Funded by JSA travel fund award

Possible new insights into strong PV in the nucleon's structure from DIS measurements

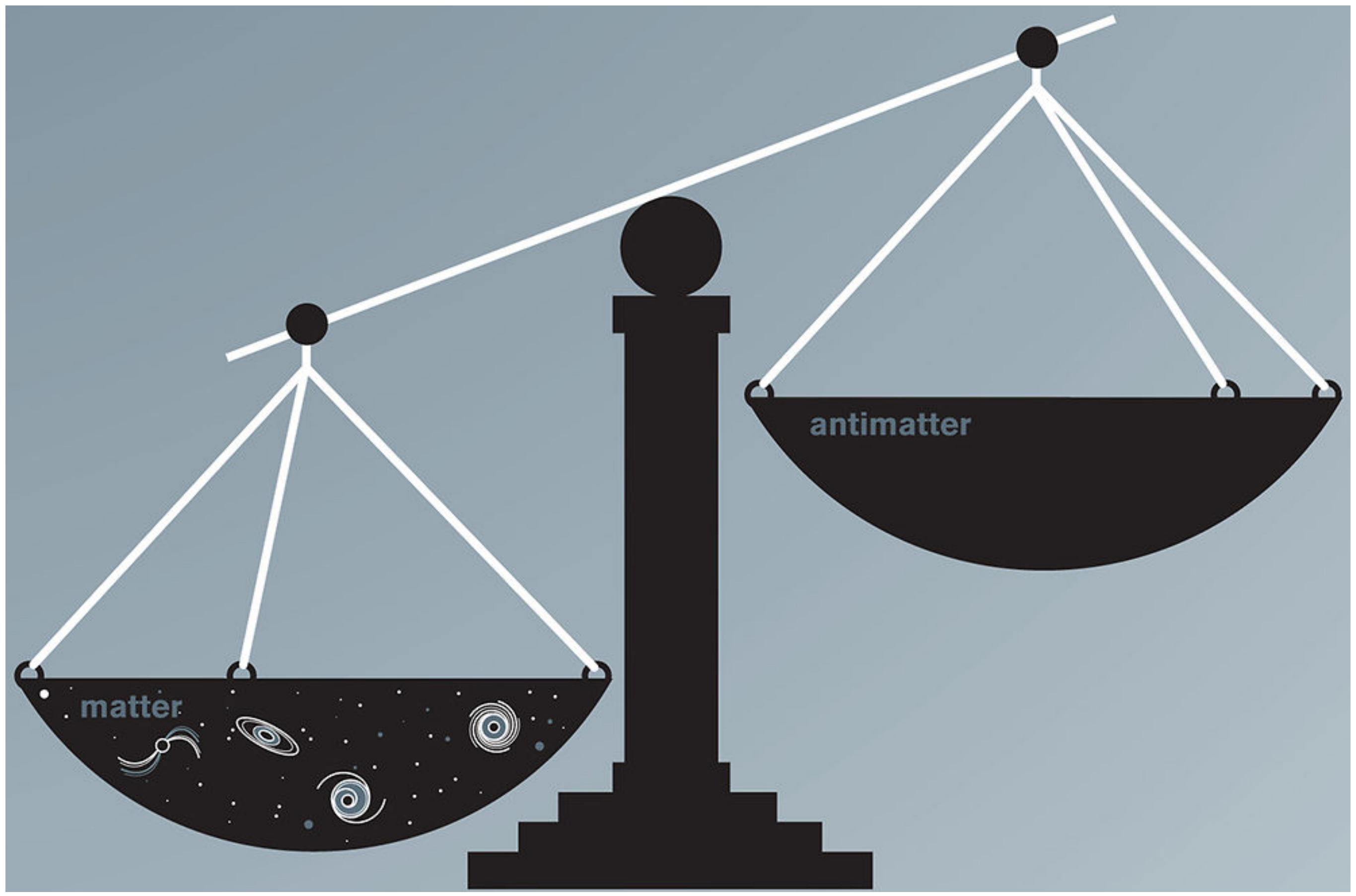
Matteo Cerutti

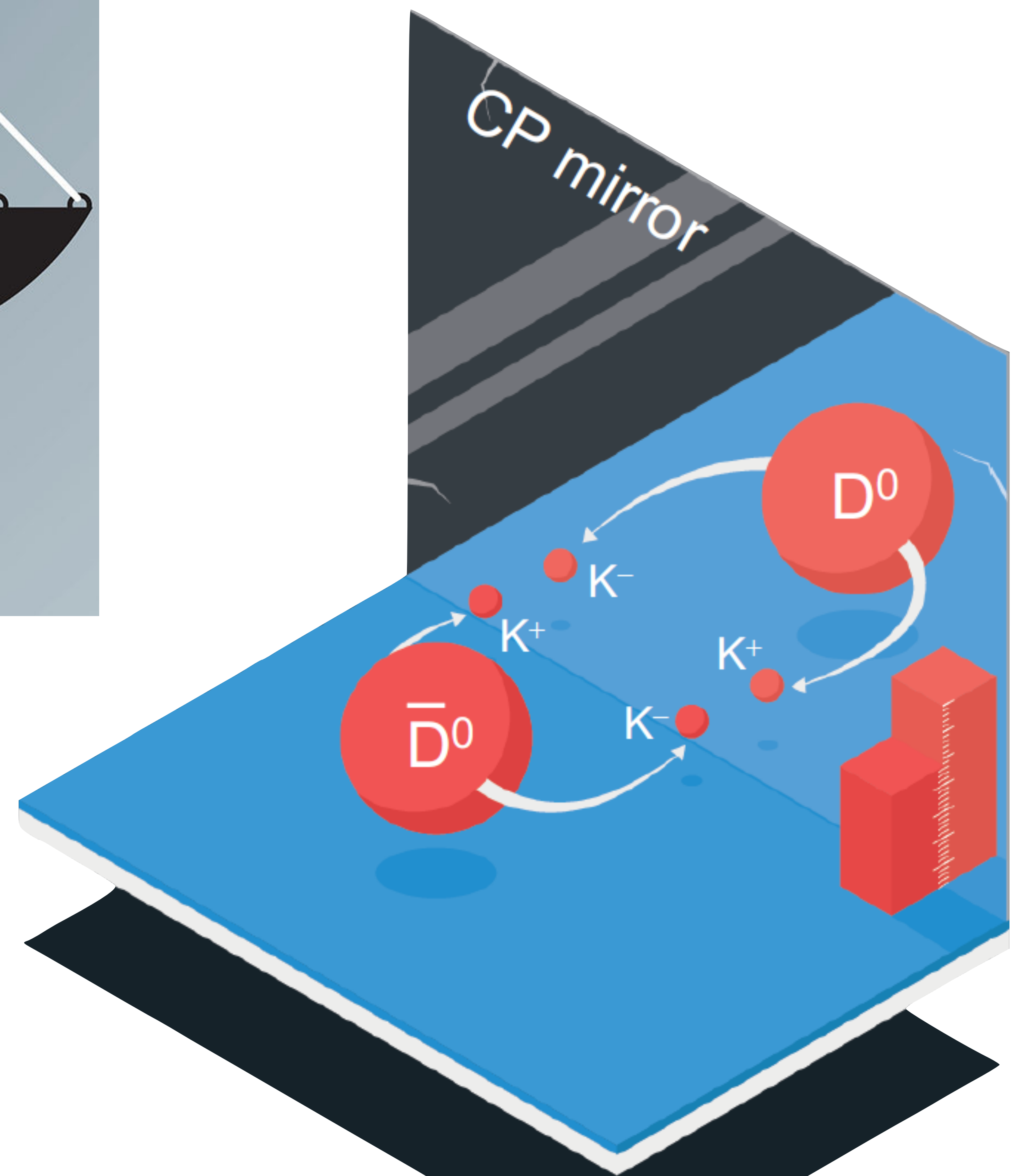
Electroweak and Beyond the Standard Model Physics at the EIC

Bacchetta, Cerutti, Radici, Zheng, PLB 849 (2024), arXiv: 2306.04704

INT Seattle, February 12, 2024

Motivations





Investigation of the
"Strong CP problem"

Motivations

EW sector

CP violation is included

Motivations

<u>EW sector</u>

Weak CP

CP violation is included

Motivations

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Weak CP

too small…

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Strong CP

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QCD sector

$$\mathcal{L}'_{\rm QCD} = \mathcal{L}_{\rm QCD} + \mathcal{L}^{\rm CP}$$

Strong CP

Motivations

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Weak CP

too small…

<u>QCD sector</u>

$$\mathcal{L}'_{\mathrm{QCD}} = \mathcal{L}_{\mathrm{QCD}} + \mathcal{L}^{\mathrm{CP}}$$

Strong CP

θ-term

SMEFT operators

Motivations

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Weak CP

CP violation is included

too small…

QCD sector

Strong CP

$$\mathcal{L}'_{\rm QCD} = \mathcal{L}_{\rm QCD} + \mathcal{L}^{\rm CP}$$

θ-term

SMEFT operators

↓

Nucleon electric dipole moment

Motivations

<u>EW sector</u>

CP violation is included

Weak CP

too small…

<u>QCD sector</u>

$$\mathcal{L}'_{\mathrm{QCD}} = \mathcal{L}_{\mathrm{QCD}} + \mathcal{L}^{\mathrm{CP}}$$

Strong CP

θ-term

SMEFT operators

↓

Nucleon electric dipole moment

never measured…

Motivations

P-symmetry

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QCD sector

QCD Lagrangian is assumed to be invariant under parity transformations

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Are there any effects of QCD P-violation on the internal structure of nucleons?

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Terms from EW sector

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Weak P-violation

✔

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Terms from QCD sector

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Terms from EW sector

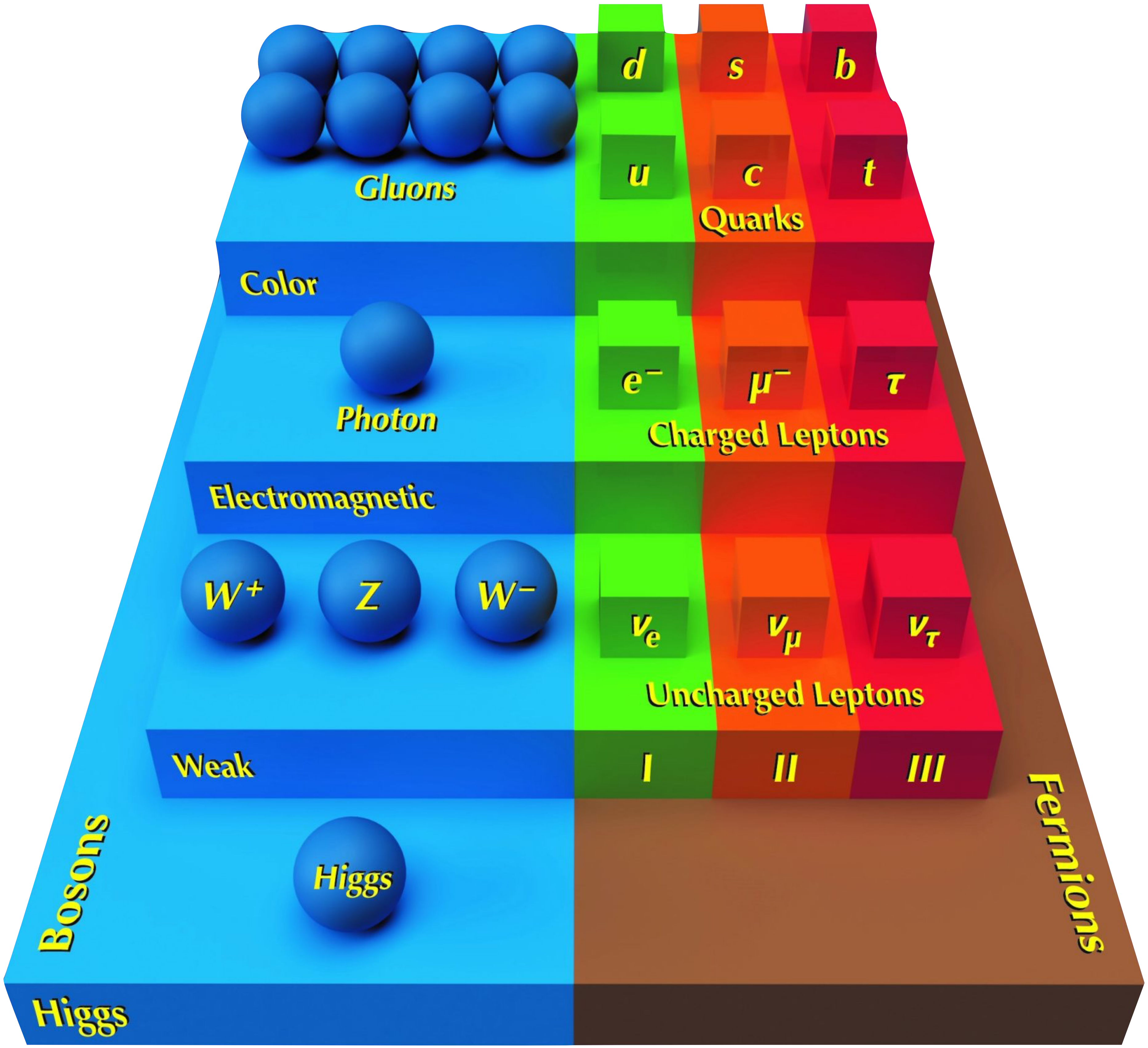
Weak P-violation

✔

Terms from QCD sector

Strong P-violation

✘


Gluons
Color
d
s
b
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c
t
Quarks
Photon
e⁻
μ⁻
τ
Charged Leptons
Electromagnetic
W⁺
Z
W⁻
νe
νμ
ντ
Uncharged Leptons
Weak
I
II
III
Higgs
Bosons
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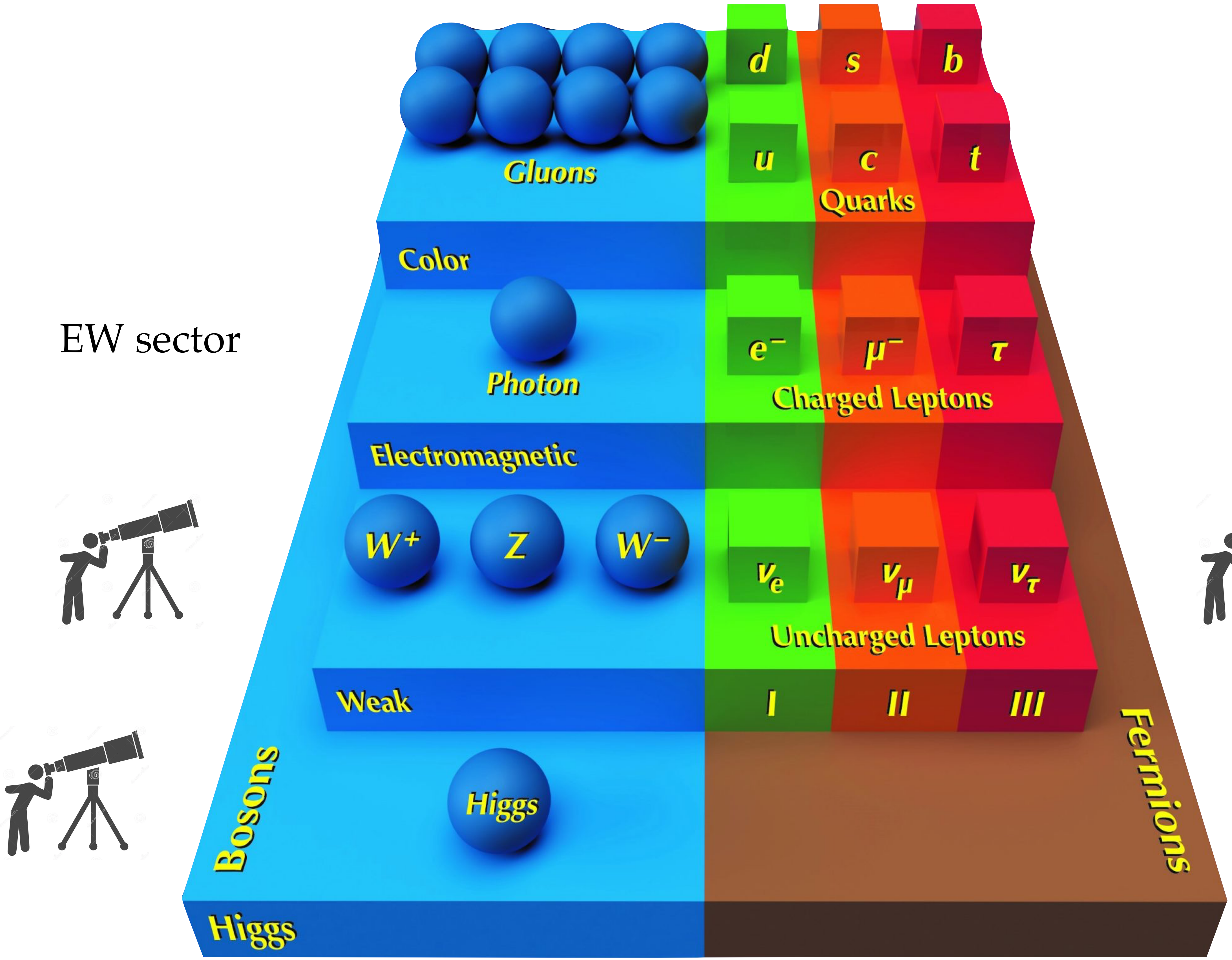
Higgs

EW sector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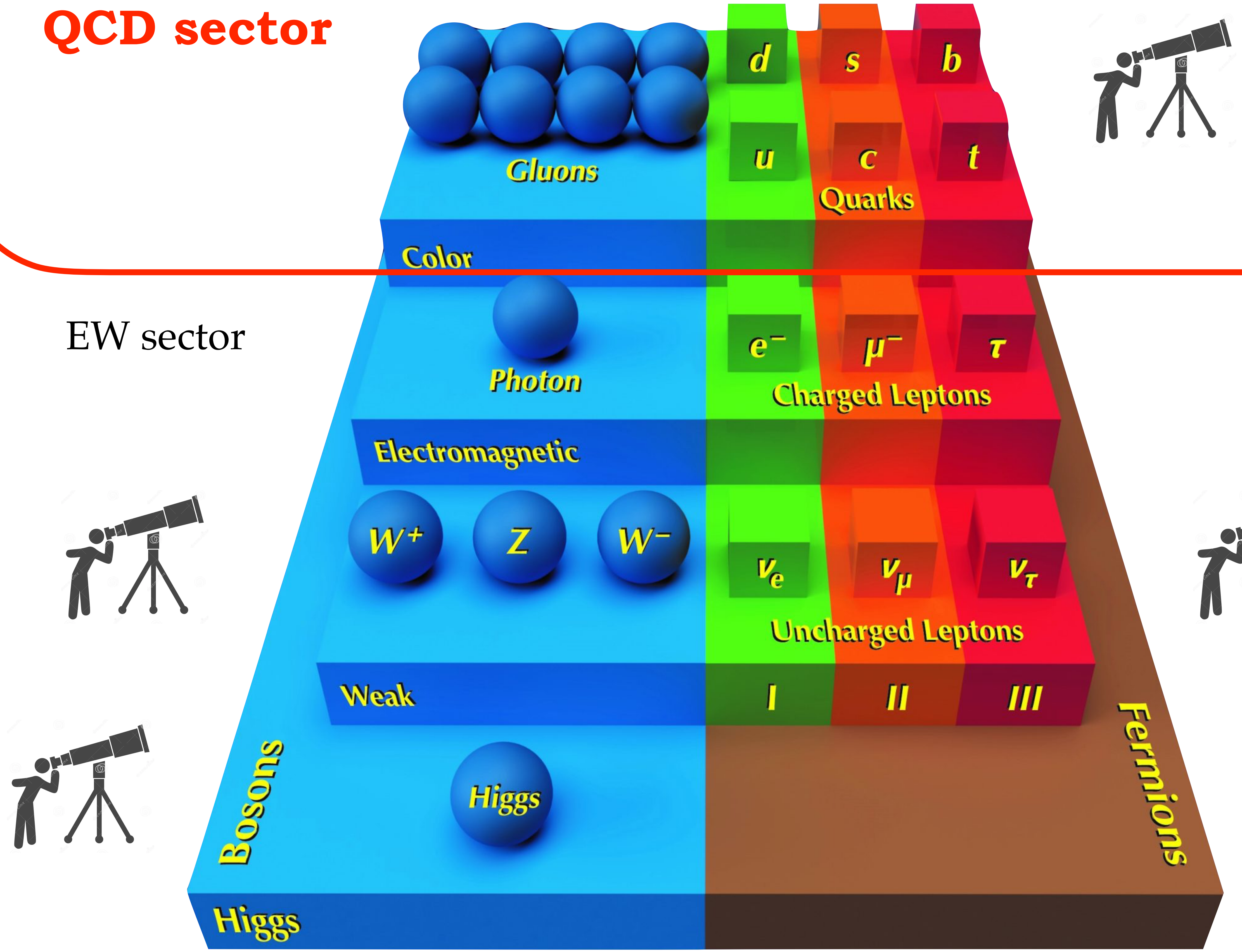
QCD sector

EW sector

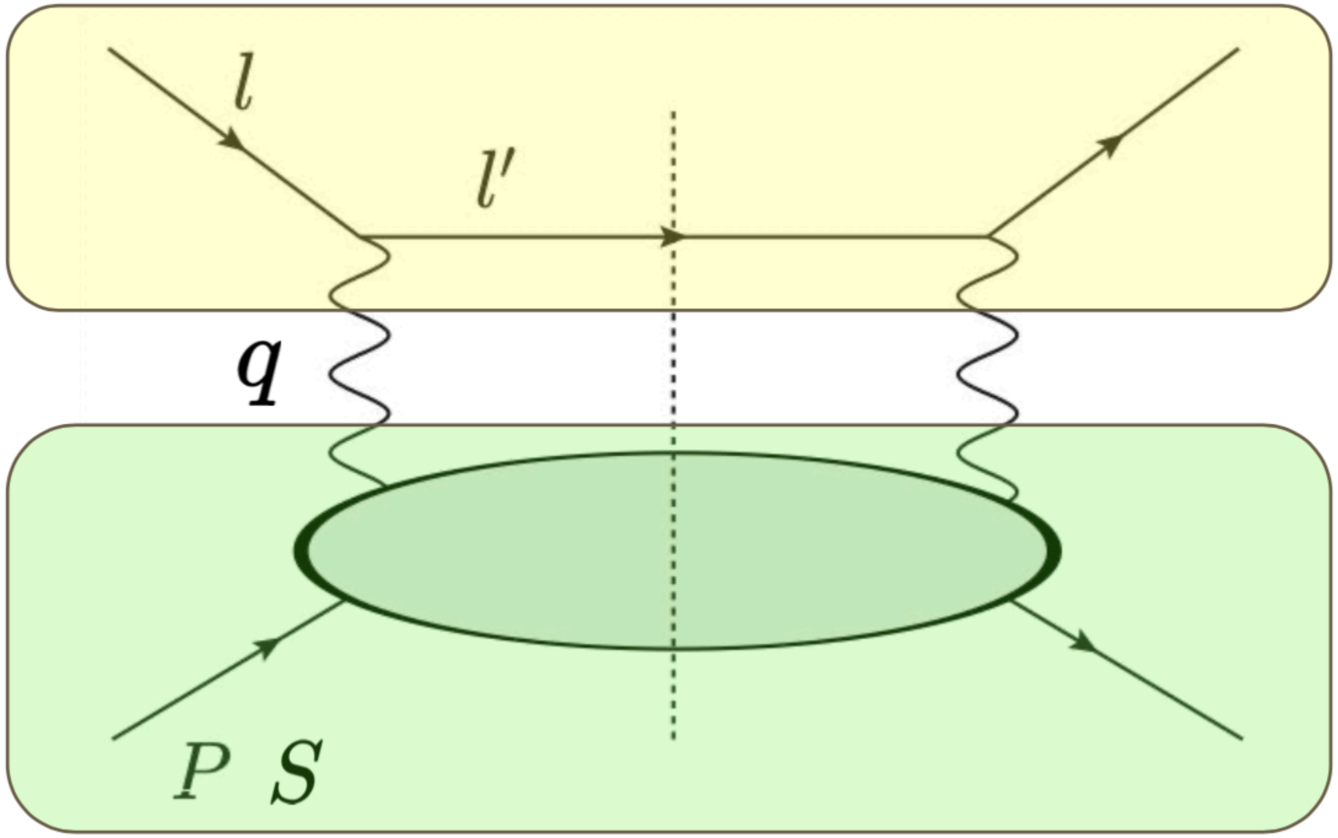


Which implications could the presence of strong P-violation cause to inclusive DIS?

DIS Cross Section

$$\frac{d^3\sigma}{dx_B dy d\phi_S} = \frac{\alpha^2 y}{2Q^4} L_{\mu\nu}(l, l', \lambda_e) \, 2MW^{\mu\nu}(q, P, S)$$

Leptonic tensor - QED
(completely
calculable)



Hadronic tensor - QCD
(NOT completely
calculable)

J. Collins, "Foundation of Perturbative QCD"

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In general

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$$\eta^\gamma = 1 \qquad \eta^{\gamma Z} = \left(\frac{G_F M_Z^2}{2\sqrt{2}\pi\alpha}\right)\frac{Q^2}{Q^2 + M_Z^2} \qquad \eta^Z = (\eta^{\gamma Z})^2$$

Hadronic Tensor (unpolarized)

$$2MW_{\mu\nu}(q,P) = \sum_X \int \frac{d^3P_X}{2E_X}\delta^4(P+q-P_X)\langle P|J_\mu^\dagger(0)|P_X\rangle\langle P_X|J_\nu(0)|P\rangle$$

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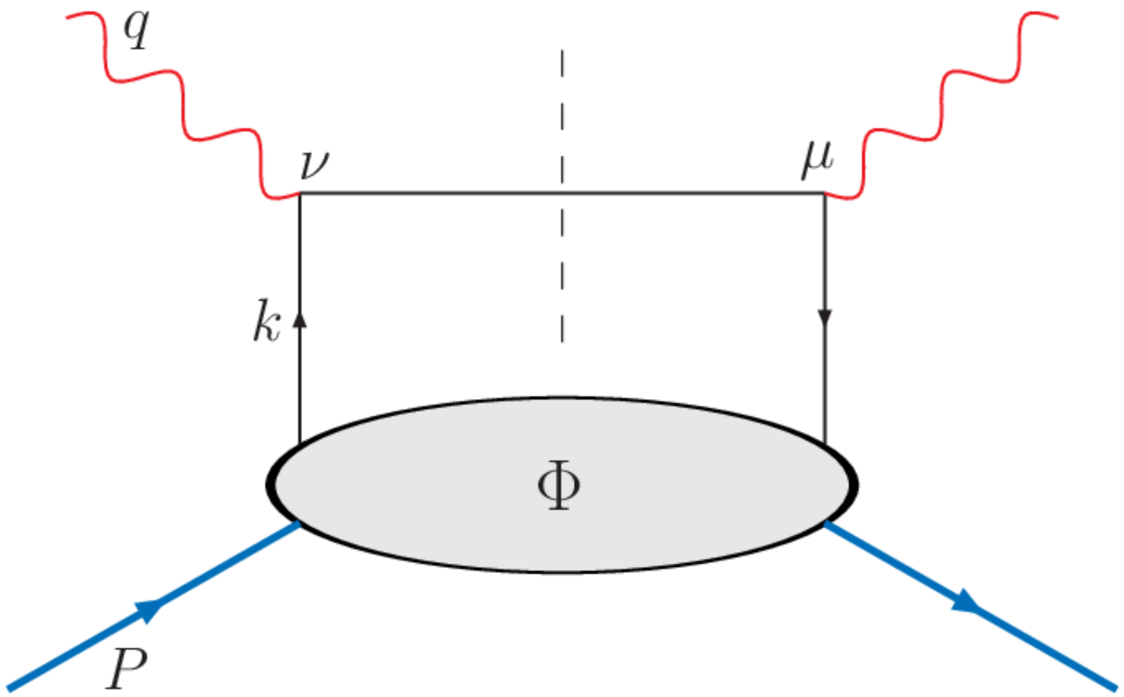

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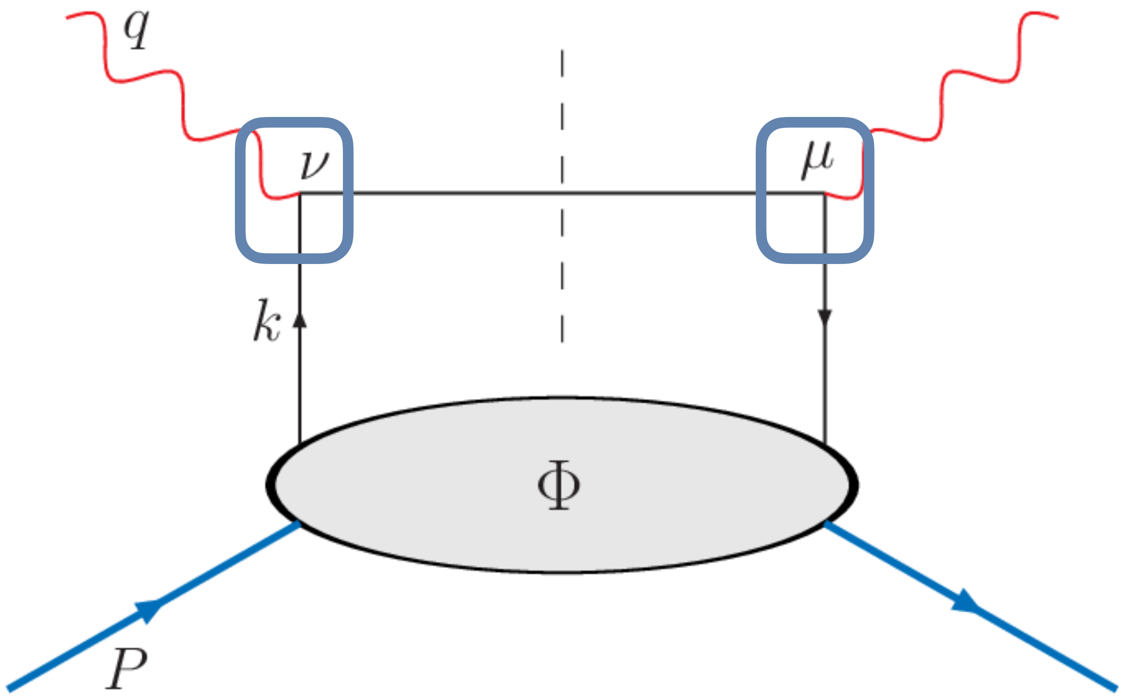

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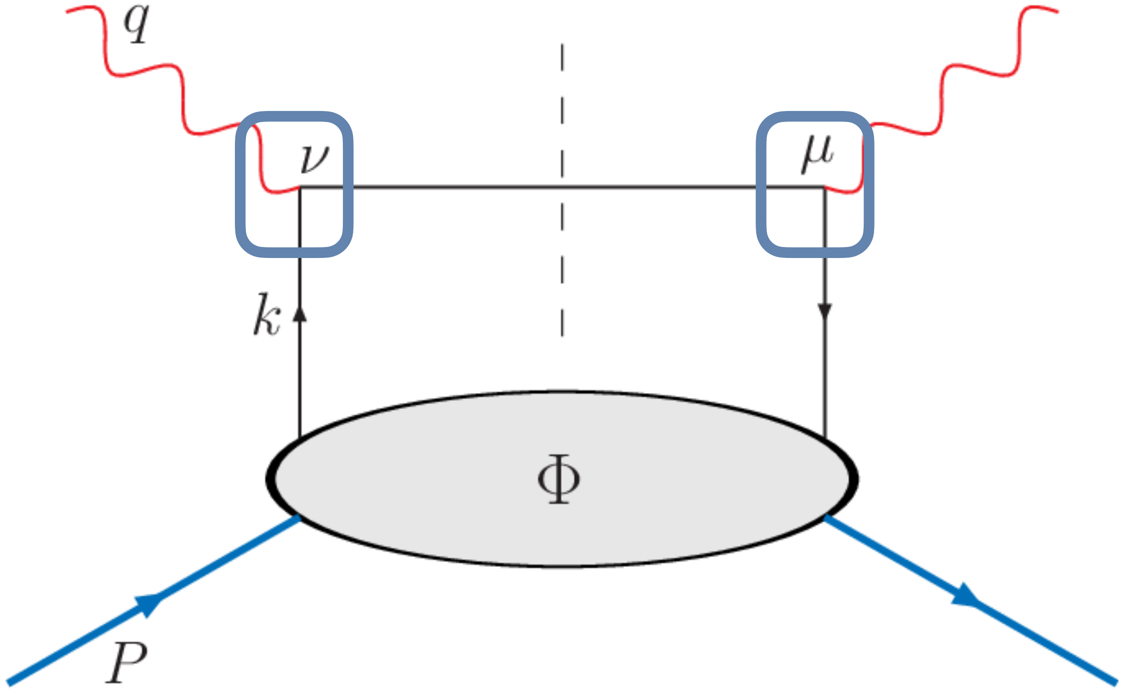

Vertices of the interactions

EW P-odd structures already present in the hadronic tensor!

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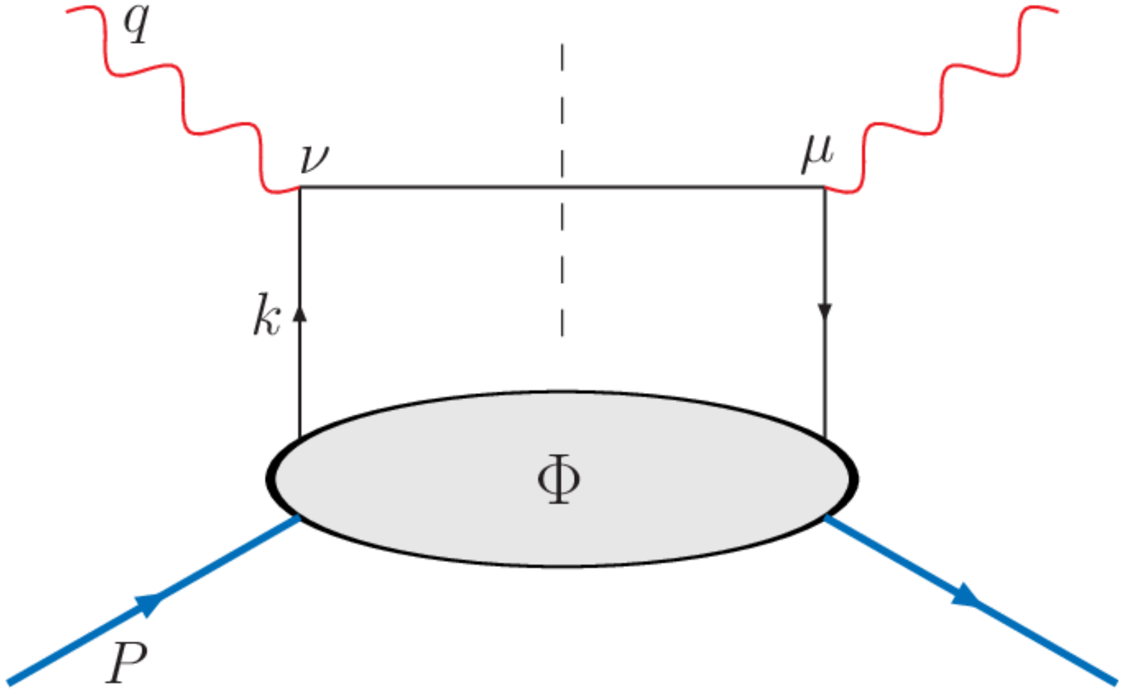

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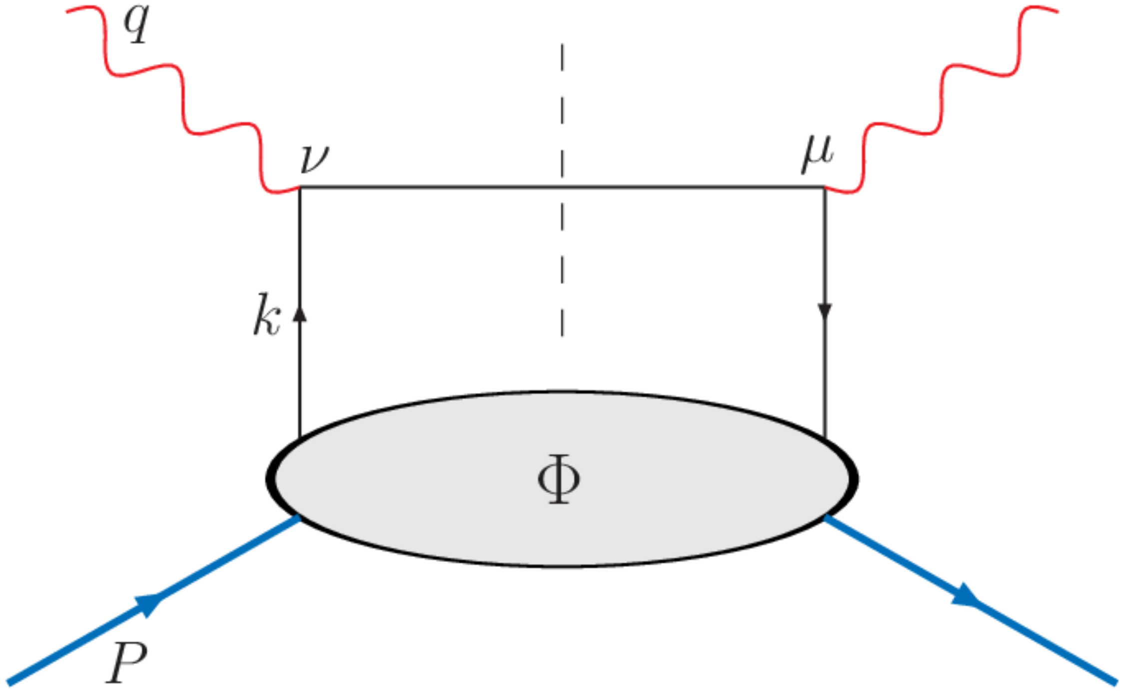

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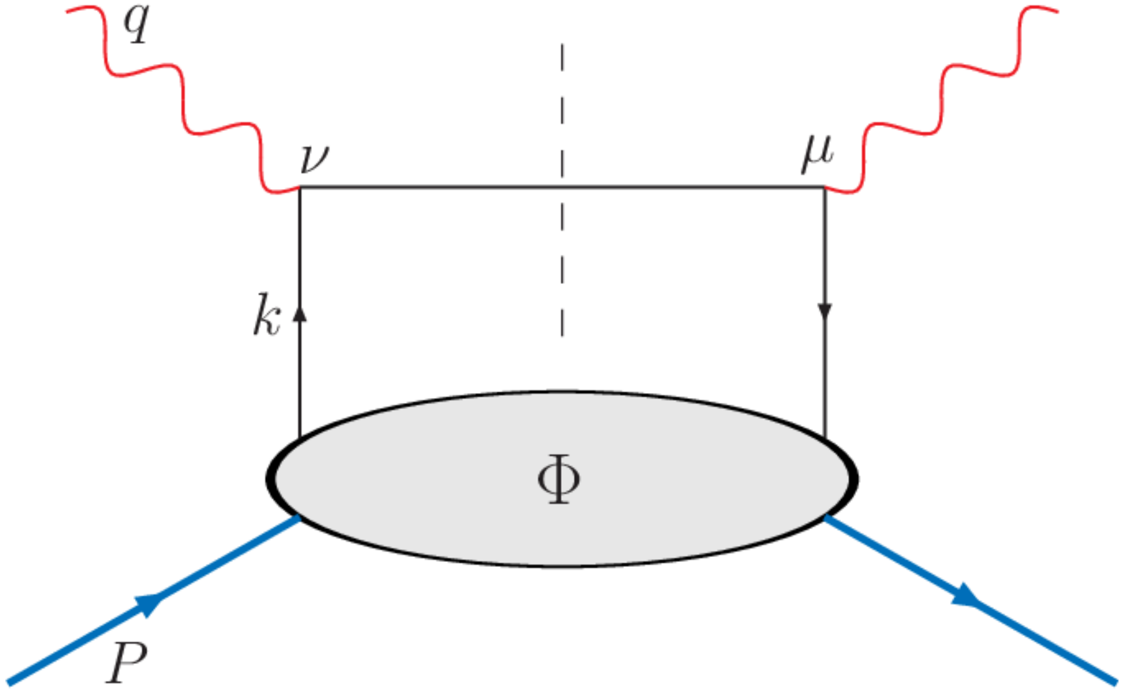

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Decomposition in partonic densities

J. Collins, "Foundation of Perturbative QCD"
M. Anselmino et al., Z. Phys. C 64, 267 (1997)

Partonic Correlator (unpolarized)

Integrated correlator

$$\Phi_{ij}(x_B) = \int \frac{d\xi^-}{2\pi} e^{ik\cdot\xi} \langle P|\bar{\psi}_j(0)\psi_i(\xi)|P\rangle_{\xi^+=\xi_T=0}$$

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Lorenz scalar

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Hermiticity

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Parity invariance

Lorenz scalar

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Hermiticity

$$\mathbb{1},\ \gamma^\mu,\ \sigma^{\mu\nu}$$

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Hermiticity	Hermiticity
Parity invariance	~~Parity invariance~~

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Leading twist contributions

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$$\Phi_{\rm PE}(x) \simeq \frac{1}{2} f_1(x)\gamma^-$$

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Lorenz scalar

Hermiticity

Parity invariance

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$$\Phi_{\mathrm{PE}}(x) \simeq \frac{1}{2} f_1(x)\gamma^-$$

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Partonic Correlator (unpolarized)

Integrated correlator

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Lorenz scalar

Hermiticity

Parity invariance

$\mathbb{1},\ \gamma^\mu,\ \sigma^{\mu\nu}$

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Leading twist contributions

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$$\Phi(x) = \Phi_{\mathrm{PE}}(x) + \Phi_{\mathrm{PV}}(x)$$

Kang, Kharzeev, PRL 106 (2011)
Yang, Int. J. Mod. Phys. A 34 (2019)

5— DIS in collinear framework

Quark Polarization

Nucleon Pol.

	U	L	T
U	$f_1(x)$		
L		$g_1(x)$	
T			$h_1(x)$

5— DIS in collinear framework

PDFs occurring in DIS processes

Quark Polarization

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PDFs occurring in DIS processes

Electric charge

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5 — DIS in collinear framework

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Axial charge

5 — DIS in collinear framework

PDFs occurring in DIS processes **with P violation**

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Anapole moment

Axial charge

Neutral-Current DIS

$$\frac{d\sigma^\pm}{dxdy} = \frac{2\pi\alpha^2}{xyQ^2}\left[\left(Y_+ + \gamma^2 y^2/2\right)\left(F_{2UU} + \lambda F^{\pm}_{2LU}\right) - y^2\left(F_{L,UU} + \lambda F^{\pm}_{L,LU}\right) - \frac{Y_-}{\sqrt{1+\gamma^2}}\left(xF^{\pm}_{3UU} + \lambda xF_{3LU}\right)\right]$$

$$\frac{d\sigma^\pm}{dxdy} = \frac{2\pi\alpha^2}{xyQ^2}\left[Y_+ F_2^\pm - y^2 F_L^\pm \mp Y_- xF_3^\pm\right]$$

Particle Data Group, Tanabashi, et al., PRD 98 (2018)

Focus: structure function $xF_3(x, Q^2)$

$$xF_{3LU}(x,Q^2) = xF_3^{(\gamma)} - g_V^e \eta_{\gamma Z} xF_3^{(\gamma Z)} + \left({g_V^e}^2 + {g_A^e}^2\right)\eta_Z xF_3^{(Z)}$$

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$$xF_3^{(\gamma)}(x,Q^2) = 0$$

$$xF_3^{(\gamma Z)}(x,Q^2) = \sum_q 2 e_q g_A^q x f_1^{(q-\bar{q})}$$

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$$x\Delta F_3^{(\gamma)}(x,Q^2) = -\sum_q e_q^2 x g_1^{\mathrm{PV}(q+\bar{q})}$$

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Additional contributions due to the new PV parton distribution

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MAIN INNOVATION OF PV-HYPOTESIS

$$x\Delta F_3^{(\gamma)}(x,Q^2) = -\sum_q e_q^2 x g_1^{\mathrm{PV}(q+\bar{q})}$$

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$$x\Delta F_3^{(Z)}(x,Q^2) = -\sum_q \left(g_V^{q2} + g_A^{q2}\right) x g_1^{\mathrm{PV}(q+\bar{q})}$$

Additional contributions due to the new PV parton distribution

Neutral-Current DIS

$$\frac{d\sigma^{\pm}}{dxdy} = \frac{2\pi\alpha^2}{xyQ^2}\Bigg[\left(Y_+ + \gamma^2 y^2/2\right)\left(F_{2UU} + \lambda F_{2LU}^{\pm}\right) - y^2\left(F_{L,UU} + \lambda F_{L,LU}^{\pm}\right) - \frac{Y_-}{\sqrt{1+\gamma^2}}\left(xF_{3UU}^{\pm} + \lambda x F_{3LU}\right)\Bigg]$$

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Standard DIS structure functions

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$$- \frac{Y_-}{\sqrt{1+\gamma^2}}\big(xF^{\pm}_{3UU} + \lambda xF_{3LU}\big)\Bigg]$$

Standard DIS structure functions

$$F_{2UU}(x,Q^2) = F_2^{(\gamma)} - g_V^e \eta_{\gamma Z} F_2^{(\gamma Z)} + \big({g_V^e}^2 + {g_A^e}^2\big)\eta_Z F_2^{(Z)},$$
$$F^{\pm}_{2LU}(x,Q^2) = \mp g_A^e \eta_{\gamma Z} F_2^{(\gamma Z)} \pm 2 g_V^e g_A^e \eta_Z F_2^{(Z)},$$
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Phenomenology

Experimental information

PVDIS Asymmetry

$$A_{\mathrm{PV}} \equiv \frac{d\sigma(\lambda = 1) - d\sigma(\lambda = -1)}{d\sigma(\lambda = 1) + d\sigma(\lambda = -1)}$$

PVDIS Collaboration, *Nature* 506 (2014)
D. Wang et al., Phys.Rev.C 91 (2015)

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$$= \frac{Y_+ F_{2LU} - y^2 F_{L,LU} - Y_- x F_{3LU}}{Y_+ F_{2UU} - y^2 F_{L,UU} - Y_- x F_{3UU}}$$

$Y_\pm = 1 \pm (1-y)^2$

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Contribution of g_1^{PV} in each of the structure functions due to γZ and Z channels

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Available experimental data sets

HERA dataset
(Run I + II combined)

H1 Collaboration, Eur. Phys. J. C 78 (2018)

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e^+ ***asymmetry: 136 data***

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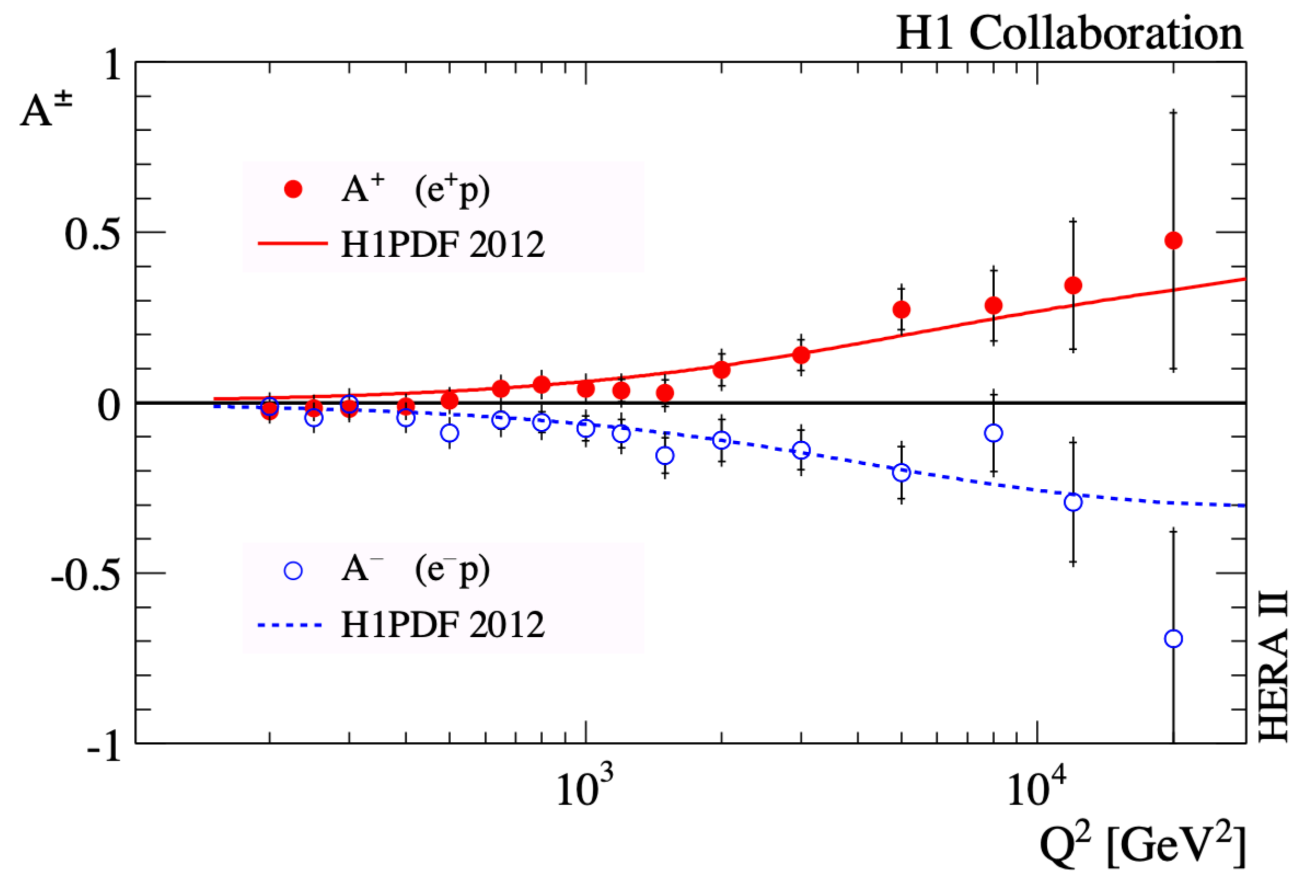

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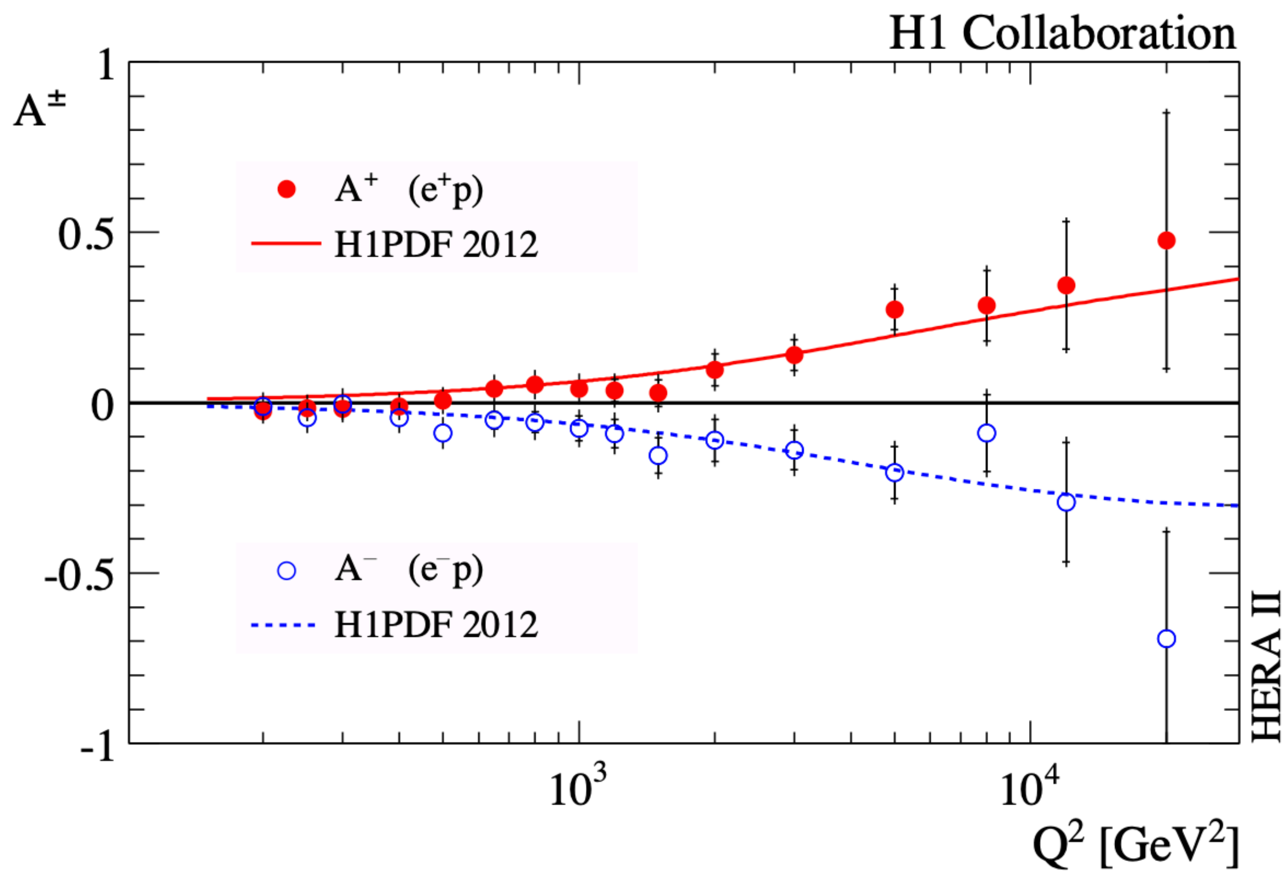

JLab6 PVDIS dataset

PVDIS Collaboration, *Nature* 506 (2014)
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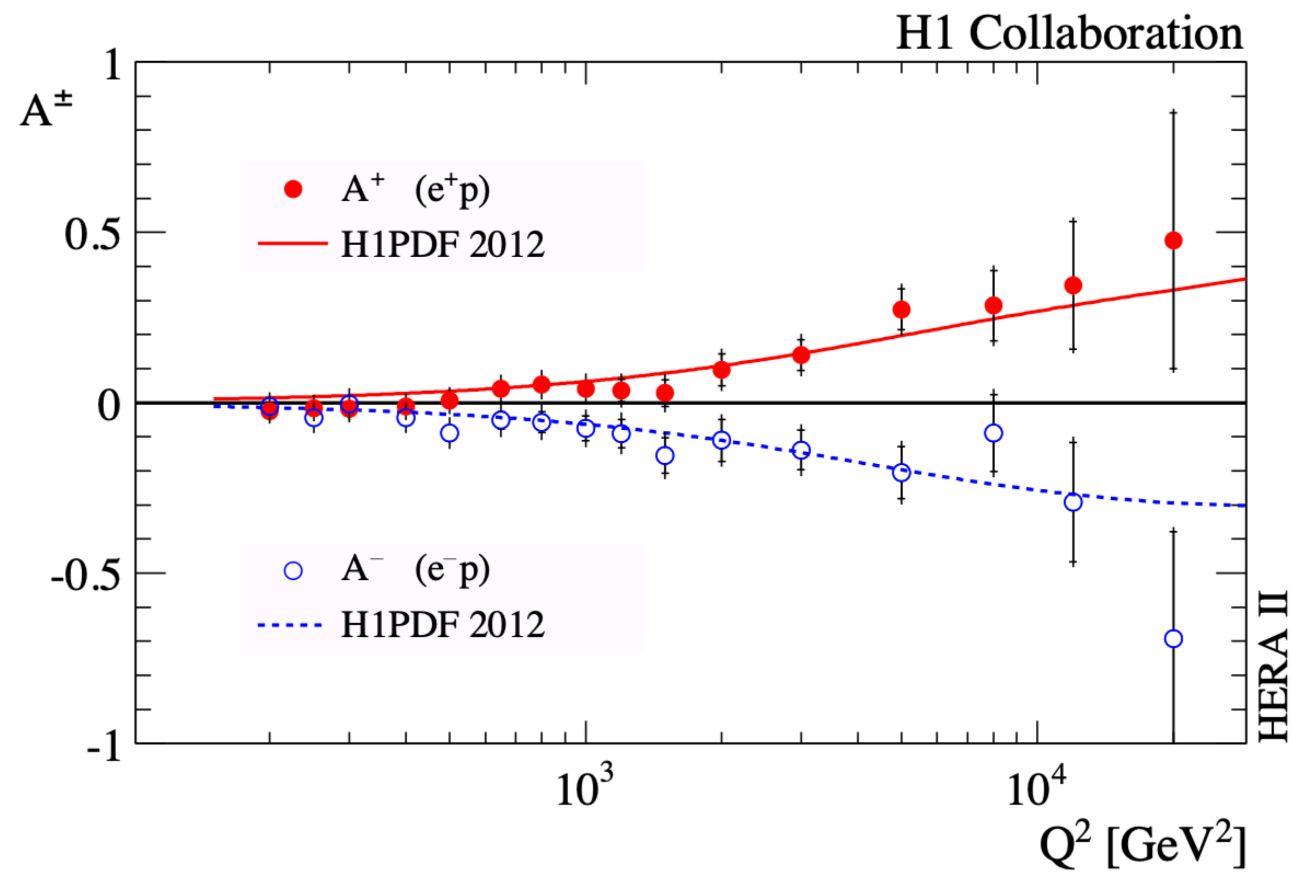

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JLab6 PVDIS dataset

PVDIS Collaboration, *Nature* 506 (2014)
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e^- asymmetry: 2 data

Available experimental data sets

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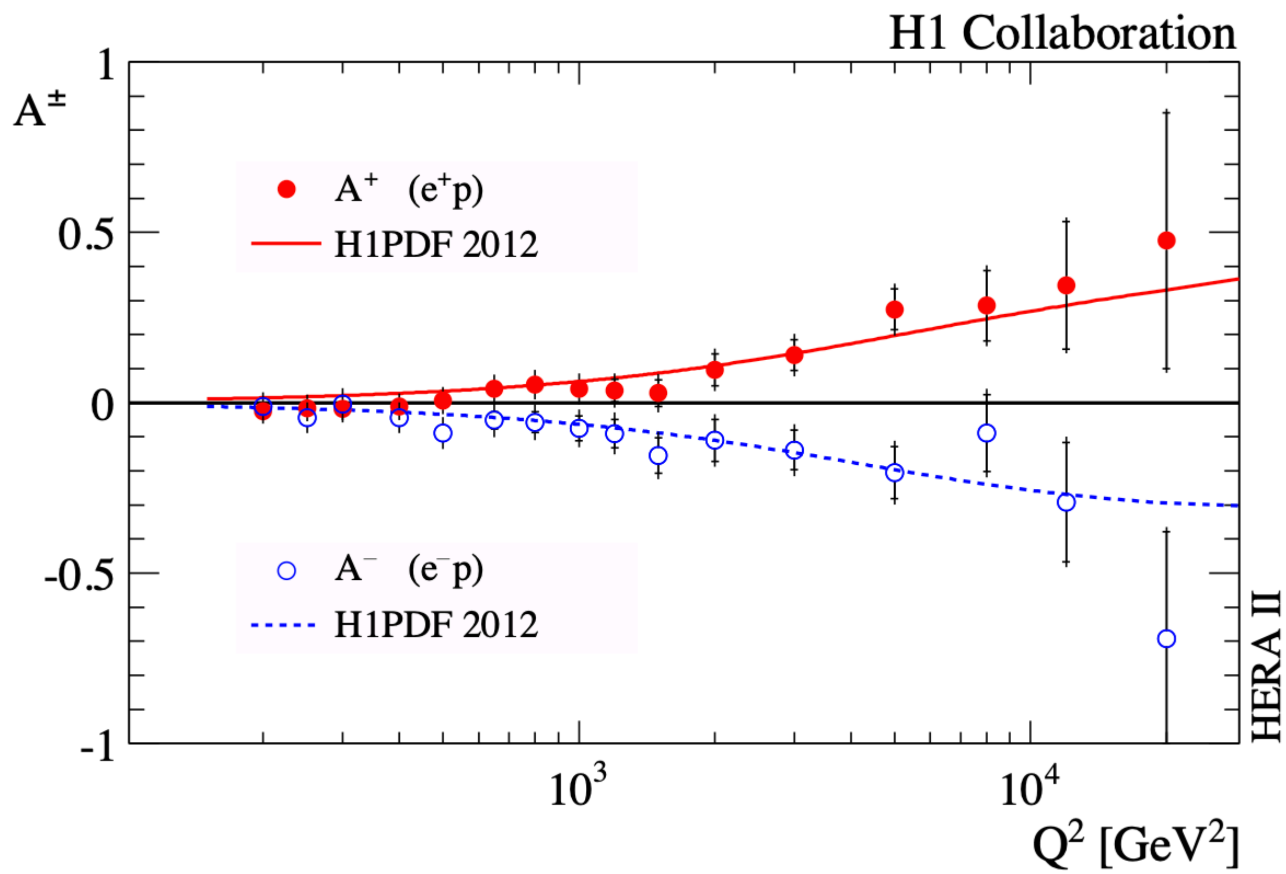

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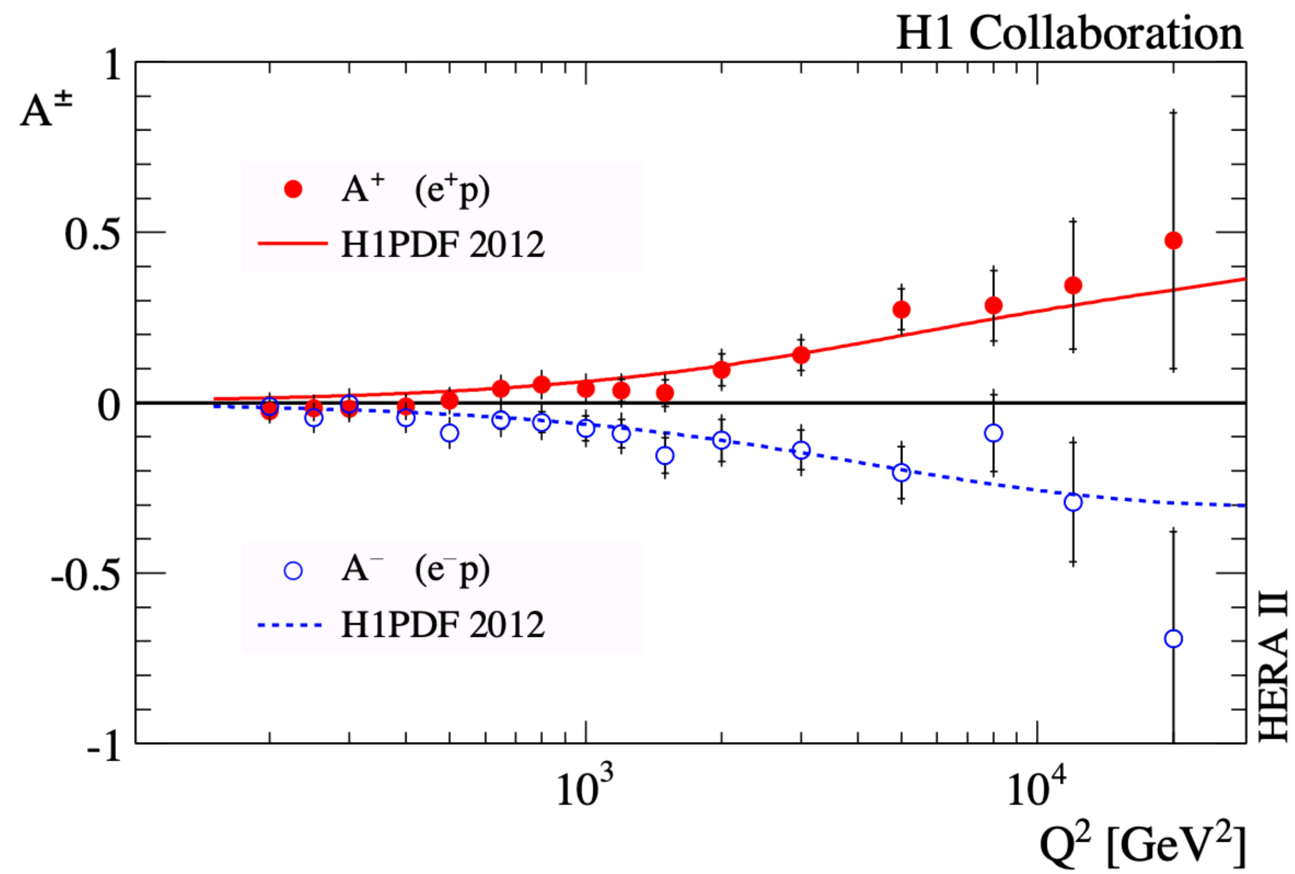

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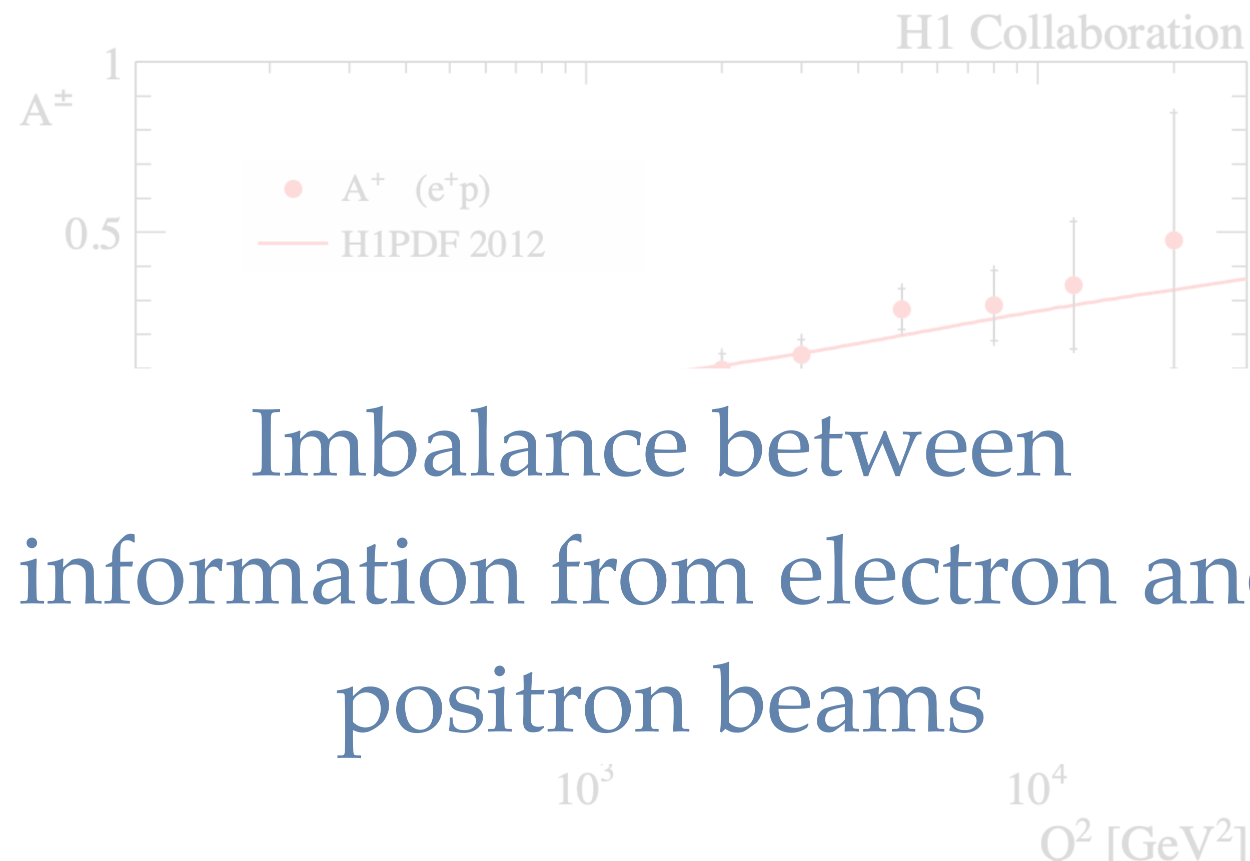

Imbalance between information from electron and positron beams

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$$
\begin{aligned}
C_{1u} &= 2g_A^e g_V^u = 2\left(-\frac{1}{2}\right)\left(\frac{1}{2} - \frac{4}{3}\sin^2\theta_W\right) \\
C_{2u} &= 2g_V^e g_A^u = 2\left(-\frac{1}{2} + 2\sin^2\theta_W\right)\left(\frac{1}{2}\right) \\
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\end{aligned}
$$

$$
\begin{aligned}
C_{1u}^{\mathrm{SM}} &= -0.1887 - 0.0011 \times \frac{2}{3}\ln(\langle Q^2\rangle/0.14\mathrm{GeV}^2) \\
C_{1d}^{\mathrm{SM}} &= 0.3419 - 0.0011 \times \frac{-1}{3}\ln(\langle Q^2\rangle/0.14\mathrm{GeV}^2) \\
C_{2u}^{\mathrm{SM}} &= -0.0351 - 0.0009\ln(\langle Q^2\rangle/0.078\ \mathrm{GeV}^2) \\
C_{2d}^{\mathrm{SM}} &= 0.0248 + 0.0007\ln(\langle Q^2\rangle/0.021\ \mathrm{GeV}^2)
\end{aligned}
$$

Parameterization of $g_1^{PV}(x, Q^2)$

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PV parton density comes from the structure

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1 parameter to be fitted

Error propagation in the analysis

PDF set for

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PDF set for $f_1(x, Q^2)$ *NNPDF4.0*

Ball et al. (NNPDF), EPJ C 82 (2022)

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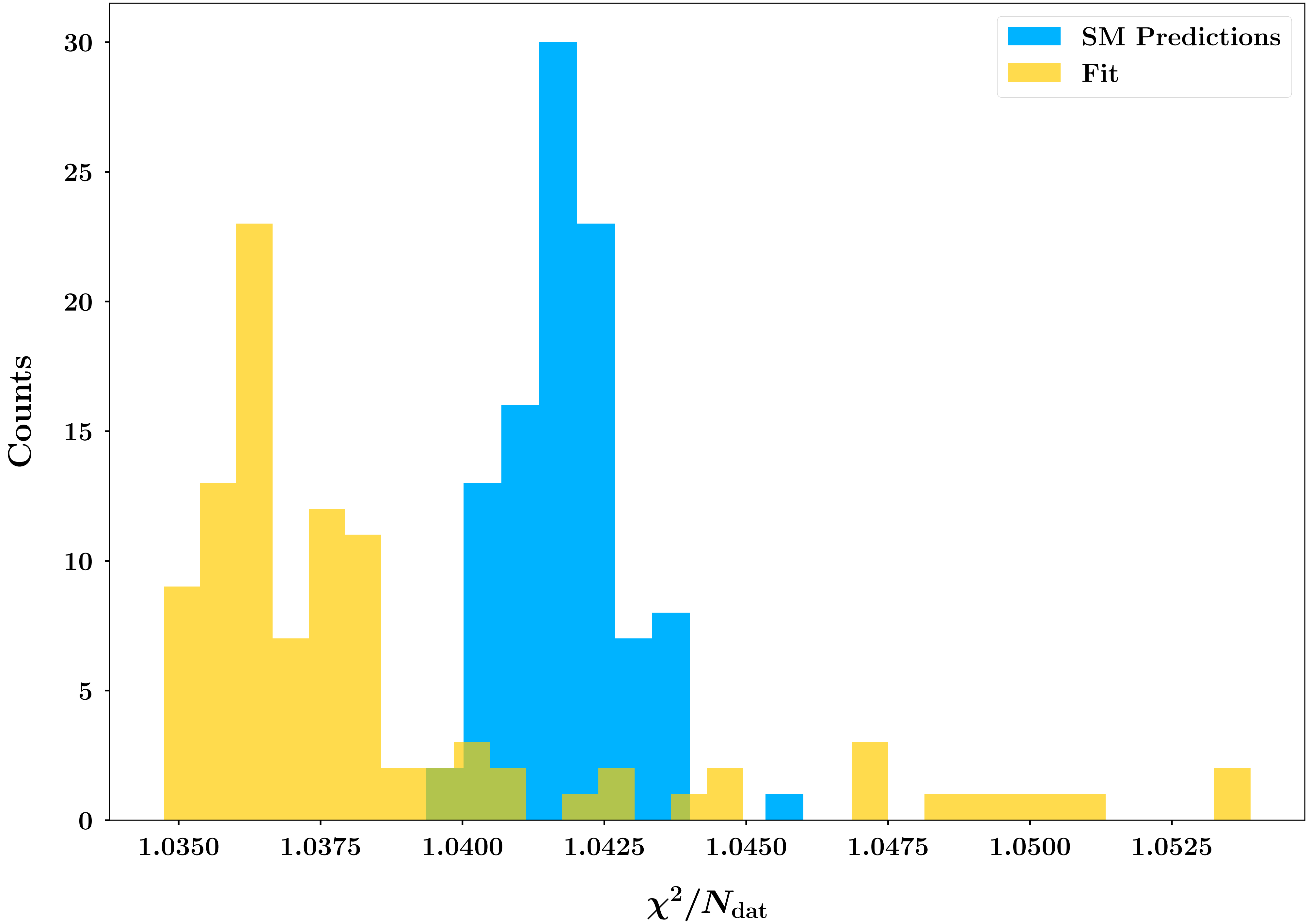
Statistical distribution of 100 values of parameter α

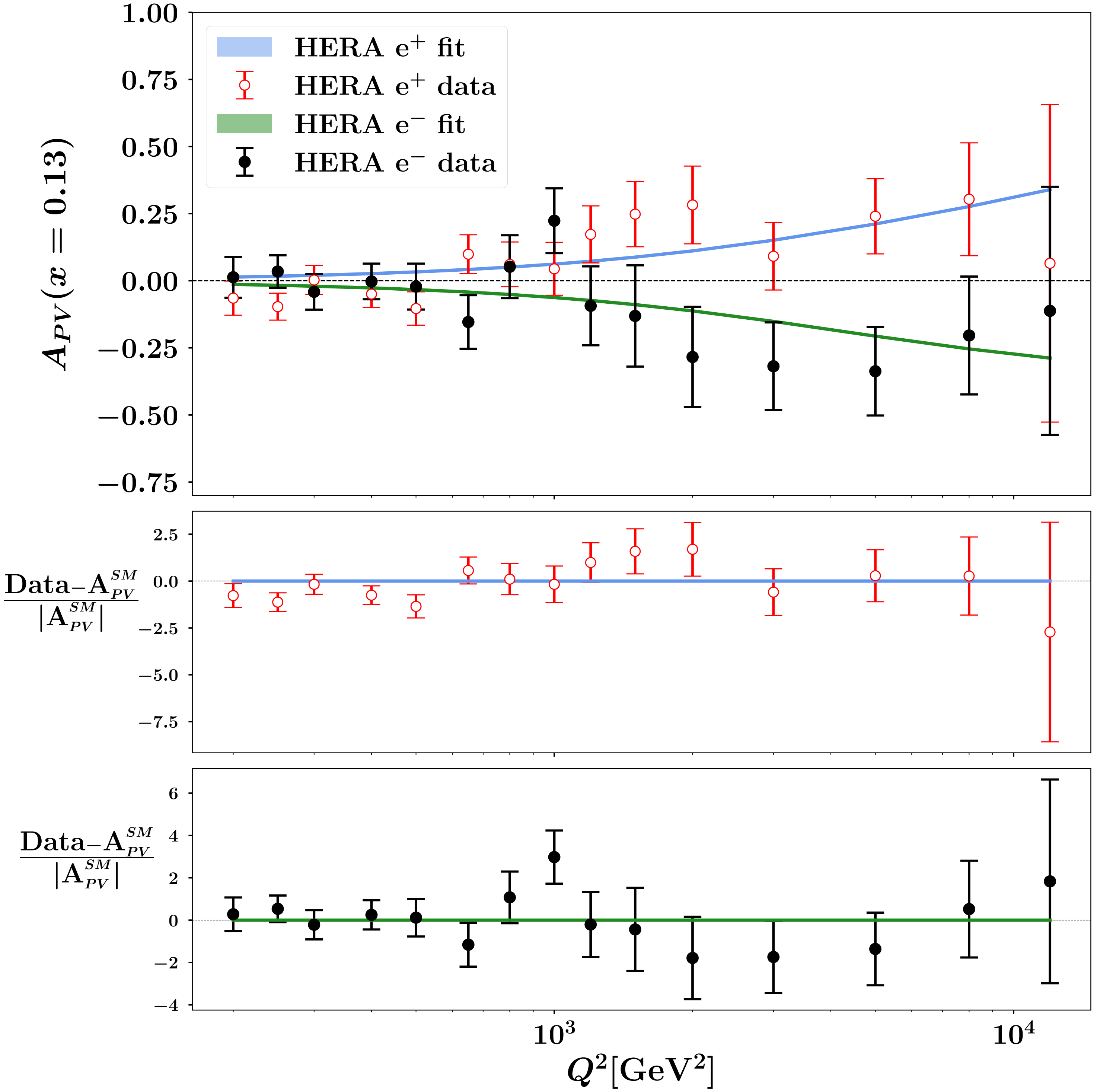
Results of the fit

	N of points	χ^2/N_{data} (SM)	χ^2/N_{data} (**Fit**)
HERA e^+	136	1.12	1.12
HERA e^-	138	0.98	0.98
JLab6	2	0.67	0.42
SLAC-E122	11	0.97	0.94
TOTAL	***287***	***1.042***	***1.037***

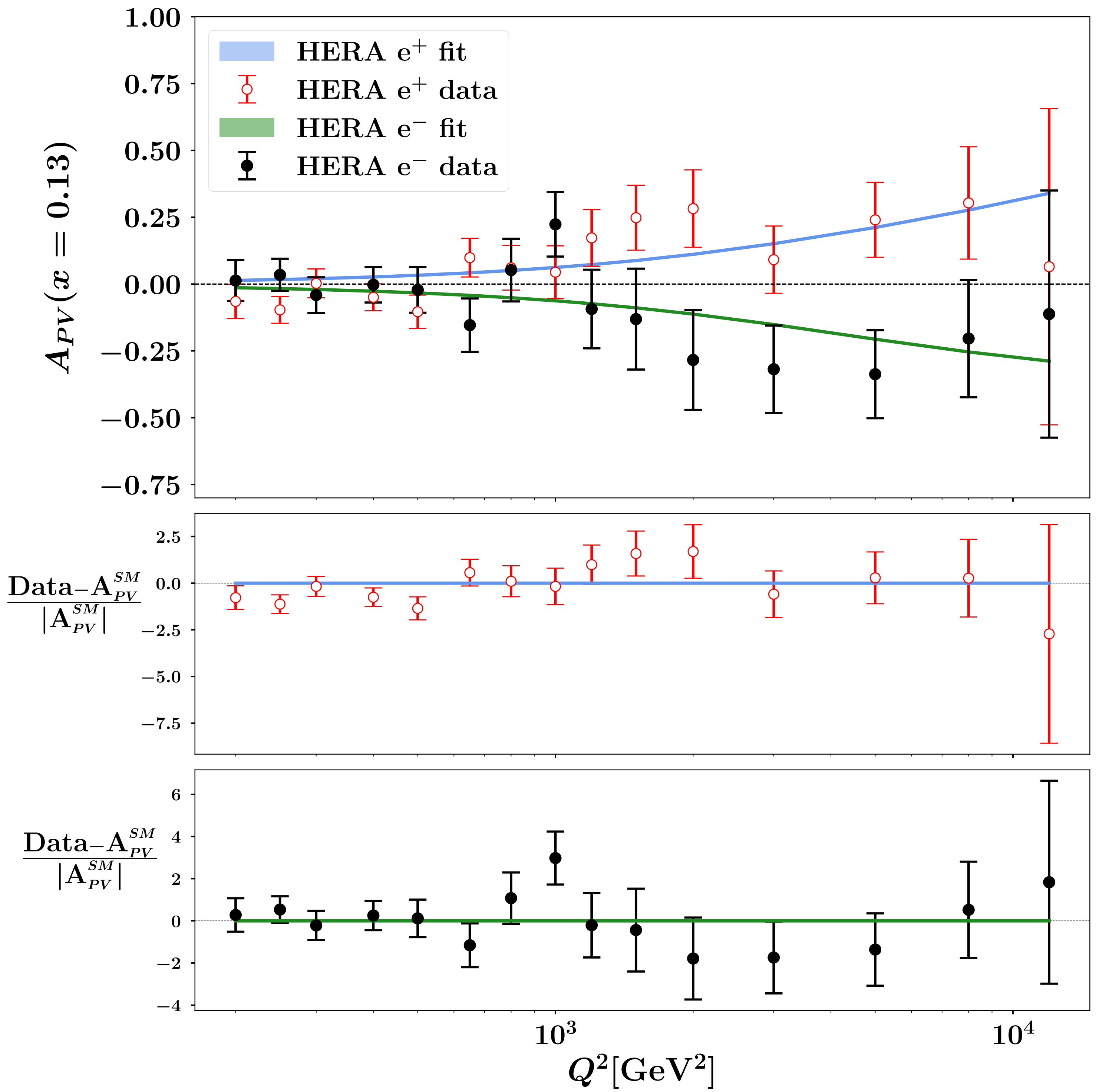
Results of the fit



Results of the fit: data vs theory



Results of the fit: data vs theory



Very small uncertainties in the predictions because the fit is dominated by data with smaller errors

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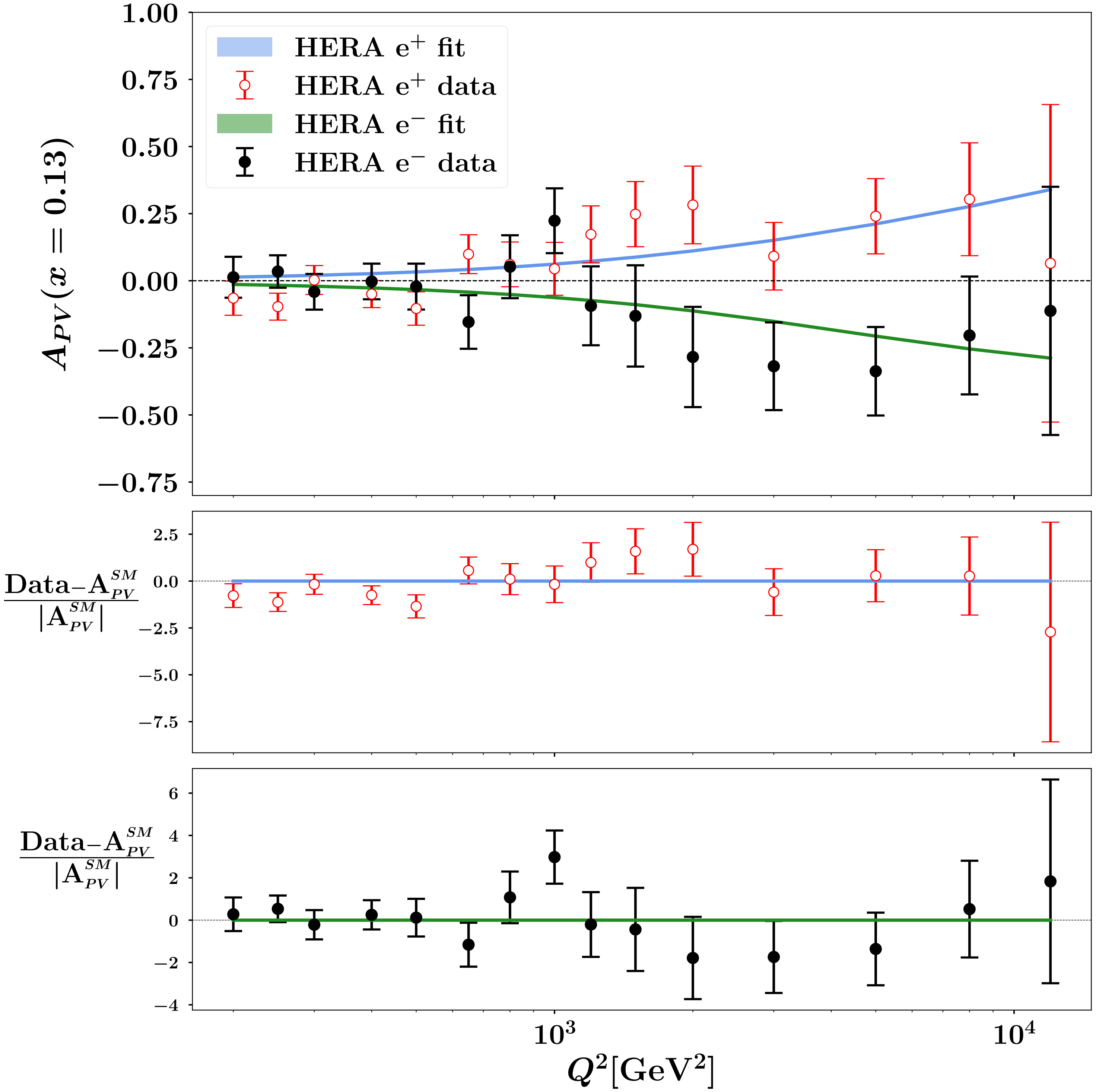

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There's room for a better description for positron asymmetry at low-Q

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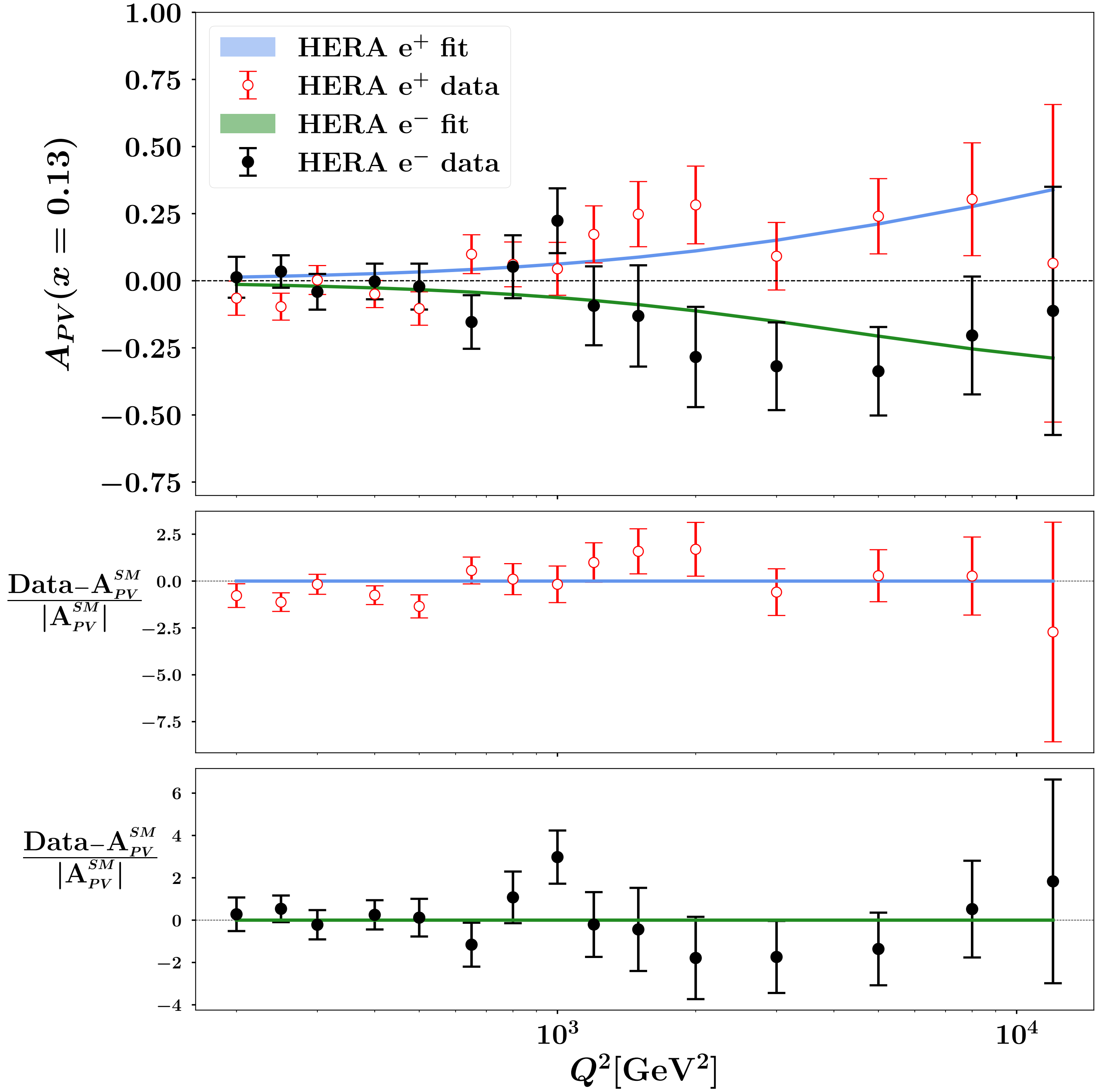

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Agreement for electron asymmetry, but too large errors at low-Q

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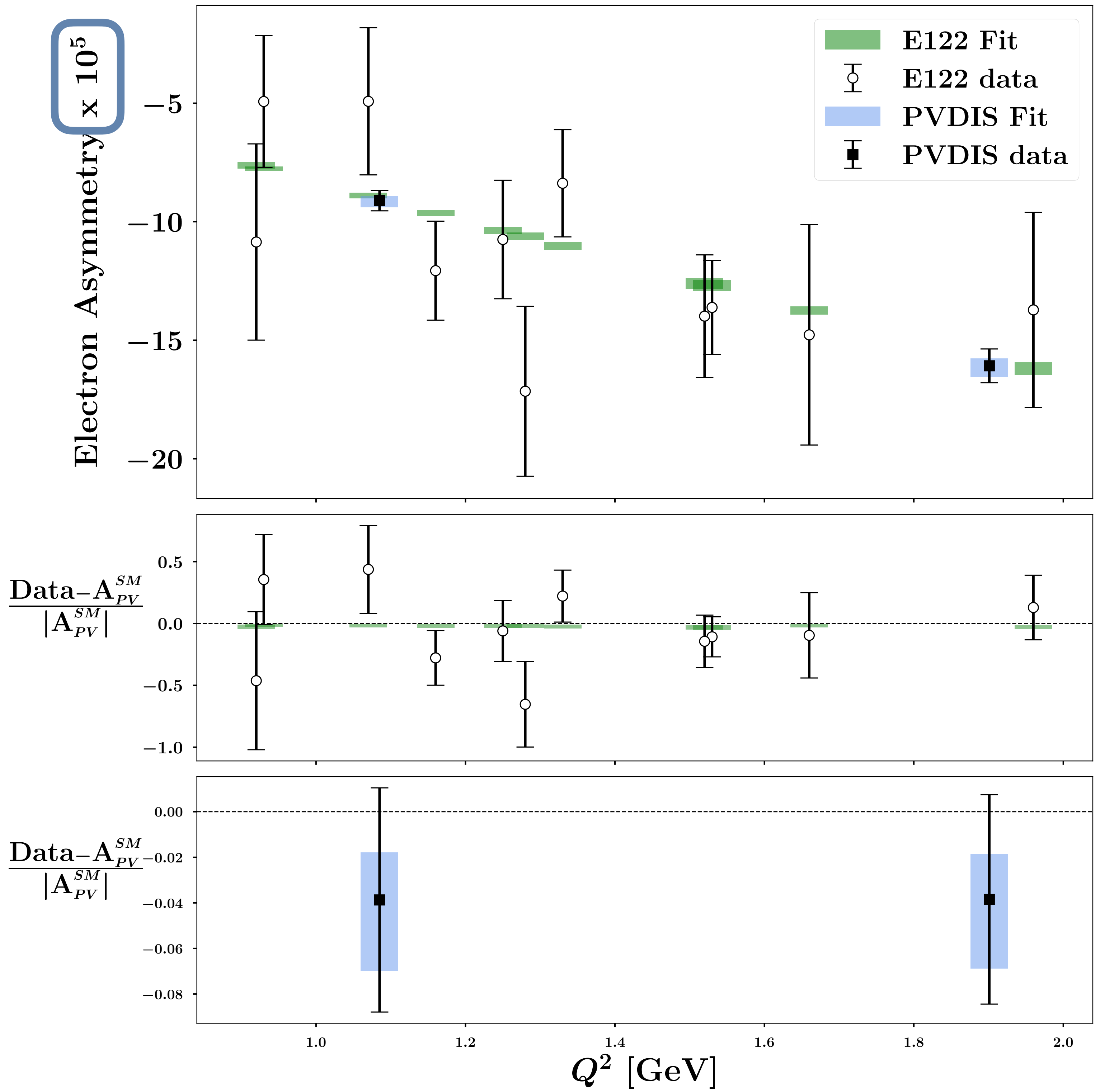

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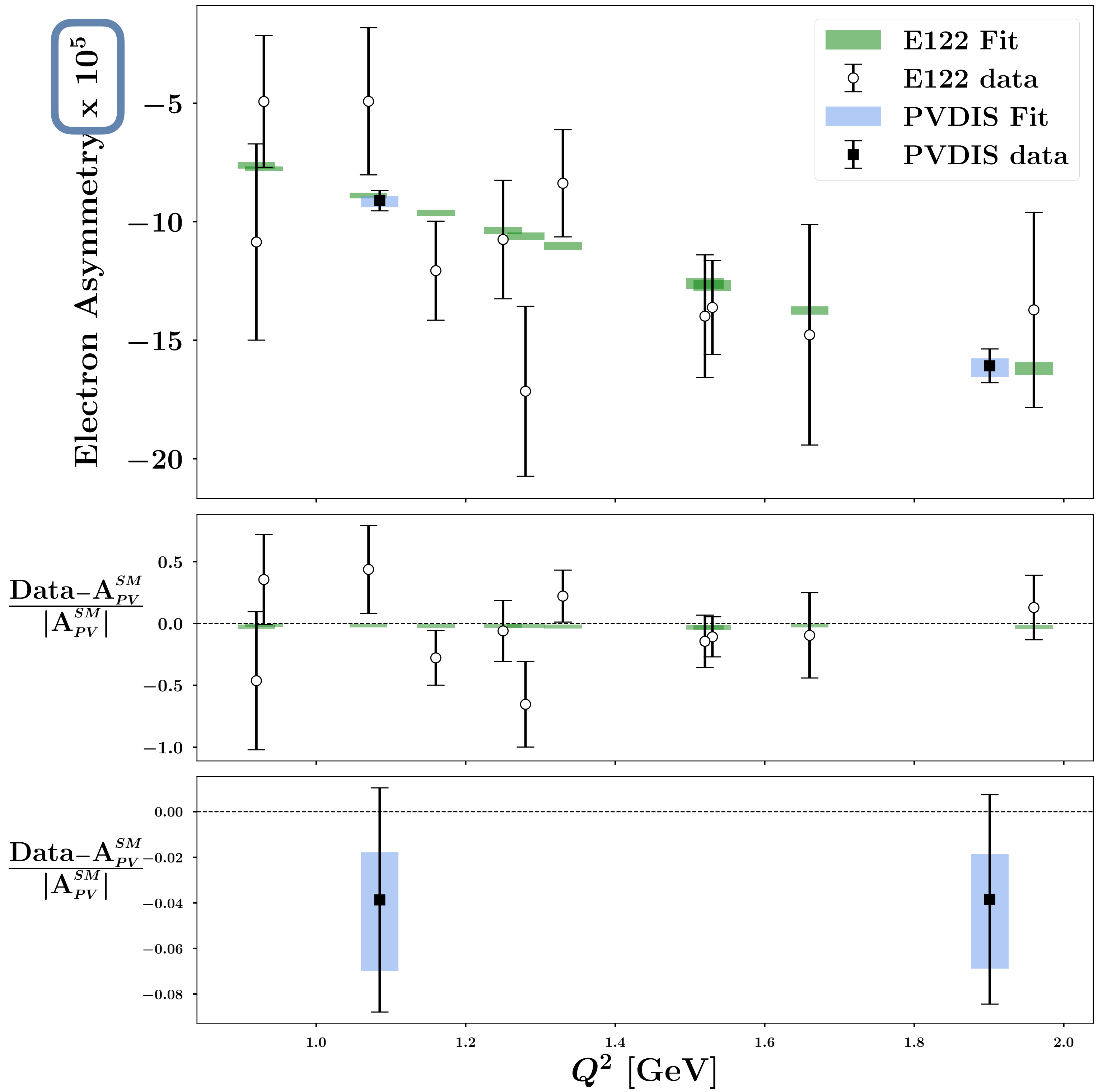

Sizeable improvement of the fit w.r.t. SM predictions

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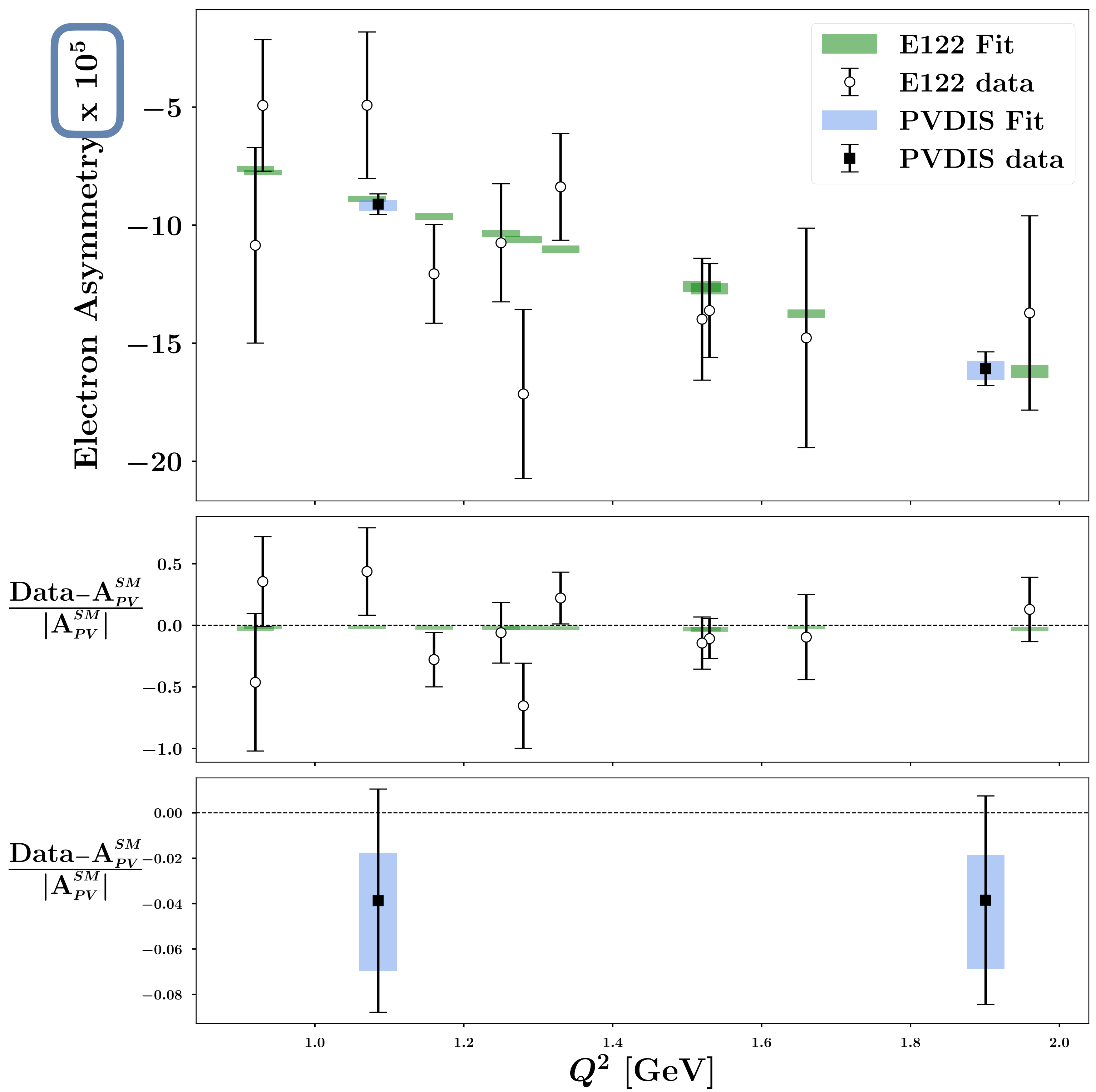

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Old dataset with still quite large experimental errors (> 20 %)

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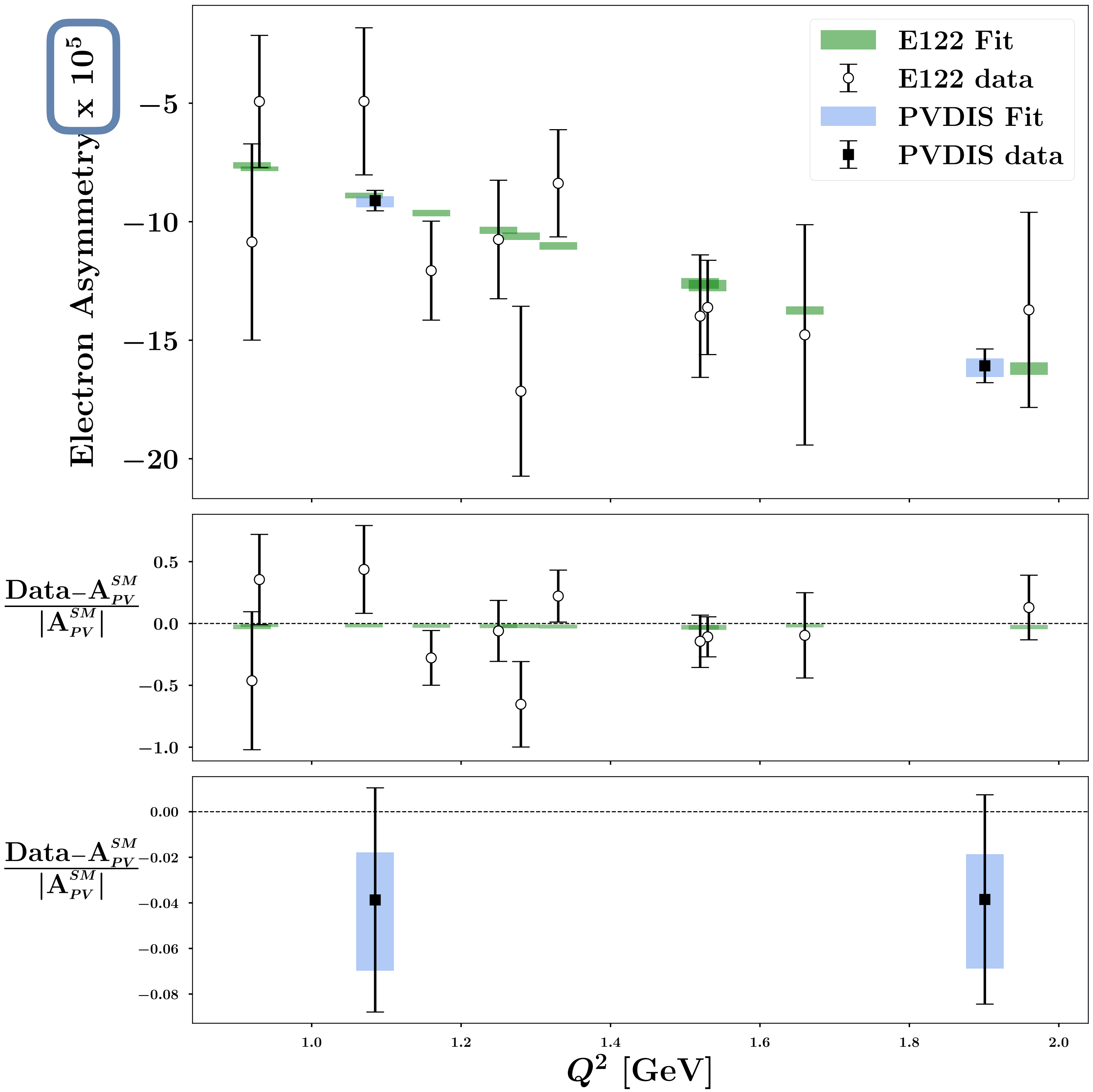

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Data points which actually drive the fit due to very small experimental errors (~ %)

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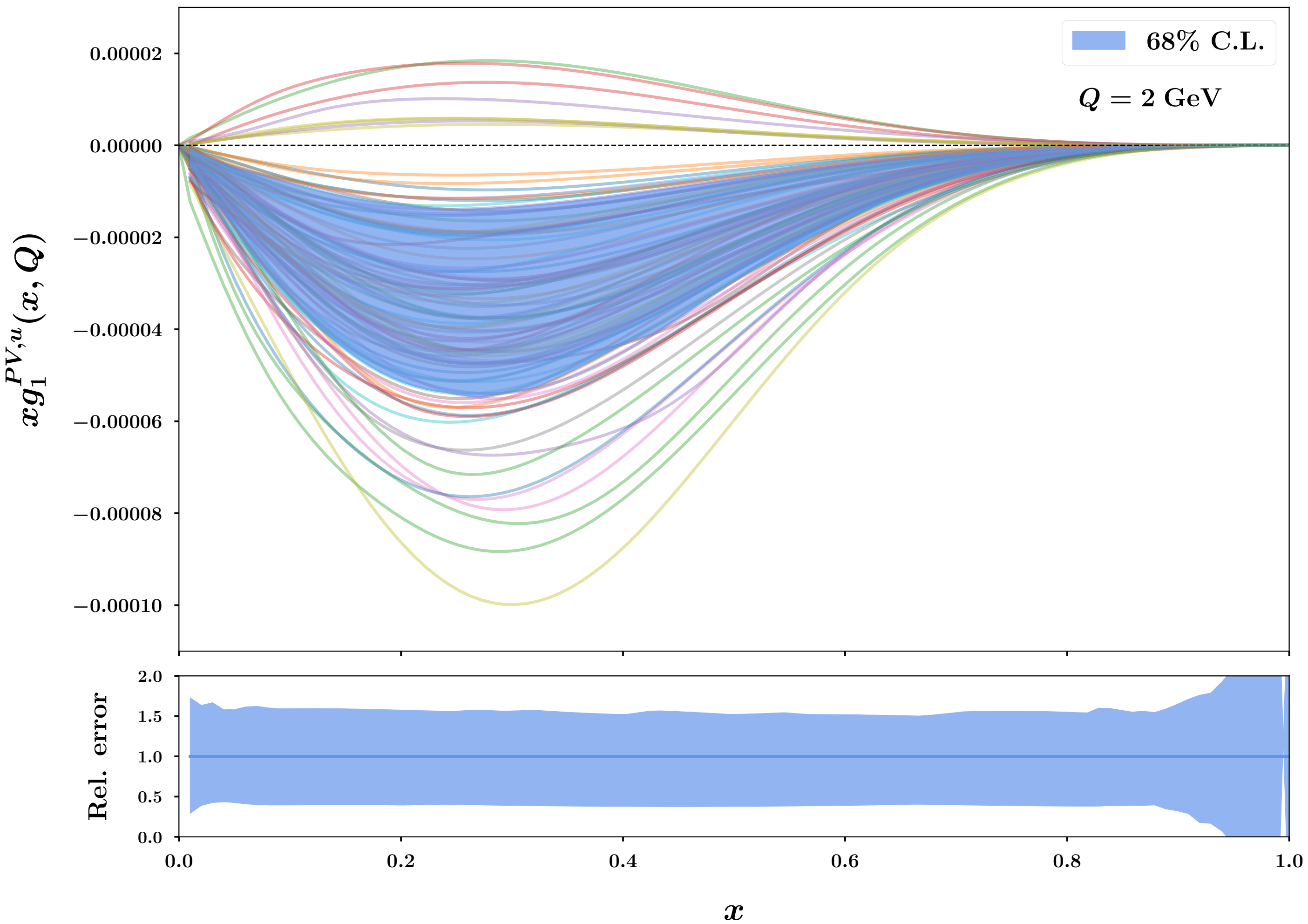

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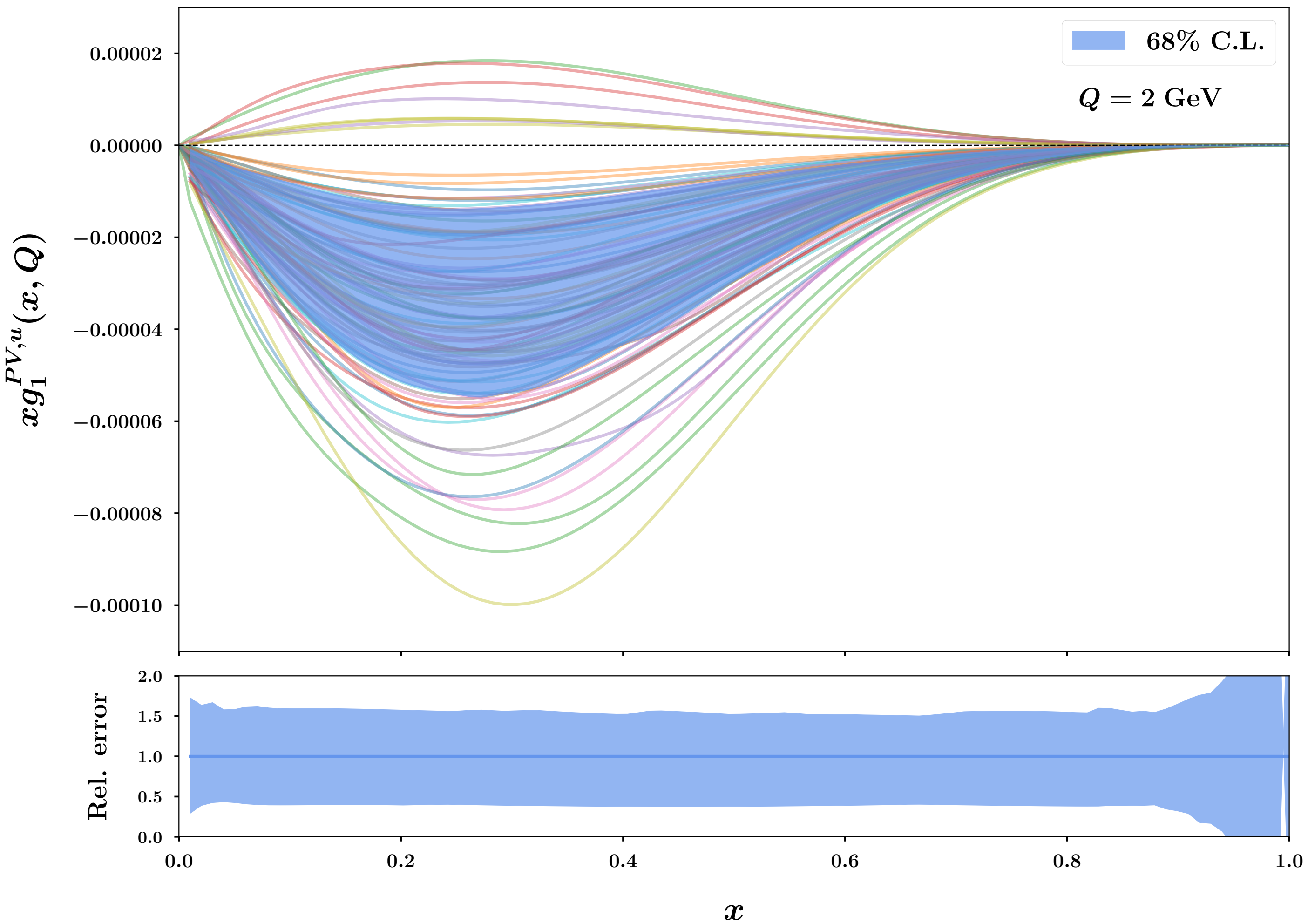
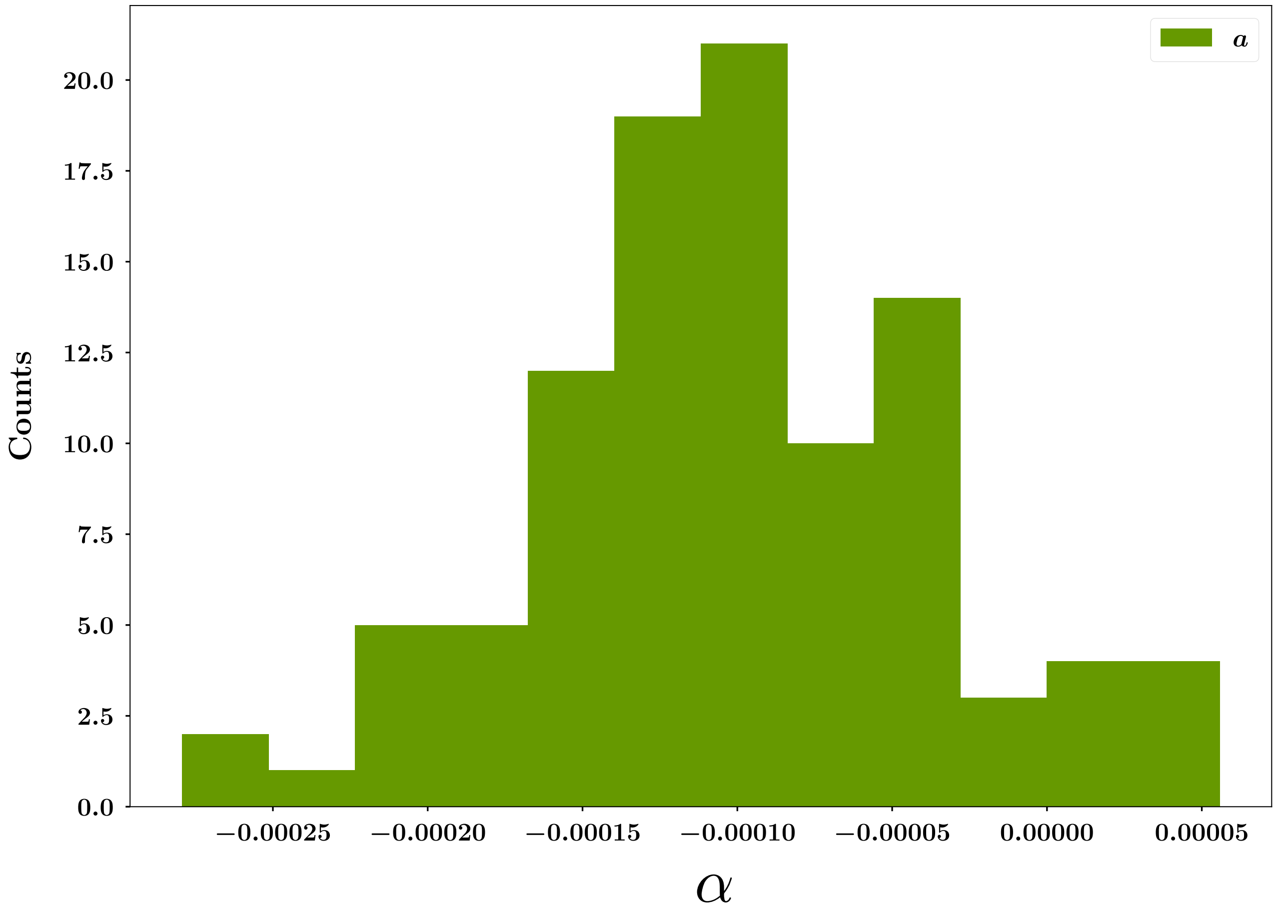
$$\alpha = (-1.01 \pm 0.66) \cdot 10^{-4}$$





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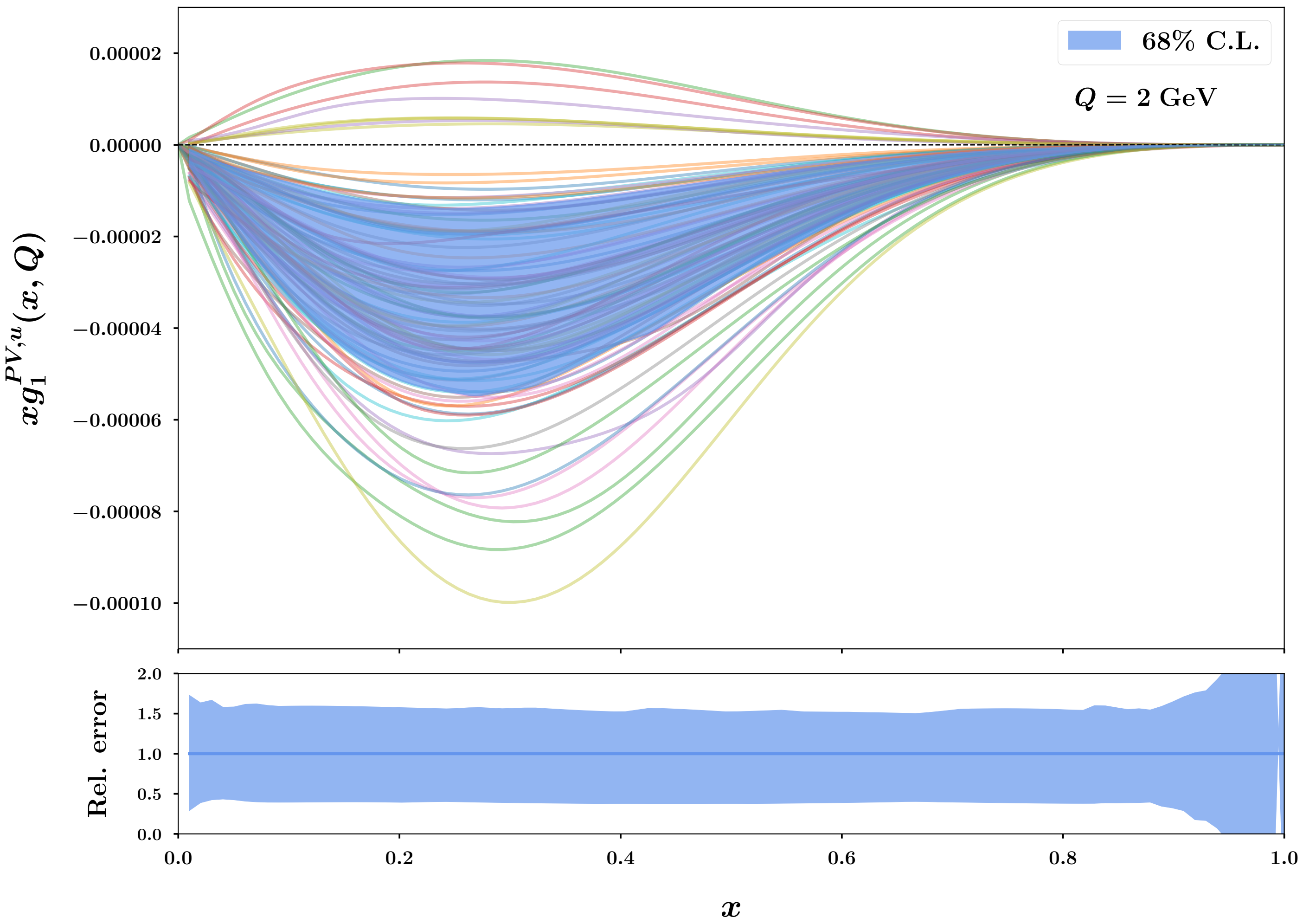
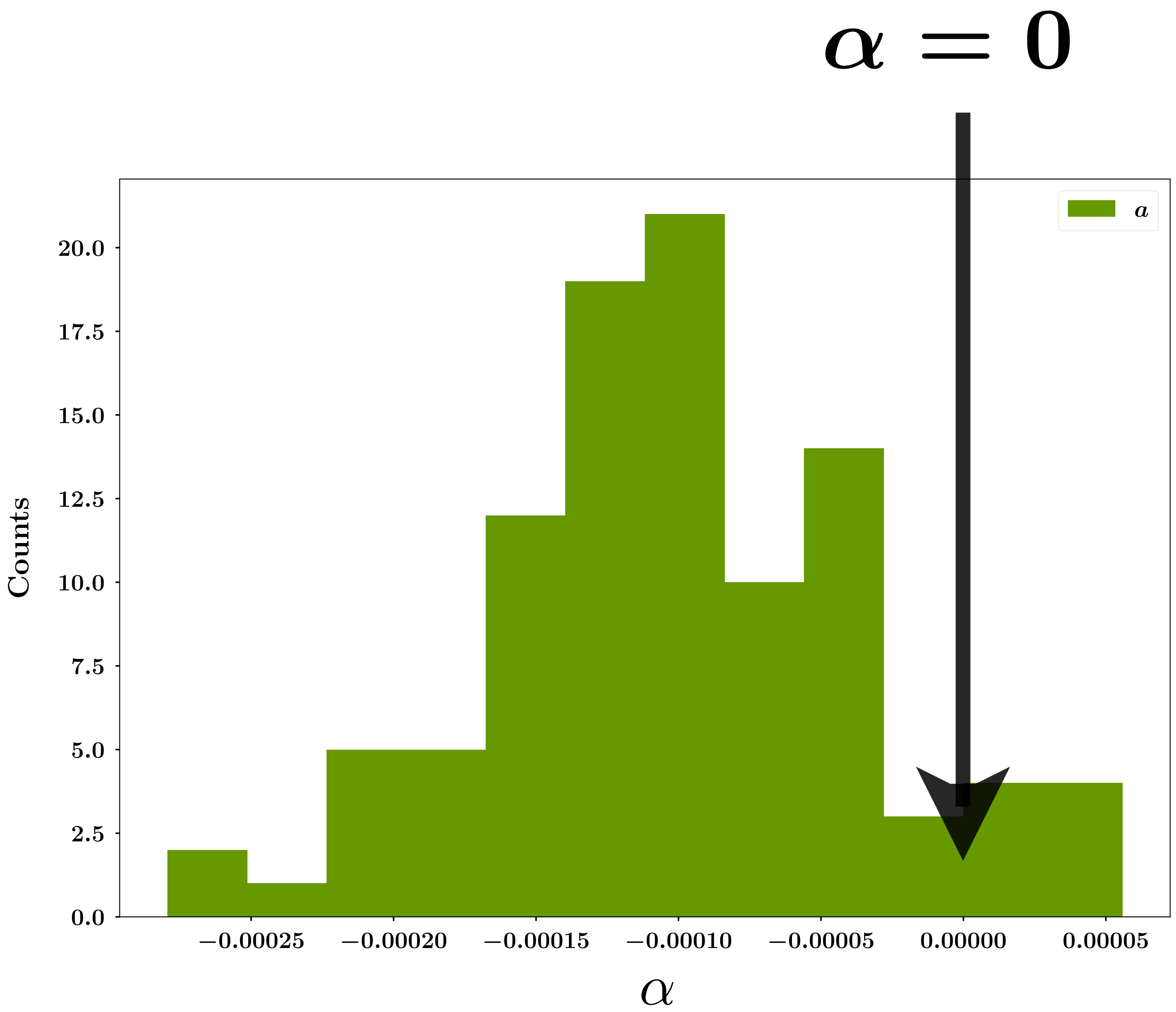
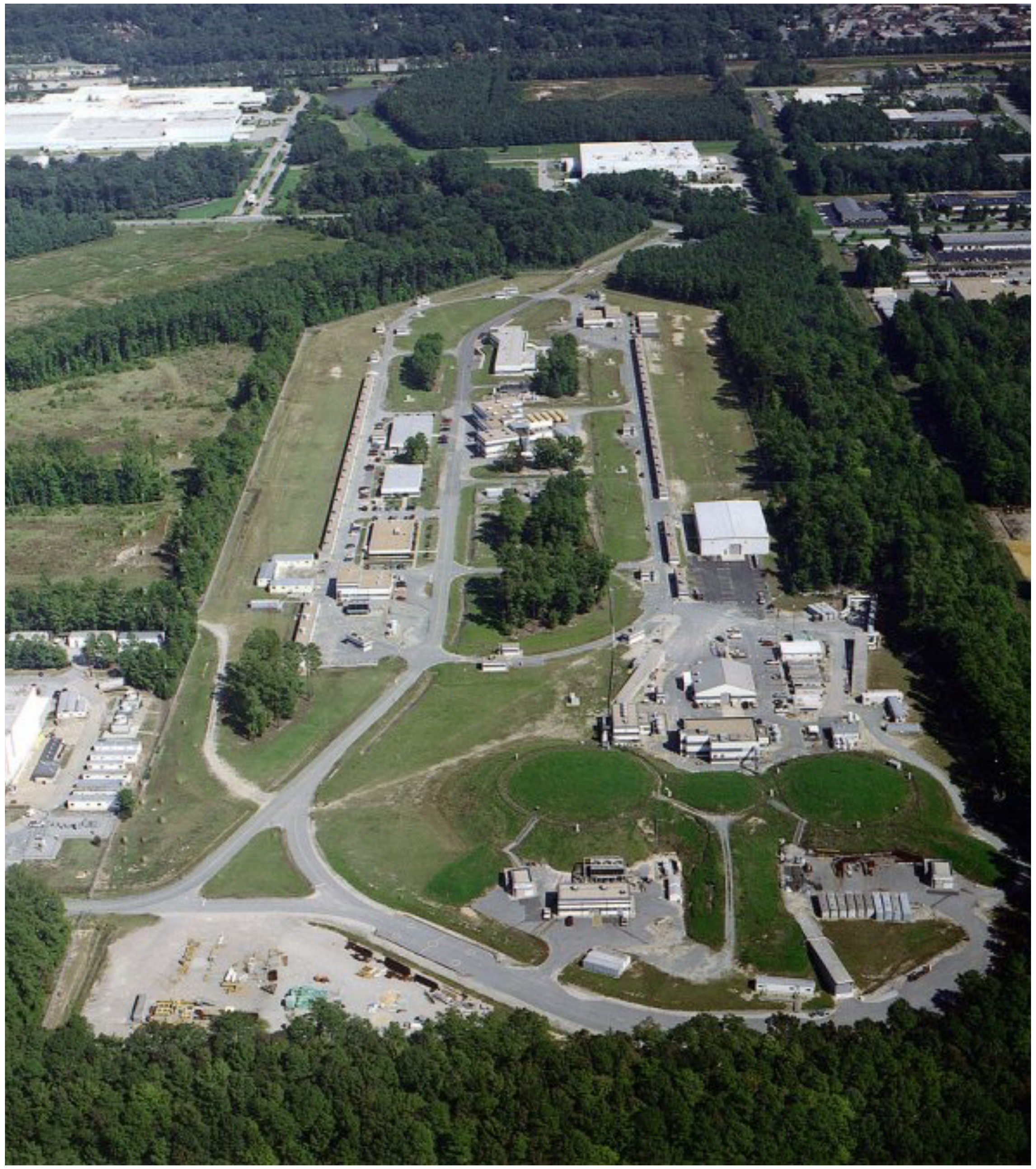
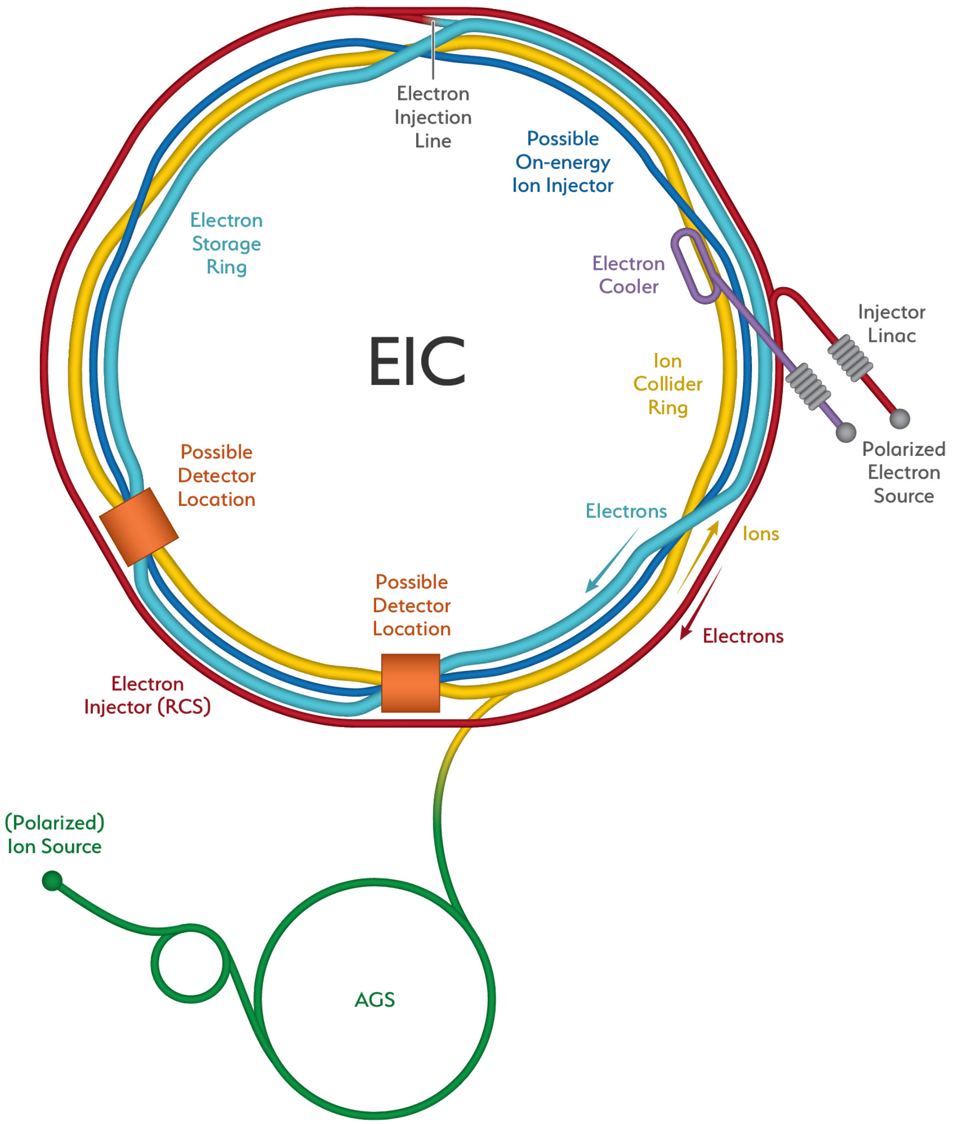




Future facilities





Impact of future data

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Wood, Bennet, Cho, et al., Science 275 (1997)
Souder, Reimer, Zheng, JLab Experiment E12-10-007 (2022 update)

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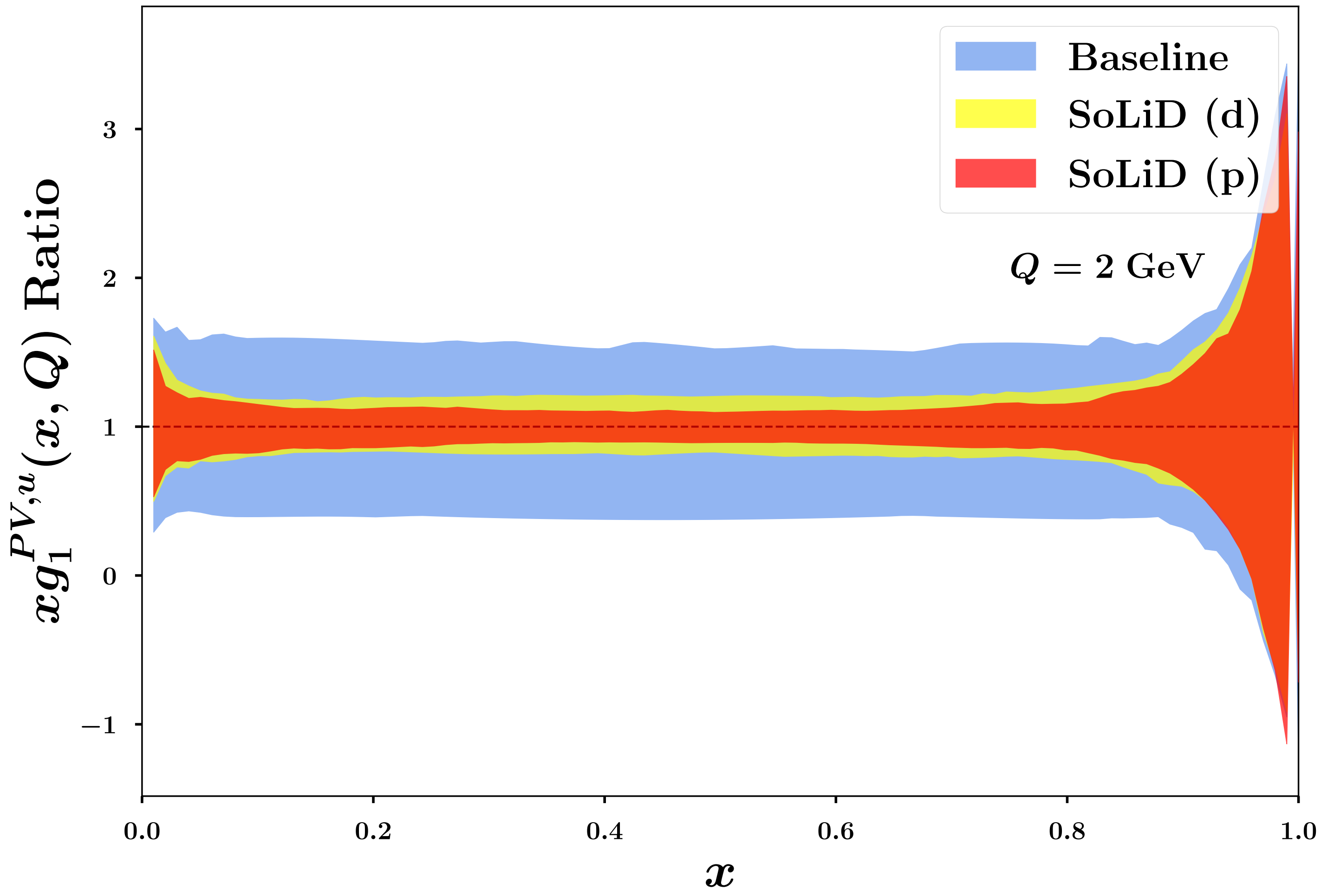

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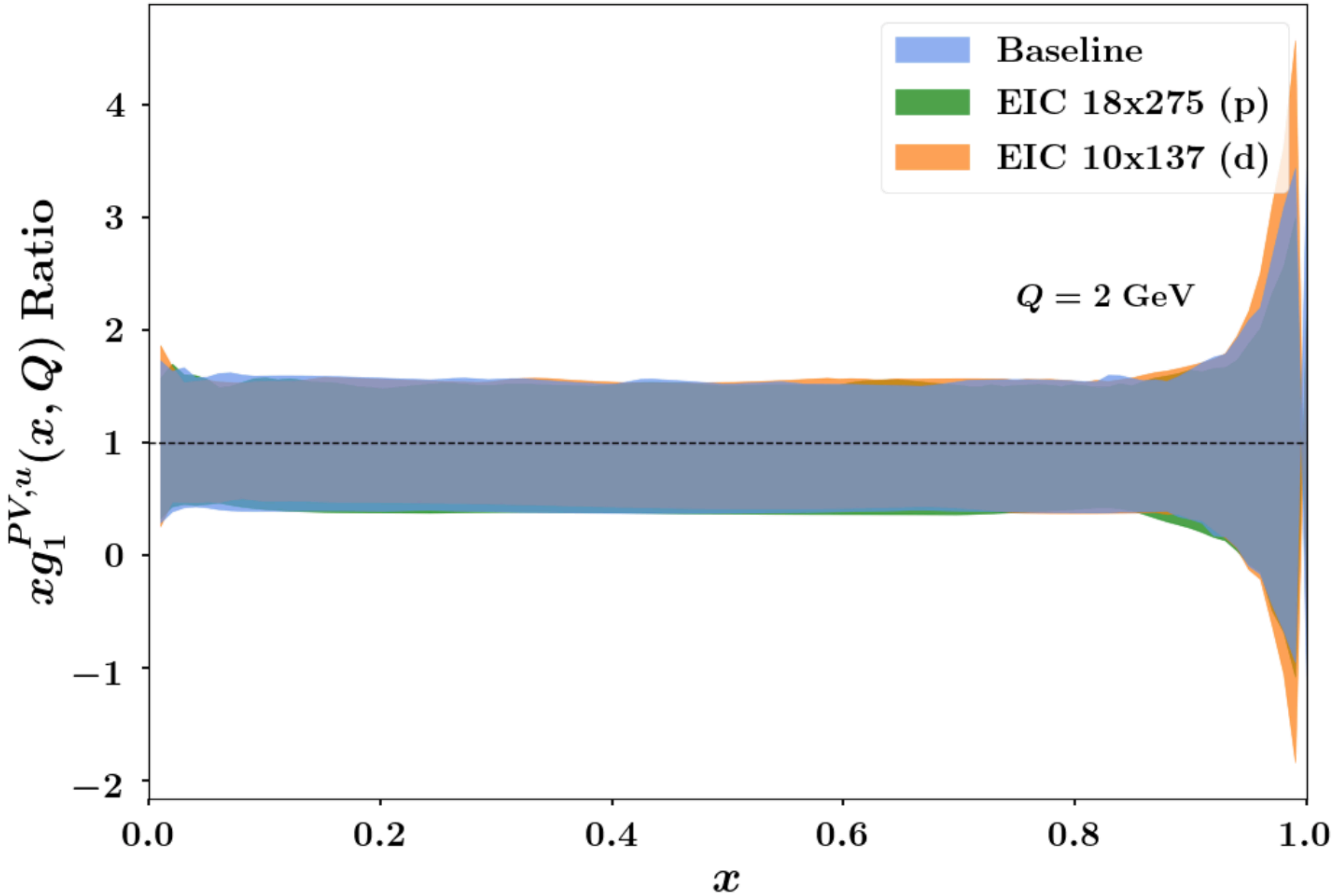

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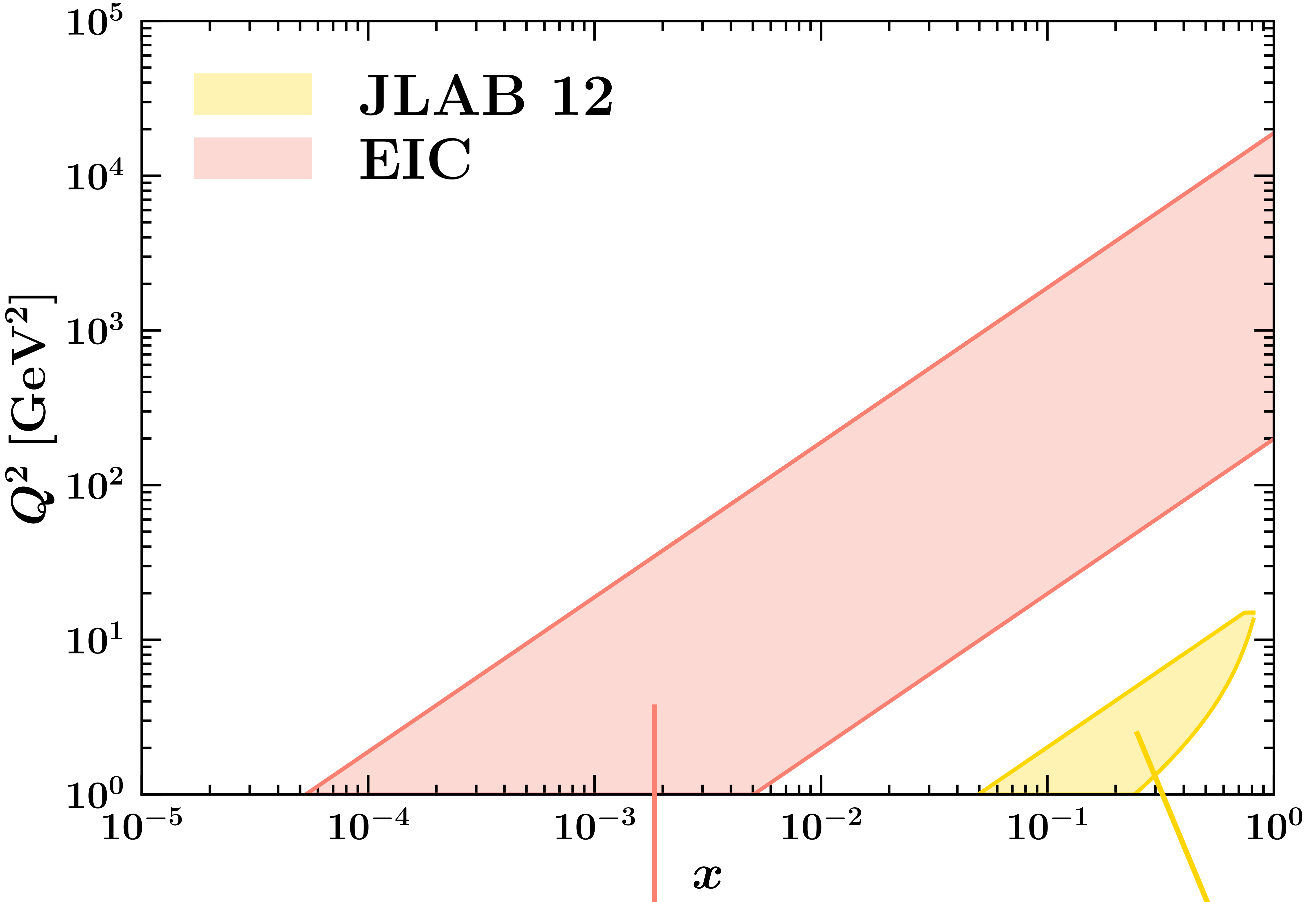

$\Delta(exp) \sim 50\%$

$\Delta(exp) \sim 0.1\%$

Step forward: dependence on x

- New model of the PV parton distribution

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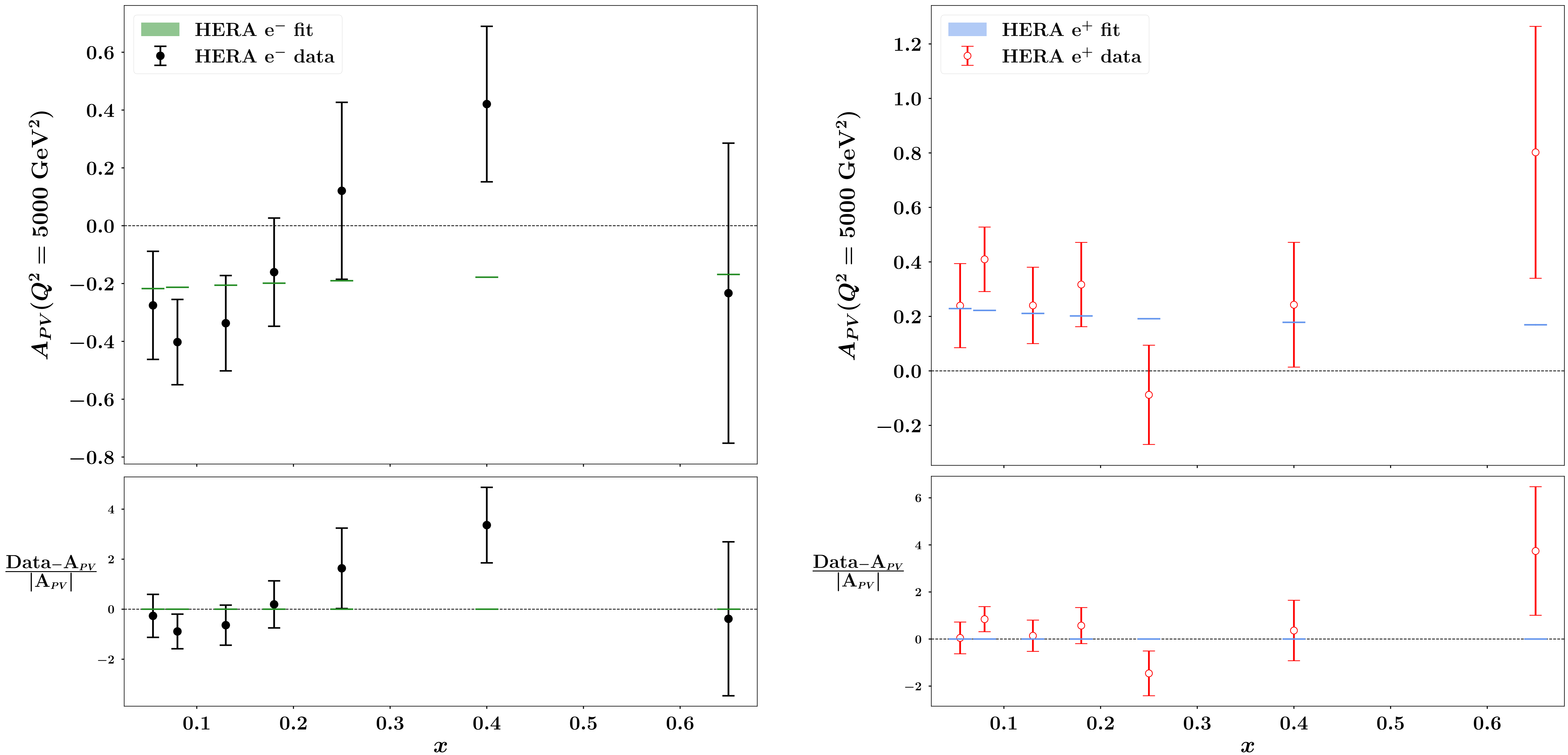

Step forward: a new CP-odd PDF

- Further investigations on a new P-odd, CP-odd distribution function arising when considering the polarisation of the target

$$
\begin{aligned}
\Phi^q(x,Q^2) = \Big\{ & f_1^q(x,Q^2) + g_1^{\mathrm{PV}q}(x,Q^2)\gamma_5 \\
& + S_L\Big(g_1^q(x,Q^2)\gamma_5 + f_{1L}^{\mathrm{PV}q}(x,Q^2)\Big) \\
& - \not{S}_T\Big(h_1^q(x,Q^2)\gamma_5 - e_{1T}^{\mathrm{PV}q}(x,Q^2)\Big)\Big\}\frac{\not{n}_+}{2}
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$$\Delta x_B g_5(x_B,Q^2) \approx \Delta x_B g_5^{(\gamma)}(x_B,Q^2) = \frac{1}{2}\sum_q e_q^2 x_B f_{1L}^{\mathrm{PV}(q-\bar{q})}$$

PDFs in DIS processes

Quark Polarization

Nucleon Pol.

	U	L	T
U	$f_1(x)$		
L		$g_1(x)$	
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Electric dipole moment

Summary

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Summary

- The strong P- violation can give origin to a new structure function in DIS cross section for one-photon exchange
- A fit of present experimental data is compatible with a non-zero contribution from a new strong PV parton density
- To better assess the presence (or not) of this PV effect we need very precise experimental data
- Improvements in the theoretical framework of our analysis are surely needed to obtain more and more accurate results