xFitter Updates: Probing Z Boson Couplings with Forward-Backward Asymmetry

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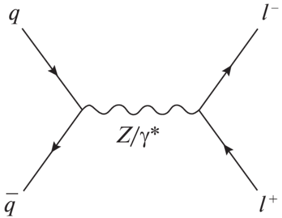
A. Anataichuk et al. "Exploring SMEFT Couplings Using the Forward-Backward Asymmetry in Neutral Current Drell-Yan Production at the LHC" arXiv:2310.19638

DIS2024 (Grenoble, France)
9 Apr 2024

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:

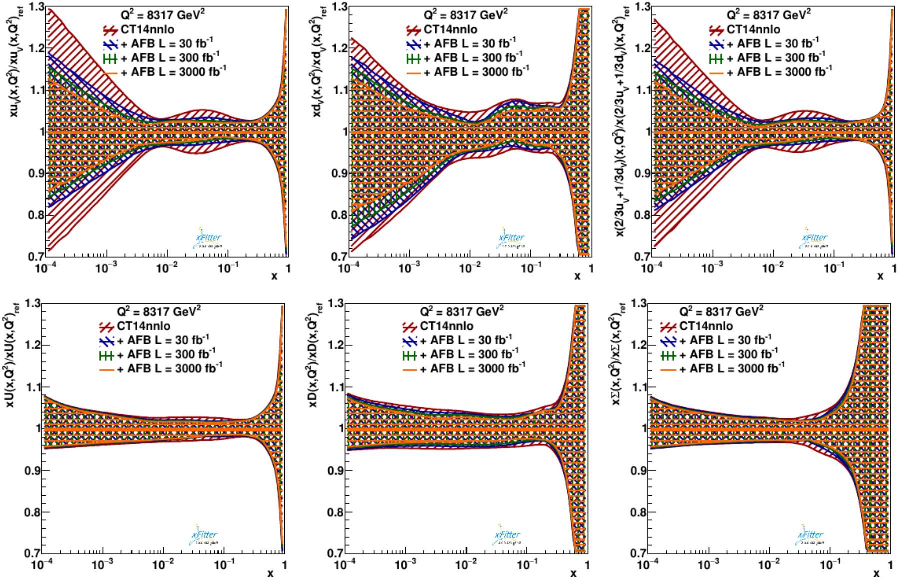
$$A^*_{\mathrm{FB}} = \frac{d\sigma/dM(\ell^+\ell^-)[\cos\theta^* > 0] - d\sigma/dM(\ell^+\ell^-)[\cos\theta^* < 0]}{d\sigma/dM(\ell^+\ell^-)[\cos\theta^* > 0] + d\sigma/dM(\ell^+\ell^-)[\cos\theta^* < 0]}$$

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

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

- **We want to explore AFB potential to constrain *Z* boson couplings at future HL-LHC**

DY AFB: PDF constraints at LHC and HL-LHC [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)
- DY cross sections (and hence AFB) depend on the Z boson coupling to fermions:

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

- In the SM:

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

- In the SMEFT up to dimension $D = 6$:

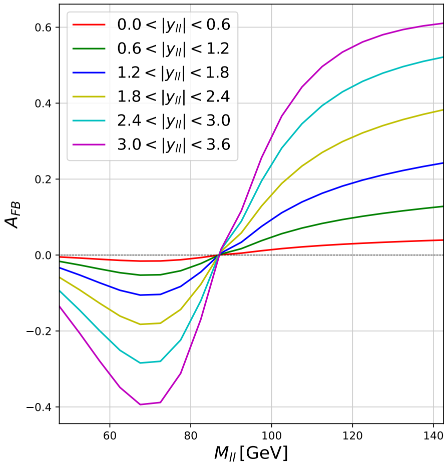
$$\mathcal{L} = \mathcal{L}^{(\mathrm{SM})} + \frac{1}{\Lambda^2}\sum_{j=1}^{N_6} C_j^{(6)}\ \mathcal{O}_j^{(6)}$$

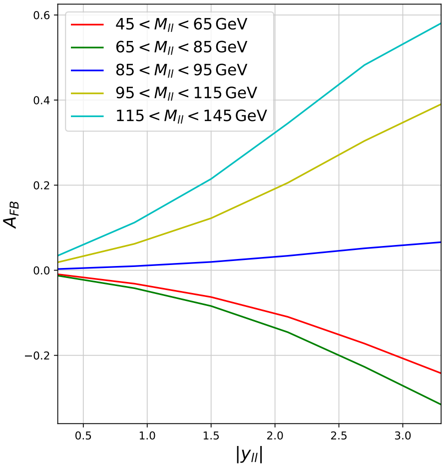
- In the dilepton mass region not too far from the Z-boson peak the whole effect of the $D = 6$ SMEFT Lagrangian is a modification of the vector boson couplings to fermions
- Couplings to leptons g_V^{Ze}, g_A^{Ze} are well constrained by LEP data
- 4-fermion operators are not included: $< 1\%$ at $M(ll) < 150$ GeV
- We fit four parameters δ (assuming $g_{A,V}^{Zu} = g_{A,V}^{Zc}$, $g_{A,V}^{Zd} = g_{A,V}^{Zs} = g_{A,V}^{Zb}$) which are $= 0$ in the SM (R, L couplings are linear combination of V, A couplings):

$$\begin{aligned} g_L^{Zu} &\equiv g_{L(\mathrm{SMEFT})}^{Zu} = g_{L(\mathrm{SM})}^{Zu} + \delta g_L^{Zu}\ , \quad & g_R^{Zu} &\equiv g_{R(\mathrm{SMEFT})}^{Zu} = g_{R(\mathrm{SM})}^{Zu} + \delta g_R^{Zu} \\ g_L^{Zd} &\equiv g_{L(\mathrm{SMEFT})}^{Zd} = g_{L(\mathrm{SM})}^{Zd} + \delta g_L^{Zd}\ , \quad & g_R^{Zd} &\equiv g_{R(\mathrm{SMEFT})}^{Zd} = g_{R(\mathrm{SM})}^{Zd} + \delta g_R^{Zd} \end{aligned}$$

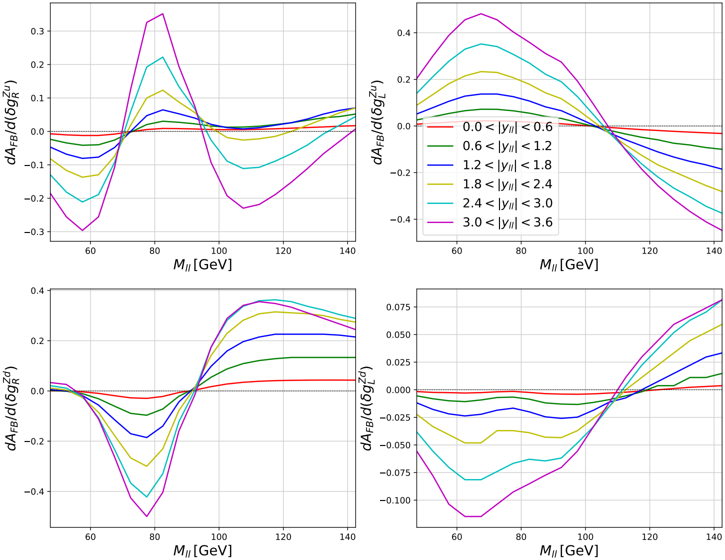
DY AFB as function of $M(ll)$ and $y(ll)$ [LO]

In order to maximize the sensistivity, we use double-differential AFB as function of $M(ll)$ and $y(ll)$



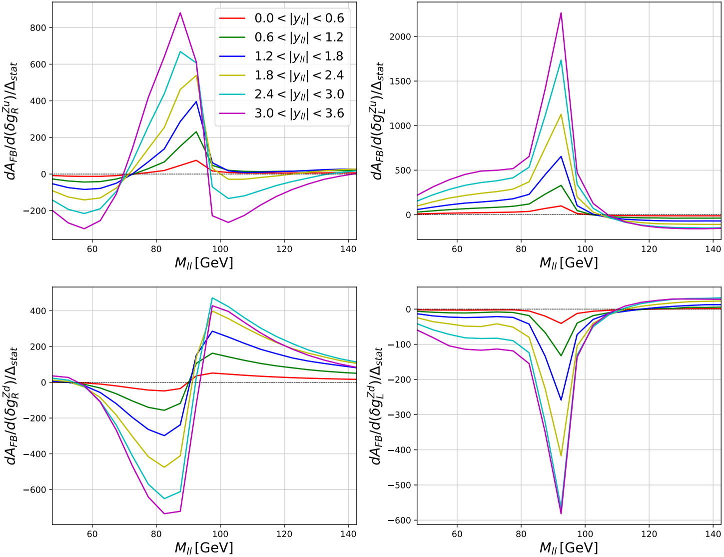


DY AFB derivatives w.r.t the couplings as a function of $M(ll)$ [LO]



- Sensitivity to the couplings comes from AFB as a function of $M(ll)$

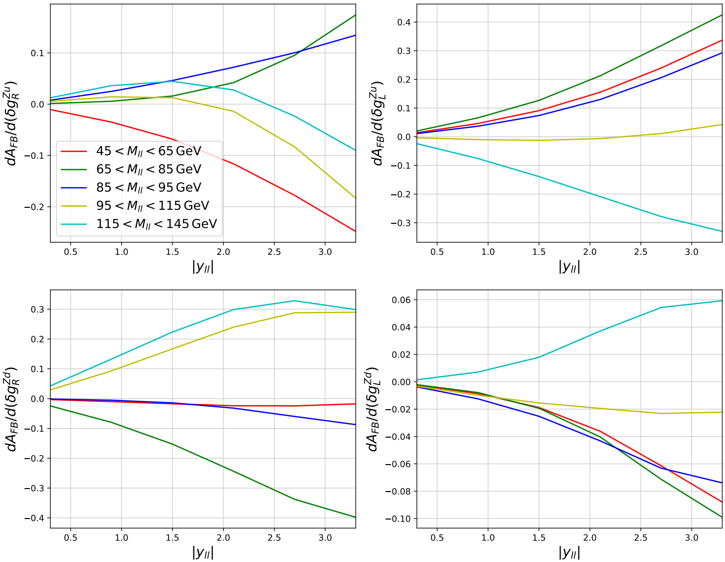
DY AFB derivatives w.r.t the couplings divided by stat. unc. (HL-LHC)



- Statistical uncertainties increase outside of the Z peak

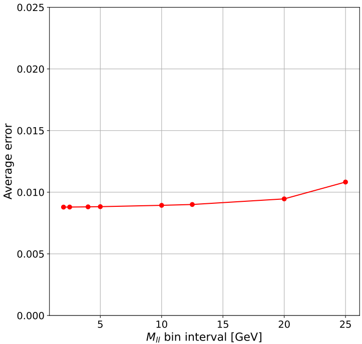
→ does not make sense to go to very low or high $M(ll)$

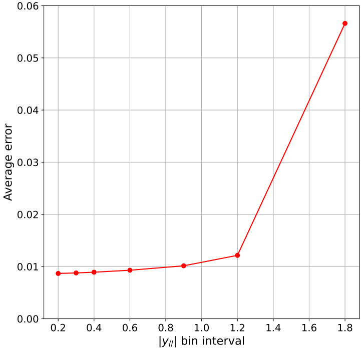
DY AFB derivatives w.r.t the couplings as a function of $y(ll)$ [LO]



- AFB $\rightarrow$ 0 as $y(ll) \rightarrow 0$ due to its definition at the LHC (w.r.t the longitudinal boost of ll)
- Best sensitivity comes from largest reachable $y(ll)$ values

Binning scheme and analysis setup





- We chose 5 GeV of $M(ll)$ and 0.6 bins of $y(ll)$ (experimentally feasible)
- Kinematic region: $45 < M(ll) < 145$ GeV, $0 < |y(ll)| < 3.6$
- Assume HL-LHC luminosity of 3000 fb^{-1} and 20% detector correction factor
- PDF uncertainties are included using the profiling technique (constrained by (pseudo-)data)
- The fits are done at LO (sensitivity study only) using **xFitter framework**

xFitter [https://xfitter.org] [https://gitlab.com/fitters/xfitter]

xFitter

Welcome to xFitter (former HERAFitter)

Proton parton distribution functions (PDFs) are essential for precision physics at the LHC and other hadron colliders. The determination of the PDFs is a complex endeavor involving several physics process. The main process is the lepton proton deep-inelastic scattering (DIS), with data collected by the HERA ep collider covering a large kinematic phase space needed to extract PDFs. Further processes (fixed target DIS, ppbar collisions etc.) provide additional constraining powers for flavour separation. In particular, the precise measurements obtained or to come from LHC will continue to improve the knowledge of the PDF.

The xFitter project is an open source QCD fit framework ready to extract PDFs and assess the impact of new data. The framework includes modules allowing for a various theoretical and methodological options, capable to fit a large number of relevant data sets from HERA, Tevatron and LHC. This framework is already used in many analyses at the LHC.

Downloads of xFitter software package

All the xFitter releases can be accessed HERE including **2.2.0 FutureFreeze** release
All the former (HERAFitter) releases can be accessed HERE.
Description: http://arxiv.org/abs/1410.4412

xFitter Meetings

xFitter Workshop at CERN 2-5 May 2023

- User's Meetings: meetings to enhance communication between users and developers (open access)
- Developer's Meeting: technical weekly meetings to ensure communication among developers (restricted access)
- Steering Group's Meeting (restricted access)

xFitter representation

- Snowmass contrubution
- List of results
- List of collected talks

Developers Info (restricted to developers)

- Internal Developments

Organisation

- **Release coordinator/Librarian** (revision of the release candidates): Sasha Glazov, Oleksandr Zenaiev
- **DESY IT Contact:** Yves Kemp

Getting help

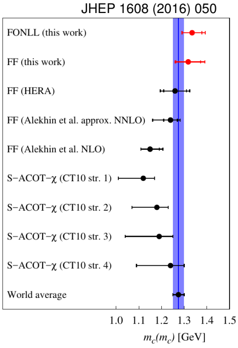
See our help forum https://groups.google.com/forum/#!forum/xfitter-users
In case of questions or problems, please post a message there (requires a google account) or send it via email xfitter-users@googlegroups.com (no account required)

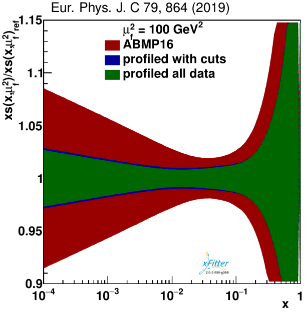
xFitter [xfitter.org] [gitlab.com/fitters/xfitter]

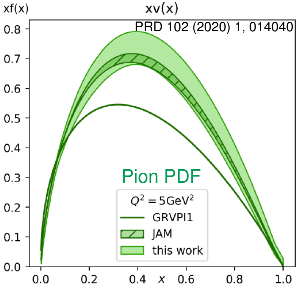
- **xFitter (HERAfitter before 2015) is a unique open-source QCD fit framework:**
  - extract PDFs and theory parameters
  - assess impact of new data
  - check consistency of experimental data
  - test different theoretical assumptions
  - . . . any exercise which involves data vs. theory
- It is widely used by LHC experiments and theorists ($>$ 100 publications)
- **Why is xFitter UNIQUE and so VERSATILE/FLEXIBLE/ADAPTABLE?**
  Because it is fully modular. E.g., hadron interactions are realized as
  - PDF parametrisation at starting scale: it is enough to type your favourite formulas
  - PDF decomposition: construct valence, sea and gluon, apply sum rules (automatic numerical integration is available)
  - PDF evolution: interfaced various codes (QCDNUM, OPENQCDRAD, APFEL, LHAPDF); one can easily interface a new code
  - hard scattering ("reaction"): again, supports various options:
    - various HQ schemes for *ep* DIS
    - some "simple" calculations, e.g. LO DY
    - interfaced external packages, e.g. HATHOR (NNLO total heavy-quark and single *t* hadroproduction) and HVQMNR (NLO heavy-quark differential hadroproduction)
    - but main emphasis is put on interfaces to **fast intepolation tables**, such as **fastNLO, ApplGrid, PineAppl**: allows us to get recent higher-order calculations (e.g. MCFM, MATRIX etc.) "for free"
  - . . . and one can change/mix all these ingredients freely!

Selected studies by the xFitter team

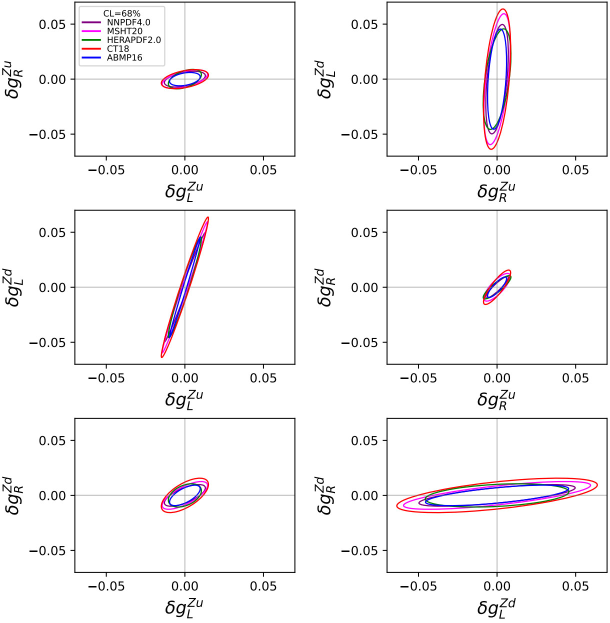
- "A determination of $m_c(m_c)$ from HERA data using a matched heavy flavor scheme" [JHEP 1608 (2016) 050]
- "Probing the strange content of the proton with charm production in charged current at LHeC" [Eur. Phys. J. C 79, 864 (2019)]
- "PDF Profiling Using the Forward-Backward Asymmetry in Neutral Current Drell-Yan Production" [JHEP 2019, 176 (2019)]
- "Parton Distribution Functions of the Charged Pion Within The xFitter Framework" [Phys.Rev.D 102 (2020) 1, 014040]



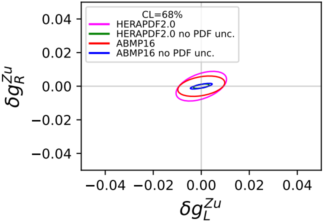




Results: fitted couplings using different PDF sets

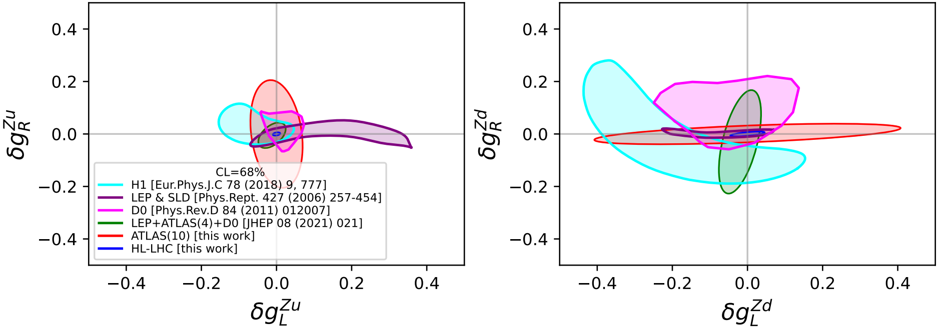


- Similar sensitivity is achieved when using different modern PDF sets
- A large fraction of the uncertainties are from PDFs



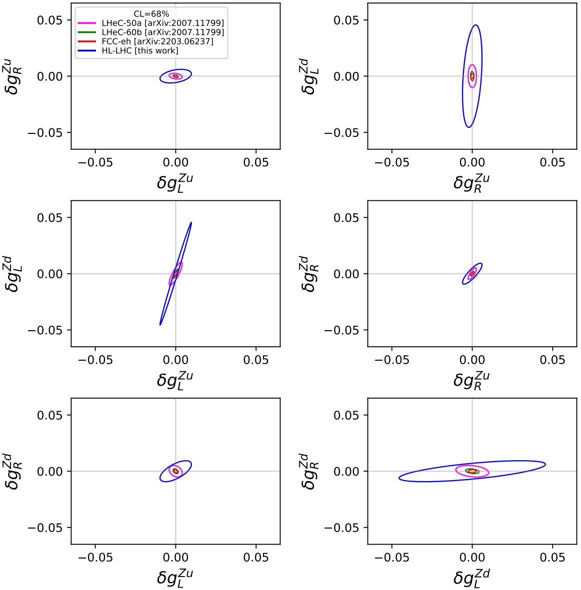
→ Ideally, a future extraction should be done in a simultaneous PDF fit

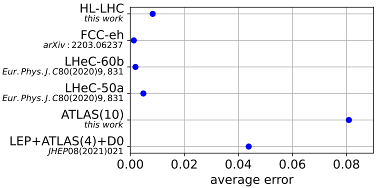
Results: comparison with existing extractions



- HL-LHC has significant potential for improving current constraints compared to the current LHC data [ATLAS(10)]

Results: comparison with other future experiments



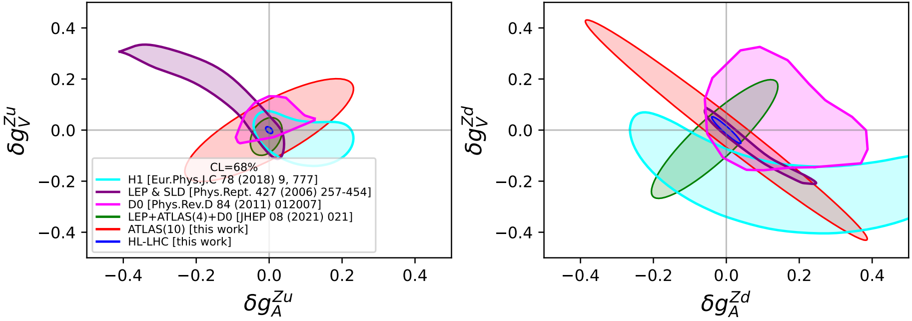


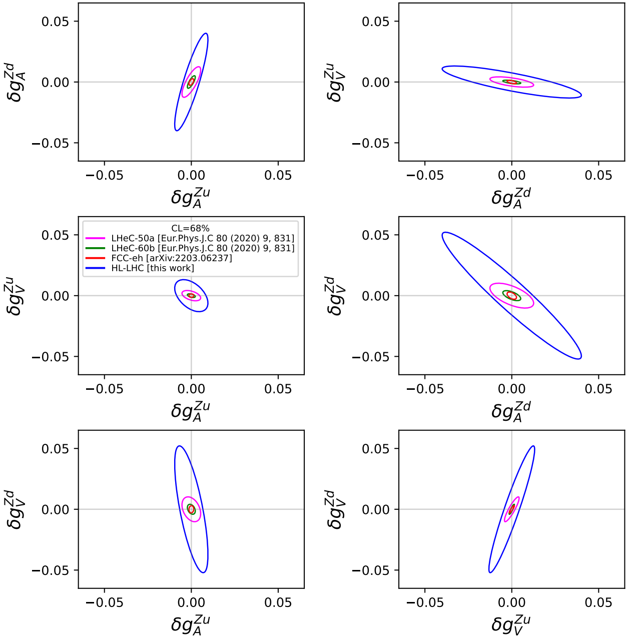
- HL-LHC significantly improves LHC limits, and approaches the precision of LHeC and FCC-eh

Summary

- AFB as a function of $M(ll)$ and $y(ll)$ is a suitable observable which provides constraints on the PDFs and Z boson couplings
- At HL-LHC it is possible to extract these couplings with 1% level precision, which approaches the precision of LHeC and FCC-eh
- We have studied the dependence on the bin widths and provide a specific 2D binning scheme to maximize the sensitivity to the couplings
- Currently, the largest uncertainty comes from the PDFs, which will be improved in the future
- xFitter [`https://gitlab.com/fitters/xfitter`] is a modern versatile and fully flexible tool which can be used for any (pseudo-)data vs theory analysis as complex as a global PDF fit
    - for example, see this talk tomorrow A. Courtoy "Fantomas4QCD: pion PDFs with epistemic uncertainties", Apr 10, 2024, 14:50 (WG1)

BACKUP


0.4
0.2
0.0
−0.2
−0.4
−0.4
−0.2
0.0
0.2
0.4
δg_V^{Zu}
δg_A^{Zu}
CL=68%
H1 [Eur.Phys.J.C 78 (2018) 9, 777]
LEP & SLD [Phys.Rept. 427 (2006) 257-454]
D0 [Phys.Rev.D 84 (2011) 012007]
LEP+ATLAS(4)+D0 [JHEP 08 (2021) 021]
ATLAS(10) [this work]
HL-LHC [this work]
δg_V^{Zd}
δg_A^{Zd}


CL=68%
LHeC-50a [Eur.Phys.J.C 80 (2020) 9, 831]
LHeC-60b [Eur.Phys.J.C 80 (2020) 9, 831]
FCC-eh [arXiv:2203.06237]
HL-LHC [this work]
δg_A^{Zu}
δg_A^{Zd}
δg_V^{Zu}
δg_V^{Zd}
−0.05
0.00
0.05

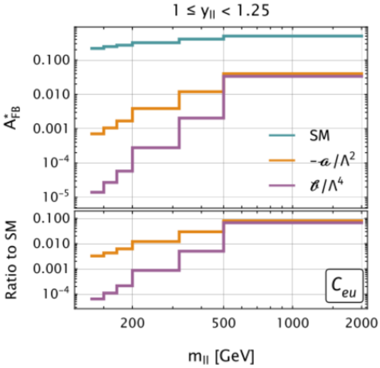


FIG. 3. The linear and quadratic SMEFT contributions to $A^*_{\rm FB}$ for the Wilson coefficients C_{eu} (left) and $C^{(1)}_{lq}$ (right), respectively. The orange and purple lines represent the linear (a/Λ^2) and quadratic (b/Λ^4) SMEFT contributions with $C = 1$ and $\Lambda = 4$ TeV, while the green line shows the SM contribution. The binning, fiducial cuts and the definition of AFB are those of dataset III in Table II.

R. Boughezal, Y. Huang and F. Petriello, “Impact of high invariant-mass Drell-Yan forward-backward asymmetry measurements on SMEFT fits”, Phys. Rev. D 108 (2023) 076008 [arXiv:2303.08257].