Probing nucleon spin structure with inclusive DIS at the EIC

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with

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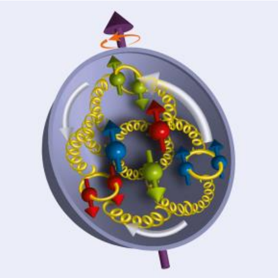
Thanks to everyone who worked on the ATHENA proposal!

Polarized PDFs and the Spin of the Proton

Proton spin

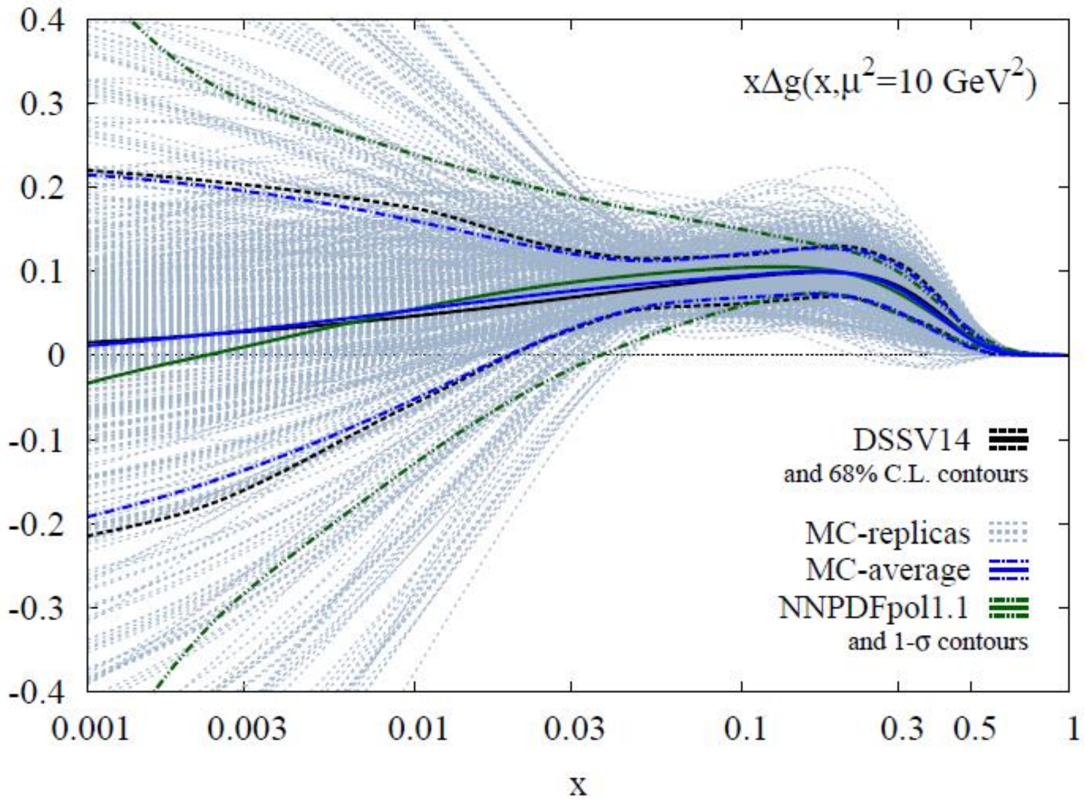


$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_Q + L_G$$

$$\Delta\Sigma = \Delta u + \Delta\bar{u} + \Delta d + \Delta\bar{d} + \Delta s + \Delta\bar{s} + \ldots$$

$$\Delta q = q^{\uparrow} - q^{\downarrow} \qquad \Delta q = \int \Delta q(x)dx$$

Phys. Rev. D **100**, 114027

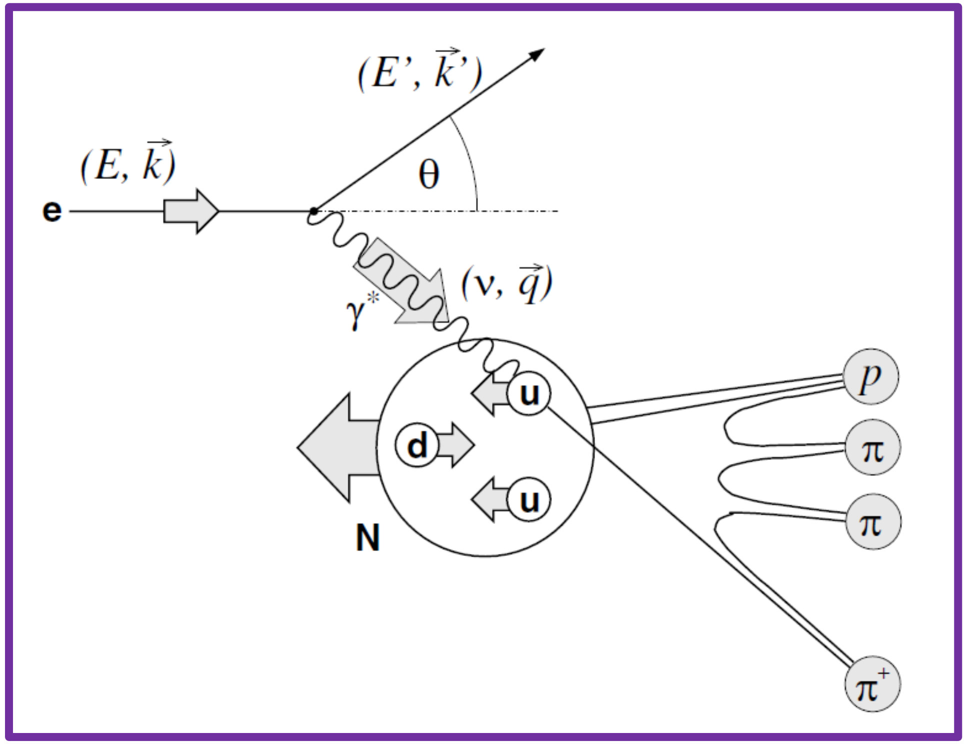


Quark spin only accounts for a portion of the proton's spin

Large uncertainty on polarized gluon PDF

Experimental channels for studying Polarized PDFs

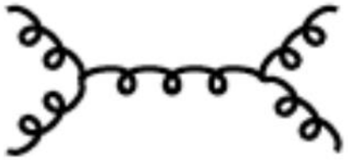
Inclusive and semi-inclusive lepton-proton (light nucleus) scattering, with longitudinally polarized proton (or light nucleus)



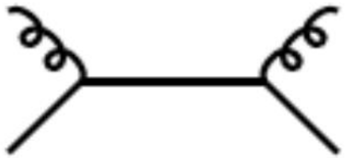
Hard proton-proton scattering with longitudinally polarized proton beams

$$p + p \to \pi + X$$

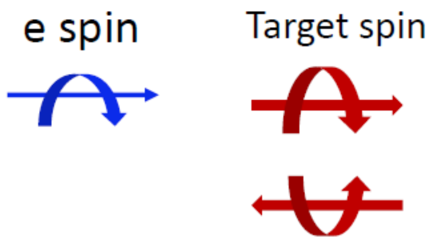
$$g + g \to g + g$$



$$q + g \to q + g$$



NC e-p cross section with Longitudinally Polarized Protons



At high Q², for electron-proton scattering:

$$\Delta\sigma = \frac{d^2\sigma}{dxdQ^2}(\lambda_n = -1, \lambda_l) - \frac{d^2\sigma}{dxdQ^2}(\lambda_n = +1, \lambda_l) = \frac{4\pi\alpha^2}{Q^4 x}\left[-Y_+ g_4 + Y_- 2x g_1 + y^2 g_L\right]$$

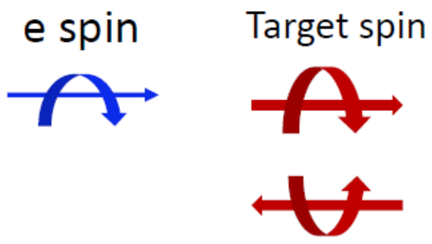
$$g_1 = -\lambda_l g_1^\gamma + \eta_z\left(\lambda_l g_v^e - g_A^e\right) g_1^{\gamma z} + \eta_z^2\left[-\lambda_l\left(\left(g_v^e\right)^2 + \left(g_A^e\right)^2\right) + 2 g_A^e g_v^e\right] g_1^z$$

$$g_{4,5} = \eta_z\left(g_v^e - \lambda_l g_A^e\right) g_{4,5}^{\gamma z} + \eta_z^2\left[-\left(g_v^e\right)^2 - \left(g_A^e\right)^2 + 2\lambda_l g_A^e g_v^e\right] g_{4,5}^z$$

$$\begin{cases} Y_\pm = 1 \pm (1-y)^2 \\ g_L = g_4 - 2x g_5 \end{cases}$$

Prog. Theor. Exp. Phys. 2020, 083C01 (2020)

NC e-p cross section with Longitudinally Polarized Protons



At high Q^2, for electron-proton scattering:

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$$g_1 = -\lambda g_1^{\gamma} + \eta_z \left(\lambda_l g_v^e - g_A^e\right) g_1^{\gamma z} + \eta_z^2 \left[-\lambda_l \left((g_v^e)^2 + (g_A^e)^2\right) + 2 g_A^e g_v^e\right] g_1^z$$

For non-zero electron beam polarization, this term dominates

$$g_{4,5} = \eta_z \left(g_v^e - \lambda_l g_A^e\right) g_{4,5}^{\gamma z} + \eta_z^2 \left[-(g_v^e)^2 - (g_A^e)^2 + 2\lambda_l g_A^e g_v^e\right] g_{4,5}^z$$

$$\begin{cases} Y_\pm = 1 \pm (1-y)^2 \\ g_L = g_4 - 2x g_5 \end{cases}$$

Prog. Theor. Exp. Phys. 2020, 083C01 (2020)

Measuring the g_1 structure function

At high Q^2, for an electron with λ=-1:

$$\Delta\sigma \approx \frac{4\pi\alpha^2}{Q^4 x}\left(Y\_2xg_1^\gamma\right)$$

$$A_{||} = \frac{\sigma\left(\lambda_n=-1,\lambda_l=-1\right)-\sigma\left(\lambda_n=+1,\lambda_l=-1\right)}{\sigma\left(\lambda_n=-1,\lambda_l=-1\right)+\sigma\left(\lambda_n=+1,\lambda_l=-1\right)} \approx \frac{Y_-}{Y_+}A_1$$

Depolarization factor

$$A_{\gamma * p} = A_1 = \frac{\sigma_{1/2}-\sigma_{3/2}}{\sigma_{1/2}+\sigma_{3/2}} = \frac{g_1^\gamma}{F_1^\gamma}$$

Prog. Theor. Exp. Phys. 2020, 083C01 (2020)

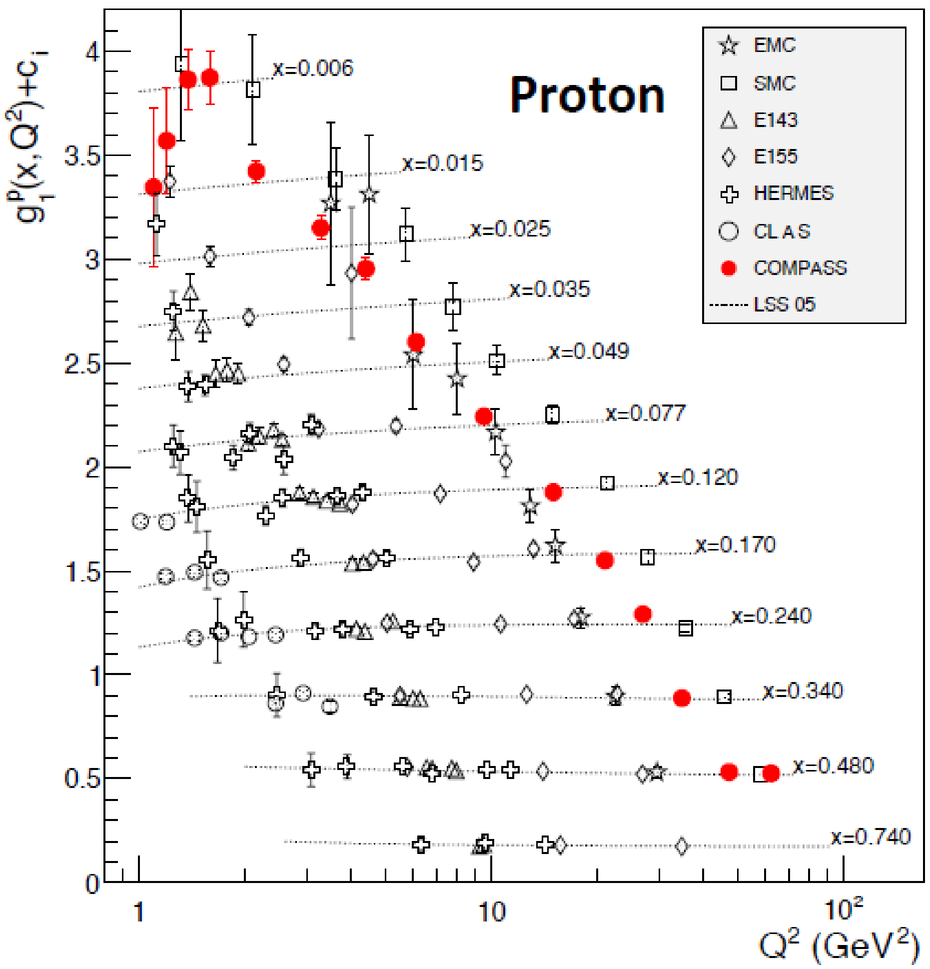
Extraction of polarized PDFs from g_1

$$g_1^{\gamma}(x, Q^2) = \sum_{i=q,g} C_i \otimes \Delta f_i$$

$$= \frac{1}{2} \sum_q e_q^2 \left[\Delta q(x, Q^2) + \Delta \bar{q}(x, Q^2)\right] \quad \textbf{at LO}$$

$$\frac{\partial \Delta f_{i=q,g}}{\partial \ln Q^2} = \sum_j P_{i,j} \otimes \Delta f_j \quad \textbf{DGLAP evolution}$$

Aidala et al.1209.2803v2

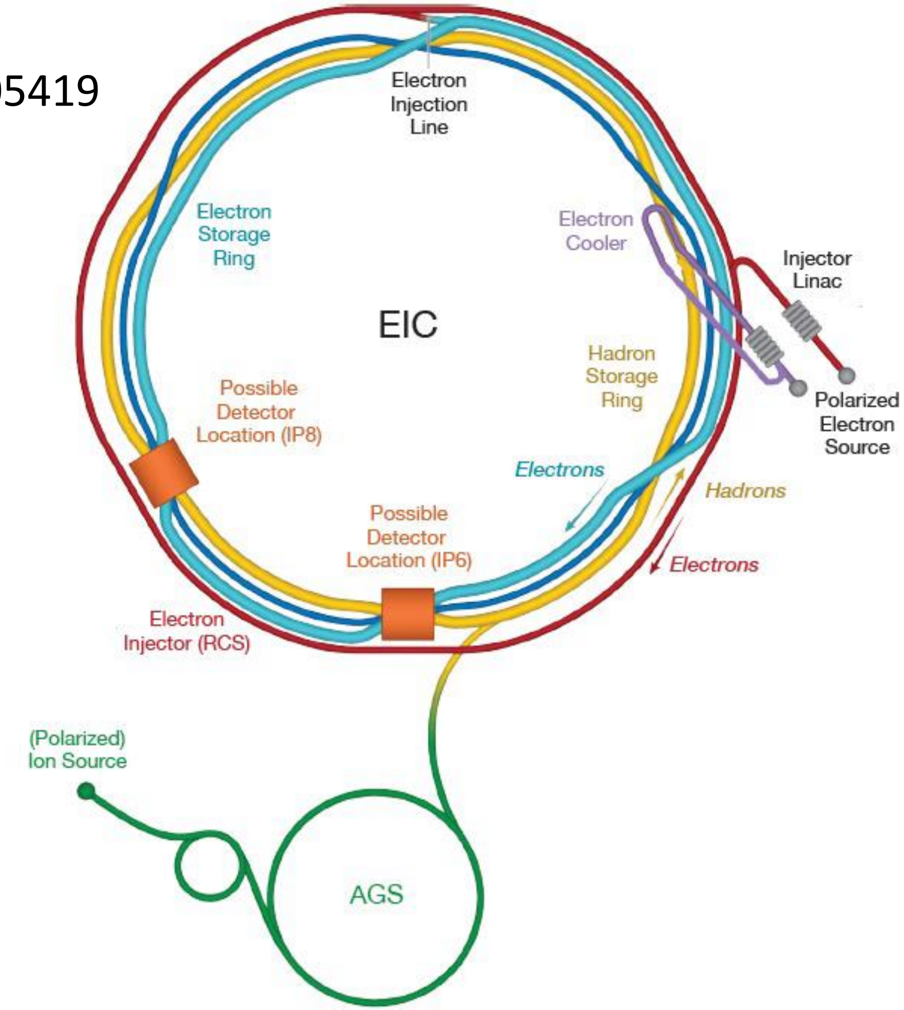


Need measurements at a wide variety of x values and scales (Q^2 values) to constrain the polarized quark and gluon PDFs

Prog. Theor. Exp. Phys. 2020, 083C01 (2020)

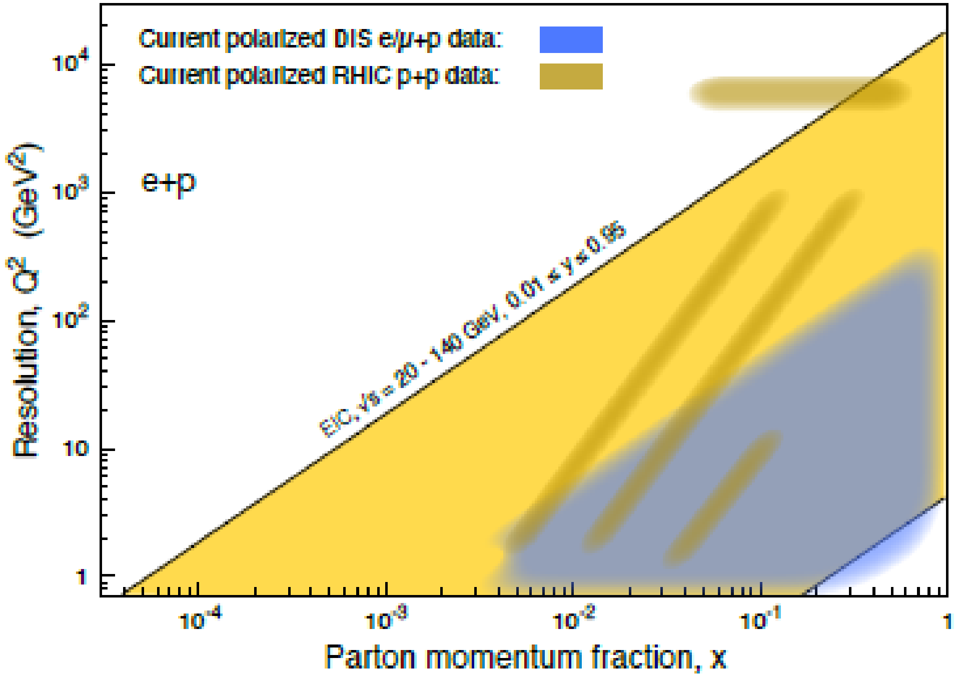
The Electron-Ion Collider (EIC): A next-generation QCD machine

arXiv: 2103.05419

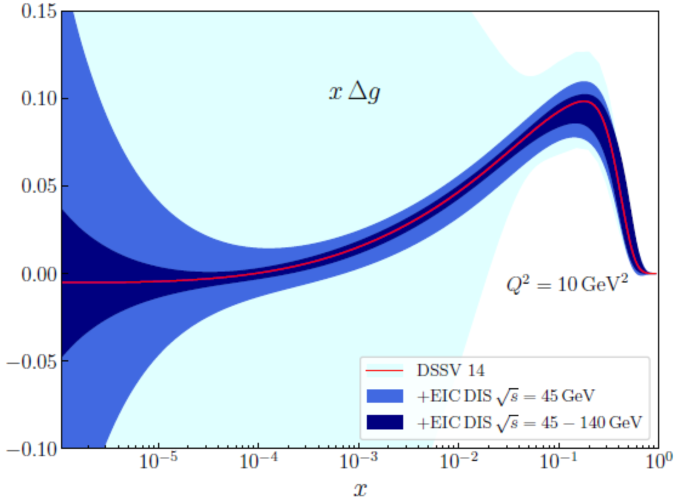


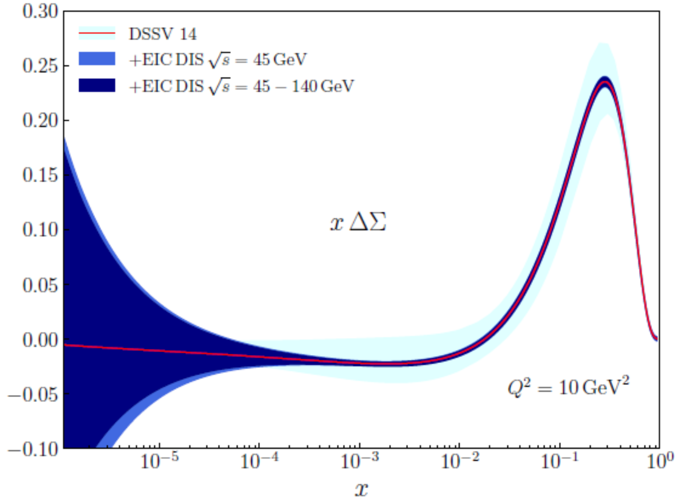
Versatile and with high-luminosity:

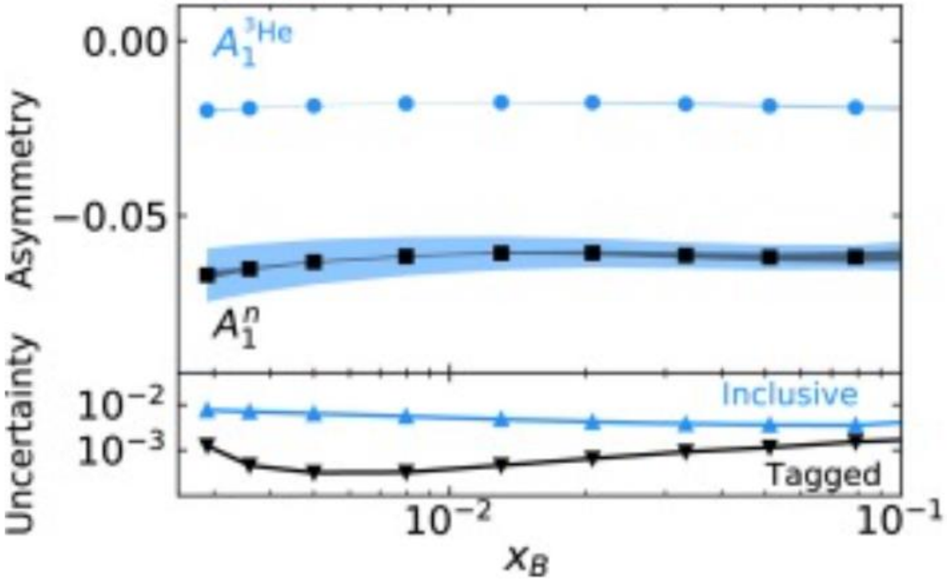
- $\sqrt{s}_{ep}$: 20 – 140 GeV
- Ion beam: Proton to Uranium
- High polarization: $P_{e,p}$ ~ 70%
- $\mathcal{L}_{max} = 10^{34} cm^{-2} s^{-1}$

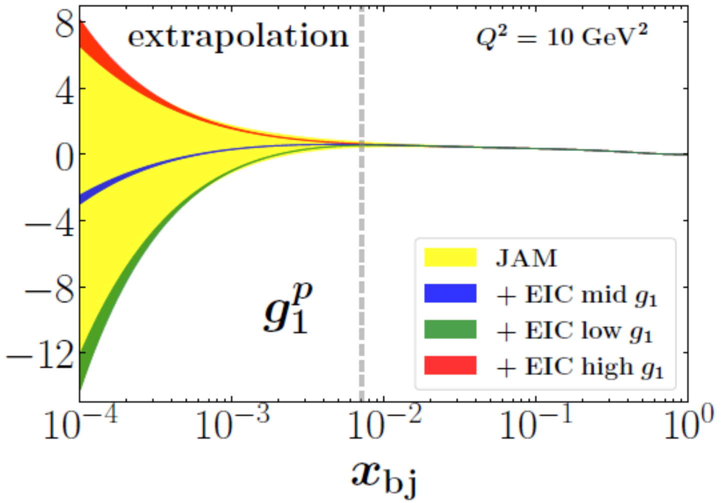


Previous EIC impact studies









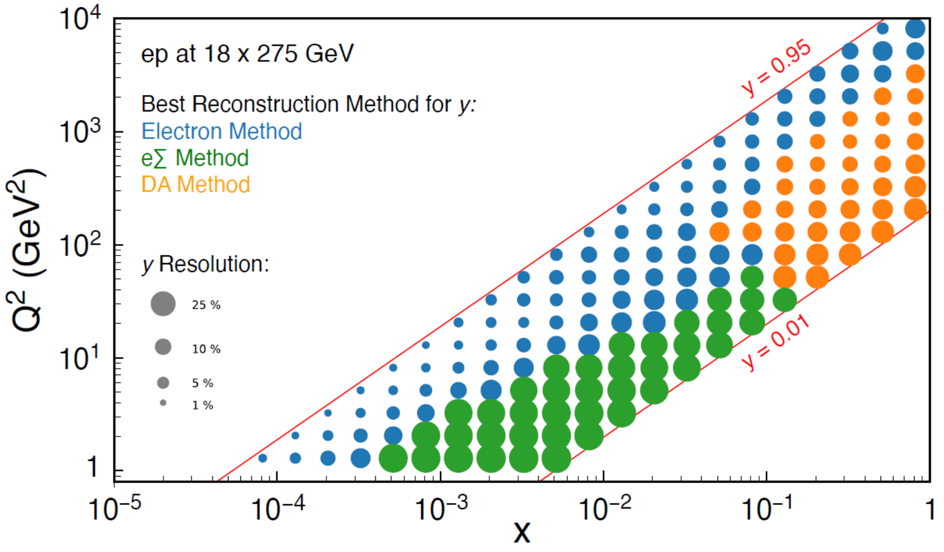
arXiv:2007.08300
arXiv: 2103.05419

Phys.Lett.B 823 (2021) 136726

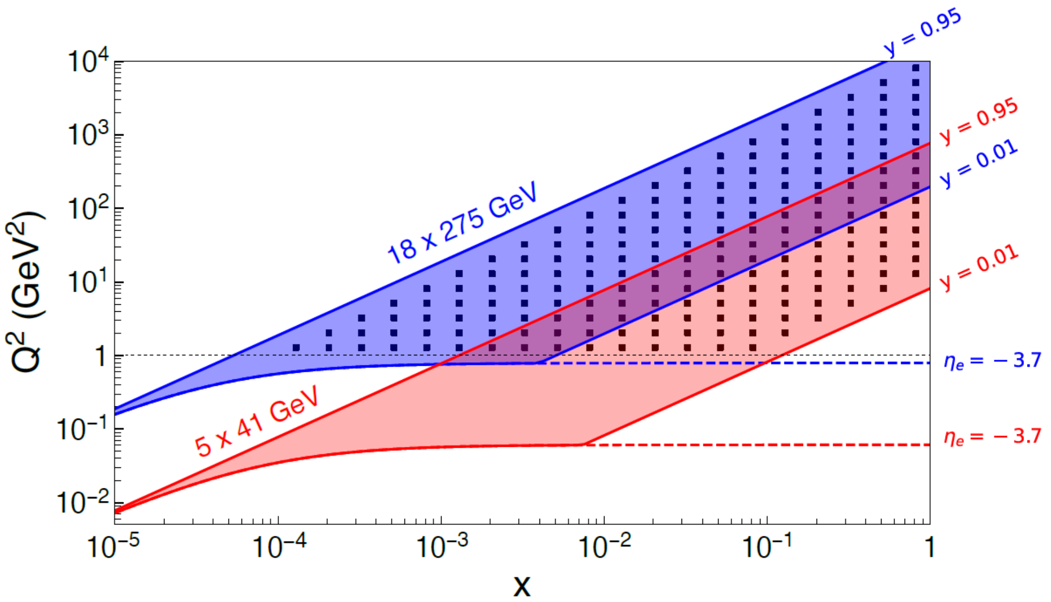
ATHENA@EIC

- ATHENA was one of three detector proposals for the EIC
- The work shown here is based on ATHENA simulation data, but the results are more-or-less equally applicable to any EIC general purpose detector
- Ongoing process to combine ATHENA with ECCE proposal for the detector at the first EIC interaction point

ATHENA input simulation data

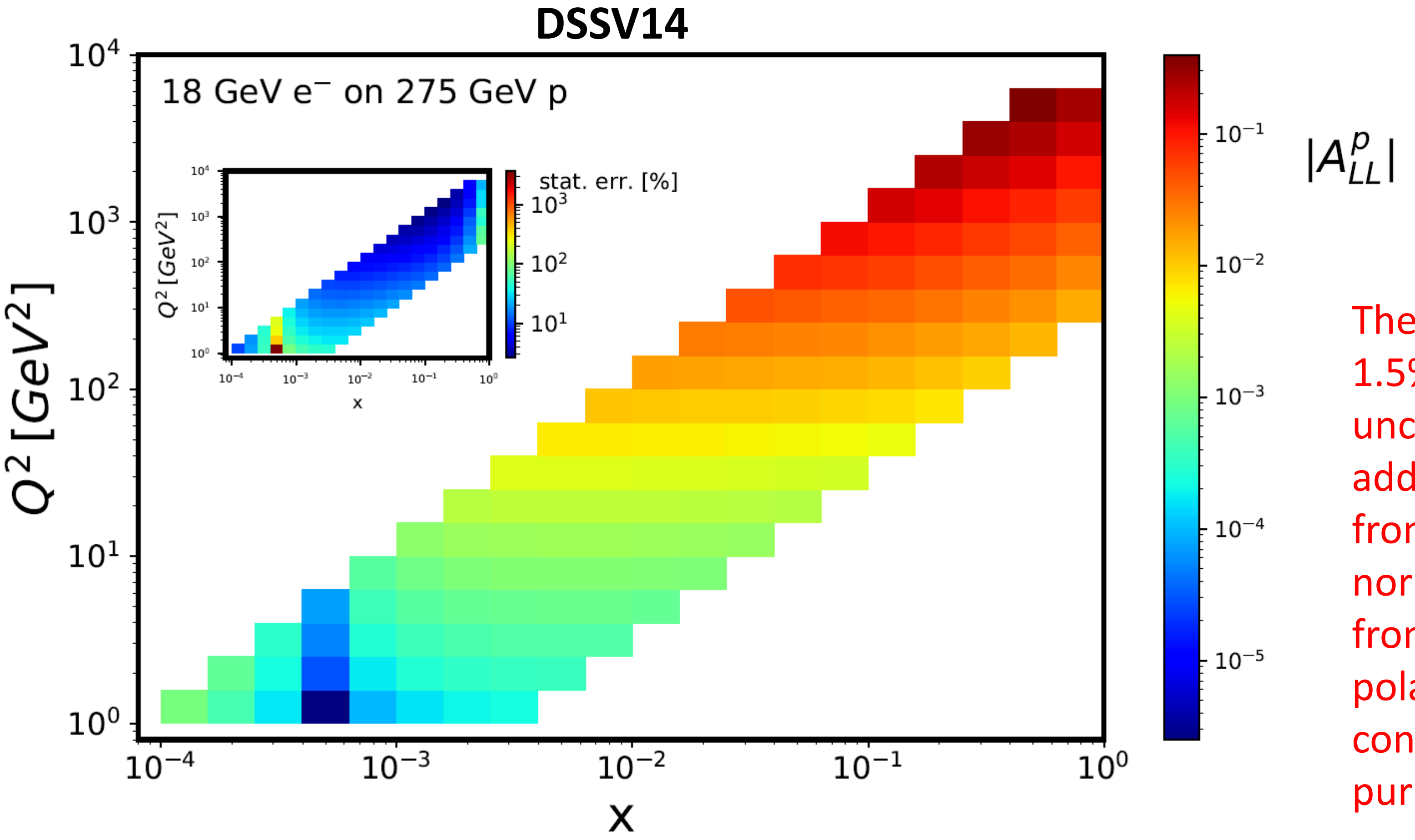


e-beam E	p-beam E	$\sqrt{s}$ (GeV)	inte. Lumi. (fb^{-1})
18	275	140	15.4
10	275	105	100.0
10	100	63	79.0
5	100	45	61.0
5	41	29	4.4



- ❑ Detailed simulation work to obtain optimized resolutions throughout phase-space – 5 bins per decade in both x and Q^2. Kinematic coverage considered is $Q^2 > 1$ GeV^2, $0.01 < y < 0.95$.
- ❑ Our group's studies were done for inclusive electron-proton scattering only.

Statistical and systematic uncertainties

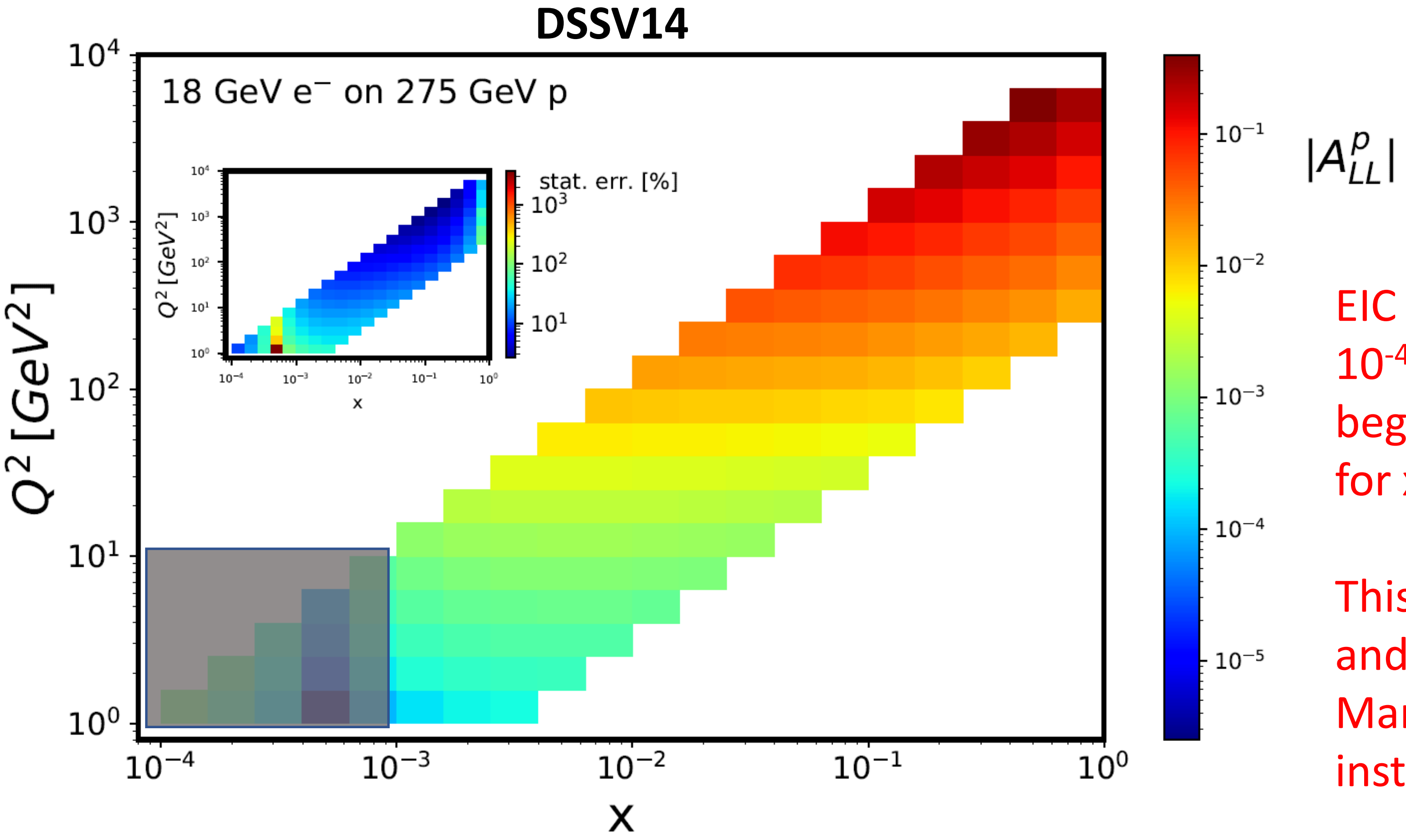


The systematic uncertainty estimation includes 1.5% point-by-point uncorrelated systematic uncertainty, 5% normalization uncertainty, and an additional systematic (shift) uncertainty of 10^{-4} from relative luminosity. The conservative 5% normalization uncertainty includes contributions from electron beam polarization (2%), proton polarization (2%), uncertainty related with pion contamination (3%, assuming 90% electron purity), and 1-2% on detector effects.

Statistical uncertainty on asymmetry measurement:

$$\sigma_{A_{LL}} = \frac{\sqrt{1 - A_{LL,meas}^2}}{P_e P_p \sqrt{N}} \approx \frac{1}{P_e P_p \sqrt{N}}$$

Statistical and systematic uncertainties



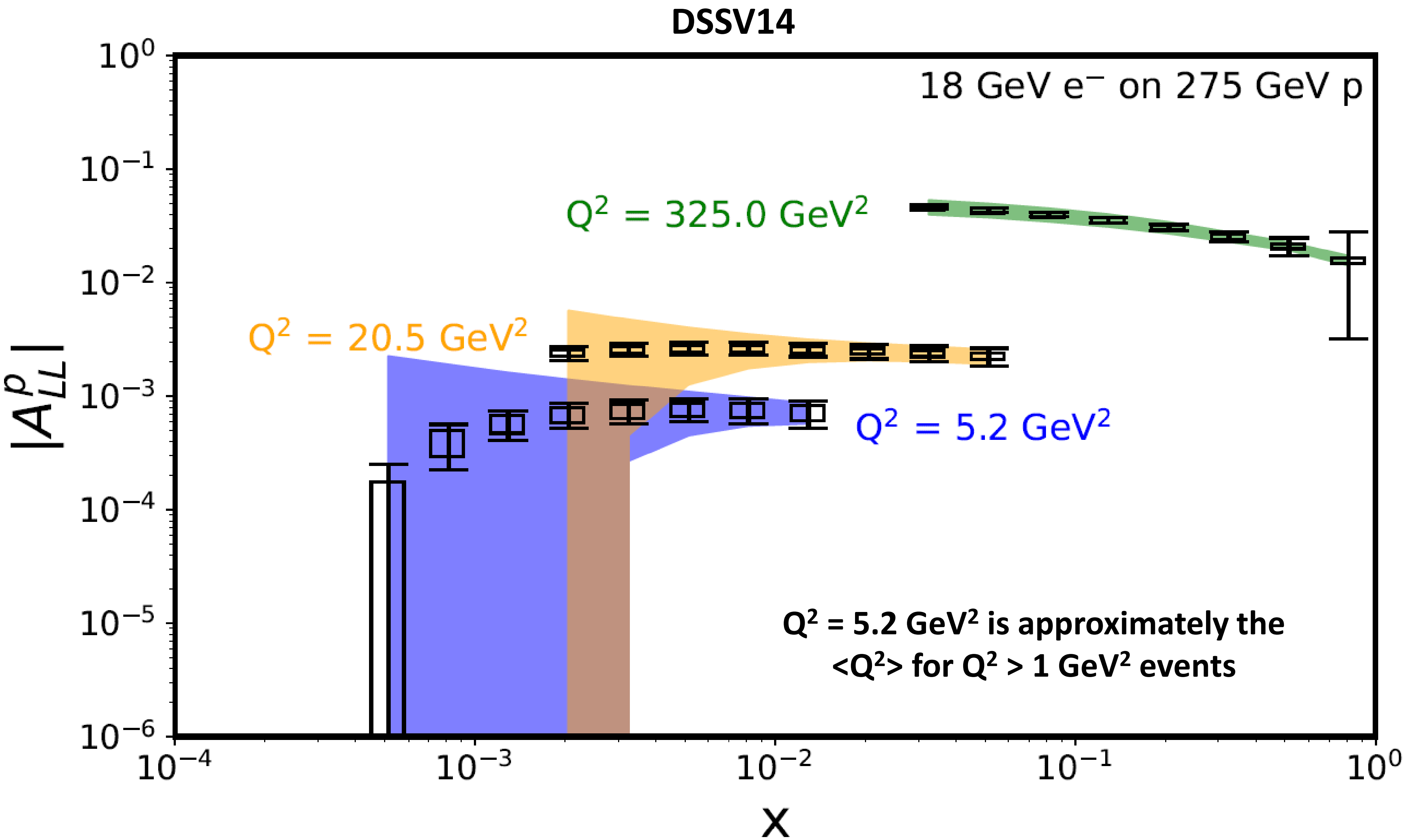
EIC kinematic coverage extends down to x of 10^{-4} for $Q^2 > 1$ GeV^2 …but statistical error begins to approach 100% of the asymmetry for $x < 10^{-3}$.

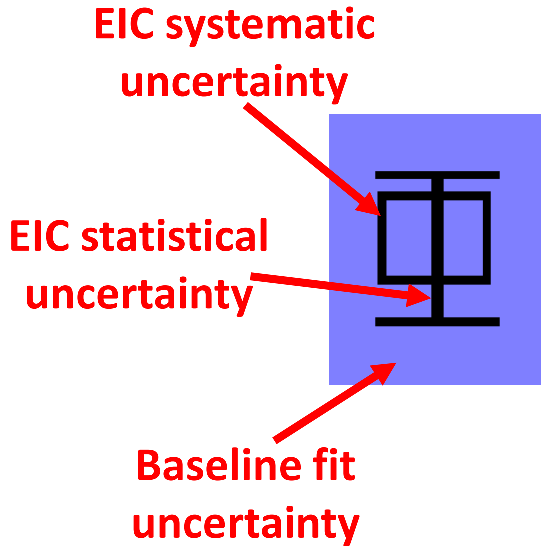
This assumes ~15 fb^{-1} integrated luminosity and 70-80% electron and proton polarization. Many years of running with high instantaneous luminosity can help.

Statistical uncertainty on asymmetry measurement:

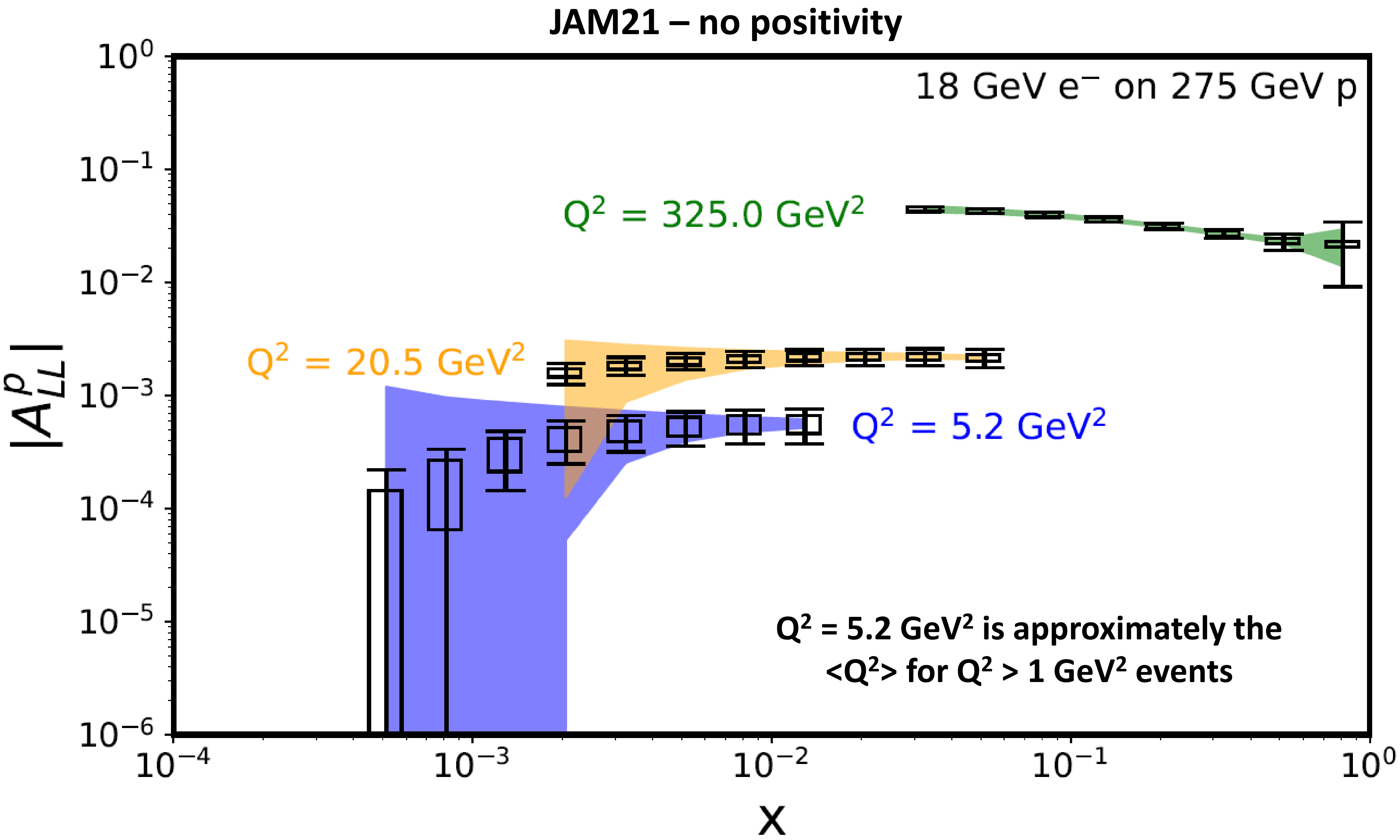
$$\sigma_{A_{LL}} = \frac{\sqrt{1 - A^2_{LL,meas}}}{P_e P_p \sqrt{N}} \approx \frac{1}{P_e P_p \sqrt{N}}$$

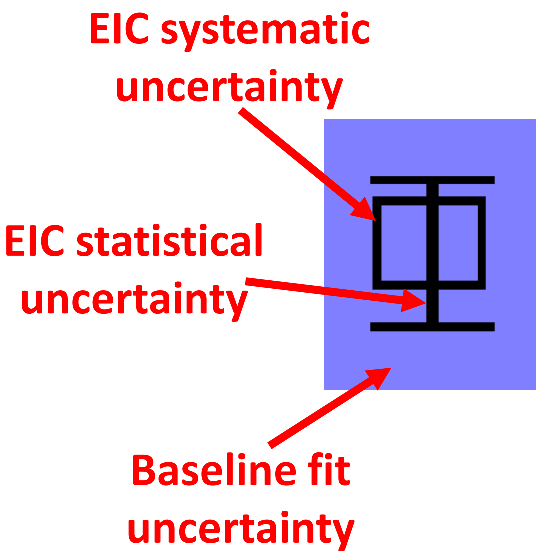
Expected EIC experimental precision



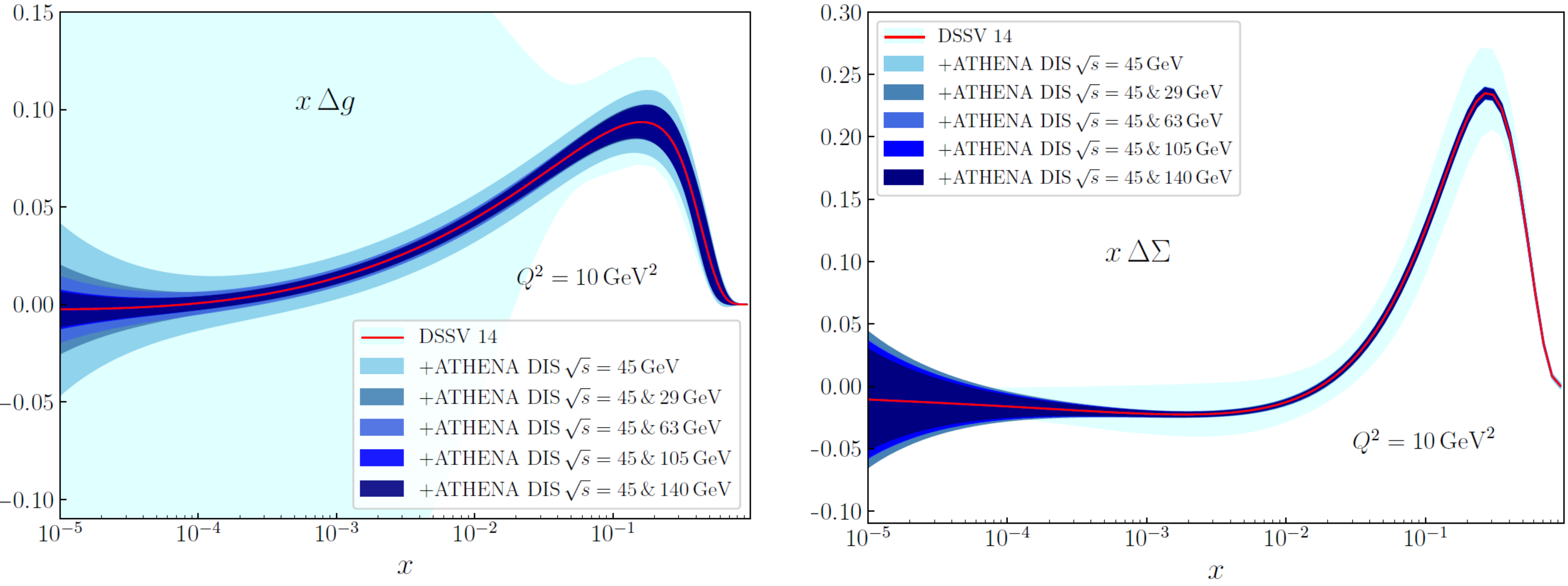


Expected EIC experimental precision



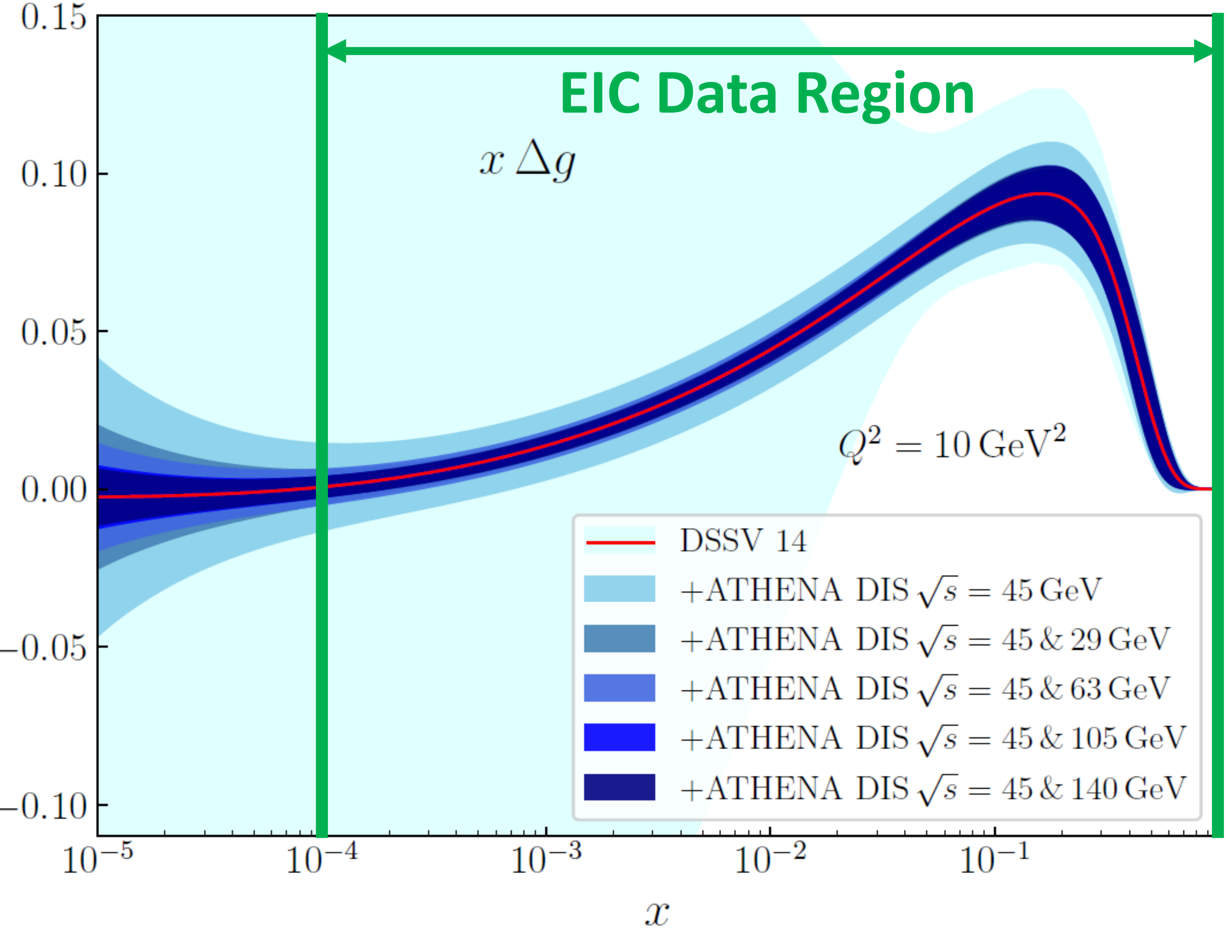


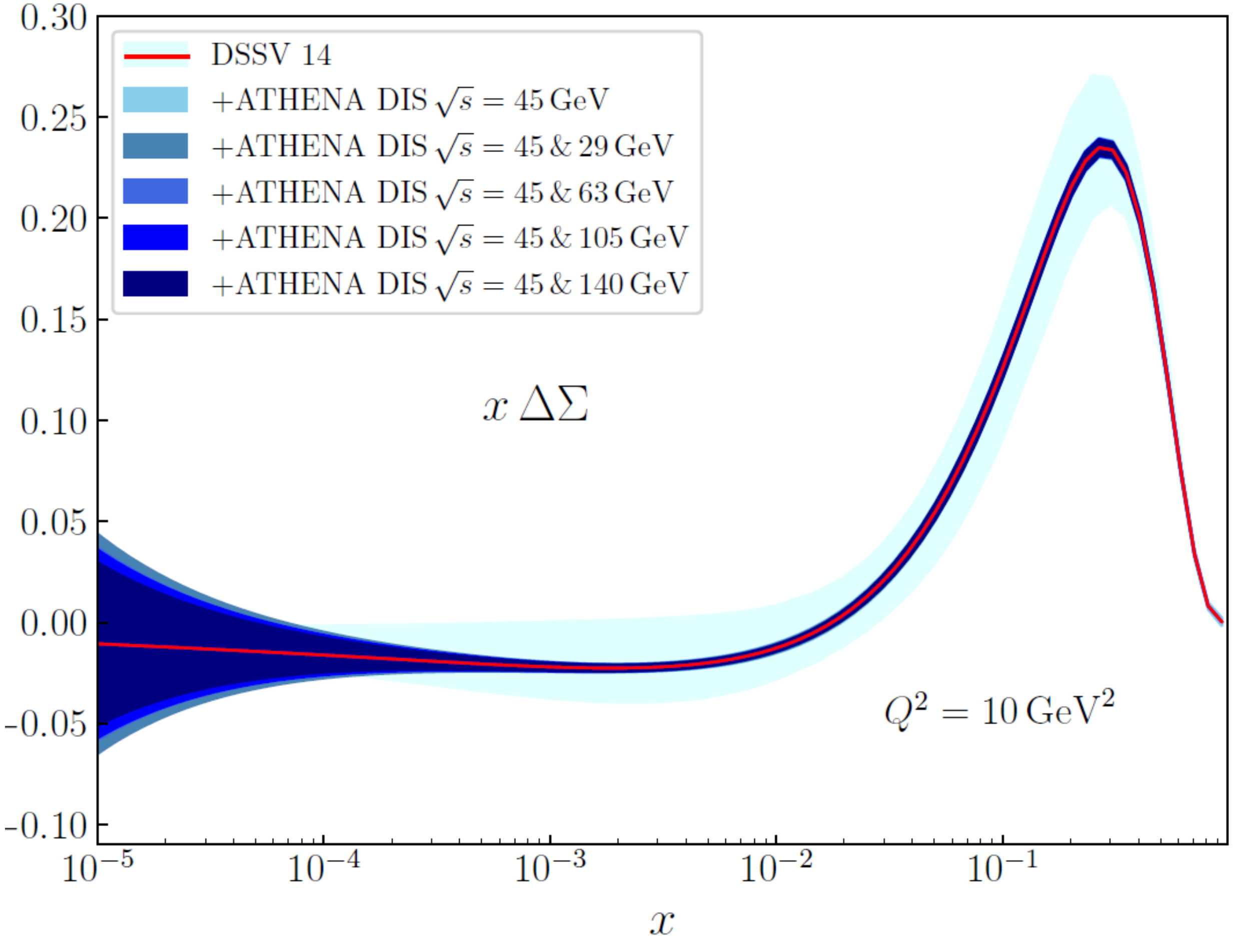
Impact of the EIC on polarized PDFs: **DSSV**



Very significant impact on polarized gluon and quark singlet PDFs using inclusive e-p only!

Impact of the EIC on polarized PDFs: **DSSV**

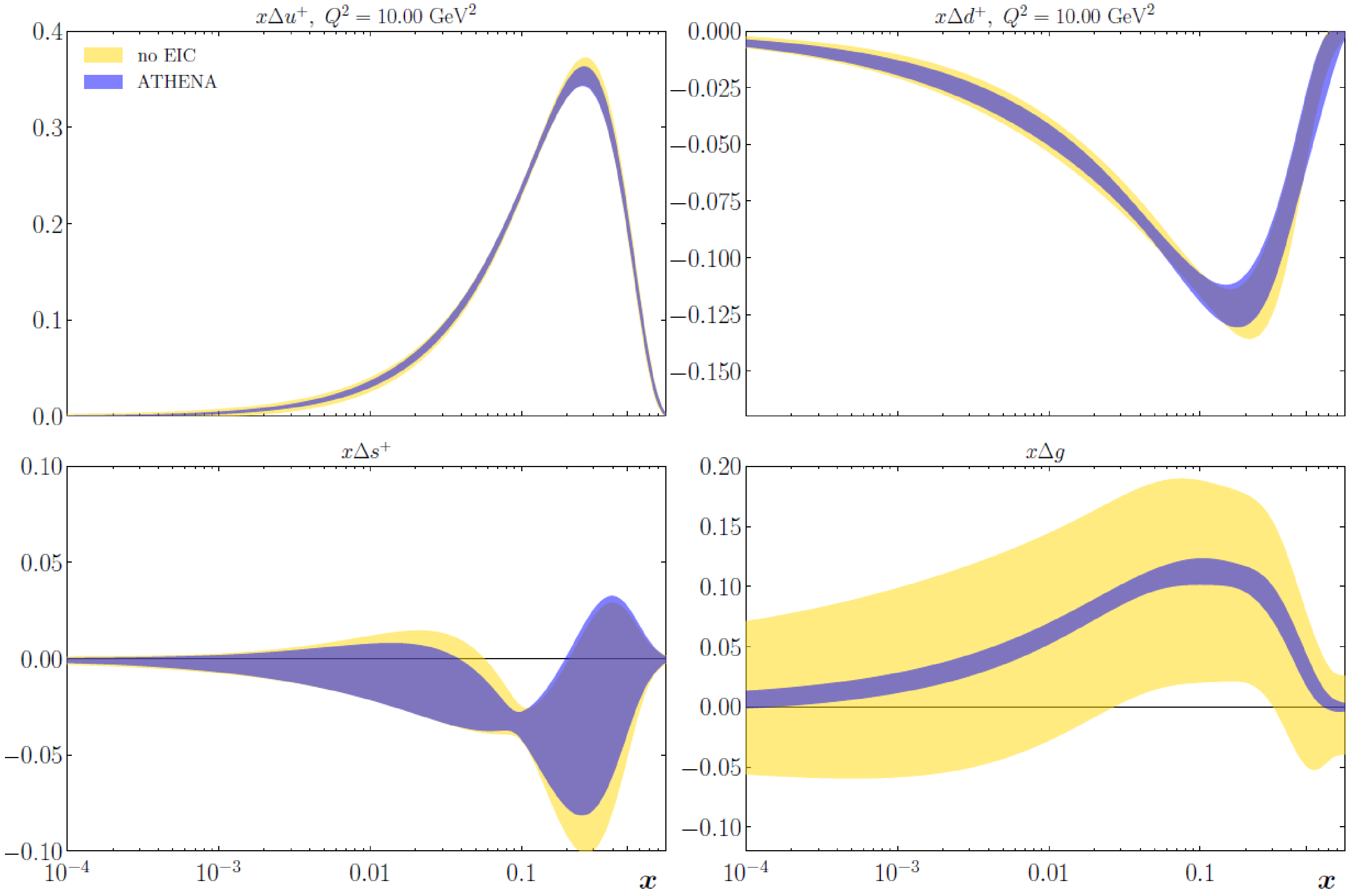




Very significant impact on polarized gluon and quark singlet PDFs using inclusive e-p only!

Impact of the EIC on polarized PDFs: **JAM21 – no positivity**

Also shows very significant impact on polarized gluon PDF and moderate impact on flavor-separated PDFs using only inclusive e-p.

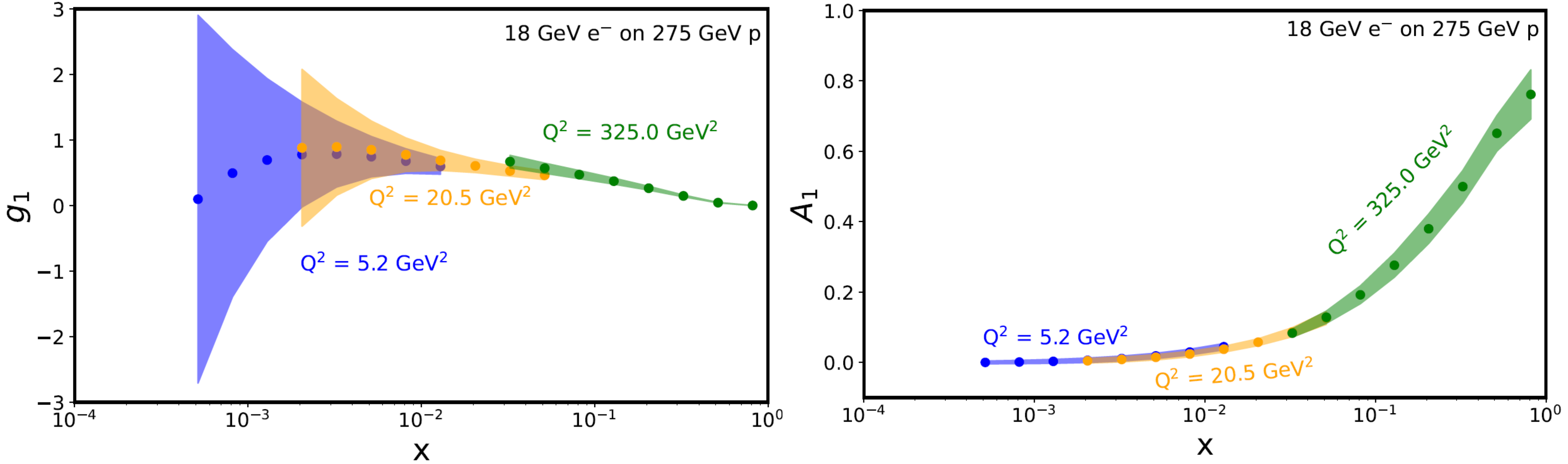


Summary

- The work done during the recent EIC detector proposals allows us to better understand the EIC's potential to study the spin structure of the nucleon.
- Analyses by the DSSV and the JAM collaborations show that inclusive electron-proton scattering at the EIC will constrain the polarized gluon PDF to a remarkable degree.

BACKUP

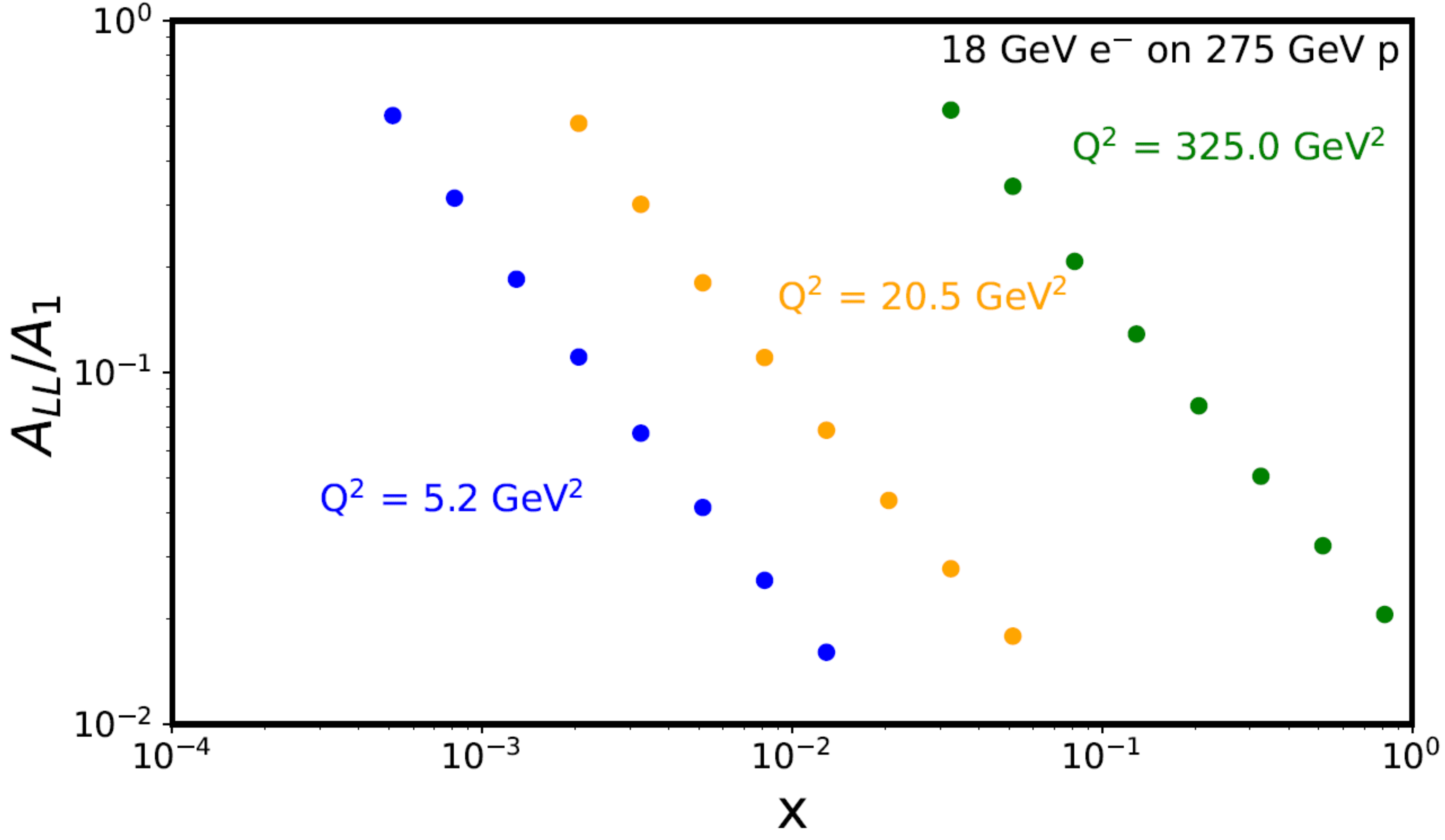
g_1, A_1



18 GeV e⁻ on 275 GeV p
Q² = 325.0 GeV²
Q² = 20.5 GeV²
Q² = 5.2 GeV²
g1
x
18 GeV e⁻ on 275 GeV p
Q² = 325.0 GeV²
Q² = 5.2 GeV²
Q² = 20.5 GeV²
A1
x

DSSV14

Depolarization factor



DSSV14