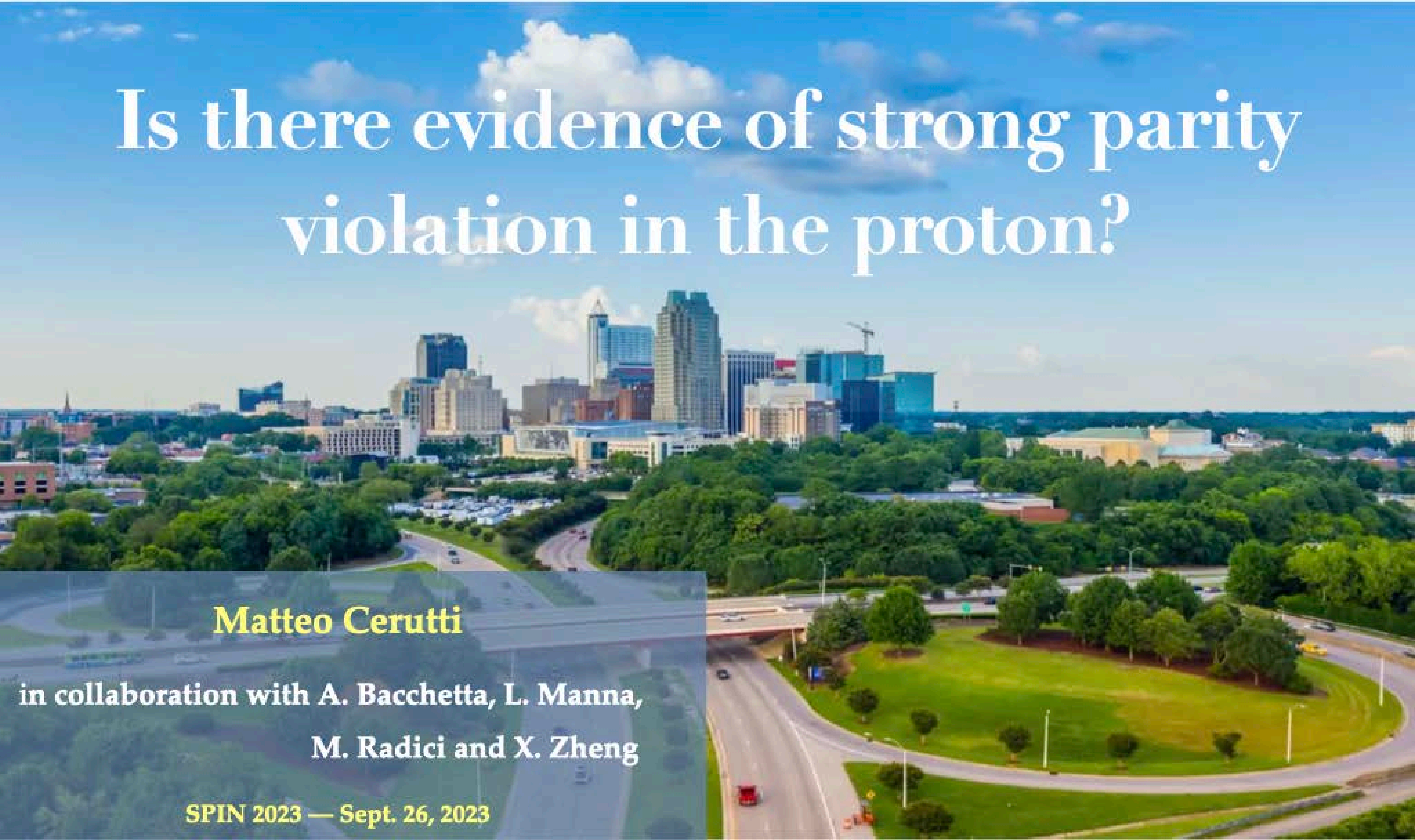
Istituto Nazionale di Fisica Nucleare

HAS QCD

HADRONIC STRUCTURE AND QUANTUM CHROMODYNAMICS

UNIVERSITÀ DI PAVIA



Is there evidence of strong parity violation in the proton?

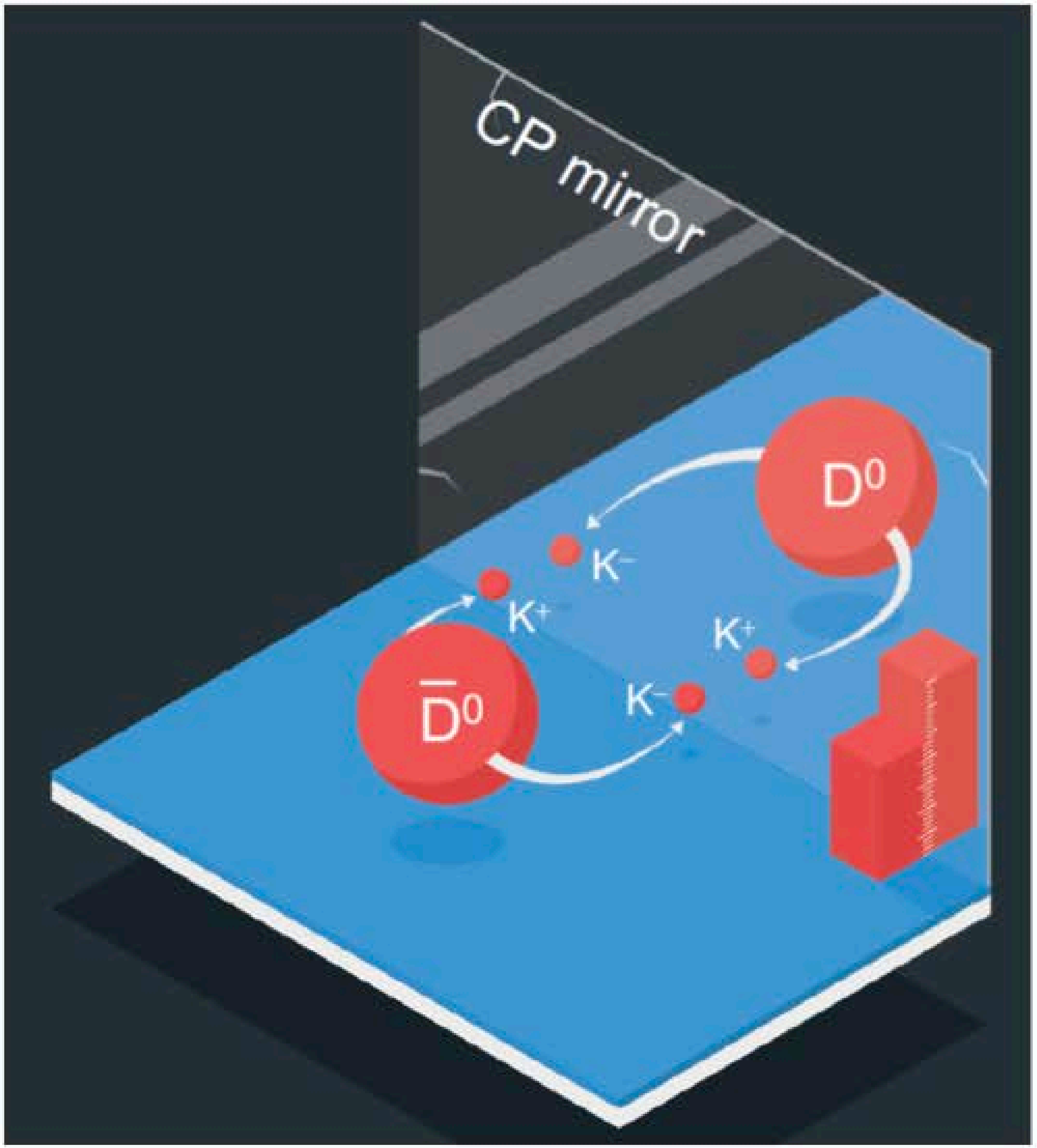
Matteo Cerutti

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

SPIN 2023 — Sept. 26, 2023

Motivations

Investigation of the
"Strong CP problem"

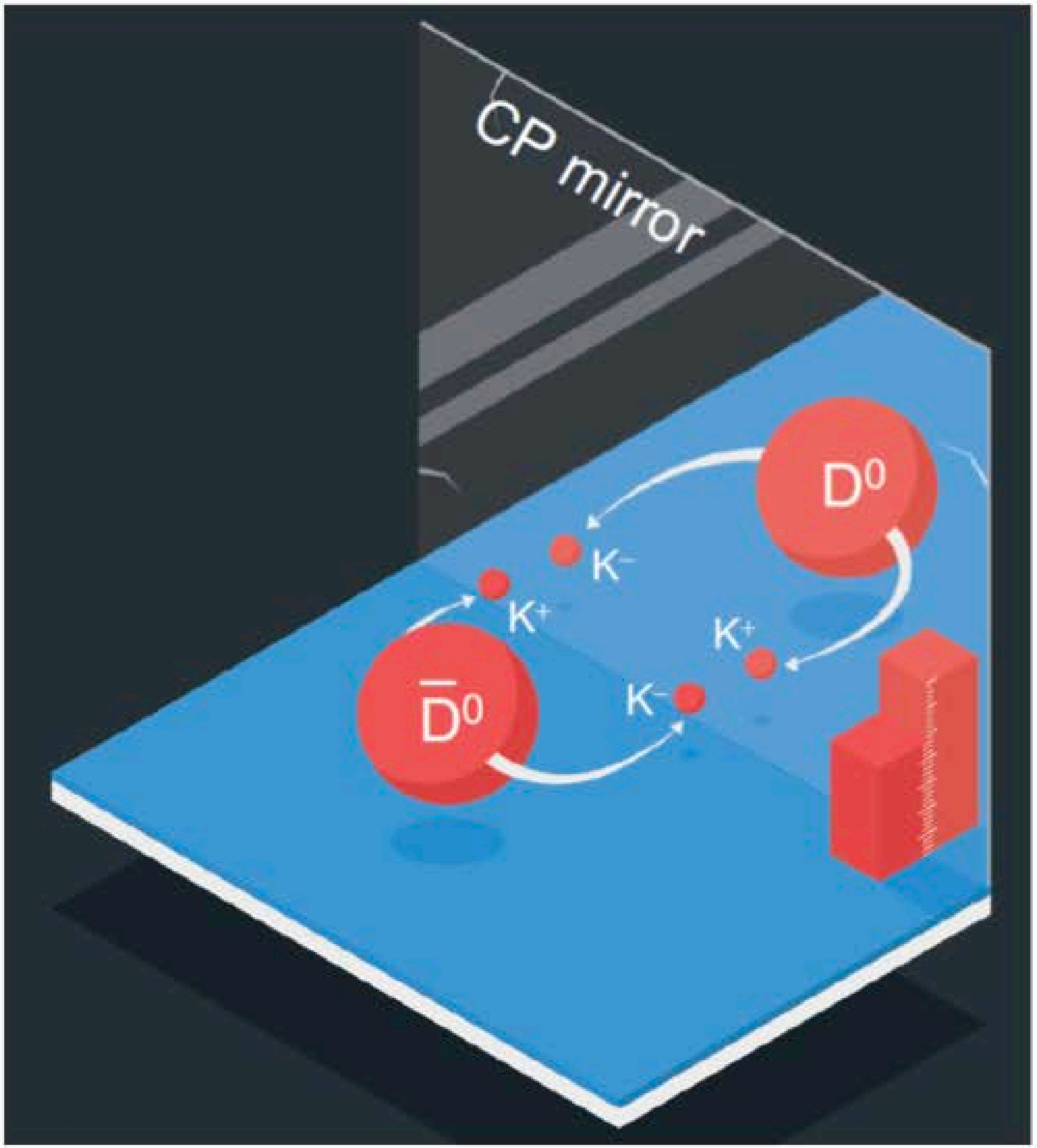


Motivations

Investigation of the
"Strong CP problem"

↓

Matter-Antimatter
imbalance



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

Motivations

P-symmetry

<u>QCD sector</u>

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Terms from EW sector

Weak P-violation

✔

Motivations

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<u>QCD sector</u>

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Terms from QCD sector

Motivations

P-symmetry

<u>QCD sector</u>

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?

PDFs in DIS process

Quark Polarization

Nucleon Pol.

	U	L	T
U			
L			
T			

PDFs in DIS process

Quark Polarization

Nucleon Pol.

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

PDFs in DIS process

Electric charge

Quark Polarization

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PDFs in DIS process

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Axial charge

PDFs in DIS process

Electric charge

Quark Polarization

Nucleon Pol.

	U	L	T
U	$f_1(x)$	$g_1^{\mathrm{PV}}(x)$	
L	$f_{1L}^{\mathrm{PV}}(x)$	$g_1(x)$	
T			

Axial charge

PDFs in DIS process

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Nucleon Pol.	U	L	T
U	$f_1(x)$	$g_1^{\mathrm{PV}}(x)$	
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Anapole moment

Axial charge

PDFs in DIS process

Electric charge

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Nucleon Pol.	U	L	T
U	$f_1(x)$	$g_1^{\mathrm{PV}}(x)$	
L	$f_{1L}^{\mathrm{PV}}(x)$	$g_1(x)$	
T			

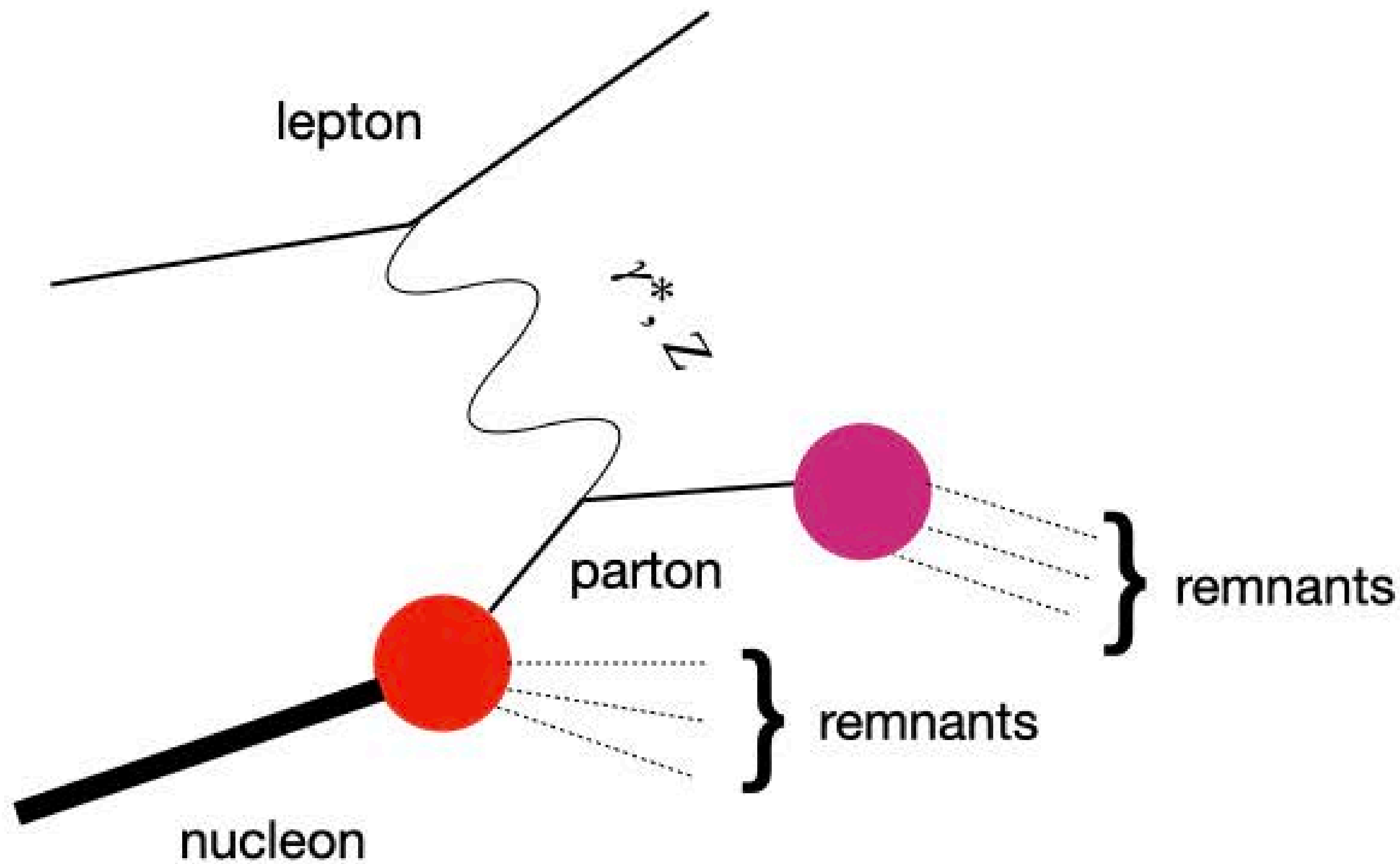
Anapole moment

Electric dipole moment

Axial charge

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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In general

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

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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)

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

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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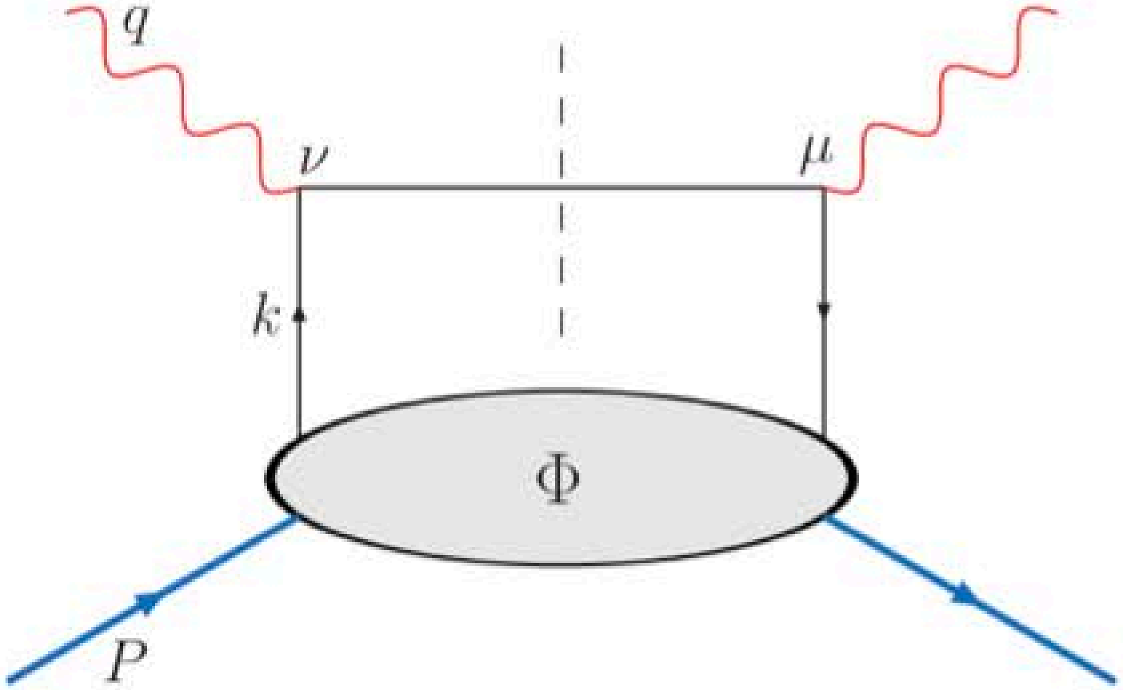

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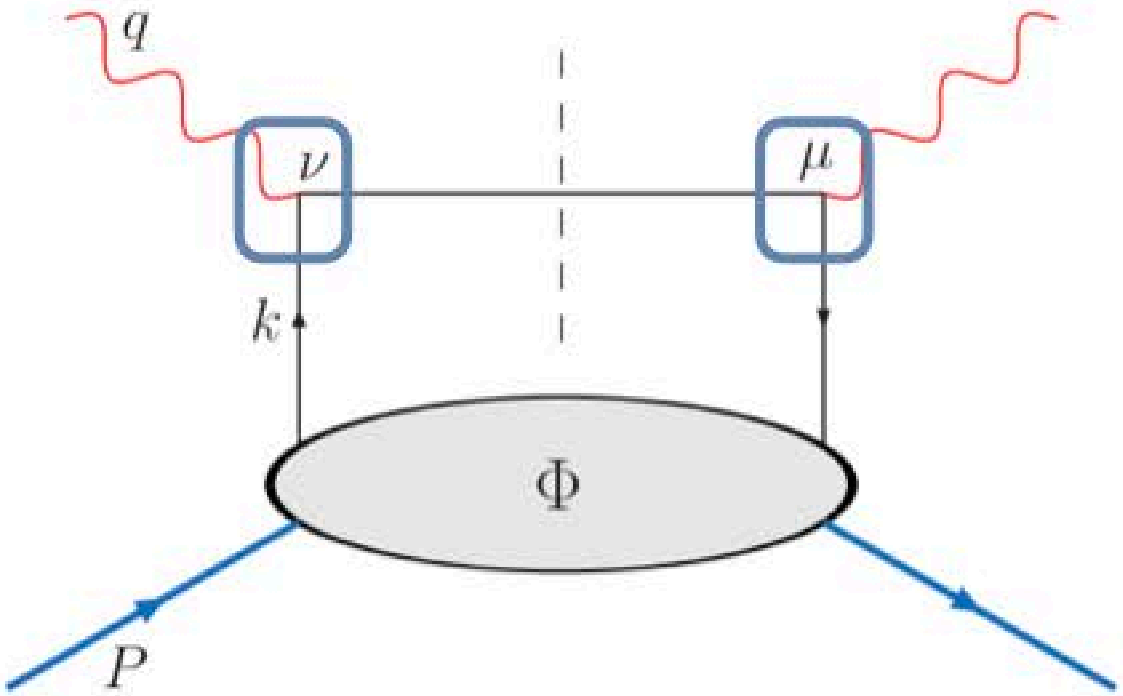

Vertices of the interactions

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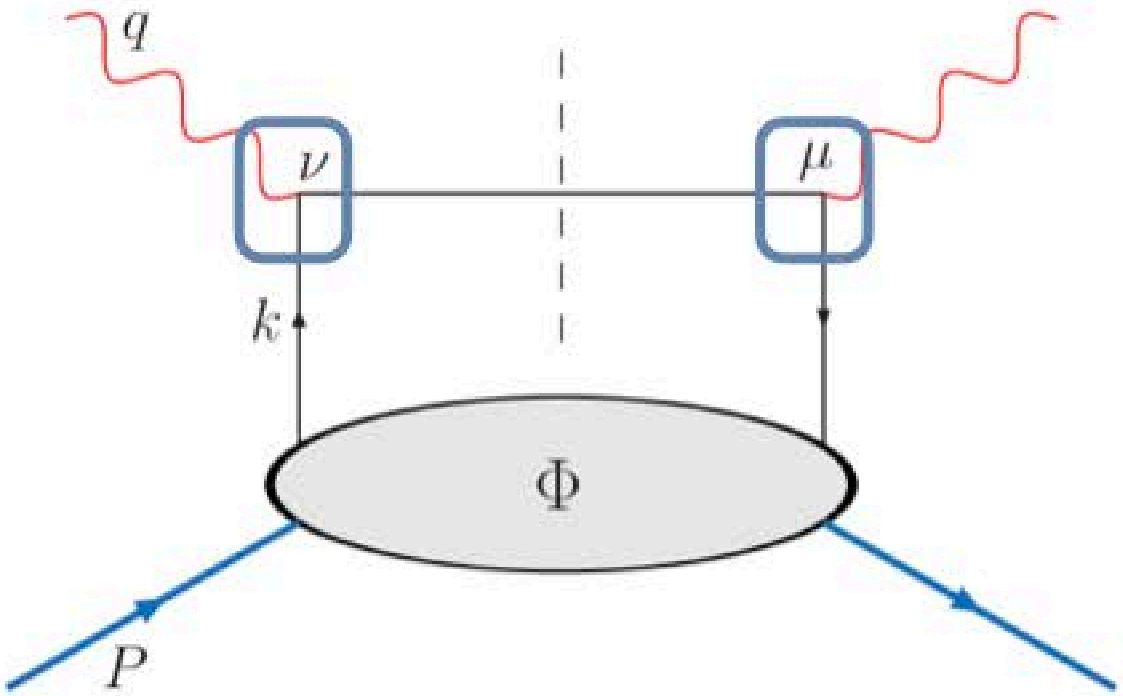

Vertices of the interactions

P-odd structures already present in the hadronic tensor!

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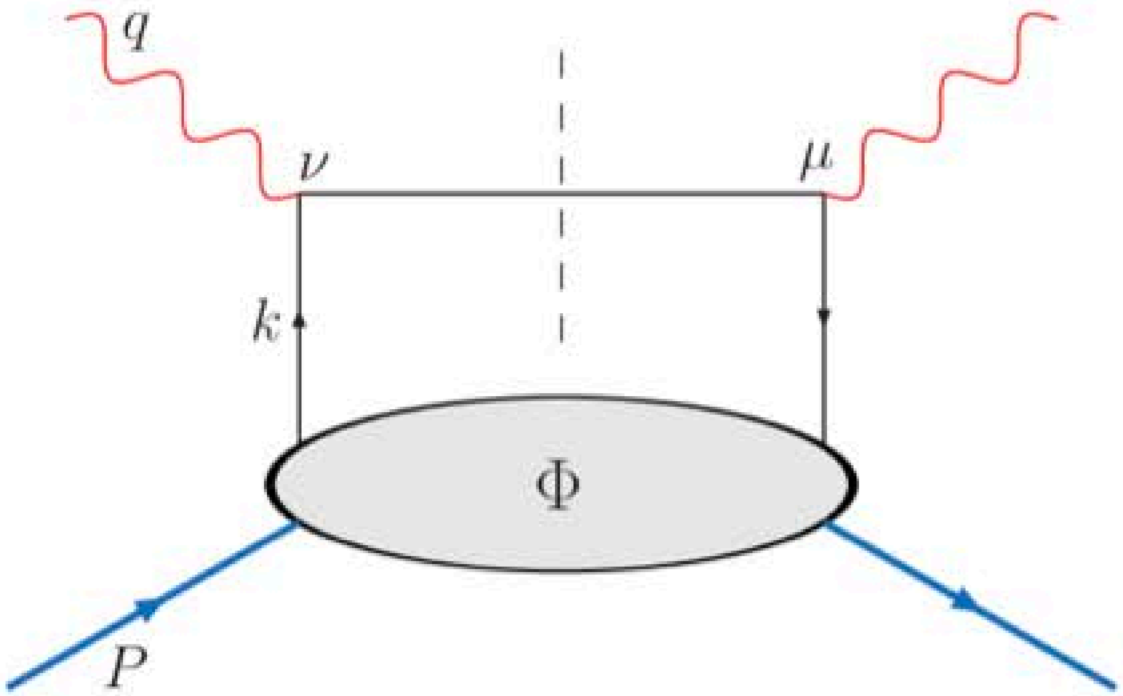

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Correlation distribution function

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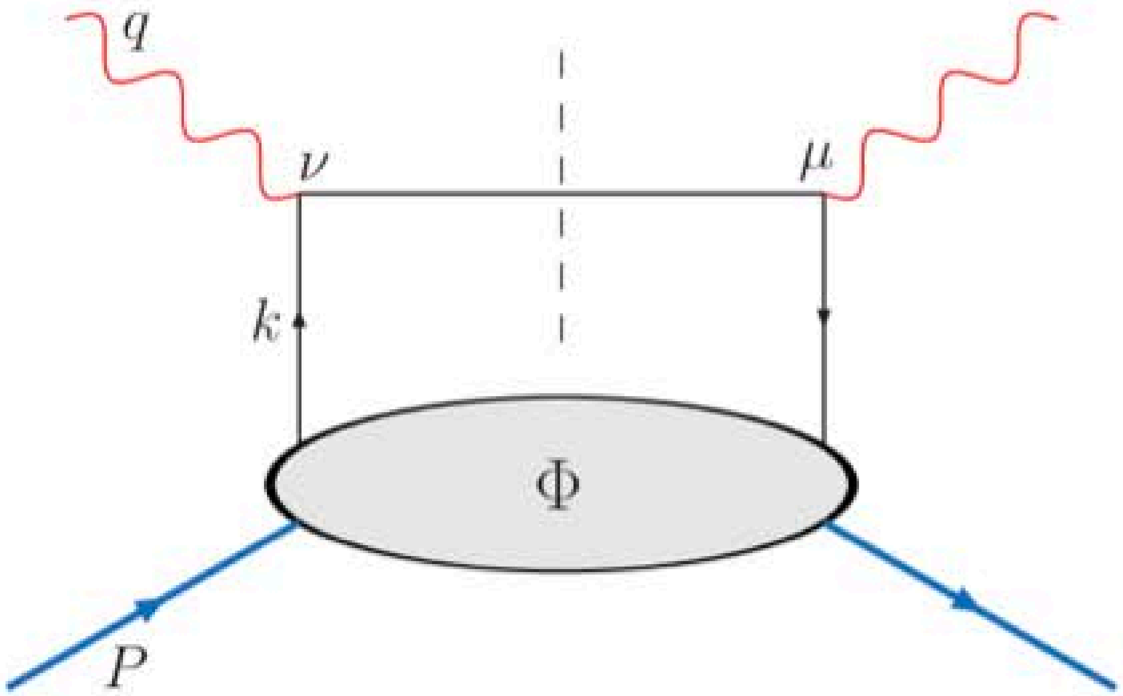

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Correlation distribution function

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

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

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

Partonic correlator (unpolarized)

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Lorenz scalar

Lorenz scalar

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Lorenz scalar

Hermiticity

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Parity invariance

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

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Lorenz scalar	Lorenz scalar
Hermiticity	Hermiticity
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

Partonic correlator (unpolarized)

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Lorenz scalar

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Leading twist contributions

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

Partonic correlator (unpolarized)

Integrated correlator

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

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

Partonic correlator (unpolarized)

Integrated correlator

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Leading twist contributions

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

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

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

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

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

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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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Neutral-current DIS

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Standard DIS structure functions

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Neutral-current DIS

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$$- y^2\left(F_{L,UU} + \lambda F^{\pm}_{L,LU}\right)$$
$$\left. - \frac{Y_-}{\sqrt{1+\gamma^2}}\left(xF^{\pm}_{3UU} + \lambda xF_{3LU}\right)\right]$$

Standard DIS structure functions

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

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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)

Experimental observable

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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

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

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

Available experimental data

HERA dataset
(Run I + II combined)

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

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

e^+ **asymmetry: 136 data**

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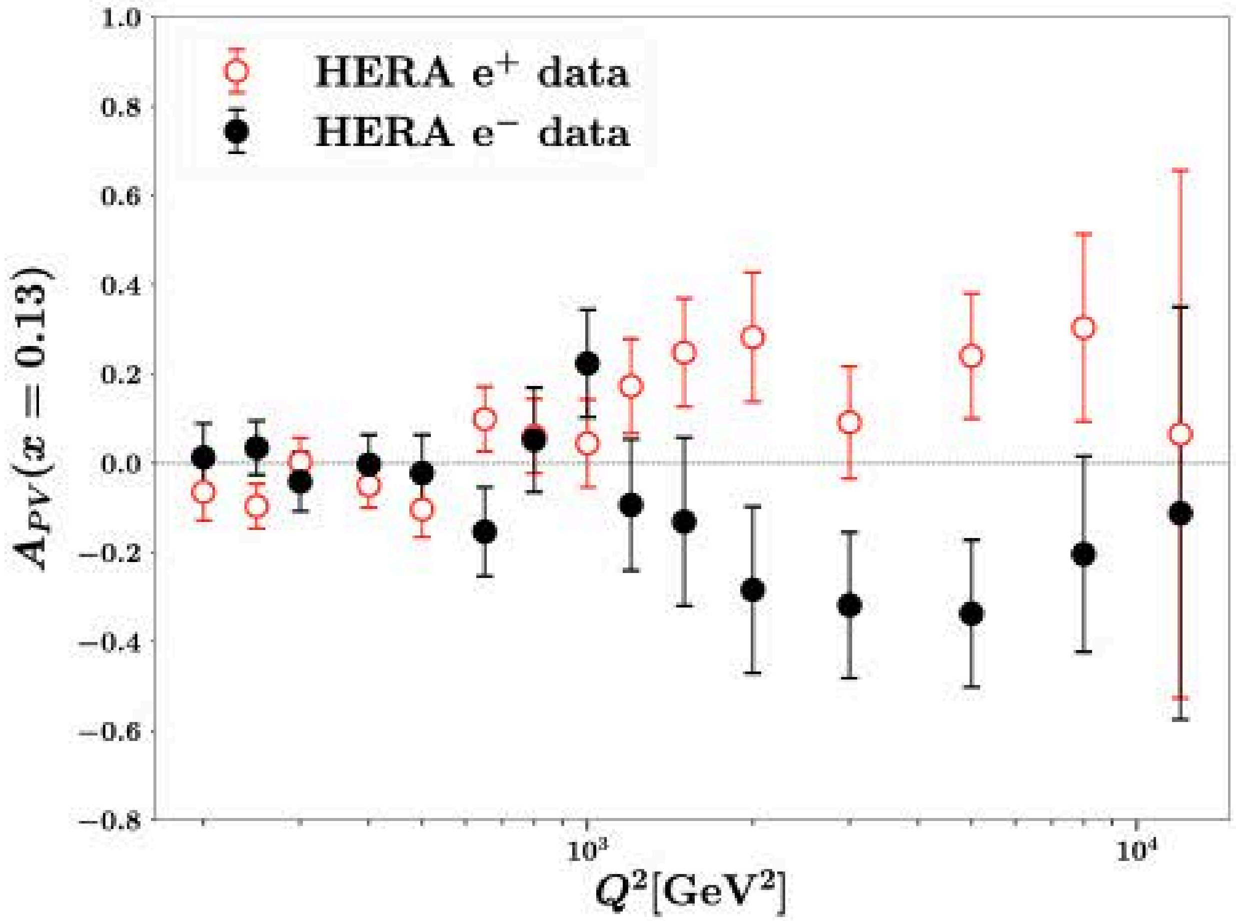

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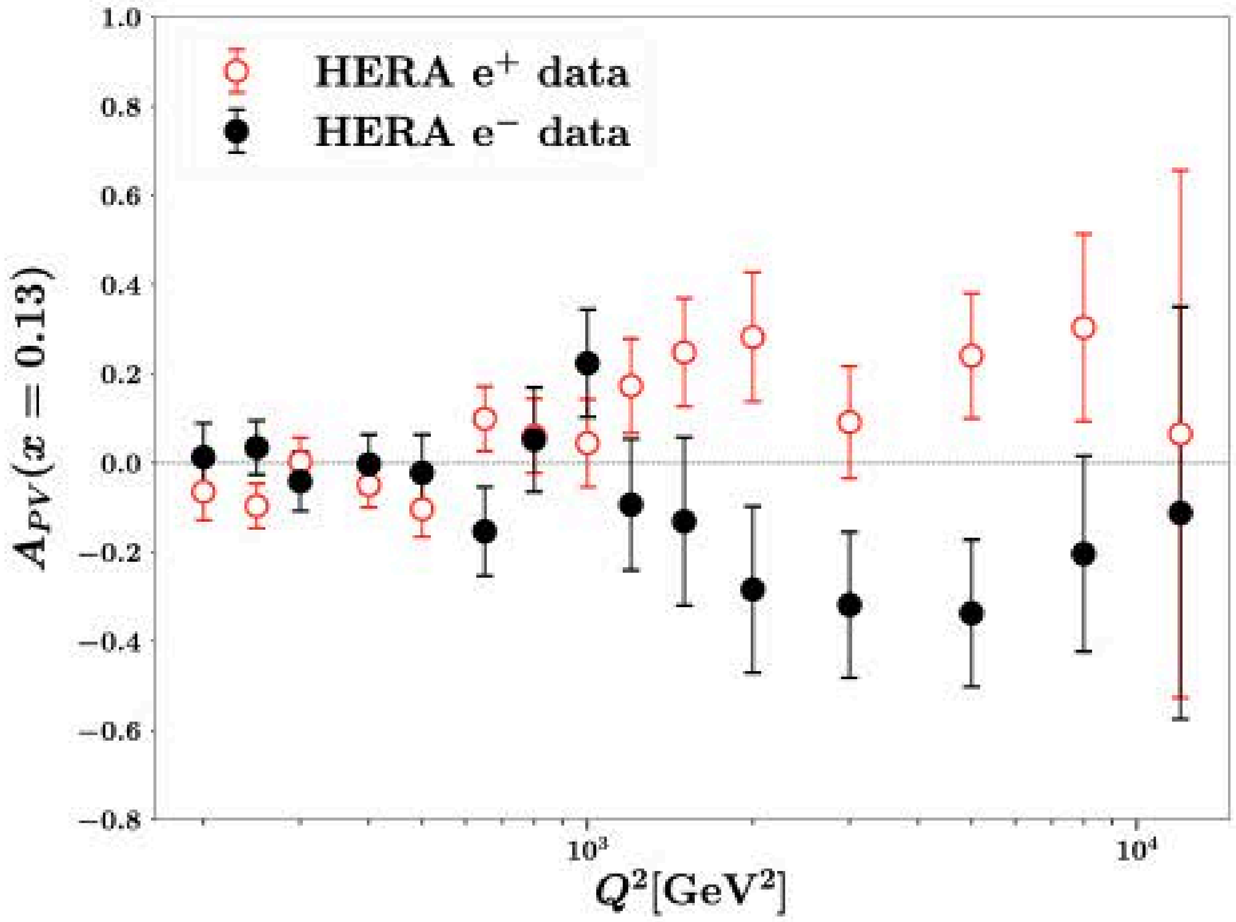

JLab6 PVDIS dataset

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

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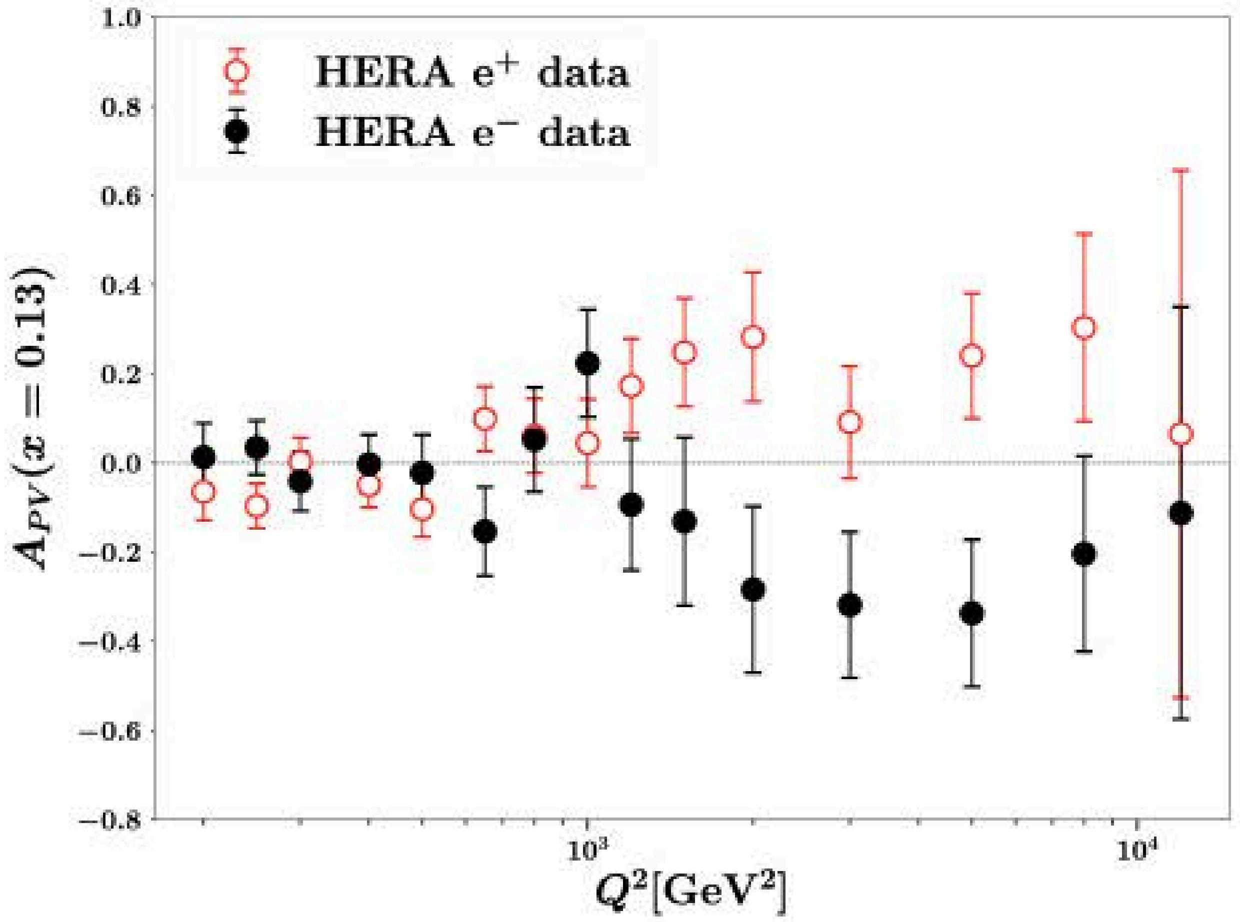

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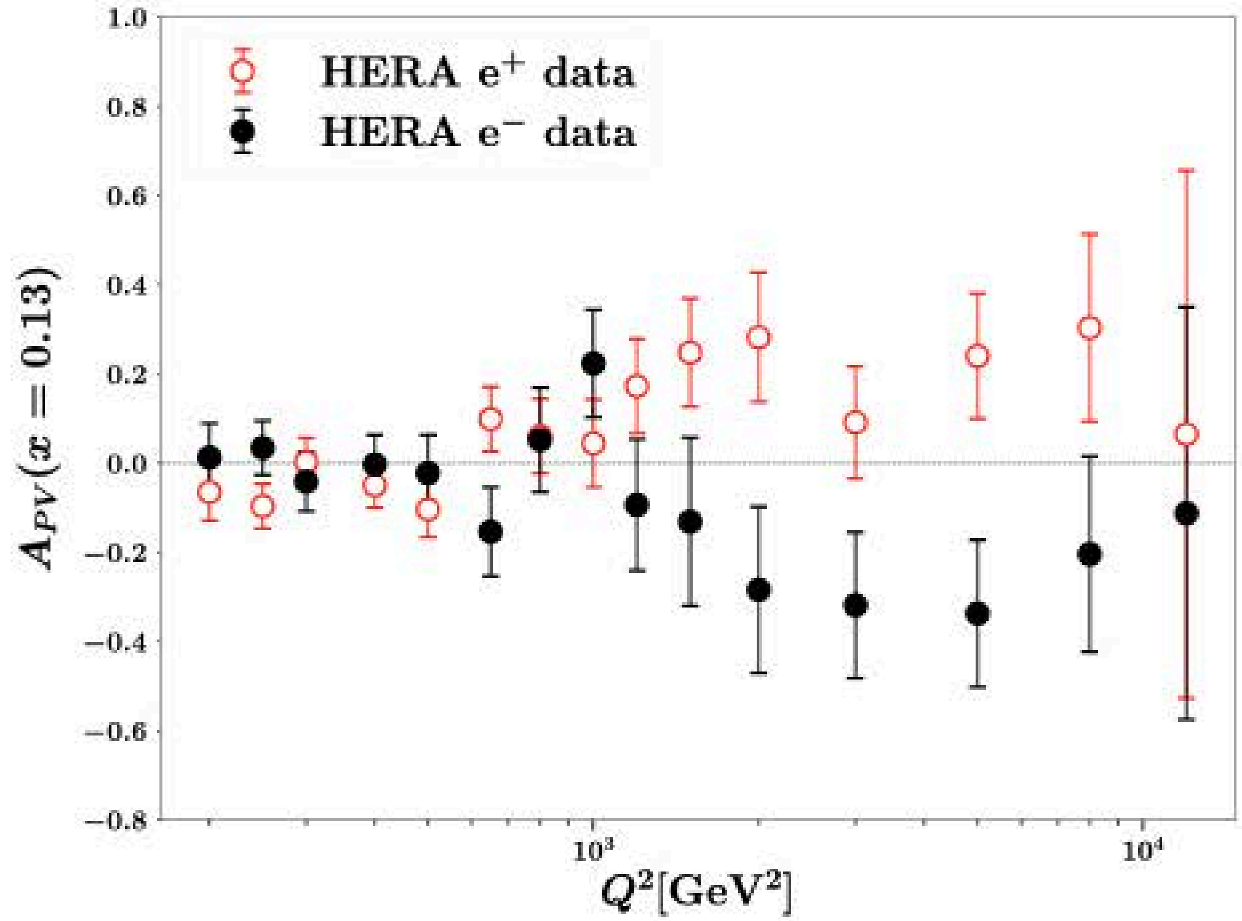

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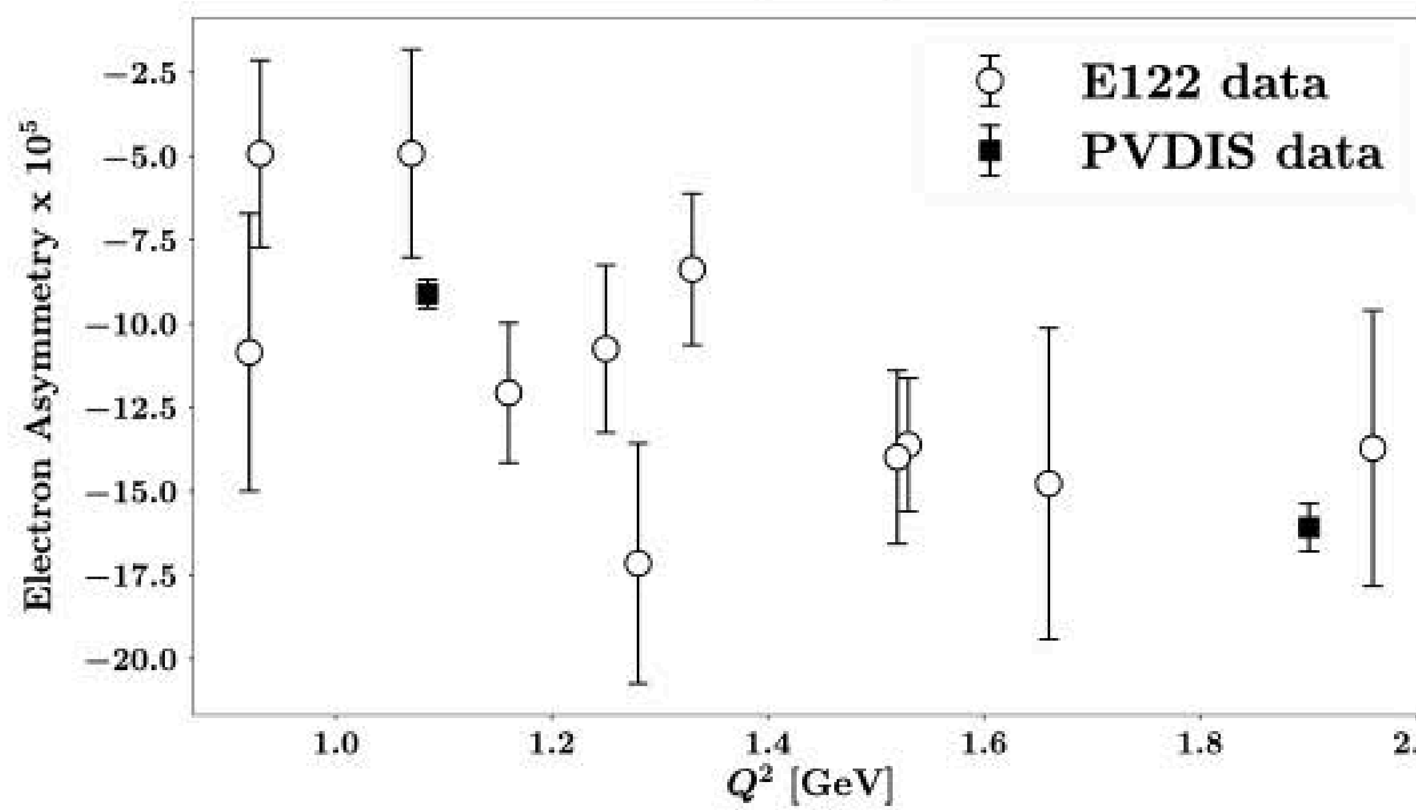

Parameterization of $g_1^{PV}(x, Q^2)$

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PV parton density comes from the structure

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1 parameter to be fitted

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***

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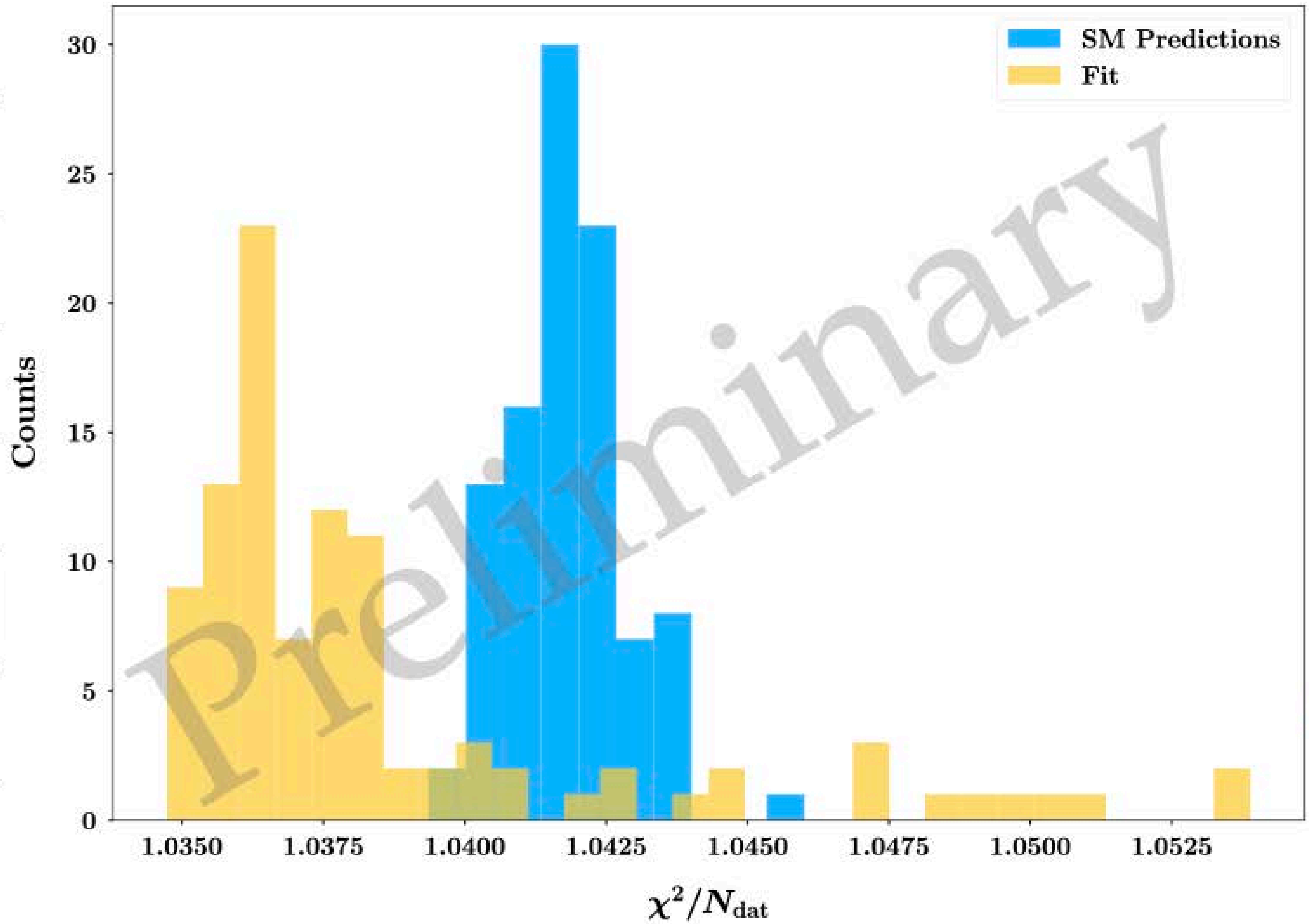
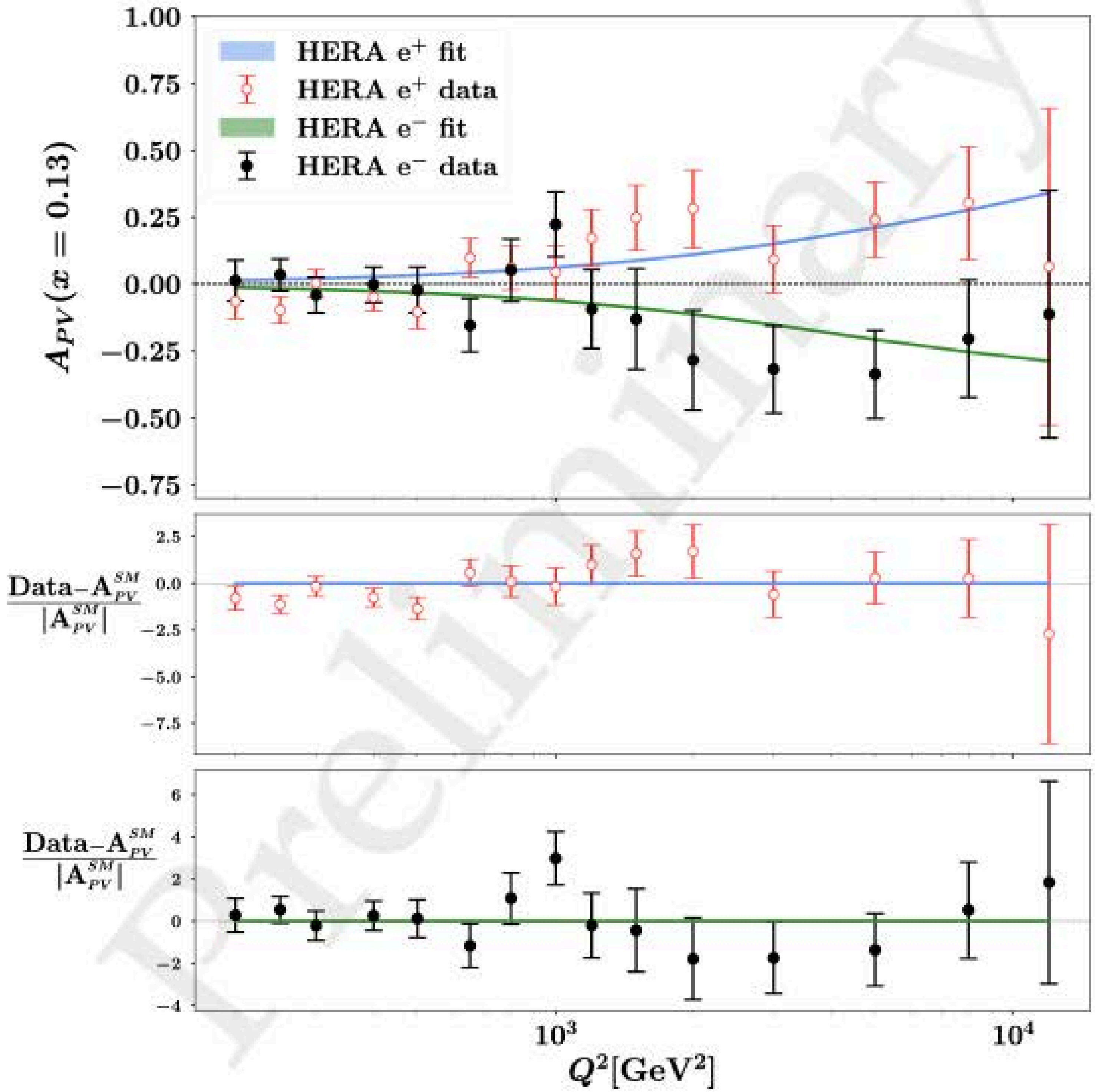


Results of the fit: data-theory comparison



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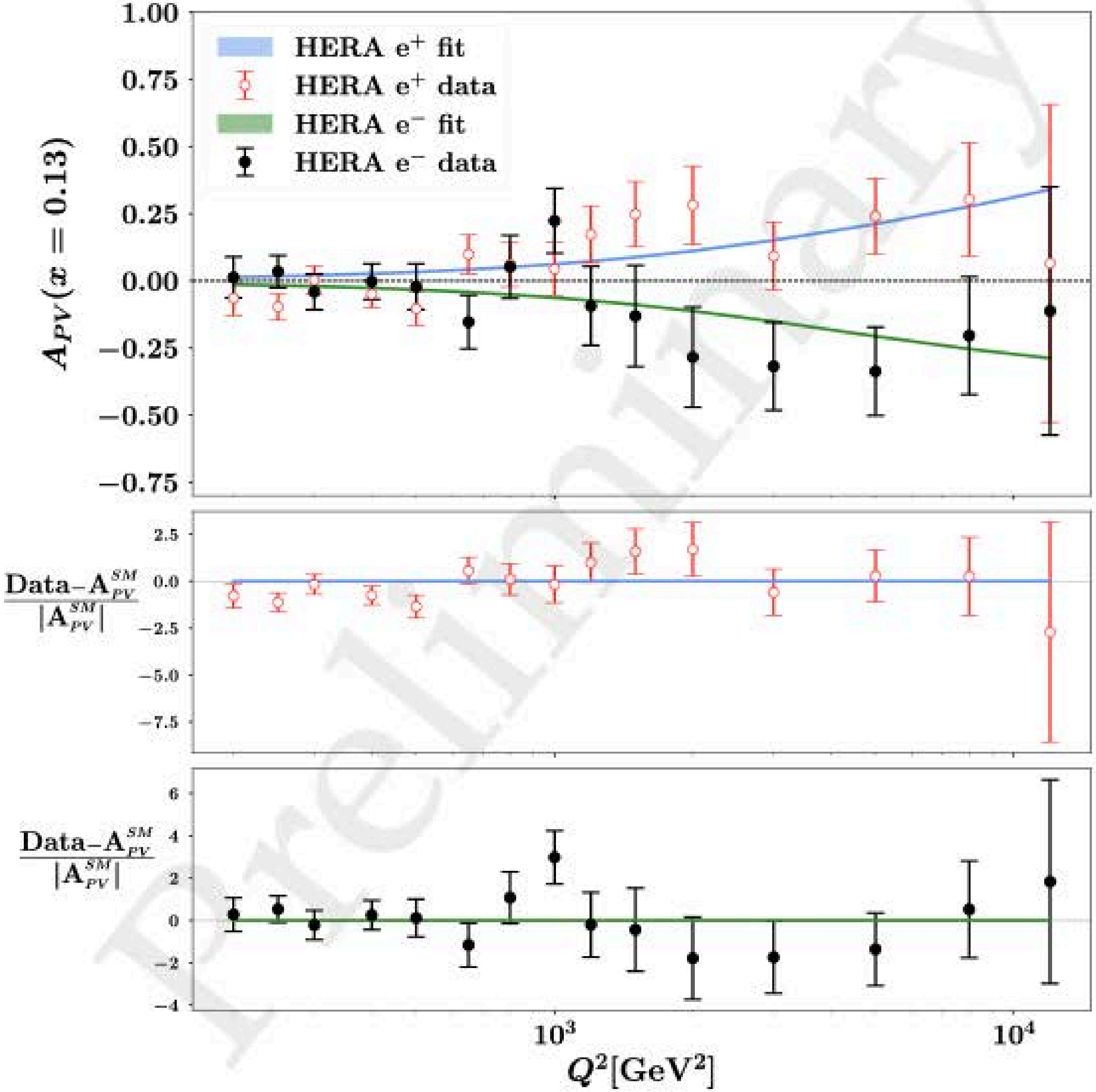

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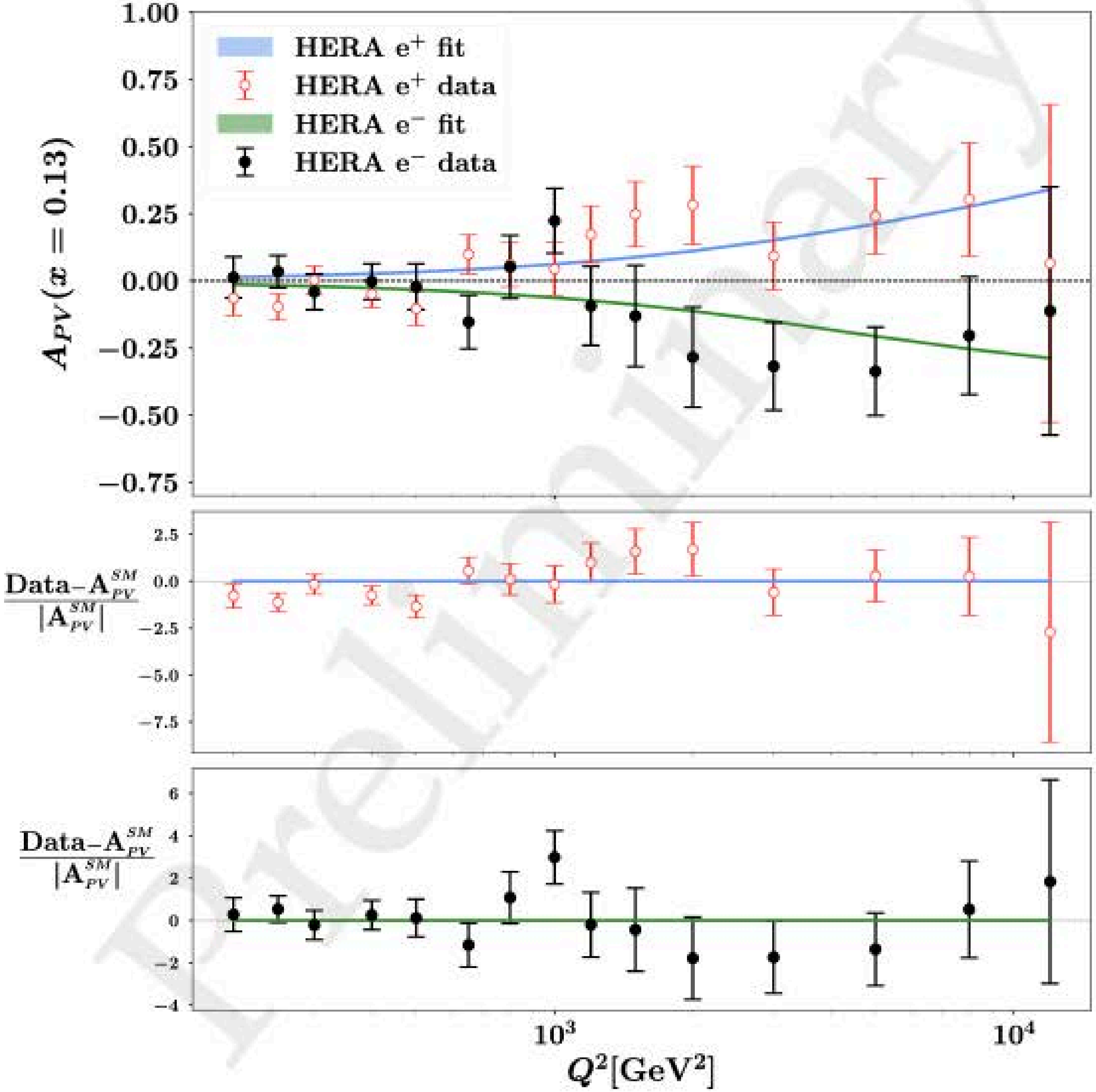

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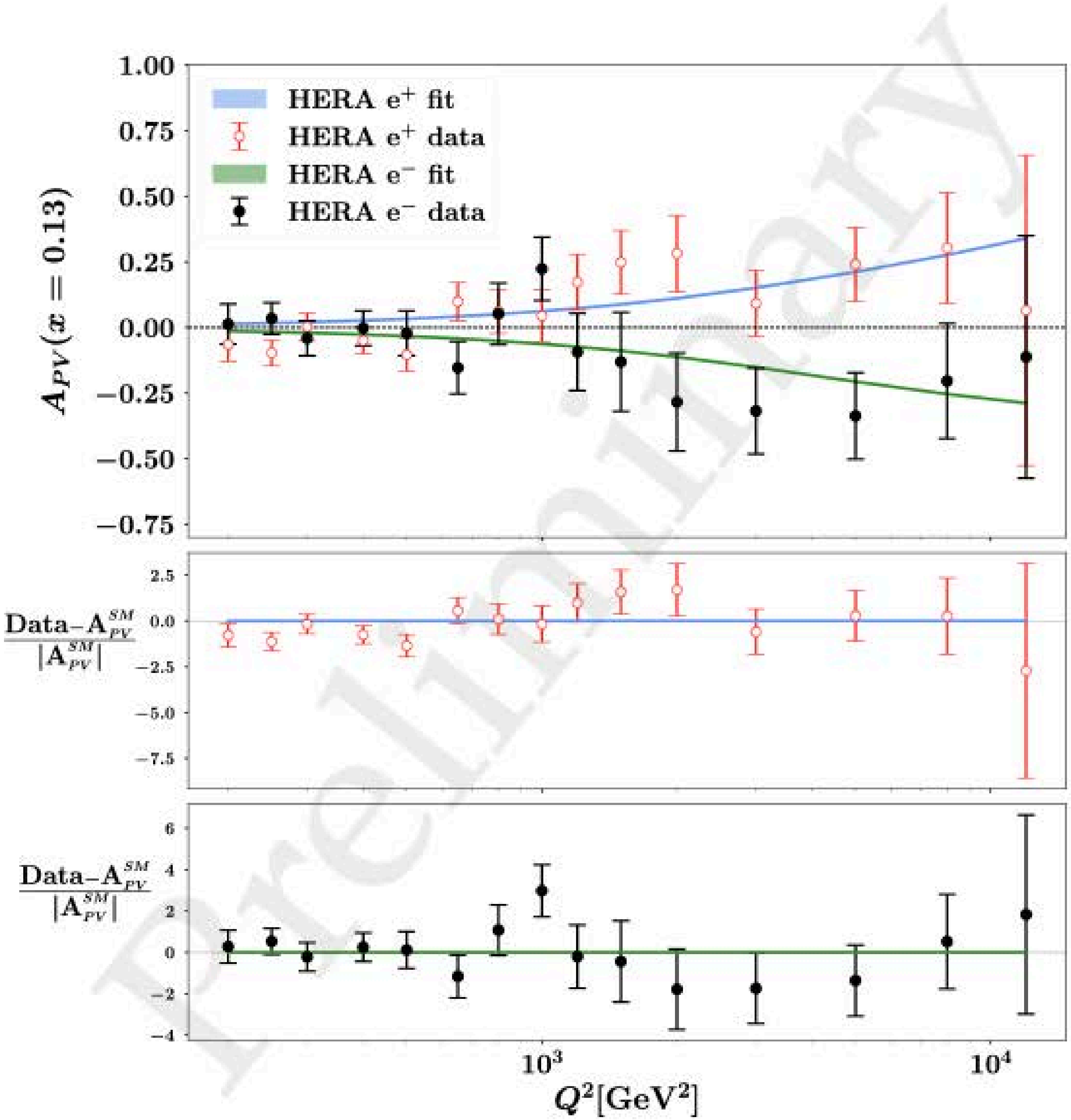

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Agreement for electron asymmetry, but too large errors at low-Q

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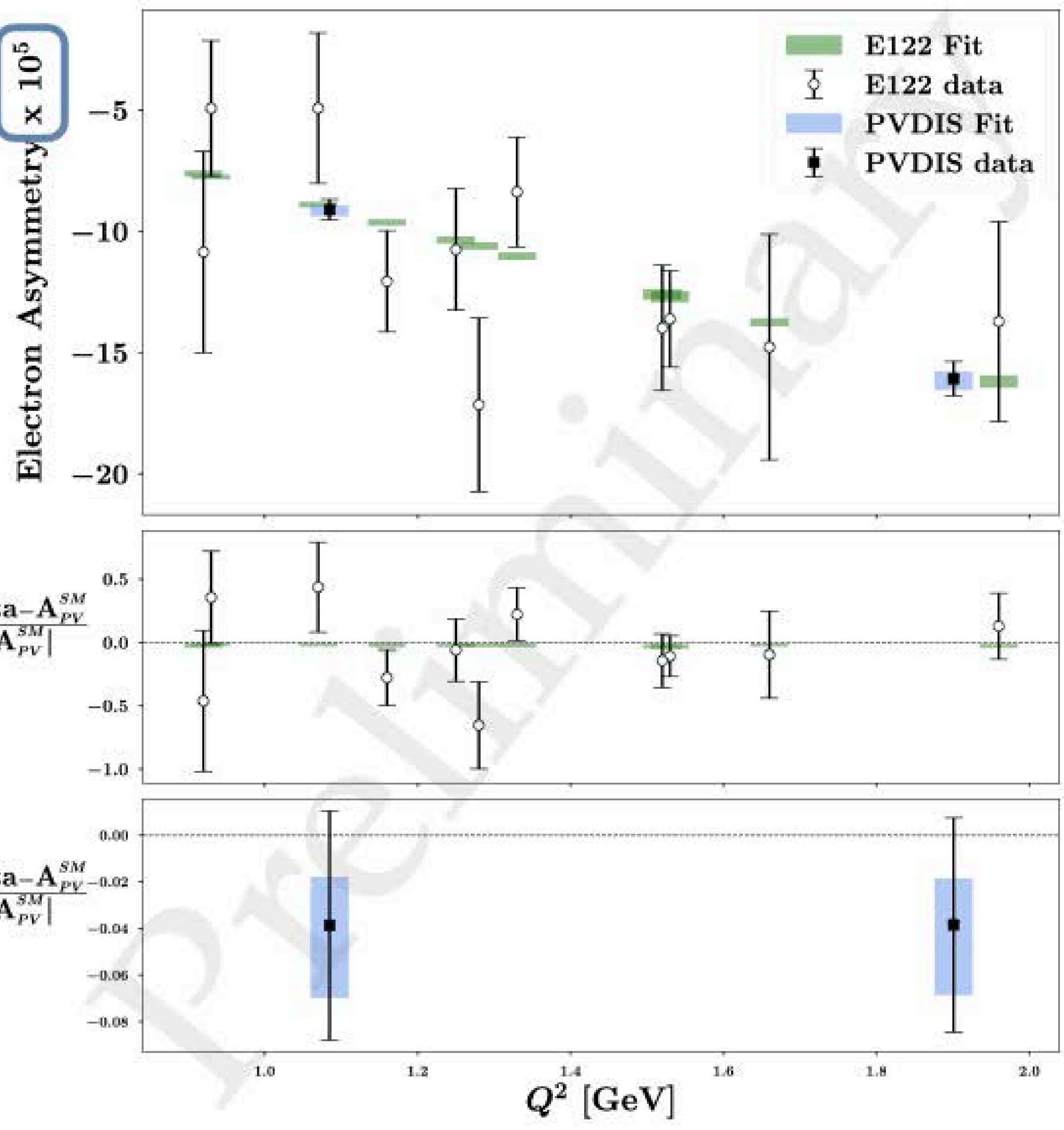

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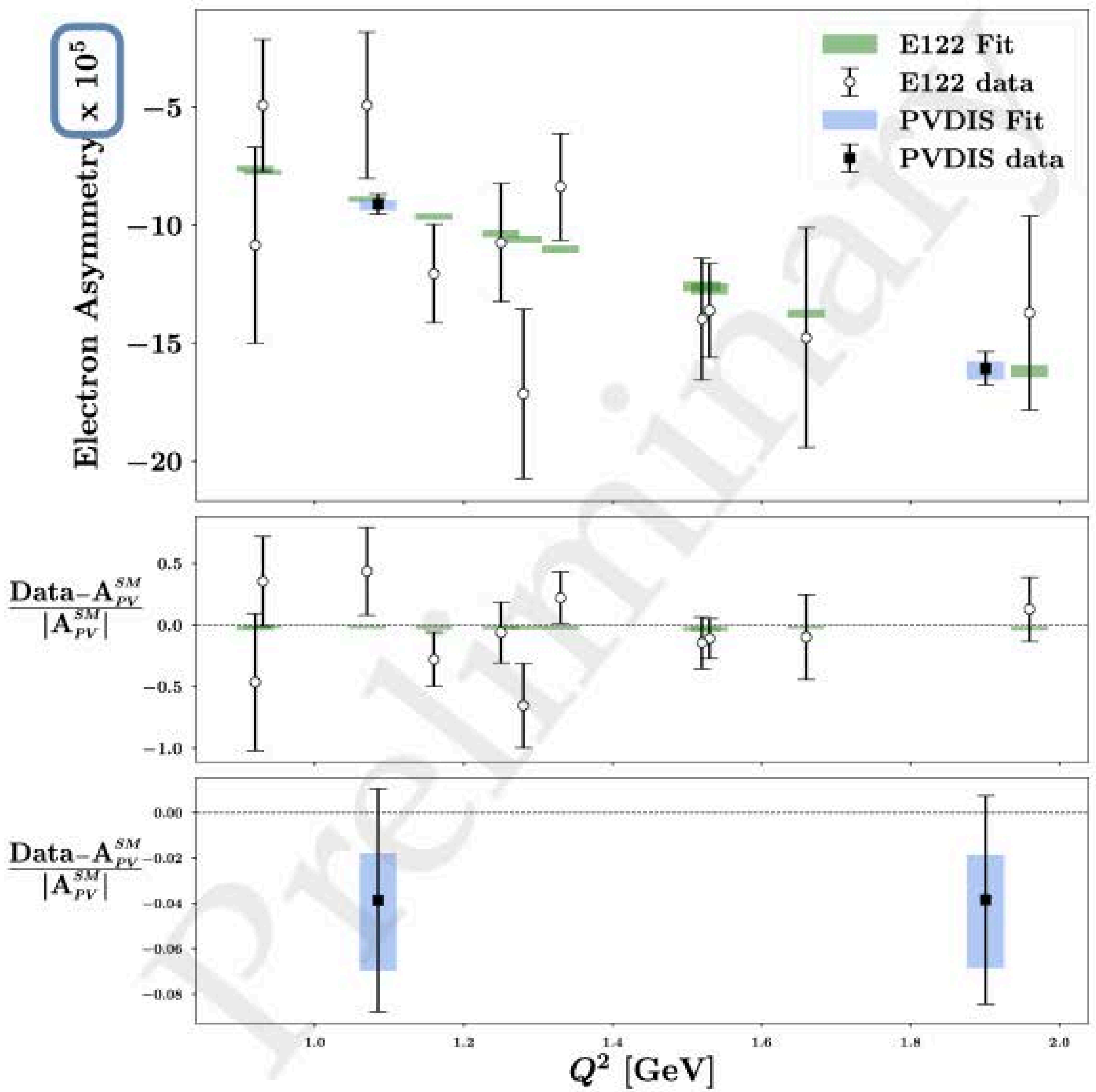

Sizeable improvement of the fit w.r.t. SM predictions

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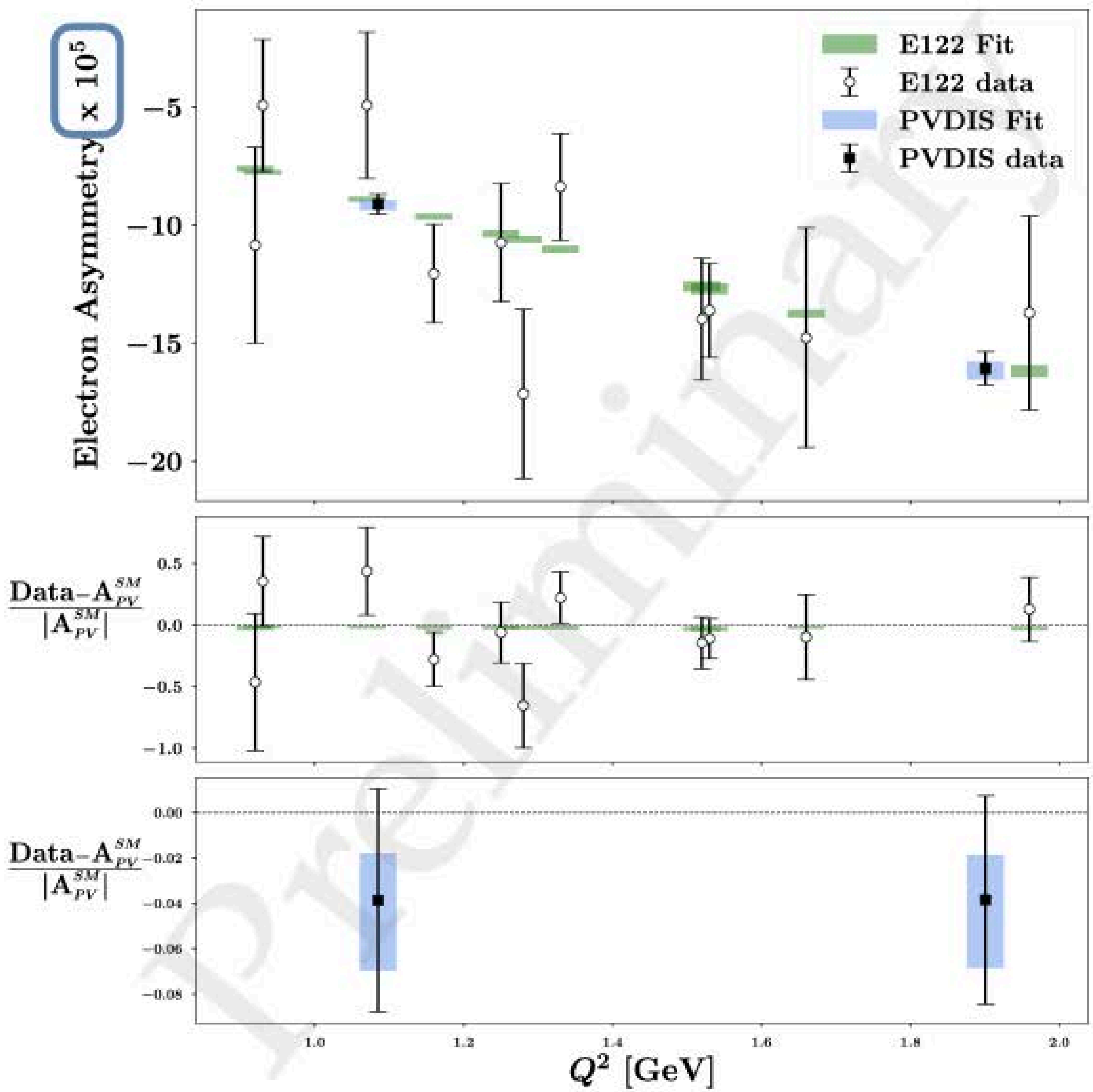

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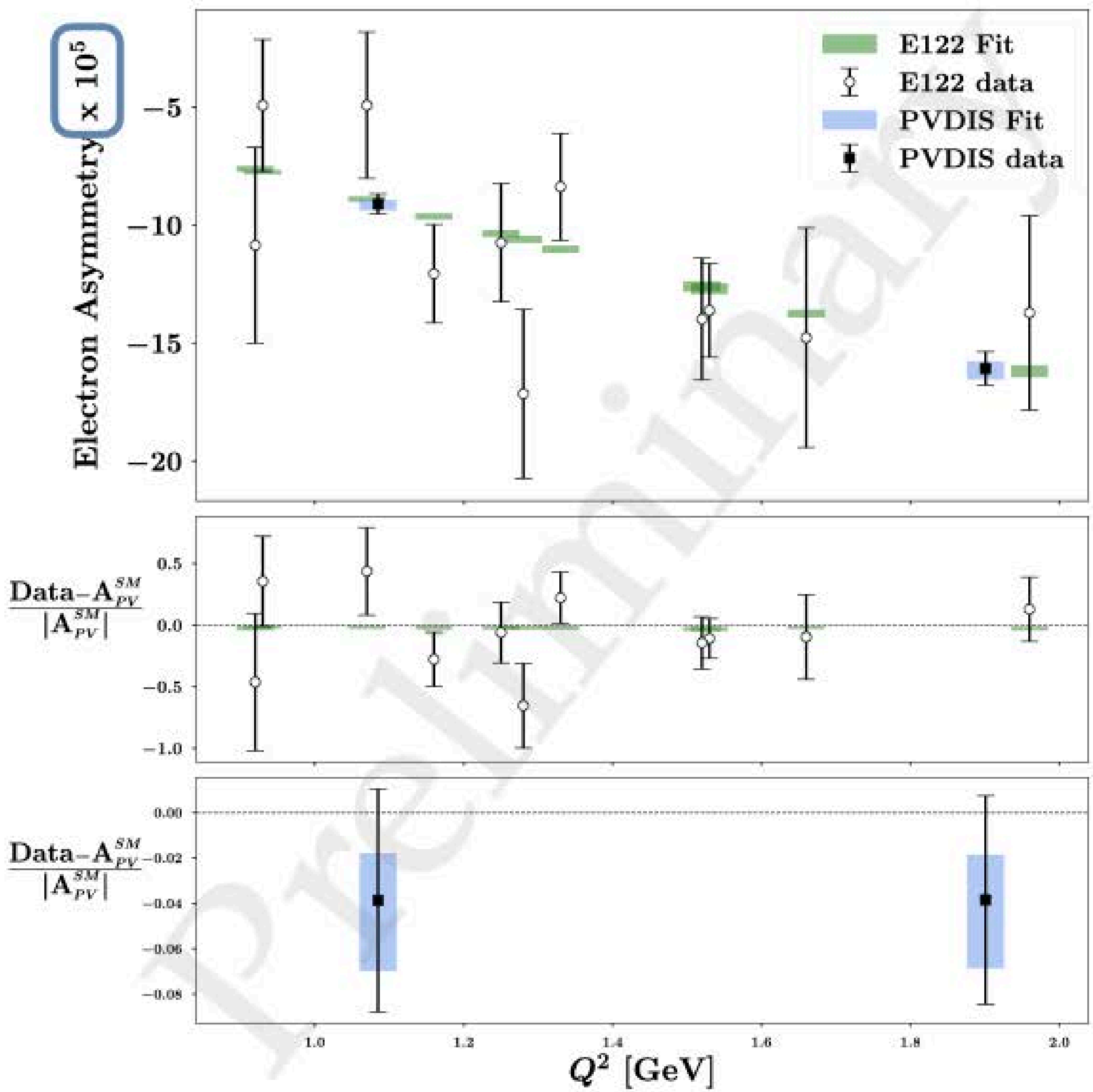

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Data points which actually drive the fit due to very small experimental errors (~ %)

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

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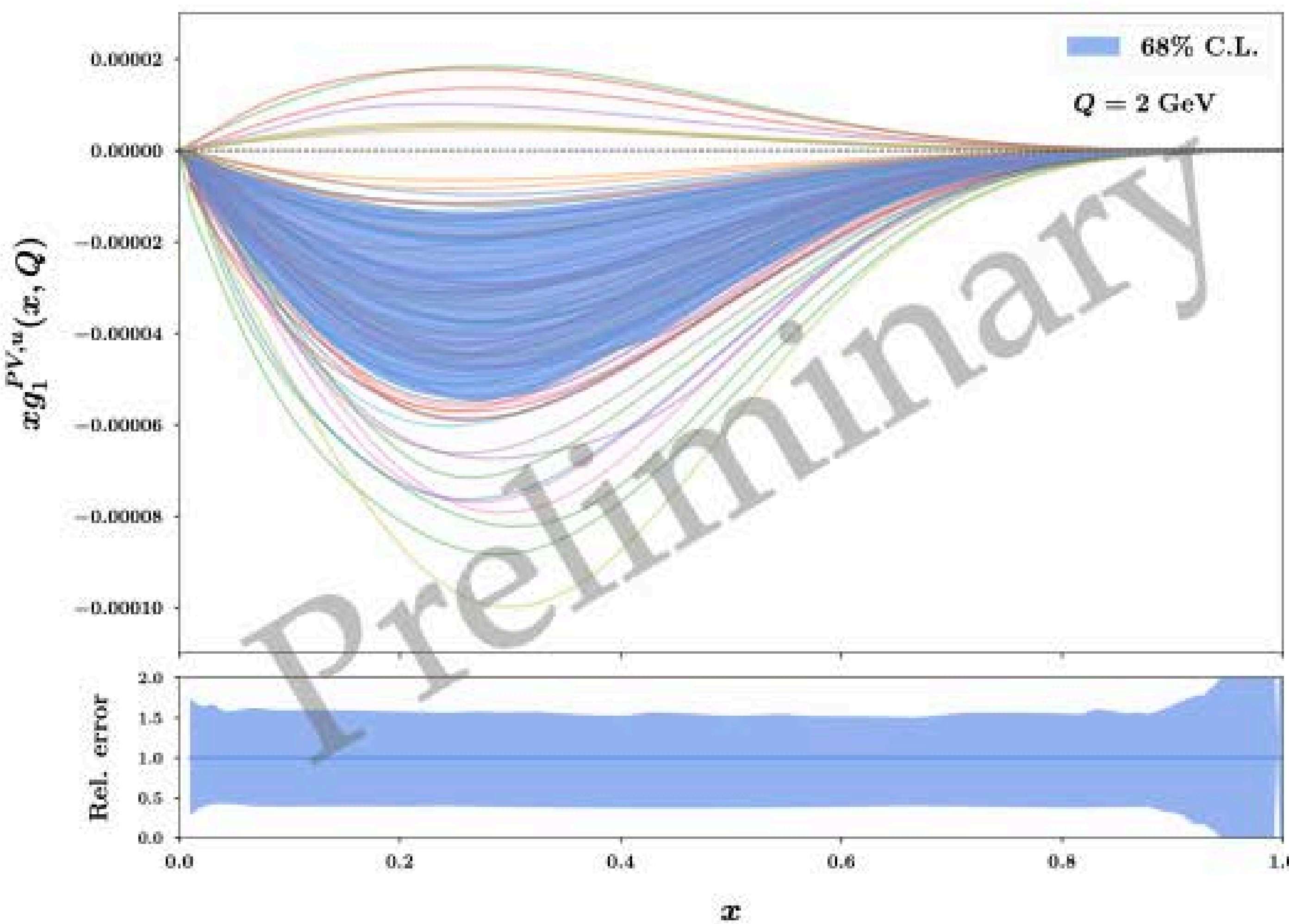

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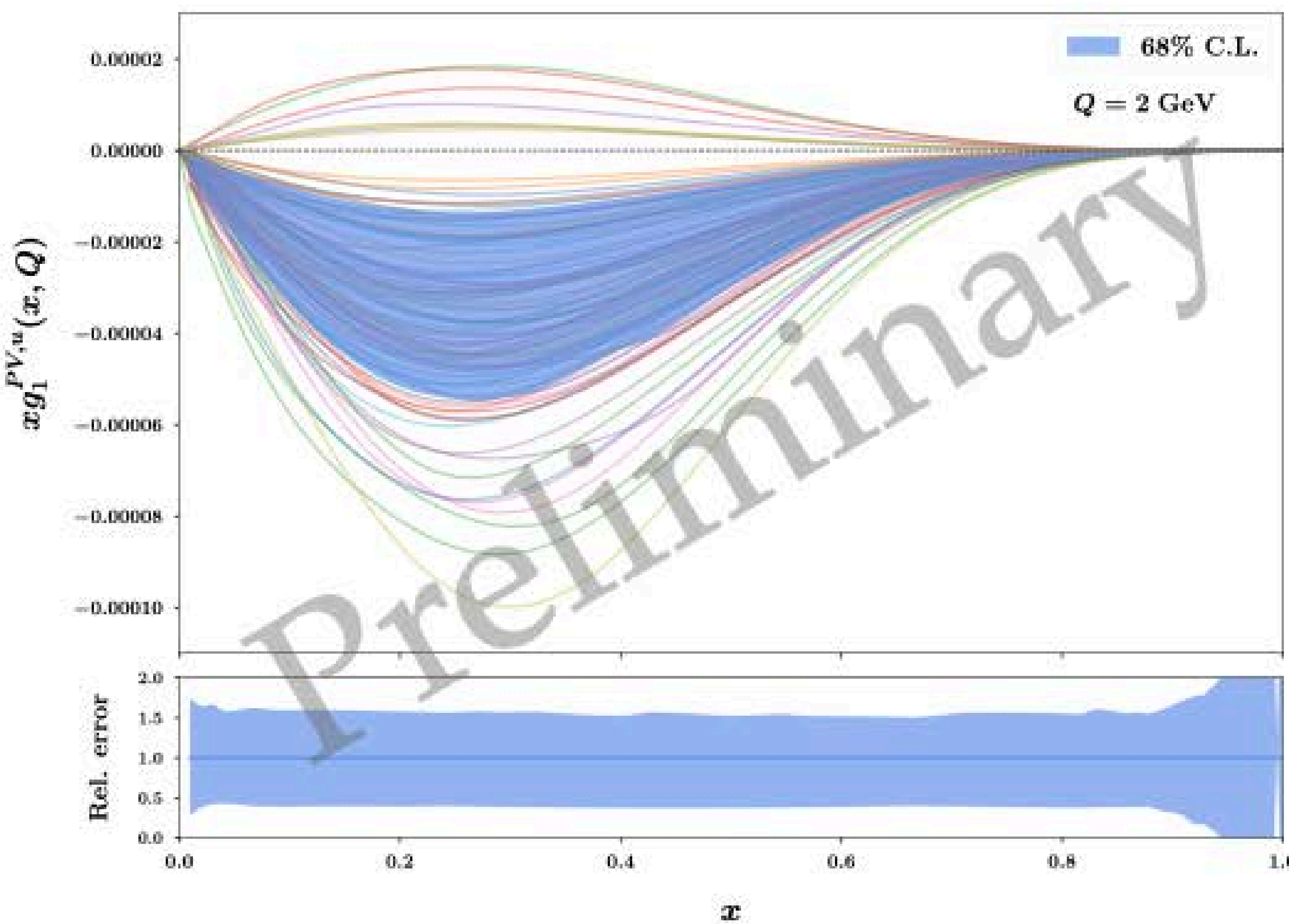

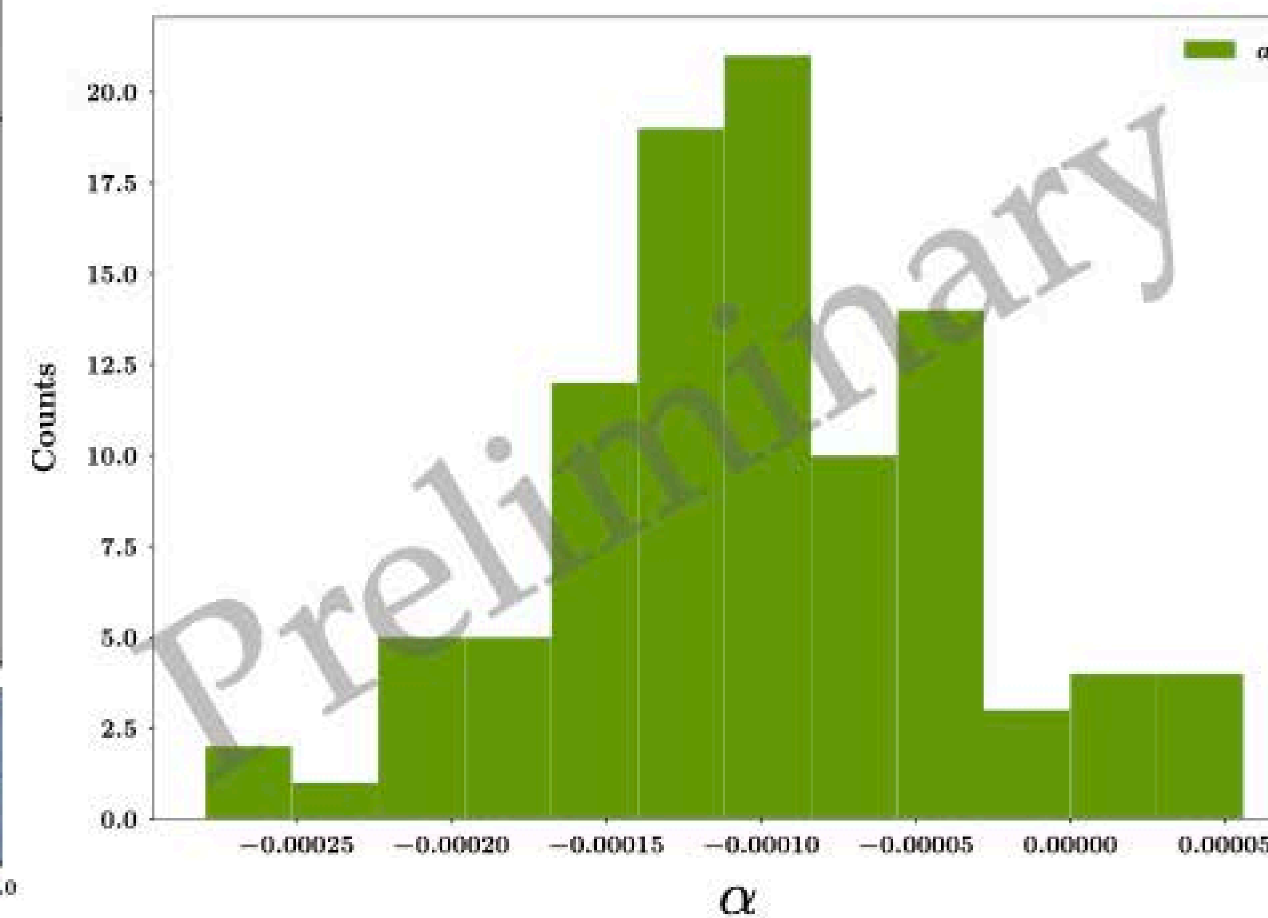

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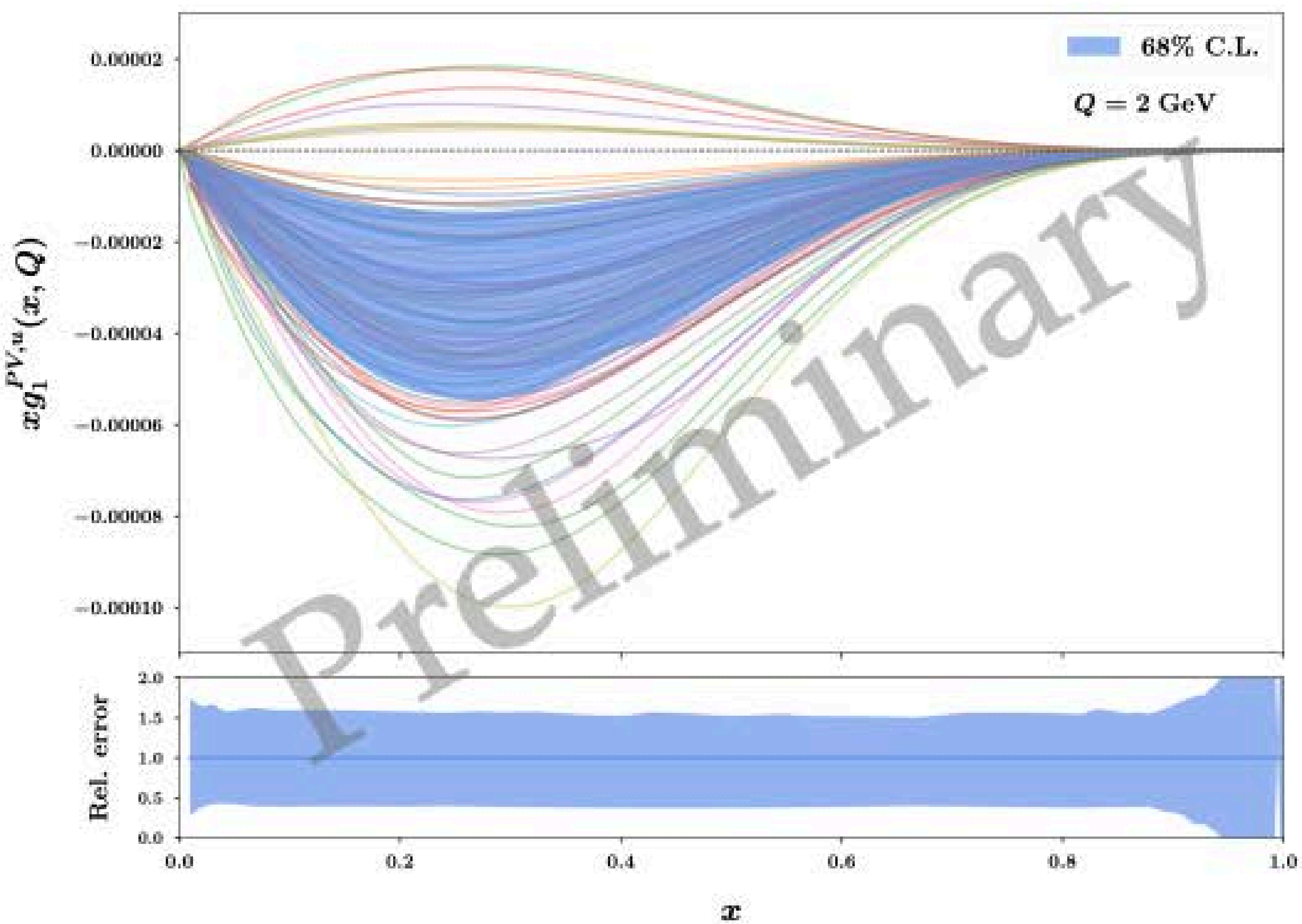

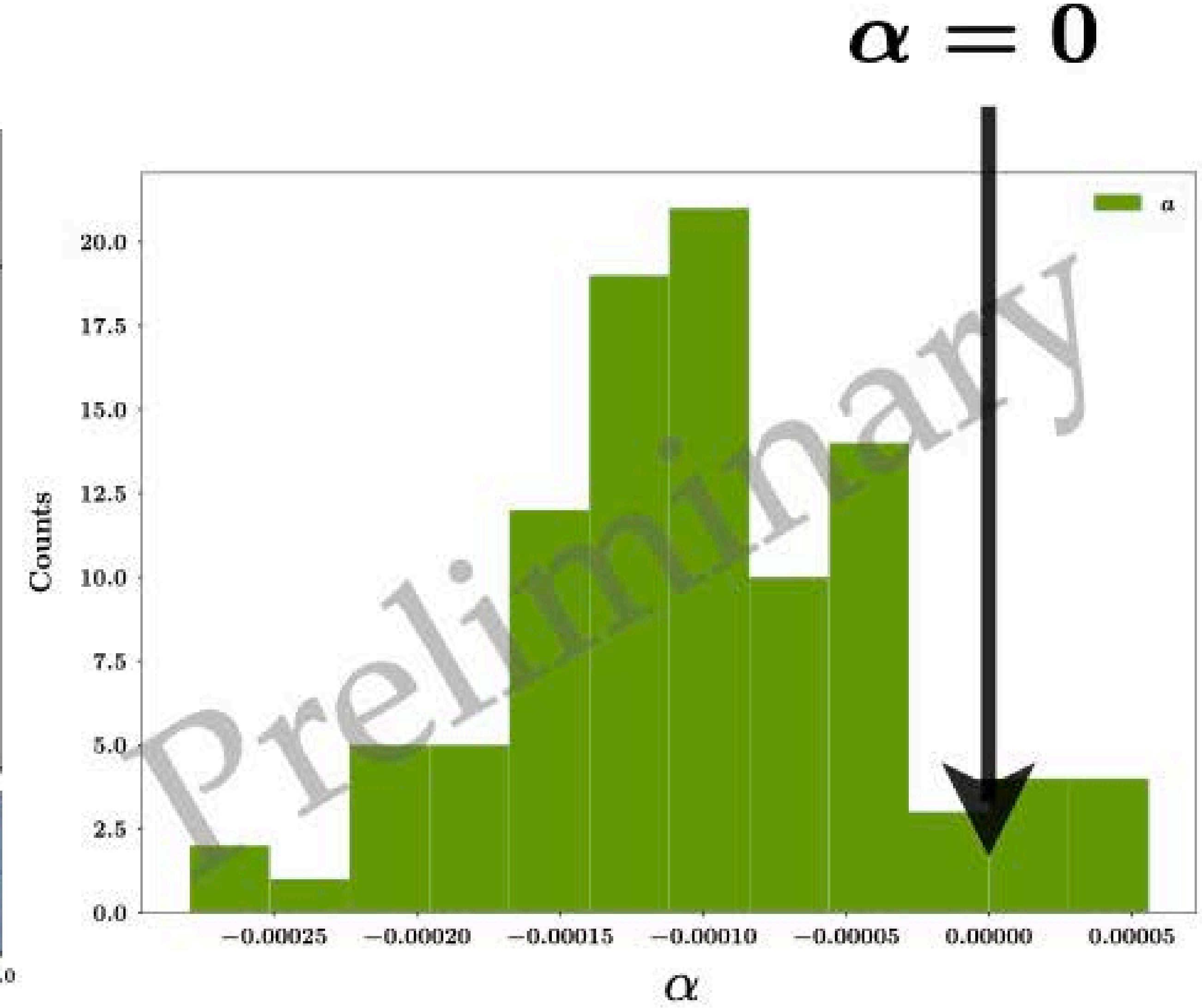

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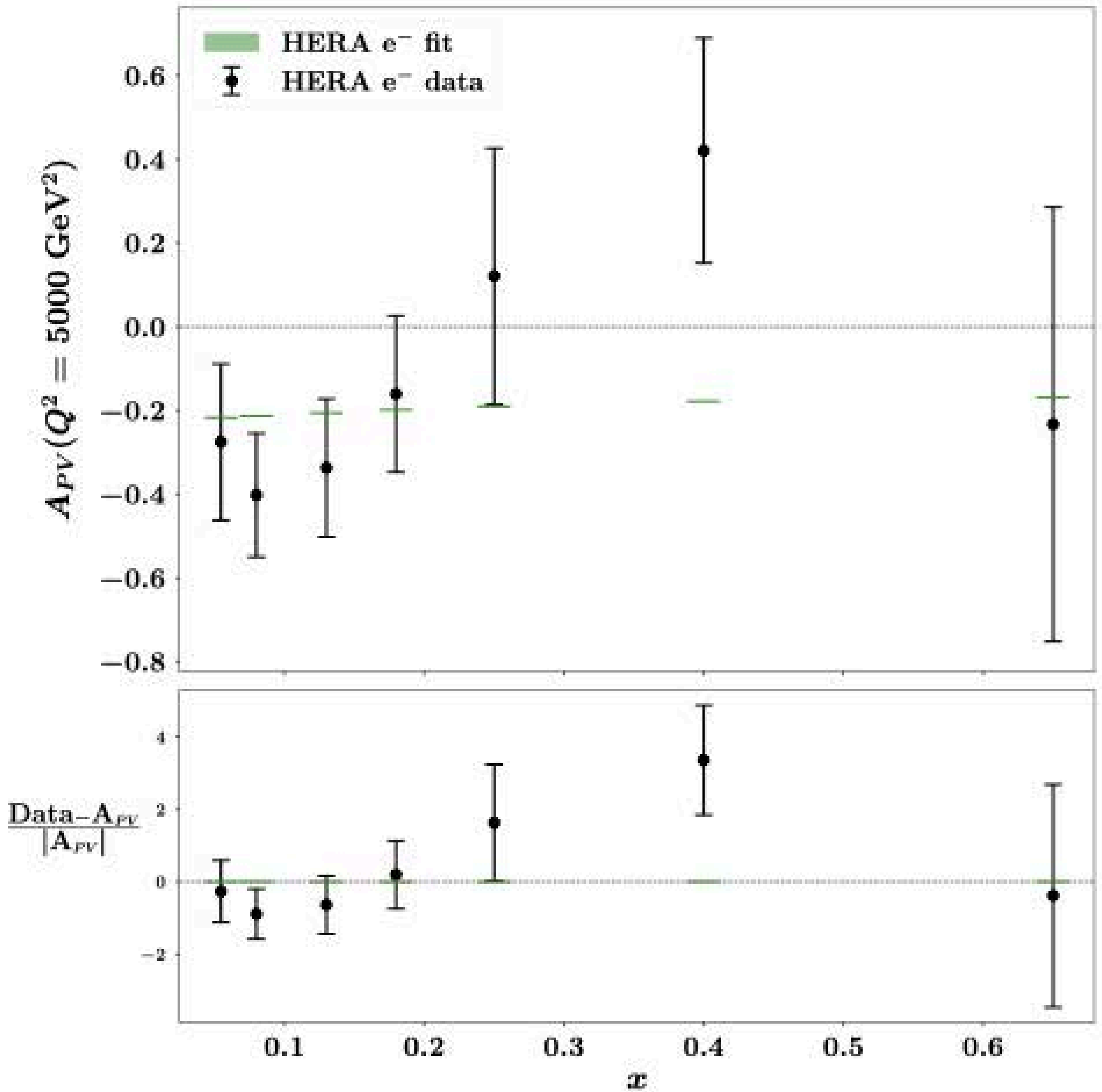
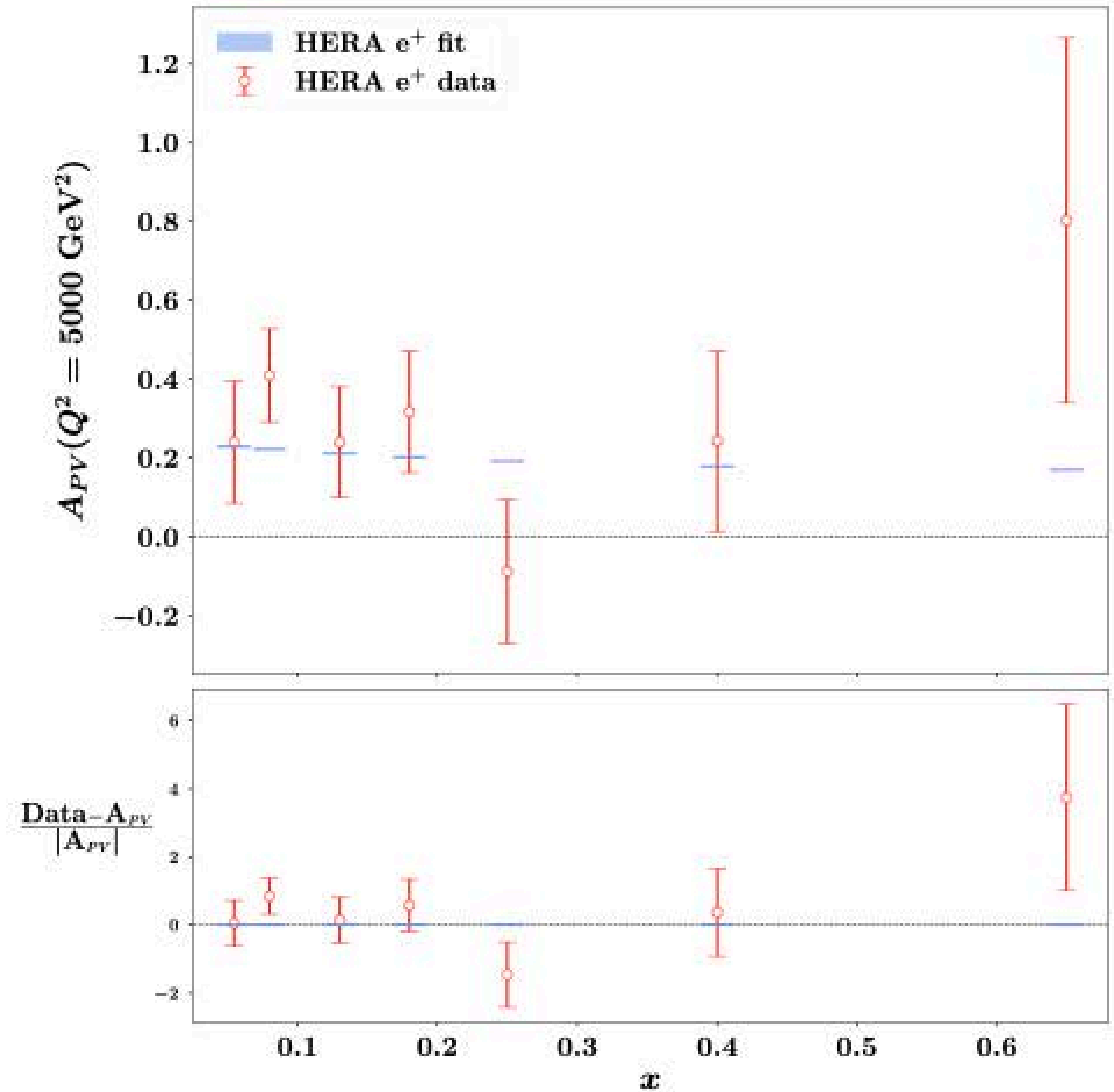
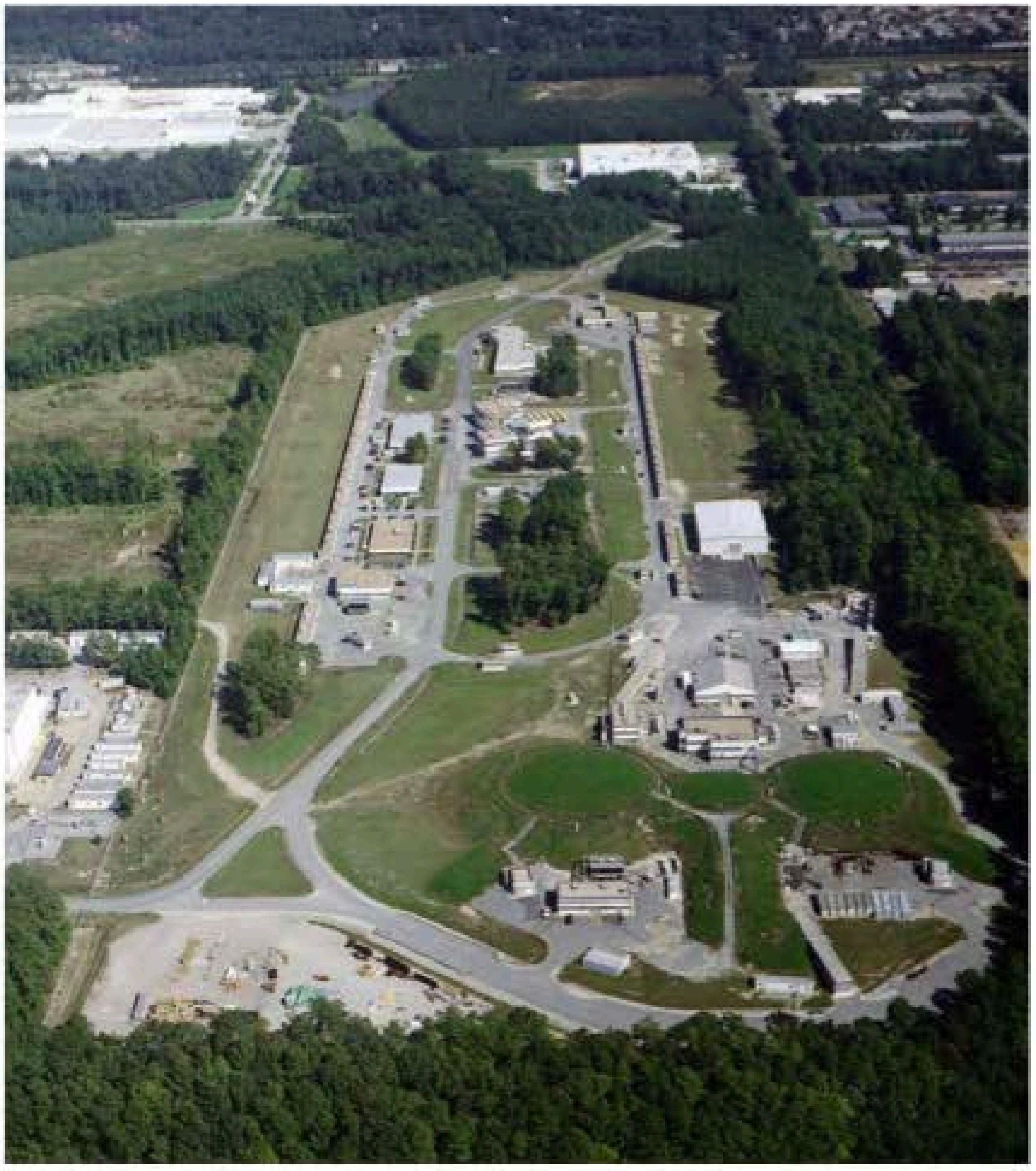
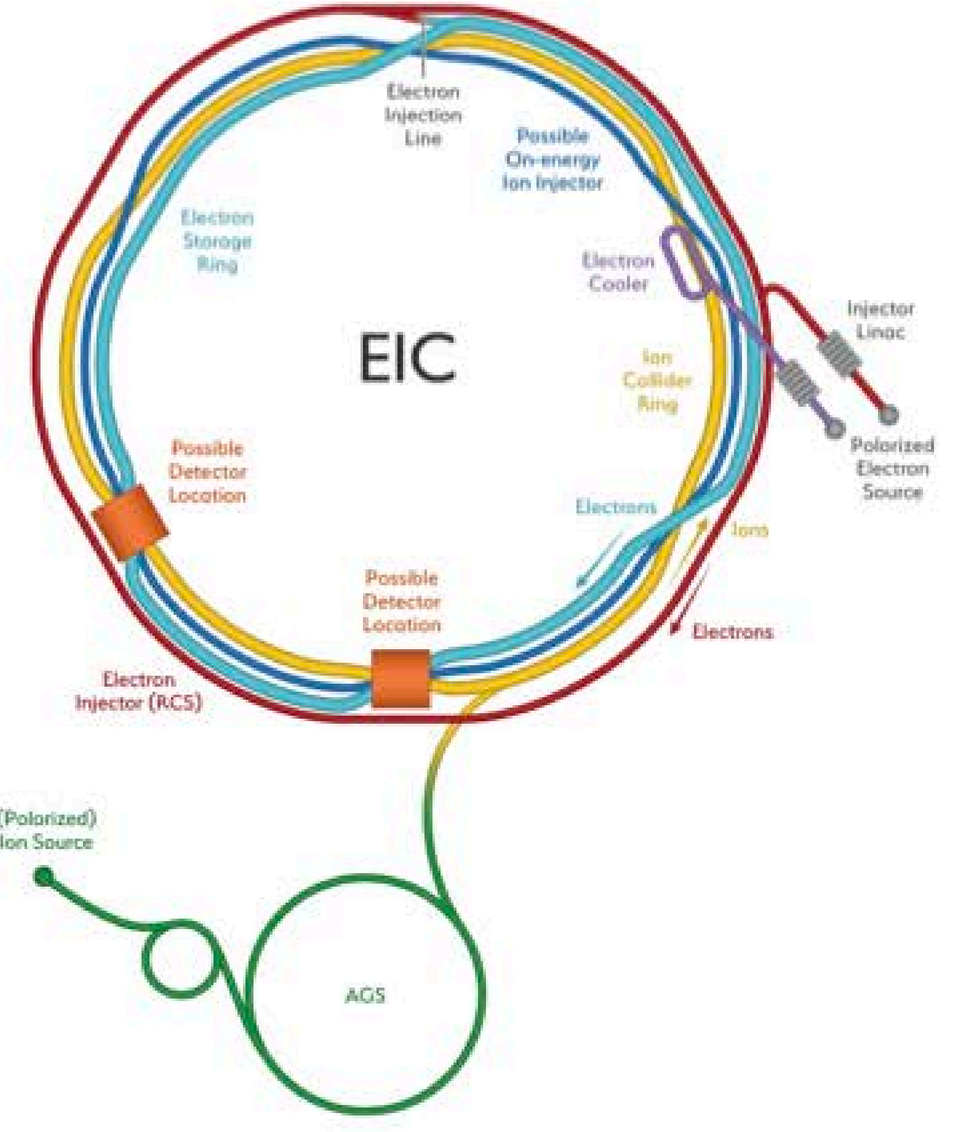




Outlook

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





Outlook

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

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

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- To better investigate its behaviour, new data are needed especially at small (medium) values of Q
- The integral of g_1^{PV} (f_{1L}^{PV}) is related to the nucleon anapole (dipole) moment and there is room for comparisons with lattice calculations

Backup

Motivations

EW sector

CP violation is included

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Weak CP

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

θ-term

SMEFT operators

Motivations

EW sector — CP violation is included

Weak CP — *too small...*

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

Strong CP

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Nucleon electric dipole moment

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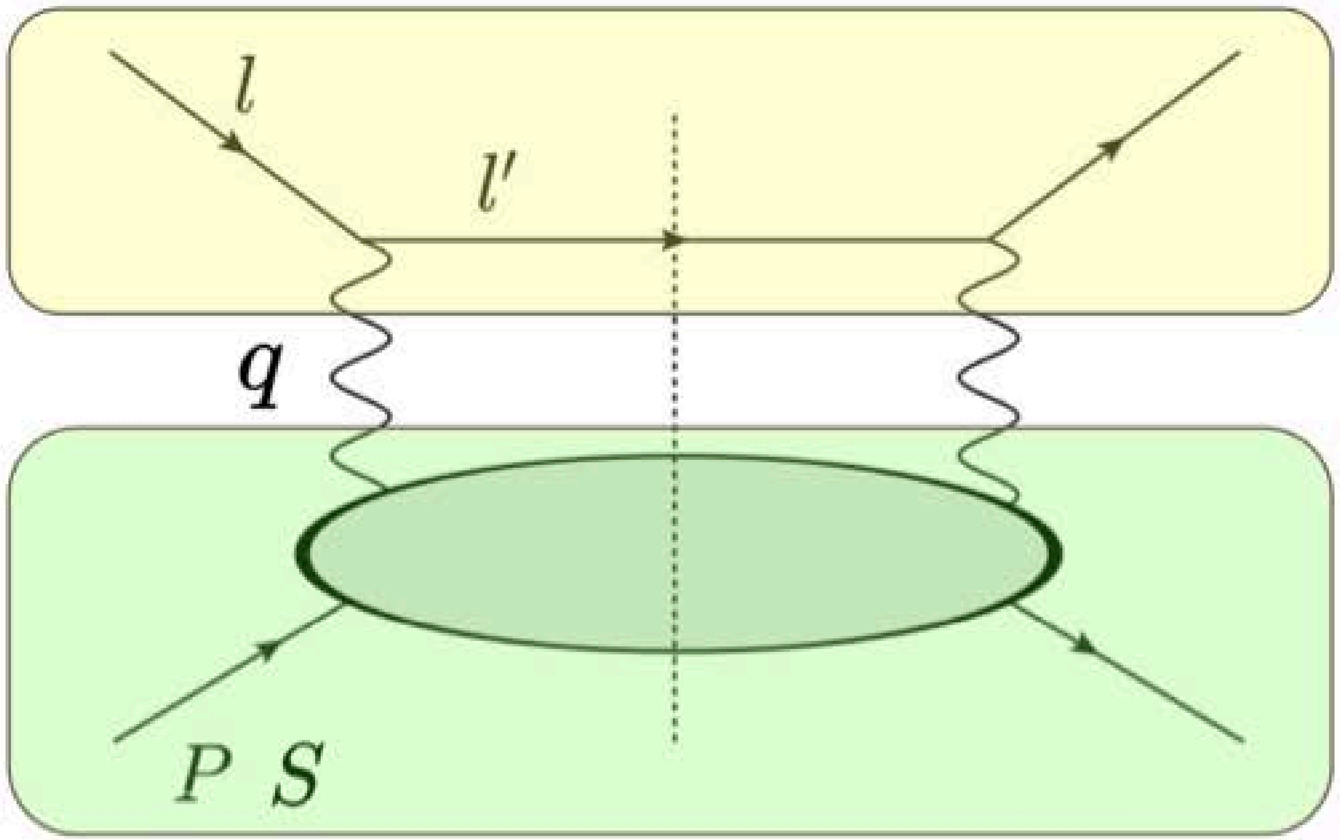
Nucleon electric dipole moment

never measured…

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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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)
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Error propagation

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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100 MC replicas of helicity PDF

Error propagation

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

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

$g_1(x, Q^2)$ *NNPDFpol1.1*

Nocera et al. (NNPDF), Nucl. Phys. B 887 (2014)

100 MC replicas of unpolarized PDF

100 MC replicas of helicity PDF

100 MC replicas experimental data

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Statistical distribution of 100 values of parameter α