Impact of PDFs on Recent LHCb Measurements

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LHC EW meeting

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Introduction

- Will cover how we have approached treatment of PDFs in precision LHCb analyses of:
  - W boson mass [2016 data, arxiv link, JHEP 01 (2022) 036]
  - Weak mixing angle [2016-2018 data, arxiv:2410.02502, accepted by JHEP]

    [please note that some extra tables covering PDF effects have been added to the weak mixing paper in journal review, and the arxiv will update to match the published version as soon as the published version appears]

Introduction

- Interplay of PDFs and LHCb measurements:
  - mW: PDF uncertainties in central and forward regions are anti-correlated. LHCb measurements therefore have power to reduce PDF uncertainties in combination with ATLAS and CMS results. [LHCb measurements therefore also provide an important check of the profiling used in the ATLAS and CMS analyses.] see e.g. Bozzi et al., EPJC 75 (2015) 601
  - Weak Mixing Angle: forward region has smallest PDF uncertainties (before profiling is applied) due to lower dilution between parton-level and particle-level in this region.

PDF Treatment

- Treatment of PDF effects very similar between the two analyses.

- Find results for each PDF set considered, with uncertainties evaluated following the prescription given by the PDF fitting group.
  - Do not yet apply PDF profiling.
  - Rescale CTEQ PDFs to 68% coverage.

PDF Treatment

- PDF uncertainties evaluated through by reweighting based on x and Q^2. Therefore extremely quick to be able to check results with additional PDFs.
  - Have confirmed reliability (for eigenvectors which exhibit largest shifts) by comparing to full generation of new samples and by comparing to in-situ weights (as found within POWHEG).
- Easily make additional cross-checks with other PDFs (e.g. NNPDF4.0, CT18Z).
- Also extremely quick to recast the result to use different PDFs for subsequent combination efforts.
  - So far LHCb is relaxed about these being ‘new’ results.

PDF Treatment

- For the quoted ‘overall result’ do not have a ‘favoured PDF’. Instead treat MSHT, CT and NNPDF equally:
  - Use ‘same generation’ PDFs produced in global PDF fits (i.e. NNPDF31, MSHT20, CT18) that consider ‘similar’ input datasets.
    - These PDFs also don’t fit cross-section results from the same data used in the LHCb precision analyses – no concerns about using/fitting the same data twice.
  - Treat PDFs as fully correlated given this overlap of input data:
    - Central value of quoted result from arithmetic average of different PDFs.
    - PDF uncertainty from arithmetic average of individual PDF uncertainties.

LHCb Results

Latest LHCb results:

$m_W = 80354 \pm 23\,(\text{stat.}) \pm 10(\text{exp.}) \pm 17(\text{theory}) \pm 9\,(\text{PDF})$ MeV [2016 data]

$\sin^2(\theta^l_{\text{eff}}) = 0.23147 \pm 0.00044(\text{stat.}) \pm 0.00005(\text{exp.}) \pm 0.00023\,(\text{theory} + \text{PDF})$

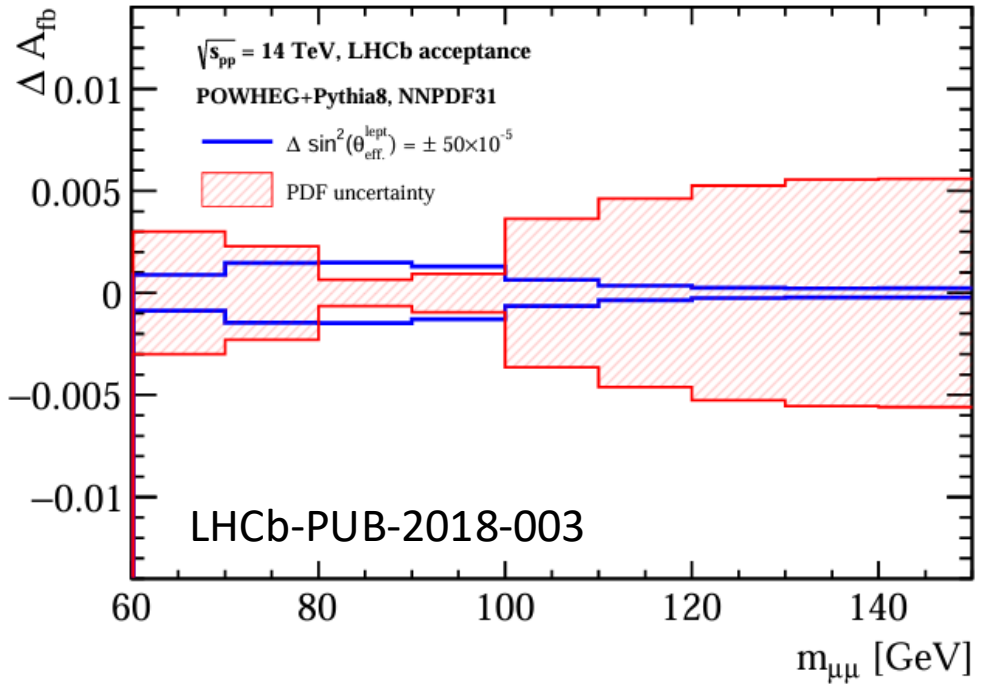
[2016, 2017, 2018 data]

- Statistical precision means that PDF profiling not currently necessary.
  - Will become potentially important for next iteration of precision analyses – especially weak mixing angle.

Weak Mixing Angle – PDF Profiling

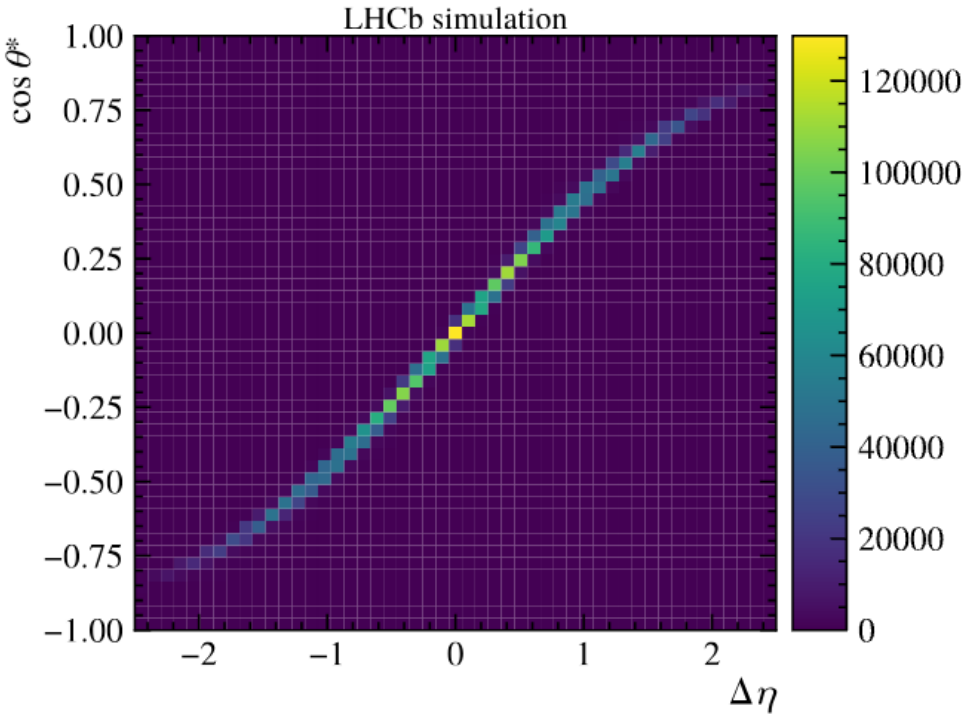
- Binning in mass gives little extra statistical sensitivity to the weak mixing angle (since most of the data are at the Z pole) but can be useful for profiling PDFs.

- With no need to profile (yet), the weak mixing angle analysis simply uses one wide bin in the invariant mass of the dimuon system.



Weak Mixing Angle – aside on binning

- Measure via A_{FB} in bins of $|\Delta\eta|$, since $|\Delta\eta|$ well measured experimentally and $\cos(\theta^*) \sim \tanh(^{\Delta\eta}/_{2})$.
- Similar approach to measuring A_4 (as you make use of the sensitivity of the events at high $\cos(\theta^*)$ to the weak mixing angle) … but has simplicity of measuring A_{FB}.
- Within LHCb acceptance provides 14% improvement in statistical sensitivity compared to no binning in $|\Delta\eta|$.



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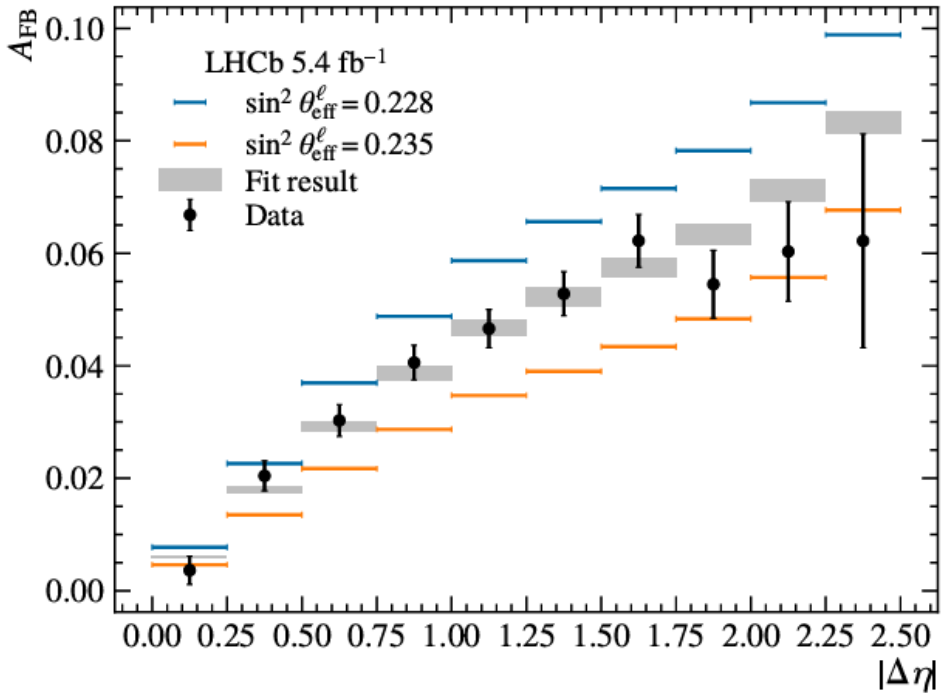


LHCb Results in more detail

Weak Mixing Angle

PDF set	$\sin^2\theta^{\ell}_{\text{eff}}$	PDF uncertainty	Shift	Fit χ^2/ndof
NNPDF31_nlo_as0118	0.23155	0.00023	–	8.4/9
CT18NLO	0.23165	0.00022	+0.00009	8.4/9
MSHT20nlo_as118	0.23137	0.00017	−0.00018	8.2/9
Arithmetic average	–	0.00021	−0.00003	–

PDF set	$\sin^2\theta^{\ell}_{\text{eff}}$	PDF uncertainty	Shift	Fit χ^2/ndof
CT18ZNLO	0.23147	0.00019	−0.00008	8.4/9
NNPDF40_nlo_as_01180	0.23142	0.00022	−0.00014	8.6/9

Shift is defined relative to NNPDF31. Note that in the analysis further corrections are made 'after' the numbers in this table for e.g. higher order EW effects – so central values shift by O(5E-5) relative to this table.

W boson mass

NNPDF31 $m_W = 80362 \pm 23_{\text{stat}} \pm 10_{\text{exp}} \pm 17_{\text{theory}} \pm 9_{\text{PDF}}\,\text{MeV},$

CT18 $m_W = 80350 \pm 23_{\text{stat}} \pm 10_{\text{exp}} \pm 17_{\text{theory}} \pm 12_{\text{PDF}}\,\text{MeV},$

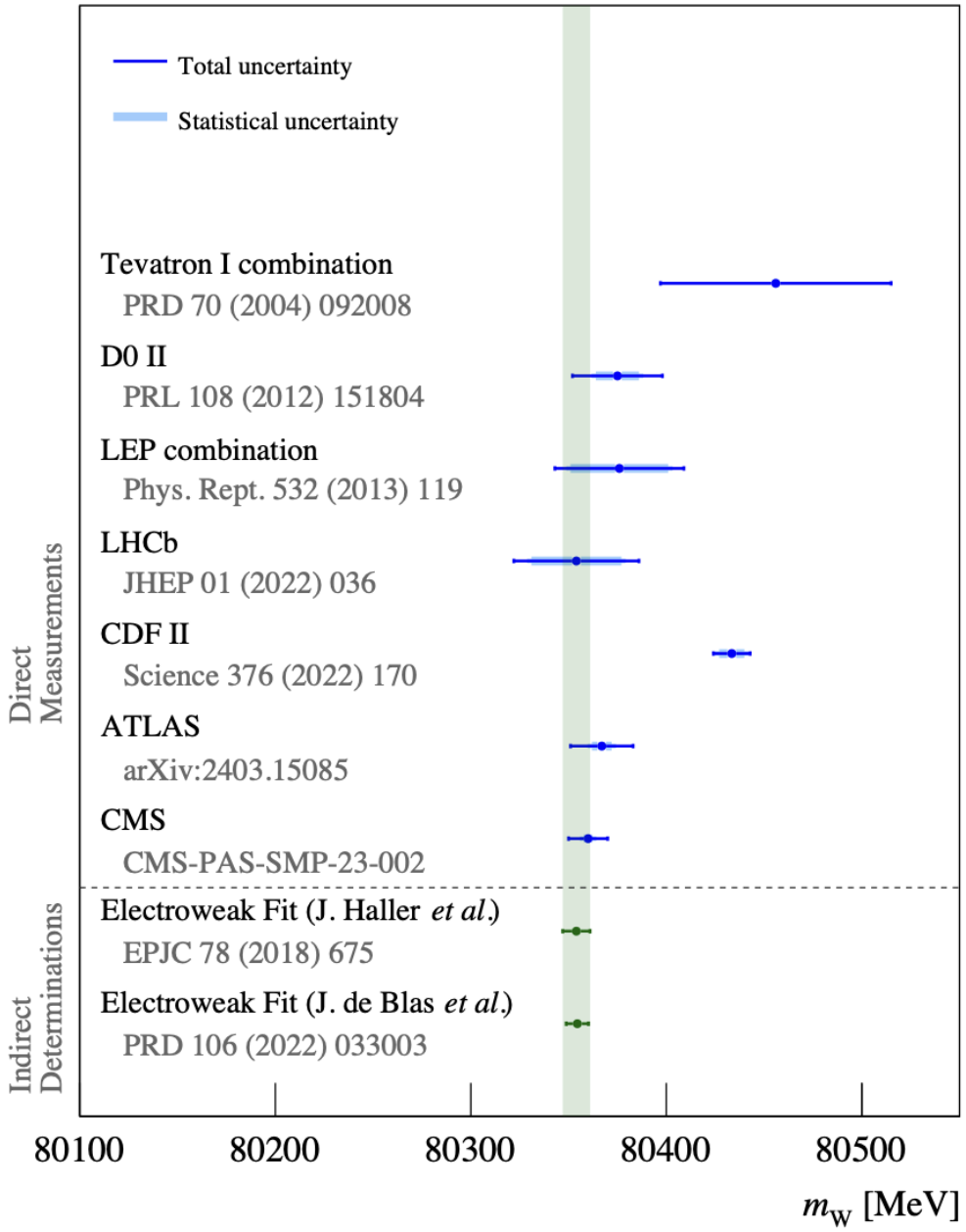
MSHT20 $m_W = 80351 \pm 23_{\text{stat}} \pm 10_{\text{exp}} \pm 17_{\text{theory}} \pm 7_{\text{PDF}}\,\text{MeV},$

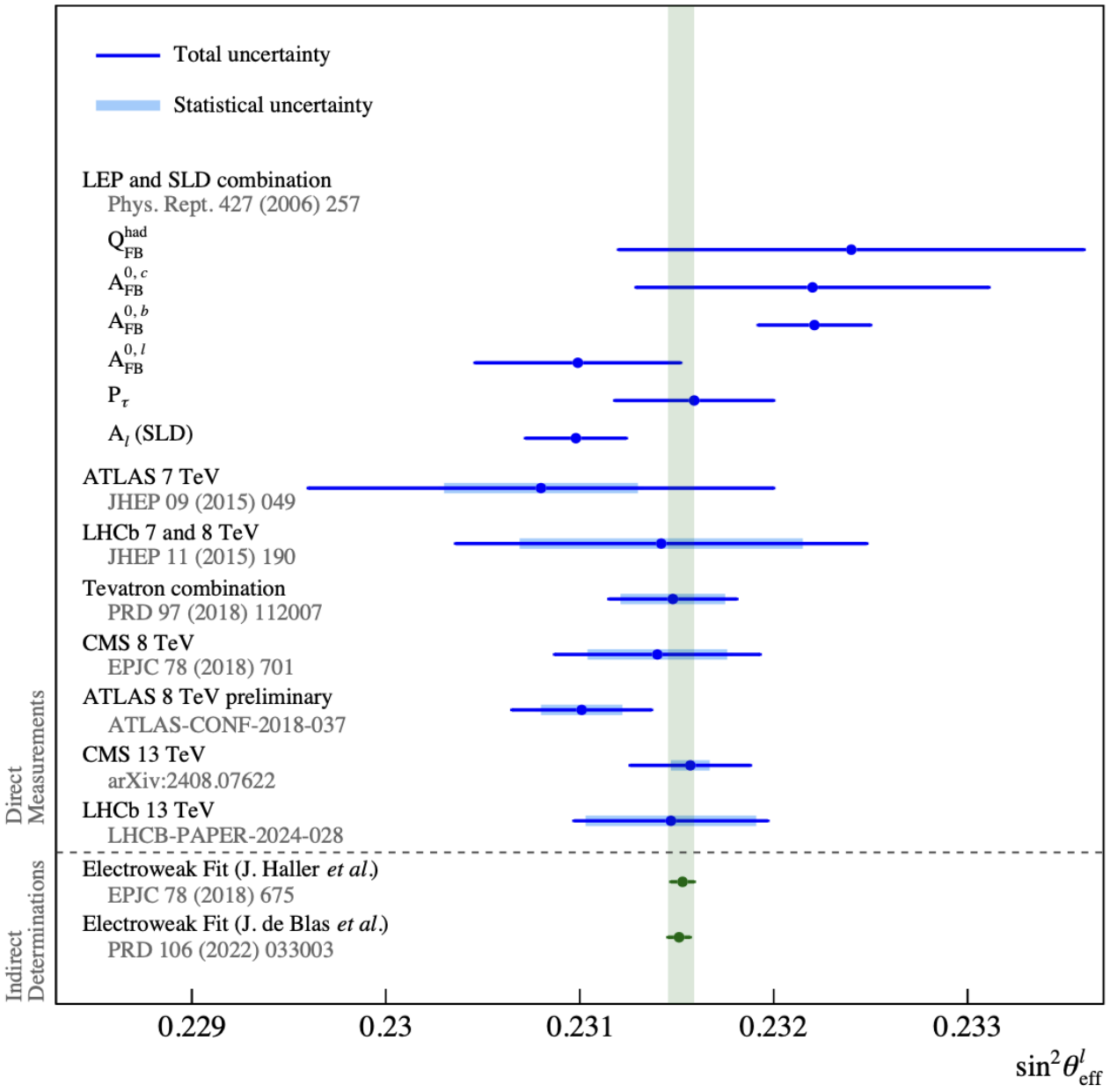
Note that in both cases the spread of results between PDF sets is roughly the same size as the quoted PDF uncertainty.

Weak Mixing Angle – crosscheck using mass bins

- Analysis cross-checks with mass binning; results are consistent.
- Some PDFs do give better fit to data in this cross-check…
  - …but only a cross-check, we don't do a full consideration of systematics for the cross-check, so do not want to infer too much here.

PDF set	$\sin^2\theta^{\ell}_{\text{eff}}$	Shift	Fit χ^2/ndof
NNPDF31_nlo_as0118	0.23133	–	13.1/6
CT18NLO	0.23139	0.00006	19.8/6
MSHT20nlo_as118	0.23119	-0.00015	10.8/6
CT18ZNLO	0.23126	-0.00007	17.1/6
NNPDF40_nlo_as_01180	0.23120	-0.00014	9.4/6


Total uncertainty
Statistical uncertainty
Tevatron I combination
PRD 70 (2004) 092008
D0 II
PRL 108 (2012) 151804
LEP combination
Phys. Rept. 532 (2013) 119
LHCb
JHEP 01 (2022) 036
CDF II
Science 376 (2022) 170
ATLAS
arXiv:2403.15085
CMS
CMS-PAS-SMP-23-002
Electroweak Fit (J. Haller et al.)
EPJC 78 (2018) 675
Electroweak Fit (J. de Blas et al.)
PRD 106 (2022) 033003
Direct Measurements
Indirect Determinations
80100
80200
80300
80400
80500
m_W [MeV]

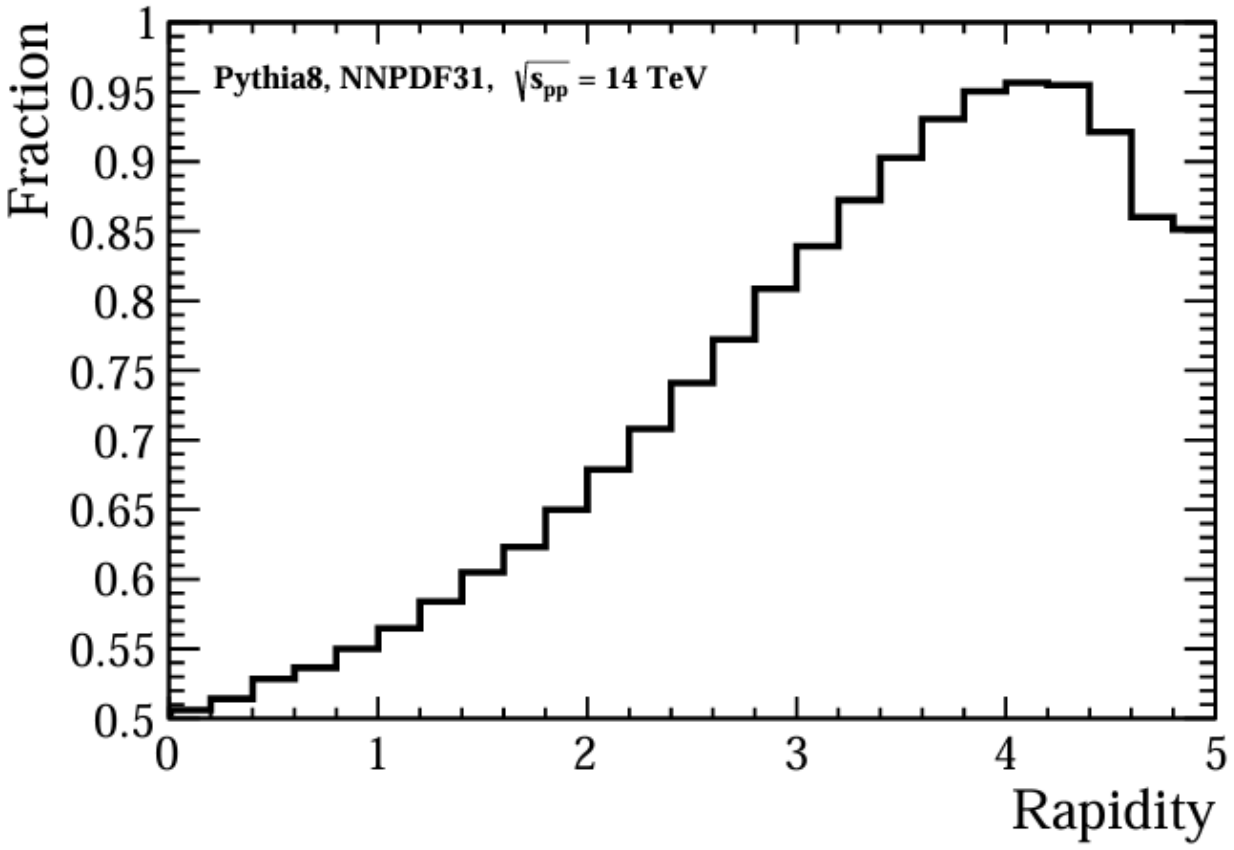

Total uncertainty
Statistical uncertainty
LEP and SLD combination
Phys. Rept. 427 (2006) 257
Q_{FB}^{had}
$A_{FB}^{0,c}$
$A_{FB}^{0,b}$
$A_{FB}^{0,l}$
P_τ
A_l (SLD)
ATLAS 7 TeV
JHEP 09 (2015) 049
LHCb 7 and 8 TeV
JHEP 11 (2015) 190
Tevatron combination
PRD 97 (2018) 112007
CMS 8 TeV
EPJC 78 (2018) 701
ATLAS 8 TeV preliminary
ATLAS-CONF-2018-037
CMS 13 TeV
arXiv:2408.07622
LHCb 13 TeV
LHCB-PAPER-2024-028
Electroweak Fit (J. Haller et al.)
EPJC 78 (2018) 675
Electroweak Fit (J. de Blas et al.)
PRD 106 (2022) 033003
Direct Measurements
Indirect Determinations
0.229
0.23
0.231
0.232
0.233
$\sin^2\theta^l_{\text{eff}}$

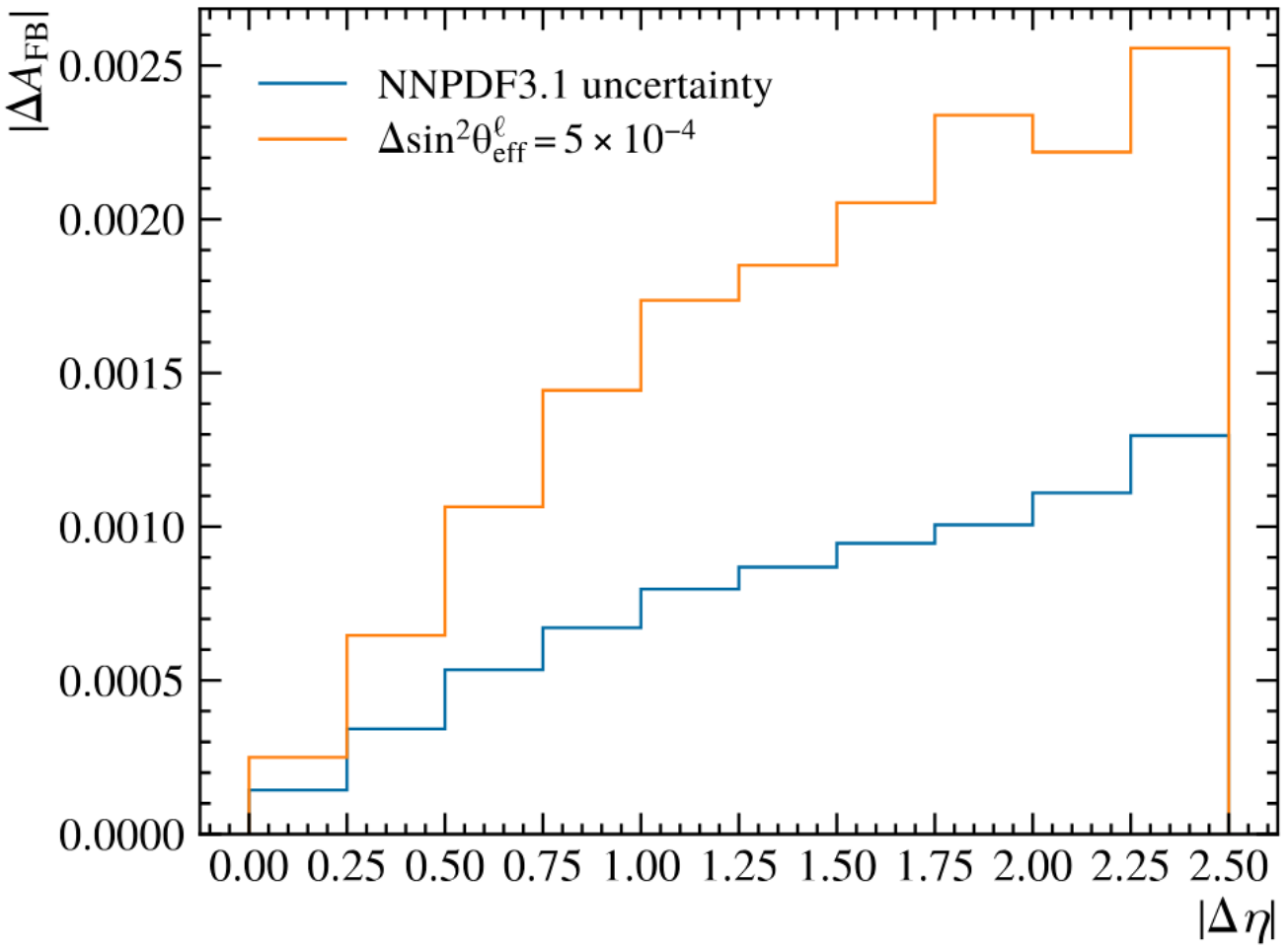
Summary

- LHCb results:
  - Follow full prescription of PDF fitting groups to evaluate uncertainties.
  - Quote central values by assuming ‘same generation’ PDFs are fully correlated and take the arithmetic average.
  - Have statistical precision that does not yet necessitate the use of PDF profiling.
  - May use PDF profiling in the next generation of results (especially weak mixing angle).
- General note: Nate Grieser will present this material at the PDF4LHC meeting.

Backups

The fraction of events where the Z boson travels in the same direction along the z-axis as the colliding quark, in proton-proton collisions with √s = 14TeV




$|\Delta A_{FB}|$
0.0025
0.0020
0.0015
0.0010
0.0005
0.0000
NNPDF3.1 uncertainty
$\Delta\sin^2\theta^{\ell}_{eff} = 5 \times 10^{-4}$
0.00 0.25 0.50 0.75 1.00 1.25 1.50 1.75 2.00 2.25 2.50
$|\Delta\eta|$