ATLAS perspective on measuring $\sin^2\theta_W$

LHC Physics Discussion

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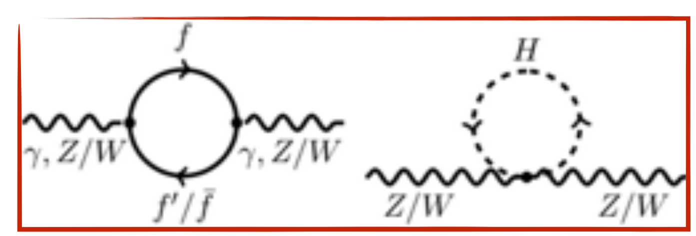
Introduction

- The gauge and scalar sectors of the SM is fully determined by four parameters (e.g. α, G_F, M_Z, M_H)
- All the other parameters can then be related by theory

$$\sin^2\theta_W = 1 - \frac{M_W^2}{M_Z^2} \qquad M_W^2 \sin^2\theta_W = \frac{\pi\alpha}{\sqrt{2}\,G_F}$$

- Other SM parameters enter through radiative corrections

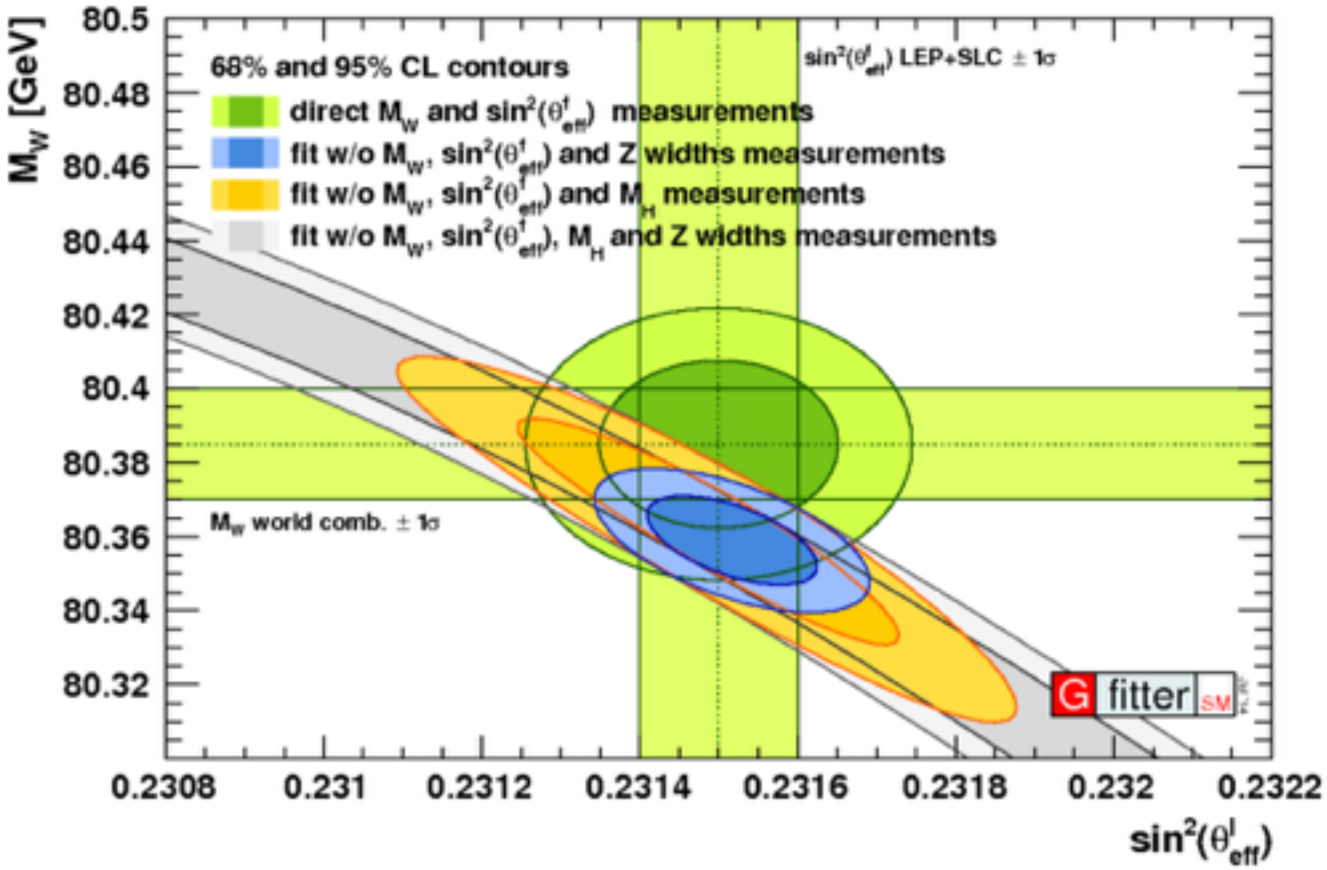
$$M_W^2 = \frac{M_Z^2}{2}\left(1+\sqrt{1-\frac{\sqrt{8\pi\alpha(1-\Delta r)}}{G_F M_Z^2}}\right)$$



$$\sin^2\theta_{\rm eff}^f = \kappa_Z^f \sin^2\theta_W \qquad g_{V,f} = \sqrt{\rho_Z^f}\left(I_3^f - 2Q^f\sin^2\theta_{\rm eff}^f\right) \qquad g_{A,f} = \sqrt{\rho_Z^f}\,I_3^f$$

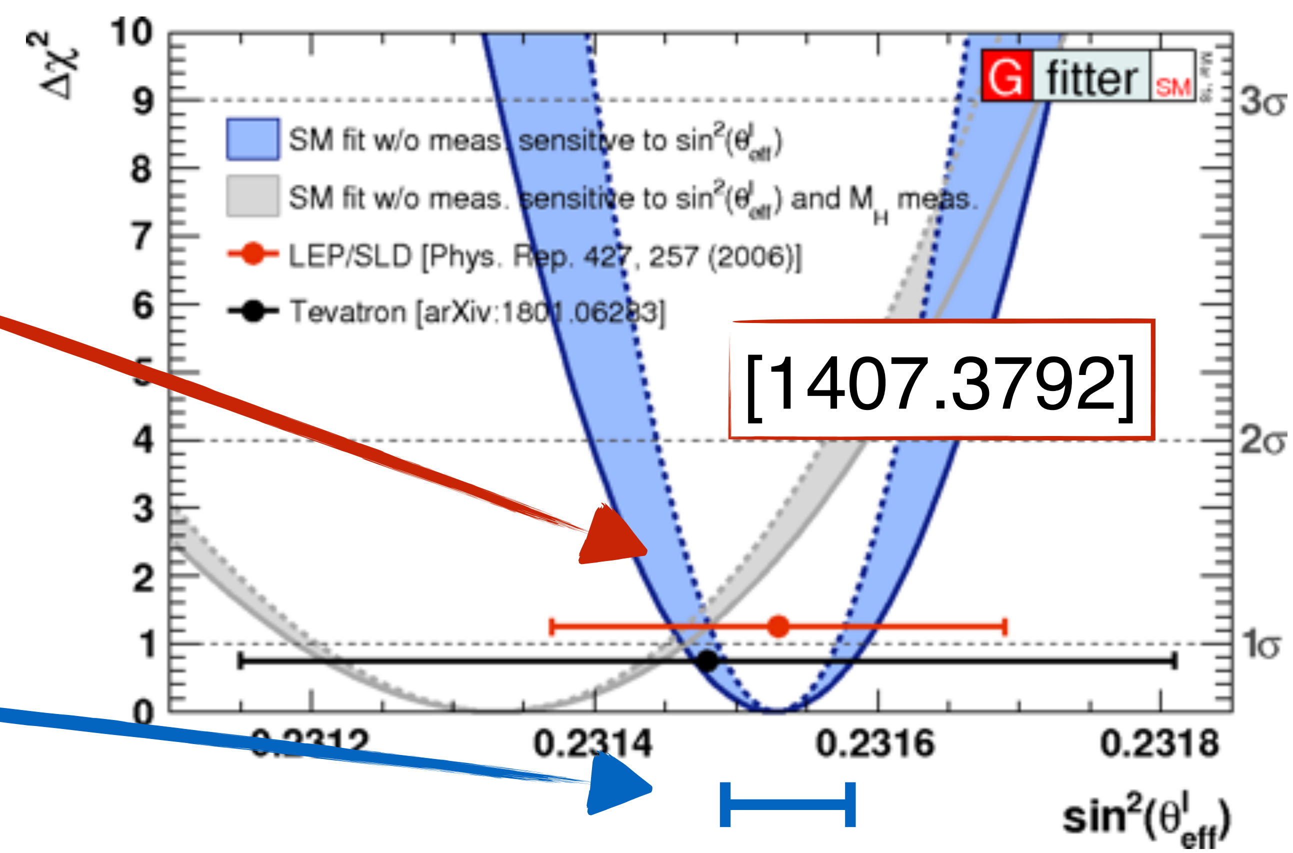
- Simultaneous measurements of different quantities allows to *over-constrain the SM* and test its internal consistency

The weak mixing angle



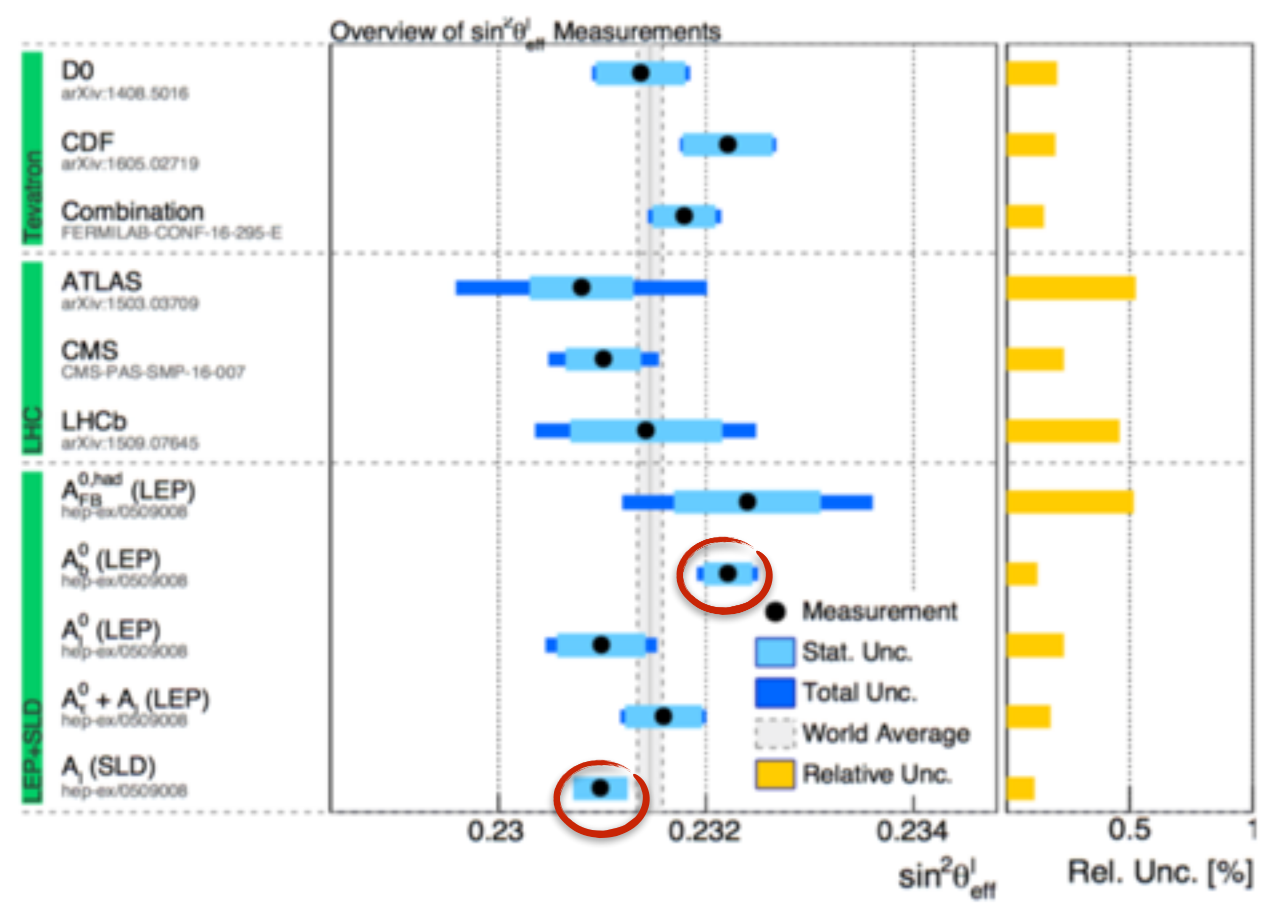
- The weak mixing angle in the SM parametrises the mixing between the EM and weak fields
- And provide and indirect determination of the W-boson mass

- Direct measurements have an average precision of ~16x10^{-5}
- Removing the direct measurements the indirect determination has a precision of ~6x10^{-5}



Existing Measurements

* The WMA has been precisely measured at LEP and SLD
  * Precision reaching 26 (29) x 10^{-5} for LEP (SLD)
  * Although the two most precise determinations ($A_{FB}^{0,b}$ at LEP and A_l^{LR} at SLD) show a *three sigma tension*
* Several measurements at hadron colliders
  * Recent combination of Tevatron results sits in between LEP and SLD with a 35x10^{-5} uncertainty
  * ATLAS 7 TeV reaches 120x10^{-5}
  * LHCb 7+8 TeV data 106x10^{-5}
  * Recent CMS 8 TeV 52x10^{-5}



* A WMA determination with a comparable precision to LEP and SLD (30x10^{-5}) would have important implications

Ai decomposition

- The Drell-Yan lepton angular distribution in boson rest frame can be decomposed into nine helicity cross-sections describing its polarisation state

unpolarised cross-section

all coefficients but A_4 vanish at LO (p_T=0)

sensitive to QCD

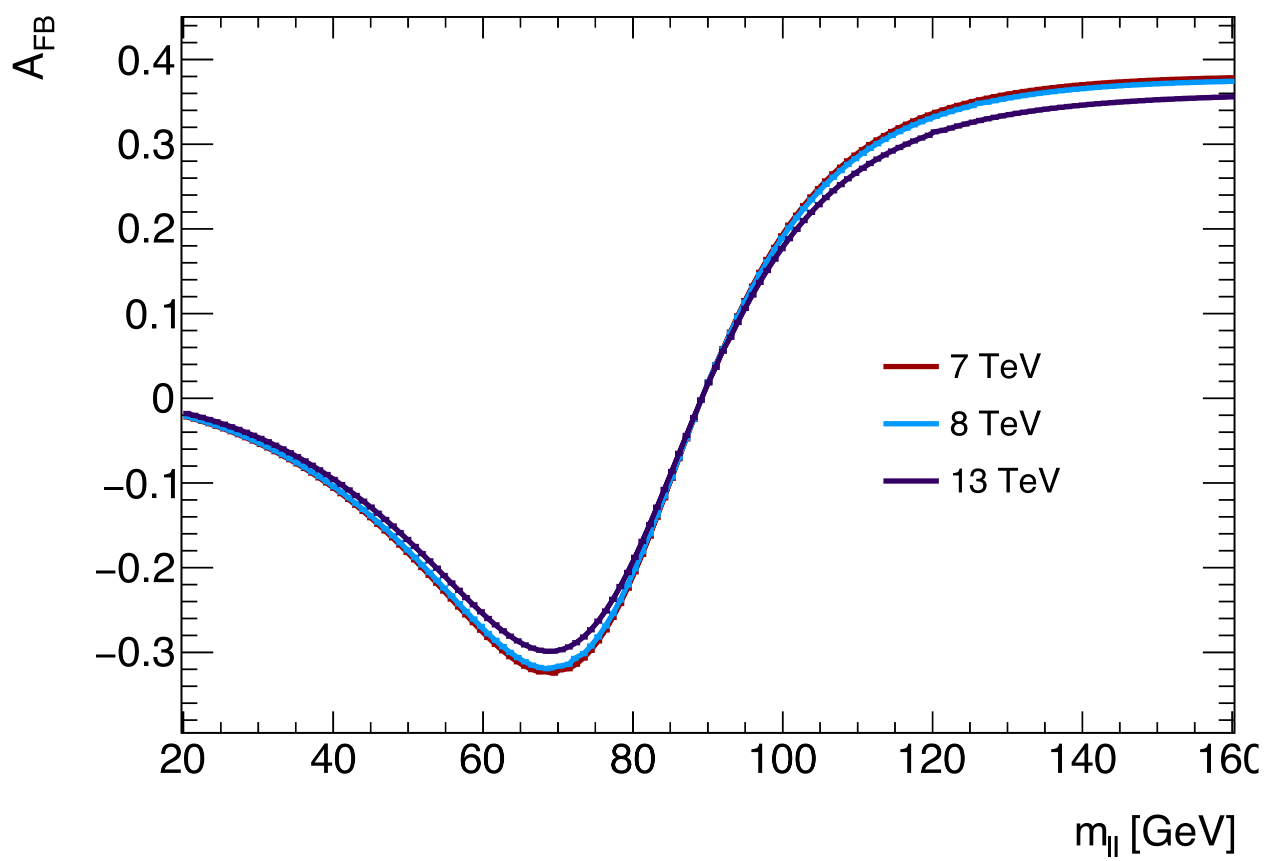
sensitive to s2w

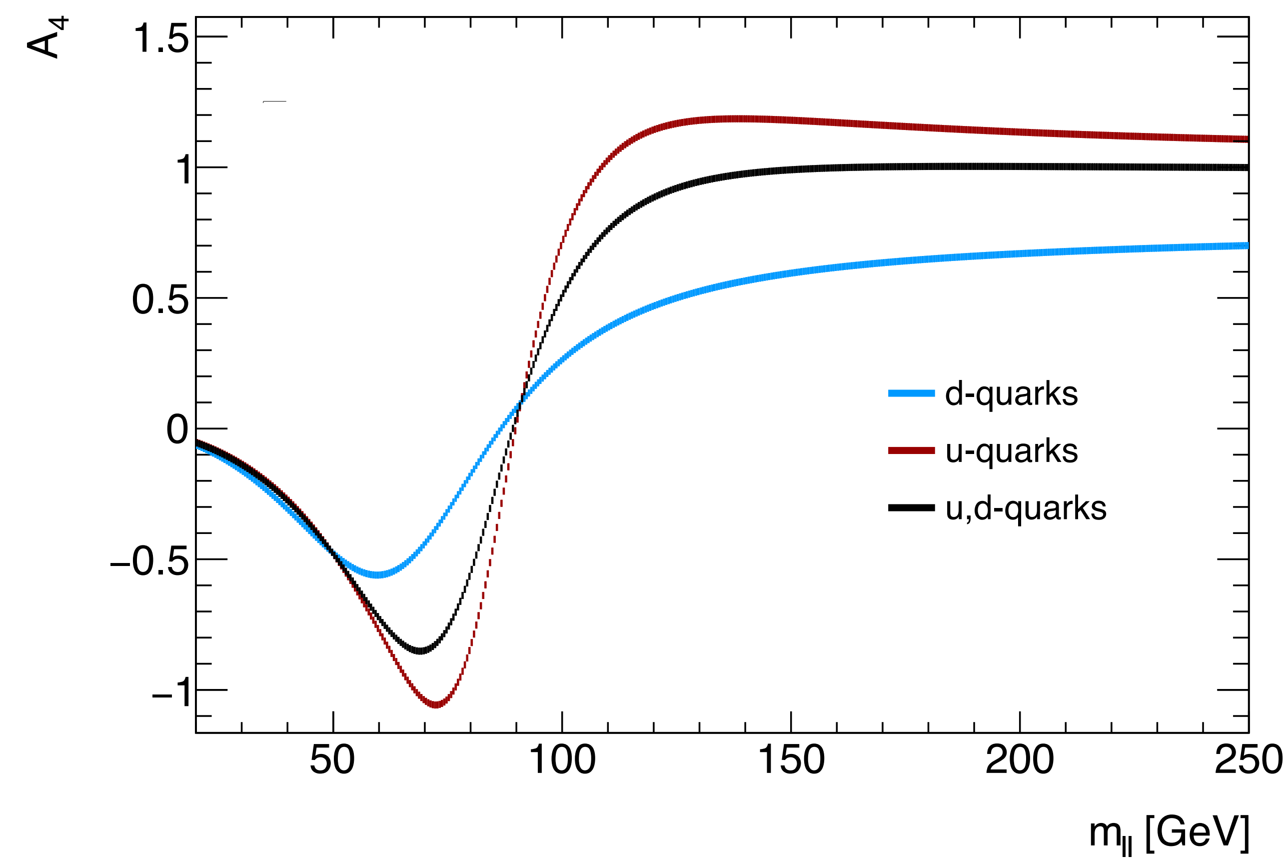
small terms

$$\frac{d\sigma}{dp_T^Z\, dy^Z\, dm^Z\, d\cos\theta\, d\phi} = \frac{3}{16\pi}\frac{d\sigma^{U+L}}{dp_T^Z\, dy^Z\, dm^Z}\Big\{(1+\cos^2\theta) + \frac{1}{2}A_0(1-3\cos^2\theta) + A_1\sin 2\theta\cos\phi$$
$$+\frac{1}{2}A_2\sin^2\theta\cos 2\phi + A_3\sin\theta\cos\phi + A_4\cos\theta$$
$$+A_5\sin^2\theta\sin 2\phi + A_6\sin 2\theta\sin\phi + A_7\sin\theta\sin\phi\Big\}.$$

- The A_4 coefficient is parity violating, introduces an asymmetry in $\cos\theta$
  - Due to the V-A structure of the weak current for the Z-boson and the interference between the photon (vector) and Z-boson (axial vector) amplitudes
  - The Z-boson self-interference contains a product of g_V from the lepton and quark vertices, and is thus related to $\sin^2\theta_W$: $g_V^f = T_3^f - 2Q_f\sin^2\theta_W$

Dilution effects

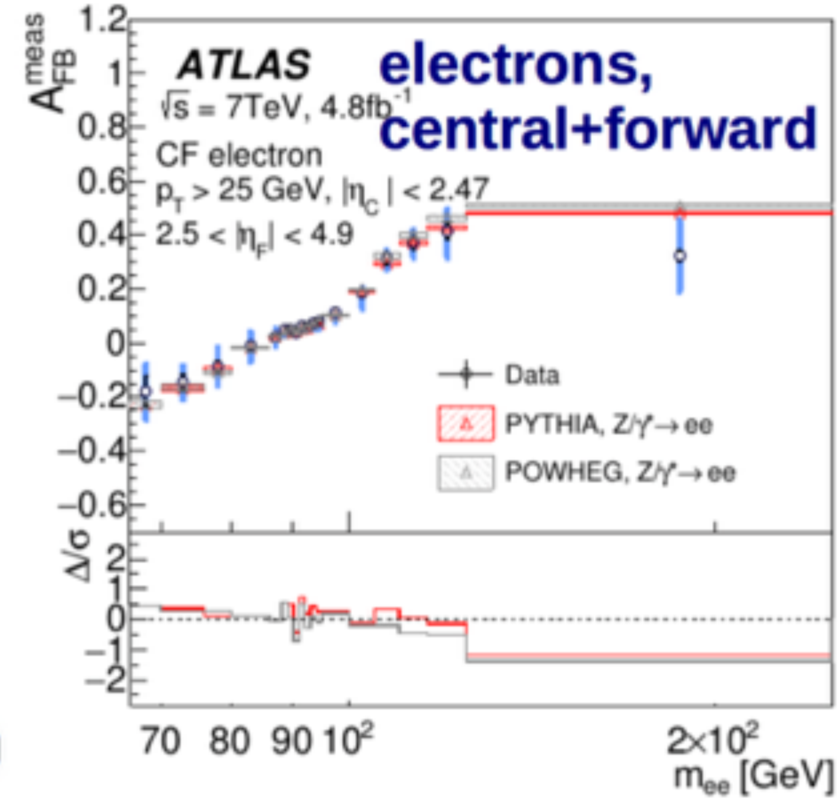




- In *pp* collisions we take the direction of the quark to be in the direction of the Z-boson rapidity (quarks carry more momentum than antiquarks)
- Due to this ambiguity there is a significant ***dilution effect***, a reduction in the measured asymmetry, which increases with beam energy (more sea-quarks)
- Much more important at the LHC than at the Tevatron!
  - Dilution from events where the antiquark has a higher x than the quark
  - Dilution as the A4 for u- and d-quarks are different
  - Also dilution from s-sbar and c-cbar events which show no asymmetry

ATLAS 7 TeV Afb

- Atlas performed a measurement of the forward-backward asymmetry with the 7 TeV dataset
  - Measured as function of m_{ll} with two central electrons (CC), one central and one forward electron (CF) and two muons
  - Directly related to A4 by: $A_4 = \frac{8}{3} A_{fb}(M_{\ell\ell}, P_T, y)$



- Extraction at reco level with template fits using a Pythia8 sample reweighed to different values of the mixing angle

	$\sin^2\theta_{\text{eff}}^{\text{lept}}$
CC electron	$0.2302 \pm 0.0009(\text{stat.}) \pm 0.0008(\text{syst.}) \pm 0.0010(\text{PDF}) = 0.2302 \pm 0.0016$
CF electron	$0.2312 \pm 0.0007(\text{stat.}) \pm 0.0008(\text{syst.}) \pm 0.0010(\text{PDF}) = 0.2312 \pm 0.0014$
Muon	$0.2307 \pm 0.0009(\text{stat.}) \pm 0.0008(\text{syst.}) \pm 0.0009(\text{PDF}) = 0.2307 \pm 0.0015$
El. combined	$0.2308 \pm 0.0006(\text{stat.}) \pm 0.0007(\text{syst.}) \pm 0.0010(\text{PDF}) = 0.2308 \pm 0.0013$
Combined	$0.2308 \pm 0.0005(\text{stat.}) \pm 0.0006(\text{syst.}) \pm 0.0009(\text{PDF}) = 0.2308 \pm 0.0012$

Nominal WMA extraction with a special ATLAS-epWZ12 LO set

PDF uncertainties propagated with the offset method

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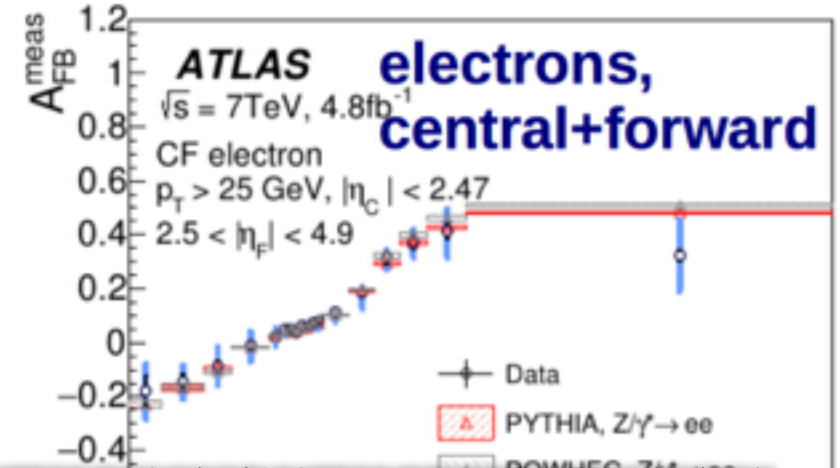

Statistical uncertainty comparable to Tevatron, but a much larger uncertainty from PDFs

Crucial to bring down the PDF uncertainty to get to a competitive measurement of the weak mixing angle

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ATLAS 8TeV measurements

* ATLAS has published two measurements of Drell-Yan production at 8 TeV sensitive to the weak mixing angle:

* [1710.05167] A measurement of triple differential fiducial cross-sections performed over a wide range of dilepton mass, rapidity and lepton polar angle in the CS frame
  - Exploit the full cross-section information, although the primary sensitivity to WMA is in A_{FB}

* [1606.00689] A direct measurement of the angular coefficients (A0 to A7) in the full phase-space via an analytical extrapolation
  - Reduced sensitivity to theory uncertainties
  - Possibly more sensitive than A_{FB} to NLO EWK effect that break the harmonic decompositions

ATLAS 8TeV measurements

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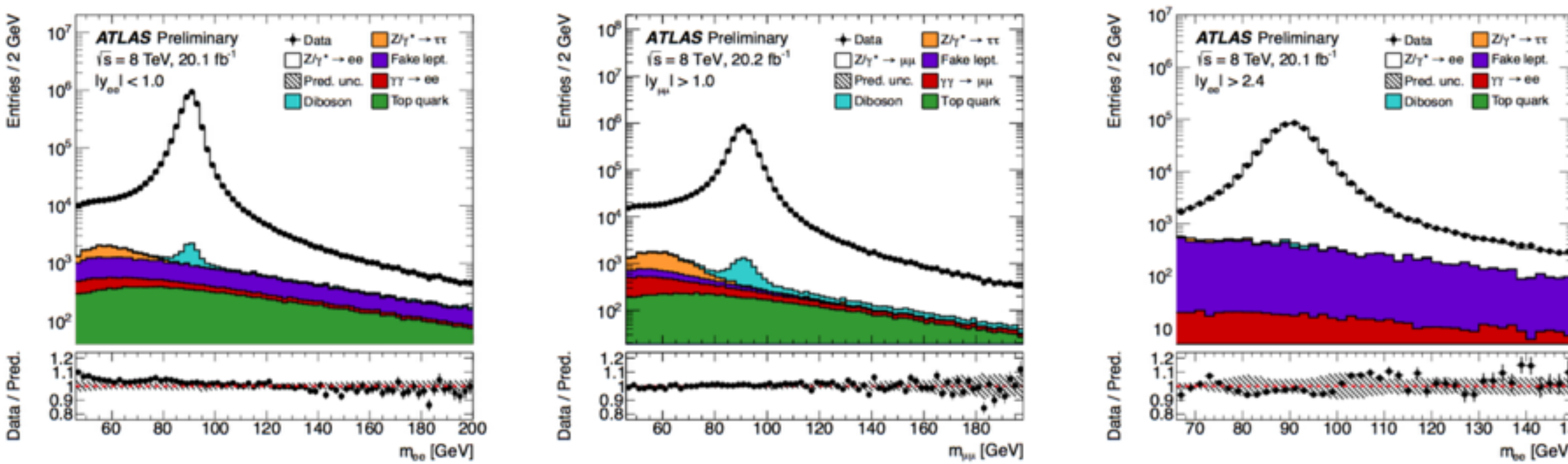
Will go through the details of the Z3D measurements and some details on current work towards an extraction of the weak mixing angle

analytical extrapolation

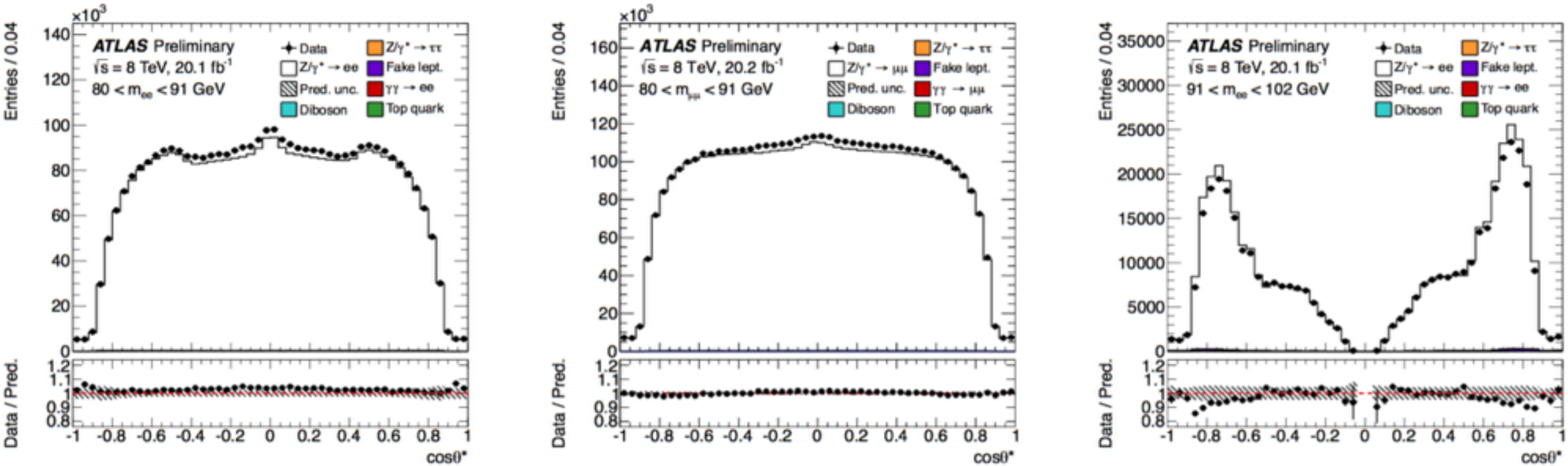
  - Reduced sensitivity to theory uncertainties
  - Possibly more sensitive than A_{FB} to NLO EWK effect that break the harmonic decompositions

Z3D MEASUREMENT DEFINITION



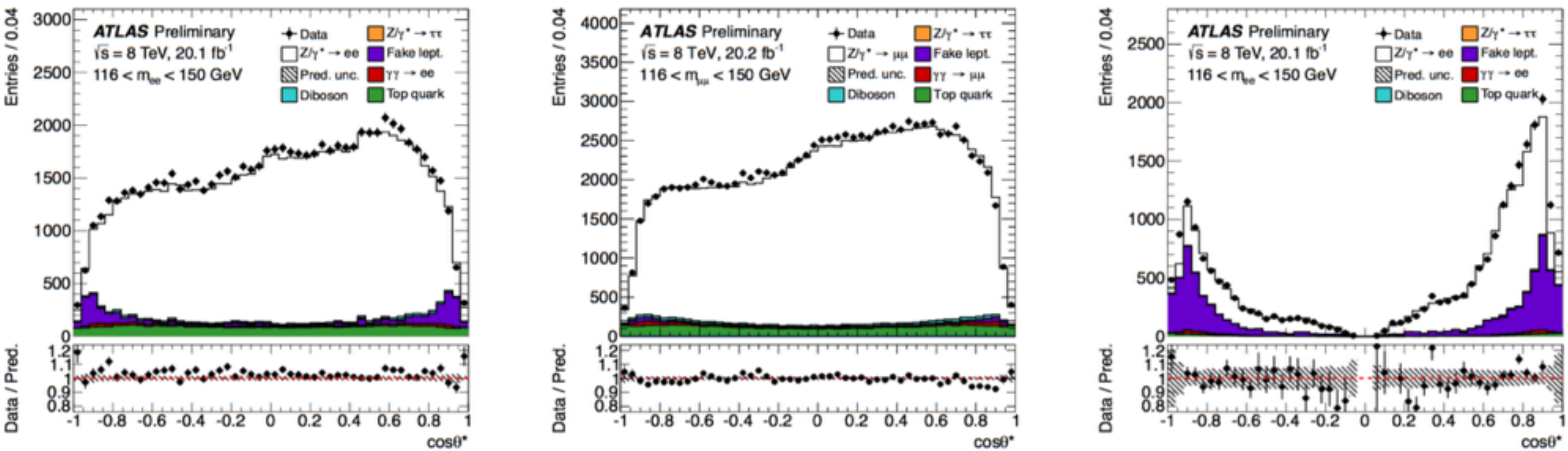
- Measurement performed using central $|\eta|<2.4$, $p_T > 20$ GeV electrons and muons in seven 46 GeV < m_{ll} < 200 GeV, twelve $y_{ll}<2.4$ and six $\cos\theta^*$ bins (2x504 in total)
- Extended using one central (p_T >25 geV) and one forward electron $|\eta|>2.5$, $p_T>20$ GeV in five 66 GeV < m_{ll} <150 GeV bins, five 1.2 < y_{ll} < 3.6 and six $\cos\theta^*$ bins (150 in total)
- Powheg+Pythia8 with CT10 PDFs and with NNLO QCD and NLO EWK k-factors used as signal model

At the peak



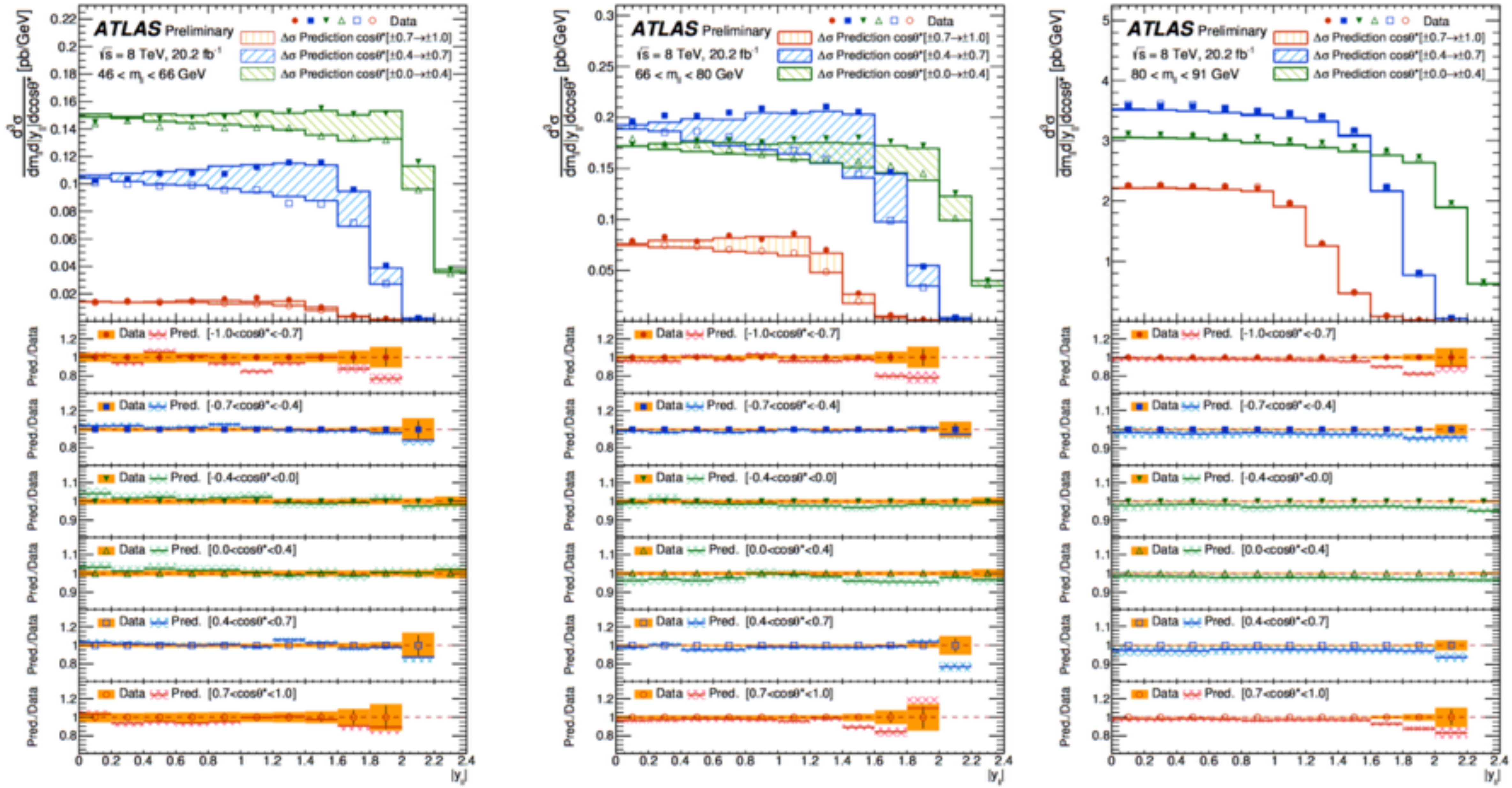
* Z-peak bins (80 GeV < m_{ll} < 91 geV and 91 GeV < m_{ll} < 102 GeV) are symmetric in and almost background free for both central-central (CC) and central-forward (CF) selections
  * CF selection extends result not only in y_{ll} but also in $\cos\theta^*$
* Systematic uncertainties dominated by lepton efficiencies (<0.5%), energy scale and resolution (~1%) and charge dependent biases in the muon momentum reconstruction (~1%)

Above the peak



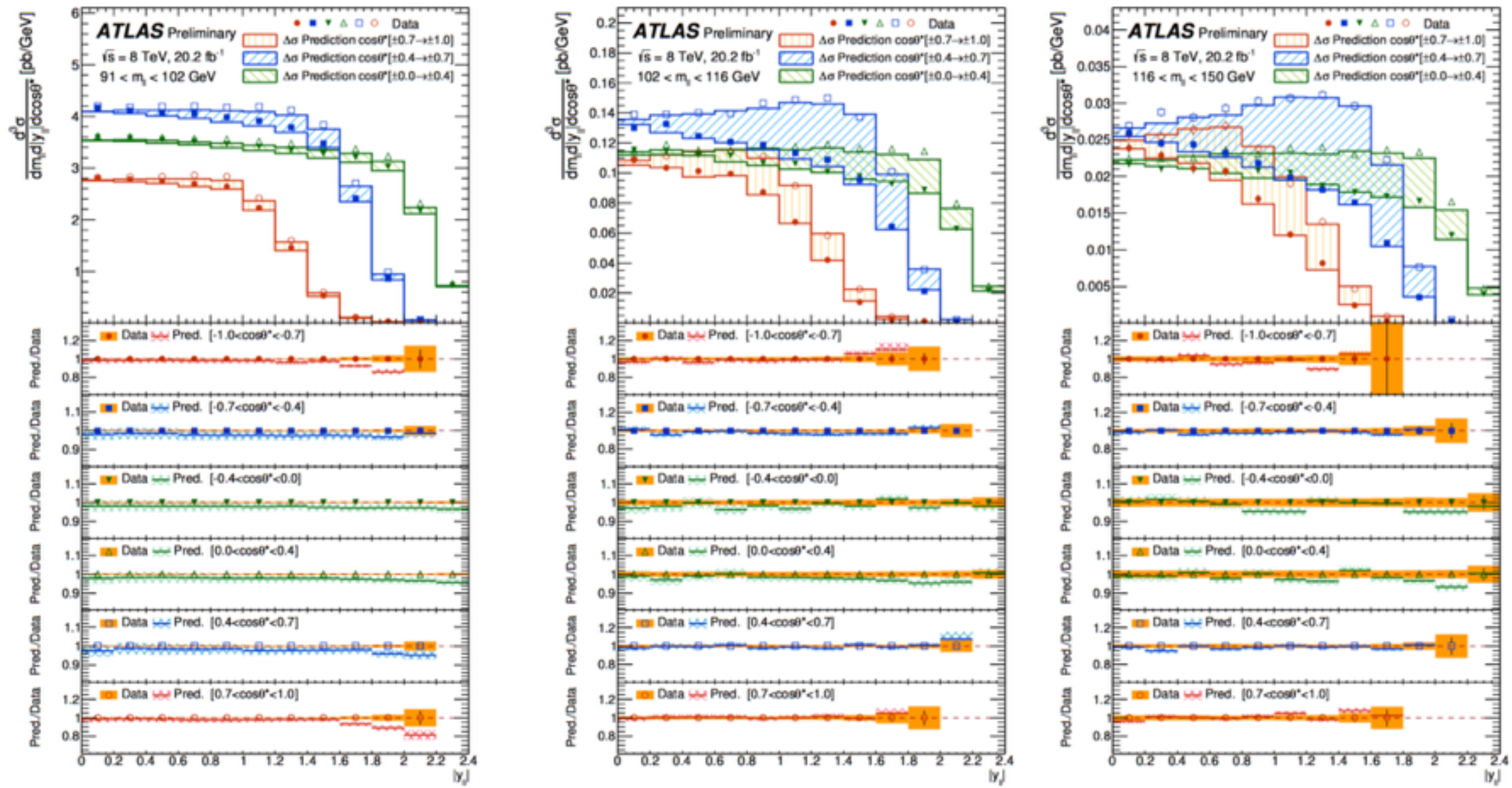
* Above the Z-peak the Forward-Backward asymmetry develops
* Backgrounds from top quark and multi jet production become sizeable (particularly for CF electrons).
    * But mostly charge-symmetric, they cancel in the A_{FB}
* Leading uncertainties are from the background subtraction and the energy resolution for the forward electrons

Z3D - Results



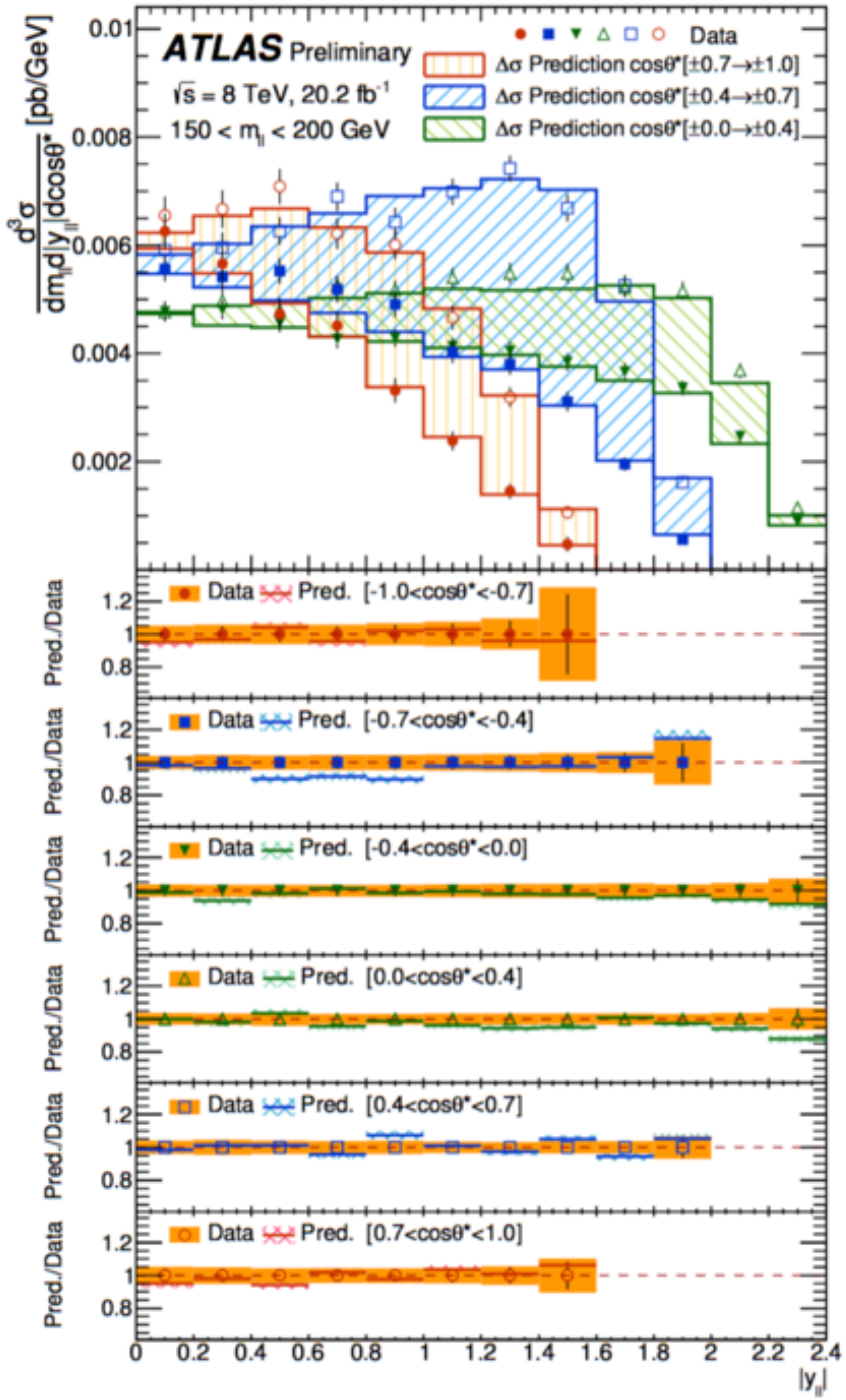
- Negative FB asymmetry below the Z-peak, vanishing at the peak
- Cross-section increasing with mass for large cosθ^*, due to a reduced impact of the fiducial selections

Z3D - Results



- The asymmetry flips sign above the Z-peak and increases at large values of m_{ll}

Z3D - Results

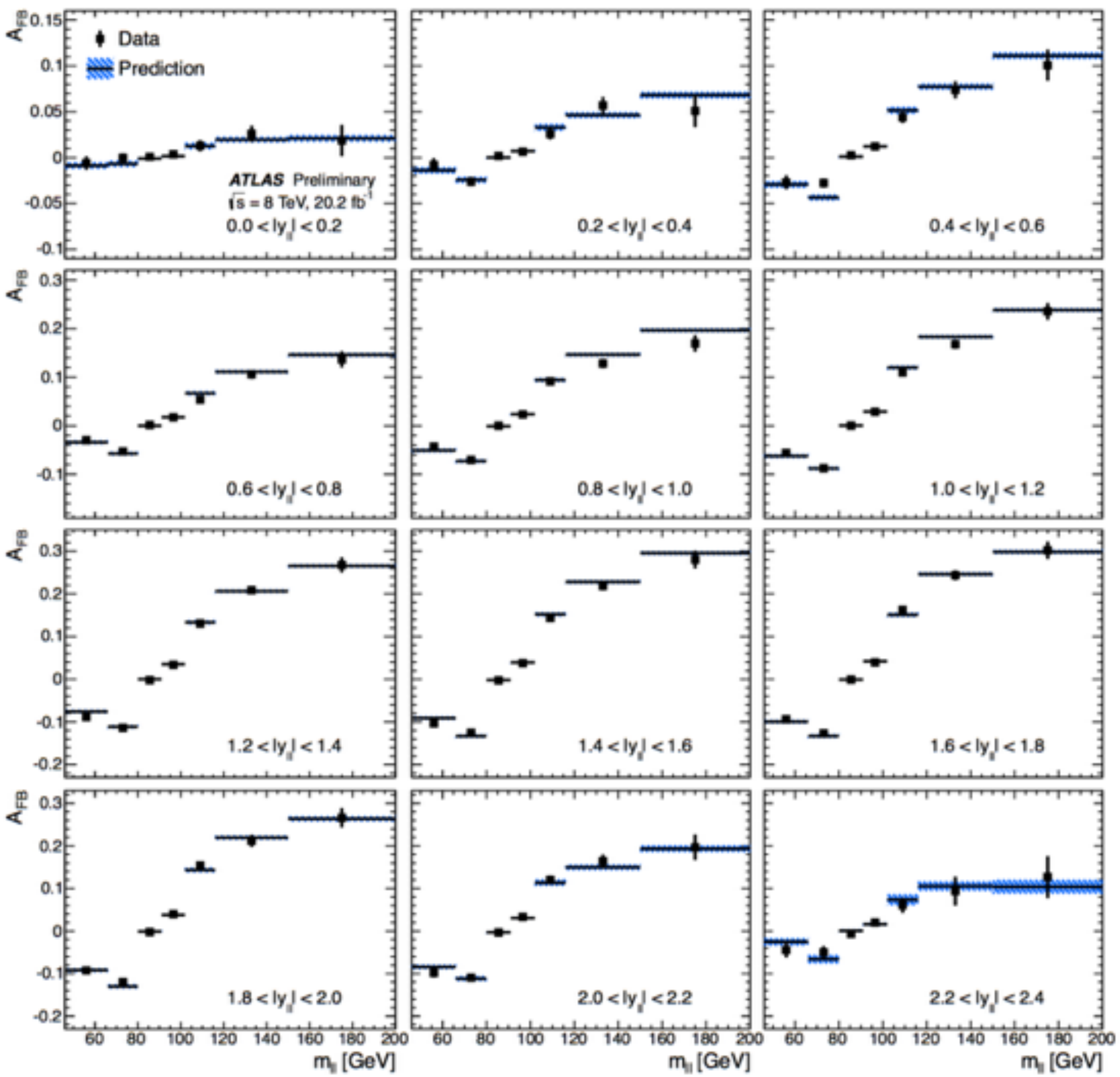


- The combination of the electron and muon channels gives a good $\chi 2/\mathrm{ndf} = 489.4/451$
- The accuracy of the measurement reaches 0.5% precision in the Z-peak region for $|y_{ll}|<1.4$
- Overall a good agreement with the Powheg based prediction

AFB - CC

- From the cross-sections, the A_{FB} can be built as:

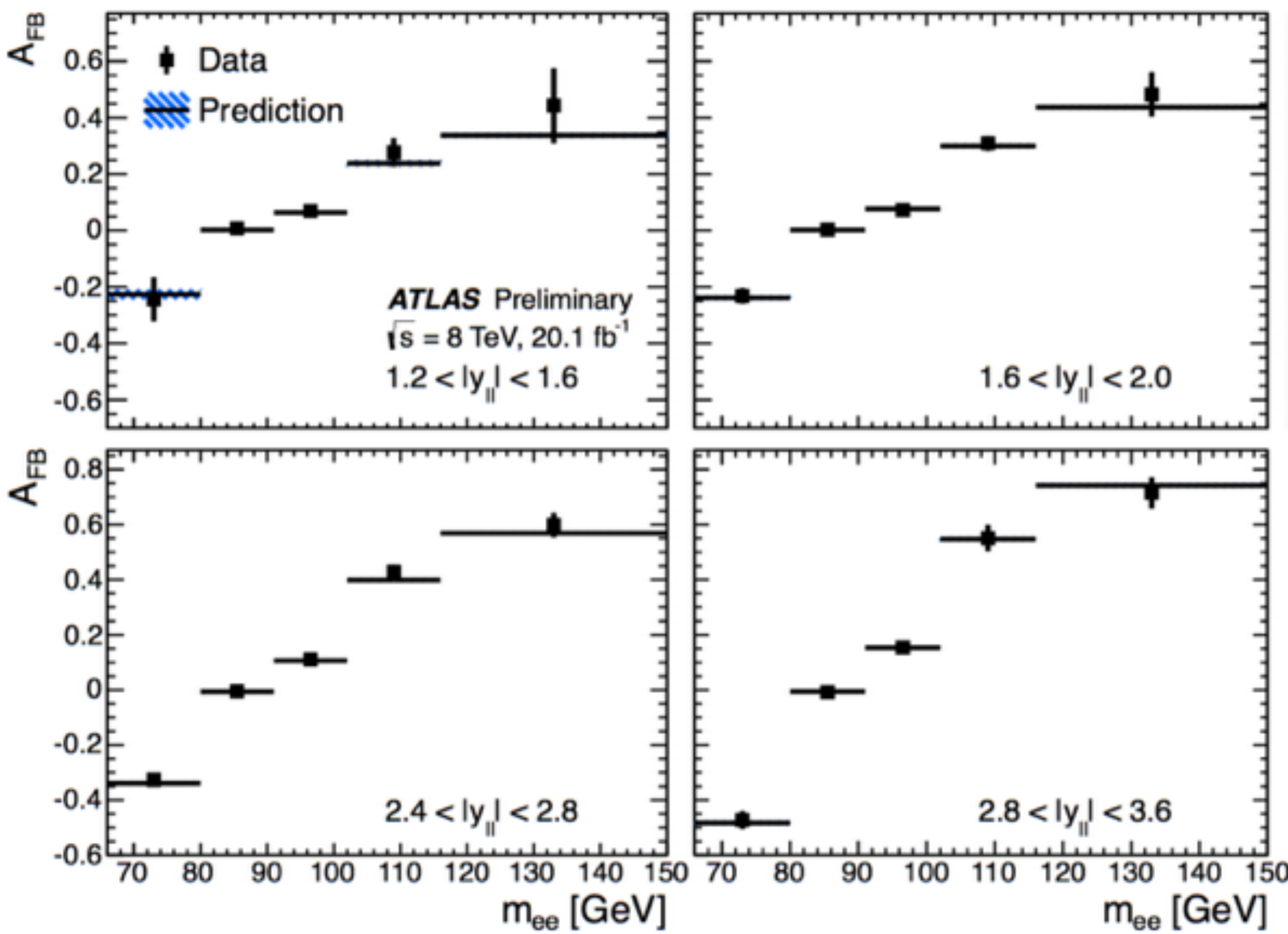
$$A_{\mathrm{FB}} = \frac{\mathrm{d}^3\sigma(\cos\theta^* > 0) - \mathrm{d}^3\sigma(\cos\theta^* < 0)}{\mathrm{d}^3\sigma(\cos\theta^* > 0) + \mathrm{d}^3\sigma(\cos\theta^* < 0)}$$



- Uncertainties symmetric in costheta mostly cancel (lepton scales and resolution)
- Asymmetry increases with increasing rapidity, flattening in the last bins due to reduced acceptance

AFB - CF

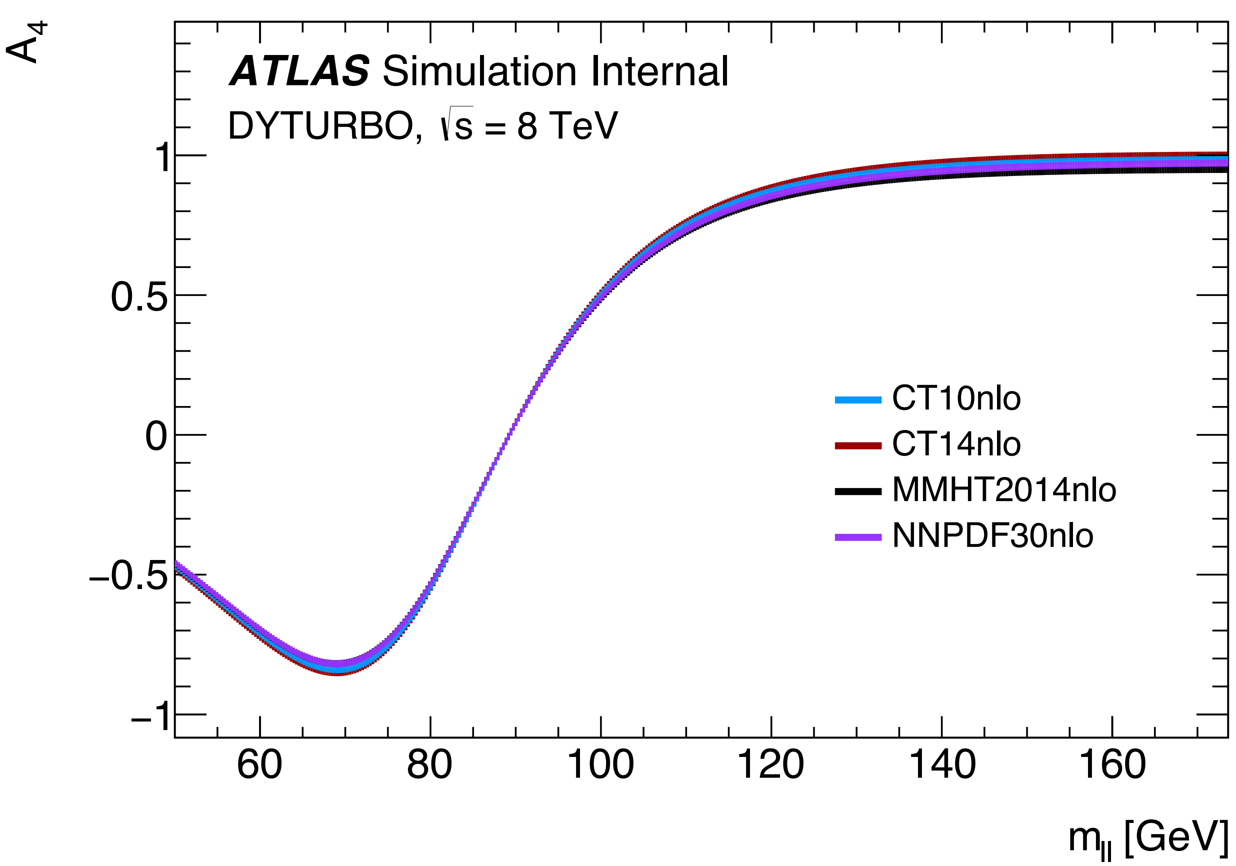
* For the CF channel cancellation of uncertainties is even more important

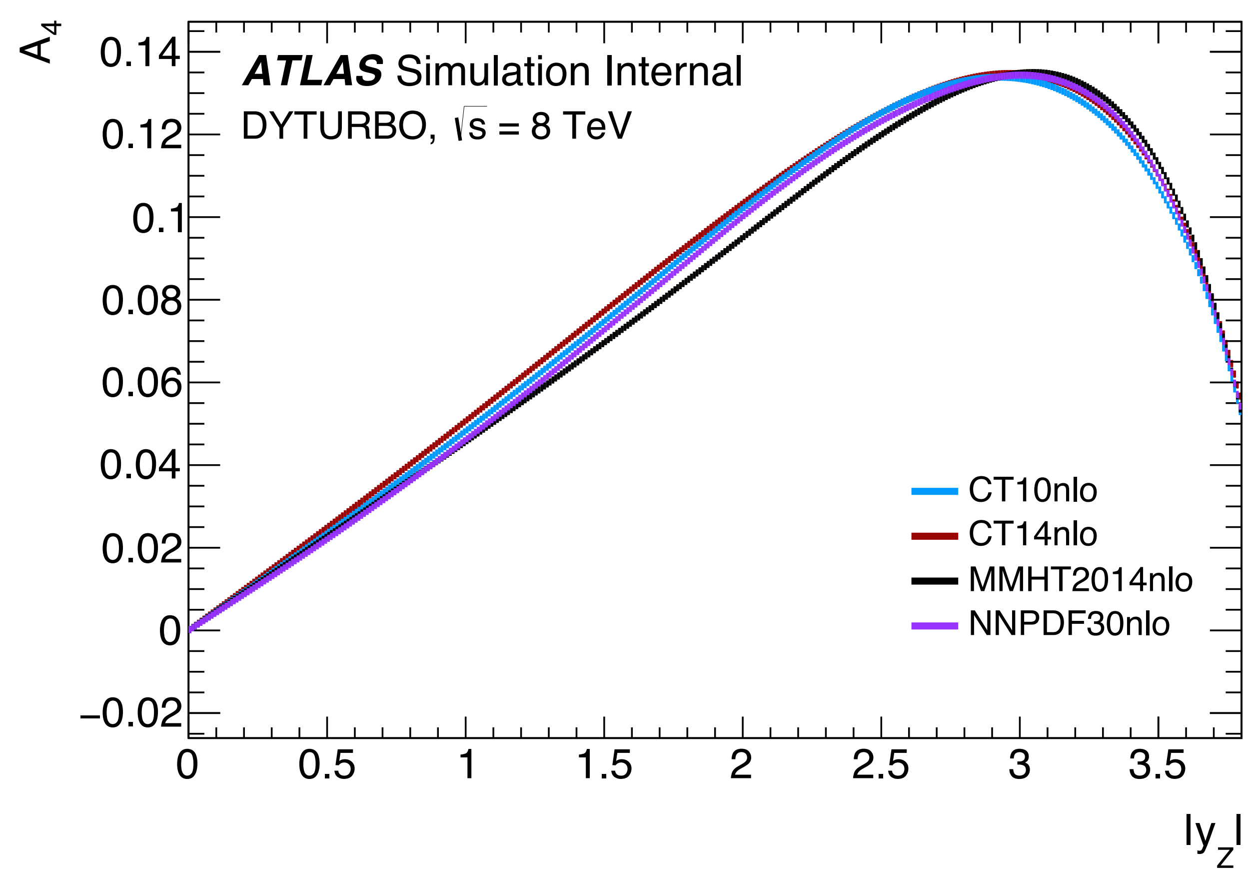


* Measured A_{FB} from -0.2 to +0.5 at lowest y_{ll} to -0.4 to +0.7 at the highest y_{ll}
* Good agreement with the Powheg based prediction

WMA extraction

- Currently working at a extracting the weak mixing angle from both the Ai and Z3D measurements
- Reduced uncertainties from PDF through simultaneous fit with WMA in enlarged phase-space
- Careful estimate of the effect of electroweak corrections
  - Non negligible at this level of precision

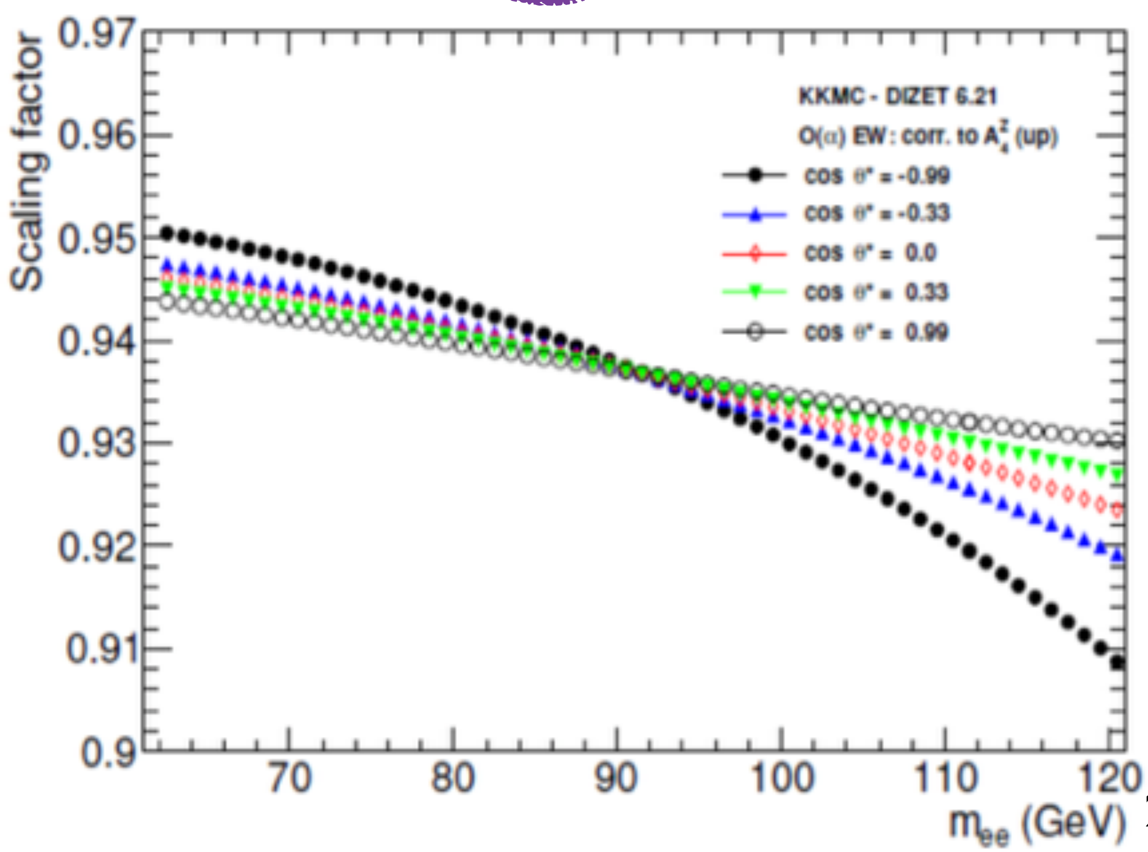


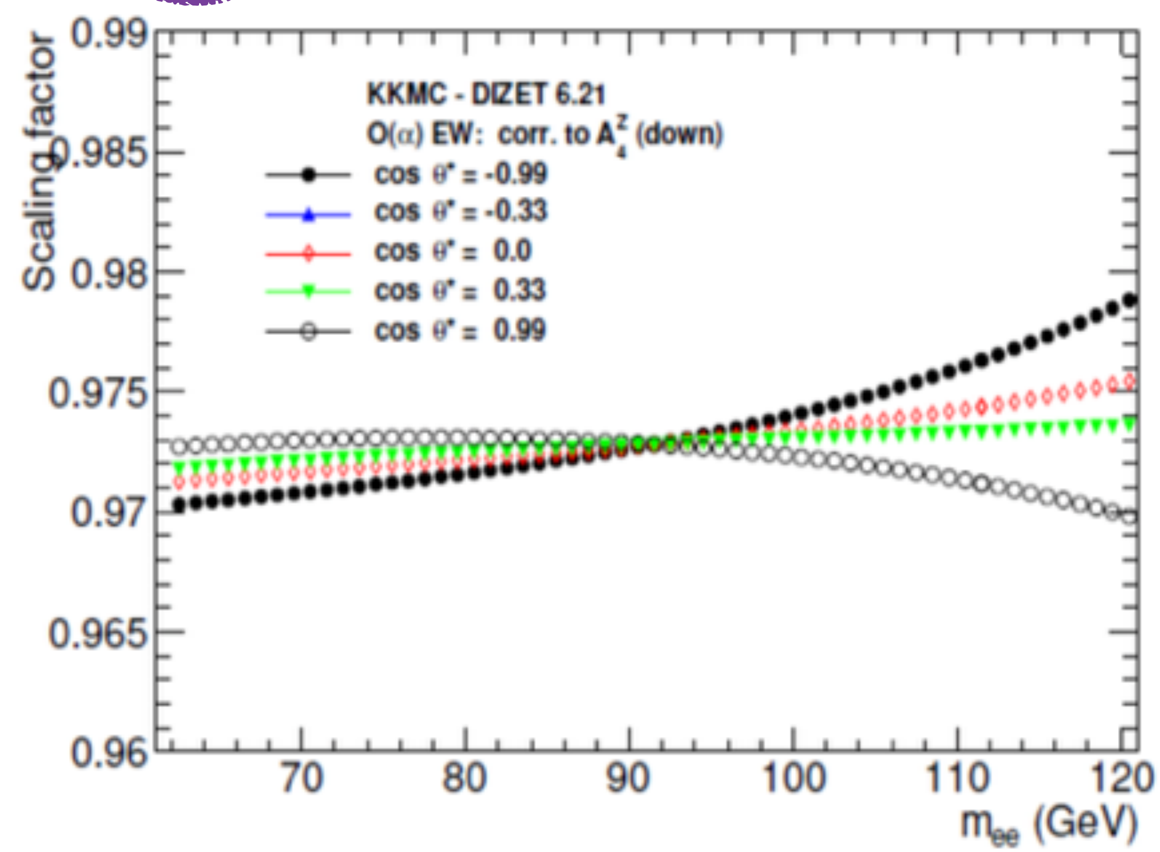


EWK corrections

- Electroweak corrections do not alter significantly the Born-level interpretation
  - Loop and vertex EWK radiative corrections can be incorporated into *complex multiplicative form-factors* which change the couplings by few percent
  - Tabulated using the ZFITTER/DIZET library (same used at LEP/Tevatron) in the on-shell scheme and for massless fermions (so they only depend on the charge and weak isospin of the fermion)

$$g_A^f \rightarrow \sqrt{\rho_{eq}}\, T_3^f \qquad g_V^f \rightarrow \sqrt{\rho_{eq}}\,(T_3^f - 2Q_f \kappa_f \sin^2\theta_W)$$





The EBA

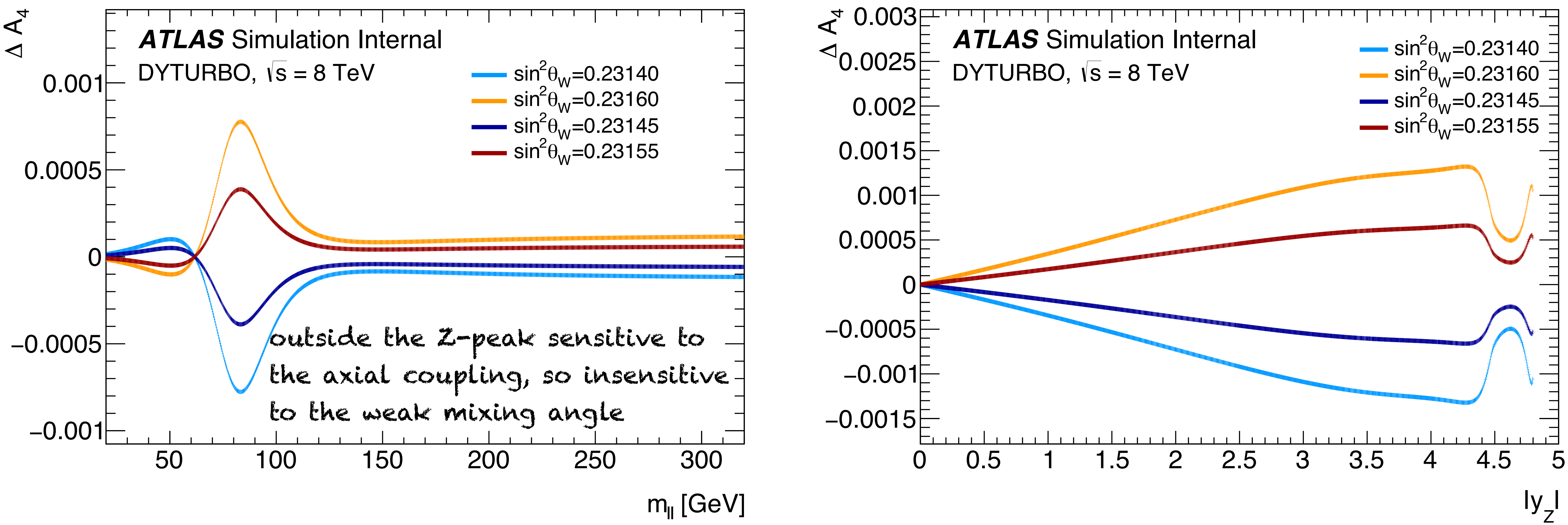
- The form factors can be applied as function of s, $\sin^2\theta_W$ into any calculation for the Drell-Yan process, leading to the so called *enhanced Born approximation* (EBA)
- Can then relate the measurement of the effective mixing angle to the on-shell angle as: $\sin^2\theta_{\rm eff}^{\rm lept} = \mathrm{Re}[\kappa_e(m_Z^2)]\sin^2\theta_W$
- $\sin^2\theta_W$(on-shell) is a constant but $\sin^2\theta^{l}_{\rm eff}(m_{ll}, f)$ is not
- In the on-shell scheme the LO relation between the mixing angle and the vector boson masses is promoted to all orders

$$\sin^2\theta_W = 1 - M_W^2/M_Z^2$$

a measurement of $\sin^2\theta_W$ is an indirect measurement of the W mass

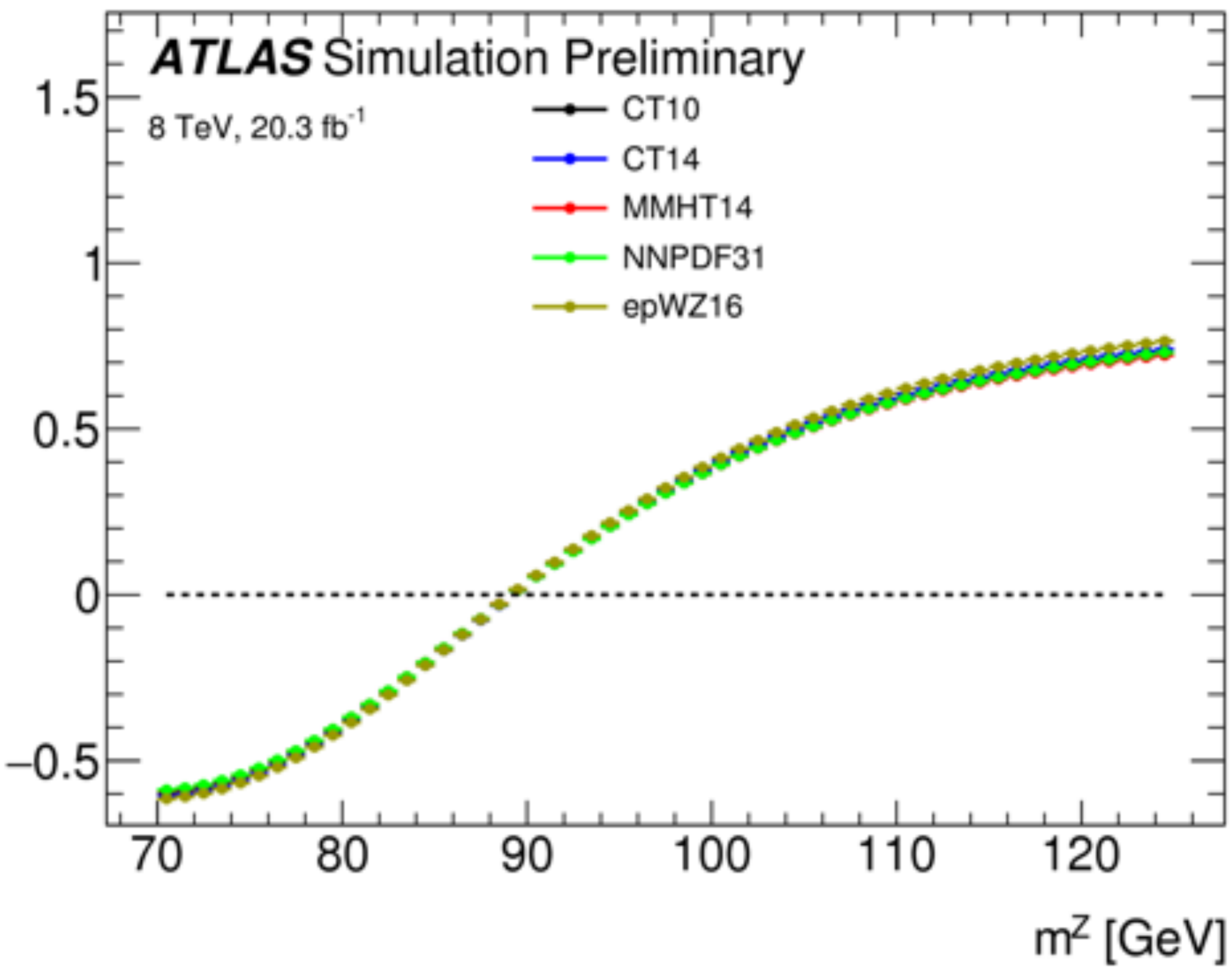
$$\boxed{\mathrm{SM}(\sin^2\theta_W) \xmapsto{\mathrm{EWK}} \sin^2\theta_{\rm eff}(s) \xleftrightarrow{\mathrm{QCD}} A_4(s),}$$

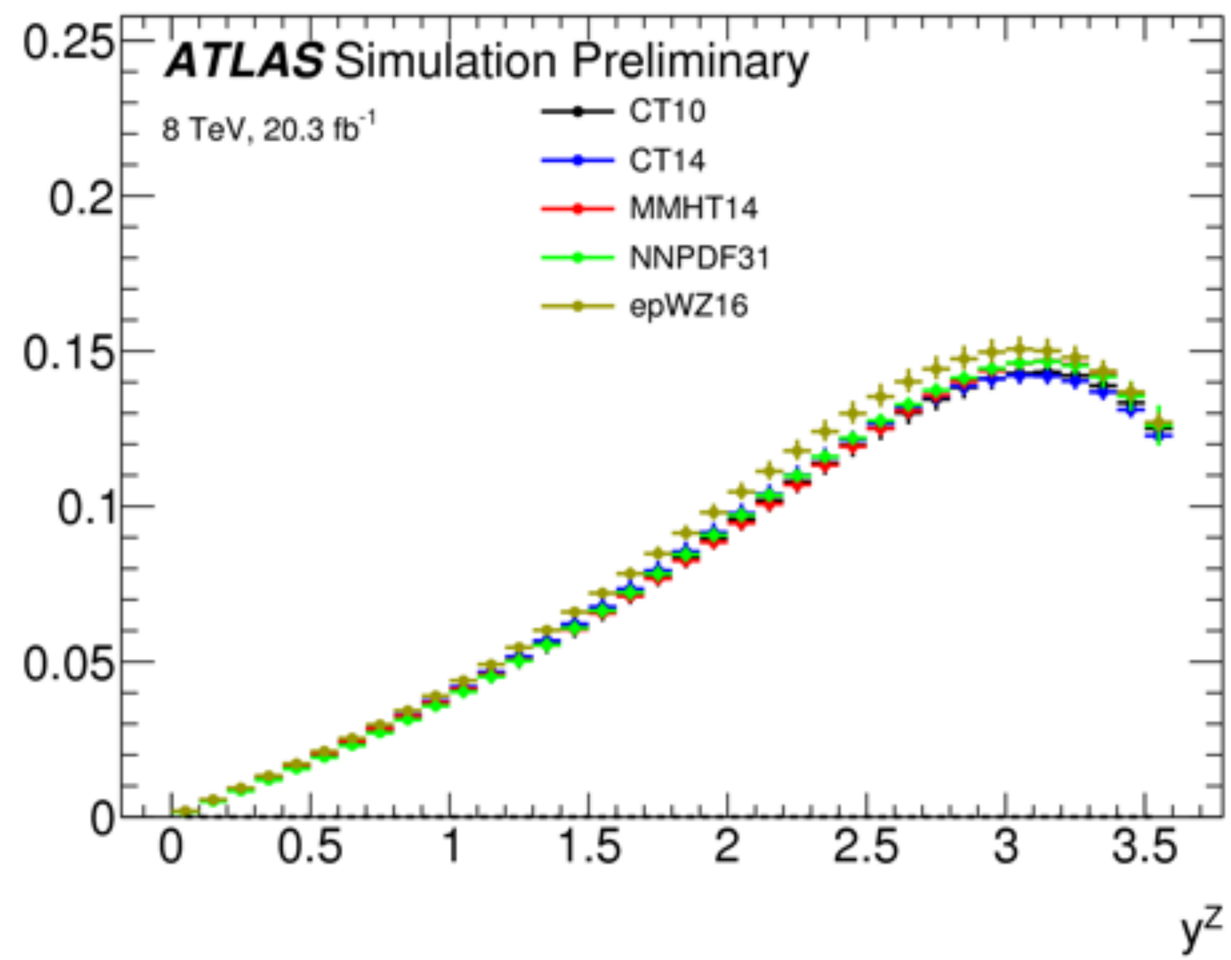
$\sin^2\theta_W$ sensitivity



- Tested the impact of $\sin^2\theta_W$ and PDF variations on A_4 as function of m_{ll}, y_{ll}
  - Computed with DYTURBO; the differences are shown with respect to a prediction done with CT10nlo and $\sin^2\theta_W$ =0.23150
  - Everything done at LO for the moment; QCD effects are not very large and easy to incorporate at a later stage

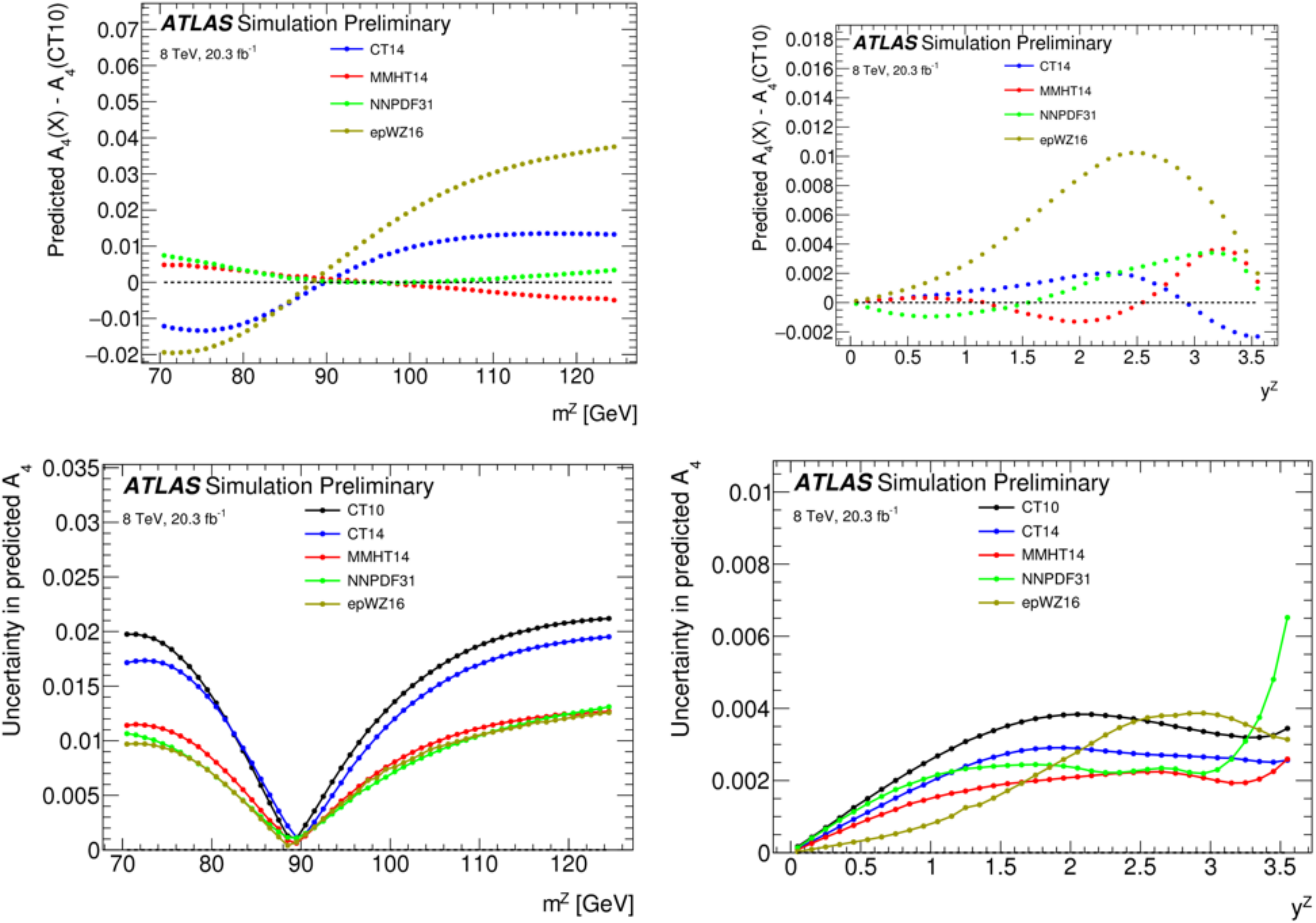
PDF sensitivity



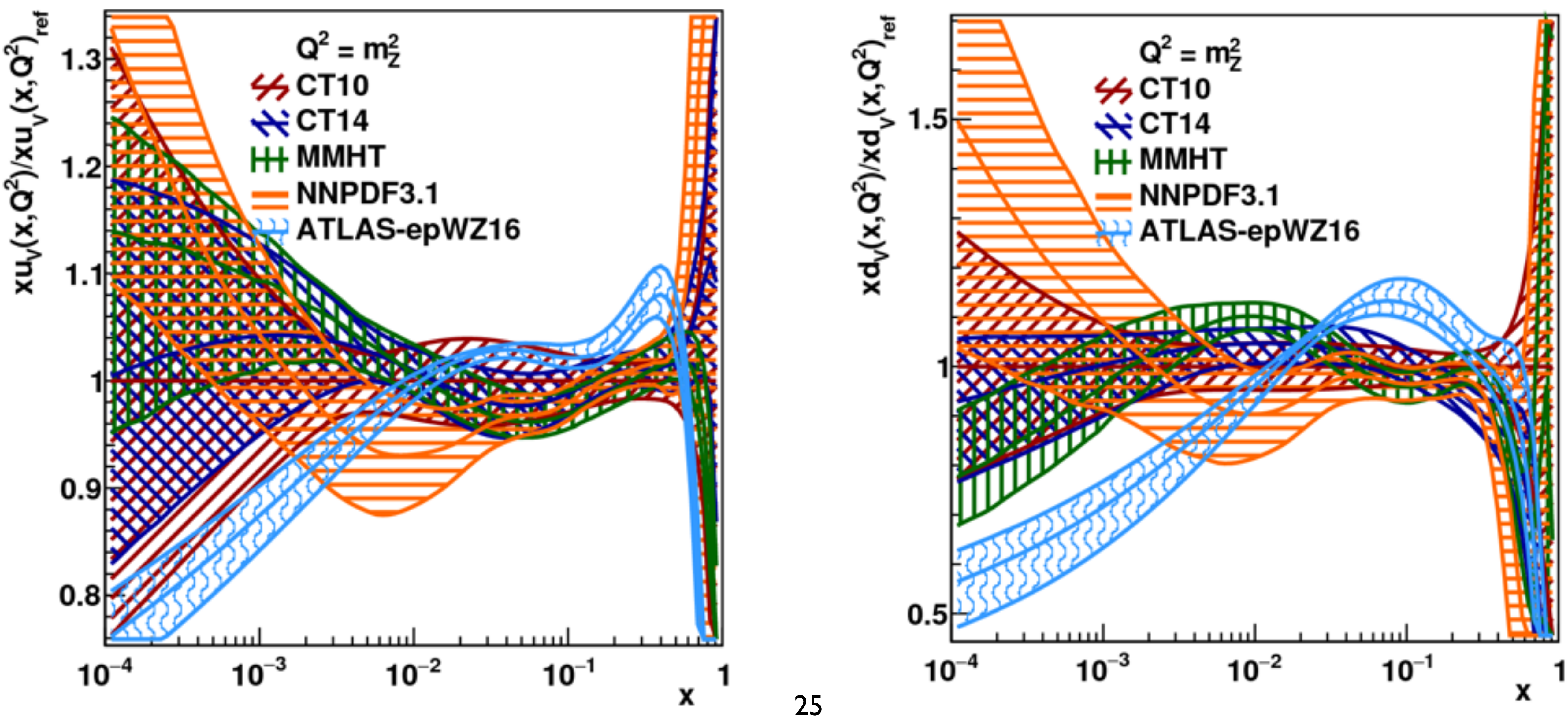


- Predictions at NLO accuracy in QCD and LO EWK using DYRES
  - ATLAS-epWZ2016 departs from the other sets
  - even after considering the uncertainty in the PDF themselves
  - Likely from the large difference in the down and valence contributions.

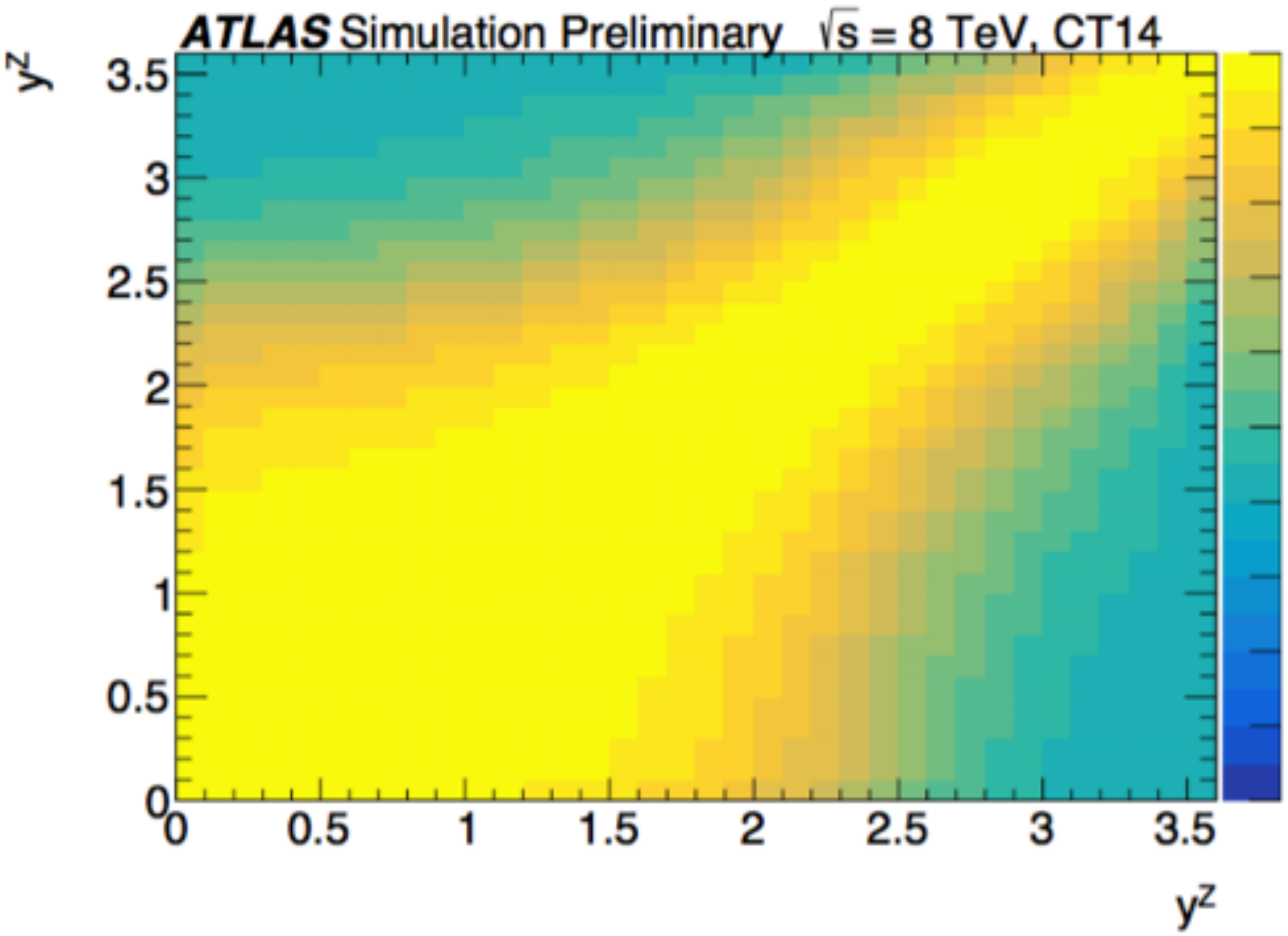
PDF sensitivity



PDF sensitivity



PDF correlations



- Interesting structures in the correlation between the predicted A_4/A_{FB} and the boson rapidity
  - Strong and positive among neighbouring yZ, become negative for distant yZ bins

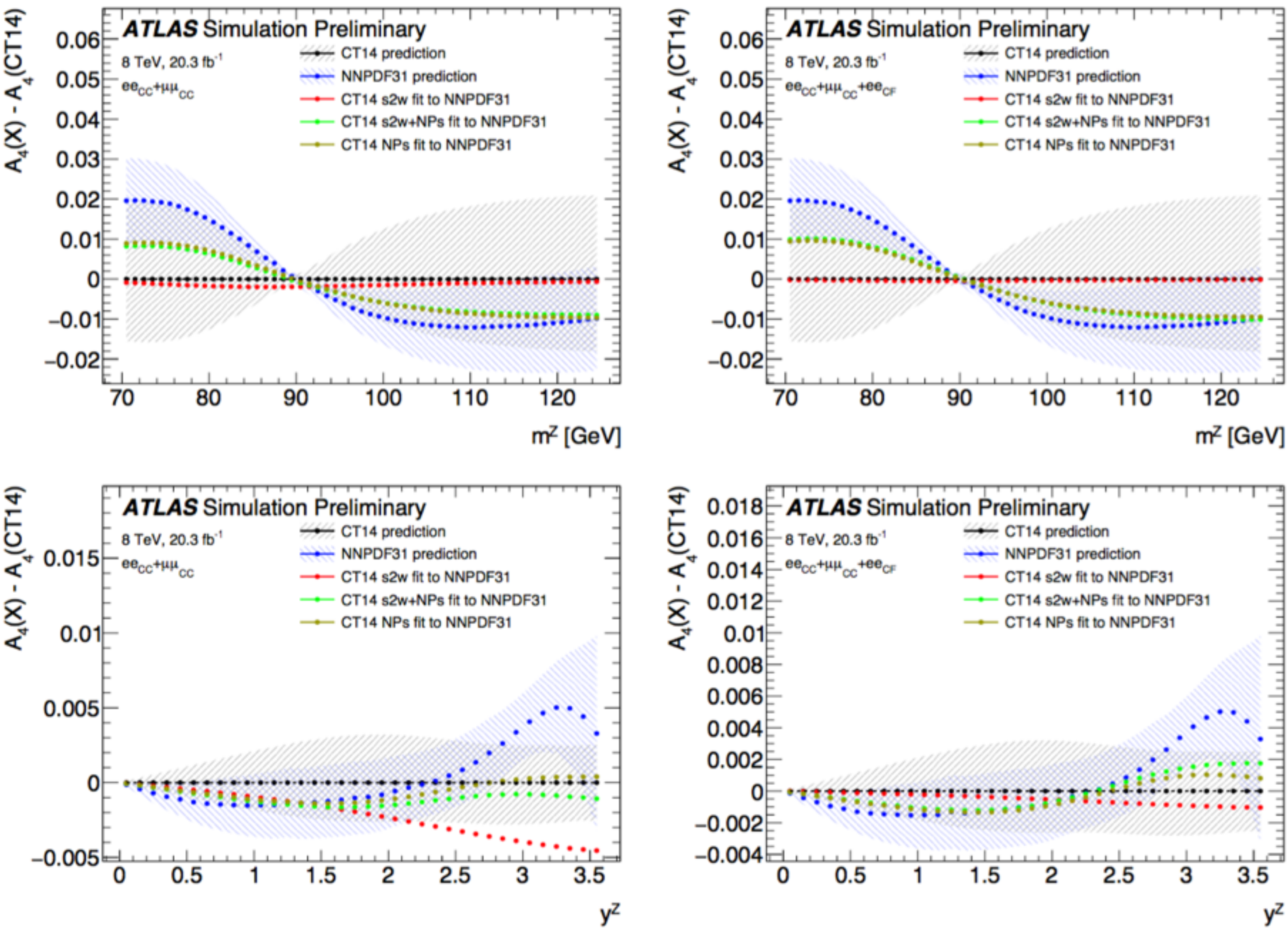
- Experimental measurements are binned in m_{ll} and y_{ll}
- The predicted pattern of correlations plays an important role in the PDF uncertainty in extractions of the weak mixing angle
  - Already exploited by the *CMS 8 TeV measurement*

PDF Sensitivity estimates

- The impact of PDF uncertainties on the weak mixing angle measurement is estimated by testing the effect of using a given PDF set in the measurement while fitting pseudo data generated with a different PDF set
- Including only statistical uncertainties in the fit

Generated pseudodata	PDFs used for interpretation of A4 versus $\sin^2\theta_W$									
	Before PDF constraint					After PDF constraint				
	CT10	CT14	MMHT14	NNPDF31	epWZ16	CT10	CT14	MMHT14	NNPDF31	epWZ16
CT10	-	33	-8.	-7	130	-	-18	22	17	-52
CT14	-33	-	-42	-41	98	27	-	44	39	-36
MMHT14	9	41	-	2	137	-29	-35	-	-4	-70
NNPDF31	8	40	-1	-	136	-16	-28	8	-	-53
epWZ16	-139	-103	-148	-148	-	87	44	93	86	-

PDF Sensitivity estimates

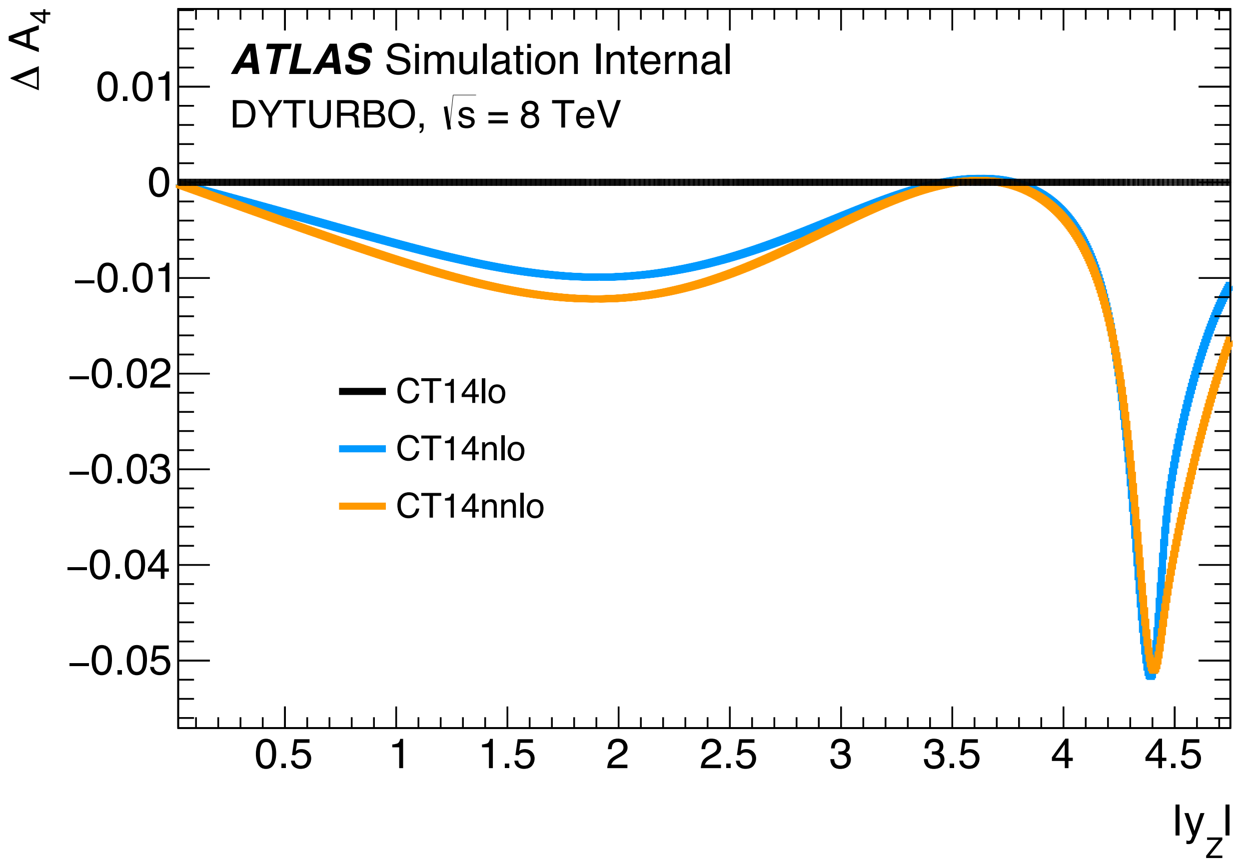


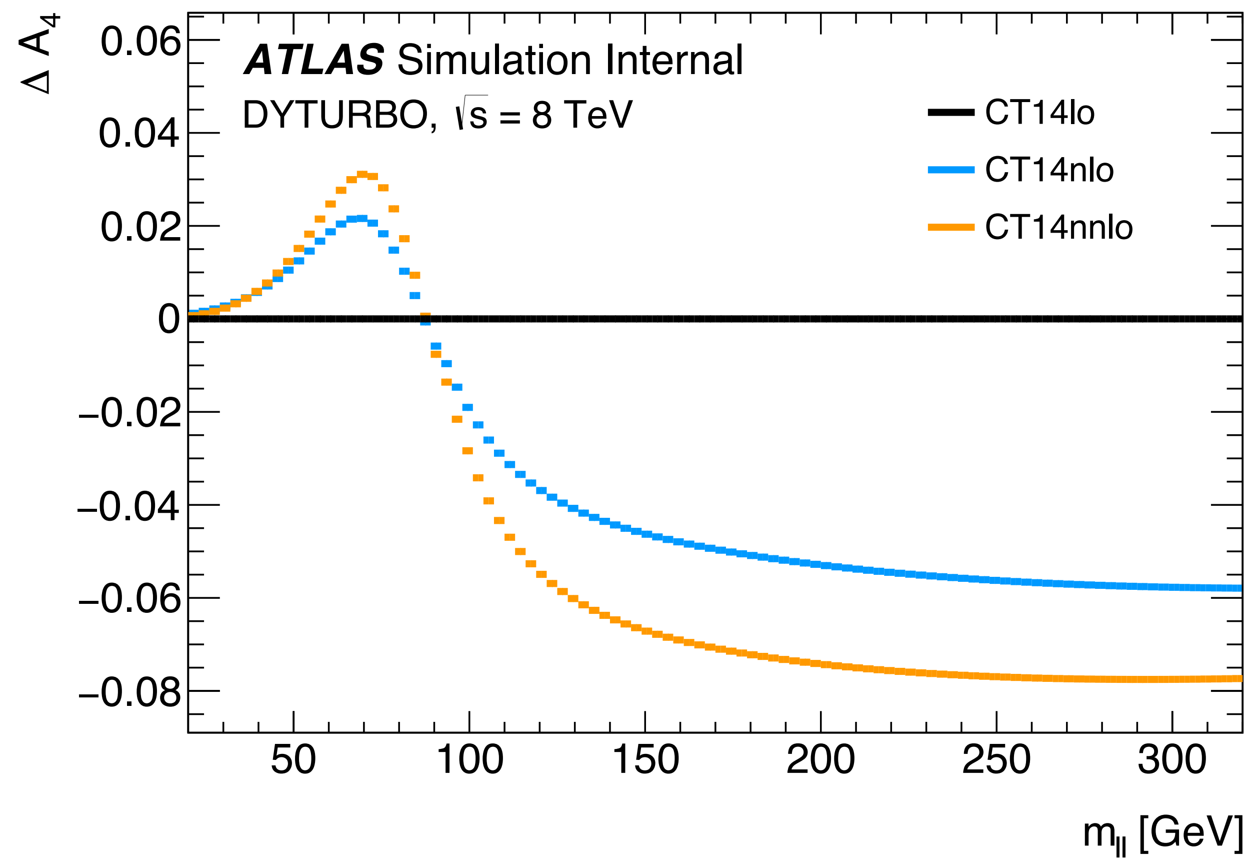
Summary

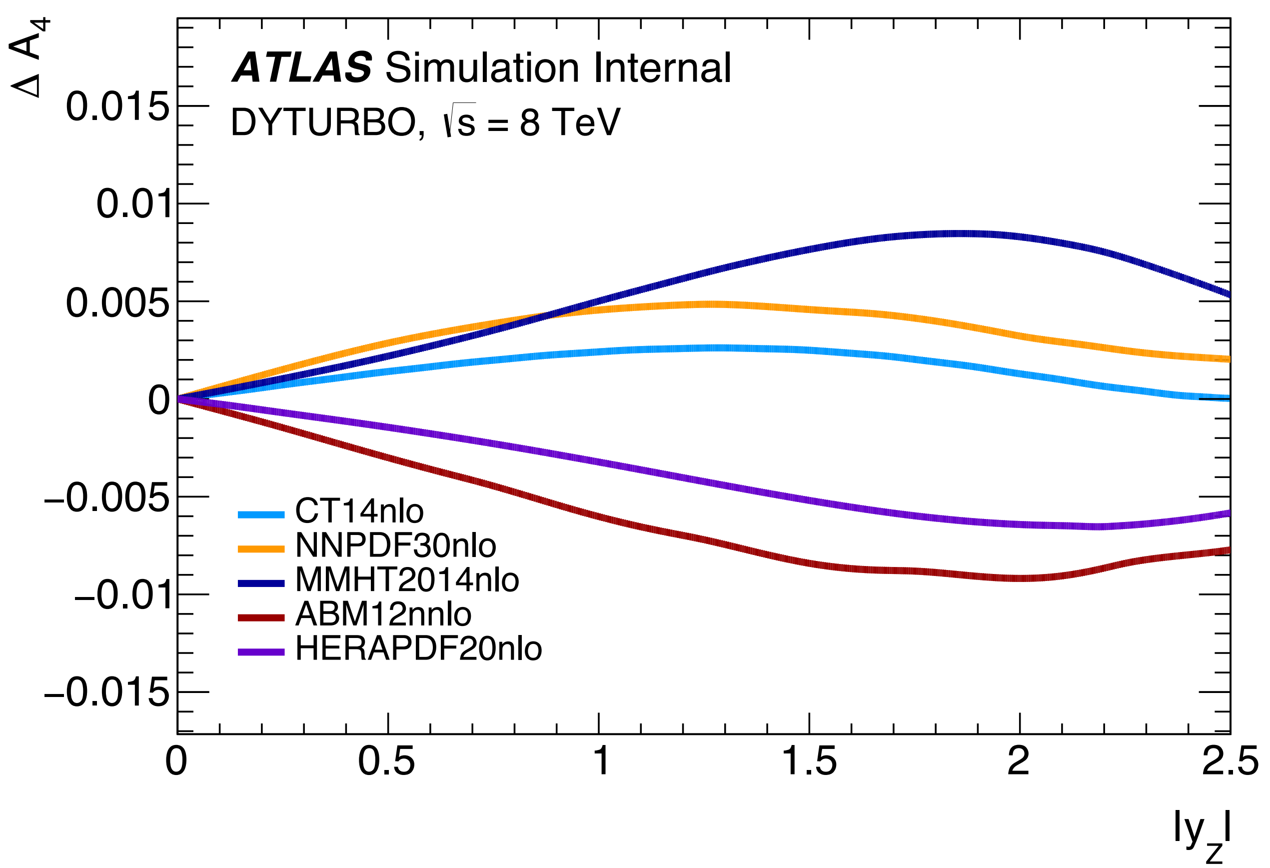
- The 8TeV measurement of $\sin^2\theta_W$ from the Ai and Z3D may reach an overall sensitivity of about 40×10^{-5}
  - To be compared with the best single experiment precision of $30\ 10^{-5}$
  - Translates in an m_W uncertainty of 20 MeV comparable to the direct measurement
- Significant reduction of PDF uncertainties when making the measurement differential
  - Constraints mostly the valence quarks with a measurement orthogonal to the inclusive W, Z
  - Crucial to reduce the total uncertainty on $\sin^2\theta_W$
- Extending the measurement outside the peak region (80,100) requires extra work, and the EW corrections and their influence needs to be carefully evaluated

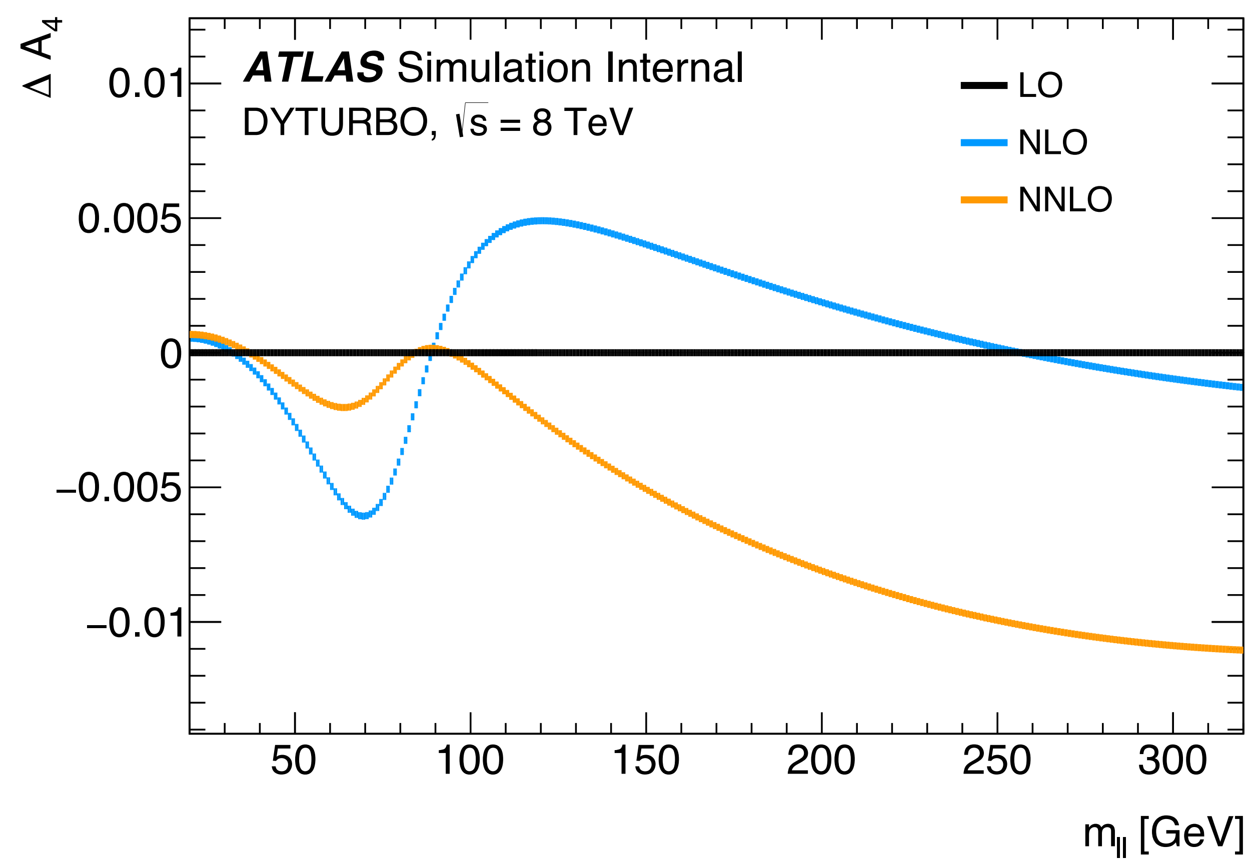
BACKUP

PDF sensitivity

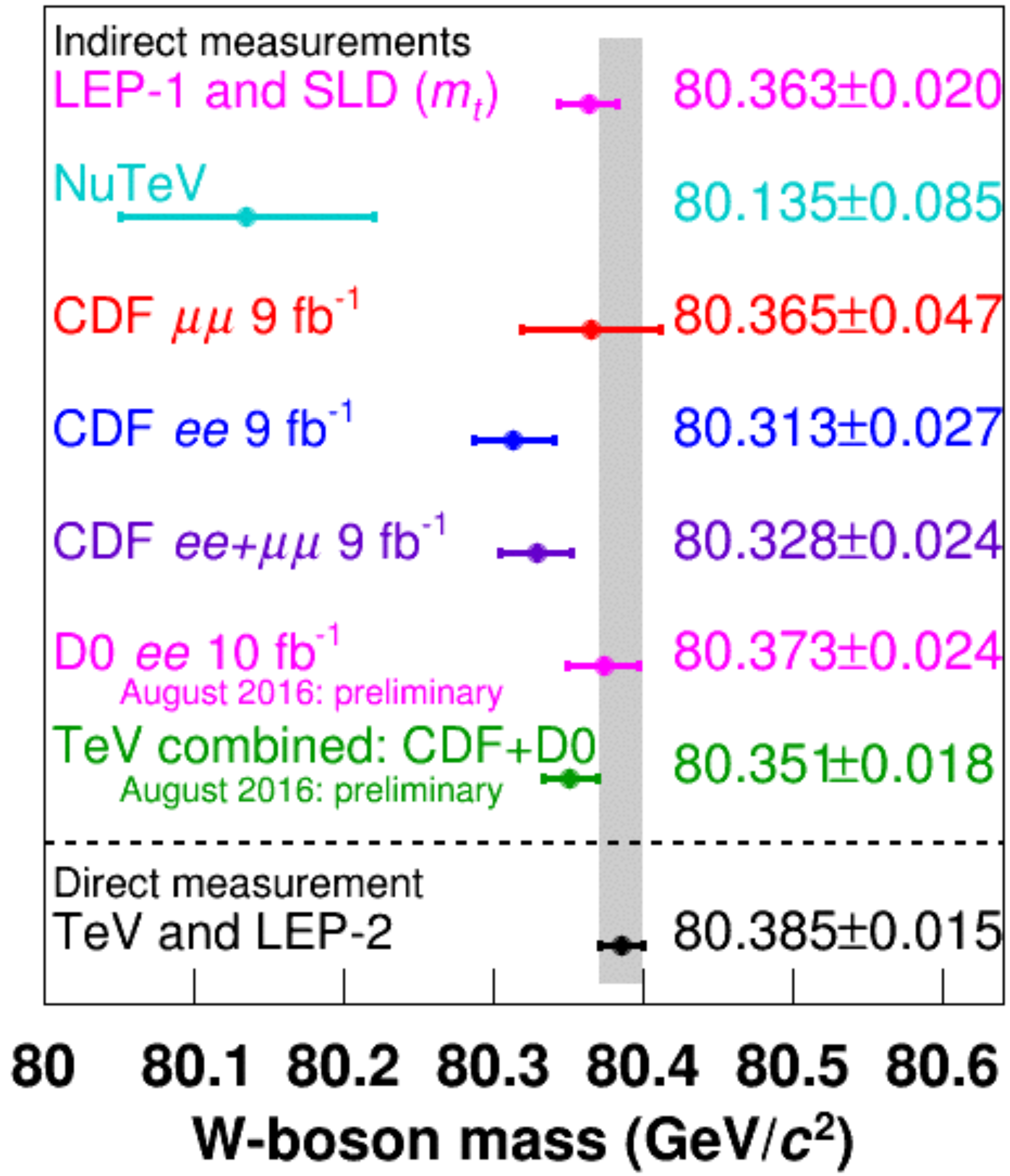




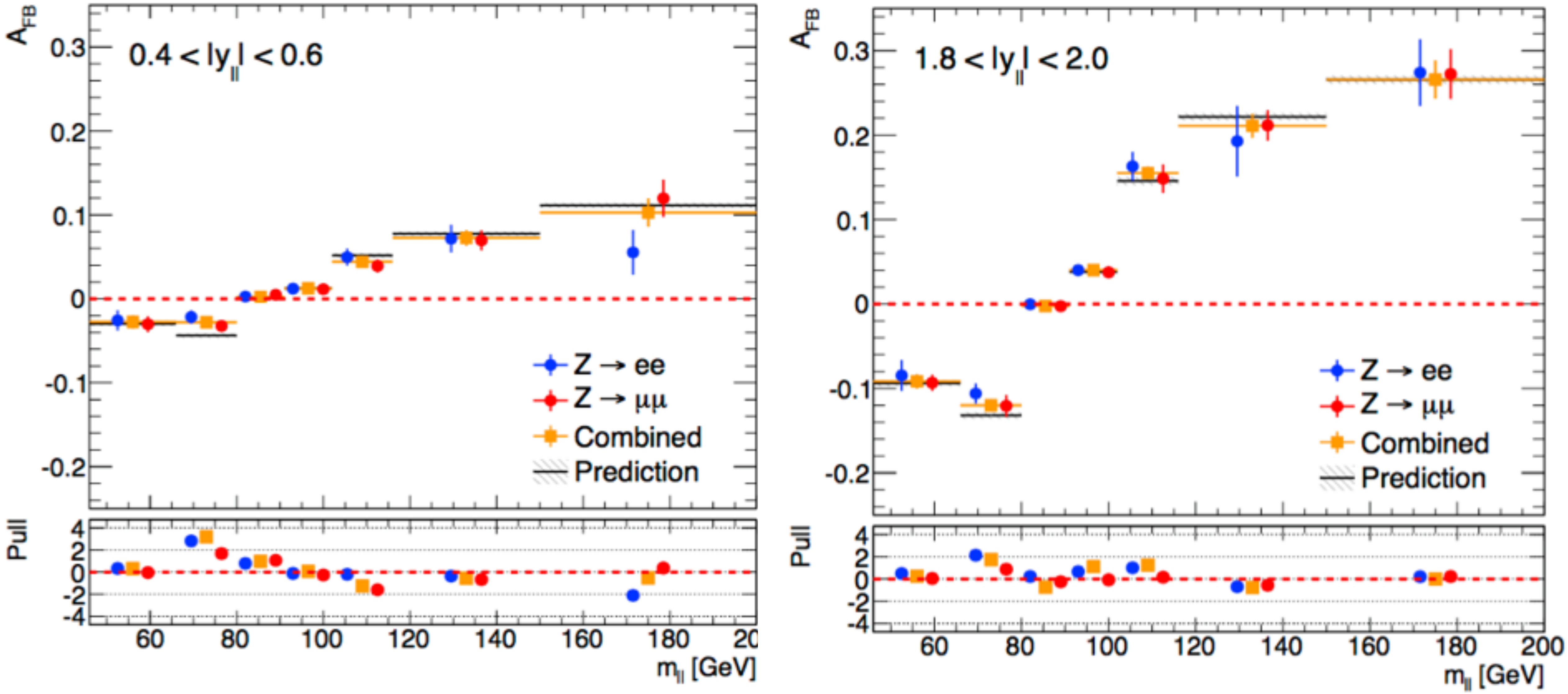




Indirect mW determination



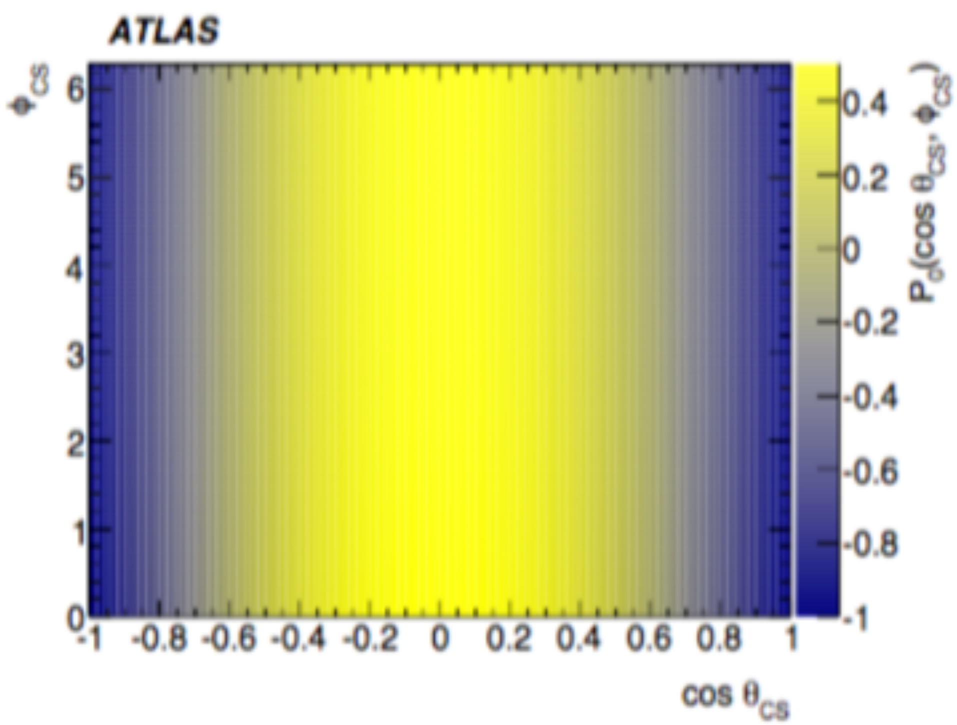
Z 3D

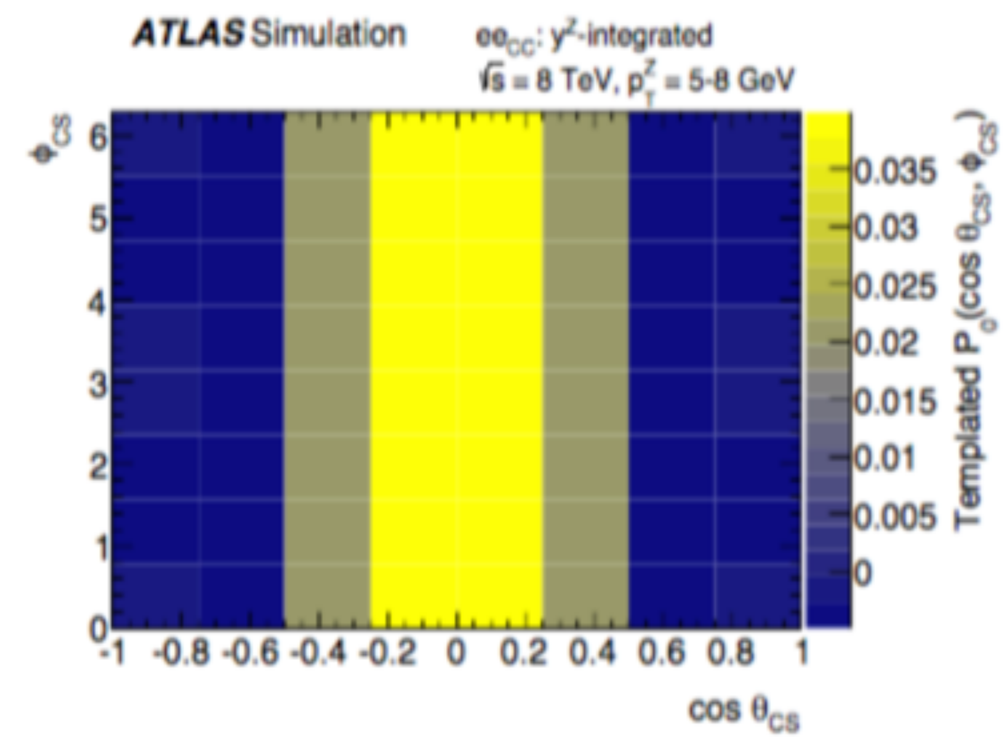


CC electrons only

	$\Delta \sin^2 \theta_W$
No PDF uncertainties	0.00052
With PDF uncertainties	0.00068

A_i coefficients are extracted from the shapes of the angular distributions exploiting the orthogonality of the P_i polynomials. The average value of the P_i polynomials relates to the A_i coefficients attached to them (moment method). Reference A_i are extracted from the full phase space and are then "folded" to the reco space using MC to model acceptance, efficiency and migrations (leptonic kinematic cuts heavily sculpt angular distributions):





Reference templates for each A_i are built in 23 p_T^Z bins (and in y^Z bins for detailed measurements). They are then fit to data to extract A_i coefficients in the full phase space.

Likelihood is built using folded polynomial and background templates.

Coefficient parameters

Background templates

$$\mathcal{L}(A_{ij},\sigma_j^{\Phi}|N) = \prod_{events}^{N}\left\{\sum_{j=1}^{23}\sigma_j^{\Phi}\alpha_j^{\Phi}L\left[t_{8,j}+\sum_{i=0}^{7}A_{ij}\times t_{ij}\right]+\sum_{B}^{bkgs}T_B+T_{Fakes}\right\}$$

Z pT normalization parameters

Folded polynomial templates

Fit is performed to the data to extract:

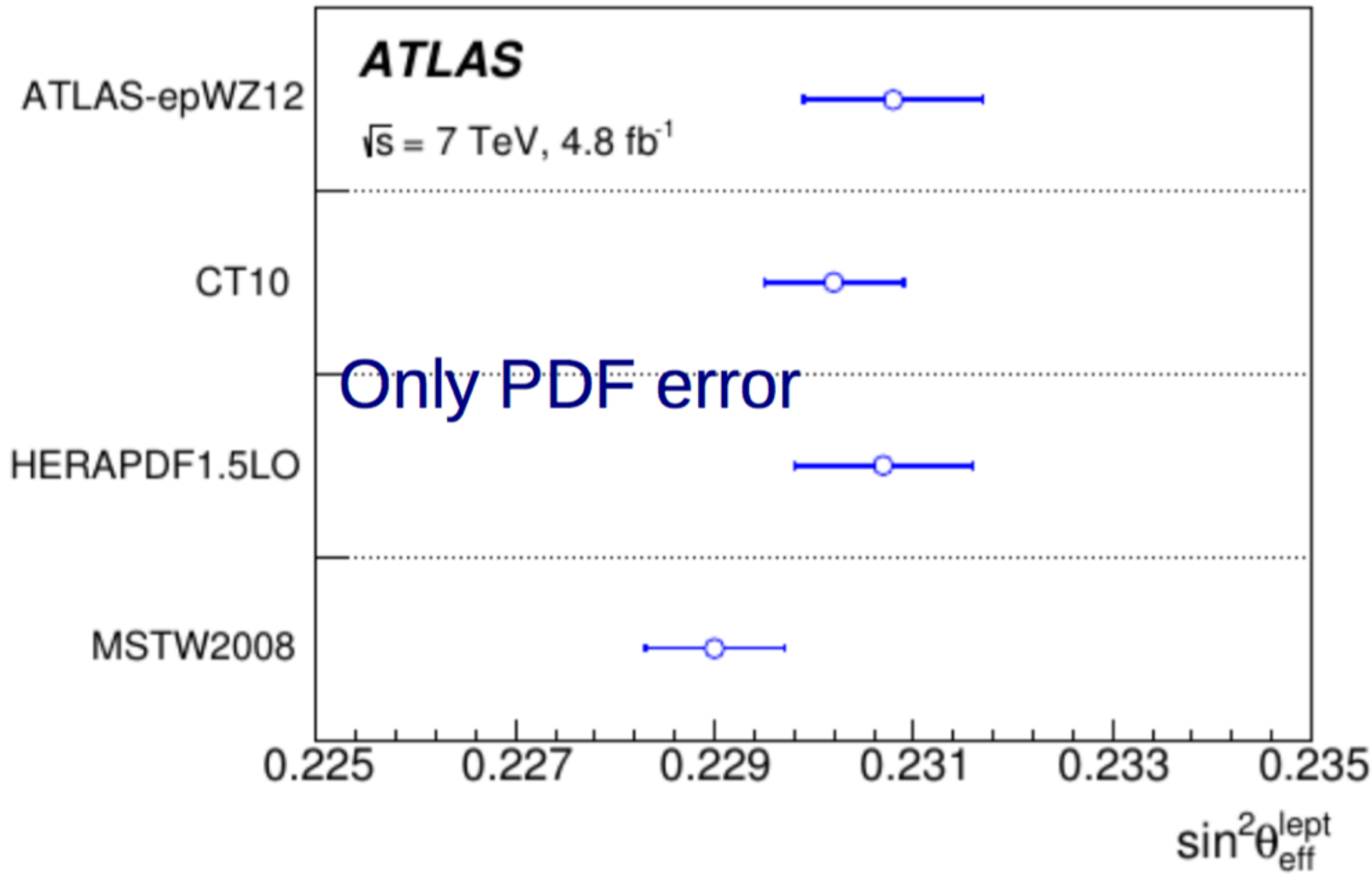
- A_i coefficients (8 in 23 p_T^Z bins),
- σ_j normalization parameters (23 p_T^Z bins):
  - σ_j scale all signal templates for each p_T^Z bin,
  - σ_j measure differential cross section in full phase space,
  - σ_j could be reparametrized to extract differential cross section normalized to the total cross section $(1/\sigma d\sigma/dp_T)$.

Systematics differences: A_i is a ratio of cross sections in one p_T^Z bin. Overall acceptance uncertainties will impact the cross section while only uncertainties on the acceptance shape in $cos\theta \times \phi$ will impact the A_i. The relative cross section is also a ratio of cross sections, but the denominator spans the entire p_T^Z range, while again an A_i is defined in a single p_T^Z bin, so this will cause some difference in the systematics between the relative cross section and an A_i.

CDF - EBA

If the EBA EW radiative corrections are included, the extracted value of $\sin^2\theta_{\rm eff}^{\rm lept}(M_Z)$ is higher by $+0.00023$ than the value extracted with no EW radiative corrections. About $+0.00008$ originate from accounting for the flavor dependence of $\sin^2\theta_{\rm eff}^{\rm lept}(M)$, $+0.00006$ originates from accounting for the mass dependence of $\sin^2\theta_{\rm eff}^{\rm lept}(M)$, and $+0.00009$ originate from accounting for the mass dependent complex EW Fitter form factors.

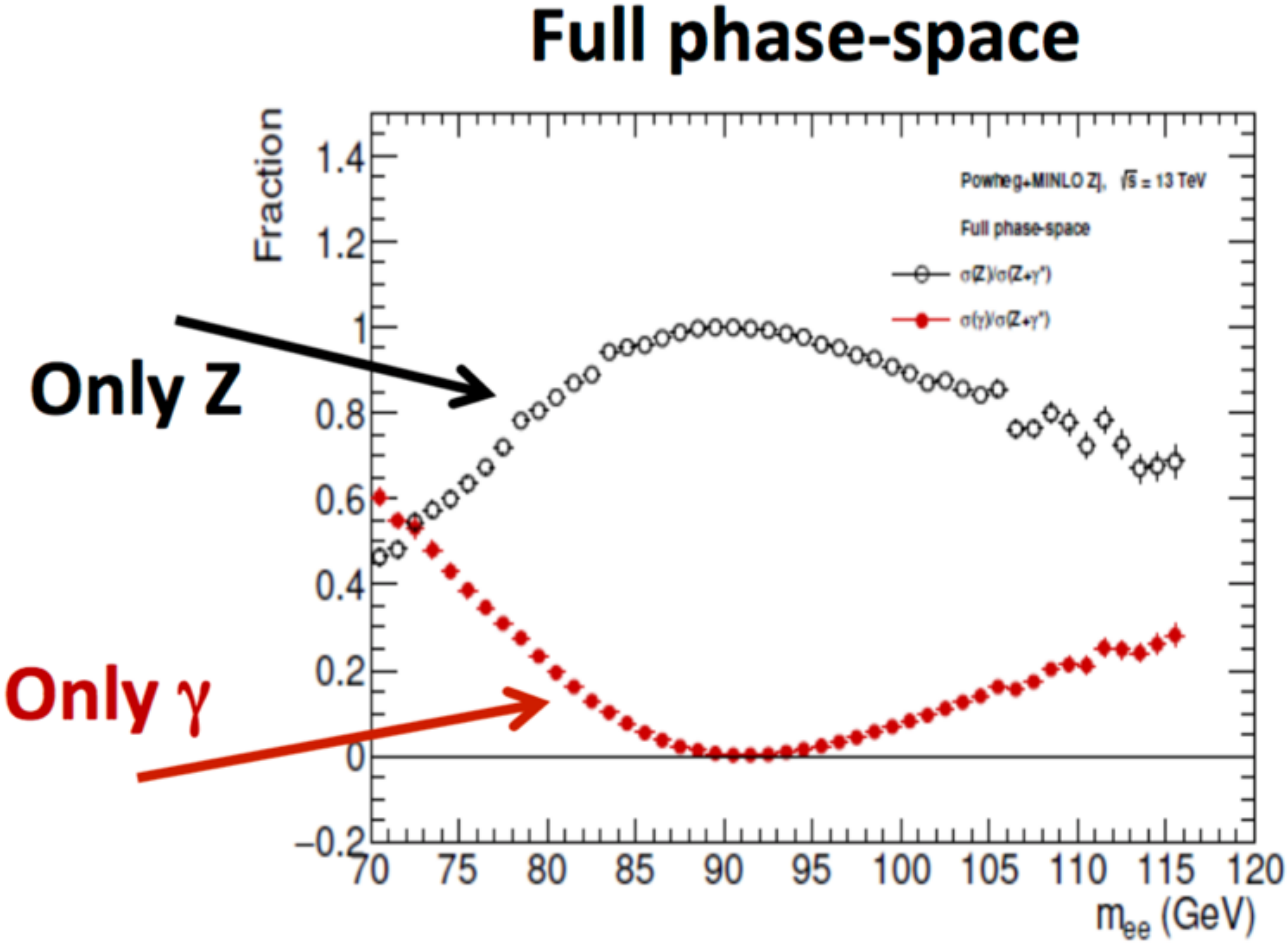
ATLAS PDF ERRORS



ATLAS breakdown

Uncertainty source	CC electrons [10^{-4}]	CF electrons [10^{-4}]	Muons [10^{-4}]	Combined [10^{-4}]
PDF	10	10	9	9
MC statistics	5	2	5	2
Electron energy scale	4	6	–	3
Electron energy resolution	4	5	–	2
Muon energy scale	–	–	5	2
Higher-order corrections	3	1	3	2
Other sources	1	1	2	2

Z-gamma* contribution



CDF COMBINED

TABLE V. Extracted values of $\sin^2\theta_{\mathrm{eff}}^{\mathrm{lept}}$ and $\sin^2\theta_W$ after averaging over the NNPDF-3.0 ensembles. The "weighted" templates denote the w_k-weighted ensembles; and $\delta\sin^2\theta_W$ is the PDF uncertainty. The uncertainties of the electroweak-mixing parameters are the measurement uncertainties $\bar{\sigma}$. For the $\bar{\chi}^2$ column, the number in parentheses is the number of mass bins of the A_{fb} measurement. The ee-channel values are from Table III, and the $\mu\mu$-channel values use the previous CDF measurement of A_{fb} with $\mu^+\mu^-$ pairs [6].

Template	Channel	$\sin^2\theta_{\mathrm{eff}}^{\mathrm{lept}}$	$\sin^2\theta_W$	$\delta\sin^2\theta_W$	$\bar{\chi}^2$
POWHEG-BOX NLO, default	$\mu\mu$	0.23140 ± 0.00086	0.22316 ± 0.00083	± 0.00029	21.0(16)
POWHEG-BOX NLO, weighted	$\mu\mu$	0.23141 ± 0.00086	0.22317 ± 0.00083	± 0.00028	20.7(16)
POWHEG-BOX NLO, default	ee	0.23249 ± 0.00049	0.22429 ± 0.00048	± 0.00020	15.9(15)
POWHEG-BOX NLO, weighted	ee	0.23248 ± 0.00049	0.22428 ± 0.00048	± 0.00018	15.4(15)
POWHEG-BOX NLO, default	$ee+\mu\mu$	0.23222 ± 0.00043	0.22401 ± 0.00041	± 0.00021	38.3(31)
POWHEG-BOX NLO, weighted	$ee+\mu\mu$	0.23221 ± 0.00043	0.22400 ± 0.00041	± 0.00016	35.9(31)
Tree LO, default	$\mu\mu$	0.23154 ± 0.00085	0.22330 ± 0.00082	± 0.00031	20.9(16)
Tree LO, weighted	$\mu\mu$	0.23153 ± 0.00085	0.22329 ± 0.00082	± 0.00029	20.5(16)
Tree LO, default	ee	0.23252 ± 0.00049	0.22432 ± 0.00047	± 0.00021	22.4(15)
Tree LO, weighted	ee	0.23250 ± 0.00049	0.22430 ± 0.00047	± 0.00021	21.5(15)
Tree LO, default	$ee+\mu\mu$	0.23228 ± 0.00042	0.22407 ± 0.00041	± 0.00023	44.4(31)
Tree LO, weighted	$ee+\mu\mu$	0.23215 ± 0.00043	0.22393 ± 0.00041	± 0.00016	37.4(31)

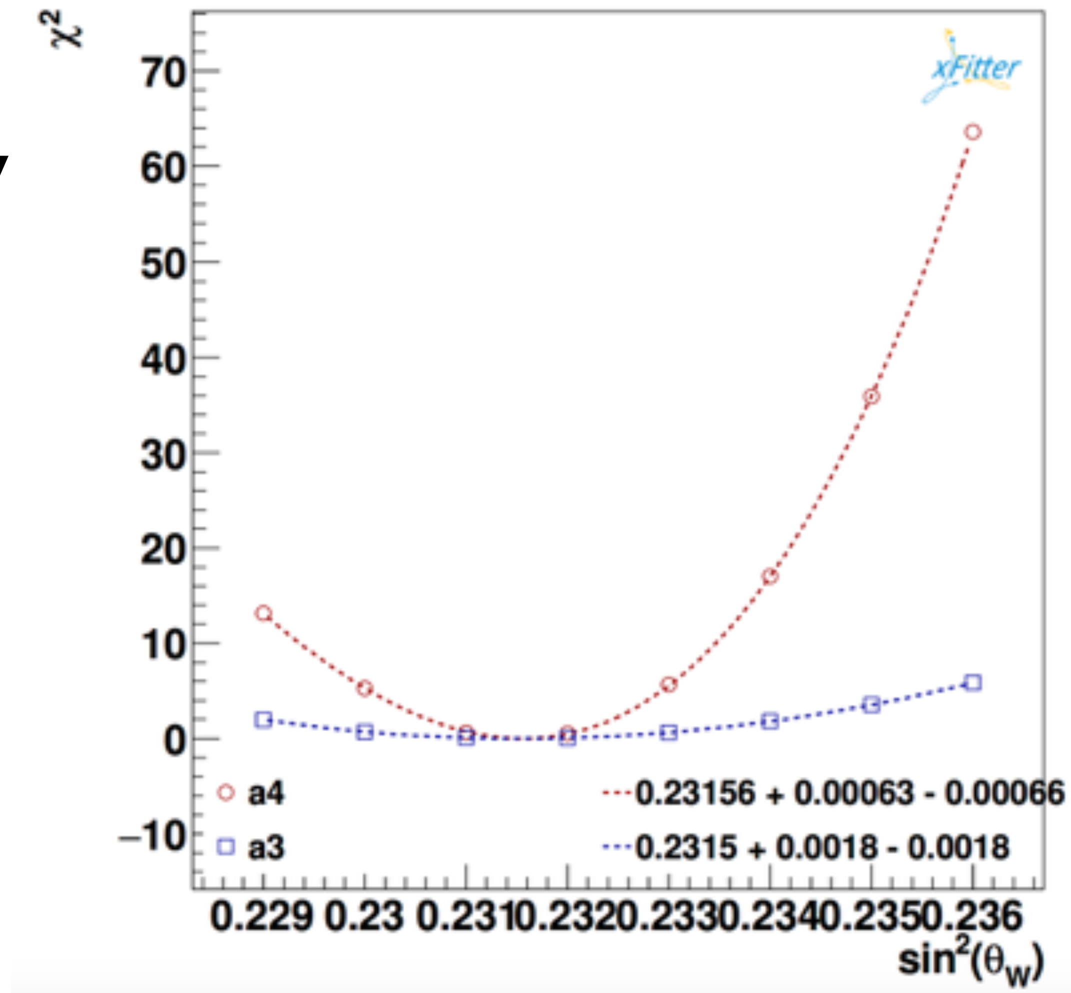
CDF combined

TABLE VI. Summary of the systematic uncertainties on the $\mu\mu$- and ee-channel combination for the electroweak-mixing parameters $\sin^2\theta_{\mathrm{eff}}^{\mathrm{lept}}$ and $\sin^2\theta_W$.

Source	$\sin^2\theta_{\mathrm{eff}}^{\mathrm{lept}}$	$\sin^2\theta_W$
Energy scale	± 0.00002	± 0.00002
Backgrounds	± 0.00003	± 0.00003
NNPDF-3.0 PDF	± 0.00016	± 0.00016
QCD scale	± 0.00006	± 0.00007
Form factor	$\cdots$	± 0.00008

Extraction from published A4

* Performed a test extraction of the s2w from the published values of A4 as function of pTZ
  * Using XFitter for chi2 minimisation
  * Predictions at each value of $\sin^2\theta_W$ from DYTURBO (LO) with CT10nlo



Source	a4	a3
Experimental	±0.00042	±0.00175
PDFs	±0.00047	±0.00048
QCD scales	±0.00008	±0.00008
Total (decomposed)	±0.00064	±0.00182
Total (from fit)	±0.00065	±0.00181

The full covariance matrix of the data is used, but no splitting into different sources of uncertainty.

Not possible to correlate the PDFs used in the measurement and those for the extraction.