Strong PV in the nucleon?

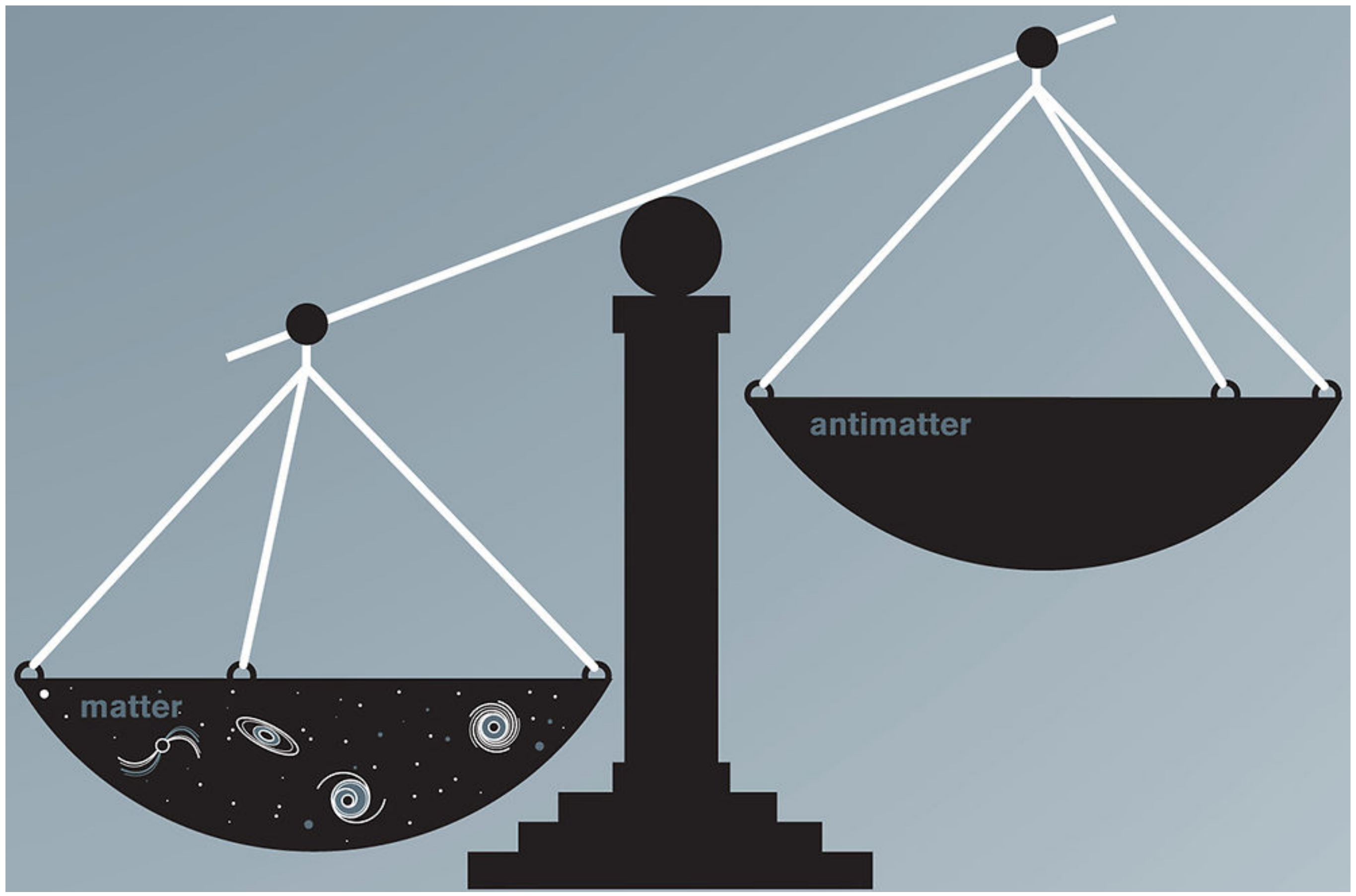
Matteo Cerutti

Bacchetta, MC, Manna, Radici, Zheng, PLB 849 (2024)

SoLID Opportunities and Challenges of
Nuclear Physics at the Luminosity Frontier

June 19, 2024

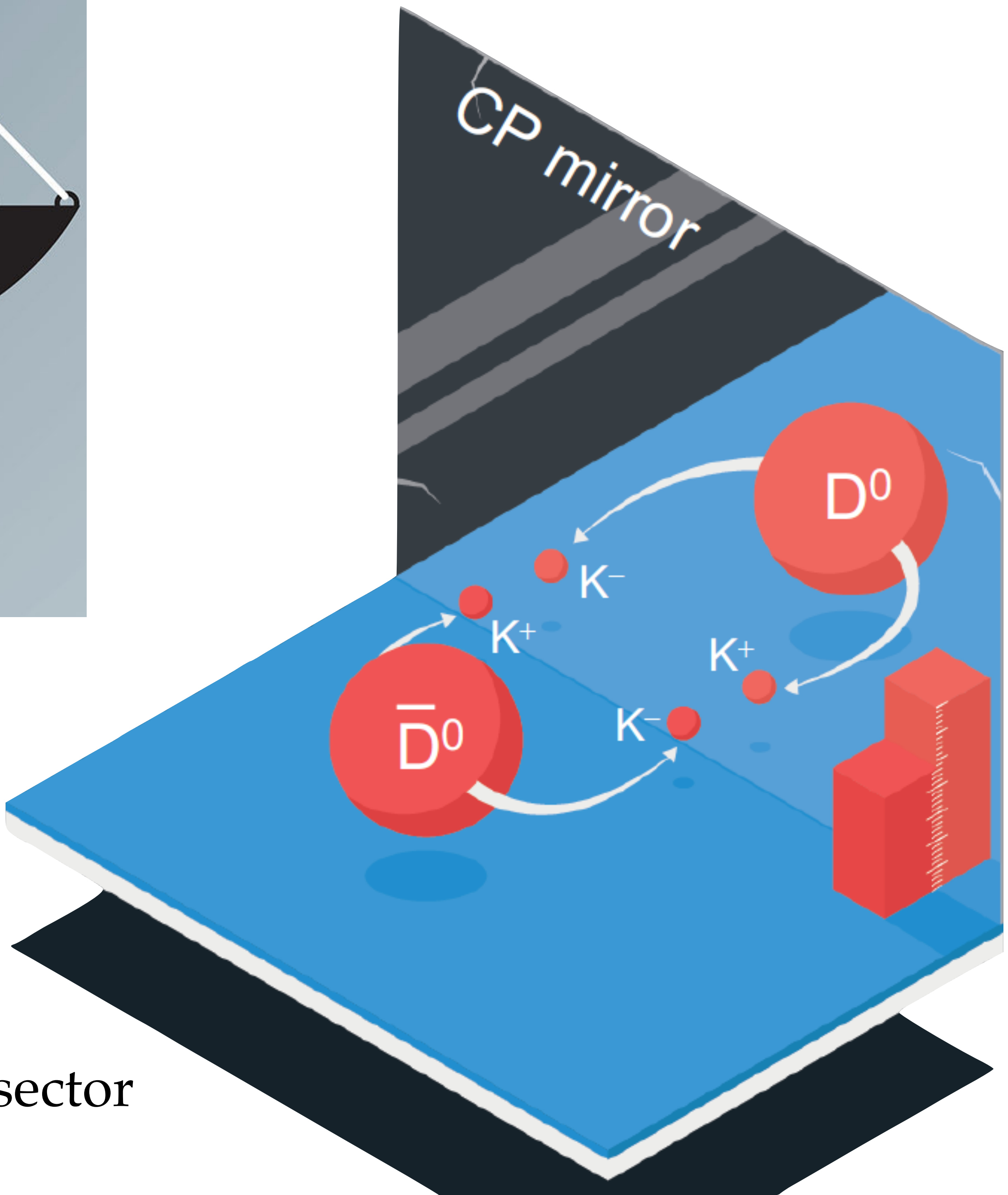
Motivations



matter-antimatter imbalance

↑

└→ CP violation in the strong sector



Motivations

EW sector

CP violation is included

Motivations

EW sector

Weak CP

CP violation is included

Motivations

EW sector

CP violation is included

Weak CP

too small…

Motivations

EW sector

CP violation is included

Weak CP

too small…

QCD sector

Motivations

EW sector

CP violation is included

Weak CP

too small…

QCD sector

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

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

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

↓

Nucleon electric dipole moment

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

"Strong CP problem"

Nucleon electric dipole moment

never measured…

Motivations

P-symmetry

Motivations

P-symmetry

<u>QCD sector</u>

QCD Lagrangian is assumed to be invariant under parity transformations

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?

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

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

✔

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

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

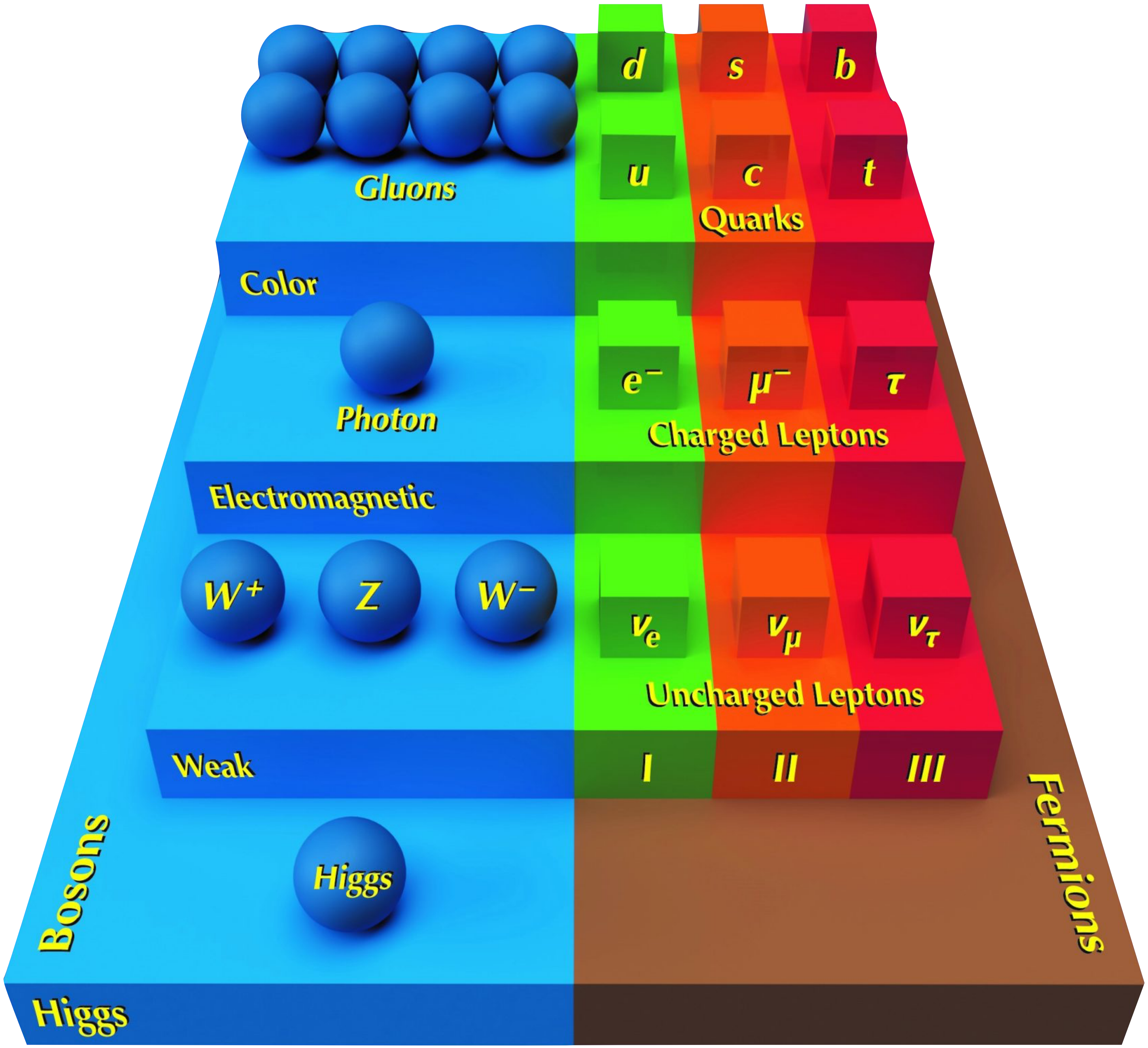
Weak P-violation

✔

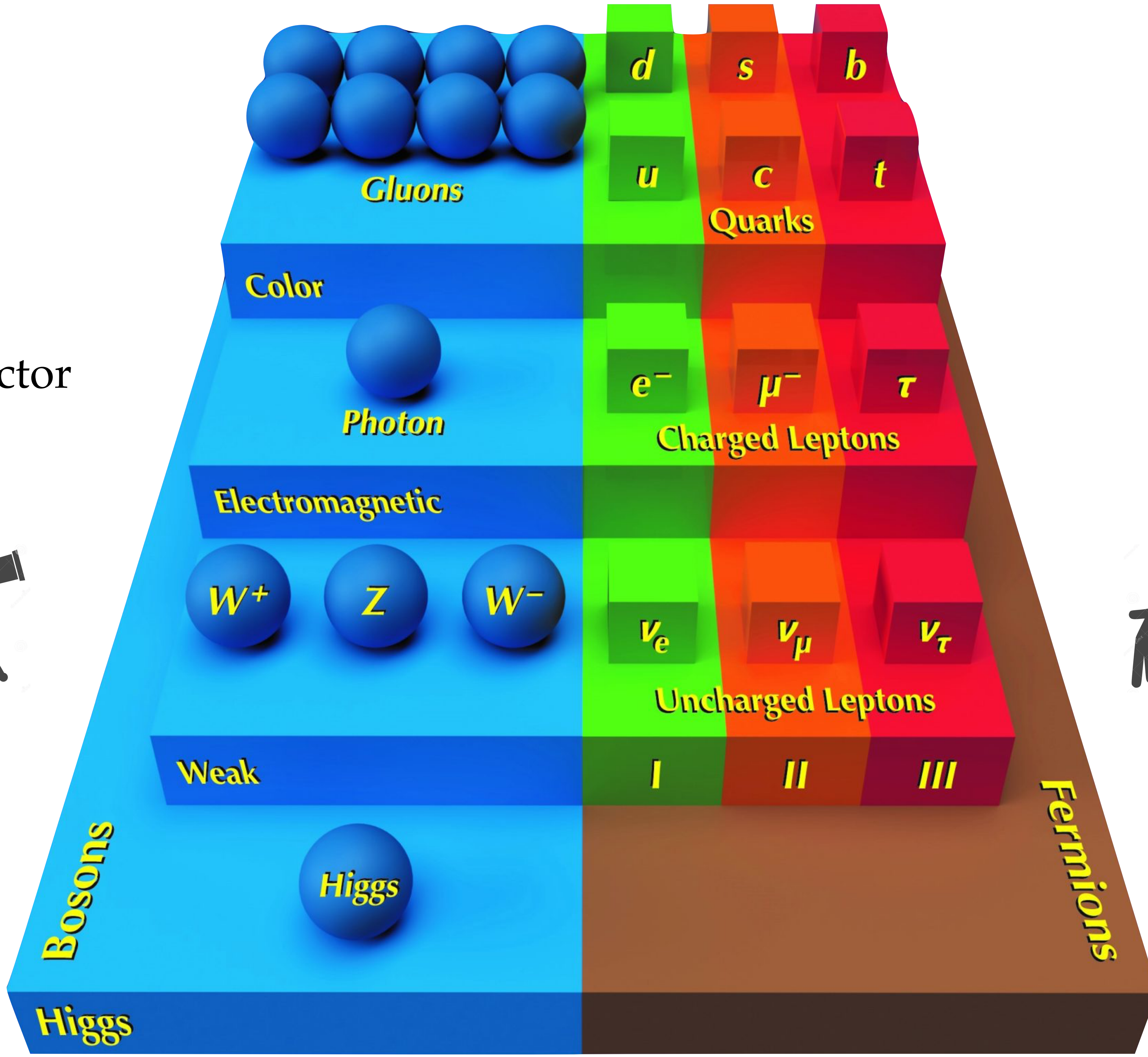
Terms from QCD sector

Strong P-violation

✘

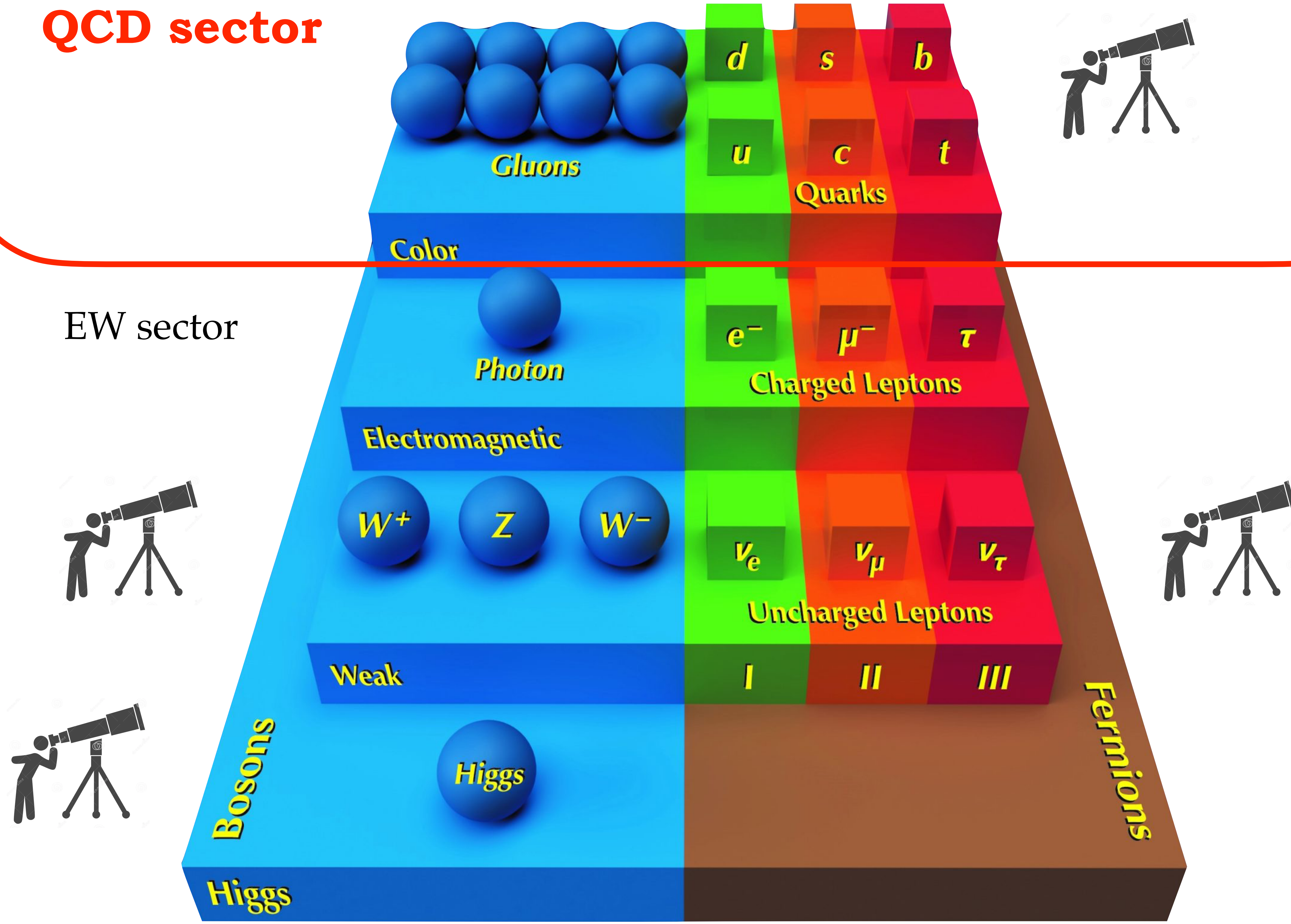

Gluons
d
s
b
u
c
t
Quarks
Color
Photon
e⁻
μ⁻
τ
Charged Leptons
Electromagnetic
W⁺
Z
W⁻
νe
νμ
ντ
Uncharged Leptons
Weak
I
II
III
Bosons
Higgs
Fermions
Higgs

EW sector


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

QCD sector

EW sector



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

DIS Cross Section

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

In general

DIS 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

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

DIS 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

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

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

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)

Integrated correlator

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

Lorenz scalar

Lorenz scalar

Partonic Correlator (unpolarized)

Integrated correlator

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

Lorenz scalar

Hermiticity

Lorenz scalar

Hermiticity

Partonic Correlator (unpolarized)

Integrated correlator

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

Lorenz scalar

Hermiticity

Parity invariance

Lorenz scalar

Hermiticity

Partonic Correlator (unpolarized)

Integrated correlator

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

Lorenz scalar

Hermiticity

Parity invariance

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

Lorenz scalar

Hermiticity

Partonic Correlator (unpolarized)

Integrated correlator

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

Lorenz scalar

Hermiticity

Parity invariance

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

Lorenz scalar

Hermiticity

~~Parity invariance~~

Partonic Correlator (unpolarized)

Integrated correlator

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

Lorenz scalar	Lorenz scalar
Hermiticity	Hermiticity
Parity invariance	~~Parity invariance~~
$\mathbb{1},\ \gamma^\mu,\ \sigma^{\mu\nu}$	$i\gamma^5,\ \gamma^\mu\gamma^5,\ i\gamma^5\sigma^{\mu\nu}$

Partonic Correlator (unpolarized)

Integrated correlator

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

Lorenz scalar	Lorenz scalar
Hermiticity	Hermiticity
Parity invariance	~~Parity invariance~~
$\mathbb{1},\ \gamma^\mu,\ \sigma^{\mu\nu}$	$i\gamma^5,\ \gamma^\mu\gamma^5,\ i\gamma^5\sigma^{\mu\nu}$

Leading twist contributions

Partonic Correlator (unpolarized)

Integrated correlator

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

Lorenz scalar	Lorenz scalar
Hermiticity	Hermiticity
Parity invariance	~~Parity invariance~~
$\mathbb{1},\ \gamma^\mu,\ \sigma^{\mu\nu}$	$i\gamma^5,\ \gamma^\mu\gamma^5,\ i\gamma^5\sigma^{\mu\nu}$

Leading twist contributions

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

Partonic Correlator (unpolarized)

Integrated correlator

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

Lorenz scalar	Lorenz scalar
Hermiticity	Hermiticity
Parity invariance	~~Parity invariance~~
$\mathbb{1},\ \gamma^\mu,\ \sigma^{\mu\nu}$	$i\gamma^5,\ \gamma^\mu\gamma^5,\ i\gamma^5\sigma^{\mu\nu}$

Leading twist contributions

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

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

Partonic Correlator (unpolarized)

Integrated correlator

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

Lorenz scalar	Lorenz scalar
Hermiticity	Hermiticity
Parity invariance	~~Parity invariance~~
$\mathbb{1},\ \gamma^\mu,\ \sigma^{\mu\nu}$	$i\gamma^5,\ \gamma^\mu\gamma^5,\ i\gamma^5\sigma^{\mu\nu}$

Leading twist contributions

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

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

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

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

DIS in collinear framework

Quark Polarization

Nucleon Pol.

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

DIS in collinear framework

PDFs occurring in DIS processes

Quark Polarization

Nucleon Pol.

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

DIS in collinear framework

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

Quark Polarization

Nucleon Pol.

	U	L	T
U	$f_1(x)$	$g_1^{\mathrm{PV}}(x)$	
L		$g_1(x)$	
T			$h_1(x)$

Neutral-Current DIS

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Additional contributions due to the new PV parton distribution

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

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

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

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

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

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

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

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

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

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

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

Additional contributions due to the new PV parton distribution

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

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

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

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

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

MAIN INNOVATION OF PV-HYPOTESIS

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

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

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

Additional contributions due to the new PV parton distribution

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)

Experimental information

PVDIS Asymmetry

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

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

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

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

Experimental information

PVDIS Asymmetry

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

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

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

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 sets

HERA dataset
(Run I + II combined)

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

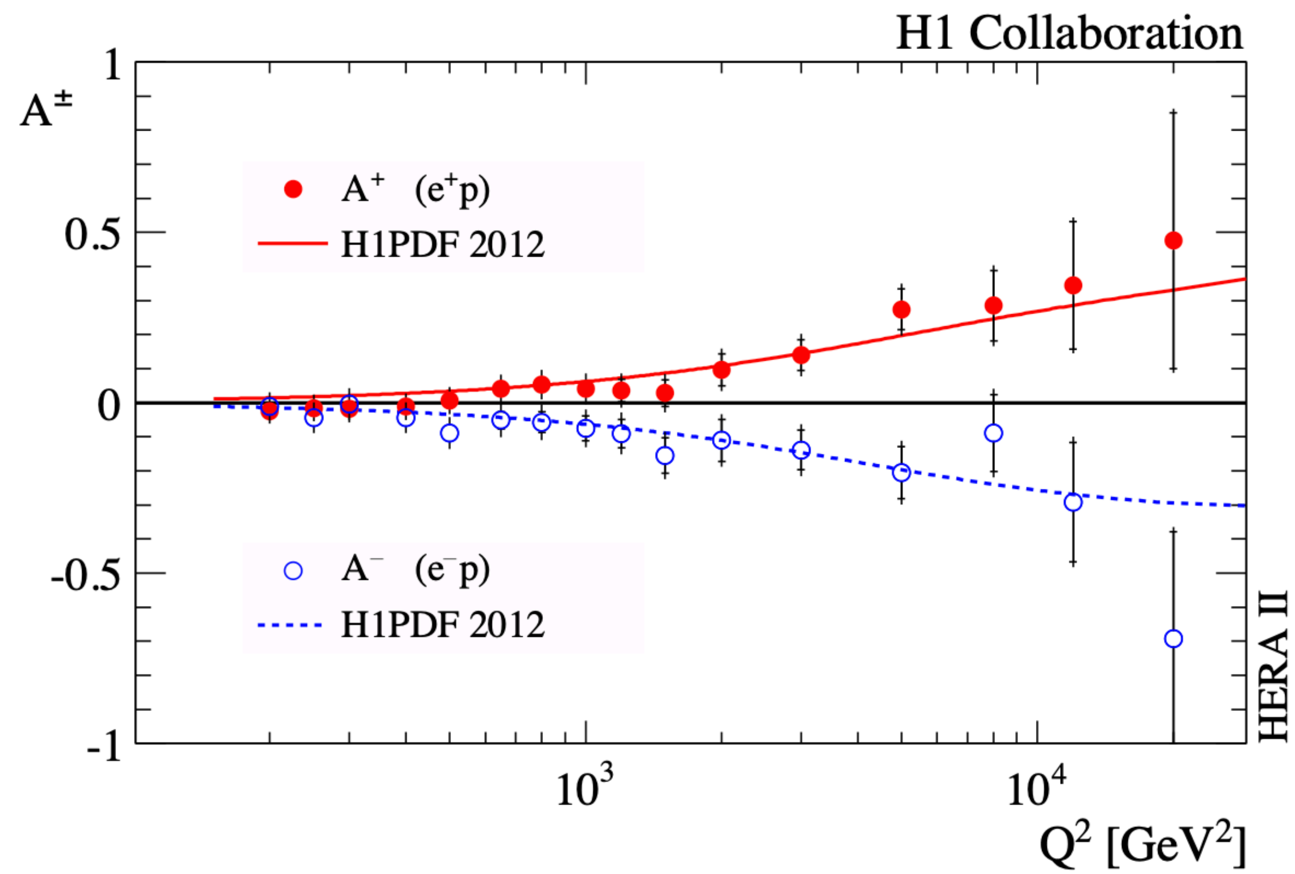
Available experimental data sets

HERA dataset
(Run I + II combined)

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

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

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



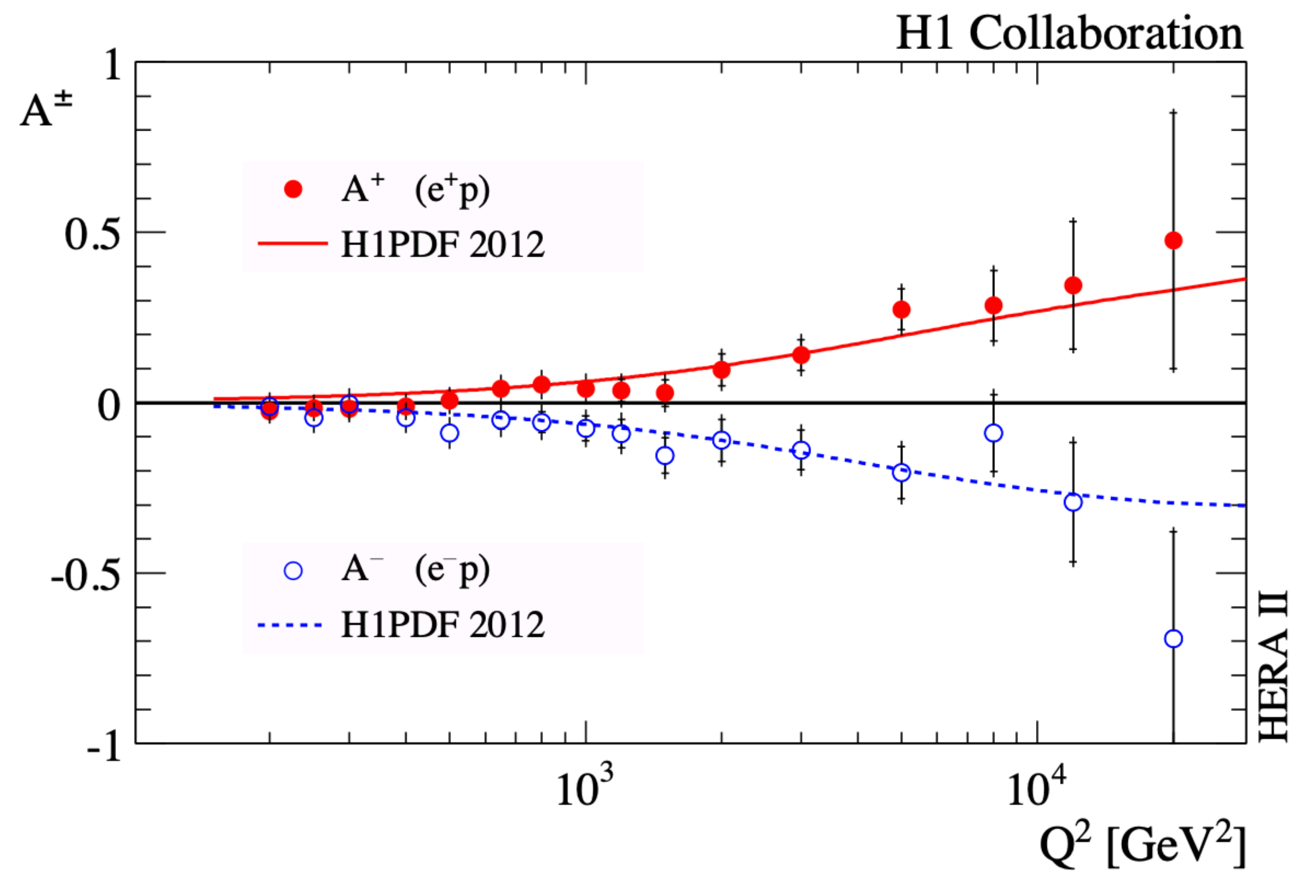
Available experimental data sets

HERA dataset
(Run I + II combined)

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

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

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



JLab6 PVDIS dataset

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

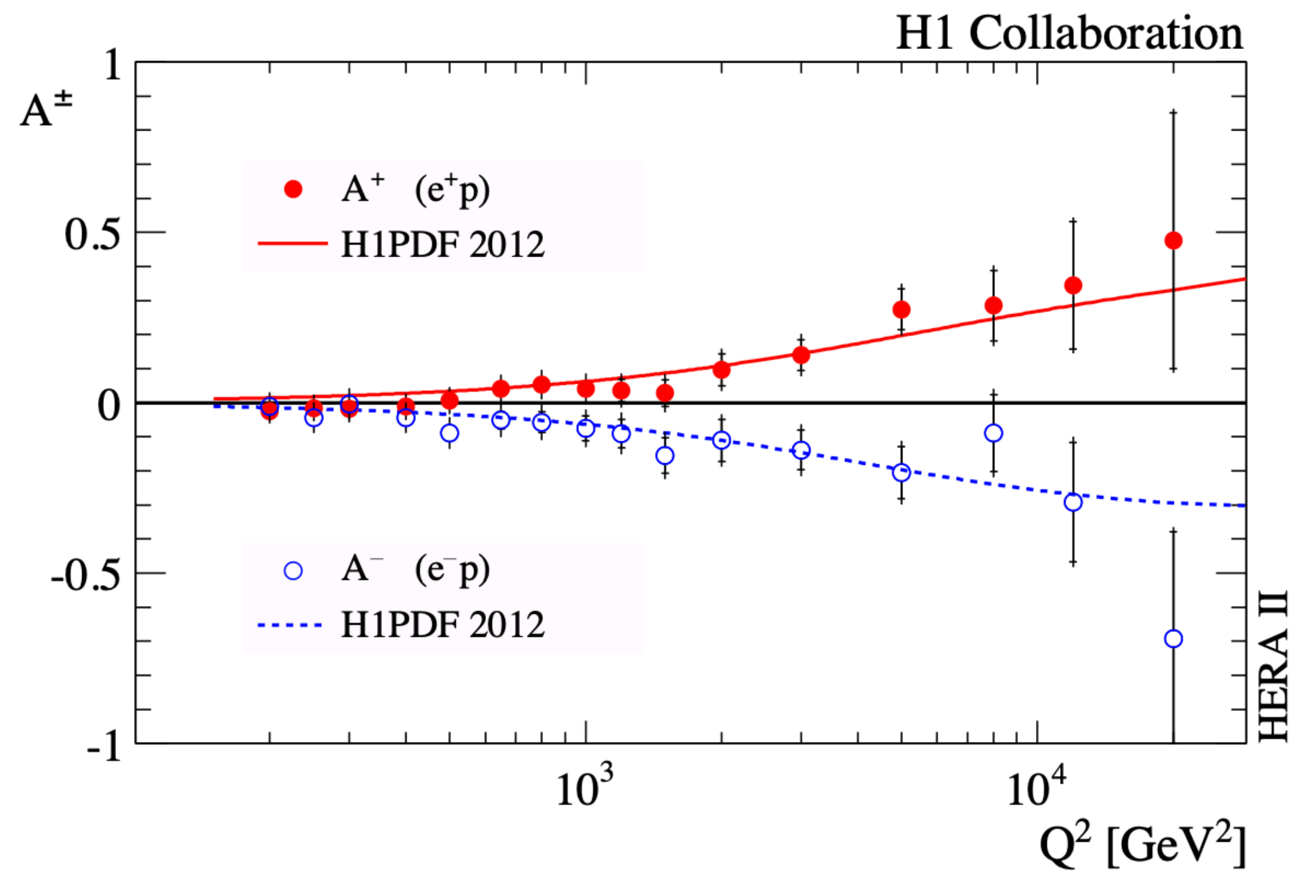
Available experimental data sets

HERA dataset
(Run I + II combined)

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

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

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



JLab6 PVDIS dataset

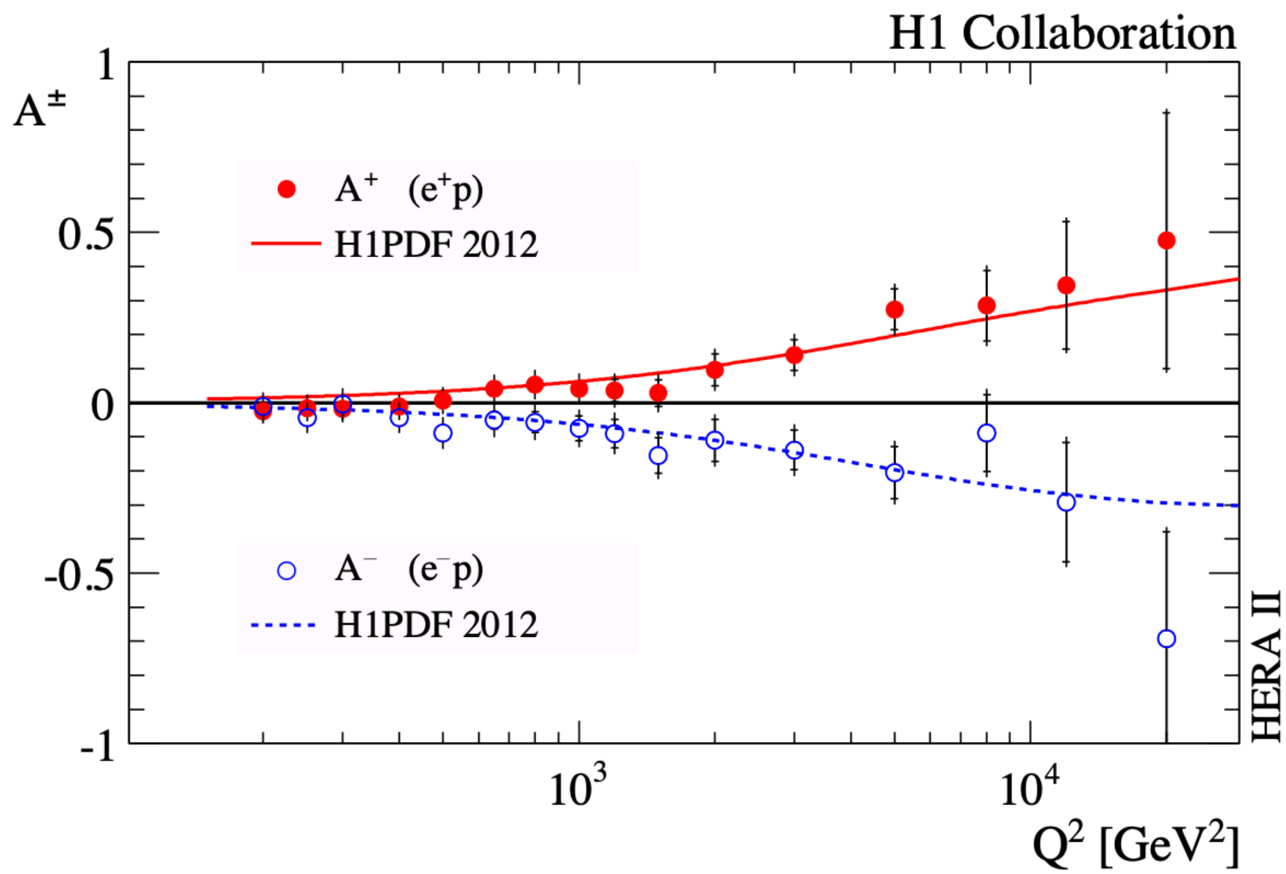
PVDIS Collaboration, *Nature* 506 (2014)
D. Wang et al., Phys.Rev.C 91 (2015)

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

Available experimental data sets

HERA dataset
(Run I + II combined)

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



e^{+} asymmetry: 136 data

e^{-} asymmetry: 138 data

JLab6 PVDIS dataset

e^{-} asymmetry: 2 data

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

SLAC-E122 dataset

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

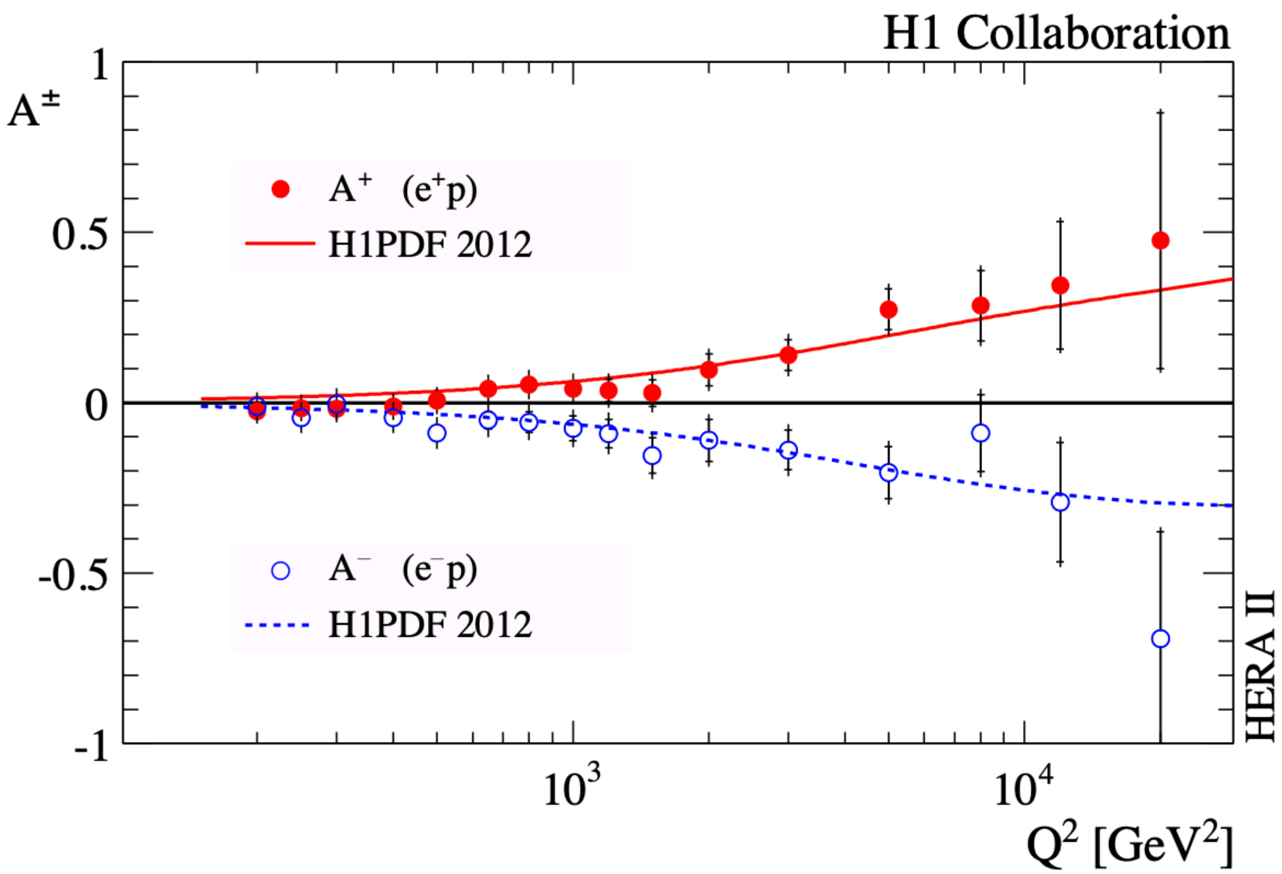
Available experimental data sets

HERA dataset
(Run I + II combined)

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

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

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



JLab6 PVDIS dataset

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

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

SLAC-E122 dataset

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

e^- ***asymmetry: 11 data***

Available experimental data sets

HERA dataset
(Run I + II combined)

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

e^+ **asymmetry: 136 data**

e^- **asymmetry: 138 data**

JLab6 PVDIS dataset

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

e^- **asymmetry: 2 data**

SLAC-E122 dataset

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

e^- **asymmetry: 11 data**

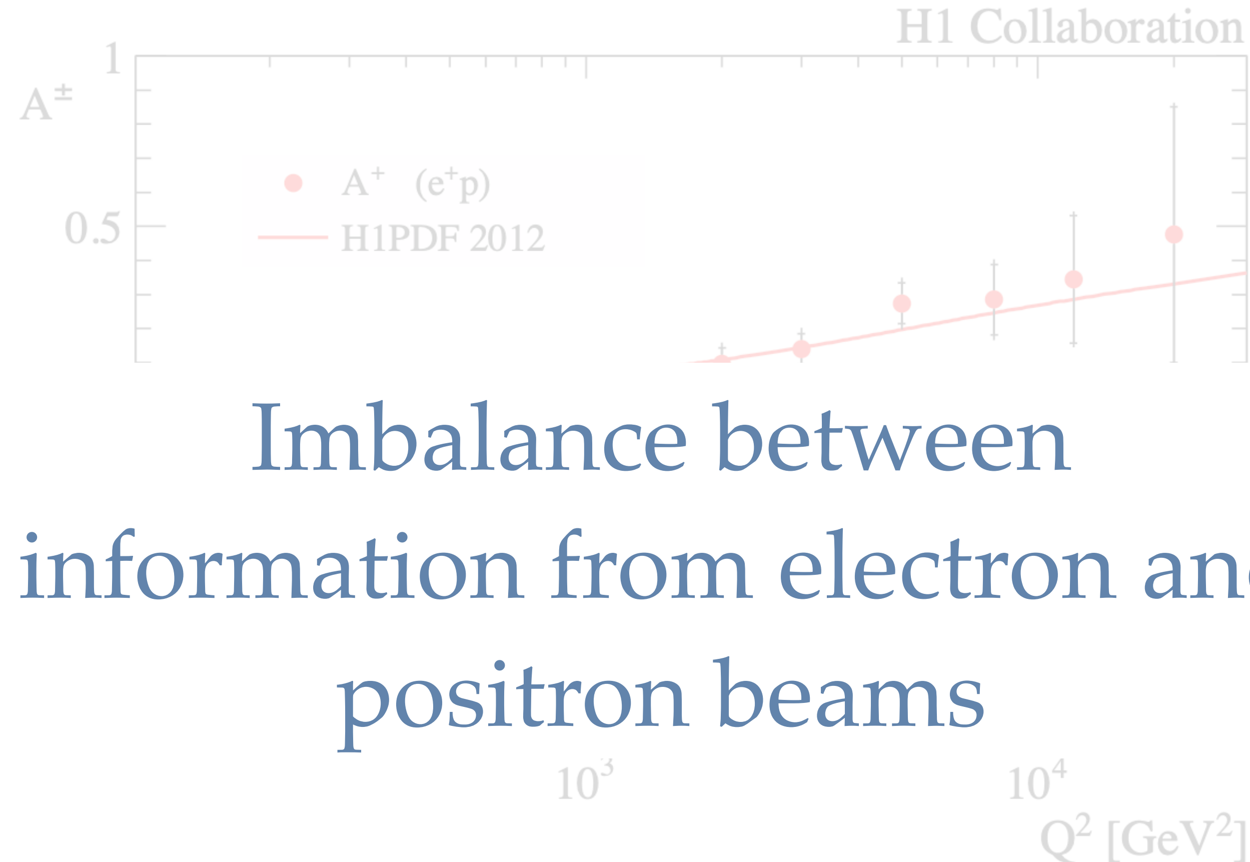
Available experimental data sets

HERA dataset
(Run I + II combined)

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

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

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



Imbalance between information from electron and positron beams

JLab6 PVDIS dataset

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

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

SLAC-E122 dataset

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

e^- ***asymmetry: 11 data***

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

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

PV parton density comes from the structure

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

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

PV parton density comes from the structure

$\gamma^5\gamma^\mu$ $\longrightarrow$ ***Same evolution as helicity PDF*** $g_1(x, Q^2)$

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

PV parton density comes from the structure

$\gamma^5\gamma^\mu$ → ***Same evolution as helicity PDF*** $g_1(x, Q^2)$

→ ***C-odd***

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

PV parton density comes from the structure

$\gamma^5\gamma^\mu$ → ***Same evolution as helicity PDF*** $g_1(x, Q^2)$

→ ***C-odd***

$$xF_3^j(x, Q^2) = \sum_q C_q^j x f_1^{(q-\bar{q})}$$

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

PV parton density comes from the structure

$\gamma^5\gamma^\mu$ → ***Same evolution as helicity PDF*** $g_1(x, Q^2)$

→ ***C-odd***

$$xF_3^j(x,Q^2) = \sum_q C_q^j x f_1^{(q-\bar{q})} \qquad \Delta x F_3^j(x,Q^2) = -\sum_q C_q'^{\,j} x \alpha g_1$$

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

PV parton density comes from the structure

$\gamma^5\gamma^\mu$ → ***Same evolution as helicity PDF*** $g_1(x, Q^2)$

→ ***C-odd***

$$xF_3^j(x, Q^2) = \sum_q C_q^j x f_1^{(q-\bar{q})} \qquad \Delta x F_3^j(x, Q^2) = -\sum_q C_q'^j x \alpha g_1^{(q+\bar{q})}$$

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

PV parton density comes from the structure

$\gamma^5\gamma^\mu$ → ***Same evolution as helicity PDF*** $g_1(x, Q^2)$

→ ***C-odd***

$$xF_3^j(x,Q^2) = \sum_q C_q^j x f_1^{(q-\bar{q})}$$

$$\Delta x F_3^j(x,Q^2) = -\sum_q C_q'^j x \alpha g_1^{(q+\bar{q})}$$

$$F_2^j(x,Q^2) = \sum_q \hat{C}_q^j x f_1^{(q+\bar{q})}$$

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

PV parton density comes from the structure

$\gamma^5\gamma^\mu$ → ***Same evolution as helicity PDF*** $g_1(x, Q^2)$

→ ***C-odd***

$$xF_3^j(x,Q^2) = \sum_q C_q^j x f_1^{(q-\bar{q})} \qquad \Delta x F_3^j(x,Q^2) = -\sum_q C_q'^j x \alpha g_1^{(q+\bar{q})}$$

$$F_2^j(x,Q^2) = \sum_q \hat{C}_q^j x f_1^{(q+\bar{q})} \qquad \Delta F_2^j(x,Q^2) = -\sum_q \hat{C}_q'^j x \alpha g_1^{(q-\bar{q})}$$

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

PV parton density comes from the structure

$\gamma^5\gamma^\mu$ → ***Same evolution as helicity PDF*** $g_1(x, Q^2)$

→ ***C-odd***

$$xF_3^j(x,Q^2) = \sum_q C_q^j x f_1^{(q-\bar{q})} \qquad \Delta x F_3^j(x,Q^2) = -\sum_q C_q'^j x \alpha g_1^{(q+\bar{q})}$$

$$F_2^j(x,Q^2) = \sum_q \hat{C}_q^j x f_1^{(q+\bar{q})} \qquad \Delta F_2^j(x,Q^2) = -\sum_q \hat{C}_q'^j x \alpha g_1^{(q-\bar{q})}$$

1 parameter to be fitted

Error propagation in the analysis

PDF set for

Error propagation in the analysis

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

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

Error propagation in the analysis

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)

Error propagation in the analysis

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

Error propagation in the analysis

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

Error propagation in the analysis

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

Error propagation in the analysis

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

Error propagation in the analysis

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

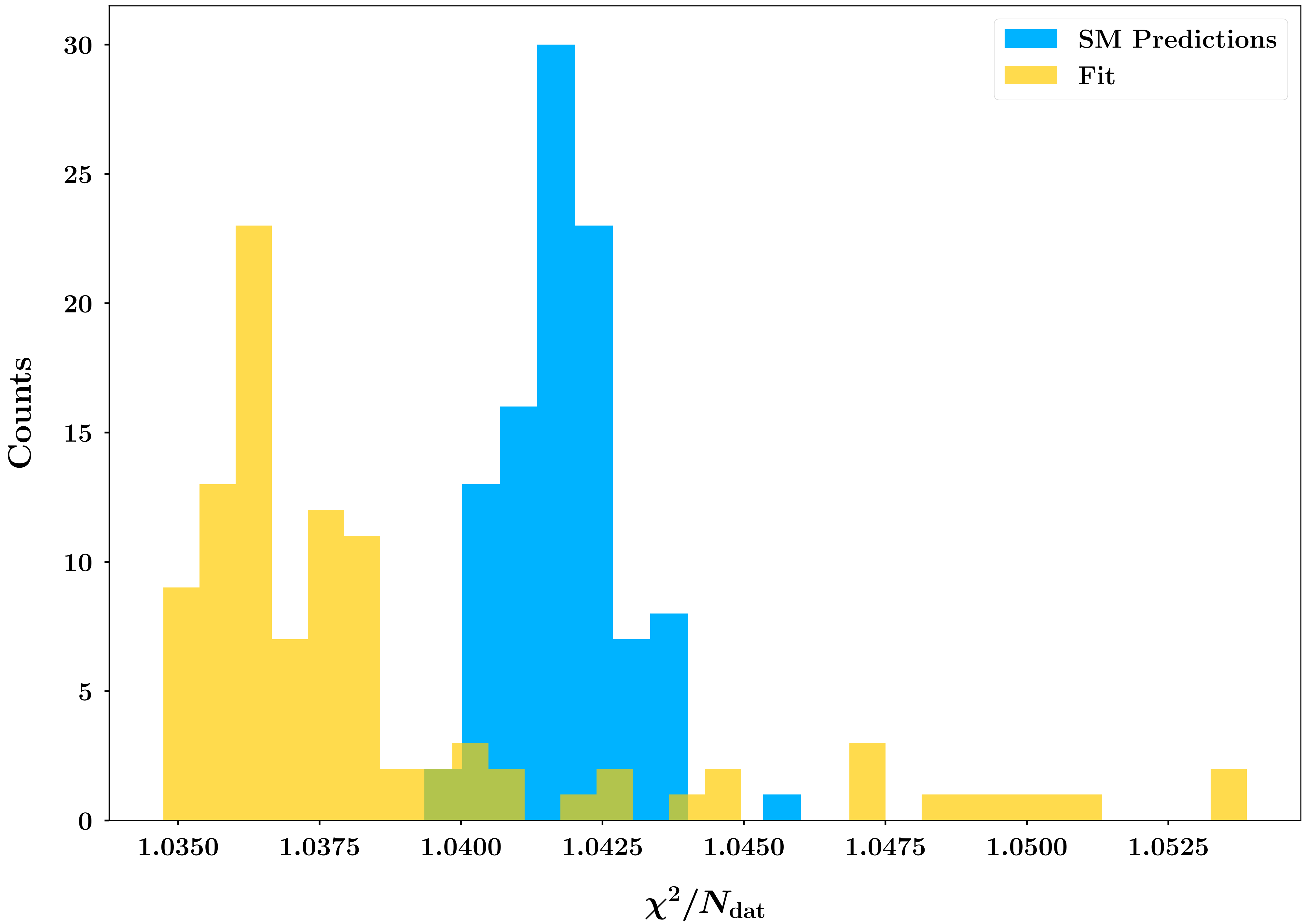
100 MC replicas experimental data

Statistical distribution of 100 values of parameter α

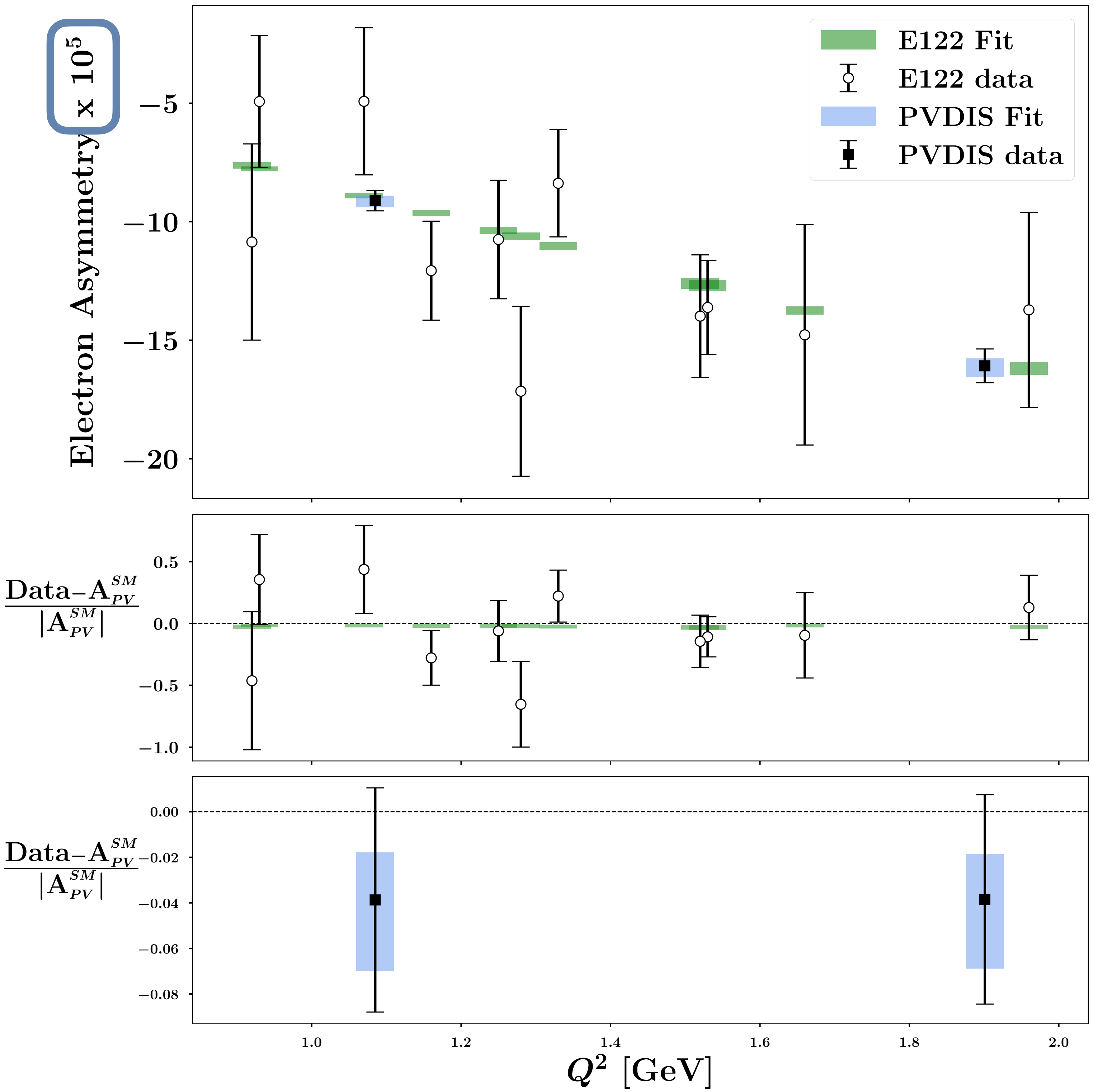
Results of the fit

	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***

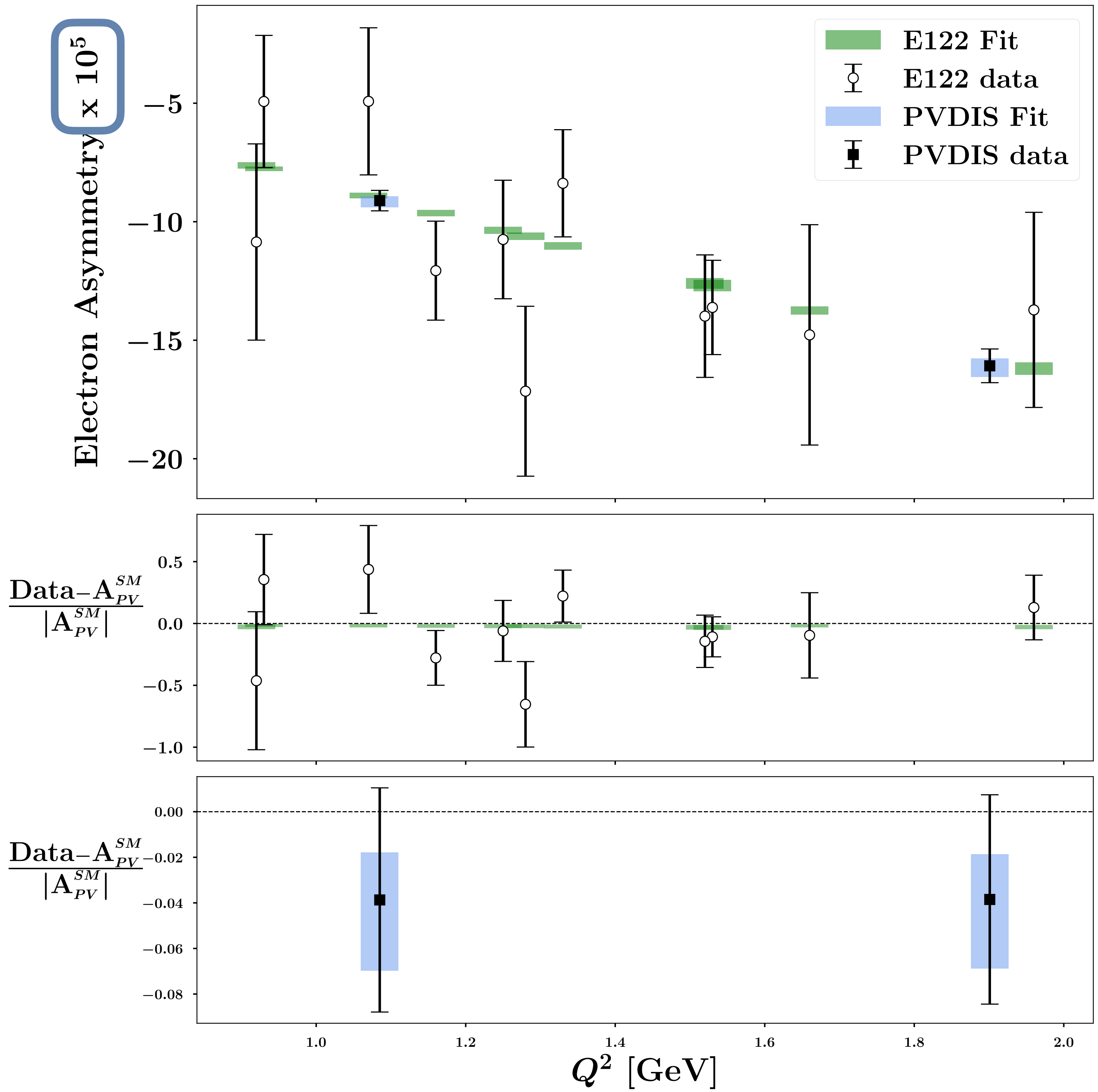
Results of the fit



Results of the fit: data vs theory

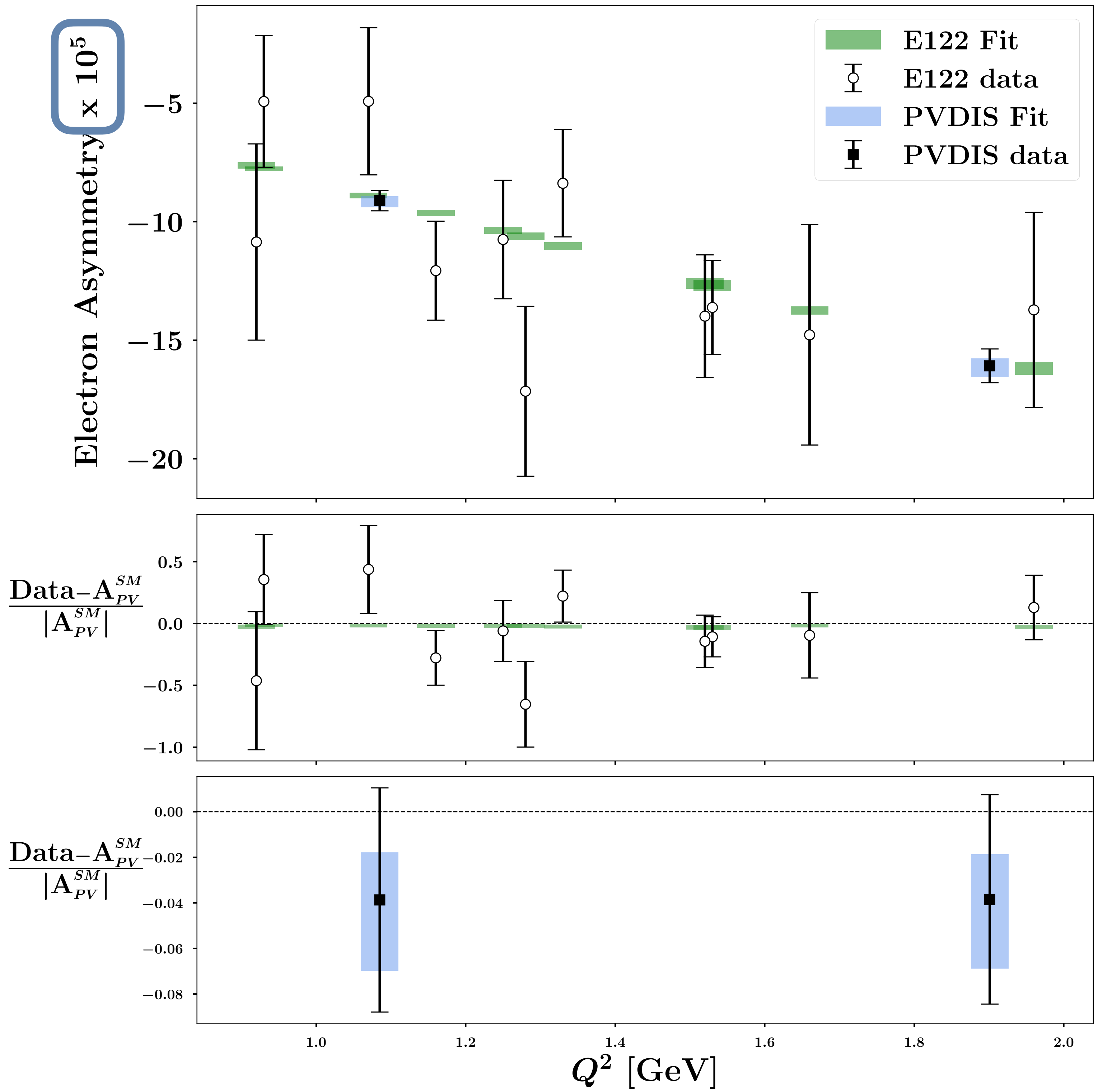


Results of the fit: data vs theory



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

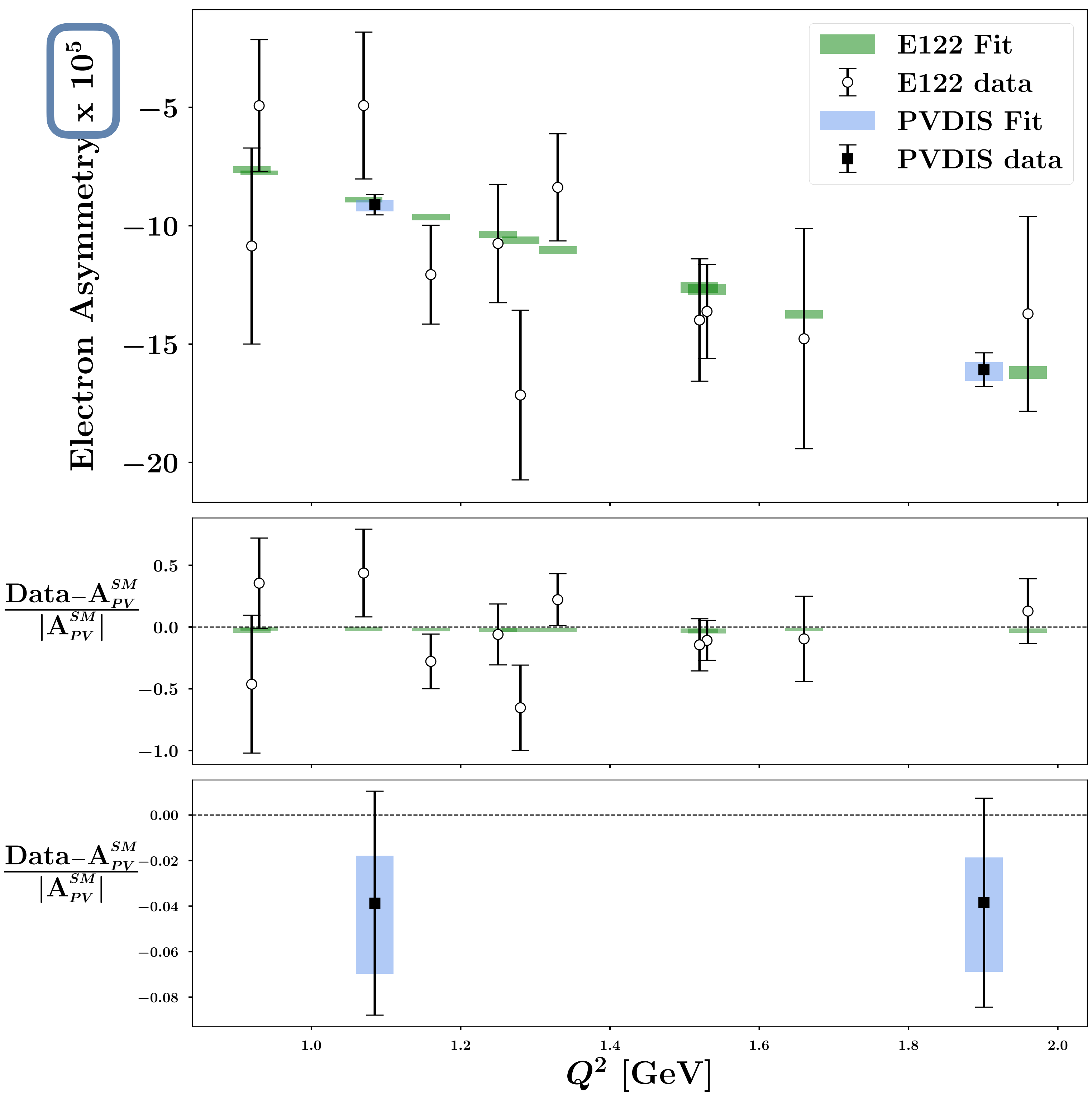
Results of the fit: data vs theory



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

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

Results of the fit: data vs theory



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 (~ %)

Results: size of the strong PV effect

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

Results: size of the strong PV effect

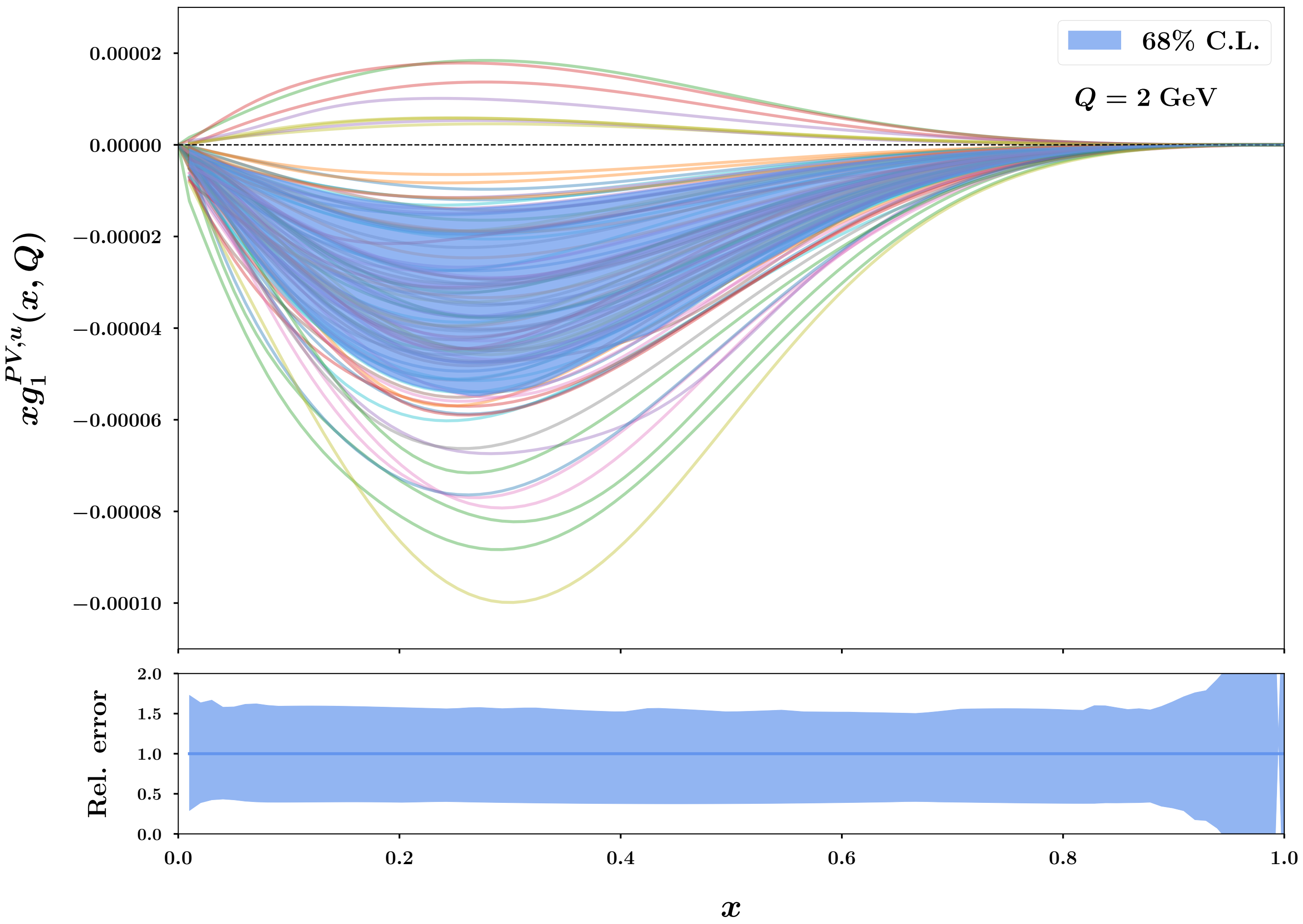
$$g_1^{\mathrm{PV}}(x) = \alpha \; g_1(x)$$

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

Results: size of the strong PV effect

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

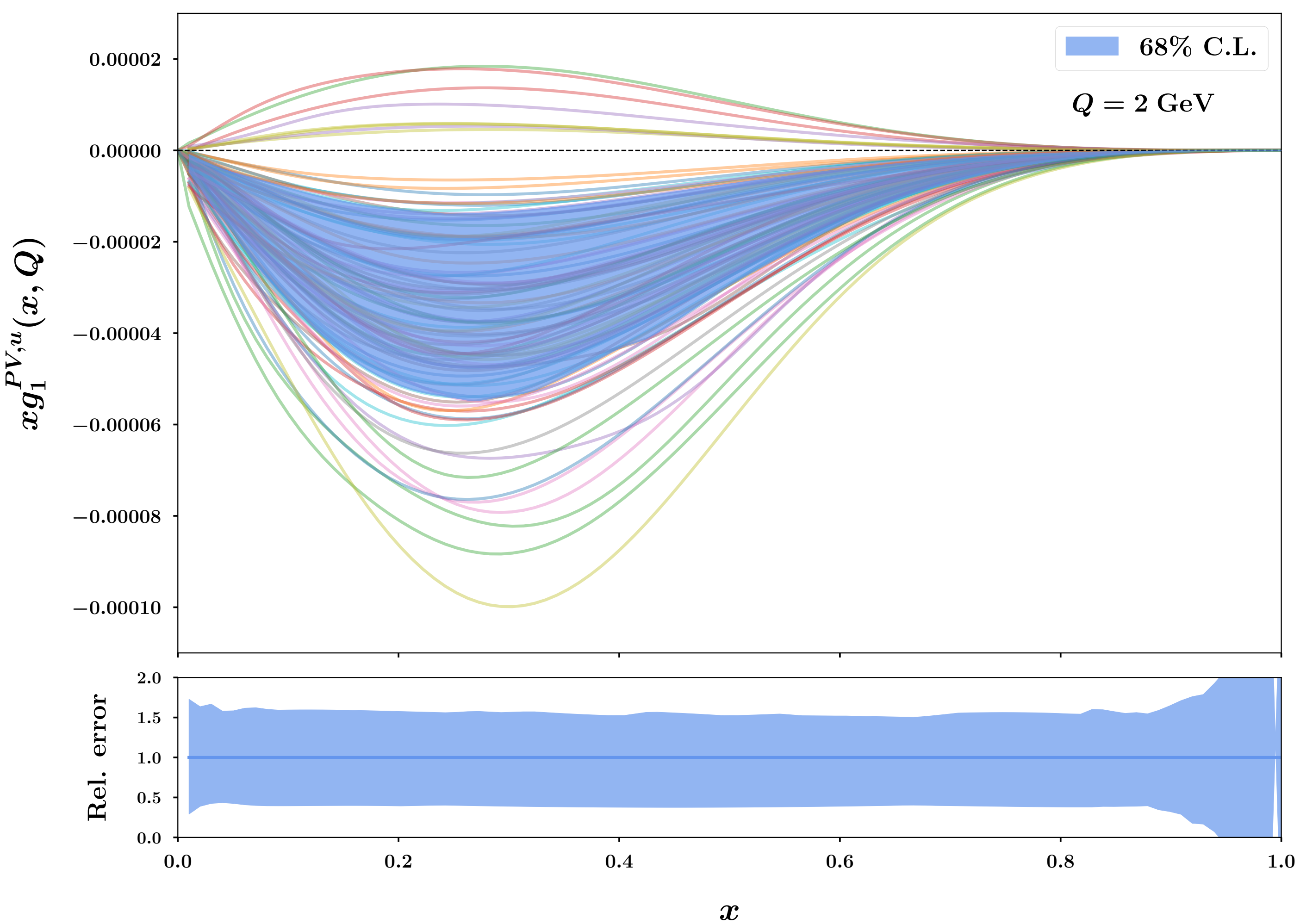
$$\alpha = (-1.01 \pm 0.66) \cdot 10^{-4}$$

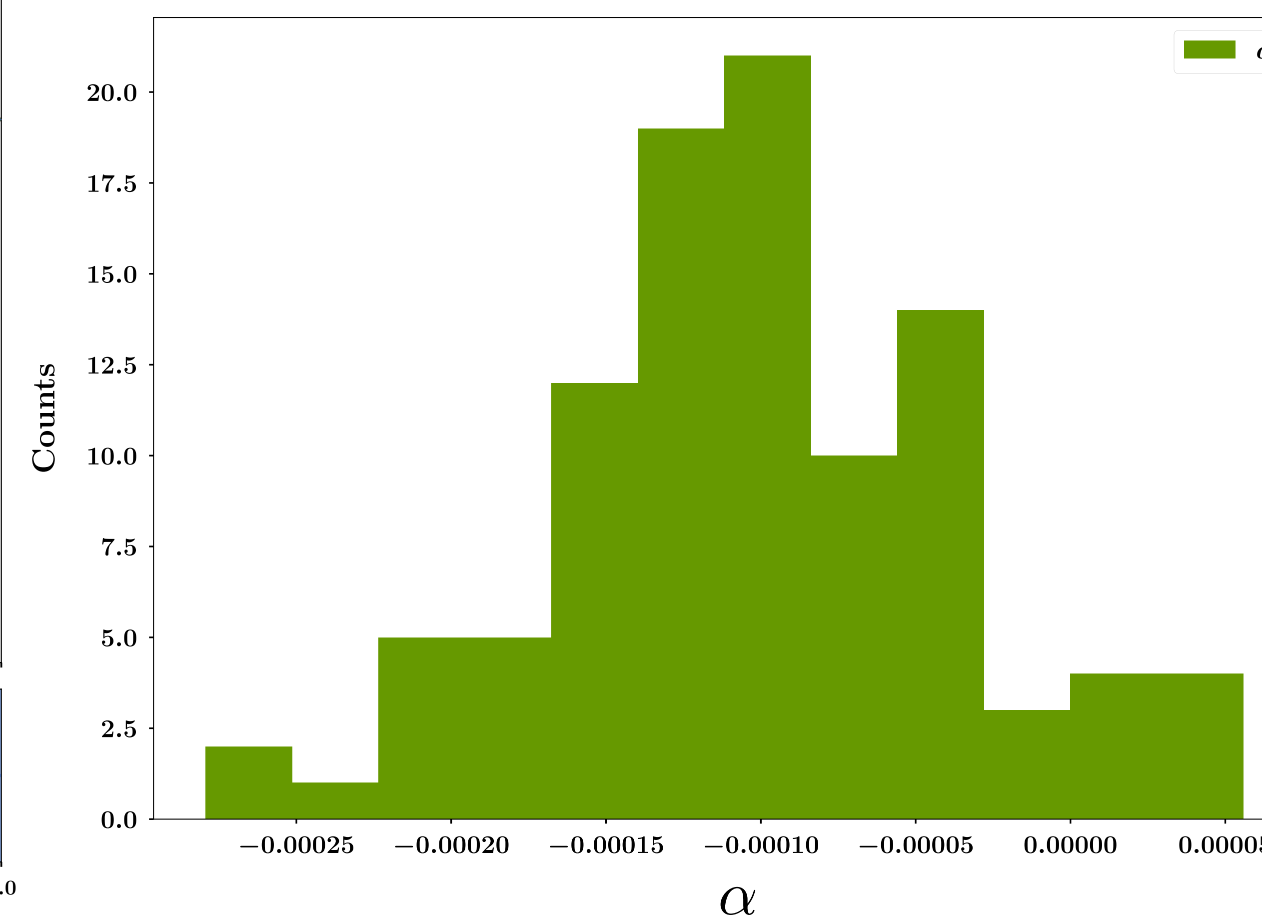


Results: size of the strong PV effect

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

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

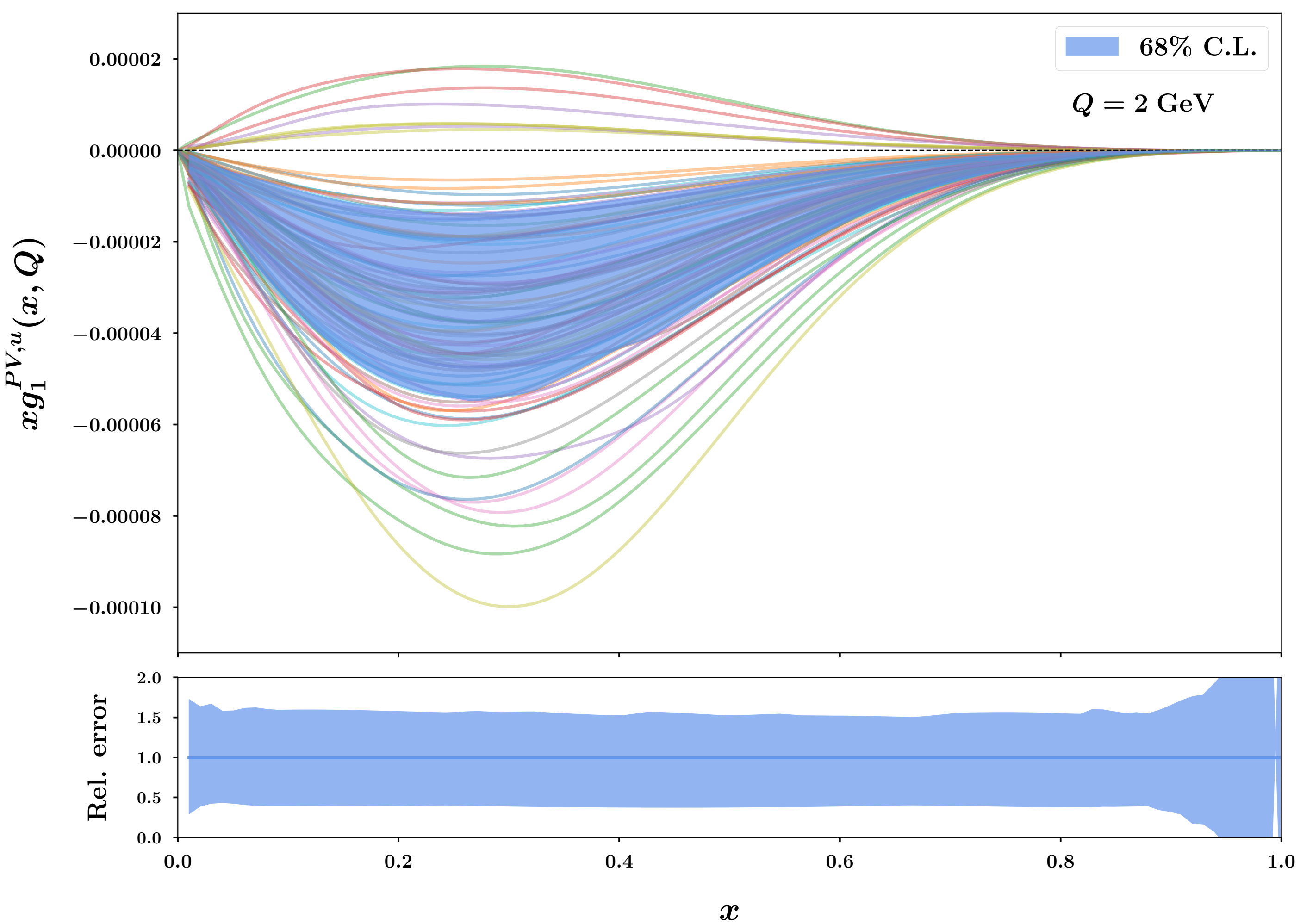




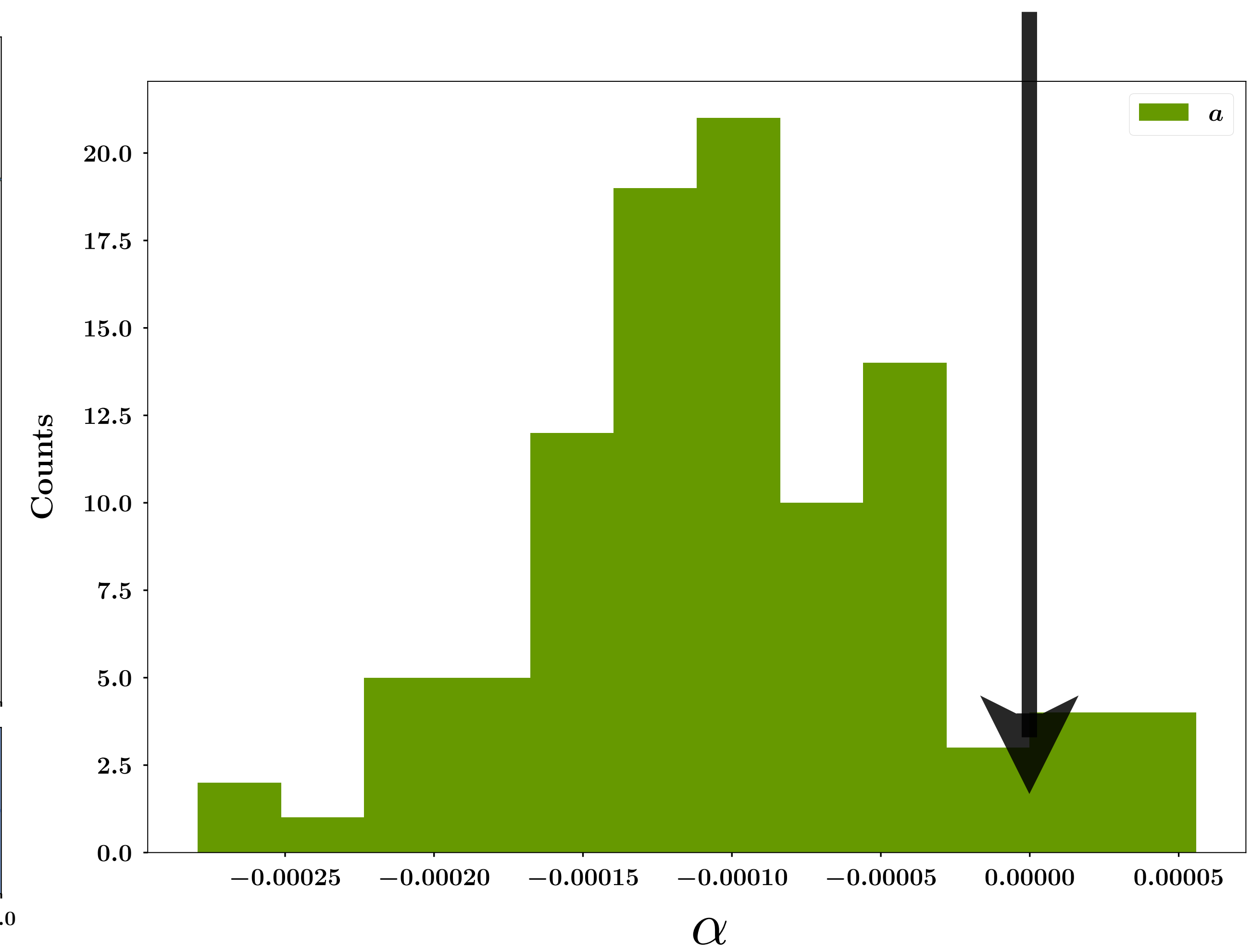
Results: size of the strong PV effect

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

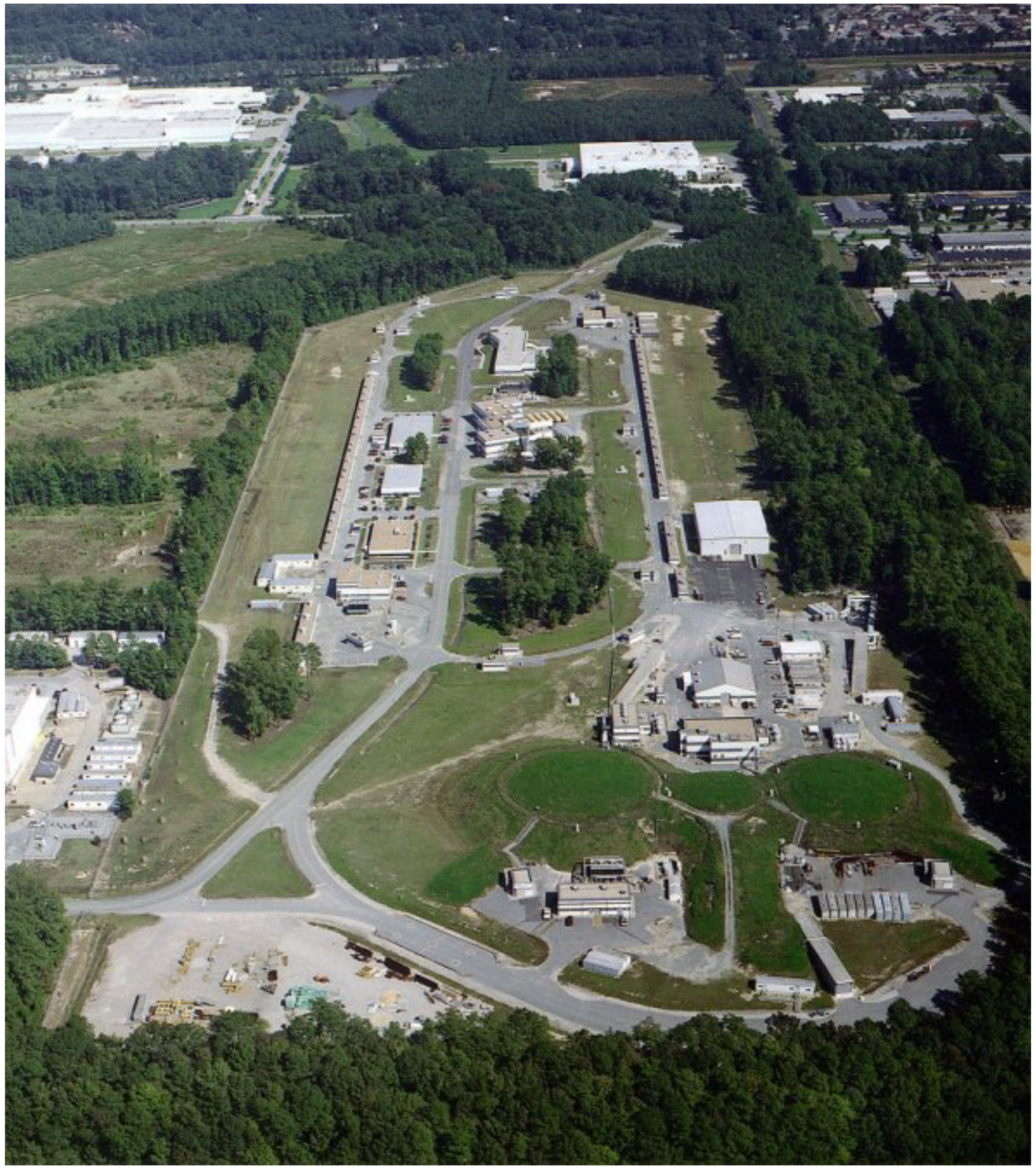
$$\alpha = (-1.01 \pm 0.66) \cdot 10^{-4}$$

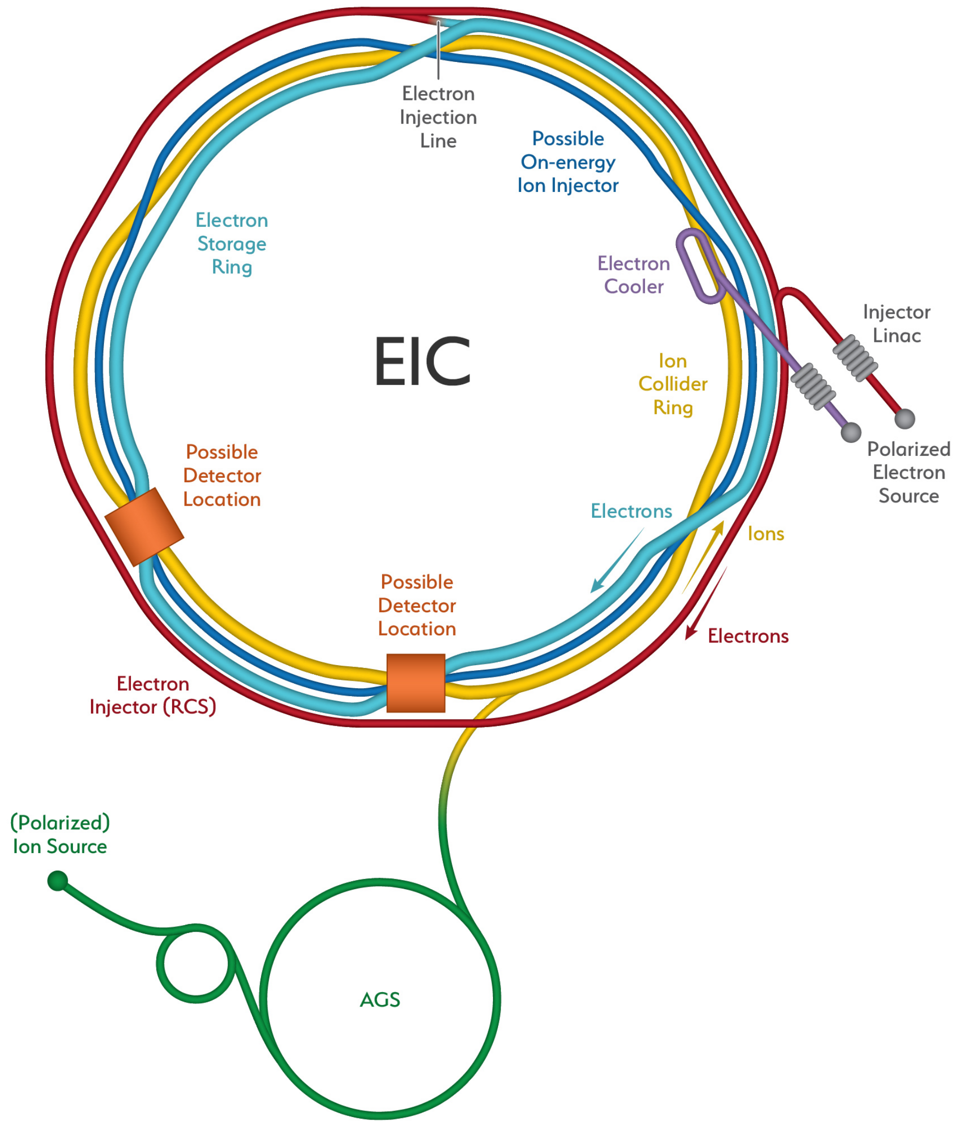


$$\boldsymbol{\alpha = 0}$$



Future facilities





Impact of future data

Impact of future data

JLab 12 GeV — SoLID detector

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

Impact of future data

JLab 12 GeV — SoLID detector

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

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

Impact of future data

JLab 12 GeV — SoLID detector

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

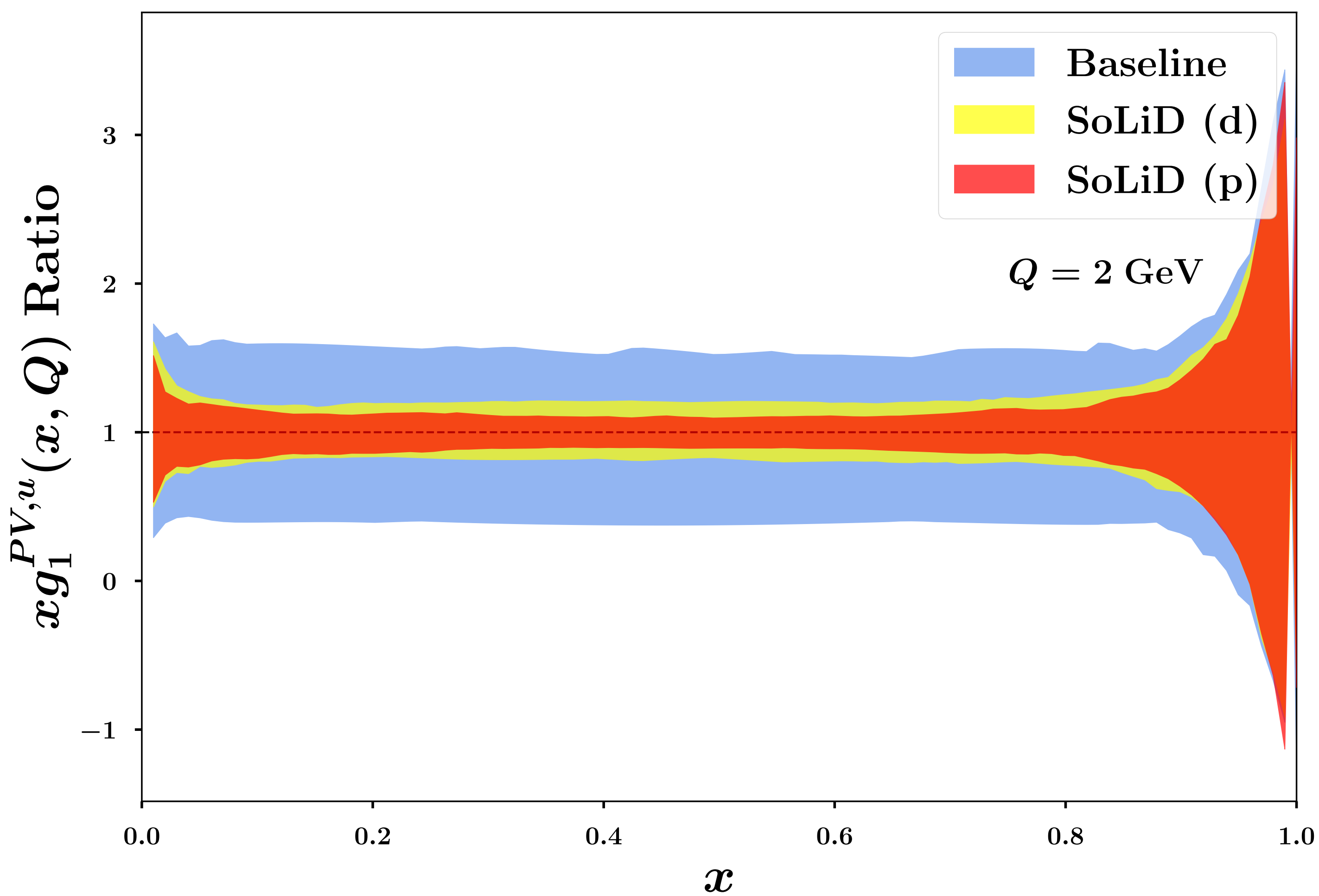
Baseline	$\alpha = (-1.01 \pm 0.66) \cdot 10^{-4}$
SoLID (d)	$\alpha = (-1.01 \pm 0.21) \cdot 10^{-4}$
SoLID (p)	$\alpha = (-1.01 \pm 0.15) \cdot 10^{-4}$

Impact of future data

JLab 12 GeV — SoLID detector

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

Baseline	$\alpha = (-1.01 \pm 0.66) \cdot 10^{-4}$
SoLID (d)	$\alpha = (-1.01 \pm 0.21) \cdot 10^{-4}$
SoLID (p)	$\alpha = (-1.01 \pm 0.15) \cdot 10^{-4}$



Step forward: dependence on x

- BSM terms in QCD that may generate PV parton distributions

$$\mathcal{L}_{\rm CPV}^{d\le 6} = -\frac{g_s^2}{32\pi^2}\bar{\theta}G\tilde{G}; \qquad d = 4 \text{ QCD } \theta\text{-term}$$

$$-\frac{i}{2}\sum_{q=u,d,s} d_q \bar{q}(\sigma\cdot F)\gamma_5 q; \qquad d = 5 \text{ quark EDM}$$

$$-\frac{i}{2}\sum_{q=u,d,s} \tilde{d}_q g_s \bar{q}(\sigma\cdot G)\gamma_5 q; \qquad d = 5 \text{ quark chromo EDM}$$

$$+ d_w \frac{g_s}{6} G\tilde{G}G; \qquad d = 6 \text{ Weinberg's 3g operator}$$

$$+\sum_i C_i^{(4q)} O_i^{(4q)}; \qquad d = 6 \text{ Four-quark operators}$$

See talk by Y-S Yoo @SPIN23

Step forward: dependence on x

- BSM terms in QCD that may generate PV parton distributions

$$
\begin{aligned}
\mathcal{L}_{\mathrm{CPV}}^{d\leq 6} = & -\frac{g_s^2}{32\pi^2}\bar{\theta}G\tilde{G}; && d=4 \text{ QCD } \theta\text{-term} \\
& -\frac{i}{2}\sum_{q=u,d,s} d_q\bar{q}(\sigma\cdot F)\gamma_5 q; && d=5 \text{ quark EDM} \\
& -\frac{i}{2}\sum_{q=u,d,s} \tilde{d}_q g_s\bar{q}(\sigma\cdot G)\gamma_5 q; && d=5 \text{ quark chromo EDM} \\
& + d_w\frac{g_s}{6}G\tilde{G}G; && d=6 \text{ Weinberg's 3g operator} \\
& + \sum_i C_i^{(4q)}O_i^{(4q)}; && d=6 \text{ Four-quark operators}
\end{aligned}
$$

See talk by Y-S Yoo @SPIN23

+ bunch of SMEFT operators

Grzadkowski, et al., JHEP 10 (2010)

Step forward: dependence on x

- BSM terms in QCD that may generate PV parton distributions

$$\mathcal{L}_{\rm CPV}^{d\le 6} = -\frac{g_s^2}{32\pi^2}\bar{\theta}G\tilde{G}; \qquad d=4 \text{ QCD } \theta\text{-term}$$

$$-\frac{i}{2}\sum_{q=u,d,s} d_q \bar{q}(\sigma\cdot F)\gamma_5 q; \qquad d=5 \text{ quark EDM}$$

$$-\frac{i}{2}\sum_{q=u,d,s} \tilde{d}_q g_s \bar{q}(\sigma\cdot G)\gamma_5 q; \qquad d=5 \text{ quark chromo EDM}$$

$$+\, d_w \frac{g_s}{6} G\tilde{G}G; \qquad d=6 \text{ Weinberg's 3g operator}$$

$$+\sum_i C_i^{(4q)} O_i^{(4q)}; \qquad d=6 \text{ Four-quark operators}$$

See talk by Y-S Yoo @SPIN23

+ bunch of SMEFT operators

Grzadkowski, et al., JHEP 10 (2010)

→ **Question to F. Petriello**

Step forward: dependence on x

Preliminary

- Spectator model for PV parton distributions

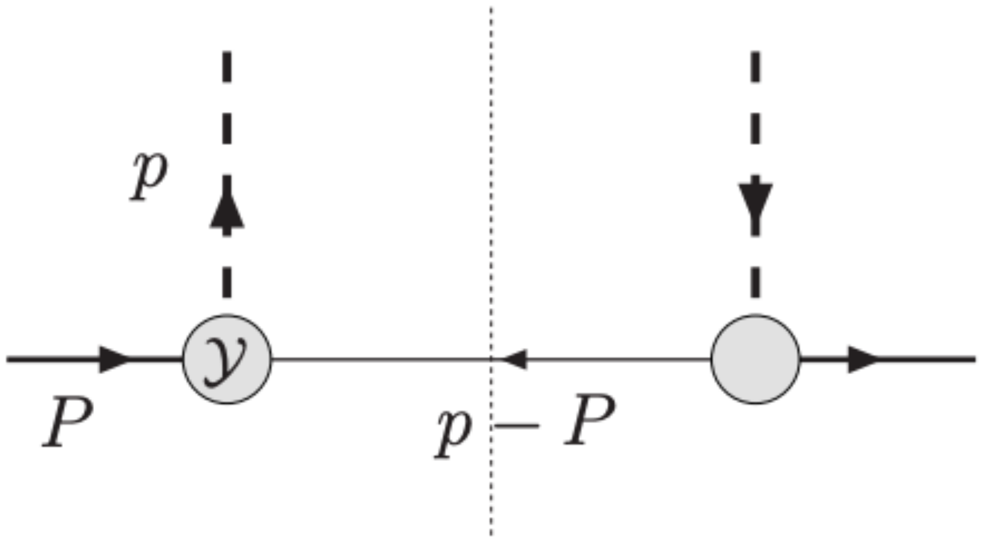
Bacchetta, Conti, Radici, PRD 78 (2008)

Step forward: dependence on x

Preliminary

- Spectator model for PV parton distributions

Bacchetta, Conti, Radici, PRD 78 (2008)

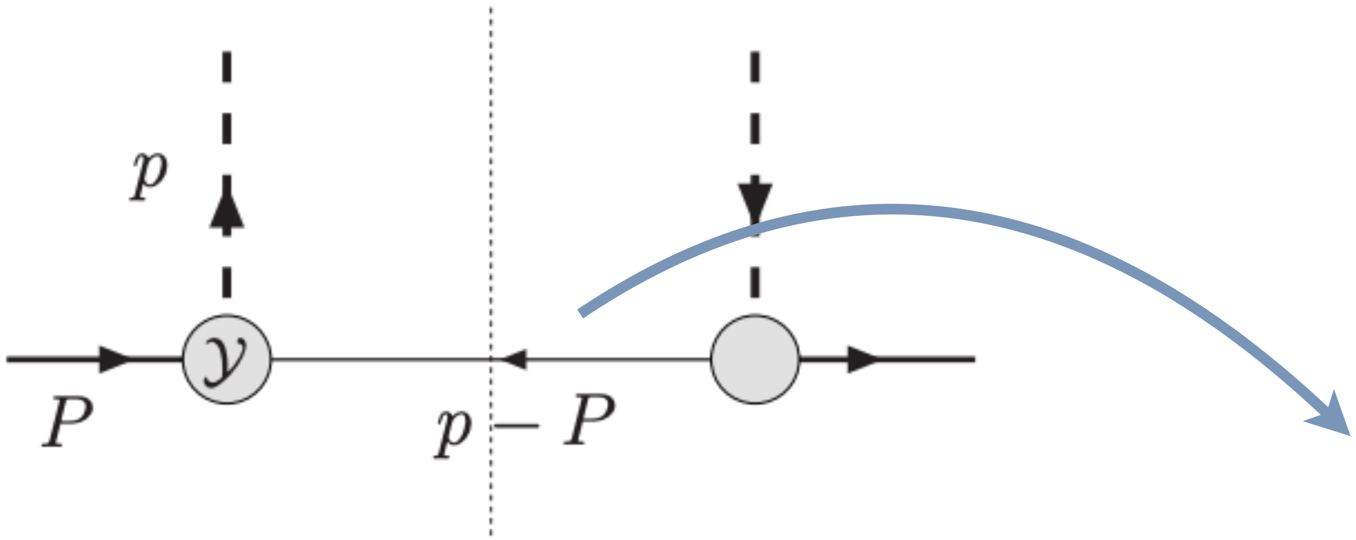


Step forward: dependence on x

Preliminary

- Spectator model for PV parton distributions

Bacchetta, Conti, Radici, PRD 78 (2008)



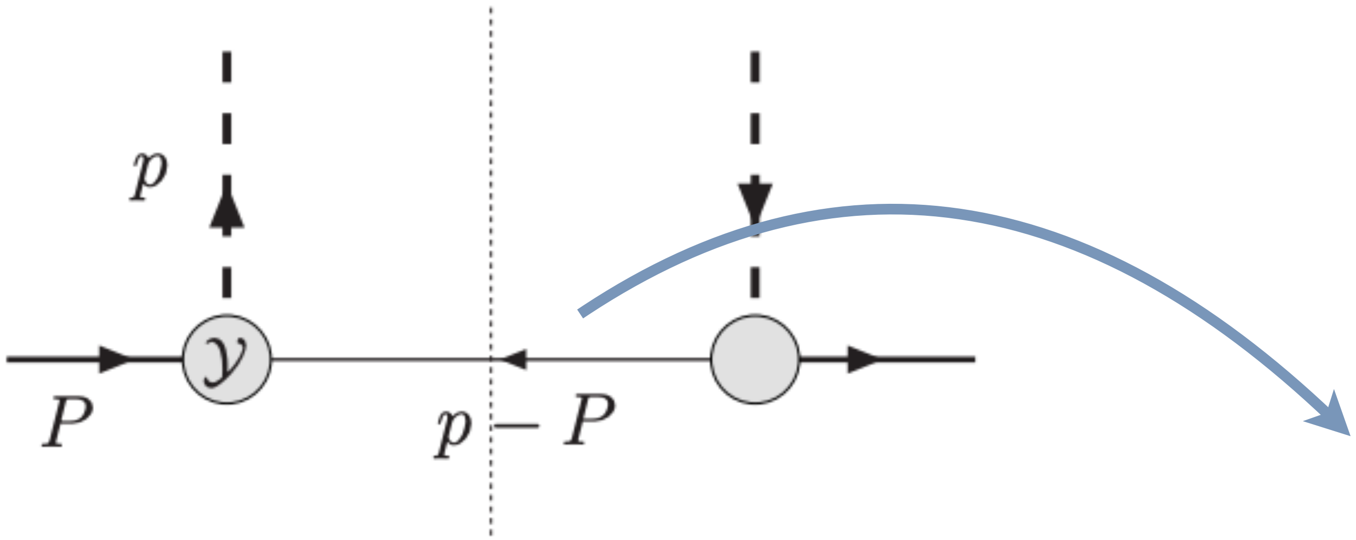
Diquark propagator

Step forward: dependence on x

Preliminary

- Spectator model for PV parton distributions

Bacchetta, Conti, Radici, PRD 78 (2008)



Diquark propagator

Scalar

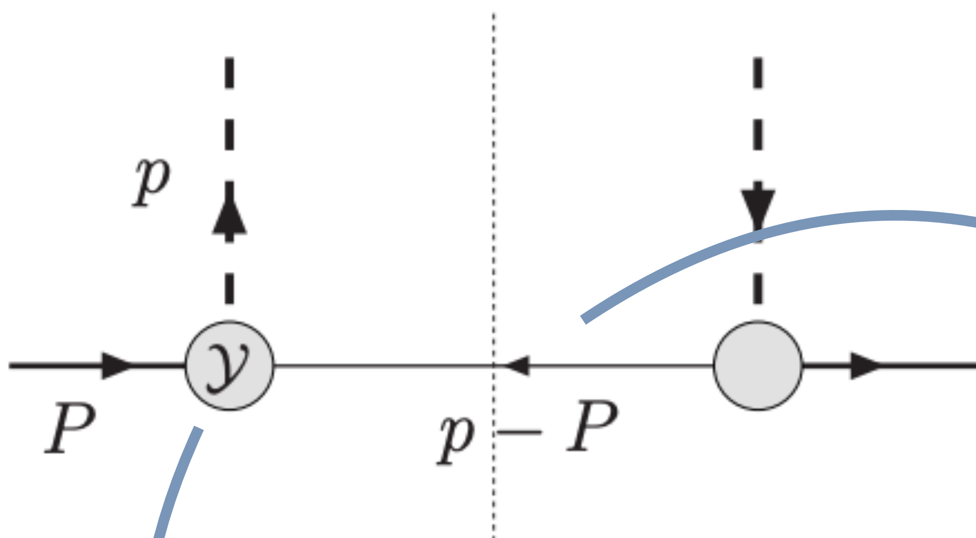
Vector

Step forward: dependence on x

Preliminary

- Spectator model for PV parton distributions

Bacchetta, Conti, Radici, PRD 78 (2008)



Diquark propagator

Scalar

Vector

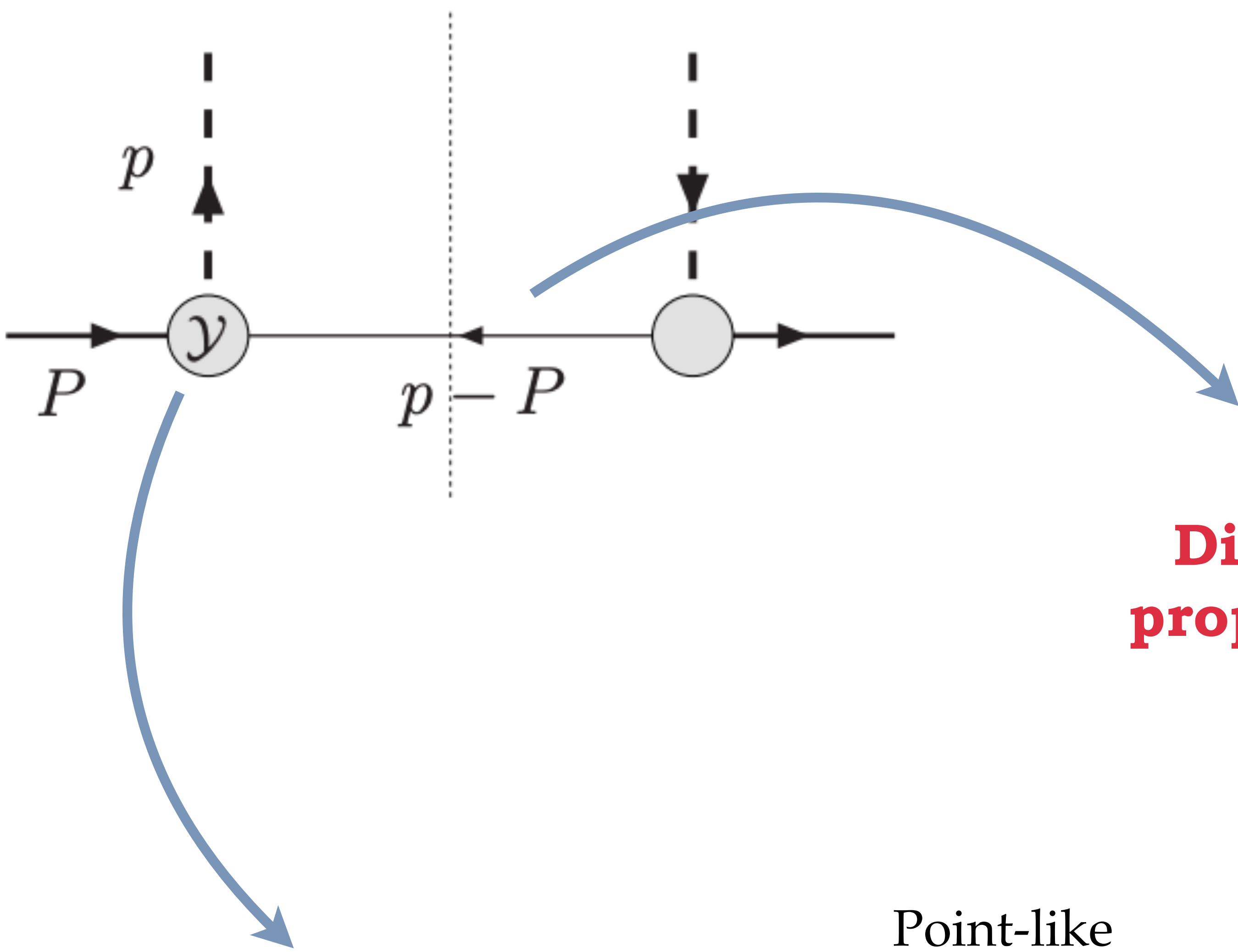
Form Factor

Step forward: dependence on x

Preliminary

- Spectator model for PV parton distributions

Bacchetta, Conti, Radici, PRD 78 (2008)



Diquark propagator

Scalar

Vector

Form Factor

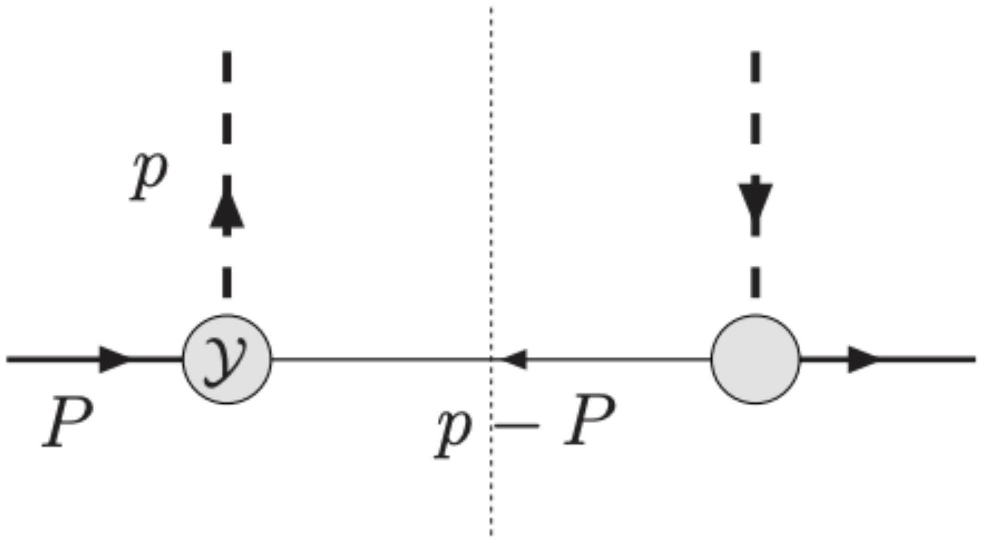
Point-like
Dipolar
Exponential

Step forward: dependence on x

Preliminary

- Spectator model for PV parton distributions

Bacchetta, Conti, Radici, PRD 78 (2008)

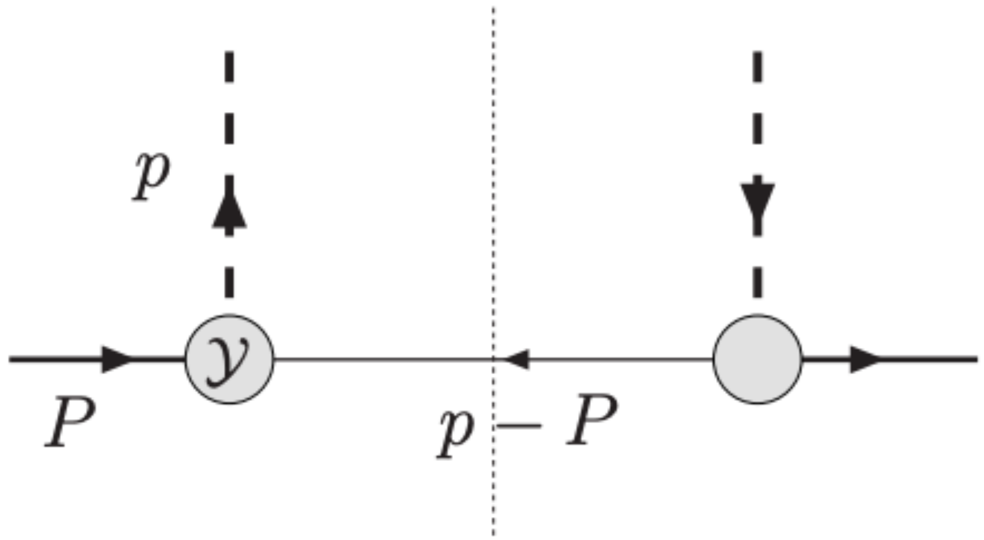


Step forward: dependence on x

Preliminary

- Spectator model for PV parton distributions

Bacchetta, Conti, Radici, PRD 78 (2008)



Diquark propagator

Scalar

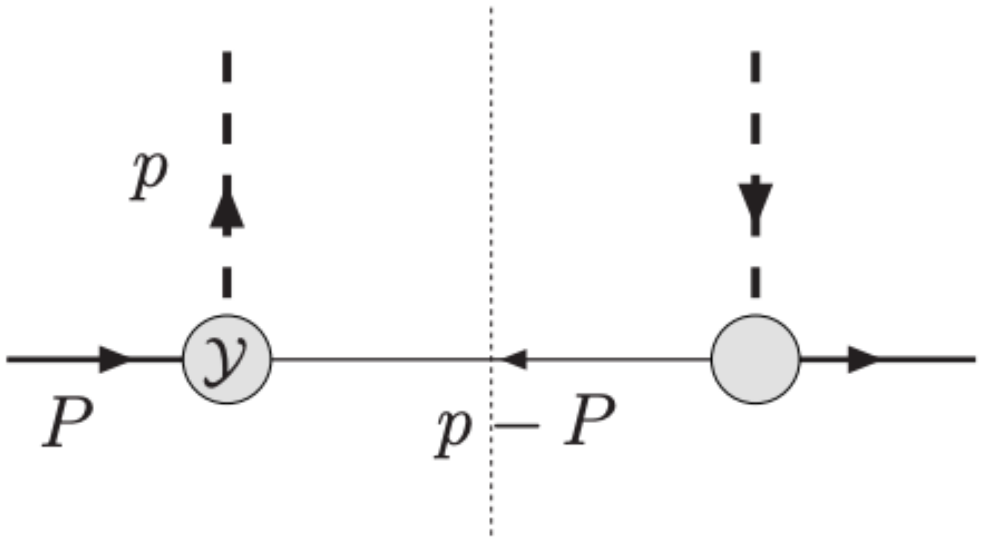
Vector

Step forward: dependence on x

Preliminary

- Spectator model for PV parton distributions

Bacchetta, Conti, Radici, PRD 78 (2008)



Diquark propagator

Scalar

Vector

$$\langle P-k|\psi(0)|P,S\rangle = \frac{i}{\not k - m}\varepsilon^*_\mu(P-k,\lambda_v)\mathcal{Y}^\mu_v U(P,S)$$

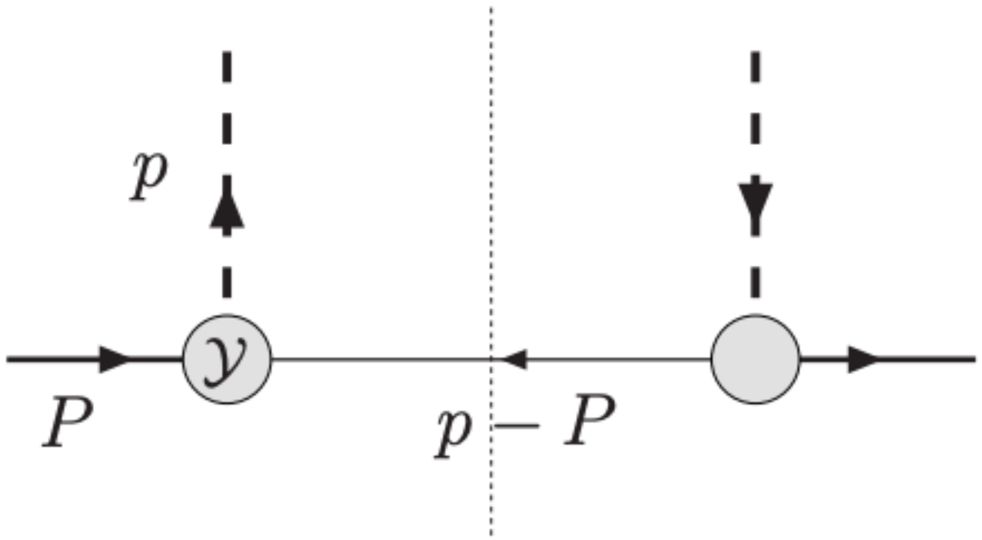
$$\mathcal{Y}^\mu_v = i\frac{g_v(k^2)}{\sqrt{2}}\gamma^\mu\gamma_5$$

Step forward: dependence on x

Preliminary

- Spectator model for PV parton distributions

Bacchetta, Conti, Radici, PRD 78 (2008)



Diquark propagator	Scalar Vector
Form Factor	Dipolar

$$\langle P-k|\psi(0)|P,S\rangle = \frac{i}{\not{k}-m}\varepsilon^*_\mu(P-k,\lambda_v)\mathcal{Y}^\mu_v U(P,S)$$

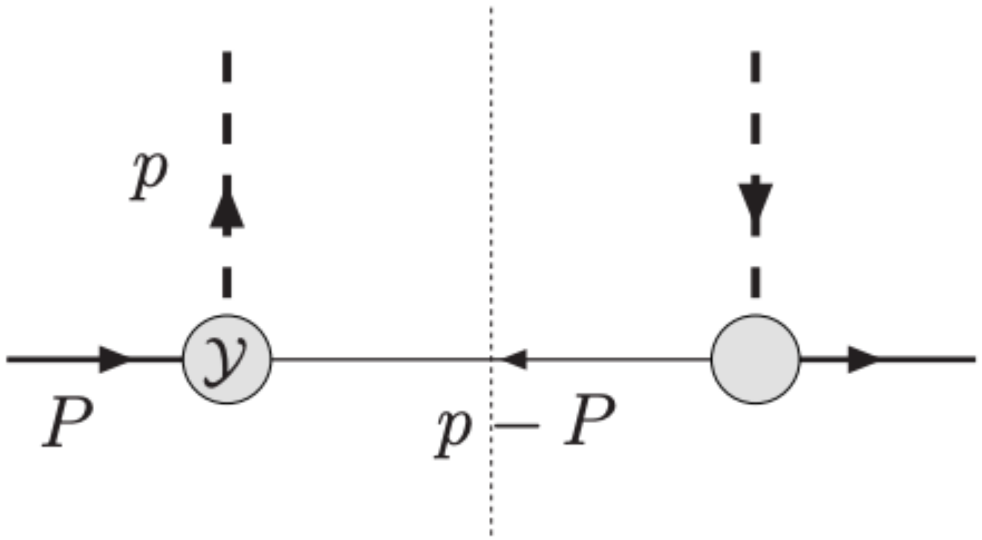
$$\mathcal{Y}^\mu_v = i\frac{g_v(k^2)}{\sqrt{2}}\gamma^\mu\gamma_5 \qquad g_X(k^2) = g_X^{\rm dip}\frac{p^2-m^2}{|p^2-\Lambda_X^2|^2}$$

Step forward: dependence on x

Preliminary

- Spectator model for PV parton distributions

Bacchetta, Conti, Radici, PRD 78 (2008)



Diquark propagator	Scalar Vector
Form Factor	Dipolar

$$\langle P-k|\psi(0)|P,S\rangle = \frac{i}{\not{k}-m}\varepsilon^*_\mu(P-k,\lambda_v)\mathcal{Y}^\mu_v U(P,S)$$

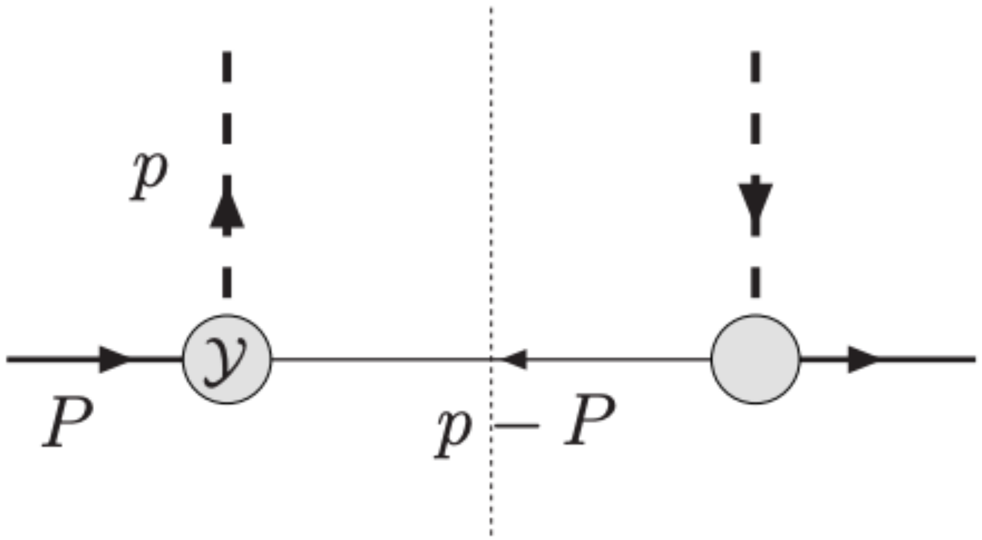
$$\mathcal{Y}^\mu_v = i\frac{g_v(k^2)}{\sqrt{2}}\gamma^\mu\gamma_5$$

Step forward: dependence on x

Preliminary

- Spectator model for PV parton distributions

Bacchetta, Conti, Radici, PRD 78 (2008)



Diquark propagator	Scalar Vector
Form Factor	Dipolar

$$\langle P-k|\psi(0)|P,S\rangle = \frac{i}{\not k - m}\varepsilon^*_\mu(P-k,\lambda_v)\mathcal{Y}^\mu_v U(P,S)$$

P-violating

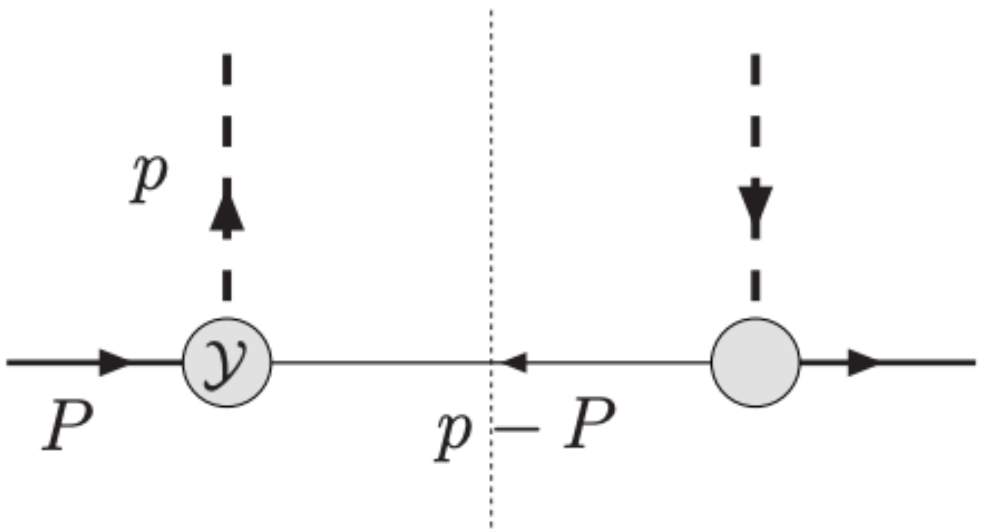
$$\mathcal{Y}^\mu_v = i\frac{g_v(k^2)}{\sqrt{2}}\gamma^\mu\gamma_5 \quad \longrightarrow \quad \mathcal{Y}^\mu_v = i\frac{g_v(k^2)}{\sqrt{2}}\gamma^\mu\gamma_5(a-b\gamma_5)$$

Step forward: dependence on x

Preliminary

- Spectator model for PV parton distributions

Bacchetta, Conti, Radici, PRD 78 (2008)

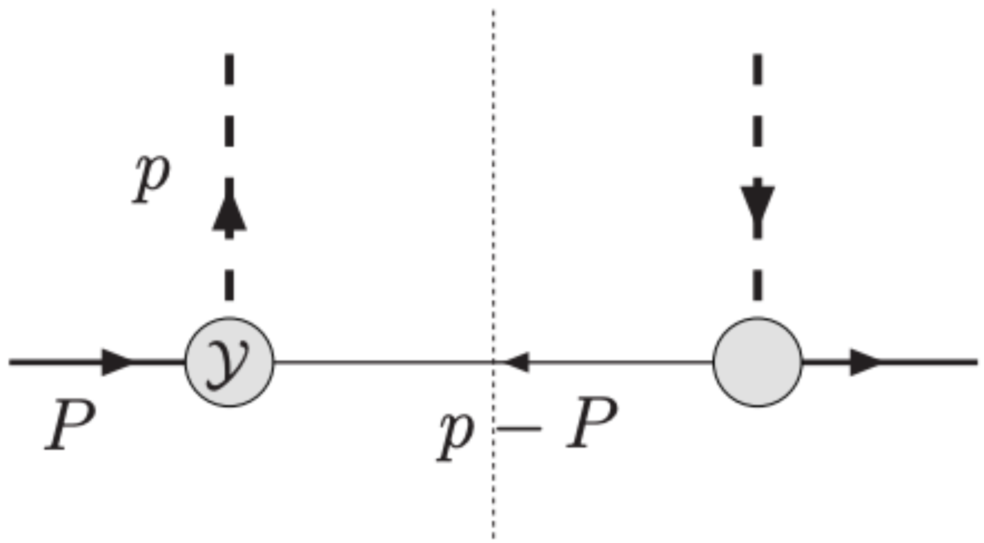


Step forward: dependence on x

Preliminary

- Spectator model for PV parton distributions

Bacchetta, Conti, Radici, PRD 78 (2008)



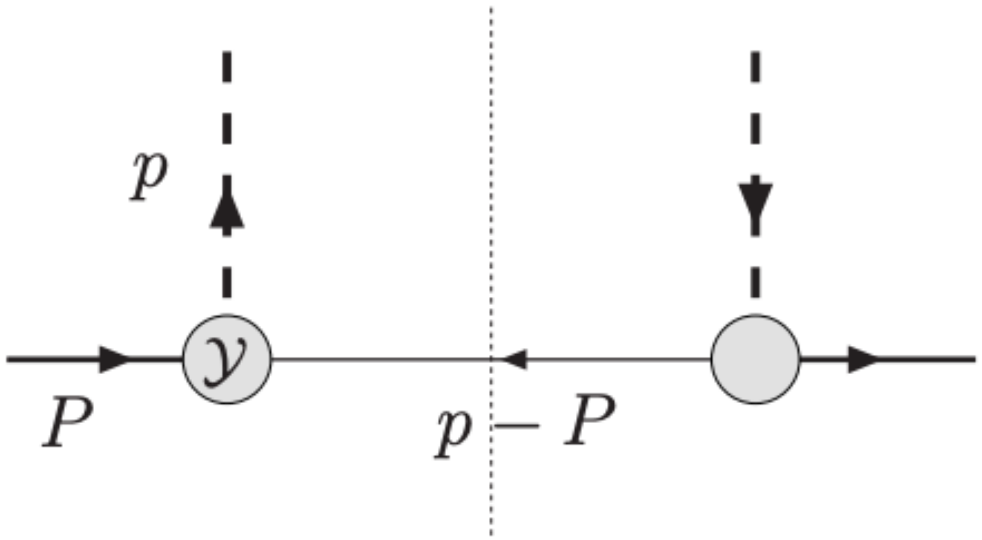
$$\mathcal{Y}_s = i g_s(k^2)(a - b\gamma_5)$$

Step forward: dependence on x

Preliminary

- Spectator model for PV parton distributions

Bacchetta, Conti, Radici, PRD 78 (2008)



$$\mathcal{Y}_s = i g_s(k^2)(a - b\gamma_5)$$

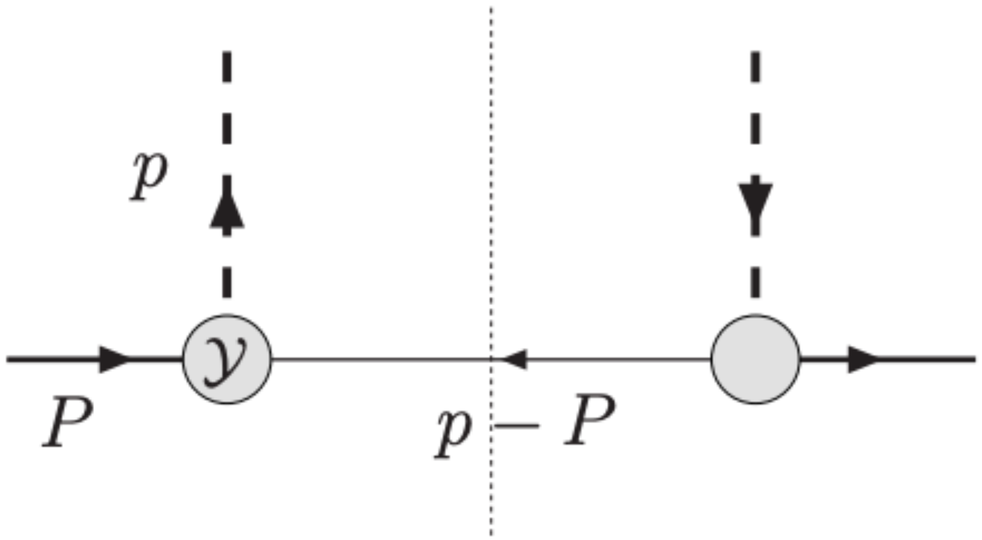
$$g_{1s}^{PV} = a\, b_s \frac{(1-x)^3 (L_s^2 - 2m^2 + 2(xM)^2}{48\pi^2 L_s^6}$$

Step forward: dependence on x

Preliminary

- Spectator model for PV parton distributions

Bacchetta, Conti, Radici, PRD 78 (2008)



$$\mathcal{Y}_s = i g_s(k^2)(a - b\gamma_5)$$

$$\mathcal{Y}_v^\mu = i \frac{g_v(k^2)}{\sqrt{2}} \gamma^\mu \gamma_5 (a - b\gamma_5)$$

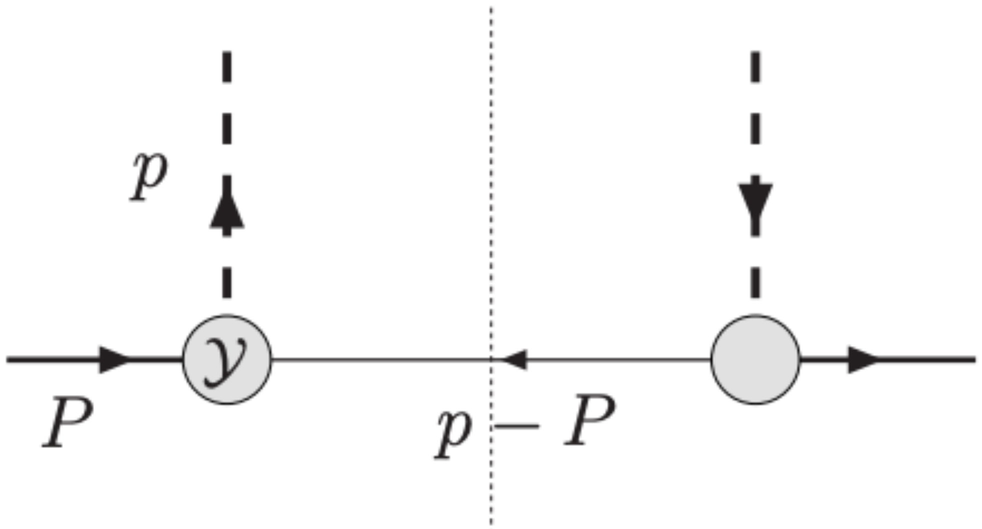
$$g_{1s}^{PV} = a\, b_s \frac{(1-x)^3 (L_s^2 - 2m^2 + 2(xM)^2}{48\pi^2 L_s^6}$$

Step forward: dependence on x

Preliminary

- Spectator model for PV parton distributions

Bacchetta, Conti, Radici, PRD 78 (2008)



$$\mathcal{Y}_s = i g_s(k^2)(a - b\gamma_5)$$

$$\mathcal{Y}_v^\mu = i\frac{g_v(k^2)}{\sqrt{2}}\gamma^\mu\gamma_5(a - b\gamma_5)$$

$$g_{1s}^{PV} = a\, b_s \frac{(1-x)^3(L_s^2 - 2m^2 + 2(xM)^2}{48\pi^2 L_s^6}$$

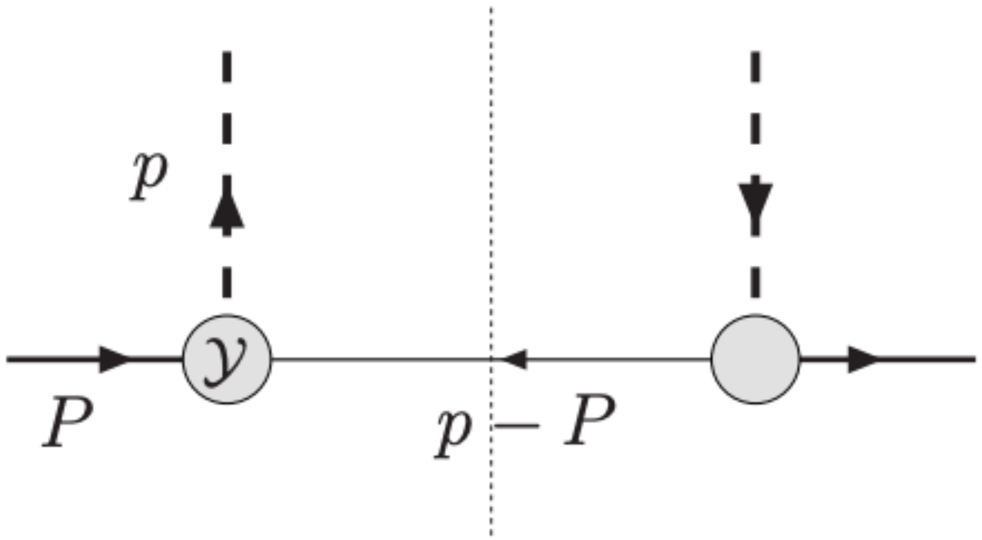
$$g_{1v}^{PV} = -a\, b_v \frac{(1-x)^2 2((xM)^2 - m^2) + L_v^2(1+x^2)}{48\pi^2 L_v^6}$$

Step forward: dependence on x

Preliminary

- Spectator model for PV parton distributions

Bacchetta, Conti, Radici, PRD 78 (2008)



$$\mathcal{Y}_s = i g_s(k^2)(a - b\gamma_5)$$

$$\mathcal{Y}_v^\mu = i\frac{g_v(k^2)}{\sqrt{2}}\gamma^\mu\gamma_5(a - b\gamma_5)$$

$$g_{1s}^{PV} = a\,b_s\frac{(1-x)^3(L_s^2 - 2m^2 + 2(xM)^2}{48\pi^2 L_s^6}$$

$$g_{1v}^{PV} = -a\,b_v\frac{(1-x)^2 2((xM)^2 - m^2) + L_v^2(1+x^2)}{48\pi^2 L_v^6}$$

$$g_{1u}^{PV} = g_s^2 N_s^2 g1_s^{PV} + g_v^2 N_v^2 g1_v^{PV}$$

Step forward: dependence on x

- Spectator model for PV parton distributions

Next steps:

Step forward: dependence on x

- Spectator model for PV parton distributions

Next steps:

  - Fit model parameters to phenomenological extraction

Step forward: dependence on x

- Spectator model for PV parton distributions

Next steps:

- Fit model parameters to phenomenological extraction

- Compare the result for g_1^{PV}/g_1 ratio

Step forward: dependence on x

- Spectator model for PV parton distributions

Next steps:

- Fit model parameters to phenomenological extraction
- Compare the result for g_1^{PV}/g_1 ratio
- Fit model parameters to experimental data

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

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

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

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

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

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

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

PDFs in DIS processes

Quark Polarization

Nucleon Pol.

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

PDFs in DIS processes

with P violation

Quark Polarization

Nucleon Pol.

	U	L	T
U	$f_1(x)$	$g_1^{\rm PV}(x)$	
L	$f_{1L}^{\rm PV}(x)$	$g_1(x)$	
T			$h_1(x)$

PDFs in DIS processes

with P violation

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			$h_1(x)$

Axial charge

PDFs in DIS processes

with P violation

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			$h_1(x)$

Anapole moment?

Axial charge

PDFs in DIS processes

with P violation

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			$h_1(x)$

Anapole moment?

Electric dipole moment?

Axial charge

Summary

Summary

- If we accept strong P- violation in the decomposition of the partonic correlator, we obtain new PV PDFs

Summary

- If we accept strong P- violation in the decomposition of the partonic correlator, we obtain new PV PDFs

- In this assumption, a new structure function in DIS cross section for one-photon exchange is generated

Summary

- If we accept strong P- violation in the decomposition of the partonic correlator, we obtain new PV PDFs

- In this assumption, a new structure function in DIS cross section for one-photon exchange is generated

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

Summary

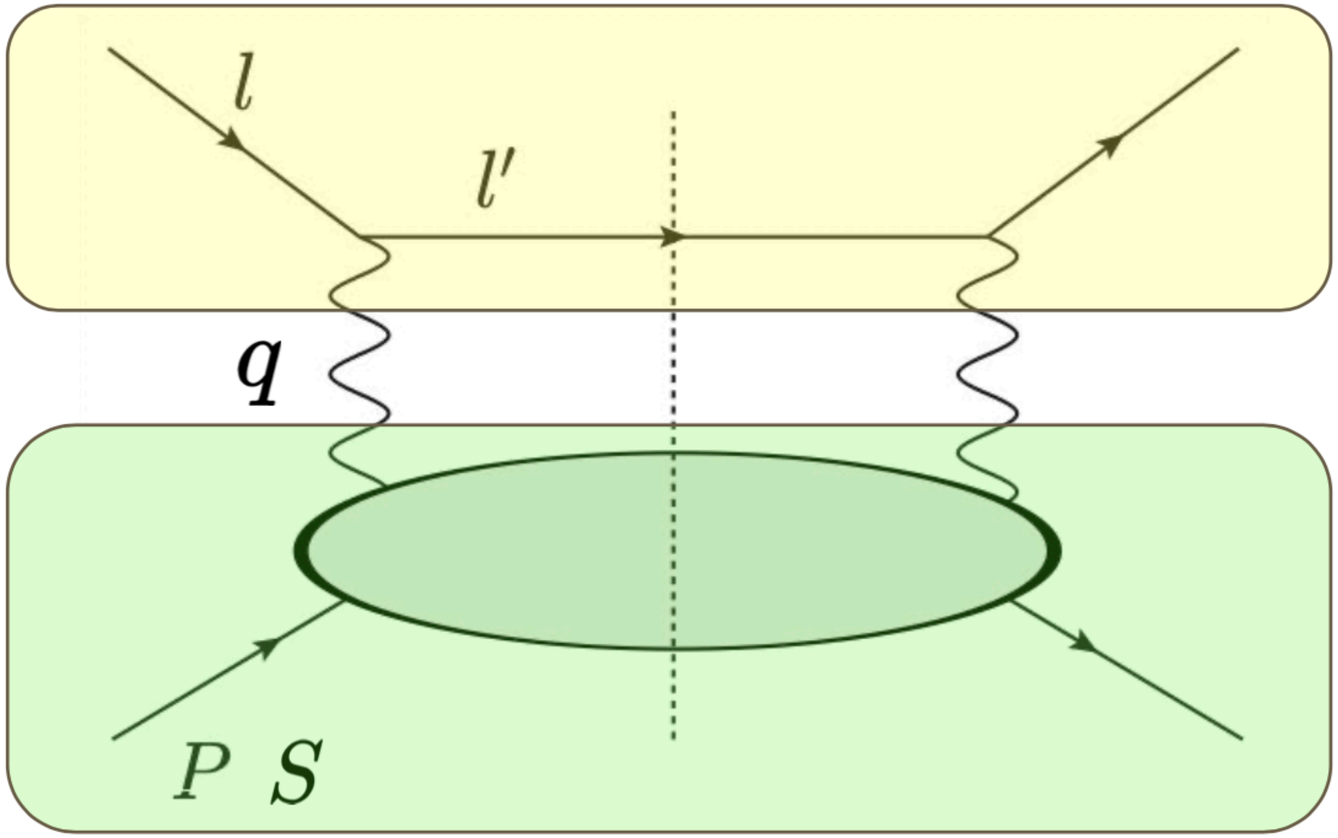
- If we accept strong P- violation in the decomposition of the partonic correlator, we obtain new PV PDFs
- In this assumption, a new structure function in DIS cross section for one-photon exchange is generated
- A fit of present experimental data is compatible with a non-zero contribution from a new strong PV parton density
- Improvements in the theoretical framework of our analysis are surely needed to obtain more and more accurate results

Backup

DIS Cross Section

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

Leptonic tensor - QED
(completely
calculable)



Hadronic tensor - QCD
(NOT completely
calculable)

J. Collins, "Foundation of Perturbative QCD"

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)

Hadronic Tensor (unpolarized)

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

Dominant contribution on the Light-Cone

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

Hadronic Tensor (unpolarized)

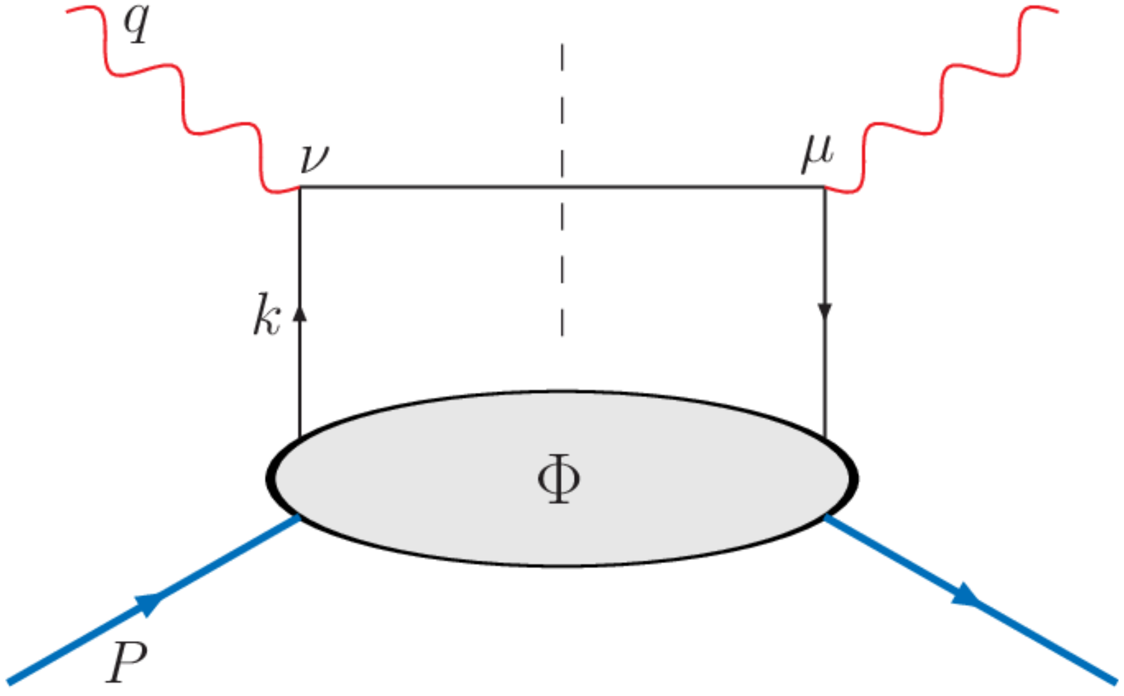
$$2MW_{\mu\nu}(q,P) = \sum_X \int \frac{d^3 P_X}{2E_X} \delta^4(P+q-P_X) \langle P | J^\dagger_\mu(0) | P_X \rangle \langle P_X | J_\nu(0) | P \rangle$$

↓ Dominant contribution on the Light-Cone

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

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

Hadronic Tensor (unpolarized)

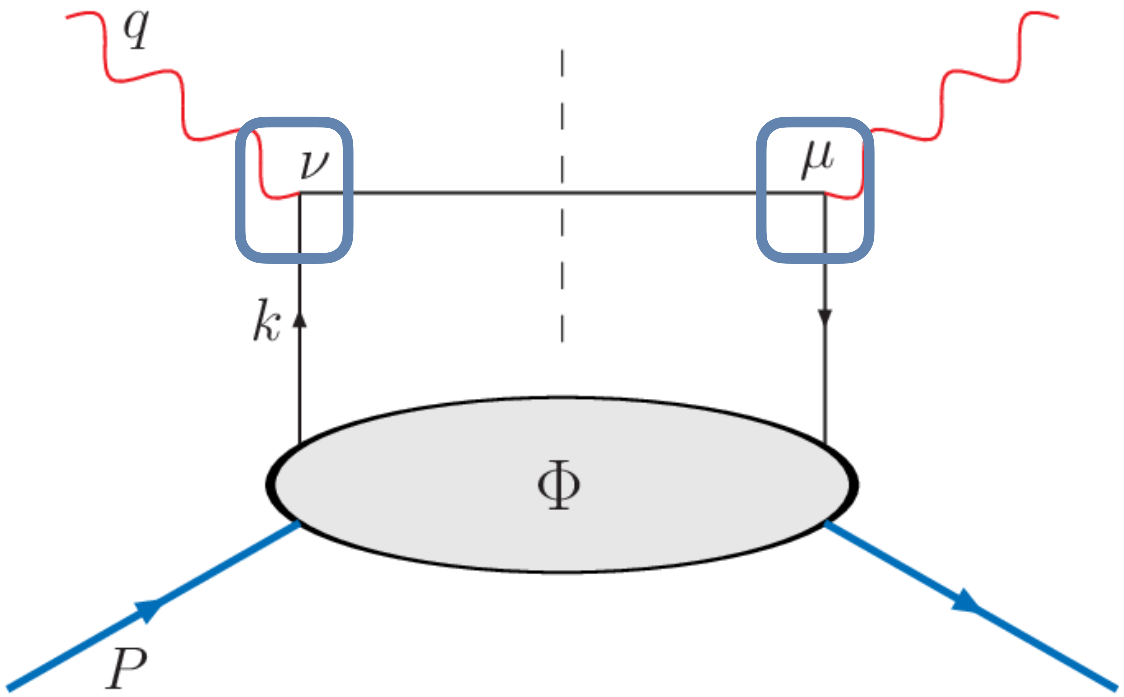


$$2MW^{\mu\nu}(q,P,S) = \sum_q e_q^2 \frac{1}{2} \mathrm{Tr}\left[\Phi(q,P,S)\Gamma^\mu \gamma^+ \Gamma^\nu\right]$$

J. Collins, "Foundation of Perturbative QCD"

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

Hadronic Tensor (unpolarized)

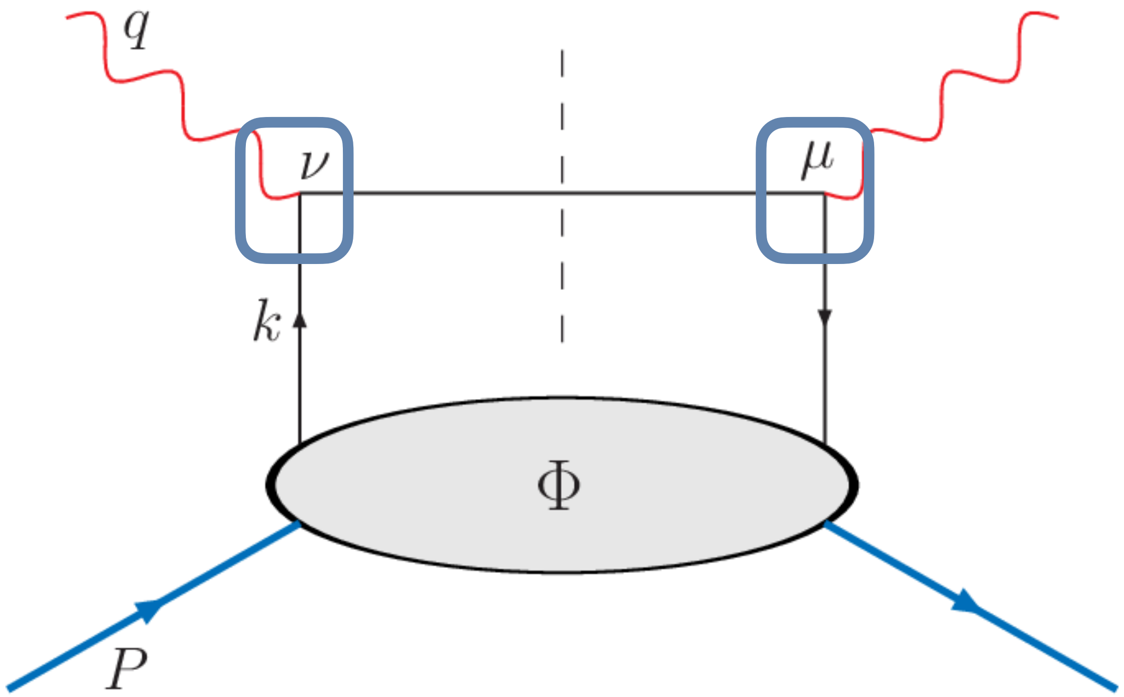


Vertices of the interactions

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

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

Hadronic Tensor (unpolarized)



Vertices of the interactions

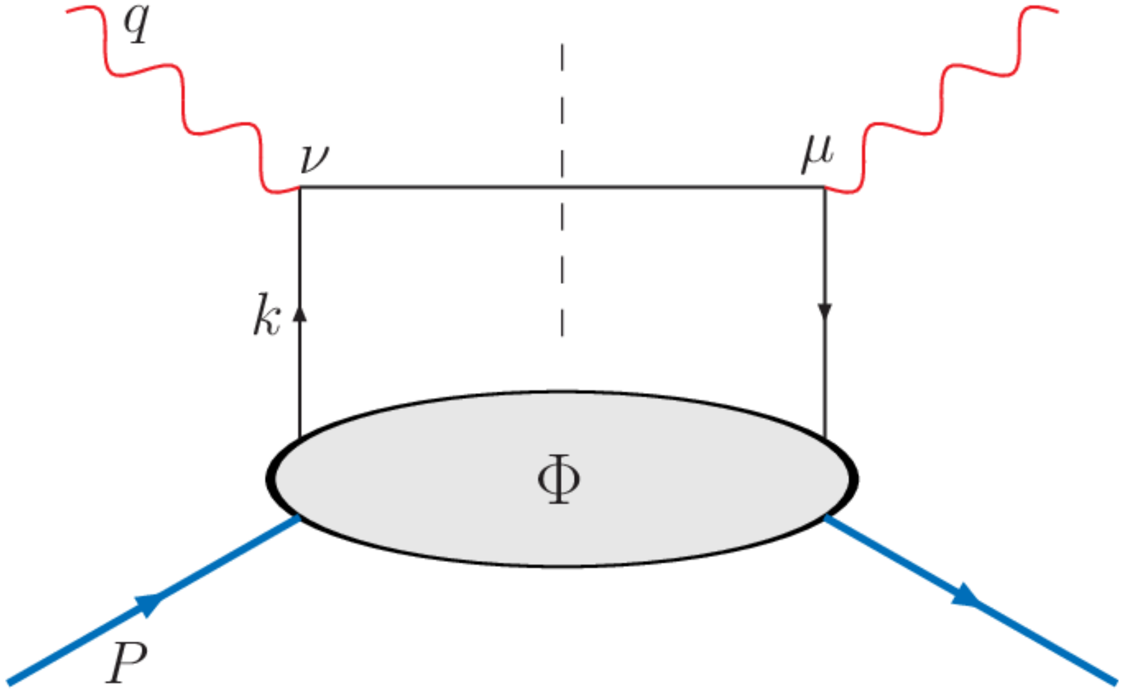
EW P-odd structures already present in the hadronic tensor!

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

J. Collins, “Foundation of Perturbative QCD”

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

Hadronic Tensor (unpolarized)



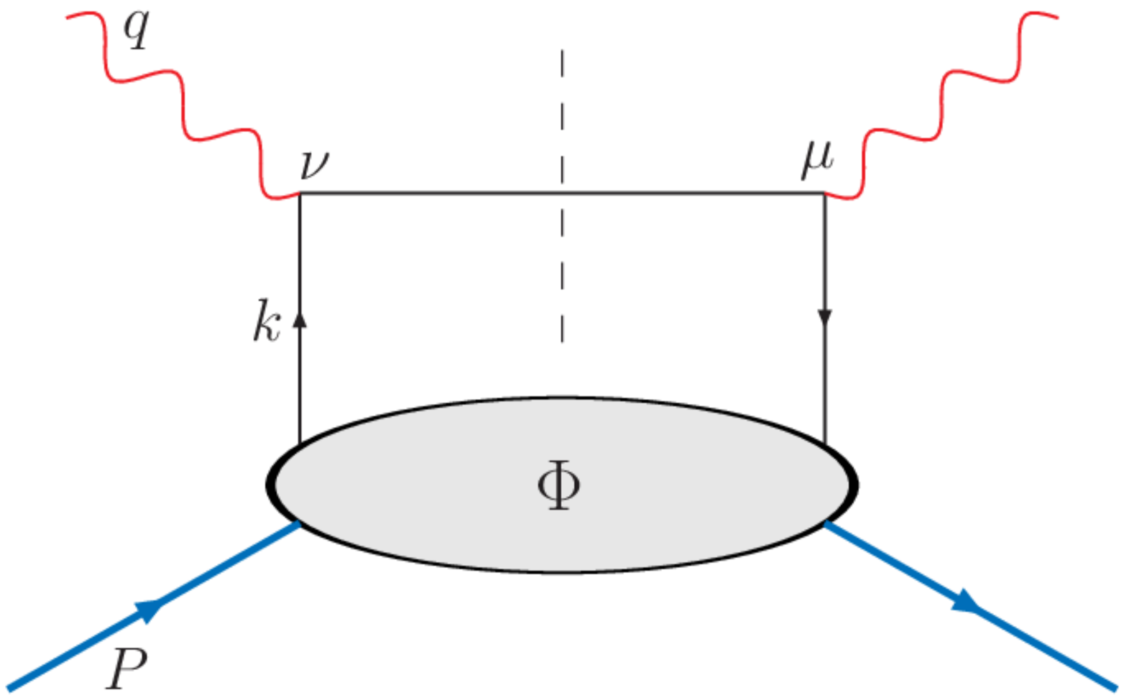
EW P-odd structures already present in the hadronic tensor!

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

Correlation distribution function

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

Hadronic Tensor (unpolarized)



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

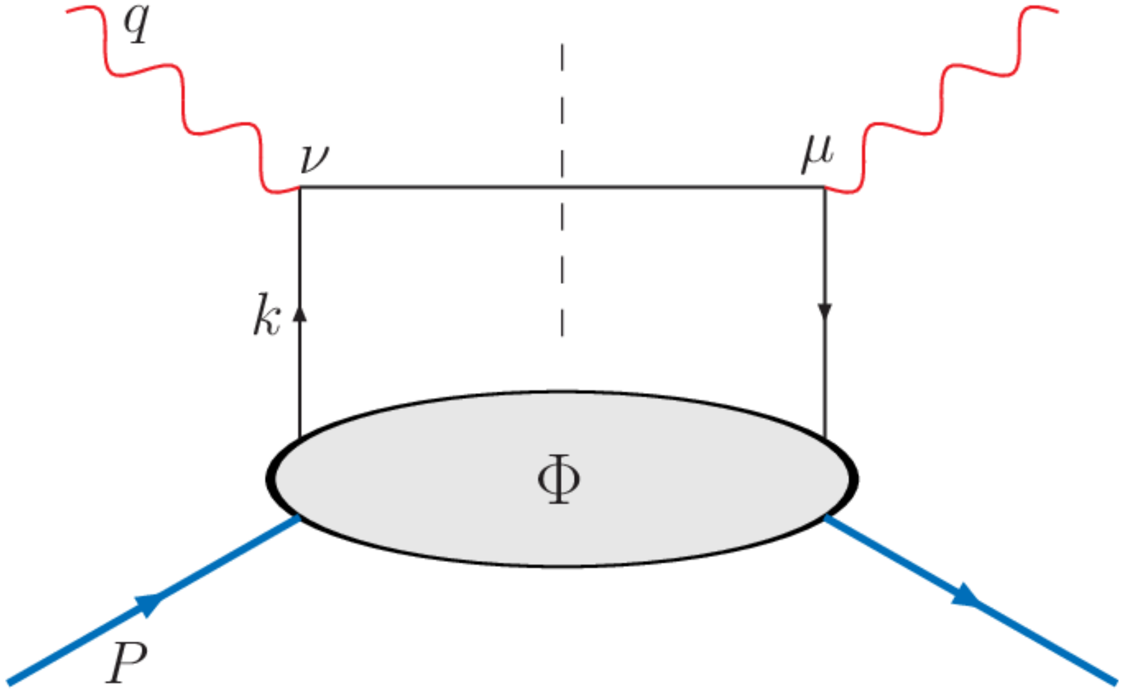
$$2MW^{\mu\nu}(q,P,S) = \sum_q e_q^2 \frac{1}{2} \mathrm{Tr}\left[\Phi(q,P,S)\Gamma^\mu \gamma^+ \Gamma^\nu\right]$$

Correlation distribution function

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

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

Hadronic Tensor (unpolarized)



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

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

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)

Neutral-Current DIS

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

Neutral-Current DIS

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

Standard DIS structure functions

Neutral-Current DIS

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

Standard DIS structure functions

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

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

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

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

Experimental data: energy range

HERA dataset

Experimental data: energy range

HERA dataset $Q^2 \in (200, 30000)\ \mathrm{GeV}^2$

Experimental data: energy range

HERA dataset

$$Q^2 \in (200, 30000)\ \mathrm{GeV}^2$$

high-energy

$Q^2 \gg M_N^2$

no need of modification of the theory

Experimental data: energy range

HERA dataset $Q^2 \in (200, 30000)\ \mathrm{GeV}^2$

high-energy

$Q^2 \gg M_N^2$

no need of modification of the theory

JLab6 + SLAC-E122 datasets

Experimental data: energy range

HERA dataset $Q^2 \in (200, 30000)\ \text{GeV}^2$

high-energy

$Q^2 \gg M_N^2$

no need of modification of the theory

JLab6 + SLAC-E122 datasets $Q^2 \in (0.9, 1.9)\ \text{GeV}^2$

low-energy

$Q^2 \simeq M_N^2$

Experimental data: energy range

HERA dataset $Q^2 \in (200, 30000)\ \text{GeV}^2$

high-energy

$Q^2 \gg M_N^2$

no need of modification of the theory

JLab6 + SLAC-E122 datasets $Q^2 \in (0.9, 1.9)\ \text{GeV}^2$

low-energy

$Q^2 \simeq M_N^2$

applicability of the theory?

Experimental data: energy range

HERA dataset $Q^2 \in (200, 30000)\ \mathrm{GeV}^2$

high-energy

$Q^2 \gg M_N^2$

no need of modification of the theory

JLab6 + SLAC-E122 datasets $Q^2 \in (0.9, 1.9)\ \mathrm{GeV}^2$

low-energy

$Q^2 \simeq M_N^2$

applicability of the theory?

Target-Mass Corrections

e.g., A. Bacchetta et al., JHEP 02 (2007)

Experimental data: energy range

HERA dataset

$Q^2 \in (200, 30000)$ GeV^2

high-energy

$Q^2 \gg M_N^2$

no need of modification of the theory

JLab6 + SLAC-E122 datasets

$Q^2 \in (0.9, 1.9)$ GeV^2

low-energy

$Q^2 \simeq M_N^2$

applicability of the theory?

Target-Mass Corrections

e.g., A. Bacchetta et al., JHEP 02 (2007)

EW radiative corrections

J. Erler, S. Su, Prog.Part.Nucl.Phys. 71 (2013)

Experimental data: energy range

HERA dataset

$Q^2 \in (200, 30000)\ \mathrm{GeV}^2$

high-energy

$Q^2 \gg M_N^2$

no need of modification of the theory

JLab6 + SLAC-E122 datasets

$Q^2 \in (0.9, 1.9)\ \mathrm{GeV}^2$

low-energy

$Q^2 \simeq M_N^2$

applicability of the theory?

Target-Mass Corrections

e.g., A. Bacchetta et al., JHEP 02 (2007)

EW radiative corrections

J. Erler, S. Su, Prog.Part.Nucl.Phys. 71 (2013)

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

Experimental data: energy range

HERA dataset

$Q^2 \in (200, 30000)\ \mathrm{GeV}^2$

high-energy

$Q^2 \gg M_N^2$

no need of modification of the theory

JLab6 + SLAC-E122 datasets

$Q^2 \in (0.9, 1.9)\ \mathrm{GeV}^2$

low-energy

$Q^2 \simeq M_N^2$

applicability of the theory?

Target-Mass Corrections

e.g., A. Bacchetta et al., JHEP 02 (2007)

EW radiative corrections

J. Erler, S. Su, Prog.Part.Nucl.Phys. 71 (2013)

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

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

Impact of future data

Electron-Ion Collider (EIC)

Abdul Khalek, et al., Nucl. Phys. A 1026 (2022)
Boughezal, Emmert, Kutz, et al., PRD 106 (2022)

Impact of future data

Electron-Ion Collider (EIC)

Abdul Khalek, et al., Nucl. Phys. A 1026 (2022)
Boughezal, Emmert, Kutz, et al., PRD 106 (2022)

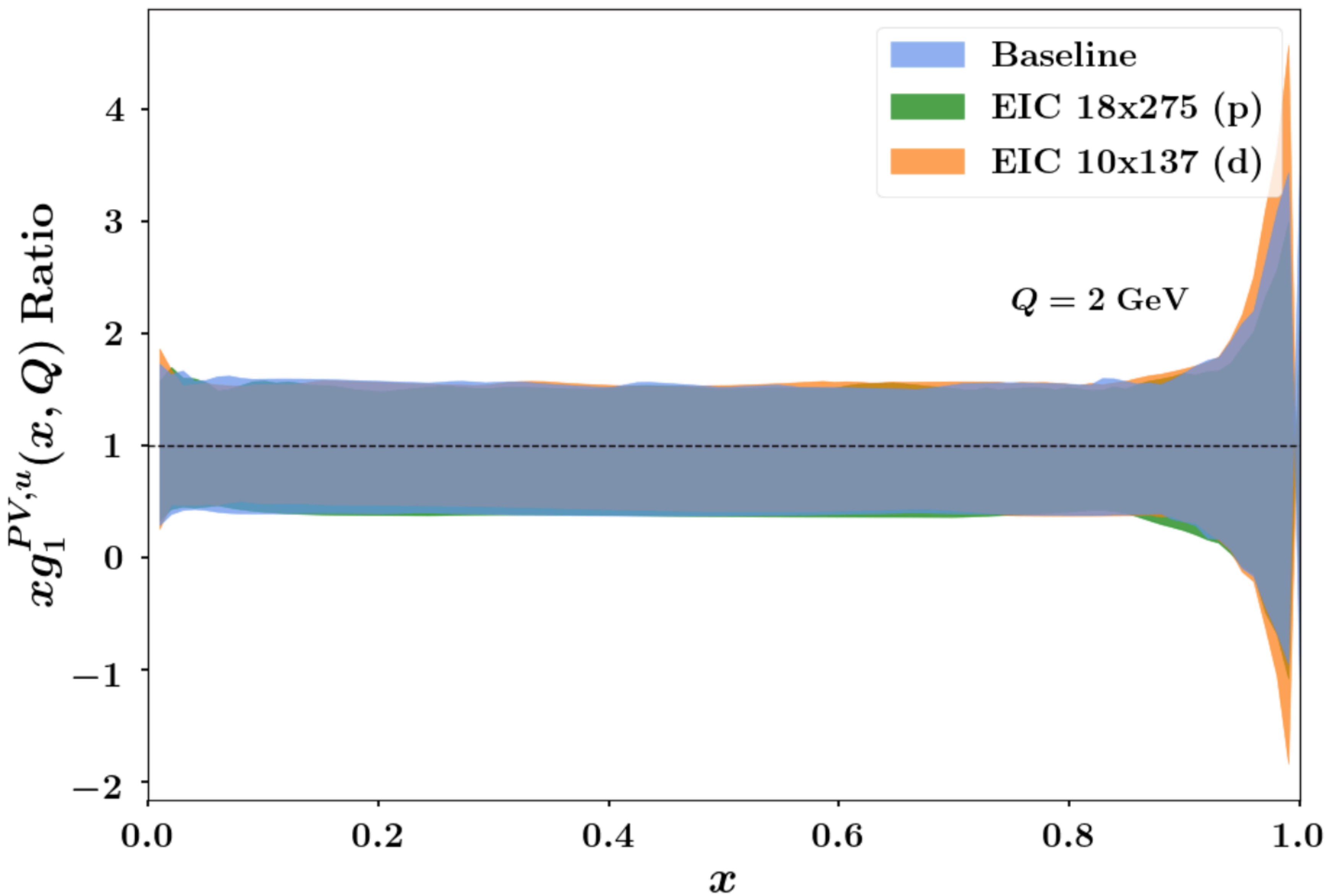
Baseline $\alpha = (-1.01 \pm 0.66) \cdot 10^{-4}$

Impact of future data

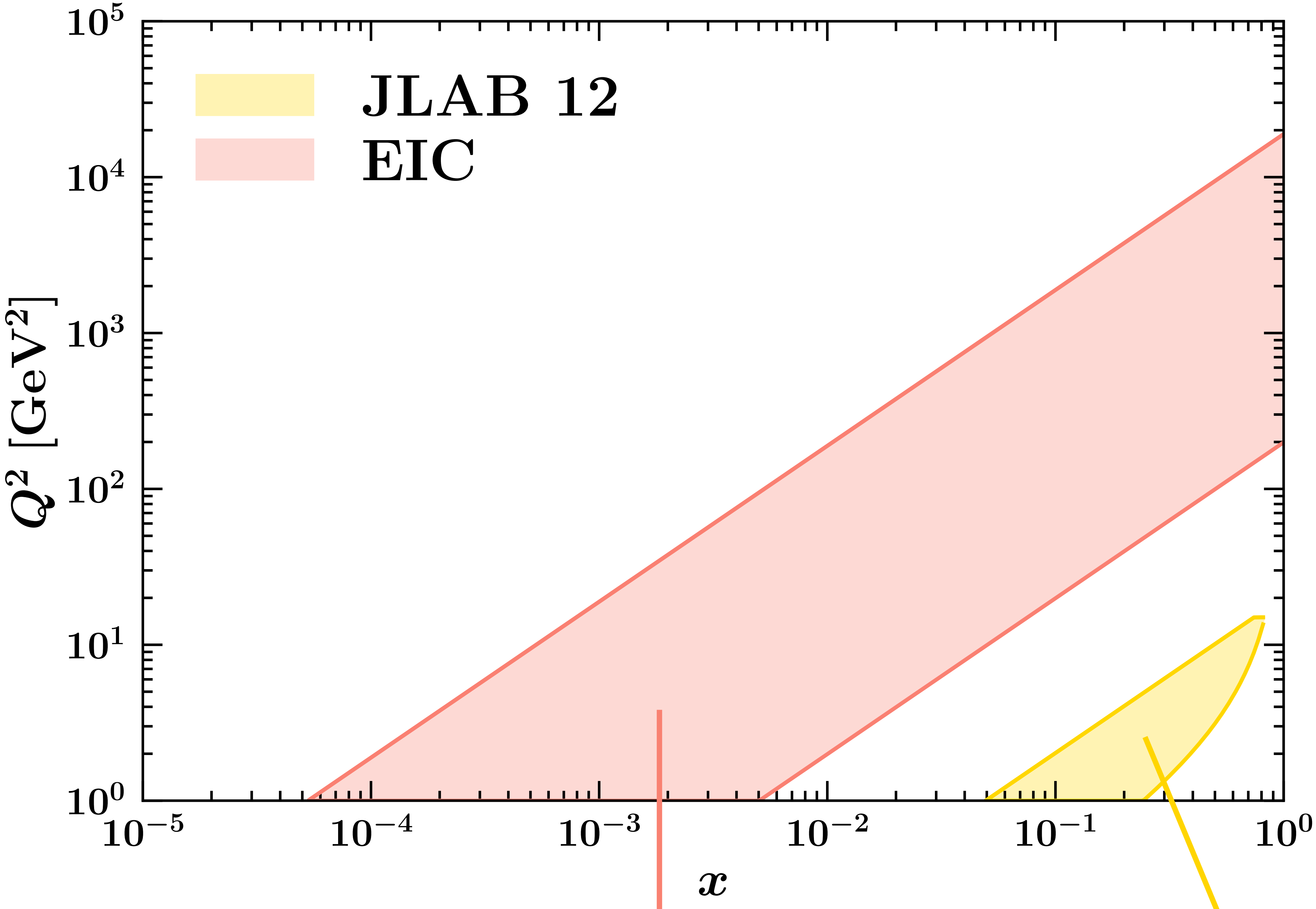
Electron-Ion Collider (EIC)

Abdul Khalek, et al., Nucl. Phys. A 1026 (2022)
Boughezal, Emmert, Kutz, et al., PRD 106 (2022)

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



Impact of future data



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

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