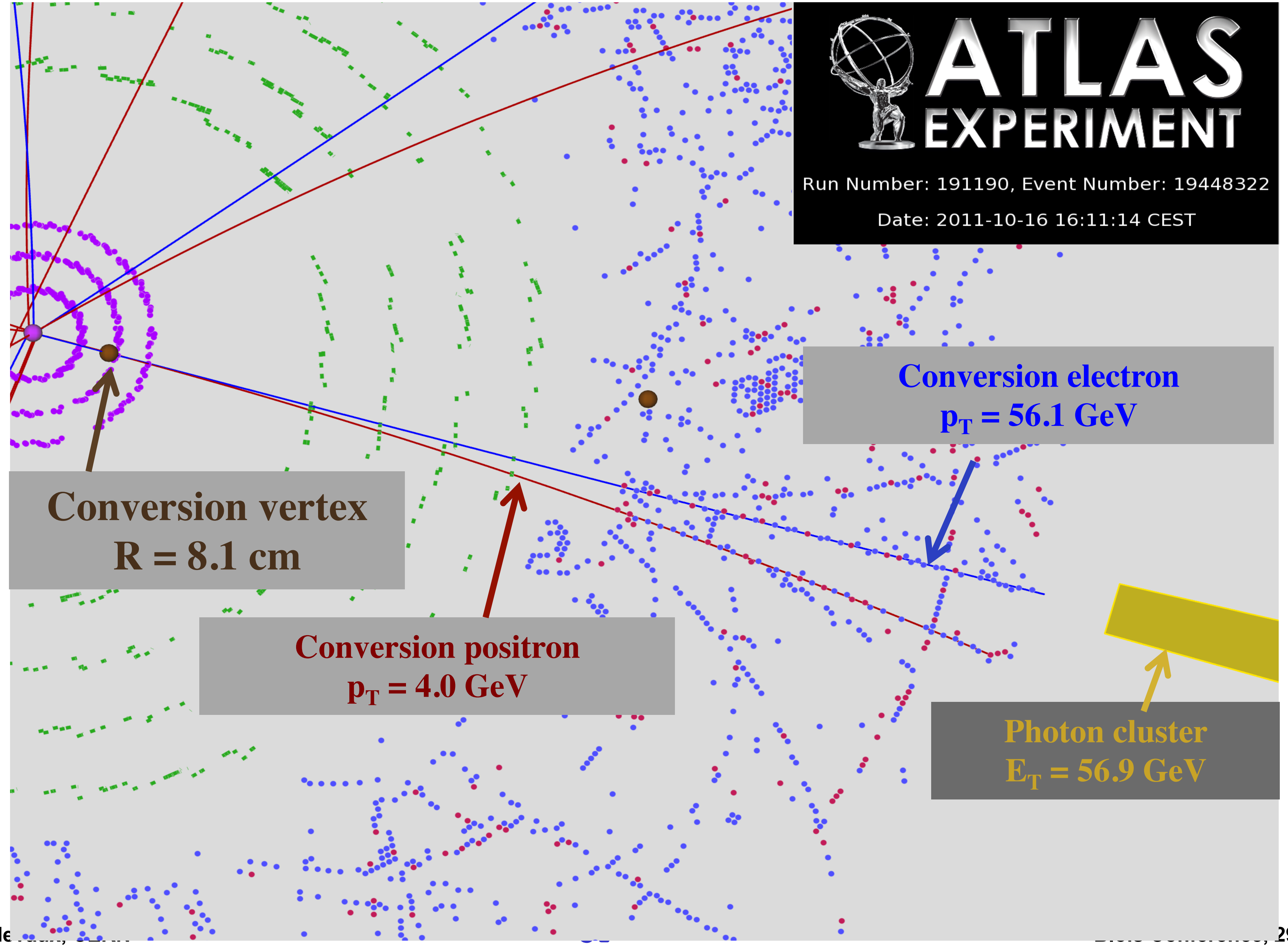

Wγ inclusive in $N_{jets}$



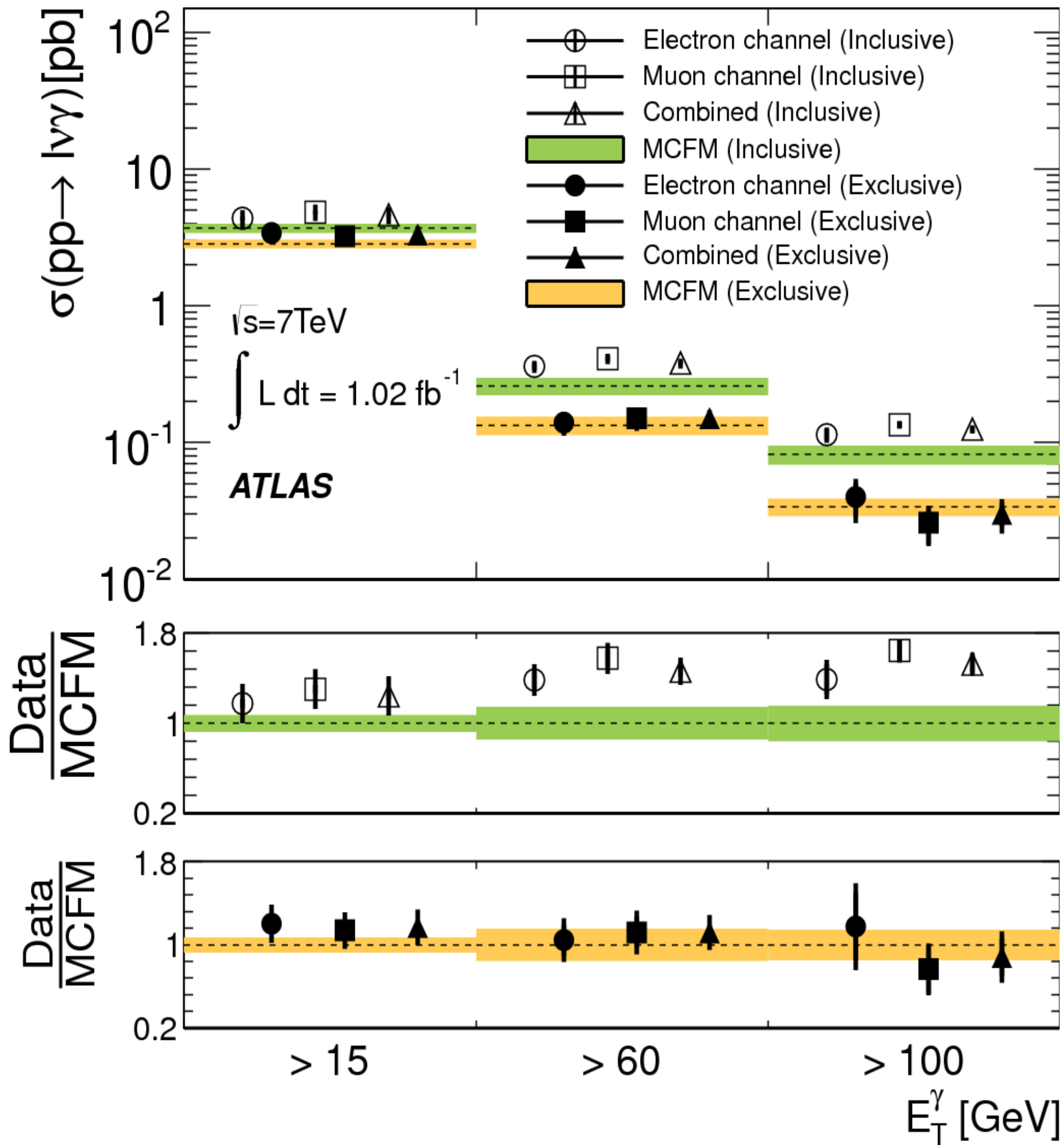

Zγ inclusive in $N_{jets}$

# Diboson measurements: Wγ and Zγ

- Need to efficiently reconstruct converted photons in high pile-up environment

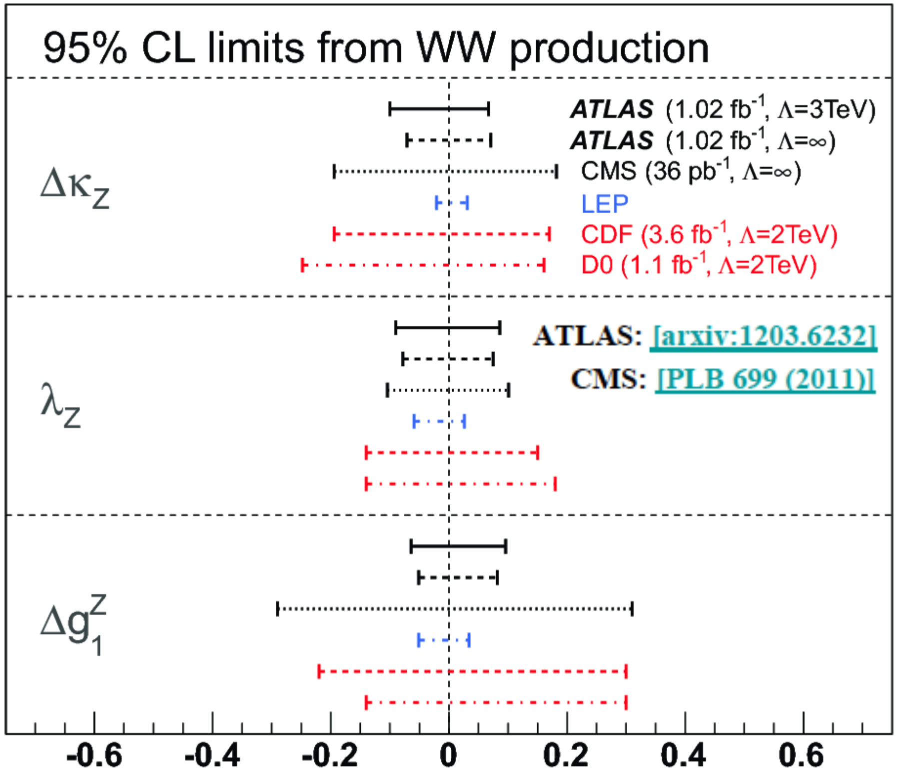


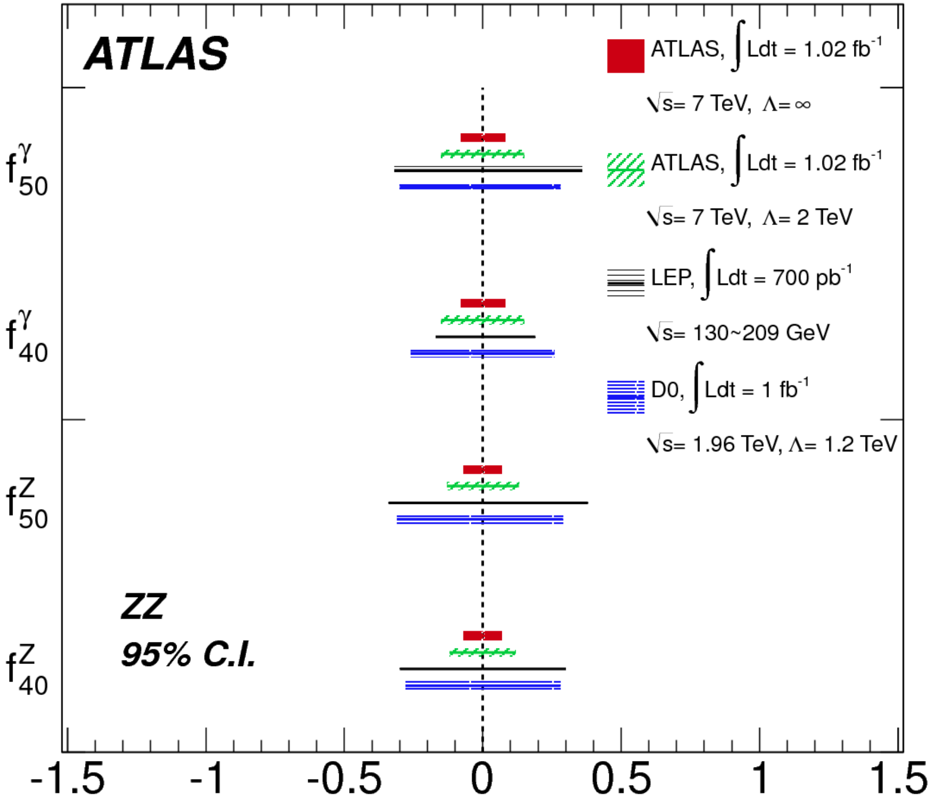
# Diboson measurements: Wγ comparison to MCFM




- Disagreement between data and MCFM for inclusive selection
- Increases as $p_T^\gamma$ increases, from data/MC = 1.24 ± 0.20 for $p_T^\gamma$ > 15 GeV to data/MC = 1.52 ± 0.31 for $p_T^\gamma$ > 100 GeV
- MCFM exclusive calc. ~ NLO but error band not quite correct
- Need improved theoretical tools:
  - NNLO calculations?
  - NLO predictions at particle level for dibosons plus one or two jets will eventually be needed
  - aMC@NLO may be a good place to start from (combination of MadGraph and Powheg)
  - eventually will need the same for WWjj

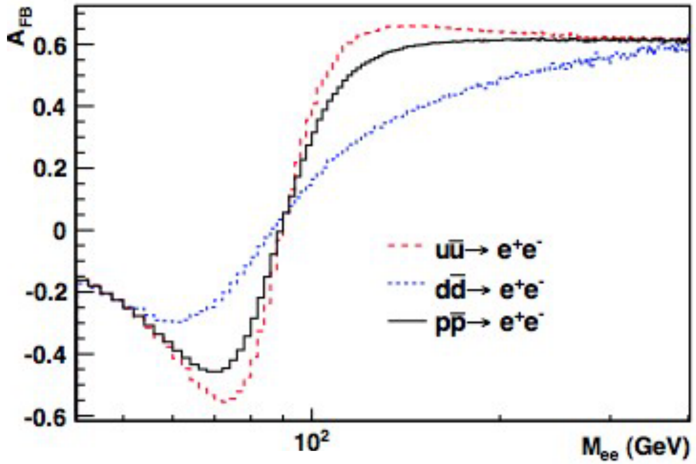
# Diboson measurements: anomalous couplings



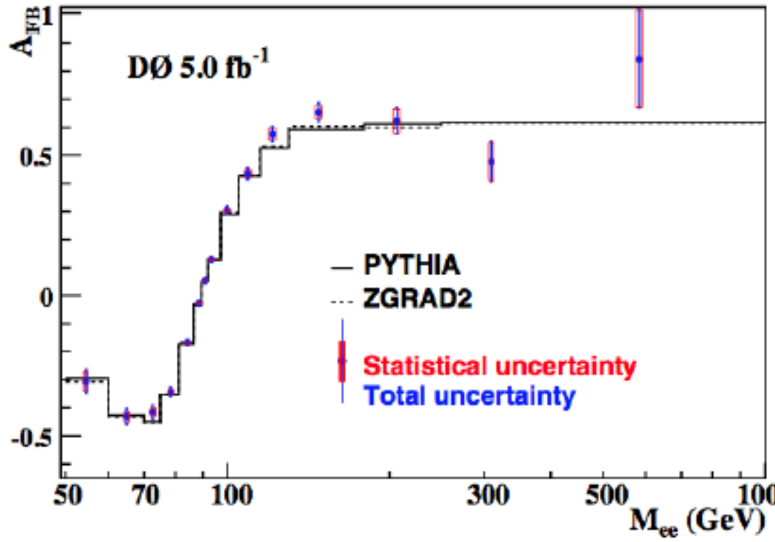



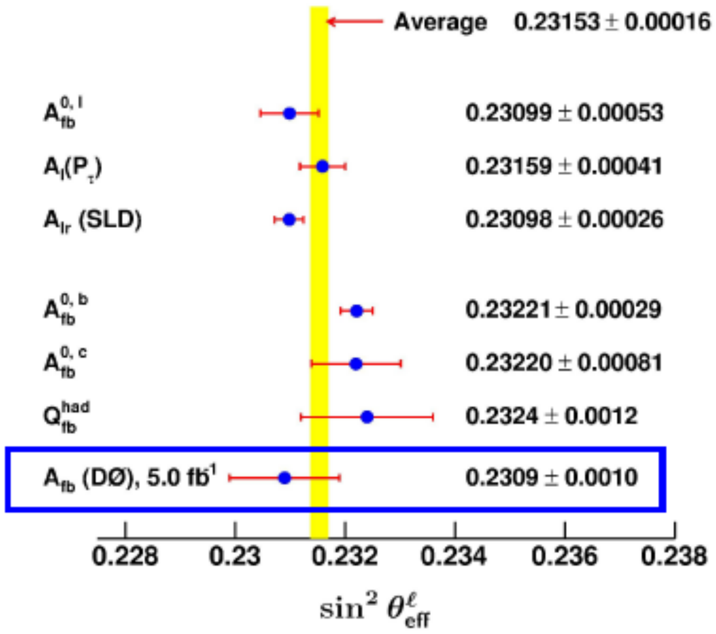

- Limits on aTGCs depend sometimes strongly on choice of cut-off L for effective Lagrangian
- At the LHC, one is close to the situation where one has to set L in the range where one is probing for the aTGCs, so another approach may be needed in the future
- Depending on the couplings and the tri-boson vertex one is probing, best sensitivity belongs to LEP, Tevatron, and sometimes now LHC

# Measurement of Z forward-backward asymmetry: beyond the legacy of LEP and Tevatron?




- Unfolded AFB agrees well with theoretical prediction
- No evidence for new physics at high mass
- Extracted $\sin^2\theta^l_{eff}$ = 0.2309 ± 0.0008 (stat.) ± 0.0006 (syst.)



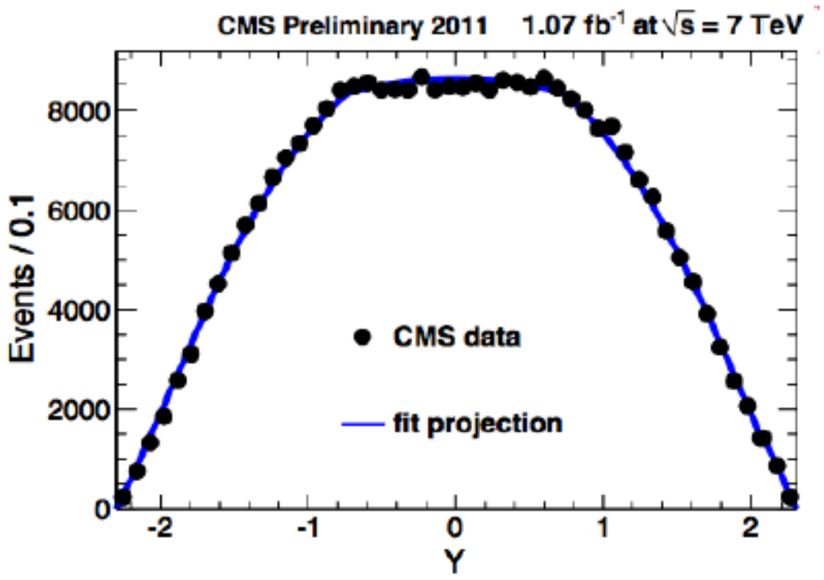

- Statistical uncertainty is still dominant
- PDF uncertainty (0.00048) is dominant in systematic uncertainty
- Most precise measurement based on Z to light quark couplings

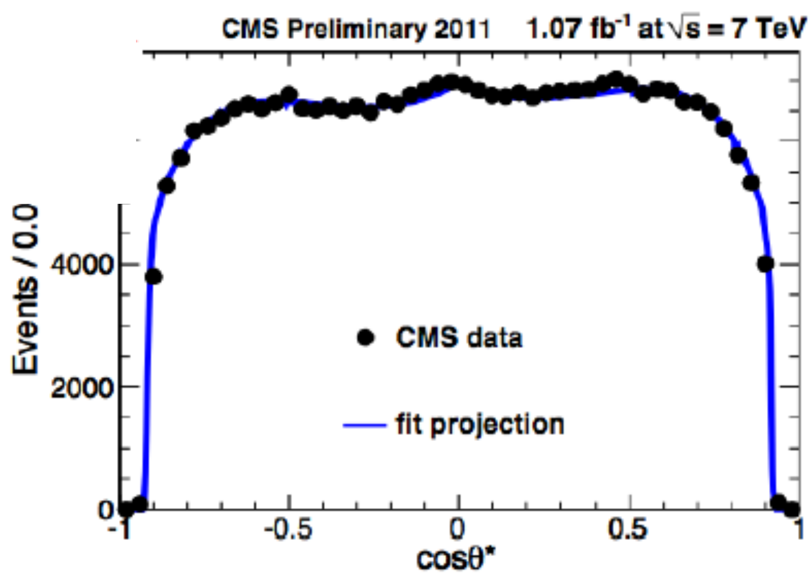
*Published: Phys. Rev. D 84, 012007 (2011)*

# Measurement of Z forward-backward asymmetry: beyond the legacy of LEP and Tevatron?

A first measurement of the effective weak mixing angle at the LHC is available from CMS.

http://dx.doi.org/10.1103/PhysRevD.84.112002




The effective weak mixing angle is extracted from the di-muon data using an unbinned extended maximum-likelihood fit.

In this fit, each event is characterised by three observables: di-lepton rapidity, di-lepton invariant mass squared, $\cos\theta^*_{CS}$

Result: $\sin^2\theta_{eff} = 0.2287 \pm 0.0020(\text{stat.}) \pm 0.0025(\text{syst.})$

| source | correction | uncertainty |
|---|---|---|
| PDF | – | ±0.0013 |
| FSR | – | ±0.0011 |
| LO model (EWK) | – | ±0.0002 |
| LO model (QCD) | +0.0012 | ±0.0012 |
| resolution and alignment | +0.0007 | ±0.0013 |
| efficiency and acceptance | – | ±0.0003 |
| background | – | ±0.0001 |
| total | +0.0019 | ±0.0025 |

**Note that largest experimental uncertainty is from alignment, even for muons!**
**A long way to go still to compete with PDG value of $\sin^2\theta_w$.**

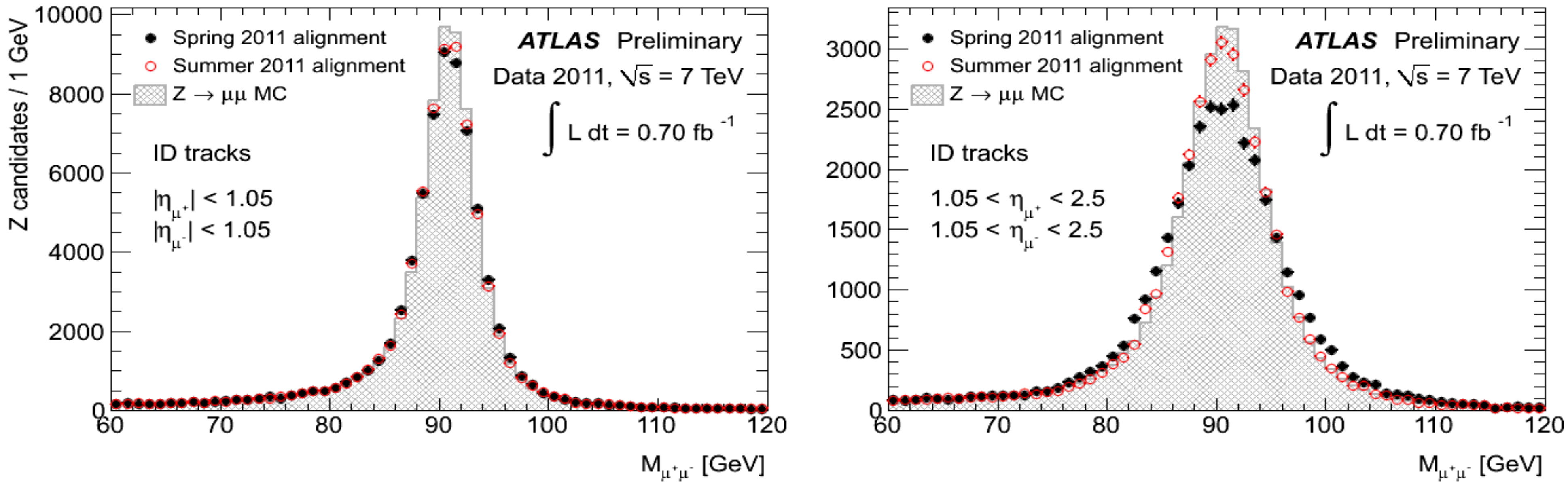
# ATLAS alignment and calibration: inner detector

- Unfortunately, alignment work for "light-weight" inner detector does not stop at minimising residuals
- Need to eliminate distortions which affect track parameters, especially impact parameter and momentum measurements (residuals are insensitive to a number of these possible distortions). Use E/p measurement for electrons and apply to muons!
- This has led to large improvement on Z to μμ experimental resolution, a factor three in end-caps (much weaker initial constraints from cosmics)

Exp. resolution expected from MC (GeV)

Additional contribution to exp. resolution from data (to be added quadratically)

| Z to μμ in ID only (250k events) | Ideal | Only residuals used in minim. | Add E/p constraint from $e^+$ vs $e^-$ |
|---|---|---|---|
| Both μ in barrel ID | 1.60 | 0.98 ± 0.01 | 0.71 ± 0.01 |
| Both μ in same end-cap ID | 3.42 | 3.03 ± 0.03 | 1.16 ± 0.01 |



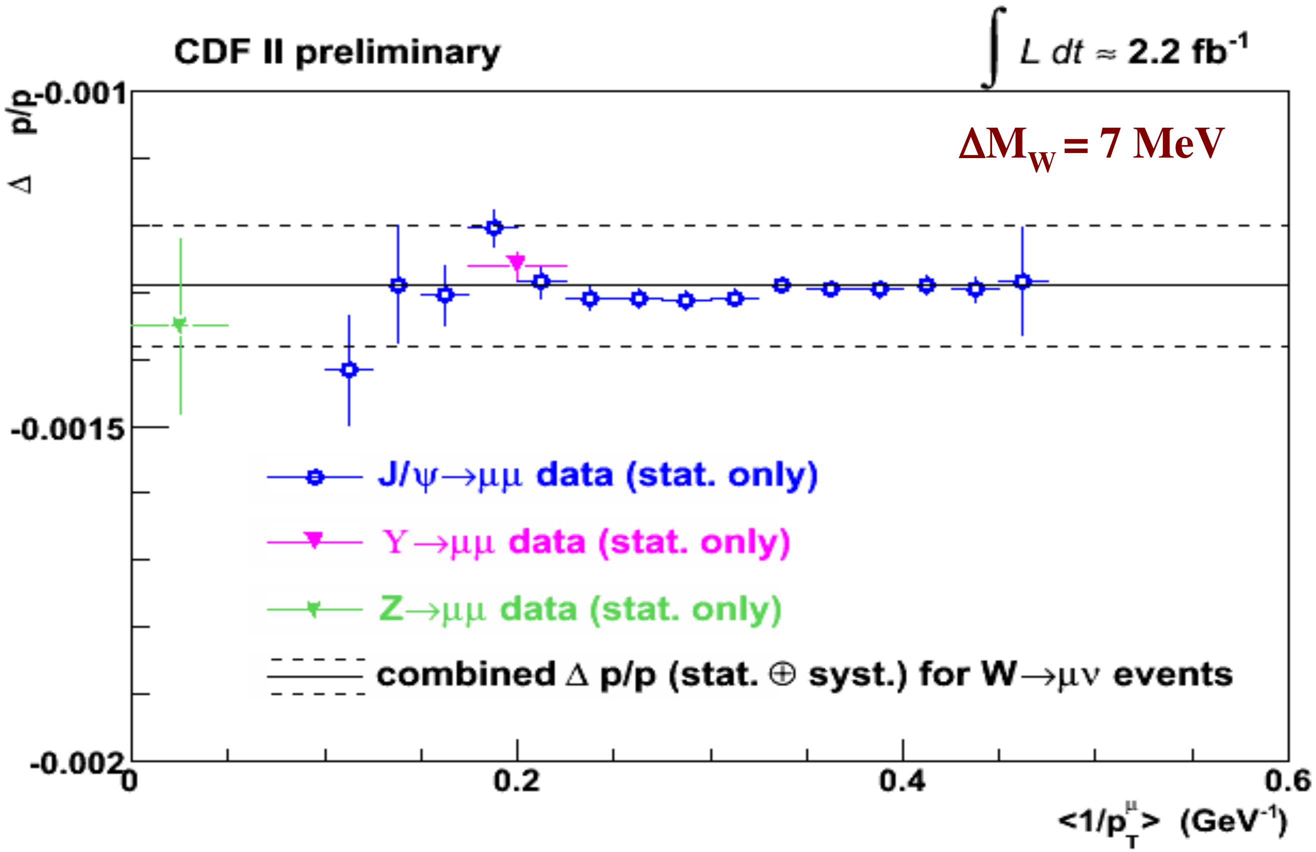
## W-boson mass measurements: Tevatron versus LEP2

## CDF: Tracker Linearity Cross-check & Combination

**Final momentum calibration using the J/ψ, Υ and Z bosons**

**Combined momentum scale correction:**

- $\Delta p/p = ( -1.29 \pm 0.07_{independent} \pm 0.05_{QED} \pm 0.02_{align} ) \times 10^{-3}$

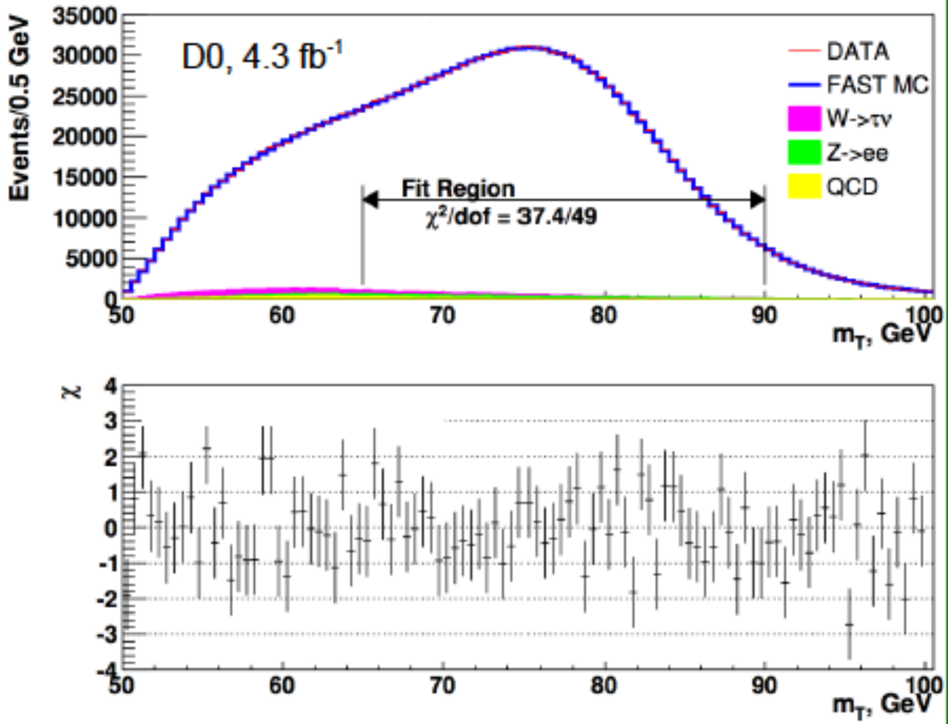
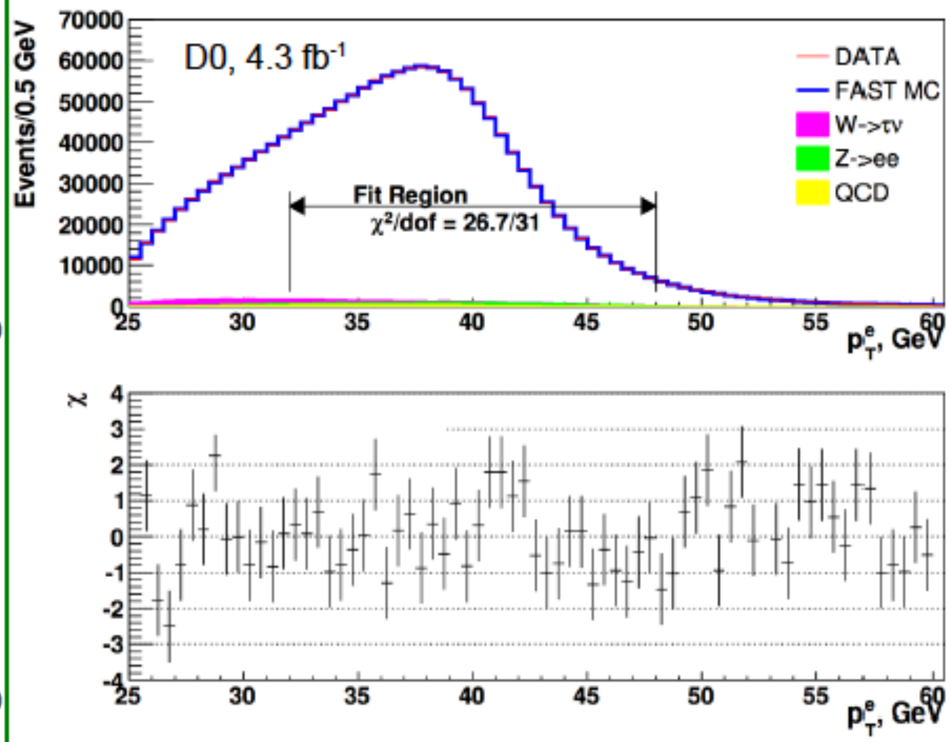


# W-boson mass measurements: Tevatron versus LEP2

## D0: use only central electrons and achieve similar accuracy!

1.68M events
central electrons ($|\eta|<1.05$)

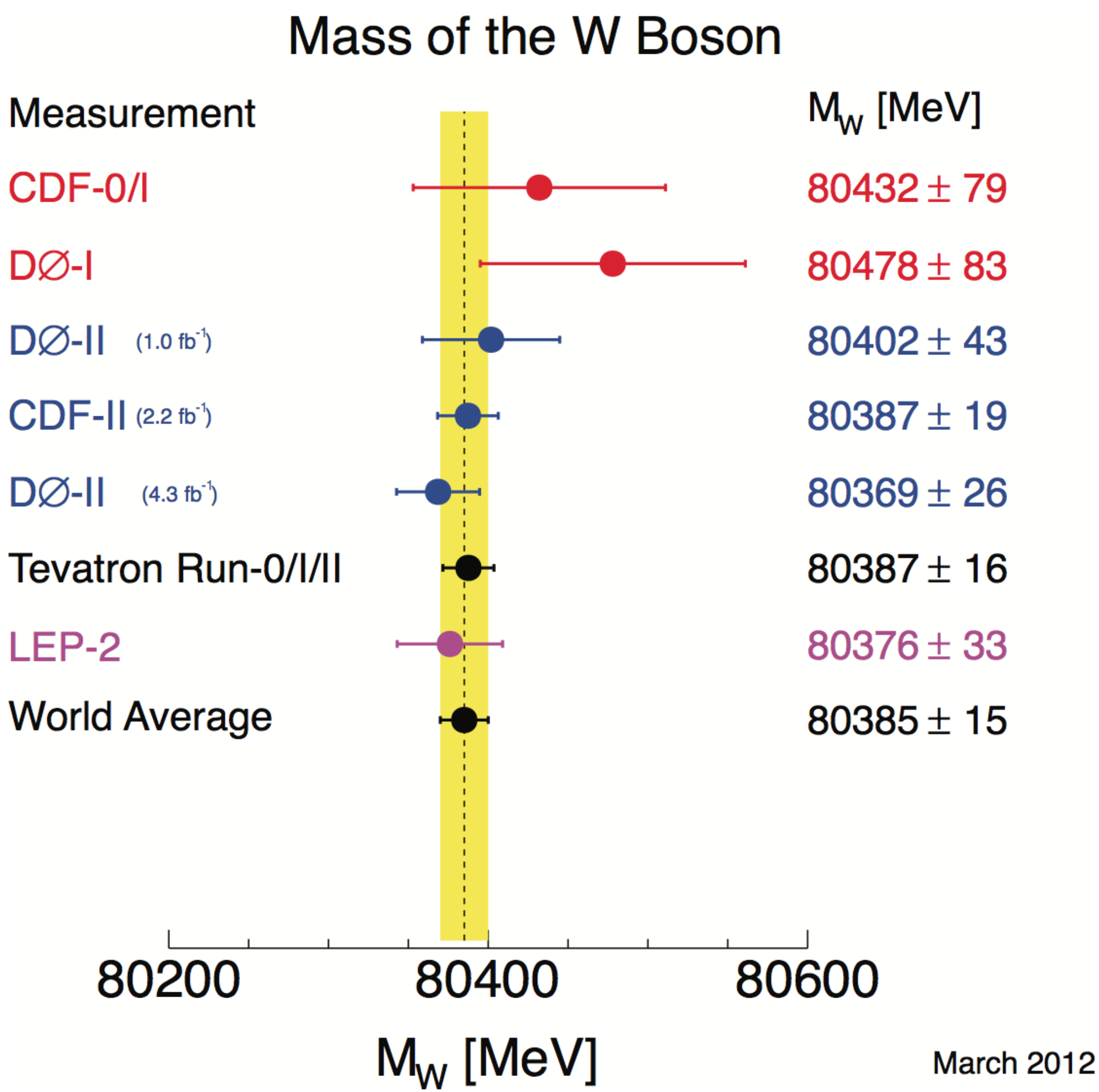
**W data**

| $m_T$ | $p_T(e)$ |
|---|---|
|  |  |
| Fit results: m(W) = 80371 ± 13 MeV (stat) | m(W) = 80343 ± 14 MeV (stat) |

# W-boson mass measurements: Tevatron versus LEP2

World average
computed by TeVEWWG
ArXiv:0908.1374
FERMILAB-TM-2439-E

**Previous world average:**
**80399 ± 23 MeV**




**New Tevatron result is significantly more precise than LEP average**

# Measurement of $m_W$ at the Tevatron: beyond the legacy of LEP!

| D0: W to eν (4+1 $fb^{-1}$) | CDF: W to eν (2.2 $fb^{-1}$) | CDF: W to μν (2.2 $fb^{-1}$) |
|---|---|---|
| 55k Z to ee | 16k Z to ee (!!) | 60k Z to μμ |
| 1.7M W (lηl < 1.05!!) | 0.5M W | 0.6M W |
| $\delta m_W$(stat) = 13 MeV | $\delta m_W$(stat) = 13 MeV | $\delta m_W$(stat) = 13 MeV |
| $\delta m_W$(syst) = 22 MeV | $\delta m_W$(syst) = 18 MeV | $\delta m_W$(stat) = 16 MeV |
| Combine with 1 $fb^{-1}$ result | Combine J/ψ&Υ to μμ with $m_Z$ from LEP!! | |
| $\delta m_W$(tot) = 23 MeV | $\delta m_W$(tot) = 19 MeV | |

- Can more than double statistics with full runII dataset
- Current incompressible systematic is 10 MeV from PDFs (not worked on yet to reduce this using Tevatron data)
- Hope to reach 10-15 MeV ultimately per experiment

→ challenge for LHC will be at the 5 MeV level

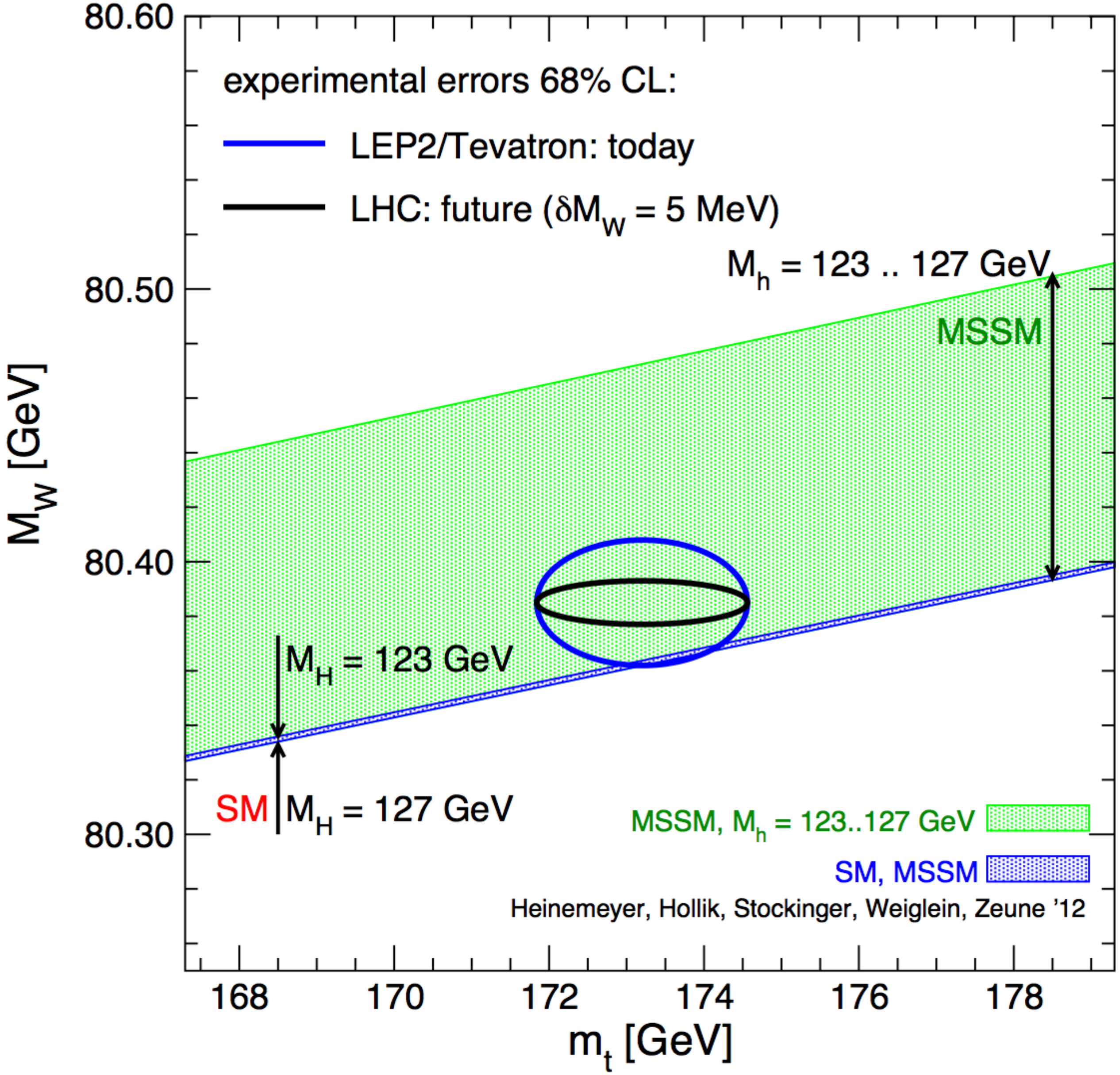
# Measurement of $m_W$ at LHC: beyond the legacy of Tevatron?

## Needs from theory colleagues

- The $p_T(W)$ distribution
  - As said, we will always compare predictions to our data, and correct them when needed. But this measurement will greatly benefit from theoretical assistance!
  - The Good Generator will
    - Incorporate all well-known theory
    - Summarize uncertainties into a few phenomenological parameters, that the experiments can fit
    - Allow to do this externally – we need to be able to do this ourselves, and iterate quickly
- PDFs
  - We have many potential handles :
    - W charge asymmetry; Z rapidity distribution
    - Low-mass Drell-Yan ($\bar{u}$ / $\bar{d}$ separation)
    - W + charm (strangeness!)
  - But some are really challenging. To define a realistic strategy, we ABSOLUTELY need to dispose of realistic PDF uncertainty estimates, and a flexible PDF fitting framework allowing us to vary parameters everywhere needed at a fast pace.

# Precision EW measurements: measure $m_W$ to ~ 5 MeV: very difficult! What for??

- **Perhaps untangle whether possibly observed Higgs boson is SM or SUSY-like?**



# Precision EW measurements: measure $m_W$ to ~ 5 MeV: very difficult! What for??

- **Perhaps untangle whether possibly observed Higgs boson is SM or SUSY-like?**

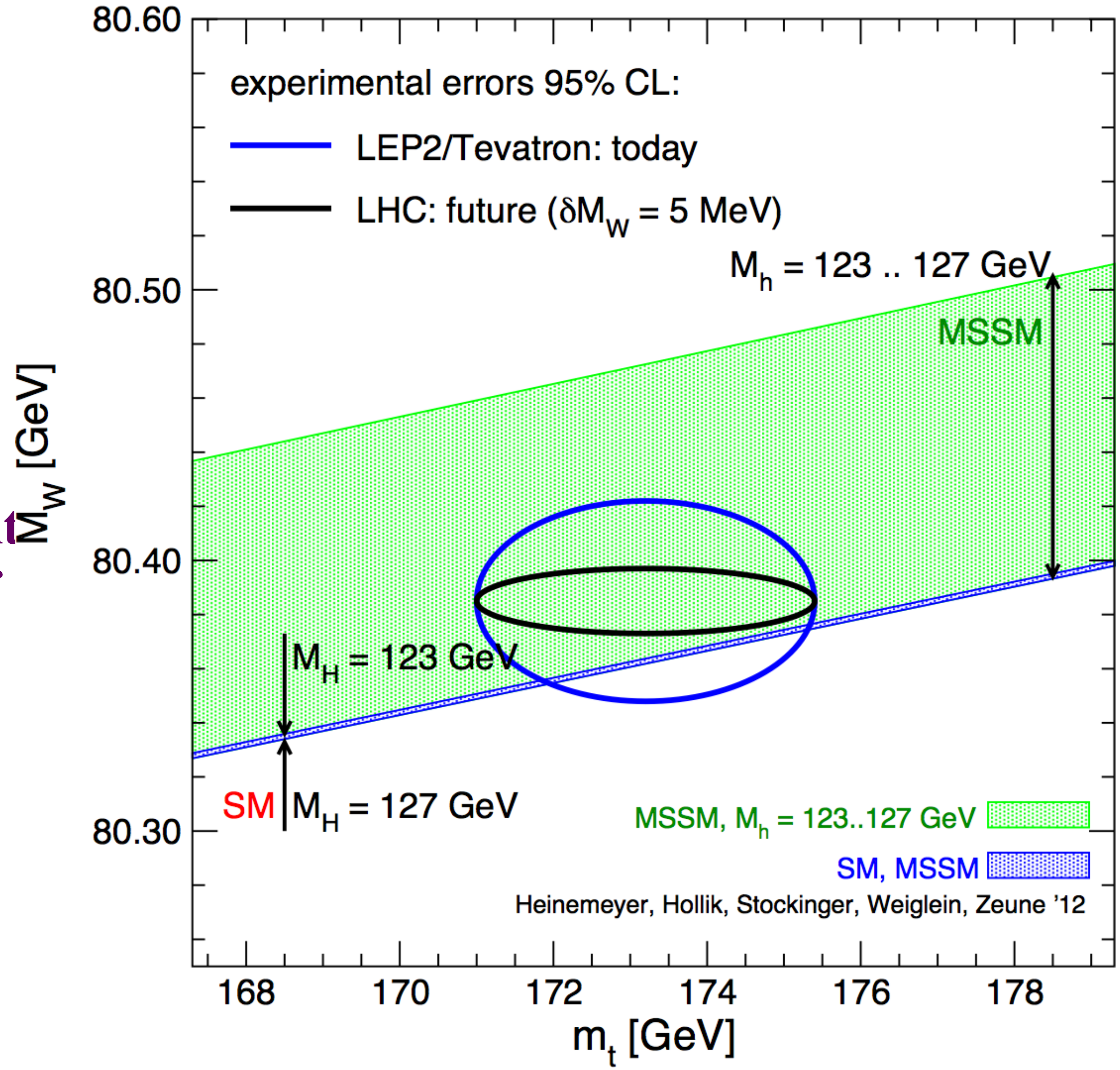
**• From 2012 to 2014 when LHC will restart at 13 TeV, our understanding of how well the SM describes fundamental interactions is quite likely to change**

**• The Tevatron community will further improve their fantastic results on $m_W$ (and $m_{top}$?)**

**• The LHC community will profit hugely from the sheer amount of excellent data the machine and detectors are delivering**

**• And there might already be riddles to solve such as the exact nature of a possibly observed scalar boson, or even better of a whole family of new particles …**

See eg http://arxiv.org/pdf/1112.3026.pdf



# Short summary

♥ Today we are able to ask questions we were not able to formulate 25-30 years ago when I was a student. This together with what nature has in store for us over the next years of physics at the LHC is what is so exciting about our field, and probably any field in fundamental research

♥ The more we progress, the longer will be the gap between the reformulation of fundamental questions in our understanding of the universe and its complexity. This gap is already ~ equal to the useful professional lifetime of a human being. This poses real problems.

♥ But the first few years of LHC performance and physics studies have been an incredible reward to all those of us who have worked so long and so hard towards this goal.

It is even more rewarding to see that the LHC detectors are slowly picking up the challenge for precision measurements in the SM.

♥ In particular, it is a huge pleasure for me to be with all of you discussing physics again after so long without any data…

♥ Even if we find the Higgs boson as early as in 2012, only the third year of LHC operation, it will be a while before it is discussed in a SM EW overview talk although this is where eventually it will belong.

# Back-up slides

# Measurement of $p_T^Z$ and $p_T^W$

- Quite precise measurement of $p_T^W$ by ATLAS in 2010, with the hadronic recoil calibrated in terms of data/MC differences using the Z → ll decays
- Similar measurement basically impossible in 2011/2012 → 2016/2017??
- Long-term goal is to have this as an ancillary measurement for high-precision measurement of $m_W$ (see later slides)

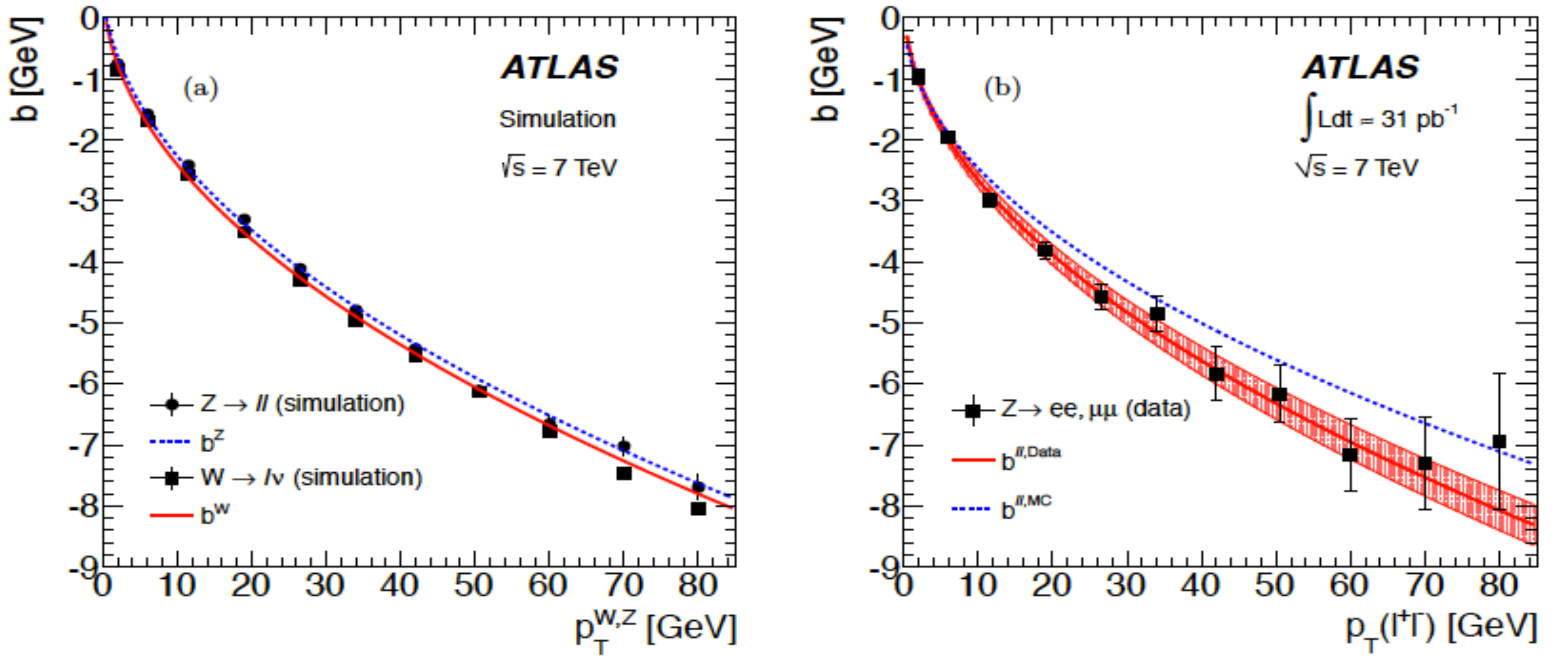
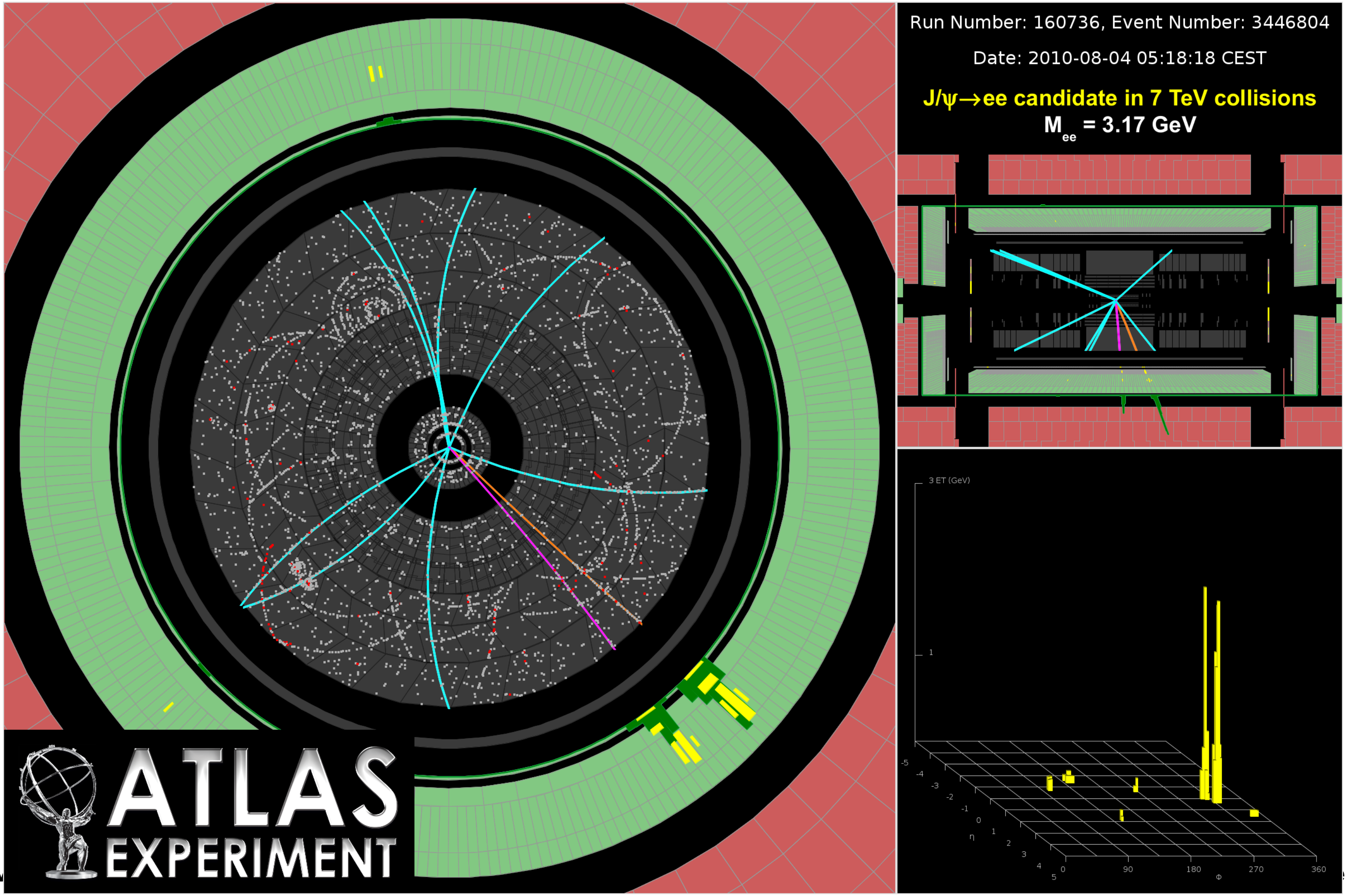



FIG. 2. **(a)** Parametrization of the recoil bias as a function of the vector boson transverse momentum, $b(p_T^{W,Z})$, in $W$ simulation (solid squares, solid line) and $Z$ simulation (solid circles, dashed line). **(b)** Parametrization of the recoil bias as a function of the reconstructed lepton pair transverse momentum, $b(p_T^{\ell\ell})$, in $Z$ simulation (dashed line) and data (solid squares, shaded band). The shaded band shows the uncertainty on the fit.

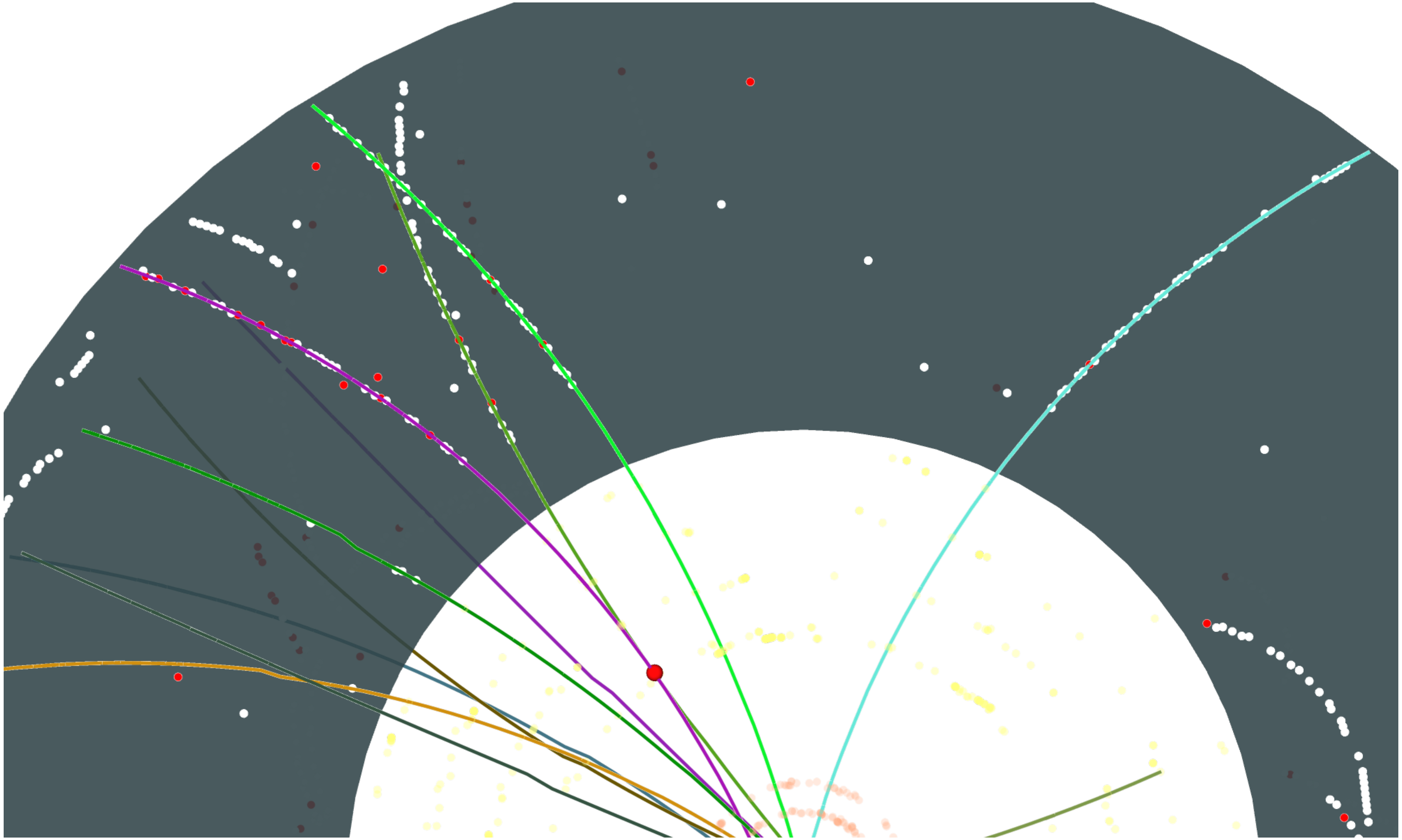
# Electrons from J/ψ decay

- Thanks to TRT, ATLAS has a J/ψ tag-and-probe trigger even at 3 $10^{33}$ luminosity. This is crucial to understand low-$p_T$ electrons for e.g. H to 4e
- J/ψ → ee events are also important for the understanding of the EM calorimeter performance (extraction of resolution, intercalibration, etc)



# Electrons from photon conversions

- TRT very powerful to track secondaries and then identify which ones are conversions. A few beautiful examples shown here for the pleasure of the eye.



# SM physics: W/Z differential measurements

- Differential distributions indicate that probing pdfs will perhaps be best achieved by using separately measurements for $W^+$, $W^-$ and Z as inputs to the fits

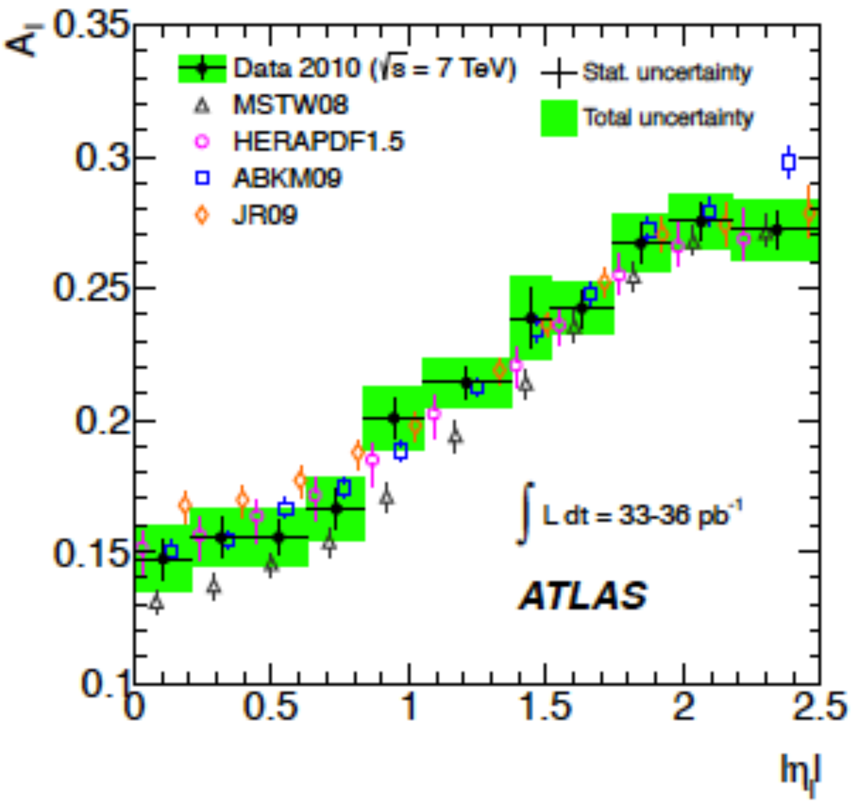
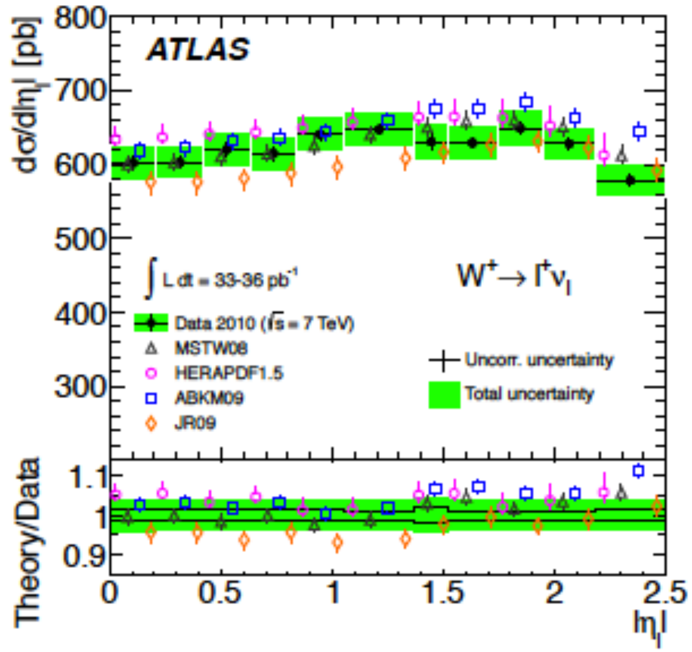
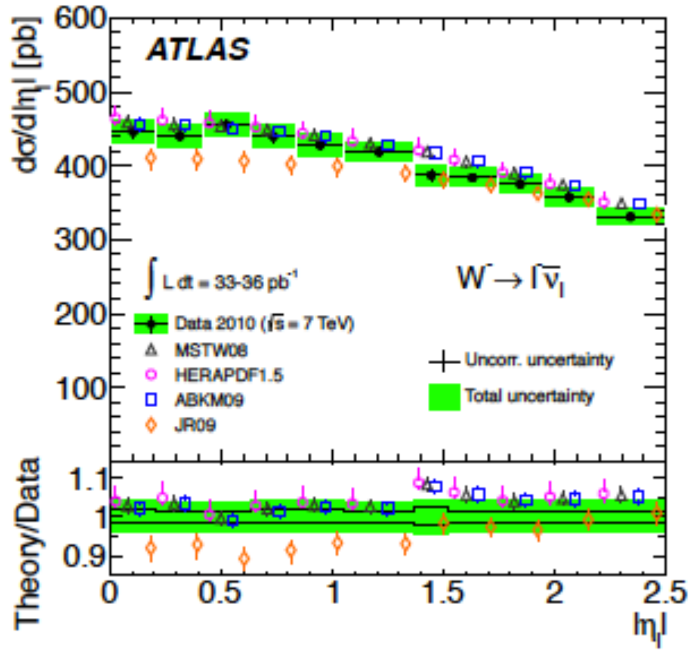


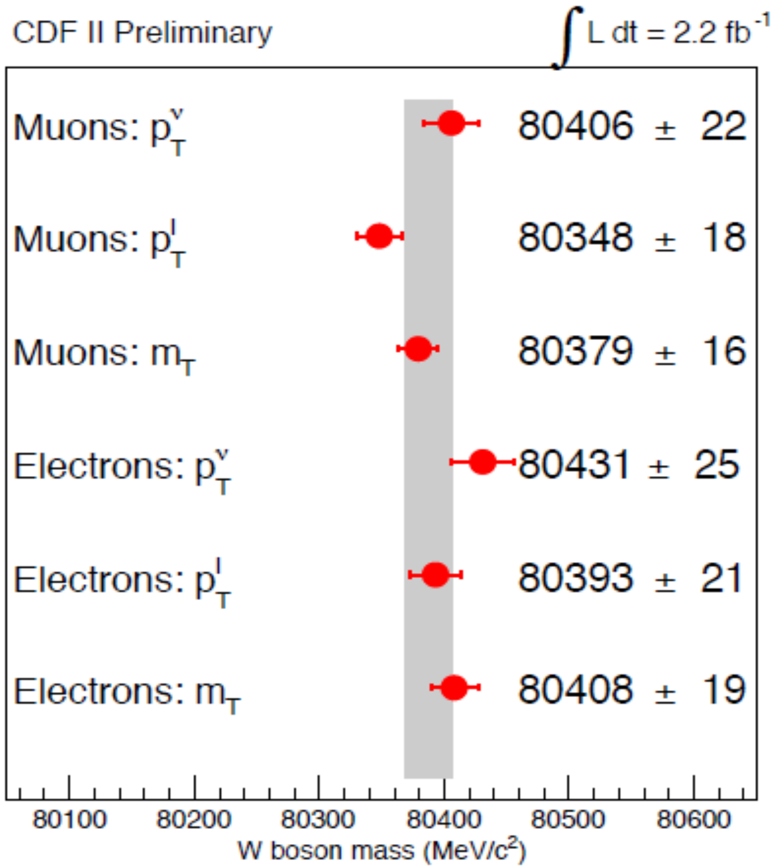

FIG. 14. *Measured W charge asymmetry as a function of lepton pseudorapidity $|\eta_l|$ compared with theoretical predictions calculated to NNLO. The kinematic requirements are $p_{T,\ell} > 20$ GeV, $p_{T,\nu} > 25$ GeV and $m_T > 40$ GeV. Theoretical points are displaced for clarity within each bin.*



# • Summary of *W* Mass Fits

| Charged Lepton | Kinematic Distribution | Fit Result (MeV) | $\chi^2$/DoF |
|---|---|---|---|
| Electron | Transverse mass | $80408 \pm 19$ | 52/48 |
| Electron | Charged lepton $p_T$ | $80393 \pm 21$ | 60/62 |
| Electron | Neutrino $p_T$ | $80431 \pm 25$ | 71/62 |
| Muon | Transverse mass | $80379 \pm 16$ | 57/48 |
| Muon | Charged lepton $p_T$ | $80348 \pm 18$ | 58/62 |
| Muon | Neutrino $p_T$ | $80406 \pm 22$ | 82/62 |

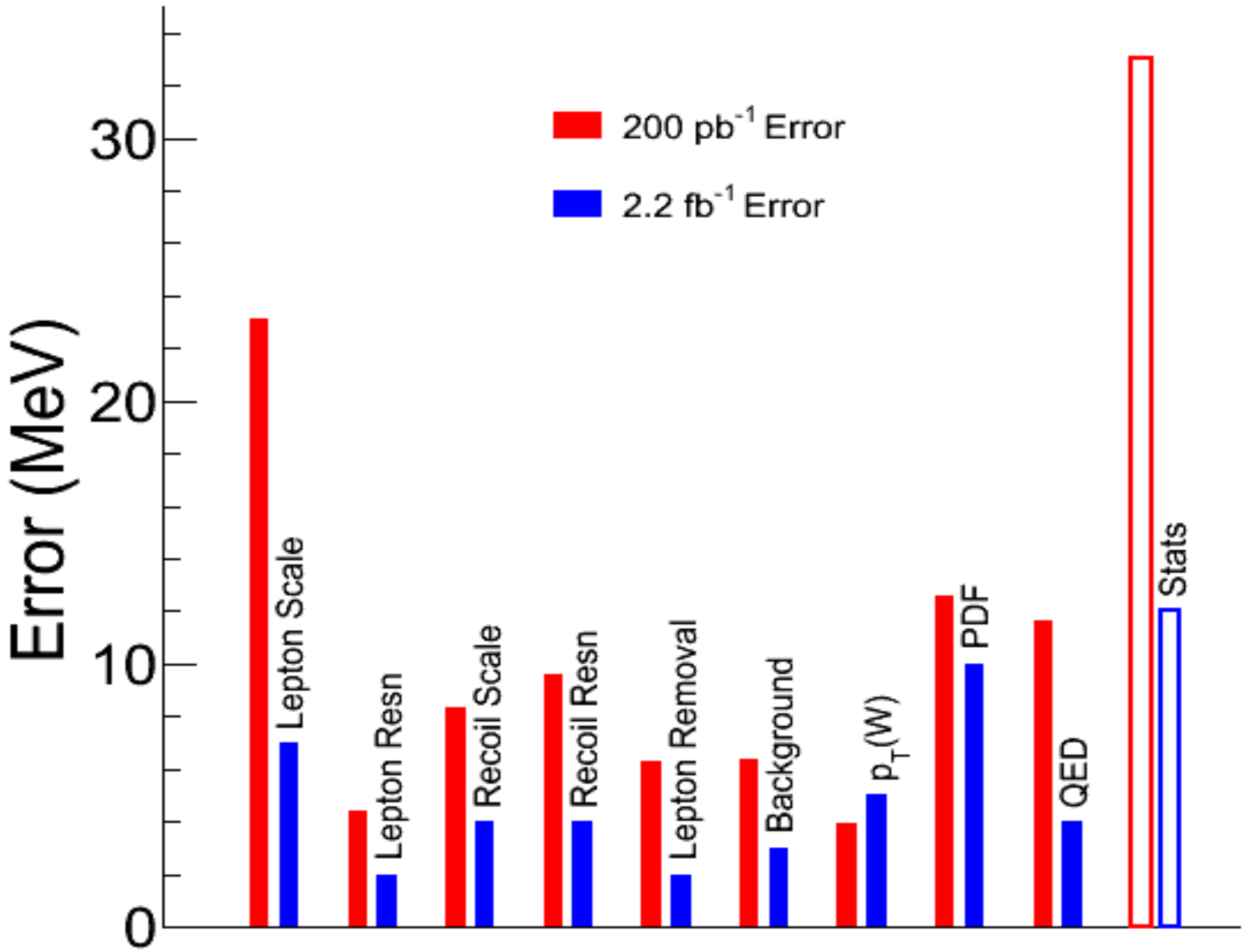


# •New CDF Result (2.2 $fb^{-1}$)
# Transverse Mass Fit Uncertainties (MeV)

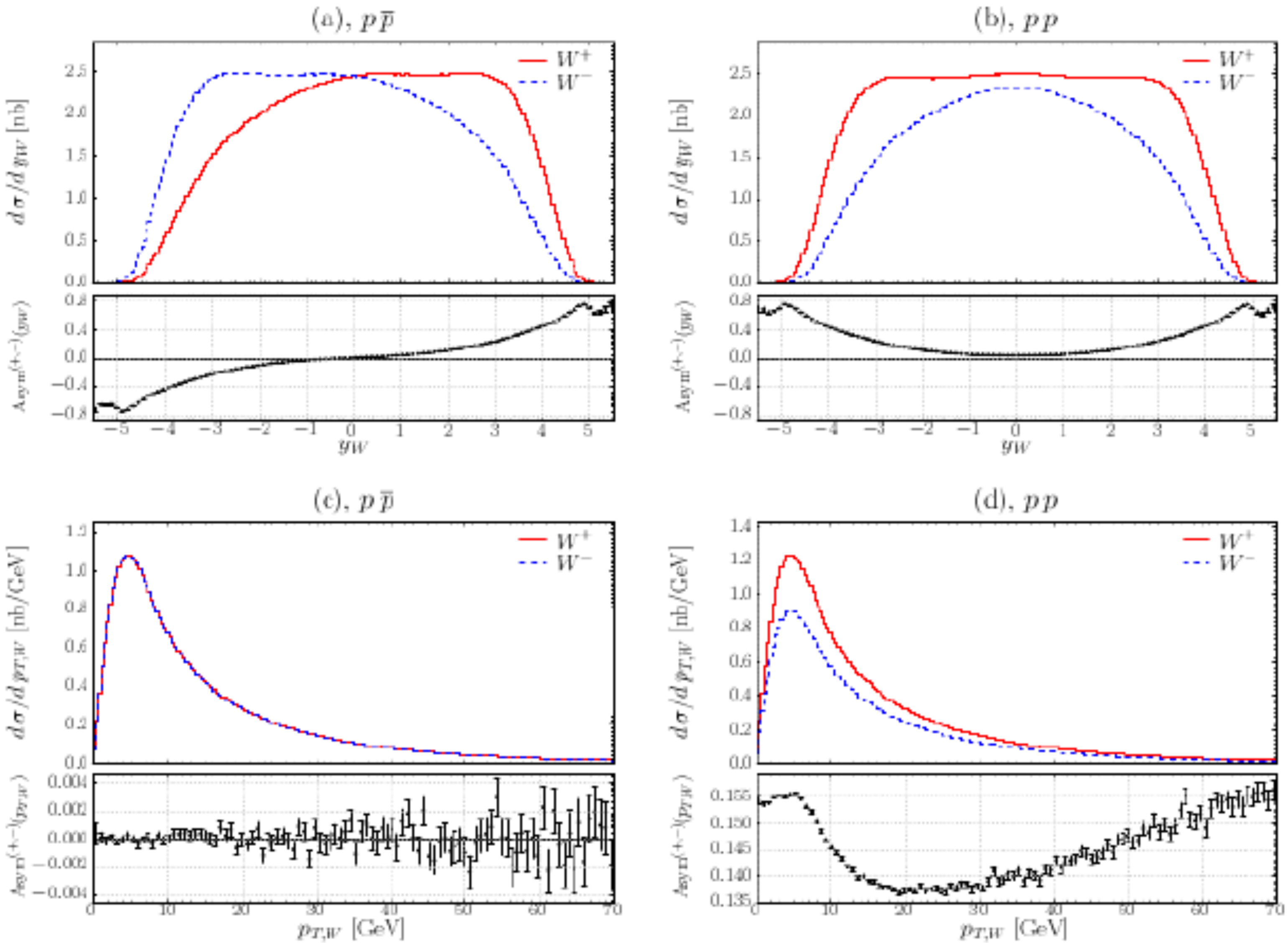
| | electrons | muons | common |
|---|---|---|---|
| W statistics | 19 | 16 | 0 |
| Lepton energy scale | 10 | 7 | 5 |
| Lepton resolution | 4 | 1 | 0 |
| Recoil energy scale | 5 | 5 | 5 |
| Recoil energy resolution | 7 | 7 | 7 |
| Selection bias | 0 | 0 | 0 |
| Lepton removal | 3 | 2 | 2 |
| Backgrounds | 4 | 3 | 0 |
| pT(W) model | 3 | 3 | 3 |
| Parton dist. Functions | 10 | 10 | 10 |
| QED rad. Corrections | 4 | 4 | 4 |
| Total systematic | 18 | 16 | 15 |
| Total | 26 | 23 | |

•**Systematic uncertainties shown in green: statistics-limited by control data samples**

# Combined W Mass Result, Error Scaling



# Measurement of $m_W$ at LHC: beyond the legacy of Tevatron?




Krasny et al, Eur.Phys.J.C69:379-397,2010

# Measurement of $m_W$ at LHC: beyond the legacy of Tevatron?

- Experimental challenges – keeping systematics below ~5 MeV requires
  - energy/momentum scale control to < $10^{-4}$ (average), ~$10^{-3}$ (locally)
  - resolution to ~1%
  - $p_T$ dependence of lepton efficiency to 1%
- Strategy to control the $p_T(W)$ distribution :
  - Rely on state of the art generators to predict the lepton distributions at given $p_T(W)$
  - Measure the pT(W) distribution from the recoil distribution, calibrating from MinBias, J/Psi, and Z boson events, separately in $W^+$ and $W^-$ events
  - Ultimately, measure $M_W$ in bins of $p_T(W)$, with two benefits
    - Exploit a sharper Jacobian peak at low $p_T(W)$ : improve the statistical sensitivity
    - $M_W^{fit}$ vs $p_T(W)$, separating by charge, provides an excellent control plot
- The y(W) distribution
  - Much information will be extracted from y(Z); also A(W); low-mass DY
  - Still, the strange contribution to W production remains critical to control