Exploring SMEFT couplings using Forward-Backward Asymmetry

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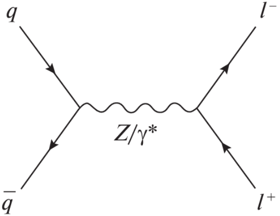
DY AFB



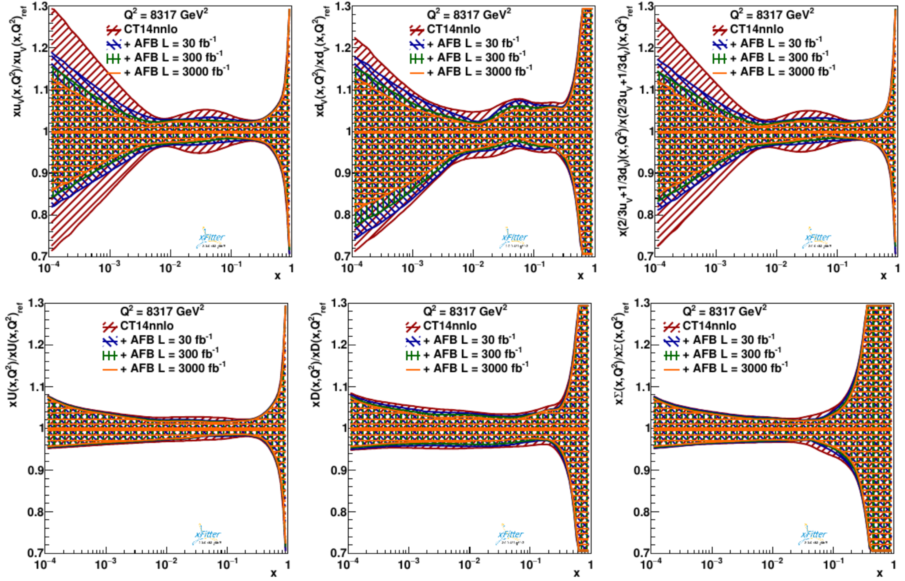
- Drell Yan (DY) lepton pair production at the LHC is a useful process to test SM and probe proton PDFs
- Forward-Backward Asymmetry (AFB) is a clean observable for which many experimental and theoretical uncertainties cancel:

$$A^*_{\mathrm{FB}} = \frac{d\sigma/dM(\ell^+\ell^-)[\cos\theta^* > 0] - d\sigma/dM(\ell^+\ell^-)[\cos\theta^* < 0]}{d\sigma/dM(\ell^+\ell^-)[\cos\theta^* > 0] + d\sigma/dM(\ell^+\ell^-)[\cos\theta^* < 0]}$$

- AFB was used to constrain PDFs (e.g. JHEP 10 (2019) 176)

$$A_{FB} \propto \frac{2}{3}u_v + \frac{1}{3}d_v$$

DY AFB: PDF constraints [JHEP 10 (2019) 176]



DY AFB in SM and SMEFT

- Traditionally AFB is used to measure the weak mixing angle (e.g. ATLAS-CONF-2018-037)
- Triple-differenetial DY x-sections (and hence AFB) depend on the Z boson coupling to fermions:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}M\mathrm{d}y\mathrm{d}\cos\theta*} = F(g_V^{Zu}, g_A^{Zu}, g_V^{Zd}, g_A^{Zd}, g_V^{Ze}, g_A^{Ze})$$

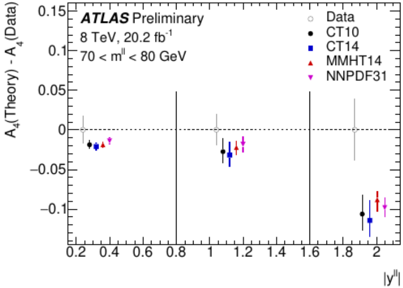
- In the SM:

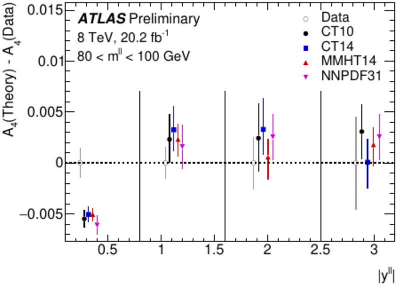
$$g_V^{Zu} = \frac{1}{2} - \frac{4}{3}\sin^2\theta_W, \quad g_A^{Zu} = \frac{1}{2}$$
$$g_V^{Zd} = -\frac{1}{2} + \frac{2}{3}\sin^2\theta_W, \quad g_A^{Zu} = -\frac{1}{2}$$

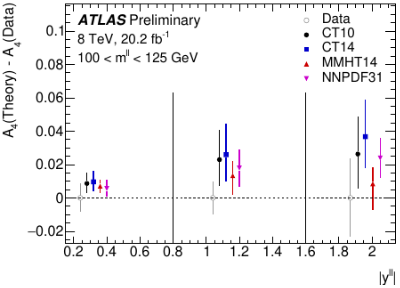
- We work with couplings to right- and left-handed fermions: $g_{V/A}^{Zf} = g_R^{Zf} \pm g_L^{Zf}$
- We do not touch g_V^{Ze}, g_A^{Ze}: they are well constrained by LEP data
- Also we do not consider 4-fermion operators ($M(l\bar{l}) < 2m_W$)
- Finally, we fit four parameters δ which are $= 0$ in the SM:

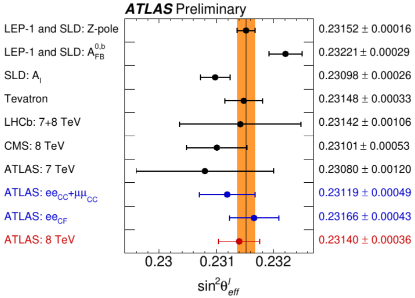
$$g_R^{Zu} = g_{R,SM}^{Zu} + \delta_{Ru}$$
$$g_L^{Zu} = g_{L,SM}^{Zu} + \delta_{Lu}$$
$$g_R^{Zd} = g_{R,SM}^{Zd} + \delta_{Rd}$$
$$g_L^{Zd} = g_{L,SM}^{Zd} + \delta_{Ld}$$

ATLAS measurement of DY AFB [ATLAS-CONF-2018-037]



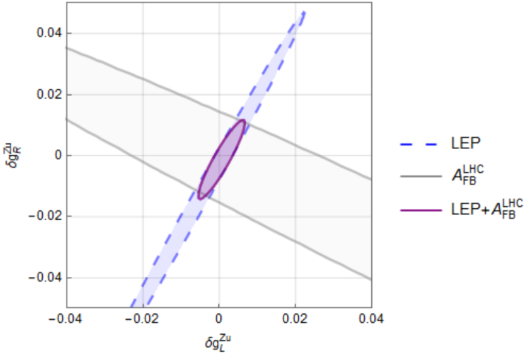






DY AFB in SMEFT

- In JHEP 08 (2021) 021 [arxiv:2103.12074] the ATLAS measurement was used (in a global fit together with other data) to study constraints on the SM couplings
- Only Z-peak region $80 < M(l\bar{l}) < 100$ GeV from ATLAS-CONF-2018-037 was used (4 bins in $y(l\bar{l})$)
- It was shown that the LHC data put **constraints on a different linear combination of the couplings compared to the LEP data**

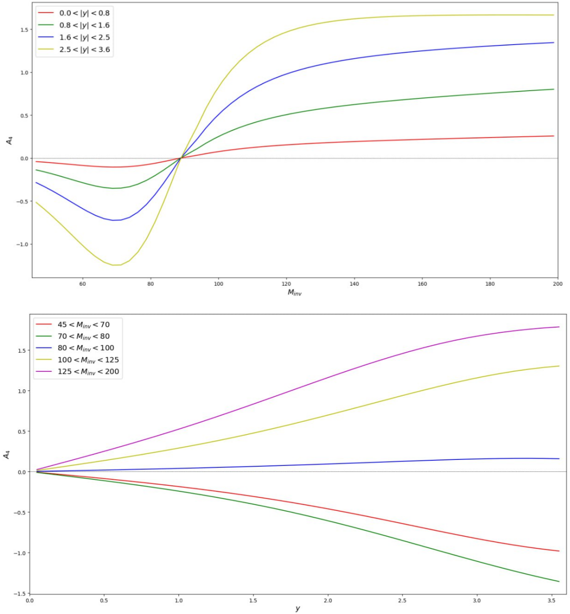


- → thus it is complementary to the LEP data
- With more bins in M and y it should be possible to put even better constraints

DY AFB in SMEFT with xFitter

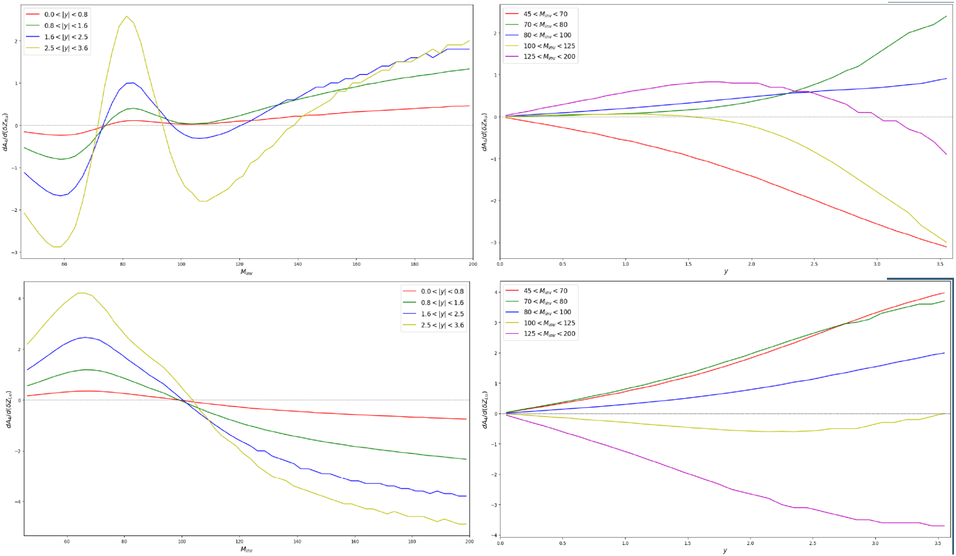
- The project was started in February 2023 by Andrii Anataichuk (bachelor student, a remote participant of the DESY Ukraine winter school)
- Roadmap of the study:
    - extend LO AFB reaction in xFitter to allow fitting the couplings [merge request]
    - "fit" the couplings using the ATLAS data (only one M bin, and all bins)
        - just a try, do not take the results seriously, as this is LO
        - still useful to study the effect of the PDF uncertainties
    - generate and fit pseudodata for HL-LHC, similar to the xFitter AFB PDF paper
- xFitter is **a very suitable tool** for this study:
    - fast analytical LO computation of DY AFB is available and easy to be modified
    - LO should be sufficient to study constraints using pseudodata, however for a cross check we have NLO APPLGRID tables generated for the AFB PDF xFitter paper
    - it is easy to generate various pseudodata sets with different binning schemes etc.
    - PDF uncertainties are easy to include in the fit using the profiler
- The results obtained during the school are documented in this report, however the analysis is ongoing by Andrii now

DY AFB as function of M and y

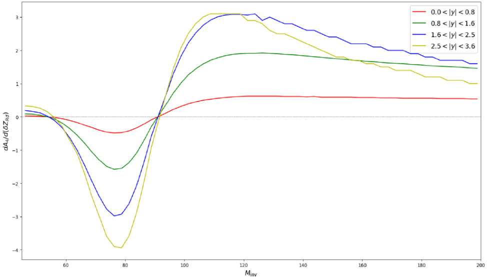


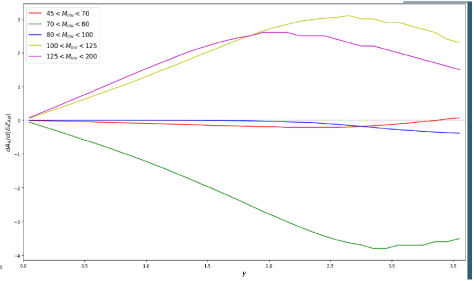
- At LHC, direct observation of the AFB is not possible since the incoming particles are protons (not quarks)
- AFB is defined w.r.t to the longitudinal boost of $l\bar{l}$, assuming that the quark has a larger momentum than the antiquark
- Therefore AFB approaches 0 as y approaches 0

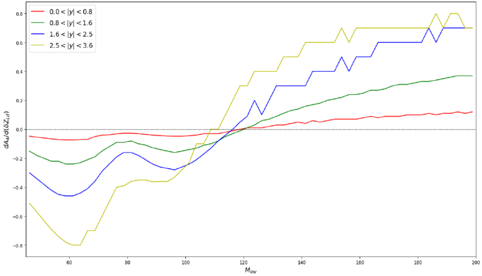
Partial derivatives of AFB w.r.t couplings as function of M and y (1)

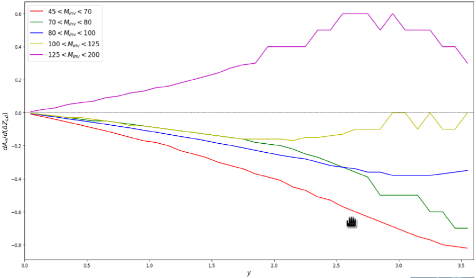


Partial derivatives of AFB w.r.t couplings as function of M and y (2)









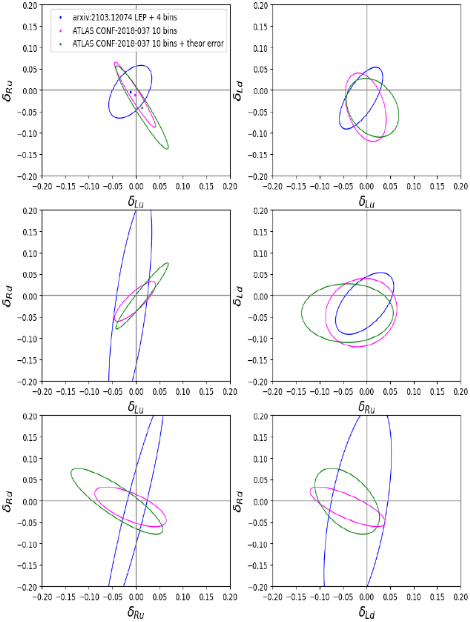
- in particular, $\mathrm{d}A_4/\mathrm{d}(\delta Z_{Rd}) \approx 0$ at $M \approx 90$ GeV, therefore using the $80 < M < 100$ GeV range is not optimal for constraining δZ_{Rd}

Fit to the ATLAS data [all 10 bins]

$$\delta_{Ru} = -0.040650 \pm 0.048806,$$
$$\delta_{Lu} = 0.012752 \pm 0.027921,$$
$$\delta_{Rd} = -0.001534 \pm 0.038547,$$
$$\delta_{Ld} = -0.041534 \pm 0.034358,$$

$$\begin{pmatrix} 1 & -0.956 & -0.855 & -0.003 \\ - & 1 & 0.964 & 0.266 \\ - & - & 1 & -0.484 \\ - & - & - & 1 \end{pmatrix}$$

- theory errors are PDF uncertainties of MMHT2014nnlo
- it is difficult to compare directly to arxiv:2103.12074, since they used LEP data also



Pseudodata

For generated pseudodata, statistical errors were propagated to A_{FB} as:

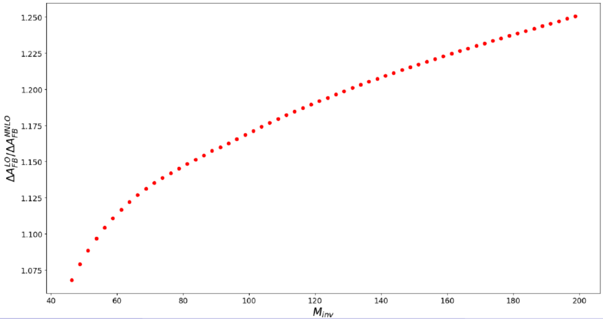
$$\Delta A_{FB} = \sqrt{\frac{1 - A_{FB}^2}{N}}, \quad (5)$$

where N is the total number of events in a specific invariant mass and rapidity interval. In our case, N is given by:

$$N = L\epsilon(\sigma_F + \sigma_B), \quad (6)$$

where L is integrated luminosity, ϵ is detector acceptance.

- Pseudodata were generated similar to the AFB xFitter paper:
  - statistical uncertainties for $L = 3000$ fb^{-1} and $\epsilon = 20\%$ detector efficiency
  - however, no scaling of statistical uncertainties with NNLO k-factors (effect 7–25%)

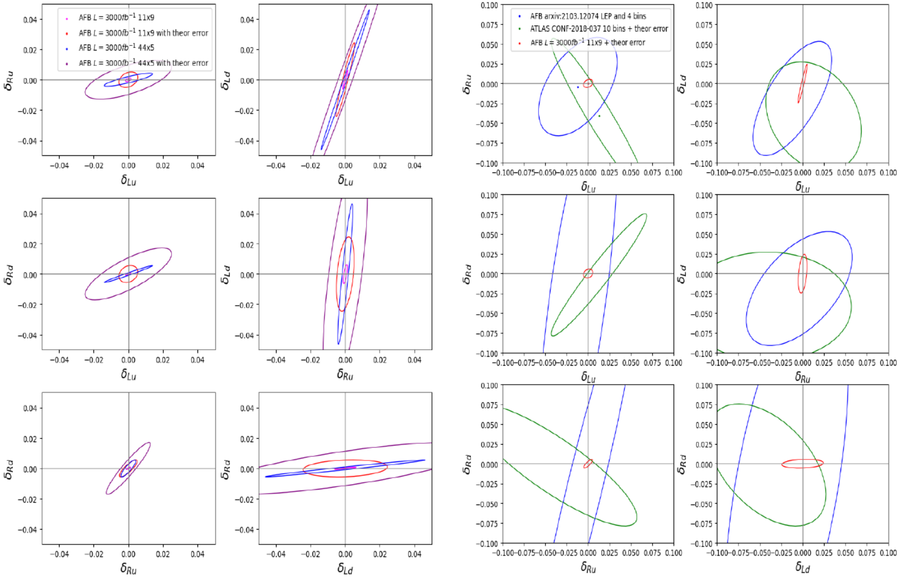


Pseudodata: binning

Initially, two binning schemes were considered (not yet final!)

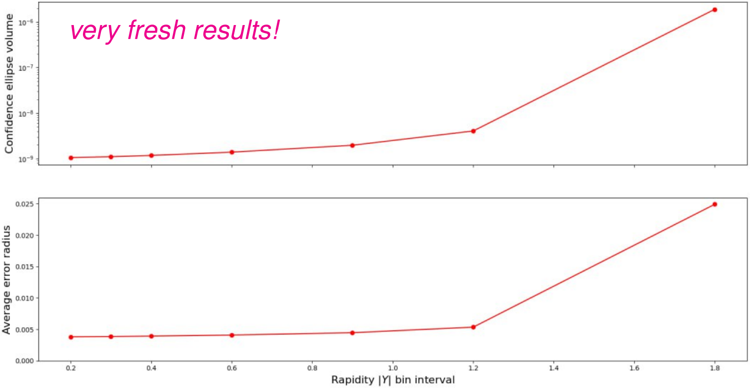
- 11 bins of M in $70 < M < 125$ GeV and 9 bins of y on $0 < |y| < 3.6$ [11×9]
- 44 bins of M in $40 < M < 150$ GeV and 5 bins of y on $0 < |y| < 2.5$ [44×5] (similar to the xFitter PDF AFB paper)

Pseudodata: fit results



Pseudodata: study of binning (work in progress)

- 11×9 pseudodata put much stronger constraints than 44×5 pseudodata:
  - probably, because of the extended y range?
- We want to do a systematic study:
  - which bin width is optimal?
  - which range is optimal?
  - etc.
- Need to have **a measure** of how strong are constraints on the coupling (one number)
  - propose to use **a volume of the 4-dimensional ellipsoid**



Summary

- Current constraints on couplings can be significantly improved with HL-LHC DY AFB data
- Plan to optimise binning of pseudodata
- Plan to study effect of proton PDF uncertainties using different PDF sets