Istituto Nazionale di Fisica Nucleare

HAS QCD
HADRONIC STRUCTURE AND QUANTUM CHROMODYNAMICS

UNIVERSITÀ DI PAVIA

Looking for strong parity violation in the proton structure

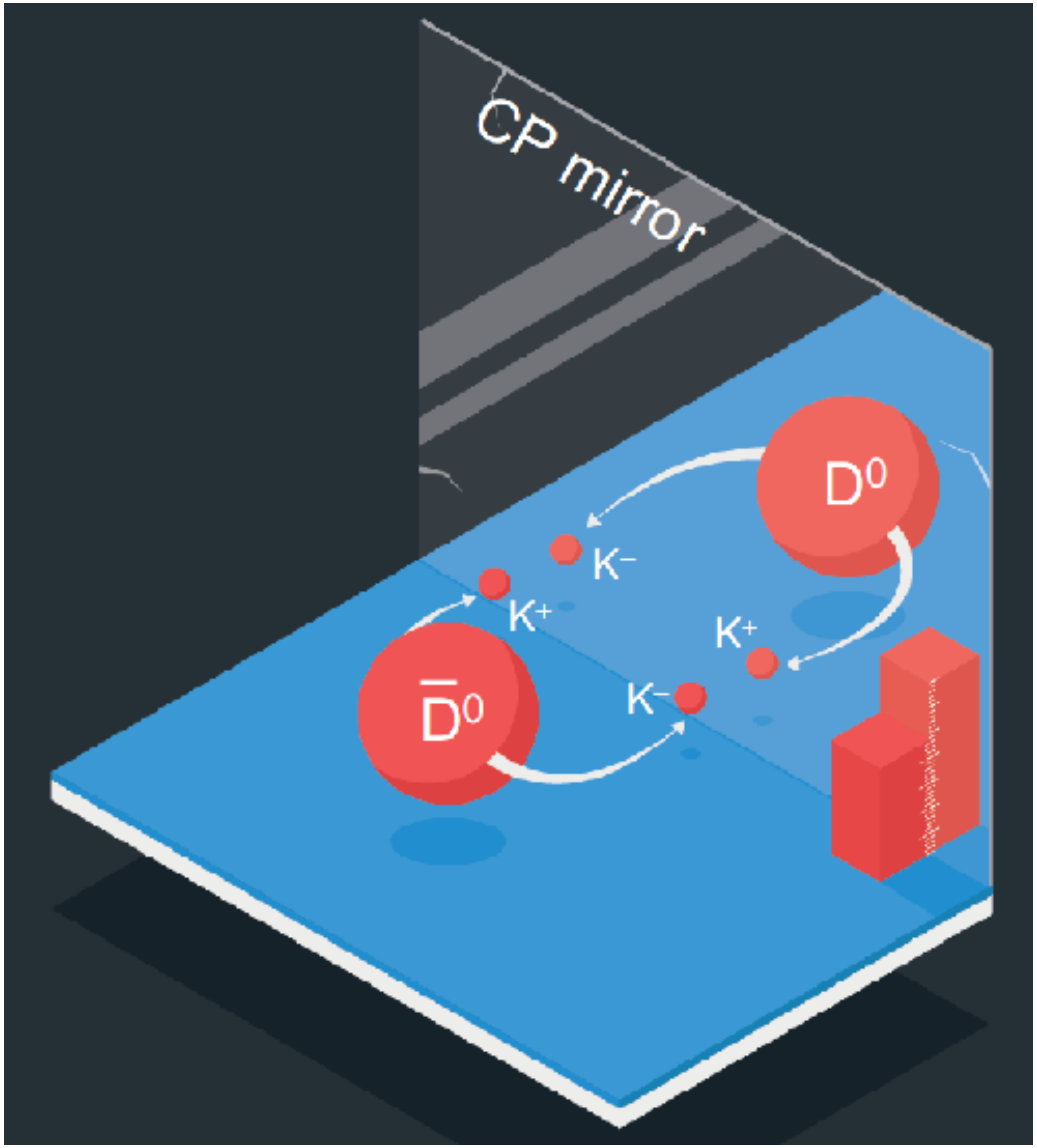
Matteo Cerutti

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

SoLID Collaboration meeting — 05/09/2023

Motivations

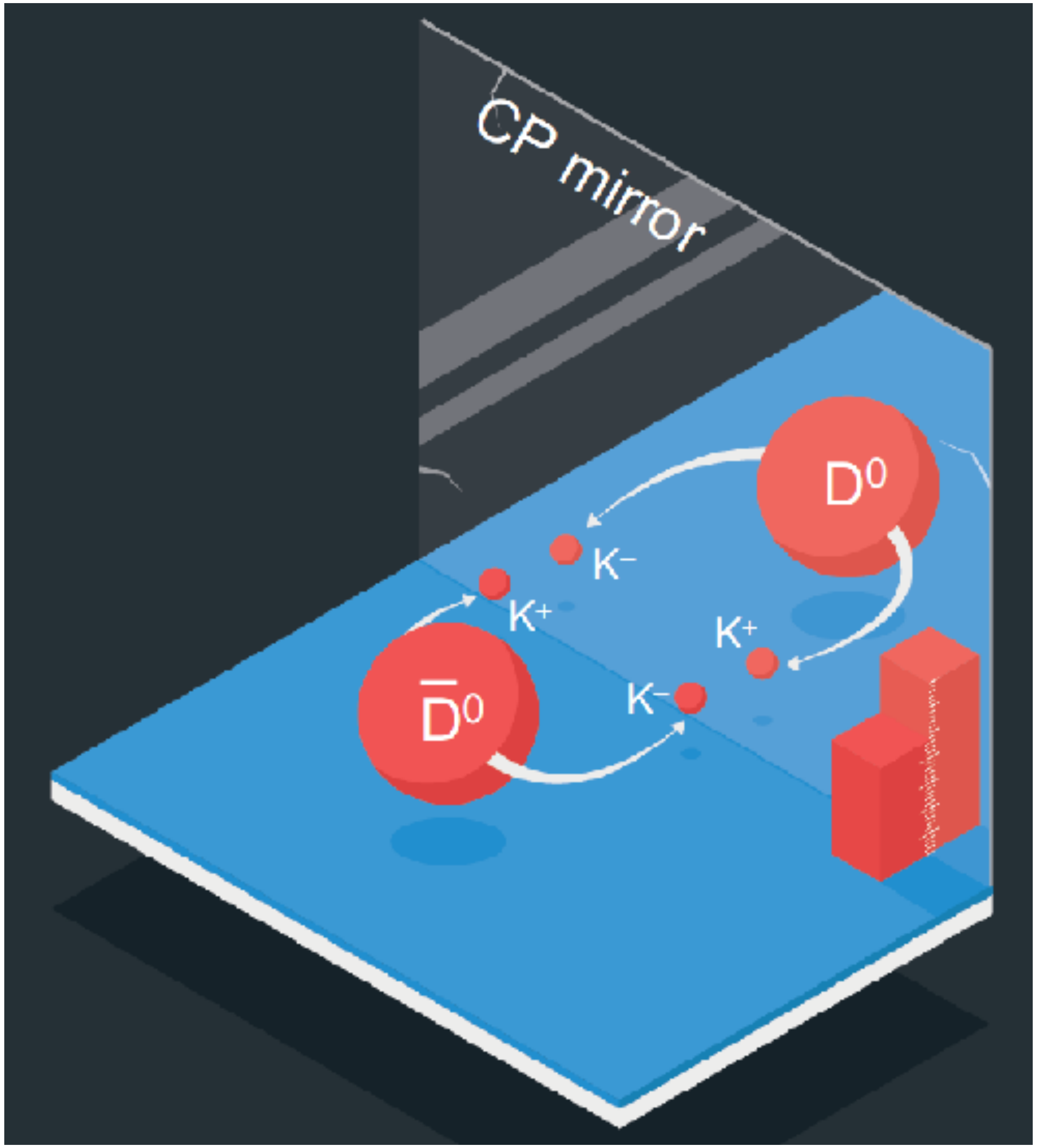
Investigation of the
“Strong CP problem”



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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Strong CP

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

Motivations

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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

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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

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CP violation is included

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QCD sector

Strong CP

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

θ-term

SMEFT operators

↓

Nucleon electric dipole moment

never measured...

Motivations

P-symmetry

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<u>QCD sector</u>

QCD Lagrangian is 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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Terms from EW sector

Weak P-violation

✔

Terms from QCD sector

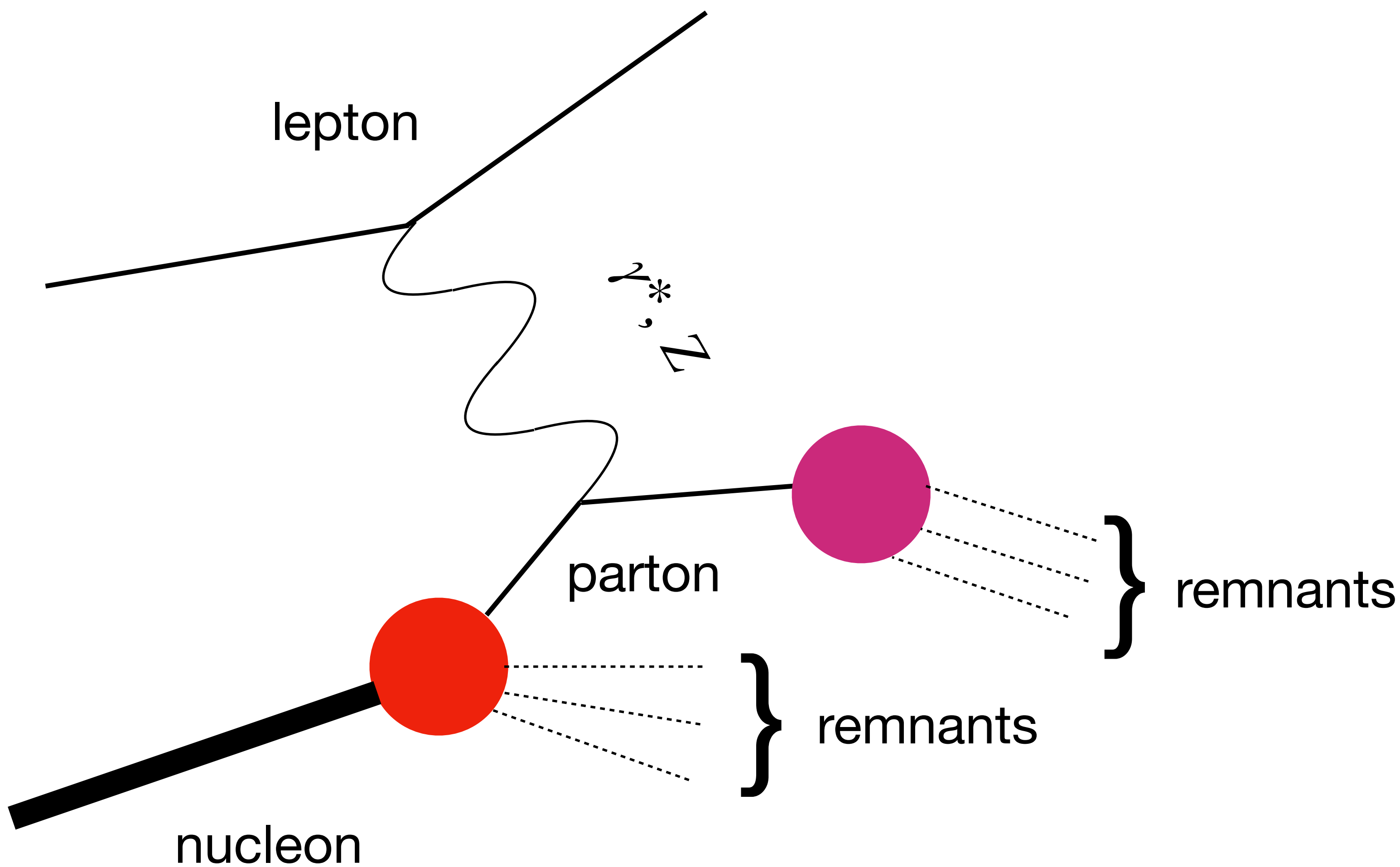
Strong P-violation

✘

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

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

Cross Section

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In general

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

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

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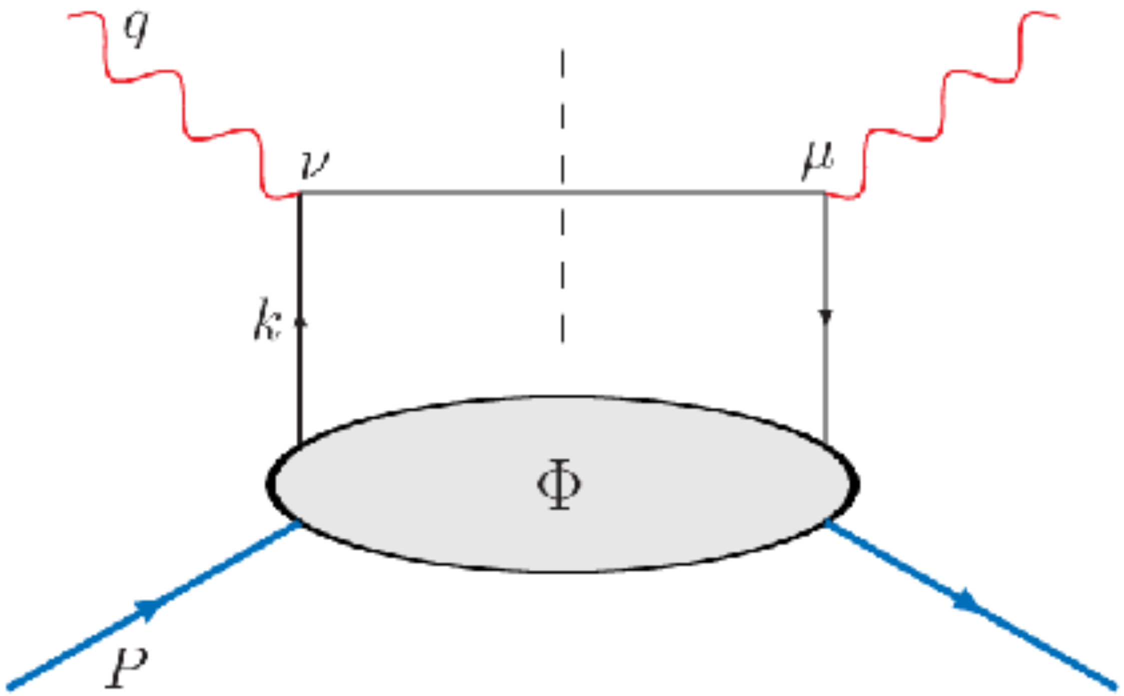

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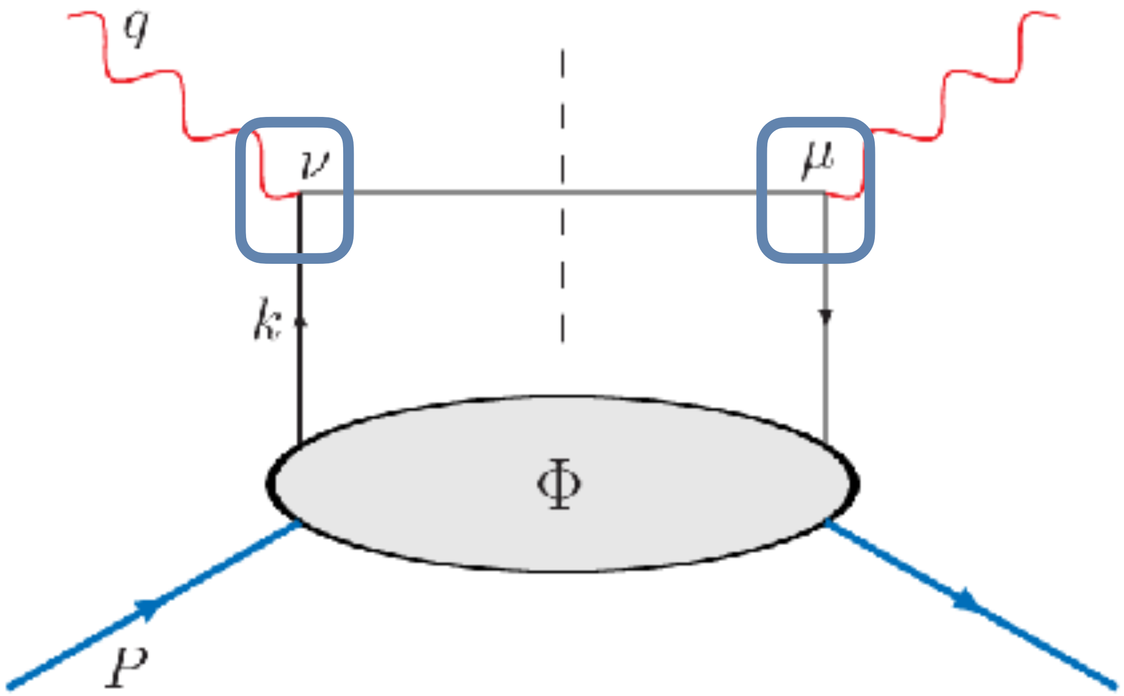

Vertices of the interactions

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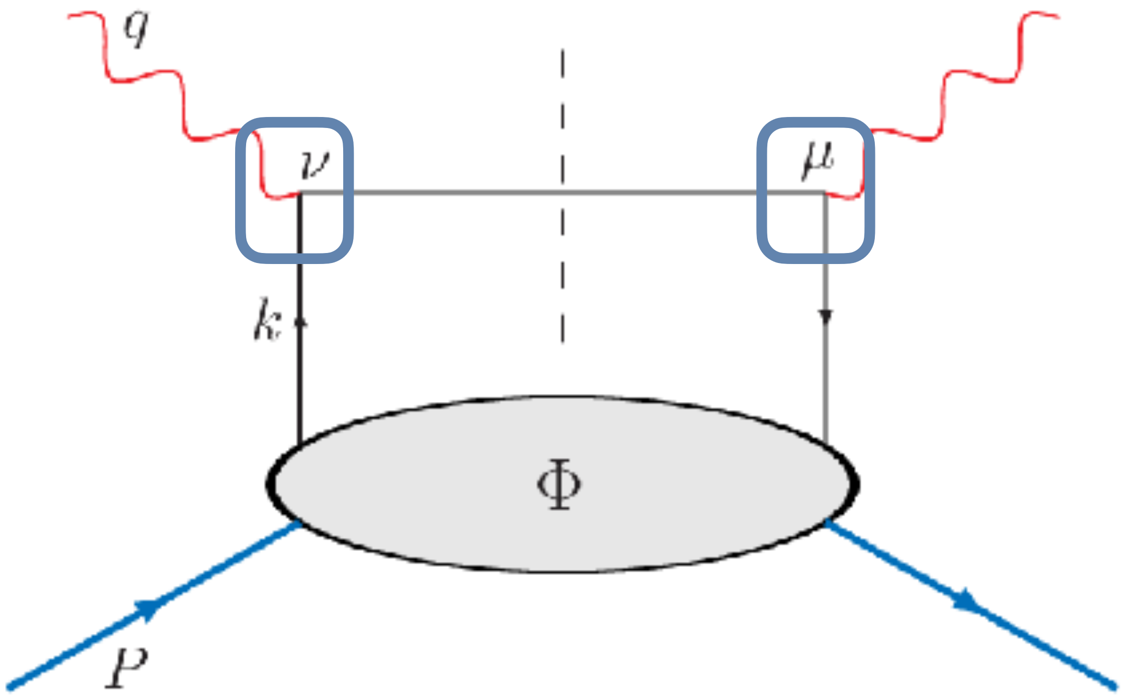

Vertices of the interactions

P-odd structures already present in the hadronic tensor!

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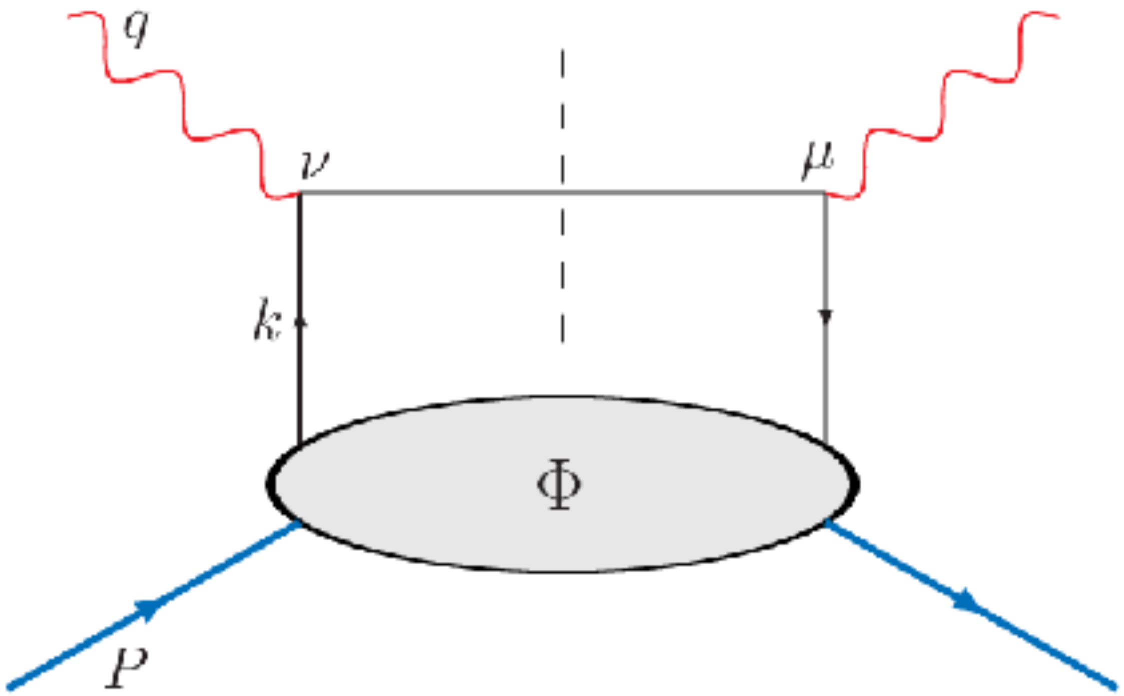

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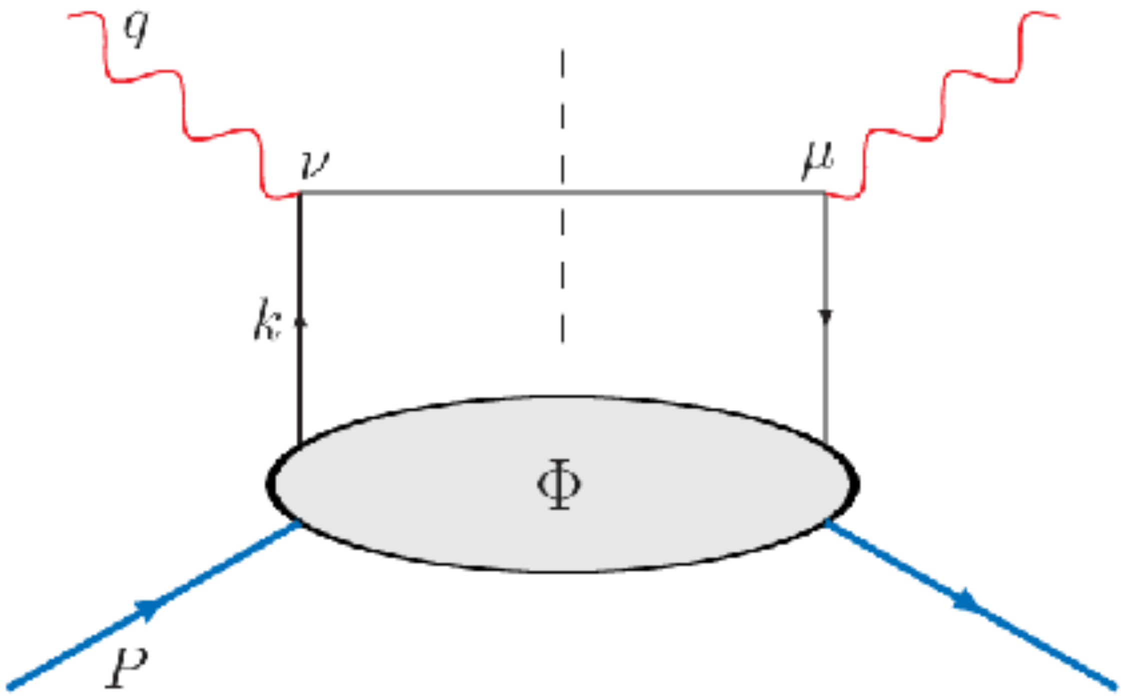

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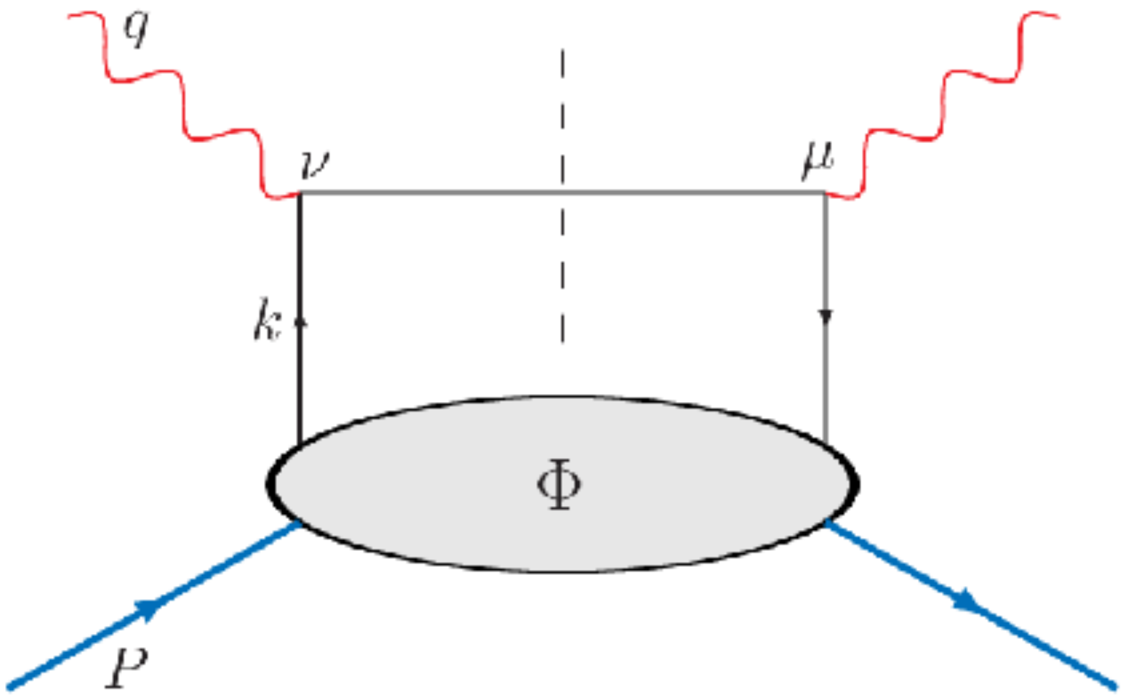

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Decomposition in partonic densities

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

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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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Leading twist contributions

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

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

Neutral-current DIS

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

$$\frac{d\sigma^{\pm}}{dxdy} = \frac{2\pi\alpha^2}{xyQ^2}\left[Y_+ F^{\pm}_2 - y^2 F^{\pm}_L \mp Y_- x F^{\pm}_3\right]$$

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

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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

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

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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)

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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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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, *JHEP* 09 (2012) 061

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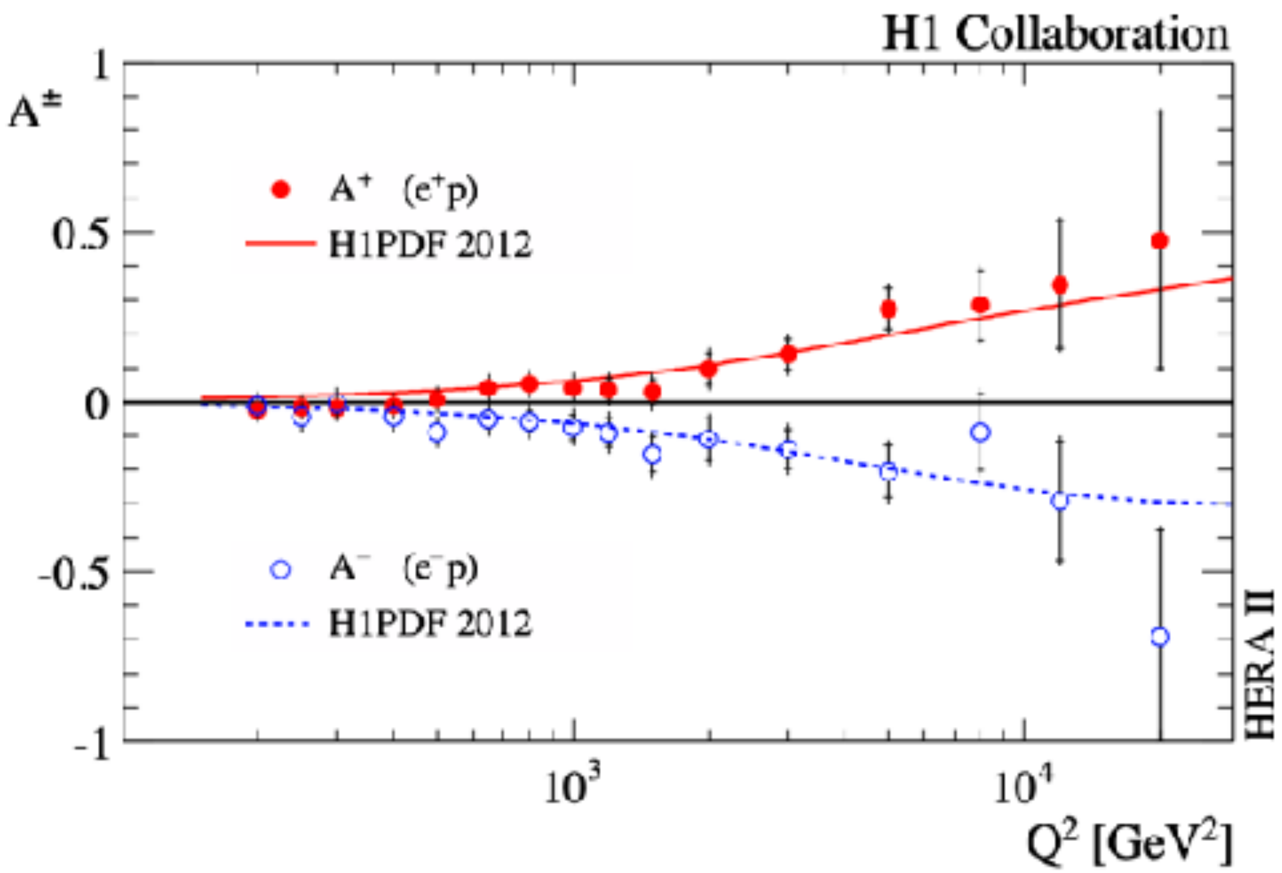
e^+ ***asymmetry: 16 data***

e^- ***asymmetry: 17 data***



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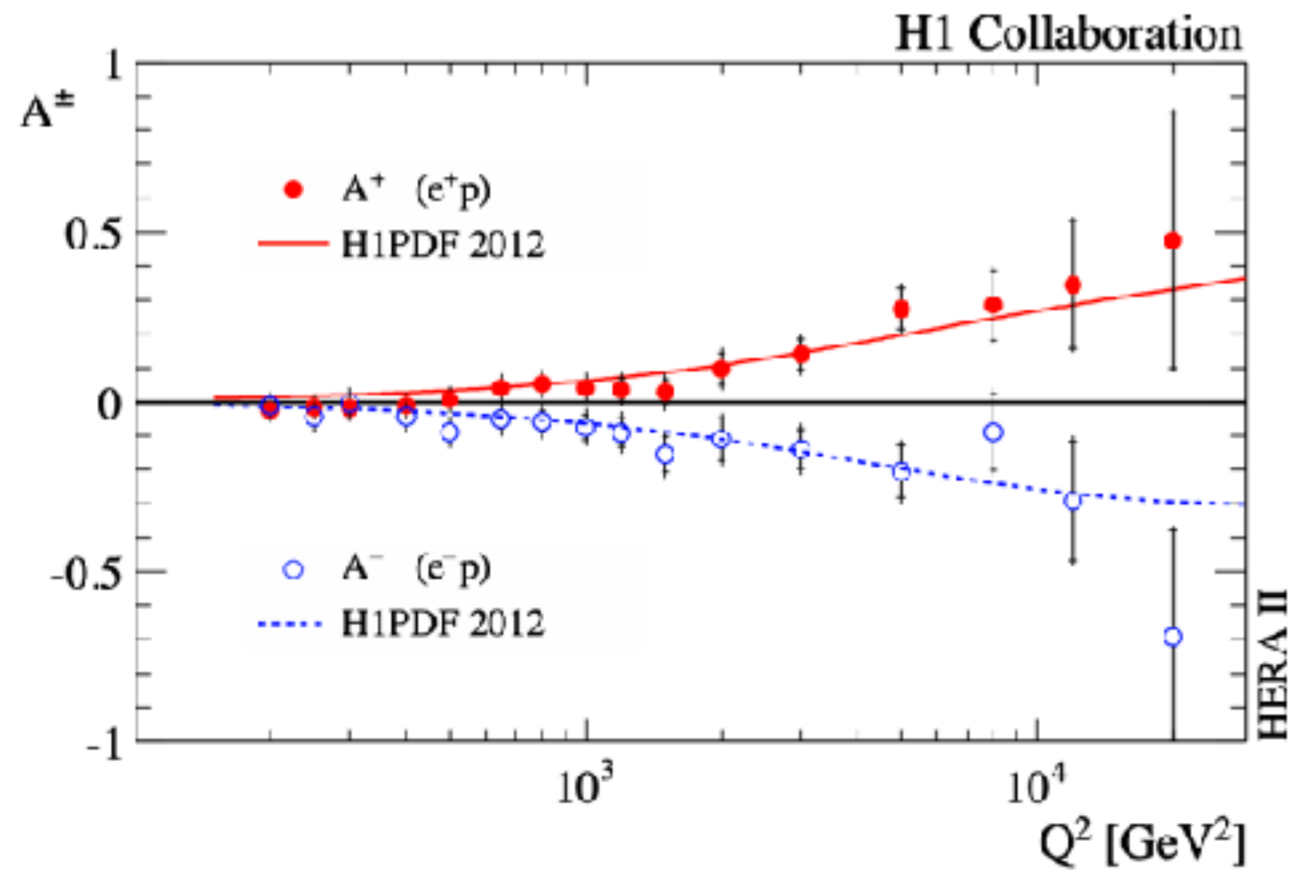

JLab6 PVDIS dataset

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

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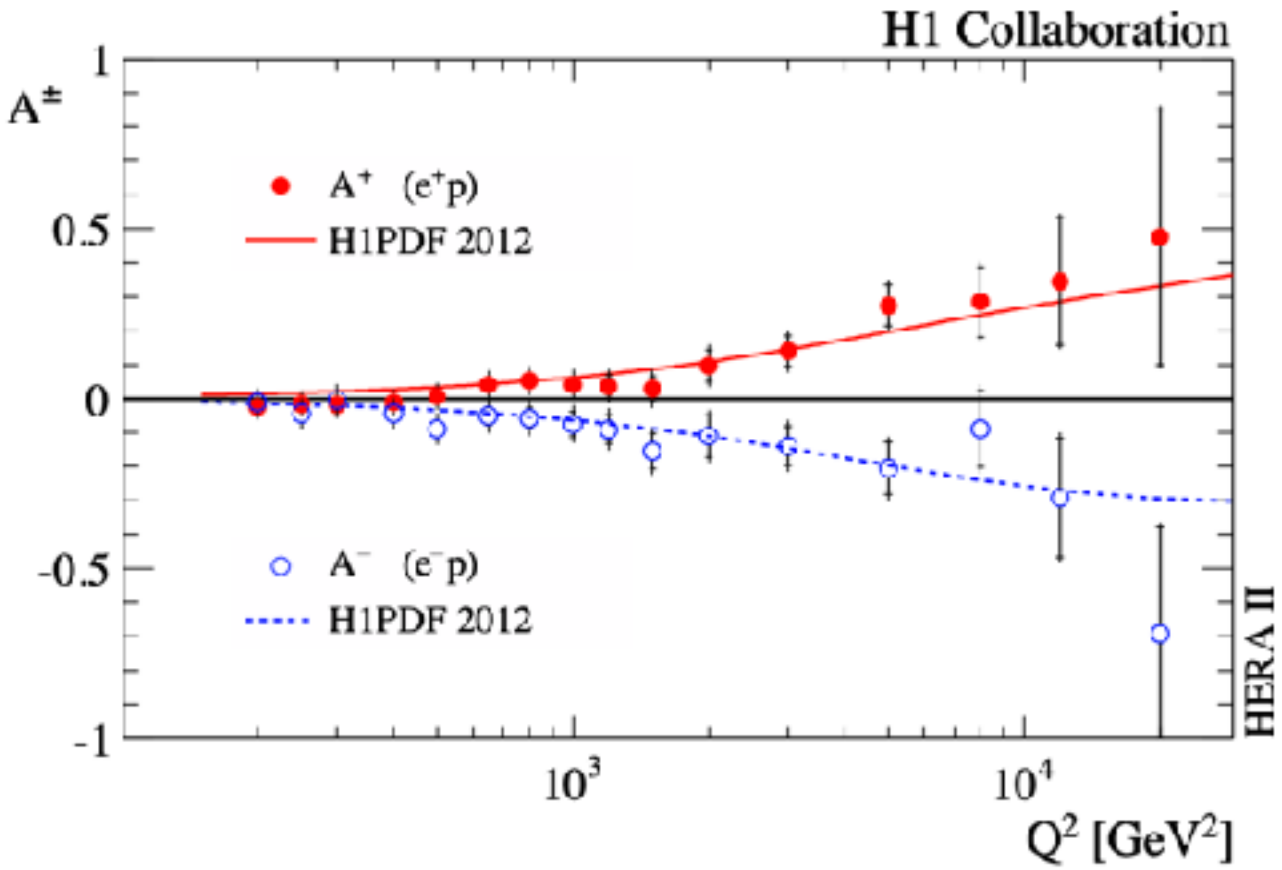

JLab6 PVDIS dataset

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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(Run I + II combined)

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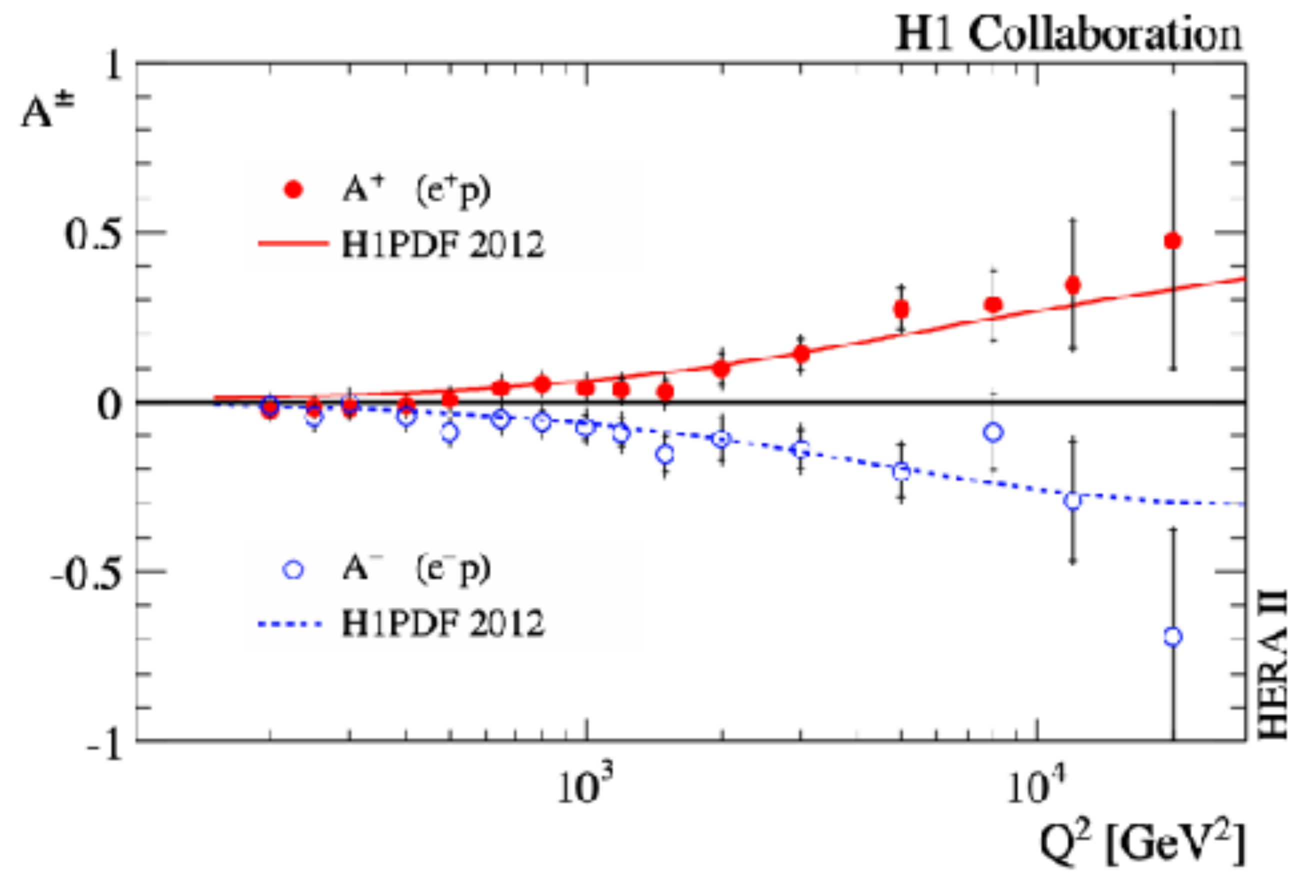

JLab6 PVDIS dataset

PVDIS Collaboration, *Nature* 506 (2014)
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SLAC-E122 dataset

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

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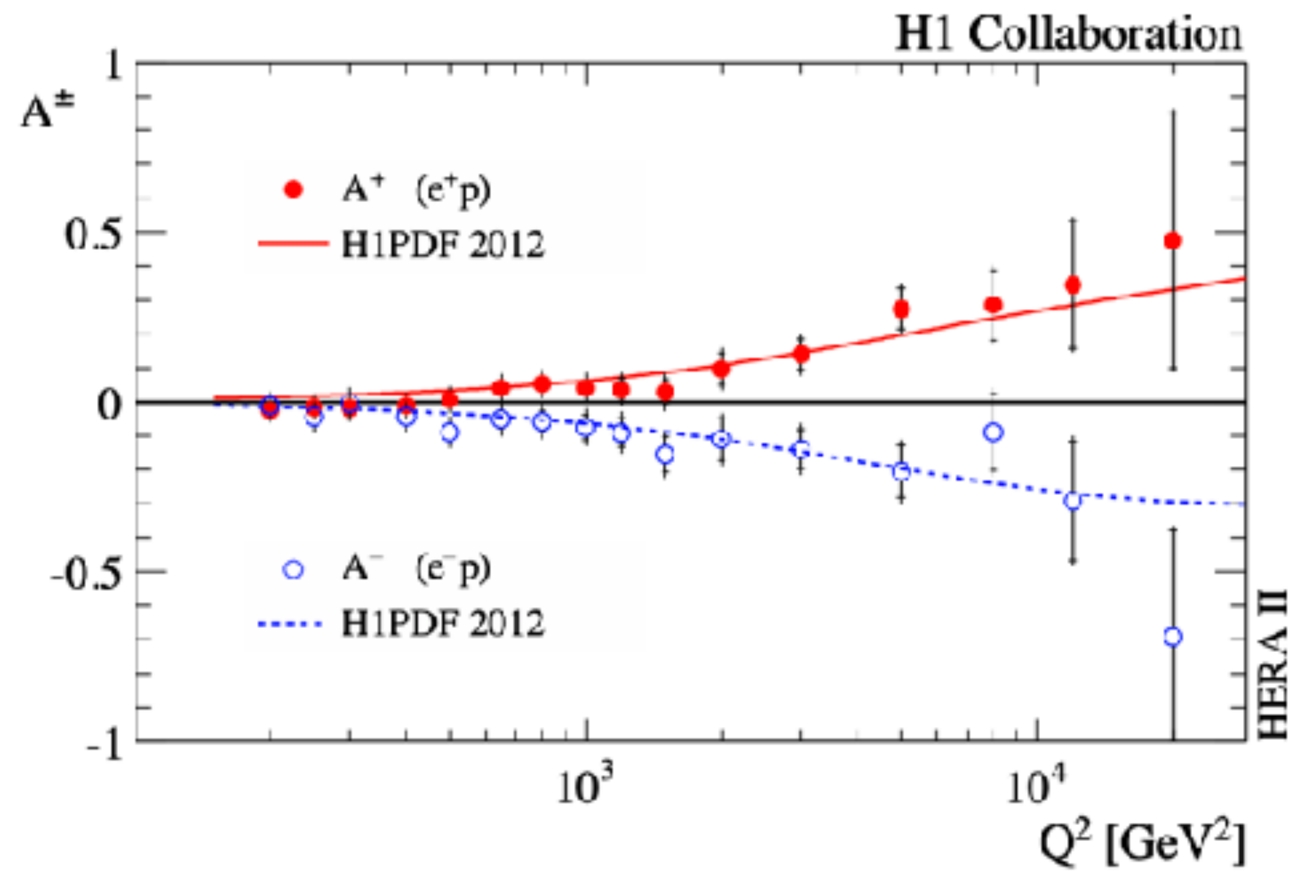

JLab6 PVDIS dataset

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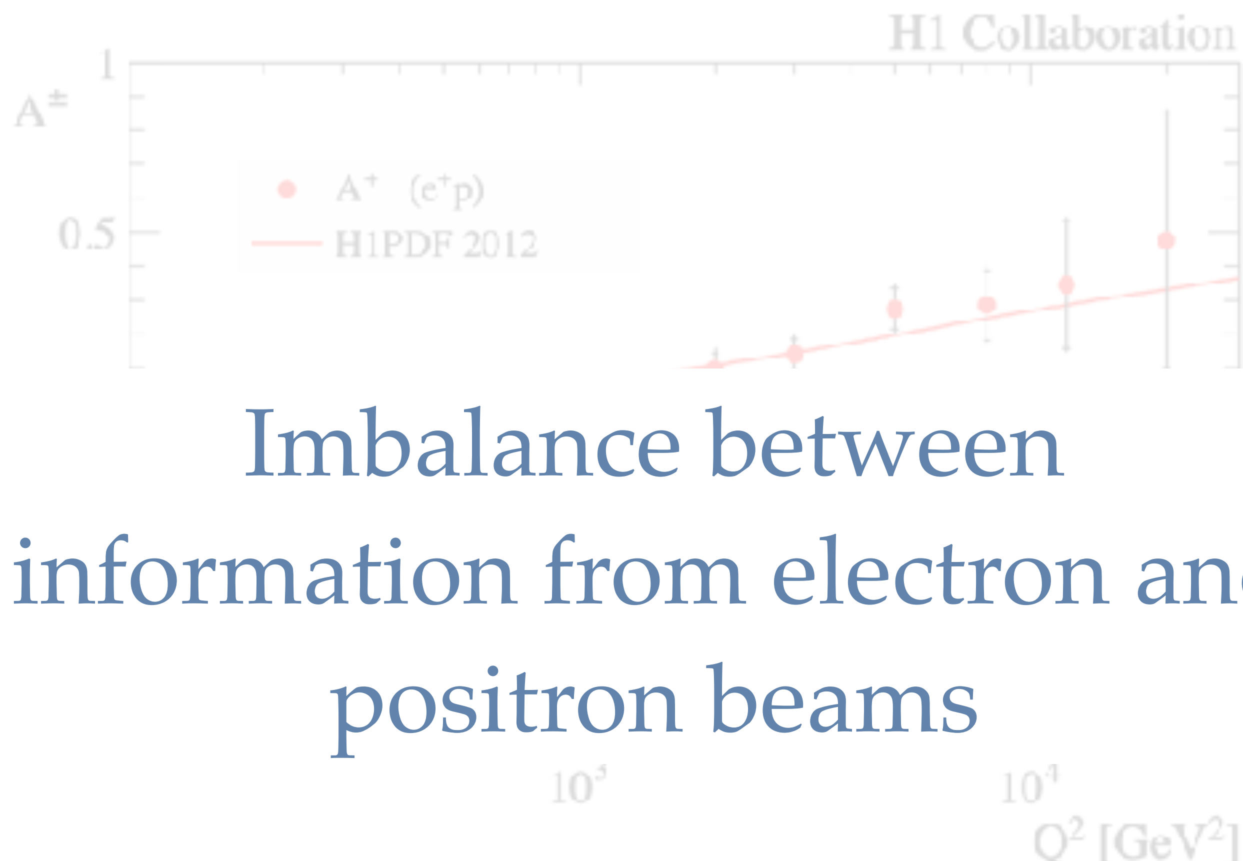

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Imbalance between information from electron and positron beams

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applicability of the theory?

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

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

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

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PV parton density comes from the structure

$$\gamma^5\gamma^\mu$$

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1 parameter to be fitted

Error propagation

PDF set for

Error propagation

PDF set for $f_1(x, Q^2)$ *NNPDF3.1*

Ball et al. (NNPDF), EPJ C 77 (2017)

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100 MC replicas of unpolarized PDF

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Statistical distribution of 100 values of parameter α

Results of the fit: χ^2 values

CASE 1: fit **WITHOUT** EW radiative corrections

	N of points	χ^2/N_{data} (SM)	χ^2/N_{data} (**Fit**)
HERA A^+	16	1.13	1.13
HERA A^-	17	0.63	0.63
JLab6 A^-	2	4.27	1.12
SLAC-E122 A^-	11	1.23	1.12
TOTAL	***46***	***1.07***	***0.90***

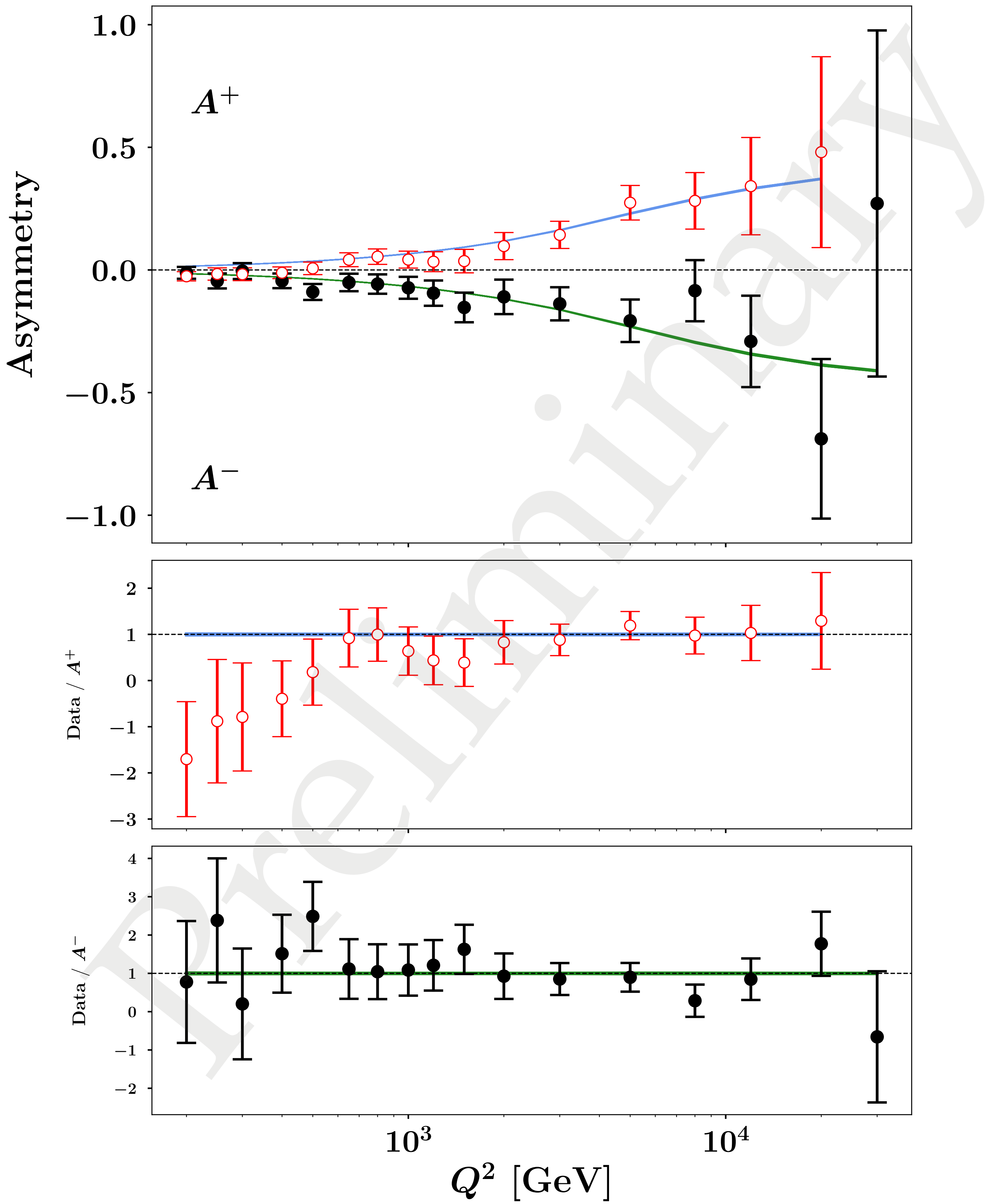
Results of the fit: χ^2 values

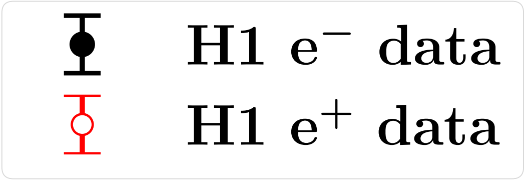
<u>CASE 2</u>: fit **WITH** EW radiative corrections

	N of points	χ^2/N_{data} (SM)	χ^2/N_{data} (**Fit**)
HERA A^+	16	1.13	1.13
HERA A^-	17	0.63	0.63
JLab6 A^-	2	1.92	0.91
SLAC-E122 A^-	11	1.13	1.09
TOTAL	***46***	***0.94***	***0.88***

Preliminary

Results of the fit: data-theory comparison





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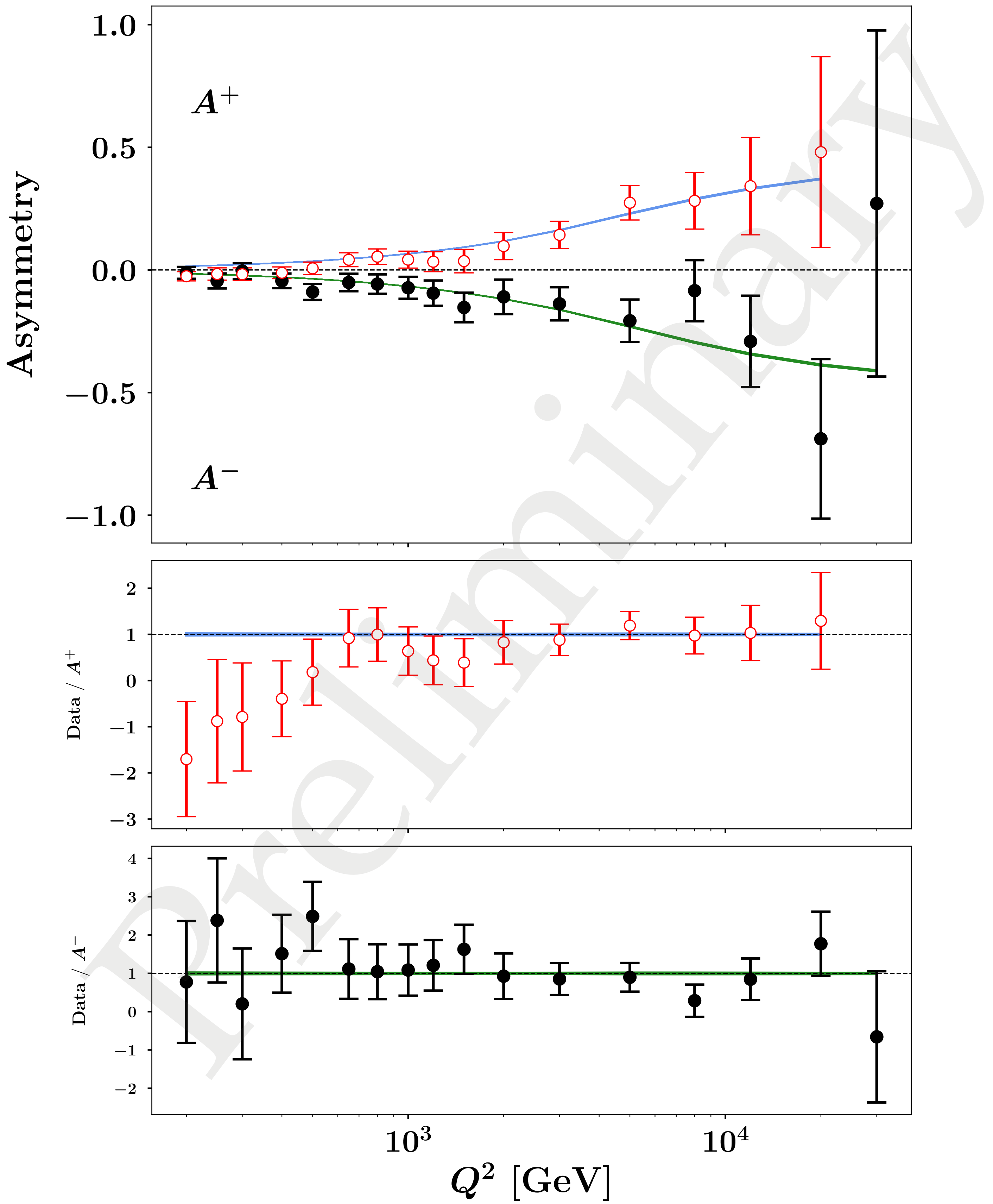

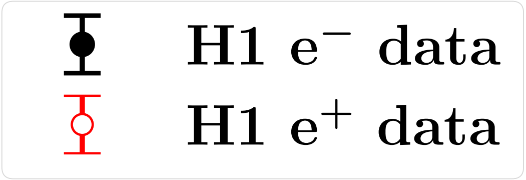

Very small errors in the predictions because the fit is dominated by data with smaller errors

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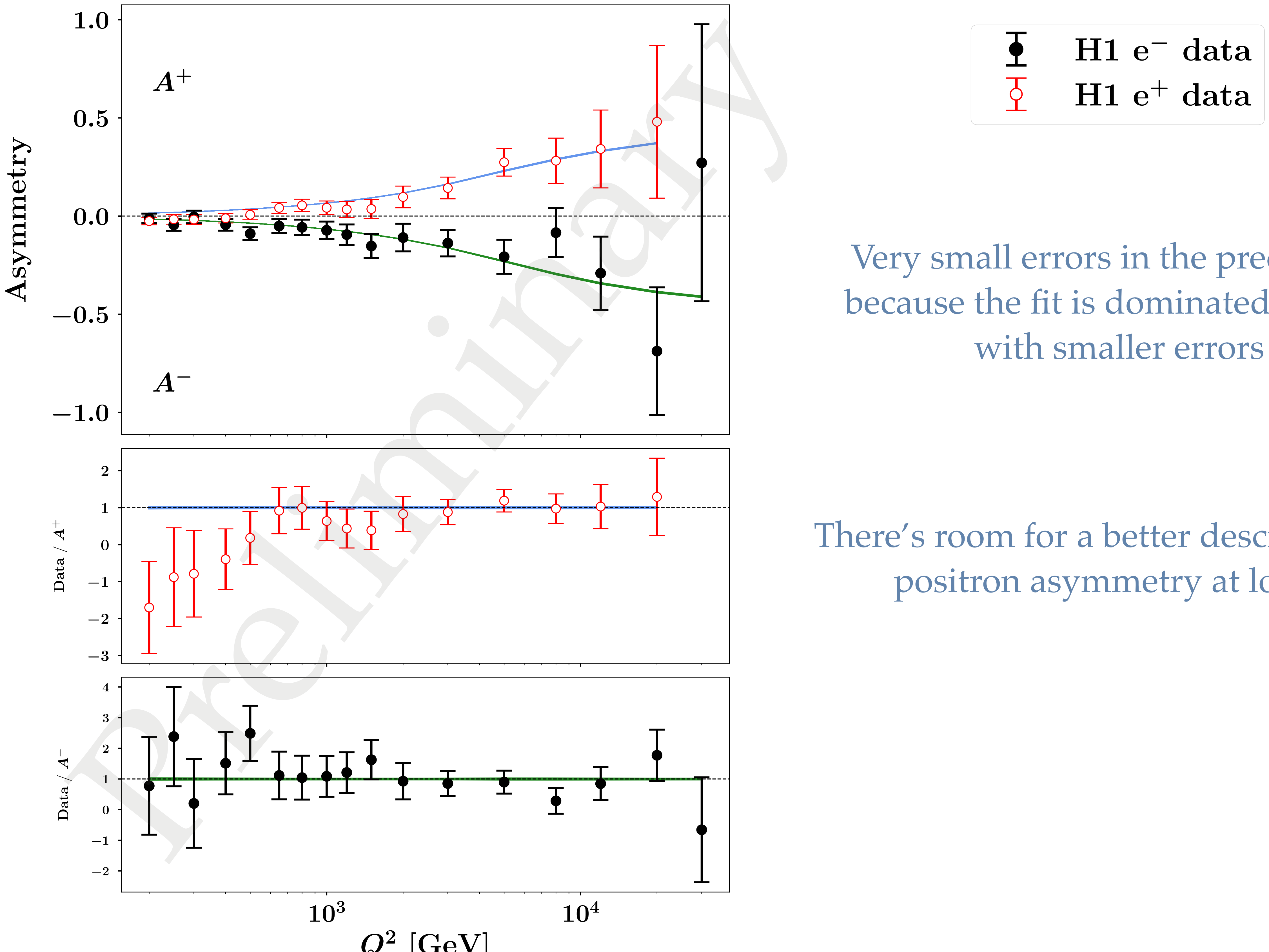

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There's room for a better description for positron asymmetry at low-Q

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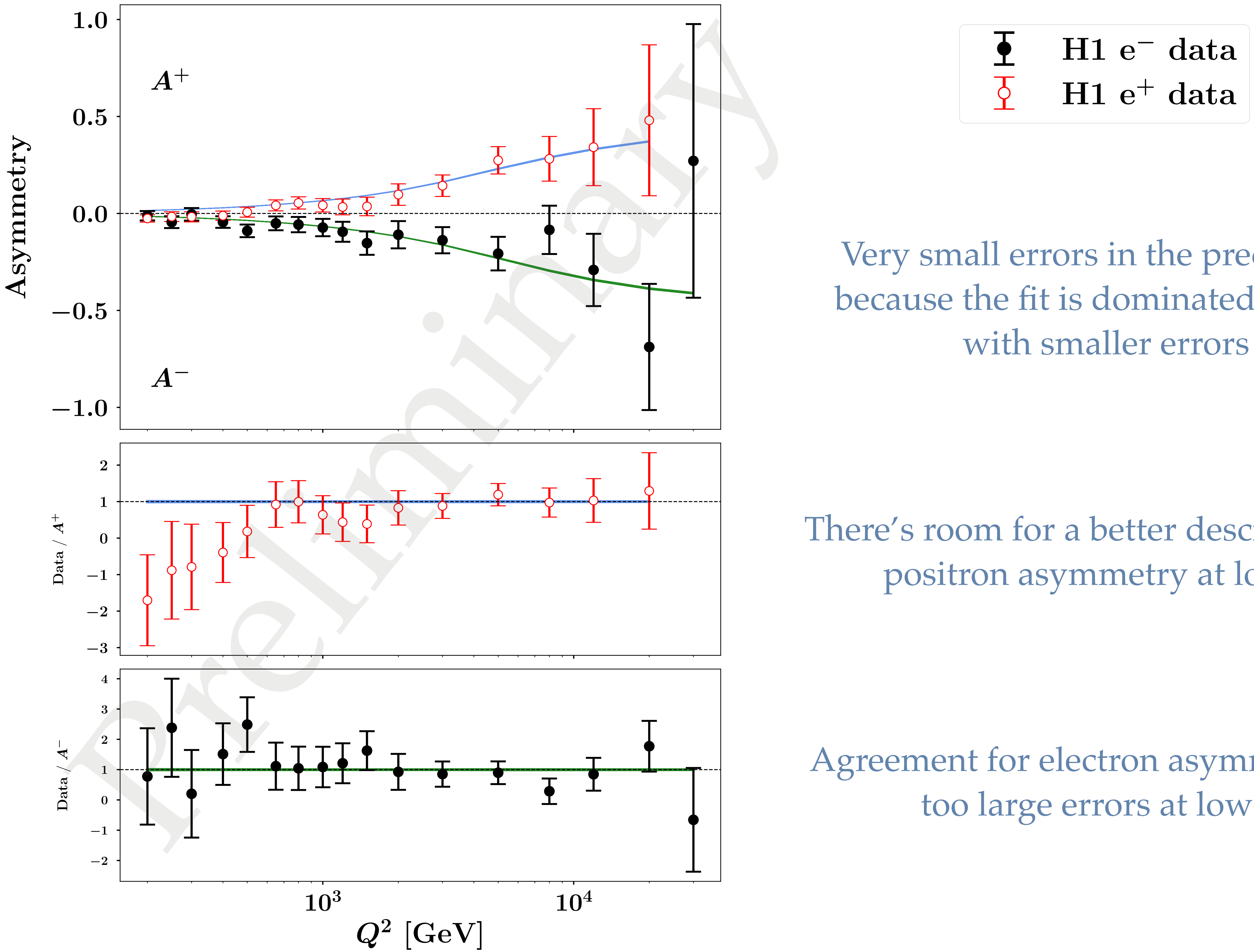

Very small errors in the predictions because the fit is dominated by data with smaller errors

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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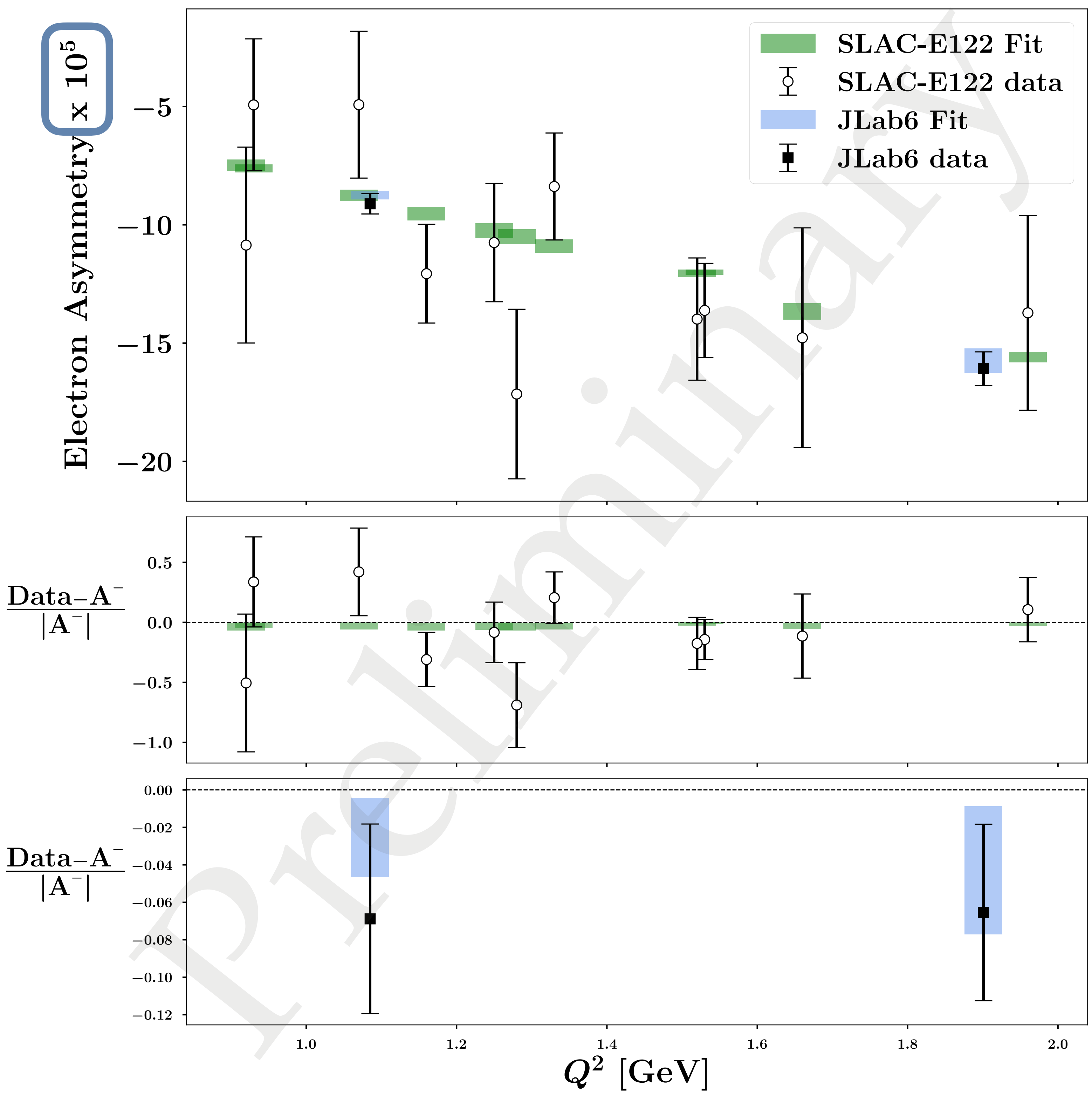

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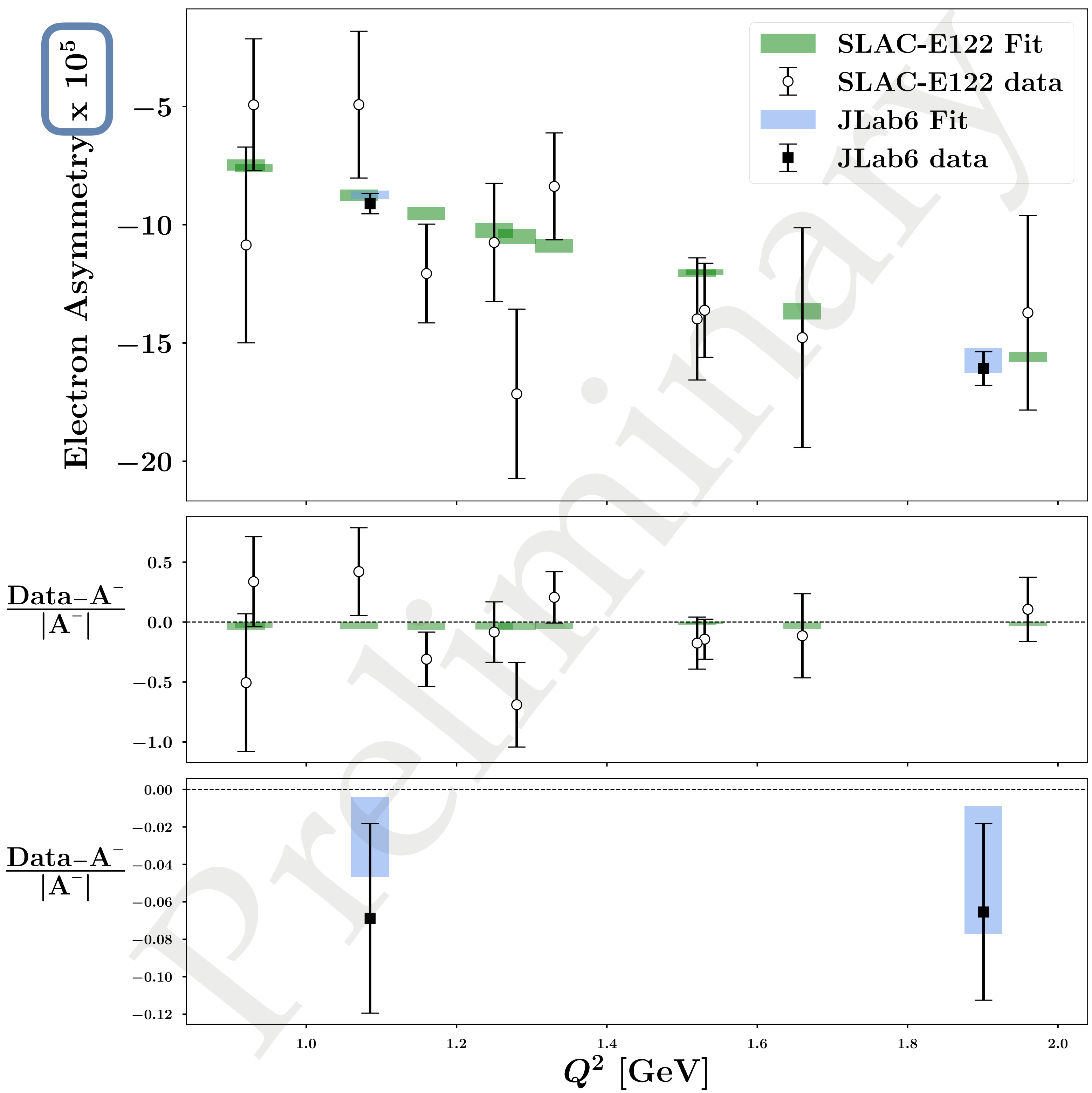

Sizeable improvement of the fit w.r.t. SM predictions

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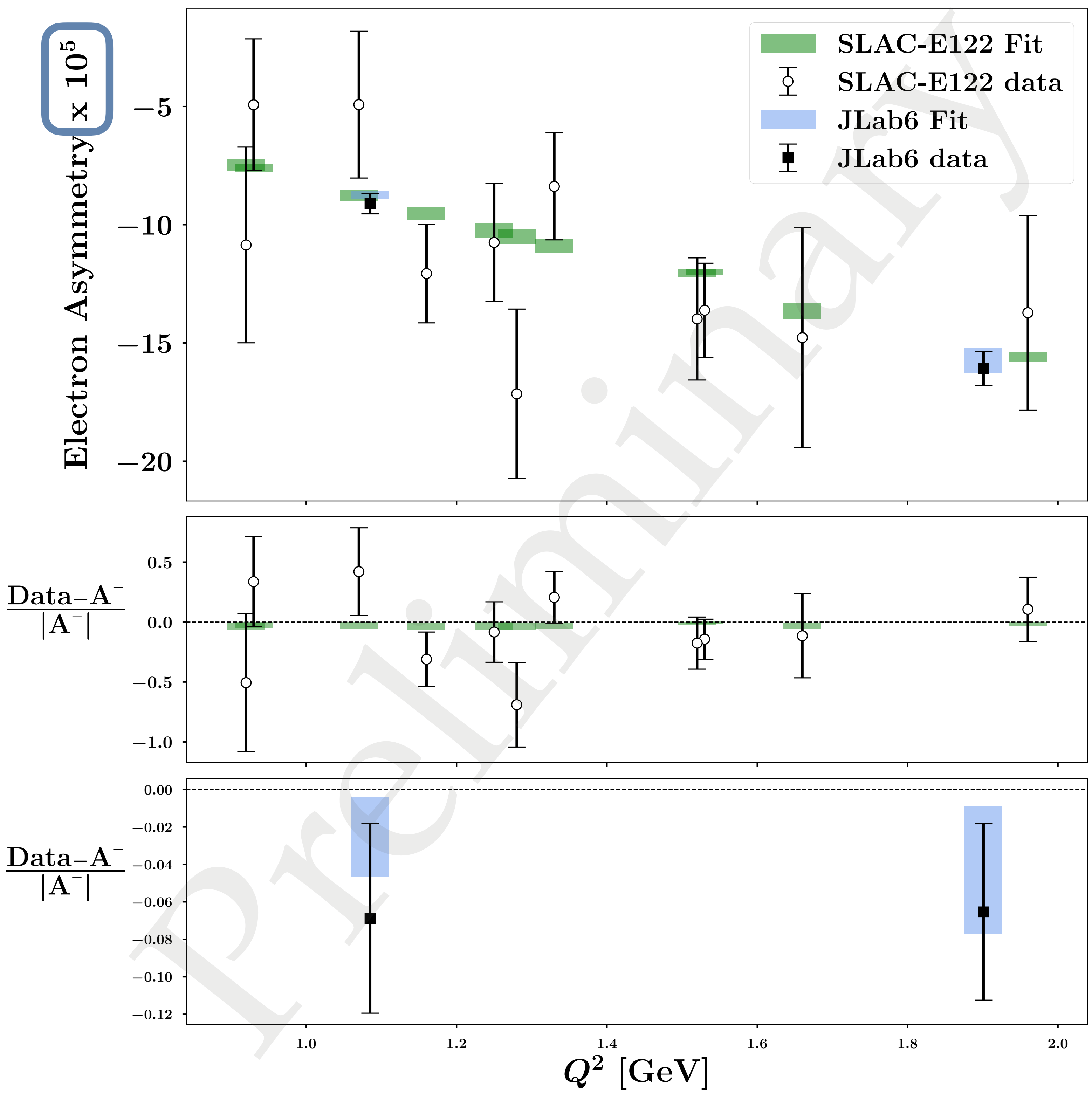

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Old dataset with still quite large experimental errors (> 20 %)

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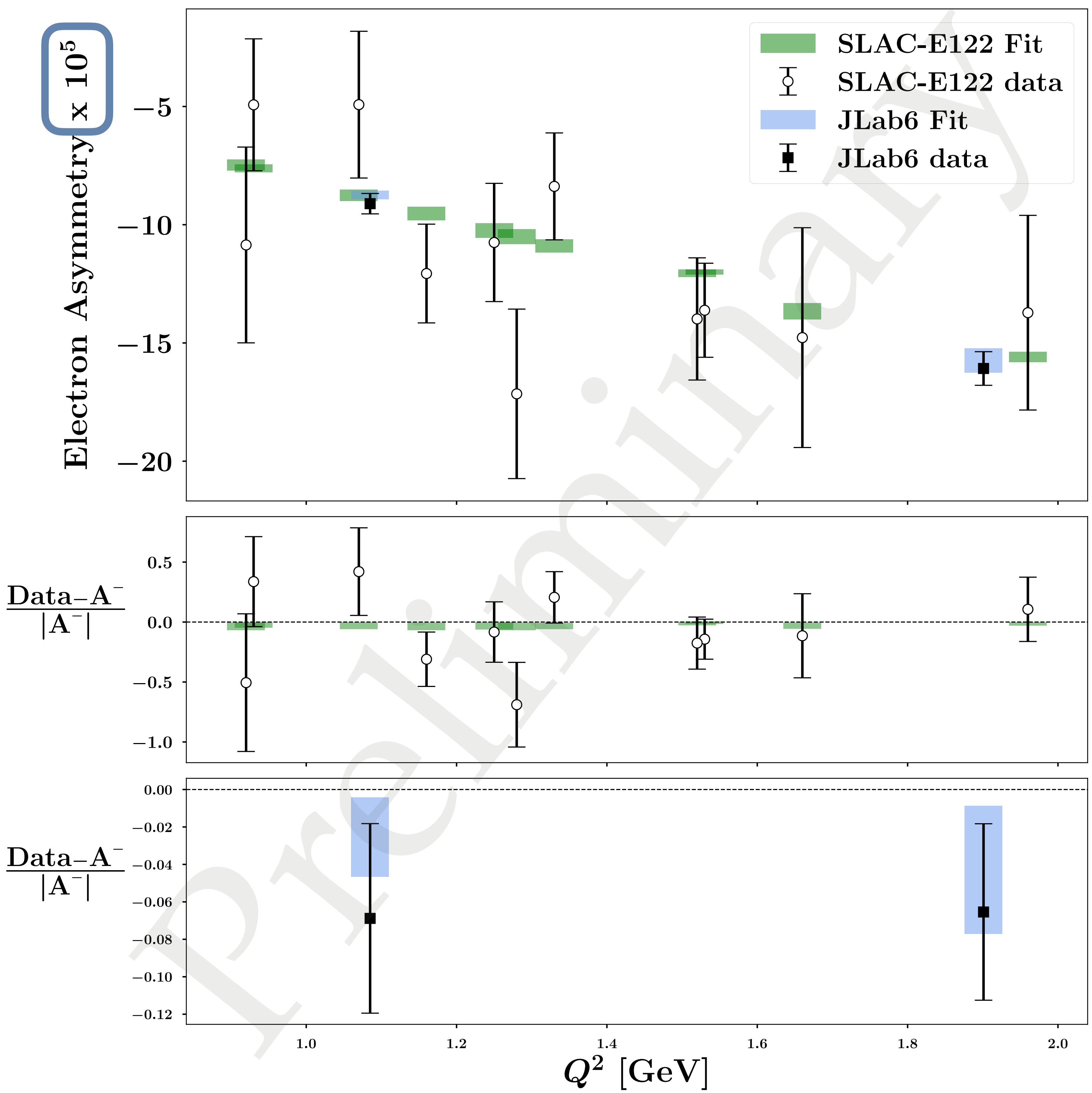


Sizeable improvement of the fit w.r.t. SM predictions

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

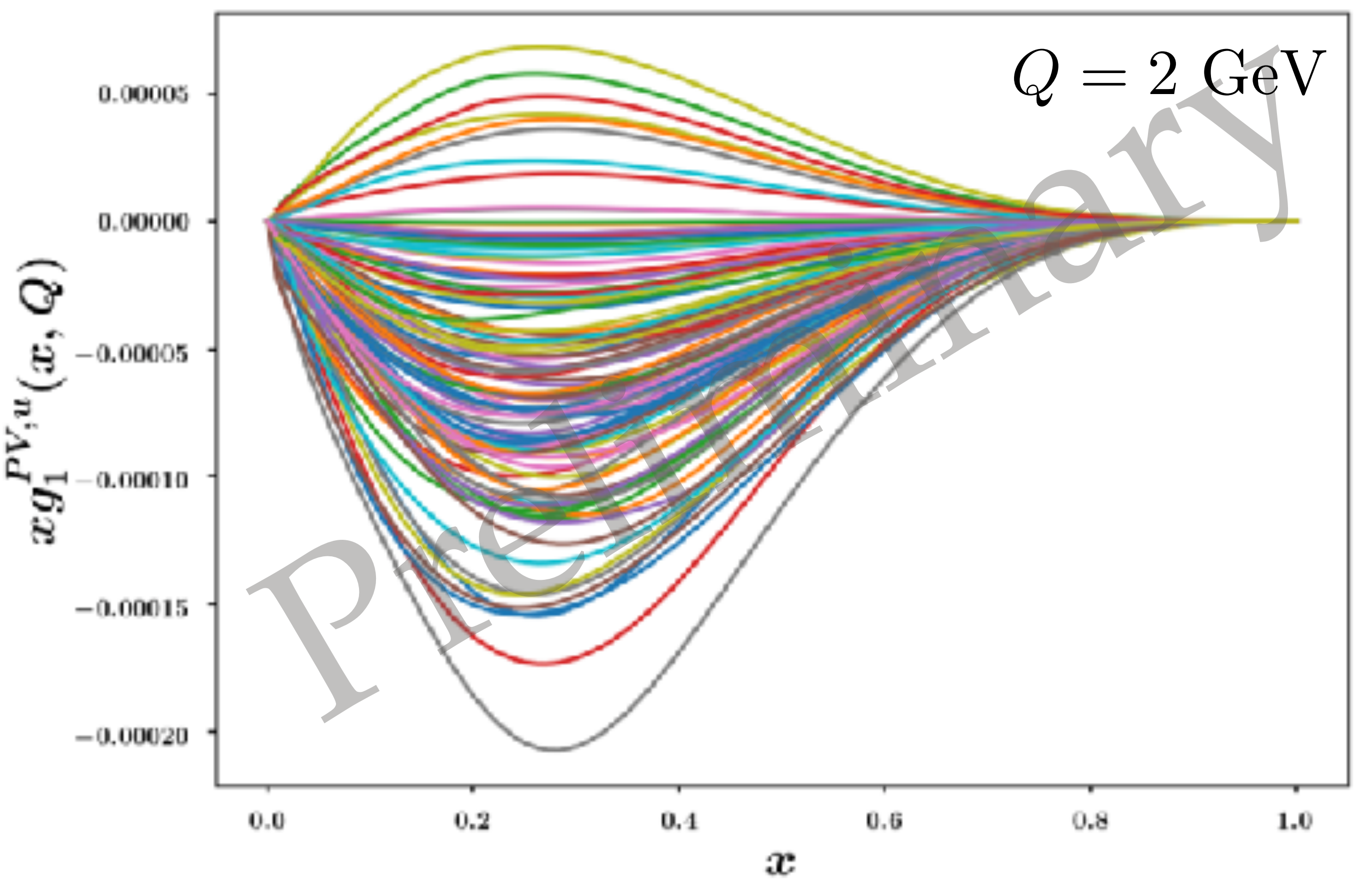
Data points which actually drive the fit due to very small experimental errors (~ 1 %)

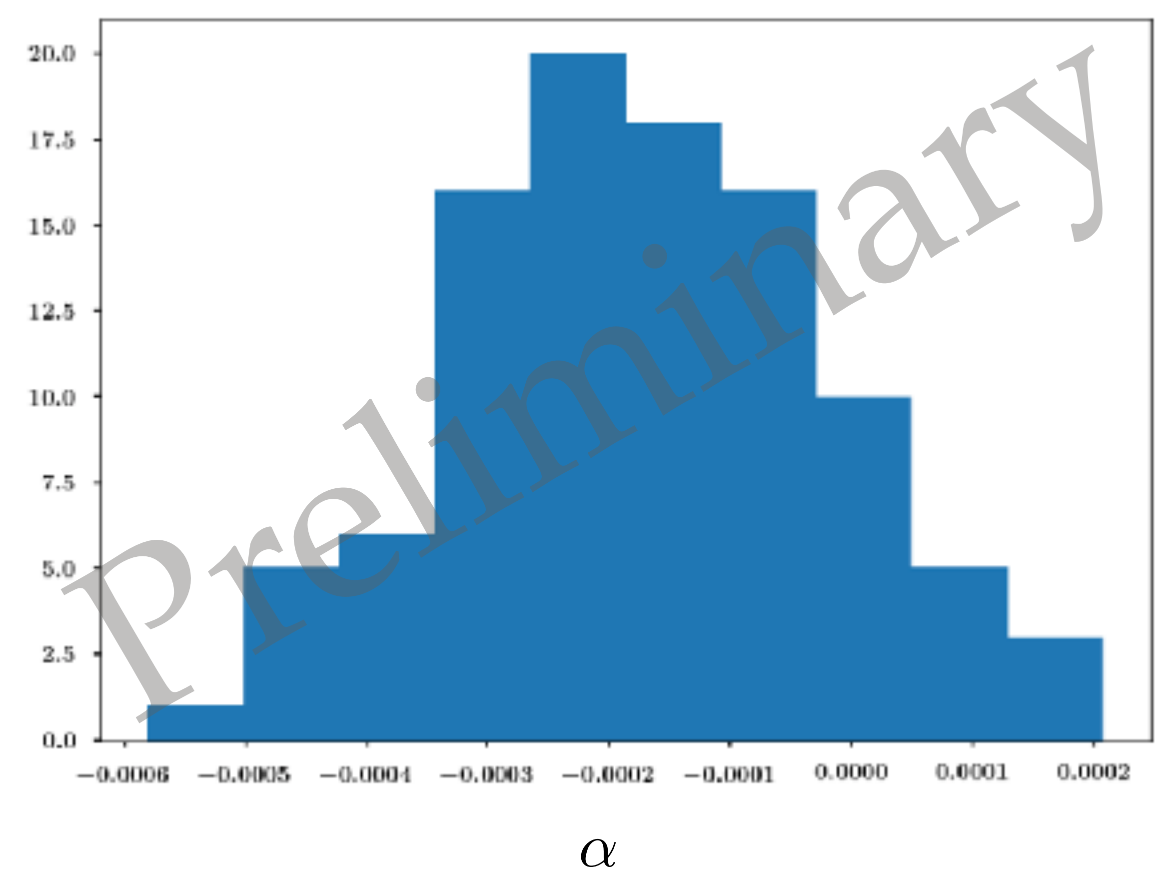
Results of the fit: $g_1^{PV}(x, Q^2)$ extraction

CASE 2 $\alpha = (-1.71 \pm 1.52) \times 10^{-4}$

fit **WITH** EW radiative corrections

CASE 1
$\alpha = (-3.20 \pm 1.53) \times 10^{-4}$





Conclusions and Outlook

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- A global fit of present experimental data is compatible with a non-zero contribution from a new strong PV parton density at 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