Probing nucleon spin structure with inclusive DIS at EIC-ATHENA

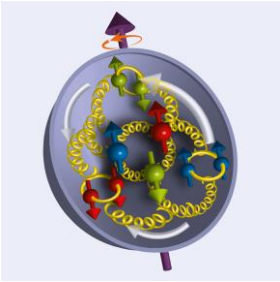
Barak Schmookler (UC Riverside),

Ignacio Borsa (Universidad de Buenos Aires), Paul Newman (Birmingham), Qinghua Xu (Shandong University), and Yiyu Zhou (South China Normal University)

Thanks to everyone who worked on the ATHENA proposal!

Polarized PDFs and the Spin of the Proton

Proton spin

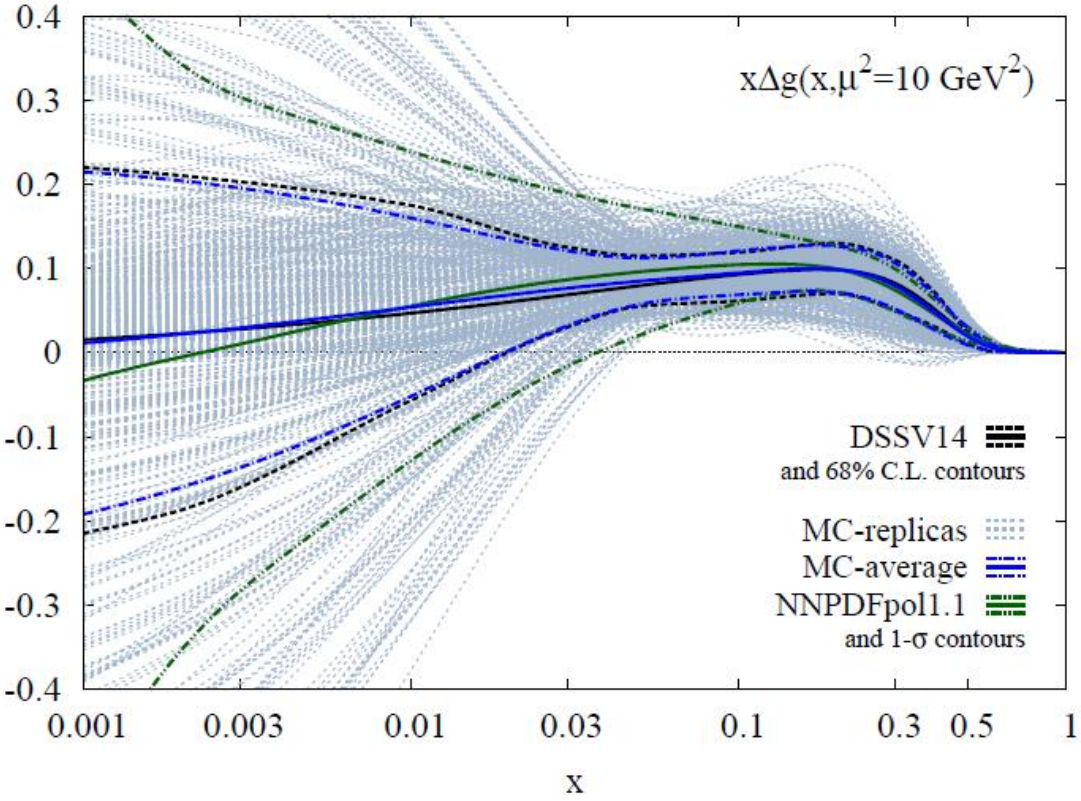


$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_Q + L_G$$

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

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

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

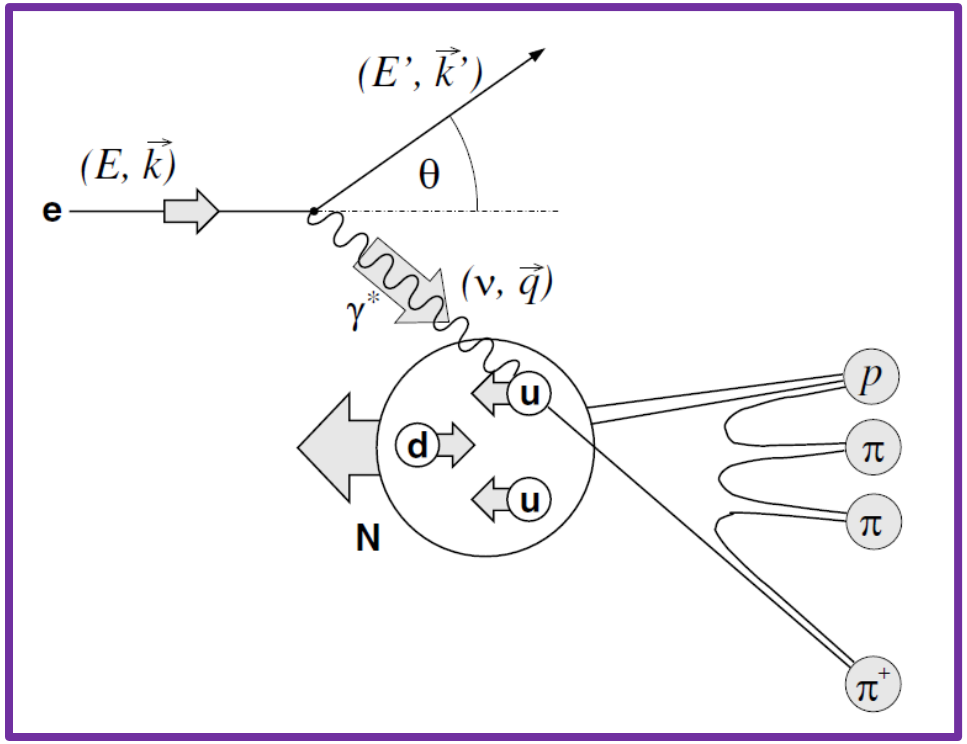


Quark spin only accounts for a portion of the proton's spin

Large uncertainty on polarized gluon PDF

Experimental channels for studying Polarized PDFs

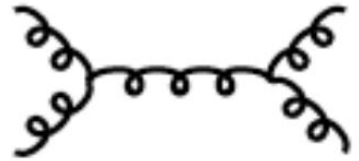
Inclusive and semi-inclusive lepton-proton (light nucleus) scattering, with longitudinally polarized proton (or light nucleus)



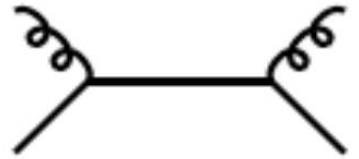
Hard proton-proton scattering with longitudinally polarized proton beams

$$p + p \rightarrow \pi + X$$

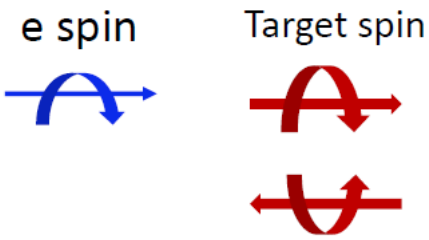
$$g + g \rightarrow g + g$$



$$q + g \rightarrow q + g$$



NC e-p cross section with Longitudinally Polarized Protons



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

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

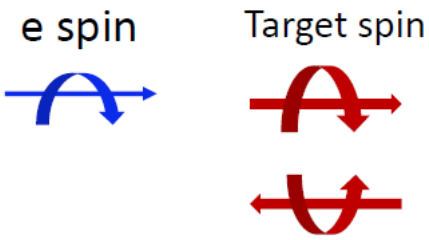
$$g_1 = -\lambda_l g_1^\gamma + \eta_z\left(\lambda_l g_v^e - g_A^e\right) g_1^{\gamma z} + \eta_z^2\left[-\lambda_l\left((g_v^e)^2 + (g_A^e)^2\right) + 2 g_A^e g_v^e\right] g_1^z$$

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

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

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

NC e-p cross section with Longitudinally Polarized Protons



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

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:

$$\Delta\sigma \approx \frac{4\pi\alpha^2}{Q^4 x}\left(Y_- 2x g_1^\gamma\right)$$

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

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

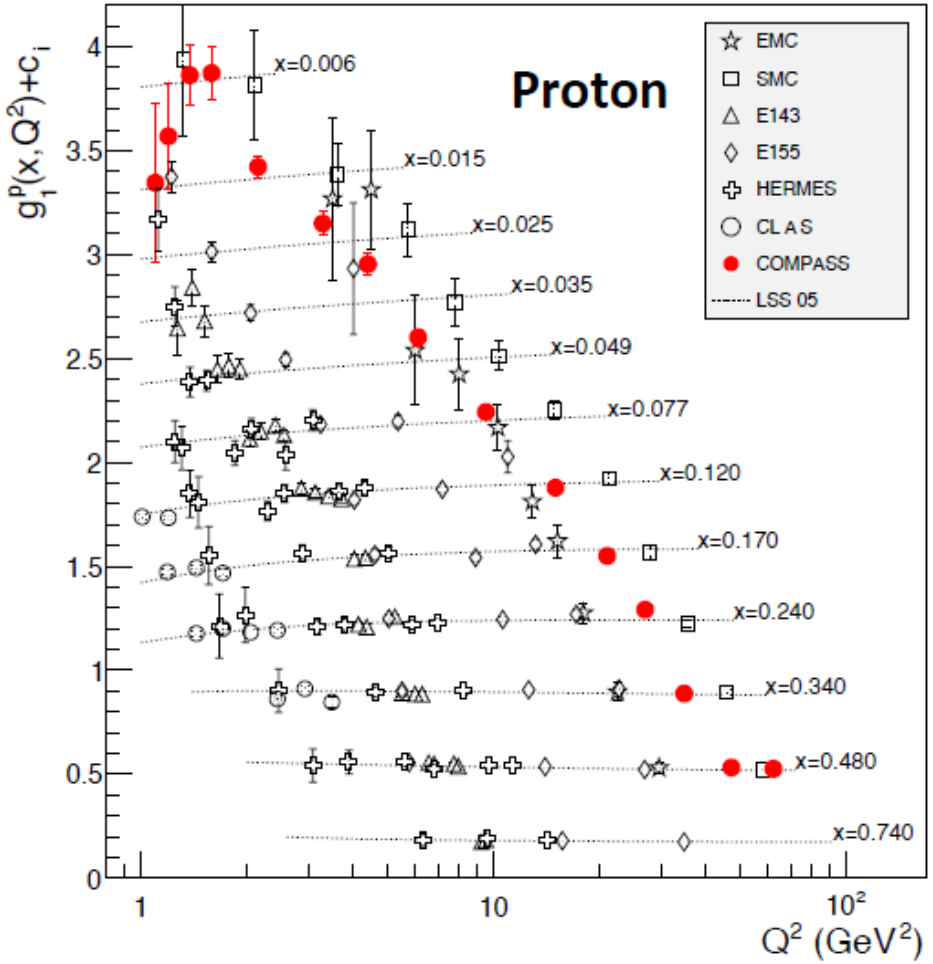
$$g_1^{\gamma}\left(x,Q^2\right) = \sum_{i=q,g} C_i \otimes \Delta f_i$$

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

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

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

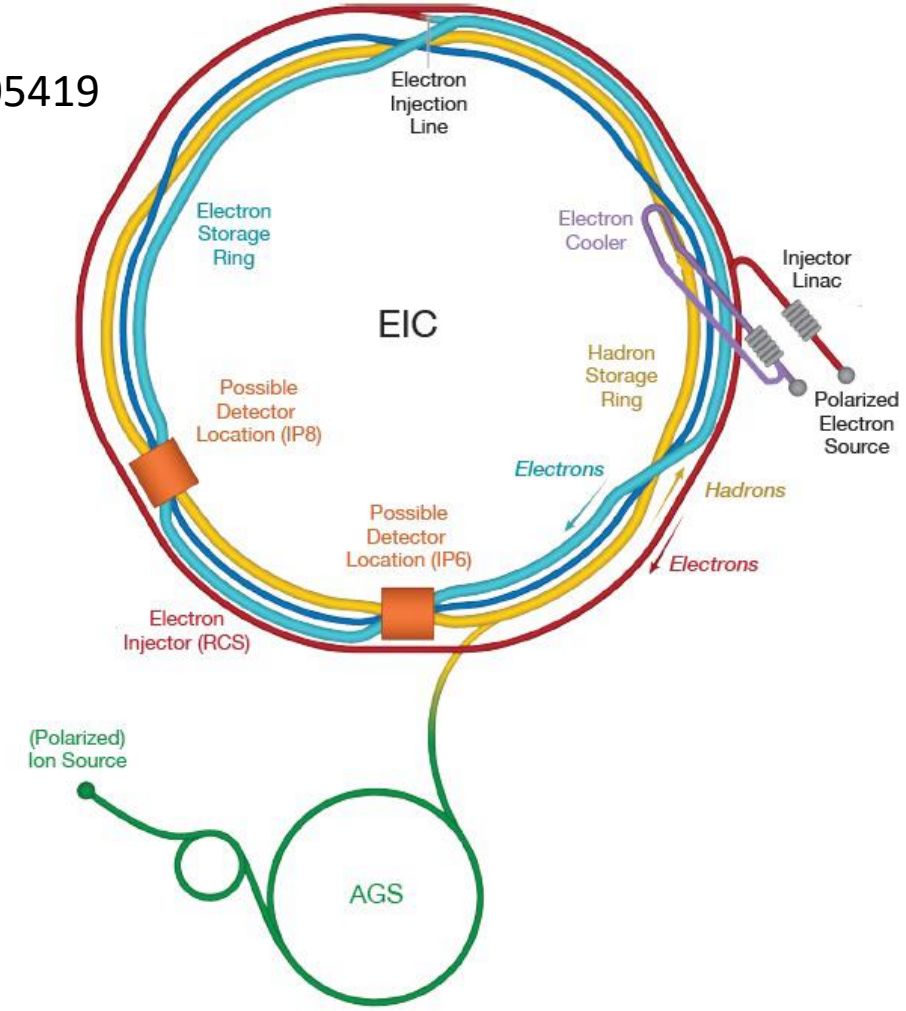
Aidala et al.1209.2803v2



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

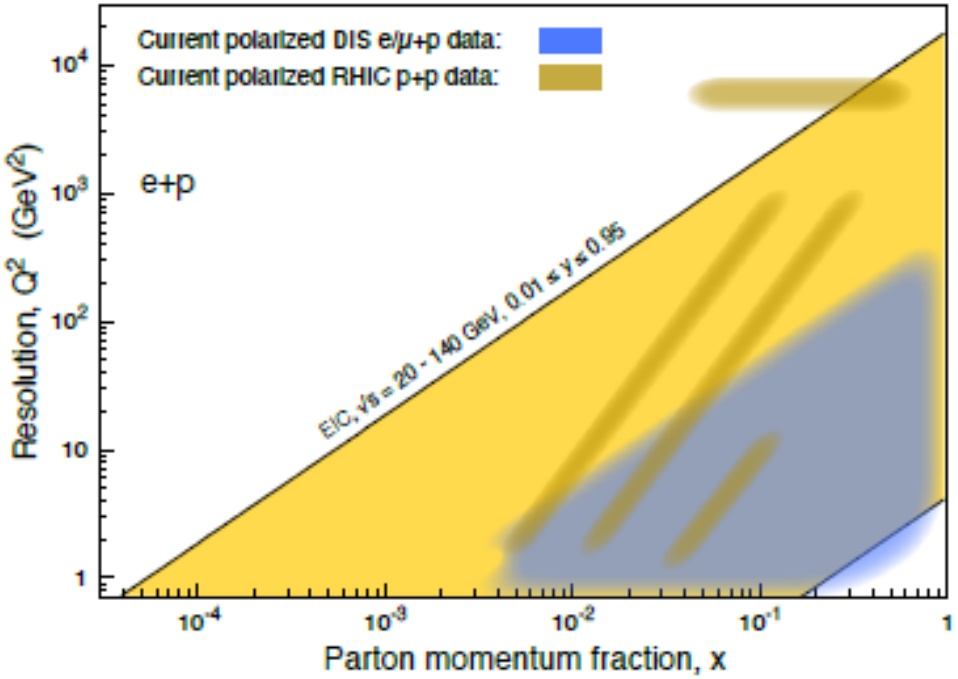
The Electron-Ion Collider (EIC): A next-generation QCD machine

arXiv: 2103.05419

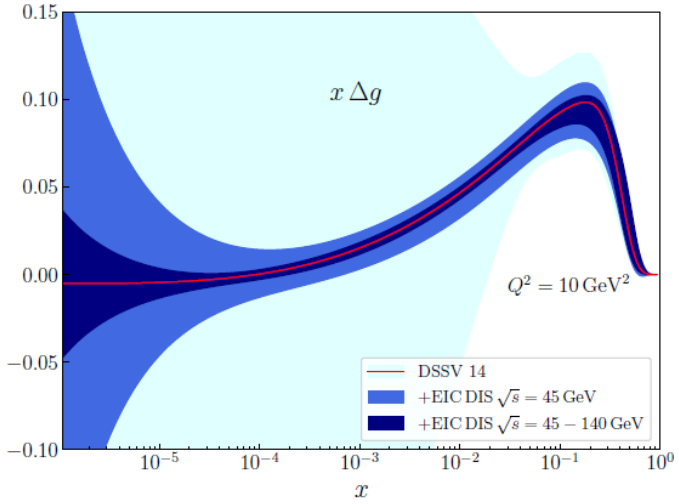


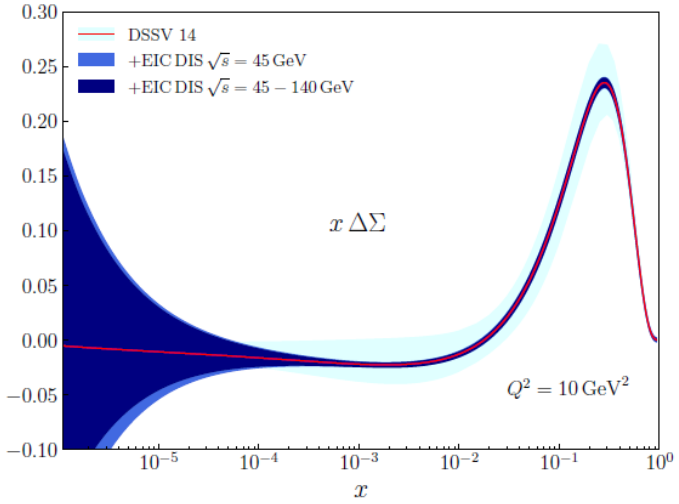
Versatile and with high-luminosity:

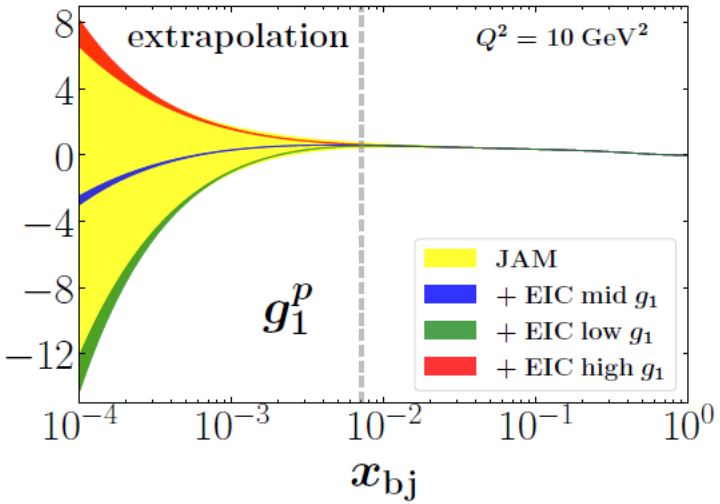
- $\sqrt{s}_{ep}$: 20 – 140 GeV
- Ion beam: Proton to Uranium
- High polarization: $P_{e,p}$ ~ 70%
- $\mathcal{L}_{max} = 10^{34} cm^{-2} s^{-1}$



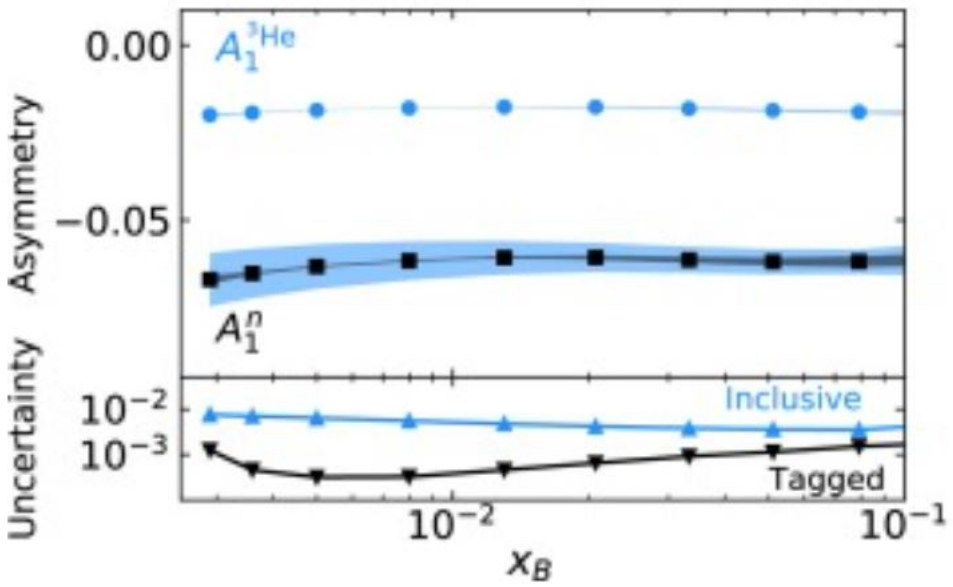
Previous EIC impact studies







arXiv:2007.08300
arXiv: 2103.05419

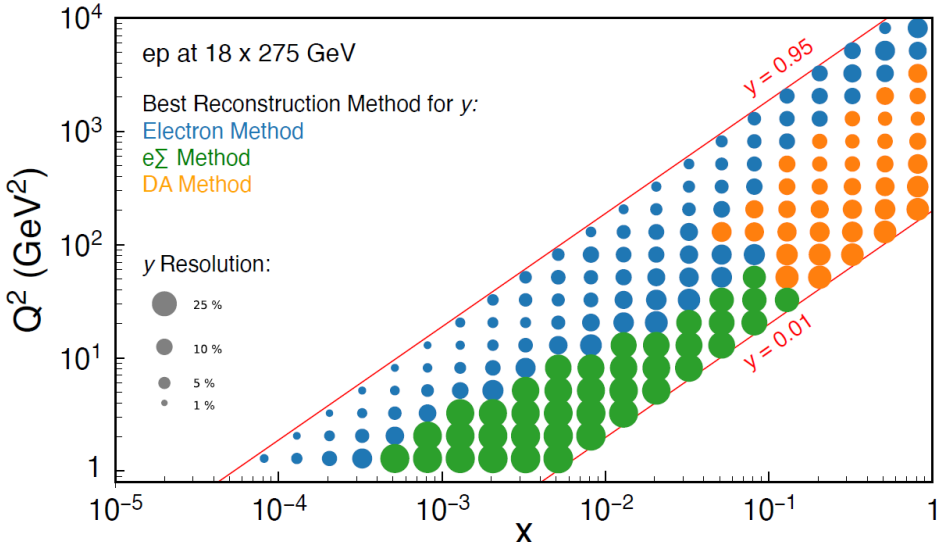


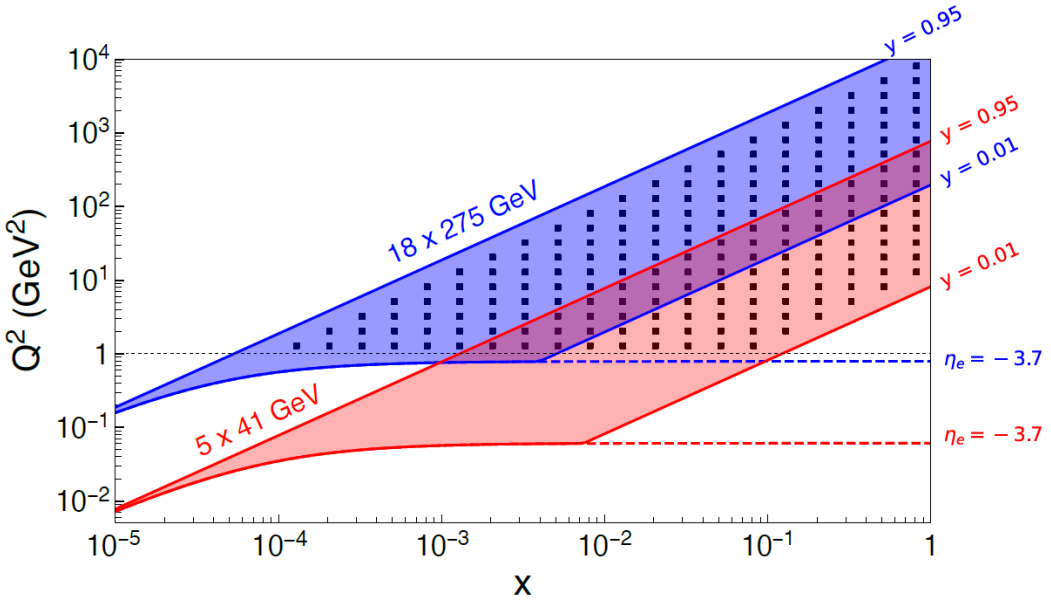
Phys.Lett.B 823 (2021) 136726

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

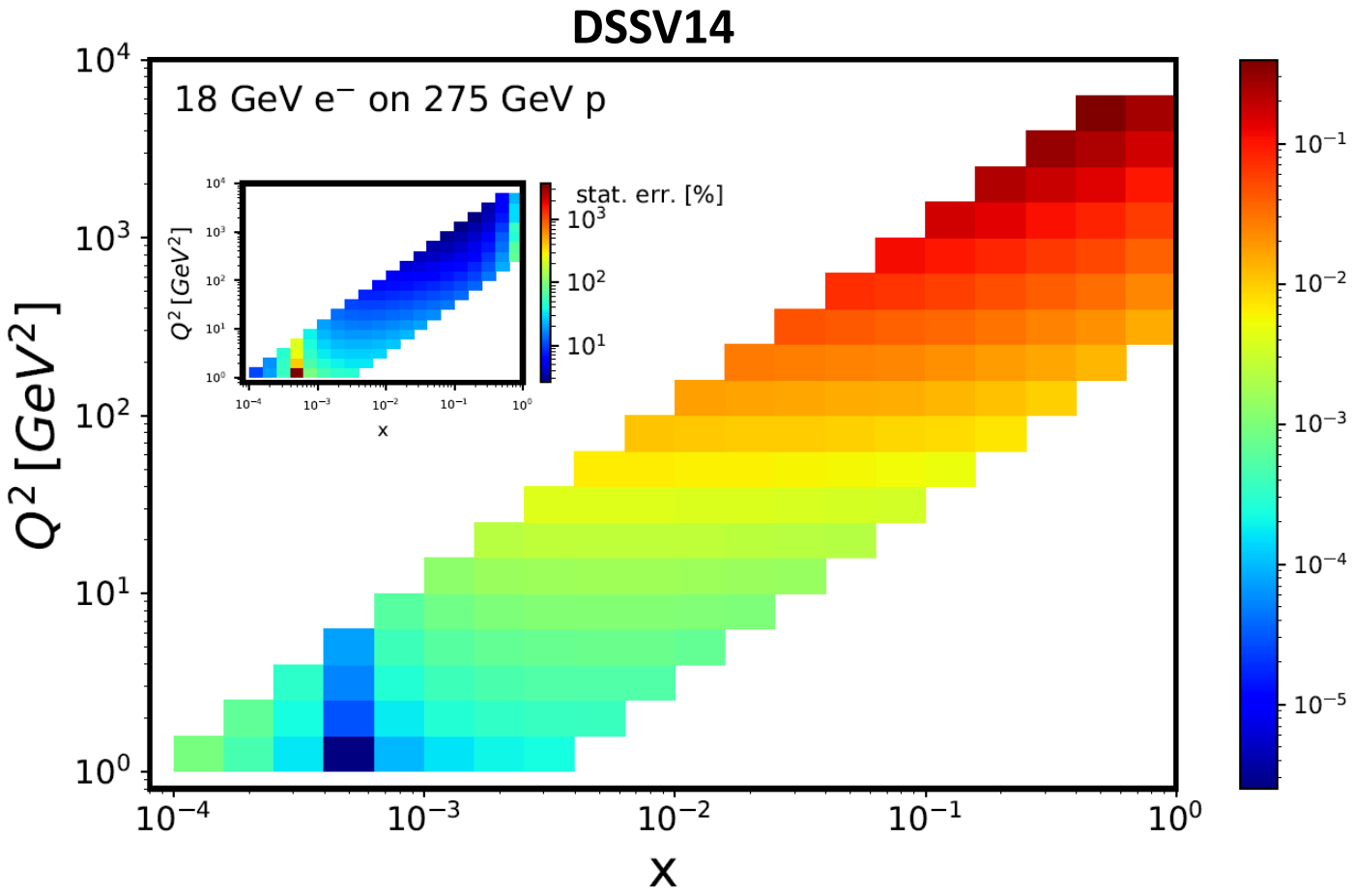




e-beam E	p-beam E	$\sqrt{s}$ (GeV)	inte. Lumi. (fb^{-1})
18	275	140	15.4
10	275	105	100.0
10	100	63	79.0
5	100	45	61.0
5	41	29	4.4

- 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, $0.01 < y < 0.95$. See poster by Stephen Maple for details.
- Our group's studies were done for inclusive electron-proton scattering only.

Statistical and systematic uncertainties

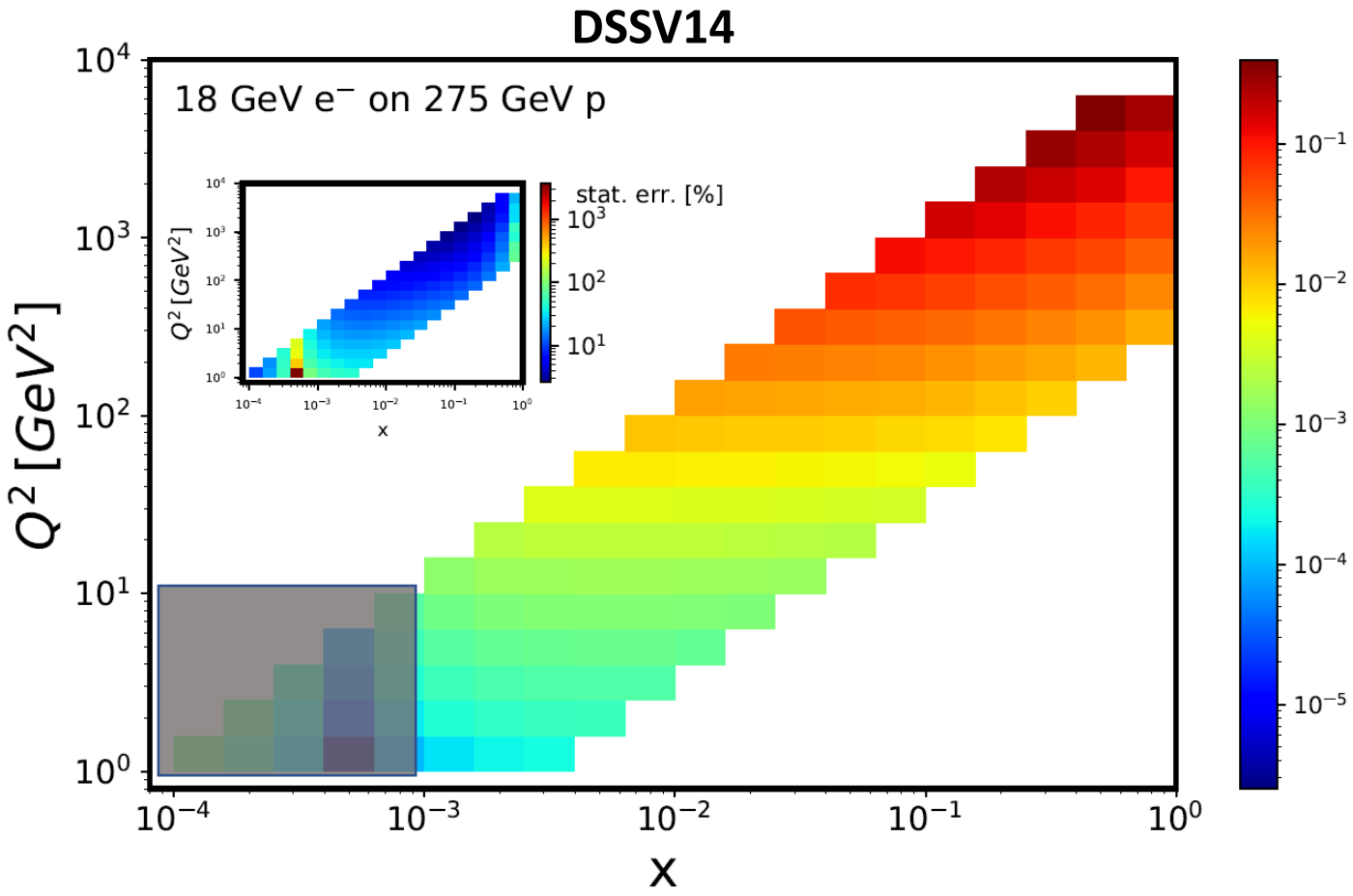


The systematic uncertainty estimation includes 1.5% point-by-point uncorrelated systematic uncertainty, 5% normalization uncertainty, and an additional systematic (shift) uncertainty of 10^{-4} from relative luminosity. The conservative 5% normalization uncertainty includes contributions from electron 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



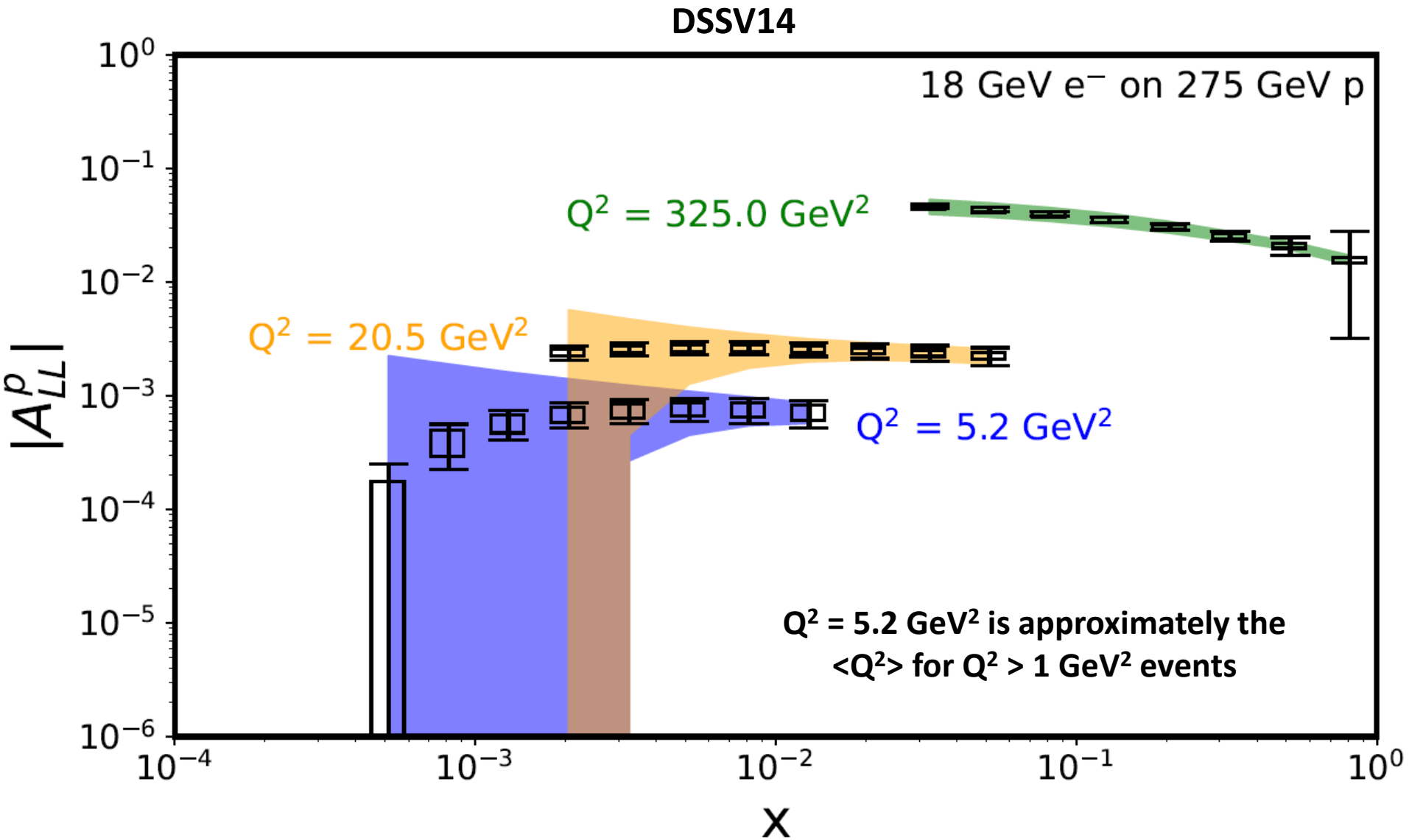
EIC kinematic coverage extends down to x of 10^{-4} for $Q^2 > 1$ GeV^2 …but statistical error begins to approach 100% of the asymmetry for $x < 10^{-3}$.

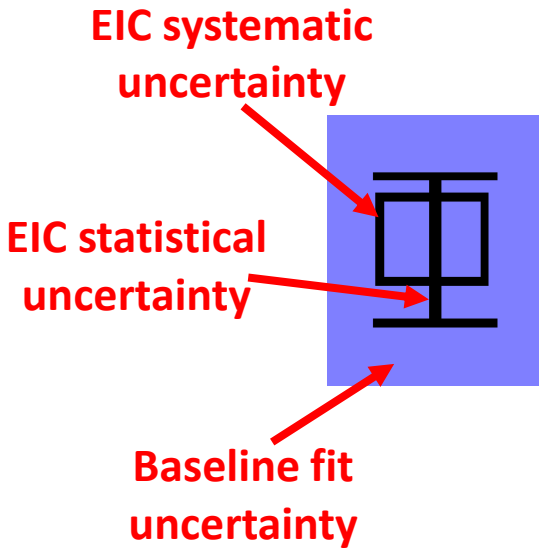
This assumes ~15 fb^{-1} integrated luminosity and 70-80% electron and proton polarization. Many years of running with high instantaneous luminosity can help.

Statistical uncertainty on asymmetry measurement:

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

Expected EIC experimental precision





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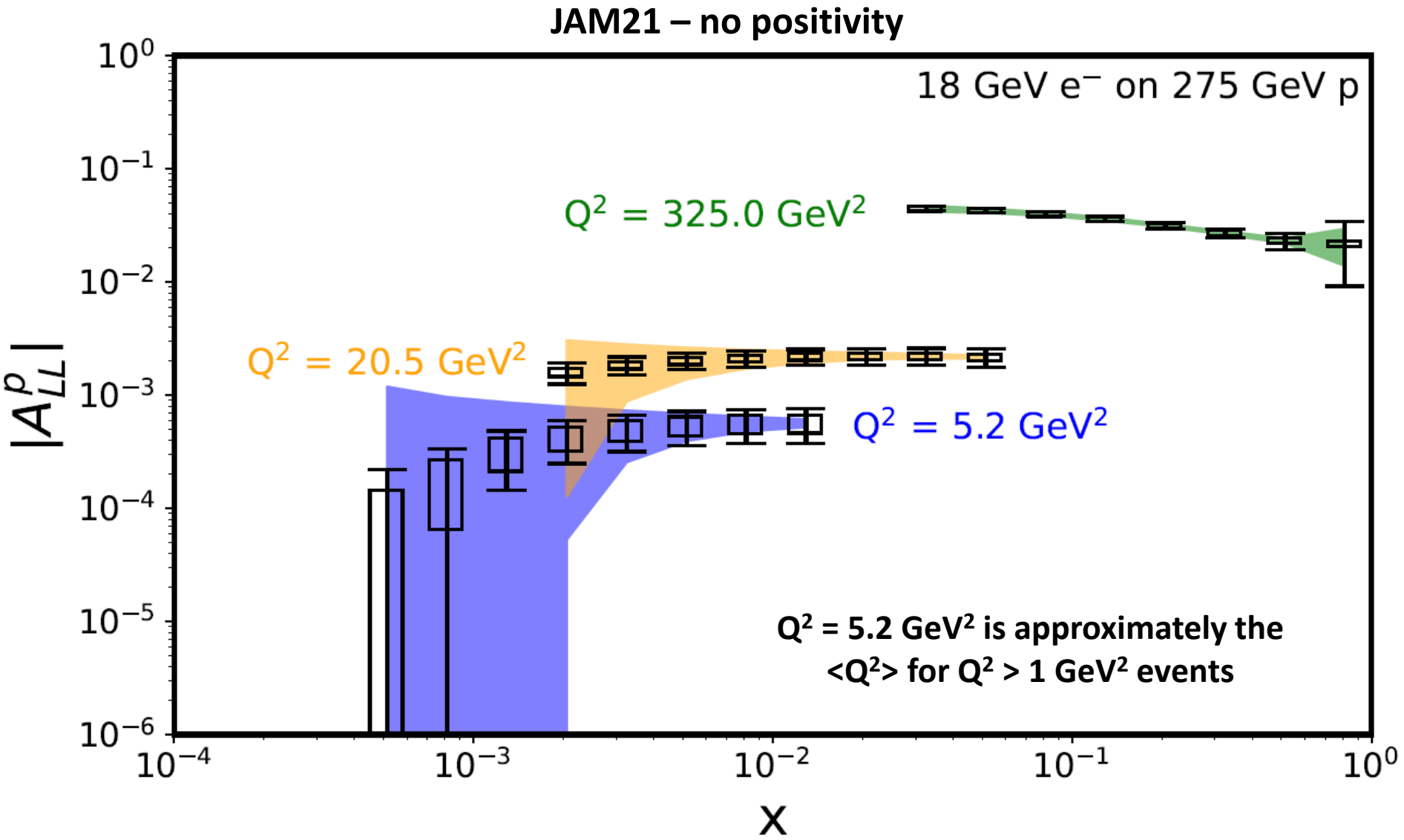
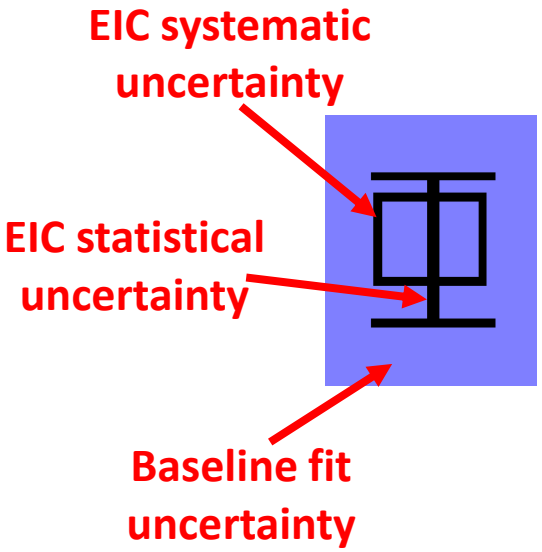
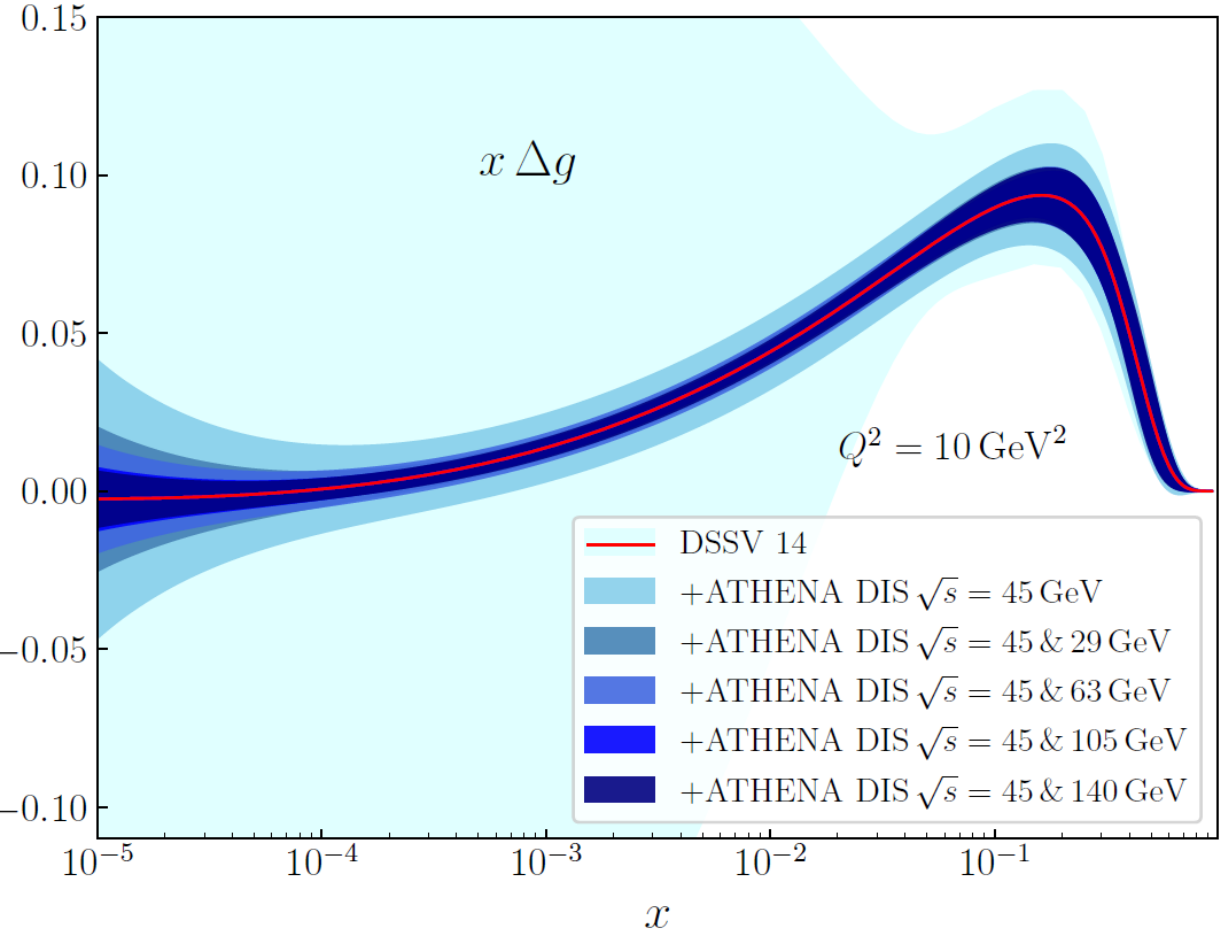
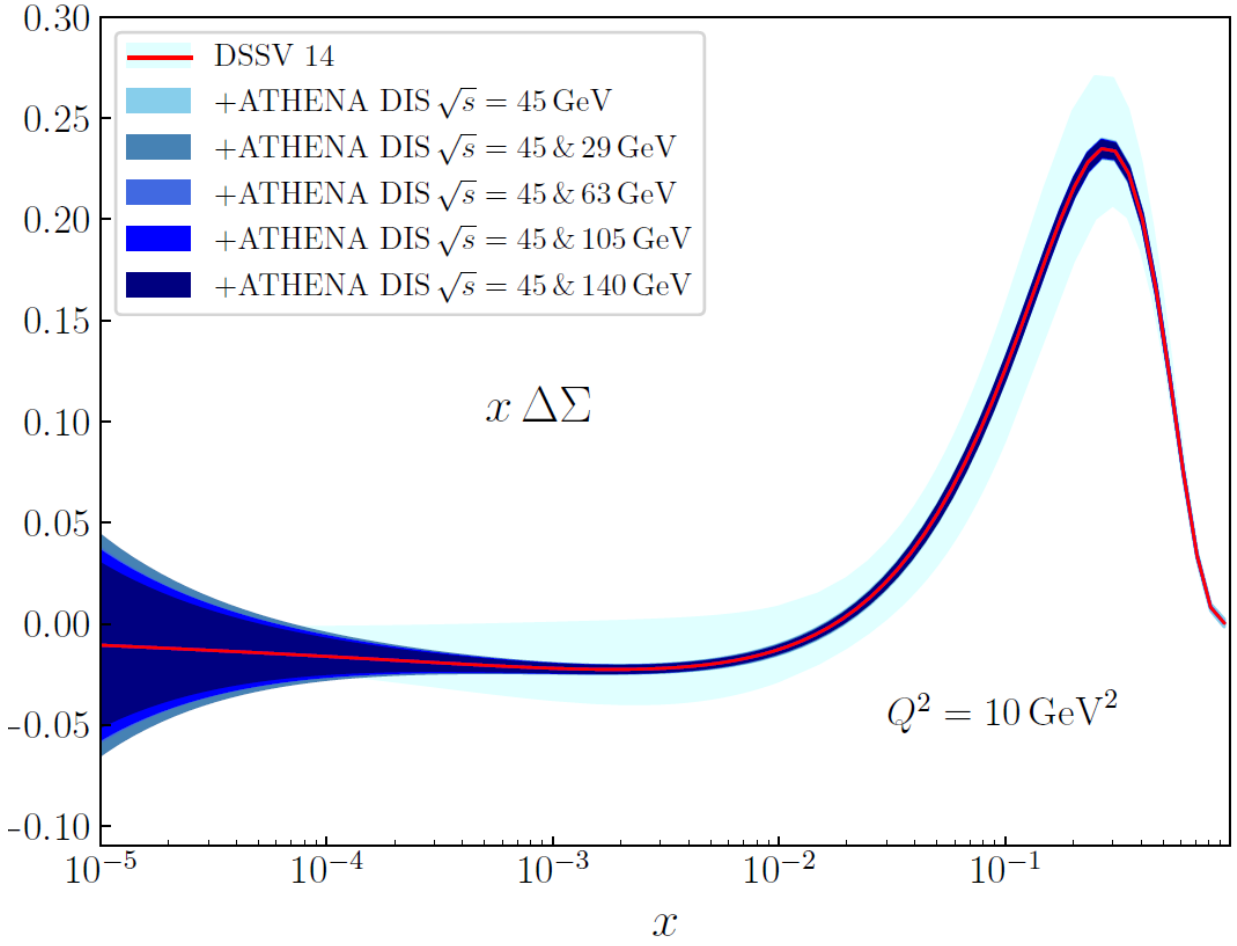




Impact of the EIC on polarized PDFs: **DSSV**





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

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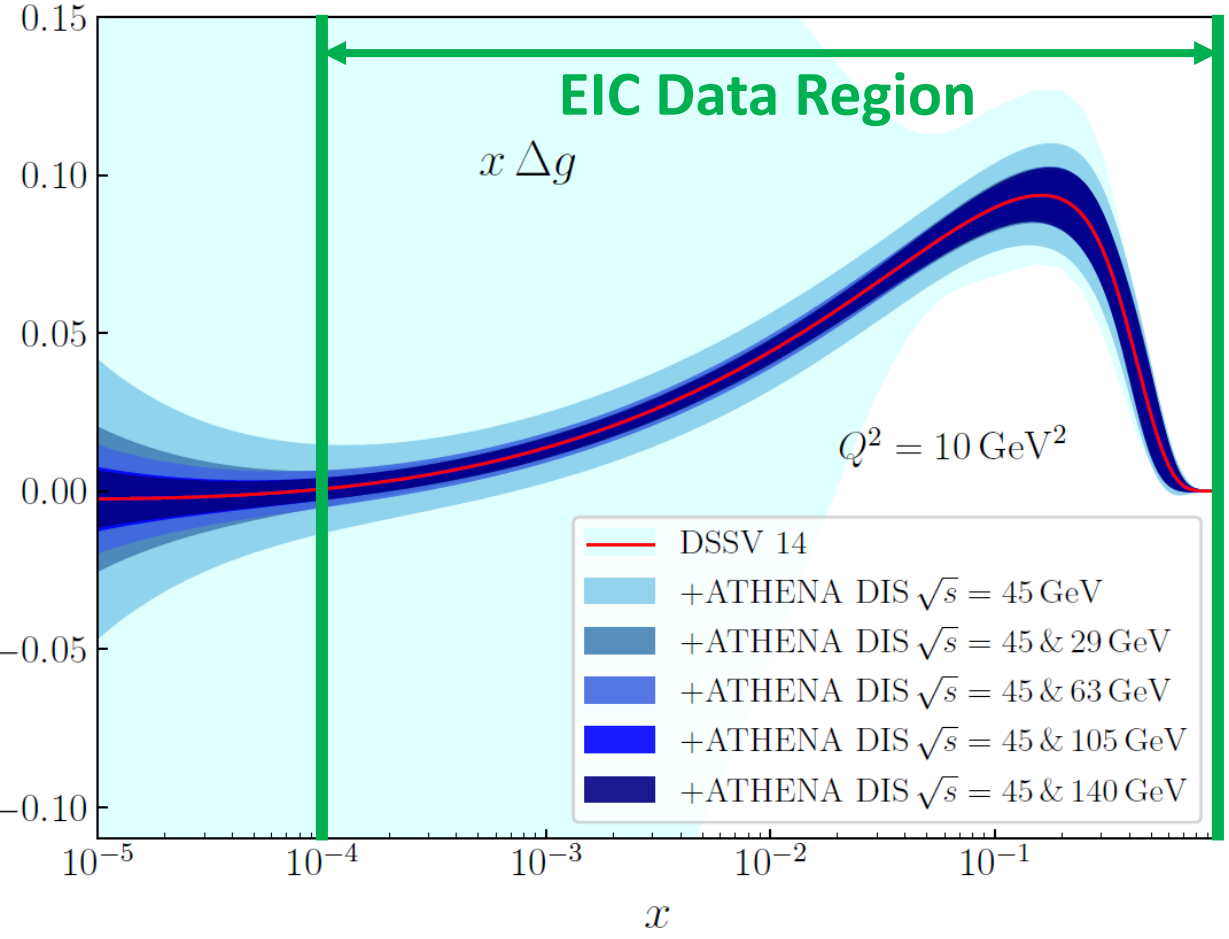
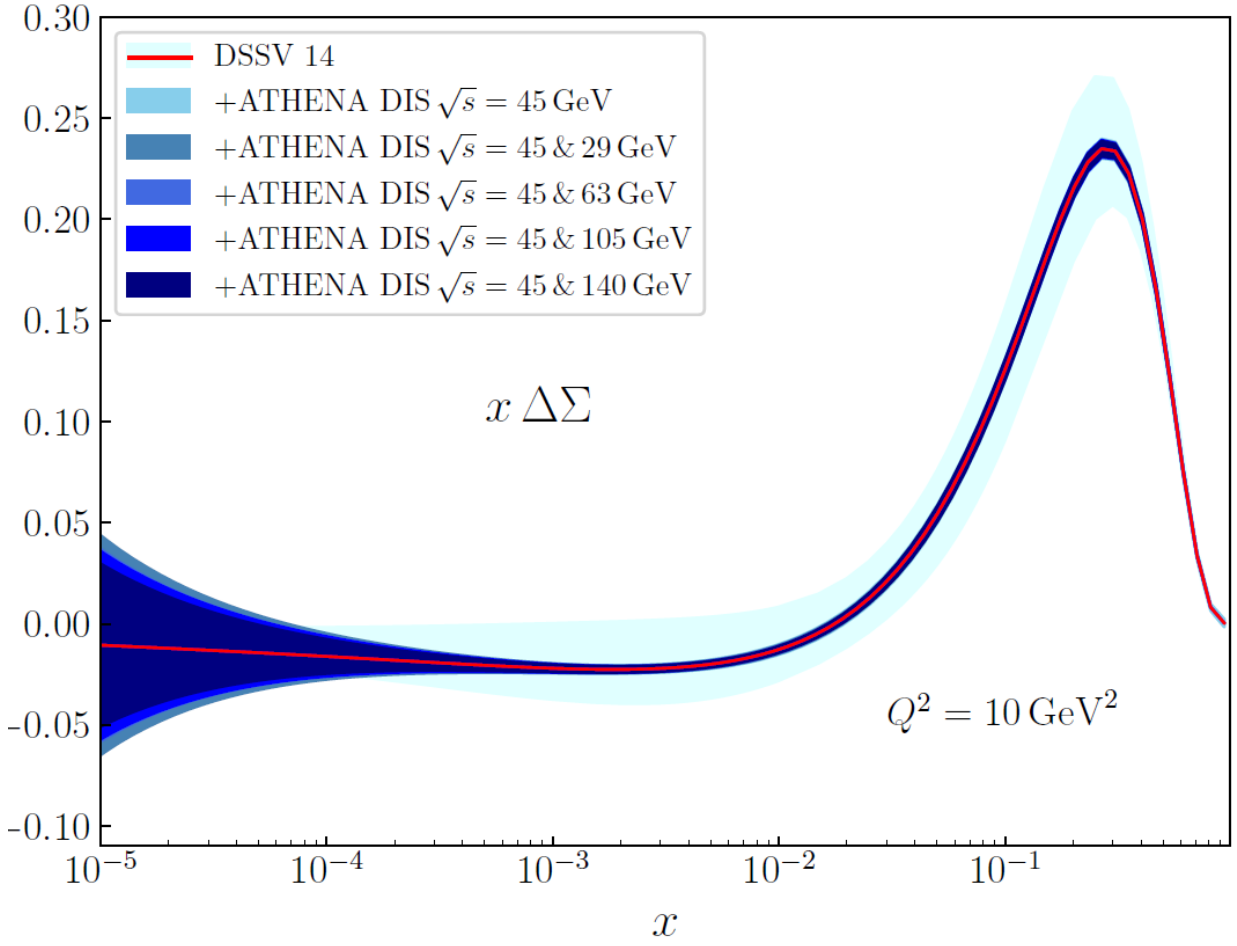
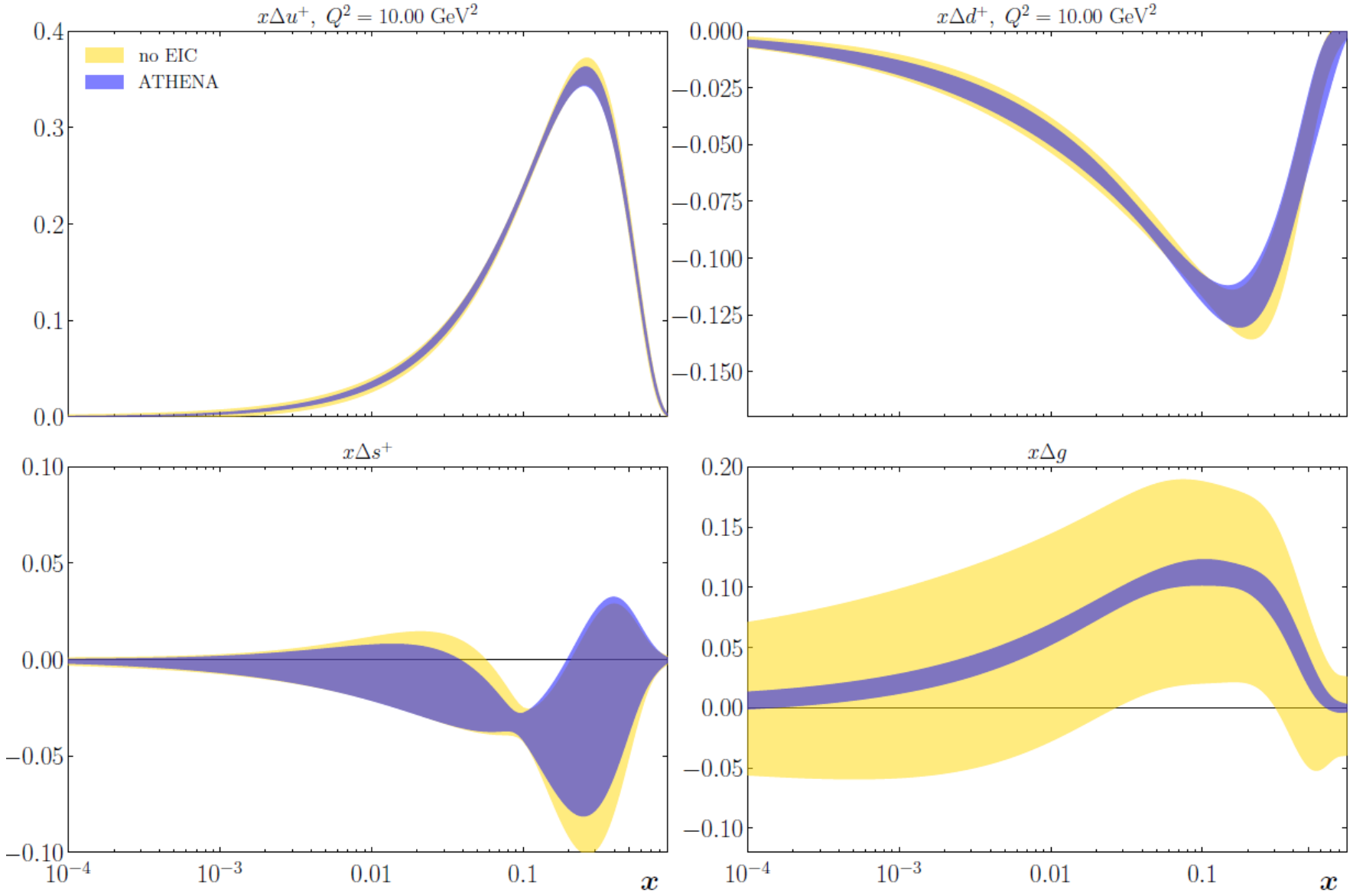




Very significant impact on polarized gluon and quark singlet PDFs using inclusive e-p only!

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.