Standard Model @ LHC
University of Freiburg 9-12 April 2013

W / Z production: transverse momentum and angular distributions at the LHC

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on behalf of the ATLAS, CMS and LHCb Collaborations

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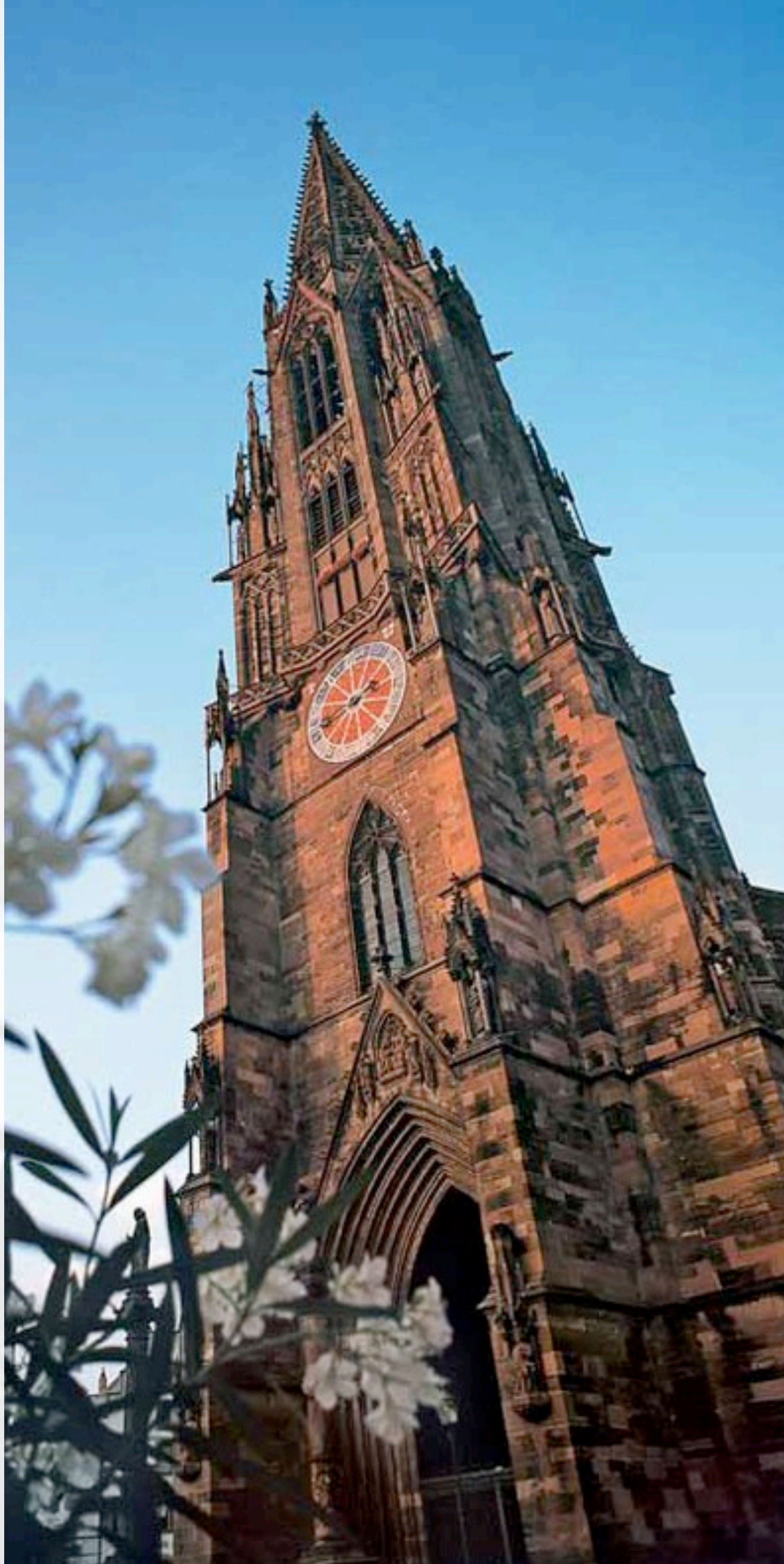
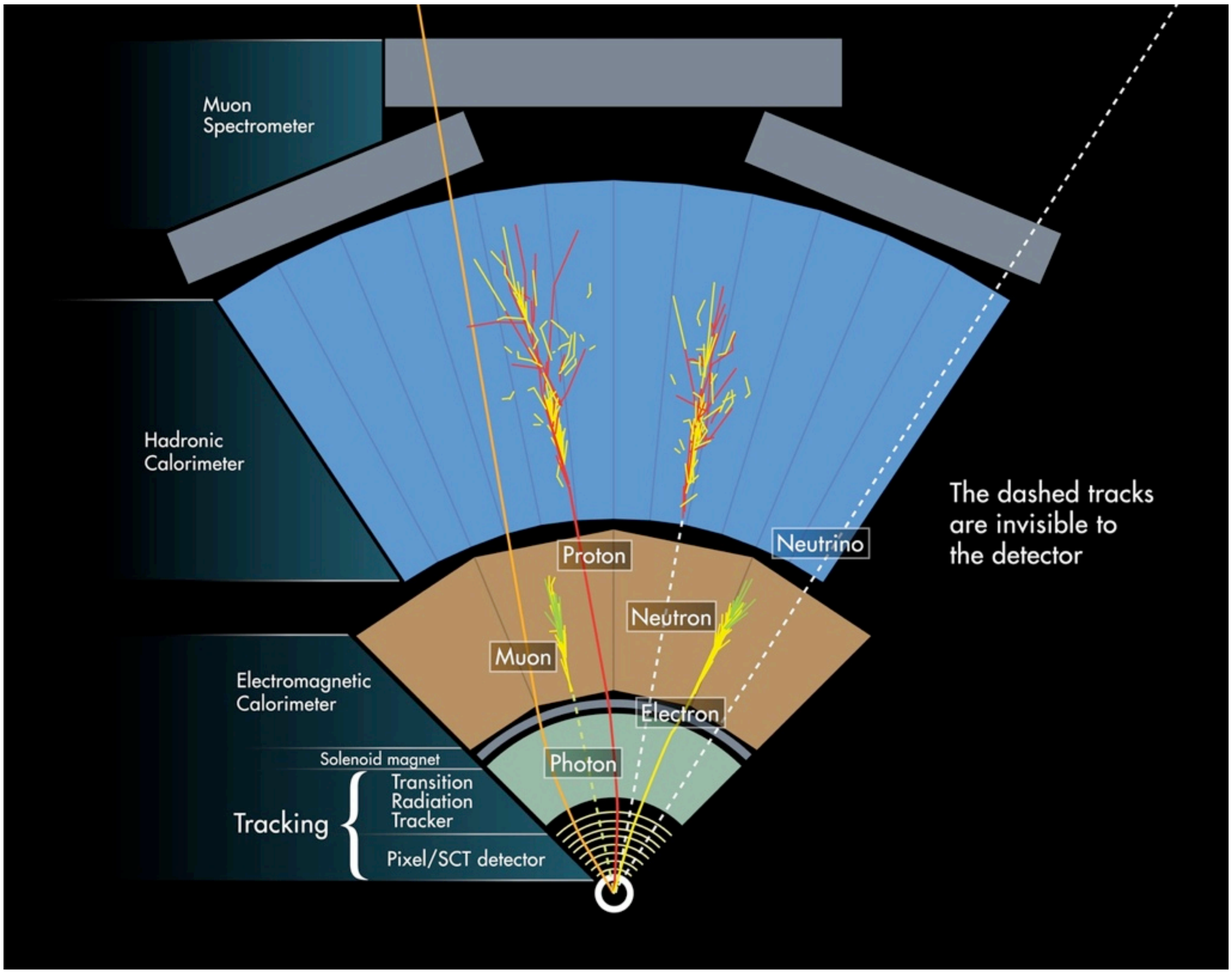


Intro and overview

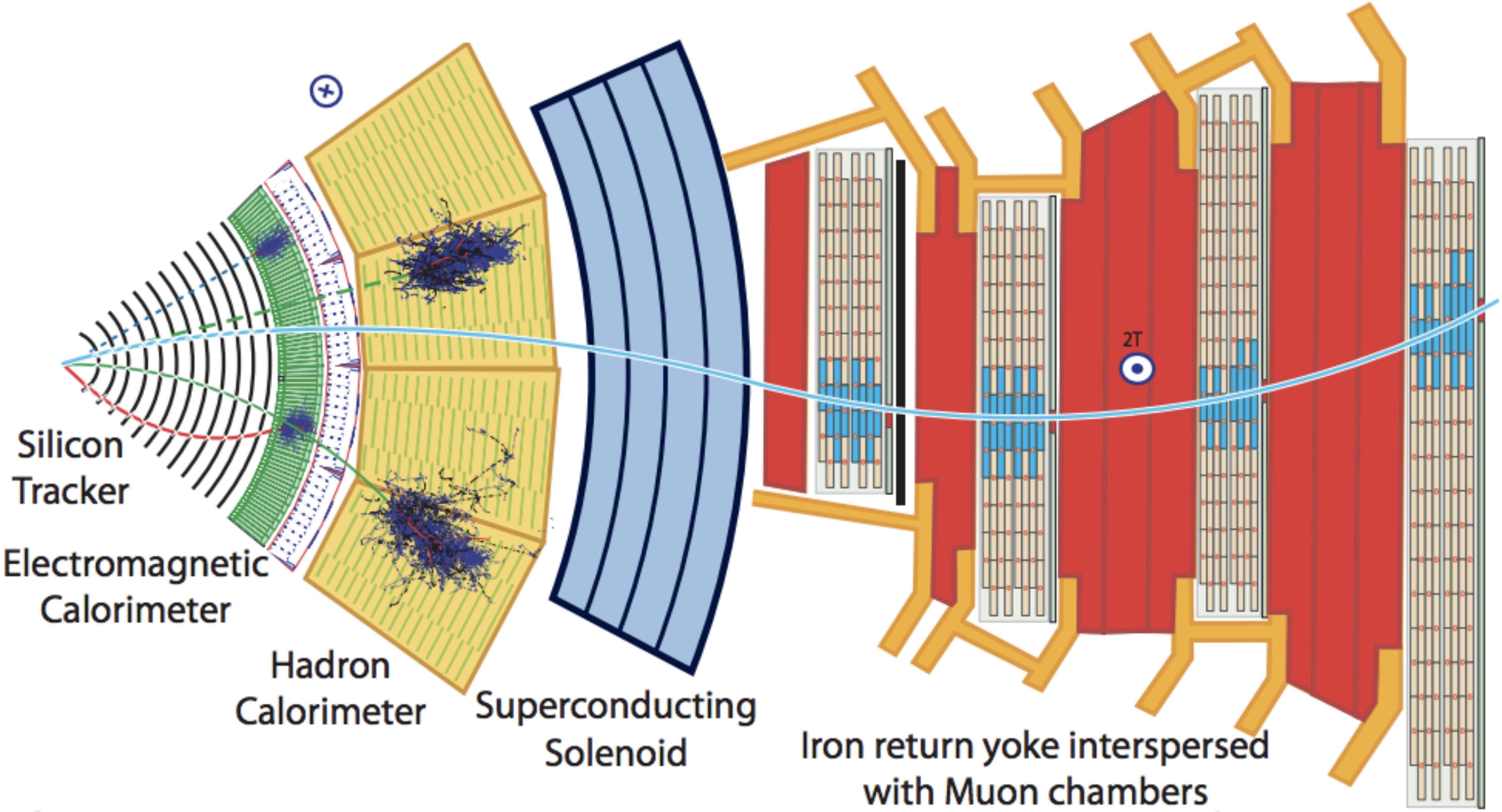
- Study of W/Z bosons kinematic features is of crucial importance for several physics topics
  - Parton density functions describing proton composition
  - Implication on precision physics (e.g. W boson mass)
- In this context LHC offers an ideal opportunity in both data taking conditions (new colliding energy) and accumulated statistics
- In the following the summary of ATLAS, CMS and LHCb results are given:

Topic	ATLAS	CMS	LHCb
$d\sigma/dp_T$	Z: 7 TeV, 36/pb - 7 TeV, 4.6/fb arXiv: 1107.2381 - arXiv:1211.6899	Z: 7 TeV, 36/pb - 8 TeV, 18.4/pb CMS-PAS-EWK-10-010 - CMS-PAS-SMP-12-025	Z: 7 TeV, 0.94/fb (e) arXiv:1212.4620
	W: 7 TeV, 31/pb arXiv:1108.6308	-	-
$d\sigma/dy$	Z: 7 TeV, 35/pb arXiv:1109.5141	Z: 7 TeV, 36/pb CMS-PAS-EWK-10-010	Z: 7 TeV, 0.94/fb (e) - 7 TeV, 37/pb arXiv:1212.4620 - arXiv:1204.1620
$d\sigma/d\eta_l$	W: 7 TeV, 35/pb arXiv:1108.6308	-	W: 7 TeV, 37/pb arXiv:1204.1620
A_{FB} (Z)	-	7 TeV, 5/fb arXiv:1207.3973	-
W charge asymmetry	7 TeV, 35/pb arXiv:1109.5141	7 TeV, 840/pb (e) - 7 TeV, 234/pb (μ) arXiv:1206.2598 - CMS-PAS-EWK-11-005	-
W polarization	7 TeV, 35/pb arXiv:1203.2165	7 TeV, 36/pb arXiv:1104.3829	-

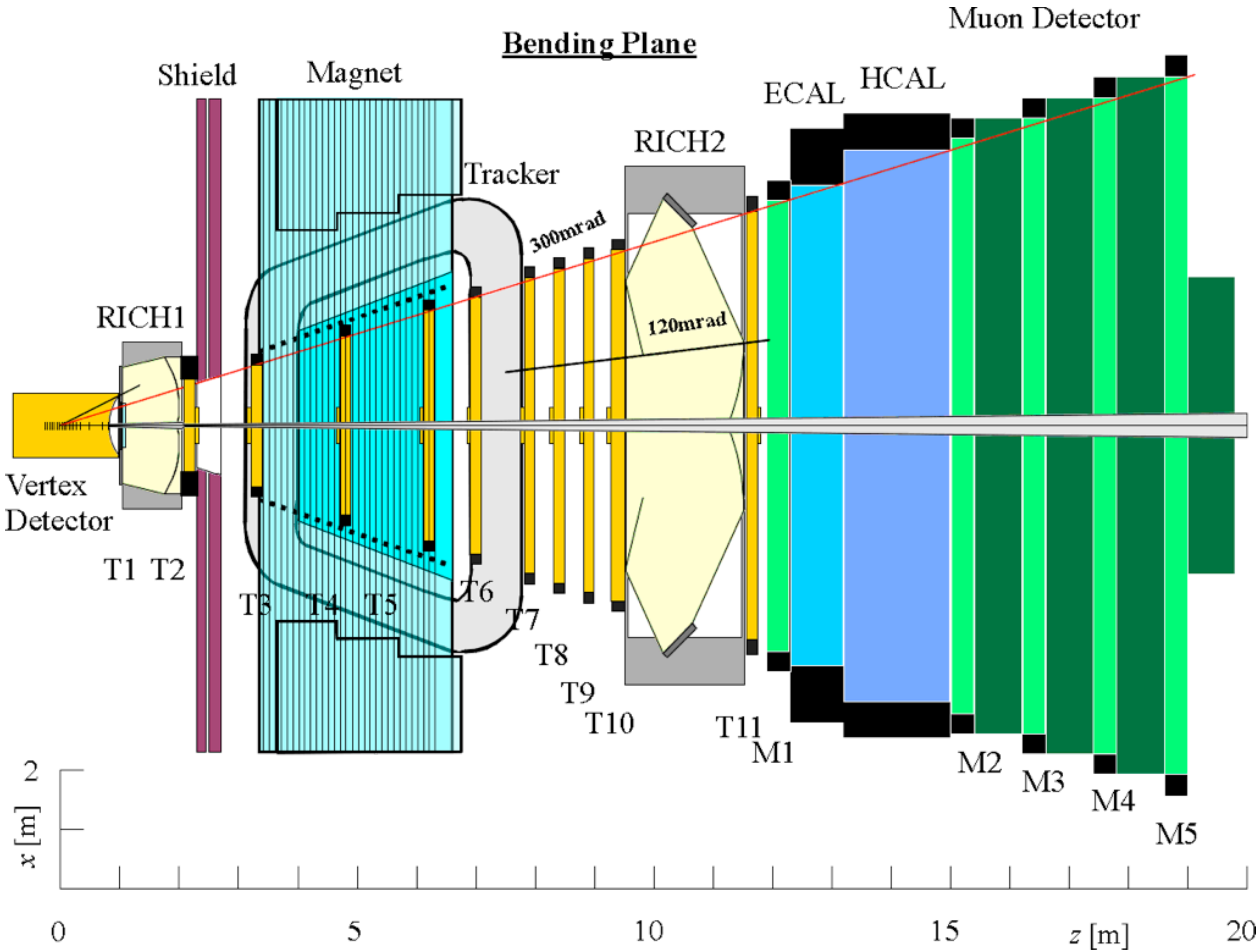
ATLAS


Muon Spectrometer
Hadronic Calorimeter
Electromagnetic Calorimeter
Solenoid magnet
Tracking
Transition Radiation Tracker
Pixel/SCT detector
Proton
Neutrino
Neutron
Muon
Electron
Photon
The dashed tracks are invisible to the detector

Compact Muon Solenoid



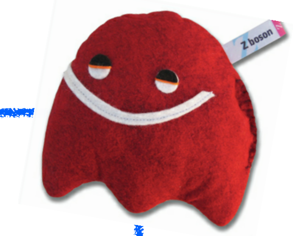
LHCb



Bending Plane
Muon Detector
Shield
Magnet
ECAL
HCAL
RICH2
Tracker
300mrad
120mrad
RICH1
Vertex
Detector
T1 T2
T3
T4
T5
T6
T7
T8
T9
T10
T11
M1
M2
M3
M4
M5
2
x [m]
0
5
10
15
z [m]
20

Common selections

Electron selection:
- E_T > 20 GeV
- $|\eta|$ < 2.4 CMS / 2.47 ATLAS
- "transition" region is excluded 1.4-1.6 CMS / 1.37-1.52 ATLAS
- 2 < η < 4.5 LHCb
- Good quality



Z selection:
- 2 SF-OS good leptons
- isolation required for muons
- 66 < m_{ll} < 116 GeV ATLAS
- 60 < m_{ll} < 120 GeV CMS & LHCb

Muon selection:
- p_T > 20 GeV
- $|\eta|$ < 2.4
- 2 < η < 4.5 LHCb
- Consistency with PV
- Good quality in ID+Muon system combination

W selection:
- 1 good isolated lepton
- E_T^{miss} > 25 GeV
- m_T > 40 GeV

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

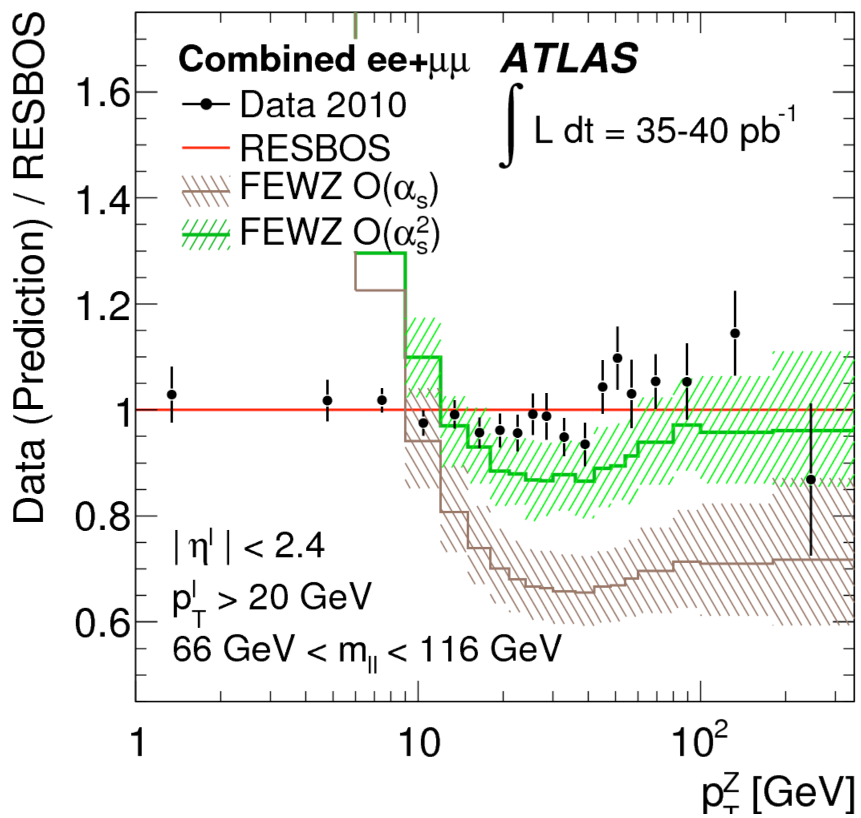
- These are the common baseline selections
- Any difference wrt/ these guidelines will be highlighted in the following

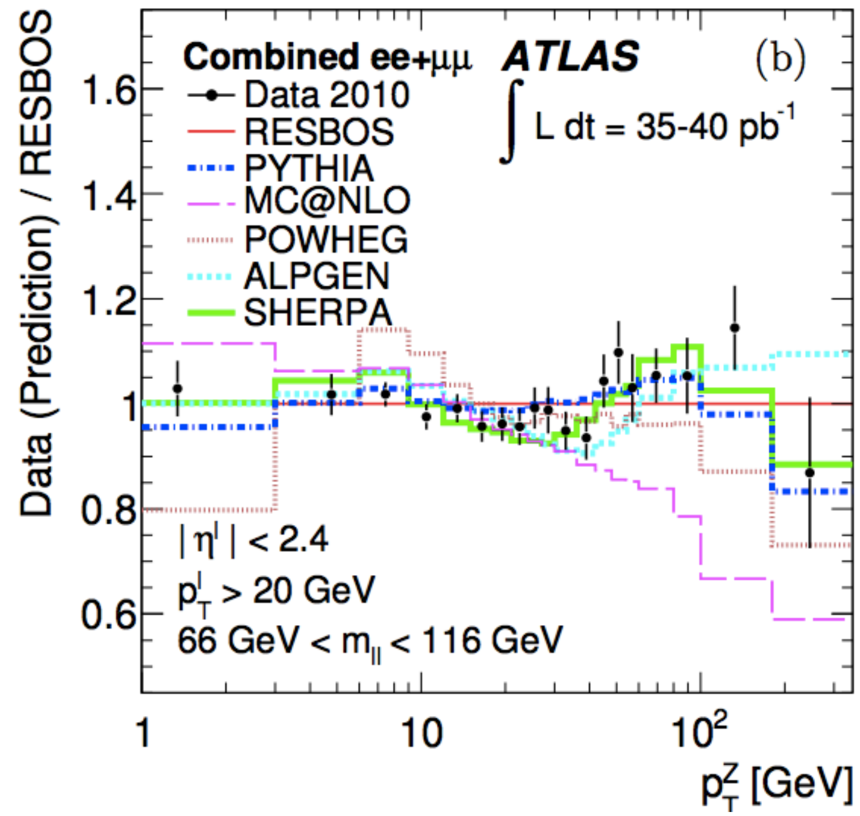
$d\sigma / dp_T$

* W and Z bosons are produced with a non-zero p_T because of quark/gluon radiation from the initial-state partons
* W/Z p_T spectra offer important testing ground for QCD dynamical effects and phenomenology which is complementary to W/Z + jets events
* Low-p_T dominated by multiple soft gluon radiation (includes perturbative effects) / intermediate p_T is dominated by first higher order corrections / high-p_T dominated by hard single gluon radiation (matrix element)
* Possibility to validate/tune existing models

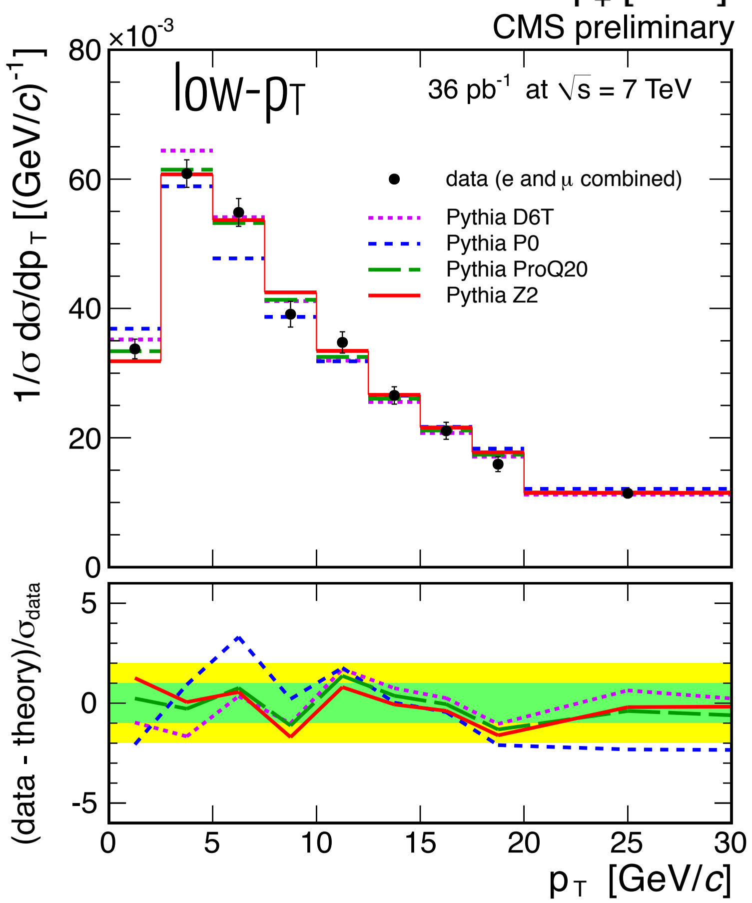
dσ / dp$_T$: Z boson - results

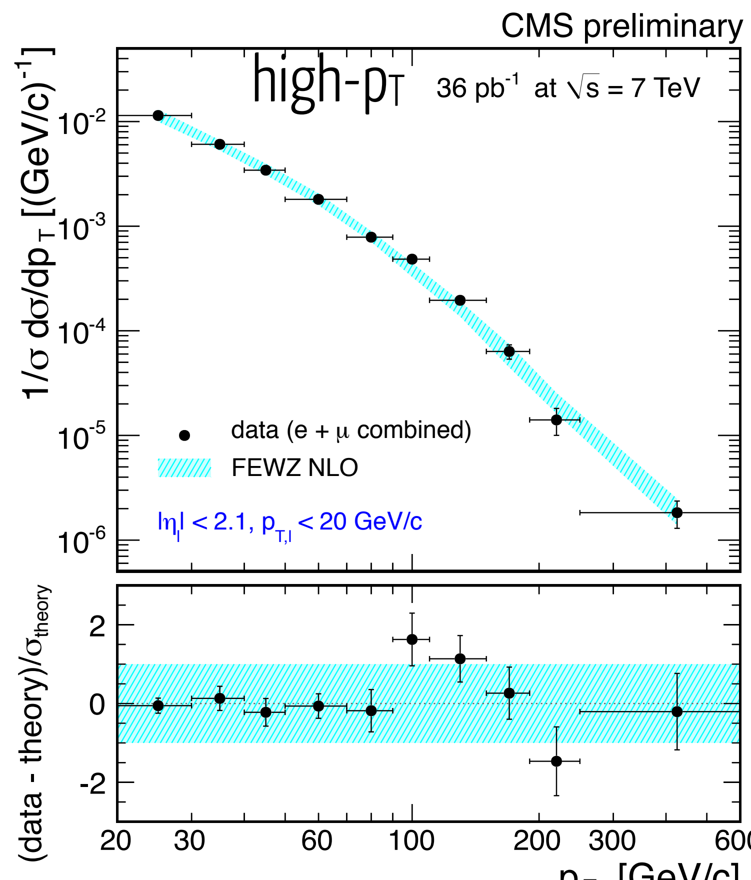
ATLAS: arXiv:1107.2381
$\sqrt{s}$ = 7 TeV, L = 36/pb





CMS: CMS-PAS-EWK-10-010
$\sqrt{s}$ = 7 TeV, L = 36/pb





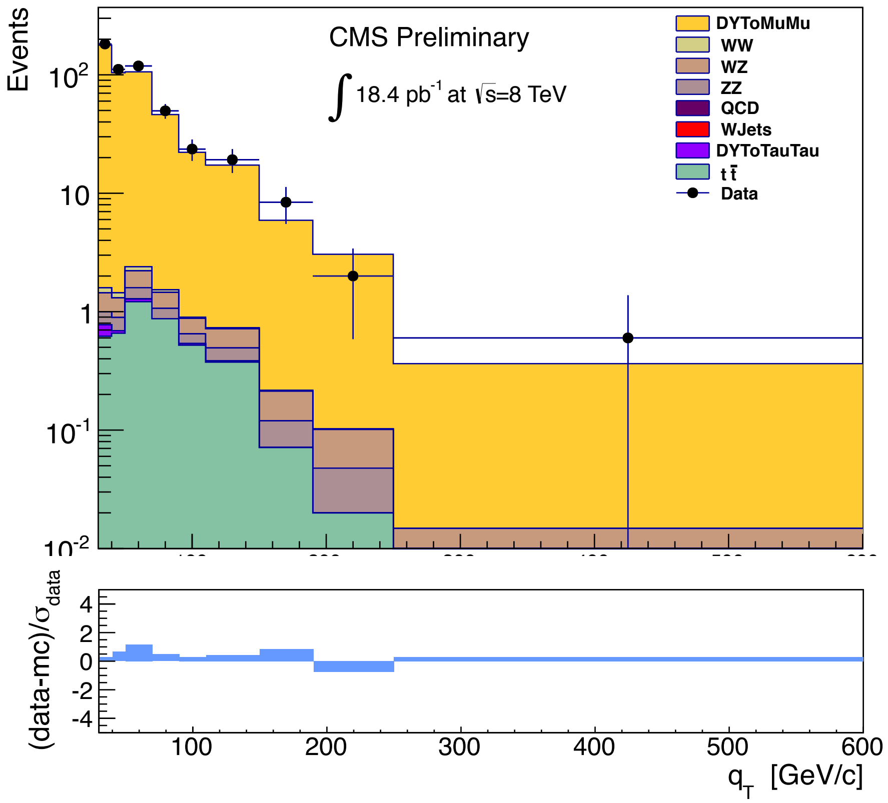
General remarks:

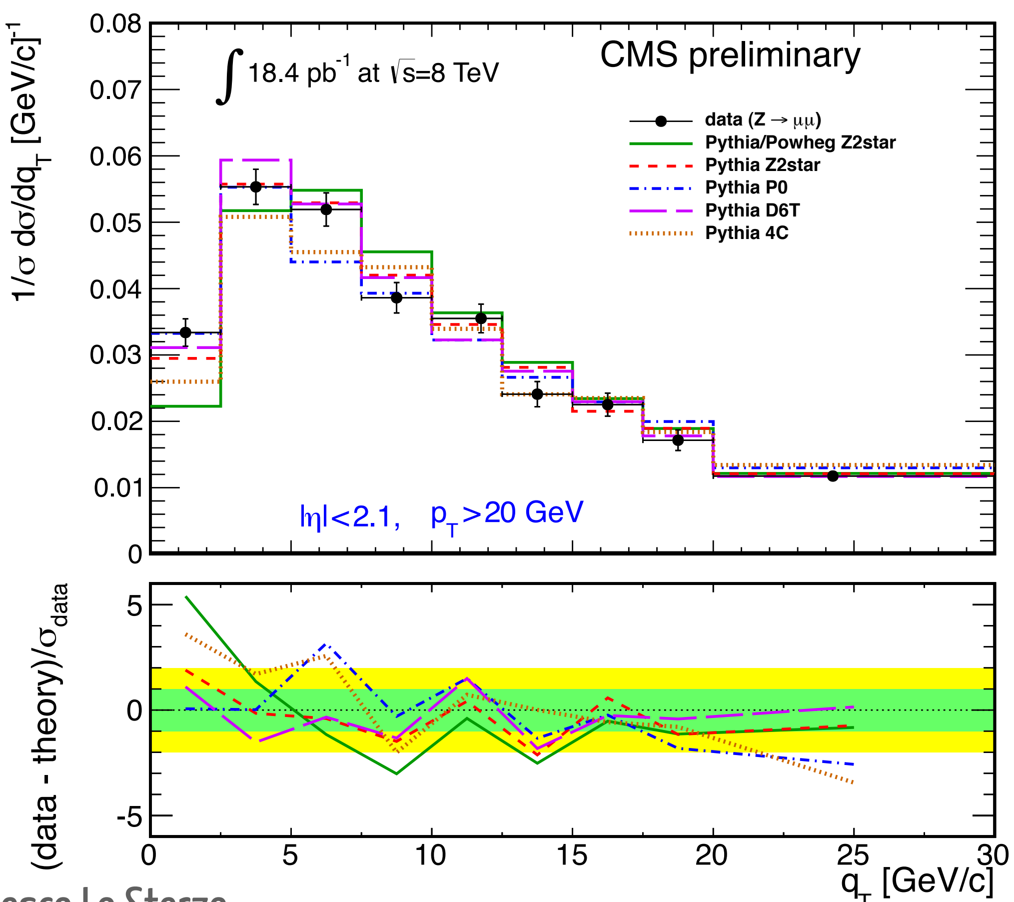
- overall good agreement with RESBOS, Pythia, Alpgen and Sherpa
- at high p$_T$ good agreement with FEWZ (ATLAS+CMS). Note that FEWS diverges at low p$_T$

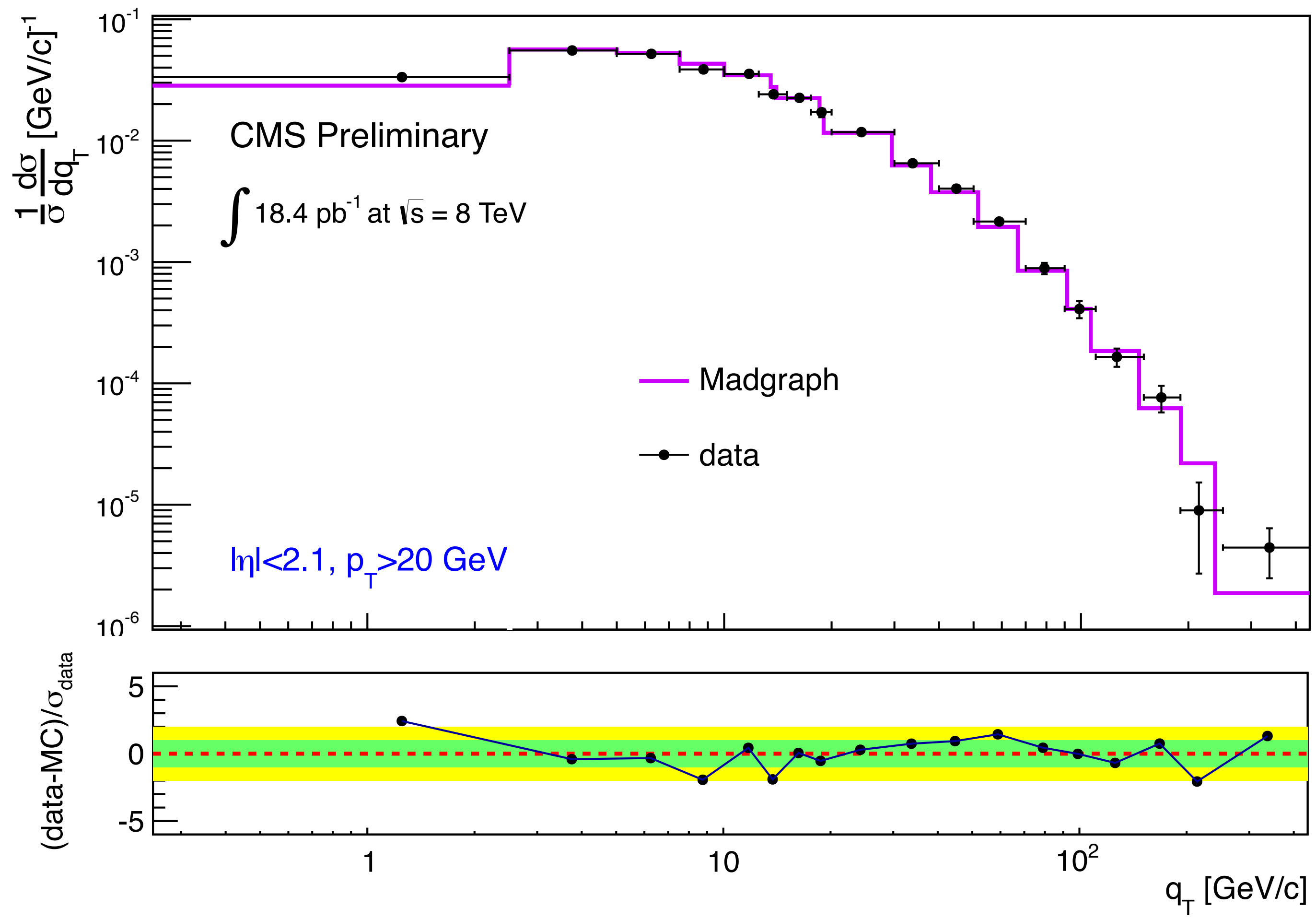
More on $d\sigma(Z) / dp_T$: CMS

CMS: $\sqrt{s}$ = 8 TeV, L = 18.4/pb - CMS-PAS-SMP-12-025

- Muon channel only
- Pythia+Z2star is good at low p_T^Z
- Madgraph+Pythia (and RESBOS) are good at high p_T^Z







$d\sigma(Z)/d\phi^*$: ATLAS

ATLAS: $\sqrt{s}$ = 7 TeV, L = 4.6/fb - arXiv:1211.6899

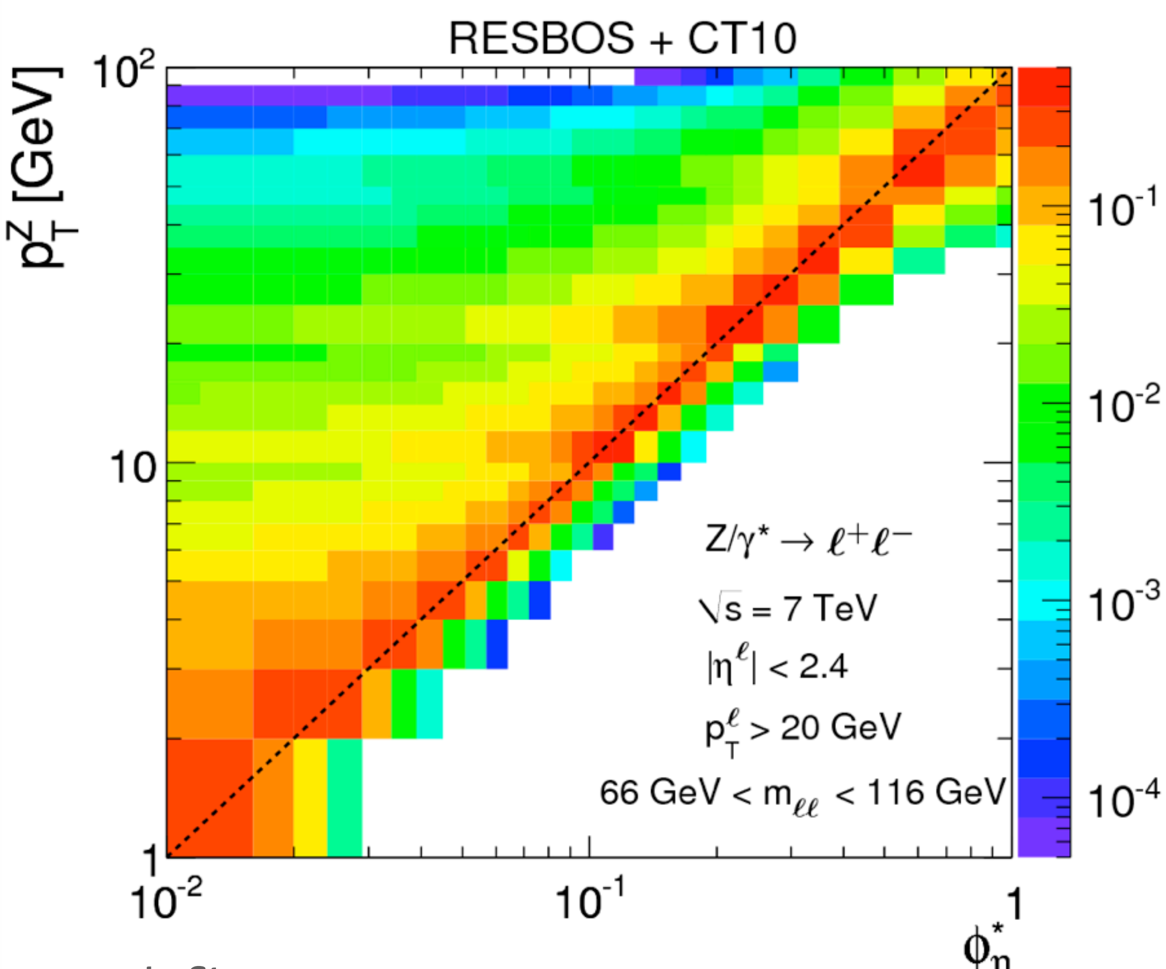
- Study of p_T^Z is limited because of experimental resolution (p_T scale, resolution)
- Alternative methods have been developed to study the same physics without being affected by those effects

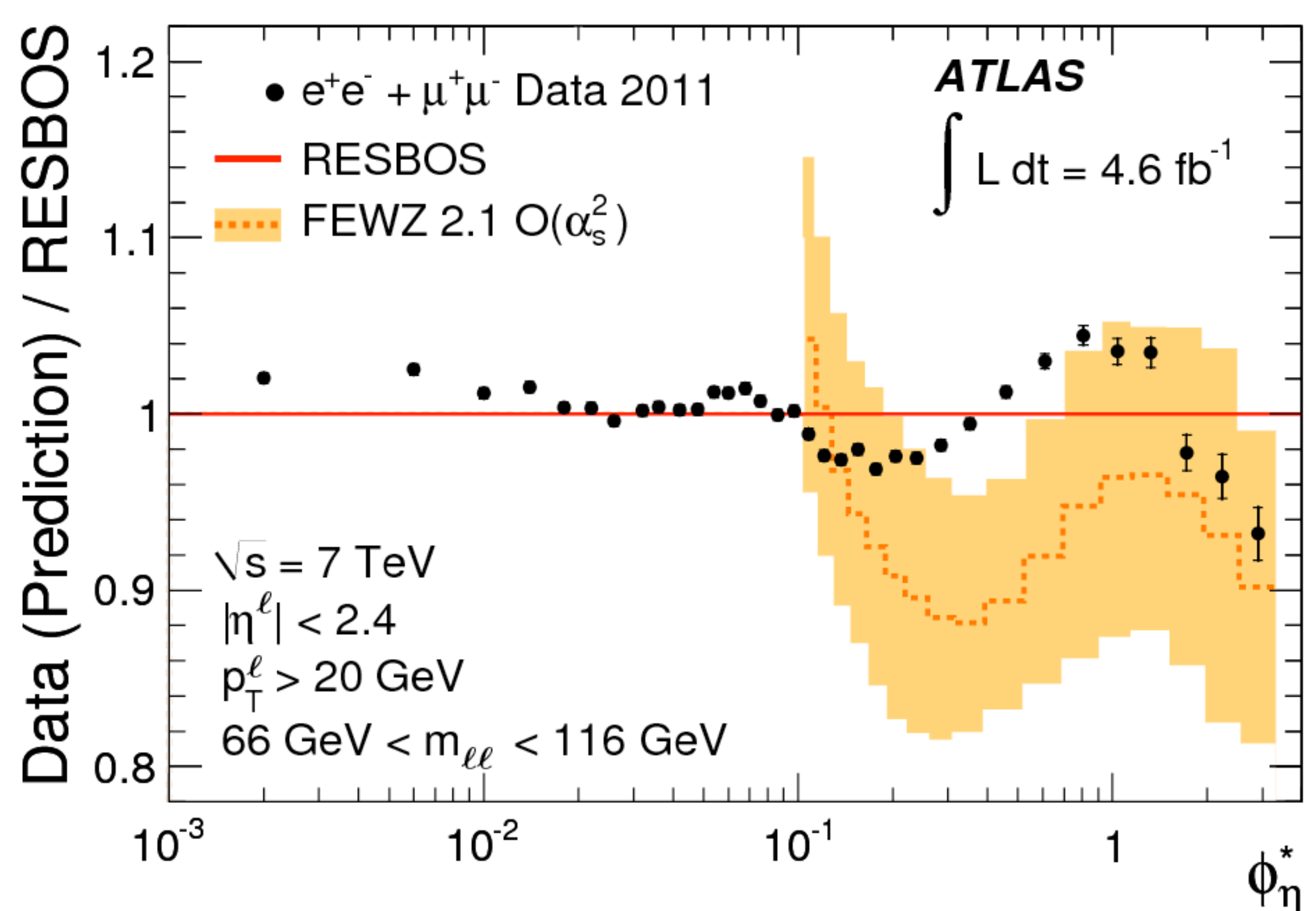
$$\phi^*_\eta = \tan(\phi_{acop}/2) \times \sin(\theta^*_\eta)$$

$$\phi_{acop} = \pi - \Delta\phi(\ell, \ell)$$

$$\cos(\theta^*_\eta) = \tanh[(\eta^- - \eta^+)/2]$$

A measurement of the scattering angle of the two leptons wrt/ the beam axis in the Z rest frame

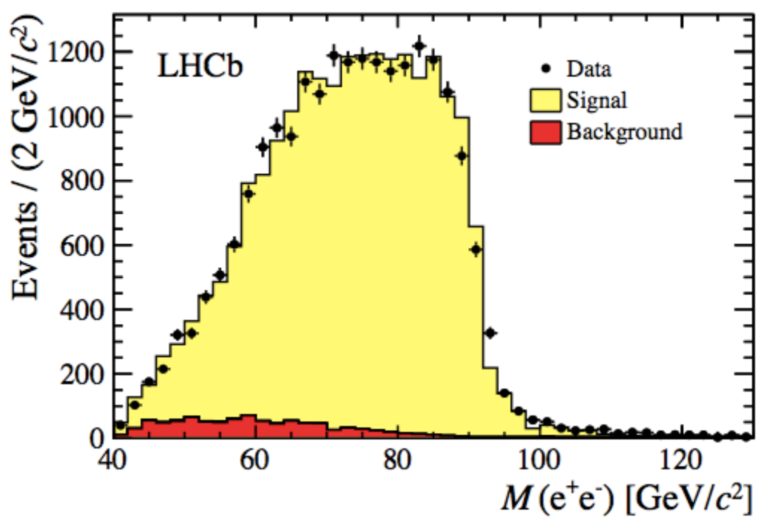




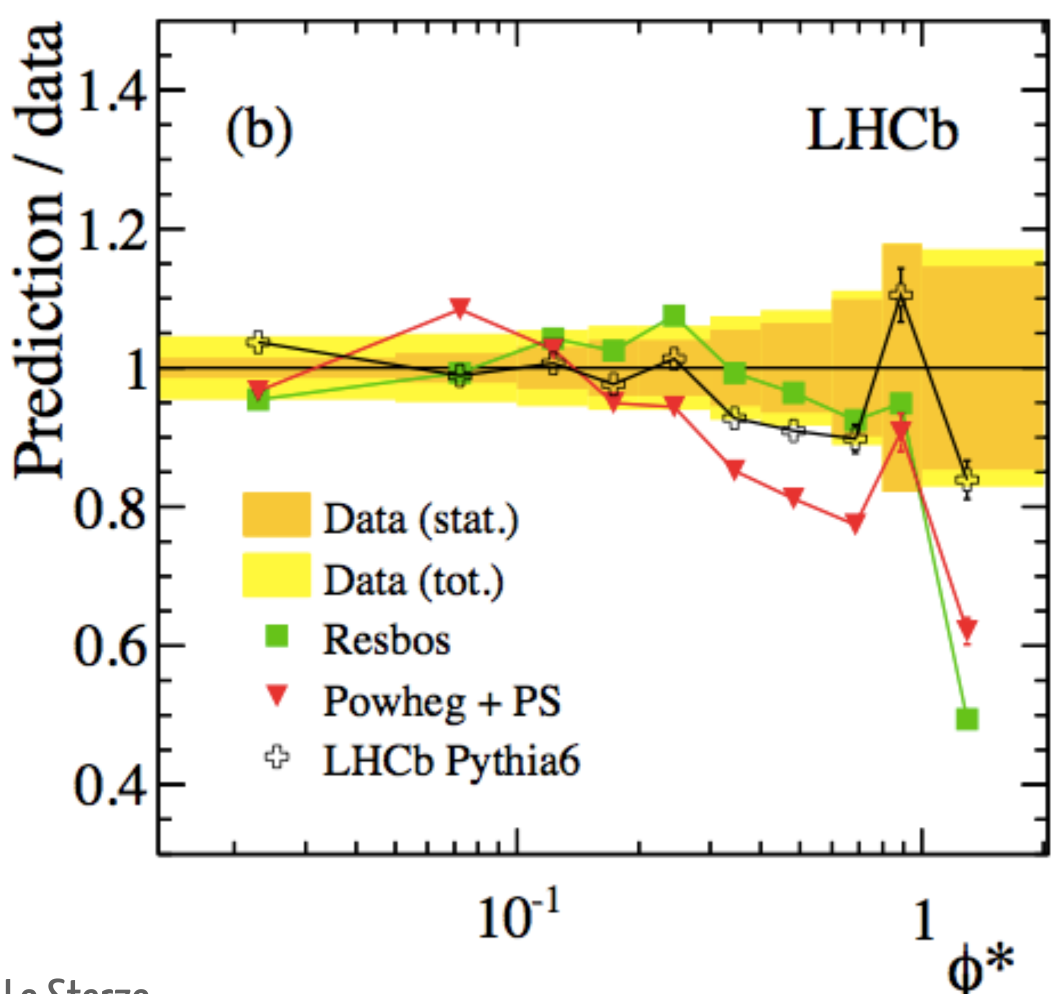
$d\sigma(Z)/d\phi^*$: results from LHCb

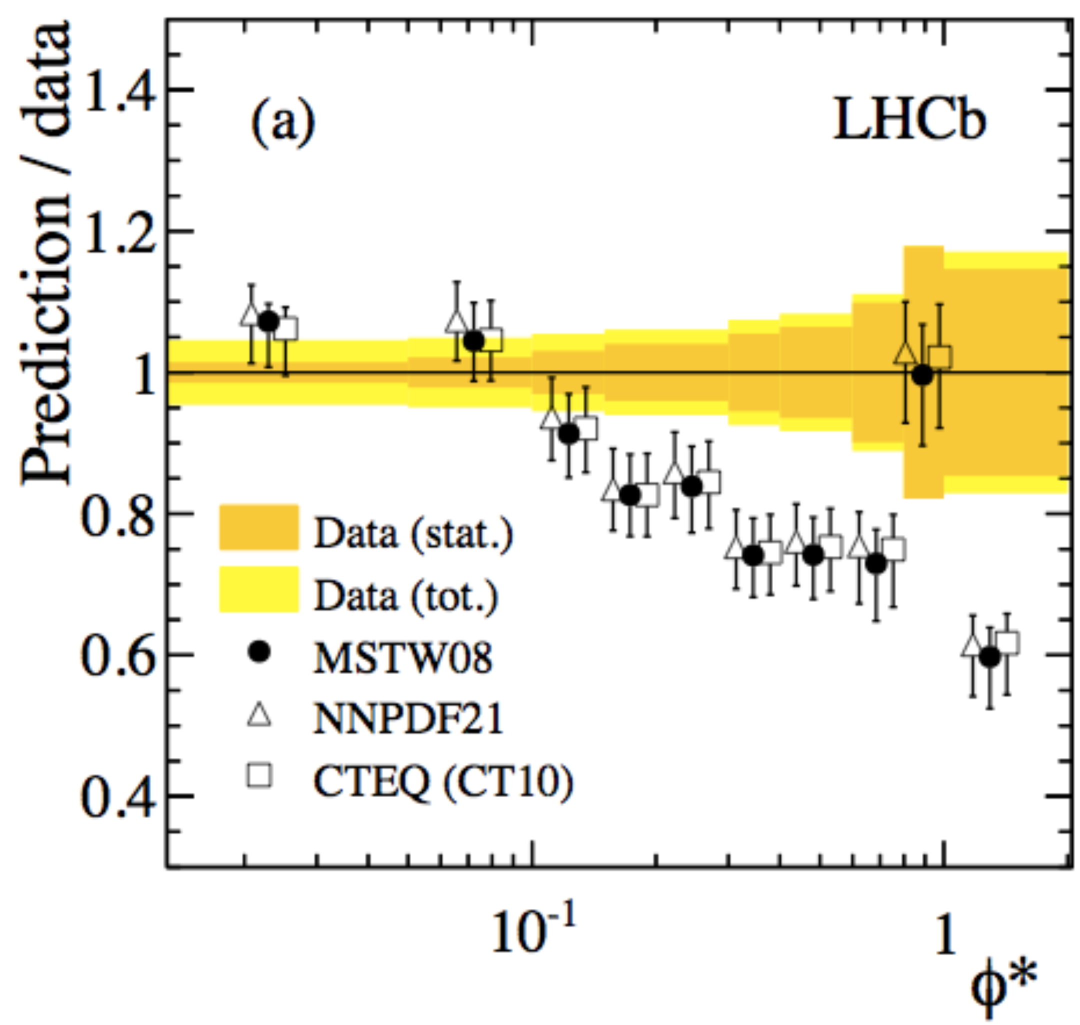
LHCb: $\sqrt{s}$ = 7 TeV, L = 0.94/fb
arXiv:1212.4620

- The peculiar LHCb structure allows to detect leptons in the very forward region, complementary to ATLAS/ CMS coverage



- e: $2 < \eta < 4.5$
- LHCb calorimeter is optimized for low-energy events and saturates for $E_T > 10$ GeV
- Very difficult to recover bremsstrahlung
- The only way to access p_T^Z physics is use the Φ^* variable
- The distribution is better modeled by calculation including higher order effects (RESBOS, Powheg, Pythia)

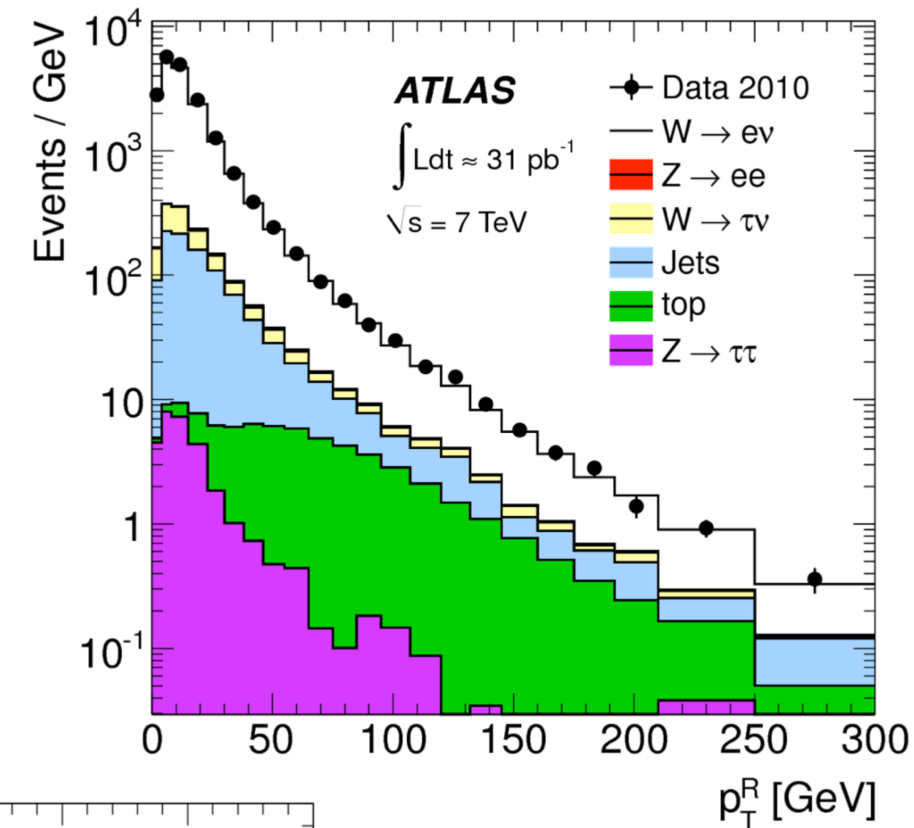


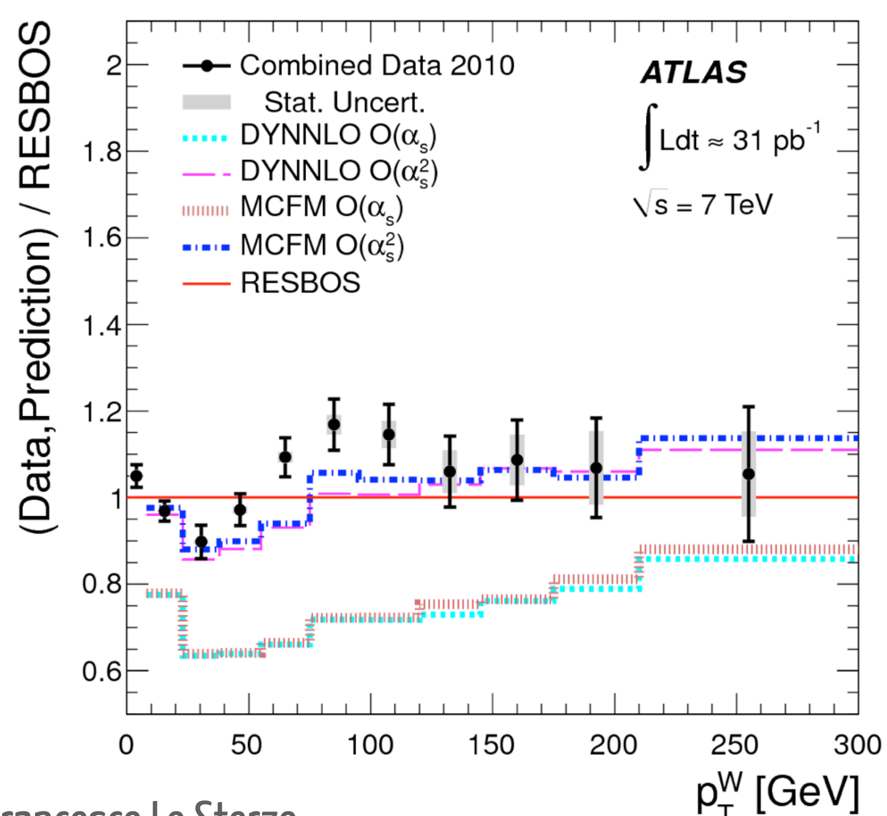


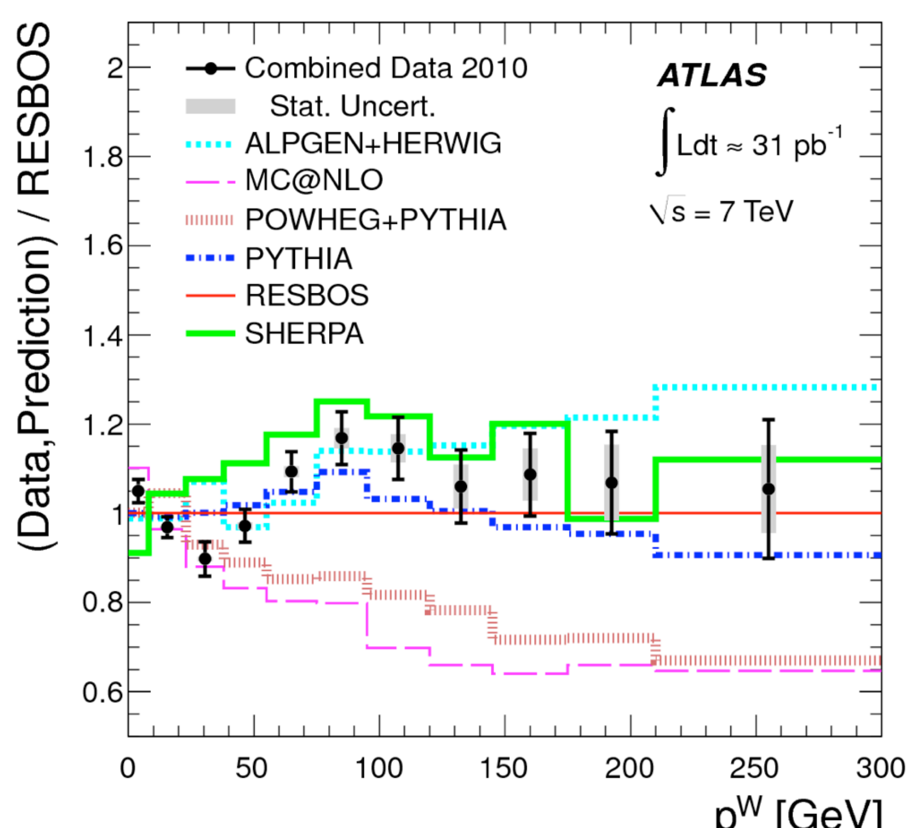
dσ / dp$_T$: W boson - ATLAS

ATLAS: $\sqrt{s}$ = 7 TeV, L = 31/pb - arXiv:1108.6308

- W p_T studies have direct relation to W mass measurement
- Because of the neutrino in the final state, p_T^W is measured indirectly from the hadronic recoil (i.e. the energy measured in the calorimeter excluding the lepton signature)
- Tests the same physics as p_T^Z but they are completely uncorrelated from the experimental point of view
- Better accuracy wrt/ p_T^Z for high p_T







- RESBOS taken as reference
- Divergences at low p_T are omitted
- Pythia, RESBOS and Sherpa provide agreement to data within 20% over the whole spectrum
- MC@NLO and Powheg+Pythia give the best agreement at very low p_T^Z, but then show a large disagreement

$d\sigma / dy$

- Rapidity distribution of the Z boson is sensitive to different parton luminosities
- Z y spectrum offer important testing ground for QCD dynamical effects and phenomenology
- Possibility to validate/tune existing models/PDFs

dσ / dy: Z boson - selections

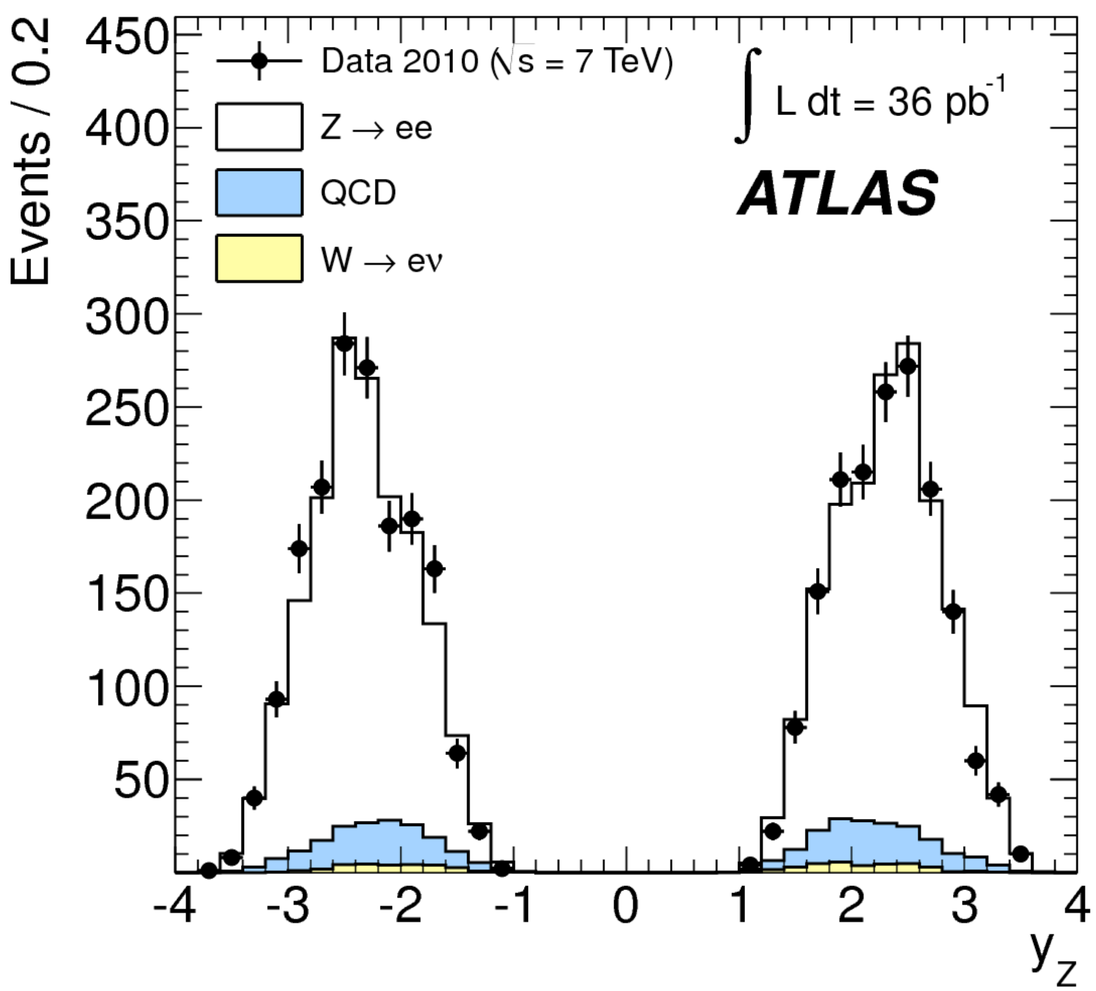
ATLAS: $\sqrt{s}$ = 7 TeV, L = 35/pb

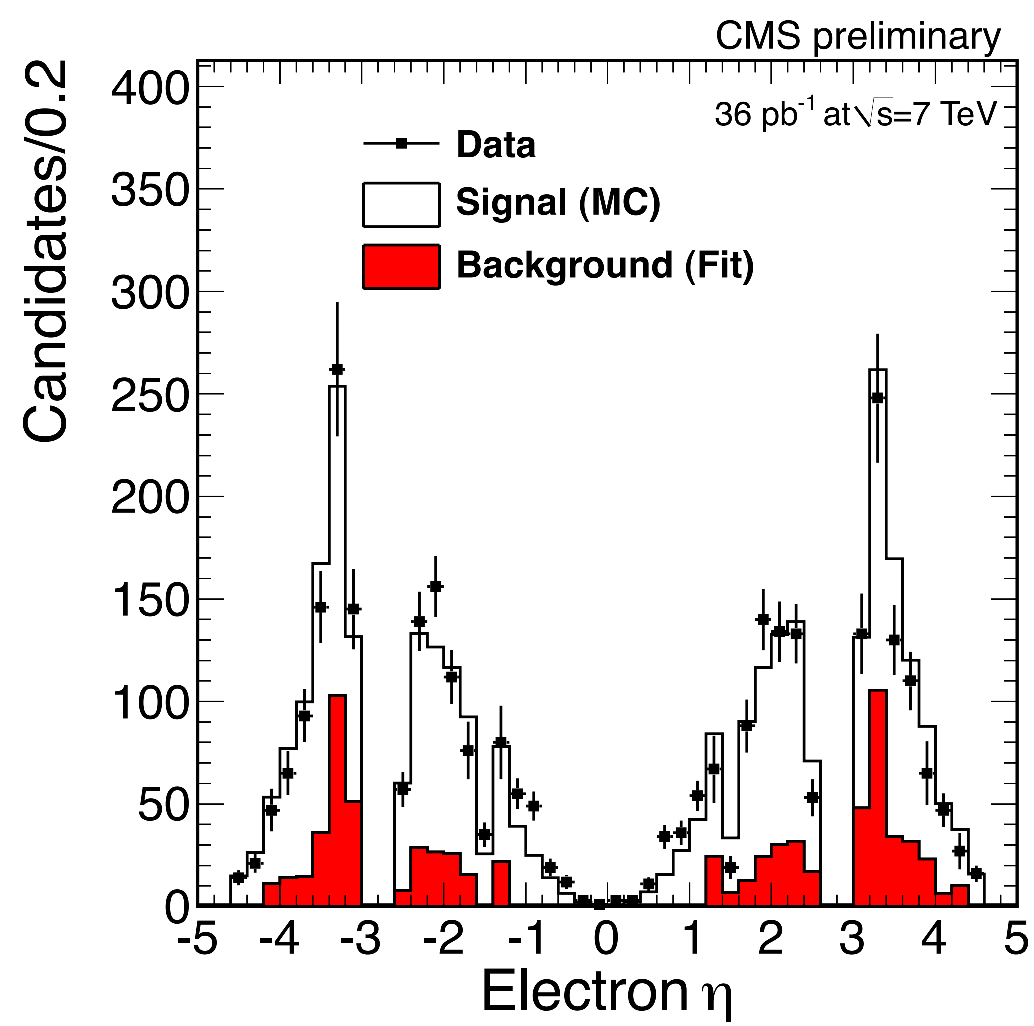
arXiv:1109.5141

CMS: $\sqrt{s}$ = 7 TeV, L = 36/pb

CMS-PAS-EWK-10-010

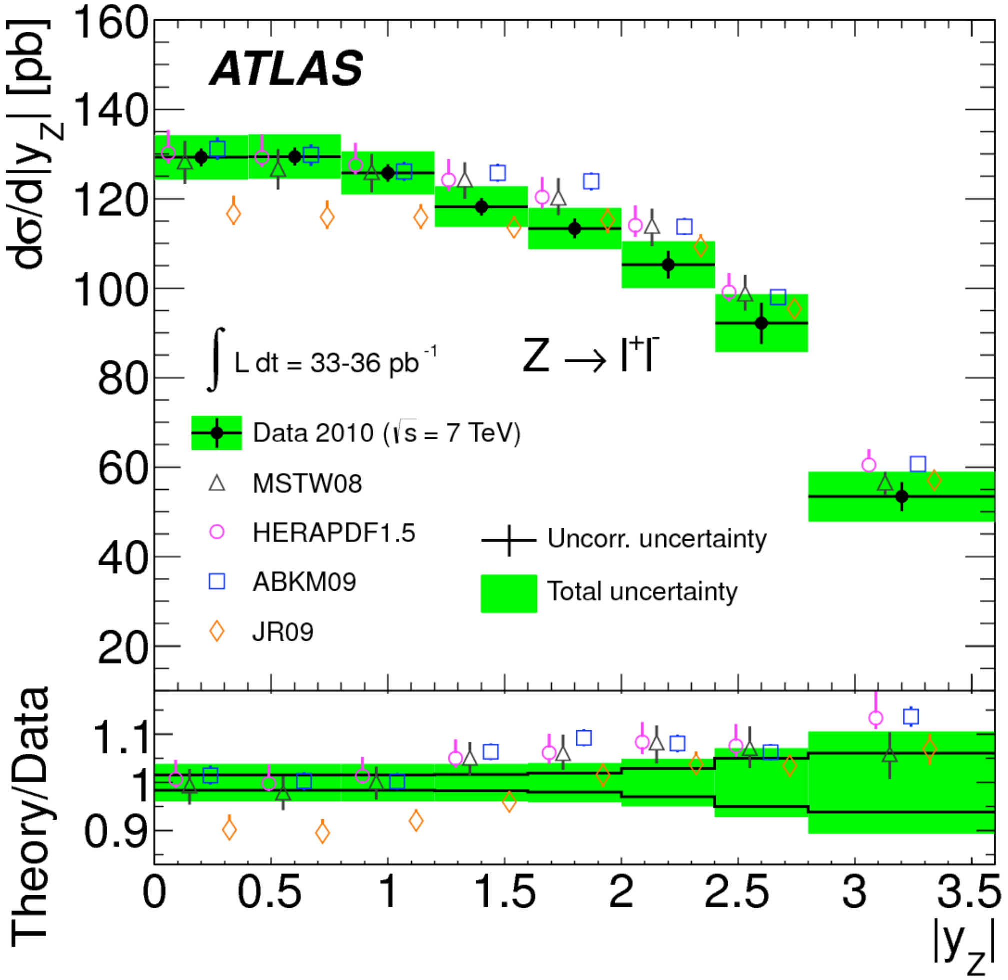
- Electron acceptance is expanded to the forward region: $|\eta| < 4.9$ (both ATLAS and CMS)
- One "tight" central electron is required



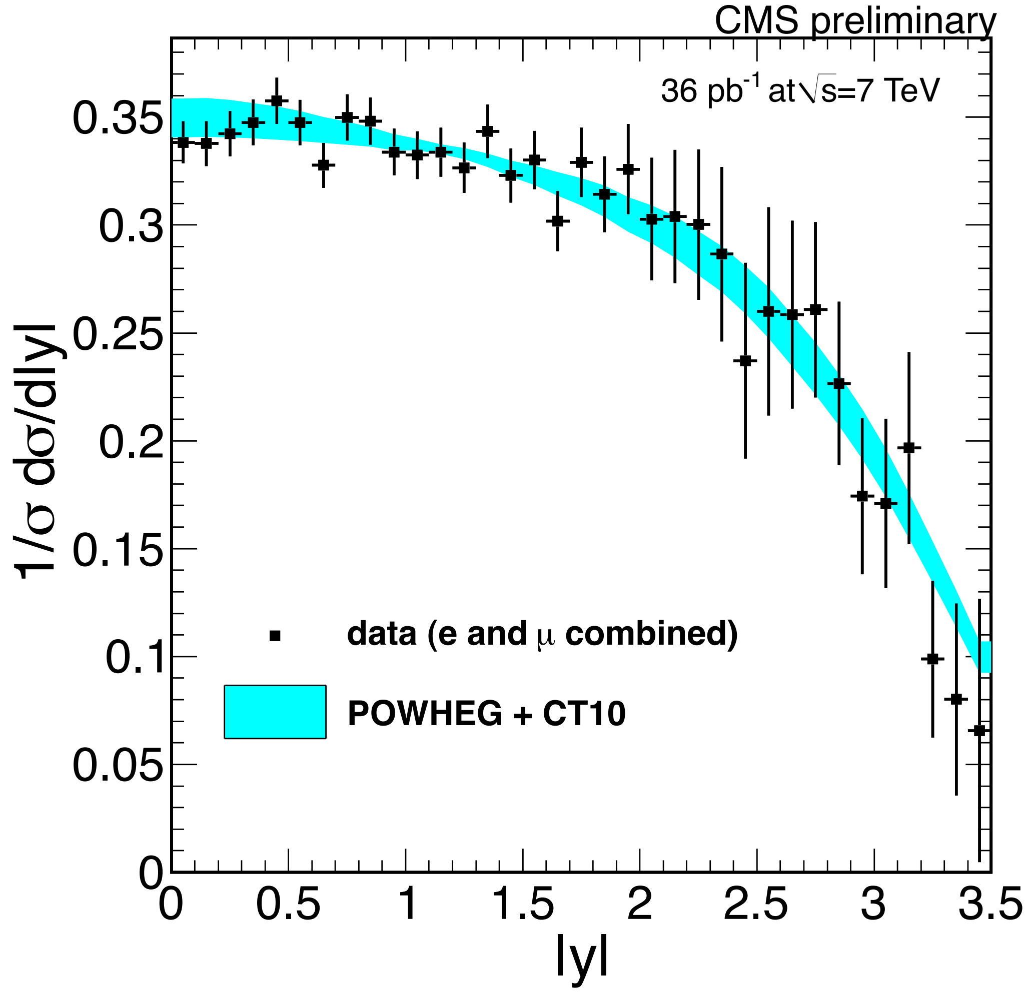


dσ / dy: Z boson - results

ATLAS: arXiv:1109.5141



CMS: CMS-PAS-EWK-10-010

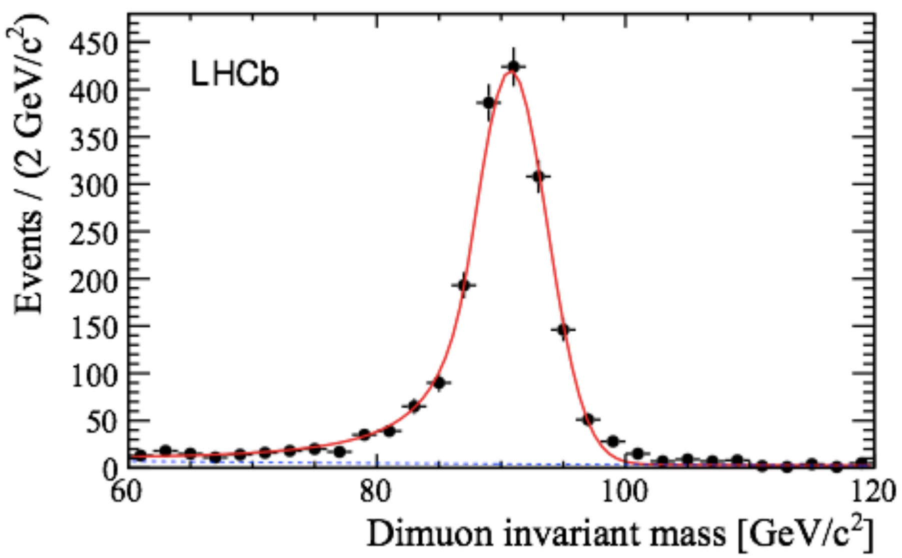


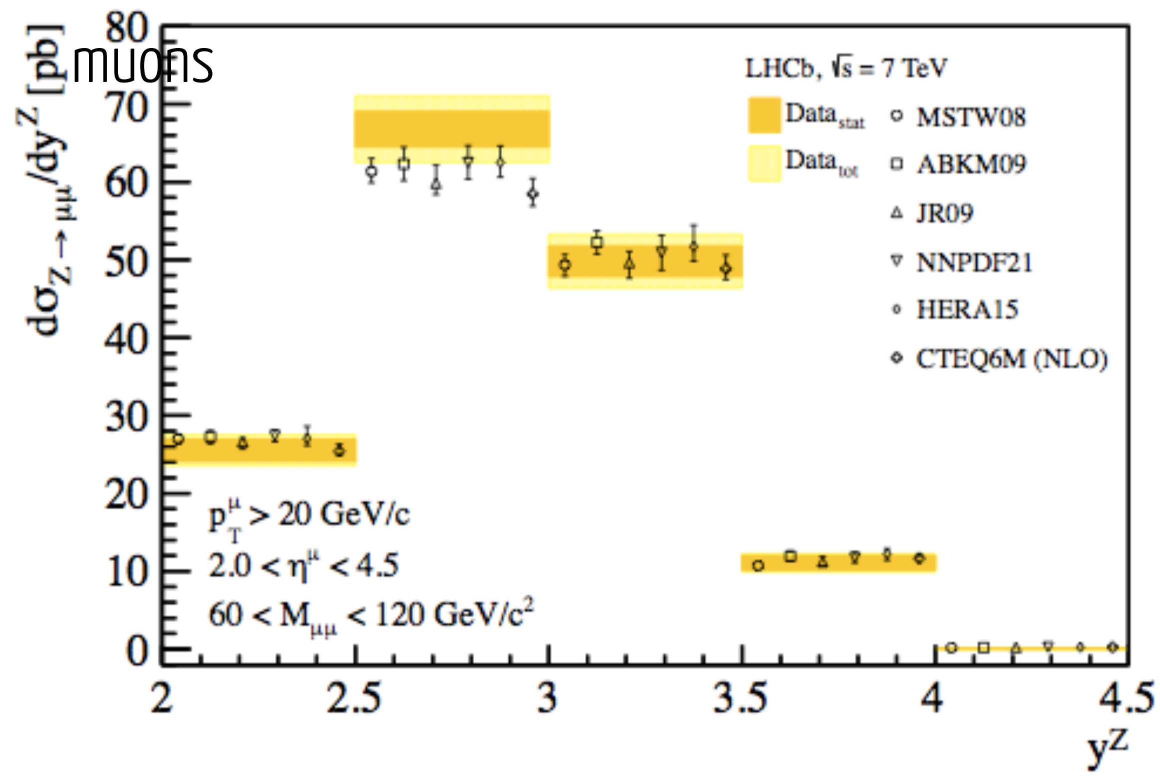
- Overall good agreement between data and theoretical predictions
- JR9 and ABKM09 PDF sets show the largest discrepancies wrt/ data
- The observed mismatches allow an improved tuning of PDFs for both uncertainties and central values

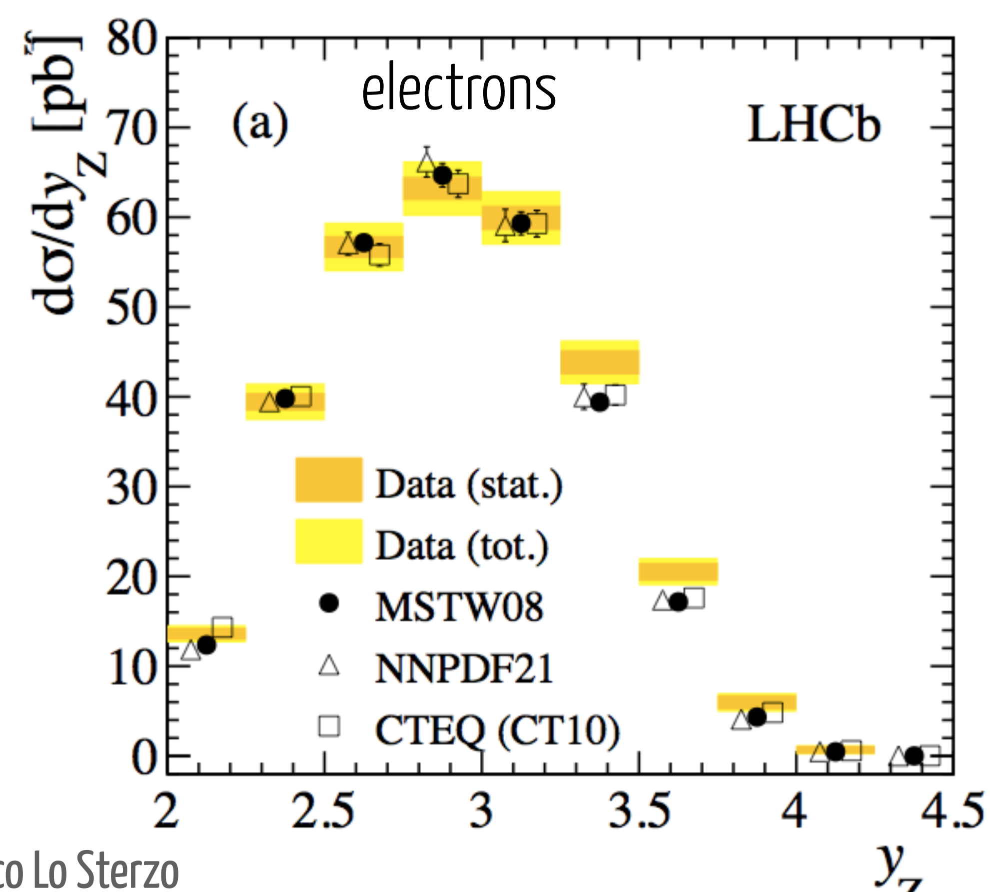
dσ(Z) / dy: results from LHCb

LHCb: $\sqrt{s}$ = 7 TeV, L = 37/pb
arXiv:1204.1620

- The peculiar LHCb structure allows to detect leptons in the very forward region, complementary to ATLAS/ CMS coverage
  - e/μ: $2 < \eta < 4.5$







- Data agree with expectations within uncertainties for electrons
- Overall good agreement between data and expectations for muons
- The differential cross section is underestimated the $2.5 < \eta < 3$ region in the muon channel

Forward-backward asymmetry

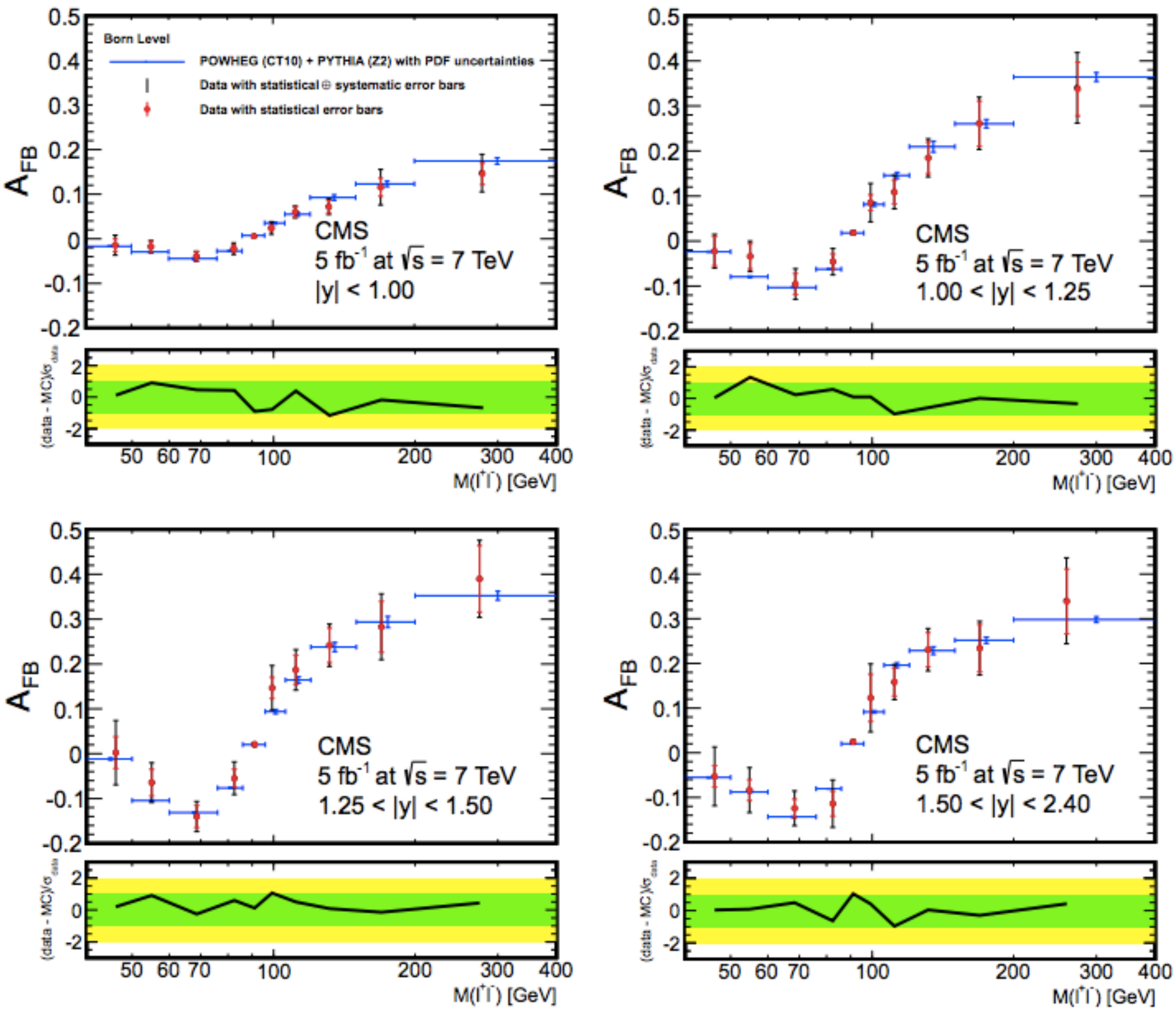
- The SM Drell-Yan Z/γ^* production contains both vector and axial-vector couplings of electroweak bosons to fermions
- This has a direct impact on the differential cross section
- The asymmetry varies as a function of m_{ll} because of the Z/γ^* interference
- Deviations from the SM predictions could be a sign of new particles (e.g. Z')
- Differential cross section:

$$\frac{d\sigma}{d\cos\theta^*} = C\left[\frac{3}{8}(1+\cos^2\theta^*) + A_{FB}\cos\theta^*\right] \qquad A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}$$

ϑ^*: emission angle of l^- relative to the quark momentum in the dilepton COM frame

Forward-backward asymmetry: Z boson - CMS

CMS: √s = 7 TeV, L = 5/fb - arXiv:1207.3973



- A_{FB} in the muon channel and the combination are the first such result at an hadron collider
- Very good agreement between electrons and muons
- Very good agreement wrt/ the SM predictions

W boson: charge asymmetry and differential cross section

- W vs η_l distribution offer important testing ground for QCD dynamical effects and phenomenology
- Possibility to validate/tune existing models
- Because of the production process

$$u\bar{d}(\bar{u}d) \longrightarrow W^{+(-)}$$

the asymmetry measurement provides important information about the proton structure and its PDFs
- This is particularly true at $10^{-3} < x < 10^{-1}$
- W^+ production is favored since the proton is uud

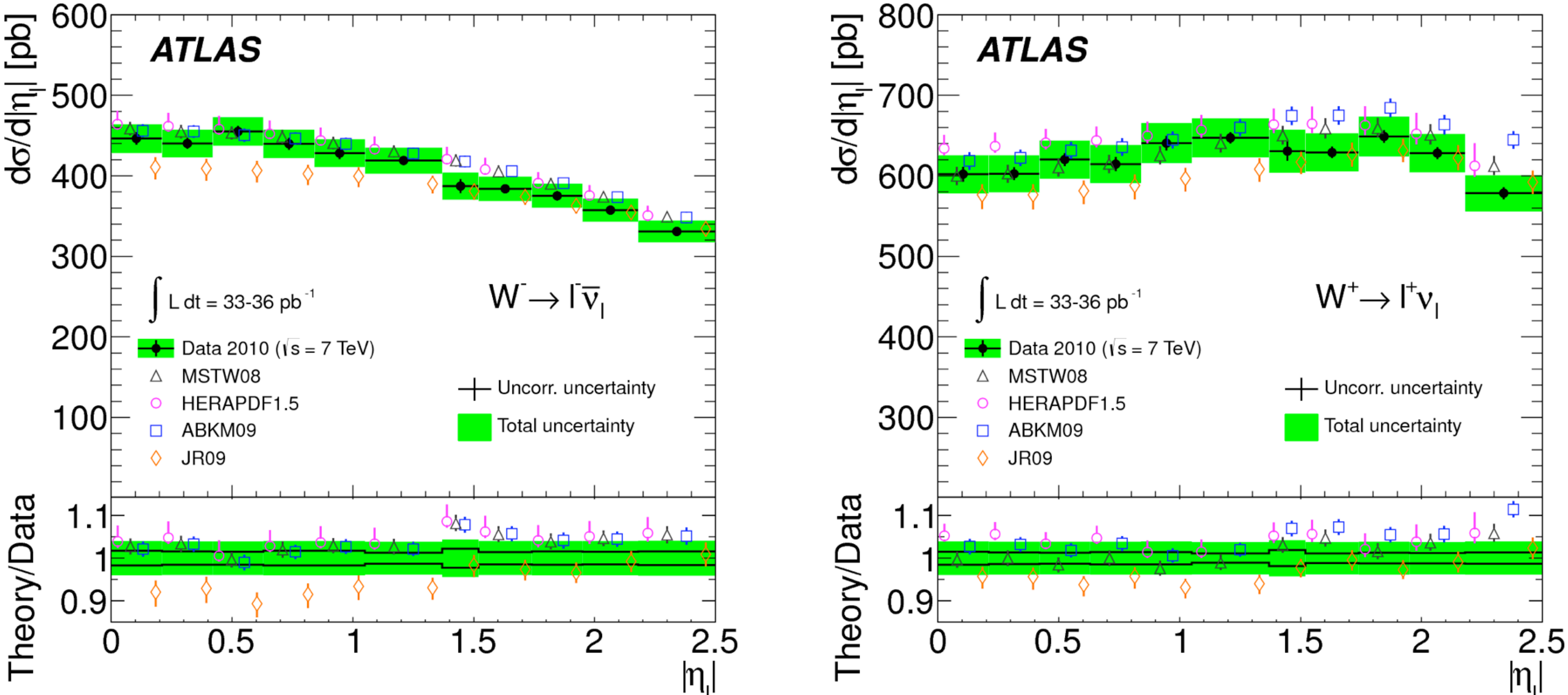
$$A = \frac{d\sigma_{W^+}/d\eta_\ell - d\sigma_{W^-}/d\eta_\ell}{d\sigma_{W^+}/d\eta_\ell + d\sigma_{W^-}/d\eta_\ell}$$

dσ / dη$_l$: W boson - ATLAS

ATLAS: $\sqrt{s}$ = 7 TeV, L = 31/pb - arXiv:1108.6308

(the same paper as dσ(Z)/dy)

Because of the presence of the neutrino the lepton η is used instead of y_W

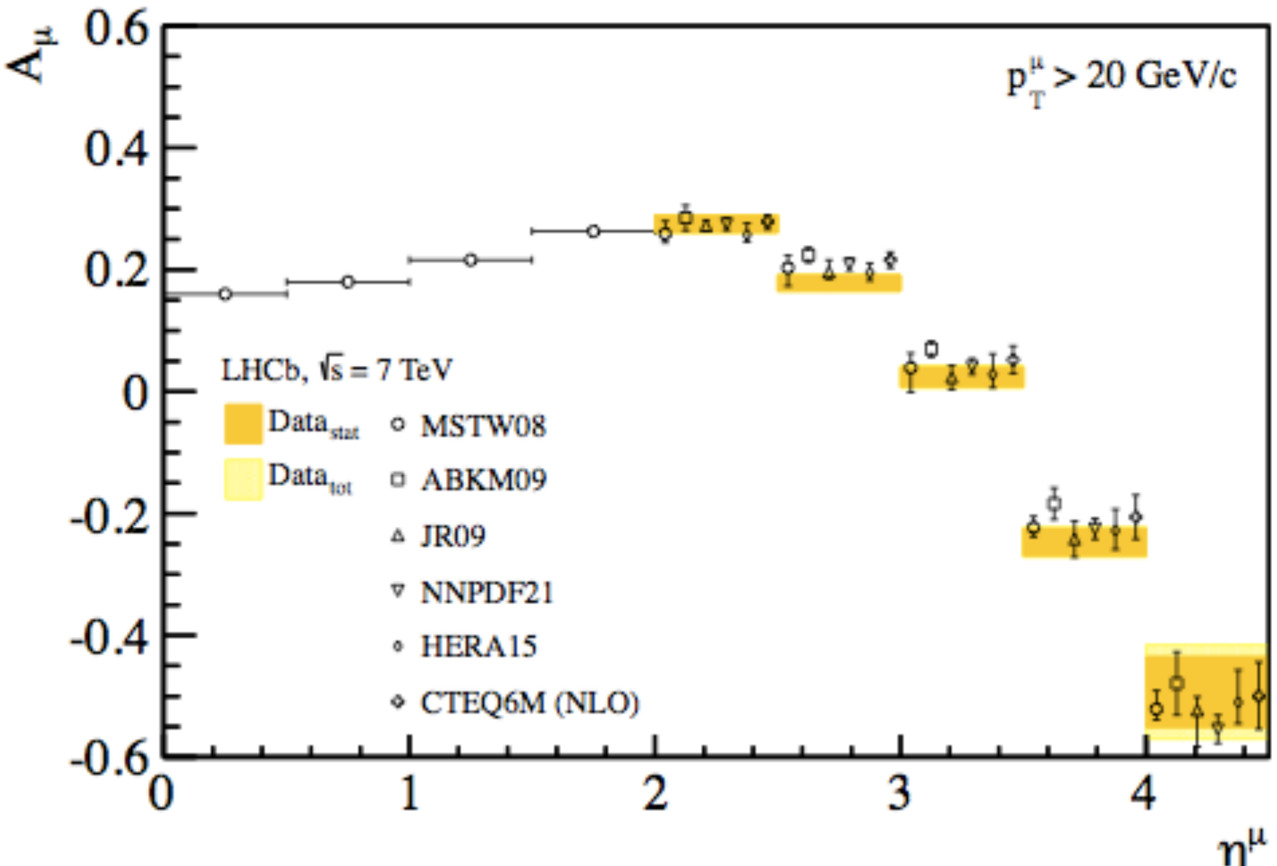


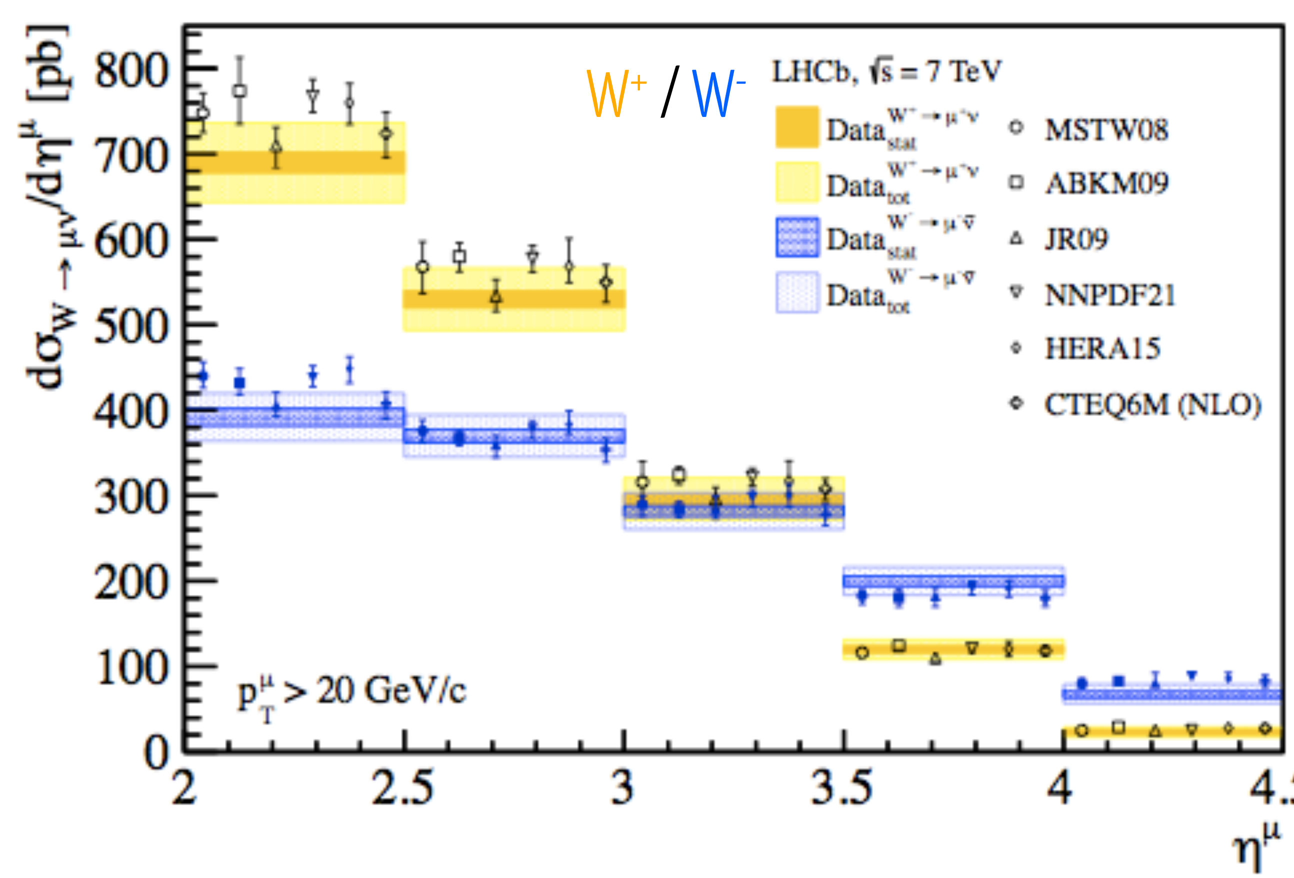
* Very good consistency between e and μ
* The typical precision is about 2%
* JR9 and ABKM09 PDF sets show the largest discrepancies wrt/ data (as in the previous slide)
* The comparison of the different predictions with data helps in tuning the models

$d\sigma / d\eta_\mu$: W boson - LHCb

LHCb: $\sqrt{s}$ = 7 TeV, L = 37/pb - arXiv:1204.1620

- The peculiar LHCb structure allows to detect leptons in the very forward region, complementary to ATLAS/CMS coverage
  - μ: $2 < \eta < 4.5$ - $20 < p_T < 70$ GeV





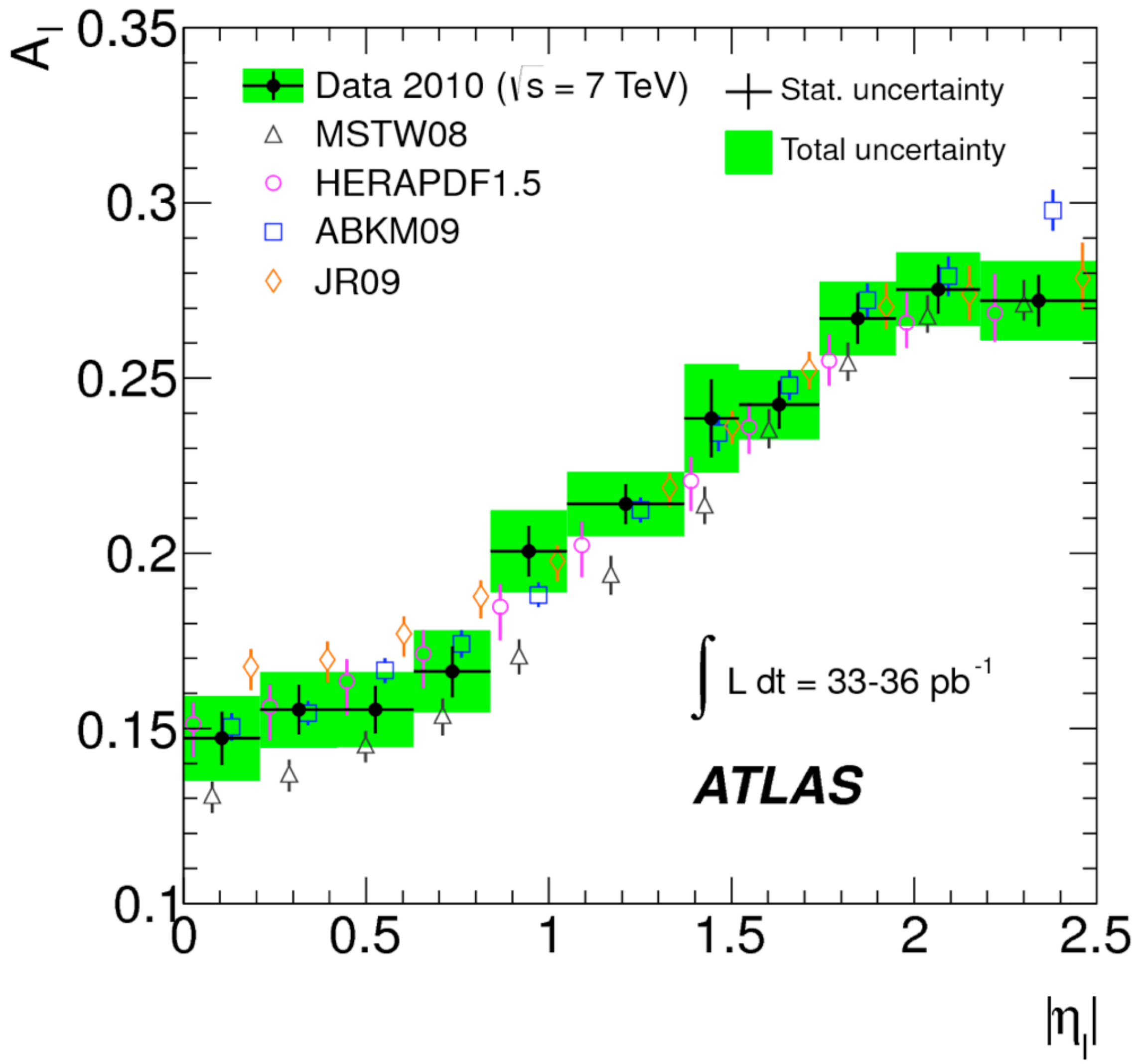
- W→$\mu\nu$ channel only
- Data points are in a region complementary to that explored by ATLAS and CMS
- The theoretical predictions are the same, but the comparison to data are in a different region
- ABKM09 overestimates the asymmetry in the majority of the bins
- The overall agreement is good for the differential cross section

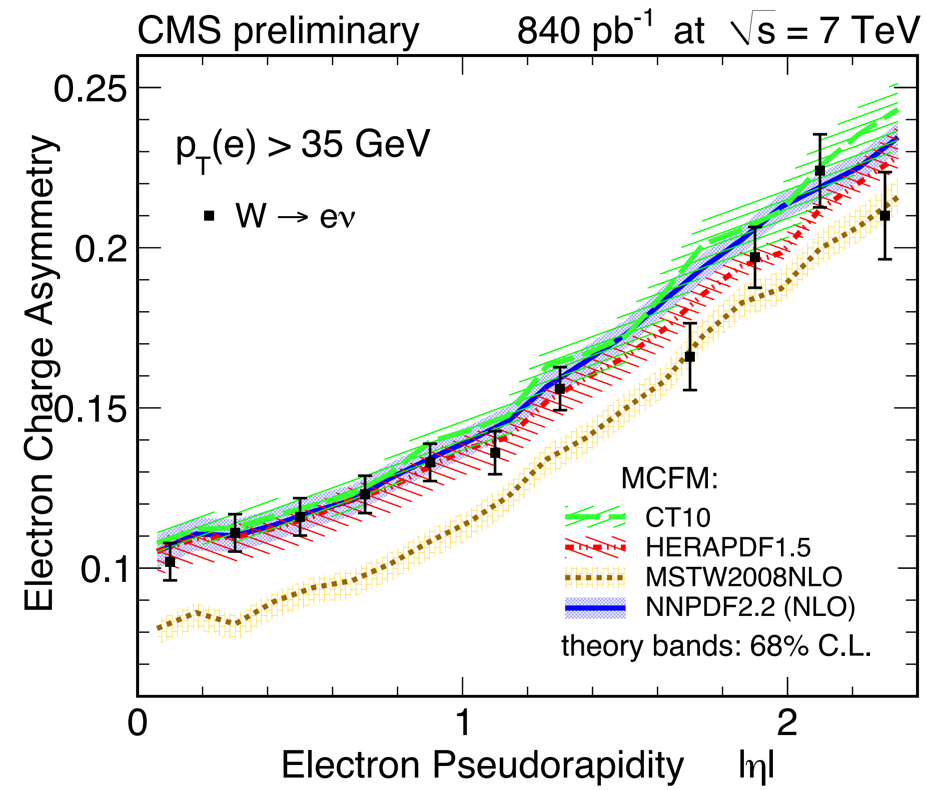
Charge asymmetry: W boson

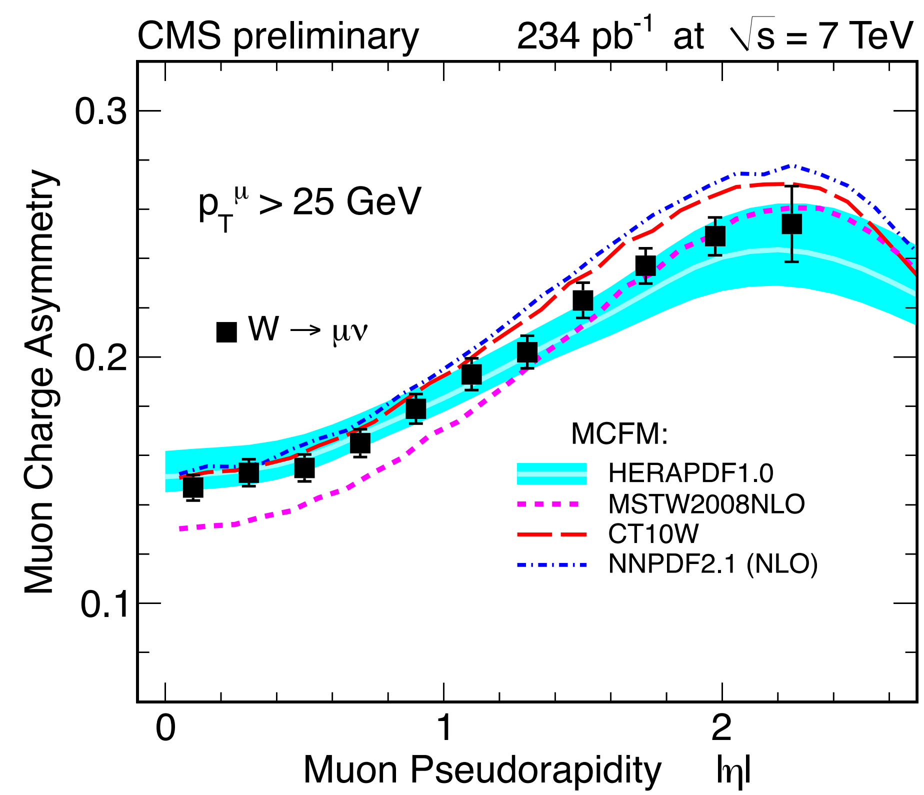
See Norbert's talk

CMS: √s = 7 TeV, L = 234/pb CMS-PAS-EWK-11-005 (μ) - √s = 7 TeV, L = 840/pb arXiv:1206.2598 (e)

ATLAS: √s = 7 TeV, L = 31/pb - arXiv:1109.5141







- ATLAS and CMS find overall agreement with the PDFs
- HERAPDF1.5 gives the best agreement for both ATLAS and CMS
- Both measurements provide stringent constraints to PDF models

W boson: polarization

- Measuring W boson polarization is crucial for understanding its production mechanism
- At high rapidity and small p_T^W leading order electroweak processes are dominant

$$u\bar{d}(\bar{u}d) \longrightarrow W^{+(-)}$$

giving rise to purely left-handed Ws

- In the central region and in the high p_T^W range more complex phenomena (also including gluons) give rise to a mixture of left-handed, right-handed and longitudinally polarized W bosons
- Anyway the according to the SM the left-handed component is still dominant

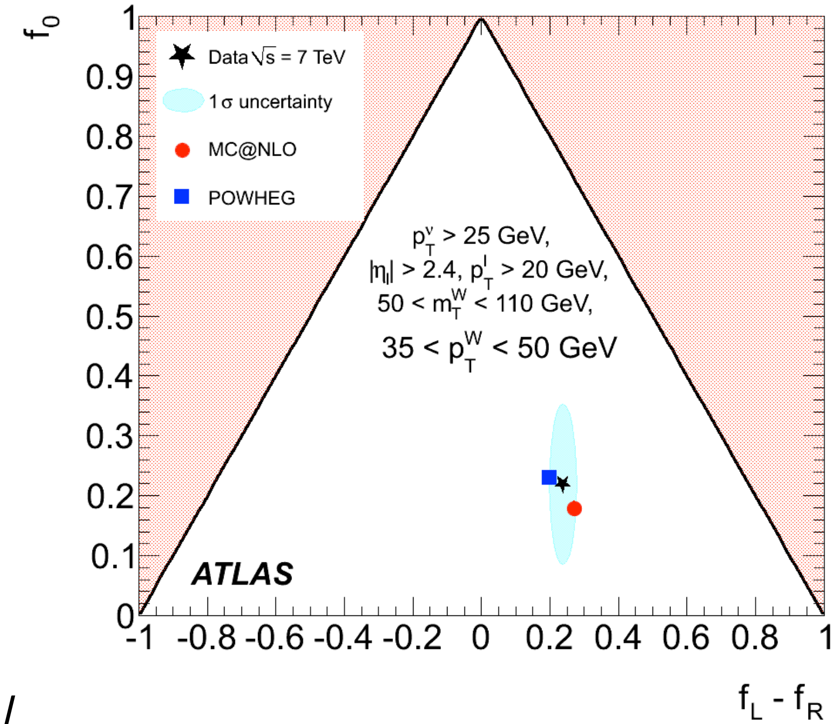
ATLAS: √s = 7 TeV, L = 35/pb
arXiv:1203.2165

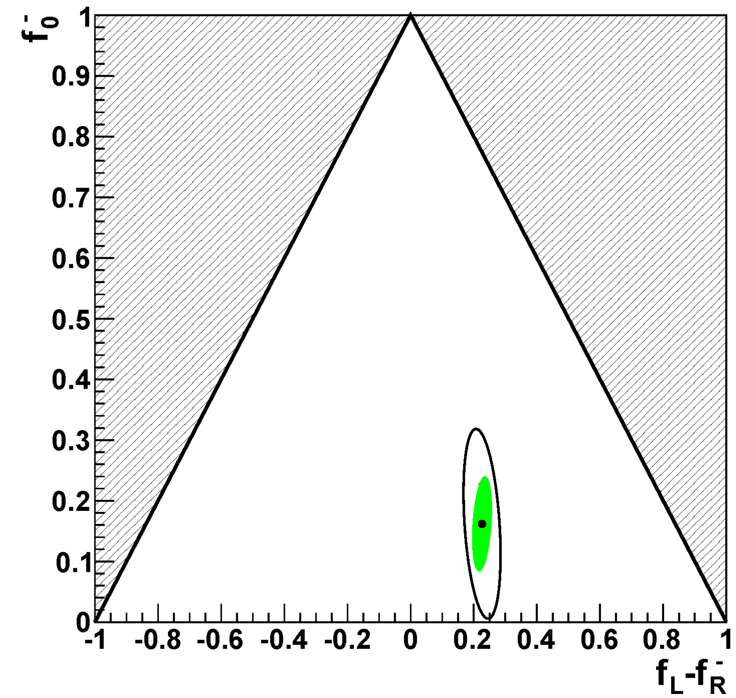
W polarization

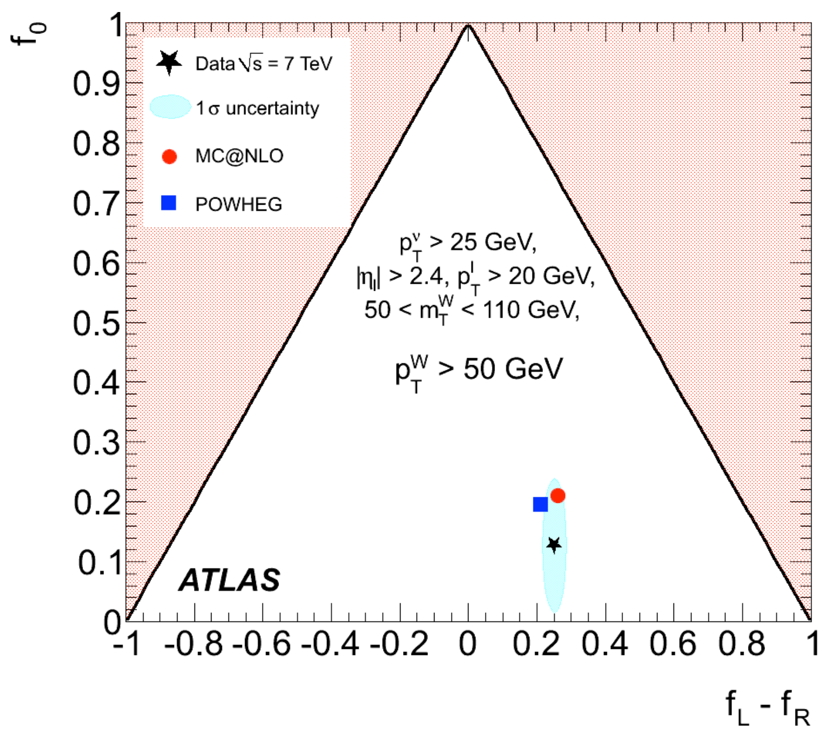
CMS: √s = 7 TeV, L = 35/pb
arXiv:1104.3829

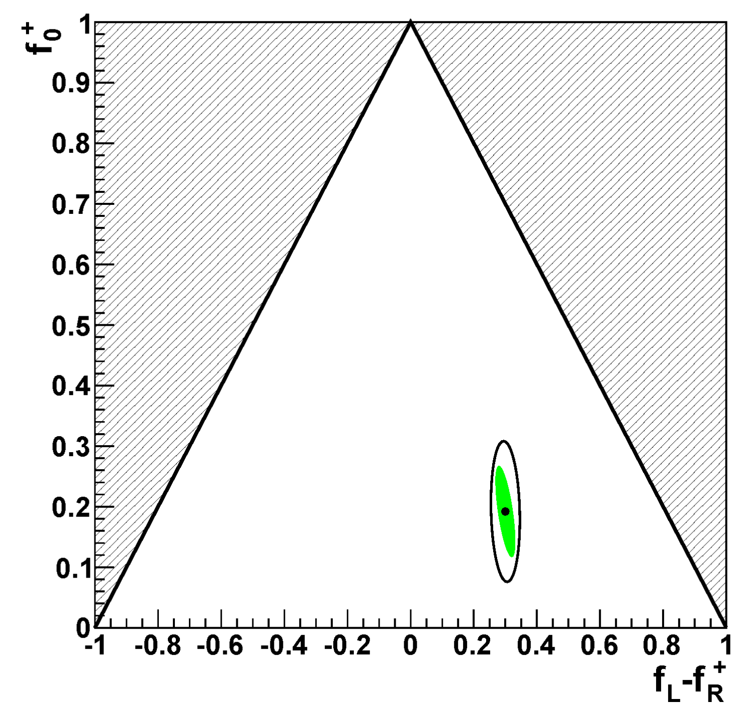
The angular distribution of the charged lepton is studied and then fitted with MC-based templates for the three polarizations

- 50 < m_T < 110 GeV
- 2 p_T^W bins used: 35-50 GeV and >50 GeV
- W^+ and W^- averaged together
- e and μ combined









- m_T > 30(50) GeV for electrons(muons)
- ≤ 3 jets p_T > 30 GeV, $|\eta|$ < 5
- p_T^W > 50 GeV
- e and μ combined

The SM predictions are confirmed: at high p_T, the W bosons are mostly left-handed. ATLAS favors Powheg wrt/ MC@NLO

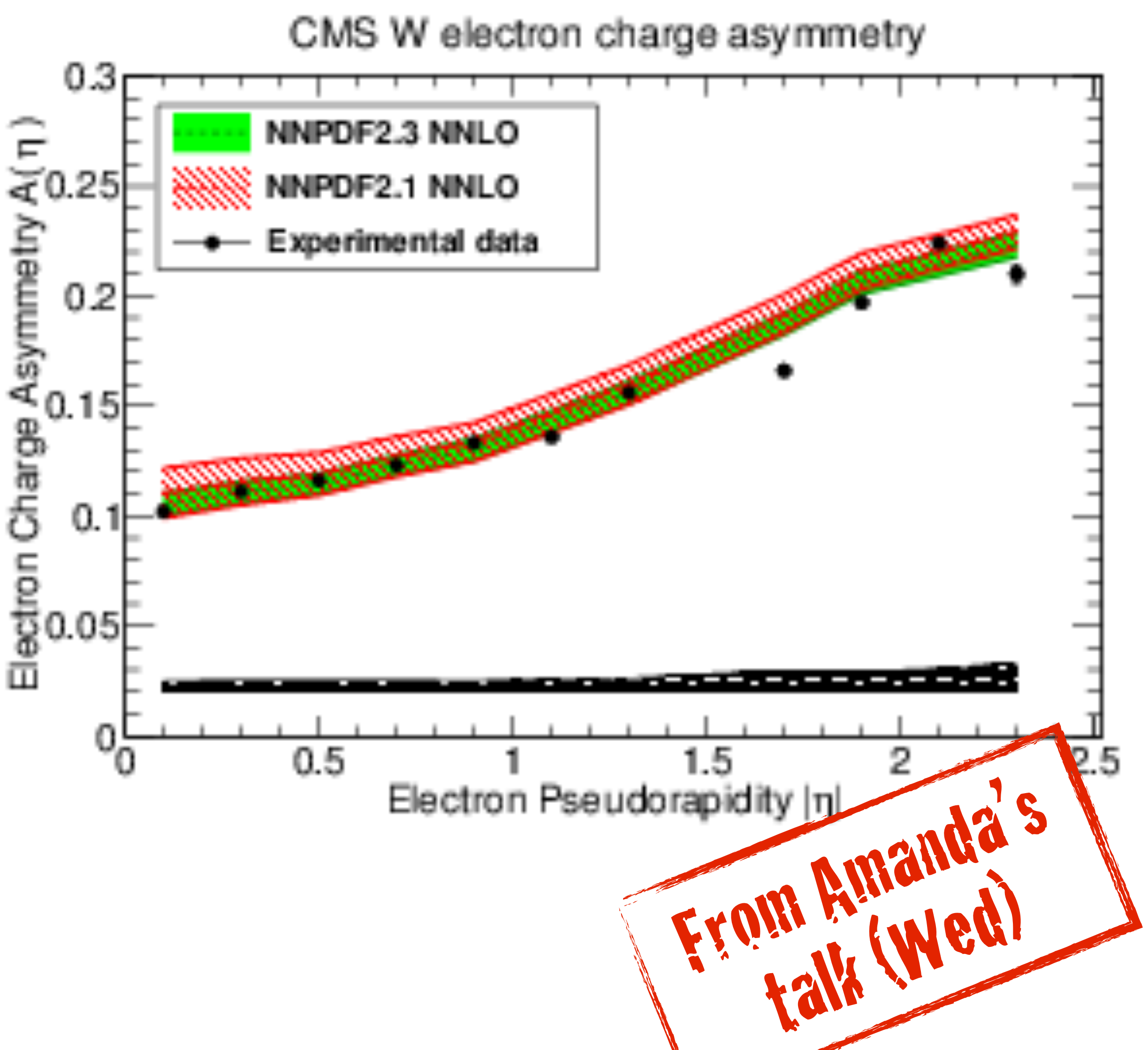
Conclusions

- The precision and accuracy reached by both ATLAS, CMS and LHCb experiment allow detailed data-expectation comparison, from which useful information can be extracted

- The detailed studies carried out at the LHC gave several input for validation/tuning of the available PDF models
- The results are in agreement with Standard Model expectations and help to reduce uncertainties in proton composition description

- New results with higher statistics are coming

- The new releases of the PDFs models (will) include the LHC results



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IT HAS BEEN
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Backup

Models

- FEWZ and DYNNLO: include fixed order $O(\alpha_S^2)$ calculations - diverge for vanishing p_T^Z
- RESBOS: soft gluon resummation (low p_T^Z) matched to fixed order pQCD at $O(\alpha_S)$ corrected to $O(\alpha_S^2)$ with K-factors (high p_T^Z)

Parton shower programs provide an all-order approximation of parton radiation in the soft and collinear region (low p_T^Z)

- Pythia and Herwig: apply weights to the first/hardest branching to merge $O(\alpha_S^0)$ and $O(\alpha_S)$ predictions in order to describe the high p_T^Z region
- Alpgen and Sherpa: tree level matrix elements for W/Z+partons matched to parton showers (avoiding double counting)

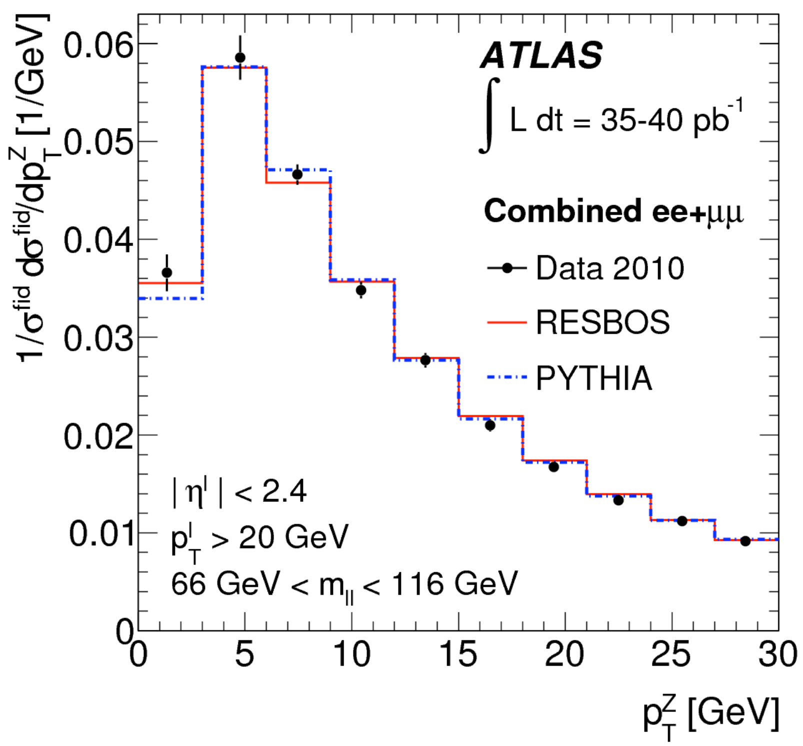
Each of these models can be used with different tunings and PDF sets

dσ / dp_T: Z boson - differential distributions

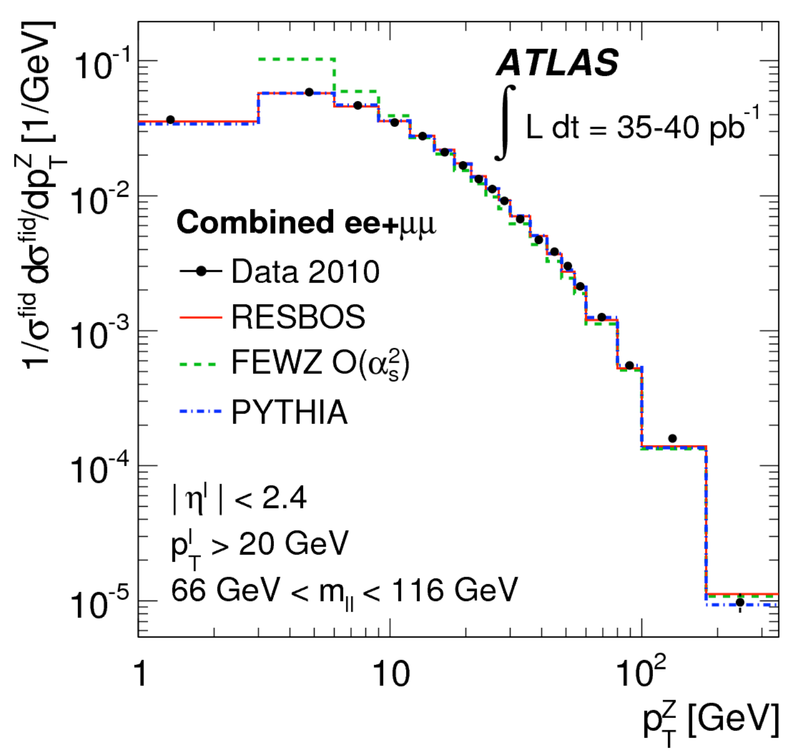
ATLAS: arXiv:1107.2381

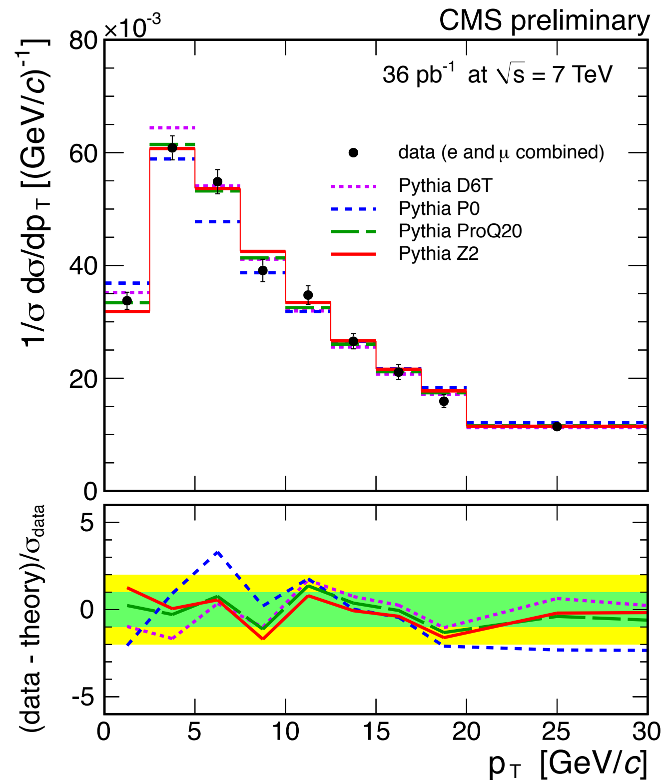
CMS: CMS-PAS-EWK-10-010

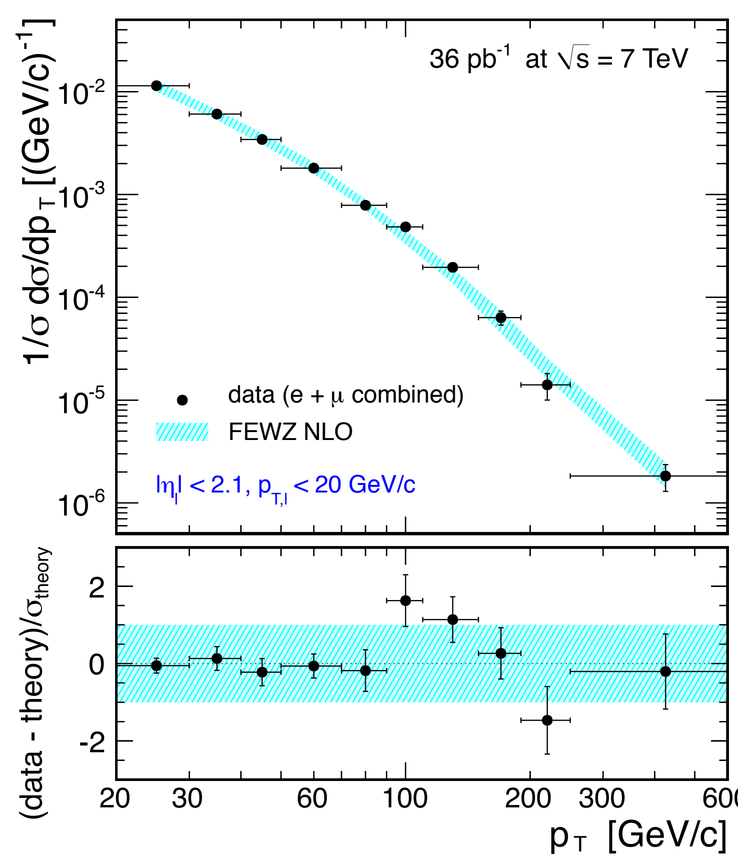
low-p_T



high-p_T





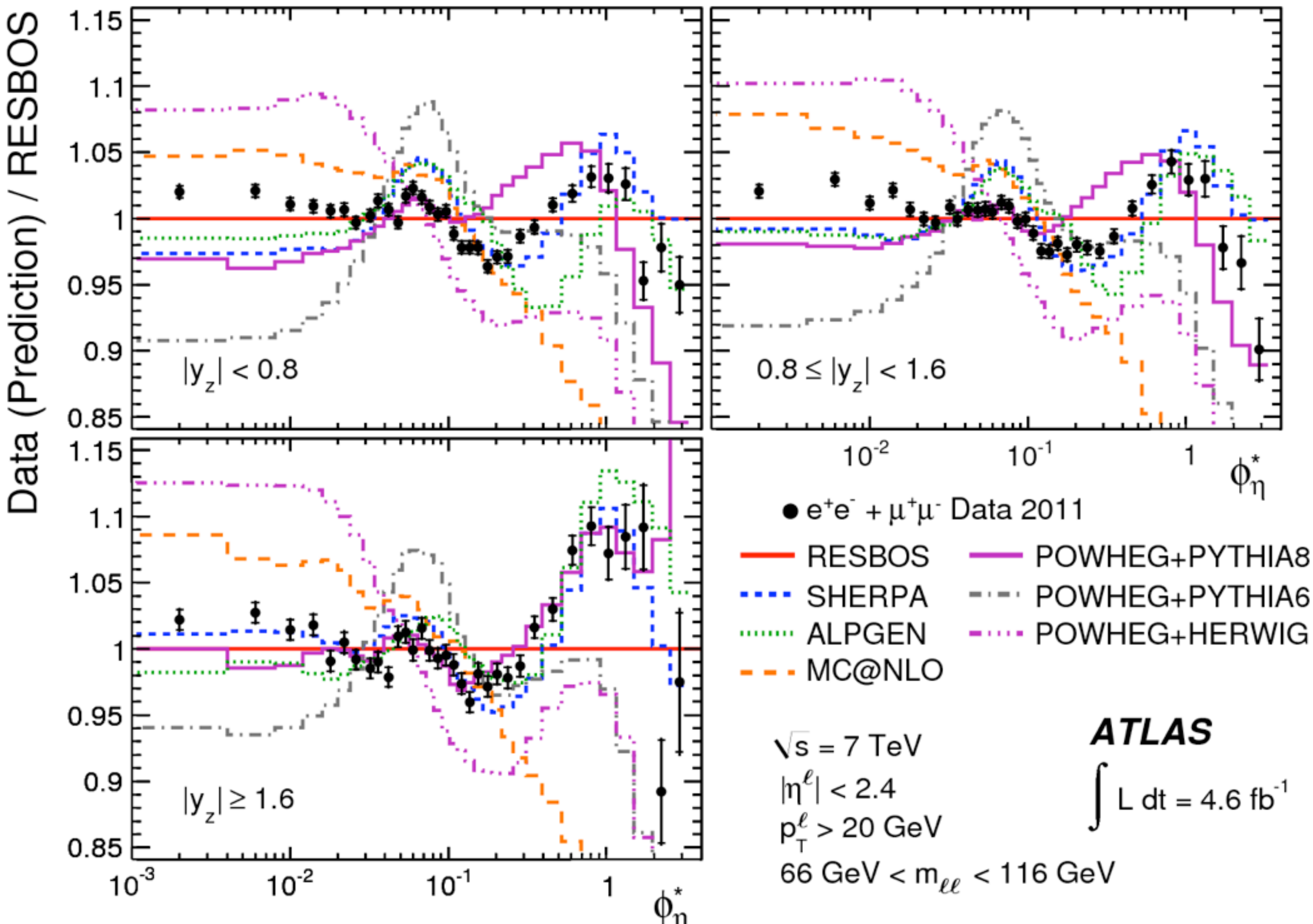


General remarks:

- at low p_T good agreement with RESBOS (ATLAS) and Pythia tuning (CMS)
- at high p_T good agreement with FEWZ (ATLAS+CMS). Not that FEWS diverges at low p_T

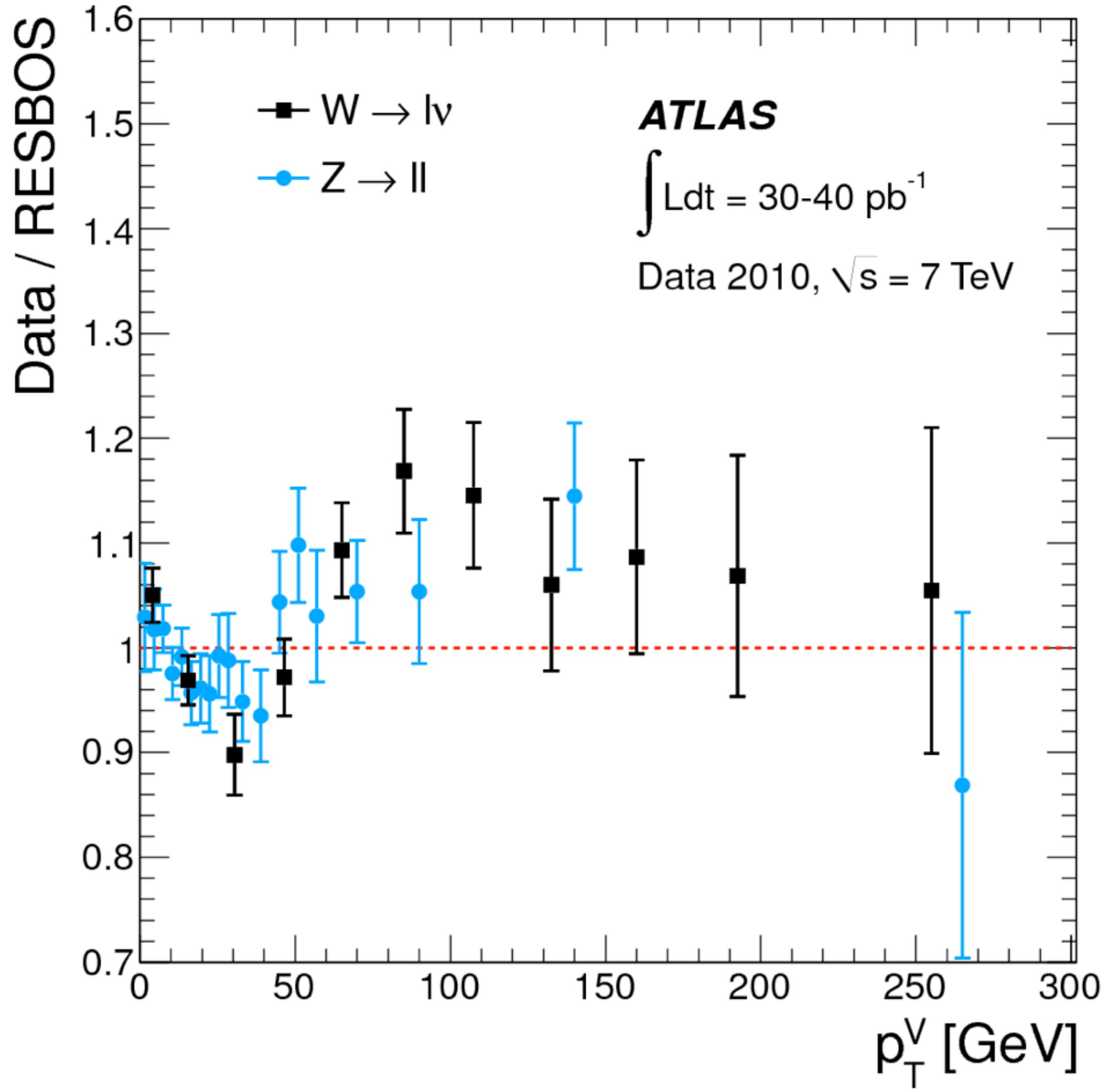
dσ(Z) / dϕ*: ATLAS (2)

ATLAS: √s = 7 TeV, L = 4.6/fb - arXiv:1211.6899



dσ / dp$_T$: W vs Z

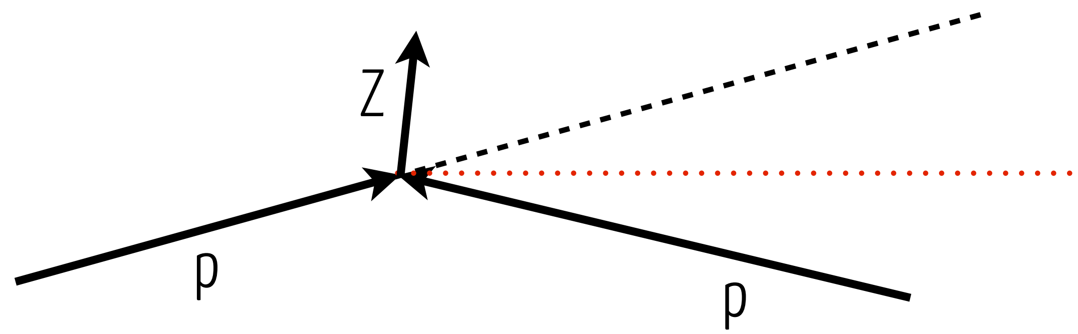
ATLAS: arXiv:1108.6308



- W and Z bosons have different masses and different cross sections so they cannot be compared directly
- Anyway the data/expectation ratio can give a qualitative insight on the agreement of the two measurements

$A_{FB}(Z)$ by CMS: details

- It is measured in the Collins-Soper frame:
  - ϑ^* is replaced by ϑ_{CS}^* defined as the angle between $p_T(l^-)$ and the axis that bisects the angle between the direction of the one proton and the direction opposite to the other proton in the Z rest frame



- The asymmetry is distorted and diluted by experimental resolutions and acceptances as well as by the unknown quark and antiquark directions
- The final result is unfolded and corrected for these effects (corrections are derived from MC studies)

W polarization - details

- W boson polarization can be measured looking at the angular distribution of the charged lepton
  - ϑ_{3D} (ATLAS): the angle between the direction of the W in the lab frame and the direction of the charged lepton in the W rest frame
- Since the W longitudinal momentum cannot be reconstructed, "reduced" variables are defined

$$\cos\theta_{2D} = \frac{\vec{p}_T^*(\ell)\cdot\vec{p}_T(W)}{|\vec{p}_T^*(\ell)||\vec{p}_T(W)|} \qquad L_P = \frac{\vec{p}_T^*(\ell)\cdot\vec{p}_T(W)}{|\vec{p}_T(W)|^2}$$

- The reduced variables are fitted in data with MC-based polarization templates