Tests of the electroweak sector sector through precision measurements at the ATLAS Experiment

Joany Manjarrés

Feb 15, 2019

Test the electroweak sector of the SM

The consistency of the SM at the LHC can be tested through:

- High precision measurements of its fundamental parameters
    - W boson mass
    - Effective weak mixing angle using $Z \rightarrow \ell\ell$
- Direct exploration of the EW symmetry breaking mechanism using diboson production
    - Low cross sections. First VBS results will be shown in the next talk by Yee.
    - We will need very large datasets (HL-LHC or beyond) and specific efforts from the theory community

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The weak mixing angle and the Standard Model

- $\sin^2\theta_W$ represent the mixing of the EM and weak fields and can be constrained :

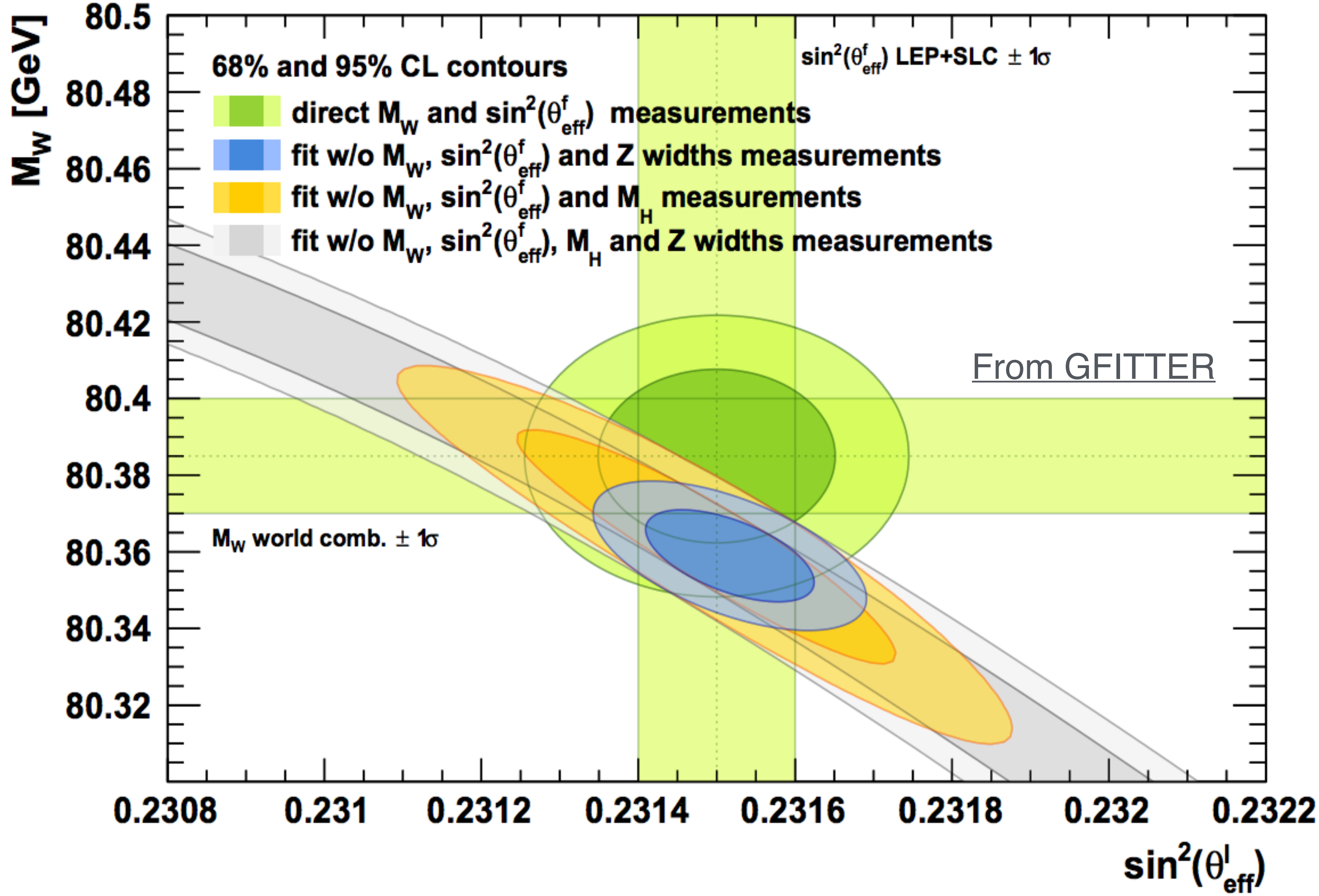
$$\sin^2\theta_W = 1 - \frac{m_W^2}{m_Z^2} \qquad m_W^2 \sin^2\theta_W = \frac{\pi\alpha_{em}}{\sqrt{2}G_F}$$

- α_{em}, G_F, m_Z → known with high precision

- Higher order virtual corrections modify this relation, yielding the fermion-flavor dependent effective weak mixing angle **$\sin^2\theta^l_{eff}$** .
- At the Z pole, the ratio of the effective vector to axial-vector coupling constants of the Z boson to leptons is expressed as a function of a single effective form factor K^l_Z

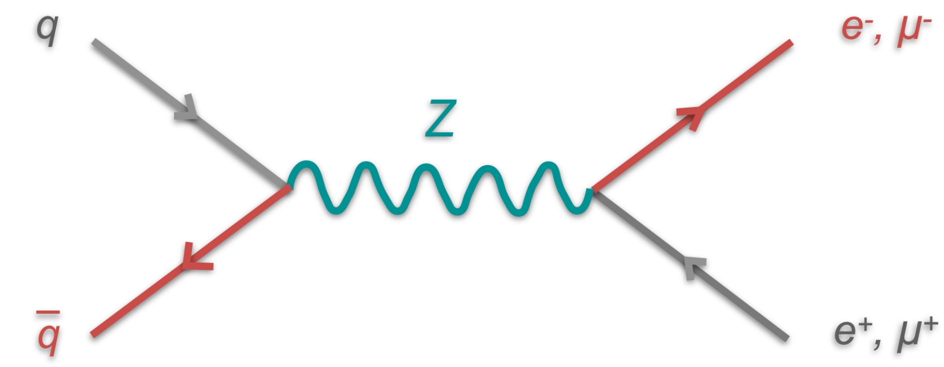
$$\sin^2\theta^l_{eff} = (1 - \frac{m_W^2}{m_Z^2})\, K^l_Z$$

Precision tests of the EW sector



- **Full EW fit: $\sin^2\theta^l_{eff}$ = 0.23150 ± 0.00006**
- Indirect determination from EW fit: $\sin^2\theta^l_{eff}$ = 0.23149 ± 0.00007
- ATLAS 7 TeV: $\sin^2\theta^l_{eff}$ = 0.23080 ± 0.00120
- Recently Tevatron measurement was released: $\sin^2\theta^l_{eff}$ = 0.23148 ± 0.00033

Weak mixing angle @LHC



- We look at the $q\bar{q} \to Z/\gamma * \to ll$ differential cross section

- At lowest order (LO) in QCD the cross section can be written

$$\frac{d\sigma}{dy^{ll}dm^{ll}d\cos\theta} = \frac{3}{16\pi}\frac{d\sigma^{U+L}}{dy^{ll}dm^{ll}}\left\{(1+\cos^2\theta) + A_4\cos\theta\right\}$$

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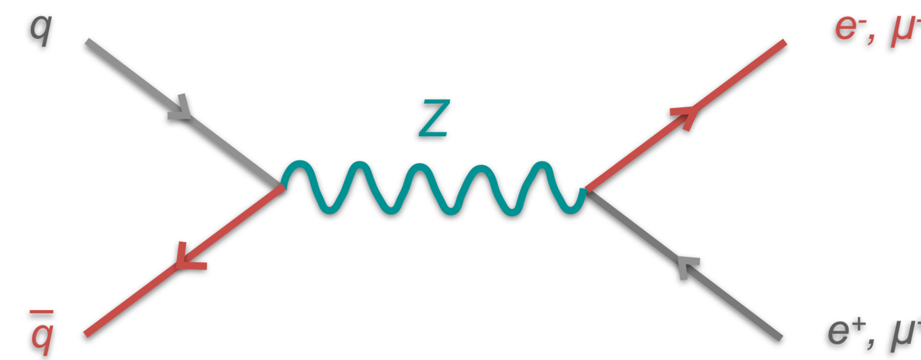

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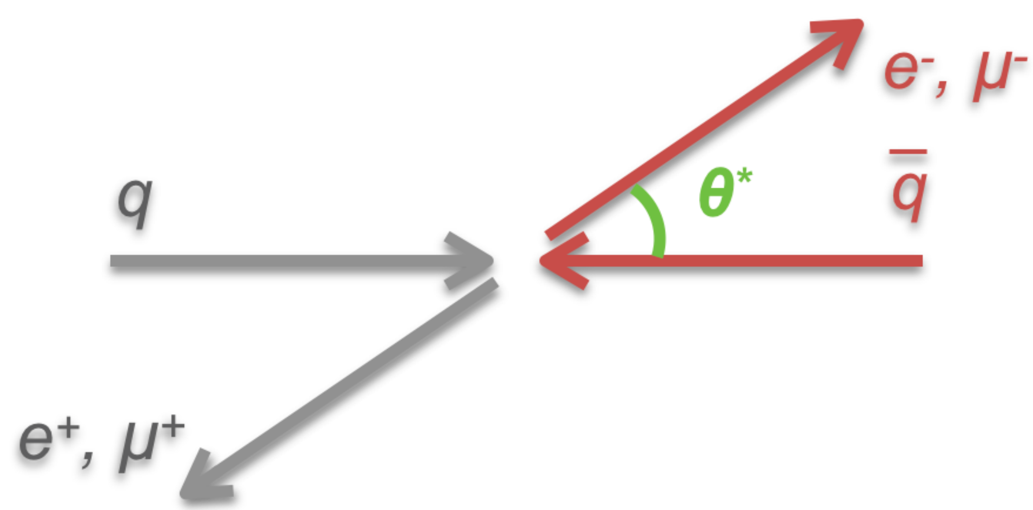
θ **lepton decay angle**

y^{ll} **dilepton rapidity**

m^{ll} **dilepton mass**



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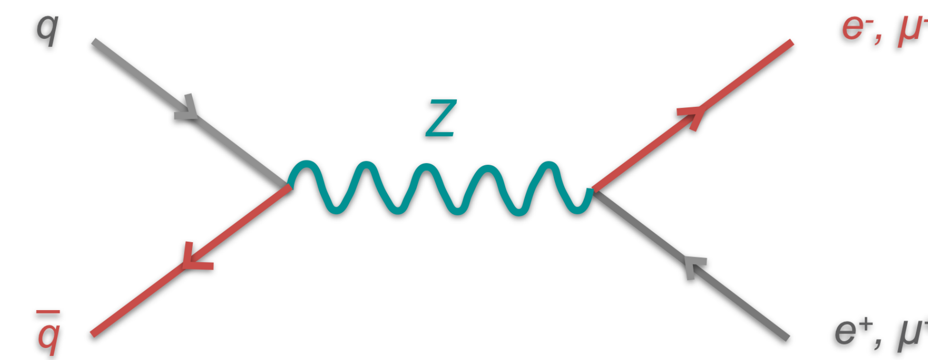

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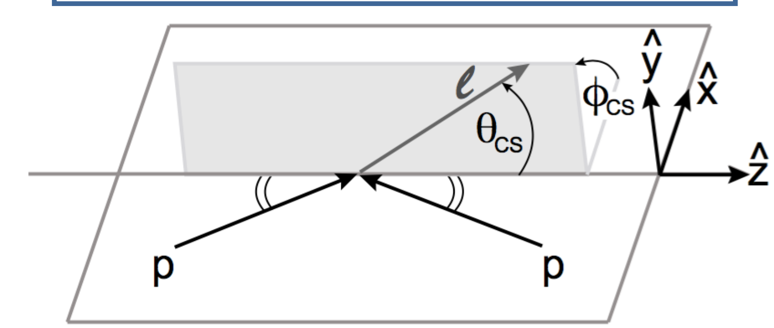
y^{ll} dilepton rapidity

m^{ll} dilepton mass

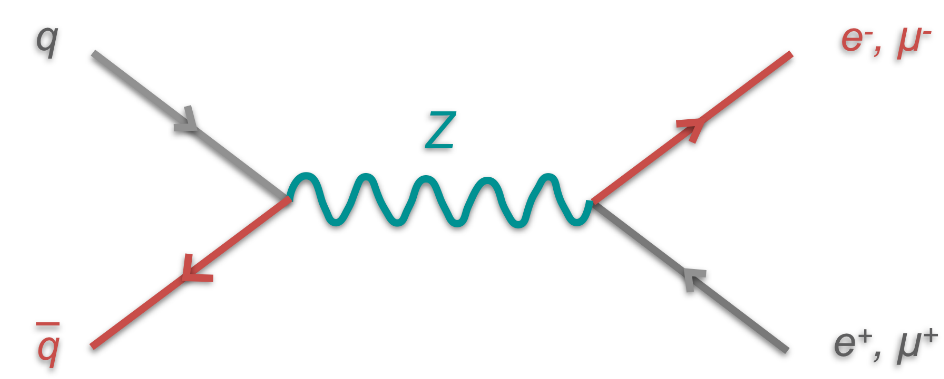
θ lepton decay angle in the Collins-Soper frame

Collins-Soper Frame



- Rest frame of di-lepton system
- z-axis bisecting directions of incoming protons

Weak mixing angle @LHC



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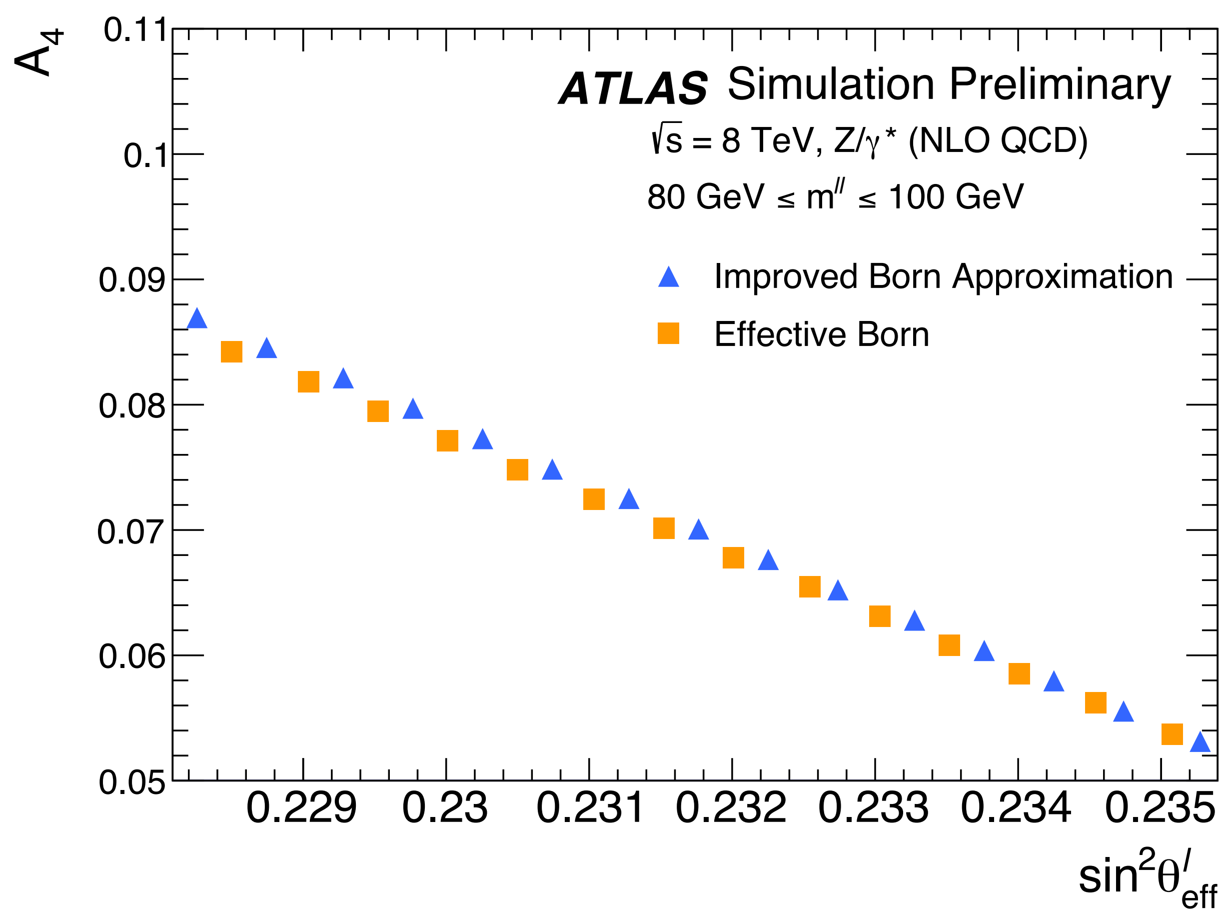
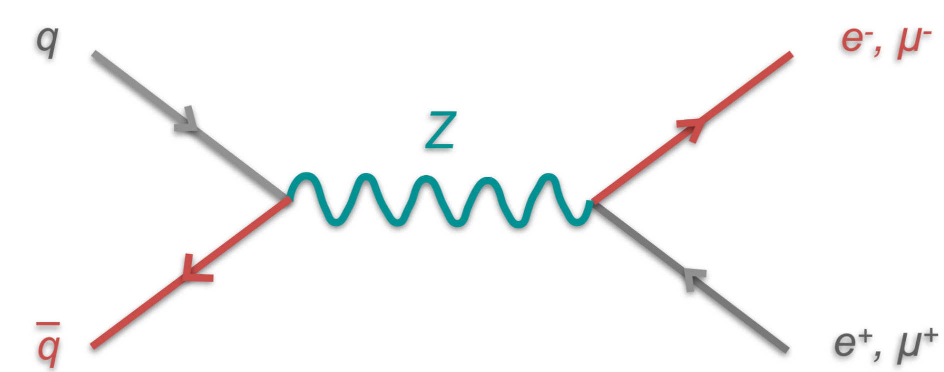
- The angular coefficient A_4 leads to measurement of $\sin^2\theta^l_{eff}$. Based on an effective linear relation.



Weak mixing angle @LHC



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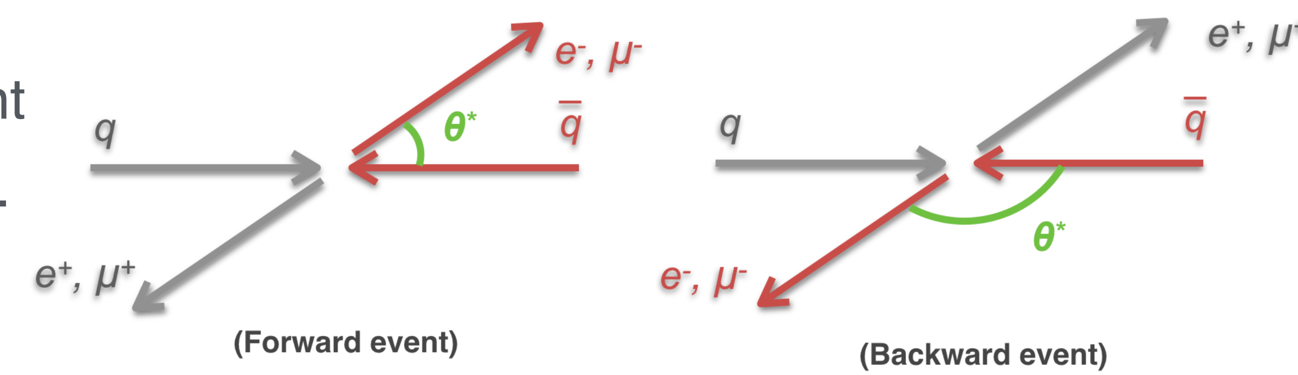


- The A_4 coefficient can be obtained from:
  - the forward-backward asymmetry
  - fit to the lepton angular distributions

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

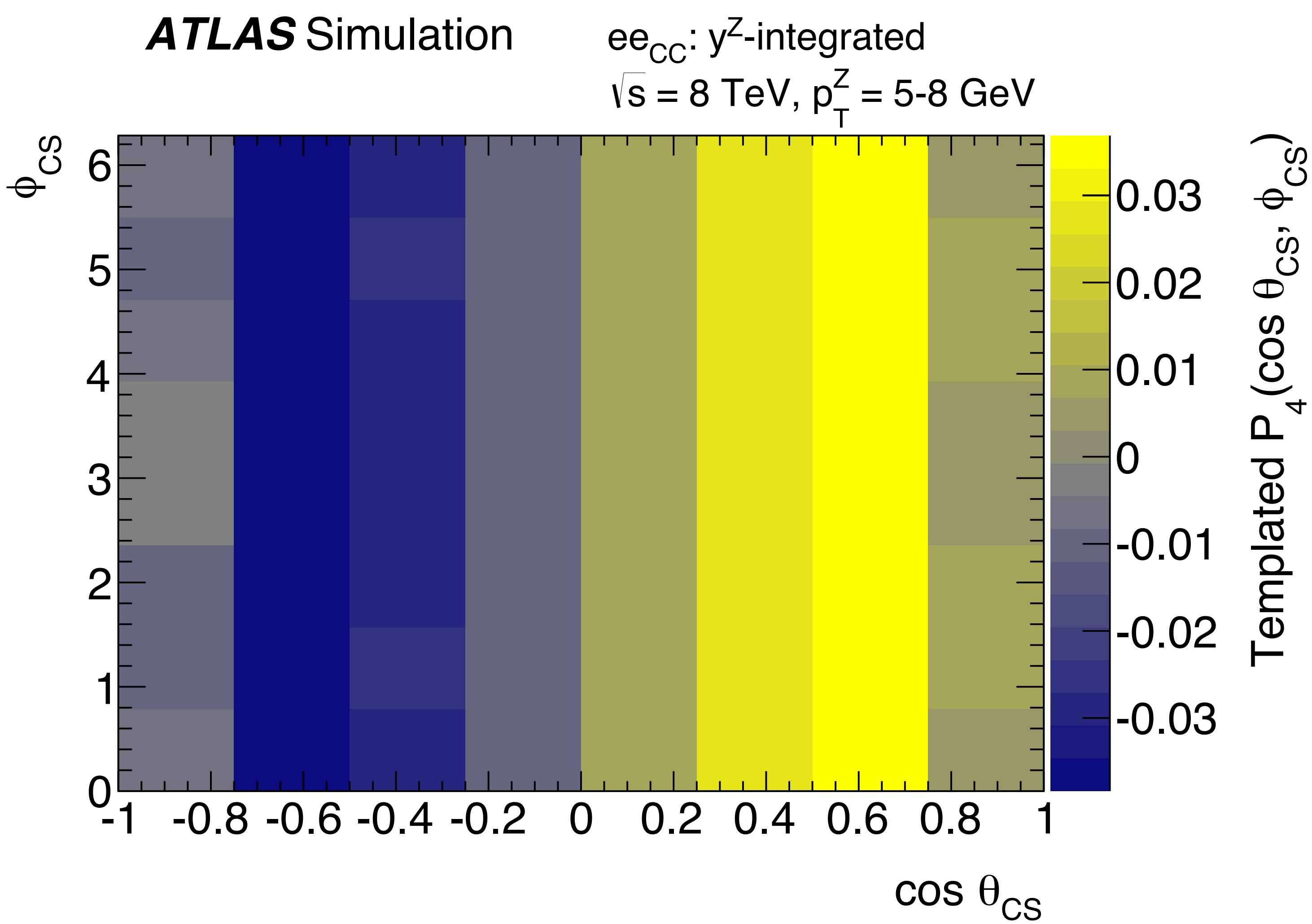
$$A_{FB} = \frac{3}{8}A_4$$ in full phase space → folding

ATLAS 8 TeV measurement strategy

$$\frac{d\sigma}{dy^{ll}dm^{ll}d\cos\theta} = \frac{3}{16\pi}\frac{d\sigma^{U+L}}{dy^{ll}dm^{ll}}\left\{(1+\cos^2\theta) + A_4\cos\theta\right\}$$

To extract A_4 use a template fit to reconstructed angular distributions. We need :

- Binned cosθ vs ϕ distribution (8×8 bins) for each y^{ll}, m^{ll} bins
- Total of 1280 bins in the (cosθ, ϕ, y^{ll}, m^{ll})



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A_4 predictions

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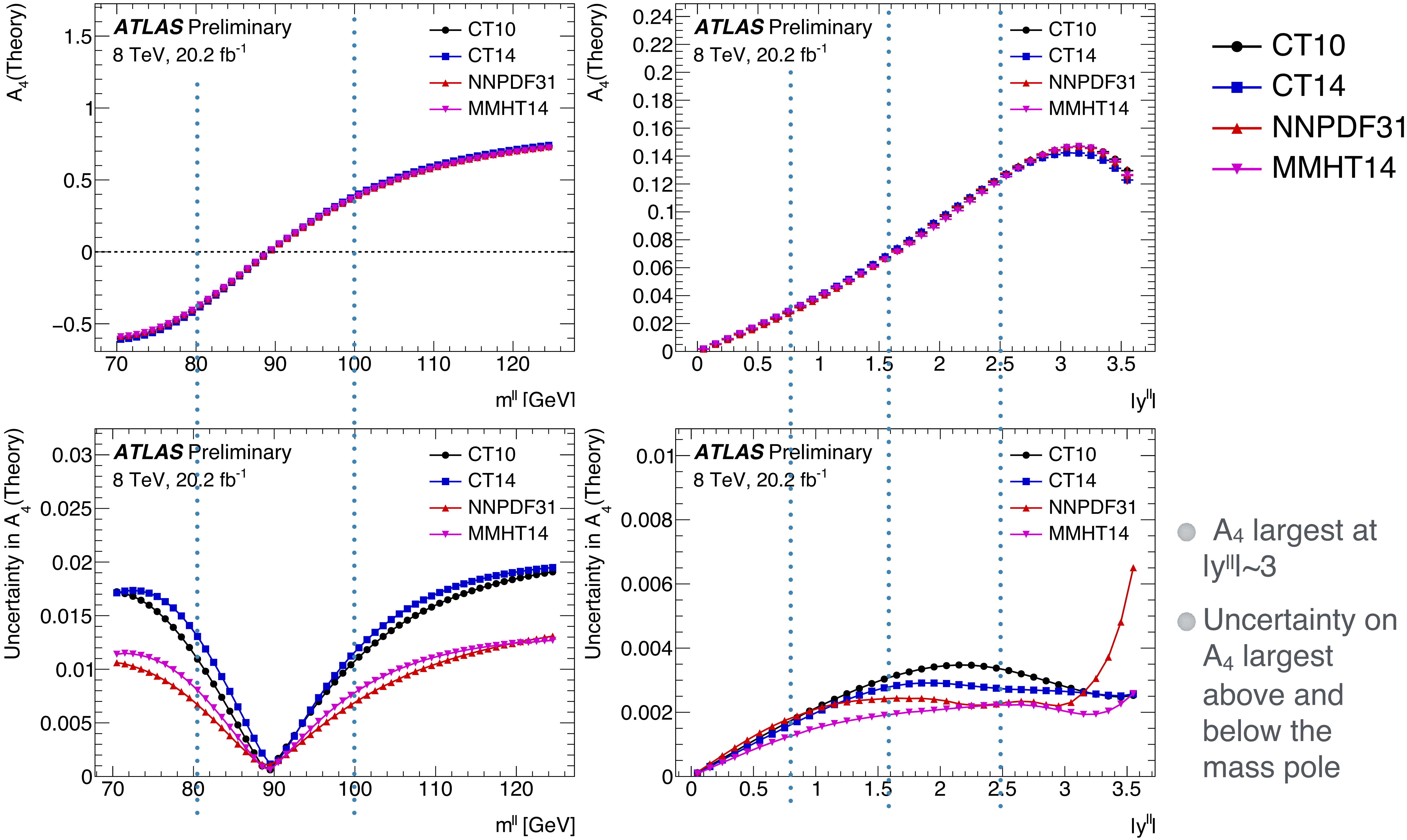

- A_4 largest at $|y^{ll}|$~3
- Uncertainty on A_4 largest above and below the mass pole

Event selection and categorization

ATLAS-CONF-2018-037

- **ee$_{CC}$**: two electrons in the central tracking and calorimetry (|η|<2.4)
  - p_T >25 GeV
  - Exactly 2 opposite sign electrons

- 3 bins in m_{ll}

  $70 < m_{ll} < 80$ GeV

  $80 < m_{ll} < 100$ GeV

  $100 < m_{ll} < 125$ GeV

- 3 bins in $|y_{ll}|$

  $|y_{ll}| < 0.8$

  $0.8 < |y_{ll}| < 1.6$

  $1.6 < |y_{ll}| < 2.5$

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

Excellent S/B, backgrounds typically few per mille

Event selection and categorization

ATLAS-CONF-2018-037

- **ee$_{CC}$**: two electrons in the central tracking and calorimetry (|η|<2.4)
  - p_T >25 GeV
  - Exactly 2 opposite sign electrons
- **μμ$_{CC}$**: two muons in the central tracking and muon systems (|η|<2.4)
  - p_T >25 GeV P_T
  - Exactly 2 opposite sign muons

- 3 bins in m_{ll}
  $70 < m_{ll} < 80$ GeV
  $80 < m_{ll} < 100$ GeV
  $100 < m_{ll} < 125$ GeV
- 3 bins in $|y_{ll}|$
  $|y_{ll}| < 0.8$
  $0.8 < |y_{ll}| < 1.6$
  $1.6 < |y_{ll}| < 2.5$

ee$_{CC}$

	$80 < m_{ll} < 100$ GeV			
$\lvert y_{ll}\rvert$	Data	Top+EW	Multijets	Non-fiducial Z
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0.8-1.6	2 084 856	0.002	0.001	< 0.001
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μμ$_{CC}$

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

Excellent S/B at the Z pole!

~15M ee+μμ pairs selected in data

Event selection and categorization

ATLAS-CONF-2018-037

- **ee_{CC}**: two electrons in the central tracking and calorimetry (|η|<2.4)
  - p_T >25 GeV
  - Exactly 2 opposite sign electrons
- **$\mu\mu_{CC}$**: two muons in the central tracking and muon systems (|η|<2.4)
  - p_T >25 GeV P_T
  - Exactly 2 opposite sign muons

- 3 bins in m_{ll}
  $70 < m_{ll} < 80$ GeV
  $80 < m_{ll} < 100$ GeV
  $100 < m_{ll} < 125$ GeV
- 3 bins in $|y_{ll}|$
  $|y_{ll}| < 0.8$
  $0.8 < |y_{ll}| < 1.6$
  $1.6 < |y_{ll}| < 2.5$

- **ee_{CF}**: one electron in central tracking/calorimetry (|η|<2.4), one in endcap/forward calorimetry (2.5 < |η| < 4.9)
  - p_T >25/20 GeV C/F
  - requirement with tighter ID than ee_{CC}

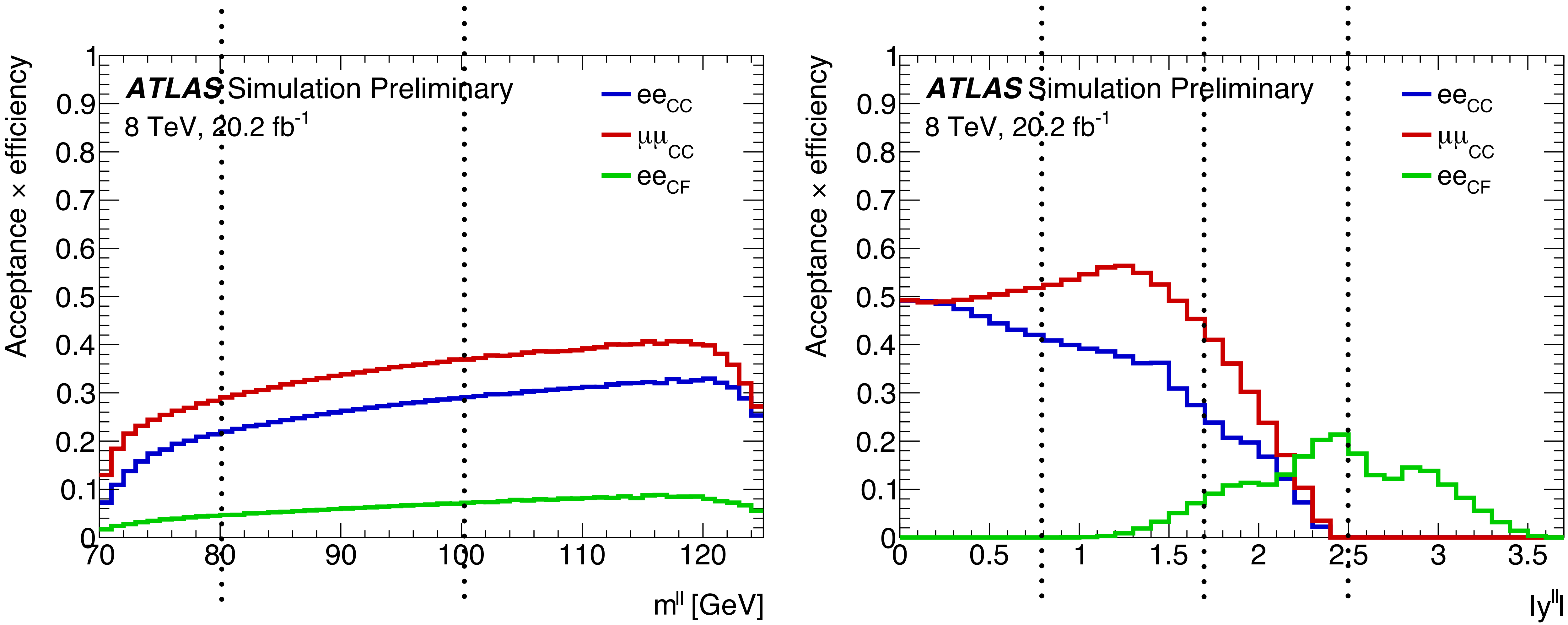
- 1 bin in m_{ll} $80 < m_{ll} < 100$ GeV
- 2 bins in $|y_{ll}|$ $2.5 < |y_{ll}| < 3.6$
  $1.6 < |y_{ll}| < 2.5$

	$80 < m_{ll} < 100$ GeV			
$\lvert y_{ll}\rvert$	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

Only 1 overlapping bin between the categories
$80<m_{ll}<100$ and $1.6<|y_{ll}|<2.5$

Event selection and categorization

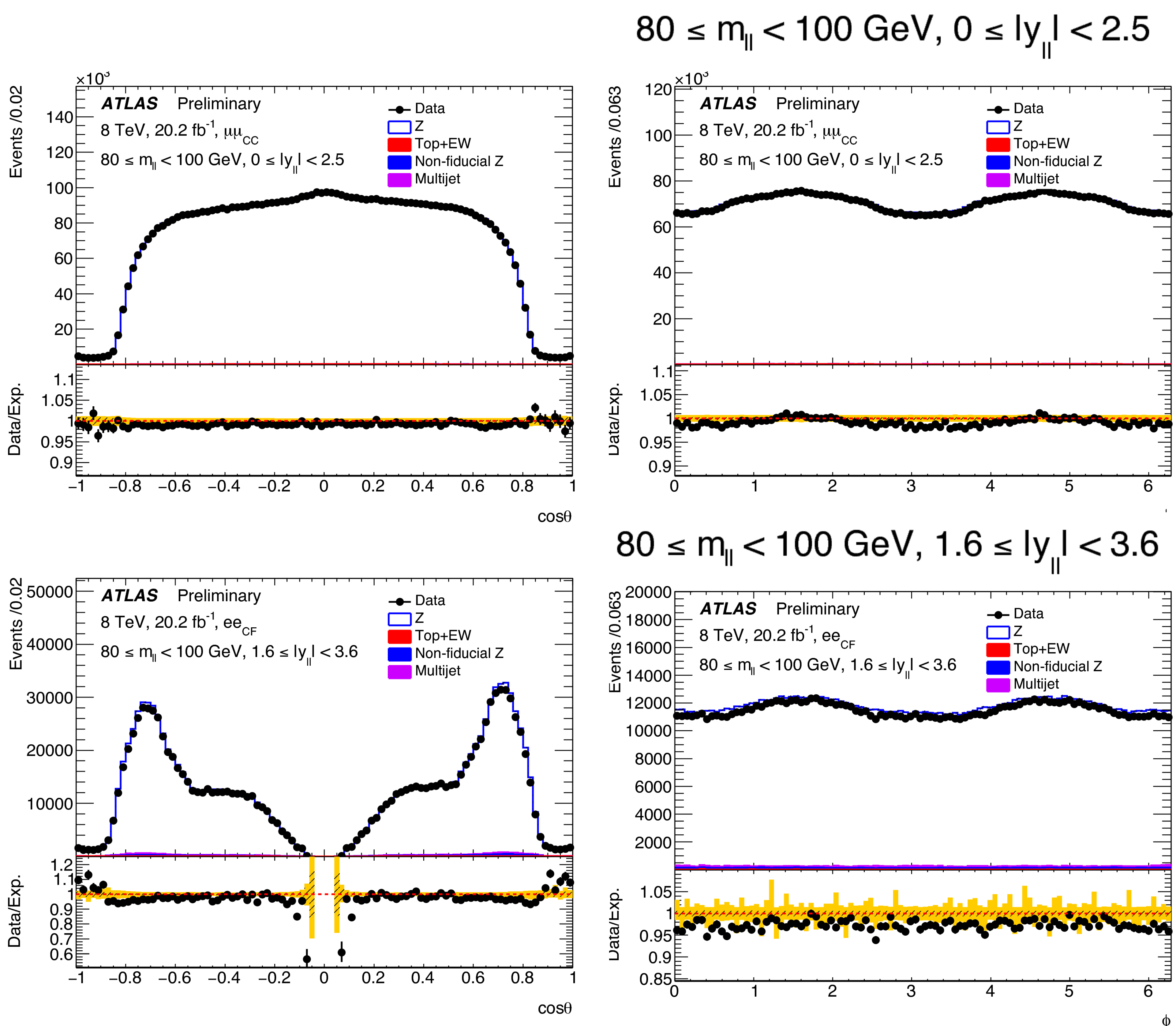
ATLAS-CONF-2018-037



- Central-forward $Z \rightarrow ee$ (ee_{CF}) production: adds extra sensitivity ($1.6 < y_{ll} < 3.6$)

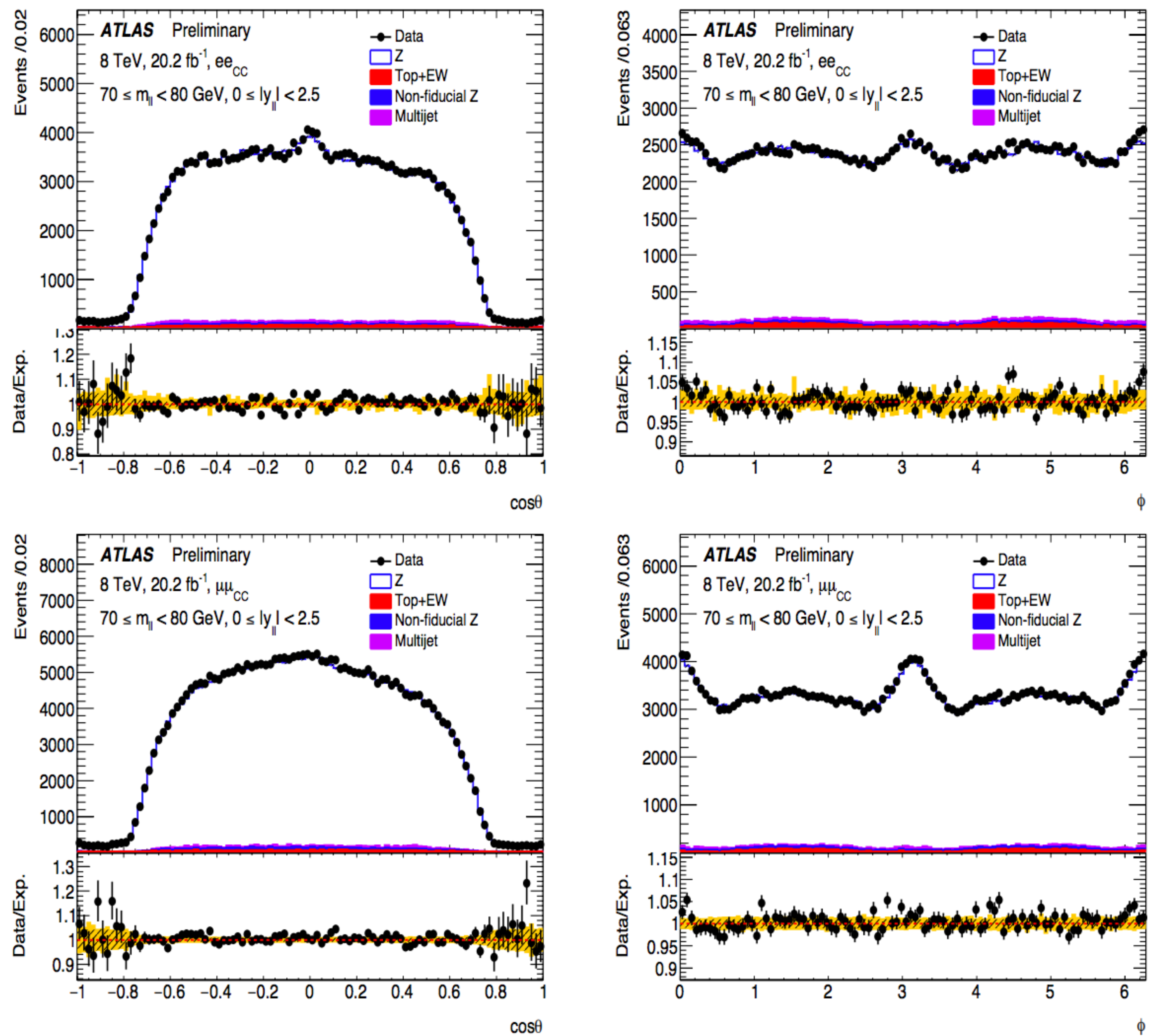
Angular distributions

- Data/MC agreement for $\mu\mu_{CC}$ and ee_{CF} in the Z pole mass region for all y. In the binning used for the extraction
- Only a small raw A_{FB} is visible for CC; a larger one emerges for CF, as expected.



Angular distributions

$70 \le m_{ll} < 80$ GeV, $0 \le |y_{ll}| < 2.5$



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- Only a small raw A_{FB} is visible for CC; a larger one emerges for CF, as expected.

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Fit uncertainties

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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

- ee_{CF} channel most precise (only 1.5M events, cf. 13.5M ee_{CC} + $\mu\mu_{CC}$) → the large η gap between the electrons gives a larger lever arm to measure θ compared to CC, further enhancing the precision.
- All three categories systematics limited, predominantly by PDF uncertainty affecting relation between A_4 and mixing angle
- MC statistics second largest systematic uncertainty

Final results

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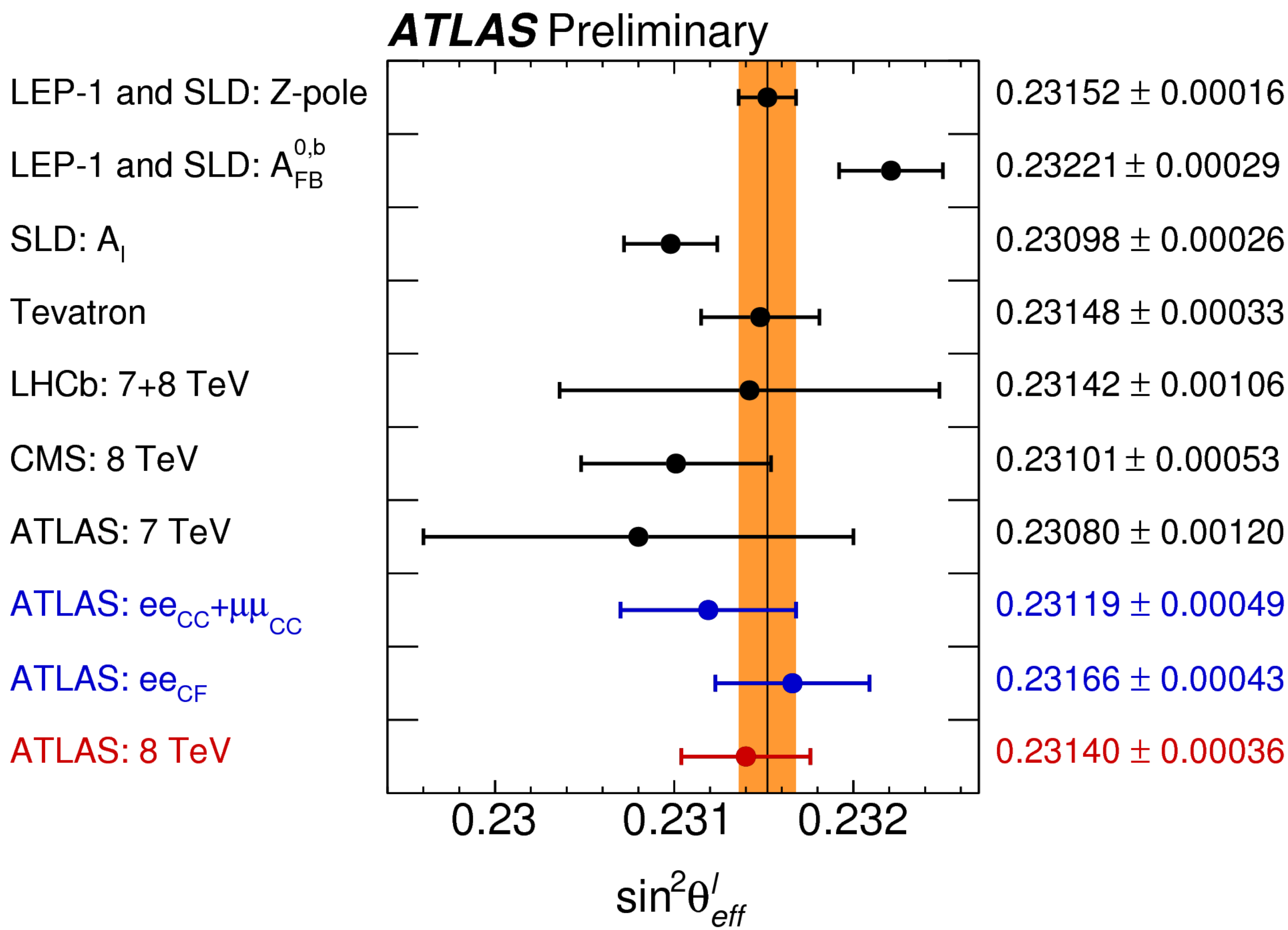
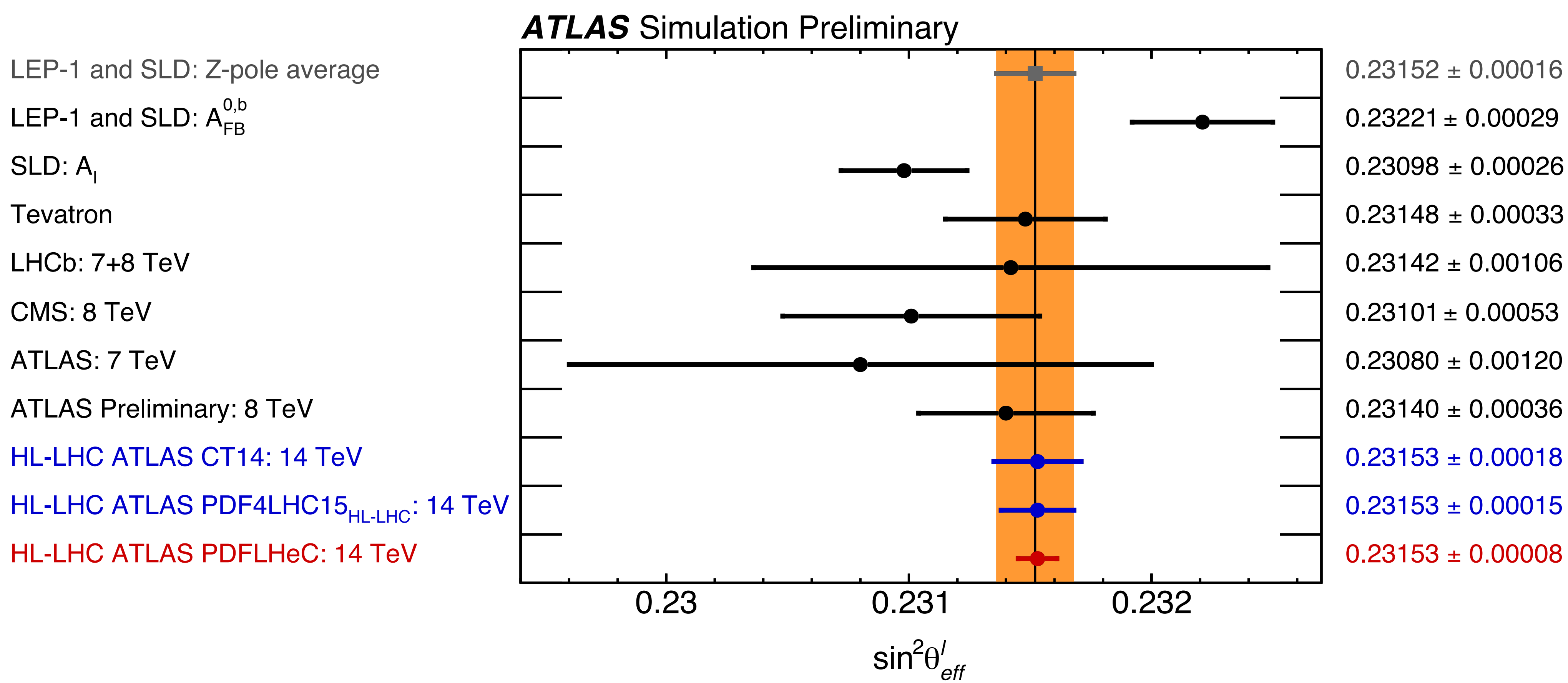
0.23140 ± 0.00021 (stat) ± 0.00024 (PDF) ± 0.00016 (syst)



- Large improvement w.r.t previous results. Comparable to Tevatron final results precision
- Smaller uncertainties than the CMS 8 TeV, which does not include ee_{CF} category.
- This measurement improves the overall consistency of the full set of measurements

Summary and perspectives

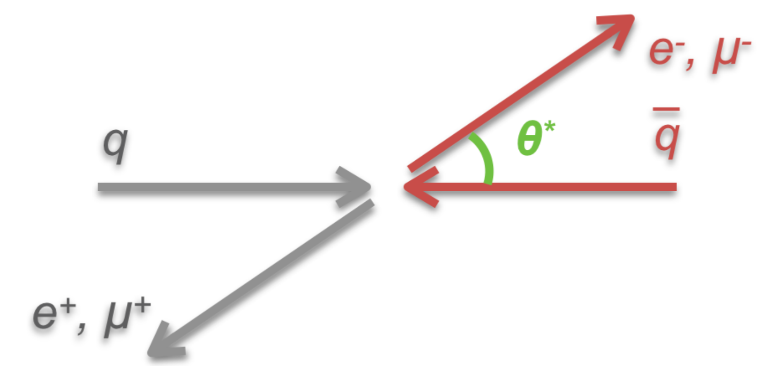
- Presented the most recent measurement of $\sin^2\theta^l_{eff}$ by the ATLAS detector
- The hadron collider measurements of $\sin^2\theta^l_{eff}$ provide consistency tests of the SM which are now relevant on a global level, but they do rely on the SM predictions
- There is more to come:
  - Results are dominated by PDF uncertainties and if we project to the future run-2 legacy measurements it seems it will still be the case
  - Work is ongoing (in the EWWG subgroup) to understand the correlation between different PDF sets so that differences between them can be disentangled
  - Prospect studies for the HL-LHC using 3000fb^{-1} at 14TeV available ATL-PHYS-PUB-2018-037



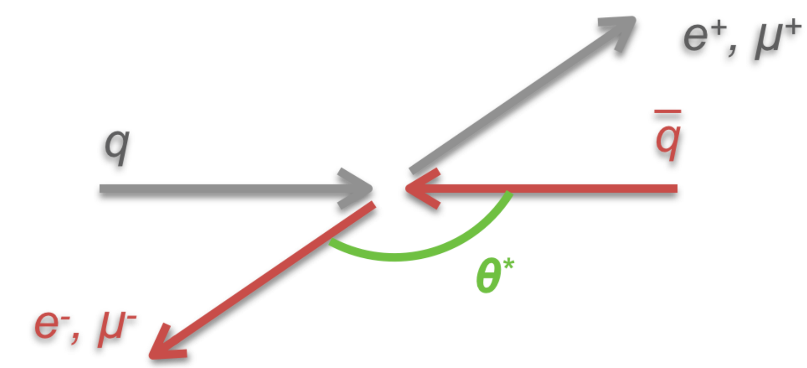
BACKUP

Weak mixing angle previous measurements

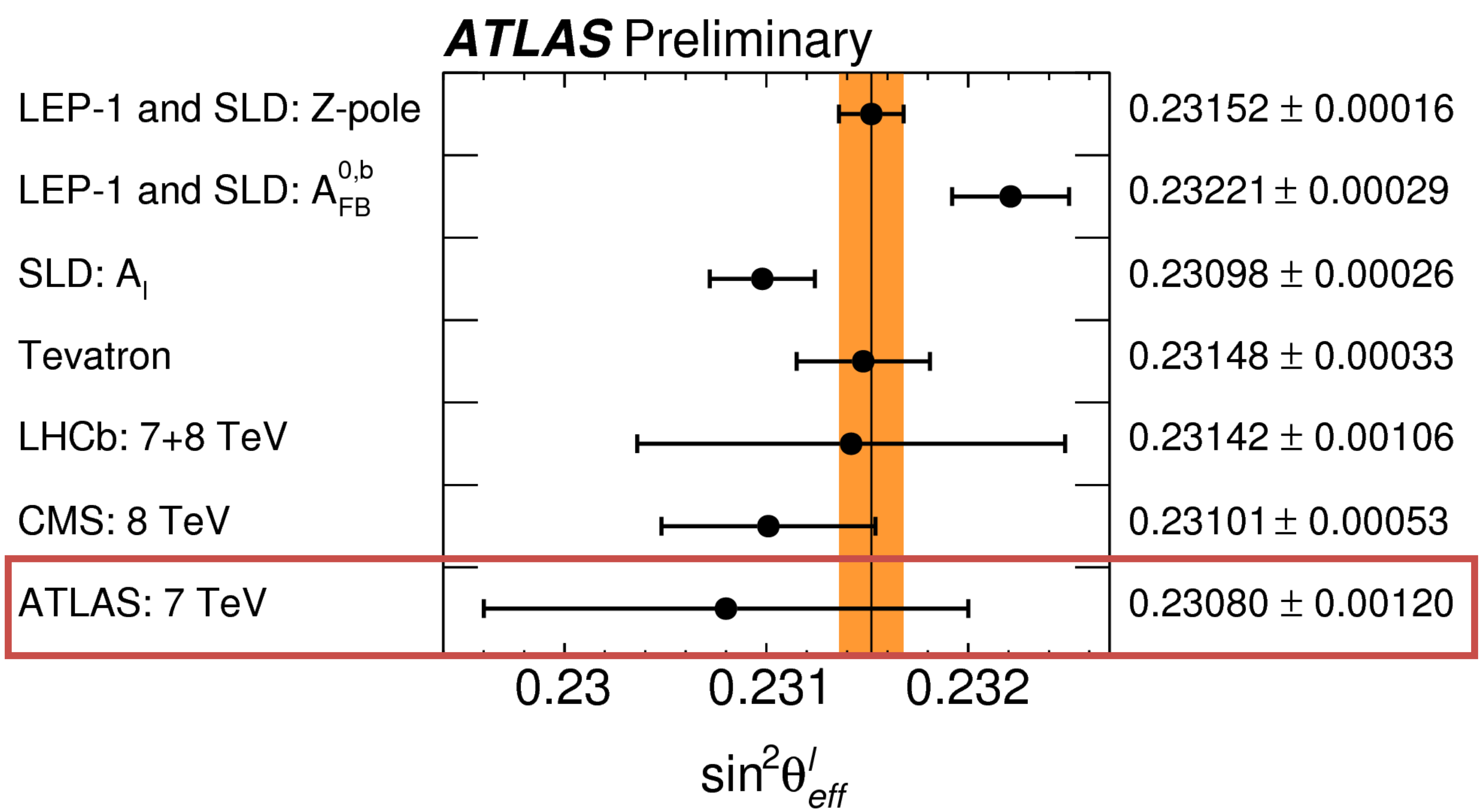
- Previous measurements from the LHC/Tevatron of the weak mixing angle were based on the forward-backward asymmetry (Need to know the direction of the interacting quarks)



(Forward event)

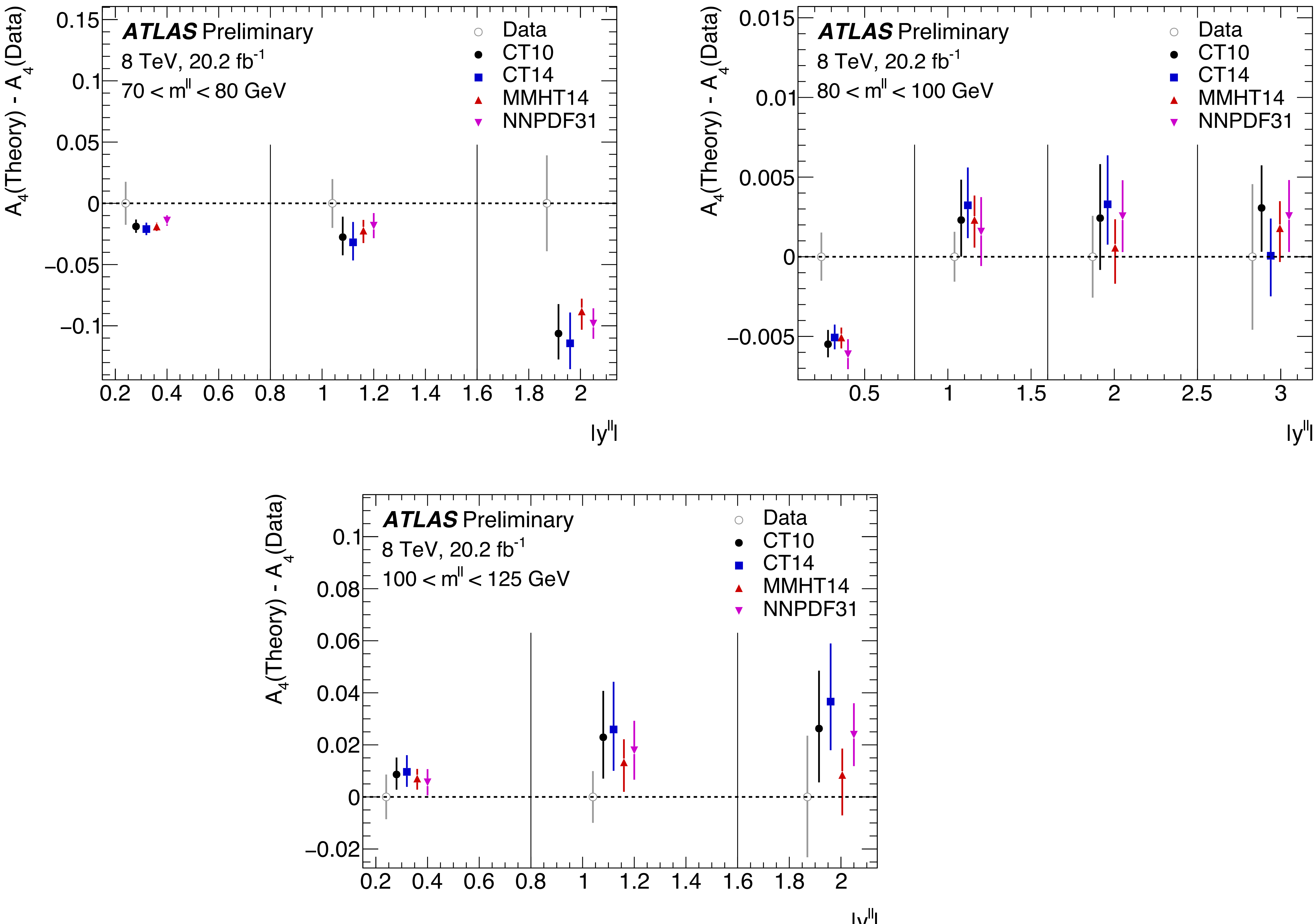


(Backward event)

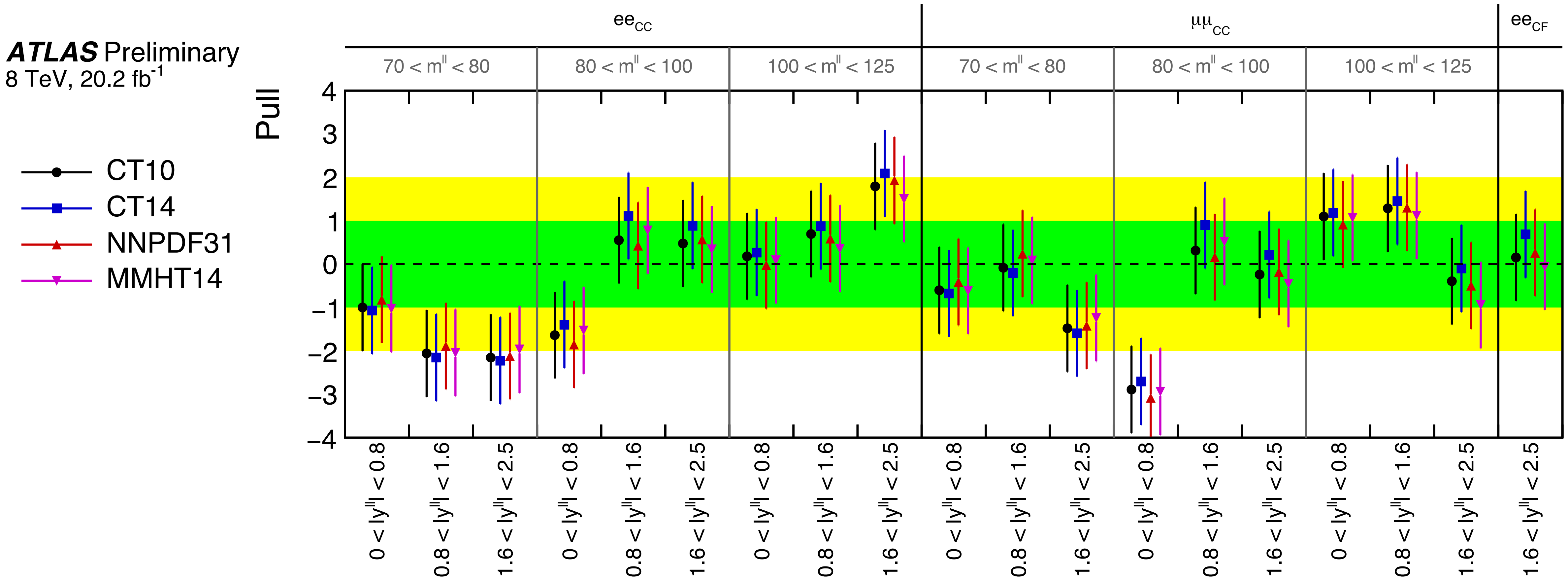


Results limited by PDF uncertainties

Results vs PDF predictions



Results compatibility



Measurement strategy

ATLAS-CONF-2018-037

- A_4 varies strongly versus m^{ll} but mostly because of Z/γ* interference
- Asymmetry due to weak mixing angle is small and ≈ constant: no need to have fine mass binning around m^Z
- Use sidebands around Z pole to constrain PDFs (see later)