A precise ATLAS measurement of $\sin^2\theta_W$

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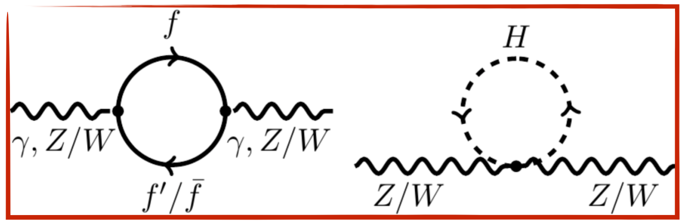
Introduction

- 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

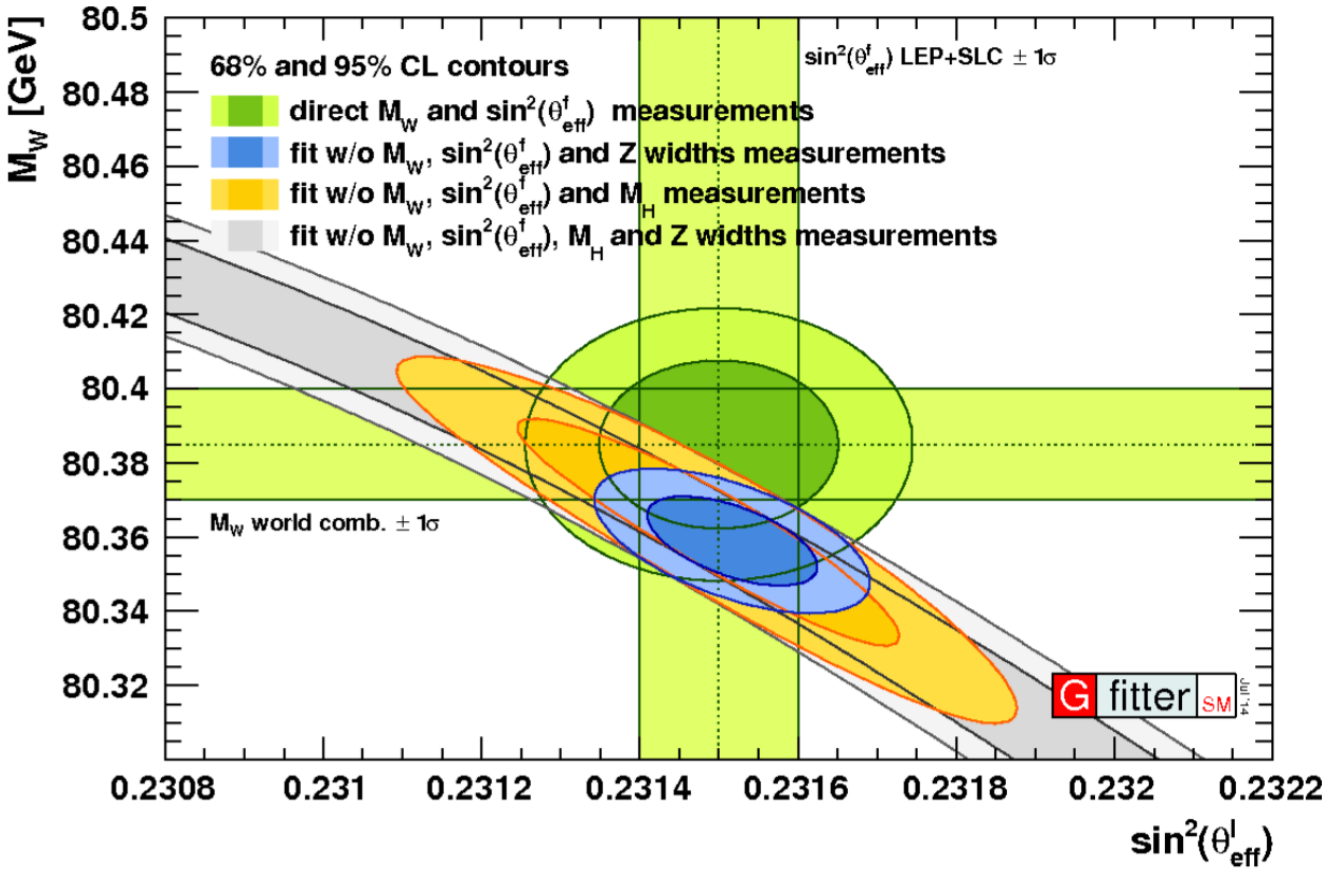
$$M_W^2 = \frac{M_Z^2}{2}\left(1 + \sqrt{1 - \frac{\sqrt{8\pi\alpha(1-\Delta r)}}{G_F M_Z^2}}\right)$$



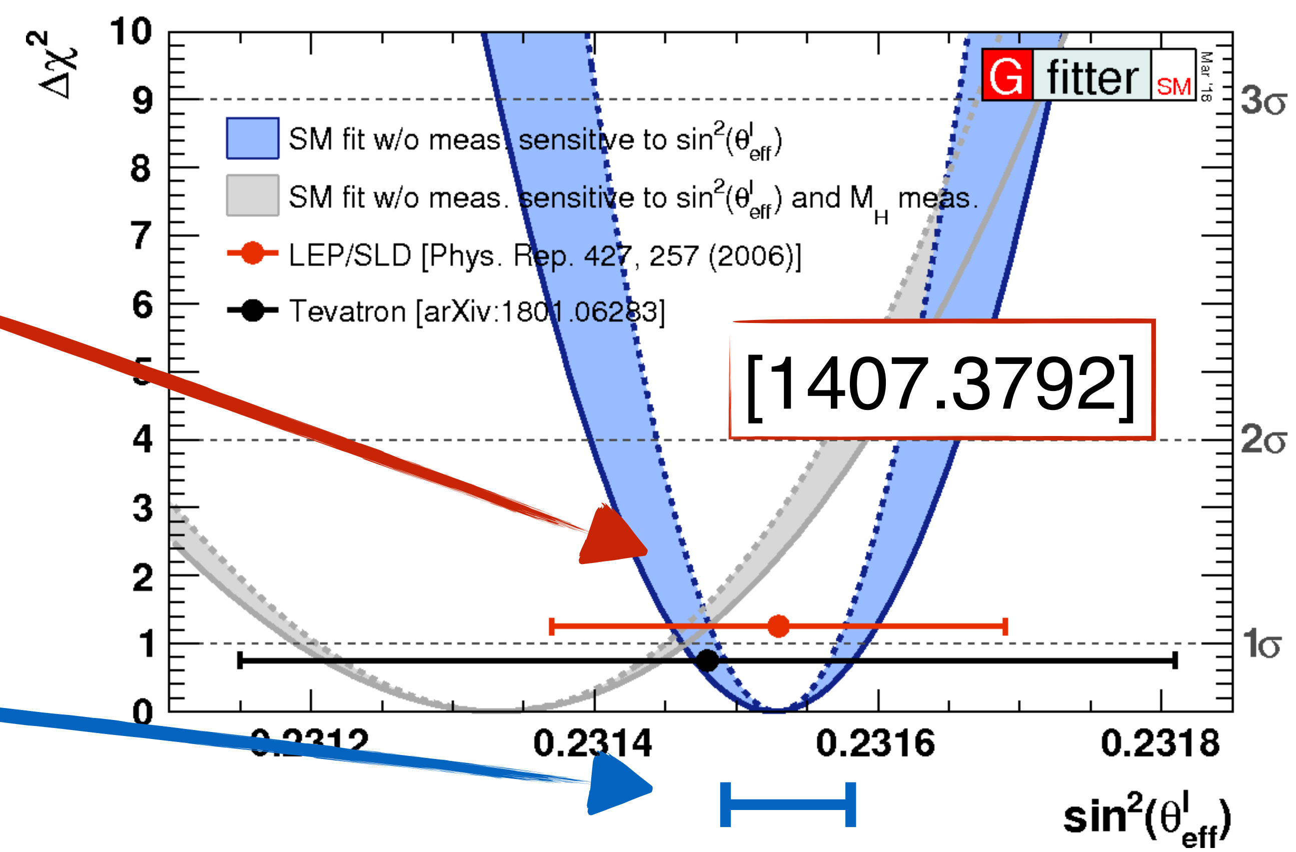
$$\sin^2\theta^f_{\text{eff}} = \kappa^f_Z \sin^2\theta_W \qquad g_{V,f} = \sqrt{\rho^f_Z}\left(I^f_3 - 2Q^f \sin^2\theta^f_{\text{eff}}\right) \qquad g_{A,f} = \sqrt{\rho^f_Z} I^f_3$$

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

The weak mixing angle



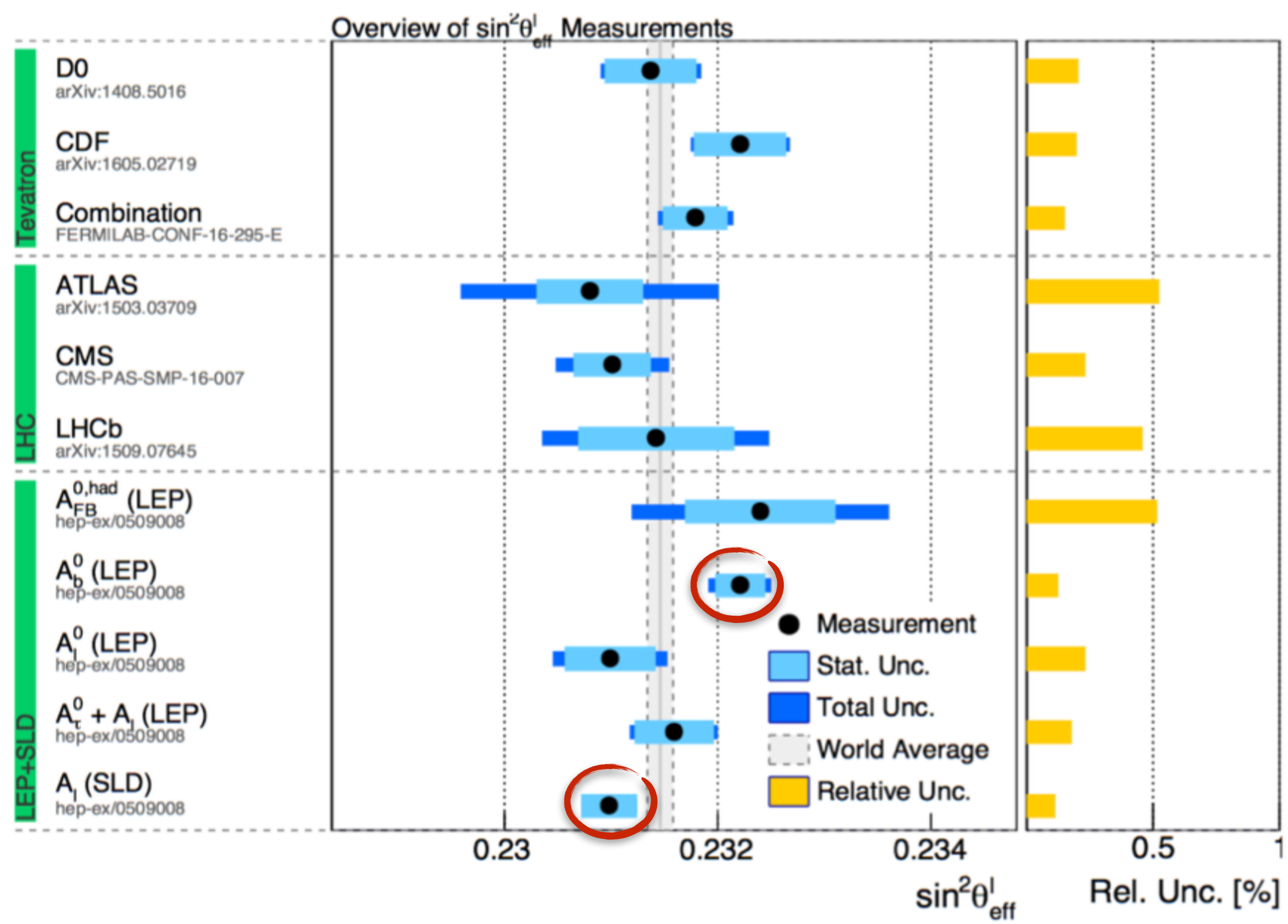
- The weak mixing angle in the SM parametrises the mixing between the EM and weak fields
- And provide and indirect determination of the W-boson mass



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

Current Measurements

- The WMA has been precisely measured at LEP and SLD
  - Precision reaching 26 (29) x 10^{-5} for LEP (SLD)
  - But the two most precise determinations ($A_{FB}^{0,b}$ at LEP and A_l^{LR} at SLD) show a *three sigma tension* with each other
- Several measurements at hadron colliders
  - Tevatron combination reaches uncertainty of 33×10^{-5}; 2.6% compatibility of the measurements
  - ATLAS 7 TeV 120×10^{-5}
  - LHCb 7+8 TeV 106×10^{-5}
  - CMS 8 TeV 52×10^{-5}



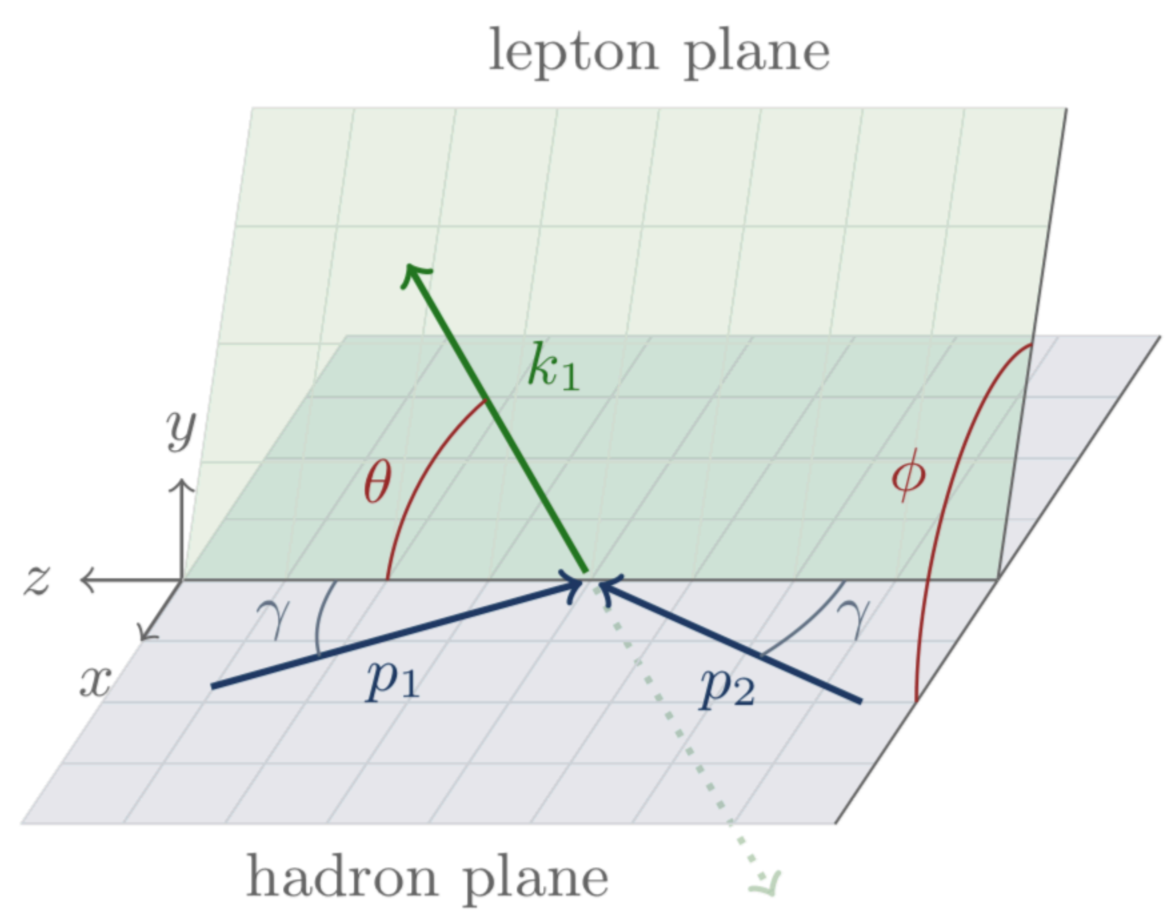
- A WMA determination with a comparable precision to LEP and SLD (30×10^{-5}) would have important implications for the global electroweak fit

How to measure it

- Presence of vector and axial-vector couplings introduces a forward-backward asymmetry. This is a parton-level effect that we measure at proton level

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

- Measured using the Collins-Soper frame: Z boson at rest, z-axis bisecting the direction of the initial state protons
- At the LHC this z-axis assignment has a two-fold ambiguity as we don't know which proton the quark came from.
- Choose the z-axis sign as sign of the (lab-frame) z-momentum of the Z boson candidate



The Ai formalism

- The Drell-Yan lepton angular distribution in boson rest frame can be decomposed into nine terms
  - An unpolarised cross-section and nine helicity amplitudes describing the polarisation state of a spin-1 particle

$$\frac{d\sigma}{dp_T^Z\, dy^Z\, dm^Z\, d\cos\theta\, d\phi} = \frac{3}{16\pi}\frac{d\sigma^{U+L}}{dp_T^Z\, dy^Z\, dm^Z}$$

unpolarised cross-section

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

sensitive to QCD

$$\{(1+\cos^2\theta) + \frac{1}{2} A_0 (1 - 3\cos^2\theta) + A_1 \sin 2\theta \cos\phi$$

sensitive to s2w

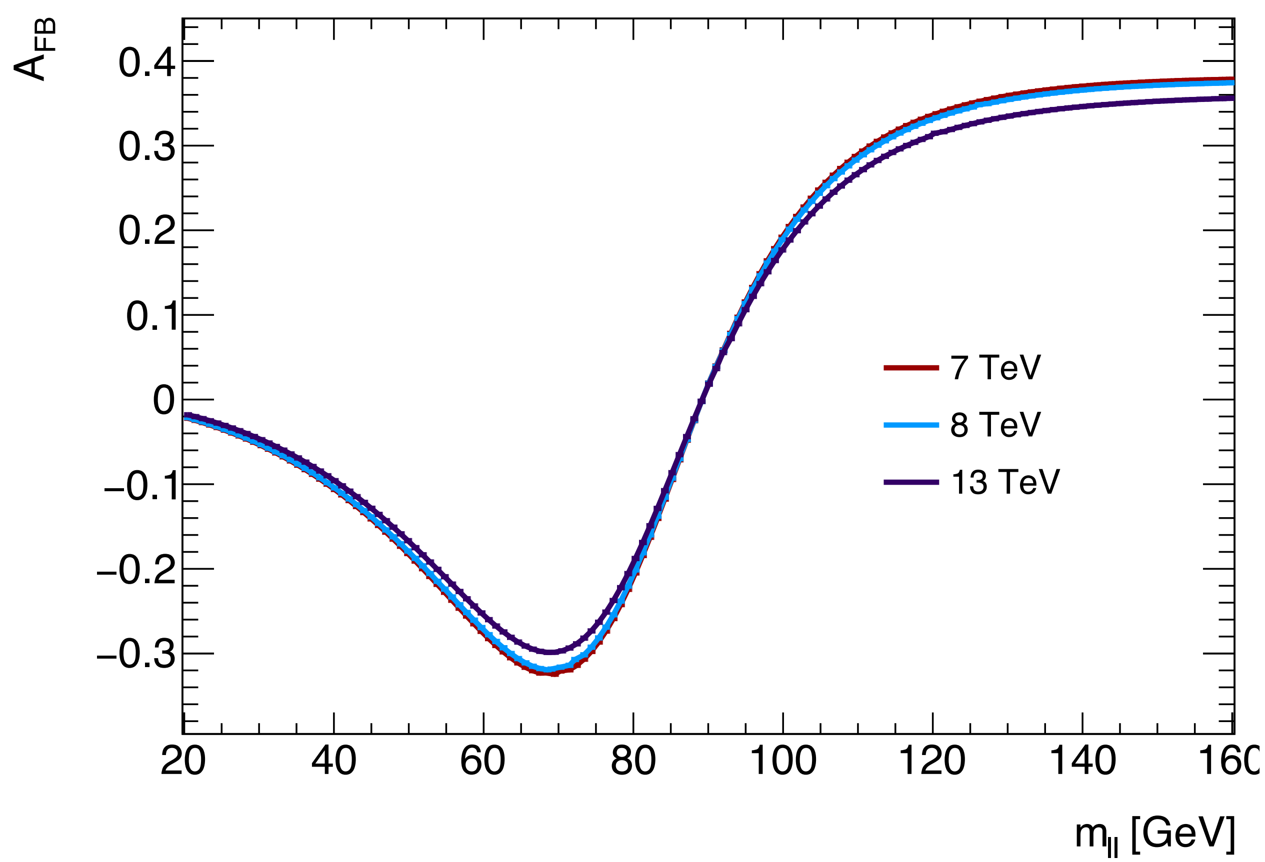
$$+ \frac{1}{2} A_2 \sin^2\theta \cos 2\phi + A_3 \sin\theta \cos\phi + A_4 \cos\theta$$

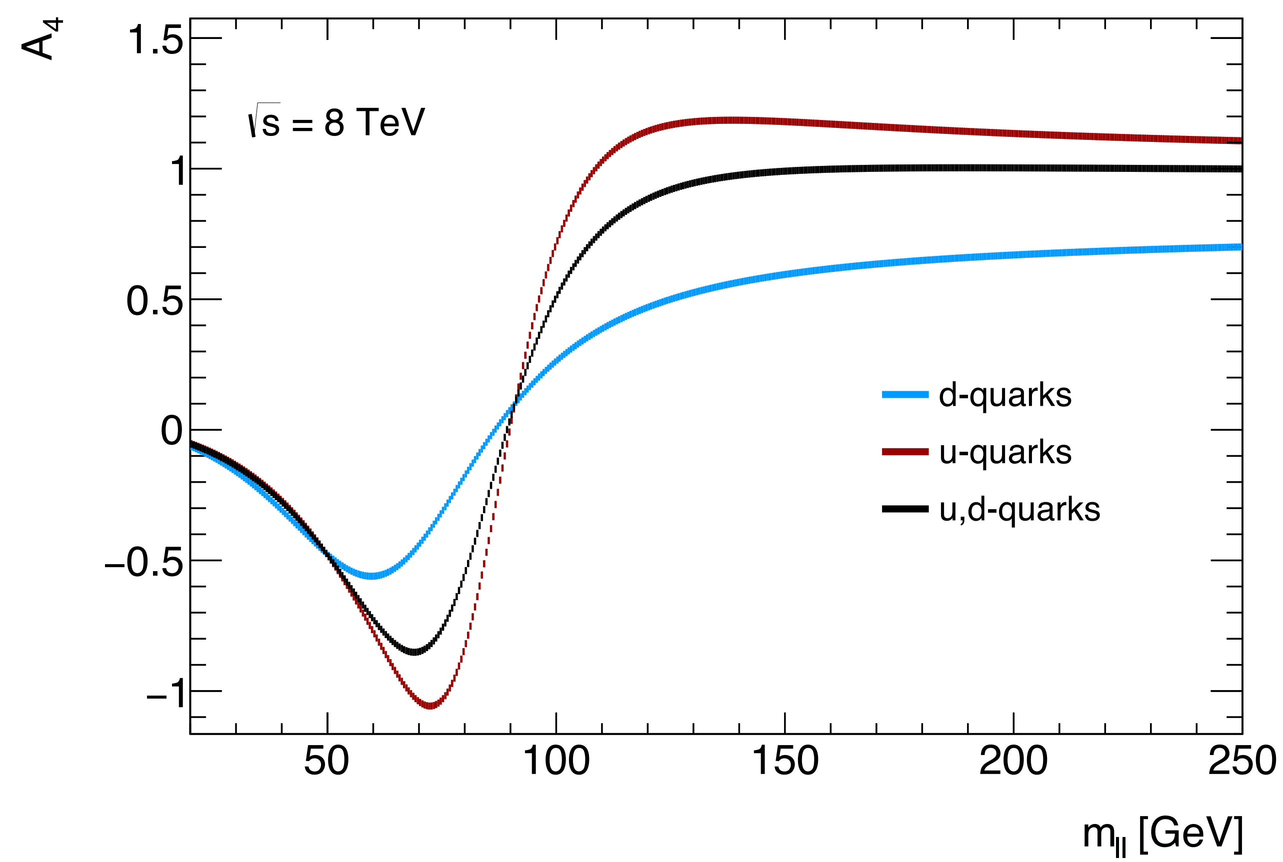
small terms

$$+ A_5 \sin^2\theta \sin 2\phi + A_6 \sin 2\theta \sin\phi + A_7 \sin\theta \sin\phi\}.$$

- The Ais encapsulate all of the QCD production dynamics
- A_{FB}=3/8 A_4 in full phase-space of the decay leptons to all orders in pQCD

PDFs and dilution



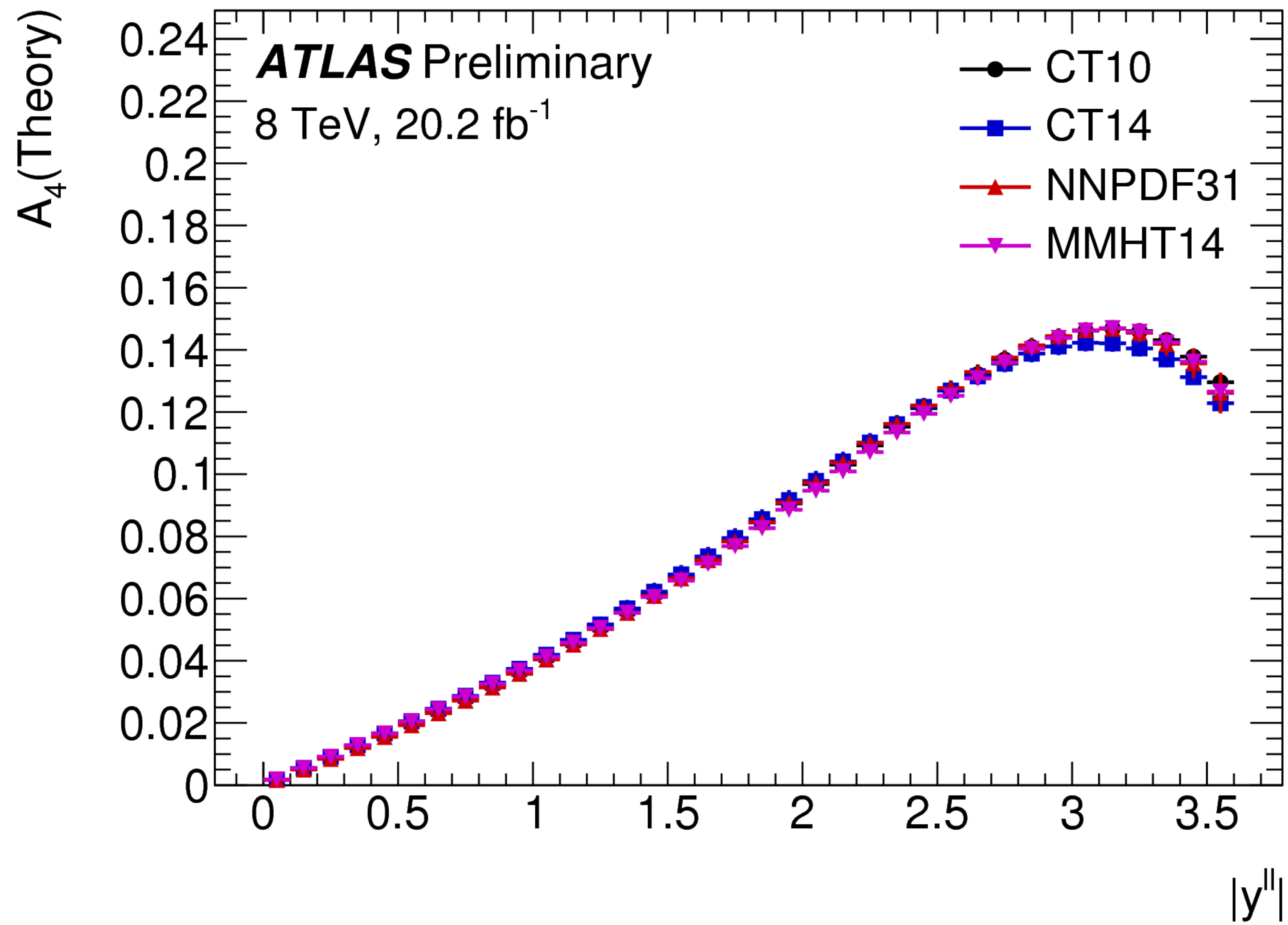


- Due to the ambiguity in the direction of the incoming quark there is a significant *dilution effect*, a reduction in the measured asymmetry, which increases with beam energy (more sea-quarks)
  - From events where the antiquark has a higher x than the quark
  - And since A_{FB} for u- and d-quarks are different
  - Also dilution from s-sbar and c-cbar events which have no asymmetry
- These effects are obviously strongly dependent on the PDFs

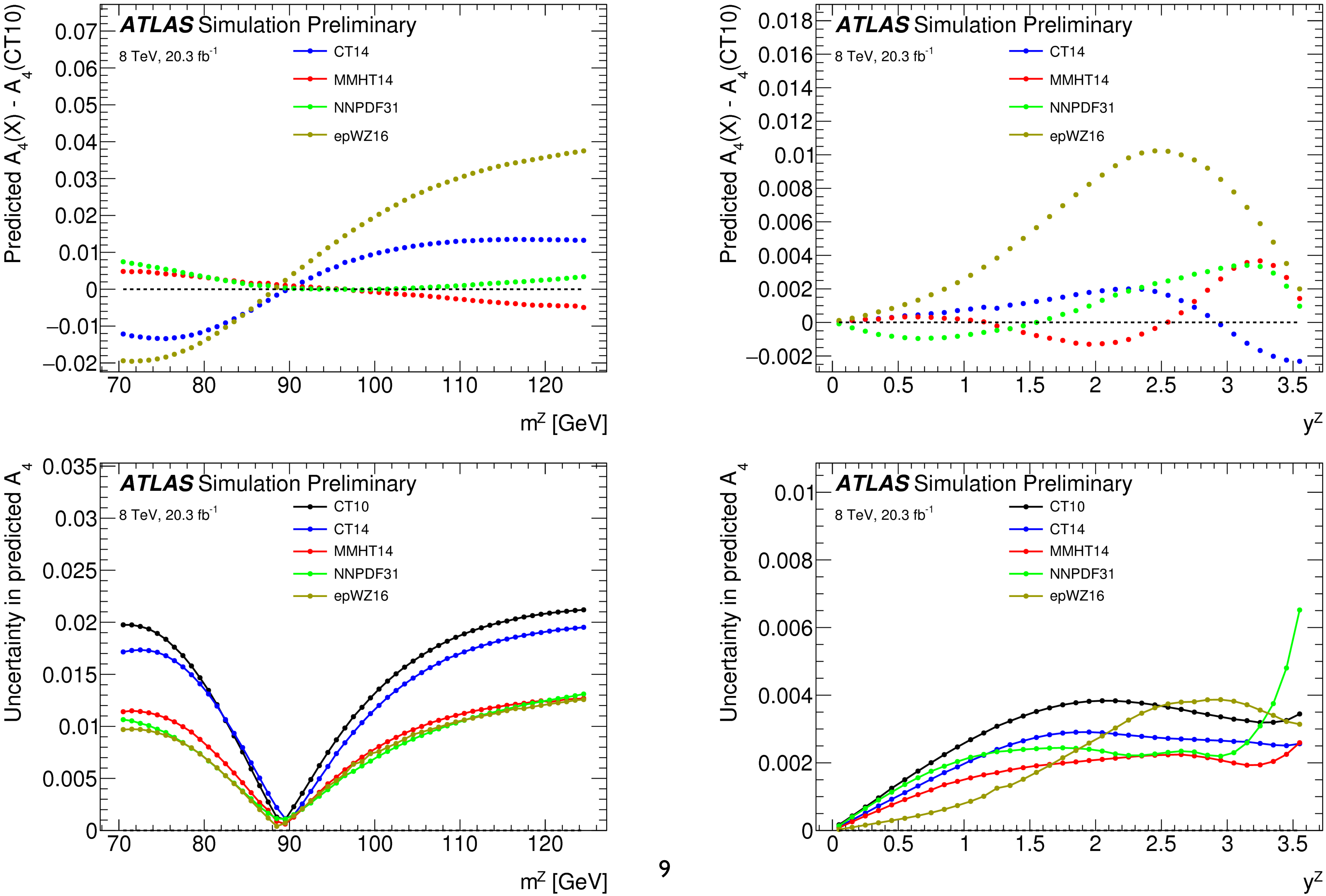
A_{FB} - RAPIDITY

* The AFB and $\sin^2\theta_W$ sensitivity to increases at high Z rapidities

  - In this region collisions involve a high-x parton and a low-x parton; the high-x parton has high change to be a valence quark, and the low-x parton the anti-quark
  - Reduced dilution from ambiguity in the sign of the z-axis

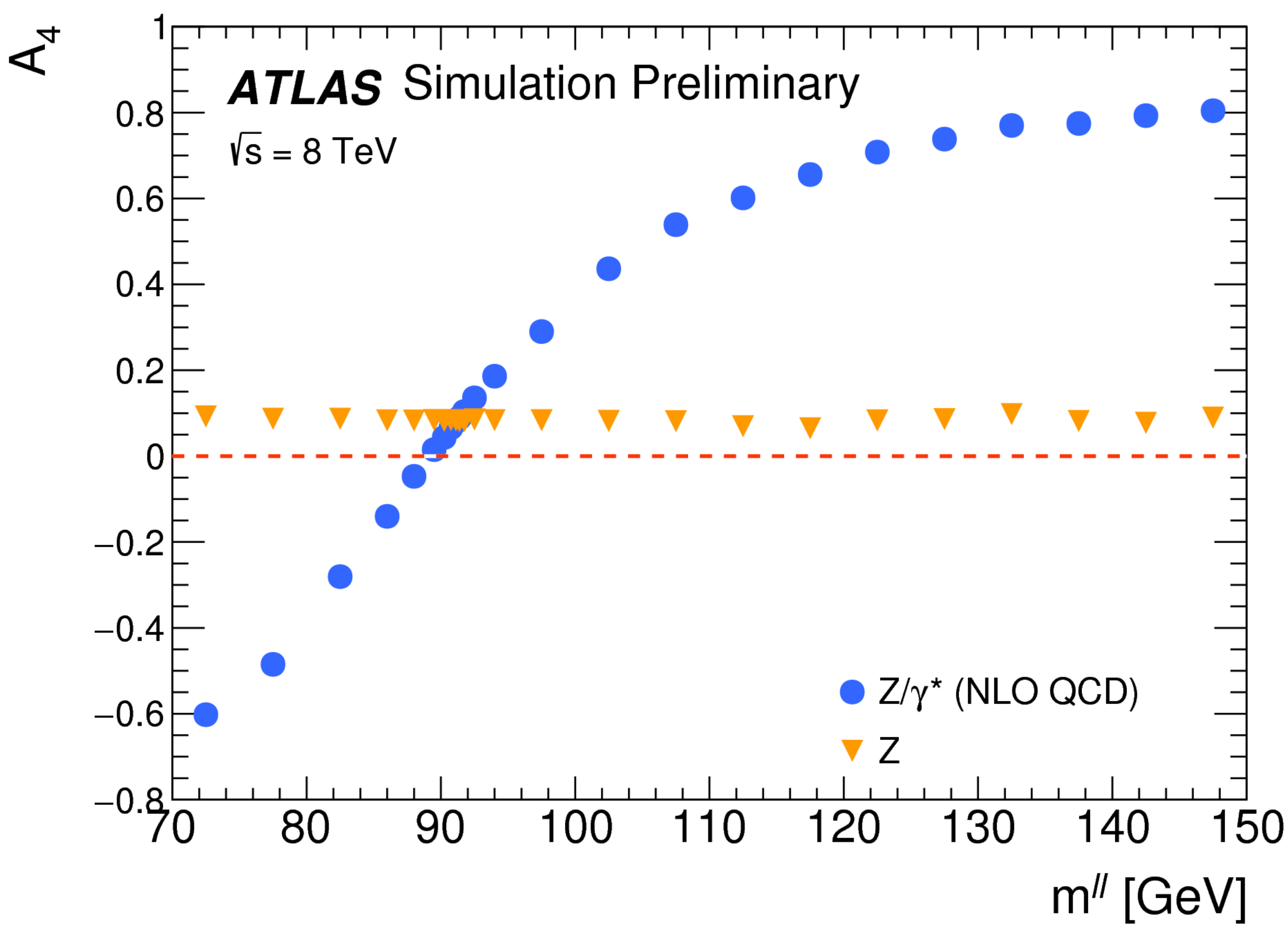


PDF sensitivity



A_{FB} - Mass dependence

- The A_{FB} (shown here for A4) has a strong dependence on m_{ll}
  - Driven by the interference between the Z and γ^* contribution
- The contribution to A_{FB} from the weak mixing angle is small and constant



- Most of the sensitivity to $\sin^2\theta_W$ is coming from the peak region
- Can use the mass dependence to constrain PDFs (see later)

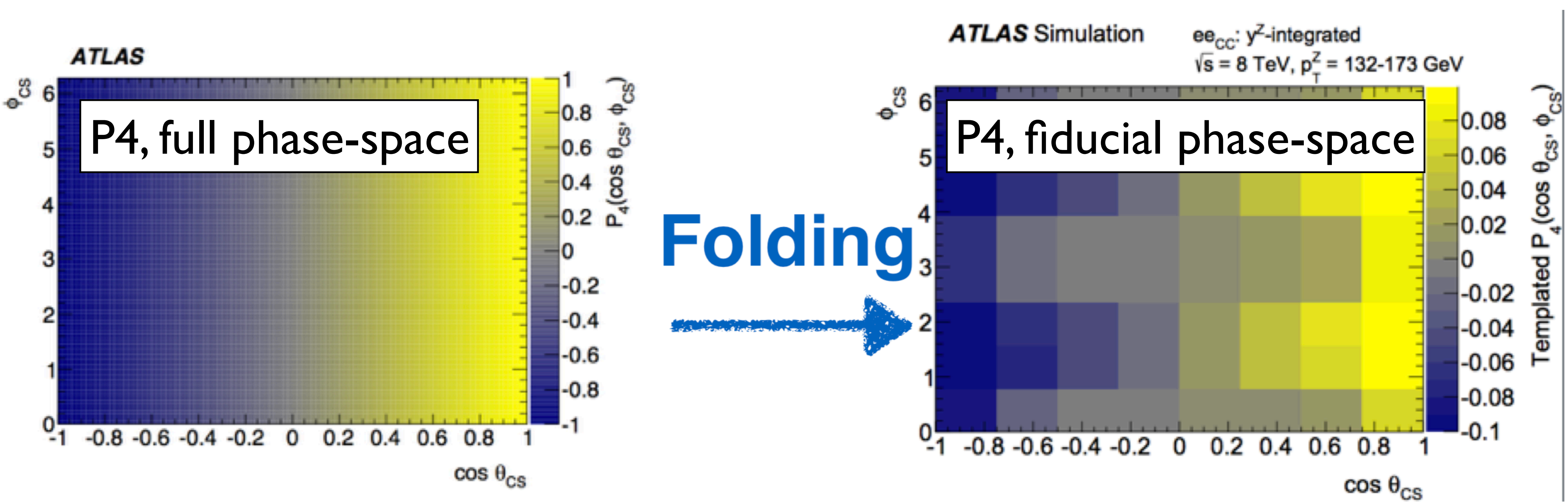
ATLAS 8TeV measurements

- 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 $\sin^2\theta_W$ is in A_{FB}
- [1606.00689] Measurement of the angular coefficients in *Z*-boson events using electron and muon pairs from data taken at sqrt(*s*) = 8 TeV with the ATLAS detector
  - Reduced sensitivity to uncertainties from extrapolation
  - Possibly more sensitive than A_{FB} to NLO EW effect that break the harmonic decompositions

The Ai measurement

- Three leptonic channels (ee^{CC}, ee^{CF}, $\mu\mu^{CC}$) and 12 analysis bins: m_Z = [70, 80, 100, 125], y_Z = [0, 0.8, 1.6, 2.5, 3.6]

- For a given point in lepton kinematics the fiducial lepton selections (p_T^Z, m^Z, y^Z) map 1 - 1 in $\cos\theta$, ϕ
- Use MC to fold analytical acceptance within the analysis bins to detector level
- Fit the reconstructed angular distributions with the folded polynomials to obtain A_{0-7} and σ^{U+L} (8 $\cos\theta^*$x8ϕ bins)



Backgrounds

- Very small amount of backgrounds
  - 0.1% for CC, 2% for CF at the pole
- W+jets and multijets from data
  - Templates reverting ID criteria fitted to isolation variables
- EW and ttbar from MC
- Non fiducial signal also from MC
  - Events outside of the fiducial phase-space, entering through migration effects

eeCC

$\|y_{ll}\|$	Data	Top+EW	Multijets	Non-fiducial Z
	$70 < m_{ll} < 80$ GeV			
0-0.8	106 718	0.023	0.015	0.010
0.8-1.6	95 814	0.015	0.020	0.010
1.6-2.5	47 078	0.012	0.041	0.009
	$80 < m_{ll} < 100$ GeV			
0-0.8	2 697 316	0.003	0.001	< 0.001
0.8-1.6	2 084 856	0.002	0.001	< 0.001
1.6-2.5	839 424	0.002	0.002	< 0.001
	$100 < m_{ll} < 125$ GeV			
0-0.8	106 855	0.034	0.016	0.023
0.8-1.6	80 403	0.025	0.019	0.027
1.6-2.5	28 805	0.015	0.025	0.029

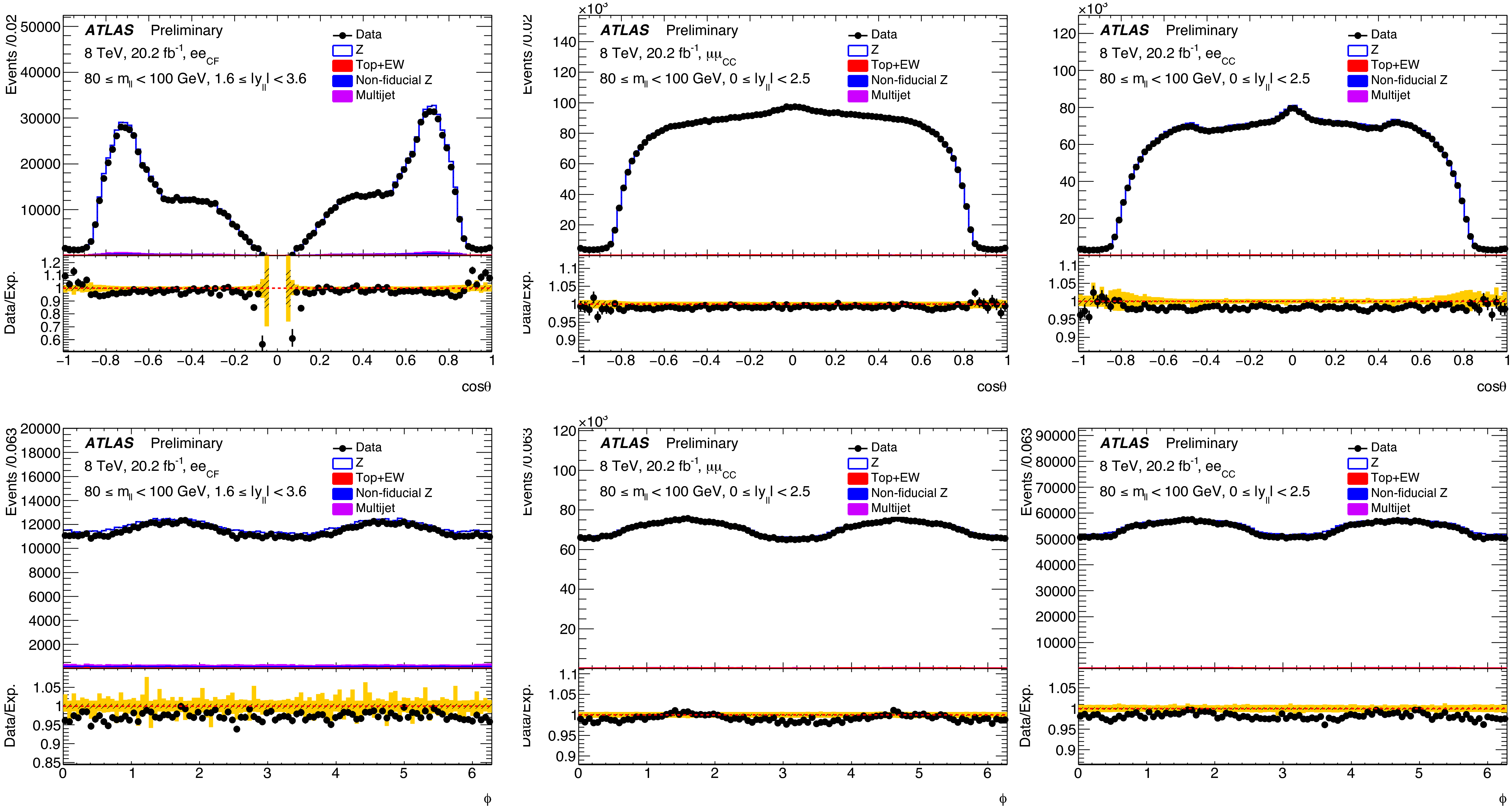
μμCC

$\|y_{ll}\|$	Data	Top+EW	Multijets	Non-fiducial Z
	$70 < m_{ll} < 80$ GeV			
0-0.8	124 050	0.019	0.017	0.009
0.8-1.6	137 984	0.015	0.014	0.014
1.6-2.5	74 976	0.010	0.011	0.019
	$80 < m_{ll} < 100$ GeV			
0-0.8	2 866 016	0.002	0.001	< 0.001
0.8-1.6	2 948 371	0.002	0.001	< 0.001
1.6-2.5	1 314 890	0.002	0.001	< 0.001
	$100 < m_{ll} < 125$ GeV			
0-0.8	119 650	0.030	0.023	0.023
0.8-1.6	122 775	0.020	0.015	0.023
1.6-2.5	55 886	0.010	0.005	0.022

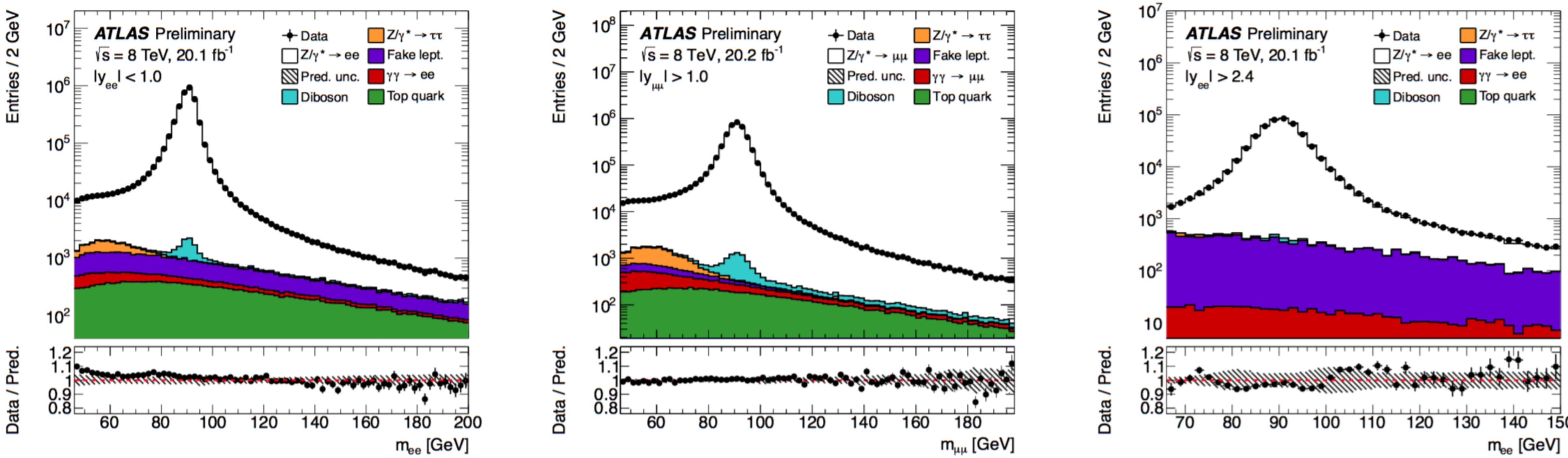
eeCF

$\|y_{ll}\|$	Data	Top+EW	Multijets	Non-fiducial Z
	$80 < m_{ll} < 100$ GeV			
1.6-2.5	702 142	0.001	0.010	0.017
2.5-3.6	441 104	0.001	0.011	0.013

Data/MC agreement

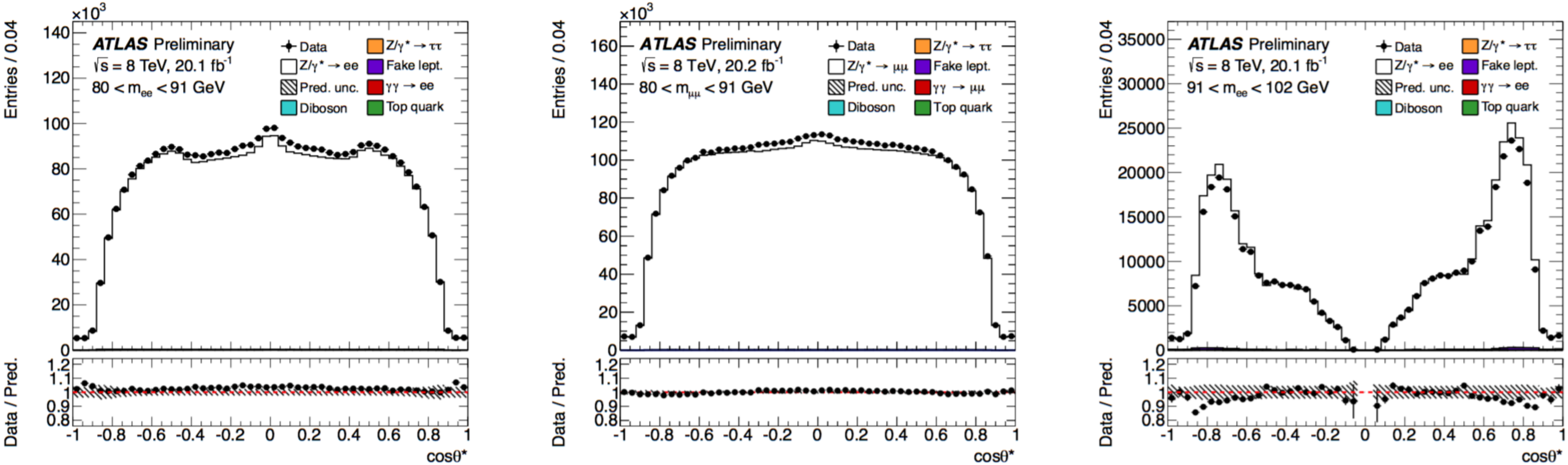


The Z3D measurement



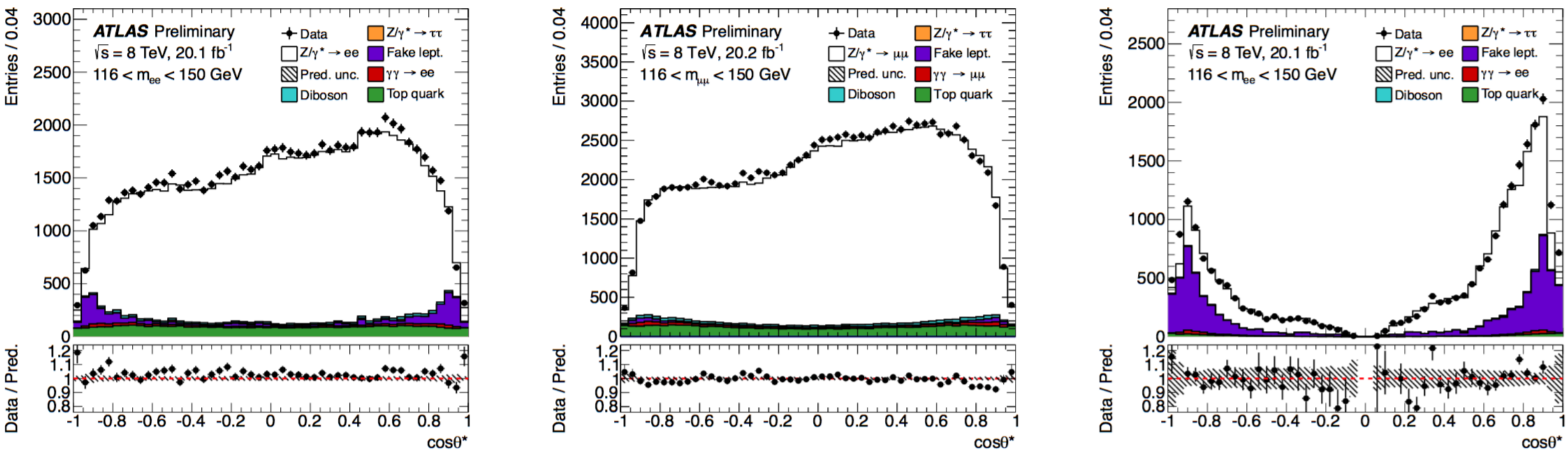
- Measurement performed using central $|\eta|<2.4$, $p_T > 20$ GeV electrons and muons in seven 46 GeV < m_{ll} < 200 GeV, twelve $y_{ll}<2.4$ and six $\cos\theta^*$ bins (2x504 in total)
- Extended using one central (p_T >25 geV) and one forward electron $|\eta|>2.5$, p_T>20 GeV in five 66 GeV < m_{ll} <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 EW 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%)

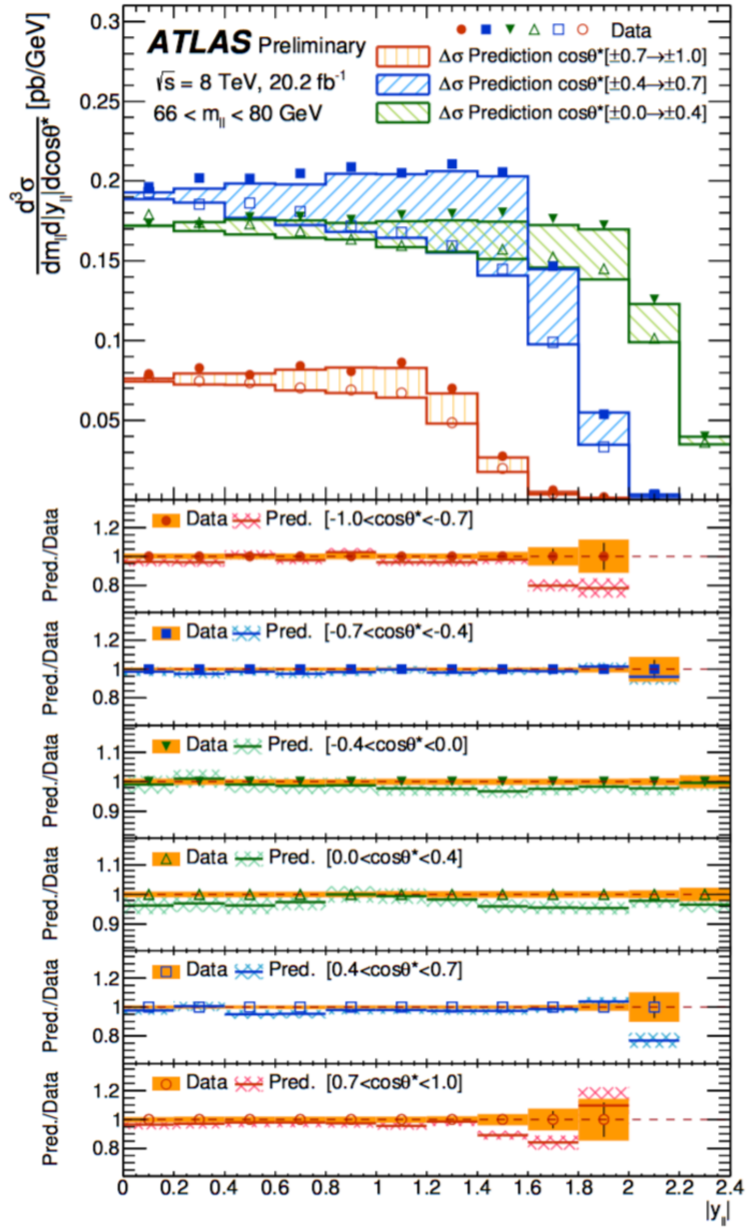
Above the peak



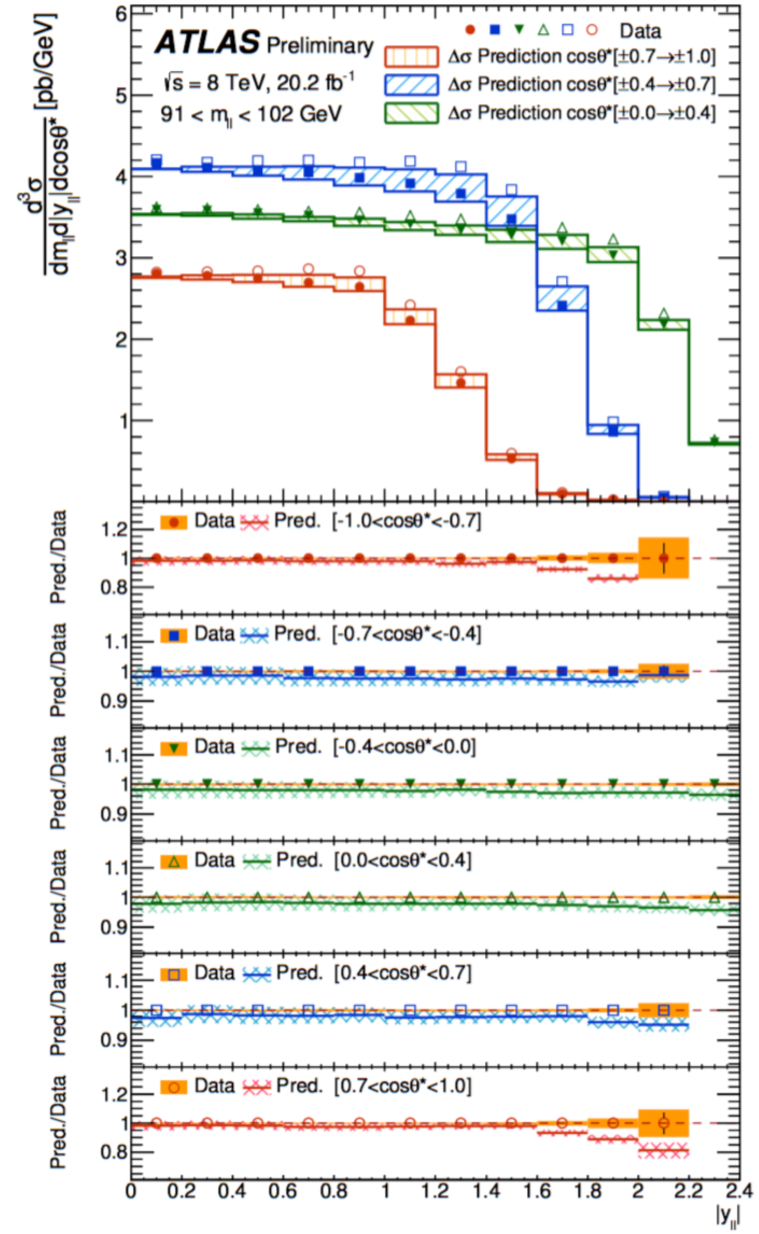
- Above the Z-peak the Forward-Backward asymmetry develops
- Backgrounds from top quark and multi jet production become sizeable (particularly for CF electrons).
  - But mostly charge-symmetric, they cancel in the A_{FB}
- Leading uncertainties are from the background subtraction and the energy resolution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

Z3D - Results

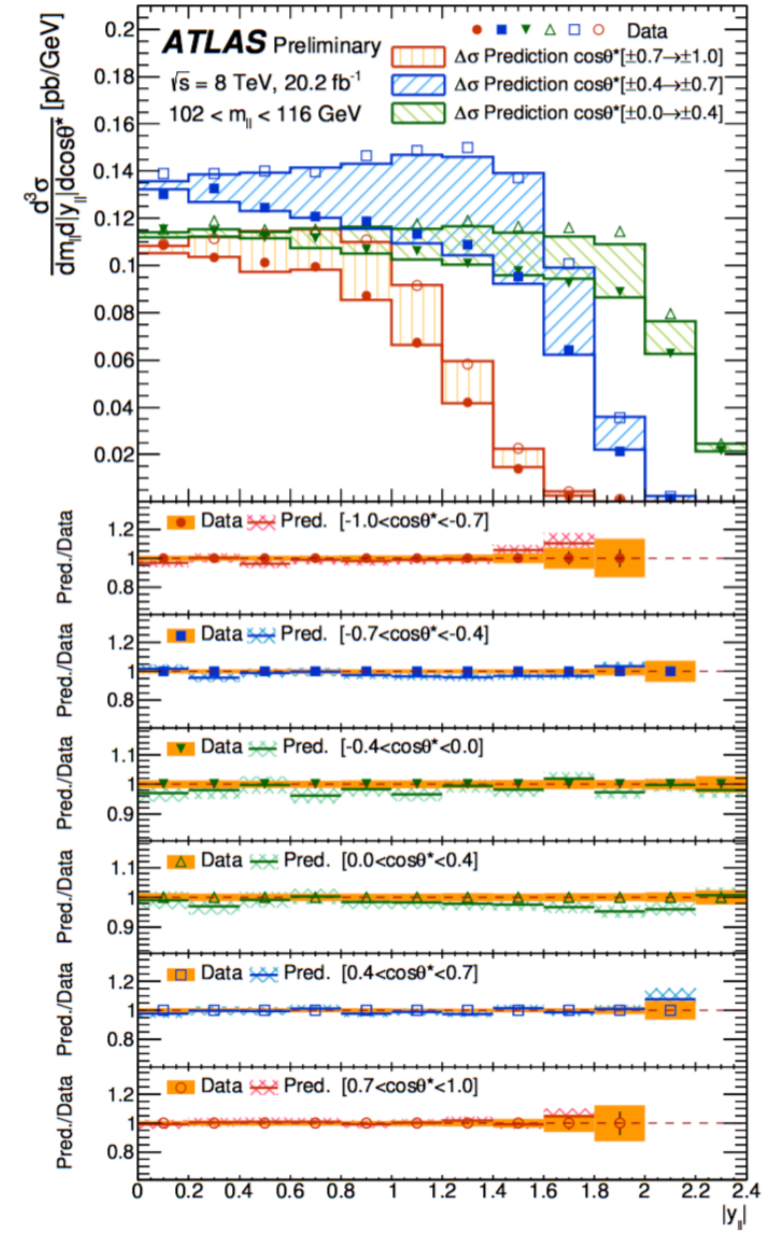
$m_{ll} < m_Z$



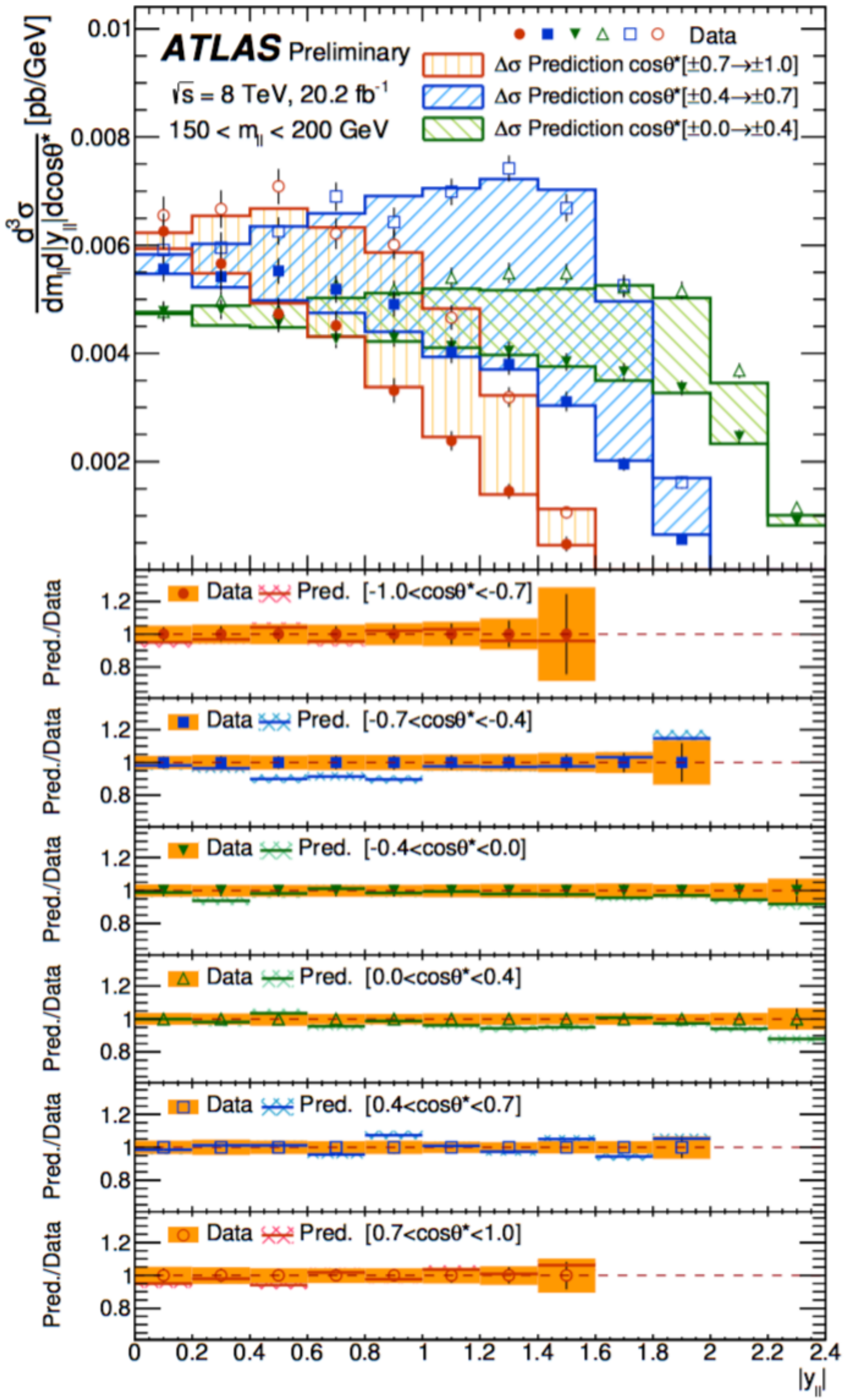
$m_{ll} \sim m_Z$



$m_{ll} > m_Z$



- Difference between $\pm \cos\theta^*$ originates the A_{FB}
- The asymmetry flips sign above the Z-peak and increases at large values of m_{ll}



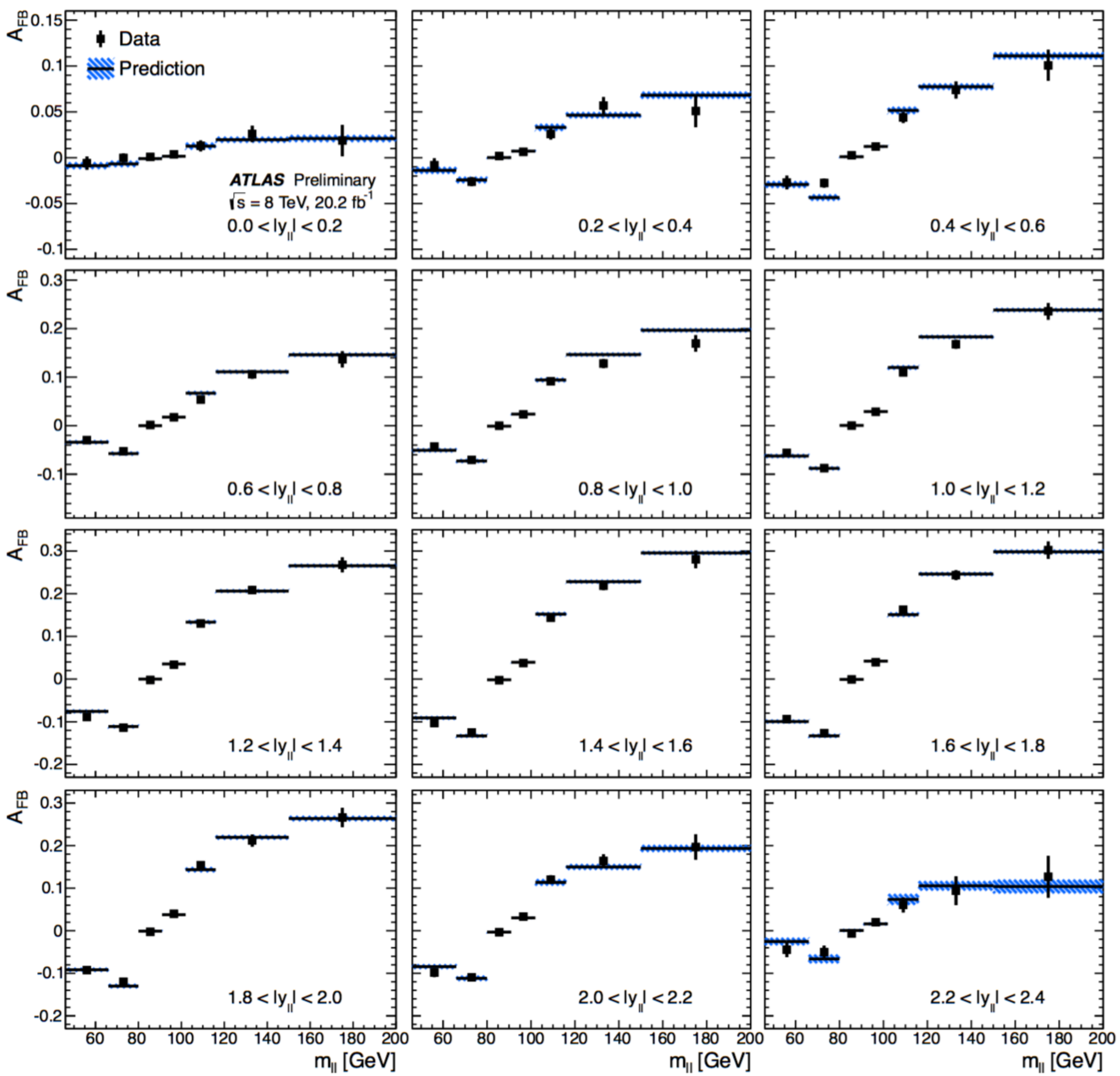
Z3D - Results

- 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:

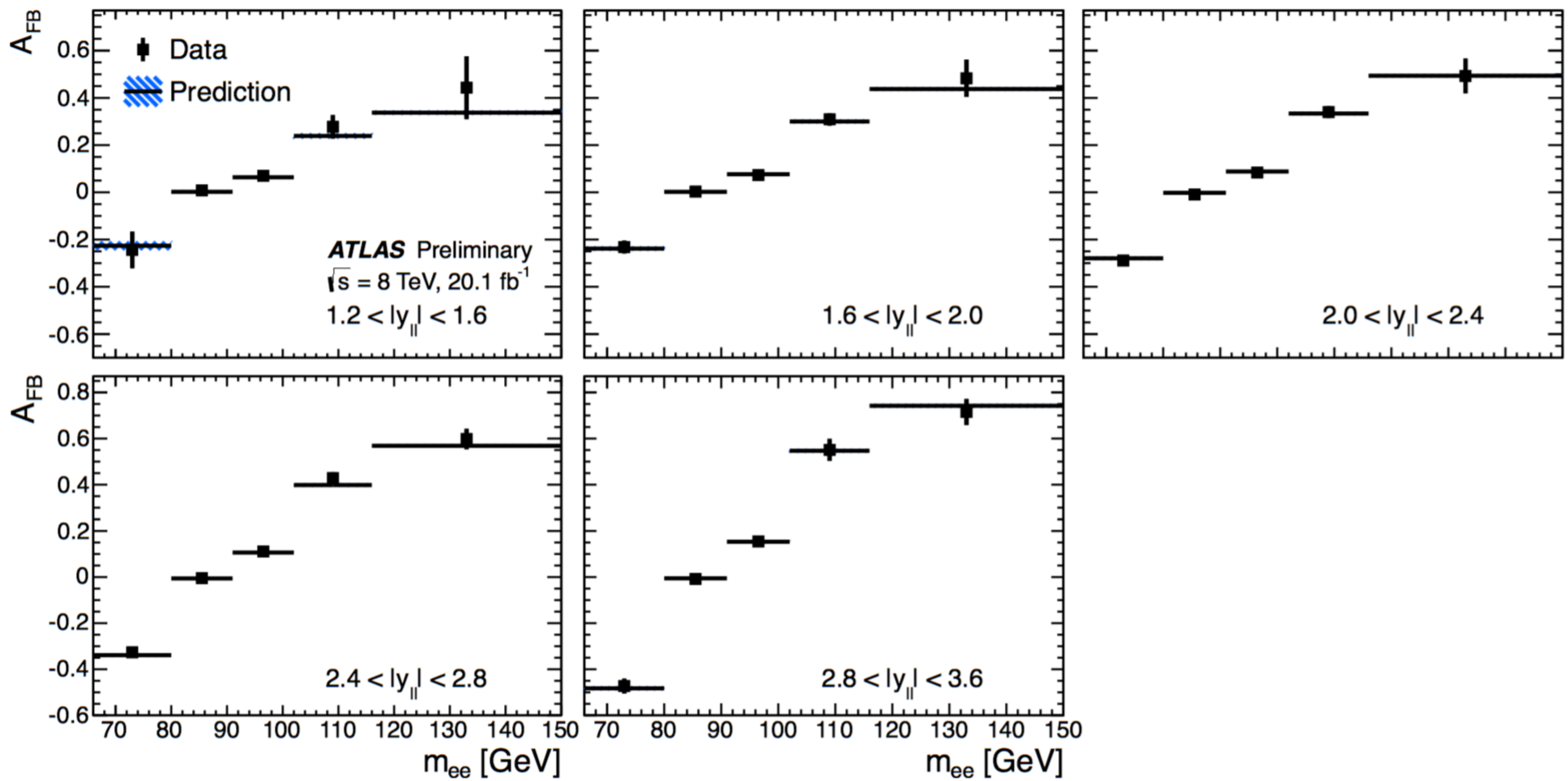
$$A_{FB} = \frac{d^3\sigma(\cos\theta^* > 0) - d^3\sigma(\cos\theta^* < 0)}{d^3\sigma(\cos\theta^* > 0) + d^3\sigma(\cos\theta^* < 0)}$$



- Uncertainties symmetric in cosθ^* 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

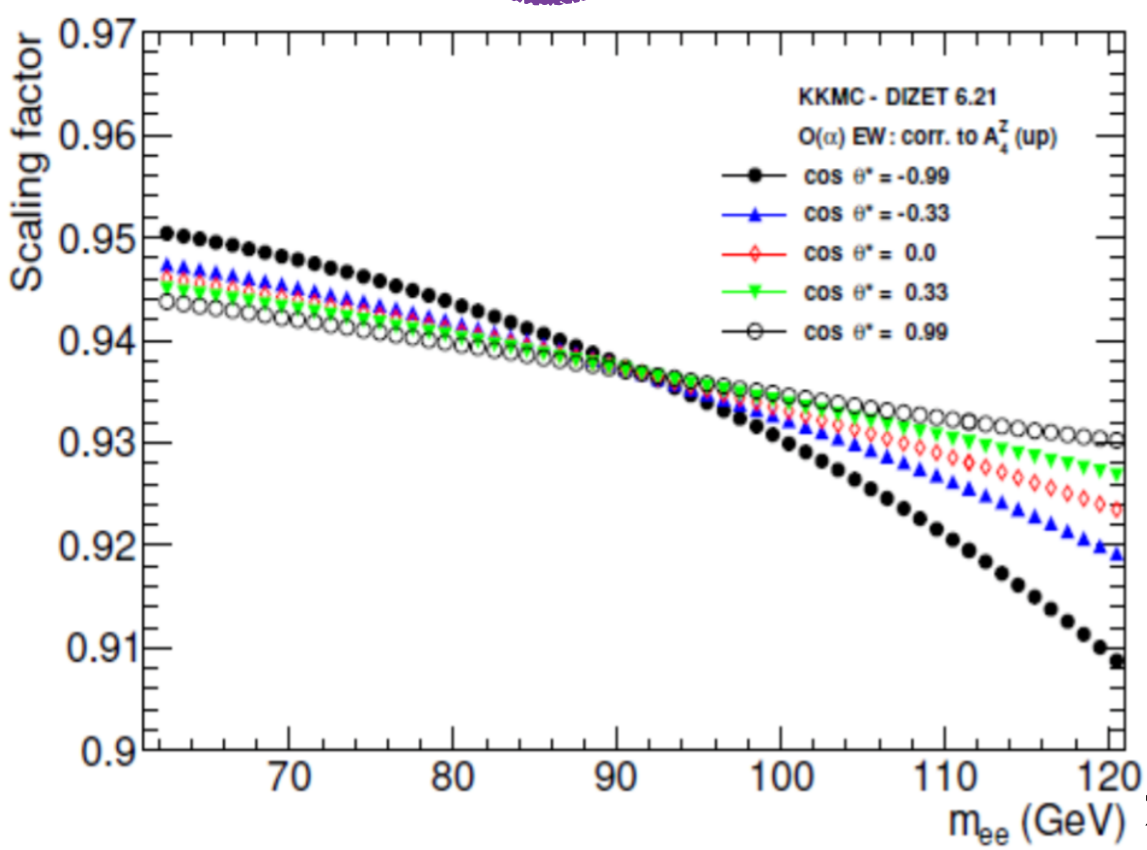


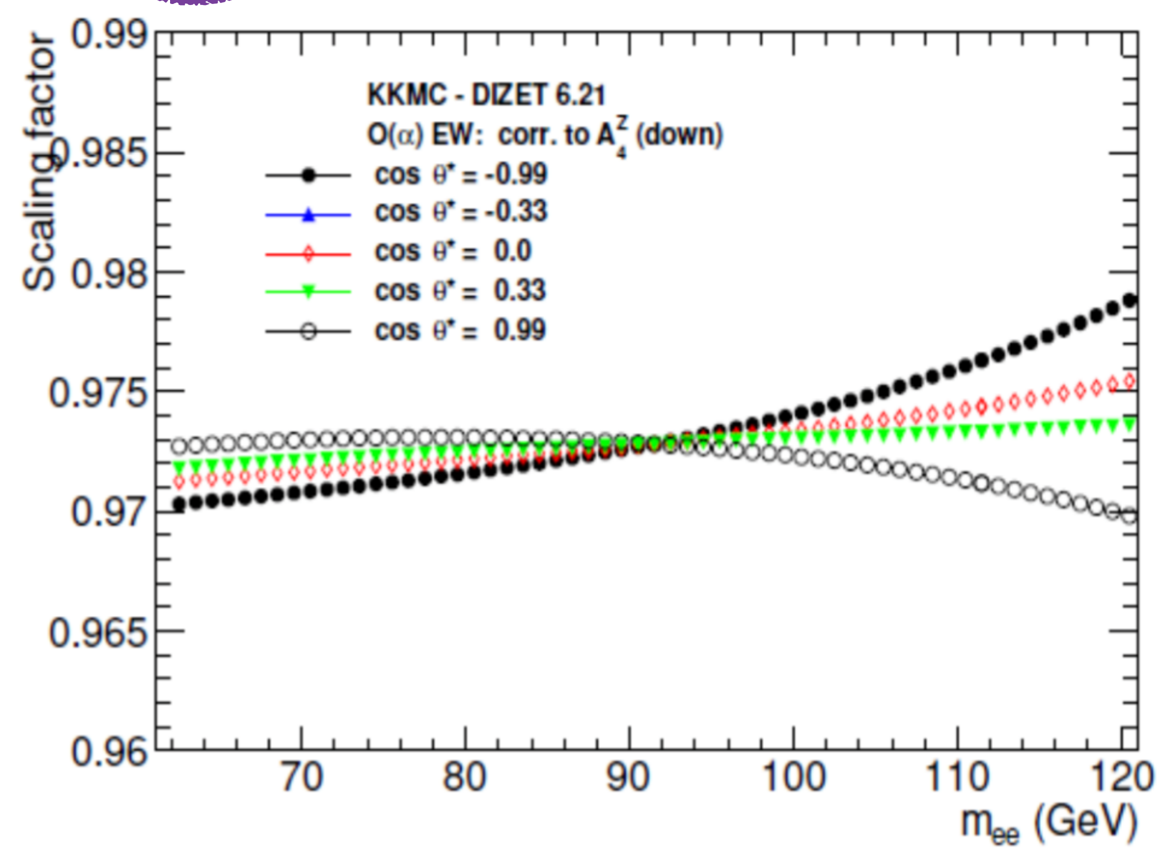
- Measured A_{FB} from -0.2 to +0.5 at lowest y_{ll} to -0.4 to +0.7 at the highest y_{ll}
- Good agreement with the Powheg based prediction

EW corrections

* Electroweak corrections do not alter significantly the Born-level interpretation
  - Loop and vertex EW virtual corrections can be incorporated into *complex multiplicative form-factors* which change the couplings
  - Tabulated using 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 IBA

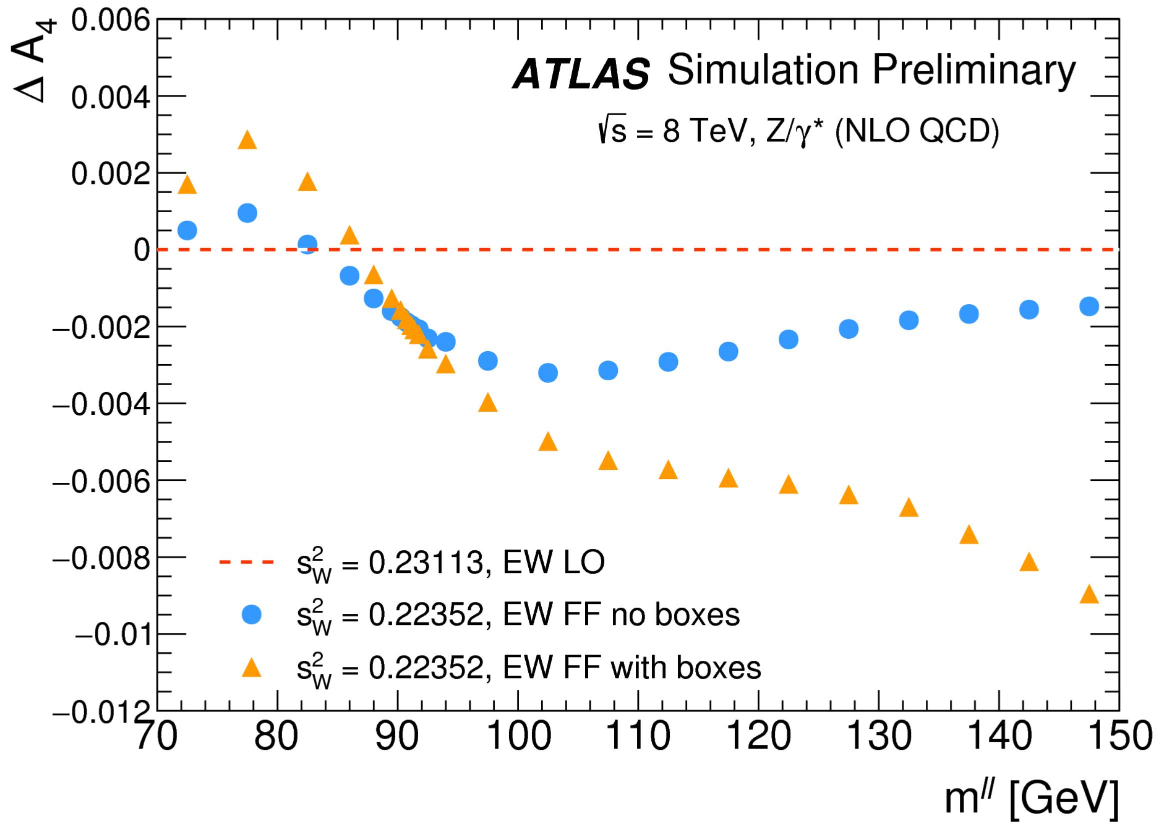
- The form factors can be applied as function of (s, t) into any calculation for the Drell-Yan process, leading to the so called *improved Born approximation* (IBA)
- Can then relate the measurement of the effective mixing angle to the on-shell angle as: $\sin^2\theta_{\text{eff}}^{\text{lept}} = \text{Re}[\kappa_e(m_Z^2)]\sin^2\theta_W$
- $\sin^2\theta_W$(on-shell) is a constant but $\sin^2\theta^l_{\text{eff}}(m_{ll}, f)$ 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

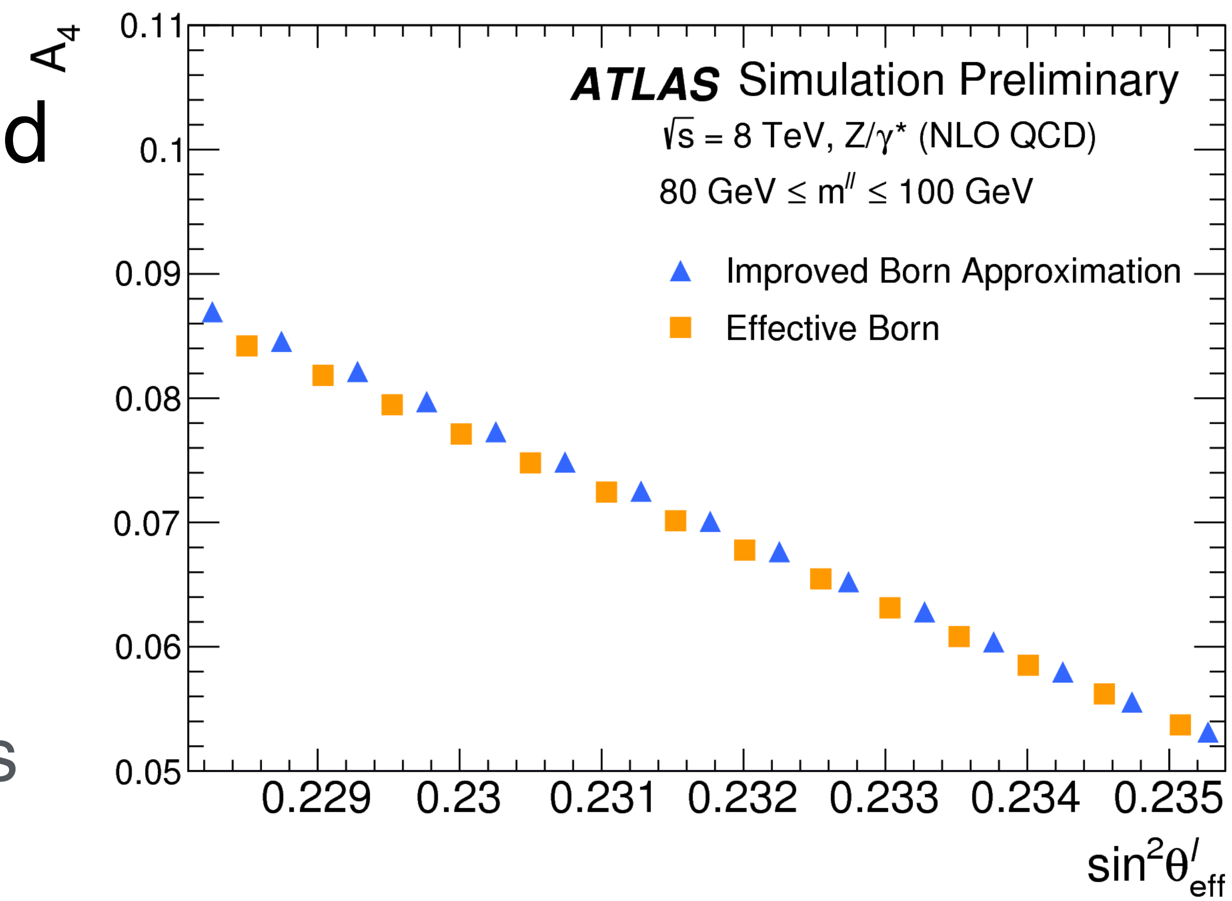
$$\text{SM}(\sin^2\theta_W) \xmapsto{\text{EWK}} \sin^2\theta_{\text{eff}}(s) \xleftrightarrow{\text{QCD}} A_4(s),$$

EW corrections impact



- Impact of EW form-factors on A4 compared to Powheg LO EW with and without including box diagrams
  - Box diagrams potentially break the factorisation assumption of the Ai decomposition
  - But impact is small around the Z-pole

- Variations of $\sin^2\theta^l_{eff}$ implemented as small of Z-boson vector couplings around PDG value
  - Overall uncertainty on the EW corrections is taken as $3\text{x}10^{-5}$, including parametric uncertainties and uncertainties on IFI/ISR effects



A4 predictions - QCD+EW

	$70 < m^{\ell\ell} < 80$ GeV			$80 < m^{\ell\ell} < 100$ GeV				$100 < m^{\ell\ell} < 125$ GeV		
$\|y^{\ell\ell}\|$	$0 - 0.8$	$0.8 - 1.6$	$1.6 - 2.5$	$0 - 0.8$	$0.8 - 1.6$	$1.6 - 2.5$	$2.5 - 3.6$	$0 - 0.8$	$0.8 - 1.6$	$1.6 - 2.5$
Central value (NNLO QCD)	−0.0870	−0.2907	−0.5970	0.0144	0.0471	0.0928	0.1464	0.1045	0.3444	0.6807
ΔA_4 (NNLO - NLO QCD)	0.0003	0.0010	0.0021	−0.0001	−0.0005	−0.0009	−0.0015	−0.0007	−0.0022	−0.0041
ΔA_4 (EW)	0.0008	0.0028	0.0056	0.0002	0.0007	0.0015	0.0026	−0.0008	−0.0026	−0.0048
$\Delta \sin^2\theta^\ell_{\text{eff}}$ (EW)	0.00129	0.00130	0.00133	0.00024	0.00024	0.00025	0.00026	−0.00120	−0.00123	−0.00119
	Uncertainties			Uncertainties				Uncertainties		
Total	0.0035	0.0094	0.0137	0.0007	0.0017	0.0021	0.0021	0.0040	0.0102	0.0140
PDF	0.0034	0.0092	0.0127	0.0007	0.0016	0.0020	0.0019	0.0039	0.0100	0.0131
QCD scales	0.0006	0.0019	0.0052	0.0003	0.0003	0.0004	0.0008	0.0005	0.0022	0.0049

- Predictions are obtained at NNLO in QCD using DYTURBO, an optimised version of DYNNLO/DYRES
  - PDF eigenvectors also computed at NNLO
- EW corrections implemented using EW weights and IBA
  - The $\sin^2\theta^l_{\text{eff}}$ dependence of A4 is determined in each bin by fitting A4 = a + b $\sin^2\theta^l_{\text{eff}}$
- Impact of EW corrections is found to be ~24 10^{-5} in the pole region, when compared to LO EW with $\sin^2\theta^l_{\text{eff}}$=0.23152

A4 measurement - sensitivity

$m^{\ell\ell}$ (GeV)	70 – 80			80 – 100				100 – 125		
$\|y^{\ell\ell}\|$	0 – 0.8	0.8 – 1.6	1.6 – 2.5	0 – 0.8	0.8 – 1.6	1.6 – 2.5	2.5 – 3.6	0 – 0.8	0.8 – 1.6	1.6 – 2.5
Prediction (MMHT14)	−0.0870	−0.2907	−0.5970	0.0144	0.0471	0.0928	0.1464	0.1045	0.3444	0.6807
	Uncertainties			Uncertainties				Uncertainties		
Total	0.0176	0.0202	0.0404	0.0015	0.0015	0.0025	0.0044	0.0083	0.0098	0.0230
Stat.	0.0153	0.0164	0.0333	0.0013	0.0013	0.0021	0.0036	0.0072	0.0078	0.0188
Syst.	0.0087	0.0117	0.0229	0.0007	0.0008	0.0013	0.0025	0.0041	0.0060	0.0133
PDF (meas.)	0.0013	0.0049	0.0048	0.0001	0.0002	0.0004	0.0007	0.0007	0.0016	0.0043
p_T^Z modelling	0.0002	0.0004	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001	0.0001	< 0.0001	0.0002
Leptons	0.0023	0.0059	0.0118	0.0002	0.0001	0.0003	0.0007	0.0014	0.0037	0.0070
Background	0.0004	0.0011	0.0064	< 0.0001	< 0.0001	< 0.0001	0.0001	0.0004	0.0017	0.0031
MC stat.	0.0082	0.0088	0.0179	0.0007	0.0007	0.0012	0.0023	0.0038	0.0041	0.0100

- Expected uncertainties on the measured A4 at the pole
- Consistent with the published Ai paper
- Dominated by statistical uncertainties
  - Both in the data and in the Monte Carlo
- PDF uncertainties on the measurement are small
  - Much smaller than the PDF uncertainties in the predictions, which are decorrelated

$\sin^2\theta^{l}_{\mathrm{eff}}$ MEASUREMENT - SENSITIVITY

Channel	ee_{CC}	$\mu\mu_{CC}$	ee_{CF}	$ee_{CC} + \mu\mu_{CC}$	$ee_{CC} + \mu\mu_{CC} + ee_{CF}$
Total	65	59	42	48	34
Stat.	47	39	29	30	21
Syst.	45	44	31	37	27
	Uncertainties in measurements				
PDF (meas.)	7	7	7	7	4
p_T^Z modelling	< 1	< 1	1	< 1	< 1
Lepton scale	5	4	6	3	3
Lepton resolution	3	1	3	1	2
Lepton efficiency	1	1	1	1	1
Electron charge misidentification	< 1	0	< 1	< 1	< 1
Muon sagitta bias	0	4	0	2	1
Background	1	1	1	1	1
MC. stat.	25	22	18	16	12
	Uncertainties in predictions				
PDF (predictions)	36	37	21	32	22
QCD scales	5	5	9	4	6
EW corrections	3	3	3	3	3

- Total uncertainty at the level of 34 10^{-5}
- CF uncertainty smaller than the combined ee+μμCC
- Dominant uncertainty from PDFs: 20 10^{-5} after profiling
- Next large uncertainty from limited MC stat: 12 10^{-5}

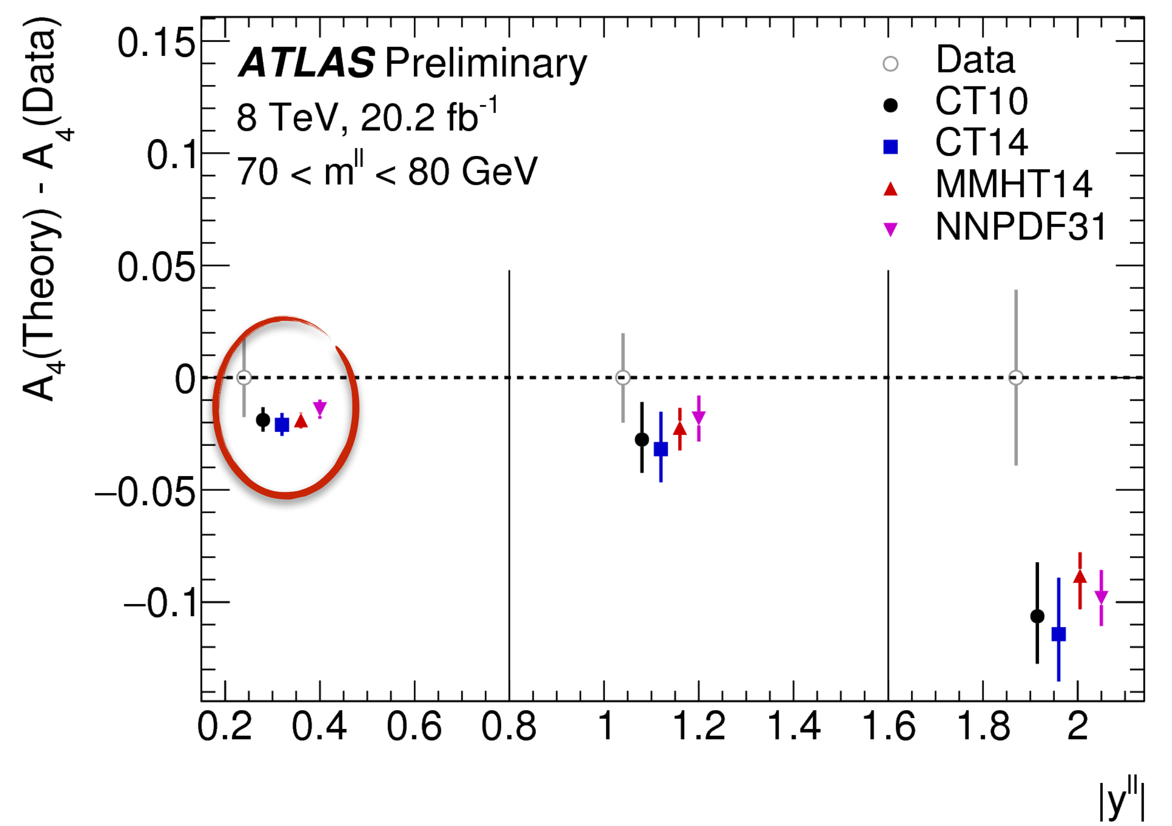
A4 measurement - Checks

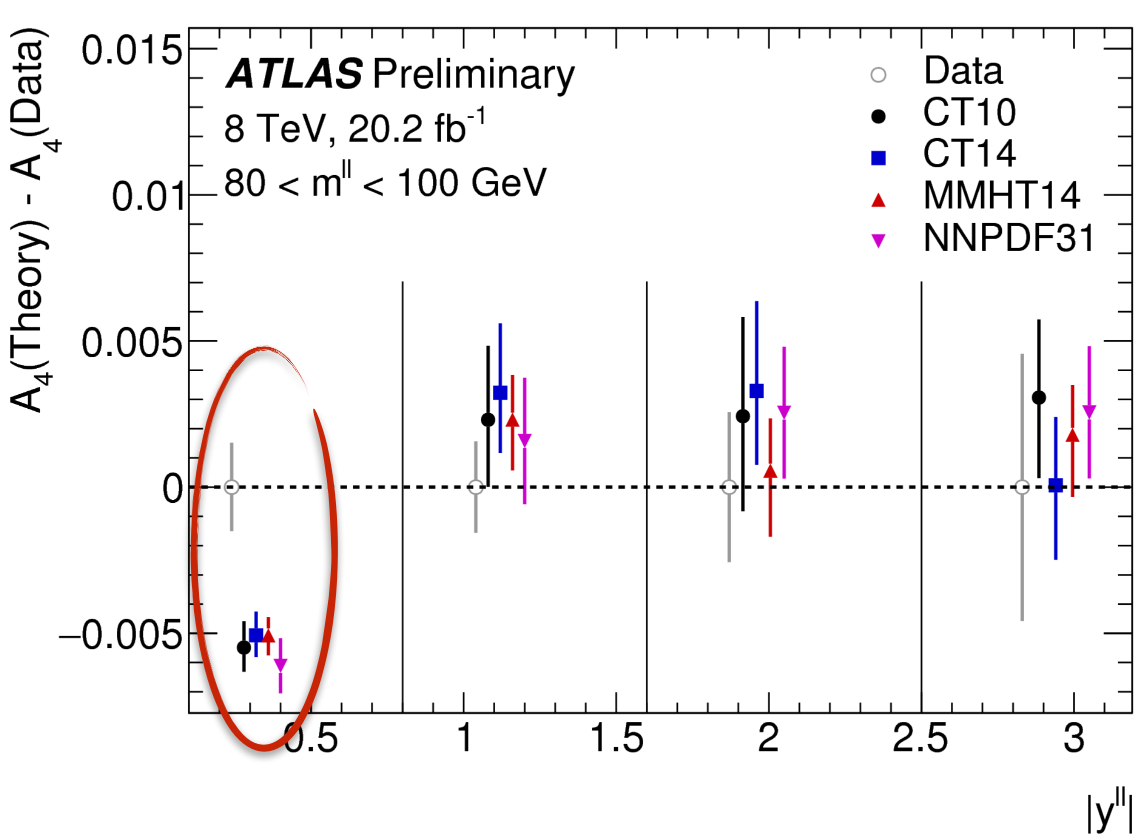
	$70 < m^{\ell\ell} < 80$ GeV			$80 < m^{\ell\ell} < 100$ GeV			$100 < m^{\ell\ell} < 125$ GeV		
$\|y^{\ell\ell}\|$	$0-0.8$	$0.8-1.6$	$1.6-2.5$	$0-0.8$	$0.8-1.6$	$1.6-2.5$	$0-0.8$	$0.8-1.6$	$1.6-2.5$
ΔA_4	0.012	0.067	0.065	-0.003	-0.001	-0.006	0.011	0.013	-0.086
	Uncertainties			Uncertainties			Uncertainties		
Total	0.034	0.039	0.078	0.003	0.003	0.007	0.017	0.019	0.045
Stat.	0.030	0.034	0.067	0.003	0.003	0.006	0.015	0.016	0.038
Syst.	0.017	0.021	0.040	0.001	0.001	0.003	0.008	0.010	0.024
PDF (meas.)	0.001	0.003	0.005	< 0.001	< 0.001	< 0.001	0.001	0.001	0.001
Leptons	0.005	0.010	0.016	< 0.001	< 0.001	< 0.001	0.002	0.007	0.012
Background	0.001	0.002	0.005	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	0.004
MC stat.	0.016	0.018	0.036	0.001	0.001	0.003	0.008	0.008	0.020

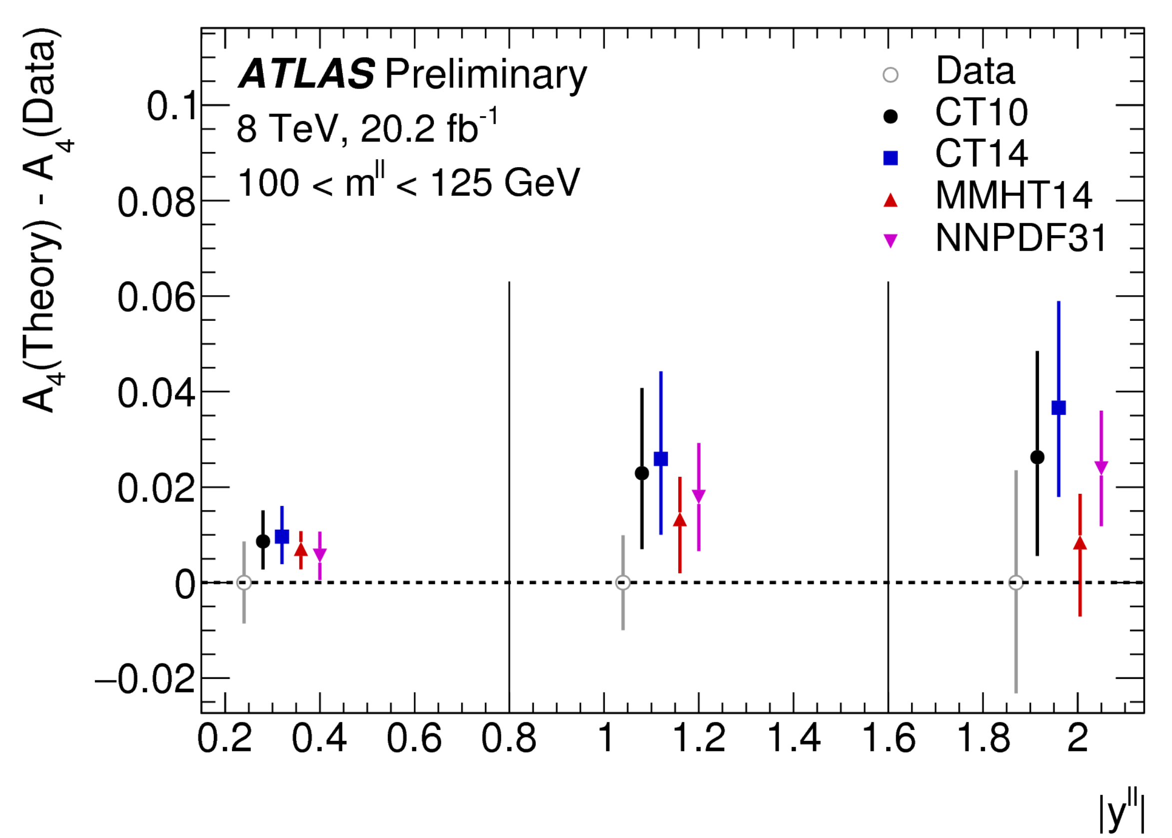
- Test of the compatibility of the measured A4 between the eeCC and μμCC for all of the measurement bins
- The p-value of the test is good, of about 34%
- One bin of the eeCF channel overlaps with eeCC, and in this bin they are found to be compatible

A4 measurement - Checks

- When looking at the combined measured A4 we see tension between data and predictions in two regions
  - At high boson rapidities below the Z-peak
  - At central rapidities in the Z-peak region





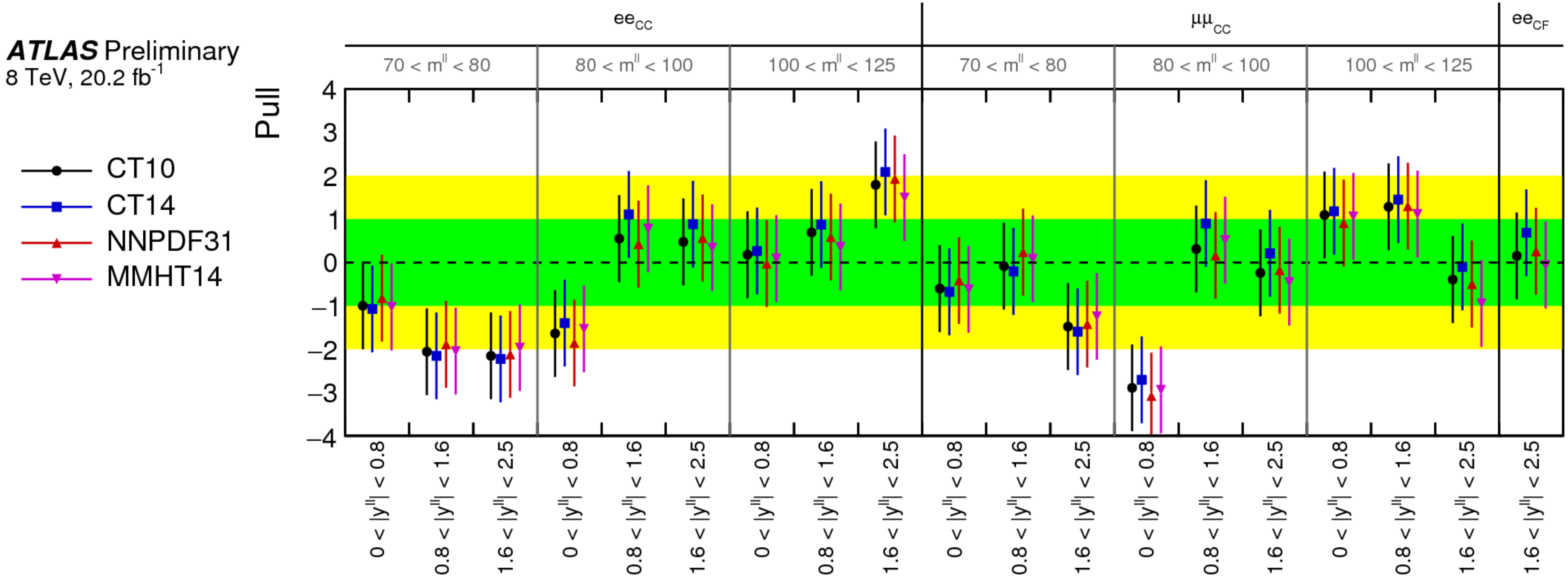


$\sin^2\theta^l_{\text{eff}}$ measurement - Checks

Tested difference	$ee_{CC} - \mu\mu_{CC}$	$ee_{CC} - ee_{CF}$	$\mu\mu_{CC} - ee_{CF}$	$ee_{CF} - (ee_{CC} + \mu\mu_{CC})$
$\Delta \sin^2 \theta^\ell_{\text{eff}}$	44	−7	−51	−32
	Uncertainties			
Total	72	70	64	57
Stat.	62	56	50	42
Syst.	37	41	40	38

- Test of the compatibility of the extracted $\sin^2\theta^l_{\text{eff}}$ in all of the measurement bins (19 measurements)
- Most stringent test is the CC/CF compatibility
  - At the level of 50 10^{-5} compared to the 30 10^{-5} expected sensitivity of the combined measurement
- Results are satisfactory for all channels

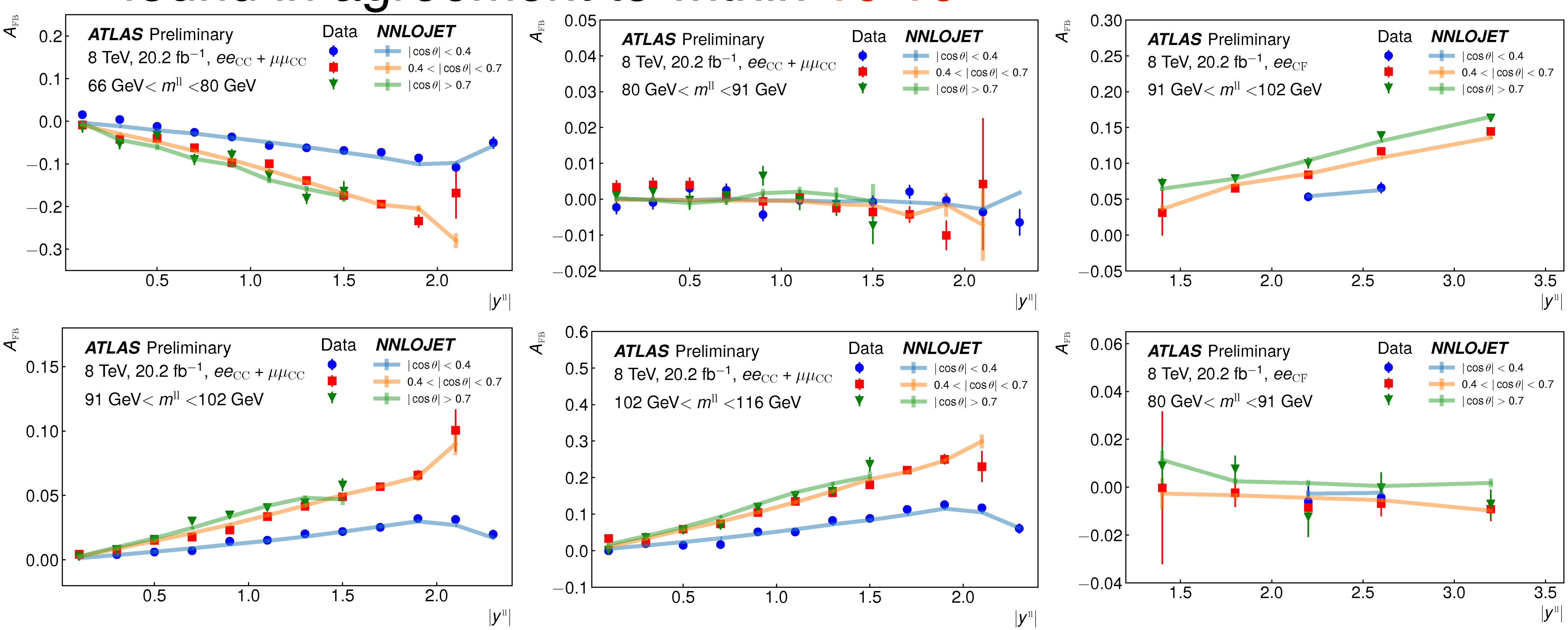
$\sin^2\theta^l_{eff}$ measurement - Checks



- Test of the compatibility of the extracted $\sin^2\theta^l_{eff}$ in all of the measurement bins (19 measurements)
- Overall fit p-value is only 3.4%
  - 3σ pulls from low y_{ll} μμCC channel

$\sin^2\theta^l_{eff}$ measurement - Z3D extraction

- A final compatibility test is performed extracting $\sin^2\theta^l_{eff}$ from the Z3D published measurement
  - All bins are converted to $A_{FB}(m_{ll}, y_{ll}, \cos)$
  - NNLOJET is used for QCD NNLO predictions
  - EW effects incorporated with weights as in the Ai analysis
- Final result has very similar sensitivity to $\sin^2\theta^l_{eff}$ which is found in agreement to within 10 10^{-5}



Results

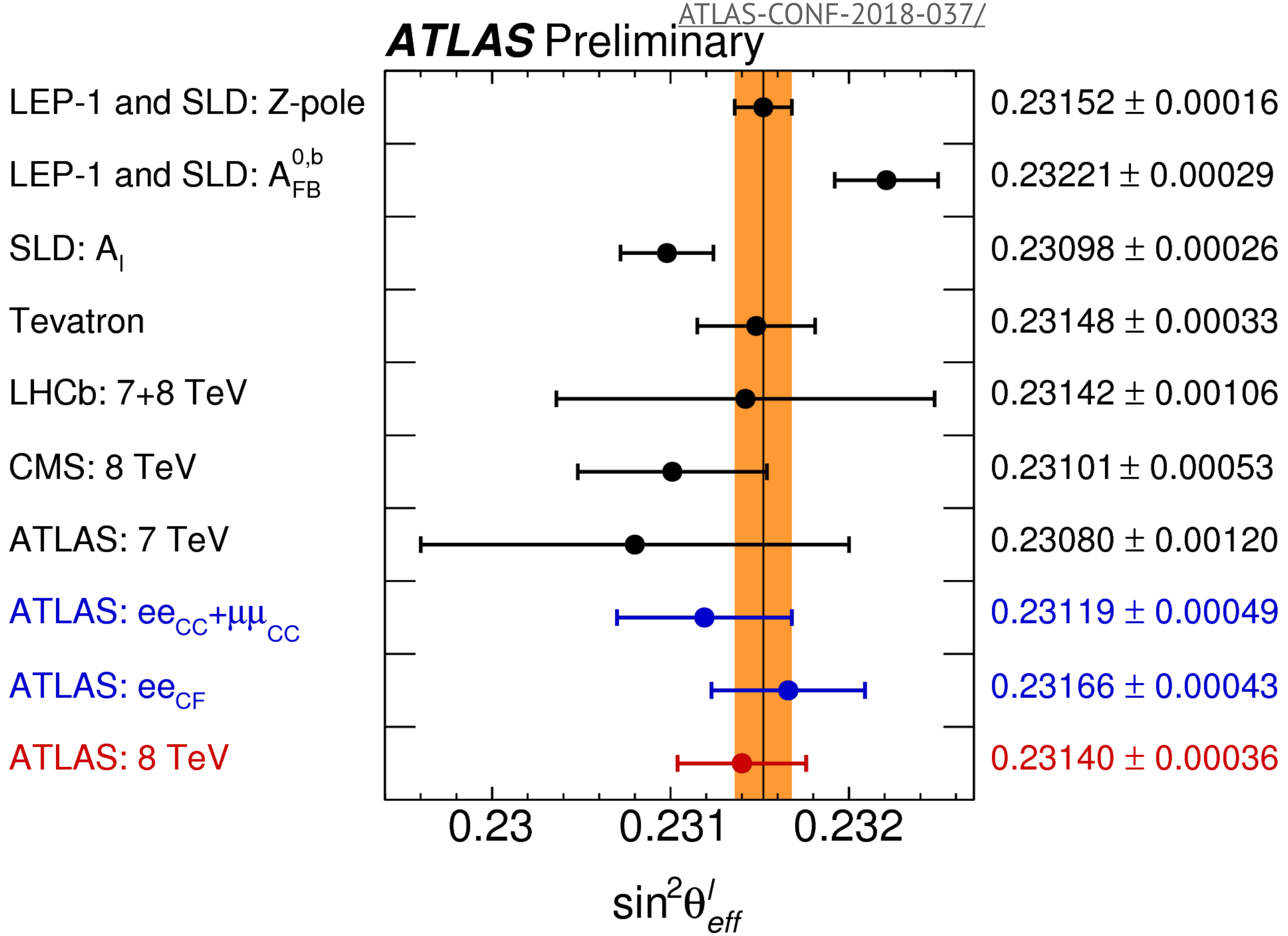
	CT10	CT14	MMHT14	NNPDF31
$\sin^2\theta^{\ell}_{\text{eff}}$	0.23118	0.23141	0.23140	0.23146
	Uncertainties in measurements			
Total	39	37	36	38
Stat.	21	21	21	21
Syst.	32	31	29	31

- The fit using MMHT14 provides the best result
  - Best fit p-value and smallest uncertainties
- Results are similar for CT14 and NNPDF31, but the uncertainty on is slightly larger
- CT10 is also included as providing the best description of our 7 TeV precise W and Z cross-sections
  - And used for our 7 TeV m_W measurement

Results

$\sin^2\theta_{eff} = 0.23101 \pm 0.00021\ (\text{stat}) \pm 0.00016\ (\text{syst}) \pm 0.00024\ (\text{PDF})$

ATLAS-CONF-2018-037/



Next Steps

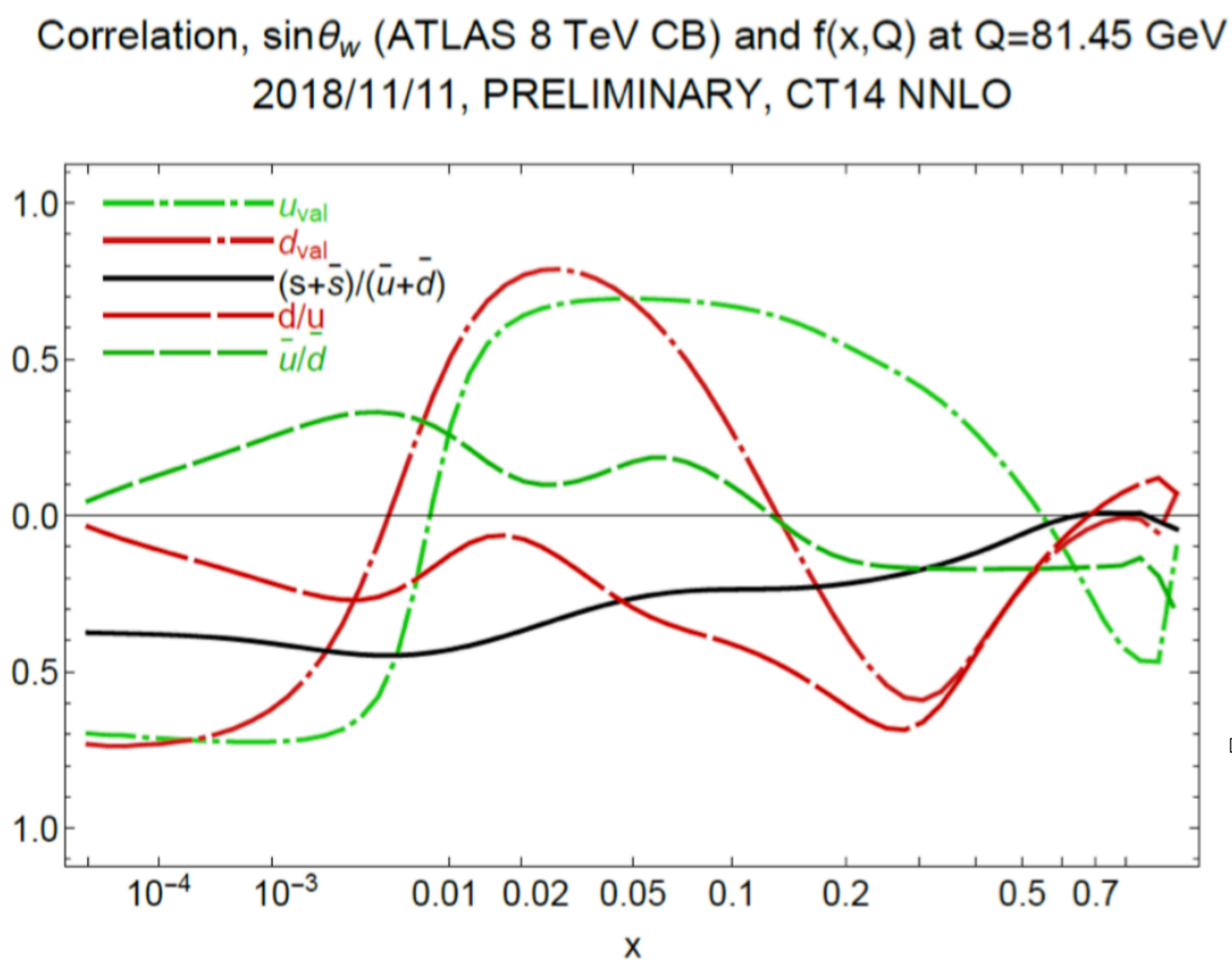
- The ATLAS 8 TeV $\sin^2\theta^l_{eff}$ (preliminary) result reaches an outstanding precision, but few unsatisfactory points remain:
    - Few bins show tensions between data and predictions
    - $\sin^2\theta^l_{eff}$ extracted with the CT10 PDF is outside of the nominal PDF uncertainty band
    - Are the LEP legacy codes (and approximations) for estimating EW effects under control?
- We are currently working towards our legacy Run1 $\sin^2\theta^l_{eff}$ measurement improving on all of those issues
- Joint effort of ATLAS CMS, LHCb and theory steered by the LHCEWKWG

Theory benchmarking

- EW form-factor approach now benchmarked against other tools: Powheg-EWK and MCSANC
  - Results found in remarkable agreement among codes
- Moved from DIZET v6.21 to v6.42 with more complete two-loop corrections and updated to the newest parametrisation for $\Delta\alpha_{had}(M_Z)$
  - Expect a shift of order 10 10^{-5} on $\sin^2\theta^l_{eff}$
- Yet to be quantified that QED ISR and IFI effects are truly negligible
- The DYTURBO predictions have also been benchmarked against NNLOJET
  - Some inconsistencies found, but their effect on $\sin^2\theta^l_{eff}$ is expected to be small

PDF PROFILING

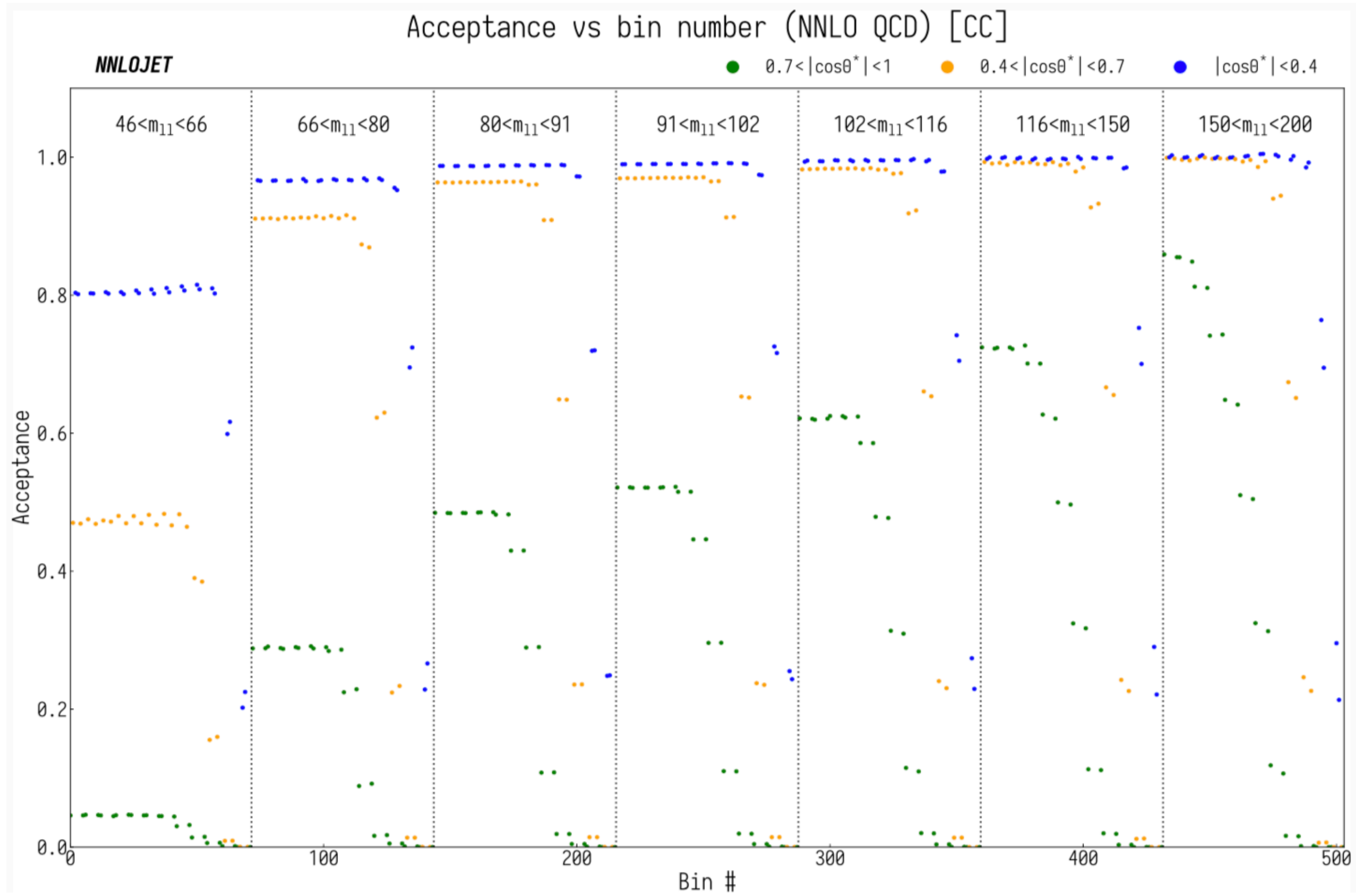
- Following the release of our result, the CT group evaluated the correlations of the $\sin^2\theta^l_{eff}$ measurement with the CT14 NNLO PDFs



- Taking as input the $\sin^2\theta^l_{eff}$ extracted with the 56 CT14 error PDFs and the CT parametrisation
- Strongest correlation with u_{val}, d_{val} at x~0.01-0.2
- Weaker correlation with $\bar{u}$, $\bar{d}$, gluon and sea PDFs

- Mostly aligning with our naive expectations

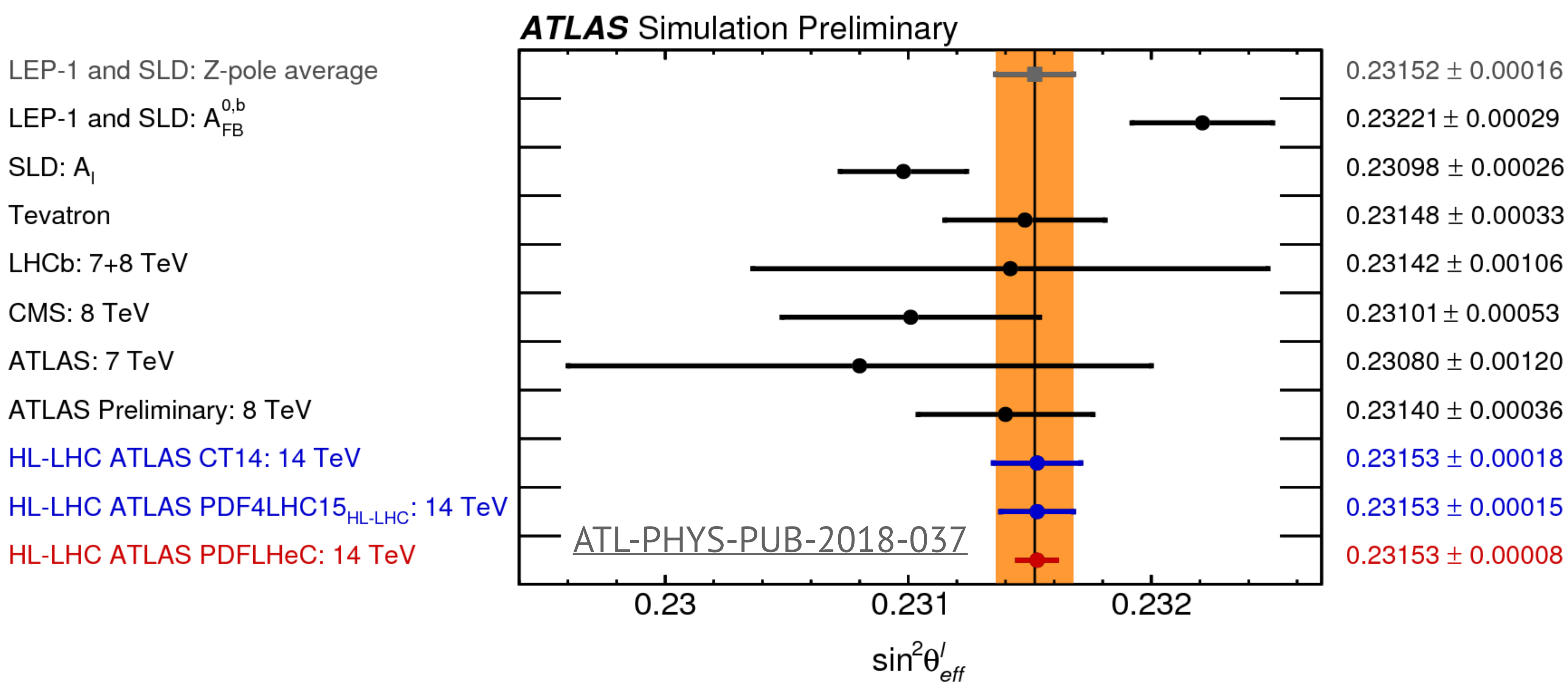
Can we do better?



- Acceptance, $A=\sigma_{fid}/\sigma_{tot}$ calculated with NNLOJET at NNLO shows strong variations vs m_{ll}, y_{ll} $\cos\theta^*$ for the Z3D bins (bin number = $72i_m+12i_y+i_{\cos\theta^*}$)
- More than 50% of the bins with low $\cos\theta^*$ and $m_{ll} > 66$ GeV have $A > 95\%$
- Can restrict the usage of cross-sections in the fit to the bins with high acceptance

HL-LHC prospects

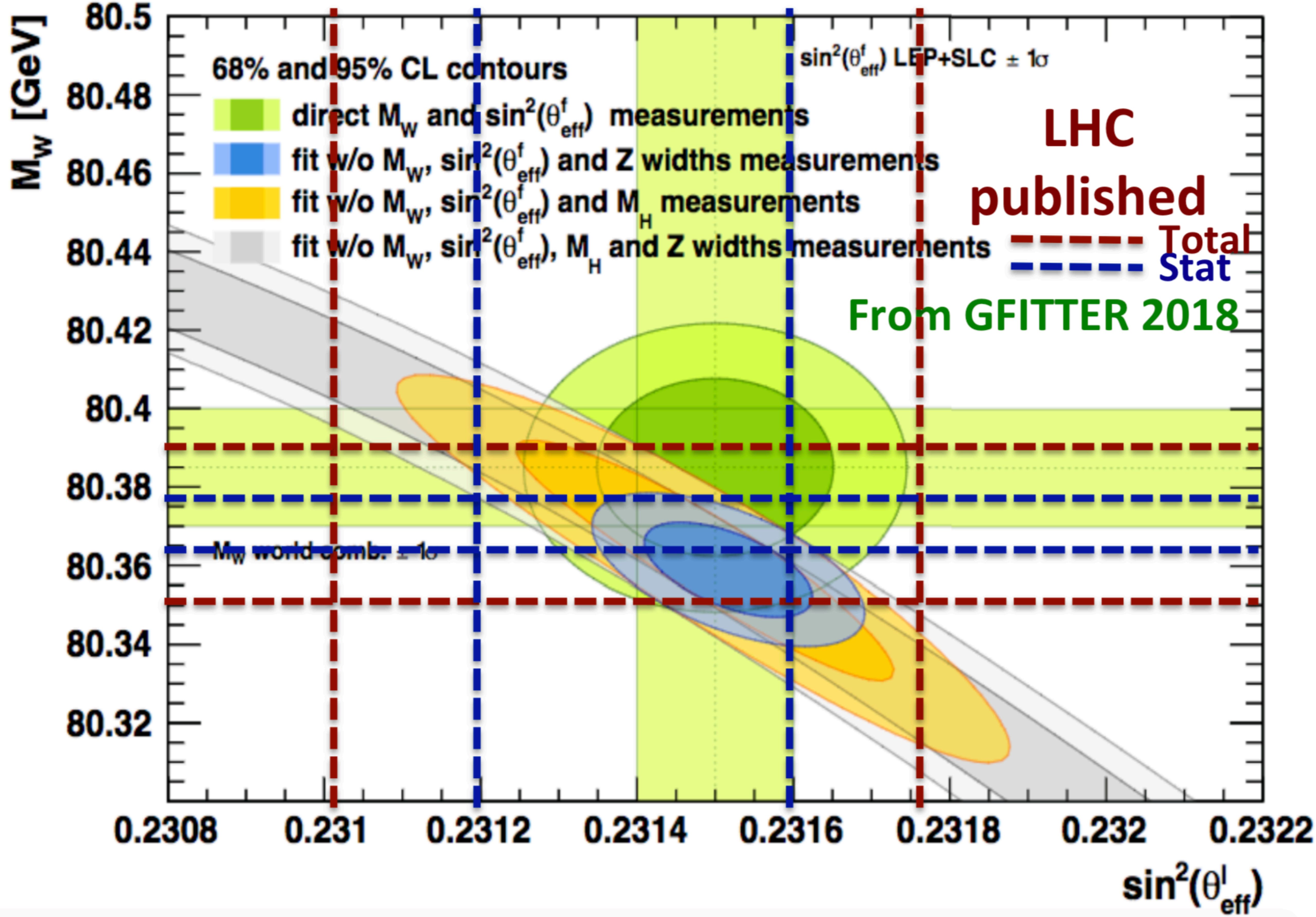
- For the HL-LHC Yellow Report we prepared few projections
  - Increase in energy enhances dilution effects
  - But increased acceptance for forward electron
- A total uncertainty of 18 10^{-5} is expected (with in-situ profiling), fully dominated by the uncertainty on PDFs (17 10^{-5})
  - Experimental uncertainty at the level of 4 10^{-5}



Summary

- Presented a preliminary ATLAS measurement of $\sin^2\theta^l_{W,eff}$ with the 8 TeV pp collision data, reaching a precision of 36 10^{-5}
  - Using a full phase-space measurement of the angular coefficients
- The final ATLAS 8TeV measurement of $\sin^2\theta_W$ from the Ai and Z3D may reach an overall sensitivity of about 30 10^{-5}
  - After the W-mass it would be another ATLAS milestone
- Measurement dominated by the PDF uncertainty
  - The many ad-hoc choices used in PDF fits start to show up at this level of precision (as was the case for the W-mass)
- Before pursuing further measurements of such kind crucial to develop a *precise prescription to asses PDF uncertainties*
  - Studies to evaluate PDF correlations ongoing in the LHCEWWKG
  - A combined QCD+EW fit to Drell-Yan data restricted to high-acceptance fiducial cross-section might allow to keep the PDF uncertainties under control

Summary



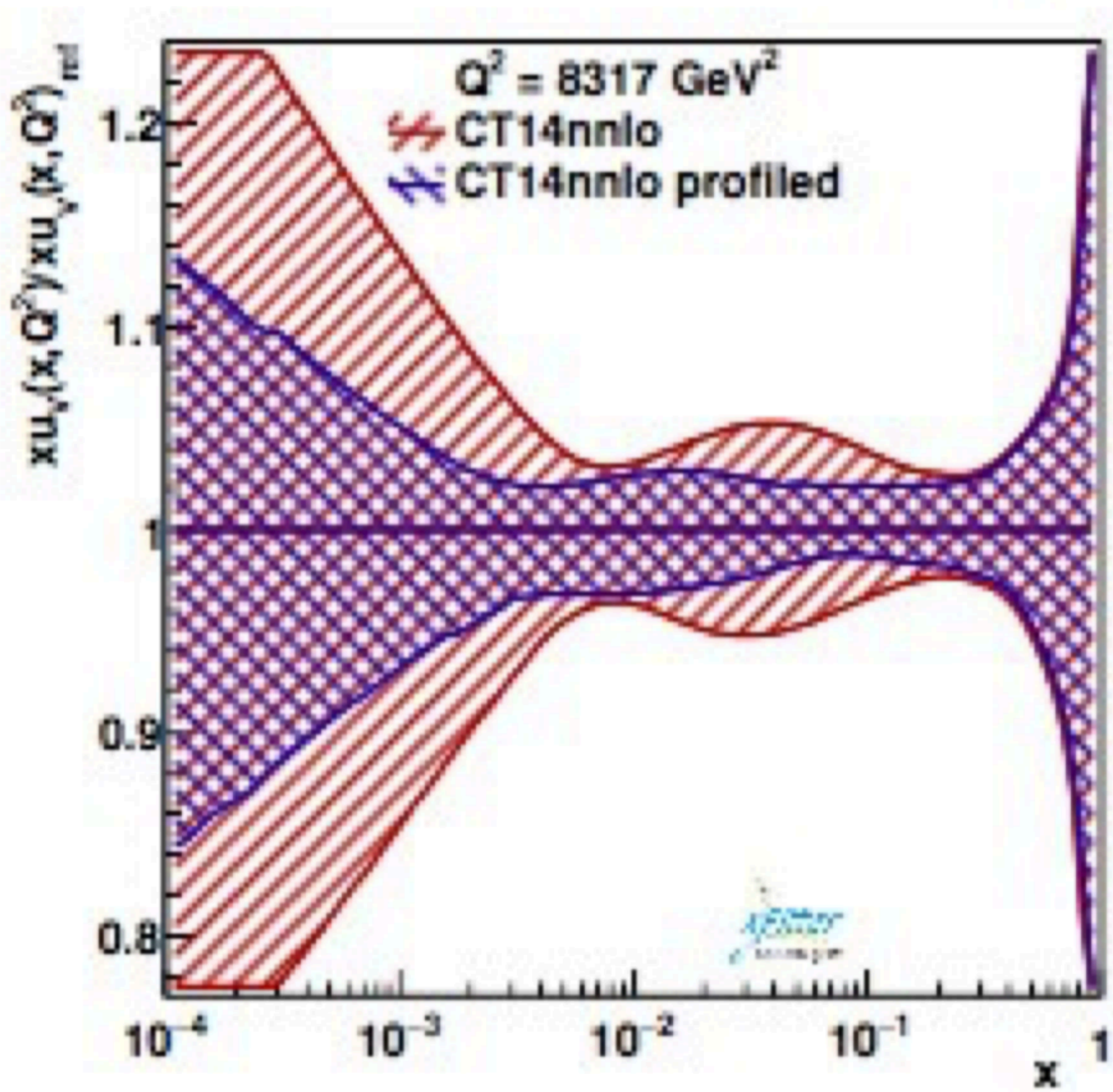
68% and 95% CL contours
direct M_W and $\sin^2(\theta^f_{eff})$ measurements
fit w/o M_W, $\sin^2(\theta^f_{eff})$ and Z widths measurements
fit w/o M_W, $\sin^2(\theta^f_{eff})$ and M_H measurements
fit w/o M_W, $\sin^2(\theta^f_{eff})$, M_H and Z widths measurements
$\sin^2(\theta^f_{eff})$ LEP+SLC ± 1σ
M_W world comb. ± 1σ
LHC
published
Total
Stat
From GFITTER 2018
M_W [GeV]
80.5
80.48
80.46
80.44
80.42
80.4
80.38
80.36
80.34
80.32
0.2308
0.231
0.2312
0.2314
0.2316
0.2318
0.232
0.2322
$\sin^2(\theta^l_{eff})$

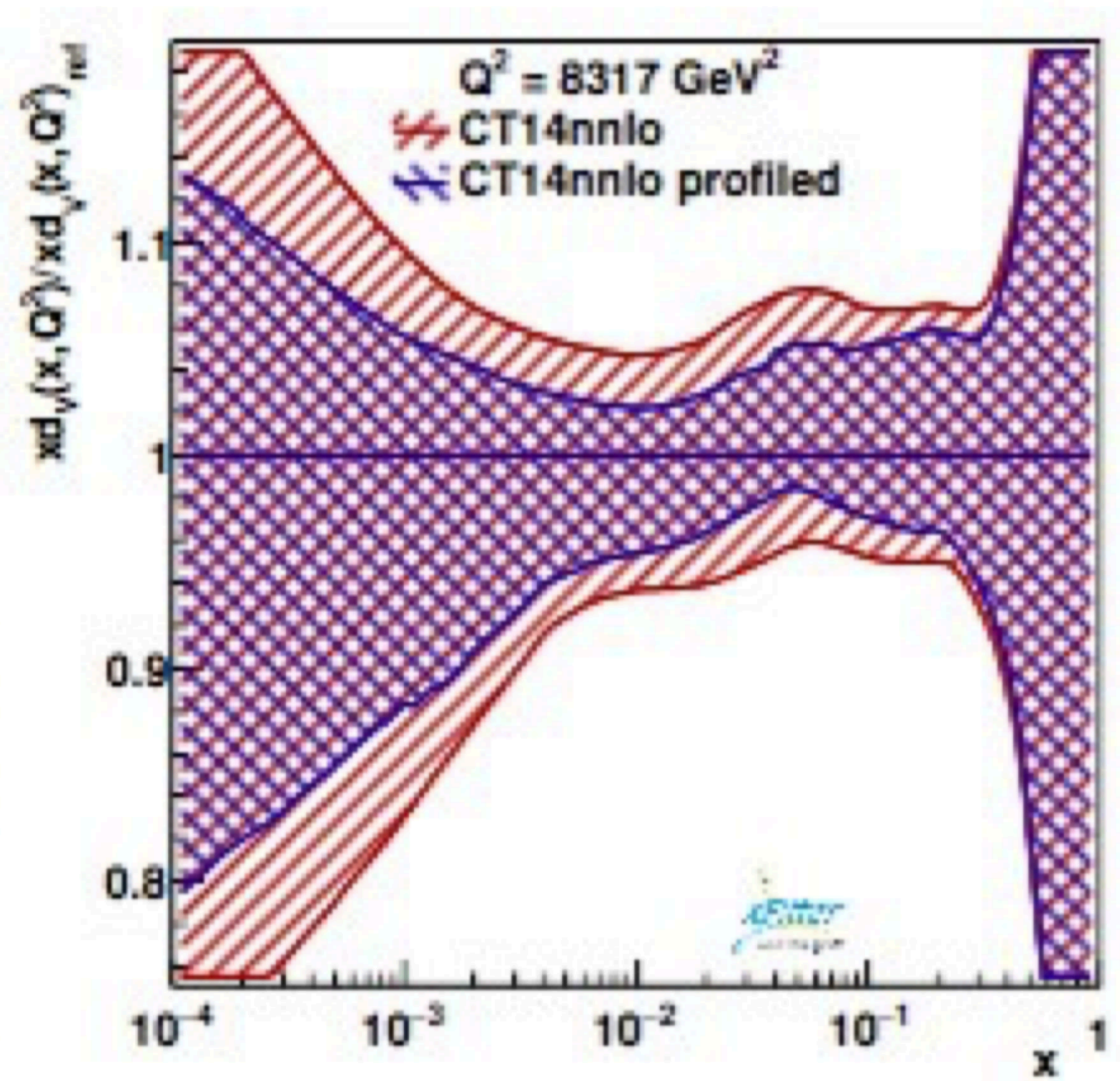
BACKUP

PDFs: can we do better?

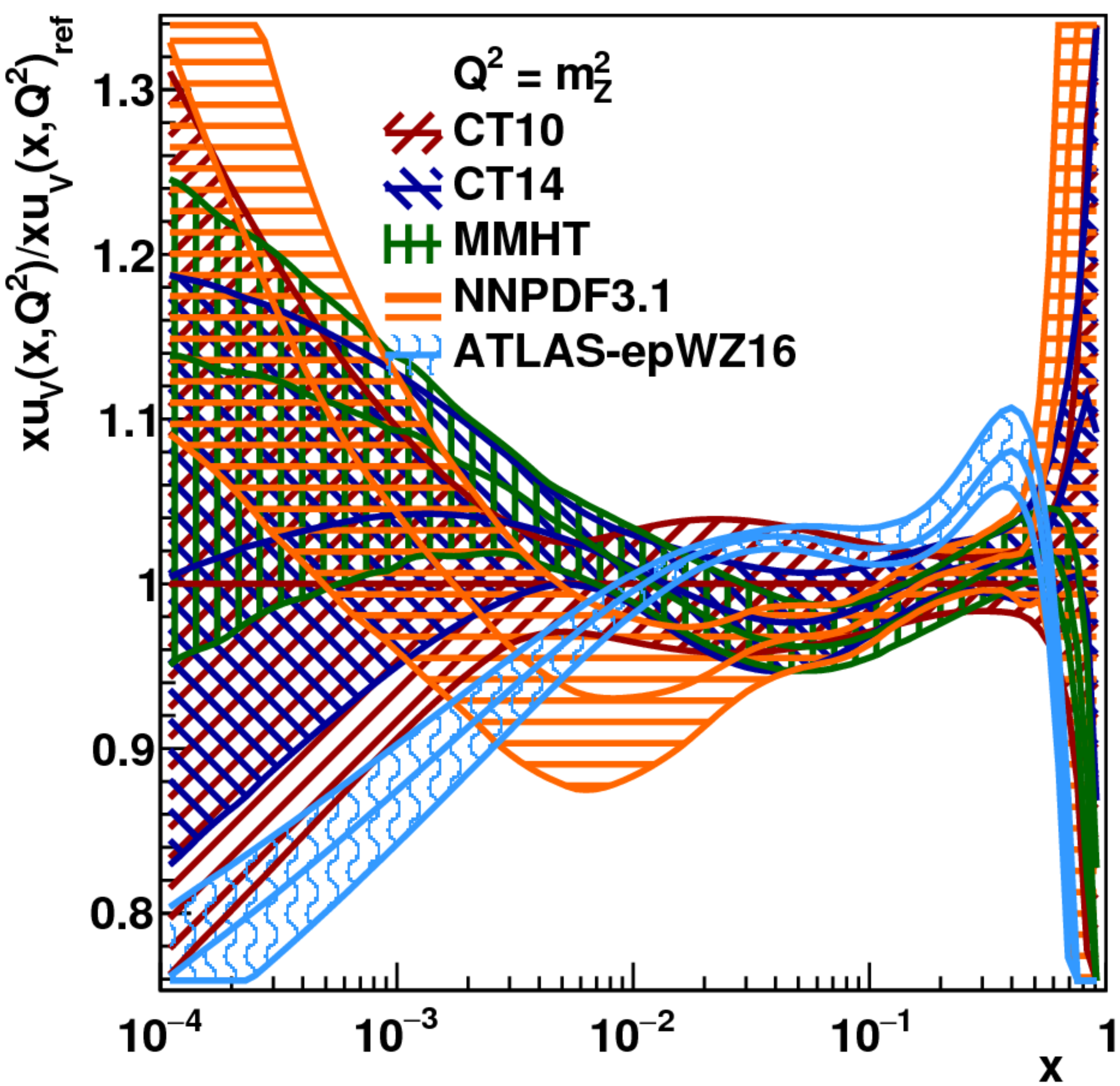
- How are PDFs constrained if fitting them to A_{FB} data?

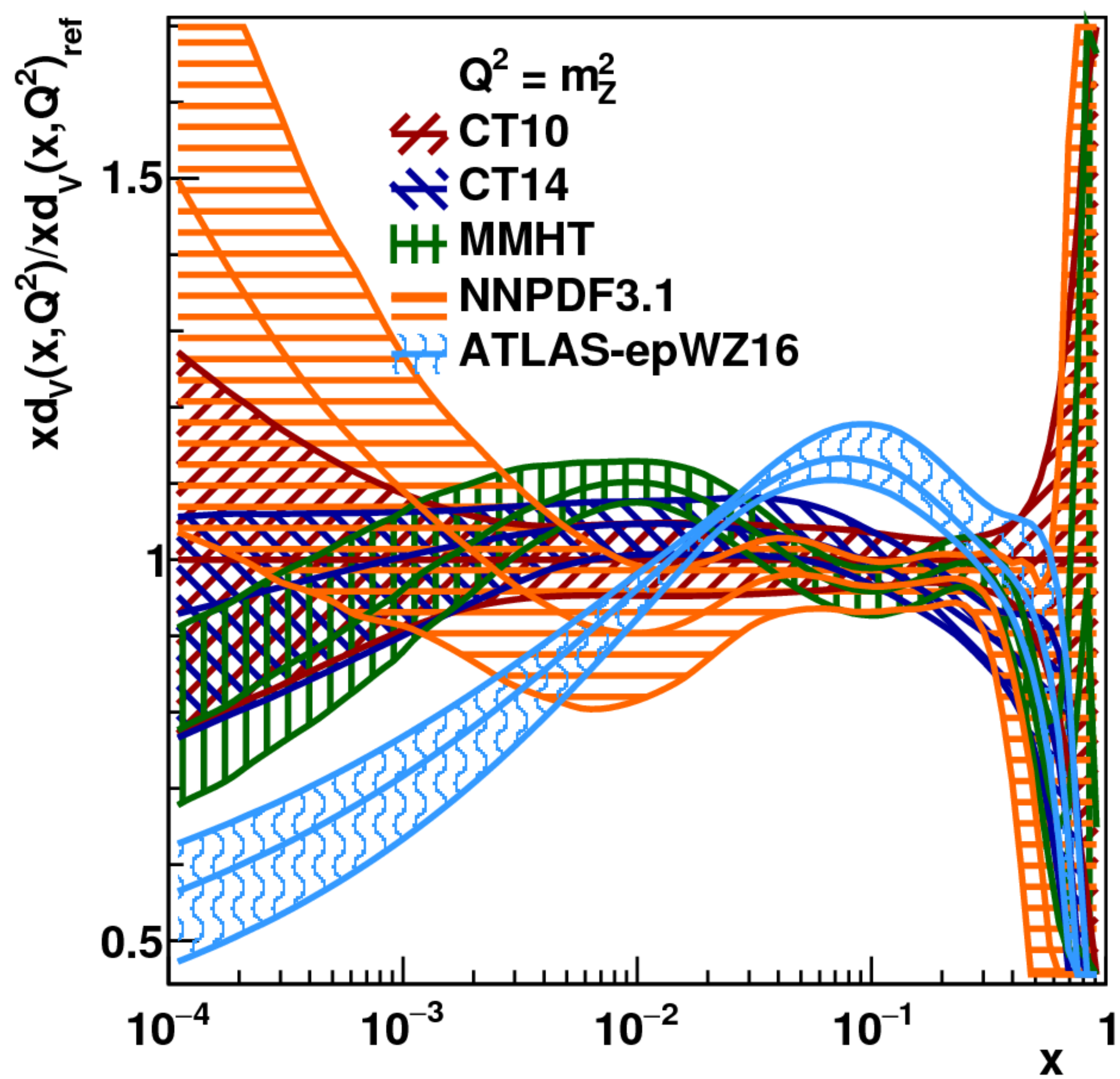
[F. Hautmann, Morion QCD 2019]



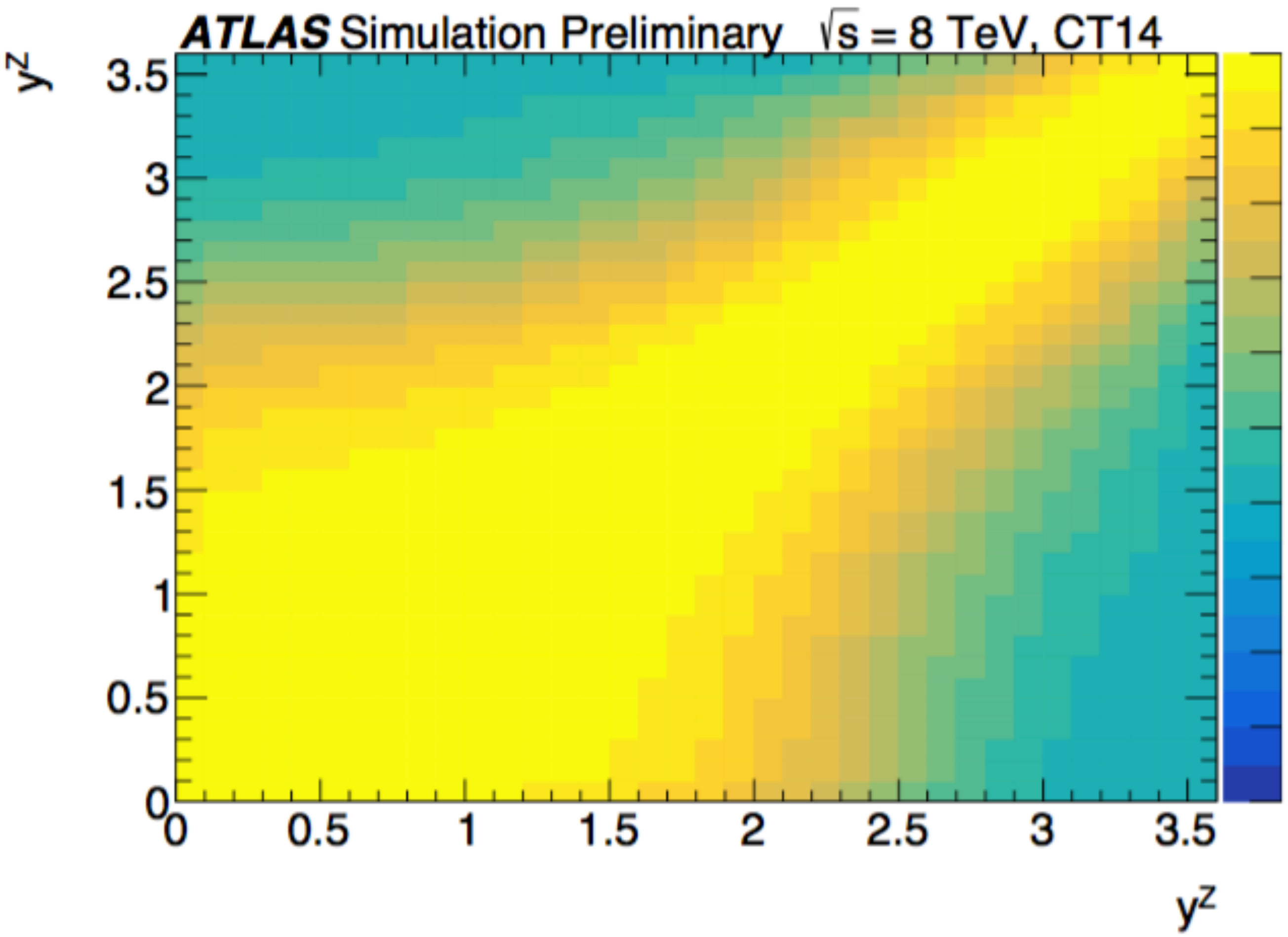


PDF sensitivity





PDF correlations



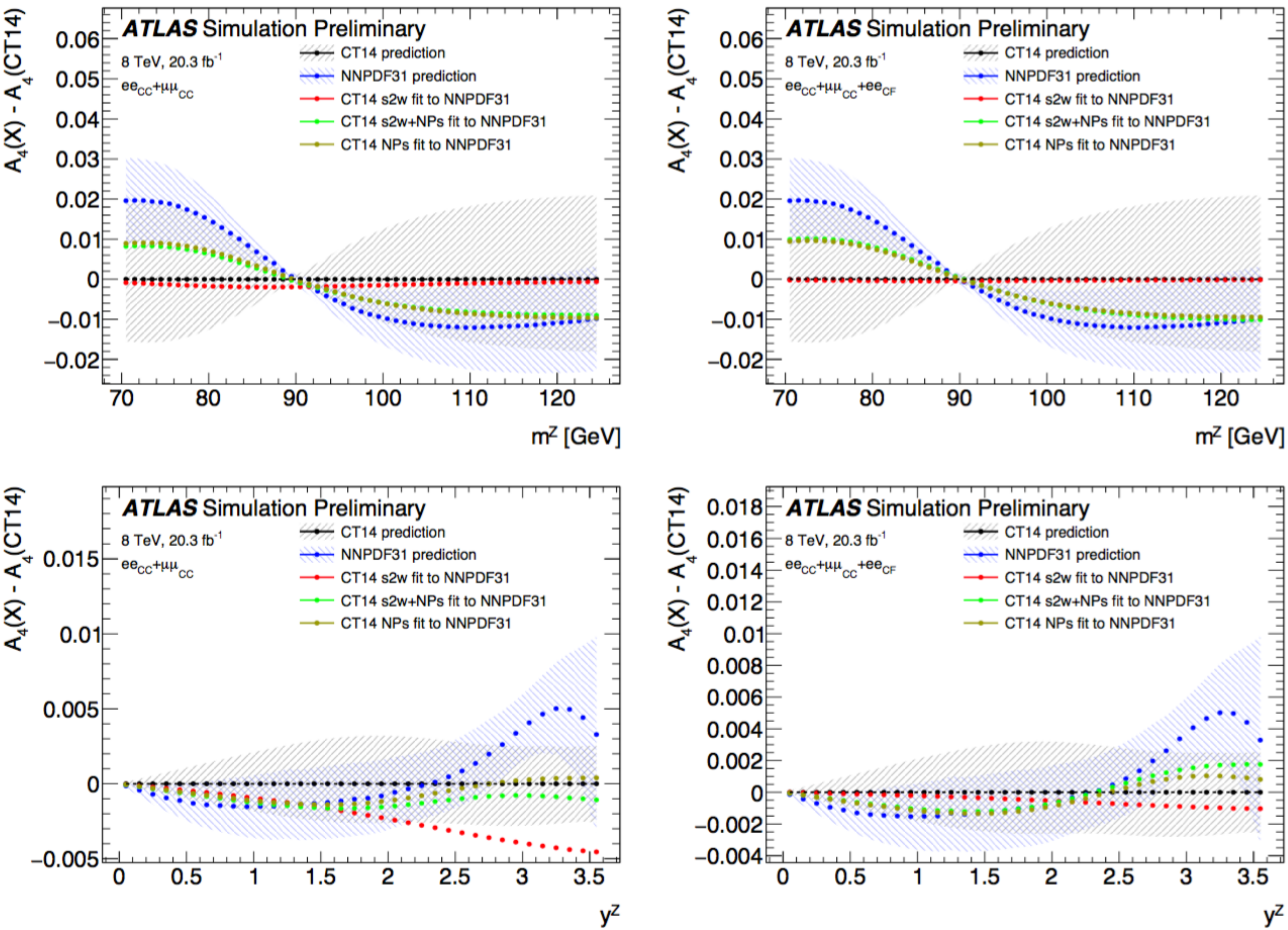
- Interesting structures in the correlation between the predicted A_4/A_{FB} and the boson rapidity
  - Strong and positive among neighbouring yZ, become negative for distant yZ bins
- Experimental measurements are binned in m_{ll} and y_{ll}
- The predicted pattern of correlations plays an important 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

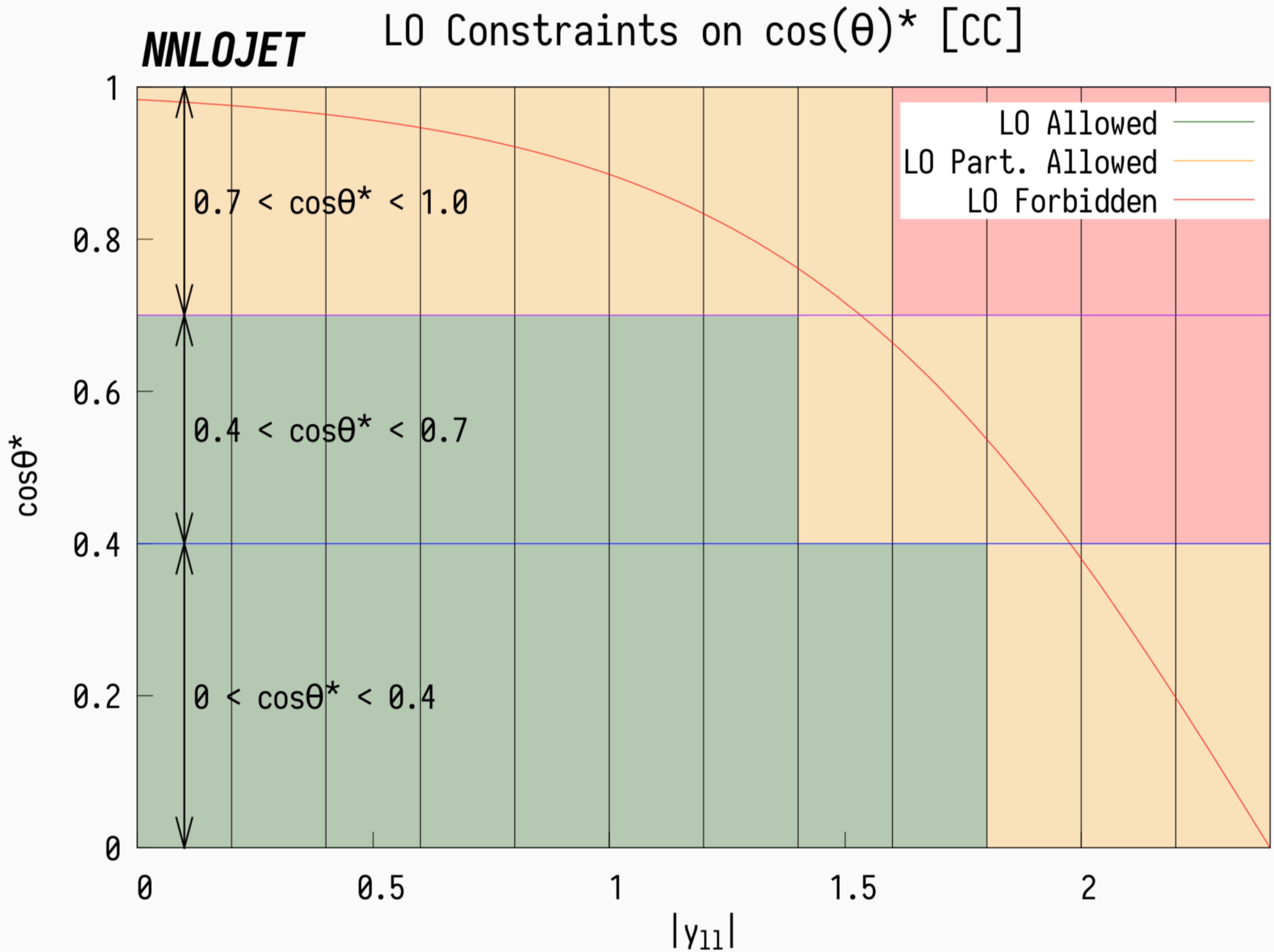


Projections

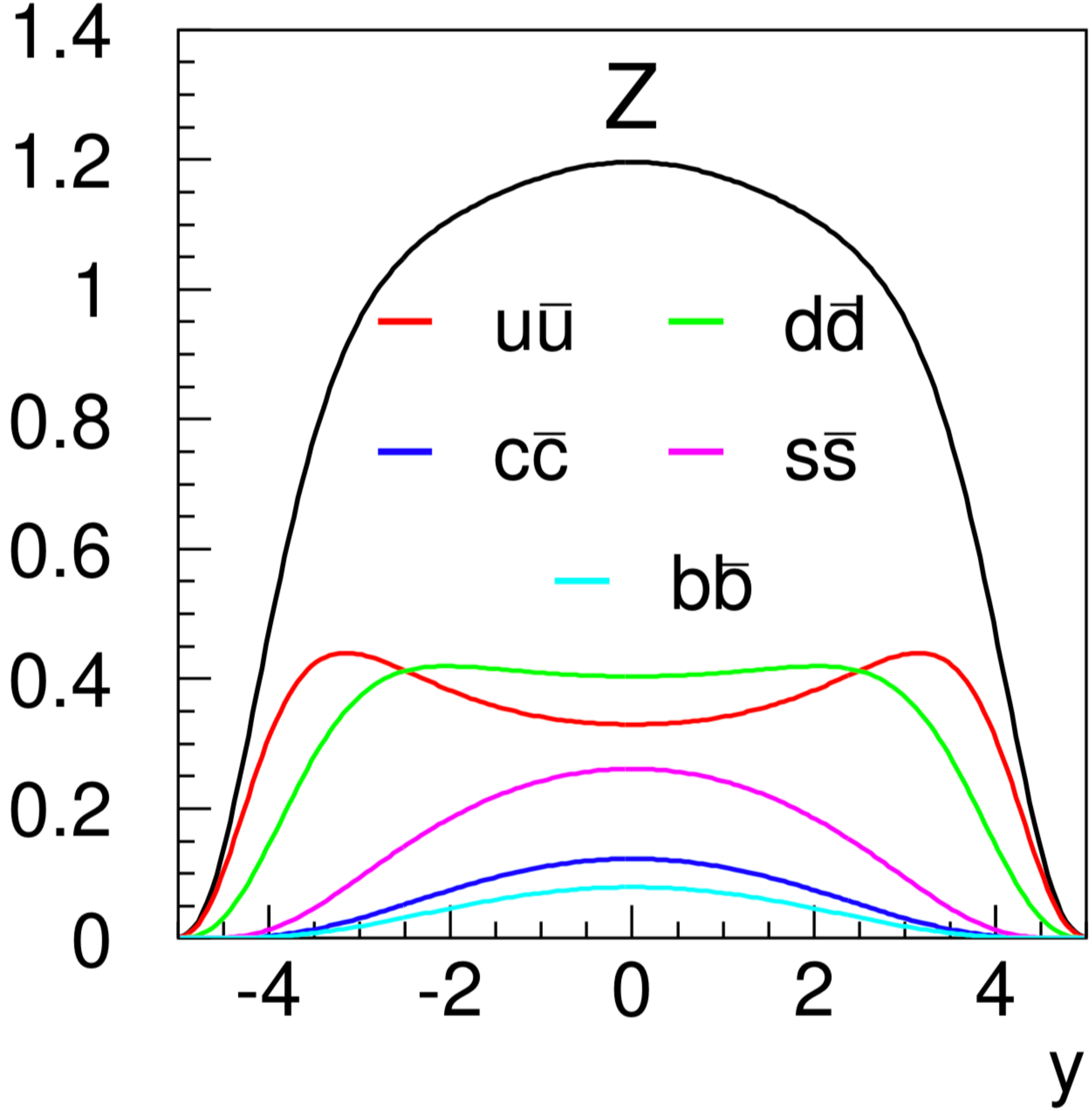
https://arxiv.org/abs/1507.02470

	CMS like detector	2016 sample	2017-18 sample
	Energy	8 TeV	13-14 TeV
	Number of reconstructed events	8.2M $\mu^+\mu^-$ 6.8M e^+e^-	120M $\mu^+\mu^-$ -
	$\Delta \sin^2 \theta_W$		
(29)	Statistical error	$\pm$ 0.00034	$\pm$ 0.00011
	Weighted PDF error	$\pm$ 0.00022	$\pm$ 0.00014
(43)	(Stat+PDF) error	$\pm$ 0.00040	$\pm$ 0.00018
	$\Delta M_W^{indirect}$	MeV	MeV
	Statistical error	$\pm$17	$\pm$5
	weighted PDF error	$\pm$11	$\pm$7
	(Stat+PDF) error	$\pm$20	$\pm$9

comparable to the direct determination



NNLOJET
LO Constraints on cos(θ)* [CC]
LO Allowed
LO Part. Allowed
LO Forbidden
0.7 < cosθ* < 1.0
0.4 < cosθ* < 0.7
0 < cosθ* < 0.4
cosθ*
|y11|
1
0.8
0.6
0.4
0.2
0
0
0.5
1
1.5
2

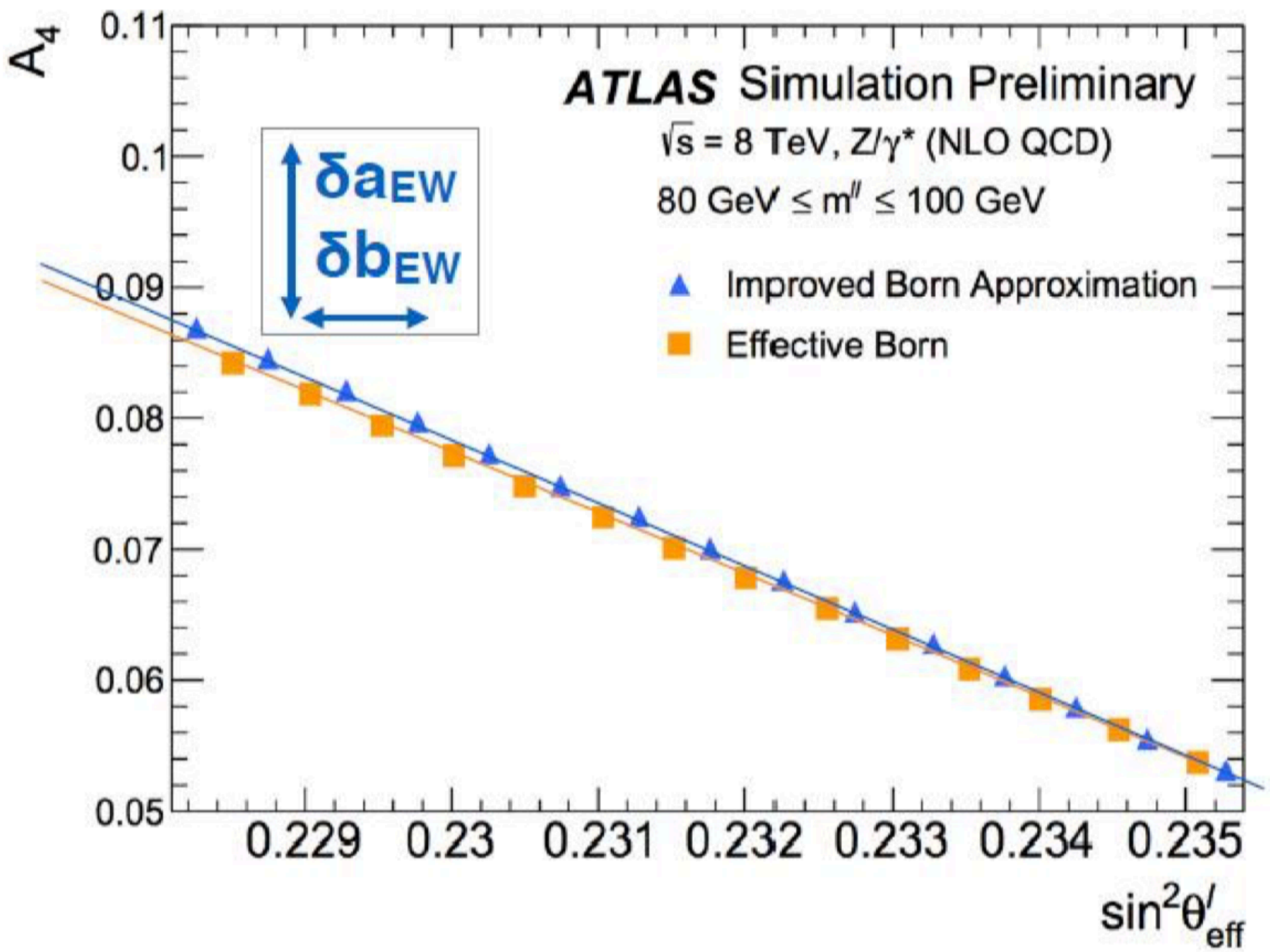


Z
$u\bar{u}$
$d\bar{d}$
$c\bar{c}$
$s\bar{s}$
$b\bar{b}$
1.4
1.2
1
0.8
0.6
0.4
0.2
0
-4
-2
0
2
4
y

Parameter	Value	Description
	Measured	
m_Z	91.1876 GeV	Mass of Z boson
m_H	125.0 GeV	Mass of Higgs boson
m_t	173.0 GeV	Mass of top quark
m_b	4.7 GeV	Mass of b quark
$1/\alpha(0)$	137.0359895(61)	QED coupling constant in Thomson limit
G_μ	$1.166389(22) \cdot 10^{-5}$ GeV^{-2}	Fermi constant from muon lifetime
	Calculated	
m_W	80.353 GeV	Mass of W boson
$\sin^2\theta_W$	0.22351946	On mass-shell-value of weak mixing angle
$\alpha(m_Z^2)$	0.00775995	
$1/\alpha(m_Z^2)$	128.86674175	
$ZPAR(6) - ZPAR(8)$	0.23175990	$sin^2\theta^{\ell}_{eff}(m_Z^2)$ (e, μ, τ)
$ZPAR(9)$	0.23164930	$sin^2\theta^{u}_{eff}(m_Z^2)$ (up quark)
$ZPAR(10)$	0.23152214	$sin^2\theta^{d}_{eff}(m_Z^2)$ (down quark)

LO EW | **NLO+HO EW**

$$A_4 = a^* \sin^2\theta_W + b \rightarrow (a+\delta a_{EW})^* \sin^2\theta^l_{eff} + (b+\delta b_{EW})$$



$$v_\ell = \quad (2 \cdot T_3^\ell - 4 \cdot q_\ell \cdot \boxed{s_W^2 \cdot K_\ell(s,t)} + \boxed{\delta_V})/\Delta$$

nominal $\sin^2\theta^l_{eff}$

Step A:

A4 calculated using PowhegZj MC. Adding term δV to vector couplings allows to derive A4($\sin^2\theta_{eff}$) dependency.

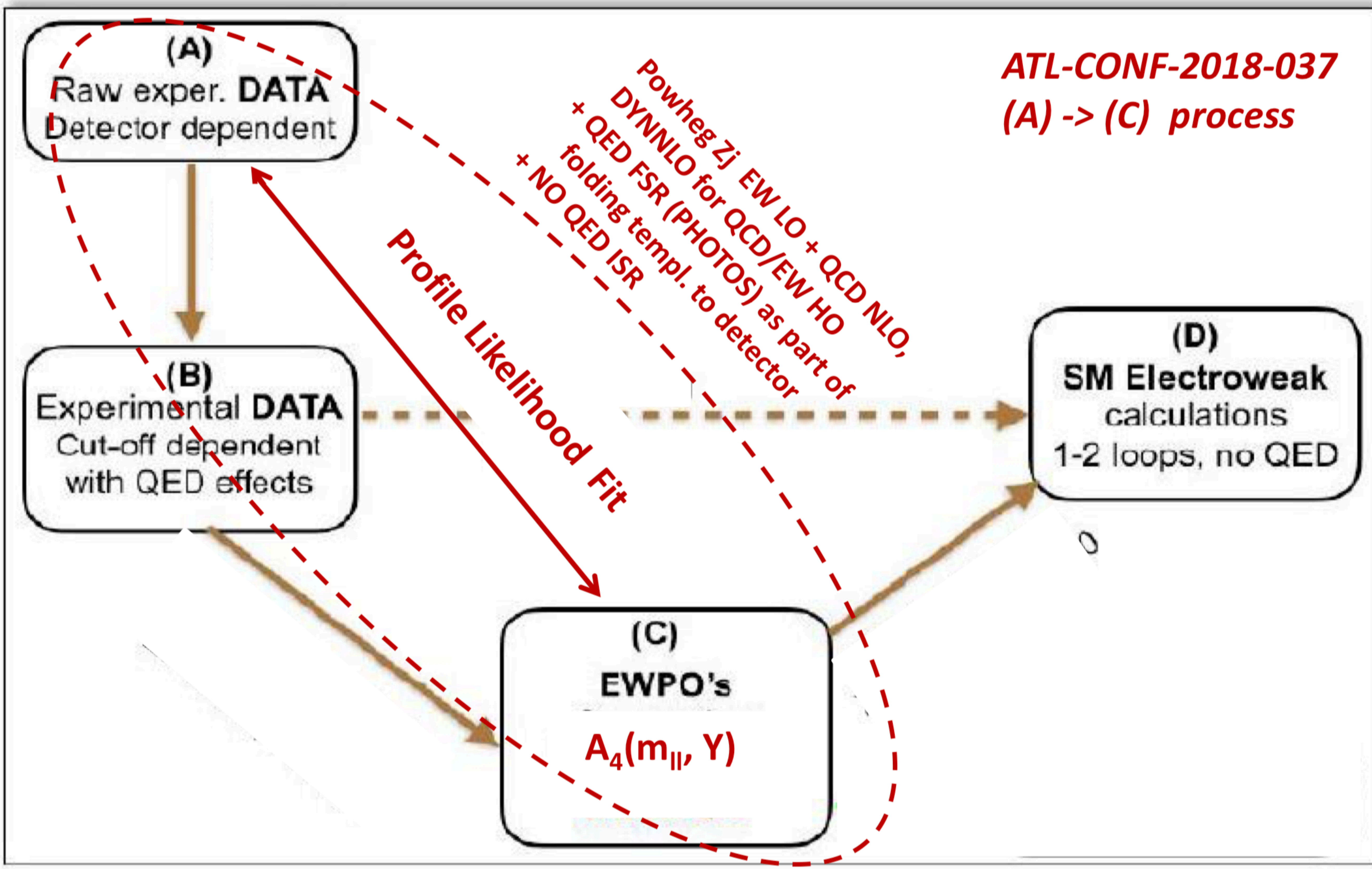
1) EW weights with form-factors from Dizet library
2) EW weights with effective Born-like couplings

– δa_{EW}, δb_{EW} calculated assuming linear relation for $\sin^2\theta_{eff}^{LEP}$ ± 100 10-5

Step B:

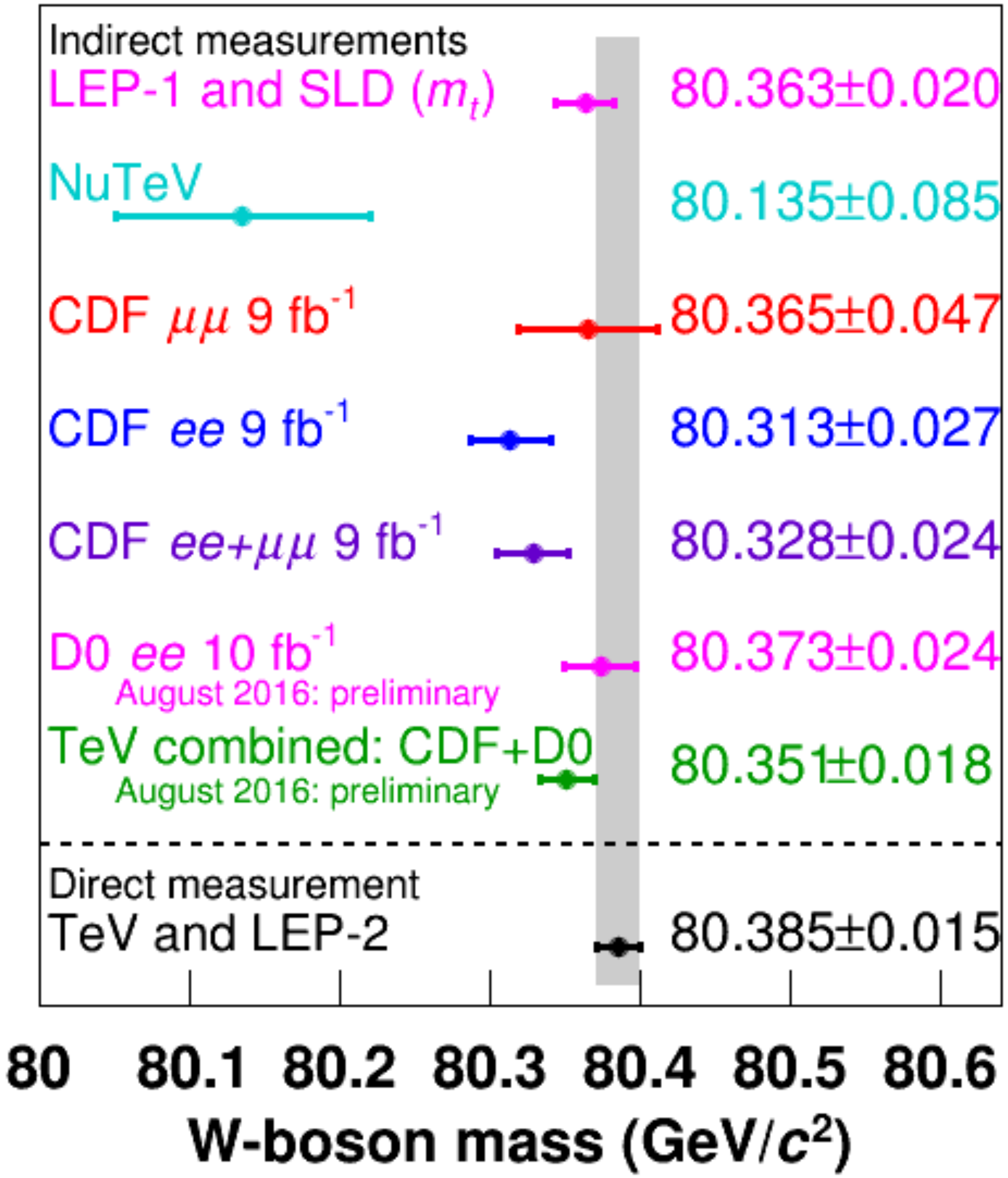
A4, a, b calculated using DYTURBO with $\sin^2\theta_W$ = 0.23152 ± 100 10-5 and Born ME

– δa_{EW}, δb_{EW} derived in step (A) applied as shift to a, b in step (B)

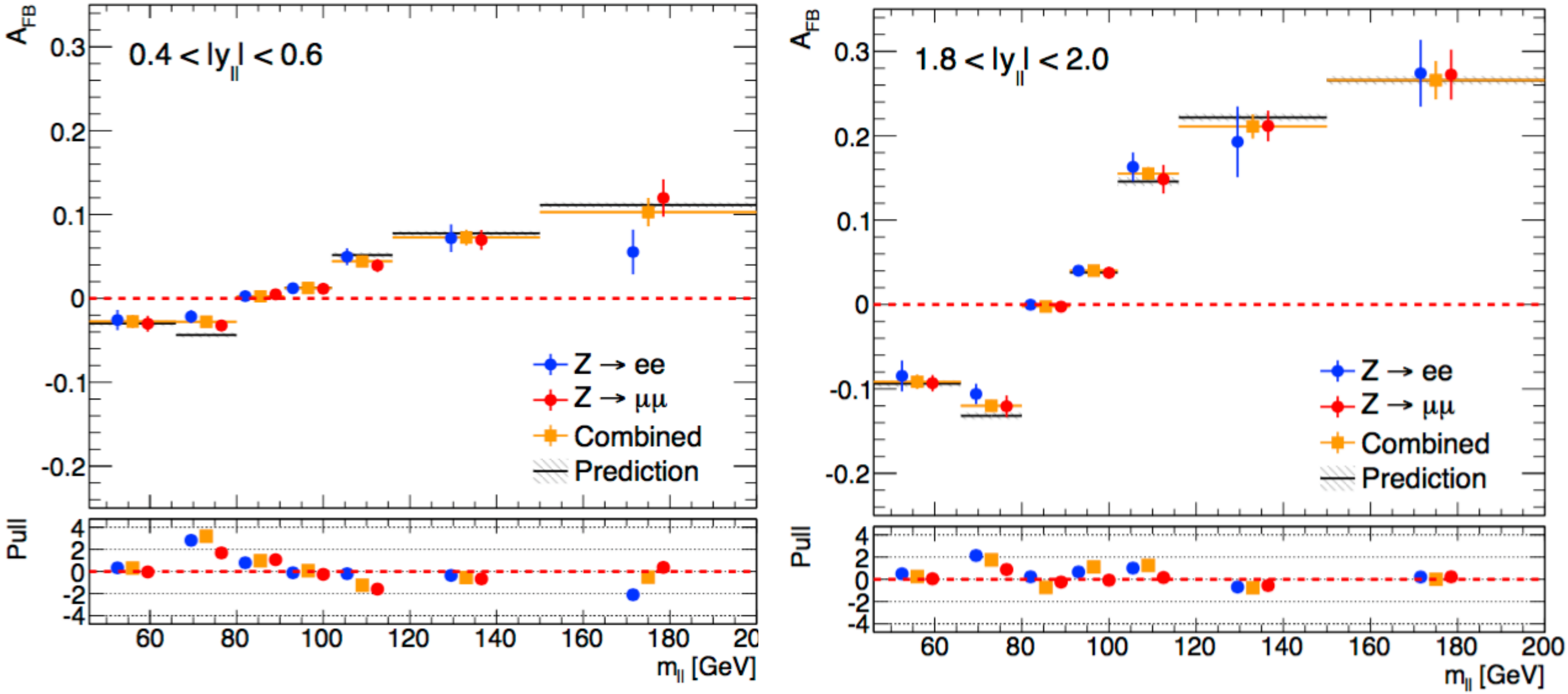


(A)
Raw exper. DATA
Detector dependent
(B)
Experimental DATA
Cut-off dependent
with QED effects
(C)
EWPO's
$A_4(m_{ll}, Y)$
(D)
SM Electroweak
calculations
1-2 loops, no QED
Profile Likelihood Fit
Powheg Zj EW LO + QCD NLO,
DYNNLO for QCD/EW HO
+ QED FSR (PHOTOS) as part of
folding templ. to detector
+ NO QED ISR
ATL-CONF-2018-037
(A) -> (C) process

Indirect mW determination



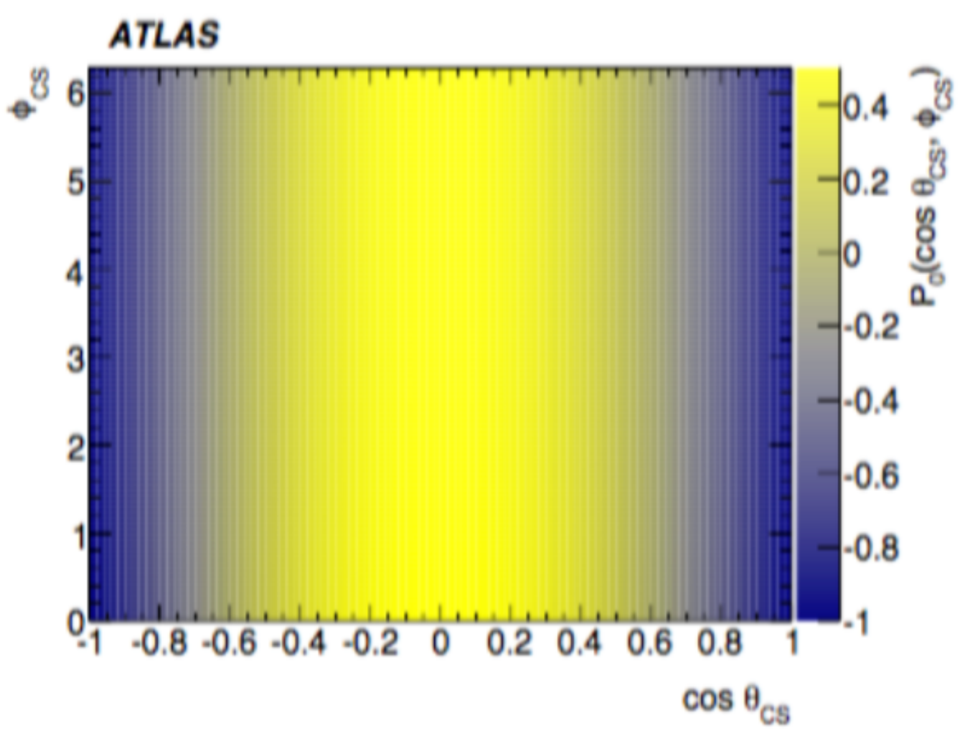
Z 3D

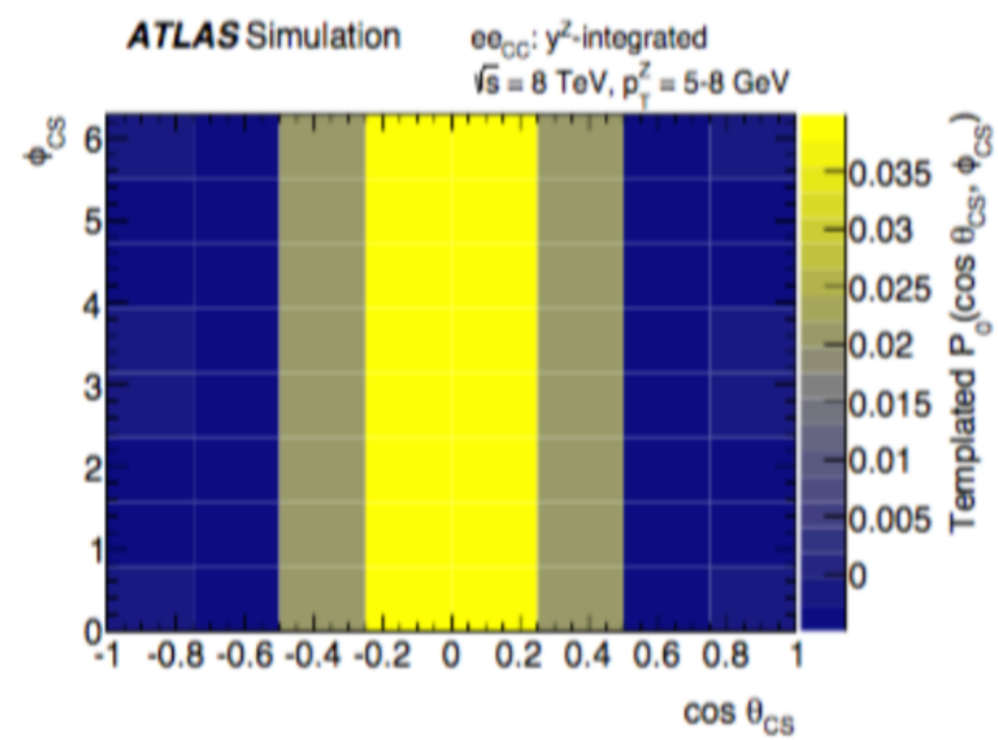


CC electrons only

	$\Delta \sin^2 \theta_W$
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**

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

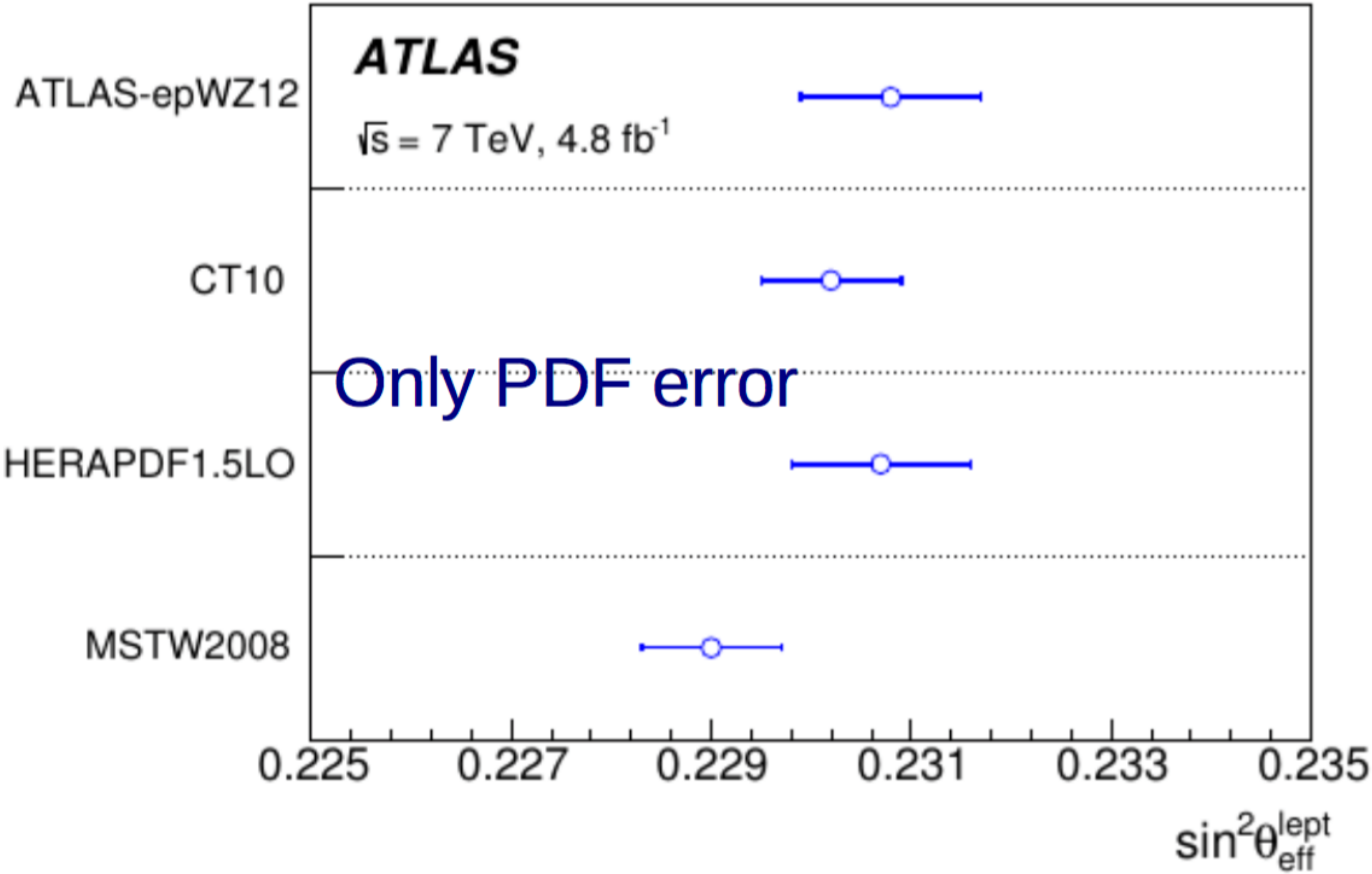
Z pT normalization parameters — **Folded polynomial templates**

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.

ATLAS PDF errors

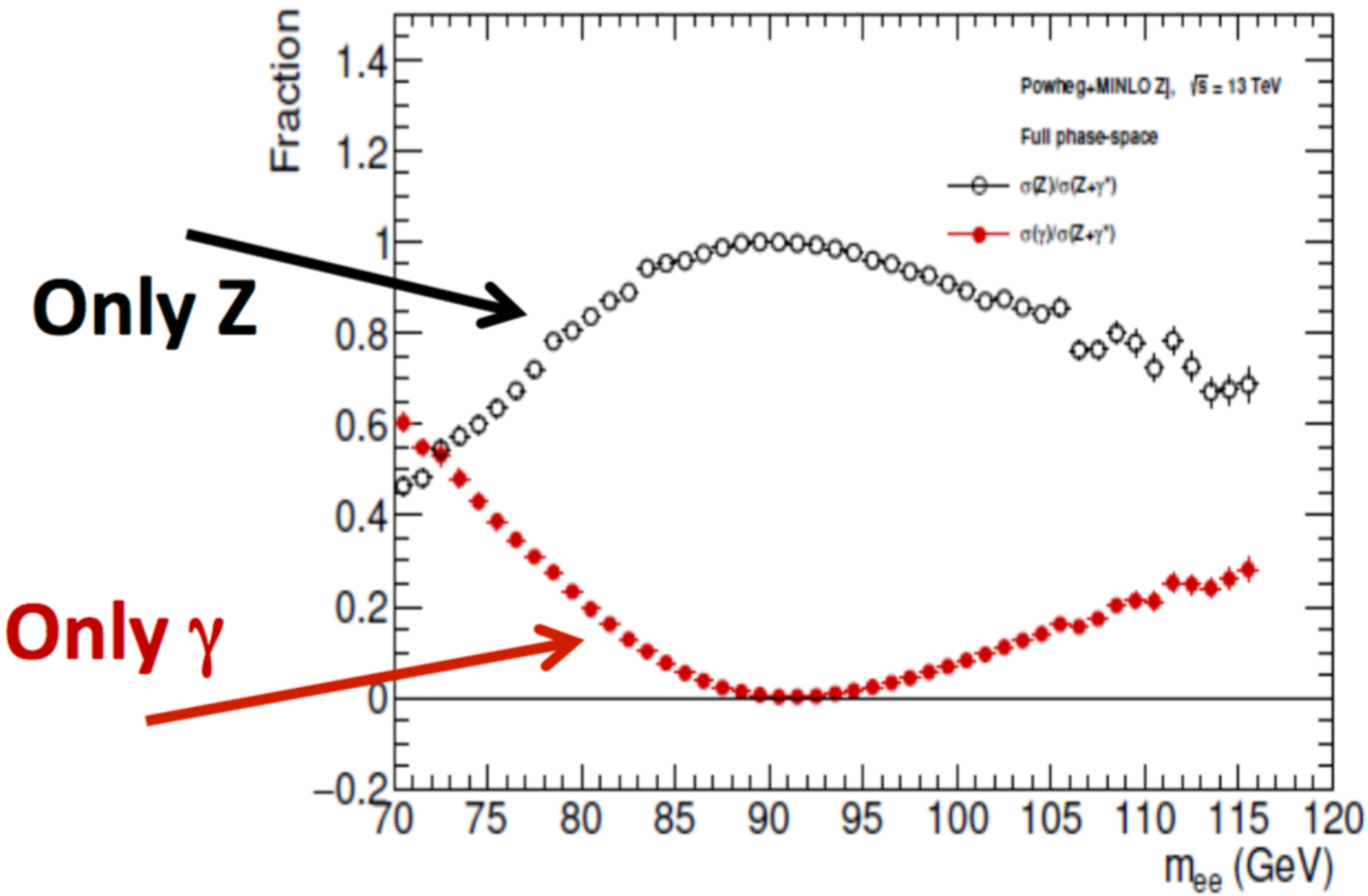


ATLAS BREAKDOWN

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

Full phase-space



CDF COMBINED

TABLE V. Extracted values of $\sin^2\theta_{\text{eff}}^{\text{lept}}$ 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	$\sin^2\theta_{\text{eff}}^{\text{lept}}$	$\sin^2\theta_W$	$\delta\sin^2\theta_W$	$\bar{\chi}^2$
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)

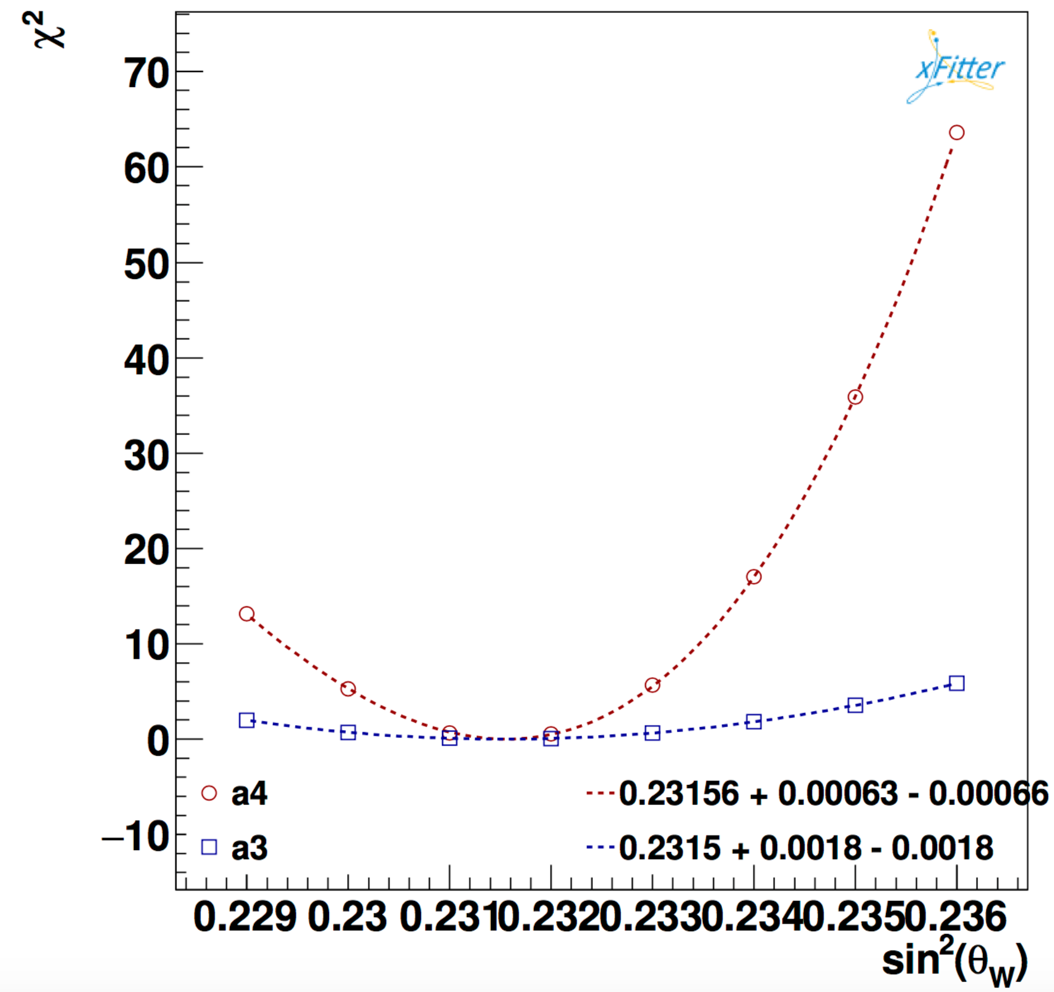
CDF combined

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

Source	$\sin^2\theta_{\rm eff}^{\rm lept}$	$\sin^2\theta_W$
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

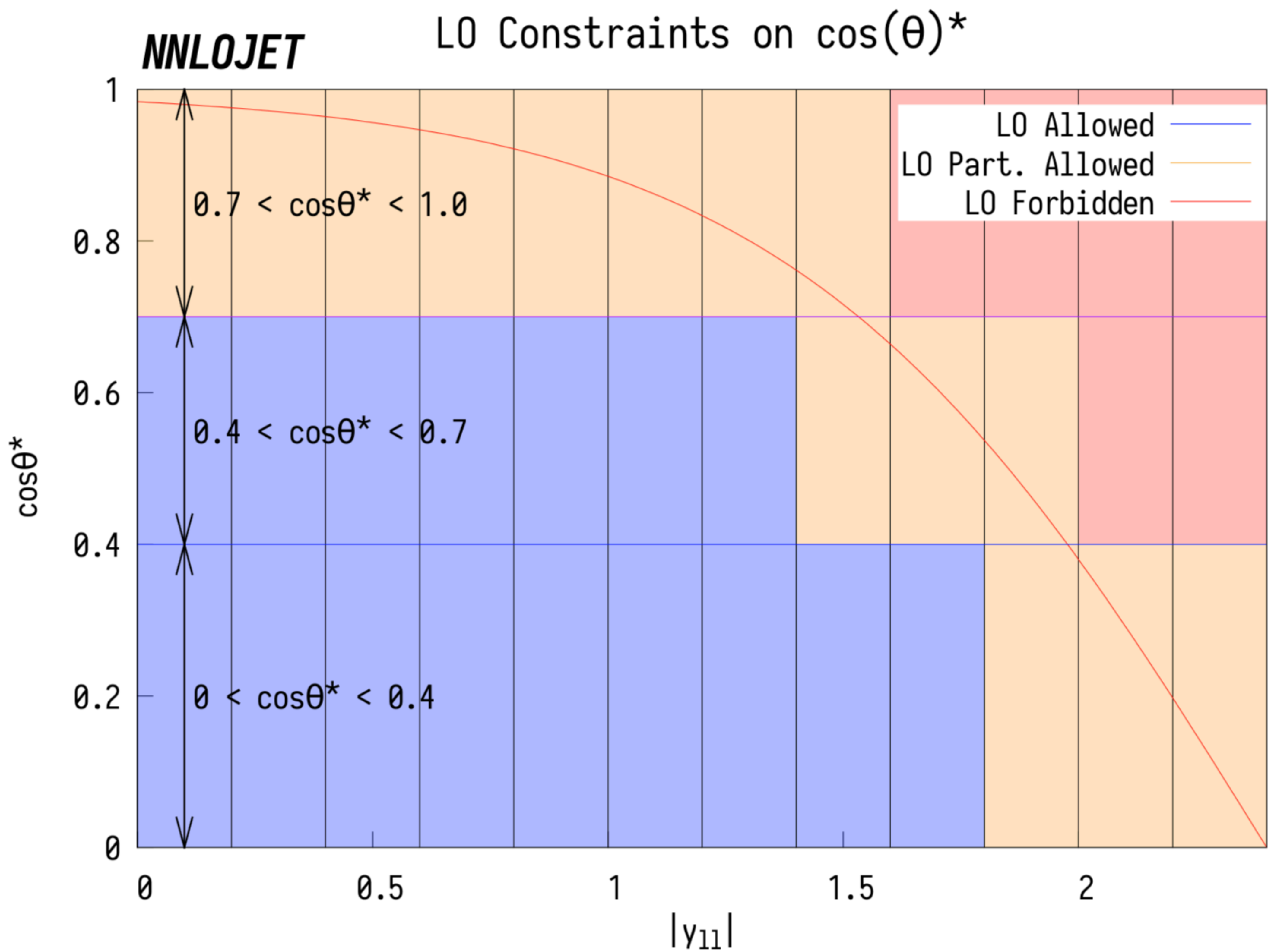
- Performed a test extraction of the s2w from the published values of A4 as function of pTZ
  - Using XFitter for chi2 minimisation
  - Predictions at each value of $\sin^2\theta_W$ from DYTURBO (LO) with CT10nlo



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.



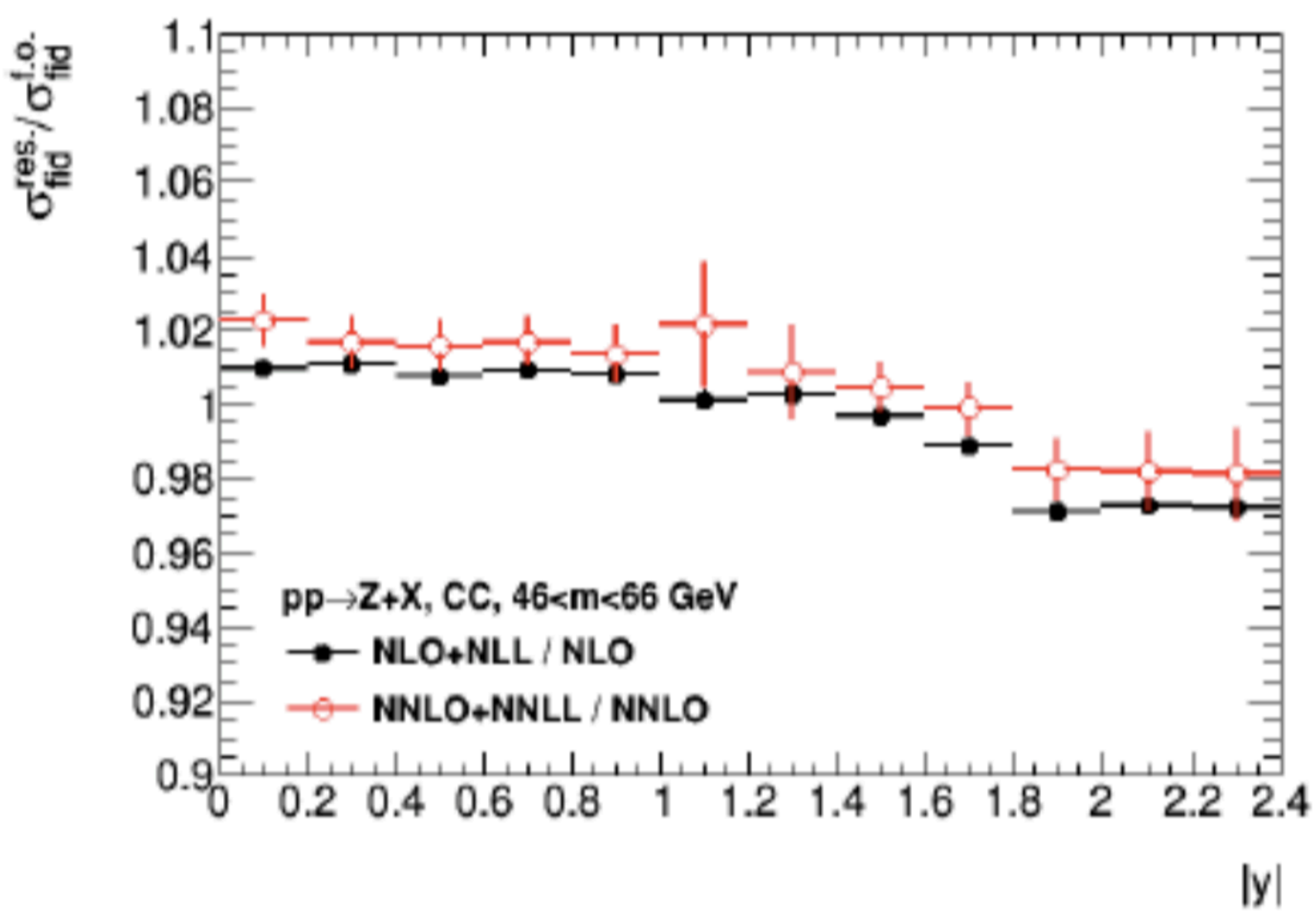
NNLOJET
LO Constraints on cos(θ)*
LO Allowed
LO Part. Allowed
LO Forbidden
0.7 < cosθ* < 1.0
0.4 < cosθ* < 0.7
0 < cosθ* < 0.4
cosθ*
|y11|
0
0.2
0.4
0.6
0.8
1
0
0.5
1
1.5
2

PDF profiling vs fits

- PDF profiling is not a replacement for a full fit
- Profiling can fail if the impact of the new data is too large
  - They can't account for methodological changes, such as in the PDFs parametrisation or modification needed to theory calculations
  - Standard versions of profiling assume a DeltaChi2=1 criterion. This is generally not the case for global fits. The impact of the new data estimated with profiling will generally be different than including the same data in a new fit.
- Are results of a PDF(+WMA) fit of the Z3D data consistent with profiling?

Issues with NNLO

- Our 7 TeV W/Z data has uncovered a discrepancy in the NNLO theory predictions used, which affects their usage in PDF fits
  - The two codes differ in their treatment of IR singularities cancellations (sector decomposition vs qT subtraction)
  - Effect depends on fiducial selection, 0.2% agreement in full phase-space, but % level differences after lepton cuts



- Soft gluon resummation should mitigate this issue
- Should be considered by future fit of precise DY data (already done by CT)
- Impact on fits to Z3D (and WMA) is yet to be evaluated

Long term possibilities

- PDF uncertainties will become even more important for future Run2/3 measurements (both WMA and W mass)
- We have no guarantee that the spread among global fits will reduce significantly in the future and differences in their methodology and theory inputs will likely not be addressed
- Effort started within the LHC EWK WG and PDF4LHC communities to estimate (using toys) correlations among different global fits
- On a longer timescale a proper QCD+EWK fit would solve most of the issues we currently have with PDFs
- And provide a framework for adding and combining additional measurements