



The University of Manchester

Weak Mixing Angle Measurements

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Weak Mixing Angle – what is it



- Key parameter in Electroweak sector of the Standard Model
- Can consider:

- $\sin^2(\theta_W) = \left(1 - \frac{m_W^2}{m_Z^2}\right)$ ← depending on scheme chosen, can be viewed as a fundamental parameter in SM, probing mixing of W and B fields.

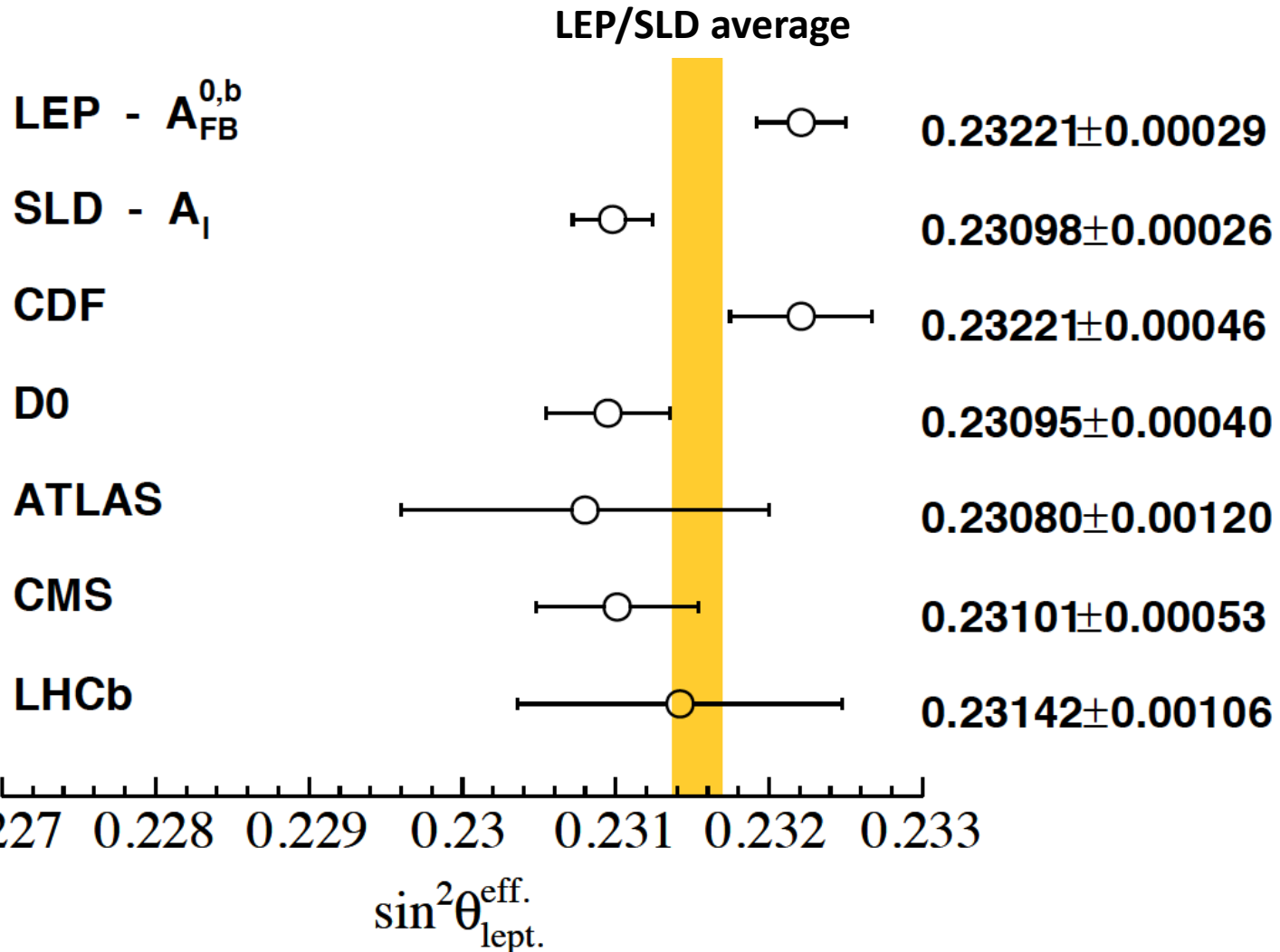
- At leading order, this is also equal to:

- $\sin^2\left(\theta_{\text{eff.}}^{\text{lept.}}\right) = \frac{1}{4|Q_l|} \left(1 - \frac{g_v}{g_a}\right)$ ← Related to the real effective (leptonic) vector and axial-vector couplings of the Z boson.

- At higher orders, vertex corrections lead to the effective angle no longer matching $\sin^2(\theta_W)$:

- $\sin^2\left(\theta_{\text{eff.}}^{\text{lept.}}\right) = \kappa_f \sin^2(\theta_W)$

Weak Mixing Angle – current status



Only showing explicitly the most precise measurements at LEP/SLD; overall average from all LEP/SLD measurements shown as gold band.

Tevatron combination reaches uncertainty of 0.00033; compatibility of measurements 2.6%.

Current ATLAS analysis only uses 7 TeV data.

Current CMS analysis uses sophisticated techniques to reduce statistical and PDF uncertainties.

Current LHCb analysis has smaller PDF uncertainties than ATLAS, but a larger stat. unc (lower lumi).

Weak Mixing Angle – further study needed

- The two most precise measurements (LEP, SLD) studied different processes and disagree by about 3σ – should investigate potential non-SM process dependence as a potential hint for new physics.
- Can be phrased as an overall test of the EW sector.
 - If we view a measurement of the angle as an indirect measurement of the W boson mass, the precision of the current world average value of $\sin^2\left(\theta_{\text{eff.}}^{\text{lept.}}\right)$, 16×10^{-5} , corresponds to a precision of 8 MeV on the W boson mass – comparable to the potential precision achievable at the LHC – so we should seek to improve our precision in mixing angle measurements.

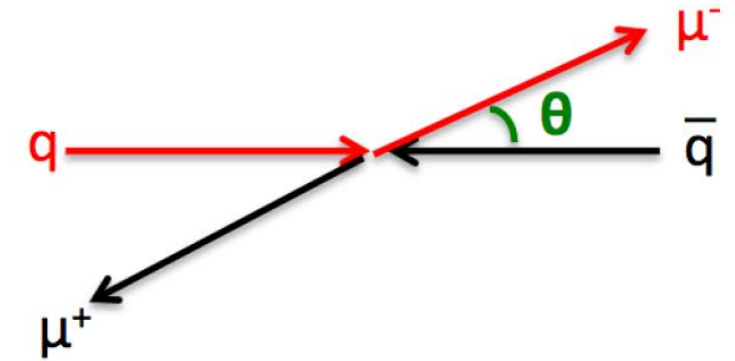
Weak Mixing Angle – LHC measurements

- Presence of vector and axial-vector couplings (and weak mixing angle) introduces a forward-backward asymmetry. This is a **parton-level phenomenon** that we measure at **proton-level**.

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

- Measure using Collins-Soper Frame – Z boson at rest; z-axis bisects direction of initial state quark/anti-quark.
- This z-axis has a two-fold ambiguity at the LHC – the quark could be in either proton: choose z-axis sign using sign of the (lab-frame) z-momentum of the Z boson candidate.

$$\frac{d\sigma}{d\cos\theta^*} \propto \frac{3}{8}A(1 + \cos^2\theta^*) + B\cos\theta^*$$



$$\cos\theta^* = \frac{2(P_1^+ P_2^- - P_1^- P_2^+)}{\sqrt{m_{\ell\ell}^2(m_{\ell\ell}^2 + p_{T,\ell\ell}^2)}} \times \frac{p_{z,\ell\ell}}{|p_{z,\ell\ell}|}$$

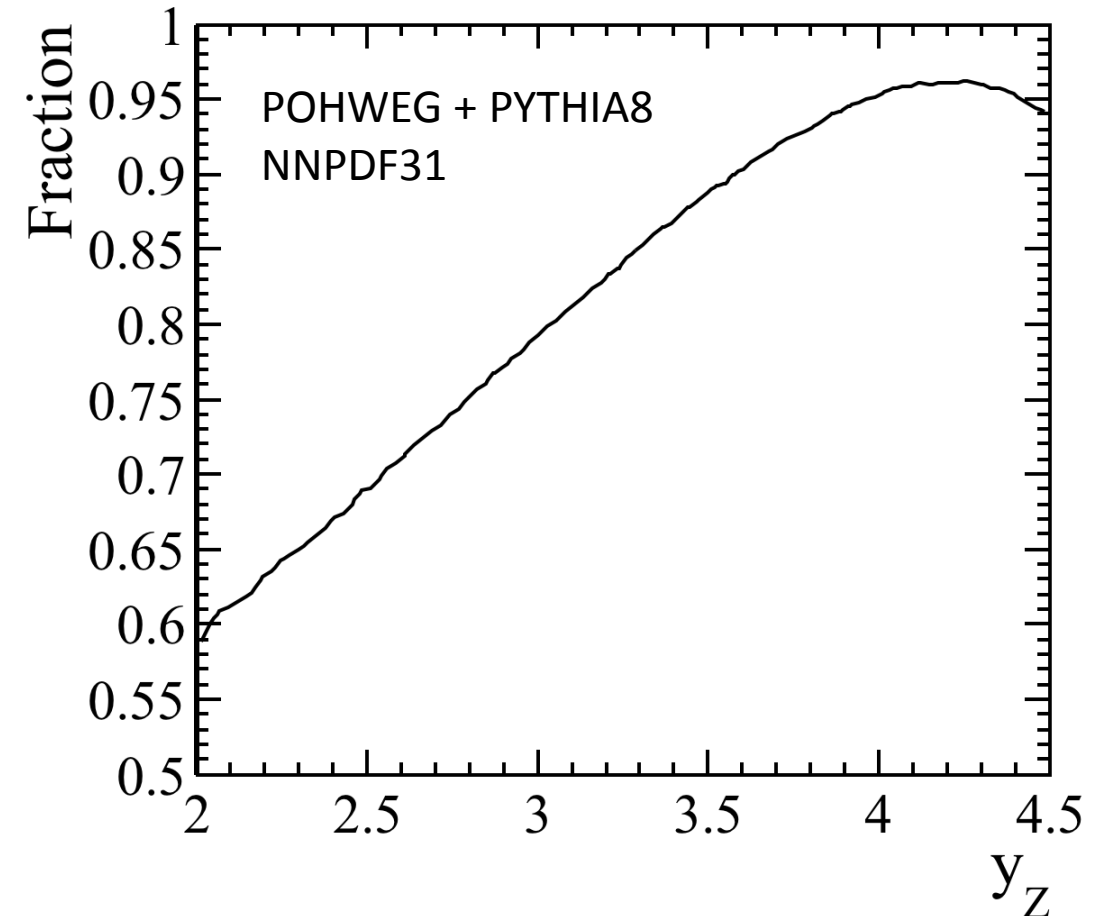
$$P_i^\pm = \frac{1}{\sqrt{2}}(E_i \pm p_{z,i})$$

Formula from 1806.00863

Weak Mixing Angle – LHC measurements

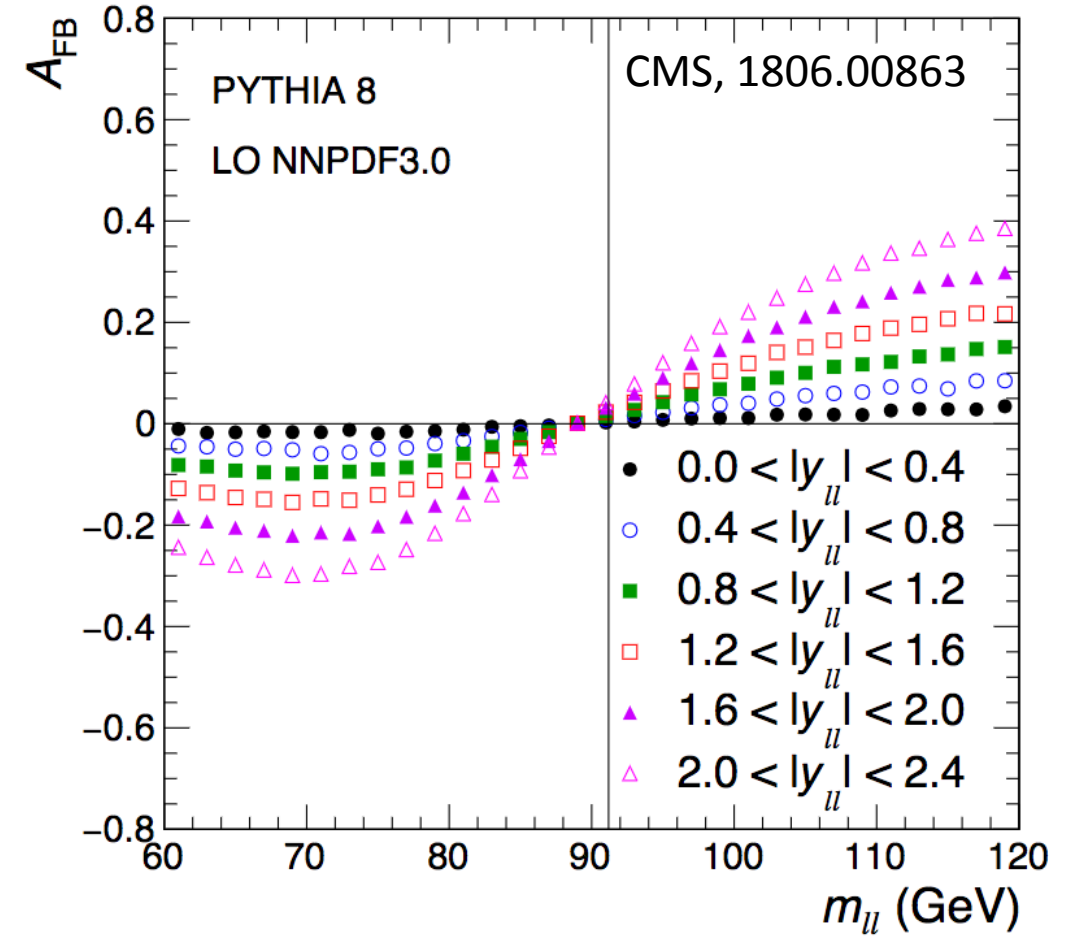
- Forward-backward asymmetry increases (and sensitivity to Weinberg angle increases) as rapidity of Z boson increases.
- At higher rapidities choice of sign of z-axis at proton-level more closely matches choice at parton-level:
 - At high rapidities, collisions involve one high-x parton and one low-x parton; high-x parton tends to be valence quarks, with the low-x parton the anti-quark (at Born level).

Collisions where Z boson follows quark direction



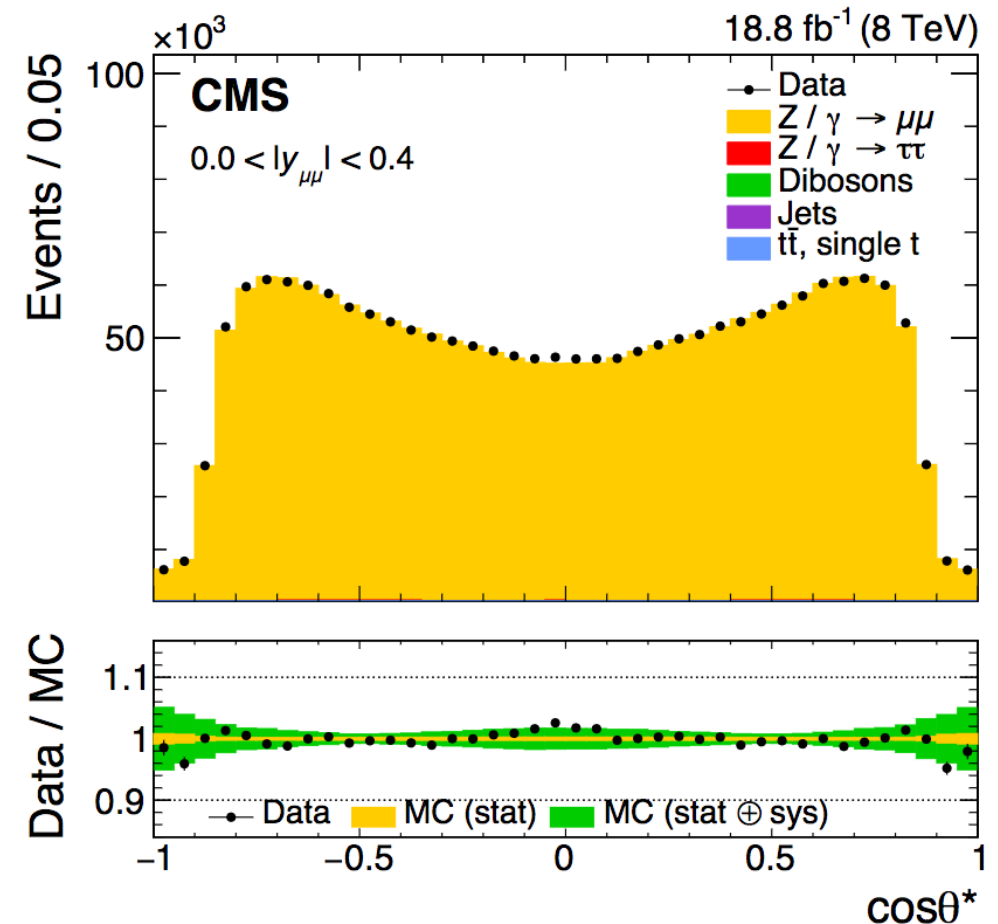
Weak Mixing Angle – LHC measurements

- Forward-backward asymmetry also shows strong dependence on the invariant mass of the dilepton system.
 - Interference between vector and axial-vector terms, and interference between the Z boson and the virtual photon contribution drives this variation.
- Can fit this variation with mass for different values of the weak mixing angle and extract preferred value of the data.



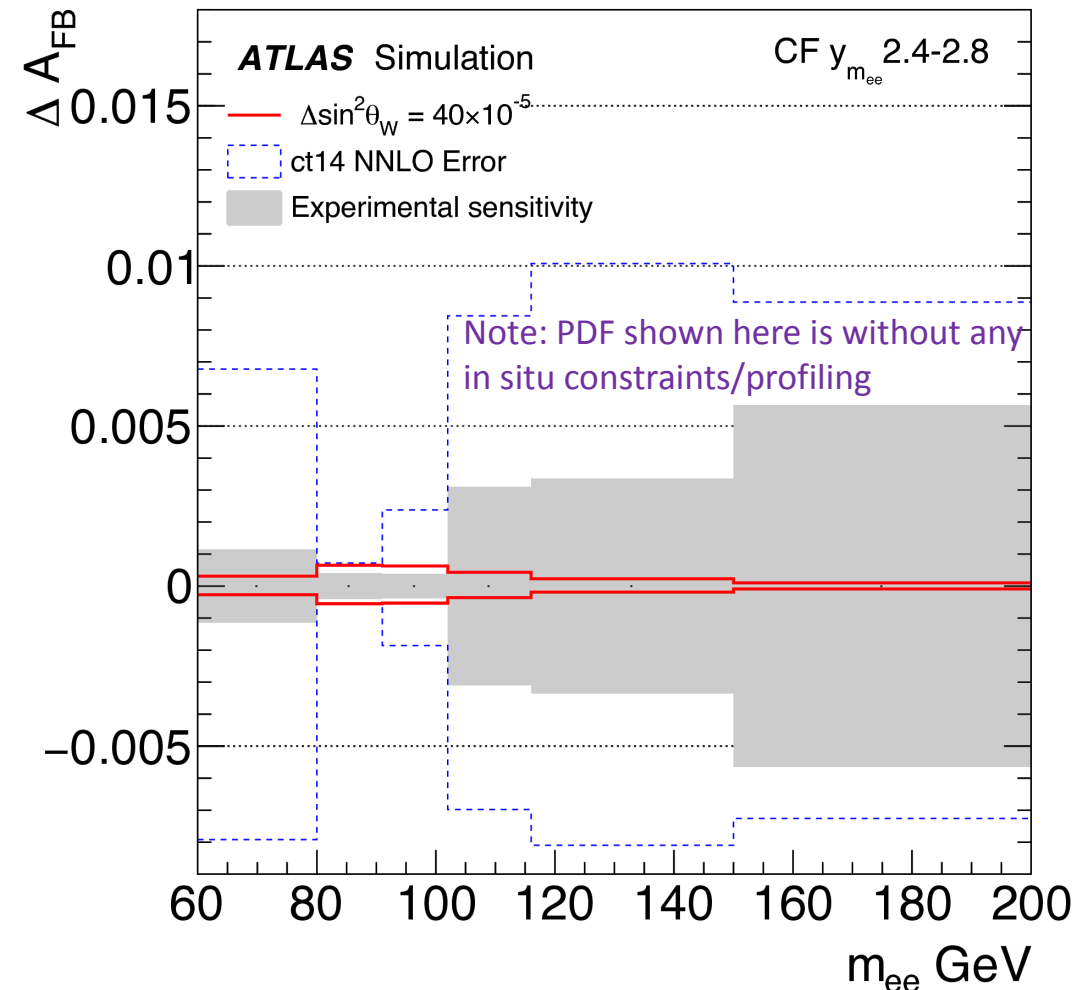
Weak Mixing Angle – LHC measurements

- Reminder: the weak mixing angle enters through terms in the differential cross-section proportional to $\cos \theta^*$. Events with $\cos \theta^* \sim 0$ have less sensitivity to the angle than events with $\cos \theta^* \sim 1$.
- Can weight events as a function of $\cos \theta^*$ to find a modified forward-backward asymmetry and improve sensitivity.
 - Typically improves sensitivity to weak mixing angle by 20-40%.
- Or can make measurement as a function of mass and rapidity using classes of events that pick out variation as function of $\cos \theta^*$ - eg CC, CF, FF events (ATLAS).



CC = Central-Central; CF = Central-Forward;
FF = Forward-Forward (not used in Run 1)

Weak Mixing Angle – PDFs



- Measurement dependent on PDFs:
 - The A_{FB} distributions are different for different flavour quarks: to know the contribution from each quark flavour we need PDFs.
 - The dilution between quark-level A_{FB} (where the direction of the quark is completely known, and the z-axis is well defined) and the proton-level A_{FB} depends on the PDFs: we need to know PDFs to know how often the sign of the z-axis at proton-level matches the quark-level choice.
- These effects are reduced in the forward region where the dilution between proton and parton level is reduced.

Weak Mixing Angle – PDFs

Used by LHCb, ATLAS in Run-1 analyses

Can extract Weinberg angle by fitting data using each PDF set from a PDF group:

- For equiprobable replicas (eg NNPDF) the RMS of this distribution sets the uncertainty; for Hessian replicas, summing variations from central value in quadrature sets uncertainty.

Can get more information from the data:

Used by CMS in Run-1 analysis

- the data includes information that inform us whether the PDFs describe data well. Can use the data to weight the PDFs, giving more weight to the PDFs that best describe the data. The weighted mean and weighted RMS set the best estimate and uncertainty on the Weinberg angle.

Weak Mixing Angle – PDFs

- Bayesian Reweighting (used for equiprobable PDF replicas) – used by CMS here:

- Discussion in the literature over weighting function to use:

NNPDF: $w_i \propto \chi_i^{n-1} e^{-\frac{1}{2}\chi_i^2}$ See eg NNPDF collab., Nucl. Phys B 855, 608 (2012)

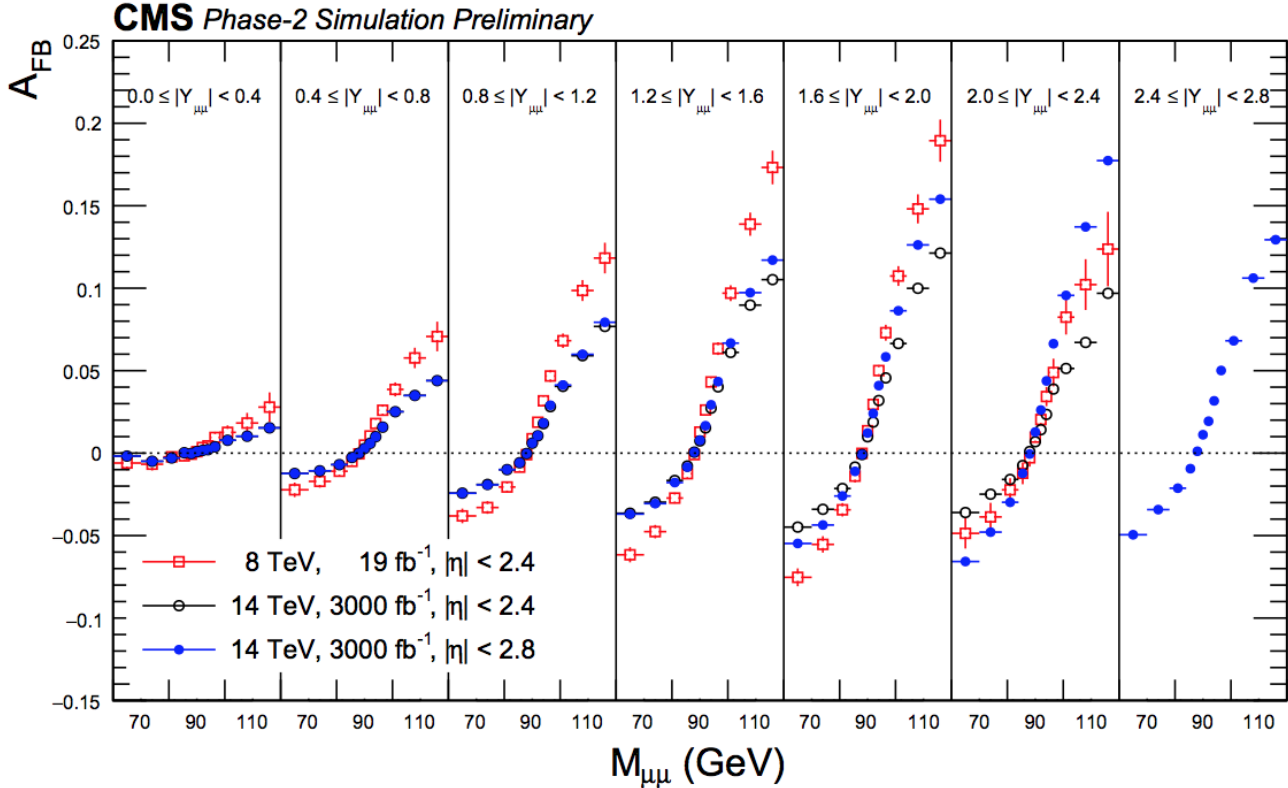
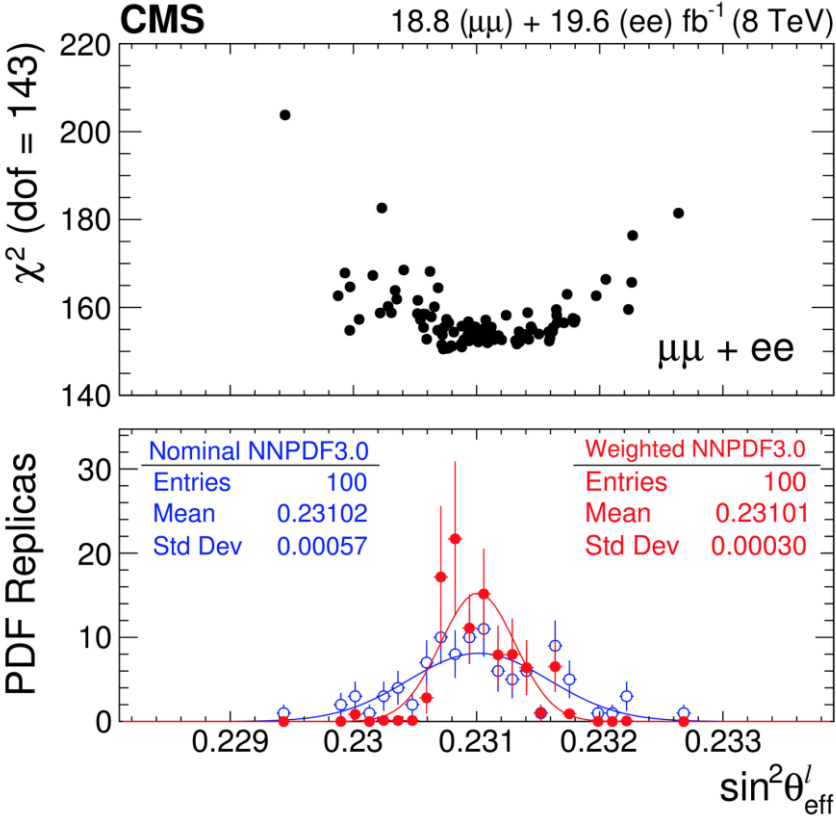
Giele and Keller; Sato et al.: $w_i \propto e^{-\frac{1}{2}\chi_i^2}$ See eg Sato *et al.*, Phys. Rev. D 89, 114020 (2014)

- PDF profiling – used by ATLAS here: See eg Paukkunen and Zurita, JHEP12(2014)100
 - Used with Hessian sets – mathematically can be shown as providing equivalent results to Giele and Keller weights in Bayesian reweighting.

Weak Mixing Angle – CMS

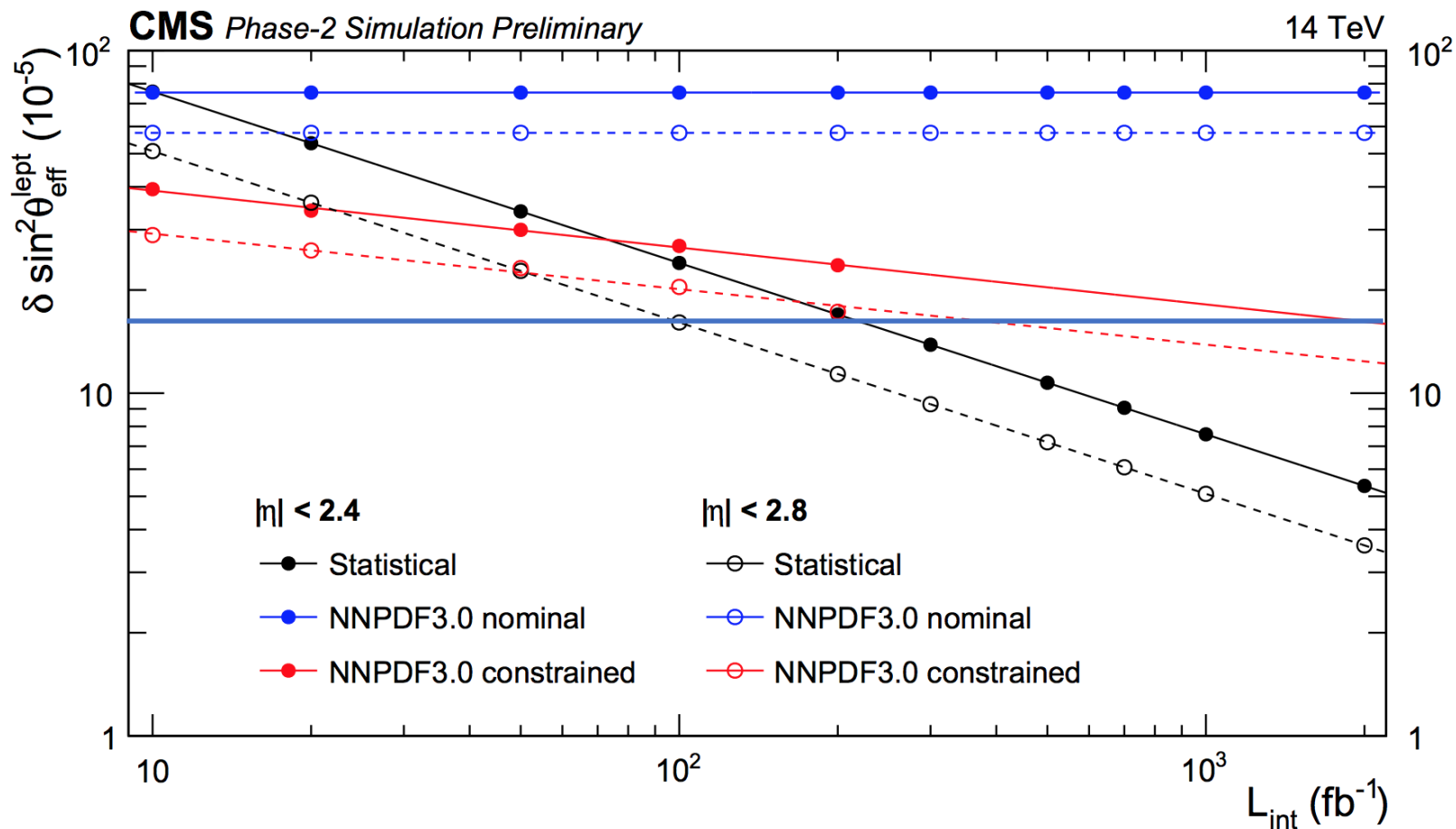
Note: dilution worse at 14 TeV than in 8 TeV collisions – lower x values probed

Different PDF replicas give different favoured values.



Extension of CMS acceptance forward during HL-LHC era increases the sensitivity to the Weinberg angle.

Weak Mixing Angle – CMS



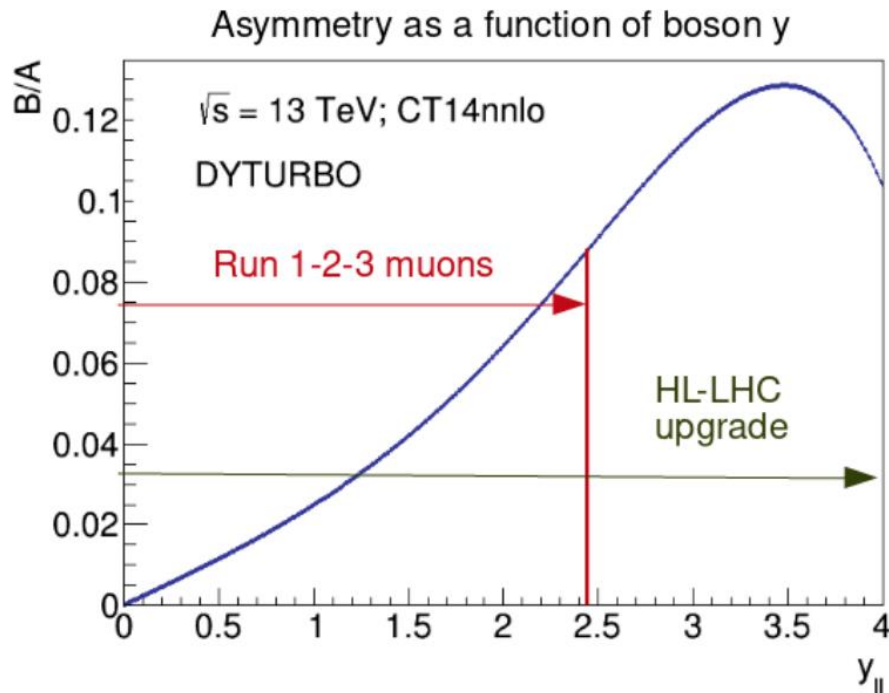
Studies here using muon channel.

CMS expect to have PDF uncertainties with precision of LEP+SLD average with $L_{\text{int}} > O(300 \text{ fb}^{-1})$ using extended acceptance.

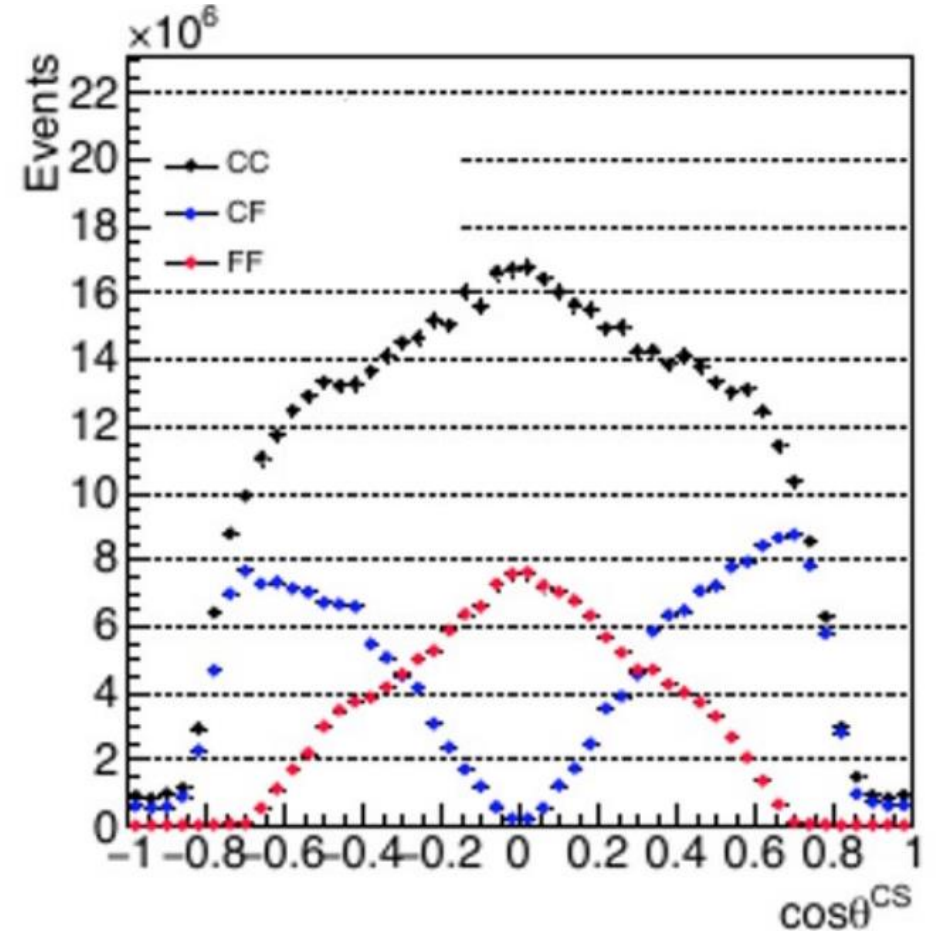
Weak Mixing Angle – ATLAS

- ATLAS also plans extended coverage in HL-LHC era – improves sensitivity.

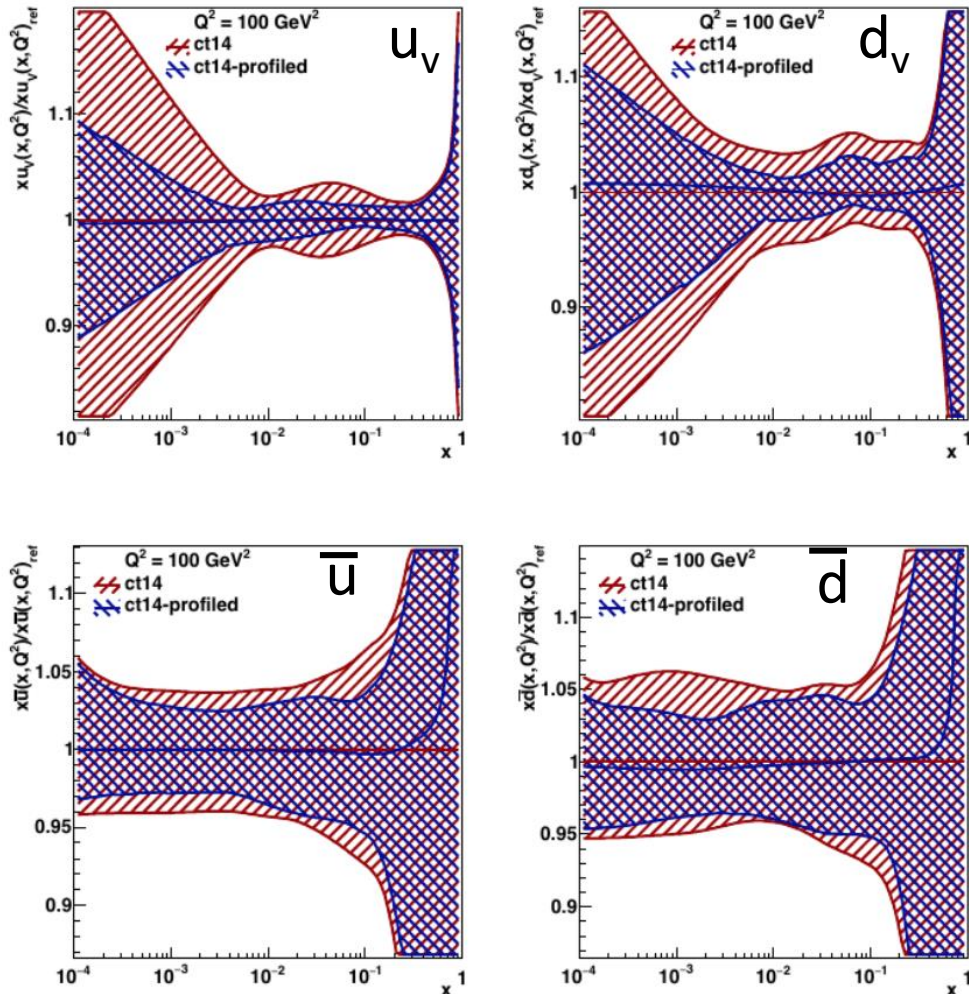
$$\frac{d\sigma}{d \cos \theta^*} \propto \frac{3}{8} A(1 + \cos^2 \theta^*) + B \cos \theta^*$$



ATLAS studies of electron channel



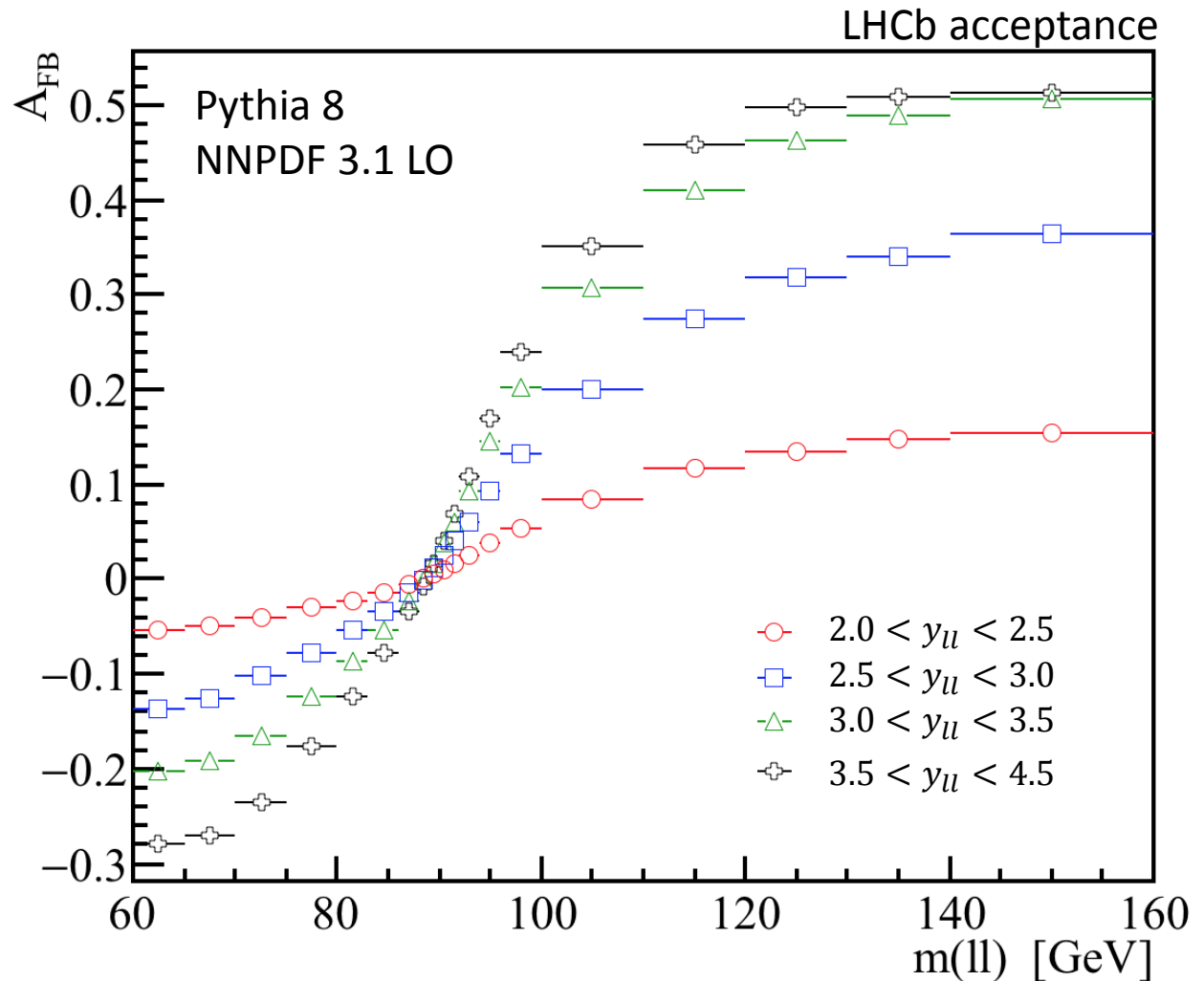
Weak Mixing Angle – ATLAS



- The total estimated uncertainty is 19×10^{-5} , dominated by PDF uncertainties (17×10^{-5}) – using in situ profiling.
- Another factor of 2 may be possible using additional PDF constraints.
- Without PDF uncertainties, the total experimental uncertainty would be 4×10^{-5} .
- ATLAS and CMS expect to reach a similar level of precision.

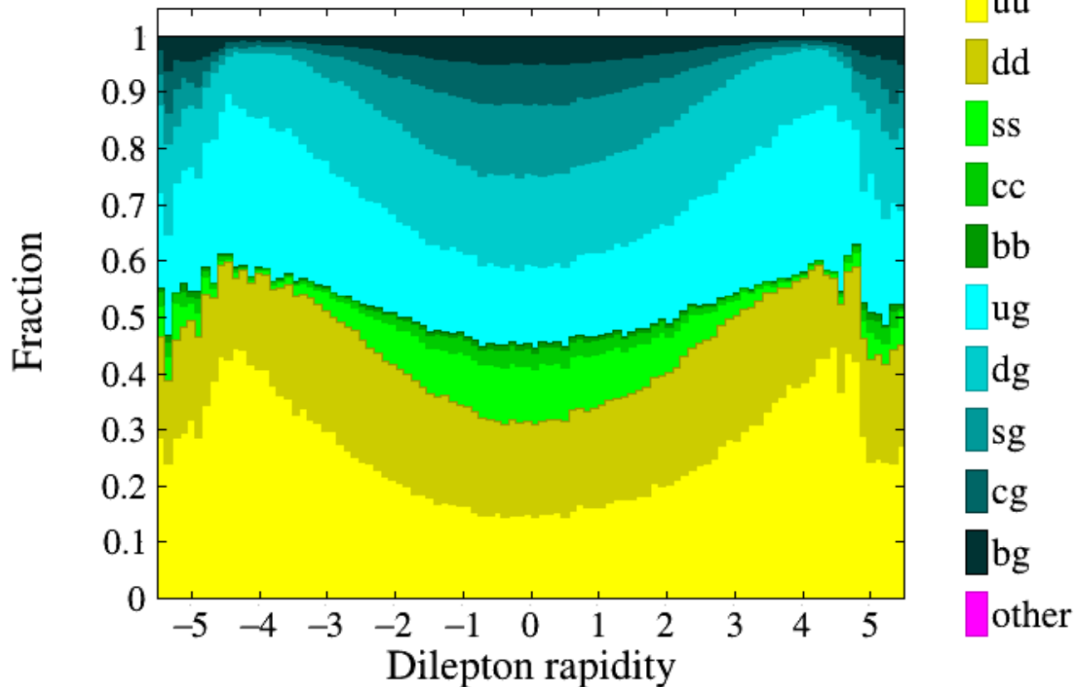
Weak Mixing Angle – LHCb

- LHCb probes high rapidity region where forward-backward asymmetry is largest:
 - Reduced effect of dilution: reduced effect of PDFs, and improved statistical sensitivity (though LHCb records less lumi than ATLAS, CMS).
 - Current measurements rely on muons
 - Future measurements will also bin in Z rapidity (first measurement had only one bin).
 - LHCb Upgrade II expects total lumi to be roughly 300 fb^{-1} in HL-LHC, and to measure electrons with equivalent precision to muons.



Weak Mixing Angle – LHCb

$$Z/\gamma^*$$



- Statistical sensitivity (\sqrt{n} scaling from existing measurement using dimuons) less than 10×10^{-5} .
- Further $1/\sqrt{2}$ achievable beyond this from including dielectron final states.
- Previous measurement by LHCb had PDF uncertainty from NNPDF23 of 45×10^{-5}
 - Existing measurements by LHCb have already significantly reduced uncertainties on PDFs since measurement (by about a factor of 2).
 - Studies ongoing to determine additional effect of in situ constraints on PDFs.

Weak Mixing Angle – additional uncertainties

- Theory:
 - QCD+EW corrections need to be understood and controlled.
 - Differences between PDFs from different global fits need to be understood.
 - Need to control impact on weak mixing angle at level well below 10×10^{-5} .
- Experimental systematic uncertainties
 - Momentum scale / energy scale effects tend to dominate.
 - HL-LHC will bring enough events to control momentum scales.
 - Need to take extreme care with correlation of PDF fits – using LHC experimental data – with the measurements we are making.
- Great possibilities ahead, but clear that work is just beginning...

Weak Mixing Angle – Conclusions

- Opportunity for the first time to measure Weak Mixing Angle to greater precision than that achieved at LEP/SLD.
- Crucial to probe the EW sector, and to search indirectly for the effects of New Physics.
- Three LHC experiments (ATLAS, CMS, LHCb) all have measurements and are developing strategies for the HL-LHC era.
- Hope to make significant contribution to Yellow Report on these studies.

BACKUP SLIDES

Existing measurements

LEP and SLD reported in: Phys. Rept. 427:257-454,2006

CDF and D0 reported in: arxiv:1801.06283, submitted to Phys. Rev. D

ATLAS: JHEP 09 (2015) 049

LHCb: JHEP 11 (2015) 190

CMS: arxiv:1806.00863, submitted to EPJC

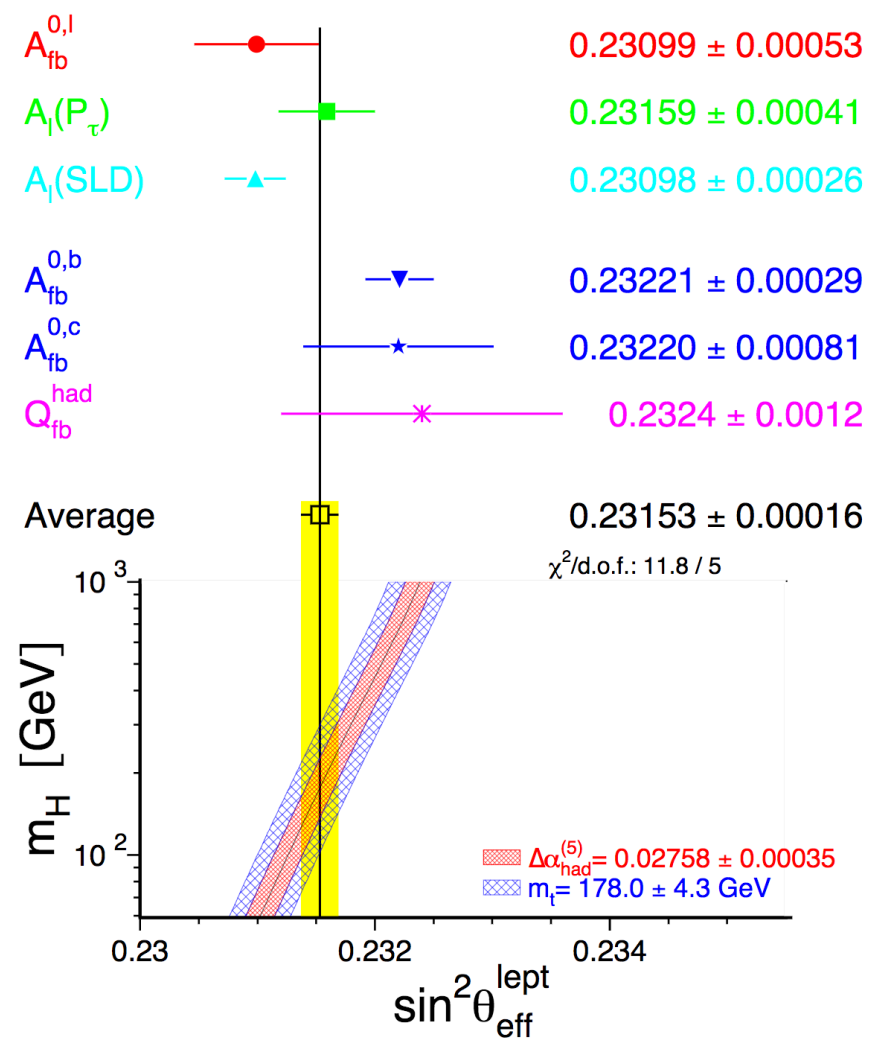
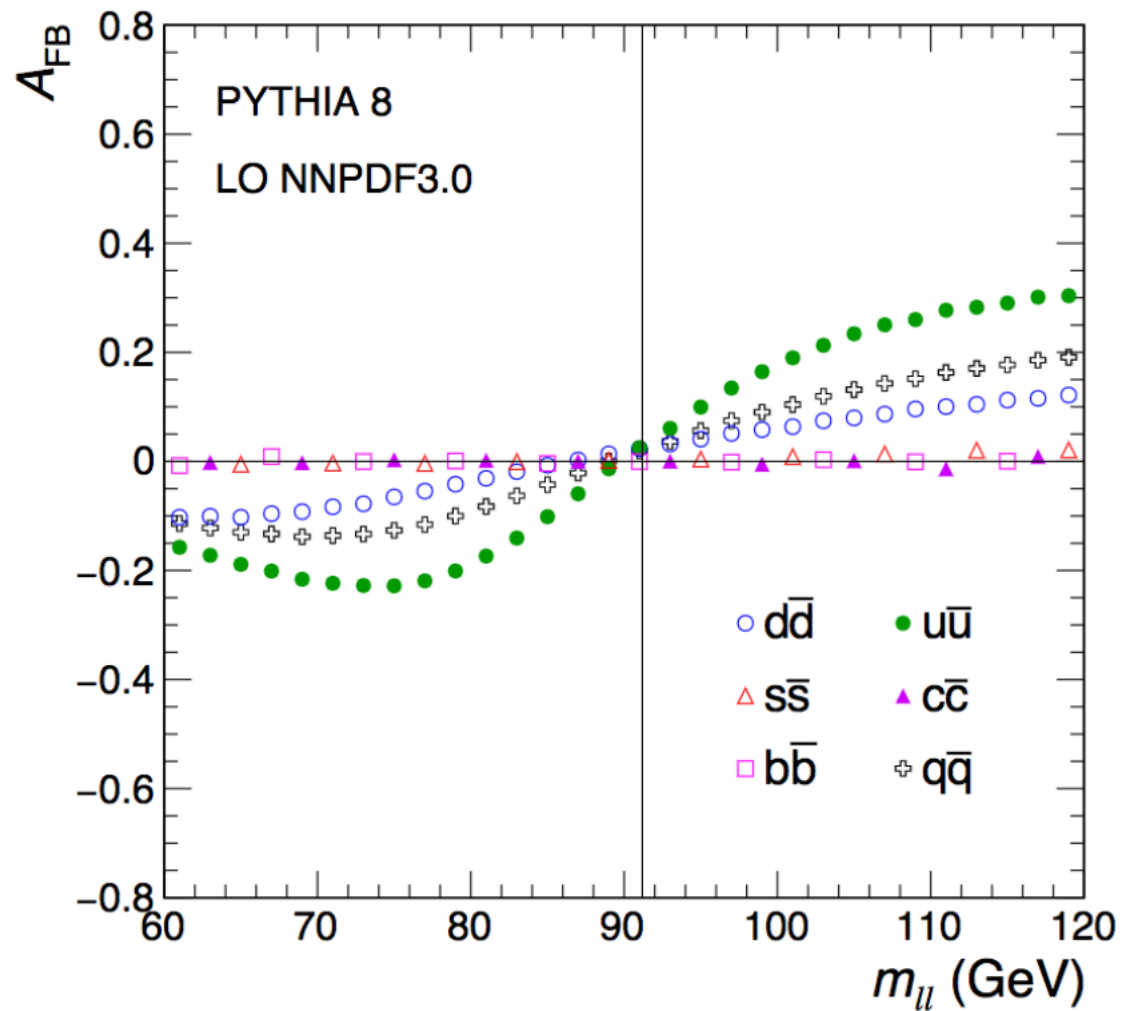
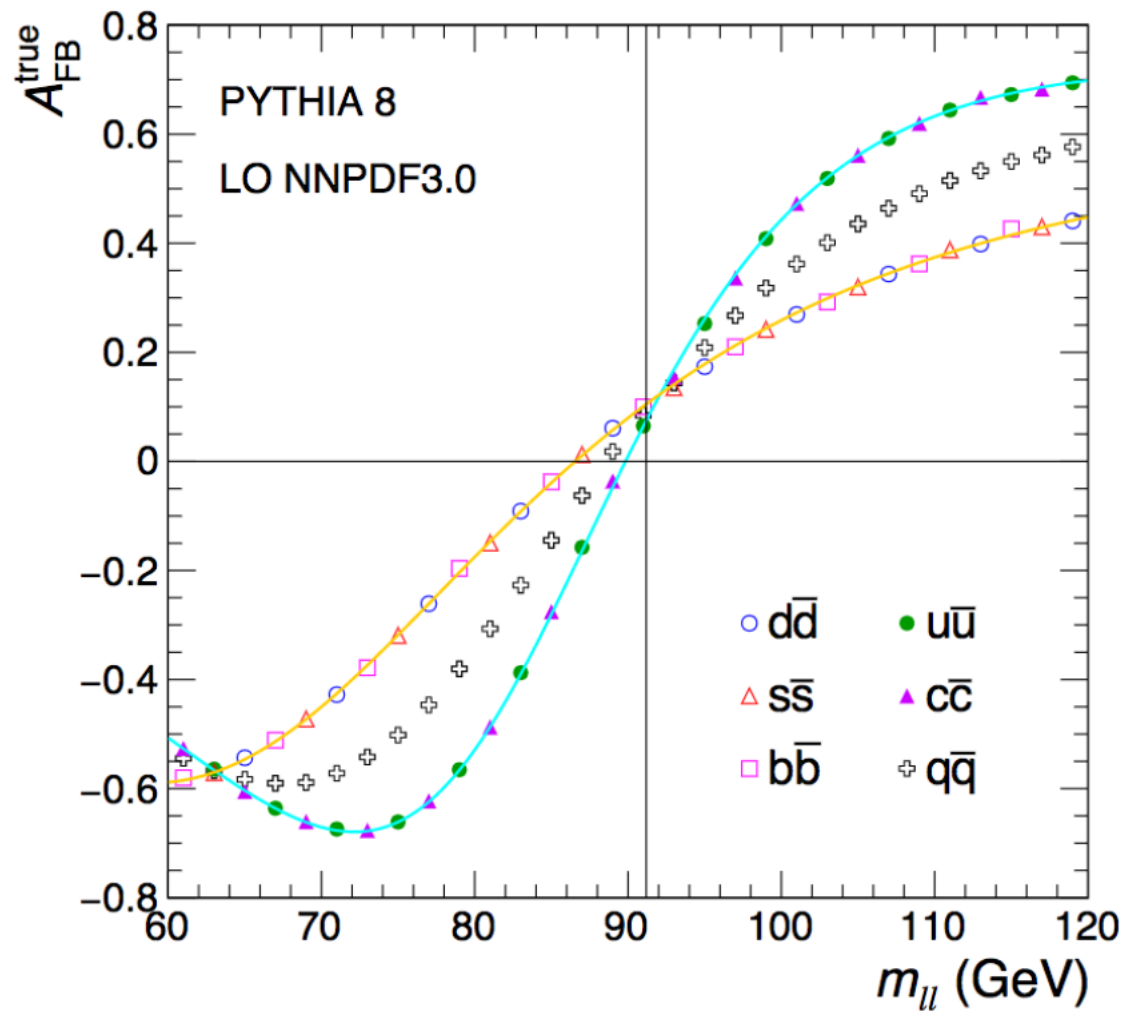


Figure 7.6: Comparison of the effective electroweak mixing angle $\sin^2 \theta_{\text{eff}}^{\text{lept}}$ derived from measurements depending on lepton couplings only (top) and also quark couplings (bottom). Also shown is the SM prediction for $\sin^2 \theta_{\text{eff}}^{\text{lept}}$ as a function of m_H . The additional uncertainty of the SM prediction is parametric and dominated by the uncertainties in $\Delta\alpha_{\text{had}}^{(5)}(m_Z^2)$ and m_t , shown as the bands. The total width of the band is the linear sum of these effects.



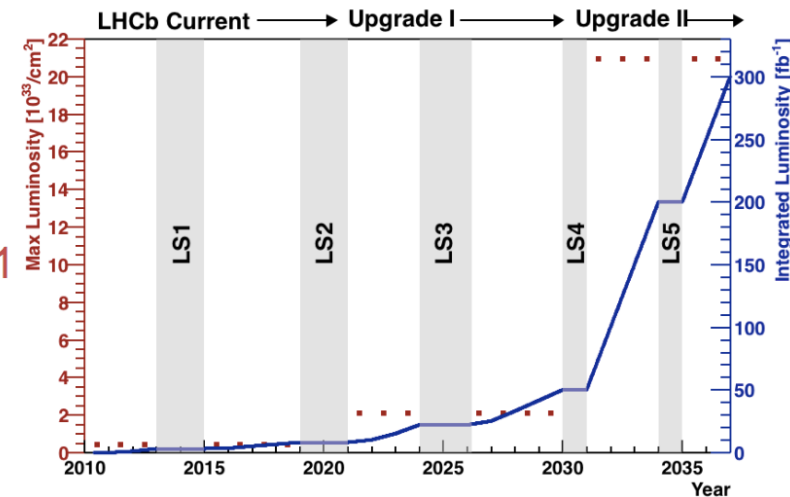
$$\frac{d\sigma}{d\Omega} \propto (1 + \cos^2 \theta) + A_0 \frac{1}{2} (1 - 3 \cos^2 \theta) + A_1 \sin 2\theta \cos \phi + A_2 \frac{1}{2} \sin^2 \theta \cos 2\phi + A_3 \sin \theta \cos \phi +$$
$$A_4 \cos \theta + A_5 \sin^2 \theta \sin 2\phi + A_6 \sin 2\theta \sin \phi + A_7 \sin \theta \sin \phi$$

CMS, Expected precision

L_{int} (fb^{-1})	$\delta_{\text{stat}} [10^{-5}]$		$\delta_{\text{nnpdf3.0}}^{\text{nominal}} [10^{-5}]$		$\delta_{\text{nnpdf3.0}}^{\text{constrained}} [10^{-5}]$	
	$ \eta < 2.4$	$ \eta < 2.8$	$ \eta < 2.4$	$ \eta < 2.8$	$ \eta < 2.4$	$ \eta < 2.8$
10	76	51	75	57	39	29
100	24	16	75	57	27	20
500	11	7	75	57	20	16
1000	8	5	75	57	18	14
3000	4	3	75	57	15	12

LHCb Timeline

- LHC Run-I (2010-2013)
- LHC Run-II (2015-2018)
 - Trigger computing increased.
- LHC Run-III, Run-IV (2021-2023, 2026-2029)
 - Major 'New' Experiment: **LHCb Upgrade [I(a), I(b)]**
 - $L = 2 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$, integrated 50 fb^{-1}
- LHC Run-V (2031-)
 - Major 'New' Experiment
LHCb Upgrade II
 $L = 2 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$, integrated 300 fb^{-1}



Slide taken from C. Parkes