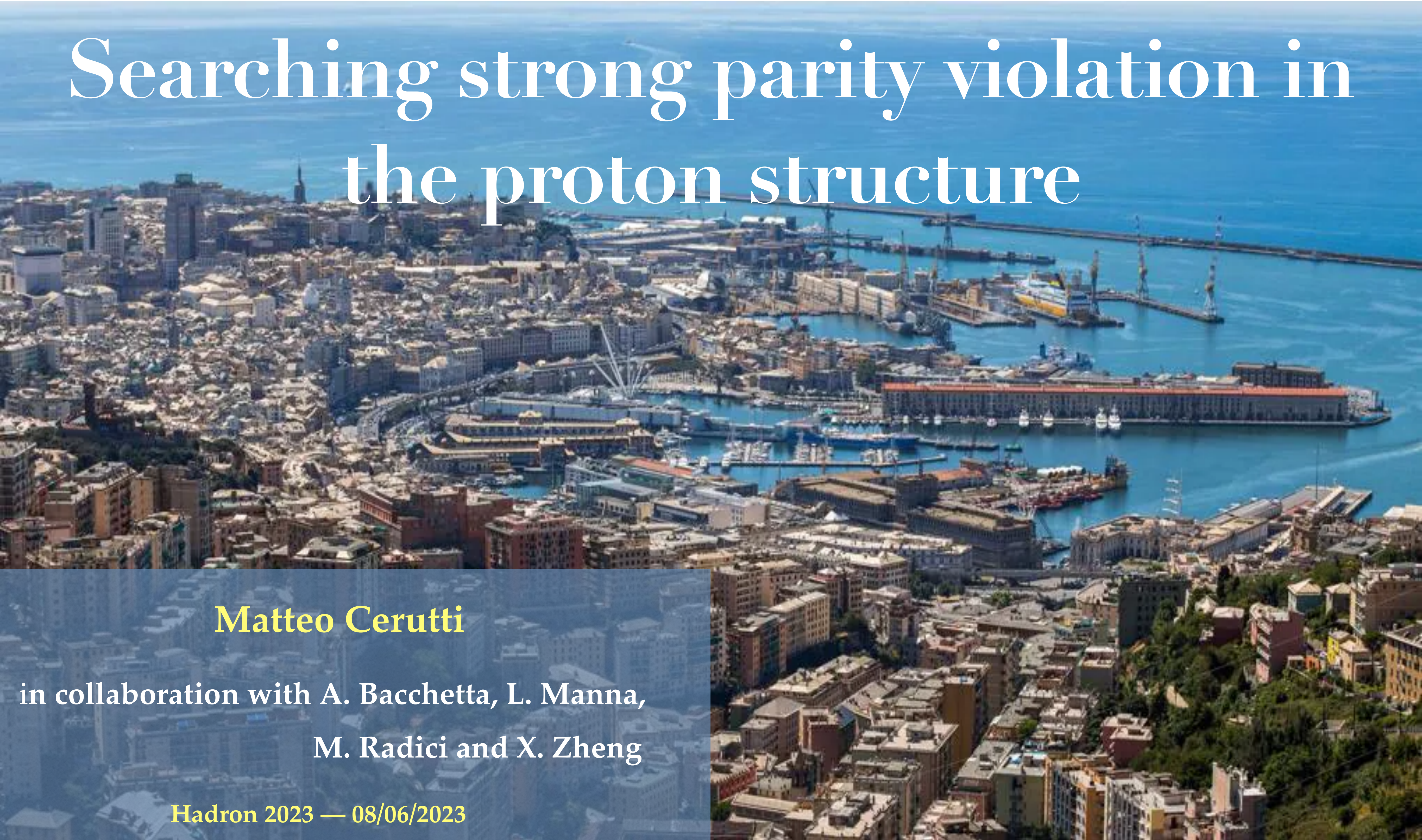
INFN Istituto Nazionale di Fisica Nucleare

HAS QCD HADRONIC STRUCTURE AND QUANTUM CHROMODYNAMICS

UNIVERSITÀ DI PAVIA



Searching strong parity violation in the proton structure

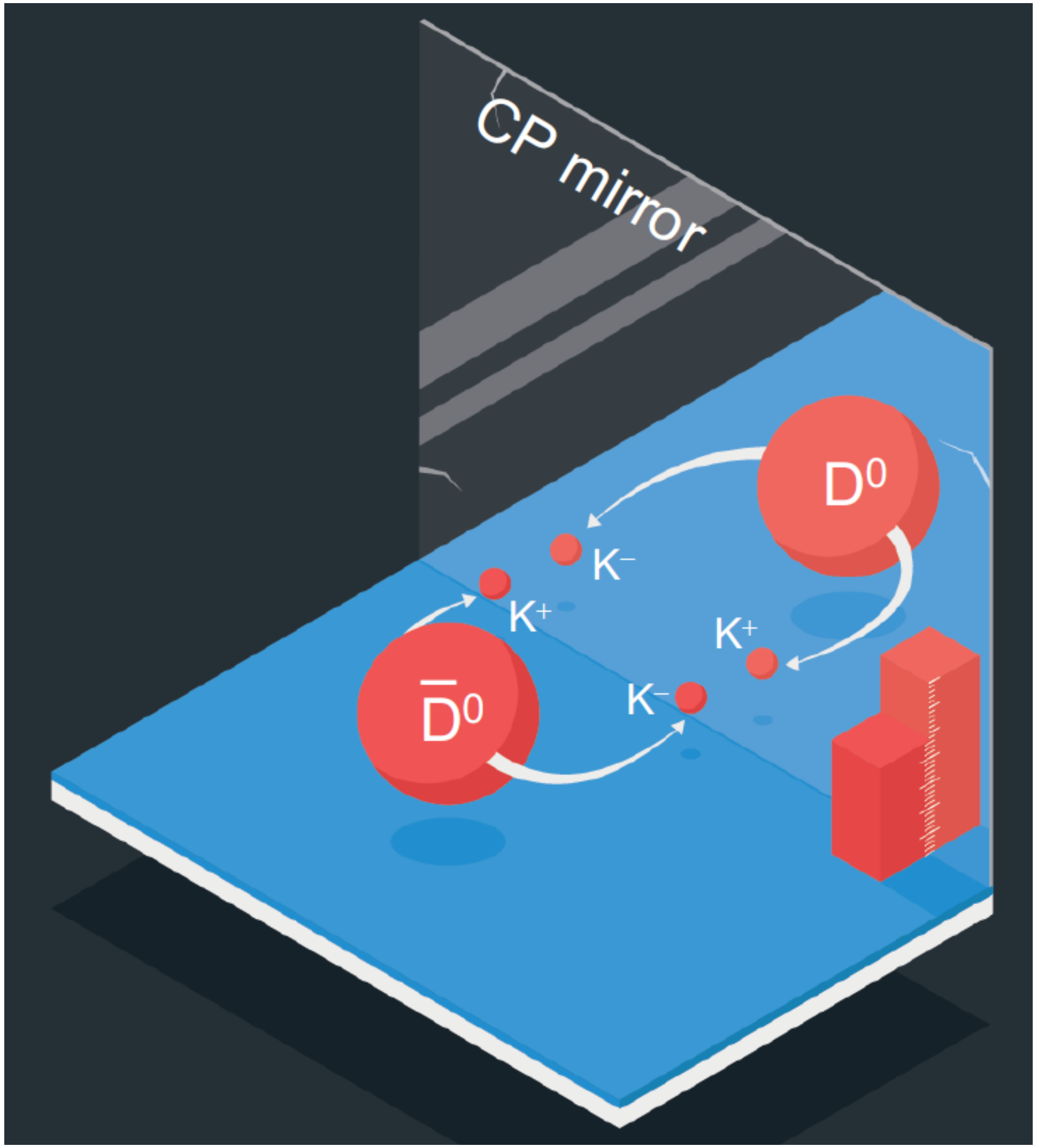
Matteo Cerutti

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

Hadron 2023 — 08/06/2023

Motivations

Investigation of the
"Strong CP problem"

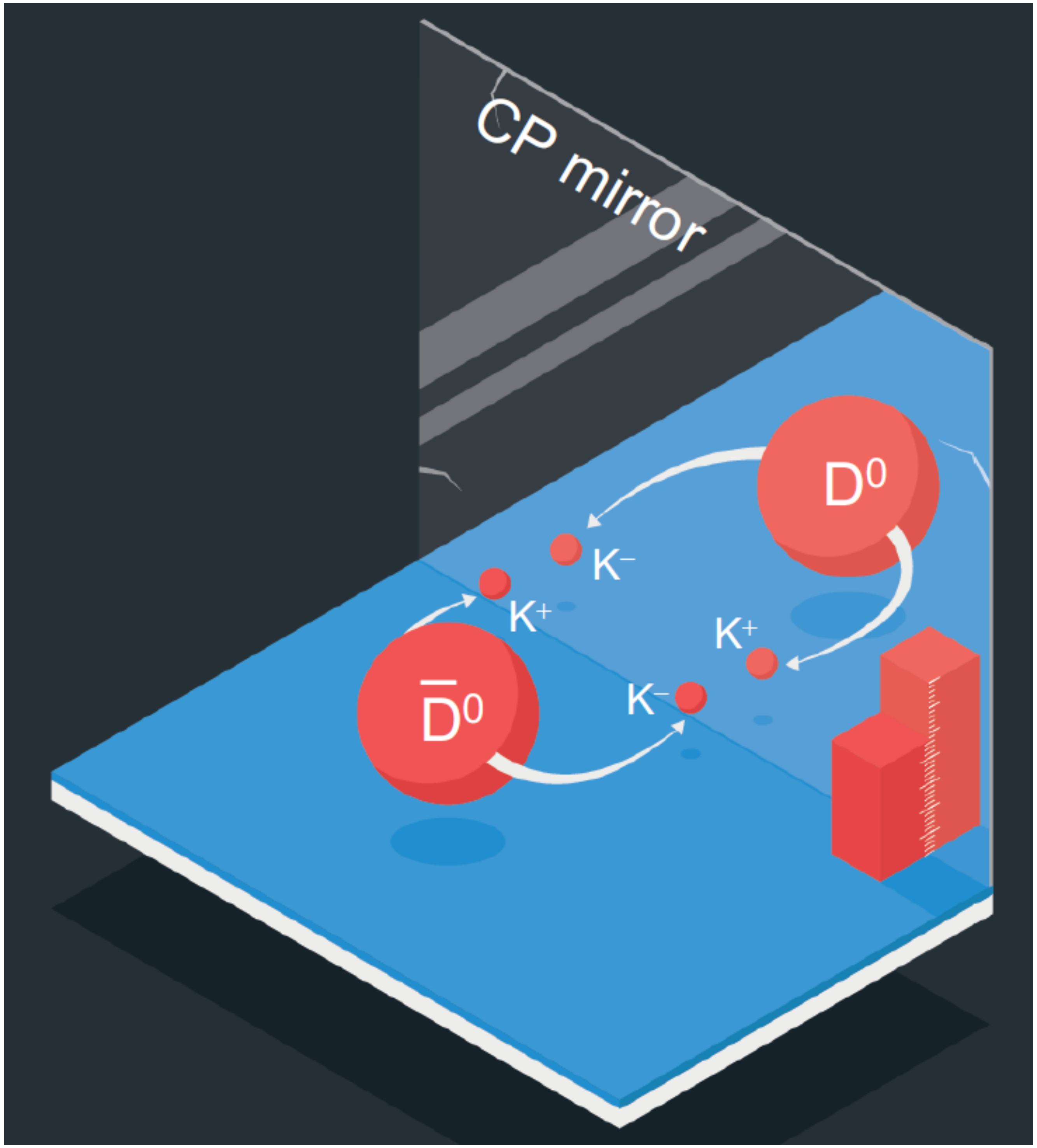


Motivations

Investigation of the
"Strong CP problem"

↓

Matter-Antimatter
imbalance



Motivations

EW sector

CP violation is included

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Weak CP

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too small…

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

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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

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QCD sector

Strong CP

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

θ-term

SMEFT operators

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Nucleon electric dipole moment

Motivations

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CP violation is included

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QCD sector

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

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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Terms from QCD sector

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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

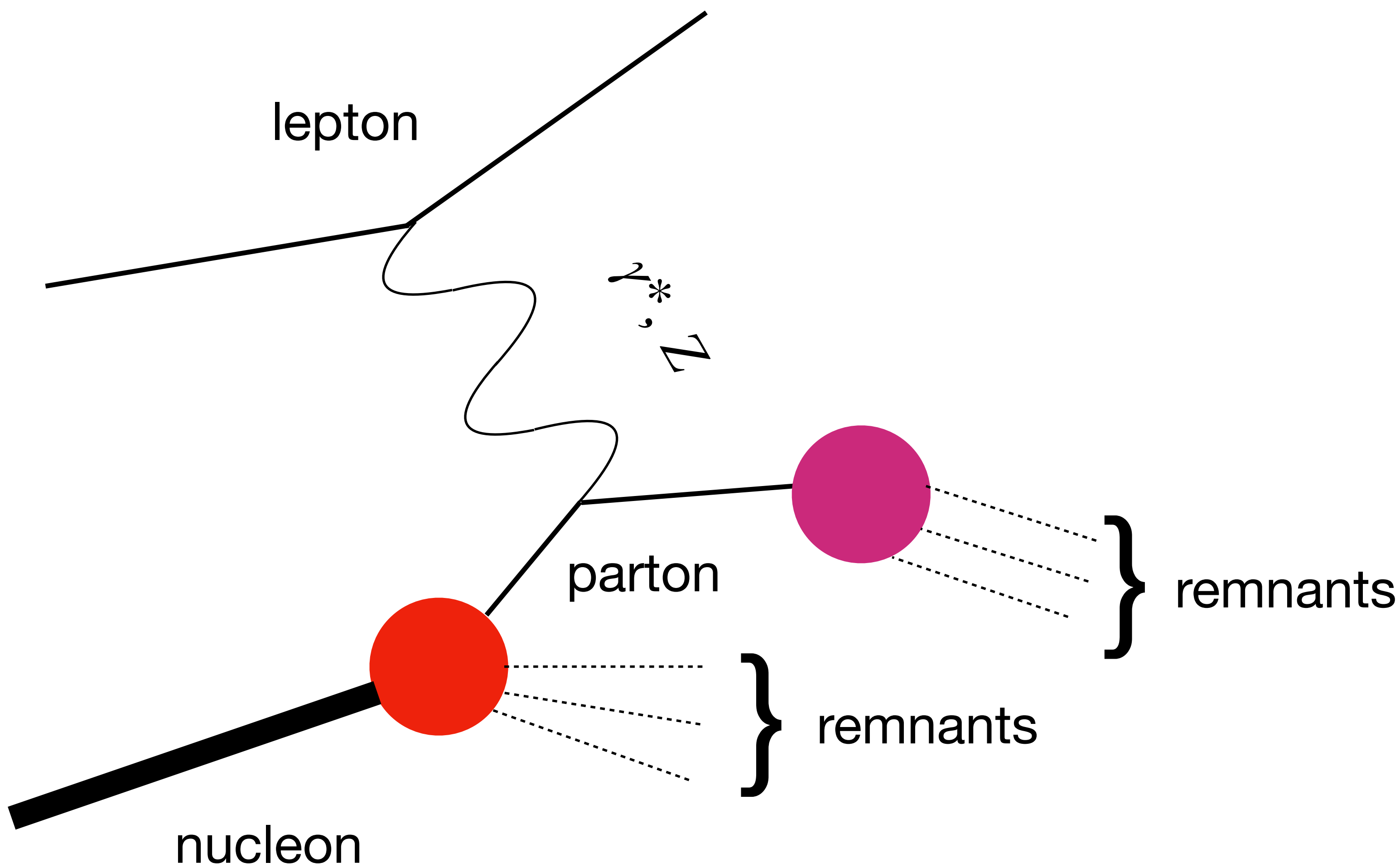
Strong P-violation

✘

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

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

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)

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

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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↓ Dominant contribution on the Light-Cone

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

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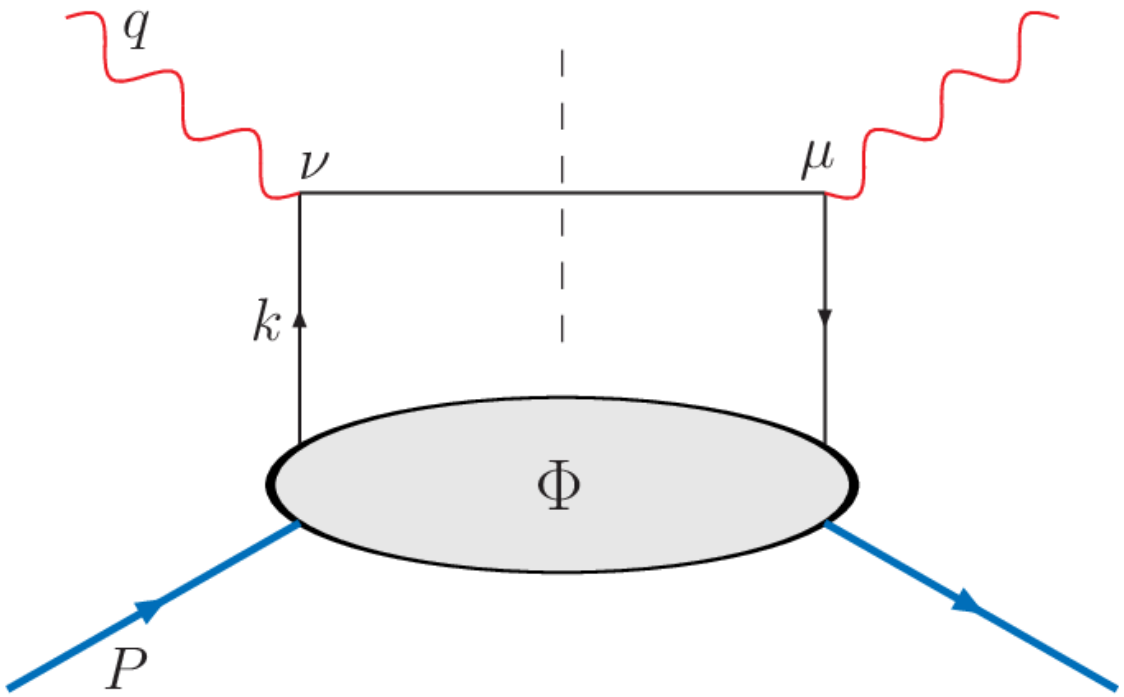

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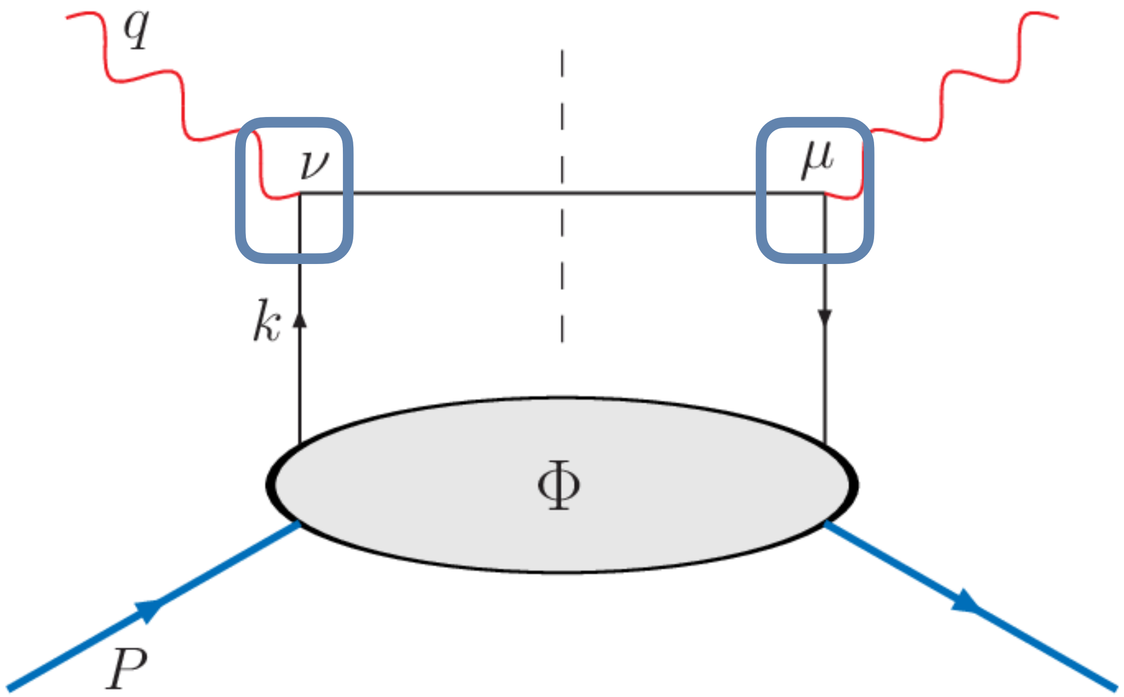

Vertices of the interactions

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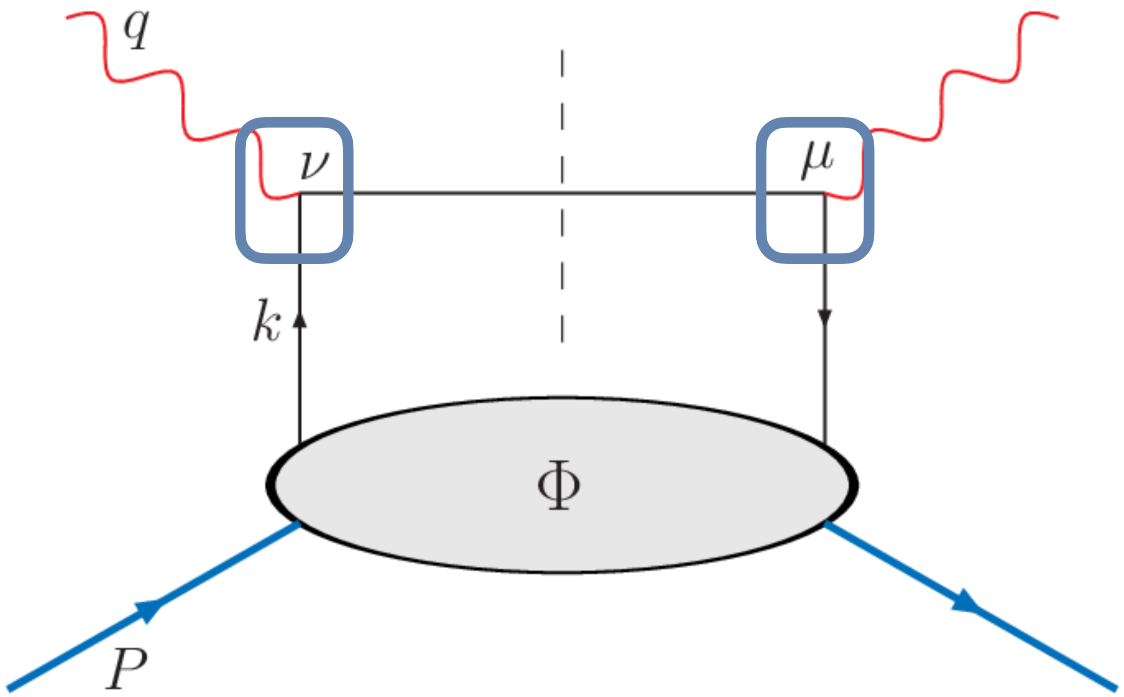

Vertices of the interactions

P-odd structures already present in the hadronic tensor!

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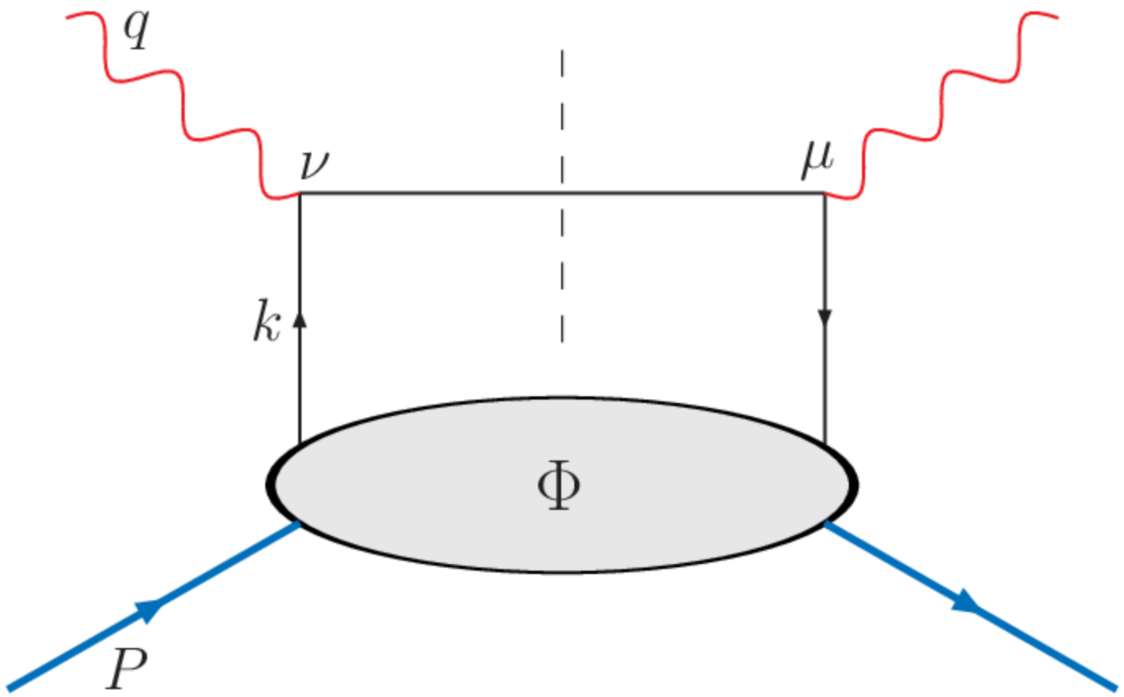

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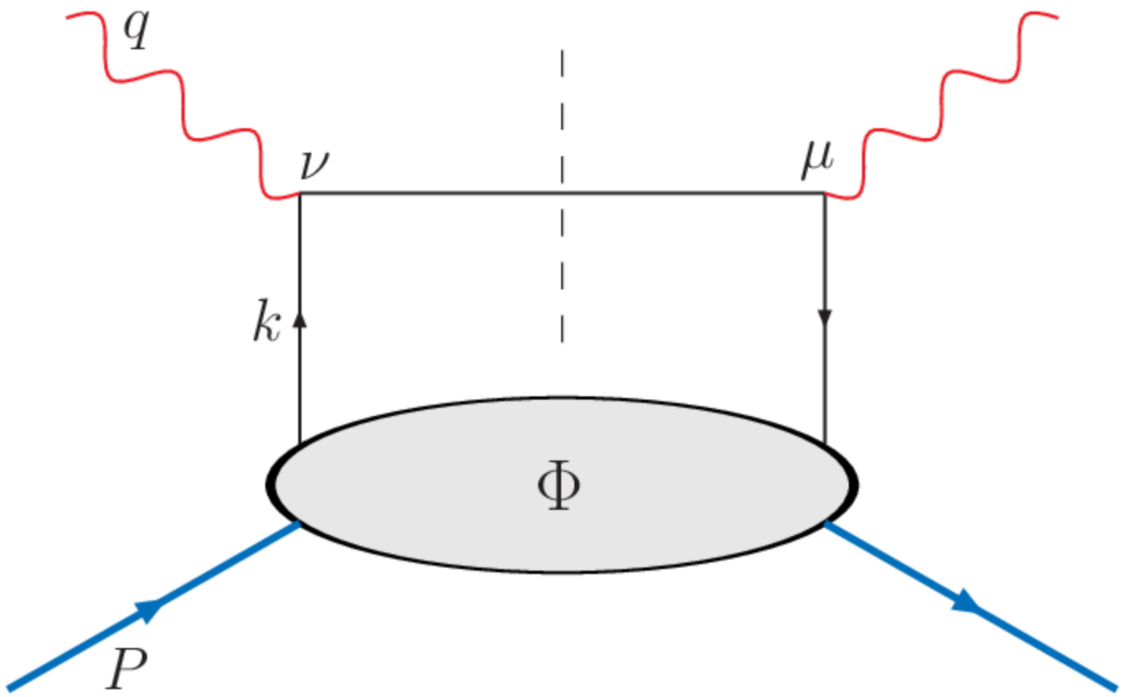

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$$\Phi_{ij}(k,P,S) = \int \frac{d^4\xi}{(2\pi)^4} e^{ik\cdot\xi} \langle P|\bar{\psi}_i(0) U(0,\xi) \psi_i(\xi)|P\rangle$$

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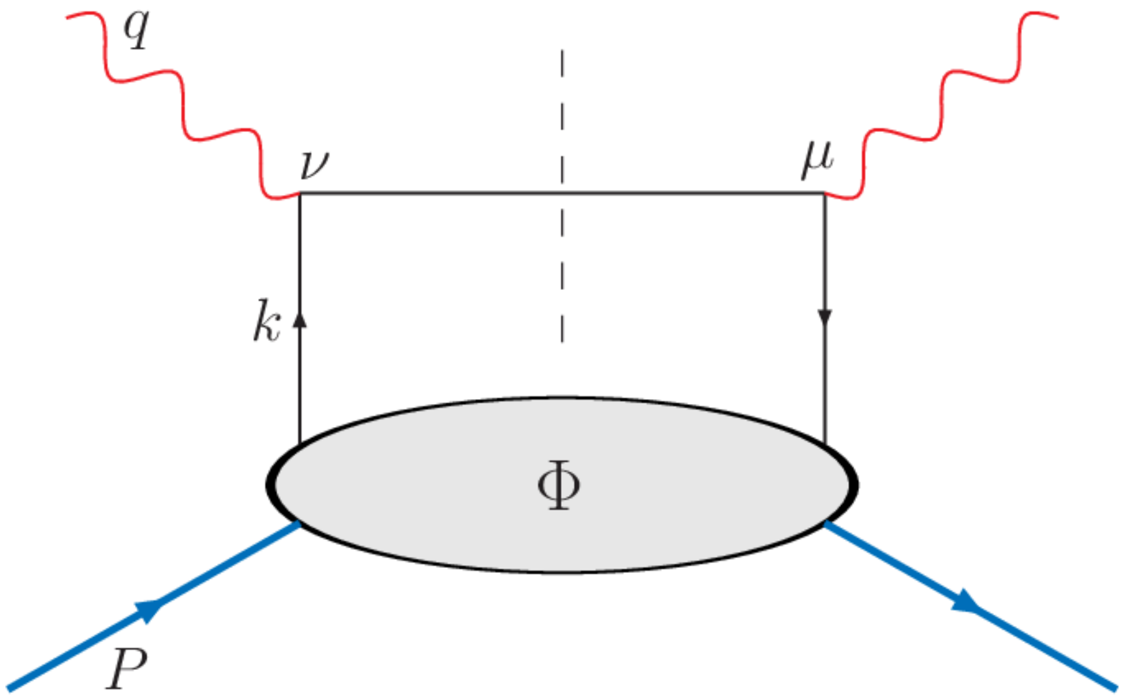

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Decomposition in partonic densities

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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Hermiticity

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Hermiticity

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

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Parity invariance	~~Parity invariance~~

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$i\gamma^5,\ \gamma^\mu\gamma^5,\ i\gamma^5\sigma^{\mu\nu}$

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Leading twist contributions

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

Partonic correlator (unpolarized)

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

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Partonic correlator (unpolarized)

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$$\Phi_{\mathrm{PE}}(x) \simeq \frac{1}{2} f_1(x)\gamma^- \qquad \Phi_{\mathrm{PV}}(x) \simeq \frac{1}{2} g_1^{\mathrm{PV}}(x)\gamma^5\gamma^-$$

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

Neutral-current DIS

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

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

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

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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

$$\begin{aligned}
F_{2UU}(x,Q^2) &= F_2^{(\gamma)} - g_V^e \eta_{\gamma Z} F_2^{(\gamma Z)} + \left({g_V^e}^2 + {g_A^e}^2\right)\eta_Z F_2^{(Z)}, \\
F^{\pm}_{2LU}(x,Q^2) &= \mp g_A^e \eta_{\gamma Z} F_2^{(\gamma Z)} \pm 2 g_V^e g_A^e \eta_Z F_2^{(Z)}, \\
xF^{\pm}_{3UU}(x,Q^2) &= \mp g_A^e \eta_{\gamma Z} x F_3^{(\gamma Z)} \pm 2 g_V^e g_A^e \eta_Z x F_3^{(Z)}, \\
xF_{3LU}(x,Q^2) &= xF_3^{(\gamma)} - g_V^e \eta_{\gamma Z} x F_3^{(\gamma Z)} + \left({g_V^e}^2 + {g_A^e}^2\right)\eta_Z x F_3^{(Z)},
\end{aligned}$$

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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)

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PVDIS Collaboration, *Nature* 506 (2014)
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$$= \frac{Y_+ F_{2LU} - y^2 F_{L,LU} - Y_- x F_{3LU}}{Y_+ F_{2UU} - y^2 F_{L,UU} - Y_- x F_{3UU}}$$

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

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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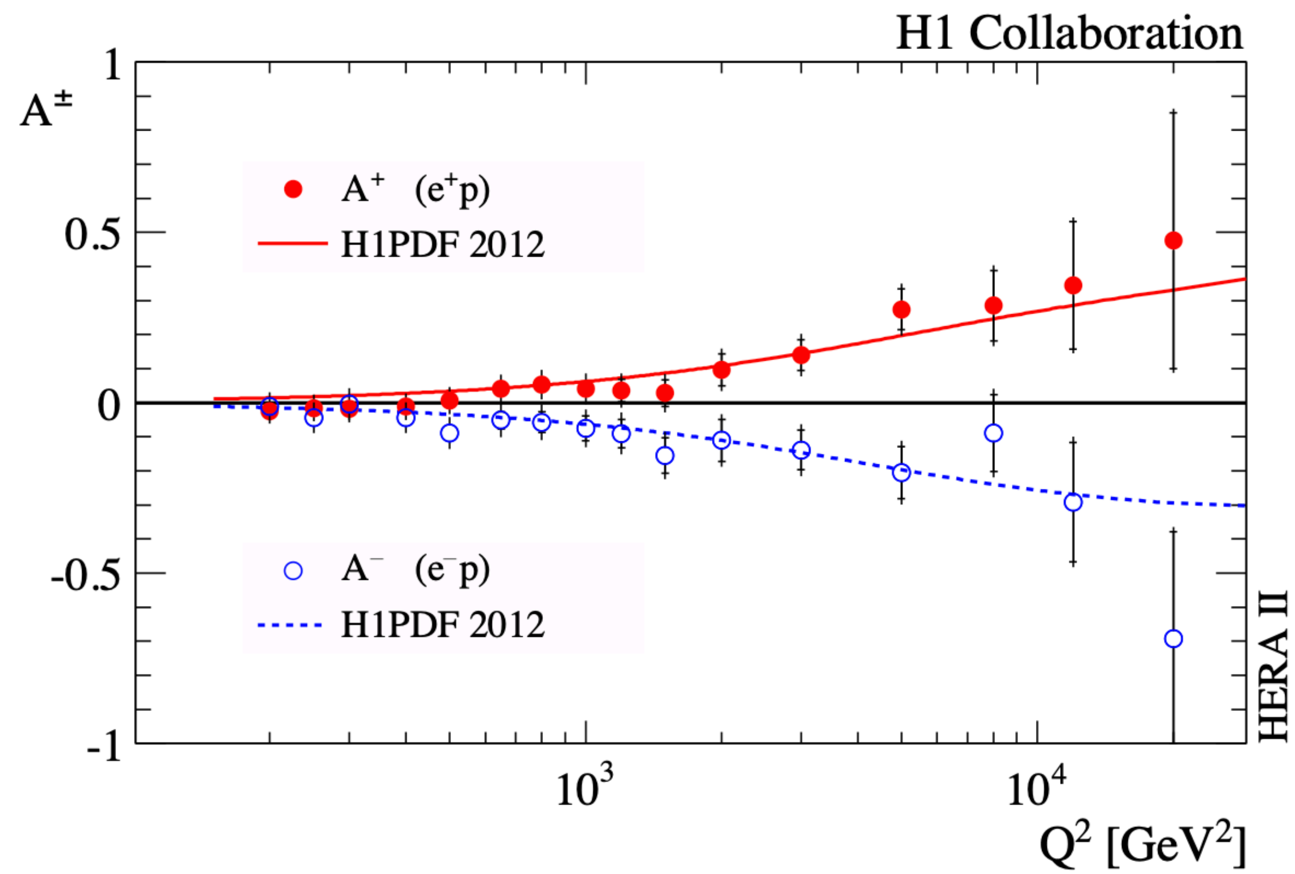
e^+ asymmetry: 136 data

e^- asymmetry: 138 data



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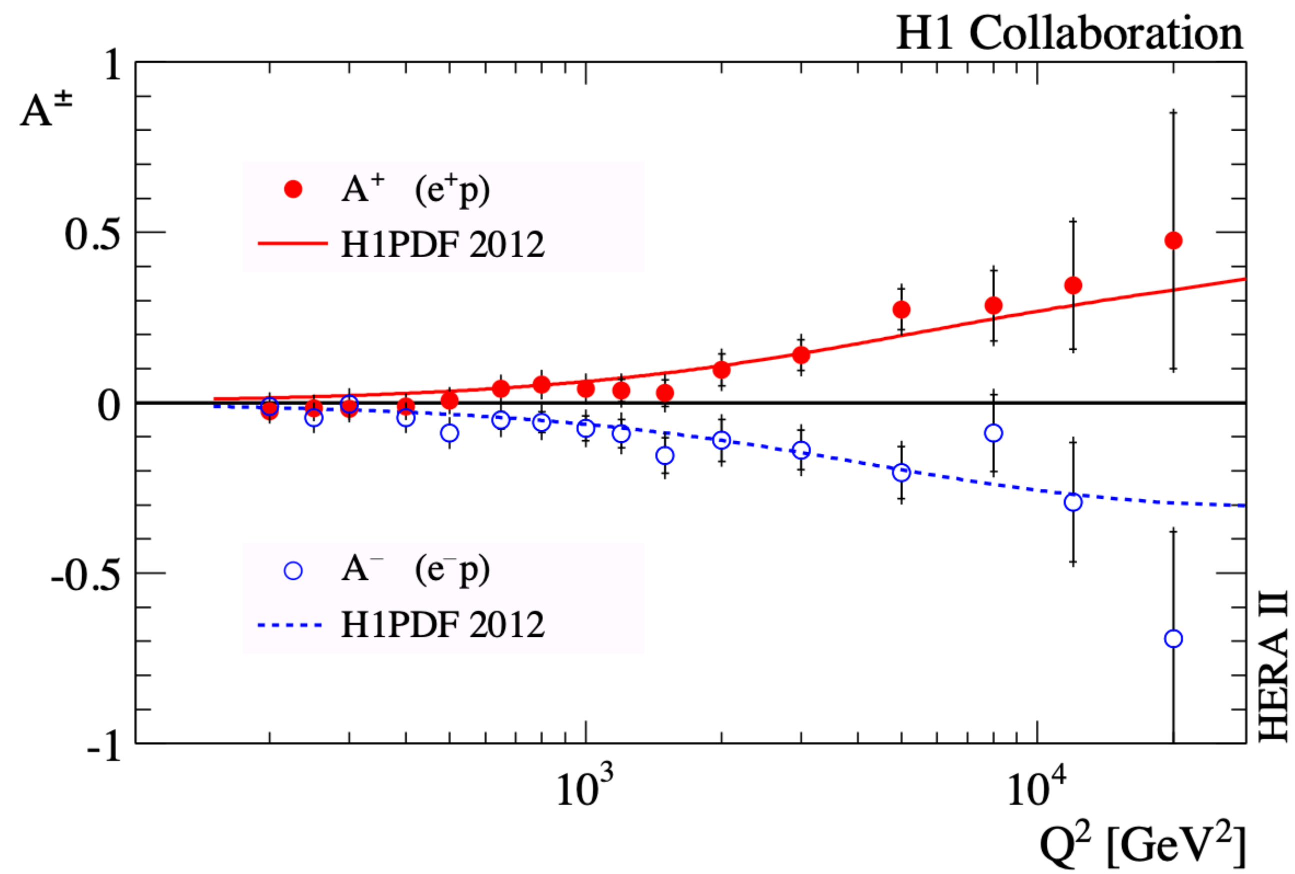

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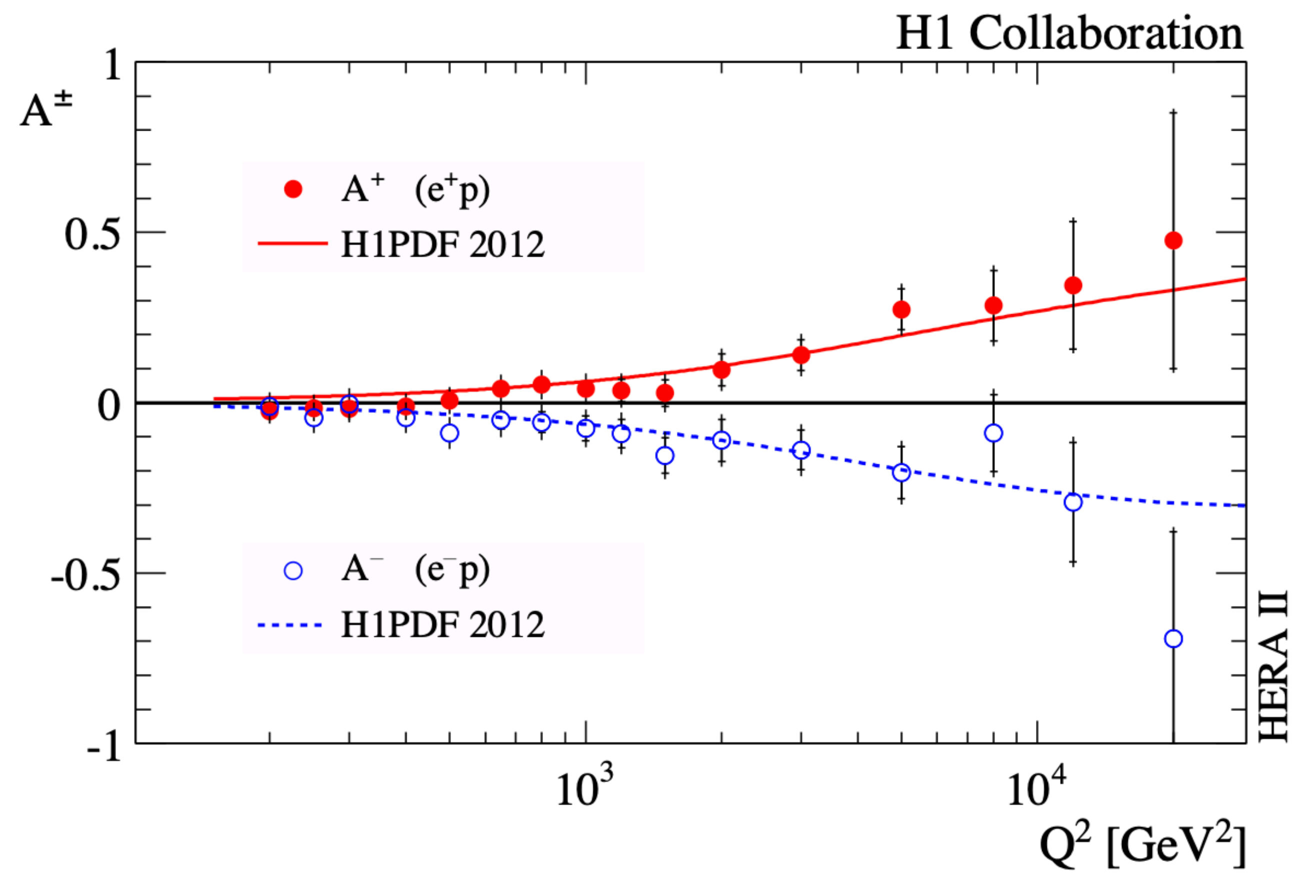

JLab6 PVDIS dataset

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

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

Available experimental data

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

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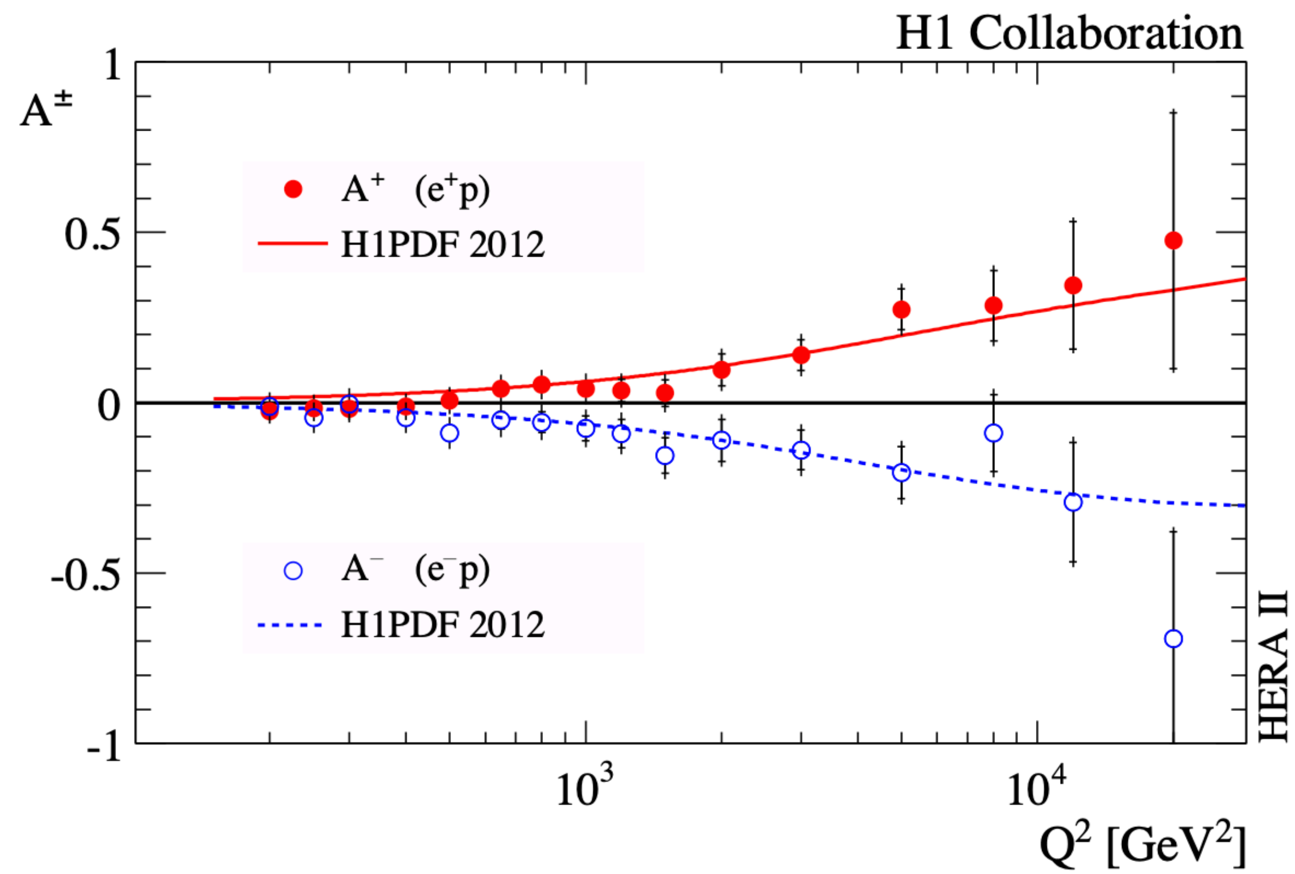

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PVDIS Collaboration, *Nature* 506 (2014)
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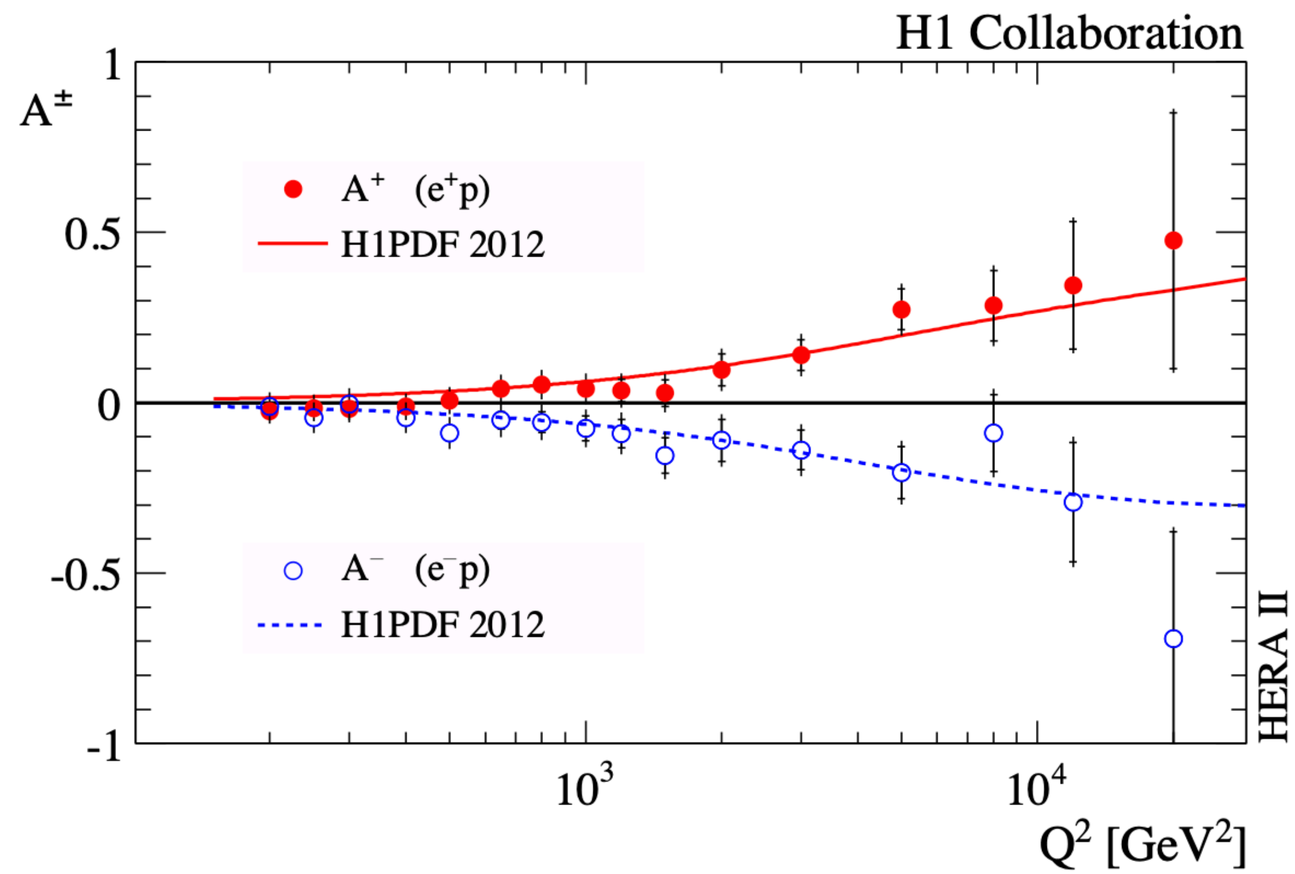

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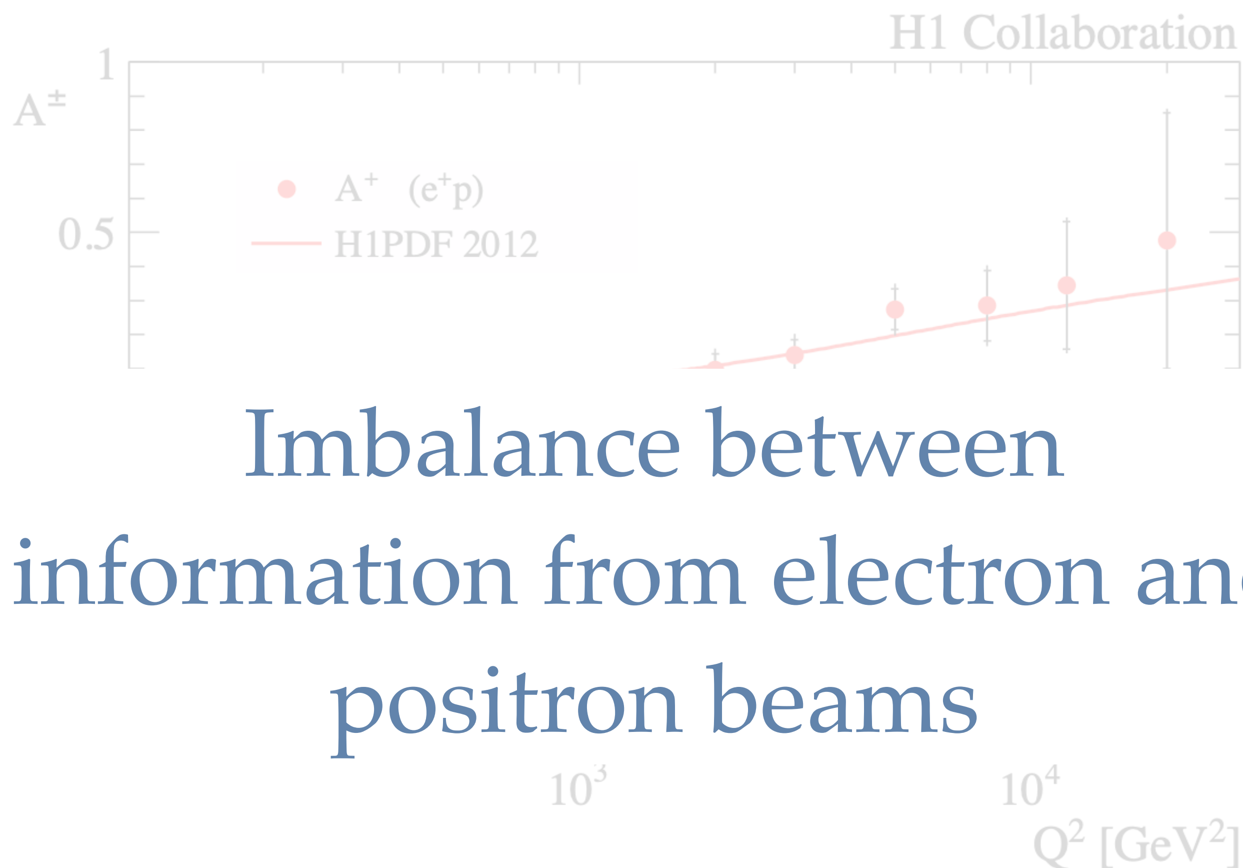

Imbalance between information from electron and positron beams

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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) \\
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1 parameter to be fitted

Error propagation

PDF set for

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

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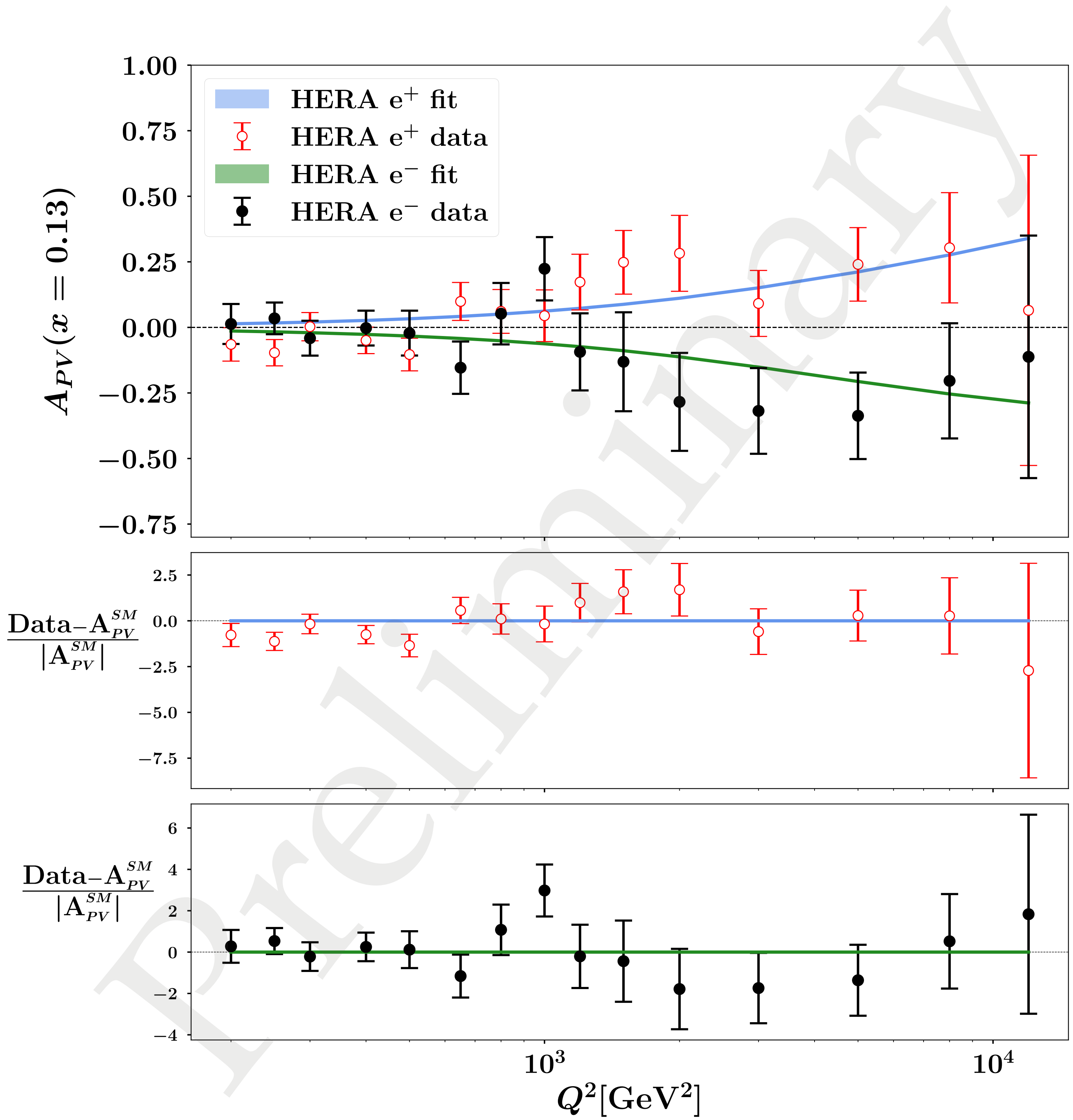
} **Statistical distribution of 100 values of parameter α**

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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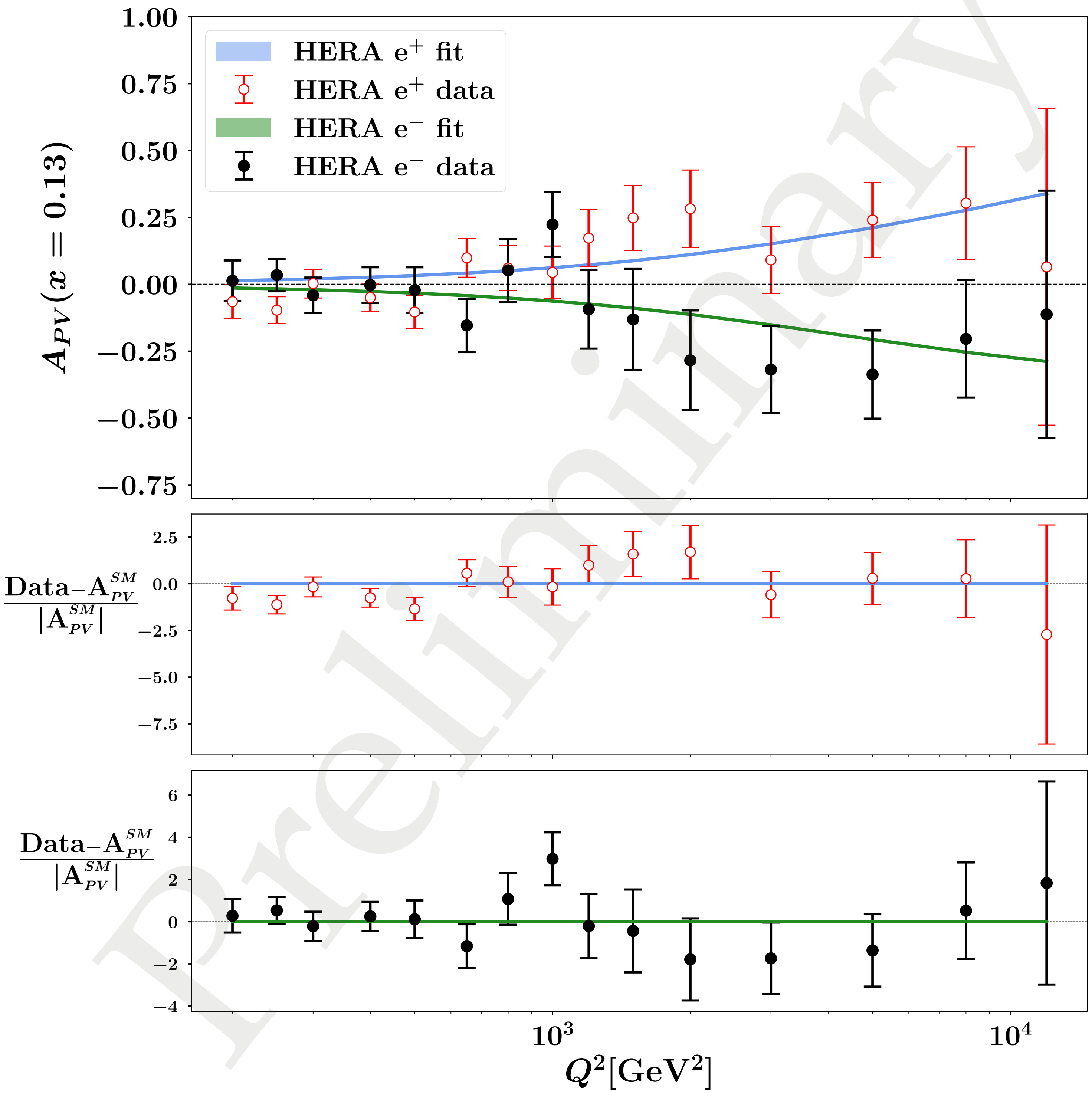

Very small uncertainties in the predictions because the fit is dominated by data with smaller errors

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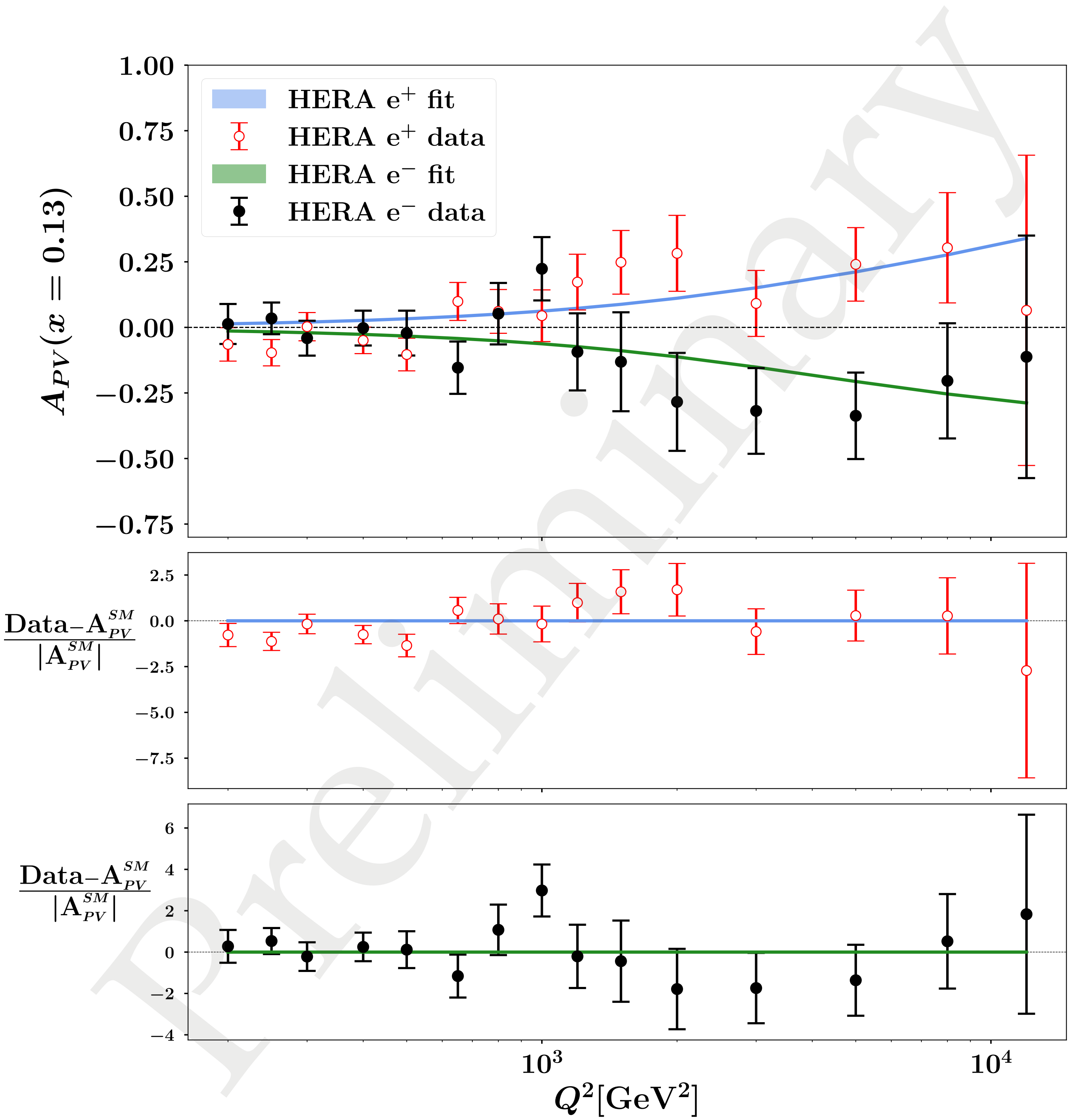

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There's room for a better description for positron asymmetry at low-Q

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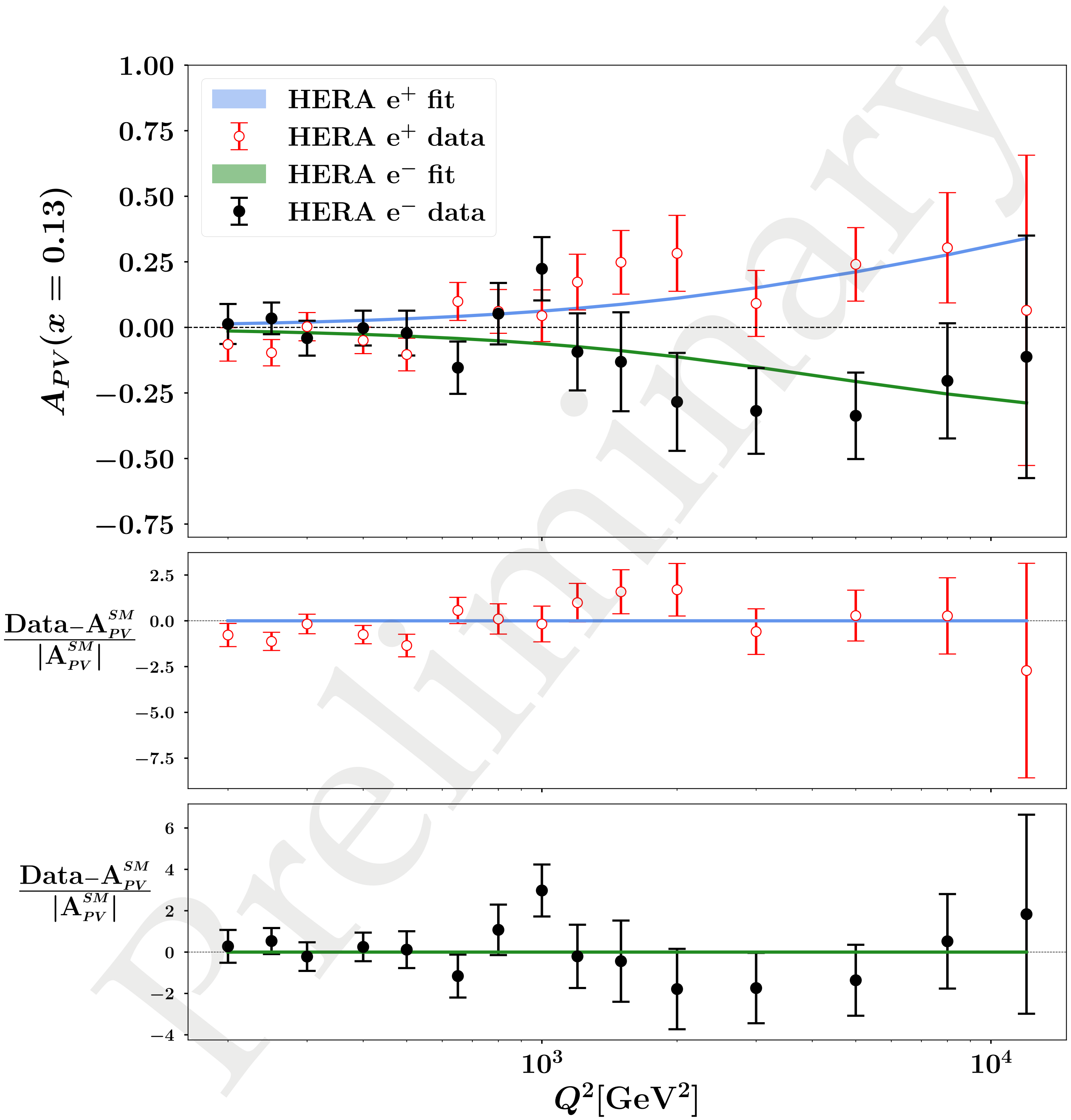

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Agreement for electron asymmetry, but too large errors at low-Q

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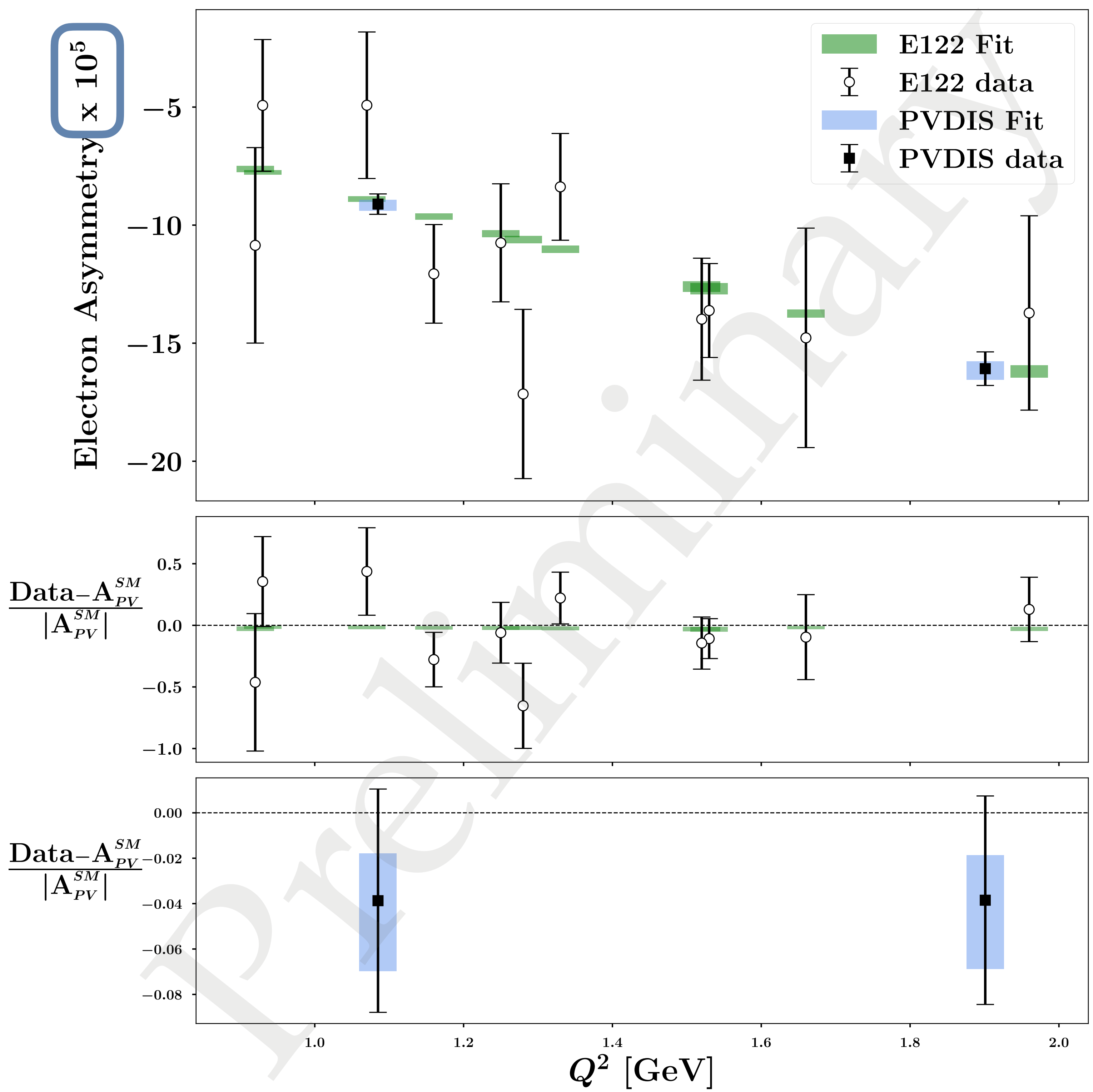

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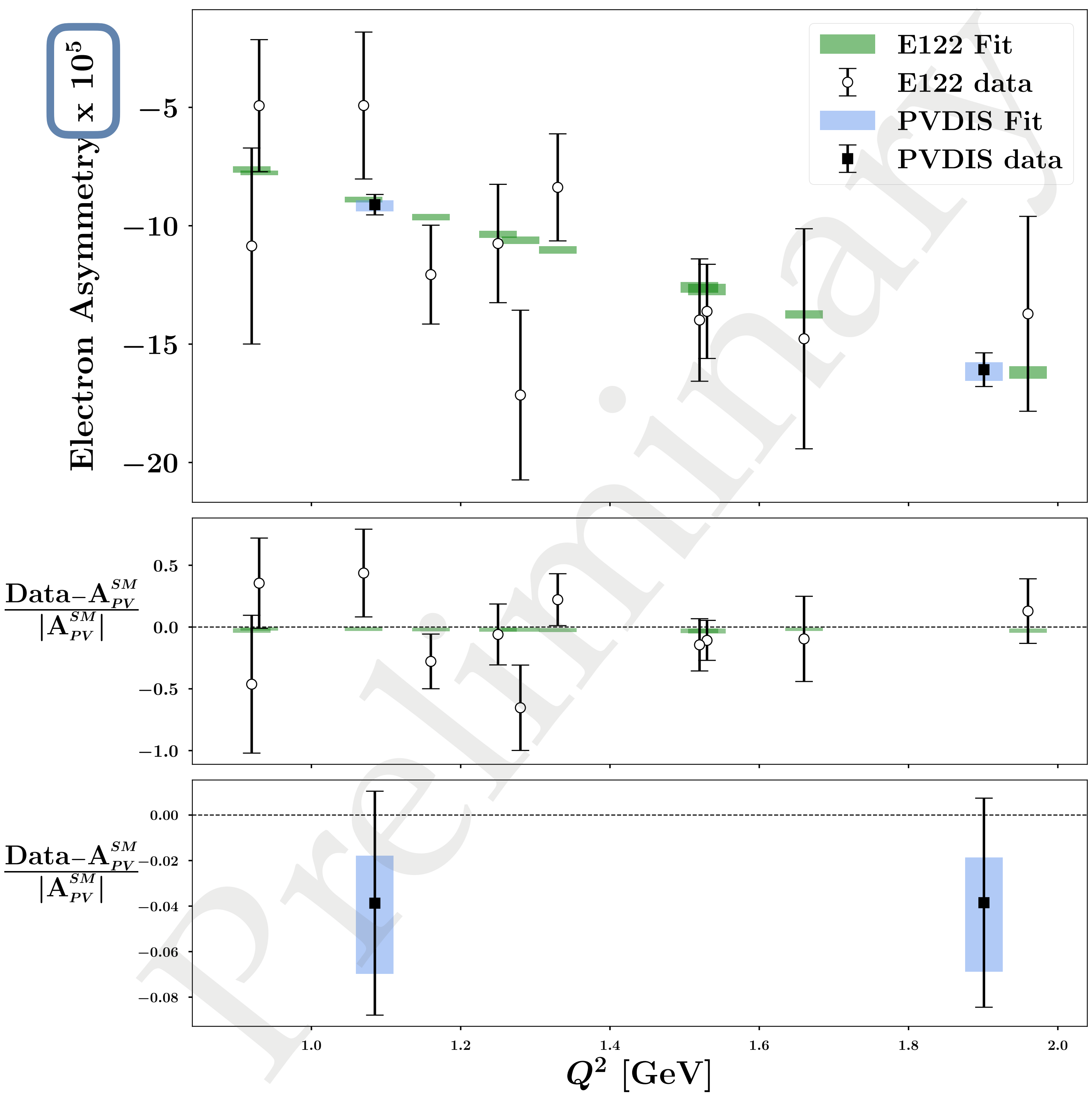

Sizeable improvement of the fit w.r.t. SM predictions

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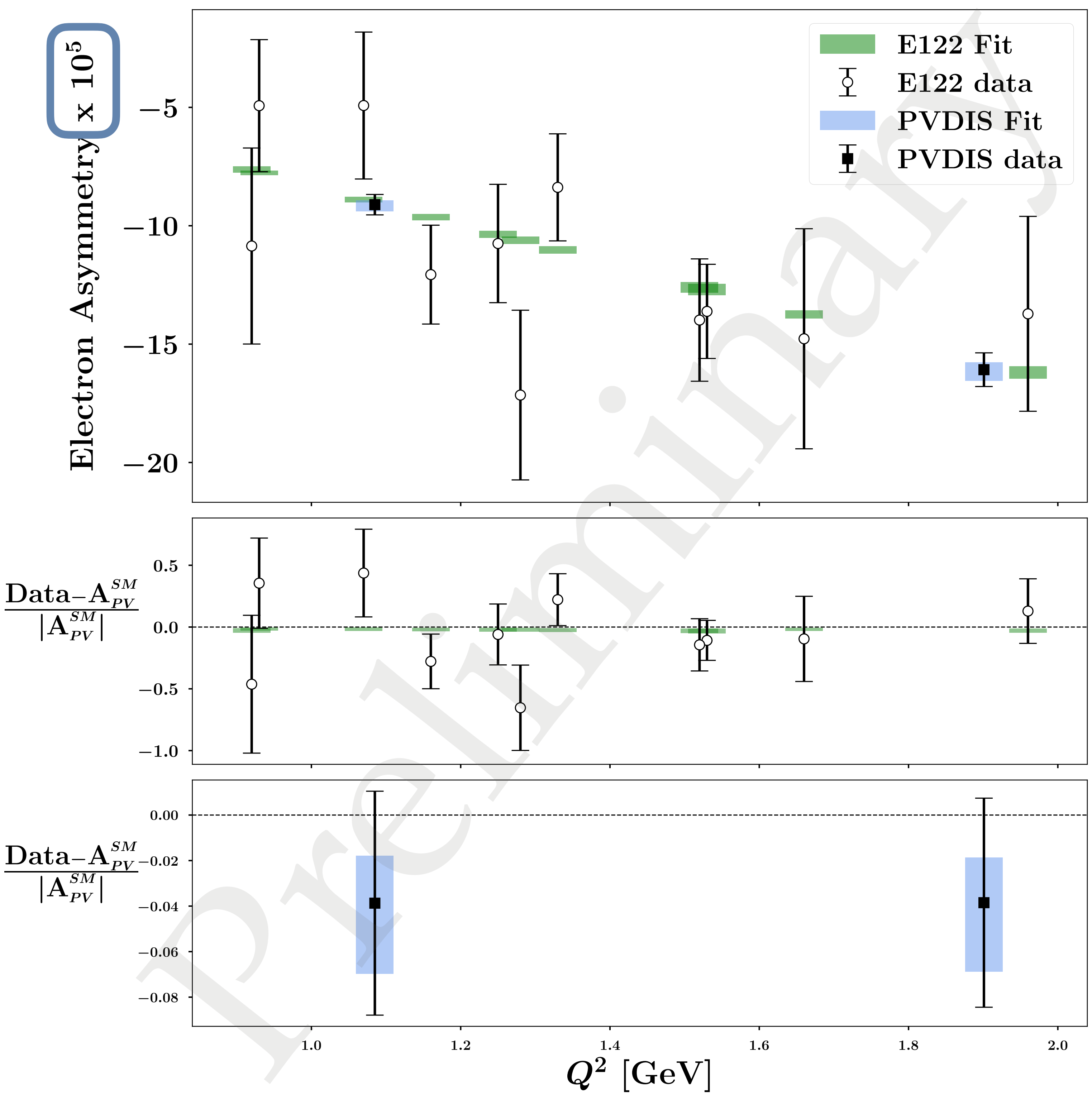

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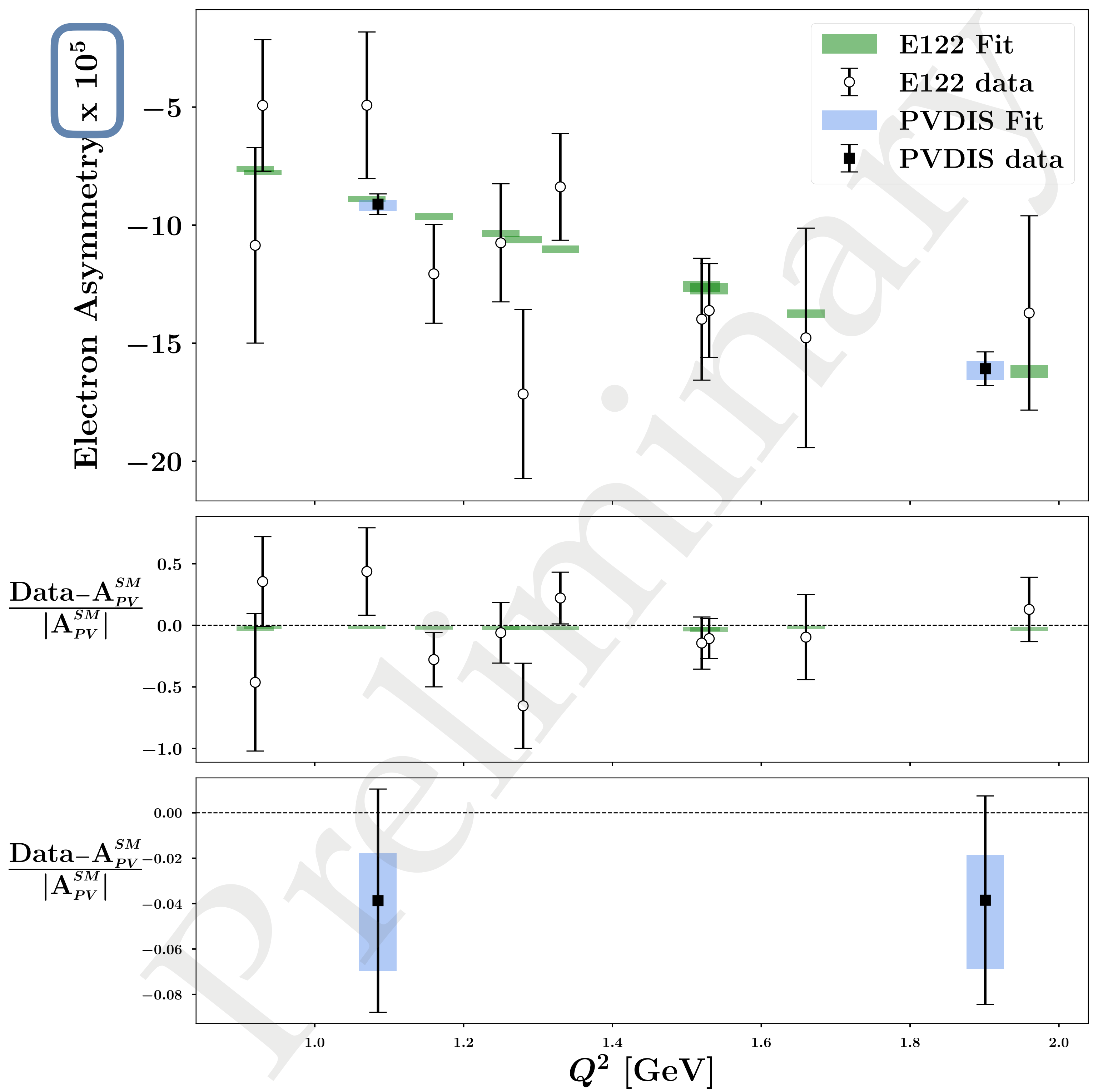

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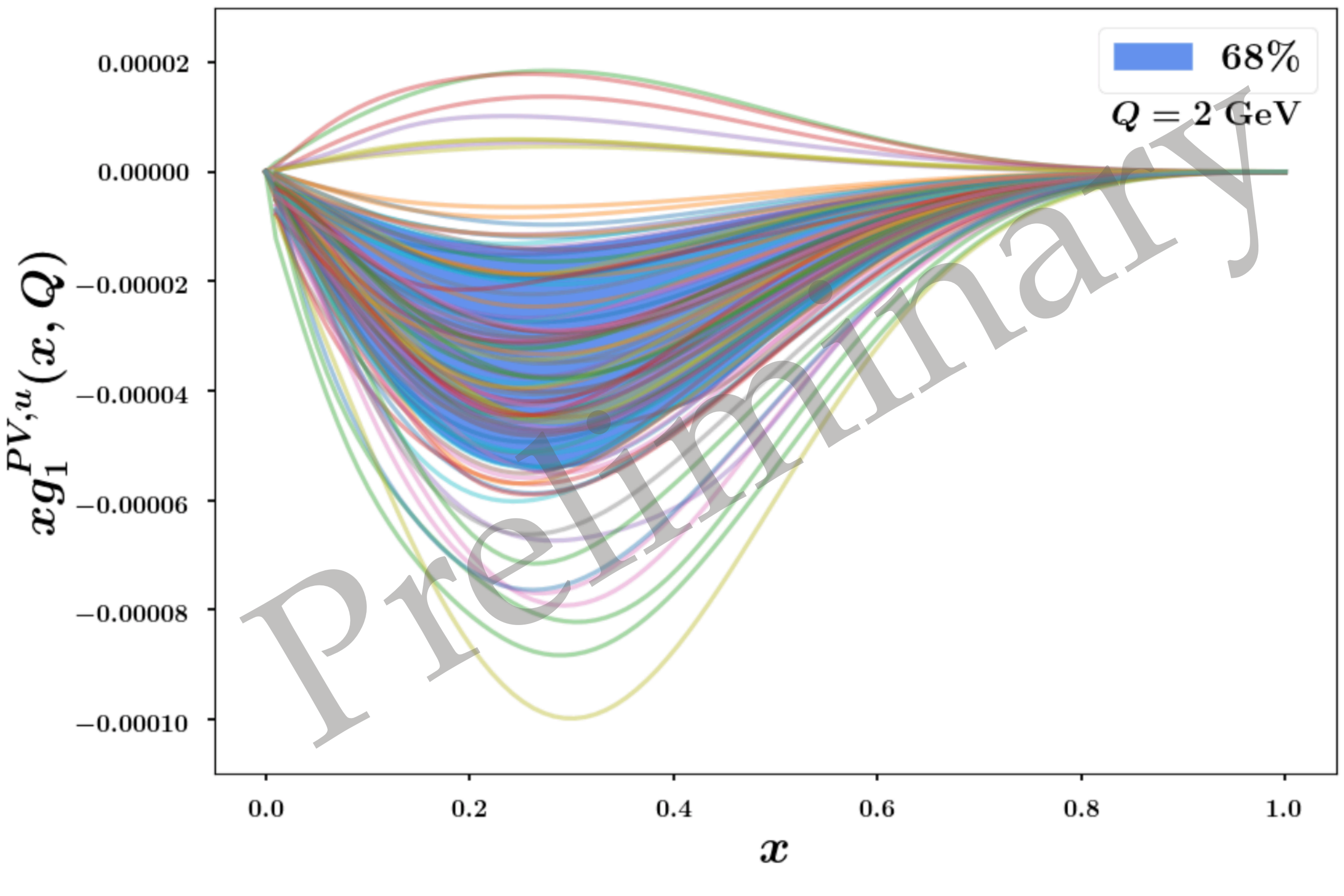
Old dataset with still quite large experimental errors (> 20 %)

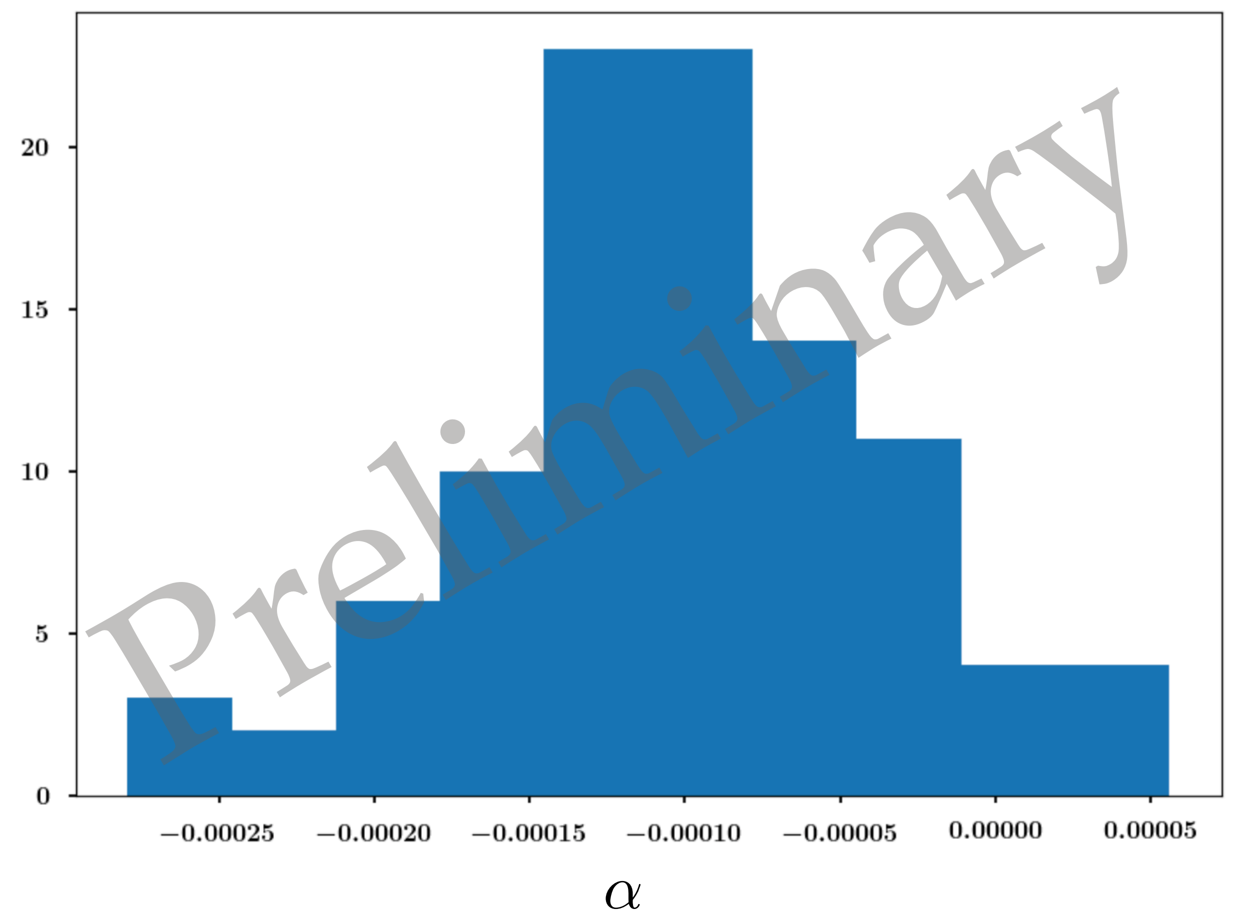
Data points which actually drive the fit due to very small experimental errors (~ %)

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

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

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





Conclusions and Outlook

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- Experimental data from positron beam are welcome to shed light on the complementarity with electron beam

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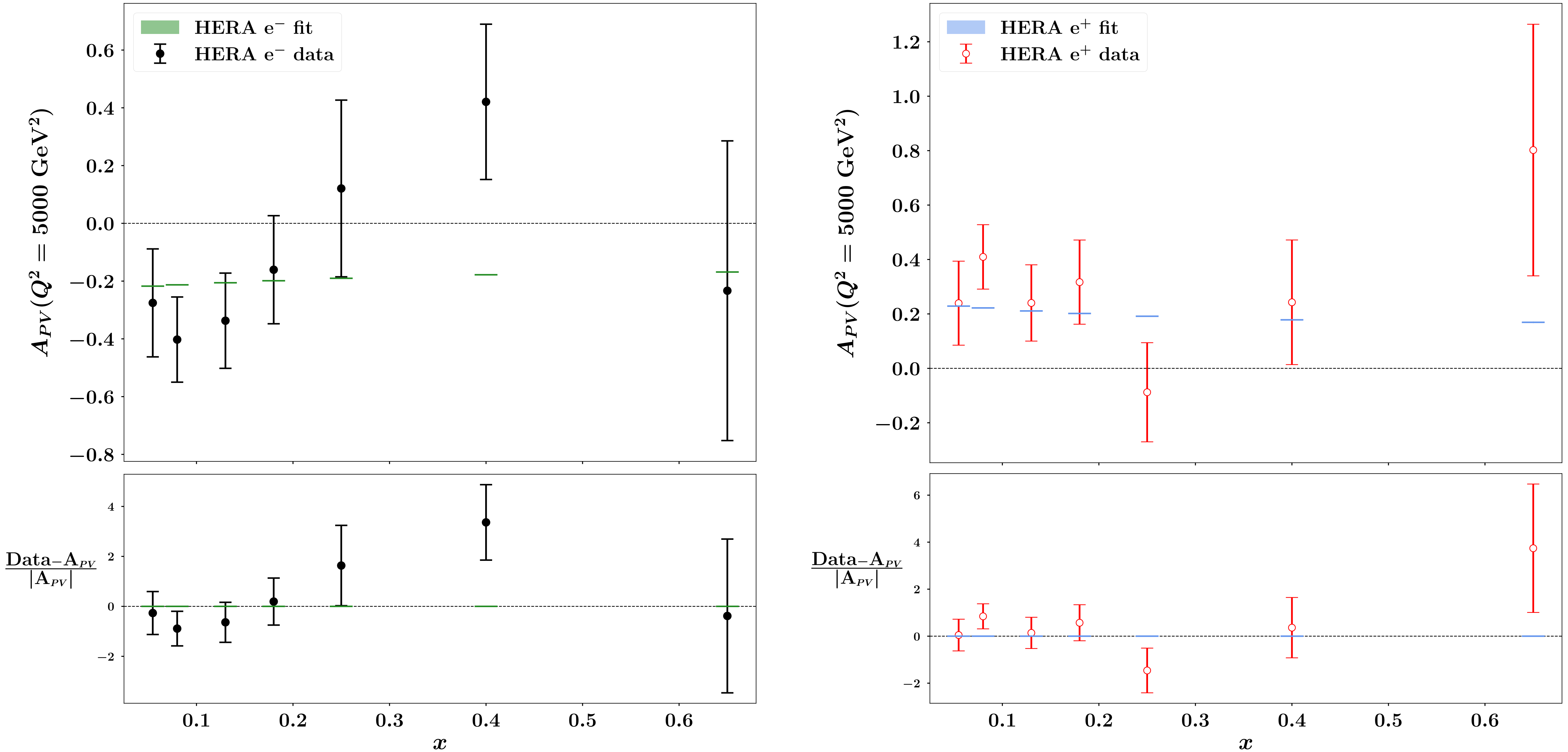
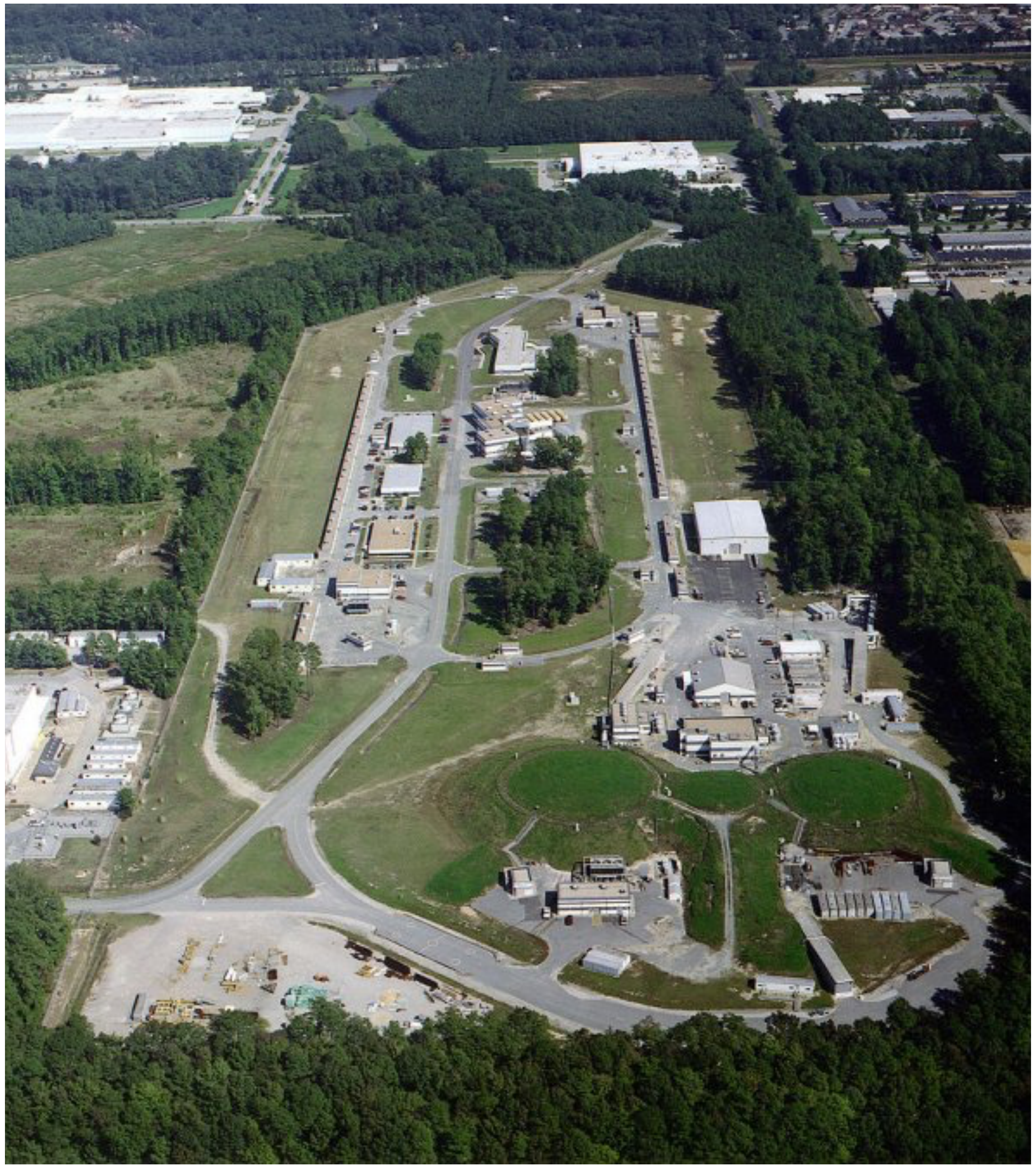
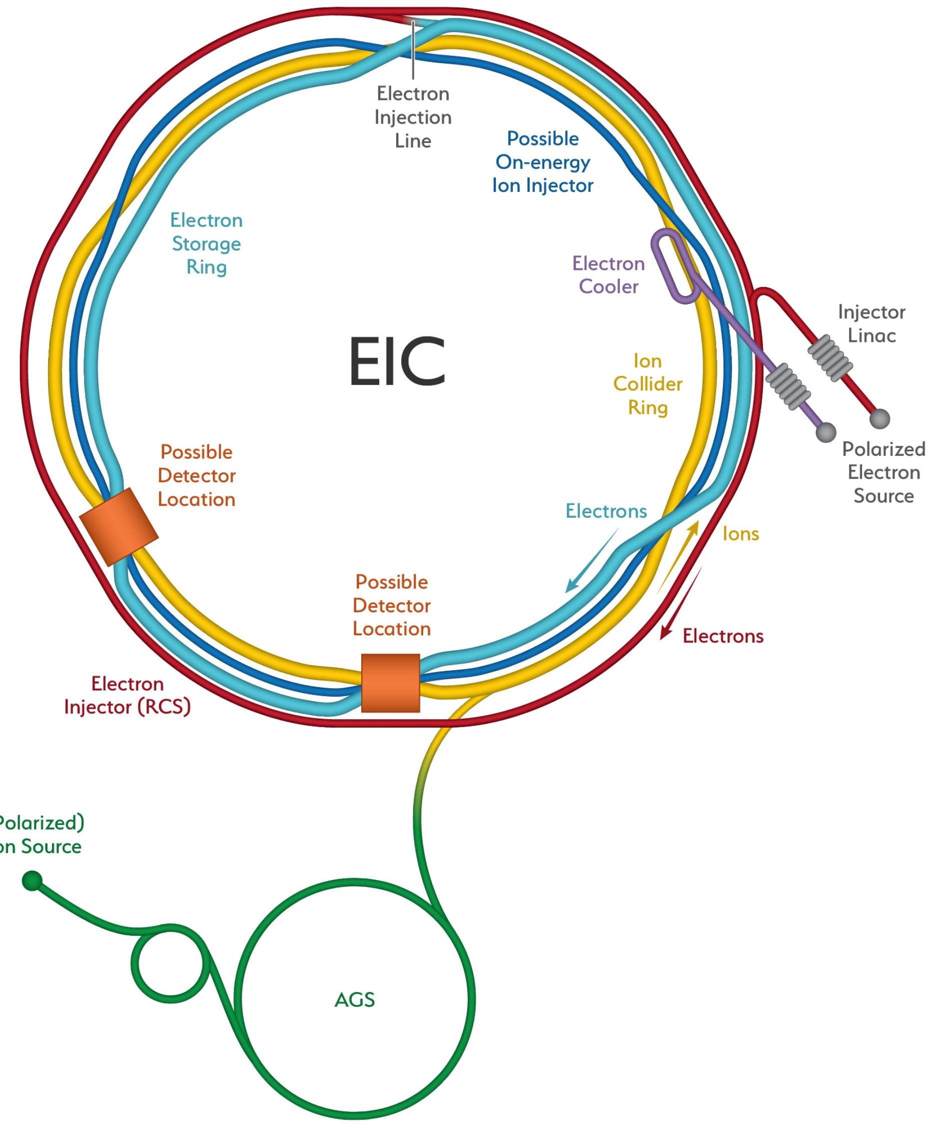


Conclusions and Outlook

- 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

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

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