Small-x Quark and Gluon Helicity Contributions to the Proton Spin Puzzle

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Based on: 2204.11898, 2306.01651, 2308.07461, and earlier publications

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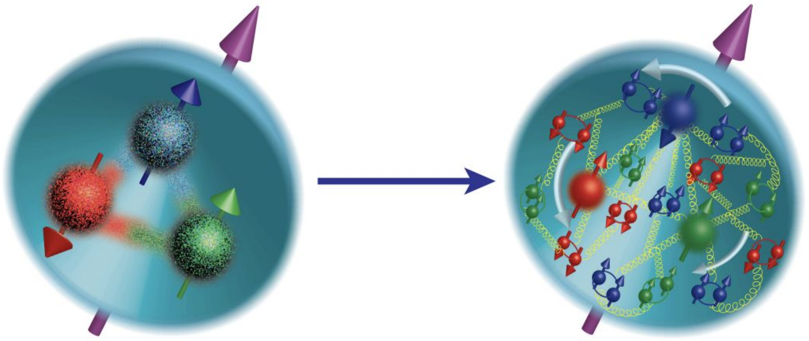
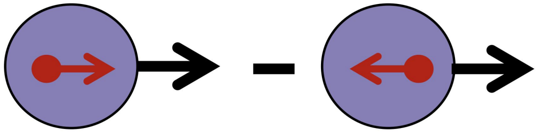
Proton Spin



- In the past, proton spin was thought to be the sum of constituent quarks spins.
- Now, we believe it to be the sum of spins of valence quarks, sea quarks and gluons, together with their orbital angular momenta (OAM).

Helicity PDF



- Helicity-dependent generalization of PDFs
- For each parton f,

$$\Delta f(x, Q^2) = f(x, Q^2, +) - f(x, Q^2, -)$$

- For quarks, we often consider the “flavor singlet” quark hPDF:

$$\Delta\Sigma(x, Q^2) = \sum_{q=u,d,s} \left[\Delta q(x, Q^2) + \Delta\bar{q}(x, Q^2)\right]$$

  and the “flavor non-singlet” quark hPDF: $\Delta q^-(x, Q^2) = \Delta q(x, Q^2) - \Delta\bar{q}(x, Q^2)$

- Gluon hPDF: $\Delta G(x, Q^2)$

Proton Helicity Sum Rule

- Jaffe-Manohar sum rule: $$\frac{1}{2} = S_q + S_G + L_q + L_G$$

  where the helicity of quarks (S_q) and gluons (S_G) are

  $$S_q(Q^2) = \frac{1}{2}\int_0^1 dx\, \Delta\Sigma(x, Q^2) \quad \text{and} \quad S_G(Q^2) = \int_0^1 dx\, \Delta G(x, Q^2)$$

- In the late 1980's, EMC measurement implied that $S_q \approx 0.05$, much lower than what would have been (1/2) had all the proton spin been carried by the constituent quarks.

$$\frac{1}{2} = S_q + S_G + L_q + L_G$$

Current Knowledge of Proton Helicity

$$S_q(Q^2) = \frac{1}{2}\int_0^1 dx\, \Delta\Sigma(x, Q^2)$$

$$S_G(Q^2) = \int_0^1 dx\, \Delta G(x, Q^2)$$

- More recently, the proton spin carried by quarks and gluon are estimated to be

$$S_q(Q^2 = 10\ \mathrm{GeV}^2) \approx \frac{1}{2}\int_{0.001}^{1} dx\, \Delta\Sigma(x, 10\ \mathrm{GeV}^2) \in [0.15, 0.20]$$

$$S_G(Q^2 = 10\ \mathrm{GeV}^2) \approx \int_{0.01}^{1} dx\, \Delta G(x, 10\ \mathrm{GeV}^2) \in [0.13, 0.26]$$

- They do not add to 1/2. The missing spin can come from:
  - Orbital angular momenta, L_q and L_G.
  - Small-x region of $\Delta\Sigma$ and ΔG. Scattering experiments can only access finitely small x. The limit will improve with EIC.

Small-x Evolution for Helicity: KPS-CTT Evolution

- Scattering experiments can only access $\Delta\Sigma$ and ΔG down to finitely small x.
- Fill the gap by finding small-x asymptotics for $\Delta\Sigma$ and ΔG via evolution in x, resumming $\alpha_s \ln^2(1/x)$. (Unpolarized BK/JIMWLK resums $\alpha_s \ln(1/x)$.)

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[2204.11898]

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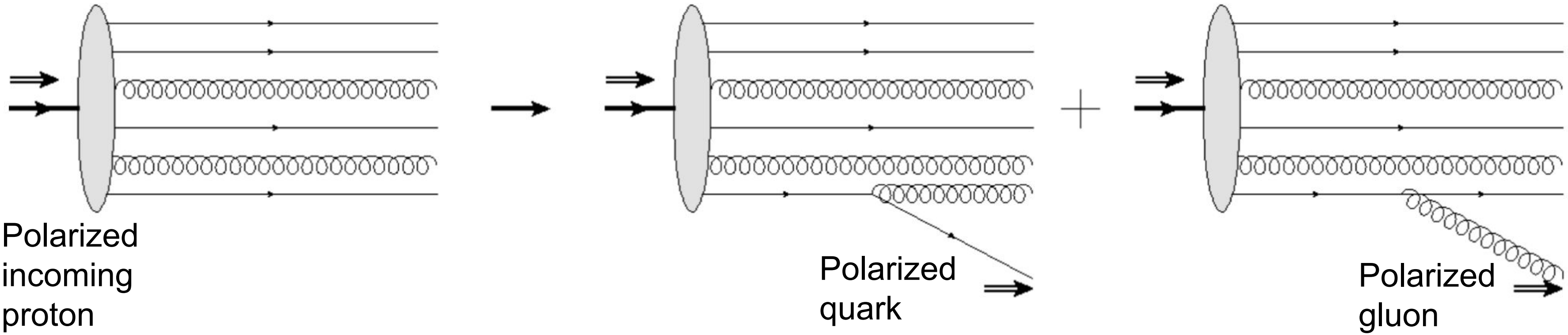
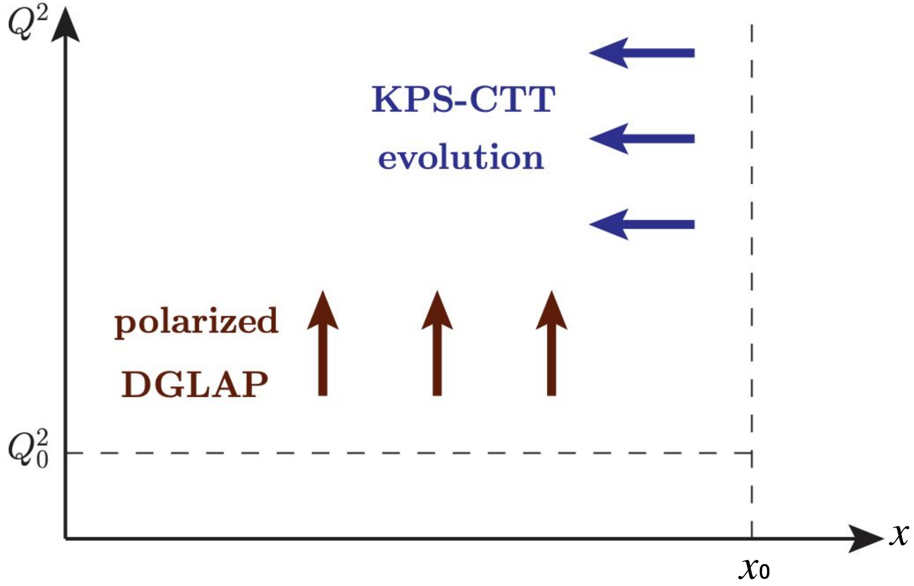


- Helicity evolution must keep track of both quark and gluon helicity, in contrast to unpolarized small-x evolution that is dominated by gluons.

Small-x Evolution for Helicity

- The KPS-CTT evolution in x is complementary to the existing polarized DGLAP evolution.



Small-x Asymptotics with Quark Exchanges

- At small x, gluons dominate → $N_c \gg 1$
- Still important to include quark exchanges (~ N_f / N_c) for helicity evolution
- Flavor non-singlet hPDF:

$$\Delta q^-(x, Q^2) = \Delta q(x, Q^2) - \Delta \bar{q}(x, Q^2) \sim \left(\frac{1}{x}\right)^{\sqrt{\alpha_s N_c/\pi}}$$

[1610.06197]

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$$\sim \Delta G(x, Q^2) \sim g_1(x, Q^2) \sim \left(\frac{1}{x}\right)^{3.43\sqrt{\alpha_s N_c/2\pi}}$$

[2306.01651]

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Smaller than 1

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Exceed 1 for $\alpha_s \gtrsim 0.18$

Infinite spin from small x???

[2306.01651]

Corrections to the DLA Evolution

- So far, KPS-CTT evolution resums $\alpha_s \ln^2(1/x)$.
- Potentially significant **single-log corrections,** resumming $\alpha_s \ln(1/x)$.
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  - Likely to include saturation mechanism
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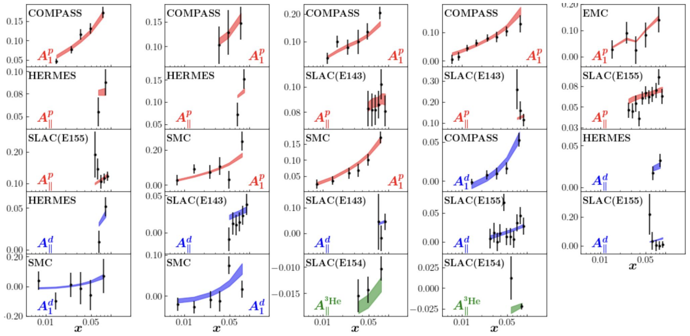
- Recently, a **running coupling correction** (daughter dipole prescription) is employed to the DLA evolution in a global fit with polarized DIS & SIDIS data.
- KPS-CTT evolution (with rc) starts at x_0 = 0.1.
- At larger x, employ generalized Born-level initial condition: [2308.07461]

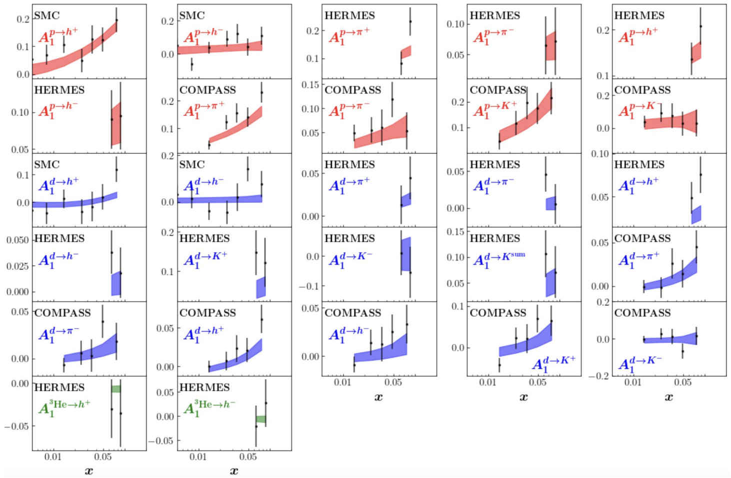
Dipole ~ a ln(rapidity) + b ln(dipole size) + c

Global Fit

[2308.07461]

- Polarized DIS and SIDIS data (A_1, $A_\parallel$, A_1^h) from SLAC, EMC, SMC, COMPASS and HERMES at $0.005 \leq x \leq 0.1$ and $1.69\ \mathrm{GeV}^2 \leq Q^2 \leq 10.4\ \mathrm{GeV}^2$.
  - Include proton, deuteron and helium-3 targets
  - For SIDIS, include $\pi^\pm$, $K^\pm$ and unidentified charged hadron productions
- In total, N_{pts} = 226 data points
- Overall, $\chi^2 / N_{\mathrm{pts}}$ = 1.03





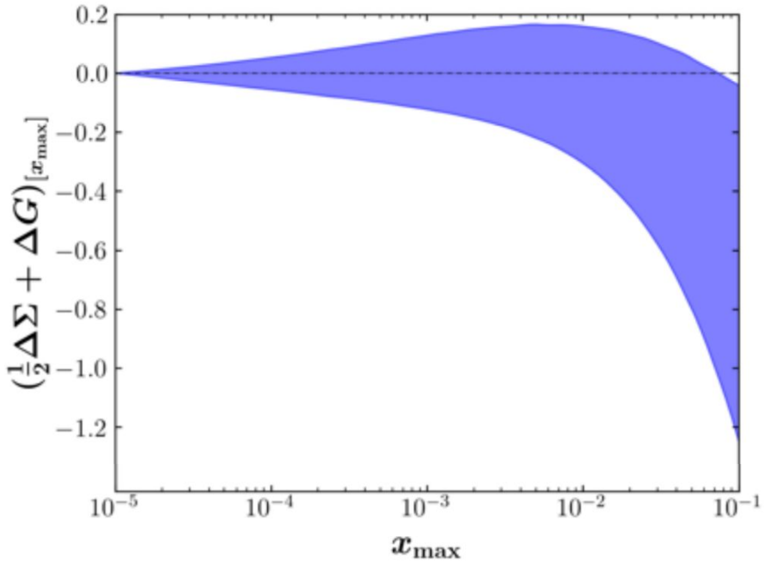
Global Fit

[2308.07461]

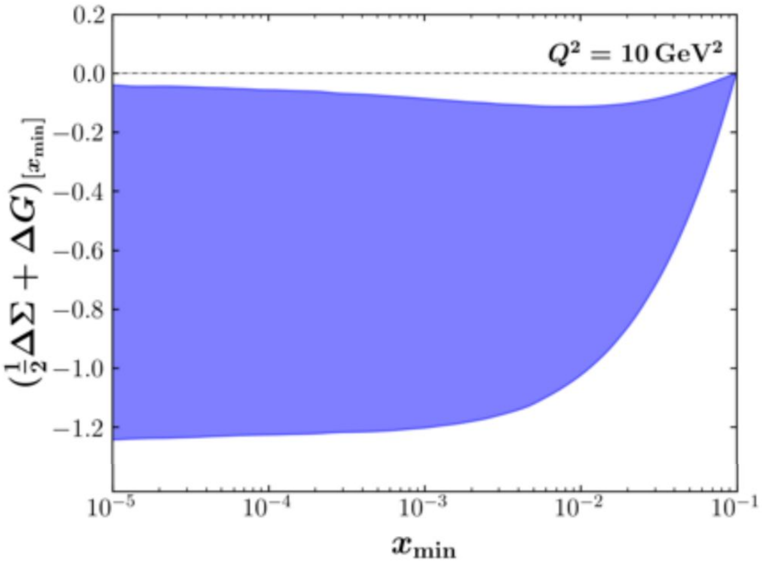
$$\int_{10^{-5}}^{0.1} \mathrm{d}x \left(\frac{1}{2}\Delta\Sigma + \Delta G\right)(x) = -0.64 \pm 0.60$$

Significant spin from small x

$[10^{-5}, x_{max}]$

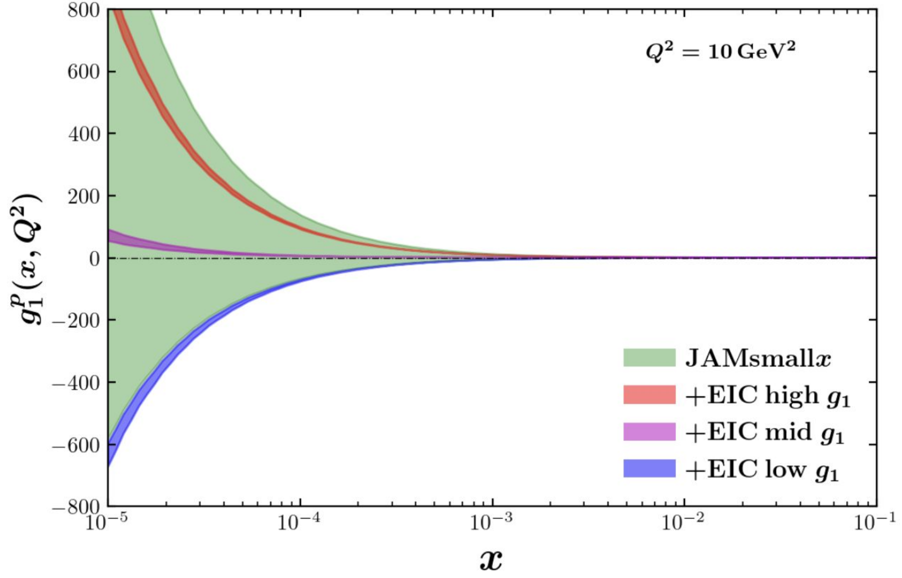


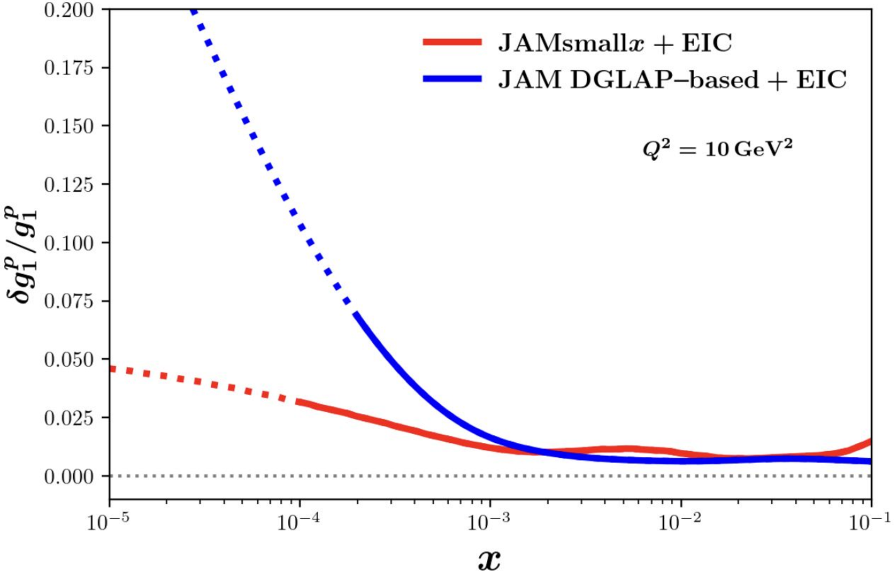
$[x_{min}, 0.1]$



Future EIC Impact

- Significant reduction of uncertainty at small x with future EIC data.





Conclusion

- Already at DLA, KPS-CTT evolution provides a promising small-x description of parton helicity, with potential improvement from future EIC results.
- Future work (stay tuned):
  - Improved global fit that includes pp particle production data
  - More deterministic initial condition using a valence-quark wave function
  - Complete single-logarithmic corrections, which will incorporate saturation
- The framework can be modified to calculate OAM's [1901.07453, 2307.09544] and other TMD's, e.g. Sivers Function [2108.03667, 2209.03538].
- Collaboration is very welcome ☺

Global Fit: hPDF Results