Overview of ATLAS 8 TeV $\sin^2\theta^l_{eff}$ measurement

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$\sin^2\theta_W$ and the Standard Model

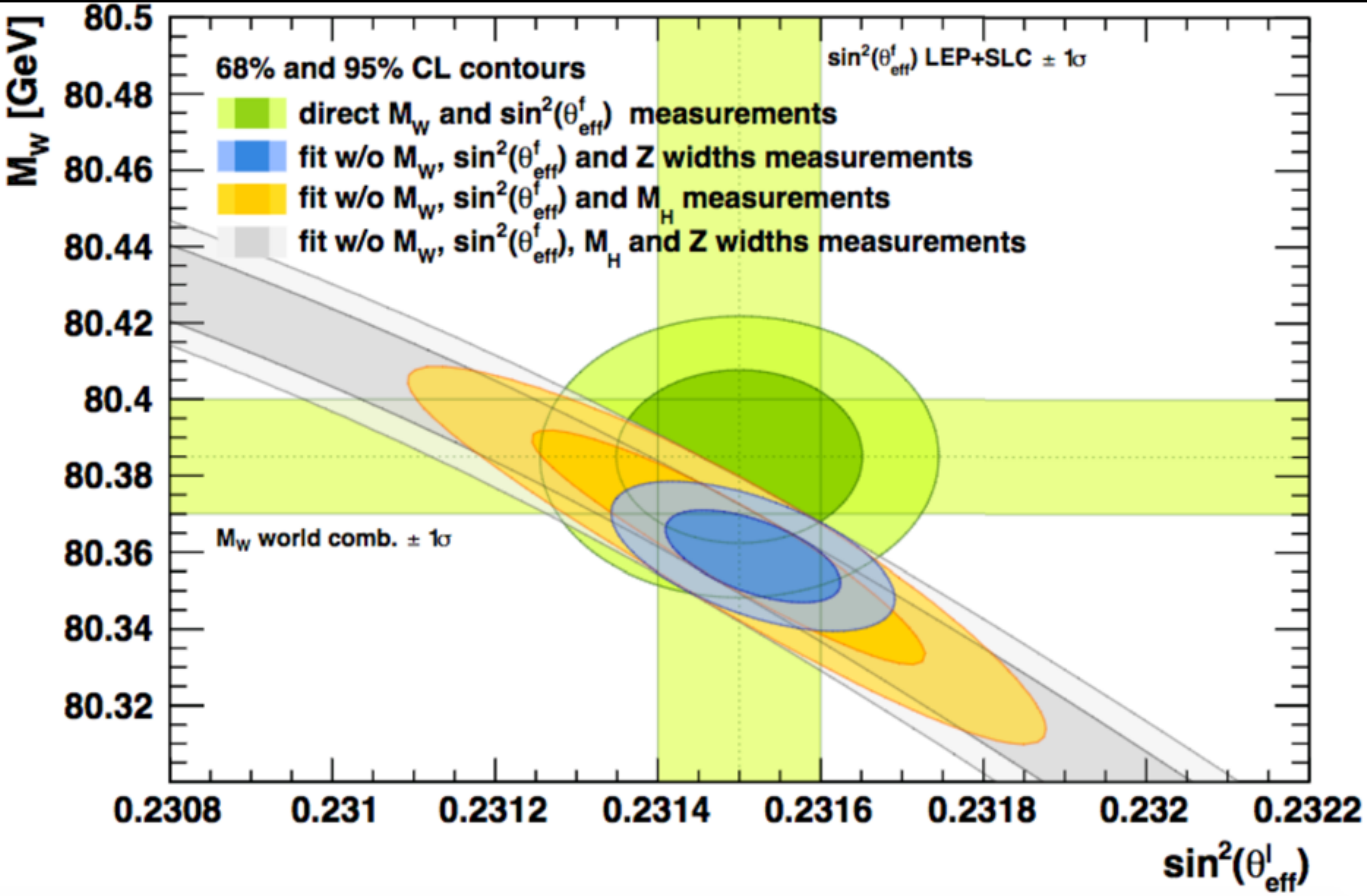
- $\sin^2\theta_W$: parameter of SM representing the mixing of the EM and weak fields
  - Relates the W- and Z-boson couplings $g_{W,Z}$, and therefore $m_{W,Z}$
  - EW corrections yield fermion-flavor dependent WMA → $\sin^2\theta^f_{eff}$

$$A_\mu = B_\mu \cos\theta_W + W^3_\mu \sin\theta_W$$
$$Z_\mu = -B_\mu \sin\theta_W + W^3_\mu \cos\theta_W$$

$$\sin^2\theta_W = 1 - g^2_W/g^2_Z = 1 - m^2_W/m^2_Z$$

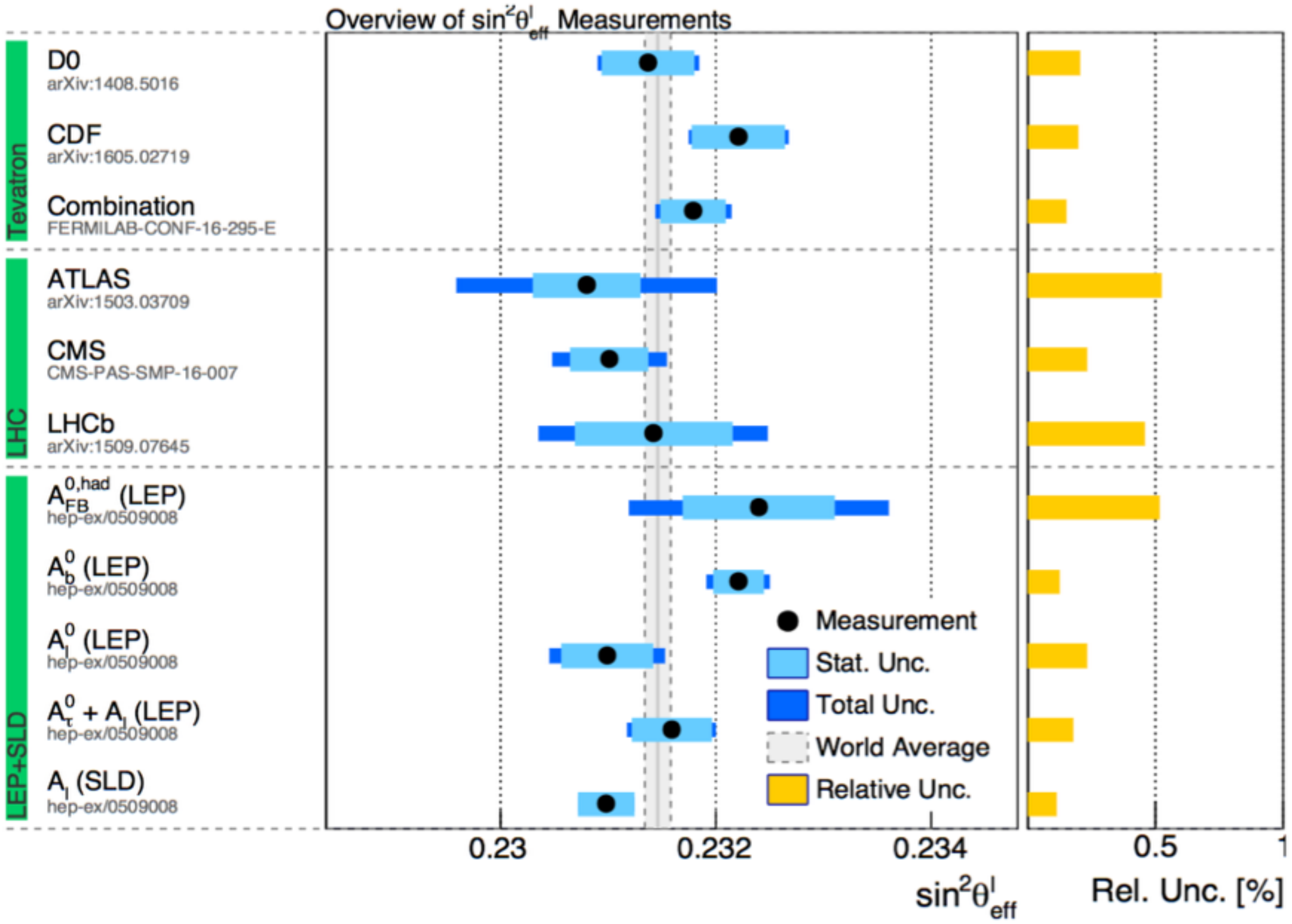
↓ EW Corr.

$$\sin^2\theta^f_{eff} = \sin^2\theta_W * K^f(s,t)$$

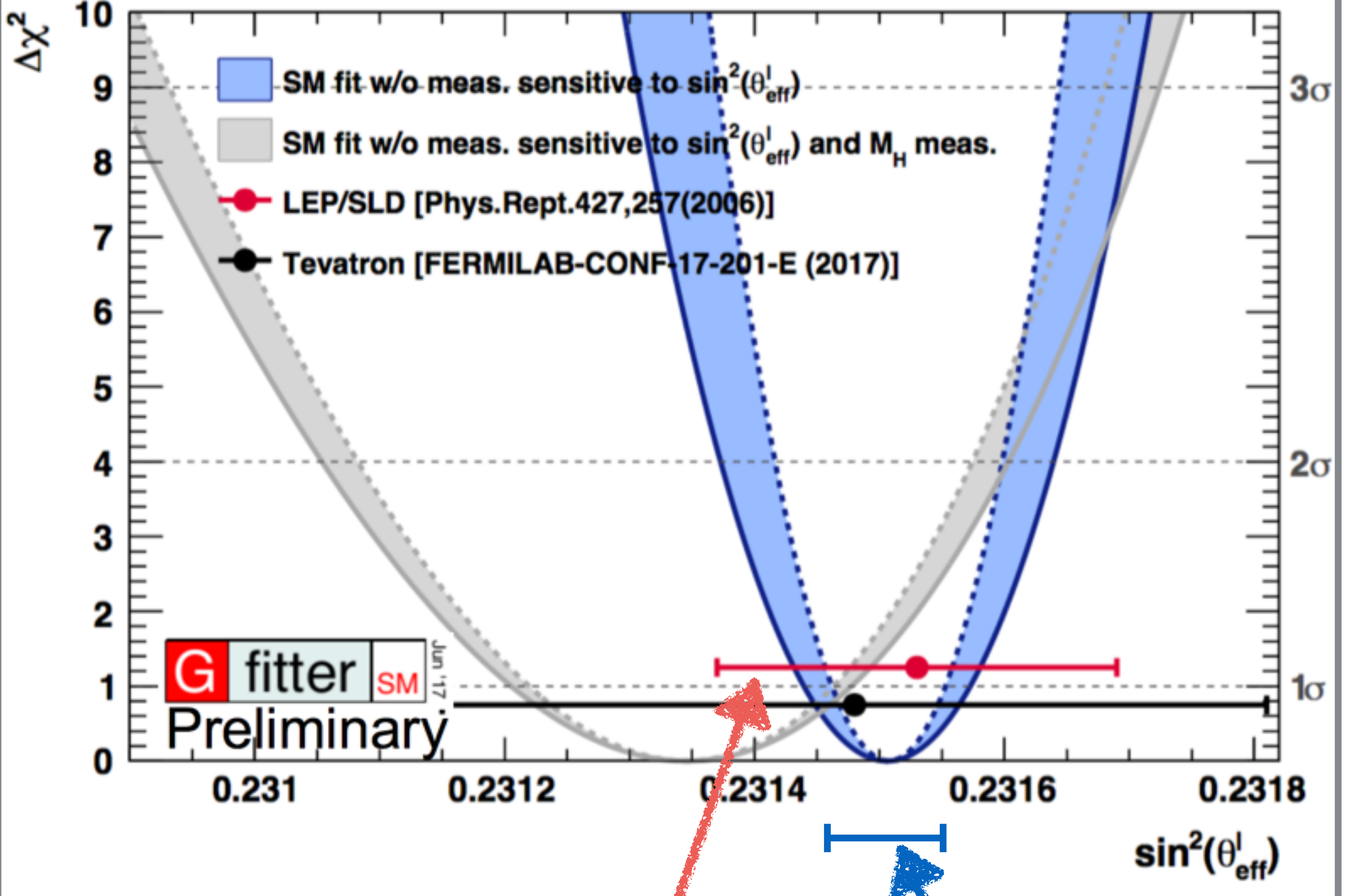


- Direct measurements of $\sin^2\theta^l_{eff}$ and m_W indirectly predict each other
- Test internal **consistency of the SM** as BSM probe
- Reanalysis of previous angular coefficient measurement (JHEP08(2016)159)
  - Optimized analysis binning
  - Improved data/MC modelling relevant to $\sin^2\theta^l_{eff}$
  - Cross-checked with "Z3D" (triple-differential cross-section) data

Previous measurements



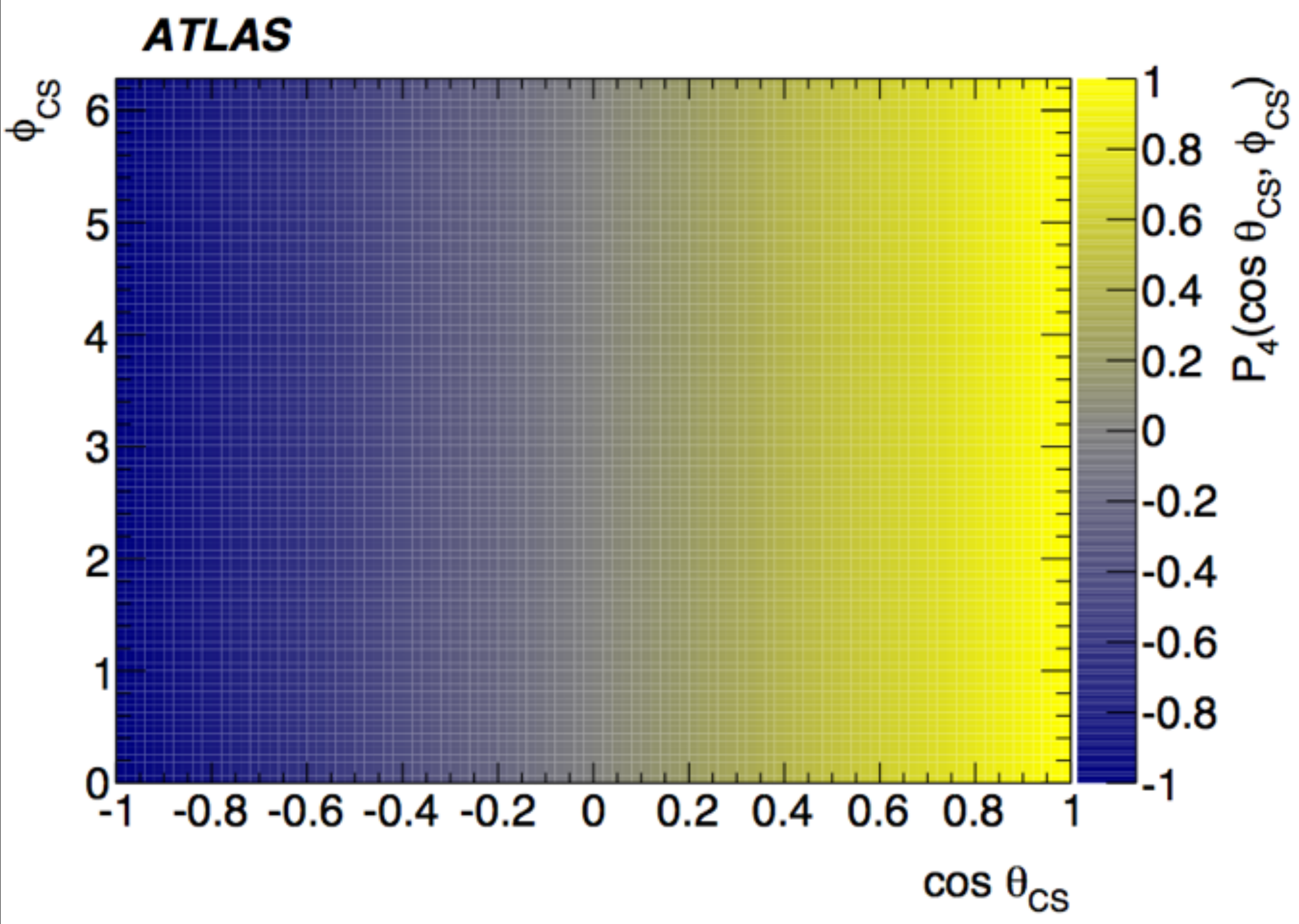
- LEP + SLD (2006): 29 and 26 x10^{-5}
- ATLAS 7 TeV (2015): 120x10^{-5}
- LHCb 7+8 TeV (2015): 106x10^{-5}
- D0+CDF (2018): 33x10^{-5}
- CMS 8 TeV (2018): 52x10^{-5}
- ATLAS 8 TeV (2018): 36x10^{-5} ⬅ Result presented here



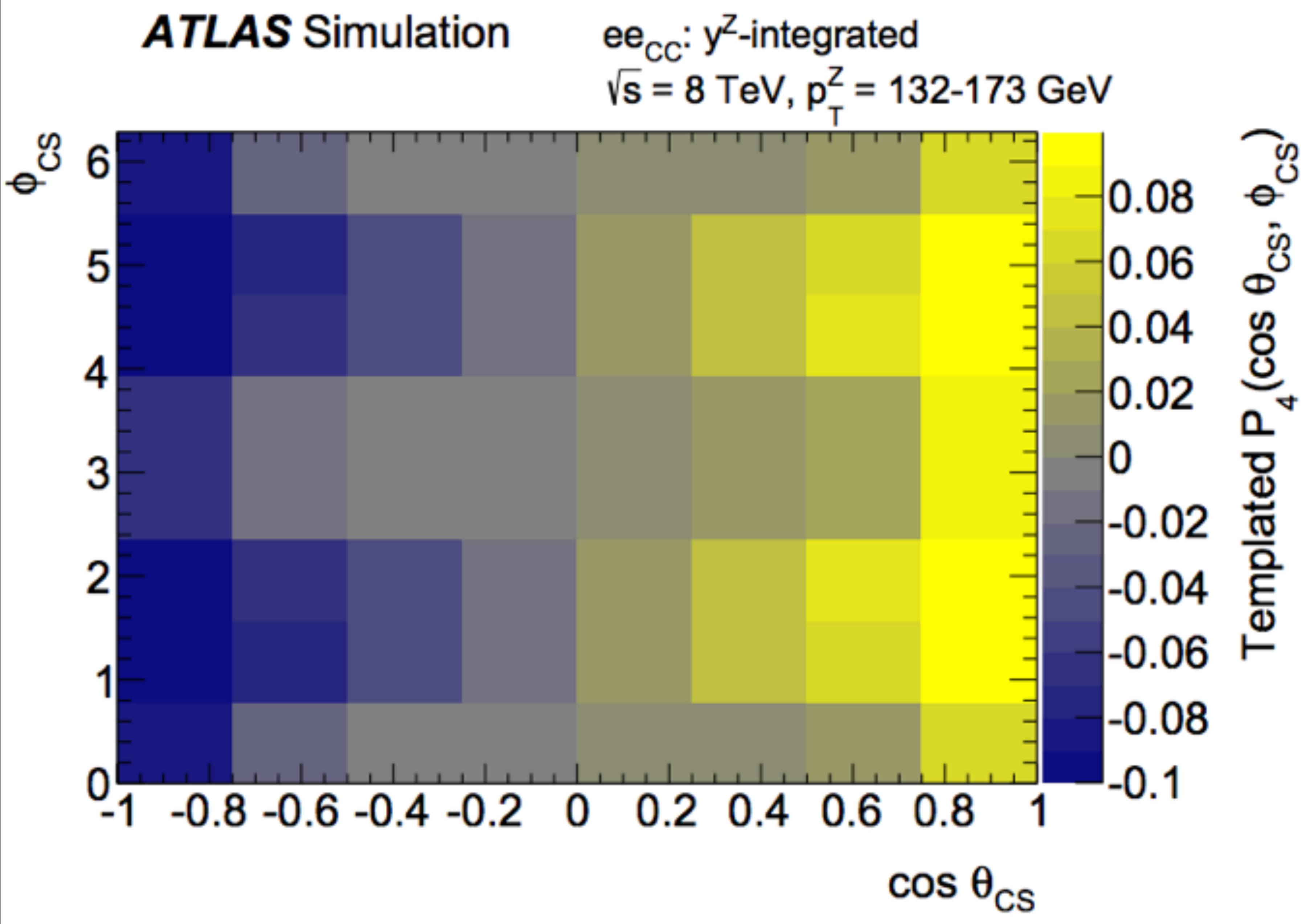
Direct measurements, average ~16x10^{-5} precision

SM prediction, from fit w/out direct measurements, ~6x10^{-5}

Methodology



Detector folding:
Acc * eff * reso

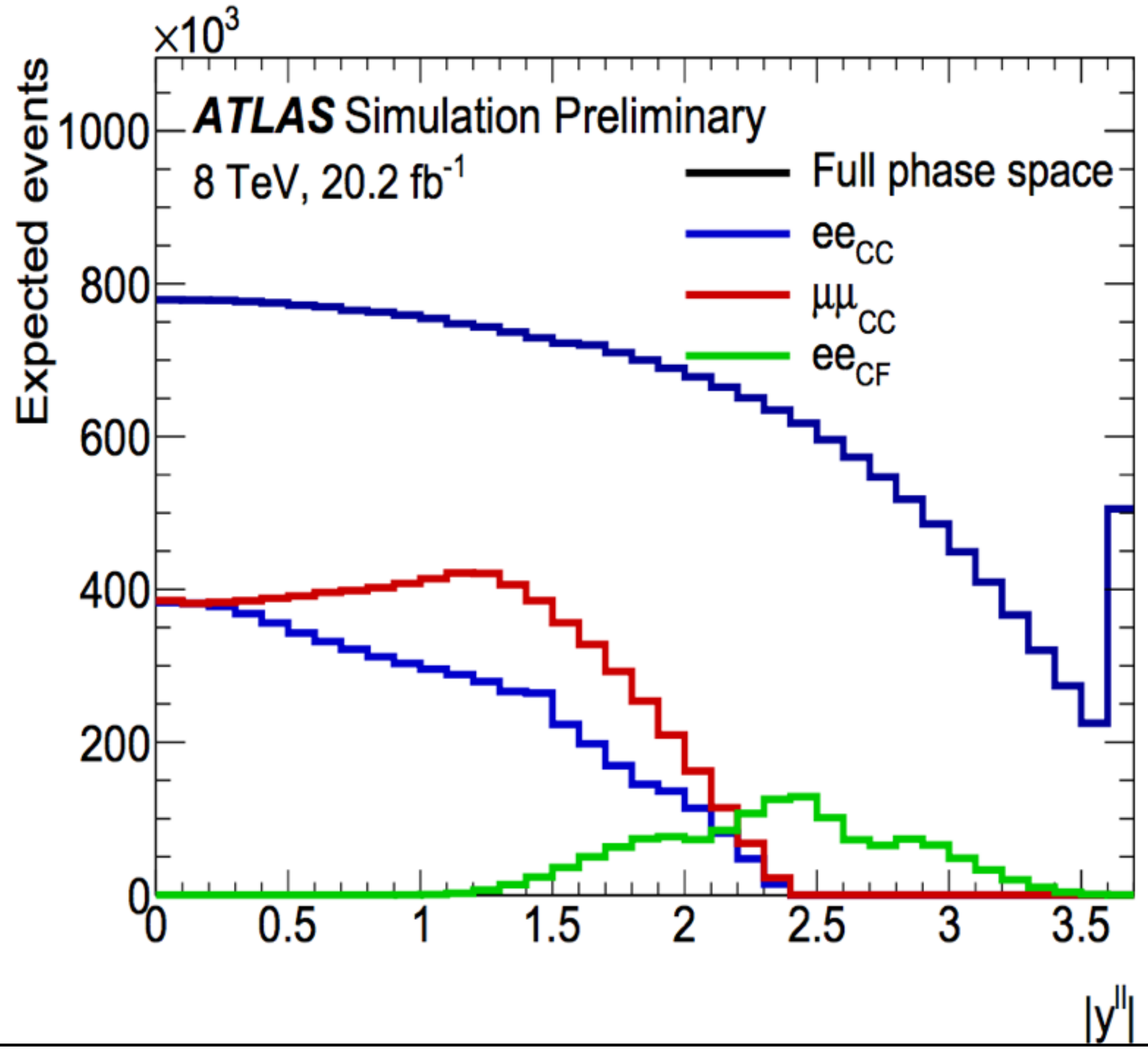


$$\frac{d^5\sigma}{dp_T^Z\, dy^Z\, dm^Z\, d\cos\theta\, d\phi} = \frac{3}{16\pi}\frac{d^3\sigma^{U+L}}{dp_T^Z\, dy^Z\, dm^Z}$$
$$\{(1+\cos^2\theta) + 1/2\, A_0(1-3\cos^2\theta) + A_1\, \sin 2\theta\, \cos\phi$$
$$+1/2\, A_2\, \sin^2\theta\, \cos 2\phi + A_3\, \sin\theta\, \cos\phi + A_4\, \cos\theta$$
$$+A_5\, \sin^2\theta\, \sin 2\phi + A_6\, \sin 2\theta\, \sin\phi + A_7\, \sin\theta\, \sin\phi\}.$$

- Use factorization of Drell-Yan cross-section in full lepton phase space
  - Production kinematics: p_T^Z, m^Z, y^Z
  - Decay angular variables: $\cos\theta$, φ
- Measure angles in Collins-Soper rest frame of Z boson
- **A_4 sensitive to $\sin^2\theta^l_{eff}$ via coupling structure**
  - Directly related to forward-backward asymmetry A_{FB}
- Fold angular polynomials $P_i(\cos\theta, \varphi)$ to detector level
- Fit to reco. angular distributions in m^Z, y^Z bins to extract A_{0-7} and σ^{U+L}
  - m^Z = [70, 80, 100, 125] GeV
  - $|y^Z|$ = [0.0, 0.8, 1.6, 2.5, 3.6]
- Use predictions of **A_4** to infer **$\sin^2\theta^l_{eff}$**

Selections and signal acceptance

- Central electrons and muons: $|\eta| < 2.4$ with $p_T > 25$ GeV
- Forward electrons: $2.5 < |\eta| < 4.9$, $p_T > 20$ GeV
- Three di-lepton channels with coverage between $0 < |y^Z| < 3.6$
  - $ee_{CC}+\mu\mu_{CC}$: 13.5M events
    - Highest statistics, low intrinsic $\sin^2\theta^l_{eff}$ sensitivity
    - Low background
    - Good for PDF constraints
    - Comparable to CMS measurement
  - ee_{CF} (1.5M events) channel covers $1.6 < |y^Z| < 3.6$
    - Low statistics, high intrinsic $\sin^2\theta^l_{eff}$ sensitivity
    - Experimentally difficult
    - Unique to ATLAS



ee_{CF}: Background fraction

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

ee_{CC}: Background fraction

$\|y_{ll}\|$	80 < m_{ll} < 100 GeV			
	Data	Top+EW	Multijets	Non-fiducial Z
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

Control plots

- Generally good modelling of angular distributions between data and MC "prefit"
- Angular coefficients measured in-situ → theory modelling corrected within fit
- Very high and very low |cosθ| regions in ee_{CF} related again to p_T^Z modelling
  - Covered by additional systematics
  - Removing these events has very little impact on measured $\sin^2\theta^l_{eff}$ ($\sim 1*10^{-5}$)
- Large lever-arm in eeCF channel: Contributes to superiority of channel

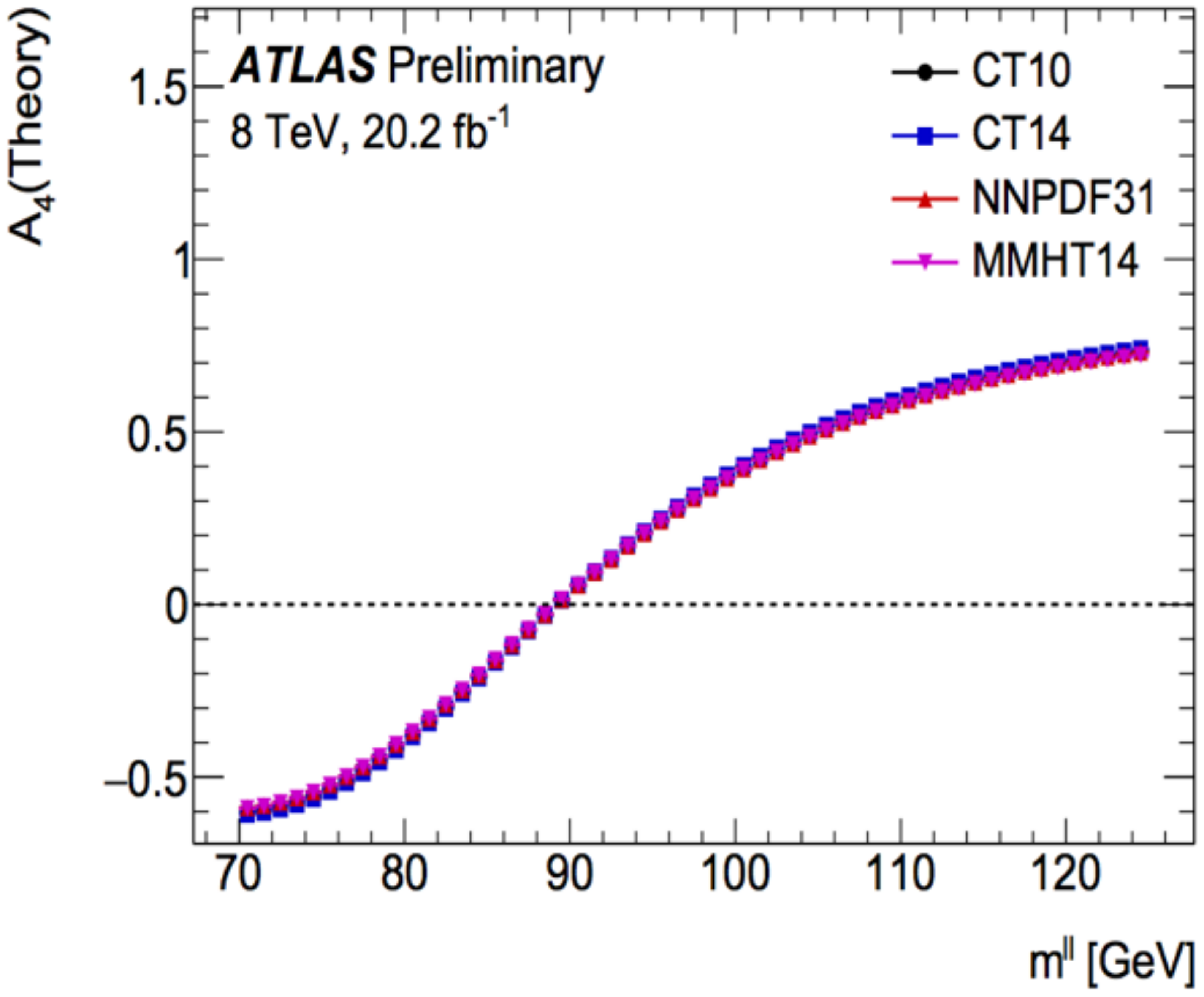
Uncertainties on A_4 measurement

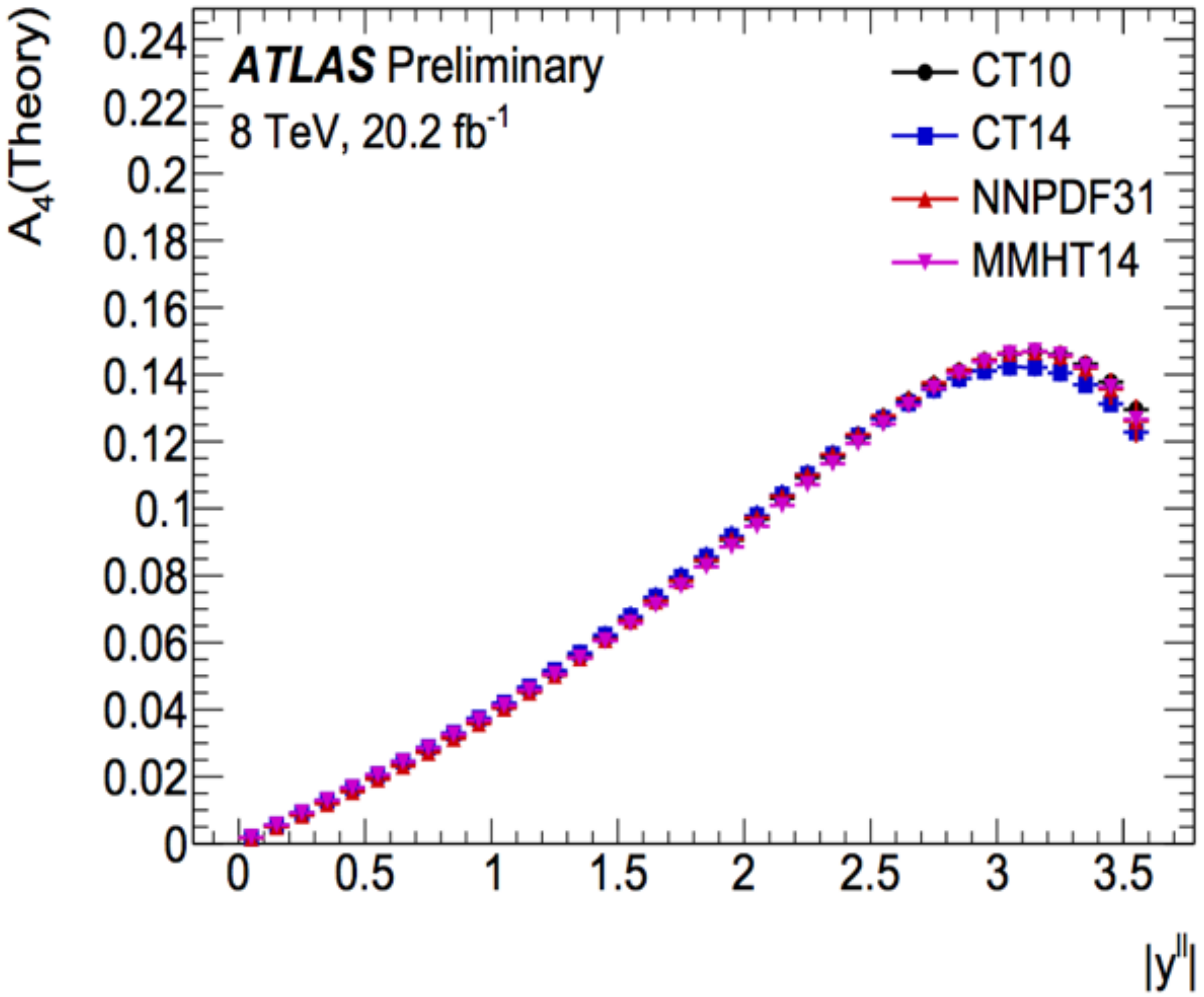
- Data and MC statistics
- Experimental and theoretical systematics
  - Leptons
    - Calibration
    - Identification
    - Reconstruction
    - Trigger
    - Isolation
  - Electron charge-flip probability
  - Misalignment: Muon sagitta bias
  - Multijet and EW+top background
  - PDFs: CT10nlo EVs
  - p_T^Z modelling in ee_{CF}
- PDF on A_4 measurement uncorrelated with those of A_4 predictions
- **Statistical uncertainties dominate measured A_4**

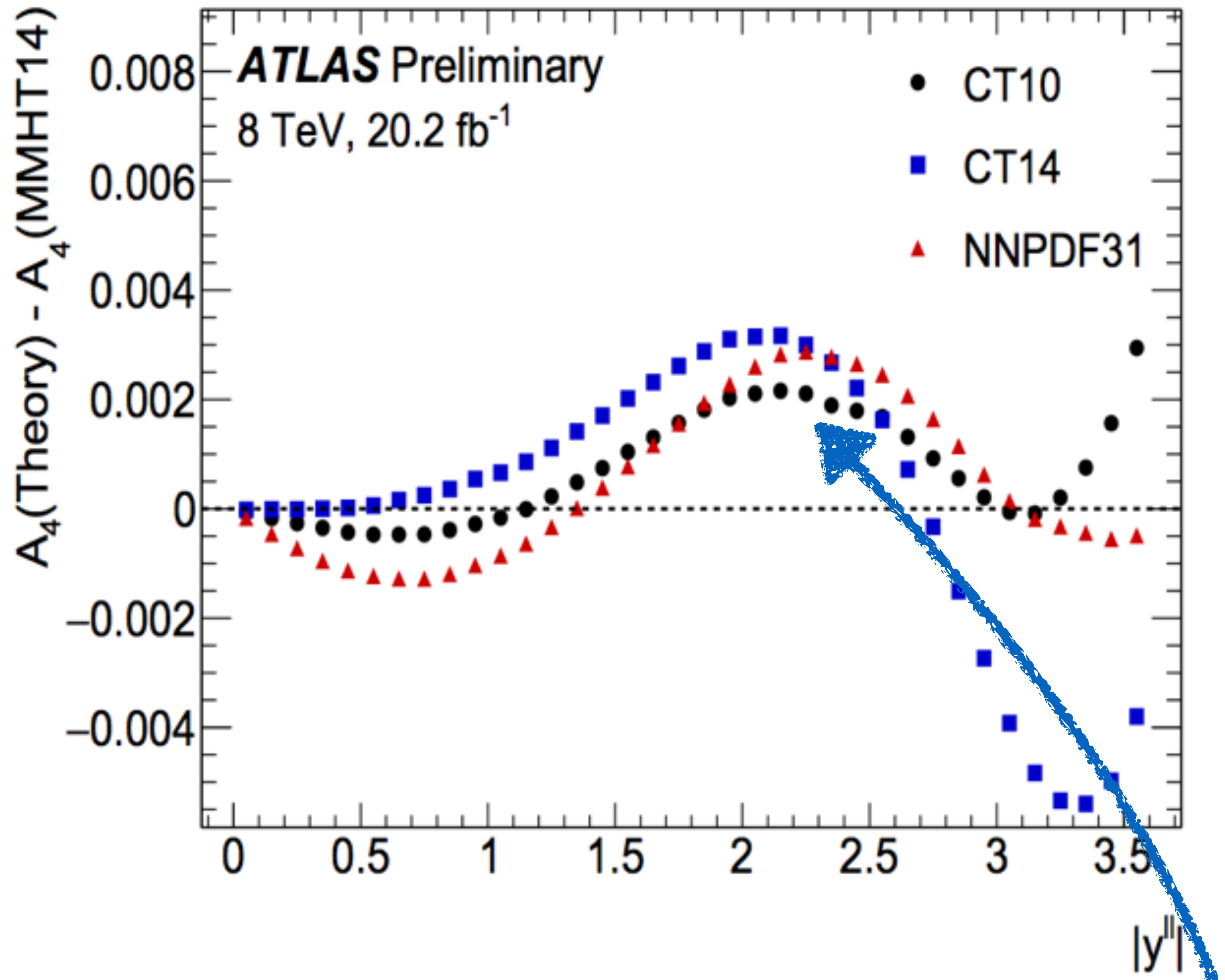
Uncertainties on measured A_4 (channels combined)

$m^{\ell\ell}$ (GeV)	80 – 100			
$\lvert y^{\ell\ell}\rvert$	0 – 0.8	0.8 – 1.6	1.6 – 2.5	2.5 – 3.6
Prediction (MMHT14)	0.0144	0.0471	0.0928	0.1464
	Uncertainties			
Total	0.0015	0.0015	0.0025	0.0044
Stat.	0.0013	0.0013	0.0021	0.0036
Syst.	0.0007	0.0008	0.0013	0.0025
PDF (meas.)	0.0001	0.0002	0.0004	0.0007
p_T^Z modelling	< 0.0001	< 0.0001	< 0.0001	< 0.0001
Leptons	0.0002	0.0001	0.0003	0.0007
Background	< 0.0001	< 0.0001	< 0.0001	0.0001
MC stat.	0.0007	0.0007	0.0012	0.0023

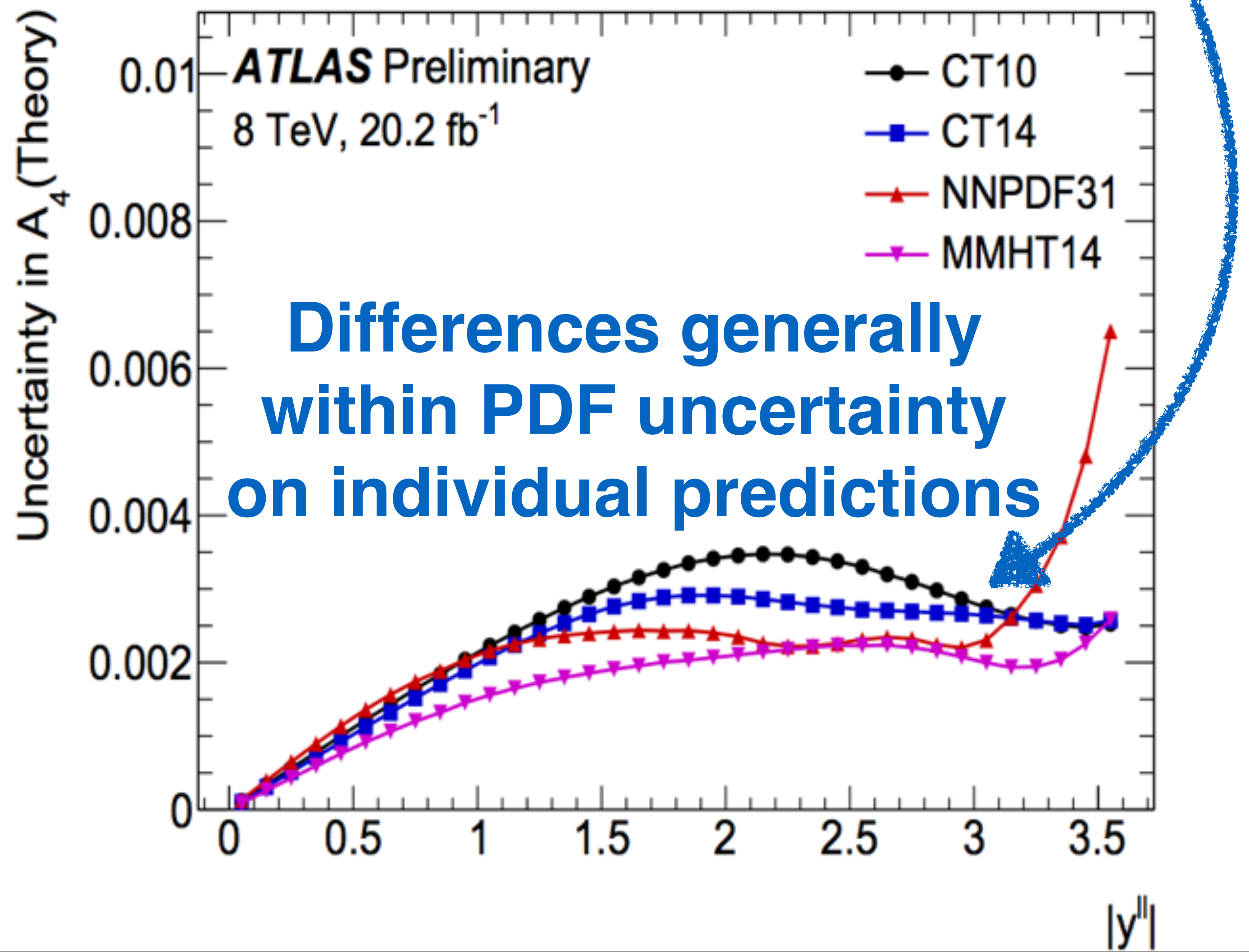
A_4 Predictions







- A_4 predictions calculated at NLO in QCD and LO EW for various PDF sets
  - CT10nnlo
  - CT14nnlo
  - NNPDF31_hessian_nnlo_pdfas
  - MMHT2014nnlo68cl
- Supplemented with NNLO QCD and NLO+HO EW corrections

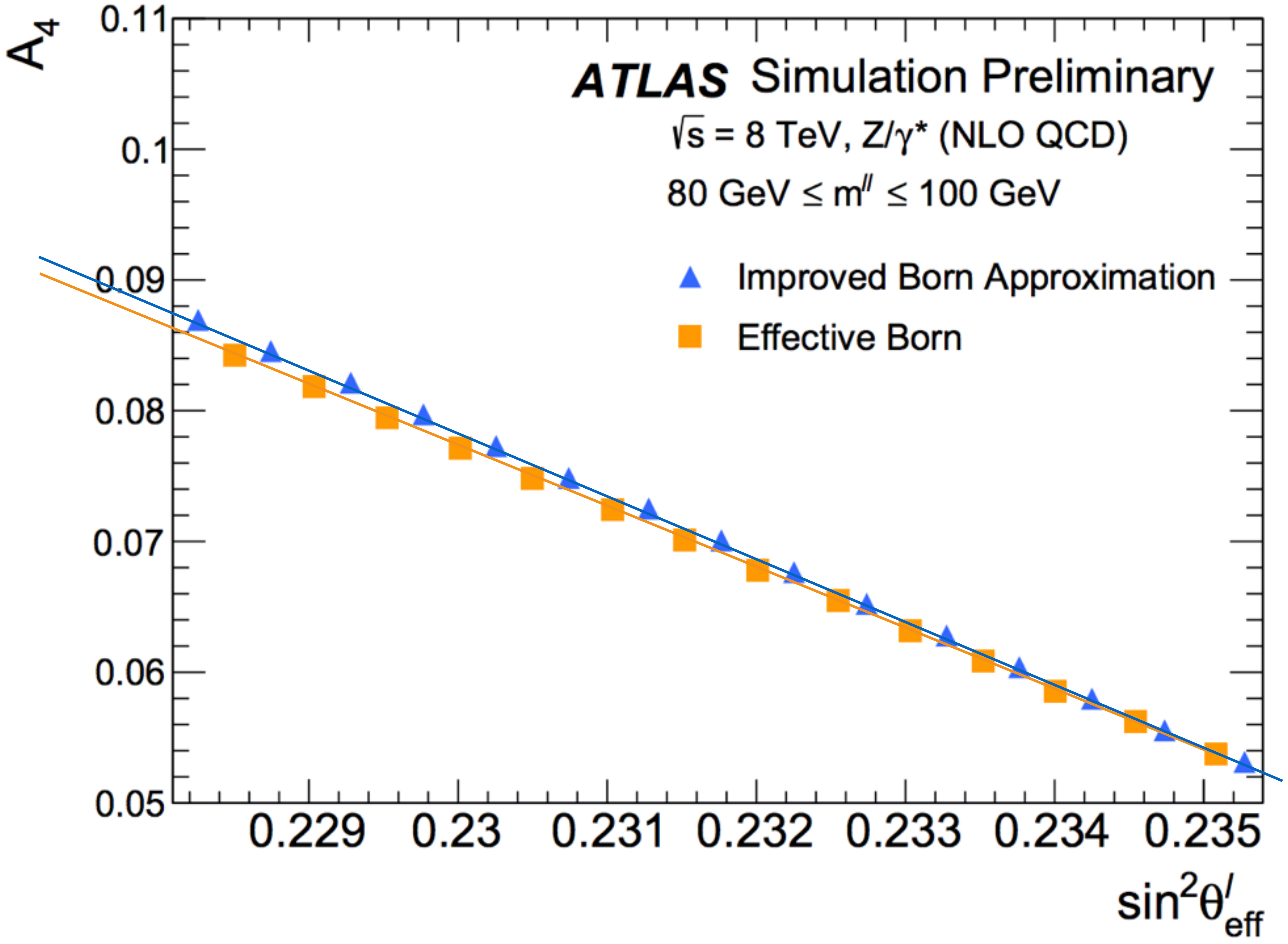


EW corrections to A_4

~Linear relation between A_4 and $\sin^2\theta^l_{eff}$

LO EW

$A_4 = a*\sin^2\theta_W + b$



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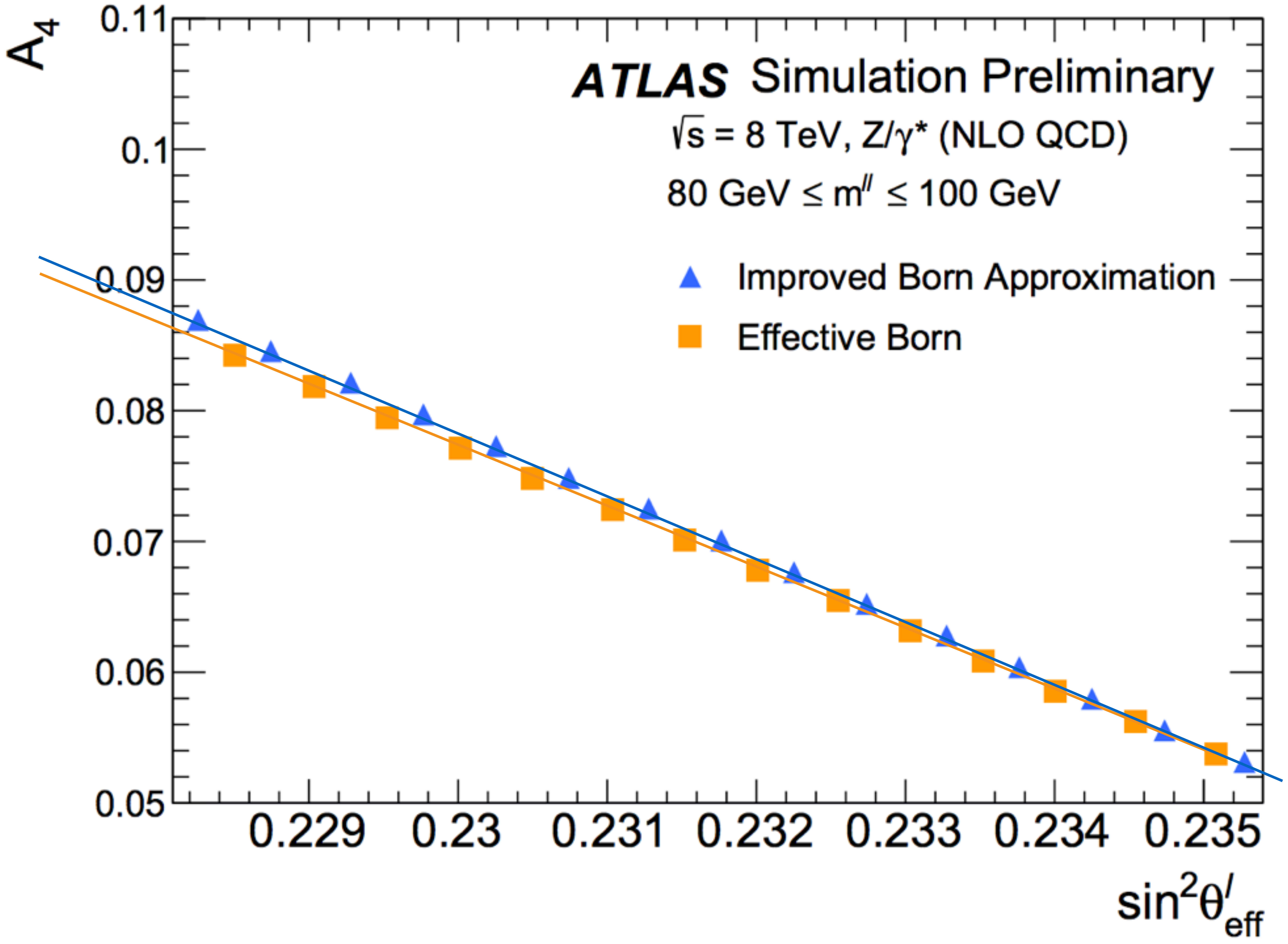


$v_f = (2^*T^f_3 - 4^*q_f^*\sin^2\theta_{W^*}\mathbf{K^f(s,t)})/\Delta$

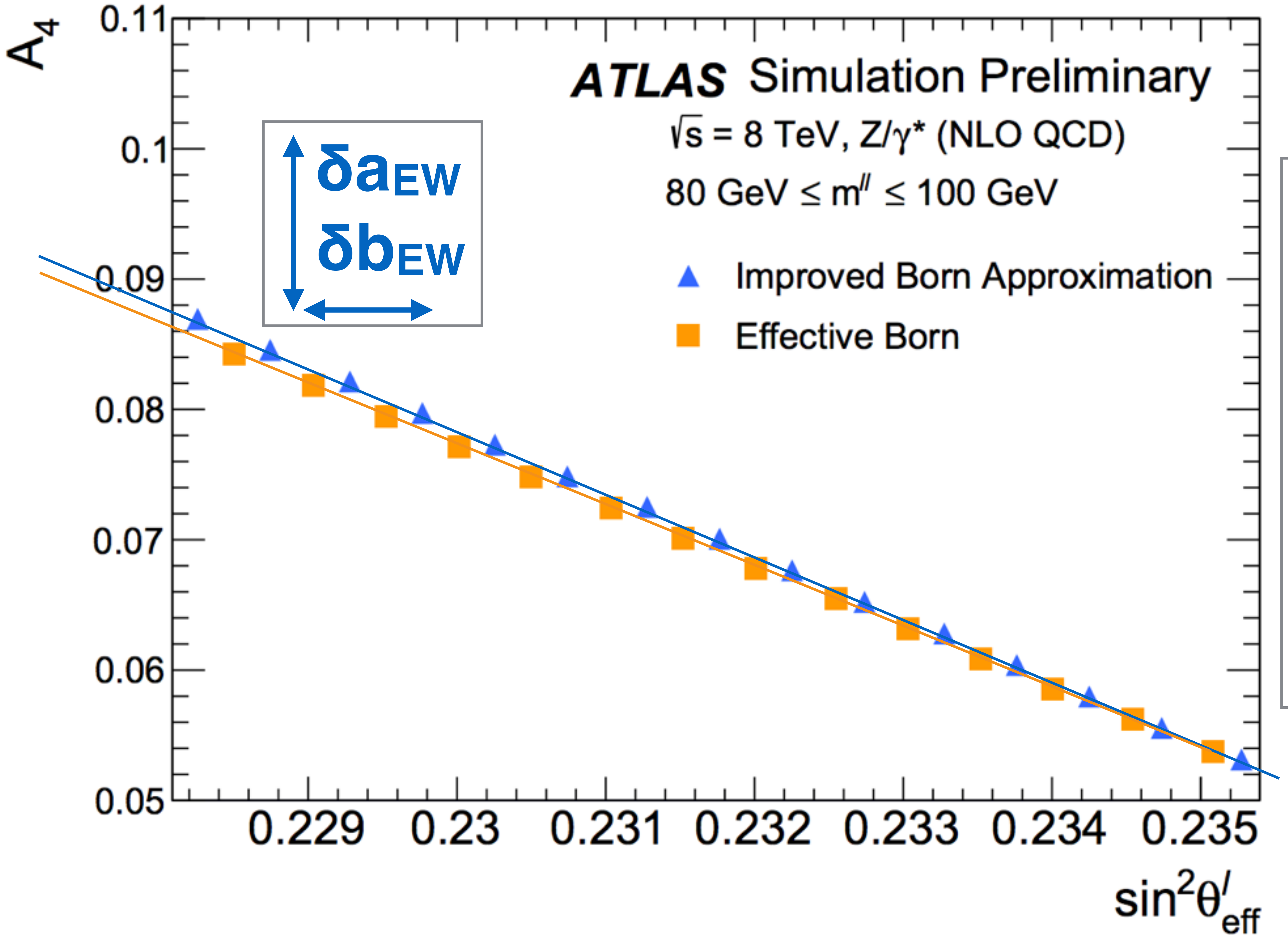
- Compute form factors $K^f(s,t)$ using DIZET libraries
- Define *effective leptonic* WMA at s=m^Z
  - $\mathbf{\sin^2\theta^{lep}_{eff}} = \sin^2\theta_W * K^{lep}(m^Z)$

EW corrections to A_4

~Linear relation between A_4 and $\sin^2\theta^l_{eff}$

LO EW | **NLO+HO EW**

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



$v_f = (2*T^f_3 - 4*q_f*\sin^2\theta_{W*}\mathbf{K^f(s,t)})/\Delta$

- Compute form factors $K^f(s,t)$ using DIZET libraries
- Define *effective leptonic* WMA at $s=m^Z$
  - $\mathbf{\sin^2\theta^{lep}_{eff}} = \sin^2\theta_W * K^{lep}(m^Z)$

$v_f = (2*T^f_3 - 4*q_f*(\sin^2\theta_{W*}K^f(s,t)\mathbf{+\delta v}))/\Delta$

- Scan $\sin^2\theta^{lep}_{eff}$ in predictions by scanning equivalent shift in coupling term
- Compute correction $\delta a_n^{EW}, \delta b_n^{EW}$ and add to LO EW predictions to obtain scan vs $\sin^2\theta^{lep}_{eff}$
- Results in **~25 * 10^{-5}** shift in measurement

A_4 predictions in analysis bins

	$70 < m^{\ell\ell} < 80$ 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
$\Delta \sin^2 \theta^{\ell}_{\rm eff}$ (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

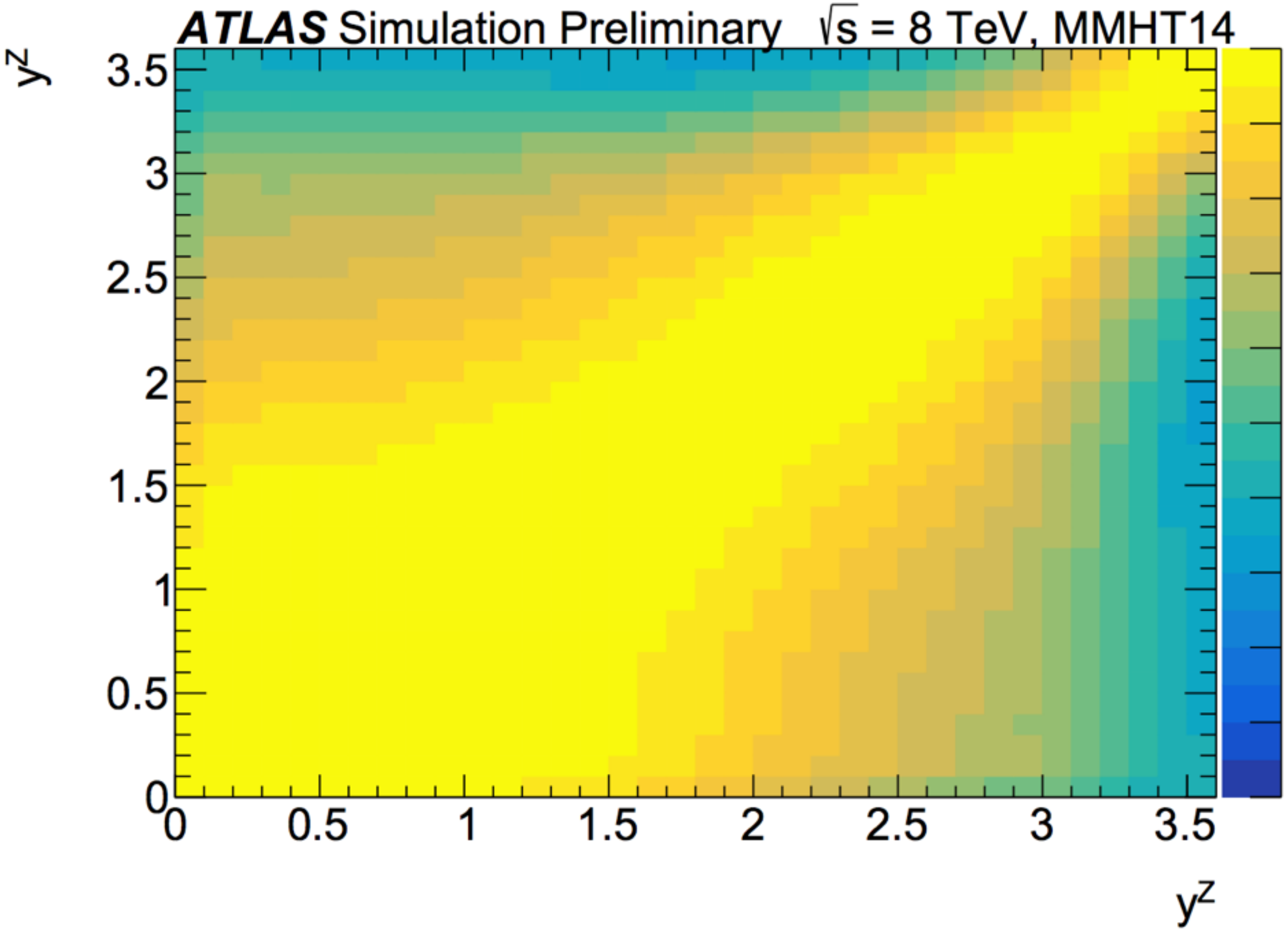
- Predicted A_4 including EW and NNLO corrections, along with their uncertainties
- PDF uncertainties dominate predictions
- QCD scale uncertainties factor 3-8 below PDF uncertainties
  - NNLO QCD correction in pole region ~2-3x larger than NLO scale uncertainties (~$5*10^{-5}$)
  - Apply NNLO correction, but keep NLO QCD scale uncertainties to be conservative

A_4 measurements, comparisons to predictions

- Comparison of measurements to A_4 predictions at $\sin^2\theta^l_{eff} = 0.23153$ for various PDF sets
- Generally good agreement
  - ~2σ discrepancy between data and prediction at low y^Z in pole region, and high y^Z in low mass sideband
  - Most sensitive regions show no discrepancies
- Uncertainty on data measurement seemingly larger than that of predictions
  - Data measurements are mostly uncorrelated between points
  - Predictions are highly correlated point to point

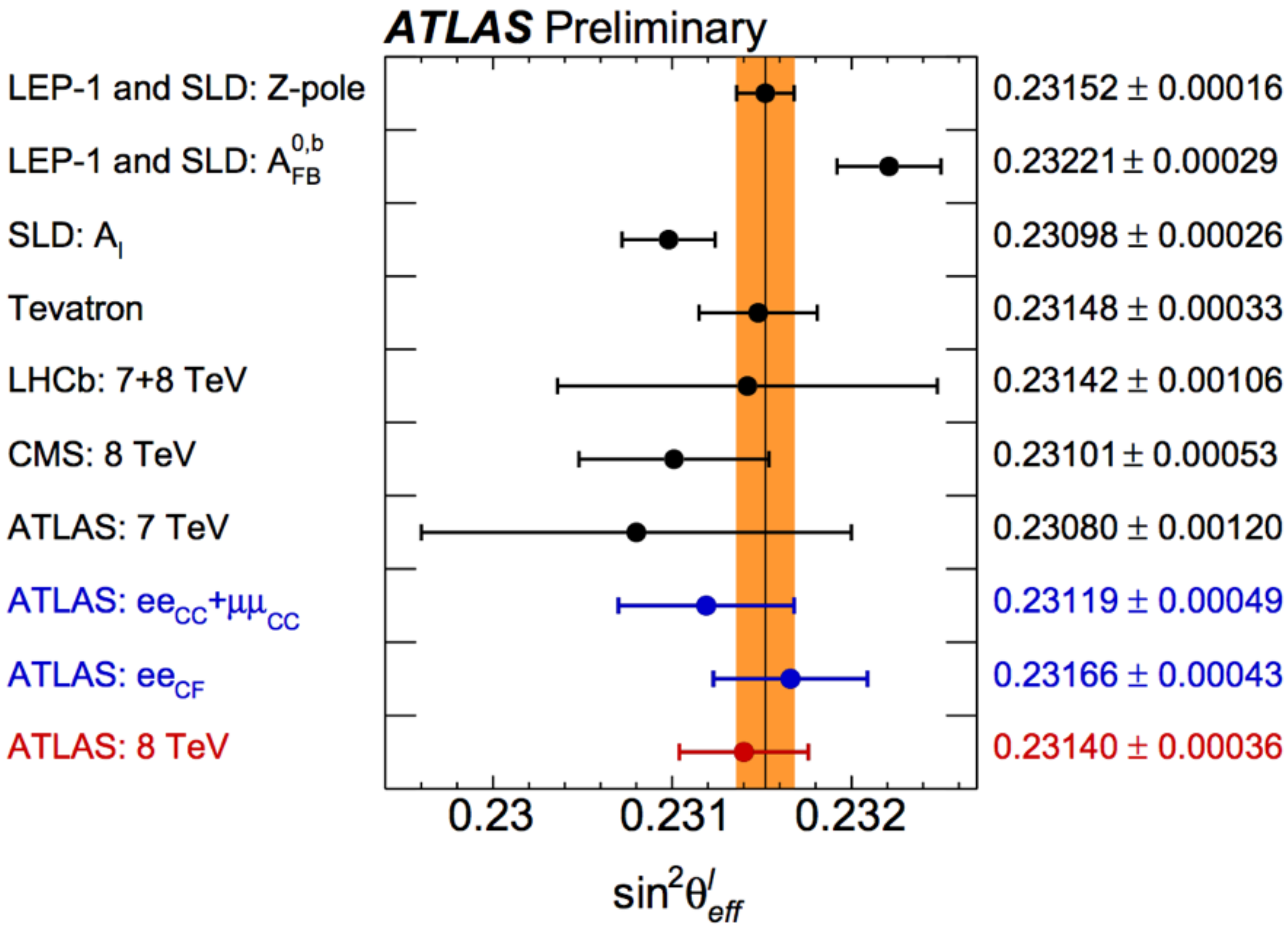
PDF profiling

Correlation of PDF uncertainty on $\sin^2\theta^l_{eff}$ measurement



- Measurements of A_4 spread across mass and rapidity
  - m^Z = [70, 80, 100, 125] GeV
  - $|y^Z|$ = [0.0, 0.8, 1.6, 2.5, 3.6]
- PDF uncertainties profiled within $A_4 \rightarrow \sin^2\theta^l_{eff}$
  - Takes advantage of non-trivial correlation structure in m^Z, y^Z to reduce PDF uncertainty
    - PDFs anti-correlated above and below mass pole
    - PDFs ~uncorrelated between high and low y^Z
- QCD scale uncertainties not profiled
  - Determined from envelope of best fit value of $\sin^2\theta^l_{eff}$ using standard 8-point variations of predictions

$\sin^2\theta^l_{eff}$ measurement / comparisons



	CT10	CT14	MMHT14	NNPDF31
$\sin^2\theta^\ell_{eff}$	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

- Preliminary result yields **$\sin^2\theta^l_{eff}$ = 0.23140 +/- 0.00036**
- eeCC+μμCC alone has uncertainty of ~$49*10^{-5}$, similar to CMS measurement
- eeCF channel brings significant improvement
- Spread between three more recent “global” PDFs ~$6*10^{-5}$
  - CT10 ~$22*10^{-5}$ away from MMHT14, which has both smallest uncertainty and yielded best χ^2
  - Similar PDF uncertainties between three more recent sets

Detailed uncertainty breakdown

Channel	ee_{CC}	$\mu\mu_{CC}$	ee_{CF}	$ee_{CC} + \mu\mu_{CC}$	$ee_{CC} + \mu\mu_{CC} + ee_{CF}$
Central value	0.23148	0.23123	0.23166	0.23119	0.23140
	Uncertainties				
Total	68	59	43	49	36
Stat.	48	40	29	31	21
Syst.	48	44	32	38	29
	Uncertainties in measurements				
PDF (meas.)	8	9	7	6	4
p_T^Z modelling	0	0	7	0	5
Lepton scale	4	4	4	4	3
Lepton resolution	6	1	2	2	1
Lepton efficiency	11	3	3	2	4
Electron charge misidentification	2	0	1	1	< 1
Muon sagitta bias	0	5	0	1	2
Background	1	2	1	1	2
MC. stat.	25	22	18	16	12
	Uncertainties in predictions				
PDF (predictions)	37	35	22	33	24
QCD scales	6	8	9	5	6
EW corrections	3	3	3	3	3

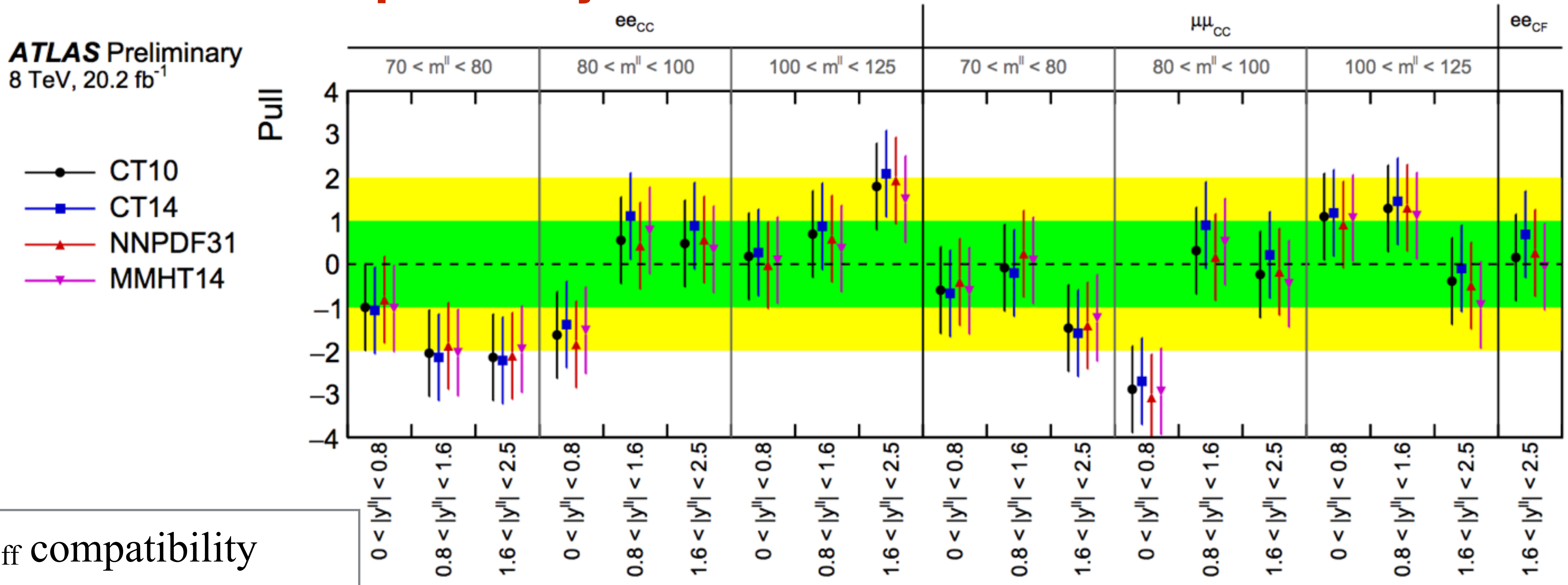
~9

A_4 compatibility

	$70 < m^{\ell\ell} < 80$ GeV			$80 < m^{\ell\ell} < 100$ GeV			$100 < m^{\ell\ell} < 125$ GeV		
$\lvert y^{\ell\ell}\rvert$	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

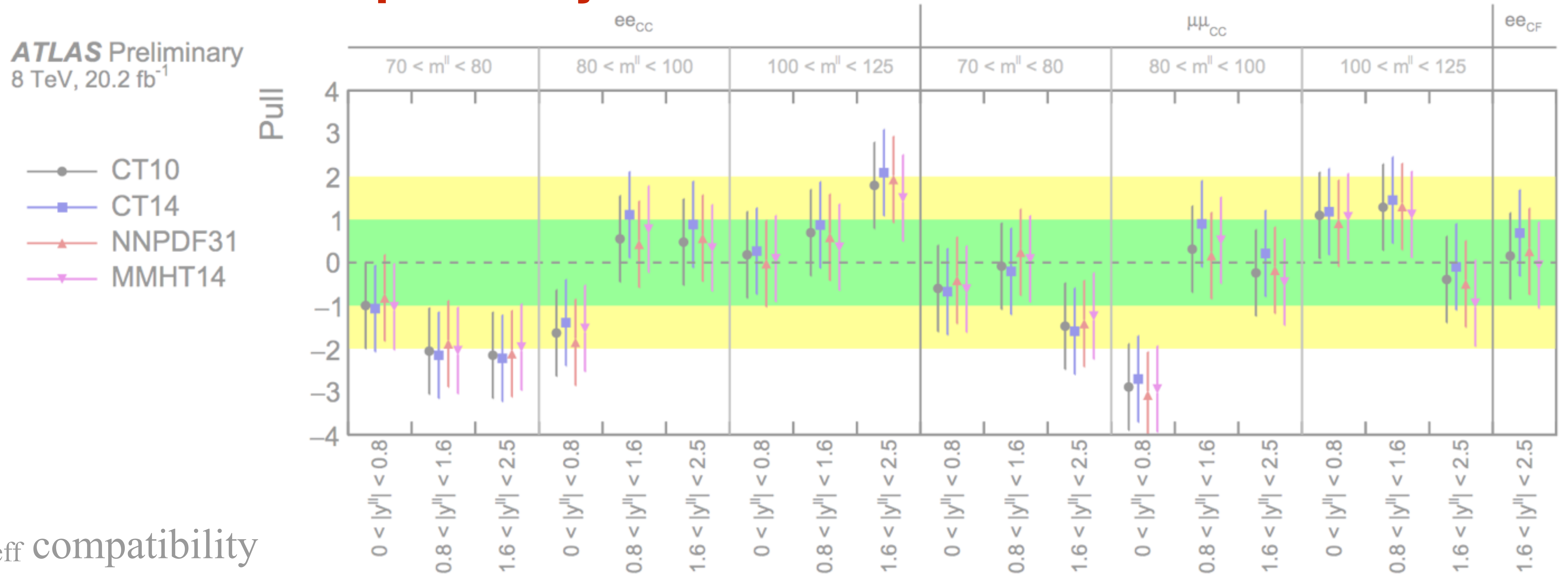
- Before unblinding A_4, compatibility was tested in A_4 between all channels, where available, to help ensure results are robust
  - $\Delta A_4 = A_4(ee_{CC}) - A_4(\mu\mu_{CC})$ for $|y^Z| < 2.5$ region
  - $\Delta A_4 = A_4(ee_{CF}) - A_4(ee_{CC}+\mu\mu_{CC})$ in overlapping $1.6 < |y^Z| < 2.5$ bin
- CC compatibility very good, $\chi2 = 10.1 / 9$, $p = 0.34$
- CF also quite compatible with CC combination: $\Delta A_4 = A_4(ee_{CF}) - A_4(ee_{CC}+\mu\mu_{CC}) = -0.007 +/- 0.0051$

Compatibility tests



- Look at two levels of $\sin^2\theta^{lep}_{eff}$ compatibility
- First: Pull of measurement between each analysis bin and channel
  - Reference w.r.t. $2.5 < |y^Z| < 3.6$ in ee_{CF}
  - One ~2.7σ pull in 0-0.8, 80-100 $\mu\mu_{CC}$
  - Global $\chi^2 = 31/19 \Rightarrow 1.8\sigma$

Compatibility tests



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- First: Pull of measurement between each analysis bin and channel
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  - One ~2.7σ pull in 0-0.8, 80-100 $\mu\mu_{CC}$
  - Global $\chi^2 = 31/19 \Rightarrow 1.8\sigma$
- Second: Difference between measurements in individual channels
  - Includes proper correlation of systematics
  - Overall very good agreement, all within 1σ

Tested difference	$ee_{CC} - \mu\mu_{CC}$	$ee_{CC} - ee_{CF}$	$\mu\mu_{CC} - ee_{CF}$	$ee_{CF} - (ee_{CC} + \mu\mu_{CC})$
Central value	44	−7	−51	−32
	Uncertainties			
Total	72	70	64	57
Stat.	62	56	50	42
Syst.	37	41	40	38

Summary

- Preliminary $\sin^2\theta^l_{eff}$ measurement from ATLAS using 8 TeV dataset
  - **$\sin^2\theta^l_{eff}$ = 0.23140 +/- 0.00036** (+/- 0.00021 stat. +/- 0.00029 syst.)
  - Compatible with previous measurements
  - Enhanced precision from use for forward electrons to probe low dilution phase space
- Future measurements / combinations with full Run II 13 TeV dataset
  - Will significantly **reduce statistical** component
  - **Larger intrinsic PDF component** due to higher levels of dilution
    - May be balanced by higher stats → **PDF profiling**
    - Somewhat uncorrelated between 8 and 13 TeV due to profiling and different x_1, x_2 phase space
- Ongoing efforts within LHC EWWG
  - Future **combinations** between experiments should prove very fruitful
  - Understanding differences between PDF sets

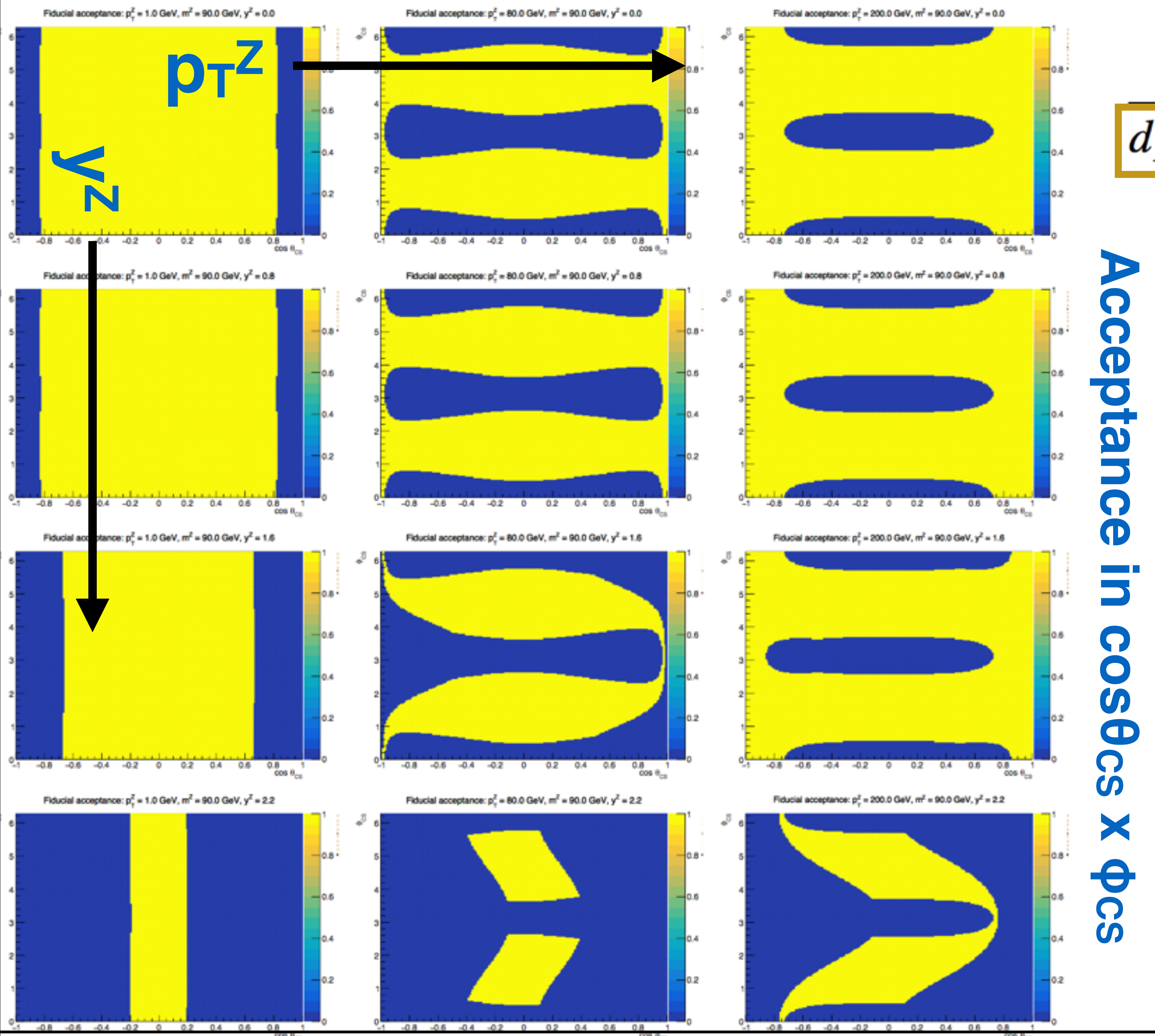
Documentation

- ATLAS CONF note: https://cds.cern.ch/record/2630340
- CMS publication: https://arxiv.org/abs/1806.00863
- LHCb publication: https://arxiv.org/abs/1509.07645
- Tevatron publication: https://arxiv.org/abs/1801.06283
- Z3D paper: https://arxiv.org/abs/1710.05167
- Ai(p_T,y) paper: https://arxiv.org/abs/1606.00689
- PDF pub note: https://cds.cern.ch/record/2310738

BACKUP

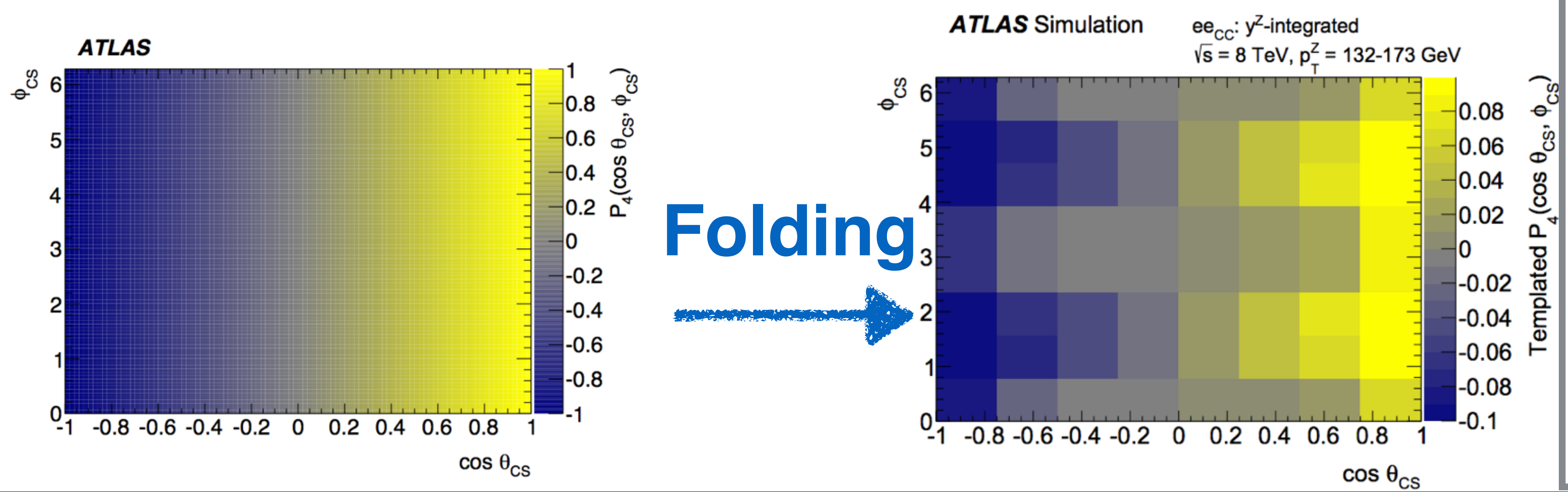
CC-like selections

Acceptance, folding methodology



$$\frac{d^5\sigma}{dp_T^Z\, dy^Z\, dm^Z\, d\cos\theta\, d\phi} = \frac{3}{16\pi}\frac{d^3\sigma^{U+L}}{dp_T^Z\, dy^Z\, dm^Z}$$
$$\{(1+\cos^2\theta) + 1/2\ A_0(1-3\cos^2\theta) + A_1\ \sin 2\theta\ \cos\phi$$
$$+1/2\ A_2\ \sin^2\theta\ \cos 2\phi + A_3\ \sin\theta\ \cos\phi + A_4\ \cos\theta$$
$$+A_5\ \sin^2\theta\ \sin 2\phi + A_6\ \sin 2\theta\ \sin\phi + A_7\ \sin\theta\ \sin\phi\}.$$

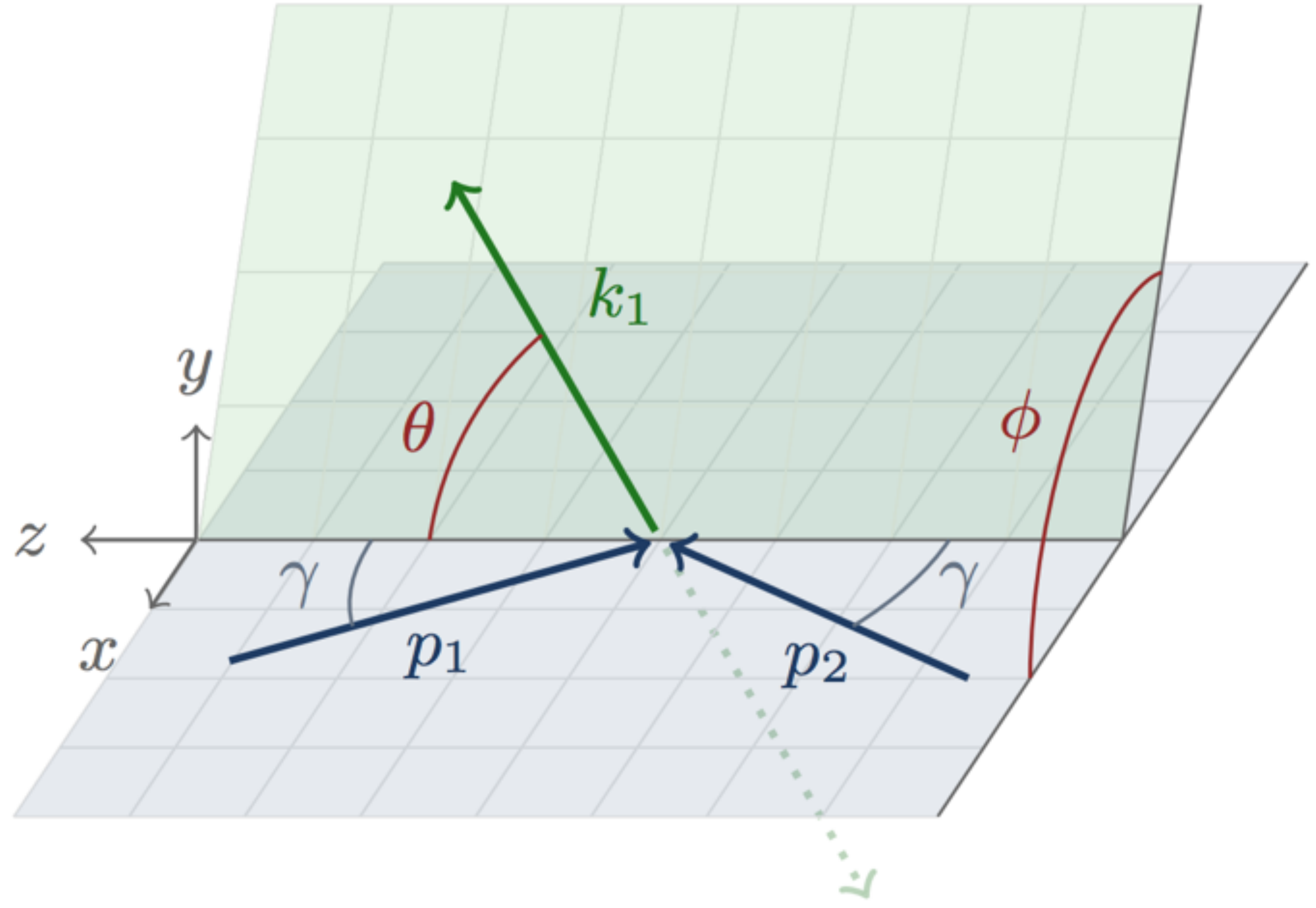
- Differential cross-section depends **only** on 5 observables
  - Z-boson kinematics: p_T^Z, m^Z, y^Z
  - Lepton decay angular variables: cosθ, φ
- **$A_{3,4}$ sensitive to $\sin^2\theta^l_{eff}$ via coupling structure**
- For a given point in Z-boson kinematics (p_T^Z, m^Z, y^Z), fiducial lepton selections on leptons map 1-1 in cosθ, φ
  - Acceptance is perfectly deterministic, and is 0 or 1
- Detector response requires us to bin in p_T^Z, m^Z, y^Z
  - Causes harmonic decomposition to break down
- Use MC to fold analytical acceptance within the analysis bins to detector level
  - **m^Z = [70, 80, 100, 125], y^Z = [0, 0.8, 1.6, 2.5, 3.6]**
- Fit reconstructed angular distributions with folded polynomials to find $A_{0\text{-}7}$ and σ^{U+L}



Measuring $\sin^2\theta_W$ at hadron colliders

$$\frac{d^5\sigma}{dp_T^Z\, dy^Z\, dm^Z\, d\cos\theta\, d\phi} = \frac{3}{16\pi}\frac{d^3\sigma^{U+L}}{dp_T^Z\, dy^Z\, dm^Z}$$
$$\{(1+\cos^2\theta) + 1/2\, A_0(1-3\cos^2\theta) + A_1\, \sin 2\theta\, \cos\phi$$
$$+1/2\, A_2\, \sin^2\theta\, \cos 2\phi + \boxed{A_3}\, \sin\theta\, \cos\phi + \boxed{A_4}\, \cos\theta$$
$$+A_5\, \sin^2\theta\, \sin 2\phi + A_6\, \sin 2\theta\, \sin\phi + A_7\, \sin\theta\, \sin\phi\}.$$

- DY differential XS has **nine** terms, which holds to all orders in QCD
  - Cross-section and angular coefficients depend on p_T^Z, y^Z, m^Z
  - Harmonic polynomials of $\cos\theta$, φ fully analytical
  - General ansatz for 2-2 process mediated by spin-1 boson
- Measure angular distributions $\cos\theta_{CS}$, φ_{CS} in Z-boson rest frame
  - $\cos\theta_{CS}$ angle between negative lepton and incoming positive quark
  - φ_{CS} azimuthal angle between proton plane and lepton
- Guess sign of $\cos\theta_{CS}$ based on Z-boson rapidity
  - yZ tends to align with direction of valence quark
  - Leads to dilution and large PDF uncertainties on predicted A4
- Two coefficients, A_3 and A_4, sensitive to $\sin^2\theta_W$ due to coupling structure
  - $A_4 = 3/8 * A_{FB}$ in full phase space of leptons
- Compare measured A_4 to their theoretical predictions for different $\sin^2\theta_W$ hypotheses



Backgrounds

- EW+ttbar background estimated from MC
  - Z -> ττ, VV, ttbar, single top, photon induced ee,μμ
- W+jets and multijet estimated from data
  - Reverse ID criteria to build templates of MJ
  - Fit MJ templates with signal vs isolation variable to obtain MJ normalization
  - Use different reversed quality criteria and isolation thresholds to estimate systematic
- Non-fiducial signal estimated from MC
  - Events that fall outside of measured Z-boson kinematics, but fall into selections due to migrations
  - Almost entirely from migrations in Mll
- In the pole region, background fraction is at the per-mil level for CC, and ~1% for CF

Signature	Generator	PDF
$Z/\gamma^* \to \ell\ell$	Powheg-Box + Pythia 8	CT10 NLO
$Z/\gamma^* \to \tau\tau$	Sherpa	CT10 NLO
$t\bar{t}$	Powheg-Box + Pythia 6	CTEQ6L1
Single top quark (Wt channel)	Powheg-Box + Pythia 8	CTEQ6L1
Dibosons	Herwig	CTEQ6L1
$\gamma\gamma \to \ell\ell$	Pythia 8	MRST2004QED NLO

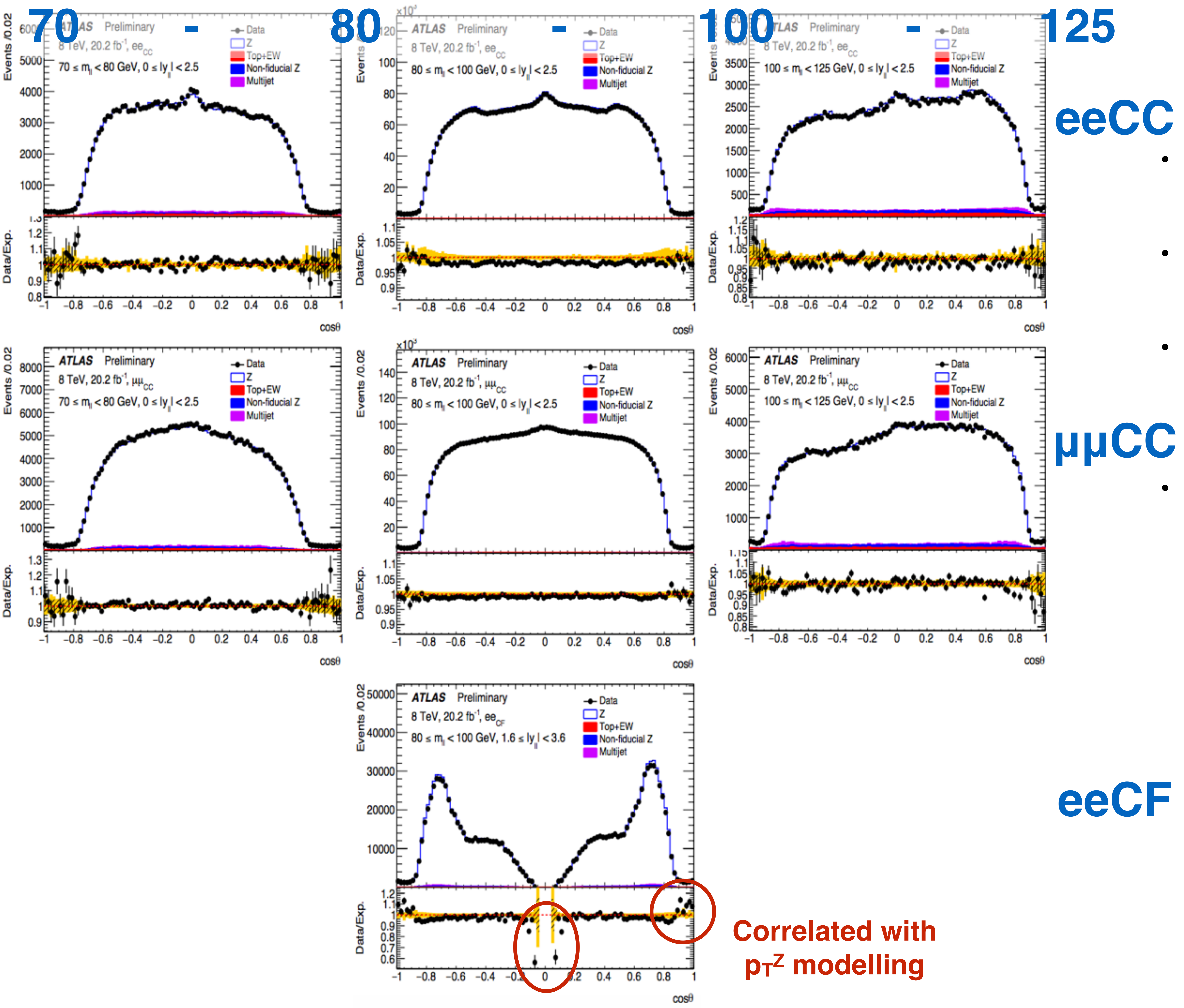
ee$_{CC}$

	$70 < m_{ll} < 80$ GeV			
$\|y_{ll}\|$	Data	Top+EW	Multijets	Non-fiducial Z
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			
$\|y_{ll}\|$	Data	Top+EW	Multijets	Non-fiducial Z
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			
$\|y_{ll}\|$	Data	Top+EW	Multijets	Non-fiducial Z
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

ee$_{CF}$

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

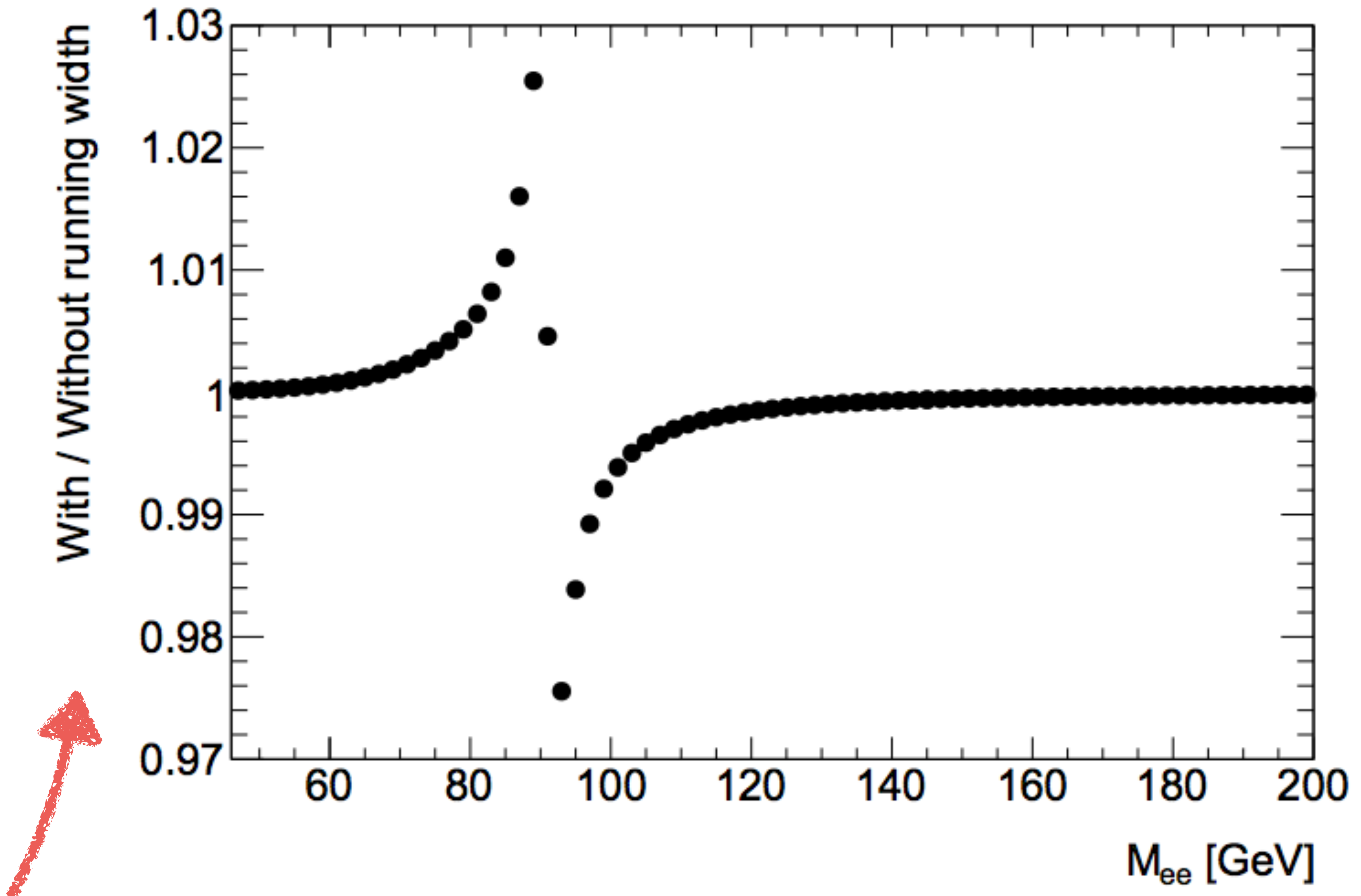
Control plots

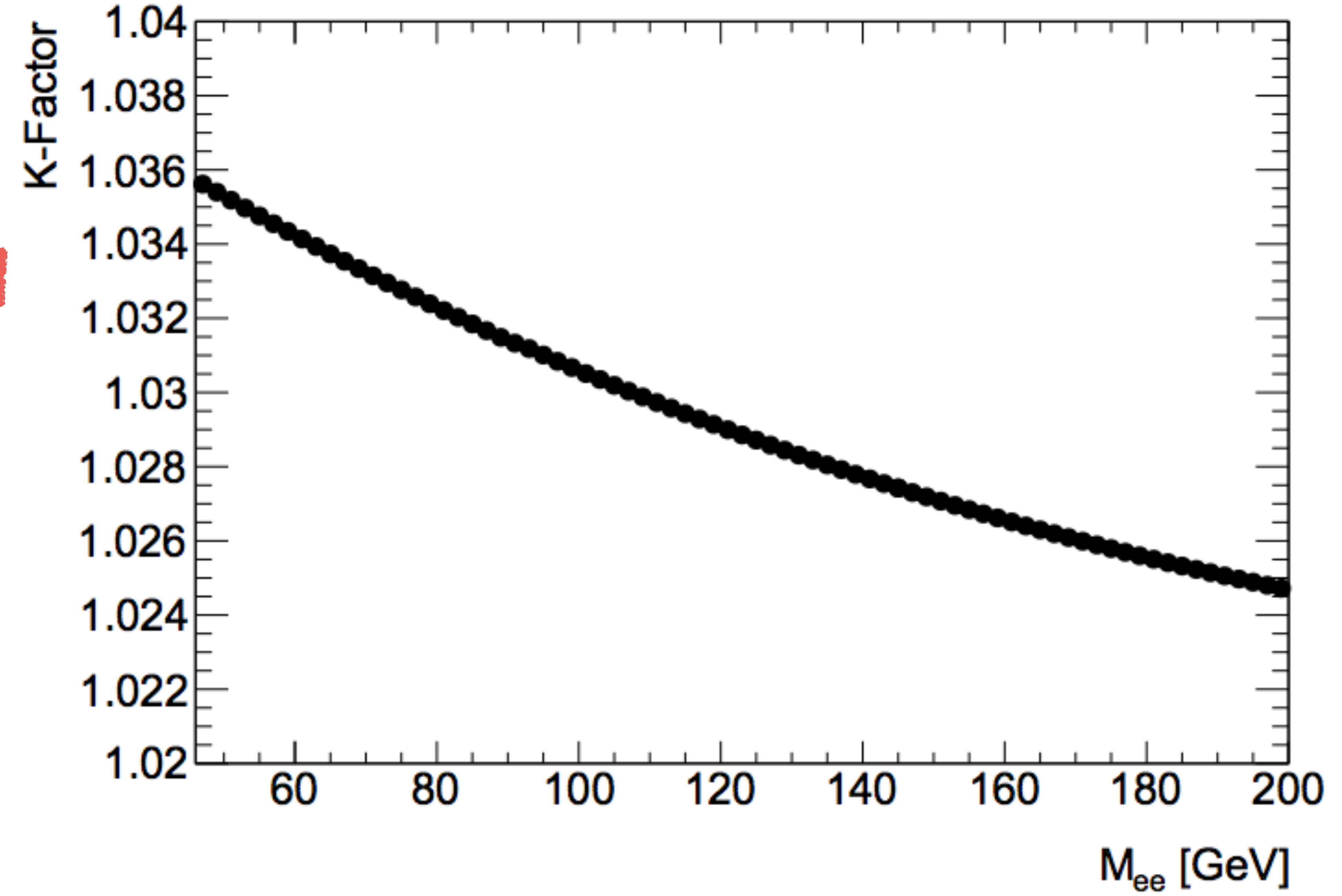


- Overall very good modelling of angular distributions in all analysis bins “prefit”
- Recall that Ais are reweighted to NLO predictions, hence no P_0-like discrepancies
- Though we measure full suite of Ais in-situ, so any discrepancy related to other Ais w/ data corrected within fit
- Small mismodelling of very high and very low |cosθ| regions in eeCF related again to p_T^Z modelling, which is covered by systematics (not included in yellow band)
    - Also checked that removing these events and very little impact on measured $\sin^2\theta^l_{eff}$ (~$1*10^{-5}$)

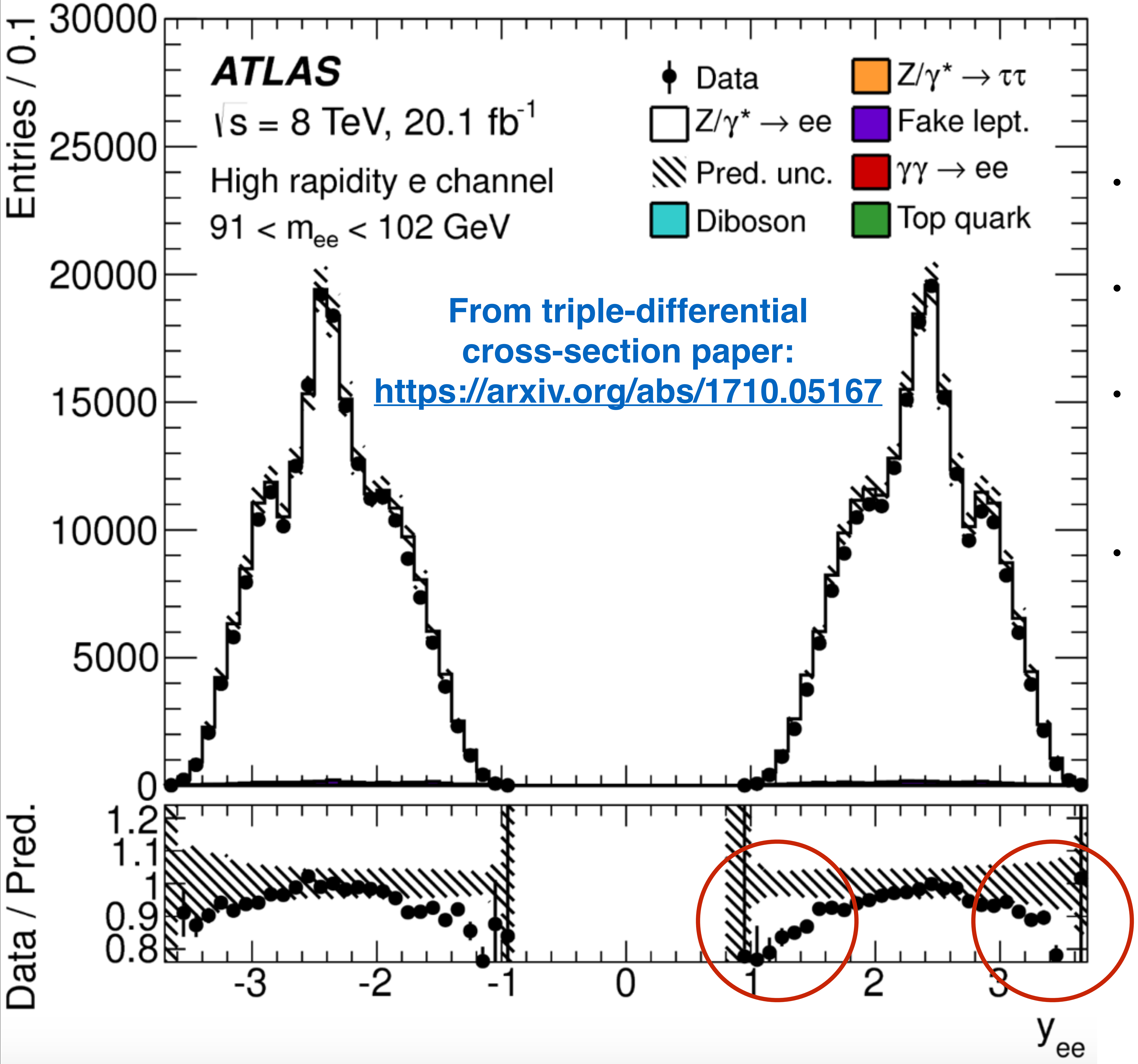
Modelling corrections

- Several corrections applied to signal MC
  - Related to behavior in p_T^Z
    - Ais reweighted to DYTurbo in fine p_T, y, m bins to remove known bug in A_0
    - Modelling of p_T^Z itself
      - Corrected in CC channels based on σ^{U+L} measured in data
      - Systematic applied in CF channel based on QCD scale uncertainties from predictions
      - Important since we're integrating over pTZ during template folding process
  - Related to behavior in m^Z
    - Lineshape corrected for running width
    - Include mass-dependent K-factors (NNLO QCD+NLO EW in mass)





p_T^Z, y^Z modelling in ee_{CF}



- Data shows large discrepancy with MC at the high and low tails of the y^Z distribution in ee_{CF} events
- Baseline generator is NLO+PS, which is insufficient to model this region
- Acceptance shape changes rapidly 2D in p_T^Z, y^Z, which leads to large acceptance uncertainties when integrating over p_T^Z
- Acceptance uncertainties from NNLO+NNLL predictions cover the discrepancy at both high and low y^Z, and are propagated into the template folding

Likelihood formalism

Cross-section parameters — Ai parameters — Polynomial templates — Background templates

$$N^n_{\mathrm{exp}}(A,\sigma,\theta) = \left\{ \sum_{j=0}^{\mathrm{N^{ana}_{bins}}} \sigma_j \times L \times \left[t^n_{8j}(\beta) + \sum_{i=0}^{7} A_{ij} \times t^n_{ij}(\beta) \right] \right\} \times \gamma^n + \sum_{B}^{\mathrm{bkgs}} T^n_B(\beta),$$

Observed events — Expected events — MC stat + NP constraints

$$\mathcal{L}(A,\sigma,\theta|N_{\mathrm{obs}}) = \prod_{n}^{N_{\mathrm{bins}}} \left\{ P(N^n_{\mathrm{obs}}|N^n_{\mathrm{exp}}(A,\sigma,\theta)) P(N^n_{\mathrm{eff}}|\gamma^n N^n_{\mathrm{eff}}) \right\} \times \prod_{m}^{M} G(0|\beta^m, 1)$$

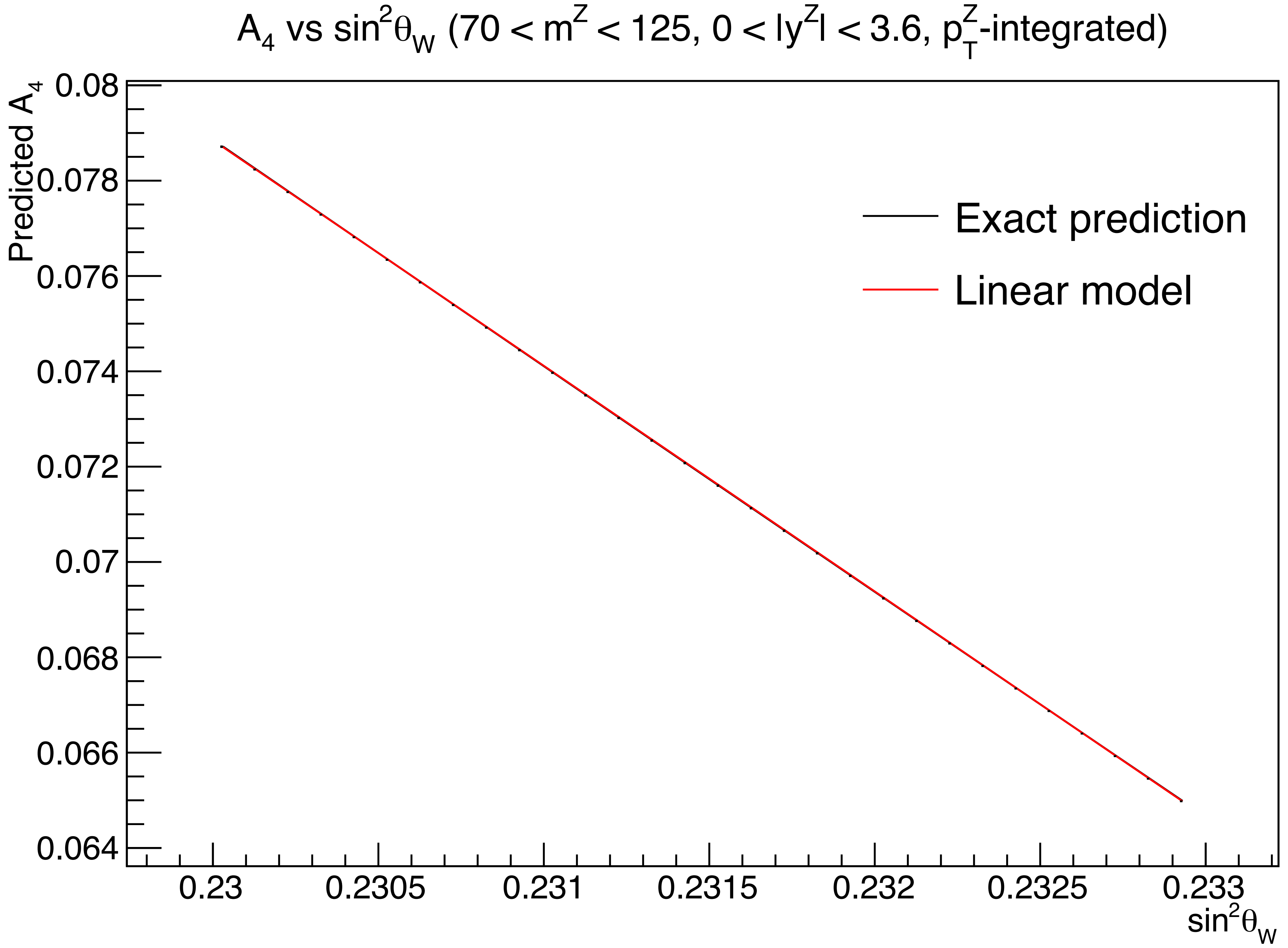
- Folded polynomial templates are used to build a likelihood
  - Variational templates also present to take into account systematic uncertainties
- Angular coefficients are parameters that normalize the polynomial templates
- Cross-section scales all signal templates independently in each measurement bin
- Background templates are added to likelihood
- Maximum likelihood fit is performed to the **reconstructed data** to determine the coefficients and cross-sections in full phase space of leptons
- A_4 parametrized in terms of $\sin^2\theta^l_{\mathrm{eff}}$ to extract this directly from the full likelihood rather than extracting from Gaussianized A_4 measurement in two-step process

A4 measurements

	$70 < m^{\ell\ell} < 80$ 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	–0.0681	–0.2684	–0.5087	0.0195	0.0448	0.0923	0.1445	0.0975	0.3311	0.6722
	Uncertainties			Uncertainties				Uncertainties		
Total	0.0176	0.0199	0.0391	0.0015	0.0016	0.0026	0.0046	0.0086	0.0099	0.0234
Stat.	0.0149	0.0160	0.0324	0.0013	0.0013	0.0021	0.0037	0.0073	0.0079	0.0188
Syst.	0.0093	0.0119	0.0220	0.0008	0.0008	0.0014	0.0027	0.0045	0.0062	0.0139
PDF (meas.)	0.0004	0.0044	0.0046	0.0001	0.0002	0.0004	0.0008	0.0009	0.0015	0.0050
p_T^Z modelling	0.0028	0.0031	0.0058	0.0003	0.0003	0.0004	0.0007	0.0014	0.0015	0.0033
Leptons	0.0044	0.0063	0.0095	0.0004	0.0003	0.0005	0.0010	0.0019	0.0040	0.0071
Background	< 0.0001	0.0008	0.0040	< 0.0001	0.0001	< 0.0001	0.0001	0.0006	0.0015	0.0023
MC stat.	0.0083	0.0089	0.0180	0.0007	0.0007	0.0012	0.0023	0.0038	0.0042	0.0102

- Combination of all three channels
- Individual A_4 measurements primarily dominated by statistical uncertainty
  - Systematics from MC statistics next leading source of uncertainty (~1/2 data stats)
  - Lepton calibration and efficiency generally ~1/2 of MC stats
  - Uncertainty from backgrounds negligible in all bins (including ee_{CF})

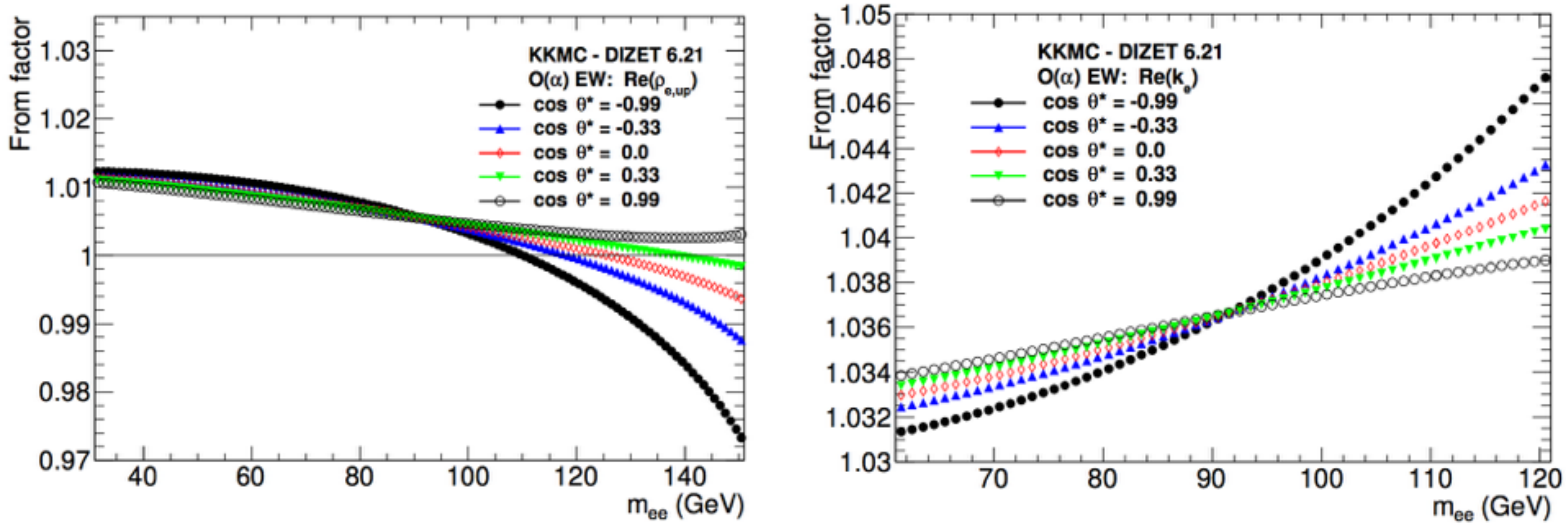
Start with DYTurbo: NLO QCD, LO EW



$v_f = (2*T^f_3 - 4*q_f*\mathbf{\sin^2\theta_W})/\Delta$

- On-shell definition of $\sin^2\theta_W$ input to prediction in $G\mu$ scheme
- Scan around PDG value and obtain A4 predictions for each analysis bin
- Build linear interpretation model
- $A_4^n(\sin^2\theta_W) = a_n*\sin^2\theta_W + b_n$

DIZET: EW corrections



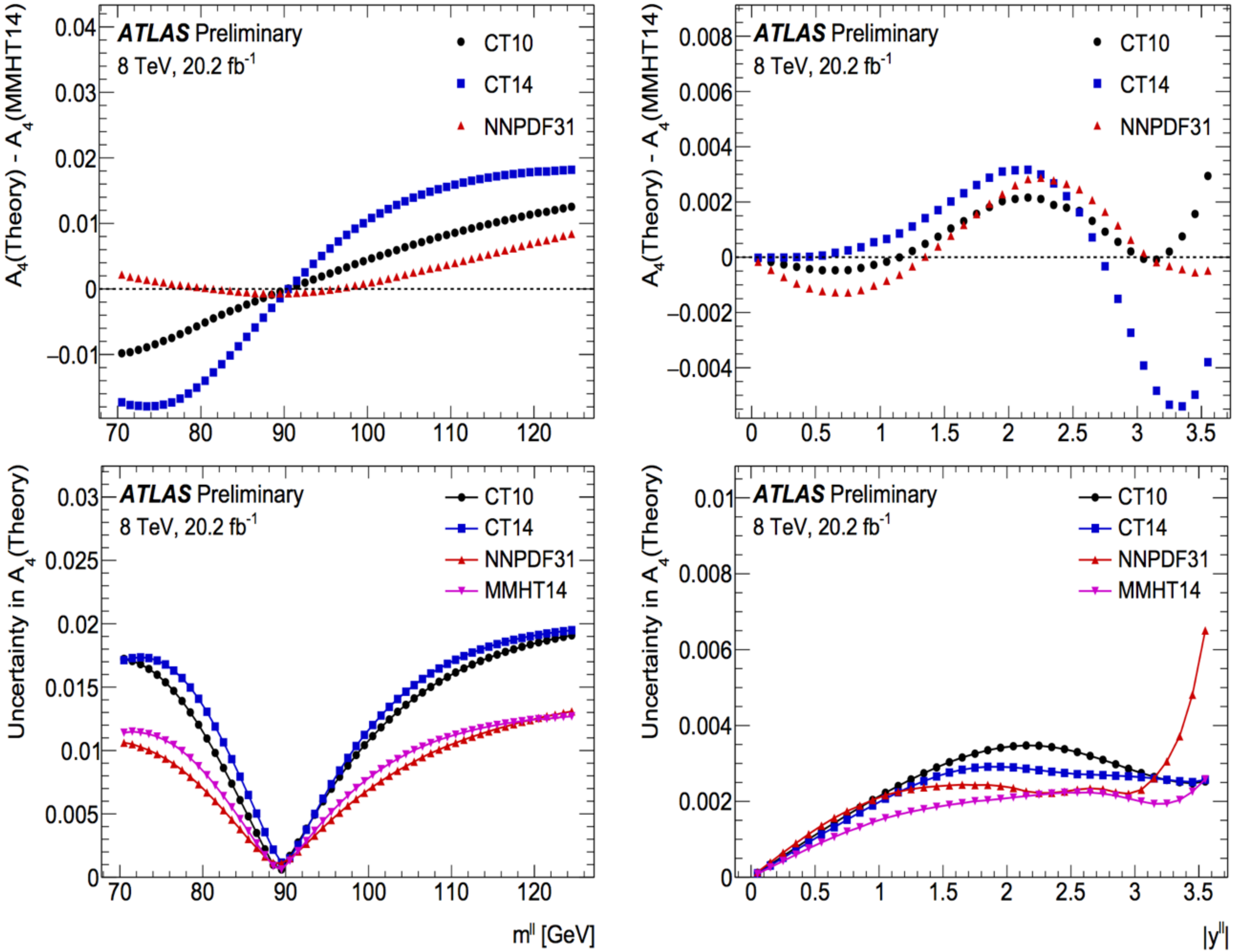
$v_f = (2*T^f_3 - 4*q_f*\sin^2\theta_W*\mathbf{K^f(s,t)})/\Delta$

- Compute form factors to couplings and propagators
- Allows us to define *effective leptonic* WMA at $s=m^Z$
  - $\mathbf{\sin^2\theta^{lep}_{eff}} = \sin^2\theta_W * K^{lep}(m^Z)$
- Embed effect of FFs on ME as weights in MC generator

$v_f = (2*T^f_3 - 4*q_f*(\sin^2\theta_W*K^f(s,t)\mathbf{+\delta v}))/\Delta$

- Scan $\sin^2\theta^{lep}_{eff}$ in MC by adding extra coupling term and computing equivalent shift in $\sin^2\theta^{lep}_{eff}$
- Compute correction $\delta a_n^{EW}, \delta b_n^{EW}$ and add to DYTurbo prediction model to obtain scan vs $\sin^2\theta^{lep}_{eff}$
- $A_4^{n,EW}(\sin^2\theta^{lep}_{eff}) = (a_n+\delta a_n^{EW})*\sin^2\theta^{lep}_{eff} + (b_n+\delta b_n^{EW})$

A_4 Predictions

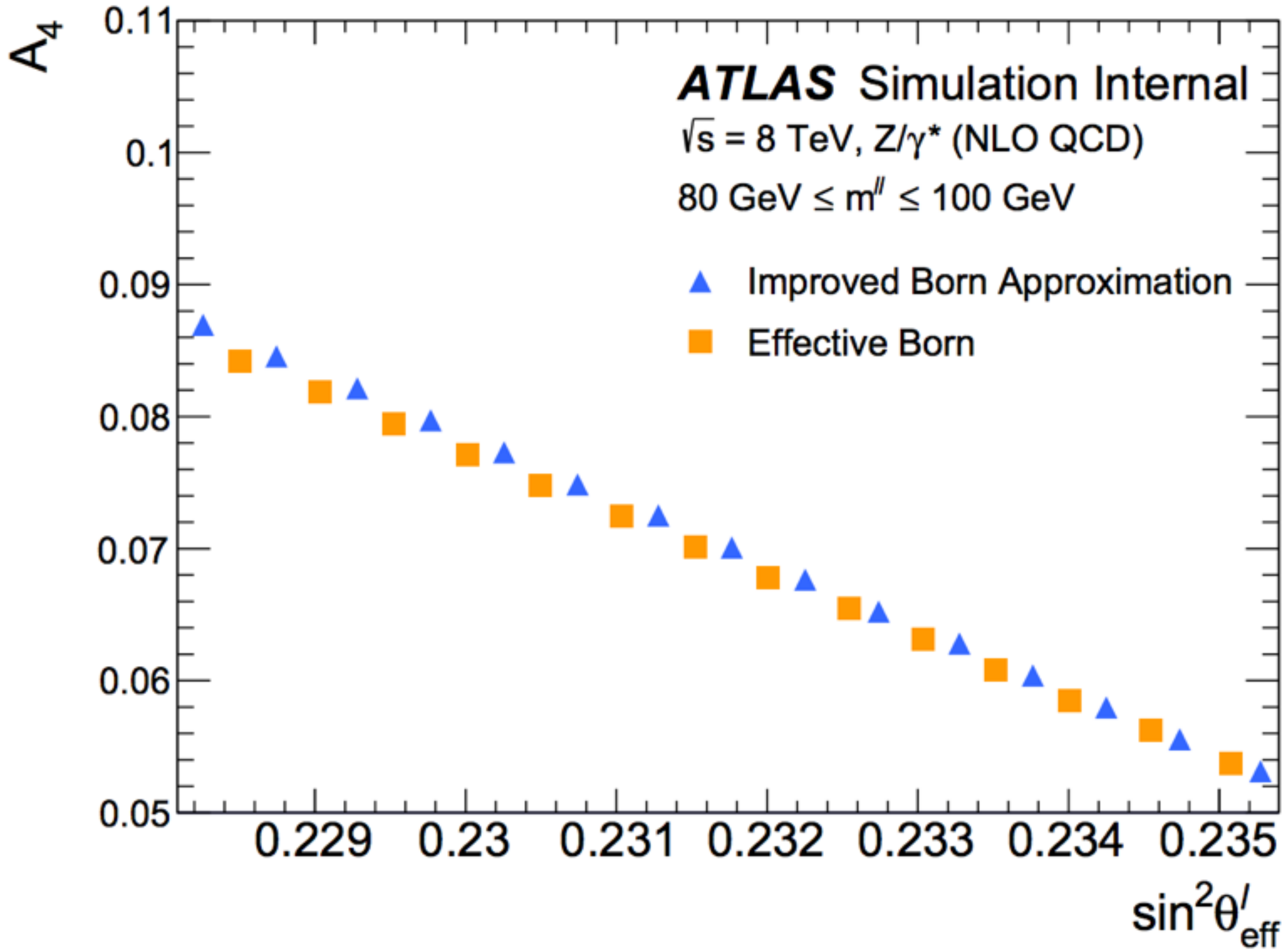


Differences generally within PDF uncertainty on individual predictions

NNLO Corrections to A_4

- Effect of correction on $\sin^2\theta^{lep}_{eff}$ found to be flat in y^Z, but has some m^Z dependence (similar to EW corrections)
  - $\Delta \sin^2\theta^{lep}_{eff}(70 < m^Z < 80, 0 < |y^Z| < 2.5) = 49*10^{-5}$
  - $\Delta \sin^2\theta^{lep}_{eff}(80 < m^Z < 100, 0 < |y^Z| < 3.6) = -15*10^{-5}$
  - $\Delta \sin^2\theta^{lep}_{eff}(100 < m^Z < 125, 0 < |y^Z| < 2.5) = -103*10^{-5}$
- Effect in pole region ~2-3x larger than NLO scale uncertainties (~$5*10^{-5}$)
  - Apply NNLO correction directly as m^Z-dependent offset to $\sin^2\theta^{lep}_{eff}$
  - Keep NLO QCD scale uncertainties
  - Keep NLO PDF uncertainties

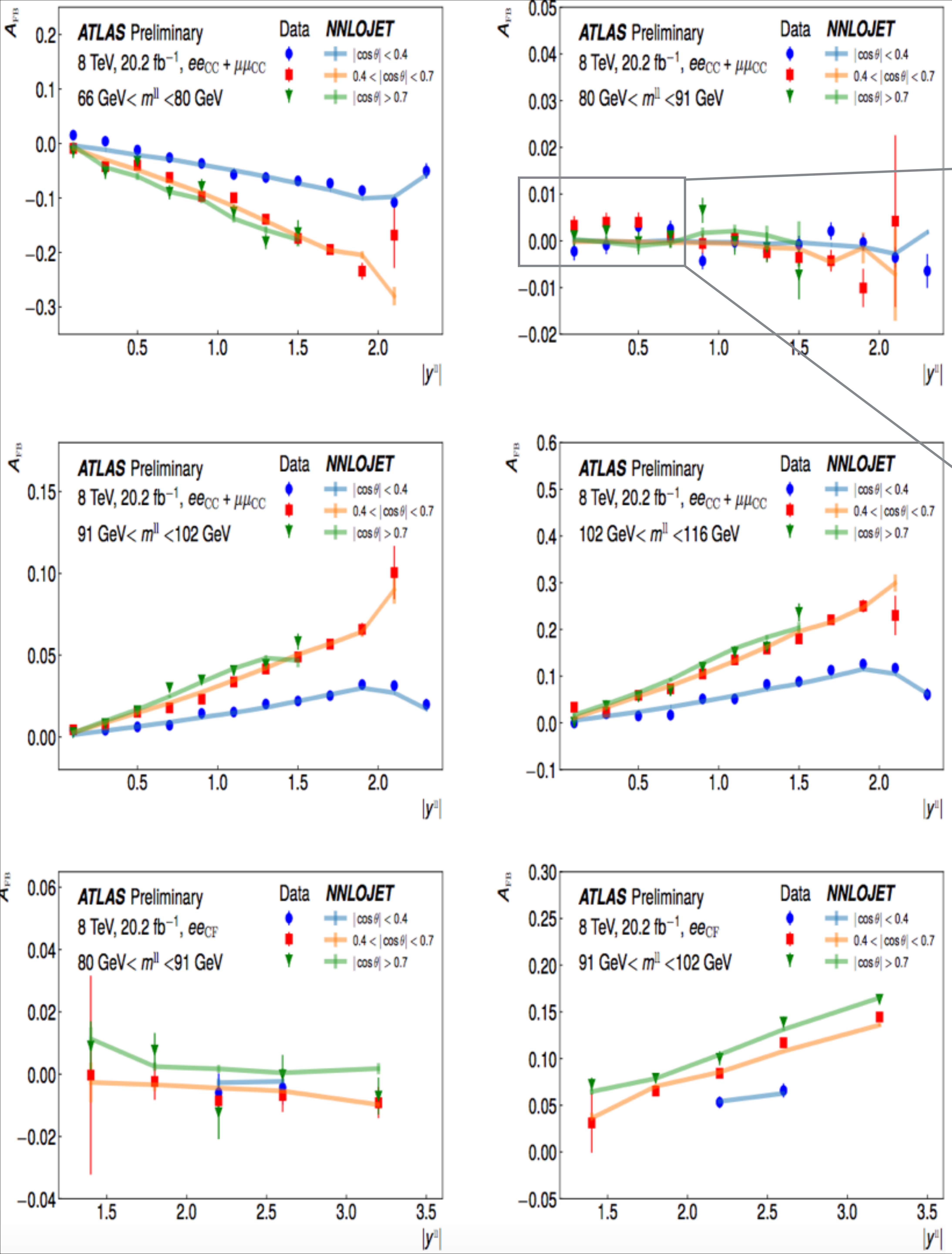
Impact of EW corrections on measurement

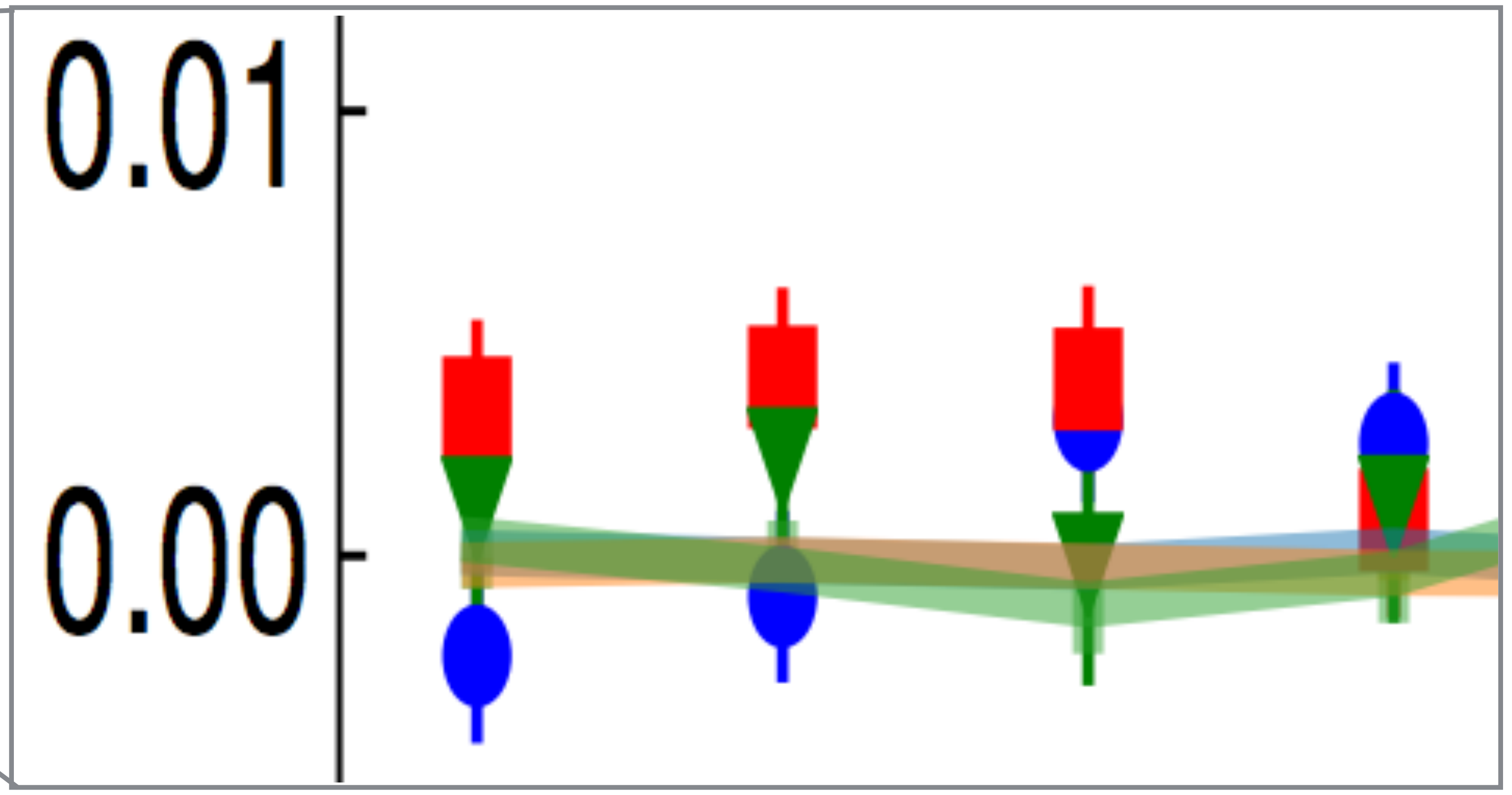


Expected impact of EW FF on $\sin^2\theta_W$ ($\times10^{-5}$, based on pseudo-data)				
		Mass bin (GeV)		
		70-80	80-100	100-125
Rapidity bin	0-0.8	129	23.6	-120
	0.8-1.6	130	24.2	-123
	1.6-2.5	133	24.7	-119
	2.5-3.6	131	25.6	-104

- Form factors are functions of s,t: $\sin^2\theta^{lep}_{eff}$ also a function of s,t
  - In FF correction to a, b, implicitly extrapolate $\sin^2\theta^{lep}_{eff}(s, t)$ in each bin to s=m^Z, so that we really measure $\mathbf{\sin^2\theta^{lep}_{eff}(m^Z)}$
- Test closure of s-dependence of EW corrections to interpretation model on a pseudo-measurement of $\sin^2\theta^{lep}_{eff}$
  - Build pseudo-data based on A4 predictions given pdg value of $\sin^2\theta^{lep}_{eff}$
  - Construct interpretation model w/ and w/out EW corrections
  - Fit each version to pseudo-data, and look at difference
- Combined effect will depend on whether PDF uncertainties are included and profiled or not, as sidebands can pull PDFs
  - $\Delta\sin^2\theta^{lep}_{eff} = 24.8$ w/out PDFs
  - $\Delta\sin^2\theta^{lep}_{eff} = 27.4$ w/ PDFs

Z3D-based measurement





- Parallel analysis based on published triple-differential (cosθ, m_{ll}, y_{ll}) cross-section
- Left shows A_{FB} derived from cross-section measurement in bins closest to those in Ai-based extraction
- The two analyses have similar sensitivity when comparing A_{FB} to A_4
- Result based on A_{FB} found to be in agreement with those from A_4
- Similar trends seen in points that deviate from predictions

PDF Closure Tests

Table of $\sin^2\theta_W$-level non-closure

- Compare closure of $\sin^2\theta_W$ for CC-only and CC+CF, before and after PDFs are free in the fit
- For CC-only, can compare to PDF uncertainty in recent CMS $\sin^2\theta_W$ measurement, $\sim 30\times10^{-5}$
- Differences mostly within 1σ of PDF uncertainty, with exception of epWZ16 and others, which can be 2-3σ away
- Closures on left are mostly symmetric, but asymmetries can come in to numbers on right since PDF NPs are different between columns
- In some cases, closure becomes worse after PDFs are allowed to vary
- In some cases, there are large (several σ) differences between closure with and without PDF NPs

Closure in $\sin^2\theta_W$, $\times10^{-5}$

CC-only

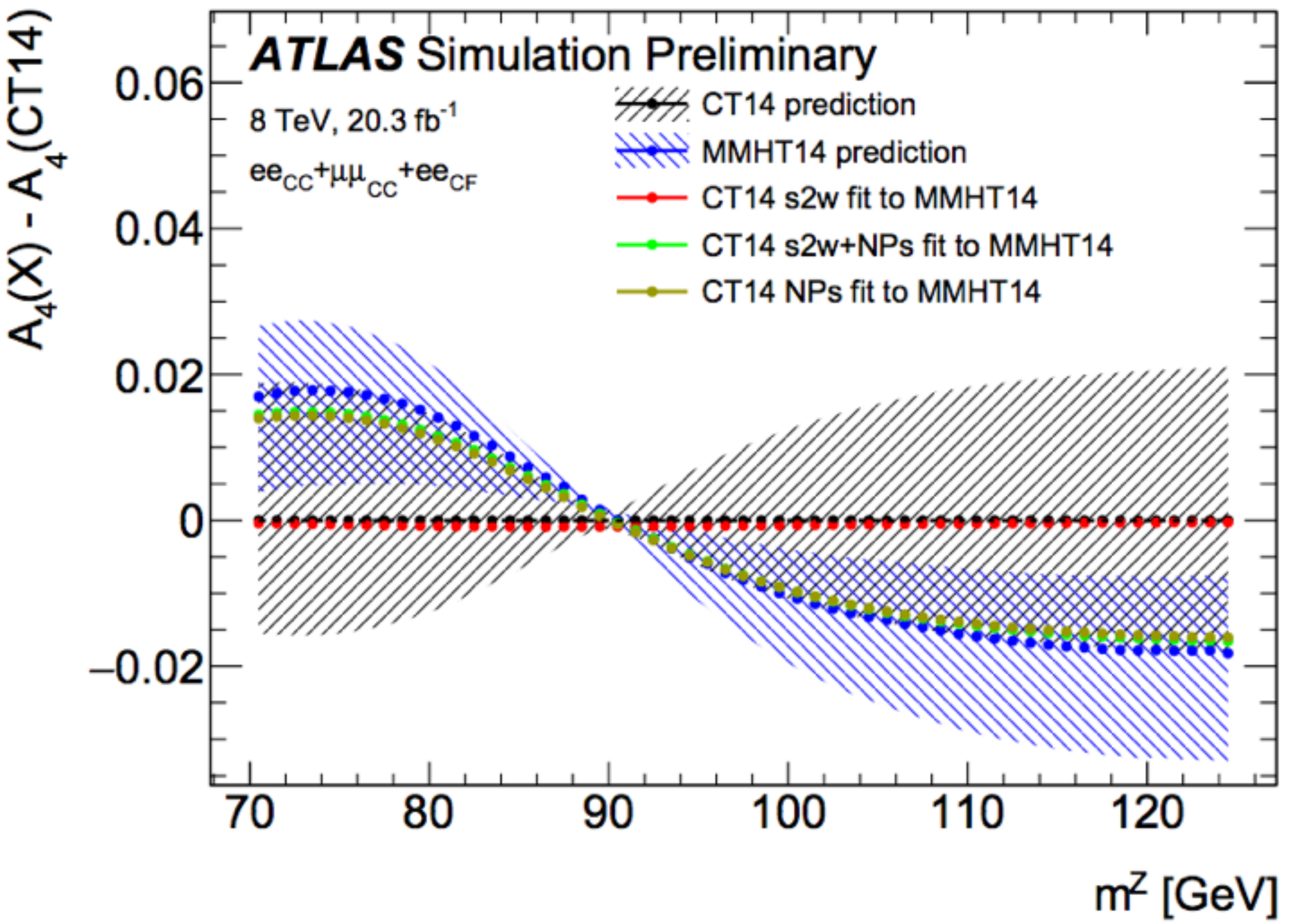
Generated pseudodata	PDFs used for interpretation of A4 versus $\sin^2\theta_W$									
	Before PDF constraint					After PDF constraint				
	CT10	CT14	MMHT14	NNPDF31	epWZ16	CT10	CT14	MMHT14	NNPDF31	epWZ16
CT10	-	33	-8.	-7	130	-	-18	22	17	-52
CT14	-33	-	-42	-41	98	27	-	44	39	-36
MMHT14	9	41	-	2	137	-29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

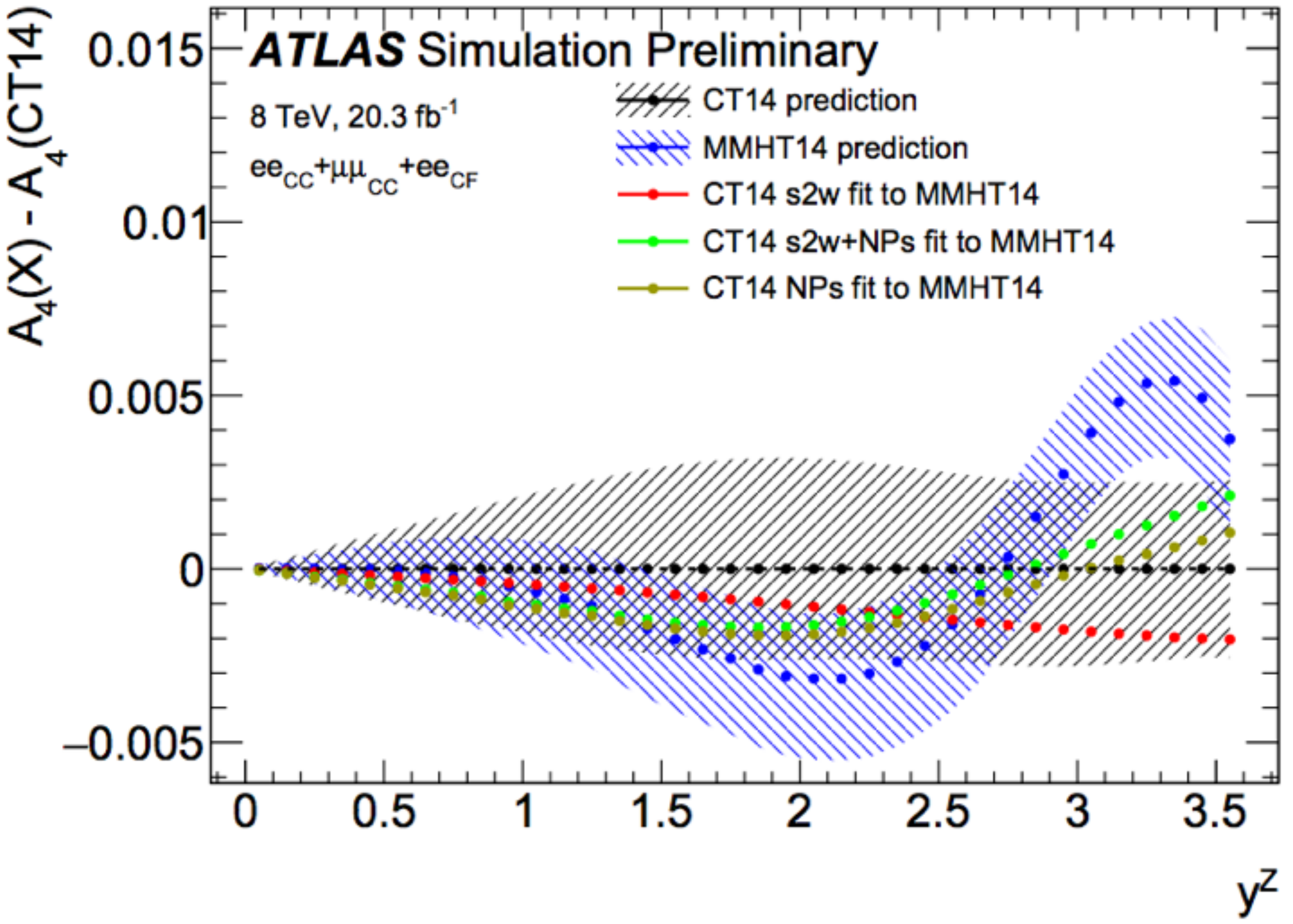
CC+CF

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	-	20	2	11	109	-	3	19	19	52
CT14	-20	-	-18	-9	91	8	-	21	21	56
MMHT14	-1	18	-	9	108	-25	-11	-	1	31
NNPDF31	-10	9	-9	-	99	-14	-9	4	-	43
epWZ16	-116	-95	-114	-105	-	-44	-66	-42	-42	-

A4-level closure

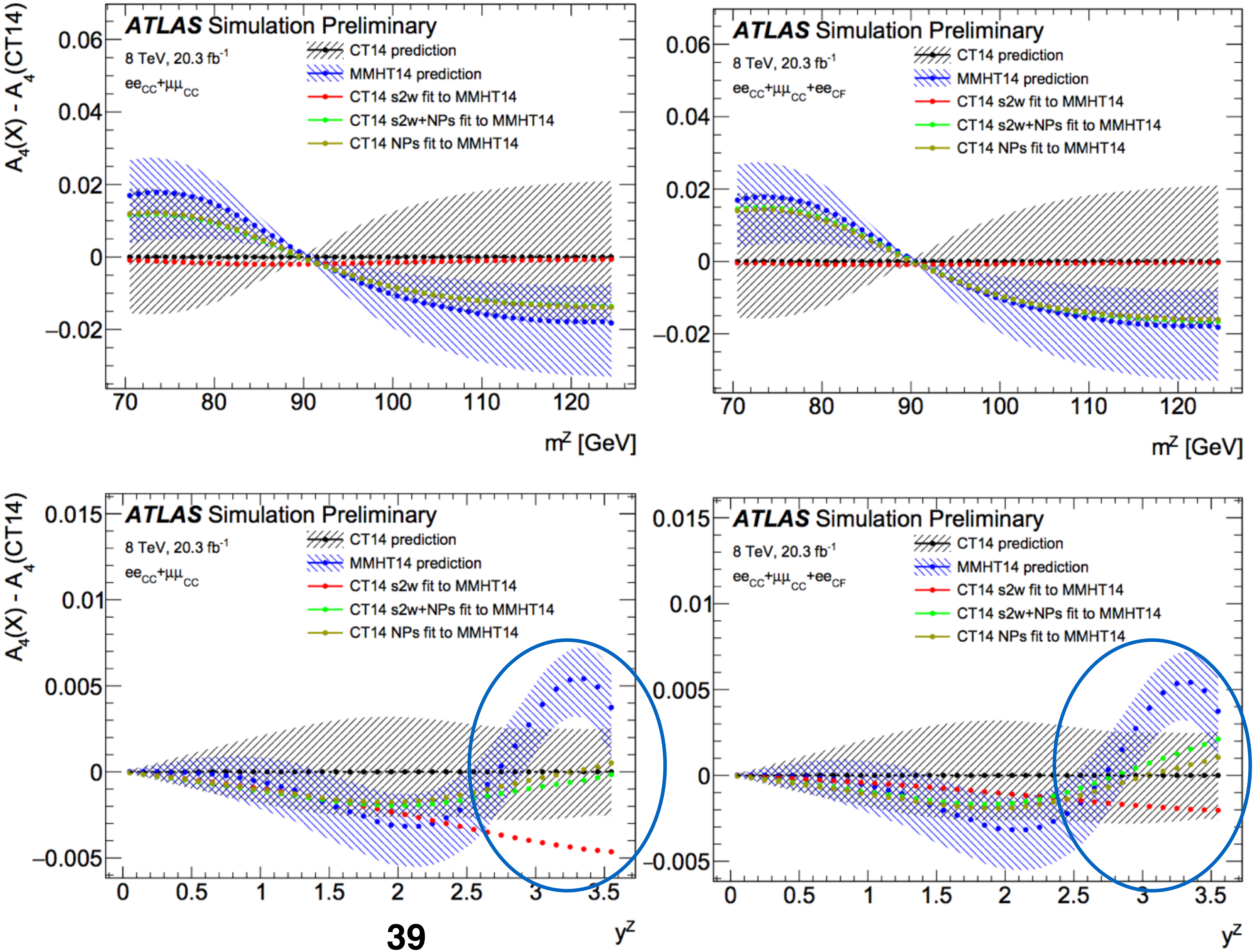
- $A_4^n(\sin^2\theta_W, \theta) = a_n(\theta)*\sin^2\theta_W + b_n(\theta)$ can be computed for any m^Z, y^Z bin
- Best fit values of $\sin^2\theta_W$ and θ can be re-injected back into A_4 predictions in any binning
- Fit can be performed under three different conditions
  - $\sin^2\theta_W$ free: Test ability of sin2θW alone to cover differences between sets
  - PDF NPs free: Test ability of PDF NPs alone to cover differences
  - $\sin^2\theta_W$+PDF NPs free: Test ability of PDFs + $\sin^2\theta_W$ to cover differences
- Plots show pre- and post-fit differences between predictions
  - Prediction 1 (interp. model) + PDF unc.
  - Prediction 2 (pseudo-data) + PDF unc.
- Ideal case: PDF NPs can cover differences between PDF sets (brown matches blue)
  - Limited data statistics and DoFs in PDF EVs cause A_4-level non-closure
  - Shape vs m^Z tends to drive fit, and matches much better than shape vs y^Z
- Post-fit value of $\sin^2\theta_W$ will in general be different than injected value
  - Difference between **red** and **black** shows how much $\sin^2\theta_W$ alone will absorb differences between PDF sets
  - Difference between **green** and **brown** shows how much $\sin^2\theta_W$ will absorb these differences after PDFs are allowed to be profiled





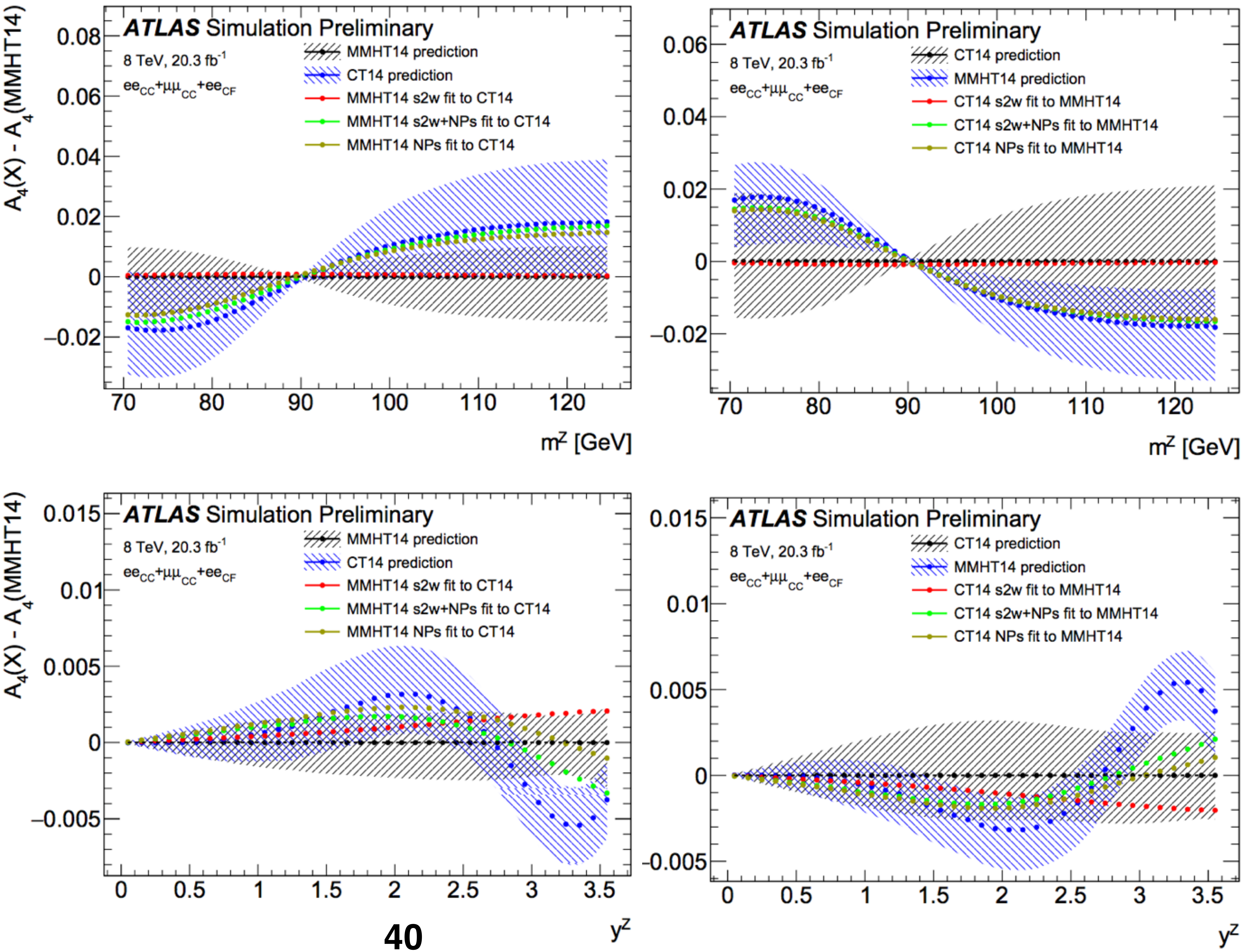
A_4-level closure

- Fits can be done also with CC channels alone, which covers only $|y^Z| < 2.5$
- Non-closure in $\sin^2\theta_W$ tends to be larger without ee_{CF}, since difference between sets are roughly monotonic at low y^Z alone
- Including high y^Z in the fit tends to stabilize non-closure, though the main motivation for including events with $|y^Z| > 2.5$ is their far greater sensitivity to $\sin^2\theta_W$



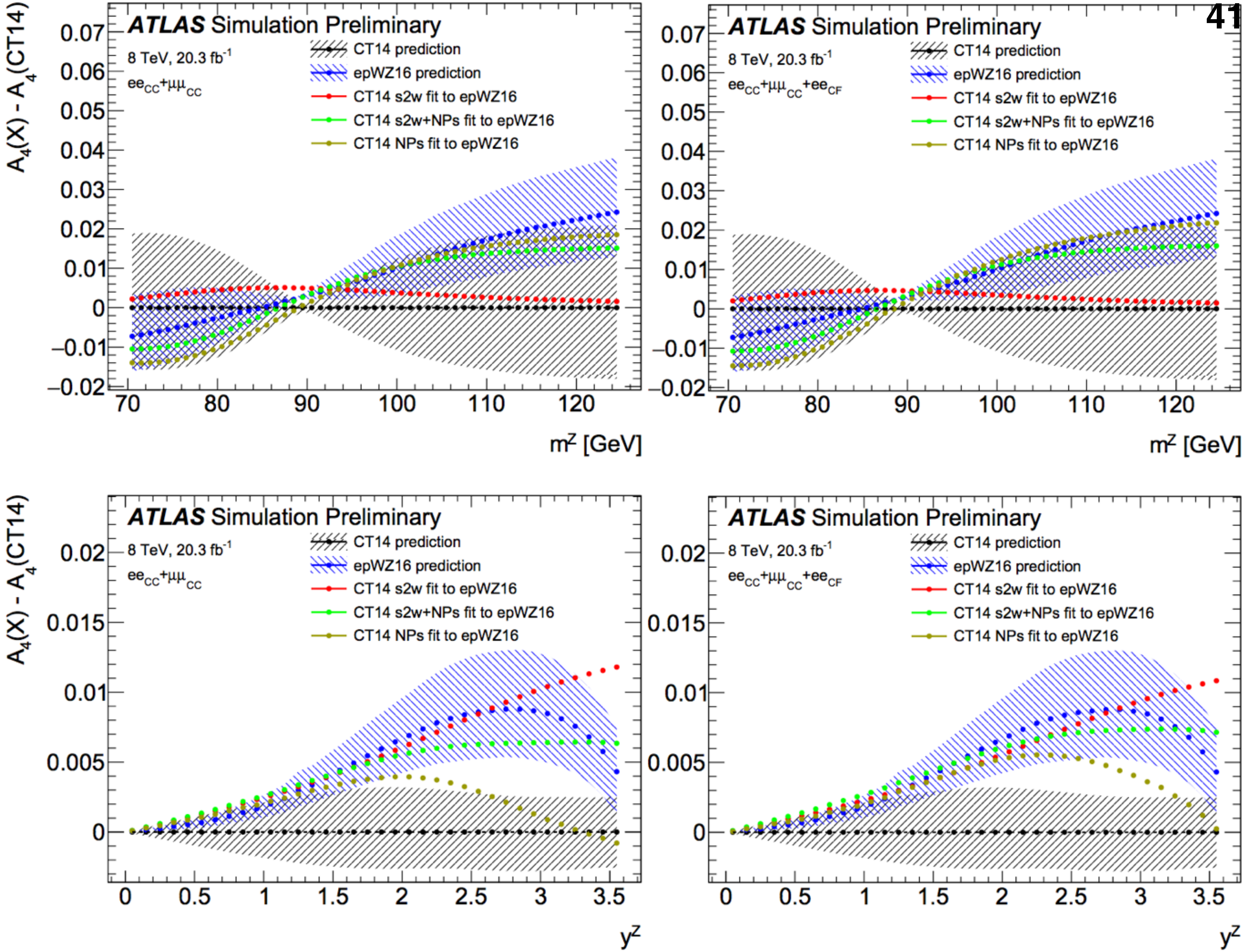
A_4-level closure

- Mirror of this can be done: swap PDF sets used for interp. and pseudo-data
- Red curve is usually quite symmetric, but differences in PDF uncertainties cause some asymmetries in post-fit closure

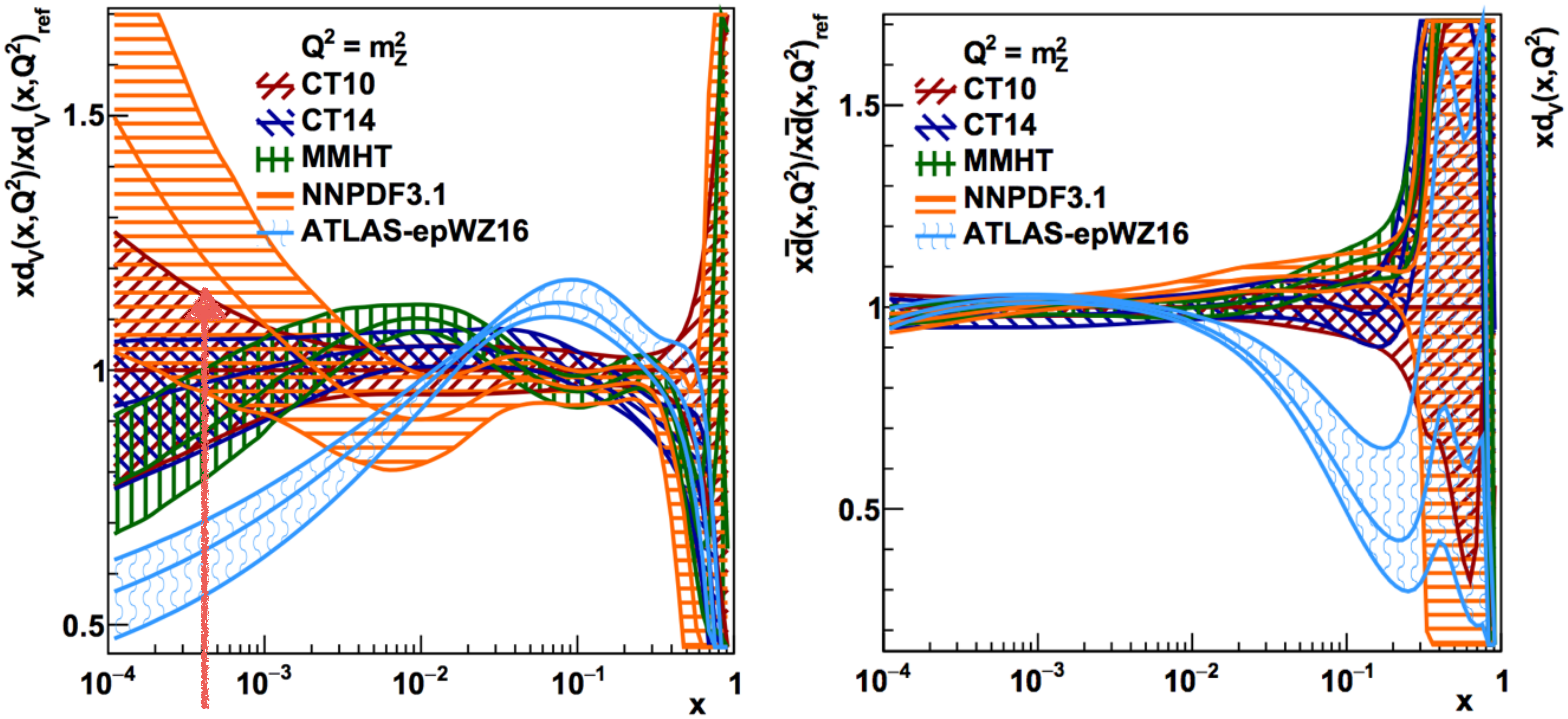


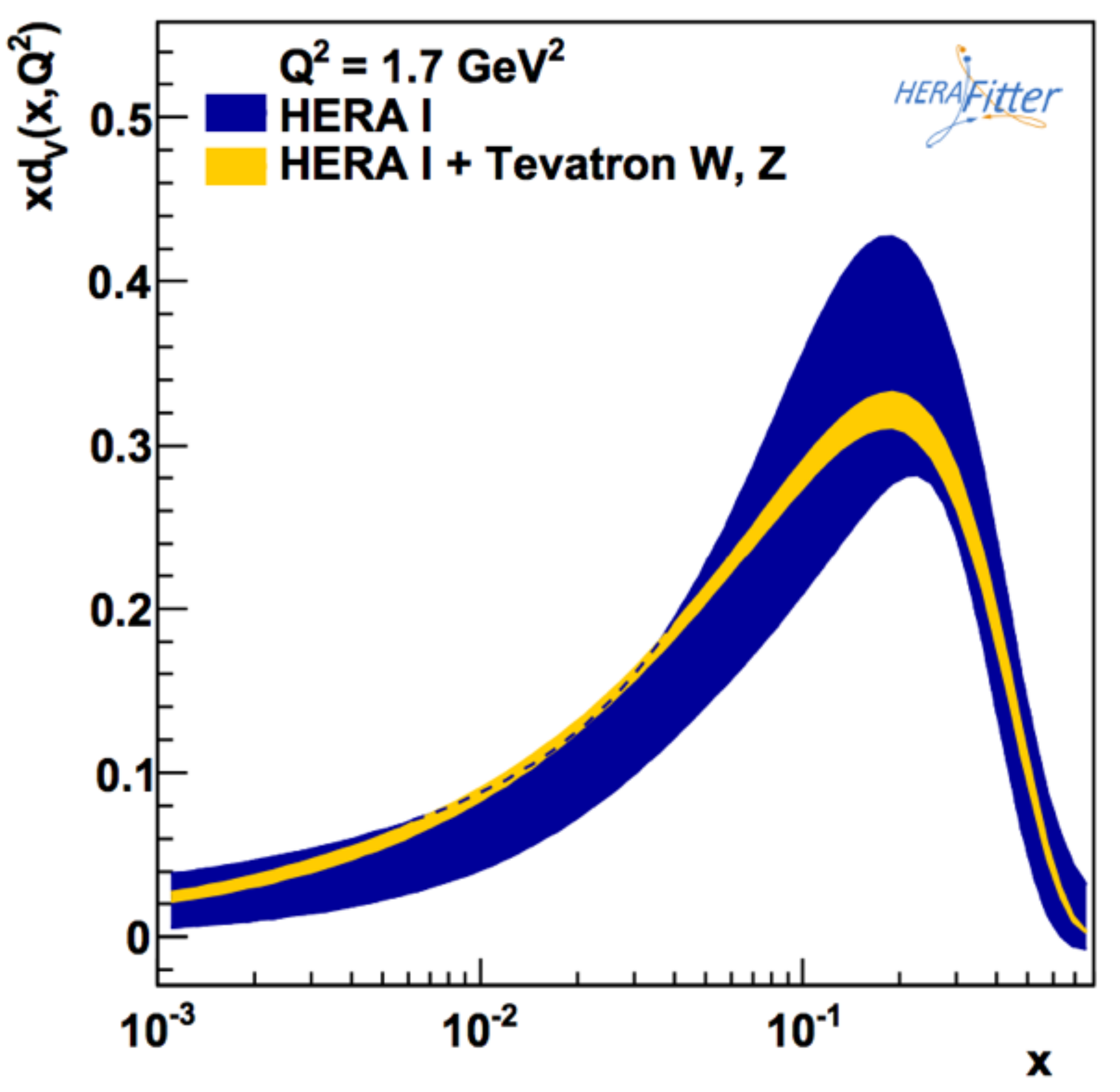
epWZ16 set

- As expected from differences in predictions, epWZ16 does not close well with other sets
- Very large differences between both red and black, and green and brown:
  - PDF NPs not able to absorb differences between sets
  - $\sin^2\theta_W$ tries to cover too much of the difference



Comparing raw PDFs between sets





https://arxiv.org/abs/1503.05221

- Difference in A_4 between epWZ16 and others driven by difference in d-valence distribution
- This is largely constrained by Tevatron W-asymmetry measurements in "global" PDF sets
- Possibly due to not-flexible-enough parametrization used within the set