
$Z A_{FB}$ and W/Z polarization measurements at LHC

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Summary

- $Z A_{FB}$ Measurement
 - $Z A_{FB}$ definition at pp colliders
 - The Collins-Soper reference frame
 - Dilution
 - The weak mixing angle
 - Measurements of $Z A_{FB}$ performed by ATLAS and CMS
 - Extraction of the weak mixing angle
- W/Z polarization at pp colliders
 - Measurement of Z polarization performed by CMS
 - Measurements of W polarization performed by ATLAS and CMS
- Possible m_W measurement at LHC
- Conclusions



Z A_{FB} Measurement

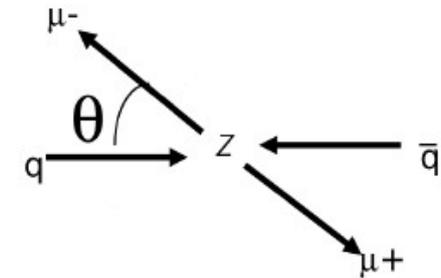
Z A_{FB}

- Differential cross section for $pp \rightarrow Z/\gamma^* \rightarrow l^+l^-$ process

$$\frac{d\sigma}{d\cos\theta} = A(1 + \cos^2\theta) + B\cos\theta$$

$$A = Q_l^2 Q_q^2 + 2Q_l Q_q g_V^q g_V^l \operatorname{Re}(\chi(s)) + (g_V^{l^2} + g_A^{l^2})(g_V^{q^2} + g_A^{q^2})|\chi(s)|^2 \quad B = \frac{3}{2}g_A^q g_A^l (Q_l Q_q \operatorname{Re}(\chi(s)) + 2g_V^q g_V^l |\chi(s)|^2)$$

- The $\cos\theta$ exhibits a forward-backward asymmetry
 - $\cos\theta > 0$: Forward event
 - $\cos\theta < 0$: Backward event



$$A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B} = \frac{\int_0^1 \frac{d\sigma}{d\cos\theta} d\cos\theta - \int_{-1}^0 \frac{d\sigma}{d\cos\theta} d\cos\theta}{\int_0^1 \frac{d\sigma}{d\cos\theta} d\cos\theta + \int_{-1}^0 \frac{d\sigma}{d\cos\theta} d\cos\theta} = \frac{N_F - N_B}{N_F + N_B} = \frac{3B}{8A}$$

- Collins-Soper reference frame adopted $\cos\theta^* = \frac{2}{Q\sqrt{Q^2 + Q_T^2}}(P_1^+ P_2^- - P_1^- P_2^+)$



$$Z A_{FB}$$

- At hadron colliders can't tell the direction of the incoming quark
 - At detector level this reflects in a *Dilution*, i.e. a reduction of the measured asymmetry
 - Assuming boost of the lepton pair is the same of the incoming quark
 - motivated by the PDFs, where valence quarks carry a larger momentum fraction on the proton momentum compared to the sea quarks, and the anti-quark must be a sea quark
 - This assumption is most likely to be correct at large rapidities
- A_{FB} directly related with a fundamental parameter of the electroweak theory , the $\sin^2\theta_w$
 - This parameter has already been measured by the experiments at LEP and Tevatron with a precision of 10^{-4} and 10^{-3} respectively
 - A precise measurement of A_{FB} allows to give a contribution to the world average measurement of $\sin^2\theta_w$



Data samples

- Z A_{FB} Measurement
 - Both ATLAS and CMS measurements presented with an integrated luminosity of 5 fb⁻¹ on 7 TeV data
 - After Event selection a yield of about 1.4M Z bosons
 - [1] arXiv:1503.03709 [hep-ex] (ATLAS A_{FB} measurement)
 - [2] Phys. Lett. B 718 (2013) 752 (CMS A_{FB} measurement)
 - [3] Phys. Rev. D 84, 112002 (2011) (CMS weak angle measurement)
- Z polarization measurement
 - CMS Measurement with 19 fb⁻¹ 8TeV data sample
 - [4] arxiv:1504.03512v1 [hep-ex] (CMS Measurement)
- W polarization measurement
 - Both ATLAS and CMS measurements done with 35 pb⁻¹ 7 TeV data sample
 - ATLAS measurement done in two ranges of p_T^W : $35 < p_T^W < 50$ GeV , $p_T^W > 50$ GeV
 - [5] Phys.Rev.Lett.107:021802,2011 (CMS W polarization measurement)
 - [6] Eur. Phys. J. C72 (2012) 2001 (ATLAS W polarization measurement)



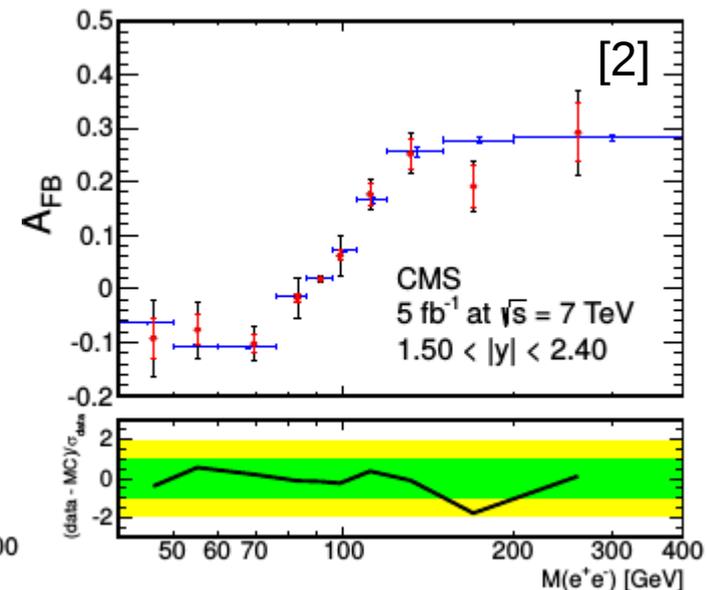
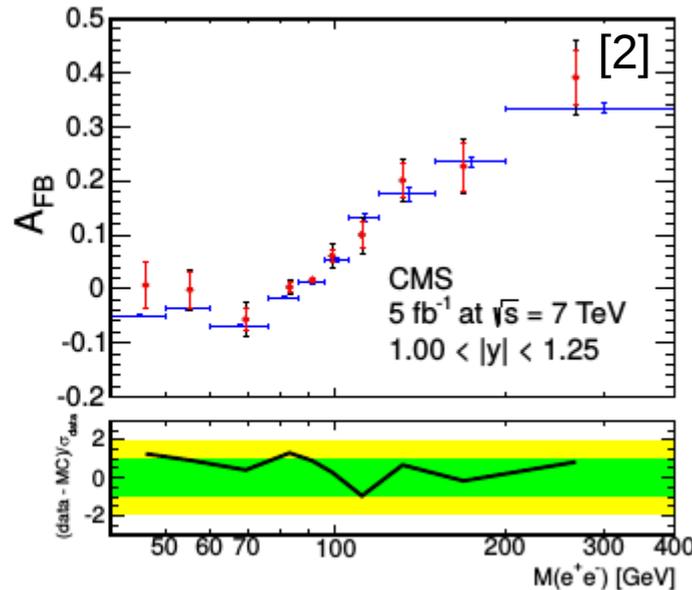
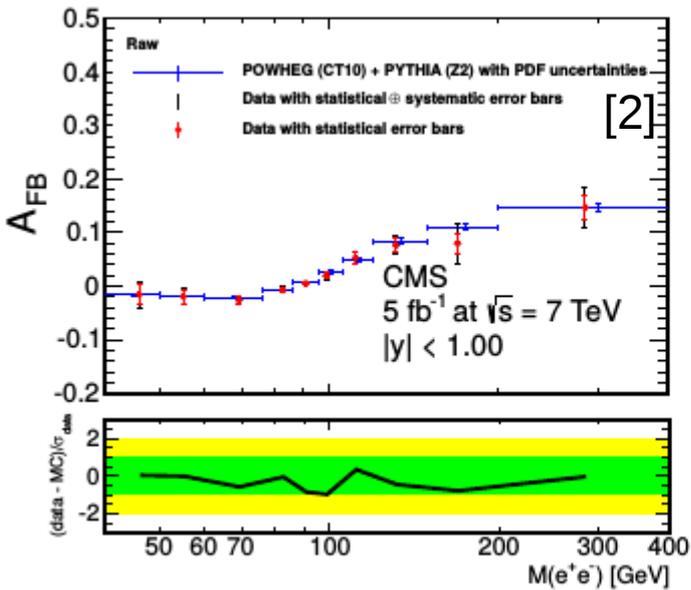
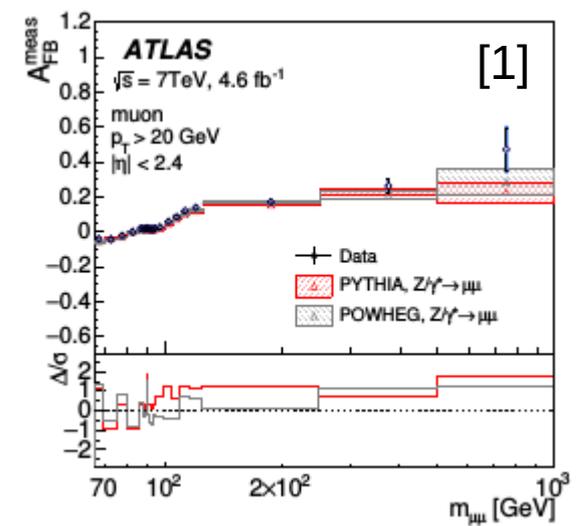
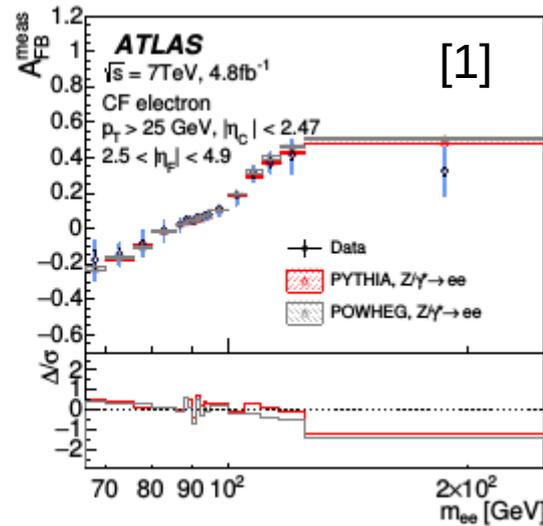
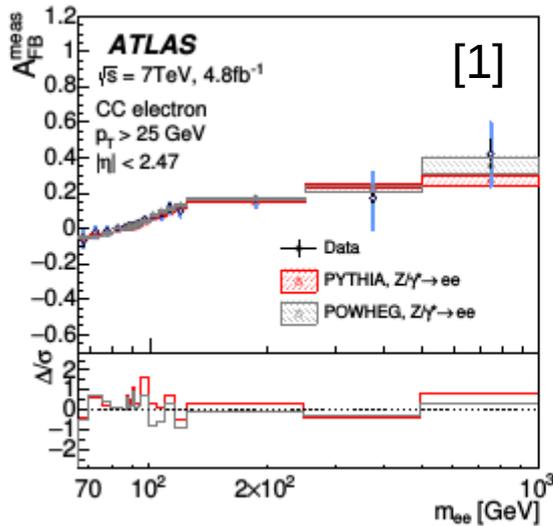
Raw A_{FB} measurement

- In bins of mass
- Count the number of forward and backward events
- Subtract the number of forward and backward events due to the background
- Compute the raw A_{FB} value using the relation

$$A_{FB} = \frac{N_{\cos \theta_{CS}^* \geq 0} - N_{\cos \theta_{CS}^* < 0}}{N_{\cos \theta_{CS}^* \geq 0} + N_{\cos \theta_{CS}^* < 0}}.$$

- Measured by ATLAS in the electron CC, CF and muon channel
 - CC : $|\eta| < 2.47$, CF : $2.5 < |\eta| < 4.9$
- Measured by CMS in muon and electron channel in four rapidity bins

Raw A_{FB} spectrum

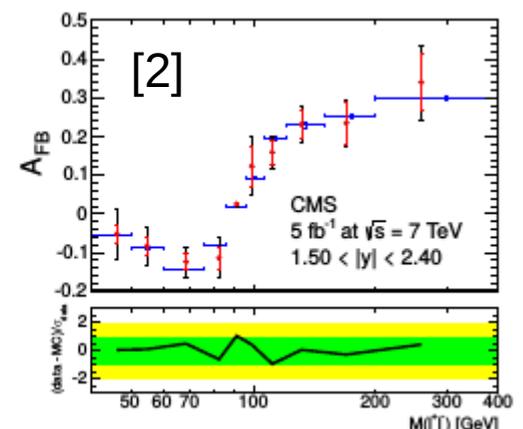
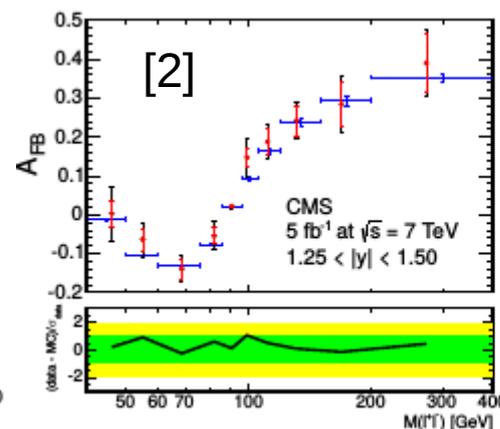
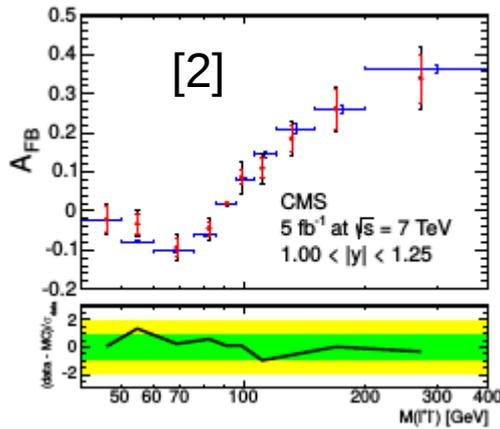
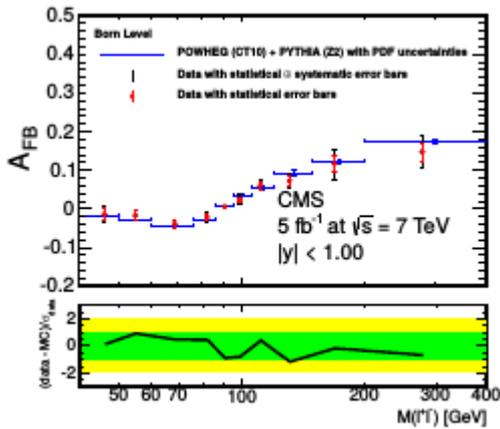
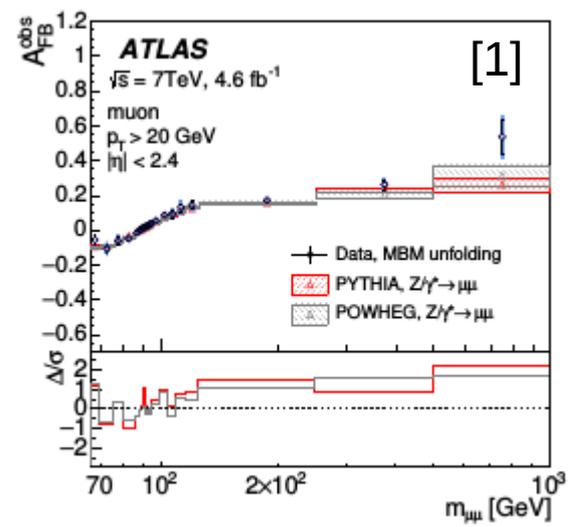
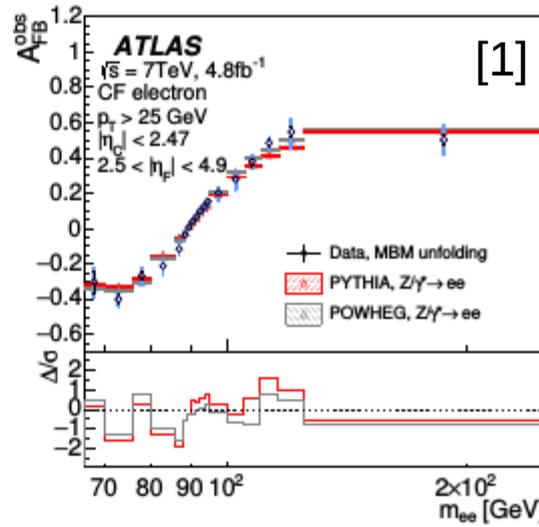
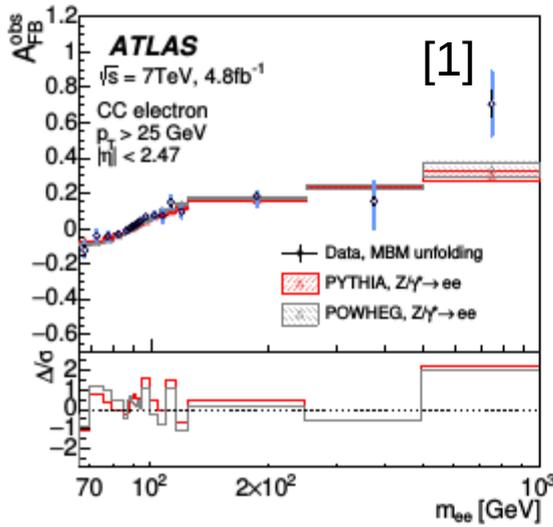




Unfolding the A_{FB} spectrum

- Raw A_{FB} measured at detector level
- **Effects to be corrected**
 - **Detector resolution & QED radiative corrections**
 - Finite resolution, reconstruction efficiencies, pileup, Final State Radiation (FSR)
 - **Dilution**
 - Misassigned quark direction
 - **Acceptance**
 - Measurement from the fiducial (measured) phase space to the full phase-space.
- **Response matrix base unfolding**
 - Construction of a matrix from the MC sample with reco vs truth information
- **Next slide shows A_{FB} distributions corrected for Detector resolution & QED**
 - ALTAS results are for electron CC, CF, muons
 - CMS results are for electron/muon combined in different rapidity regions

Unfolded A_{FB} spectrum



Weak mixing angle measurement

- A_{FB} directly related with weak mixing angle $\sin^2\theta_w$
- ATLAS measures the weak mixing angle using a template fit method

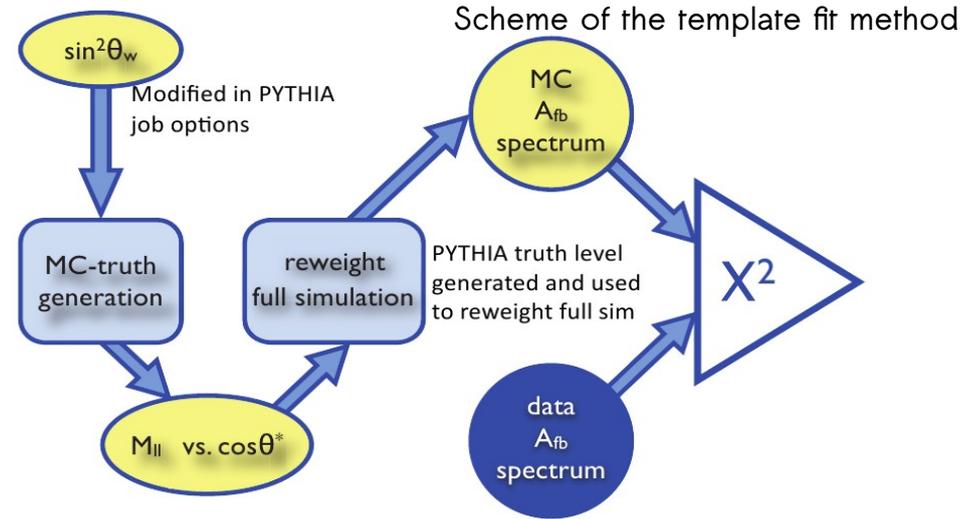
22.4/16 CC electron

$\chi^2/ndf = 21.9/16$ CF electron

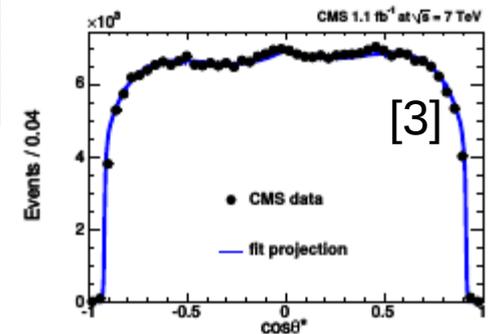
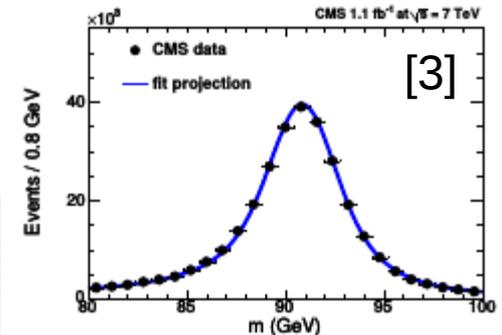
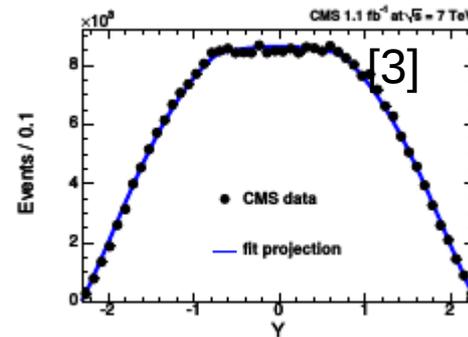
22.6/16 muon

- CMS measurement done using an unbinned maximum likelihood fit on the Y , m , $\cos\theta^*$ distributions

$$\mathcal{L} = \exp(-n_{\text{sig}} - n_{\text{bkg}}) \prod_i \left(n_{\text{sig}} \times \mathcal{P}_{\text{sig}}(\vec{x}_i; \theta_{\text{eff}}; \vec{\xi}) + n_{\text{bkg}} \times \mathcal{P}_{\text{bkg}}(\vec{x}_i; \vec{\xi}) \right)$$



CMS fit results





Weak mixing angle measurement

- ATLAS final measurement has been obtained with *ATLAS-epWZ12* PDF set
- Muon, electron CC, electron CF and combined result
- Dominated by systematic uncertainty on the PDF set
- 0.1σ with the most precise leptonic asymmetry measurement (from SLD)
- 1σ with the LEP measurement
- 0.3σ with PDG Fit
- CMS measurement done in the muon channel with 1.1 fb^{-1} and with CT10 PDF set
- Statistical and systematic uncertainties comparable

ATLAS combined result

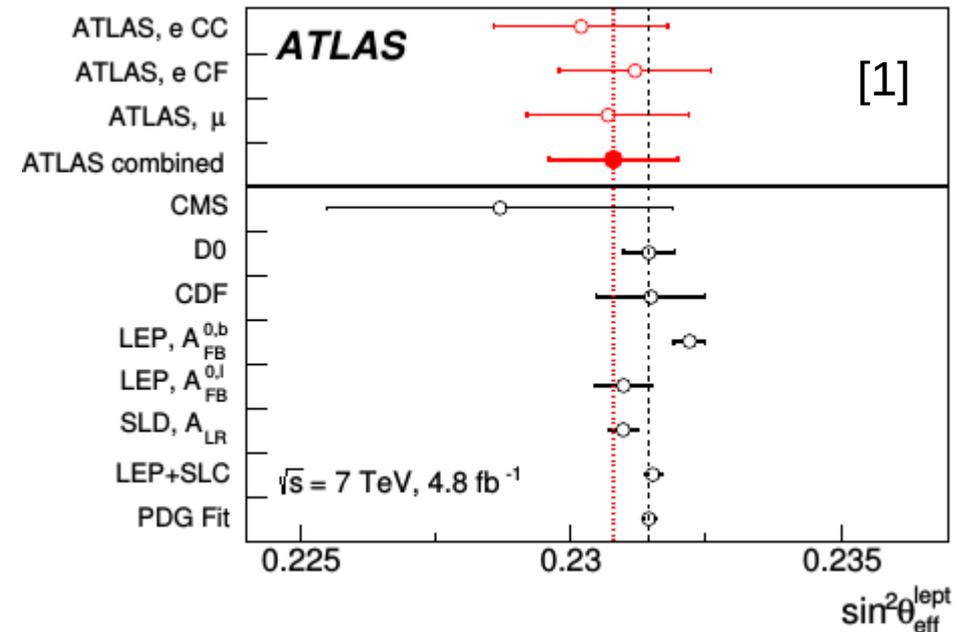
$$\sin^2\theta_W^{\text{eff}} = 0.2308 \pm 0.0005(\text{stat.}) \pm 0.0011(\text{syst.})$$

CMS result

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

PDG fit

$$\sin^2\theta_W^{\text{eff}} = 0.23146 \pm 0.00012$$





- W/Z polarization measurements



W/Z polarization

$$\frac{d^2\sigma}{d\cos\theta^*d\phi^*} \propto \left[(1 + \cos^2\theta^*) + A_0\frac{1}{2}(1 - 3\cos^2\theta^*) + A_1\sin(2\theta^*)\cos\phi^* + A_2\frac{1}{2}\sin^2\theta^*\cos(2\phi^*) \right. \\ \left. + A_3\sin\theta^*\cos\phi^* + A_4\cos\theta^* + A_5\sin^2\theta^*\sin(2\phi^*) + A_6\sin(2\theta^*)\sin\phi^* + A_7\sin\theta^*\sin\phi^* \right].$$

- Z boson polarization measurement uses Collins-Soper reference frame
- W polarization measurement relies on “helicity” rest frame
 - W from $e\nu$ and $\mu\nu$ decay channels
 - In this case $\cos\theta^*$ is the angle between lepton and the flight direction of the W boson
 - Measure of f_0, f_L, f_R : longitudinal, left-handed, right-handed fractions of produced W bosons

$$A_0^\pm \propto f_0^\pm \quad A_4^\pm \propto \mp(f_L^\pm - f_R^\pm)$$

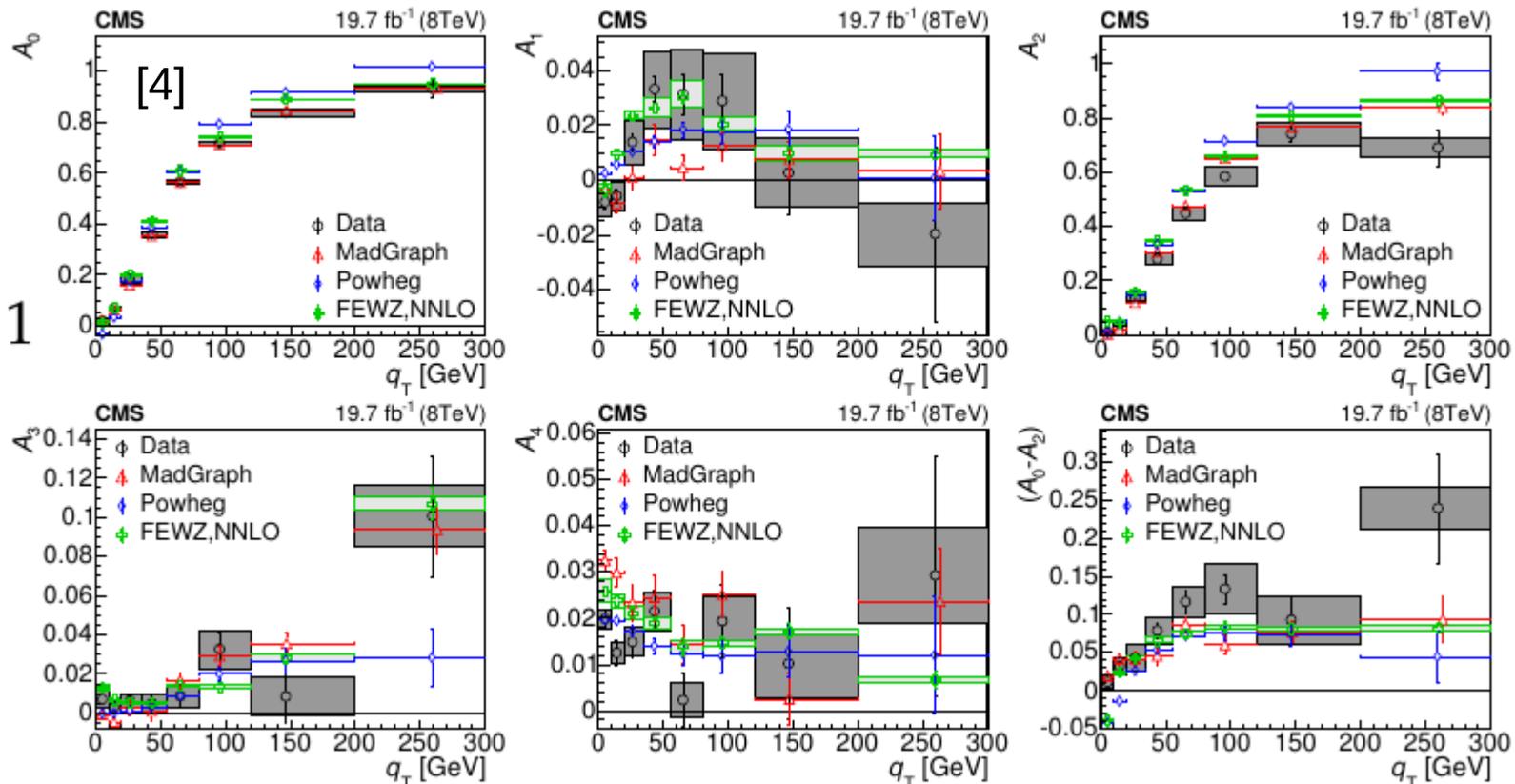
- Unknown neutrino momentum on the beam axis gives an ambiguity in the W momentum determination
 - Use a variable that is strongly correlated with $\cos\theta^*$
 - Lepton transverse momentum projection onto the W transverse momentum

$$L_P = \frac{\vec{p}_T(\ell) \cdot \vec{p}_T(W)}{|\vec{p}_T(W)|^2}$$

Z polarization measurement

- High statistics allows to perform a measurement of the $\cos\theta^*$ vs. ϕ^* plane, in eight bins of Z transverse momentum and two bins of rapidity
- Binned maximum likelihood fit on $\cos\theta^*$ vs. ϕ^* distributions produced by MC
- Result is compared with MadGraph, PowHeg and FEWZ NNLO predictions

$|y| < 1$



W polarization measurement

- ATLAS: Fit on MC templates with different helicity states

	$35 < p_T^W < 50 \text{ GeV}$	$p_T^W > 50 \text{ GeV}$
electron		
f_0 (%)	$20.1 \pm 6.9 \pm 12.0 \pm 5.0$	$17.7 \pm 4.3 \pm 9.0 \pm 6.0$
$f_L - f_R$ (%)	$26.0 \pm 2.8 \pm 3.4 \pm 2.0$	$25.5 \pm 2.6 \pm 2.0 \pm 2.0$
muon		
f_0 (%)	$23.6 \pm 3.8 \pm 12.0 \pm 7.2$	$7.6 \pm 4.8 \pm 9.0 \pm 5.2$
$f_L - f_R$ (%)	$21.7 \pm 3.0 \pm 3.6 \pm 2.0$	$25.0 \pm 2.5 \pm 2.3 \pm 2.5$

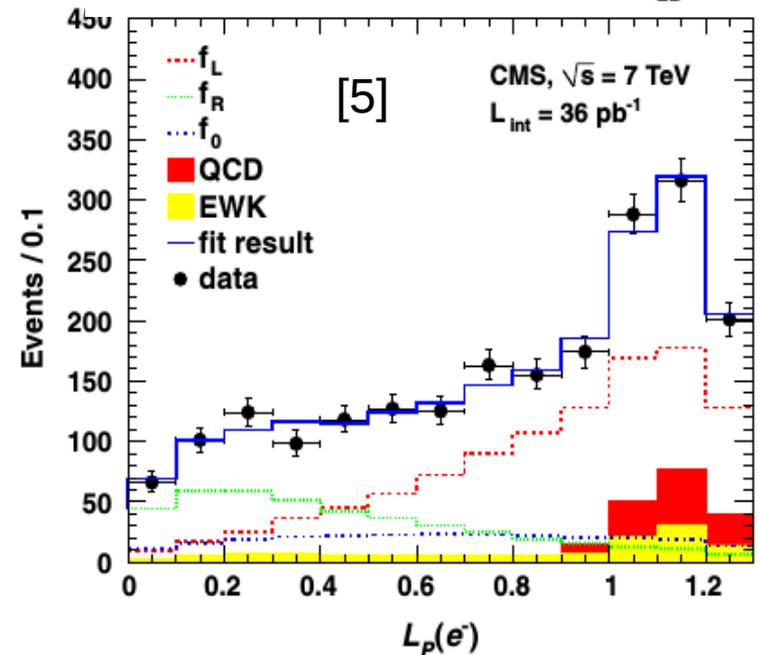
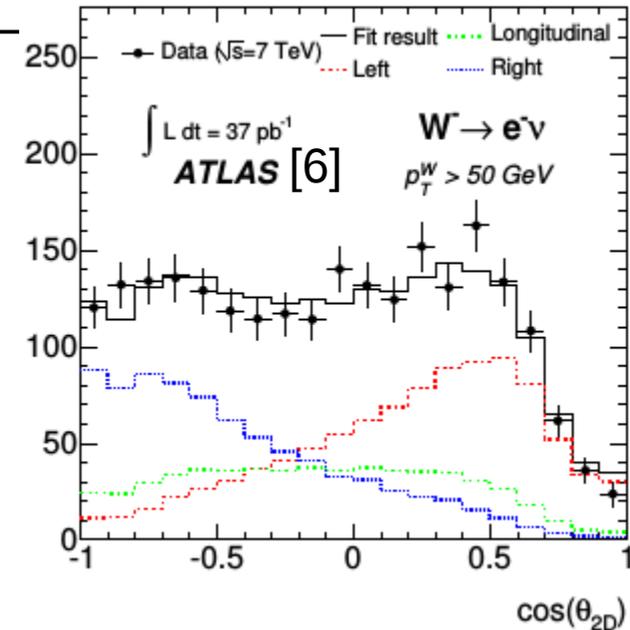
- CMS: binned maximum likelihood fit on the L_p distribution giving

$$(f_L - f_R)^- = 0.240 \pm 0.036(\text{stat}) \pm$$

$$f_0^- = 0.183 \pm 0.087(\text{stat}) \pm 0.123(\text{syst}) (\text{syst})$$

$$(f_L - f_R)^+ = 0.310 \pm 0.036(\text{stat}) \pm 0.017(\text{syst})$$

$$f_0^+ = 0.171 \pm 0.085(\text{stat}) \pm 0.099(\text{syst})$$



Possible W mass measurement

- Very challenging measurement at hadron colliders
 - Impossibility of knowing the initial parton momentum in the collision
 - Impossibility of knowing the neutrino longitudinal momentum
- Already measured at Tevatron with a sample of about 1M W candidates
 - Combined D0 and CDF measurement more precise than LEP2
- Statistical uncertainty already smaller than systematic with just 2011 data at LHC
- Can be measured using MC template fit on transverse kinematical distributions

$$\mathbf{m}_T = \sqrt{2 E_T^\ell \cancel{E}_T (1 - \cos \Delta\phi_{\ell\nu})} \quad \text{Affected by detector resolution}$$

$$\mathbf{p}_T^\ell \quad \text{Affected by } p_T^W \text{ modelling}$$

$$\mathbf{p}_T^\nu = \cancel{E}_T \quad \text{Affected by both}$$

- Some important differences at LHC
 - Higher pile-up environment \rightarrow affect hadronic recoil calibration
 - Different theoretical uncertainties : pp instead of ppbar
 - Different energy regime : 7, 8, 13 TeV
 - W charge asymmetry
- Detailed study on the experimental and theoretical needs for this measurement can be found at <https://indico.cern.ch/event/340393/contribution/8/material/slides/4.pdf>



Conclusions

- Presented EW measurements from ATLAS and CMS
- **Z A_{FB} Measurement**
 - Measured at 7 TeV with 5 fb⁻¹ luminosity by both experiments
 - Measured in electron and muon channel, in different rapidity regions.
 - Measured both at detector level and corrected for detector resolution & QED effects
- **Z polarization measurement**
 - Fresh result on 19 fb⁻¹ data
 - Angular coefficients measured in eight p_T^Z bins and in two rapidity bins
- **W polarization measurement**
 - Measured by ATLAS and CMS on a 35 pb⁻¹ sample
 - ATLAS measurement also performed two p_T^W regions
- All measurements show a good agreement with the Standard Model predictions.
- Precision on the measurements is still determined by systematic uncertainties, in particular by PDF uncertainty.