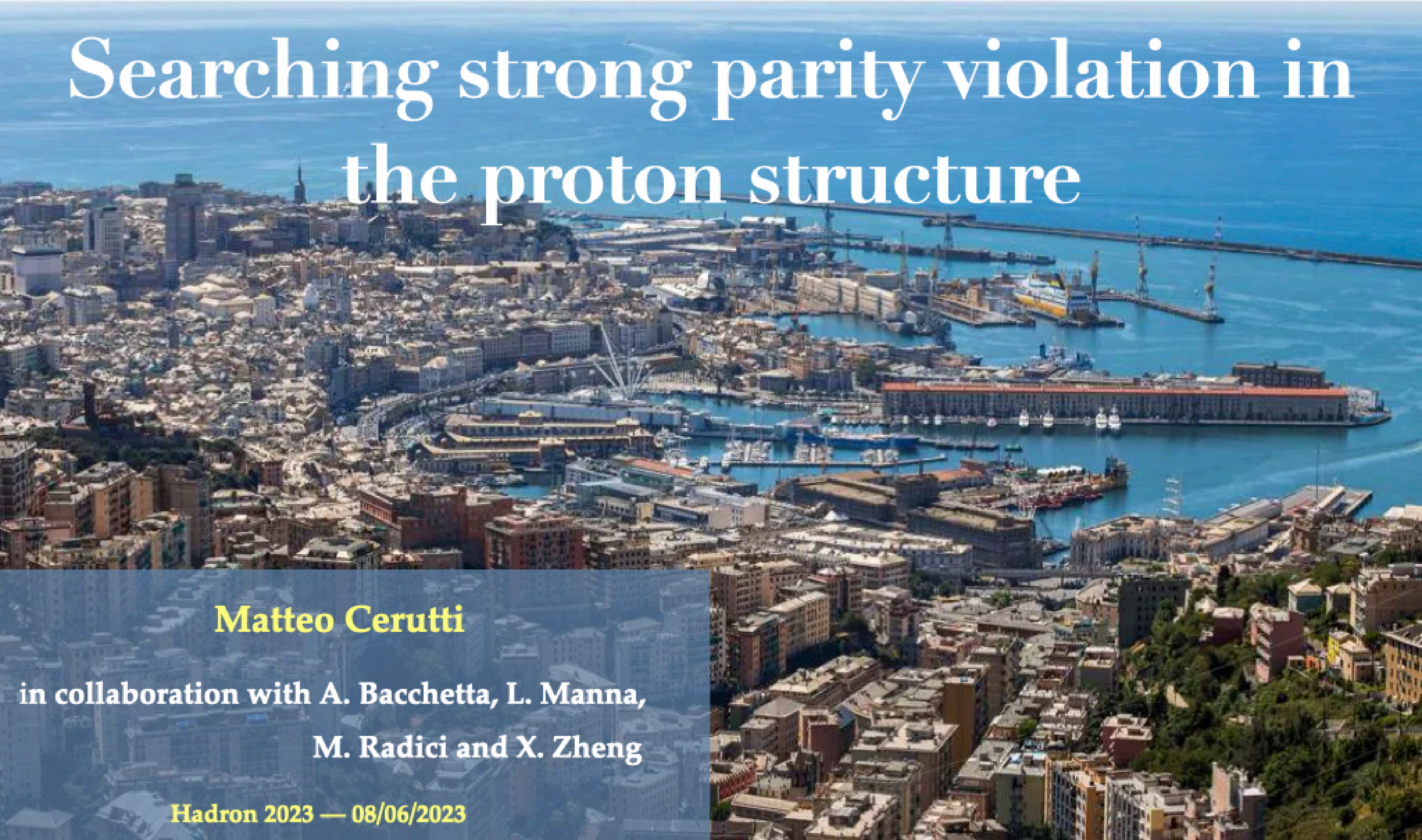
INFN
Istituto Nazionale di Fisica Nucleare

HAS QCD
HADRONIC STRUCTURE AND QUANTUM CHROMODYNAMICS

UNIVERSITÀ DI PAVIA



Searching strong parity violation in the proton structure

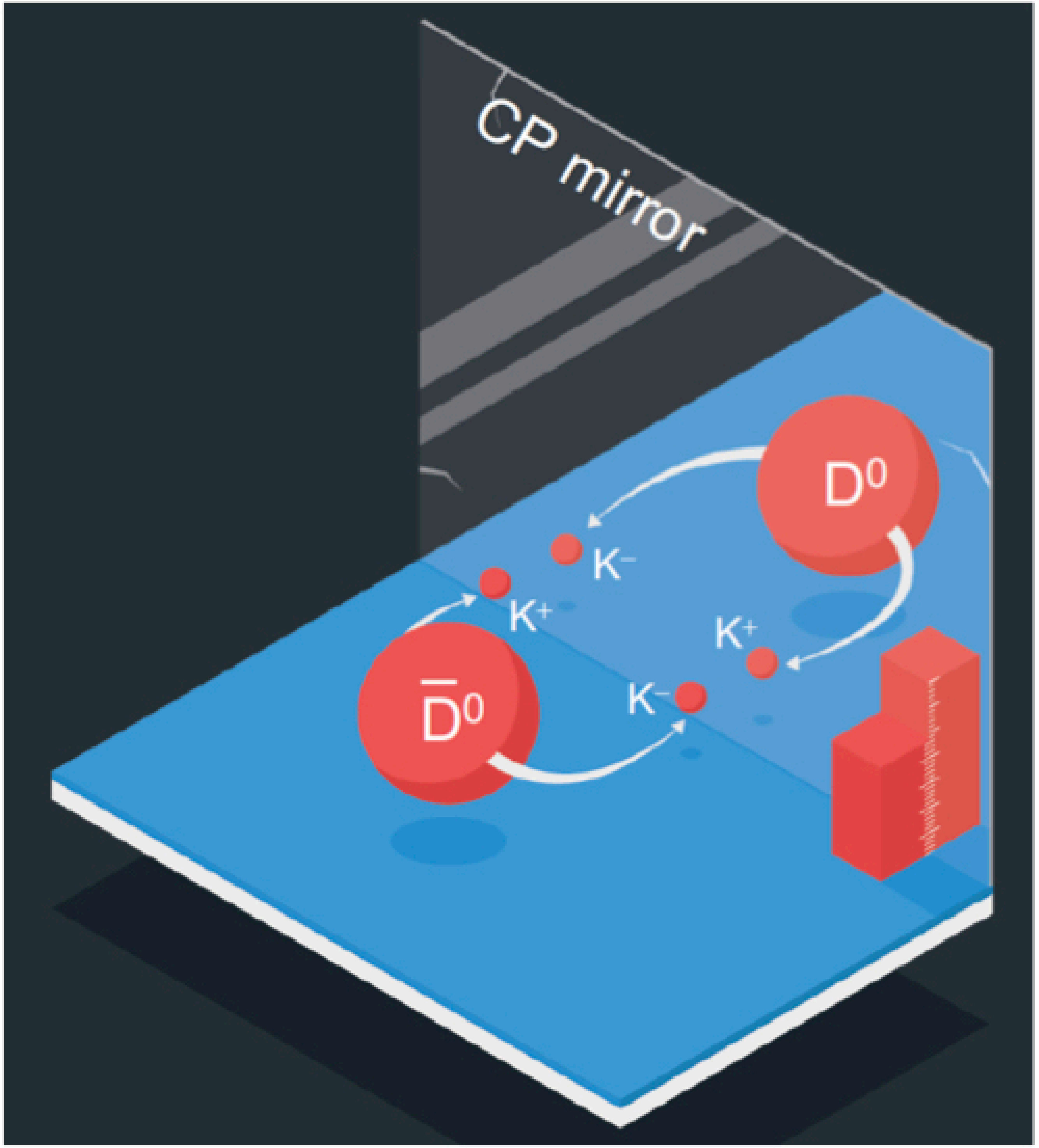
Matteo Cerutti

in collaboration with A. Bacchetta, L. Manna, M. Radici and X. Zheng

Hadron 2023 — 08/06/2023

Motivations

Investigation of the
"Strong CP problem"

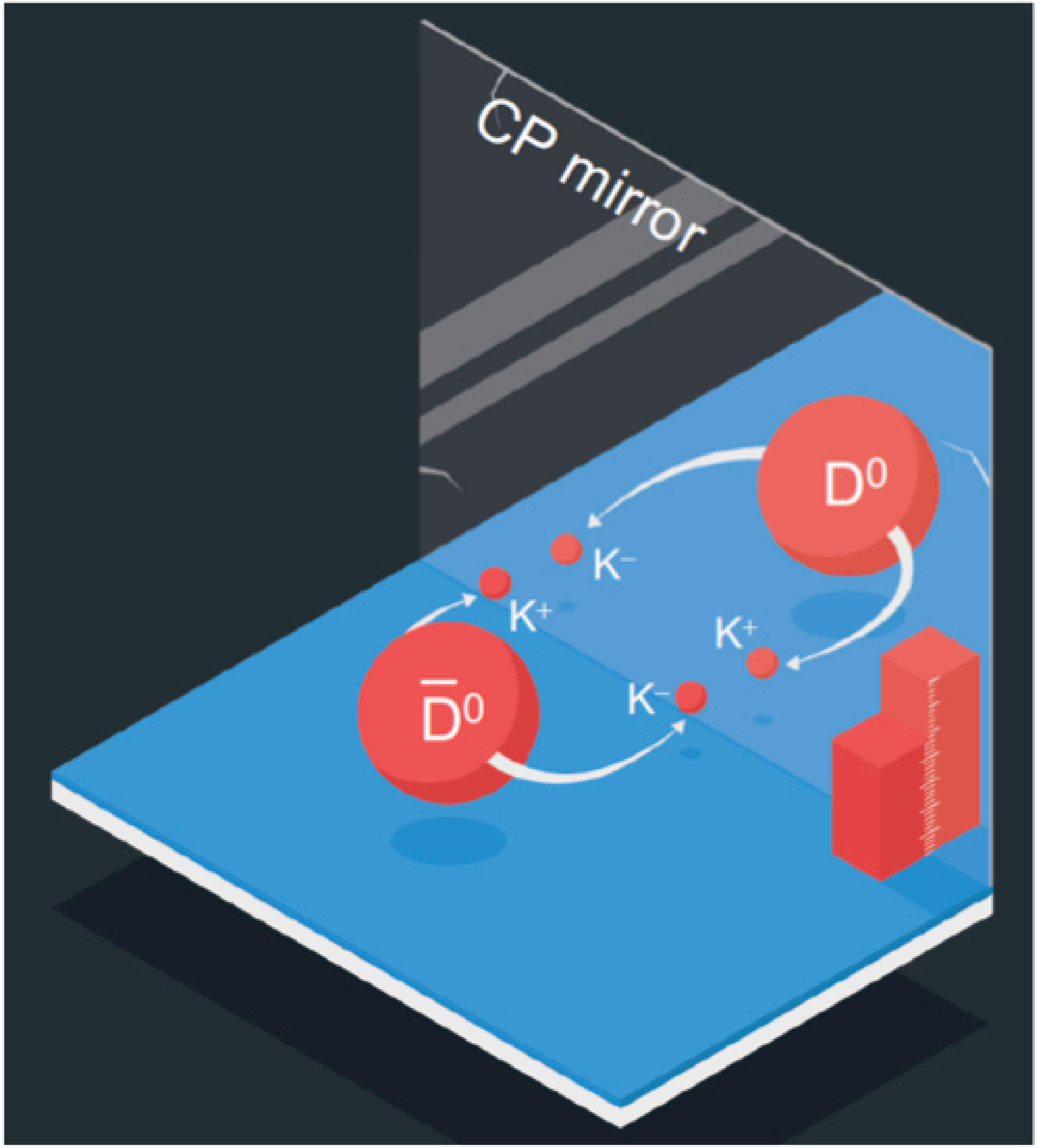


Motivations

Investigation of the
"Strong CP problem"

↓

Matter-Antimatter
imbalance



Motivations

EW sector CP violation is included

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Weak CP

Motivations

EW sector — CP violation is included

Weak CP — ***too small…***

Motivations

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QCD sector

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Strong CP

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<u>QCD sector</u>

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

Strong CP

Motivations

EW sector — CP violation is included

Weak CP — *too small...*

QCD sector

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

Strong CP

θ-term

SMEFT operators

Motivations

EW sector

Weak CP

CP violation is included

too small…

QCD sector

Strong CP

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

θ-term

SMEFT operators

↓

Nucleon electric dipole moment

Motivations

EW sector

CP violation is included

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too small…

QCD sector

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

Strong CP

θ-term

SMEFT operators

↓

Nucleon electric dipole moment

never measured…

Motivations

P-symmetry

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<u>QCD sector</u>

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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Terms from EW sector

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Terms from QCD sector

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QCD Lagrangian is assumed to be invariant under parity transformations

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

Terms from EW sector

Weak P-violation

✔

Terms from QCD sector

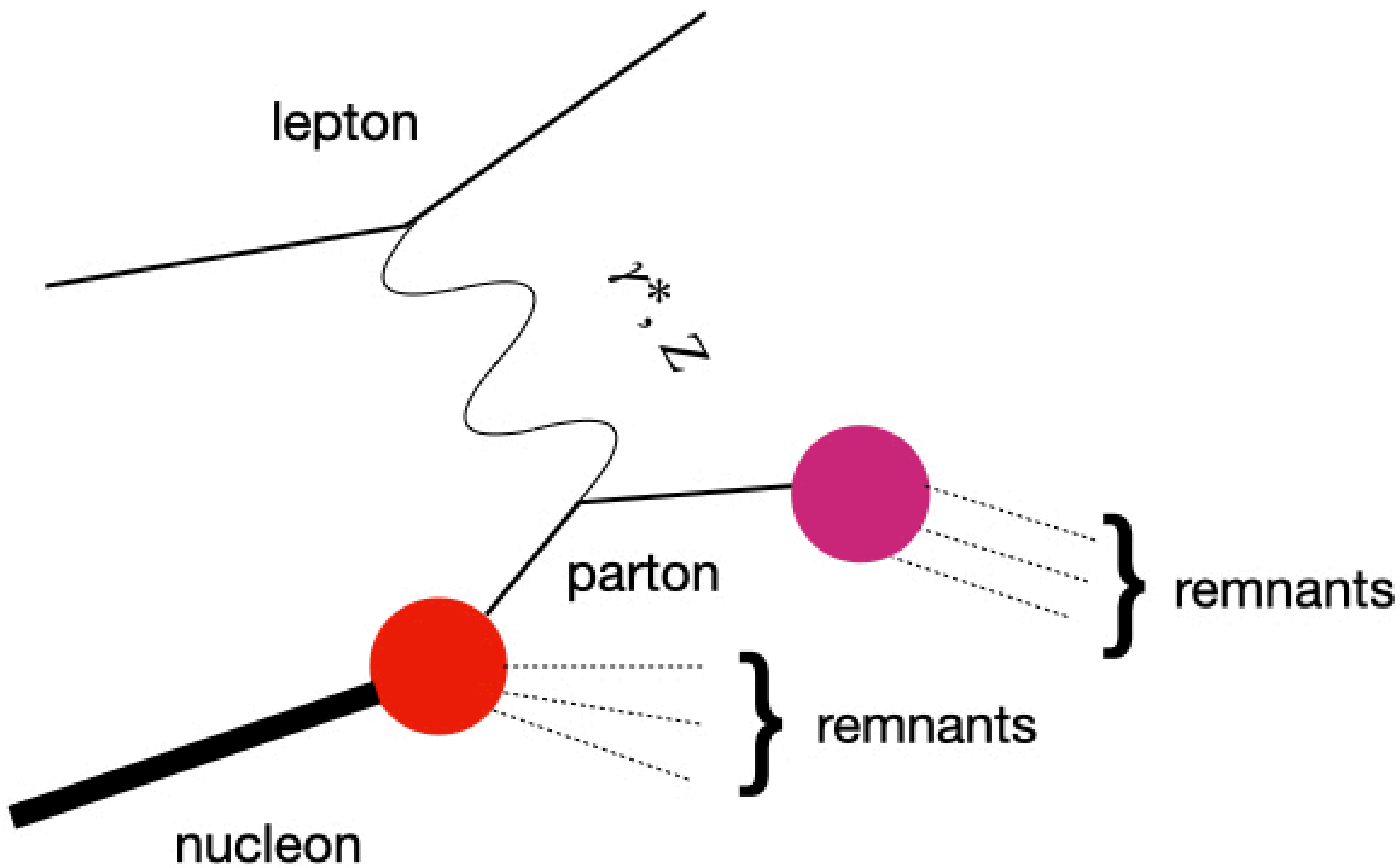
Strong P-violation

✘

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

DIS process

$$l(\ell) + N(P) \to \gamma^*(q) \to l(\ell') + X$$



Cross Section

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

In general

Cross Section

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$$\frac{d^3\sigma}{dx_B dy d\phi_S} = \frac{\alpha^2 y}{2Q^4} \sum_{j=\gamma,\gamma Z, Z} \eta^j L^{(j)}_{\mu\nu}(l, l'; \lambda_e) 2MW^{\mu\nu}(q, P, S)$$

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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)

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

J. Collins, "Foundation of Perturbative QCD"

M. Anselmino et al., Z. Phys. C 64, 267 (1997)

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Dominant contribution on the Light-Cone

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$$2MW^{\mu\nu}(q,P,S) = \sum_q e_q^2 \frac{1}{2} \mathrm{Tr}\left[\Phi(q,P,S)\Gamma^\mu\gamma^+\Gamma^\nu\right]$$

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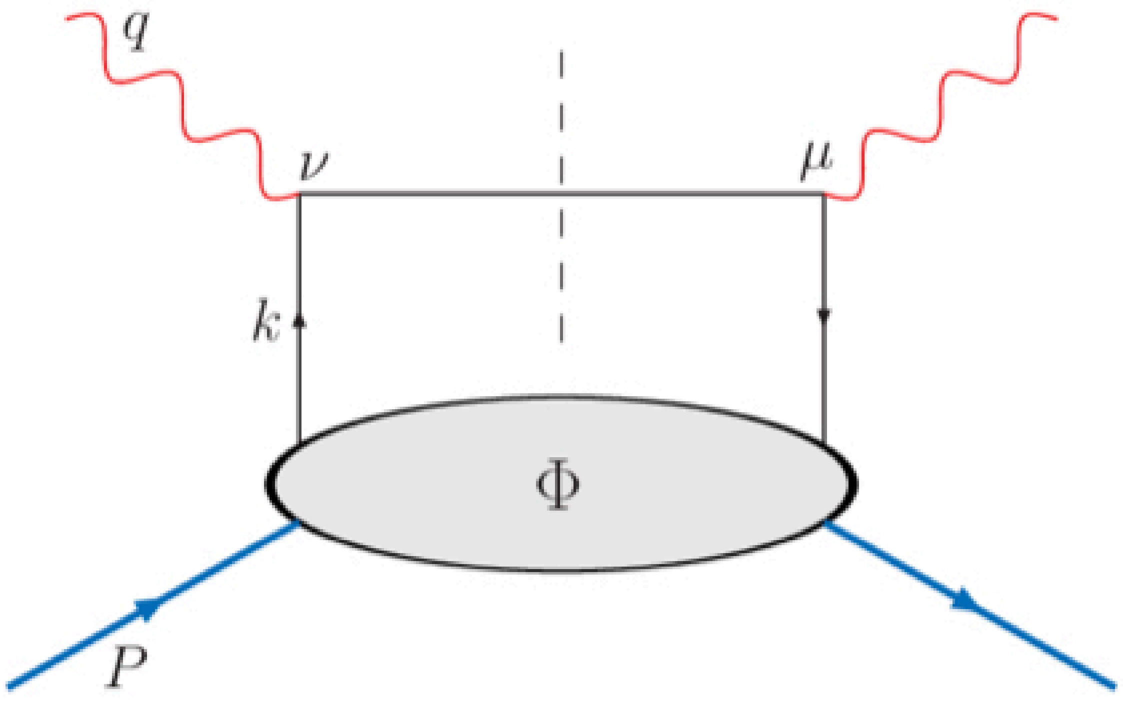

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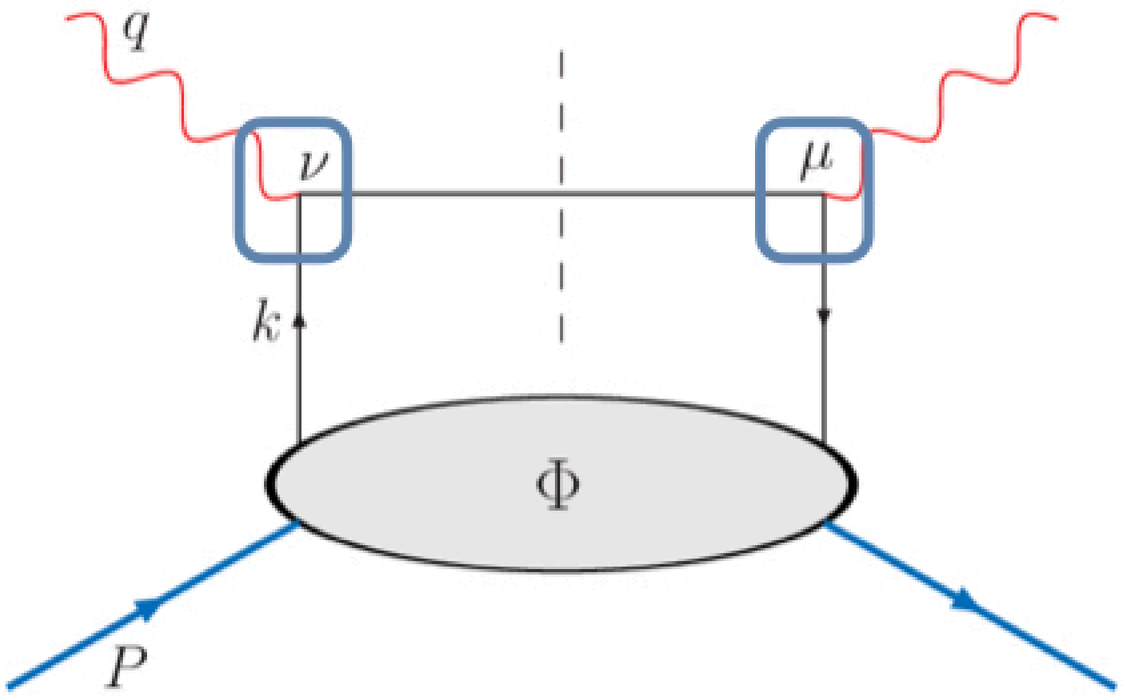

Vertices of the interactions

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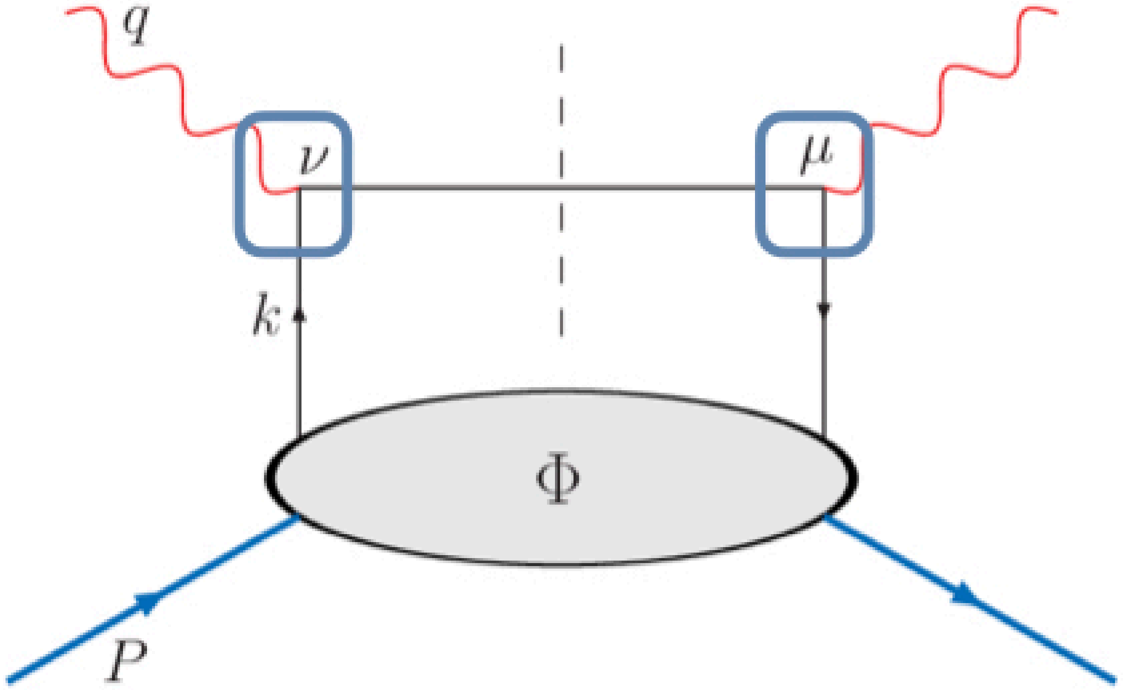

Vertices of the interactions

P-odd structures already present in the hadronic tensor!

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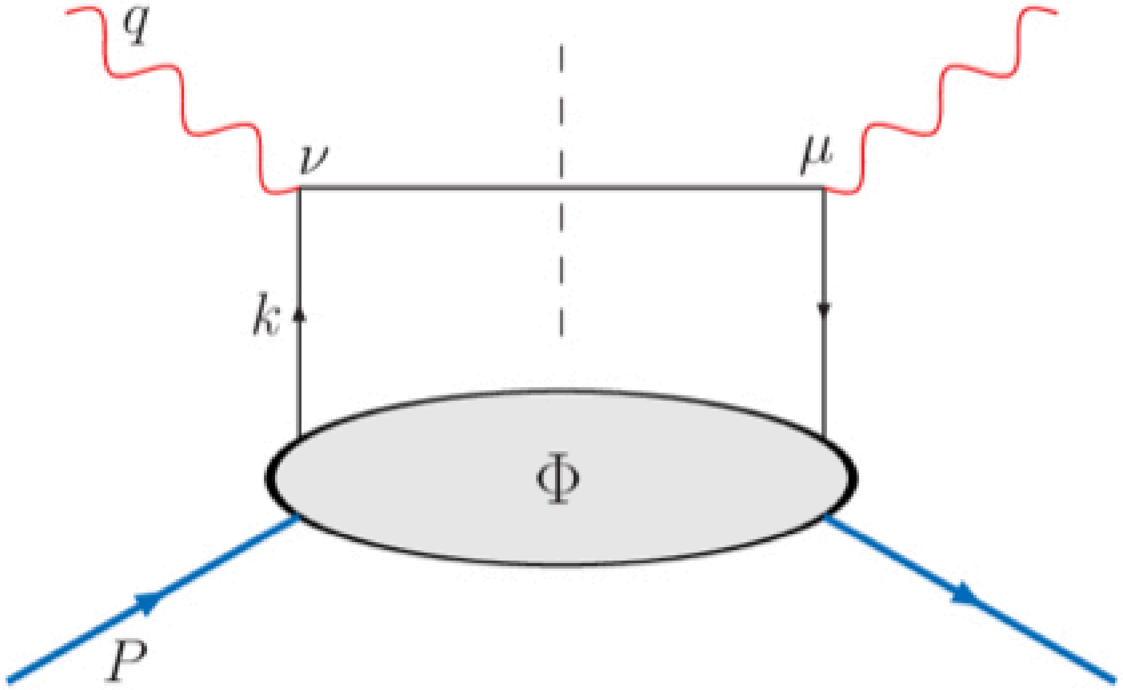

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Correlation distribution function

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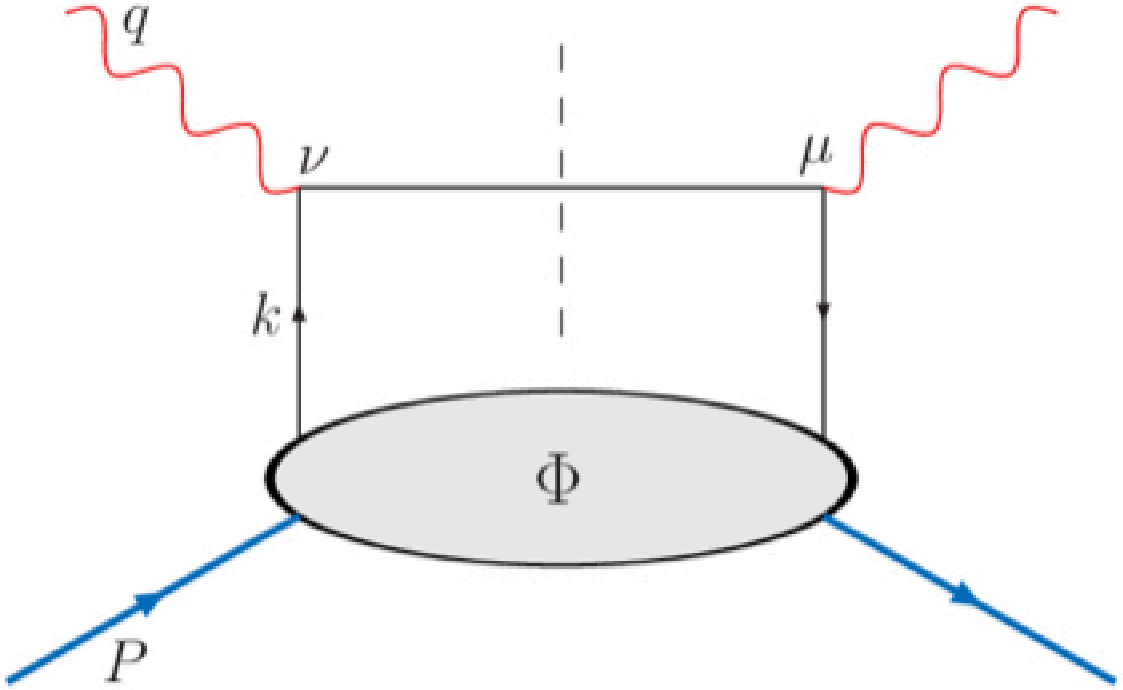

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$$\Phi_{ij}(k,P,S) = \int \frac{d^4\xi}{(2\pi)^4} e^{ik\cdot\xi} \langle P|\bar{\psi}_i(0)U(0,\xi)\psi_i(\xi)|P\rangle$$

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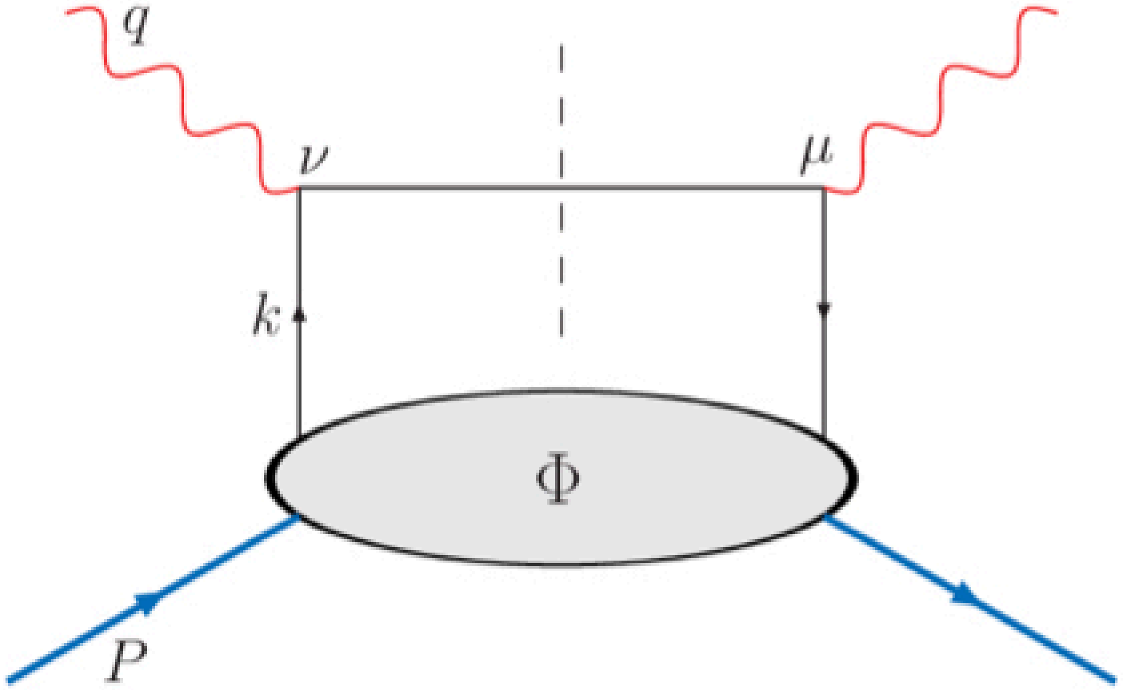

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Decomposition in partonic densities

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

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Lorenz scalar	Lorenz scalar
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Leading twist contributions

Partonic correlator (unpolarized)

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Leading twist contributions

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

Partonic correlator (unpolarized)

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

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Partonic correlator (unpolarized)

Integrated correlator

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

$$\Phi_{\rm PV}(x) \simeq \frac{1}{2} g_1^{\rm PV}(x)\gamma^5\gamma^-$$

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

Neutral-current DIS

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

$$\frac{d\sigma^{\pm}}{dxdy} = \frac{2\pi\alpha^2}{xyQ^2}\left[Y_+ F_2^{\pm} - y^2 F_L^{\pm} \mp Y_- x F_3^{\pm}\right]$$

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

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

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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

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Standard DIS structure functions

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Standard DIS structure functions

$$F_{2UU}(x,Q^2) = F_2^{(\gamma)} - g_V^e \eta_{\gamma Z} F_2^{(\gamma Z)} + \left({g_V^e}^2 + {g_A^e}^2\right)\eta_Z F_2^{(Z)},$$

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

$$xF^{\pm}_{3UU}(x,Q^2) = \mp g_A^e \eta_{\gamma Z} xF_3^{(\gamma Z)} \pm 2 g_V^e g_A^e \eta_Z xF_3^{(Z)},$$

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

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Phenomenology

Experimental observable

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)

Experimental observable

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

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

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

Experimental observable

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)

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

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

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

Available experimental data

HERA dataset
(Run I + II combined)

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

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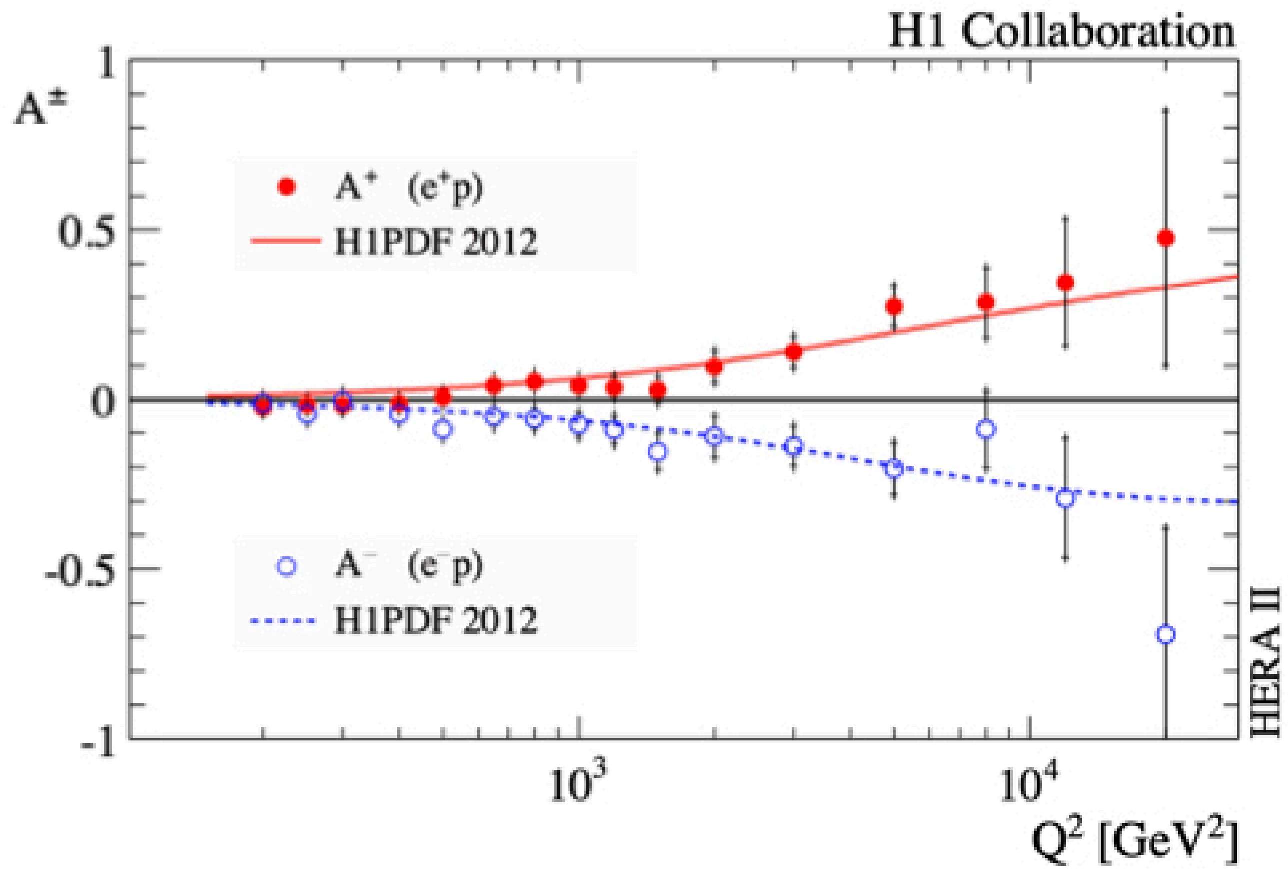
e^+ ***asymmetry: 136 data***

e^- ***asymmetry: 138 data***



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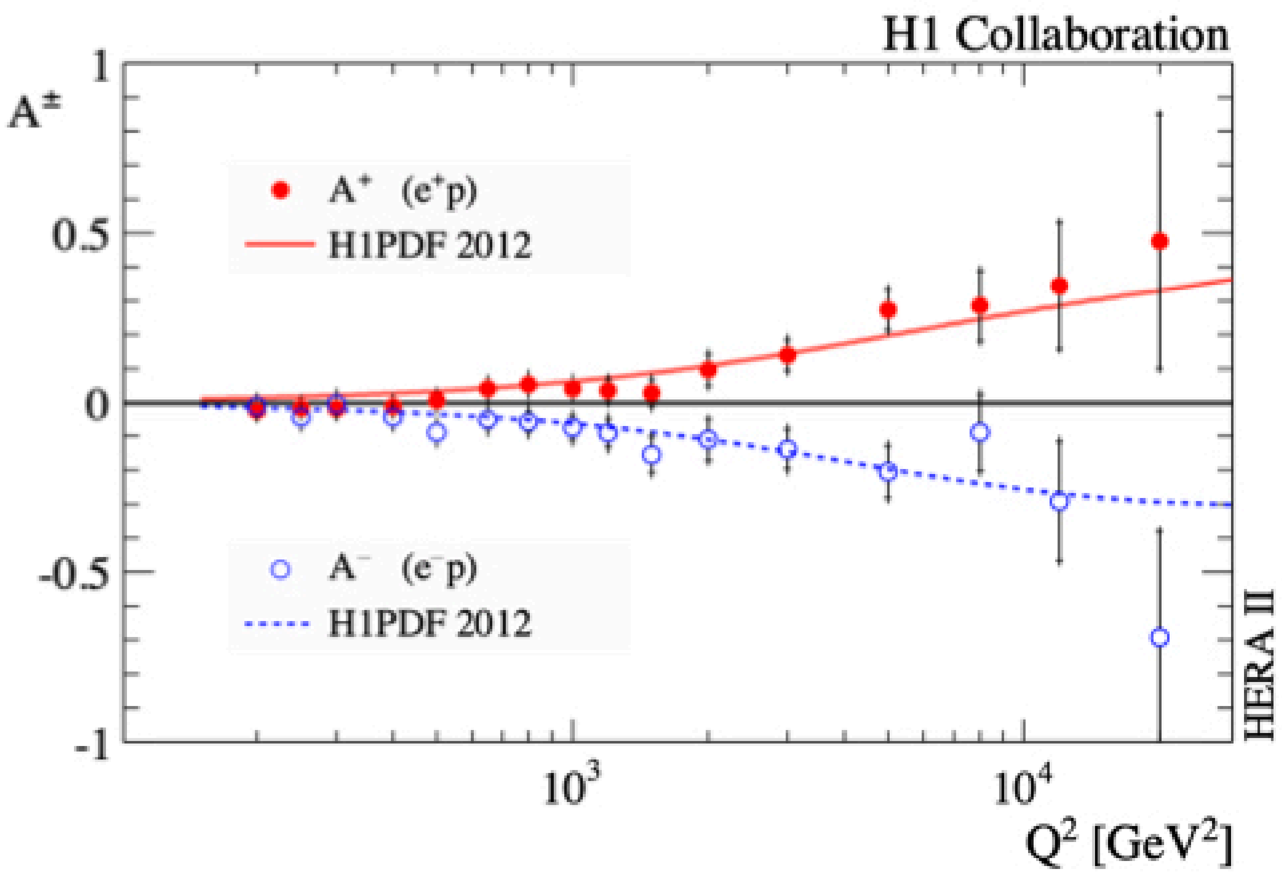

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JLab6 PVDIS dataset

PVDIS Collaboration, *Nature* 506 (2014)
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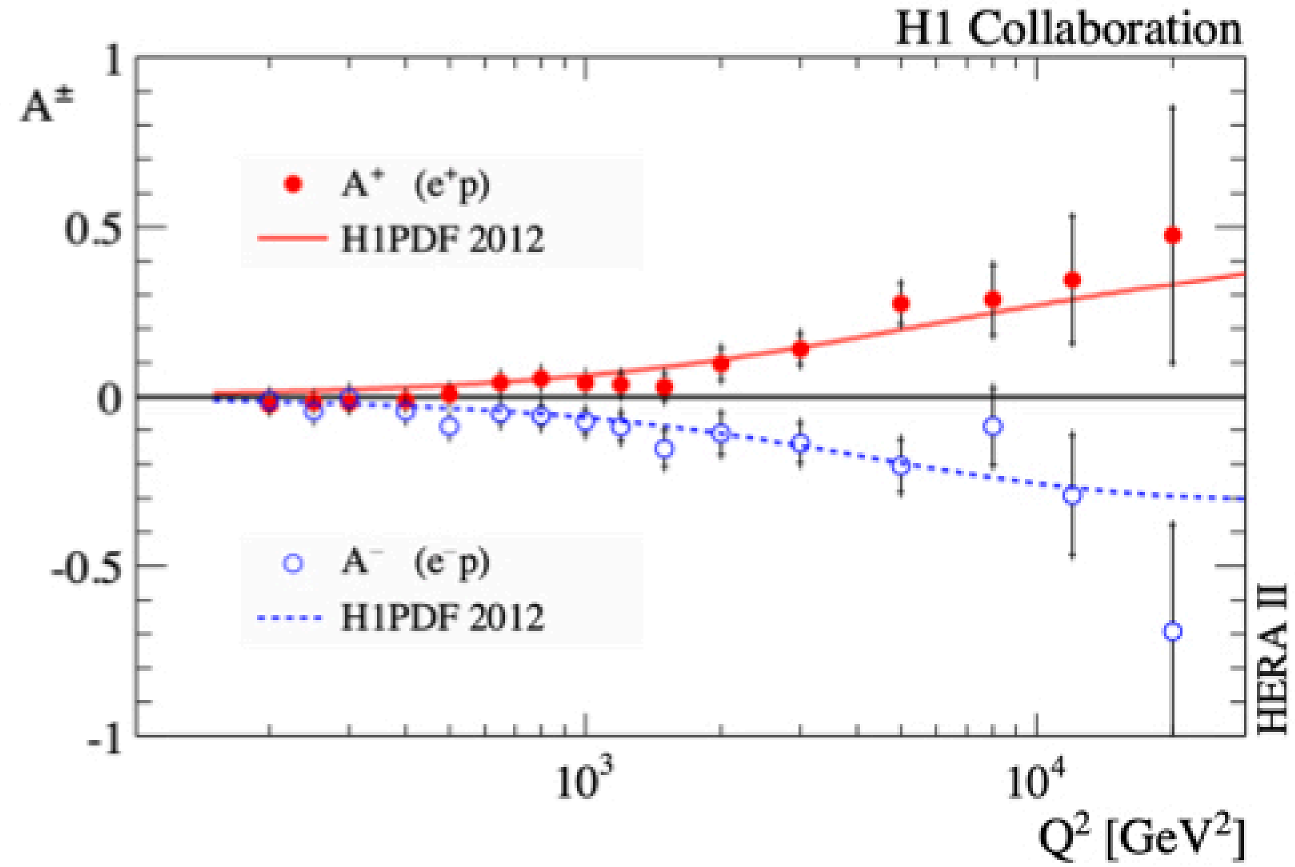

JLab6 PVDIS dataset

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

e^- ***asymmetry: 2 data***

Available experimental data

HERA dataset
(Run I + II combined)

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

e^+ **asymmetry: 136 data**

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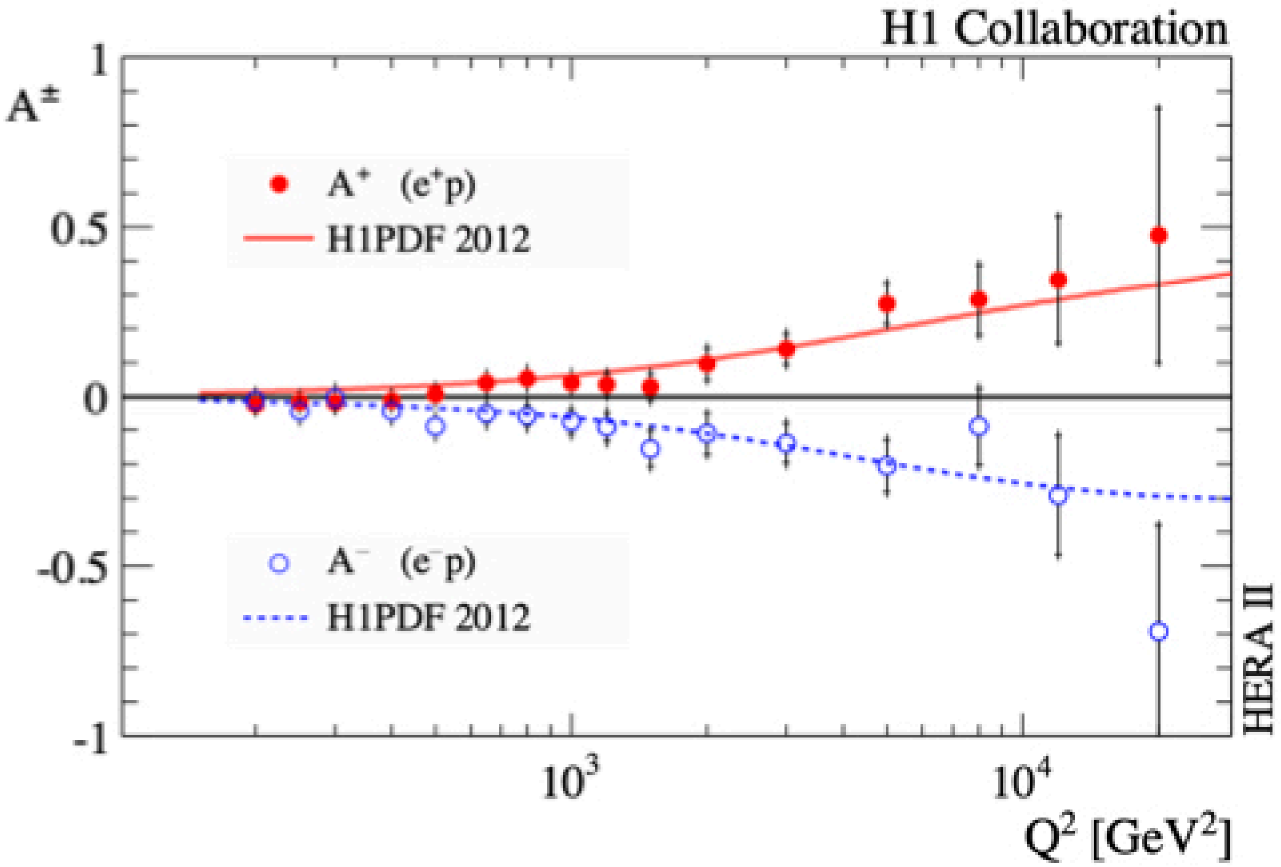

JLab6 PVDIS dataset

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

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SLAC-E122 dataset

C.Y. Prescott et al., Phys. Lett. B (1979)

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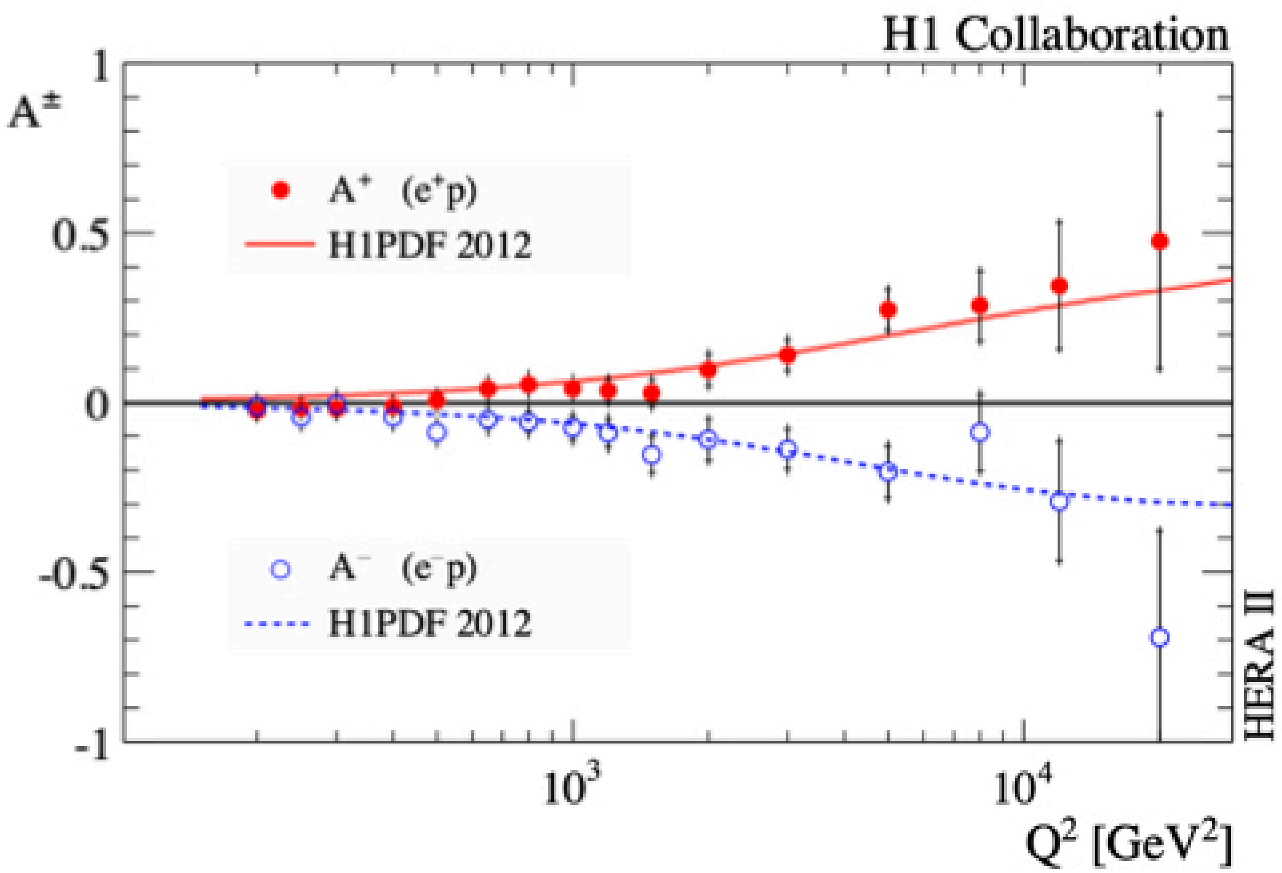

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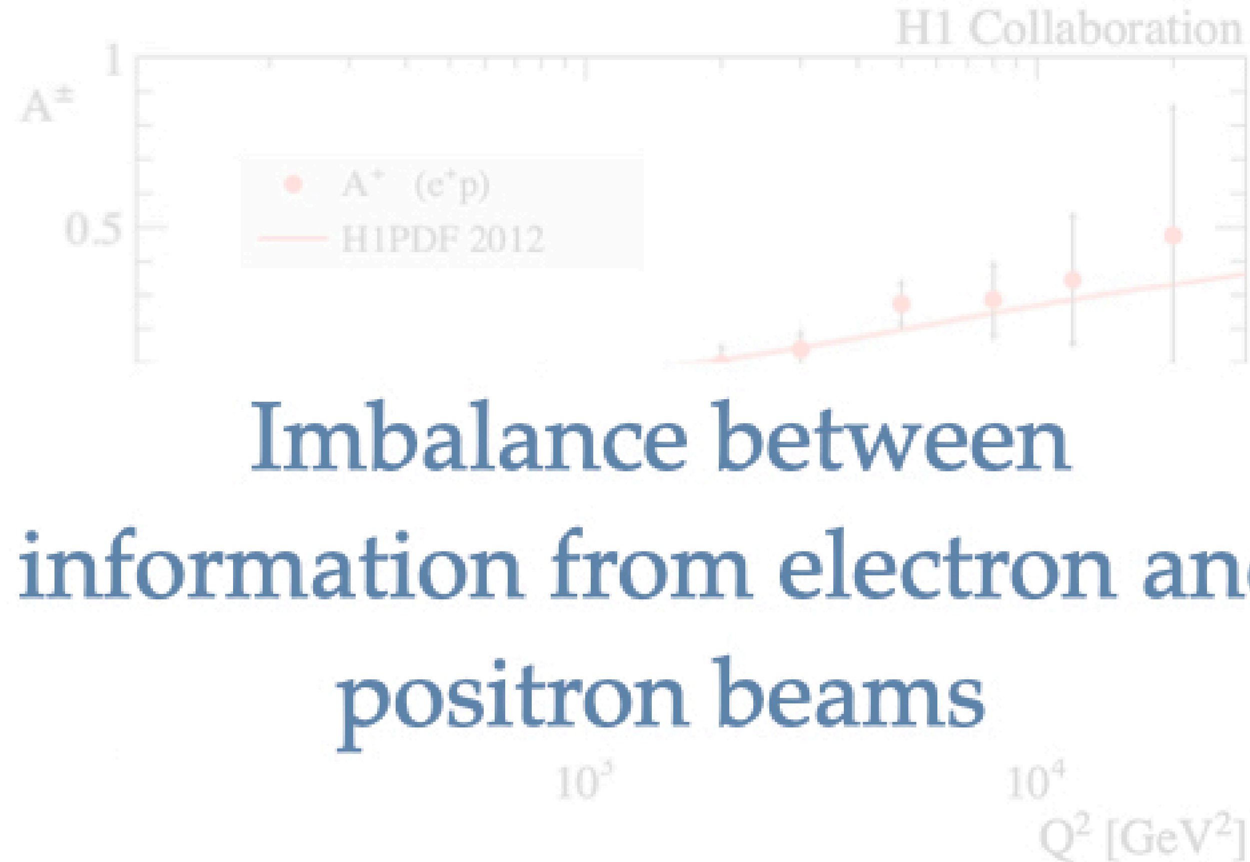

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Imbalance between information from electron and positron beams

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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) \\
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\end{aligned}
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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}
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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

PDF set for

Error propagation

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

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

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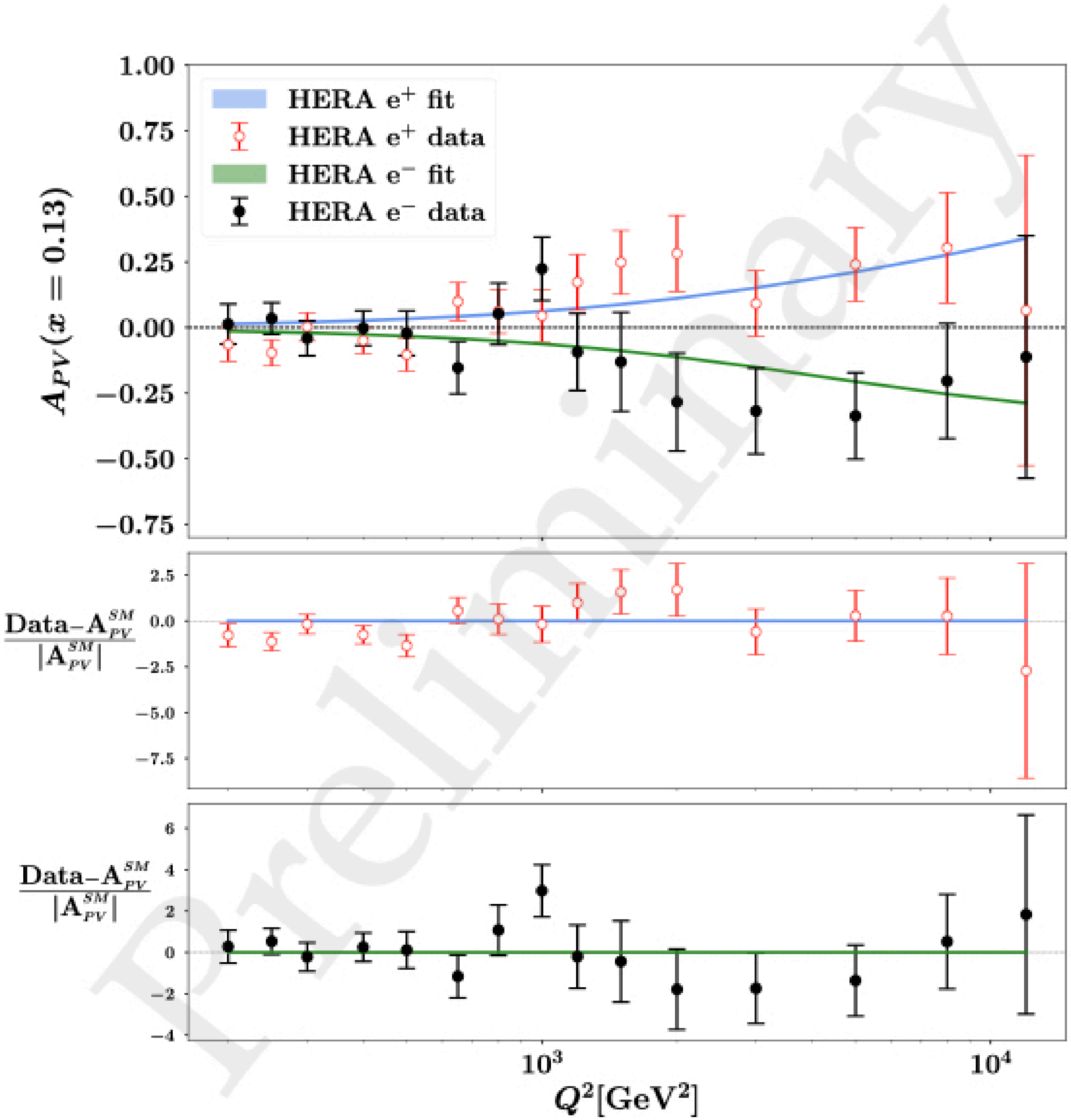
Statistical distribution of 100 values of parameter α

Results of the fit: χ^2 values

Fit **WITH** EW radiative corrections

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

Results of the fit: data-theory comparison



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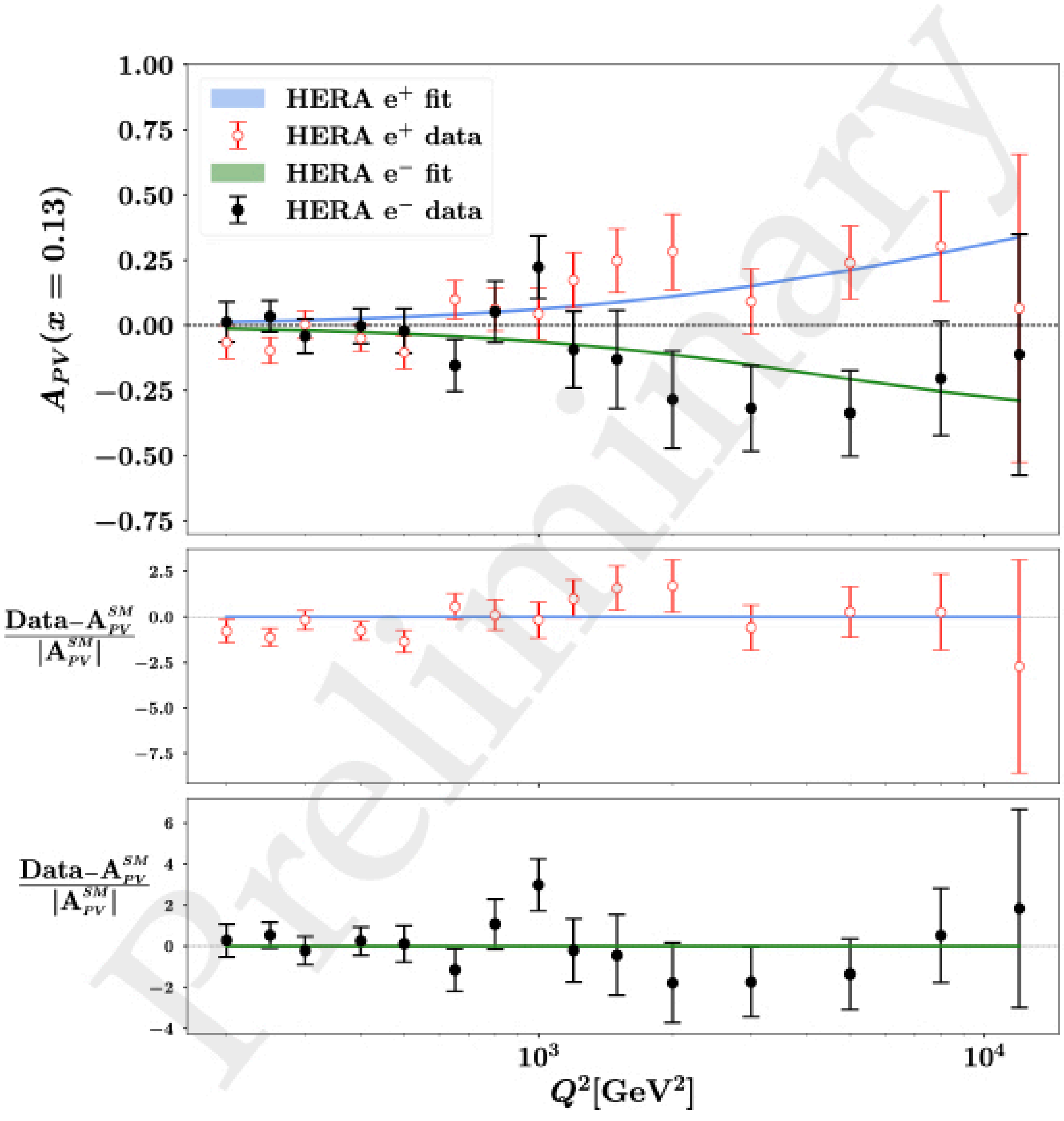

Very small uncertainties in the predictions because the fit is dominated by data with smaller errors

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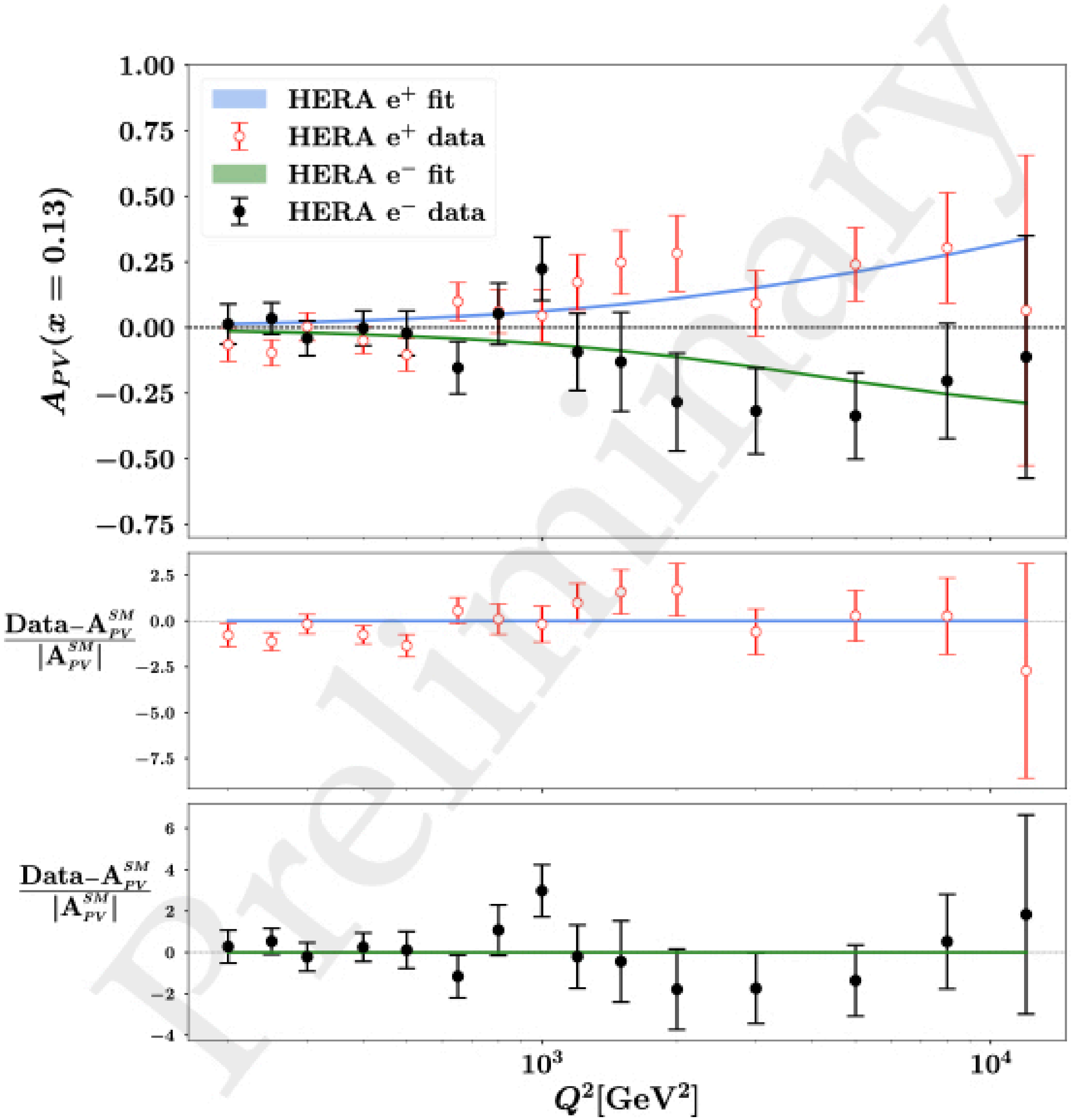

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There's room for a better description for positron asymmetry at low-Q

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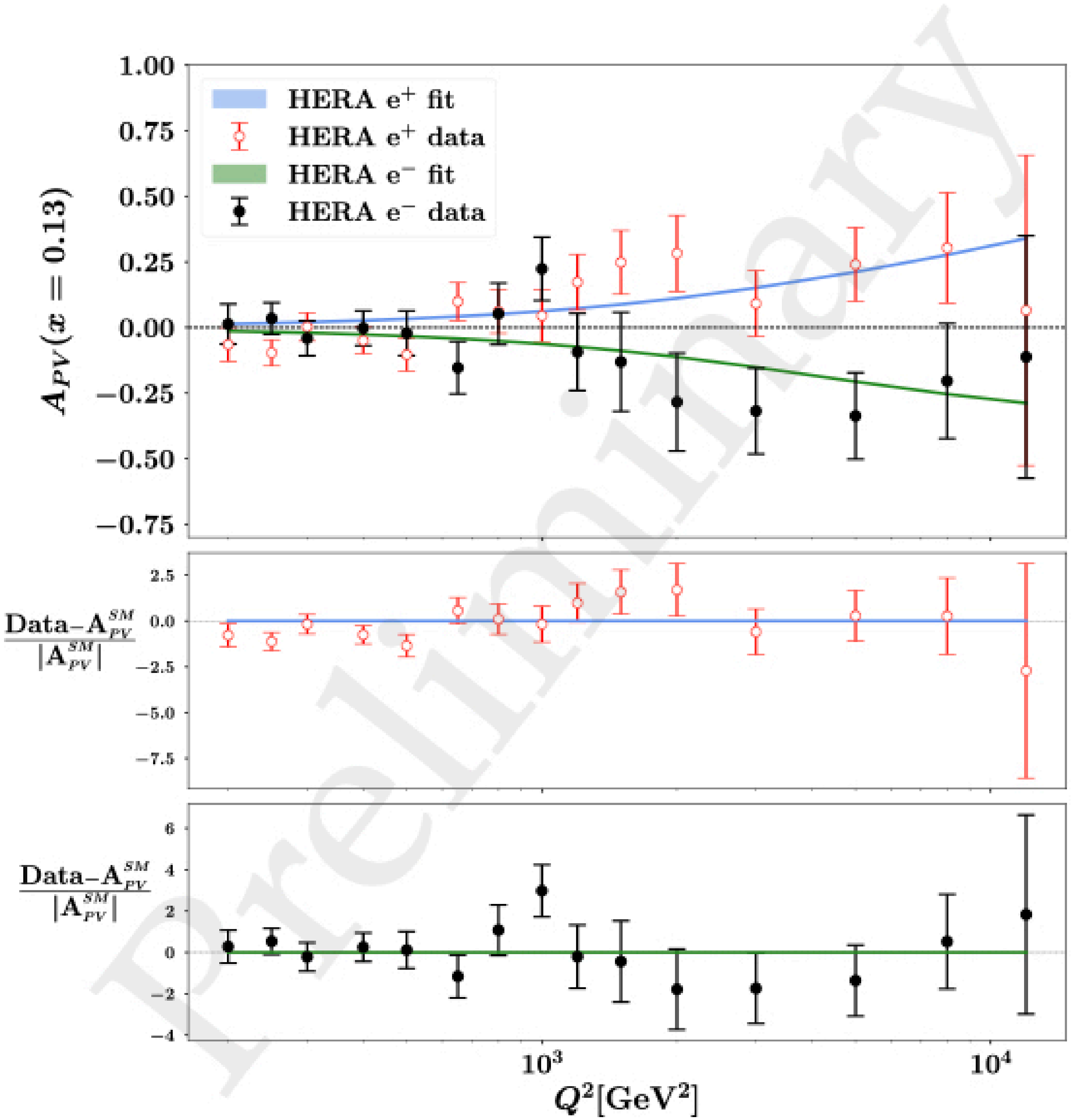

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There's room for a better description for positron asymmetry at low-Q

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

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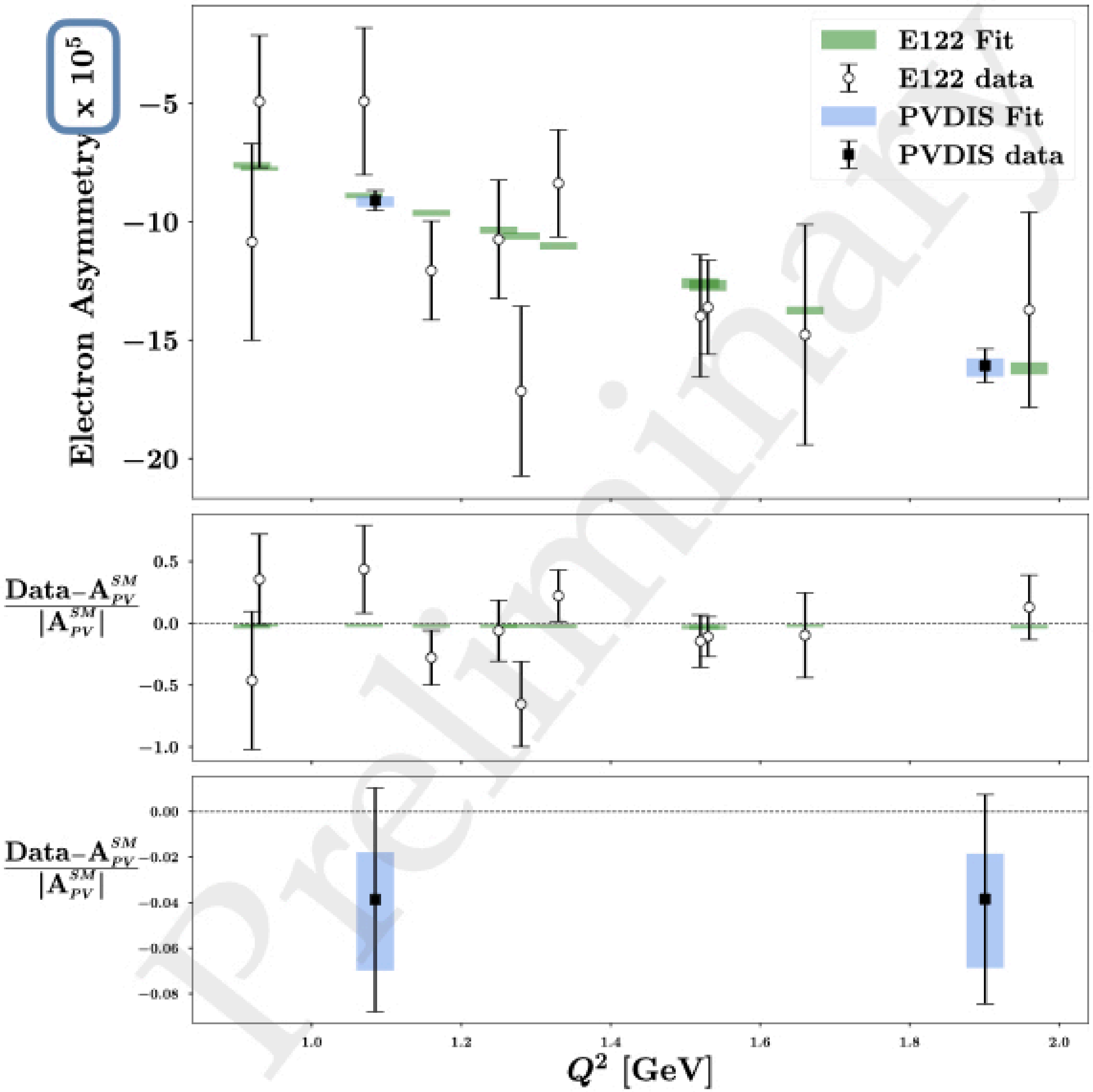

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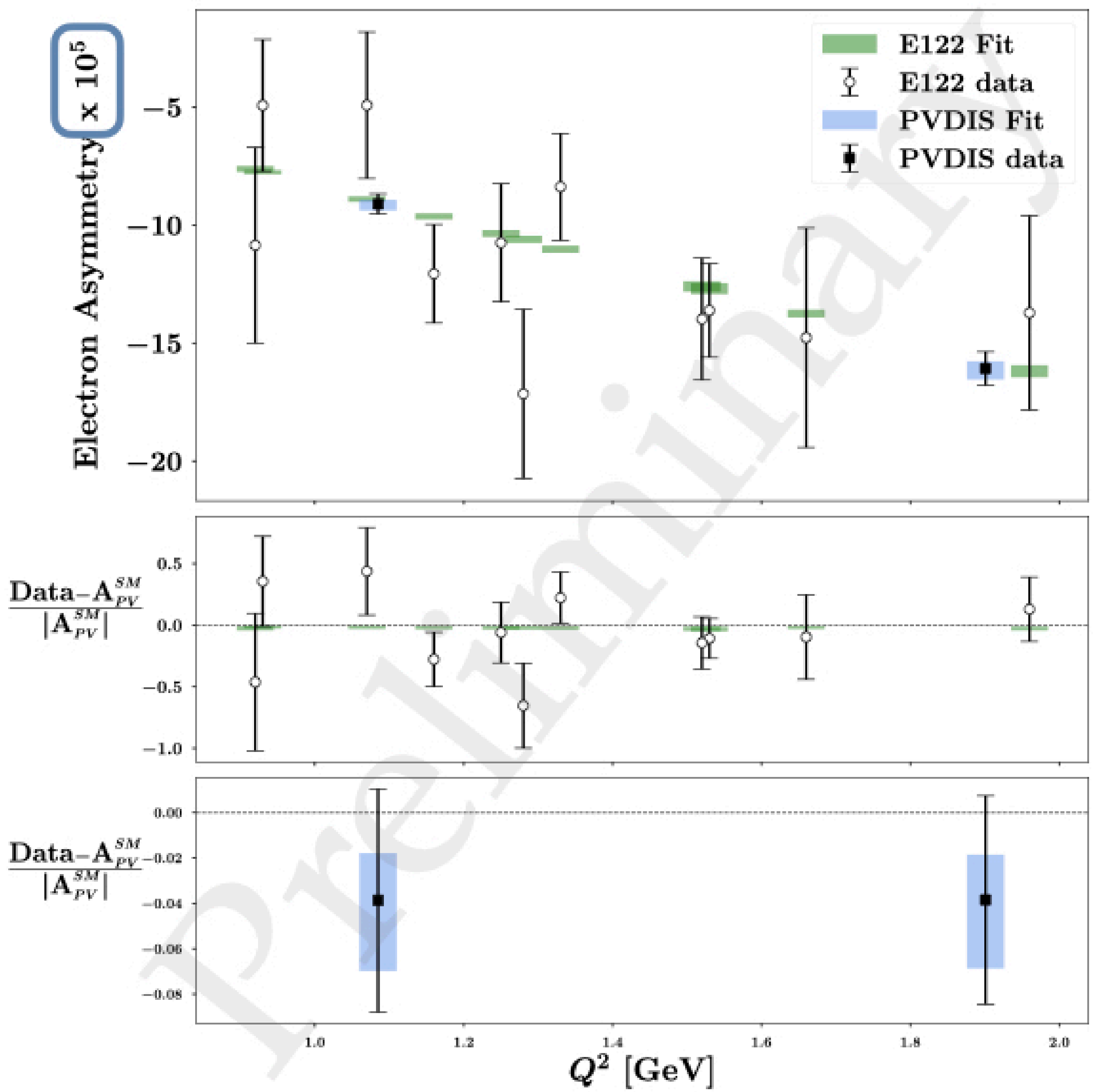

Sizeable improvement of the fit w.r.t. SM predictions

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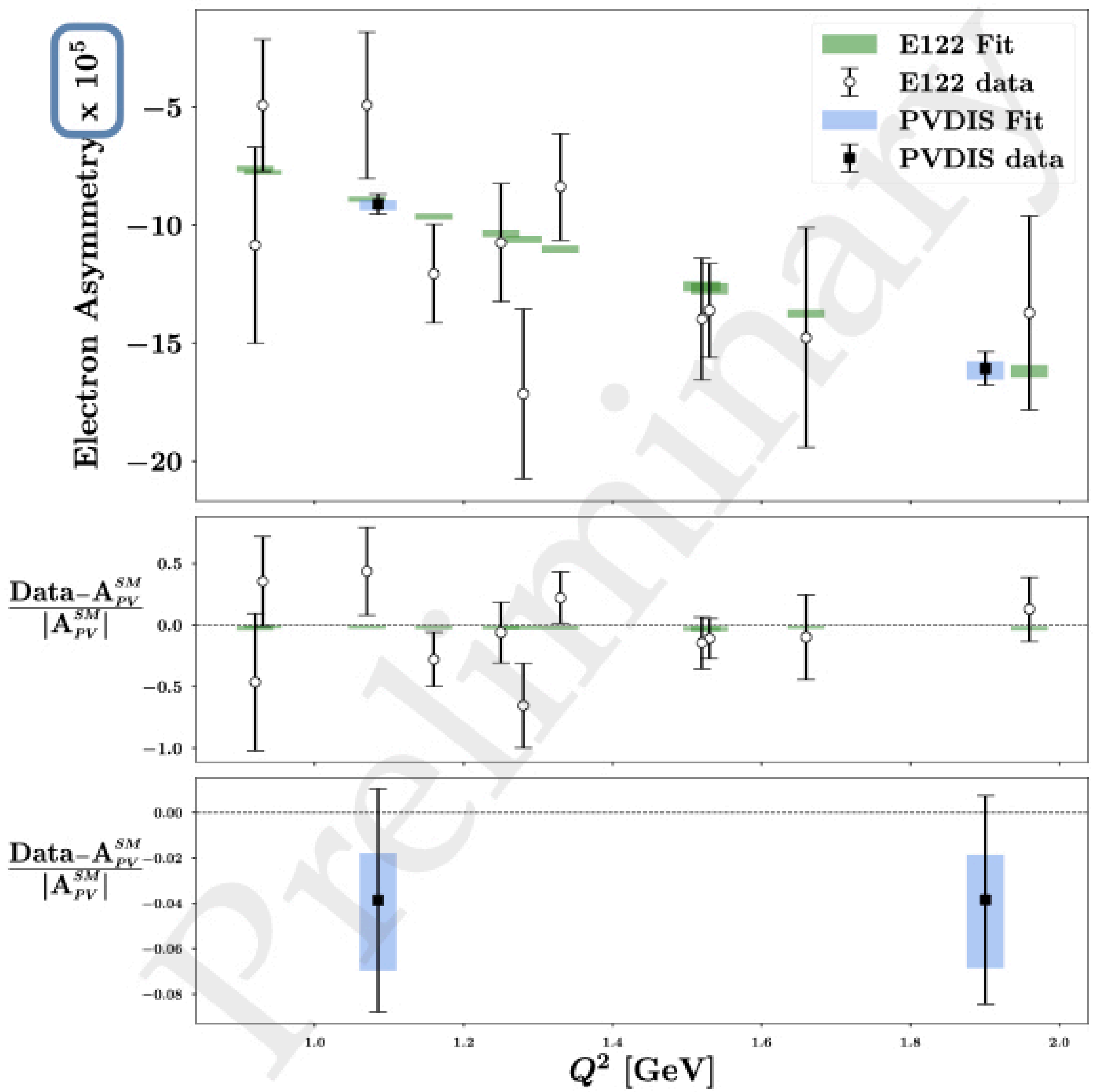

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Old dataset with still quite large experimental errors (> 20 %)

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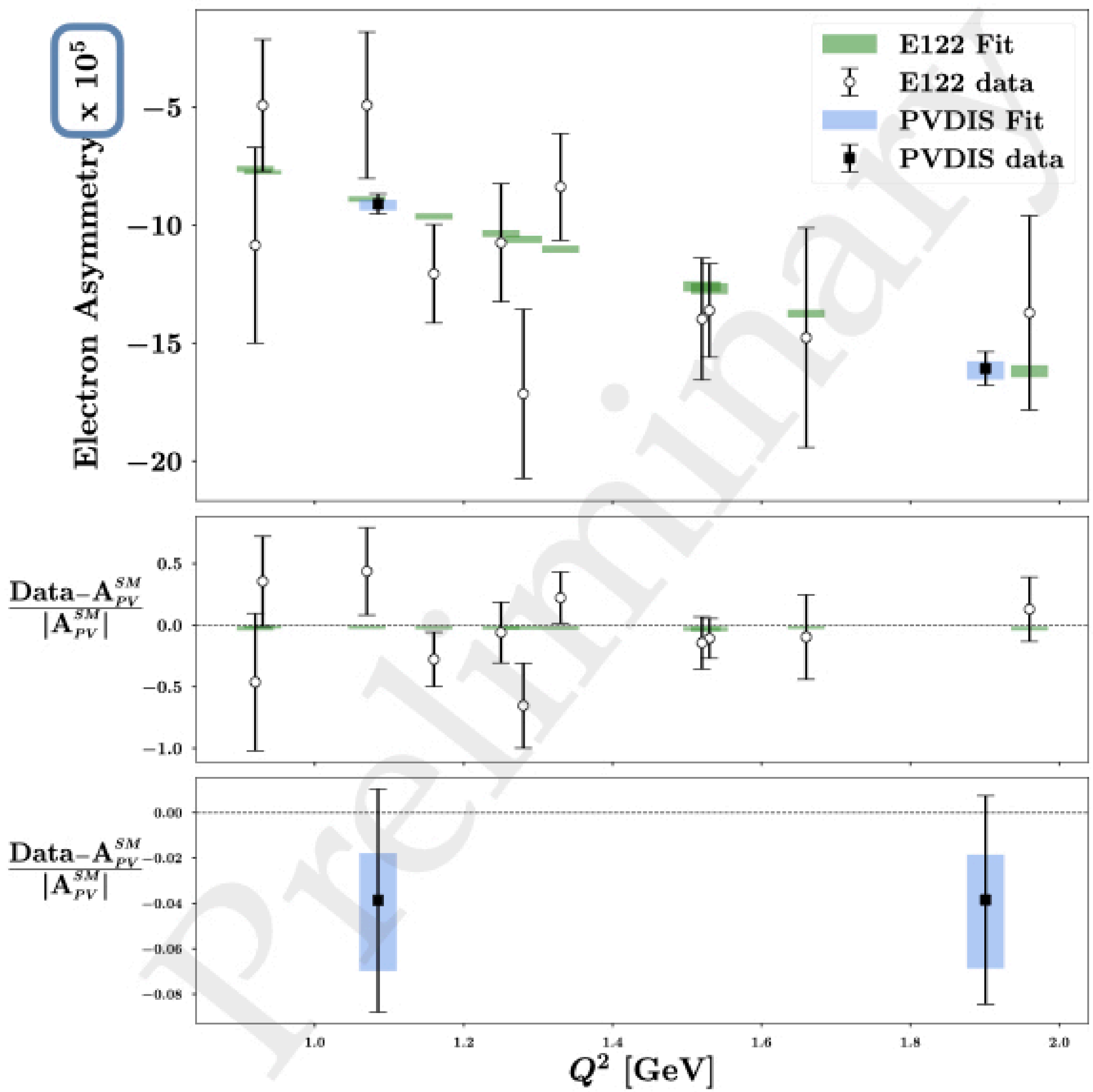

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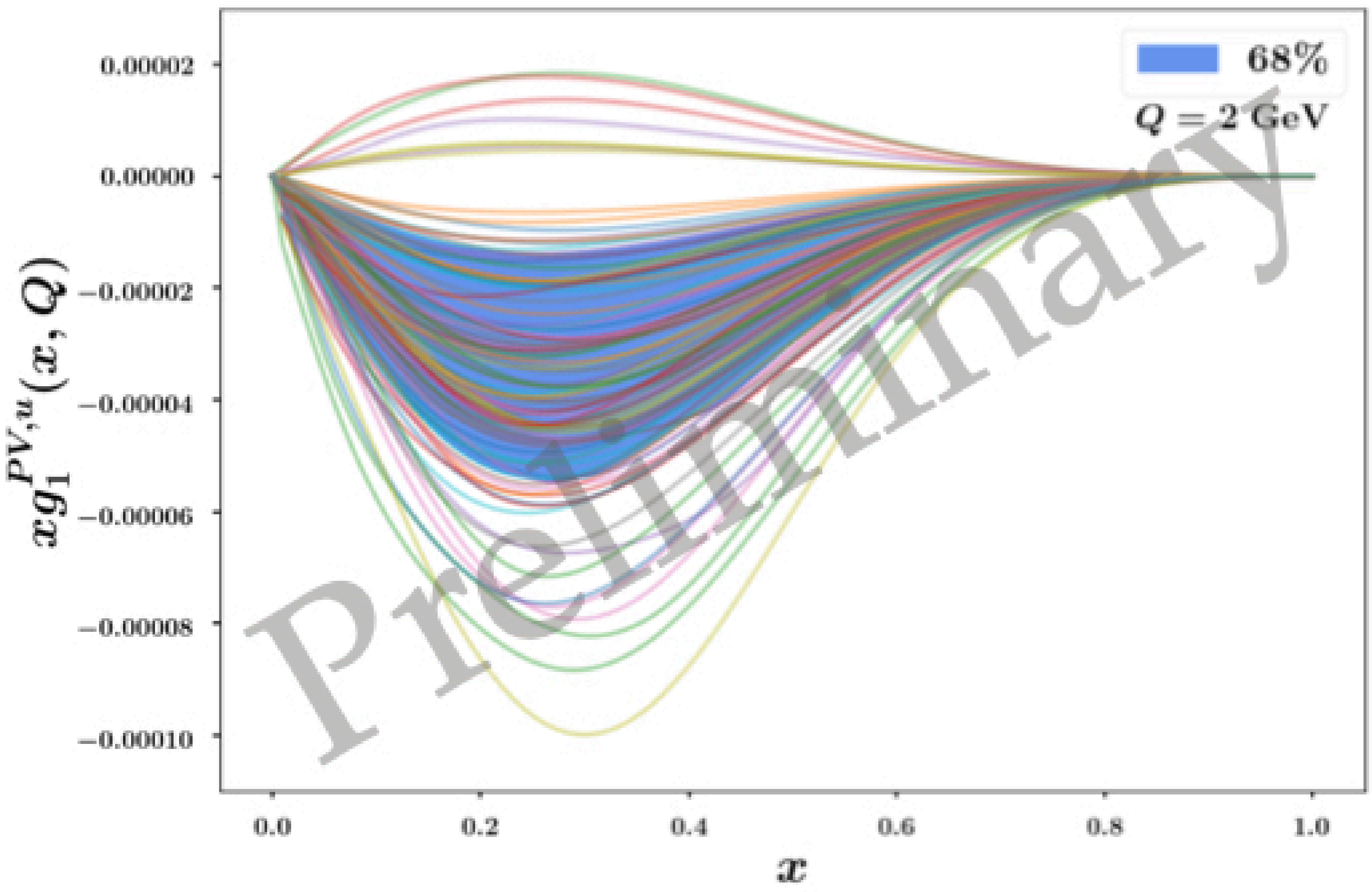
Old dataset with still quite large experimental errors (> 20 %)

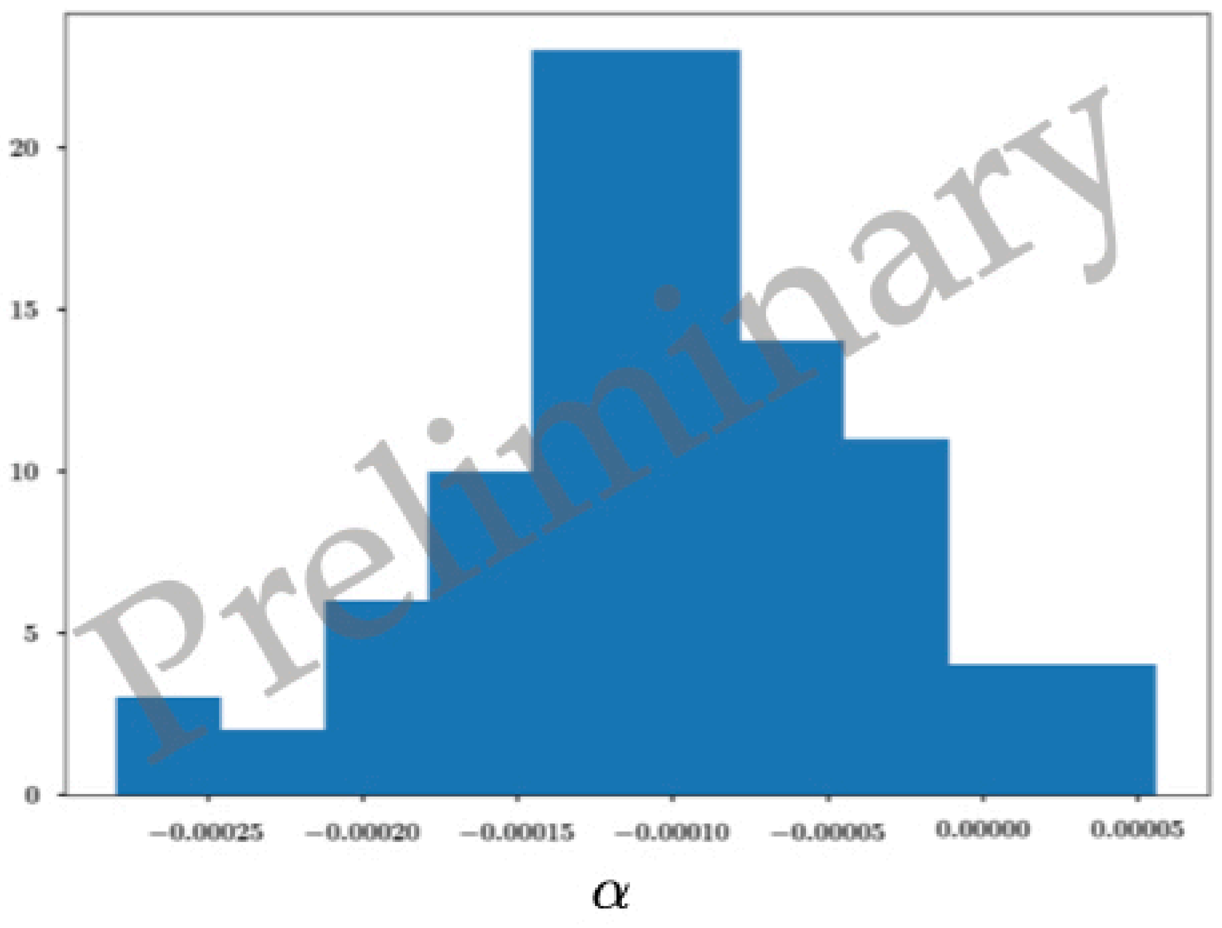
Data points which actually drive the fit due to very small experimental errors (~ %)

Results of the fit: $g_1^{PV}(x, Q^2)$ extraction

$$g_1^{\mathrm{PV}}(x) = \alpha \; g_1(x)$$

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





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- A fit of present experimental data is compatible with a non-zero contribution from a new strong PV parton density at more than 1 sigma
- To better investigate its behaviour, new data are needed especially at small (medium) values of Q
- Experimental data from positron beam are welcome to shed light on the complementarity with electron beam

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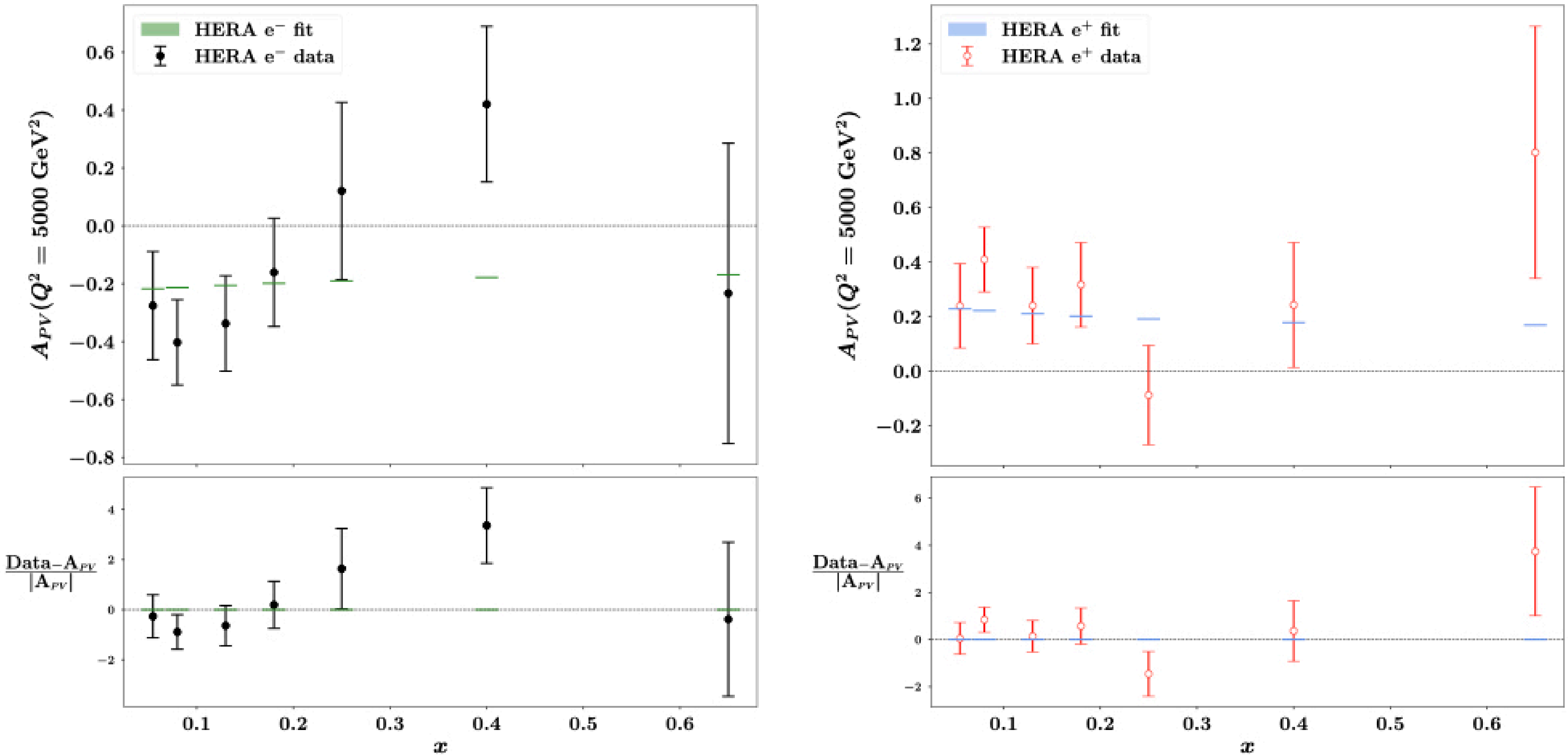
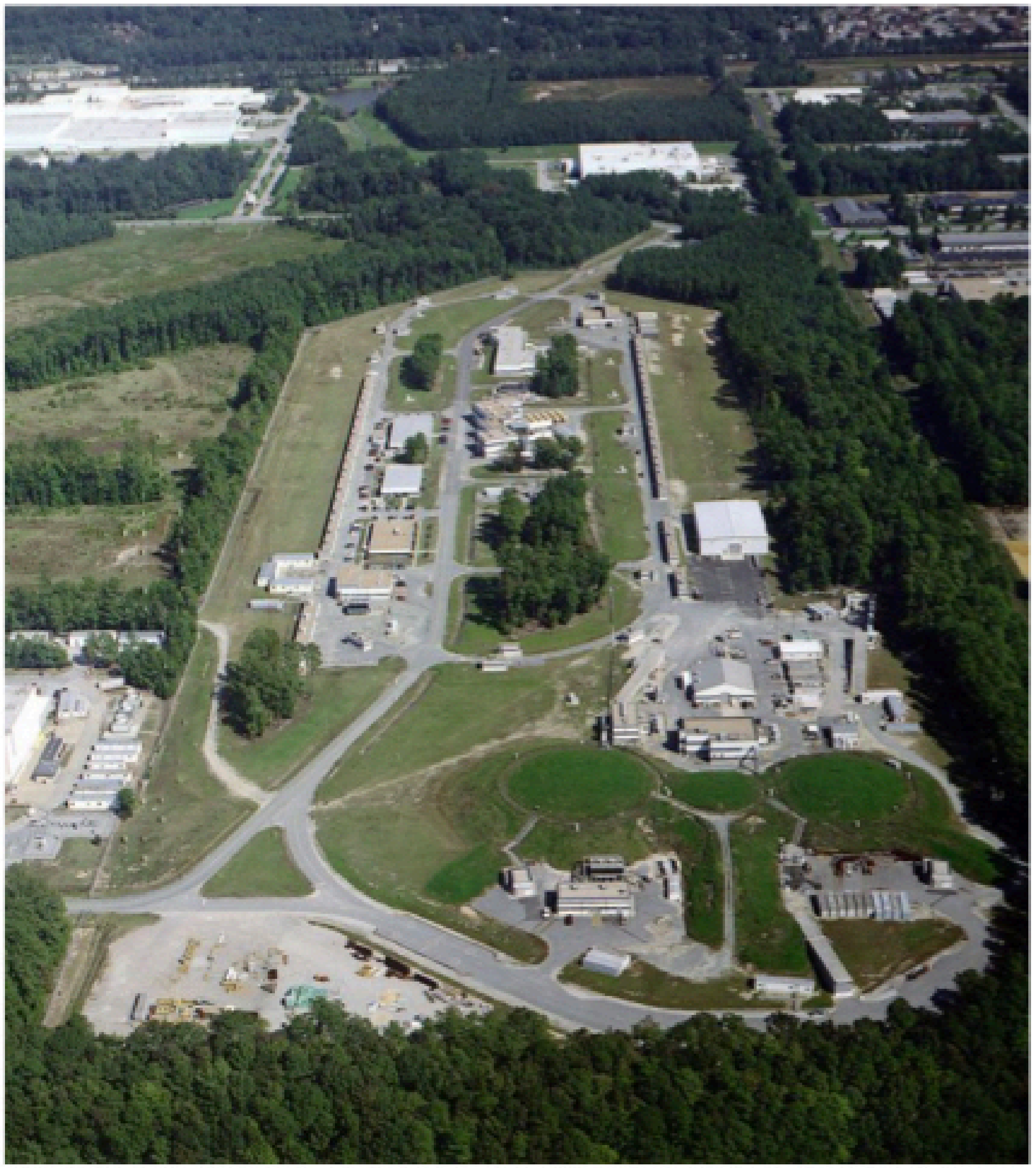
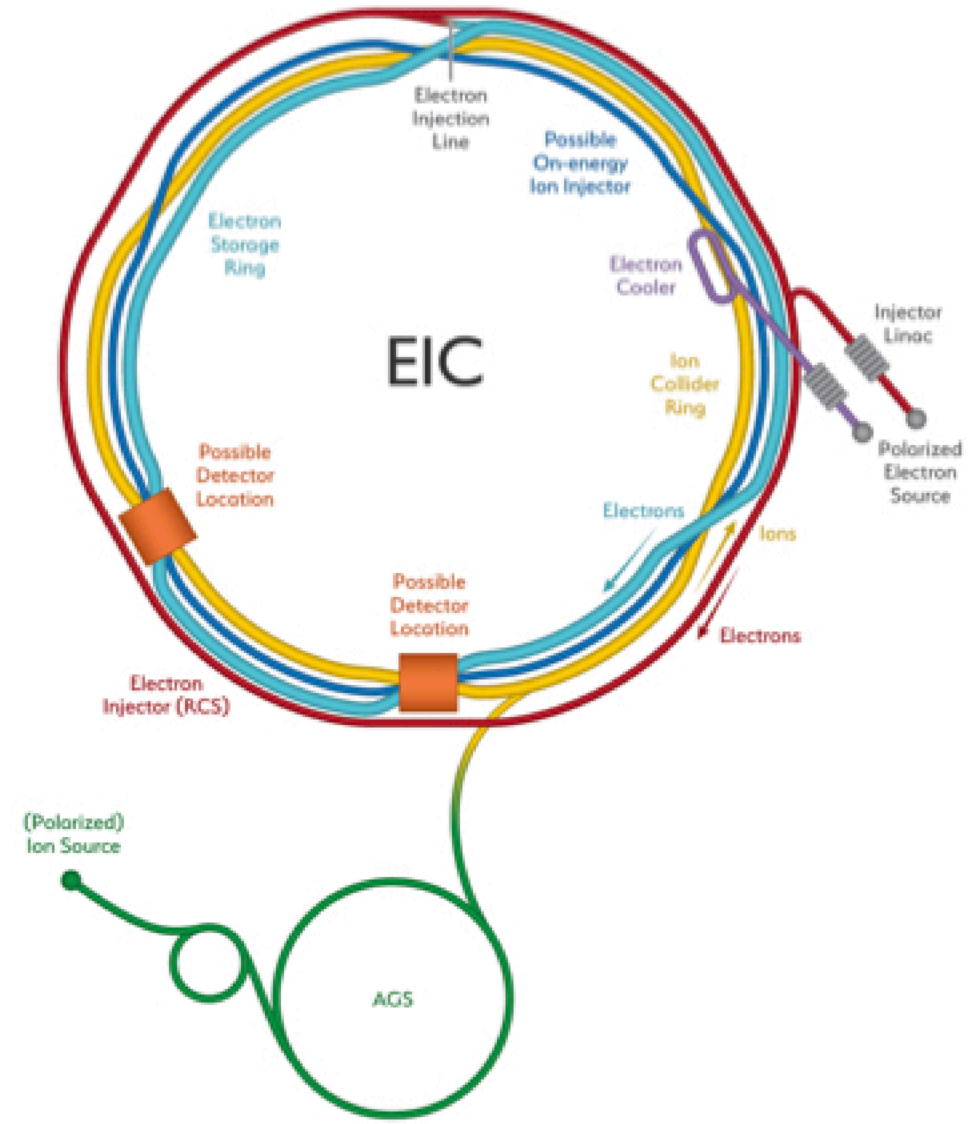


Conclusions and Outlook

- Predictions of the size of the PV distribution can be made in the kinematic domains of JLab12, JLab20+(?) and EIC





Conclusions and Outlook

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

$$\Phi^q(x,Q^2) = \Big\{ f_1^q(x,Q^2) + g_1^{\mathrm{PV}q}(x,Q^2)\gamma_5 \\ + S_L\Big(g_1^q(x,Q^2)\gamma_5 + f_{1L}^{\mathrm{PV}q}(x,Q^2)\Big) \\ - \not{S}_T\Big(h_1^q(x,Q^2)\gamma_5 - e_{1T}^{\mathrm{PV}q}(x,Q^2)\Big)\Big\}\frac{\not{n}_+}{2}$$

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

$$\Phi^q(x,Q^2) = \Big\{ f_1^q(x,Q^2) + g_1^{\mathrm{PV}q}(x,Q^2)\gamma_5 + S_L\Big(g_1^q(x,Q^2)\gamma_5 + \boxed{f_{1L}^{\mathrm{PV}q}(x,Q^2)}\Big) - \not{S}_T\Big(h_1^q(x,Q^2)\gamma_5 - e_{1T}^{\mathrm{PV}q}(x,Q^2)\Big)\Big\}\frac{\not{n}_+}{2}$$

$$\Delta x_B g_5(x_B,Q^2) \approx \Delta x_B g_5^{(\gamma)}(x_B,Q^2) = \frac{1}{2}\sum_q e_q^2 x_B f_{1L}^{\mathrm{PV}(q-\bar{q})}$$