Constraining PDFs and probing Z boson couplings with Forward-Backward Asymmetry using xFitter

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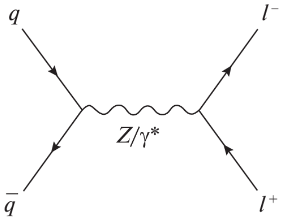
A. Anataichuk et al. "Exploring SMEFT Couplings Using the Forward-Backward Asymmetry in Neutral Current Drell-Yan Production at the LHC" arXiv:2310.19638 (accepted by EPJC)

Resummation, Evolution, Factorization 2024 (Saclay, France)
18 Oct 2024

DY production at LHC

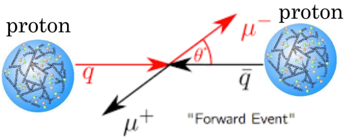


- Drell Yan (DY) lepton pair production at the LHC is a useful process to test SM and probe proton PDFs (quark and antiquark distributions). At LO QCD:

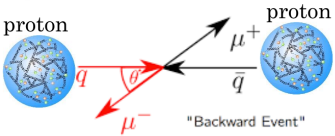
$$\frac{d\sigma}{dM(ll)dy(ll)dcos\theta} \sim \frac{d\sigma}{dM(ll)dy(ll)}\left[(1+cos^2\theta)+A_4cos\theta\right]$$

- The θ angle is defined w.r.t the direction of the boost of the di-lepton system *ll* (correlated with the direction of the incoming quark)

σ_F cross-section from forward events



σ_B cross-section from backward events

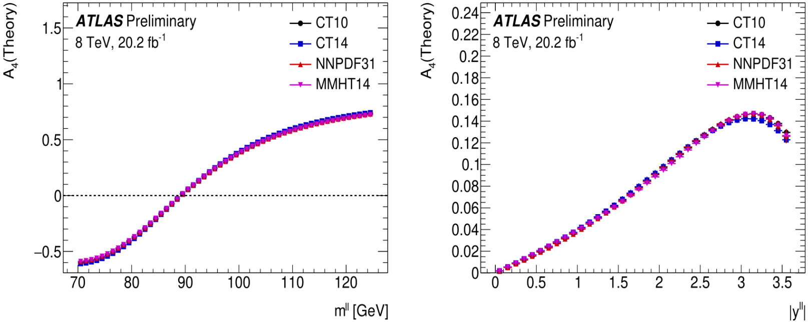


- Forward-Backward Asymmetry (AFB) is a clean observable for which many experimental and theoretical uncertainties cancel:

$$A_{FB} = 3/8 A_4 = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}$$

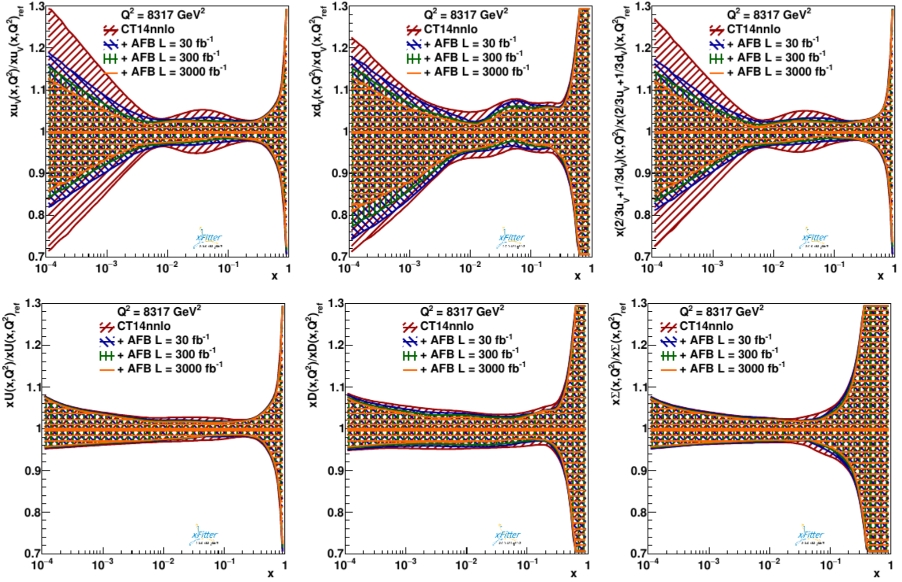
$$= \frac{d^2\sigma/dM(ll)dy(ll)[cos\theta^* > 0] - d^2\sigma/dM(ll)dy(ll)[cos\theta^* < 0]}{d^2\sigma/dM(ll)dy(ll)[cos\theta^* > 0] + d^2\sigma/dM(ll)dy(ll)[cos\theta^* < 0]}$$

- . . . but AFB is still sensitive to the PDFs [ATLAS-CONF-2018-037]:



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

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)
- **We explore AFB potential to constrain Z boson couplings at future HL-LHC**
- DY cross sections (and hence AFB) depend on the Z boson coupling to fermions:

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

- In the SM:

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

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

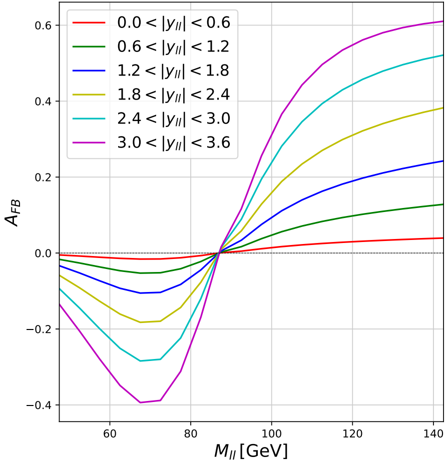
$$\mathcal{L} = \mathcal{L}^{(\mathrm{SM})} + \frac{1}{\Lambda^2}\sum_{j=1}^{N_6} C_j^{(6)}\,\mathcal{O}_j^{(6)}$$

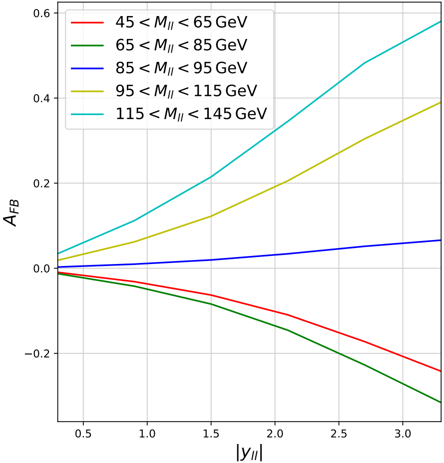
- In the dilepton mass region not too far from the Z-boson peak the whole effect of the $D = 6$ SMEFT Lagrangian is a modification of the vector boson couplings to fermions
- Couplings to leptons g_V^{Ze}, g_A^{Ze} are well constrained by LEP data
- 4-fermion operators are not included: $< 1\%$ at $M(ll)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

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

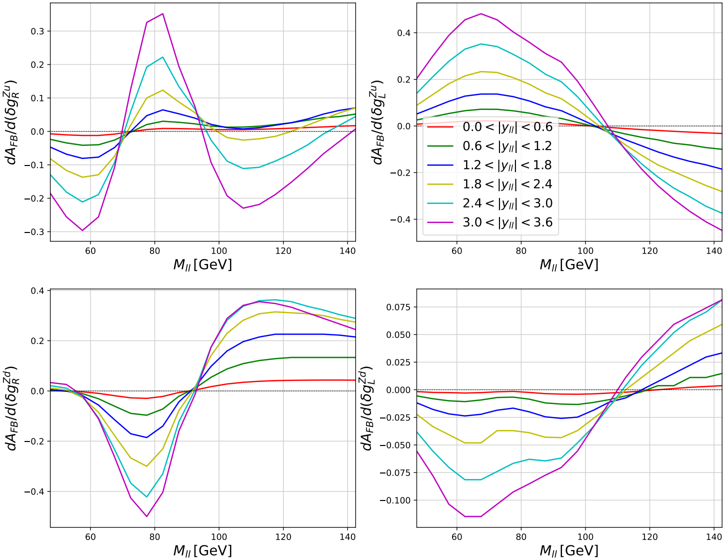
DY AFB as function of $M(ll)$ and $y(ll)$ [LO]

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



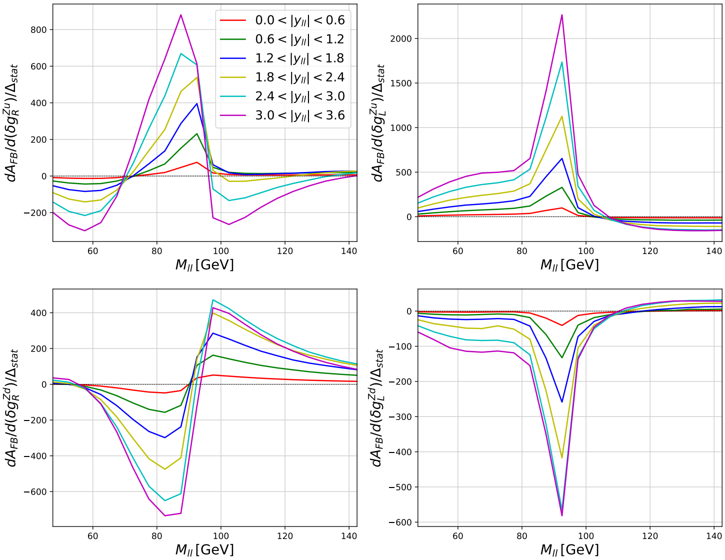


DY AFB derivatives w.r.t the couplings as a function of $M(ll)$ [LO]



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

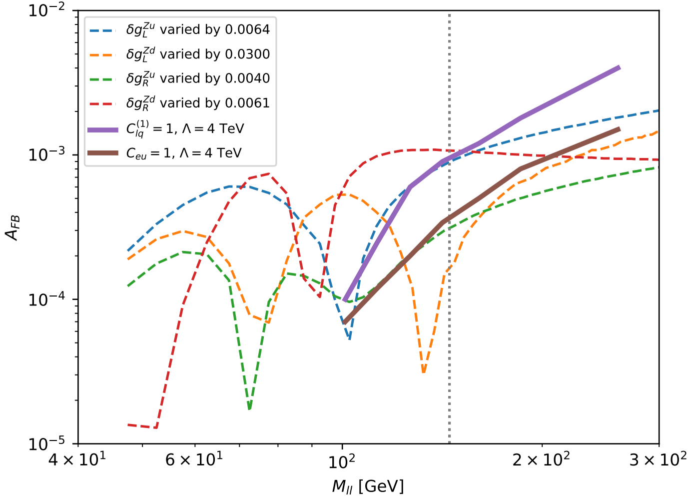
DY AFB derivatives w.r.t the couplings divided by stat. unc. (HL-LHC)



- Statistical uncertainties increase outside of the Z peak

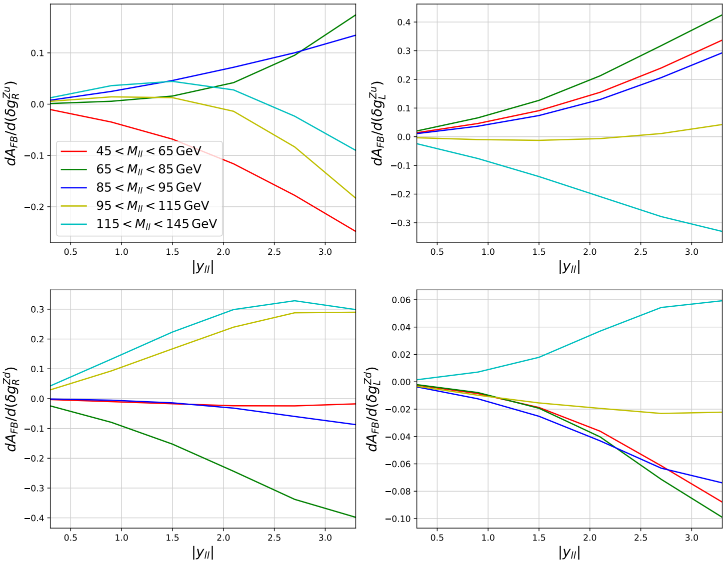
→ we do not go to very low or high $M(ll)$ [also minimise impact of 4-fermion operators]

Impact of four-fermion operators: removed by $M(ll) < 150$ GeV



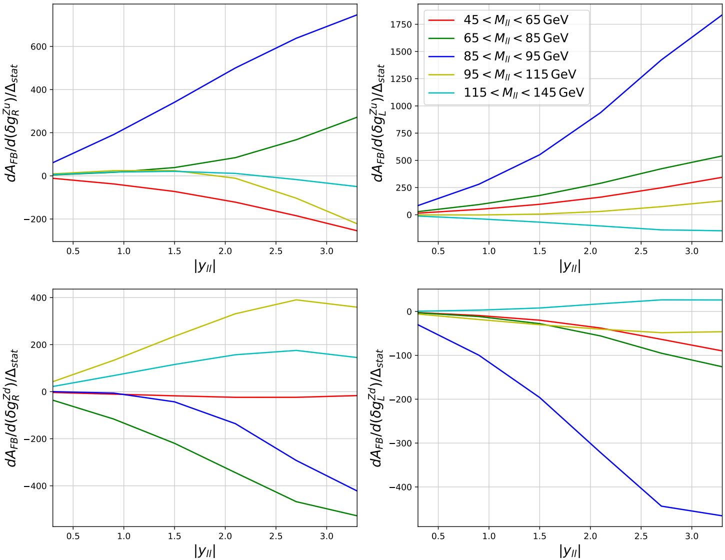
R. Boughezal, Y. Huang and F. Petriello, "Impact of high invariant-mass Drell-Yan forward-backward asymmetry measurements on SMEFT fits", Phys. Rev. D 108 (2023) 076008 [arXiv:2303.08257].

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: limited by detector acceptance

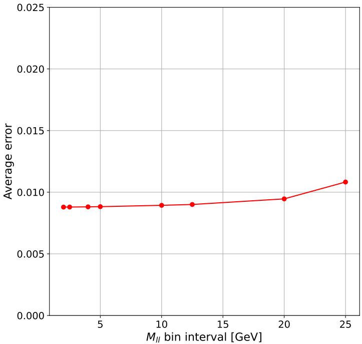
DY AFB derivatives w.r.t the couplings divided by stat. unc. (HL-LHC)

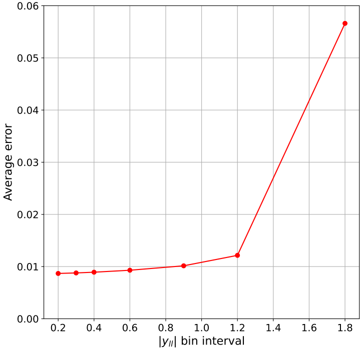


- Statistical uncertainties increase outside of the Z peak

→ we do not go to very low or high $M(ll)$ [also minimise impact of 4-fermion operators]

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**

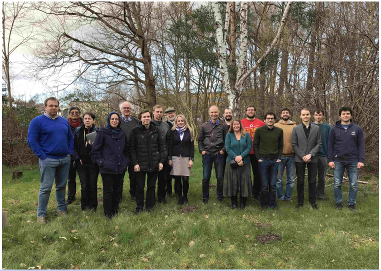
Welcome to xFitter (former HERAFitter)

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 processes. The main process is 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, pp-bar collisions, etc.) provide additional constraining powers for flavor separation. In particular, the precise measurements obtained from or yet to come from the LHC will continue to improve the knowledge of the PDF.

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

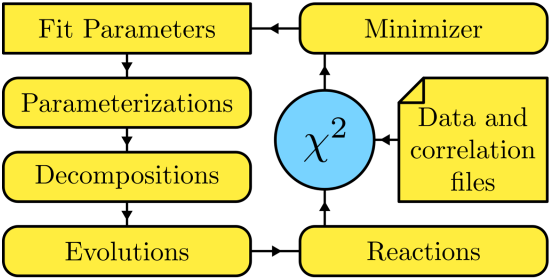
Downloads of the xFitter software package

(!) **xFitter-2.0.1 release** is publicly available.
All the xFitter releases can be accessed HERE.
Description: arXiv:1410.4412



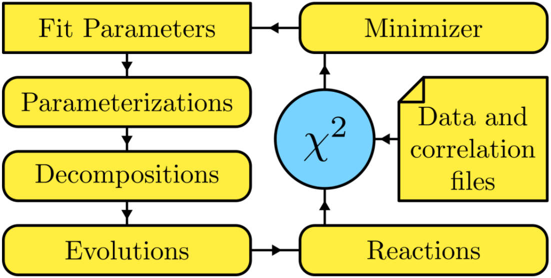
Overview of xFitter [gitlab.com/fitters/xfitter]

I. Novikov



- **xFitter (HERAfitter before 2015) is a unique open-source QCD fit framework:**
  - extract PDFs and theory parameters
  - assess impact of new experimental (pseudo-)data and check consistency
  - test different theoretical assumptions
  - . . . any exercise which involves data vs. theory
- It is widely used by LHC experiments and theorists ($>$ 100 publications)

Flexibility of xFitter (1)

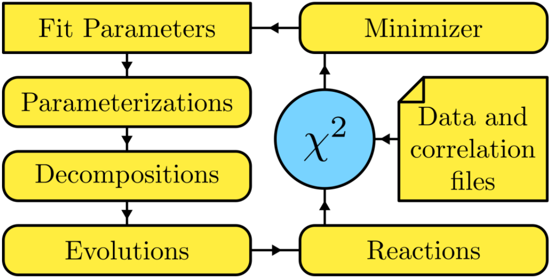


Why is xFitter UNIQUE and so VERSATILE/FLEXIBLE/ADAPTABLE?
Because it is fully modular.

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, **APFEL++, HOPPET (new!)** for PDF evolution up to **approximte N^{3}LO** (TMD PDF evolution is also available in (inofficial) branch)
- hard scattering ("reaction"): very many processes are available

Flexibility of xFitter (2)

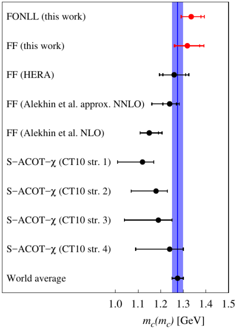


- hard scattering (“reaction”): very many processes are available
  - various heavy-quark schemes for *ep* DIS
  - some “simple” calculations, e.g. LO DY (used in this work)
  - interfaced external packages, e.g. HATHOR (NNLO total heavy-quark and single *t* hadroproduction) and HVQMNR (NLO heavy-quark 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”
- Flexible χ^2 implementation (tretment of experimental uncertainties)
- χ^2 minimisation: MINUIT, CERES
- **. . . and one can change/mix all these ingredients freely!**

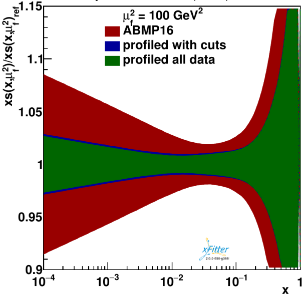
Selected studies by the xFitter team

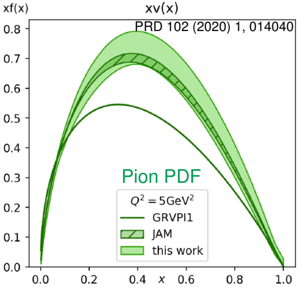
- “A determination of $m_c(m_c)$ from HERA data using a matched heavy flavor scheme” [JHEP 1608 (2016) 050]
- “Probing the strange content of the proton with charm production in charged current at LHeC” [Eur. Phys. J. C 79, 864 (2019)]
- “PDF Profiling Using the Forward-Backward Asymmetry in Neutral 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]

JHEP 1608 (2016) 050

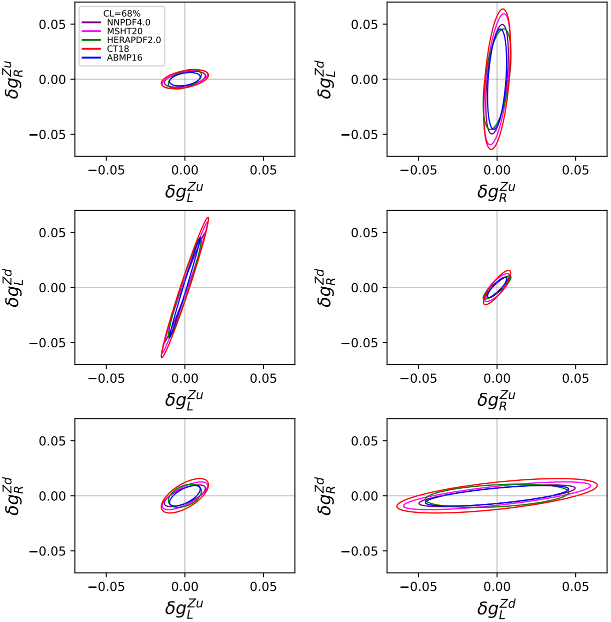


Eur. Phys. J. C 79, 864 (2019)

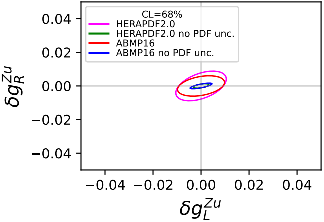




Results: fitted couplings using different PDF sets

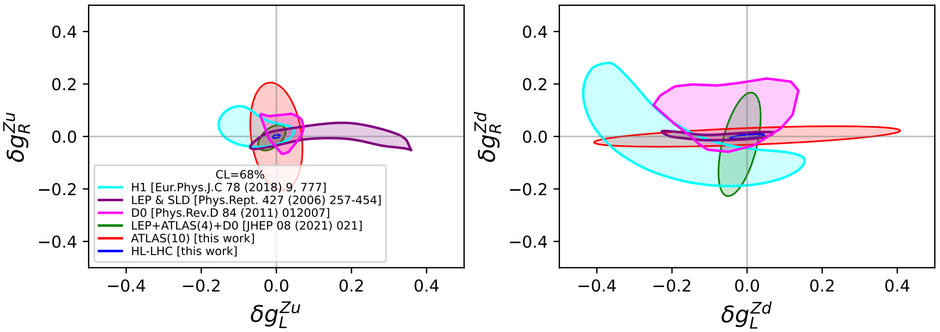


- Similar sensitivity is achieved when using different modern PDF sets
- A large fraction of the uncertainties are from PDFs



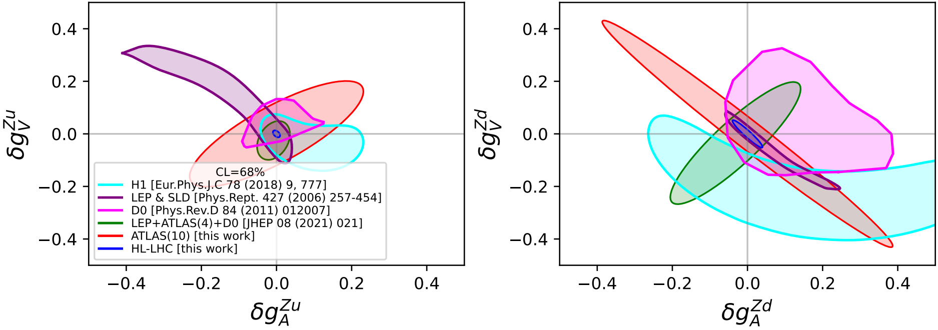
→ Ideally, a future extraction should be done in a simultaneous PDF fit

Results: comparison with existing extractions



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

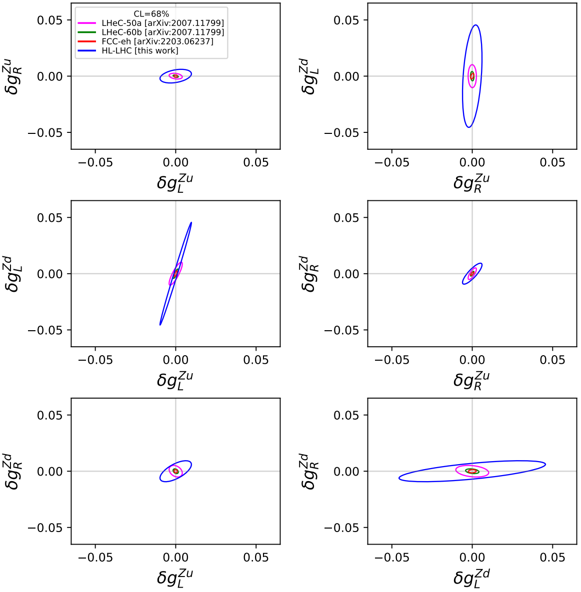
Results for axial and vector couplings

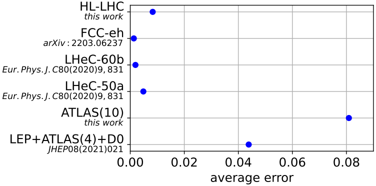


- All results were obtained also for axial and vector couplings:

$$g_V^{Zu} = g_R^{Zu} + g_L^{Zu}\,, \quad g_A^{Zu} = g_R^{Zu} - g_L^{Zu}\,,$$
$$g_V^{Zd} = g_R^{Zd} + g_L^{Zd}\,, \quad g_A^{Zd} = g_R^{Zd} - g_L^{Zd}\,.$$

Results: comparison with other future experiments



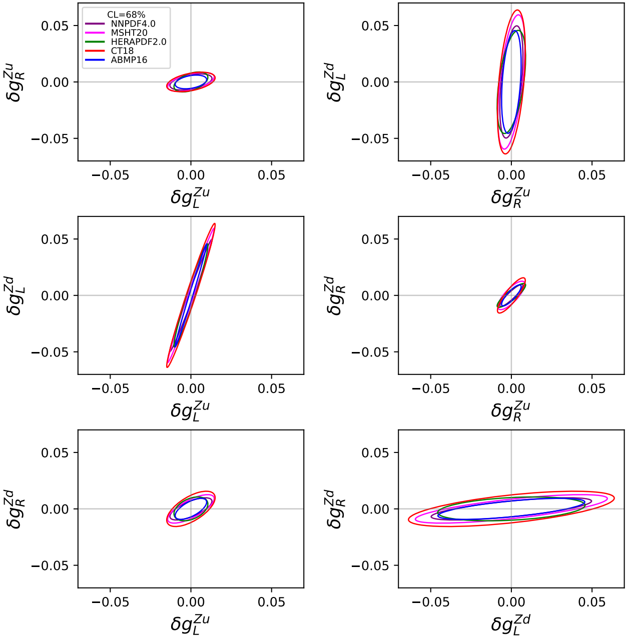


- HL-LHC significantly improves LHC limits, and approaches the precision of LHeC and FCC-eh

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

BACKUP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HERAPDF2.0
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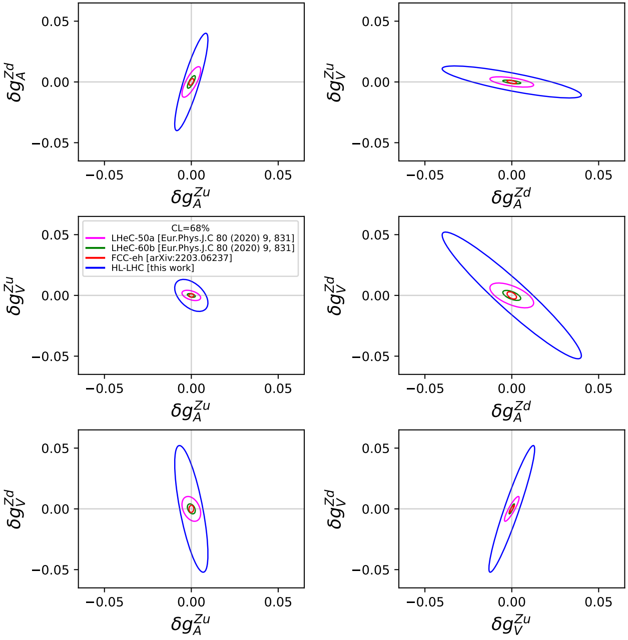
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LHeC-50a [Eur.Phys.J.C 80 (2020) 9, 831]
LHeC-60b [Eur.Phys.J.C 80 (2020) 9, 831]
FCC-eh [arXiv:2203.06237]
HL-LHC [this work]
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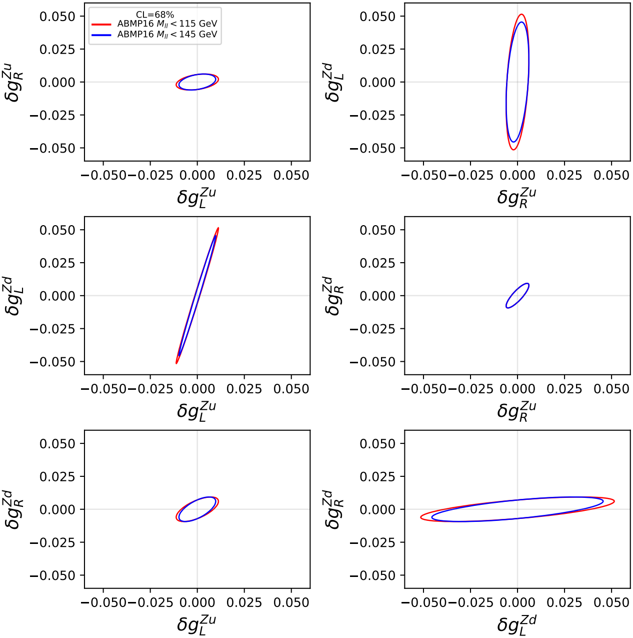
CL=68%
ABMP16 $M_{ll} < 115$ GeV
ABMP16 $M_{ll} < 145$ GeV
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