Determination of the Weak Mixing Angle

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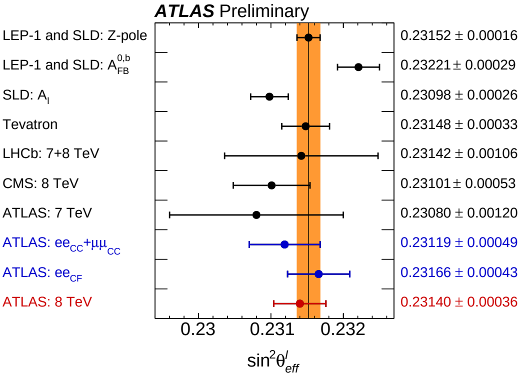
QCD@LHC2022

What is the weak mixing angle

- Key parameter in the electroweak sector of the SM
  - $\sin^2(\theta_w) = 1 - \frac{m_w^2}{m_z^2}$,
- We can also define an effective leptonic mixing angle which at leading order
  - $k_\ell \sin^2(\theta_w) = \sin^2(\theta_{eff}^{lep}) = \frac{1}{4|Q_l|}\left(1 - \frac{g_\nu}{g_a}\right)$
- Electroweak radiative corrections in k_ℓ are accurately calculated in standard model
- Precise $\sin^2(\theta_{eff}^{lep})$ measurement can probe new physics contributions to m_W (an indirect m_W measurement) and k_ℓ

Current Status

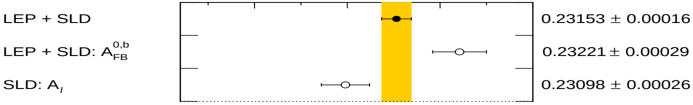


ATLAS-CONF-2018-037

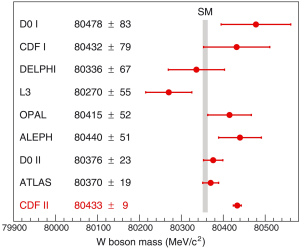
- Current precision driven by LEP/SLD
- Hadron collider measurements are becoming competitive

Importance of Precision measurements of $\sin^2(\theta^{lep}_{eff})$

- The 2 most precise measurements LEP and SLD measurements disagree by $\sim 3\sigma$. Could be hint of non standard model processes



CMS, arxiv: 1806.00863



- The recent W mass measurement from CDF II has tensions with other measurements and disagrees with the SM at an order of 7σ

CDF II, DOI: 10.1126/science.abk1781

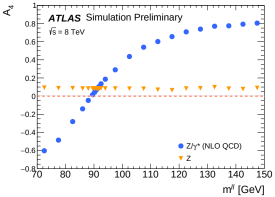
Measuring $\sin^2(\theta^{lep}_{eff})$ at the LHC

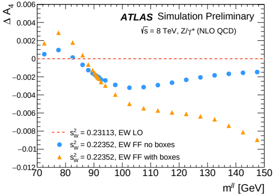
- The full differential cross section in leading order

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

- At first order, only the annhiliation $q\bar{q} \to Z$ is present

$$\frac{d\sigma}{d(\cos\theta^*)} \propto 1 + \cos^2\theta^* + A_4\cos\theta^*,$$



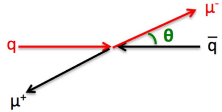


ATLAS-CONF-2018-037
CMS, arxiv: 1806.00863

Measuring $\sin^2(\theta_{eff}^{lep})$ at the LHC

- The mixing of vector and axial vector couplings creates a forwards backwards asymmetry in the decay of Z bosons to dilepton pairs
$$q\bar{q} \rightarrow Z/\gamma^* \rightarrow \ell\bar{\ell}$$
- Meaure this asymmetry Collins-Soper rest frame (CS frame)
- $A_{FB} = \frac{3}{8}A_4 = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}$
- The Z-axis of the CS frame is along the direction of the $q\bar{q}$ collision
- Z boson rapidity defines the quark direction

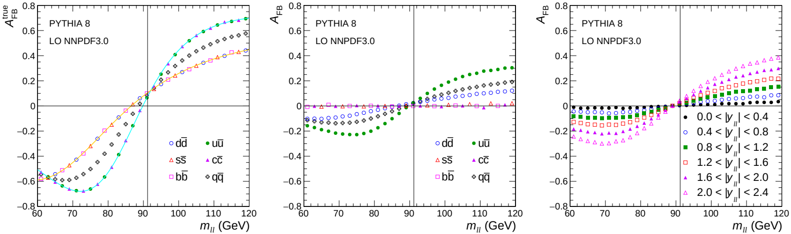
$$\frac{d\sigma}{d\cos\theta^*} = A(1+\cos^2\theta^*) + B\cos\theta^*$$



$$\cos\theta^* = \frac{2(P_1^+ P_2^1 - P_1^- P_2^+)}{\sqrt{m_{ll}^2(m_{ll}^2 + p_{T,ll}^2)}} \frac{p_{Z,ll}}{|p_{Z,ll}|}$$

CMS, arxiv: 1806.00863

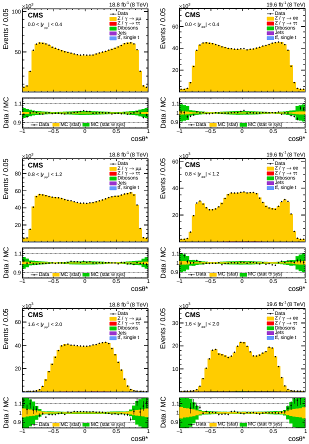
- A_{FB} increases with the rapidity of the Z boson, Y_Z
- Only valence quarks contribute to A_{FB}
- At higher Y_Z the high X parton is likely to be a valence quark and the low X parton the antiquark



CMS, arxiv: 1806.00863

Weighted A_{FB}

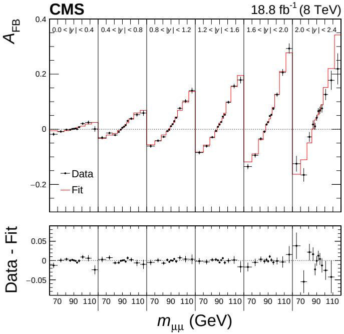
- Weight A_{FB} by $\cos\theta^*$
- Weighted A_{FB} cancels uncertainties that come from efficiencies and acceptance



A. Bodek, Eur.Phys.J.C67:321-334,2010
CMS, arxiv: 1806.00863

Extracting $\sin^2(\theta_{eff}^{lep})$

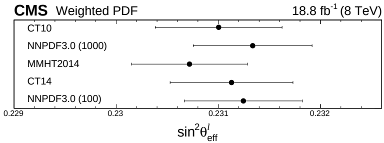
- A_{FB} has a high dependence on mass, this comes from interference of Z with virtual photon
- By creating templates by varying the value of $\sin^2(\theta_w)$ we can test which value that the data agrees with

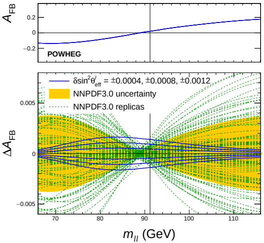


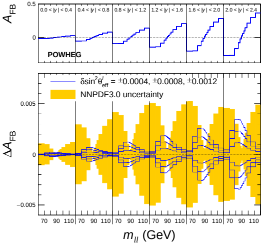
CMS, arxiv: 1806.00863

PDFs

- Measurment of $\sin^2(\theta_{eff}^{lep})$ has strong dependence on PDFs
- Less effect in high rapidity regions
- ATLAS and CMS constrain PDFs in situ





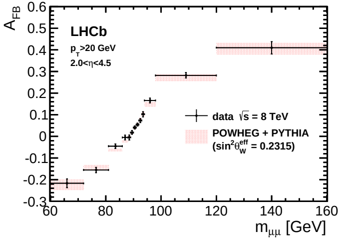


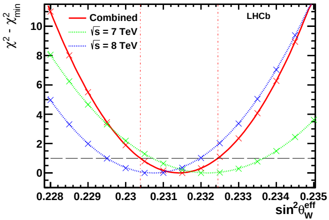
CMS, arxiv: 1806.00863
A. Bodek, Eur. Phy. J. C76:115

- Combination of 7TeV ($1fb^{-1}$) and 8TeV ($2fb^{-1}$) data
- Measurement uses the dimuon channel
- High rapidity measurement $2.0 < Y < 4.5$ with raw A_{FB}

$$\sin^2(\theta_{eff}^{lep}) = 0.23142 \pm .0011$$

- The error breaks down as ± 0.00073 (statistical), ± 0.00052 (systematic) and ± 0.00056 (theoretical)



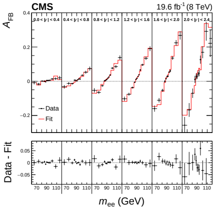


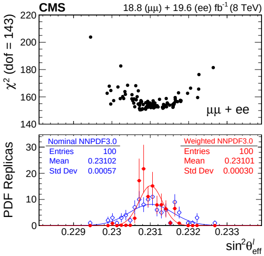
CMS Result (arxiv: 1806.00863)

- Measurement made on 8TeV data
- $18.8 fb^{-1}$ in the dimuon channel and $19.6 fb^{-1}$ in the dielectron channel
- Uses weighted A_{fb} and constrains PDFs using the high mass region

$$\sin^2(\theta_{eff}^{lep}) = 0.23101 \pm 0.00053$$

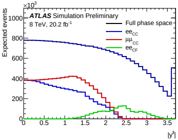
- The error breaks down as ± 0.00036 (stat) ± 0.00018 (syst) ± 0.00016 (theo) ± 0.00031 (parton distributions in proton)

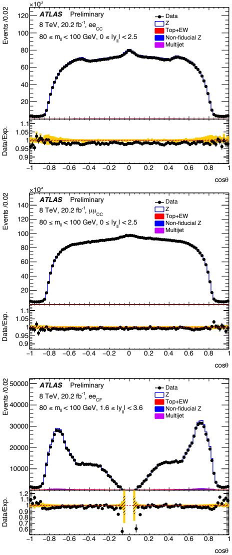




ATLAS Result (ATLAS-CONF-2018-037)

- Measurement made on 8TeV data with $20.2fb^{-1}$
- 6 million electron pairs, 7.5 million muon pairs
- Using events with a forward electron extends the rapidity coverage to 3.6
- 1.5 million electron pairs with a forward electron (reconstructed from calorimeter, no tracker)

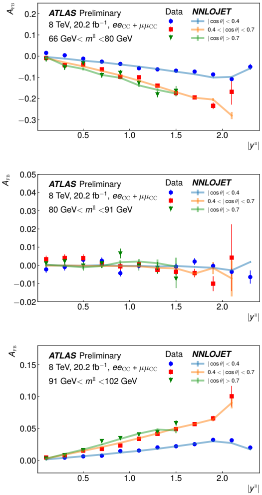




- Extracts weak mixing angle from $A_4(m, y)$ instead of A_{FB}

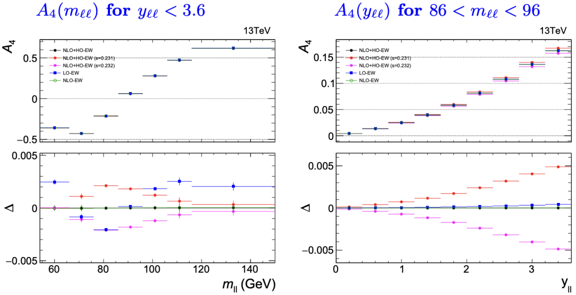
  $\sin^2(\theta_{eff}^{lep}) = 0.23101 \pm 0.00036$

- The error breaks down as ± 0.00021 (stat) ± 0.00024 (PDF) ± 0.00016 (syst.)



LHC EW working group activities

- Tuned comparison/benchmarking of NLO and higher order weak and QED corrections, including FSR, ISR and IFI
- Main focus on $\frac{d\sigma}{dM(\ell\ell)}$ and A_{FB}
- Studying various electroweak input schemes, in particular new $\sin(\theta_W)$ EW input scheme, which is needed for this measurement
- Preparatory studies in view of Run2 and future combinations

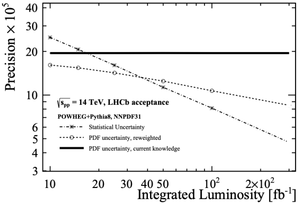


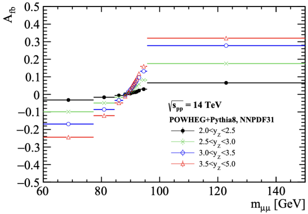
Future measurements

- CMS Hi-lumi extended acceptance projections (CMS-PAS-FTR-17-001)
- ATLAS projections (ATL-PHYS-PUB-2018-037)
- LHCb projections (LHCb-PUB-2018-013)

LHCb in HL-LHC

- The statistical sensitivity can be expected to improve by up to a factor of $\sqrt{2}$
- Increased statistics will also allow for the analysis to be done as a function of rapidity
- Expect uncertainties to be competitive with LEP+SLD at $L > 100 fb^{-1}$

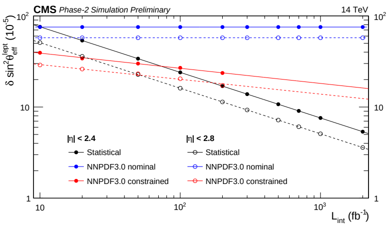


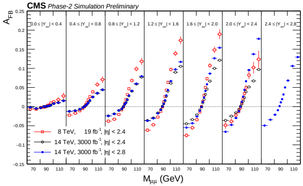


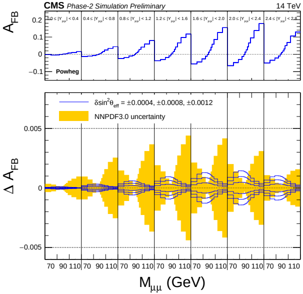
LHCb-PUB-2018-013

CMS in HL-LHC

- Extension of tracker will increase acceptance to Z rapididties up to 2.8
- Studies in the muon channel predict to have uncertainties on PDFs competitive with LEP+SLD at $L > 300 fb^{-1}$



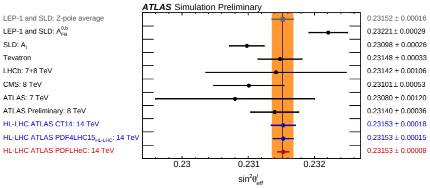


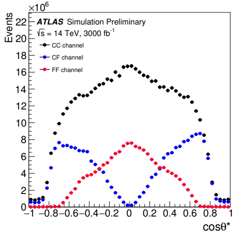


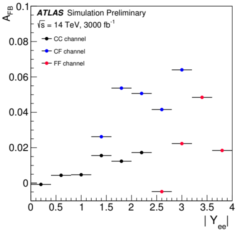
CMS-PAS-FTR-17-001

ATLAS in HL-LHC

- Extension of inner tracker from $|\eta| \leq 2.4$ to $|\eta| \leq 4.0$
- Projections for $L > 300 fb^{-1}$ for different PDF scenarios







ATL-PHYS-PUB-2018-037

Conclusions

- Important probe to test the SM in the electroweak sector and to search indirectly for new physics
- Run2 uncertainties expected to be competitive with LEP/SLD
- The LHC (ATLAS, CMS, LHCb) has promising plans for future measurements, and for combinations of these measurements

University of Rochester DOE Grant Number
Research supported by the U.S. Department of Energy under grant number DE-SC0008475.