Small-x Helicity Evolution and the Proton Spin Puzzle

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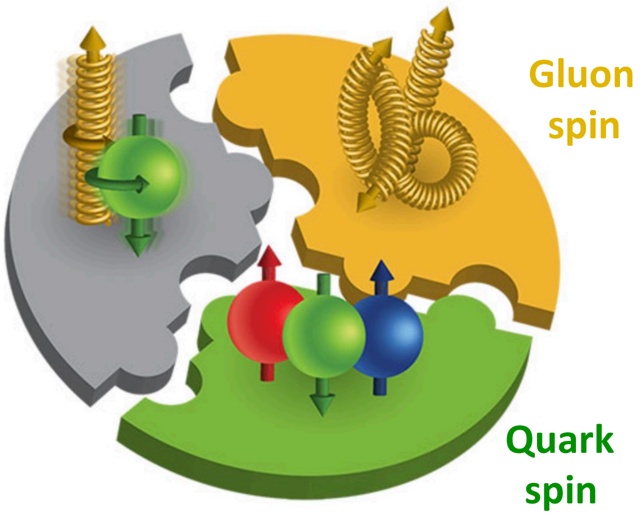
Outline

- Background and motivation
- Theoretical results – small-*x* helicity evolution
- Phenomenological results – fit of the world polarized DIS data
- A possible path to resolving the spin puzzle
- Summary and outlook

Background and Motivation

Proton “spin puzzle”



total spin of quarks

total spin of gluons

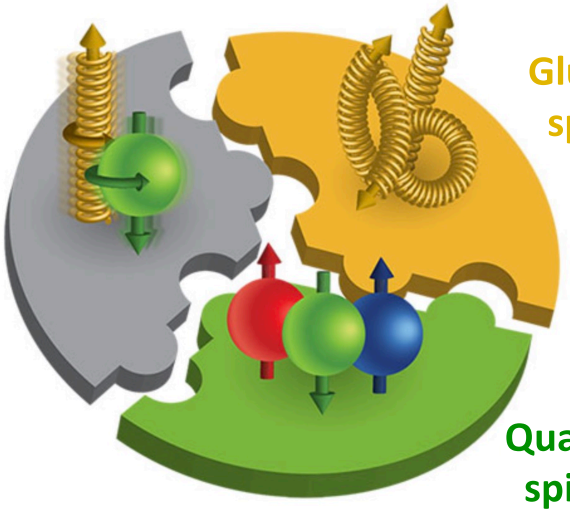
$$\frac{1}{2} = S_q + \mathcal{L}_q + S_g + \mathcal{L}_g$$

total OAM of quarks

total OAM of gluons

Jaffe-Manohar definition (1990)

Proton "spin puzzle"



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$$\frac{1}{2} = S_q + \mathcal{L}_q + S_g + \mathcal{L}_g$$

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total OAM of gluons

Jaffe-Manohar definition (1990)

$$S_q = \frac{1}{2}\int_0^1 dx \left[\sum_{q=u,d,s} (\Delta q + \Delta\bar{q})(x,Q^2)\right] \equiv \frac{1}{2}\int_0^1 dx\, \Delta\Sigma(x,Q^2)$$

$$S_g = \int_0^1 dx\, \Delta g(x,Q^2)$$

Proton "spin puzzle"

$$\frac{1}{2} = \overset{\text{total spin of quarks}\nearrow}{S_q} + \underset{\swarrow\text{total OAM of quarks}}{\mathcal{L}_q} + \overset{\text{total spin of gluons}\nearrow}{S_g} + \underset{\searrow\text{total OAM of gluons}}{\mathcal{L}_g}$$

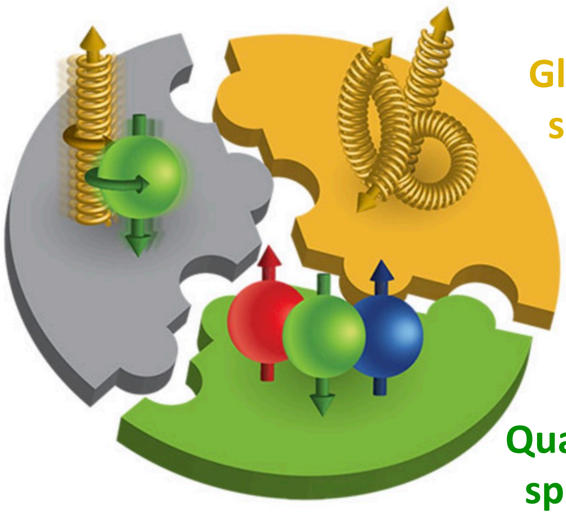
Jaffe-Manohar definition (1990)

$$S_q(Q^2 = 10\,\mathrm{GeV}^2) \approx 0.15 \div 0.20$$

$$S_g(Q^2 = 10\,\mathrm{GeV}^2) \approx 0.13 \div 0.26$$

$$\mathcal{L}_q + \mathcal{L}_g = \text{whatever is left}$$

Proton "spin puzzle"



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$$\mathcal{L}_q + \mathcal{L}_g = \text{whatever is left}$$

…but there are a few (significant) caveats

1) The calculations of S_q and S_g are based on *truncated* integrals – can *never* measure down to $x = 0$!

$$S_q = \frac{1}{2}\int_{\mathbf{0.001}}^{1} dx\,\Delta\Sigma(x,Q^2) \qquad S_g = \int_{\mathbf{0.05}}^{1} dx\,\Delta g(x,Q^2)$$

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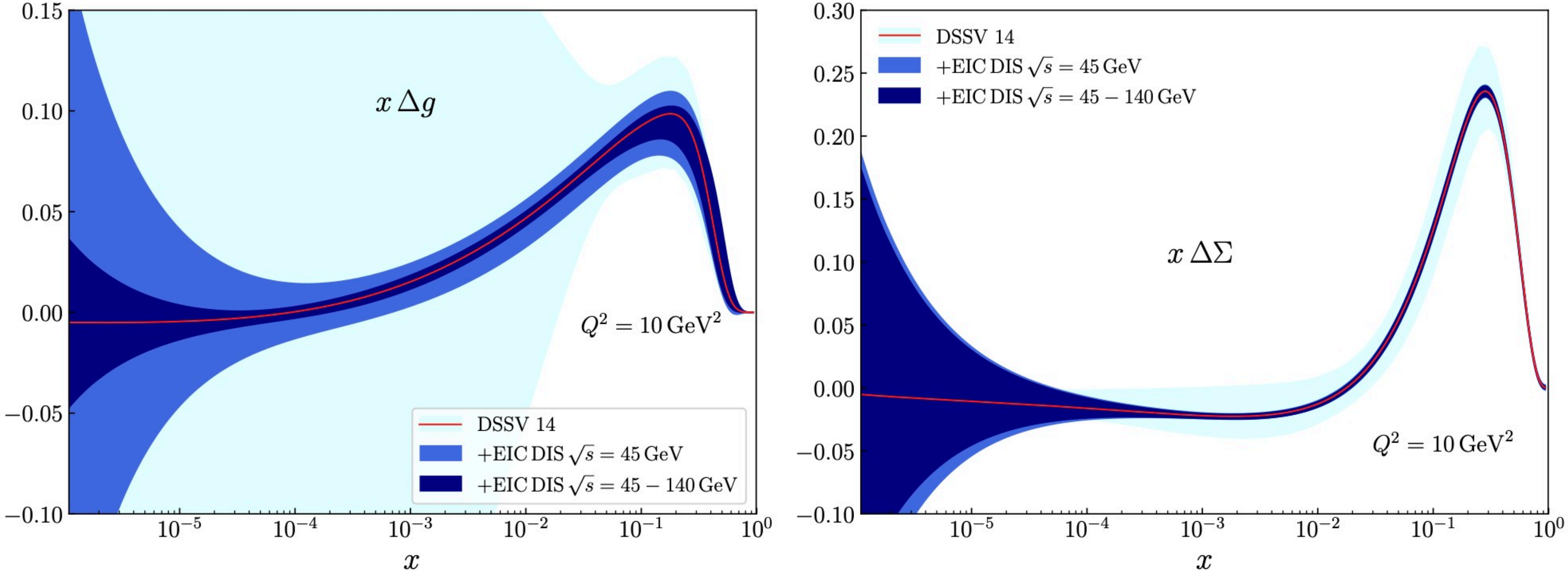
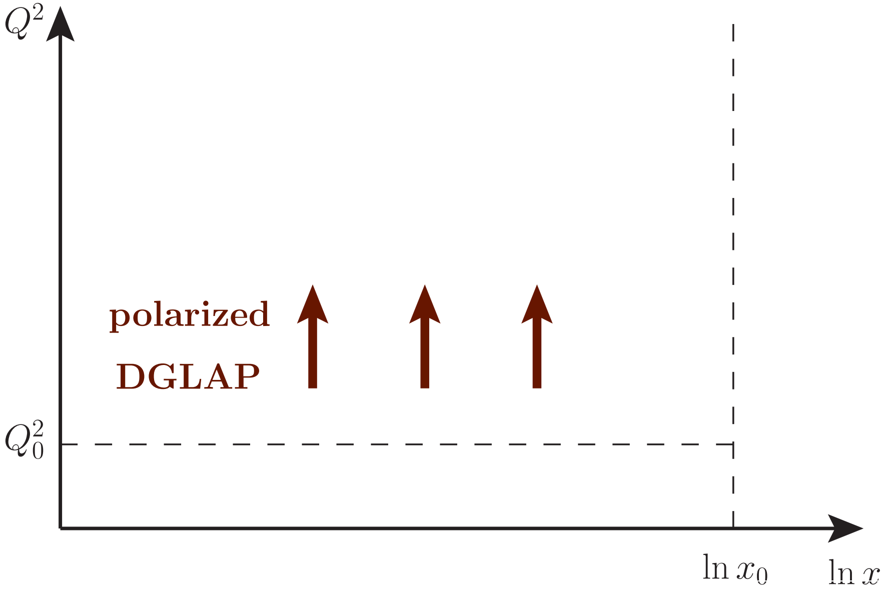
2) The extractions for ***Δ*Σ**(x) and ***Δg***(x) have large uncertainties at small x *even including EIC data*!

Borsa, et al. (2020)



- The main reason for these issues is that "standard" extractions of helicity PDFs use DGLAP evolution and *parametrize* the *x* dependence at some initial scale Q_0 and then evolve to higher Q



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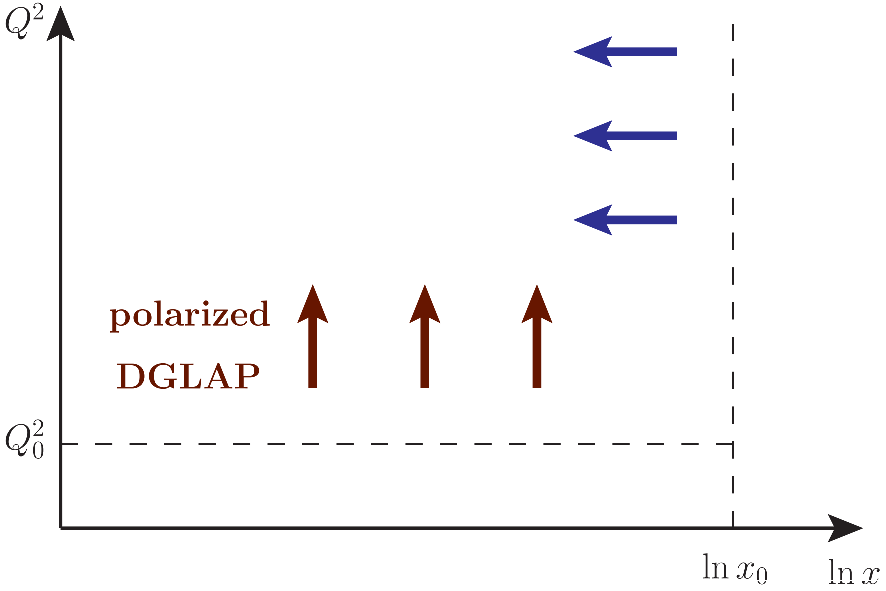
- What is needed are evolution equations for helicity PDFs that evolve in *x* instead of *Q* and can *predict* the behavior of helicity PDFs down to very small *x* (beyond what the EIC will reach) from *first principles QCD*



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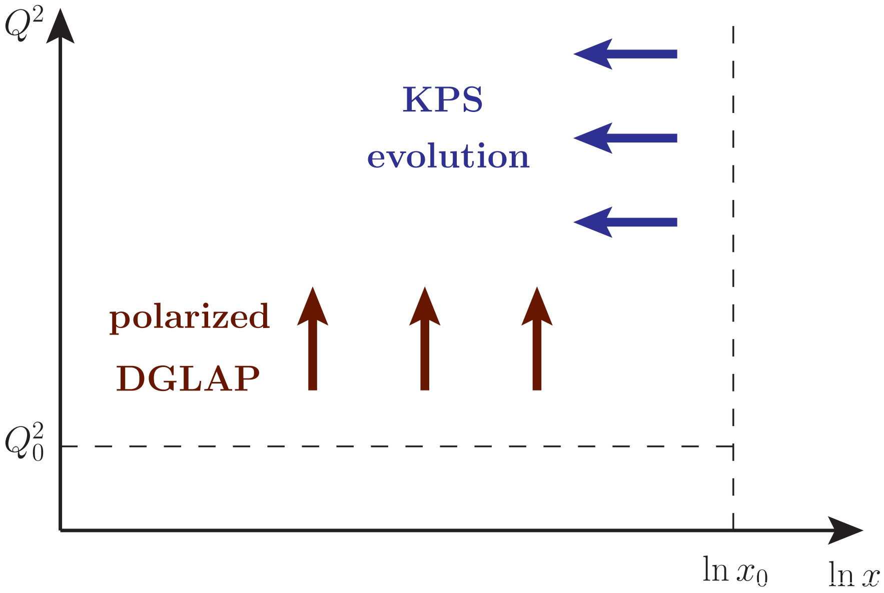

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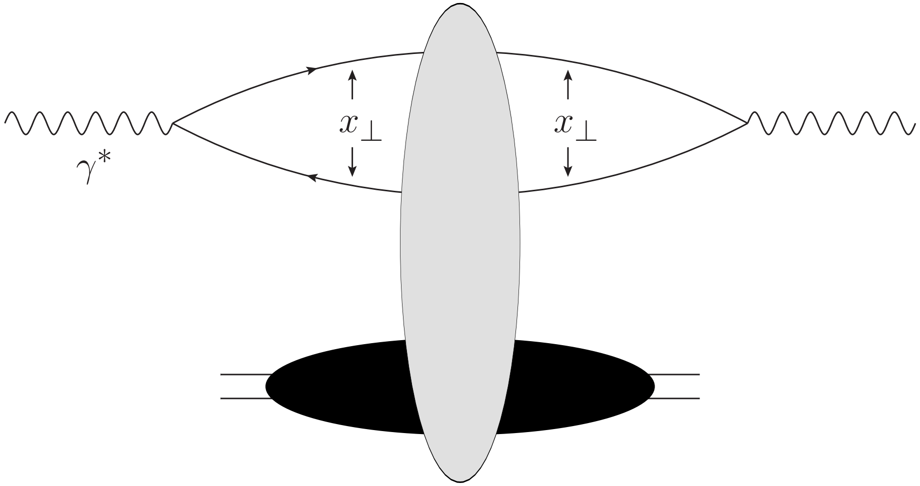
If we want to resolve the spin crisis, and accurately calculate values for S_q and S_g (integrating down to $x = 0$), we need to incorporate KPS evolution into phenomenological extractions of helicity PDFs

Theoretical Results – Small-*x* Helicity Evolution

- At small *x*, a process like DIS is dominated by the virtual photon splitting into a dipole:



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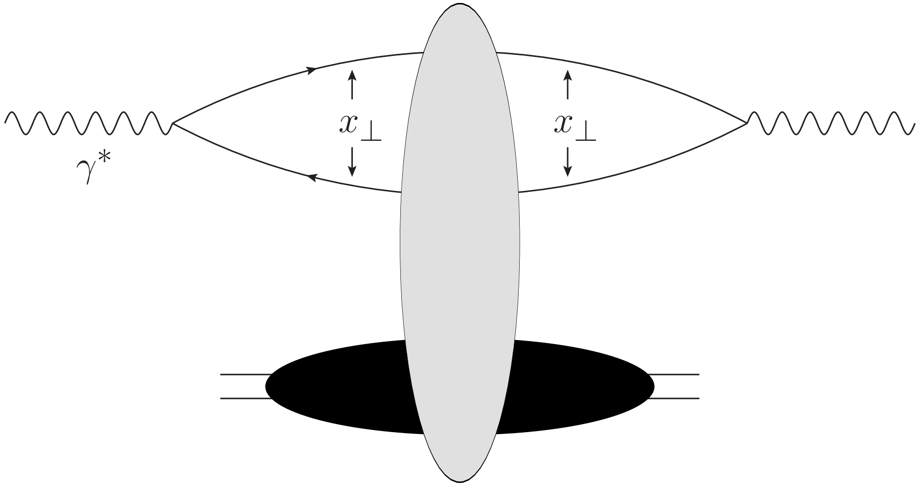

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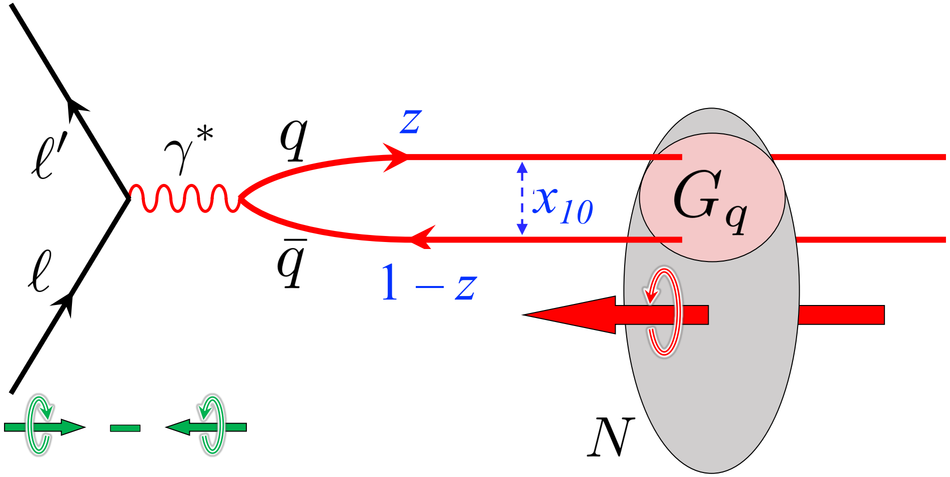
- All flavor singlet small-x helicity quantities (e.g., $\Delta\Sigma(x)$) depend on the "polarized dipole amplitude" $G_q(x_{10}\,, zs)$



$s = Q^2(1-x)/x$ is the invariant mass squared of the γ^*N system

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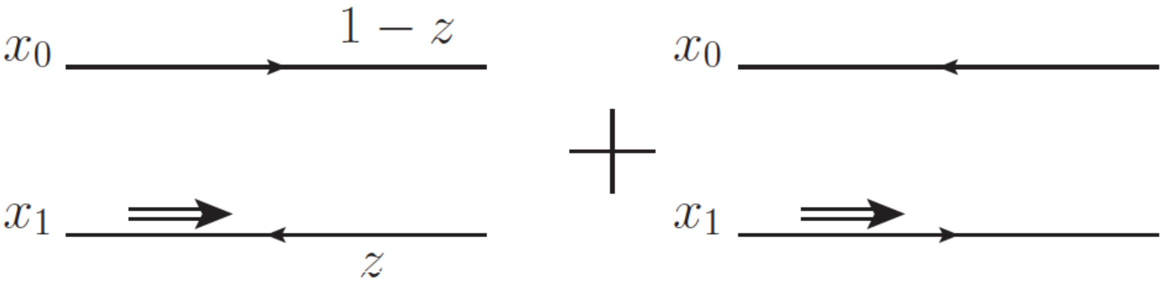

$$G_{10}(z) \equiv \frac{1}{2N_c} \text{Re} \left\langle\!\!\left\langle \text{T tr}\left[V_{\underline{0}} V_{\underline{1}}^{pol\,\dagger}\right] + \text{T tr}\left[V_{\underline{1}}^{pol} V_{\underline{0}}^{\dagger}\right] \right\rangle\!\!\right\rangle(z)$$

unpolarized quark

polarized quark: eikonal propagation, non-eikonal spin-dependent interaction

$$V_{\underline{x}} = \mathcal{P} \exp\left[ig \int\limits_{-\infty}^{\infty} dx^- A^+(0^+, x^-, \underline{x})\right]$$

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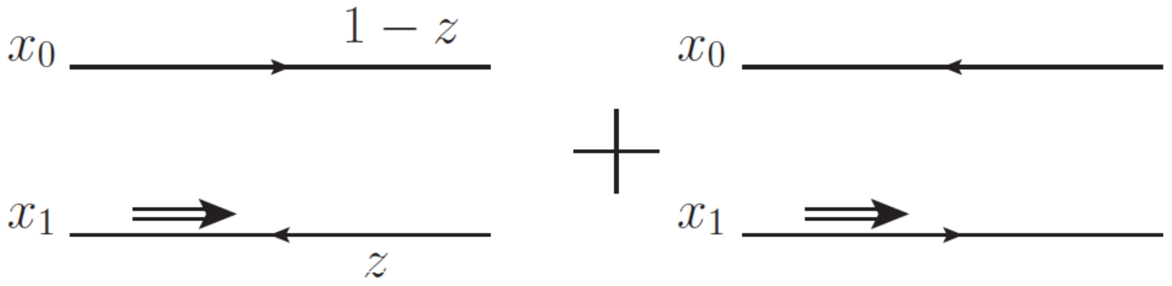

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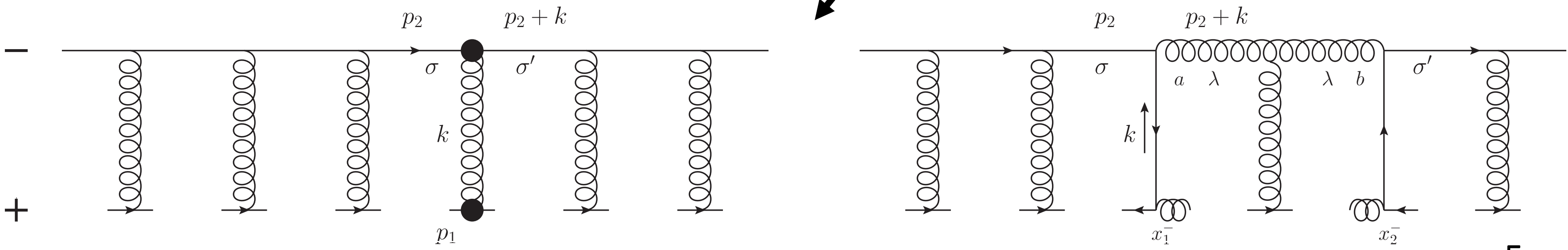
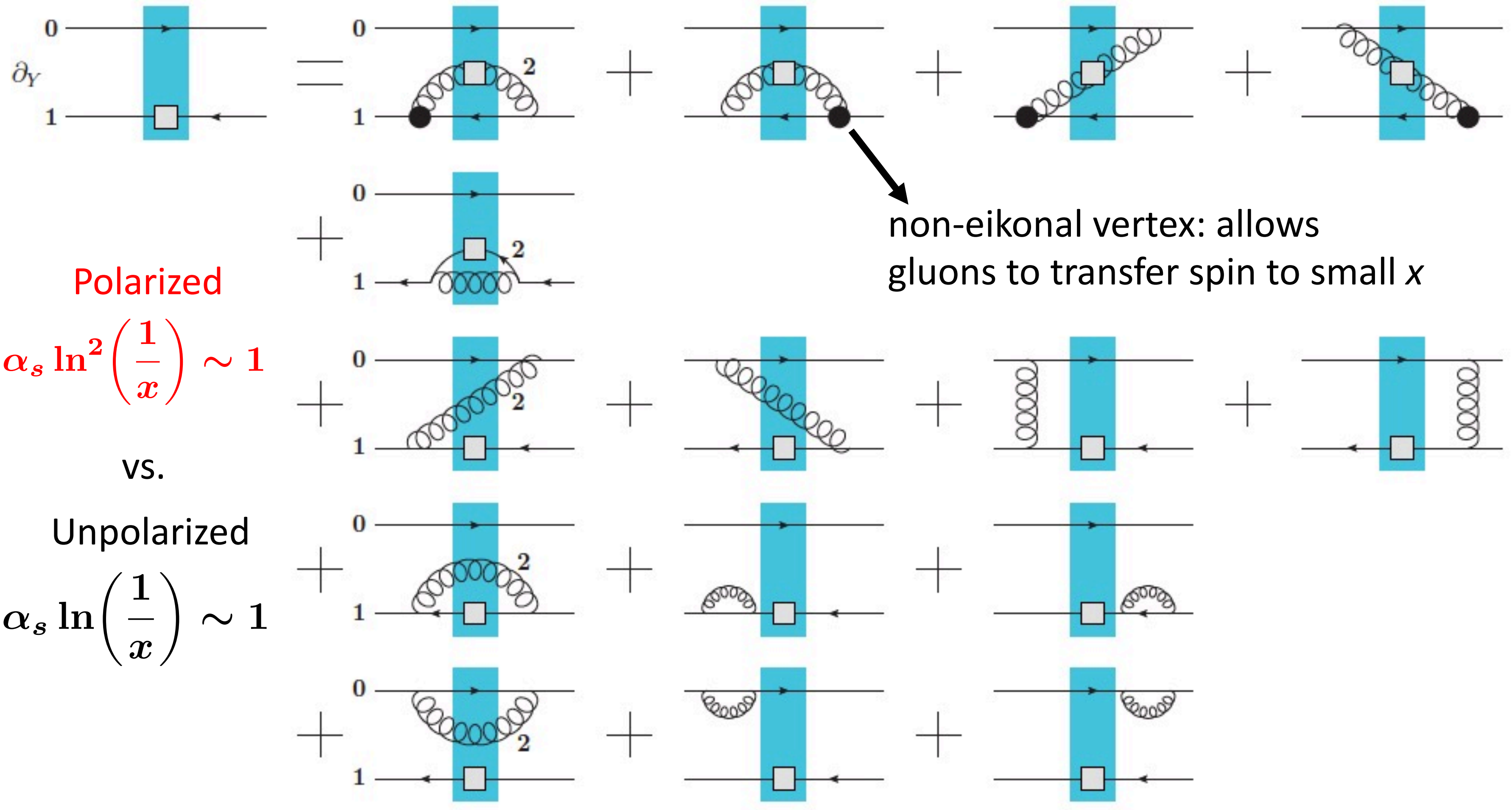


- The evolution of the polarized dipole amplitude diagrammatically takes on the following form (Kovchegov, DP, Sievert: JHEP **1601** (2016), PRL **118** (2017), PRD **95** (2017), PLB **772** (2017), JHEP **1710** (2017); Kovchegov & Sievert PRD **99** (2019))



non-eikonal vertex: allows gluons to transfer spin to small *x*

Polarized

$$\alpha_s \ln^2\left(\frac{1}{x}\right) \sim 1$$

vs.

Unpolarized

$$\alpha_s \ln\left(\frac{1}{x}\right) \sim 1$$

- The evolution equations close in the large-N_c (and large-N_c & -N_f) limit:

$$G_q(s_{10},\eta) = G_q^{(0)}(s_{10},\eta) + \underbrace{\int_{s_{10}}^{\eta} d\eta' \int_{s_{10}}^{\eta'} ds_{21} \left[\Gamma_q(s_{10},s_{21},\eta') + 3G_q(s_{21},\eta')\right]}_{\text{flavor } \textit{independent} \text{ evolution}}$$

polarized dipole amplitude

flavor dependent initial condition

$$\eta \equiv \sqrt{\frac{\alpha_s N_c}{2\pi}} \ln \frac{zs}{\Lambda^2}$$

$$s_{ij} \equiv \sqrt{\frac{\alpha_s N_c}{2\pi}} \ln \frac{1}{x_{ij}^2 \Lambda^2}$$

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“neighbor dipole”

$$\Gamma_q(s_{10},s_{21},\eta') = G_q^{(0)}(s_{10},\eta') + \int\limits_{s_{10}}^{\eta'} d\eta'' \int\limits_{\max[s_{10}\,,\,s_{21}-\eta'+\eta'']}^{\eta''} ds_{32} \left[\Gamma_q(s_{10},s_{32},\eta'') + 3G_q(s_{32},\eta'')\right]$$

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$$s_{ij} \equiv \sqrt{\frac{\alpha_s N_c}{2\pi}} \ln \frac{1}{x_{ij}^2 \Lambda^2}$$

- In the asymptotic high-energy regime (Kovchegov, DP, Sievert PRL **118** (2017))

$$\Delta\Sigma(x) \sim \left(\frac{1}{x}\right)^{\alpha_h^q} \quad \text{with} \quad \alpha_h^q = \frac{4}{\sqrt{3}}\sqrt{\frac{\alpha_s N_c}{2\pi}} \approx 2.31\sqrt{\frac{\alpha_s N_c}{2\pi}} \overset{\alpha_s=0.3}{\approx} 0.874$$

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- Using a different operator,

$$G_{10}^i(z) \equiv \frac{1}{4N_c}\int\limits_{-\infty}^{\infty} dx^- \left\langle \mathrm{tr}\left[V_{\underline{0}}[\infty,-\infty]V_{\underline{1}}[-\infty,x^-]\,(-ig)\,\tilde{A}^i(x^-,\underline{x})\,V_{\underline{1}}[x^-,\infty]\right] + \text{c.c.}\right\rangle(z)$$

one can derive the small-x evolution for ***Δg***(x) and finds the following high-energy asymptotics (Kovchegov, DP, Sievert JHEP **118** (2017)):

$$\Delta g(x) \sim \left(\frac{1}{x}\right)^{\alpha_h^G} \quad \text{with} \quad \alpha_h^G = \frac{13}{4\sqrt{3}}\sqrt{\frac{\alpha_s N_c}{2\pi}} \approx 1.88\sqrt{\frac{\alpha_s N_c}{2\pi}} \overset{\alpha_s=0.3}{\approx} 0.712$$

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➡ $S_q \gg S_g$ at small x

Phenomenological Results – Fit of the World Polarized DIS Data

D. Adamiak, Y. Kovchegov, W. Melnitchouk, DP, N. Sato and M. Sievert,
PRD **104**, L031501 (2021) [arXiv:2102.06159 [hep-ph]]

- Using the polarized dipole amplitude, we can calculate

$$\Delta q^+(x,Q^2) \equiv \Delta q(x,Q^2) + \Delta\bar{q}(x,Q^2)$$

$$= \frac{1}{\alpha_s\,\pi^2} \int\limits_0^{\ln\frac{Q^2}{x\,\Lambda^2}} d\eta \int\limits_{\max\left\{\eta-\ln\frac{1}{x},0\right\}}^{\eta} ds_{10}\;\; G_q(s_{10},\eta)$$

and at LO

$$g_1(x,Q^2) = \frac{1}{2}\sum_q e_q^2\,\Delta q^+(x,Q^2)$$

This allows us to carry out a fit of the world polarized DIS data on A_1 and $A_{||}$

$$A_1 \sim A_{\|} = \frac{\sigma_{+-} - \sigma_{++}}{\sigma_{+-} + \sigma_{++}} \sim \frac{g_1}{F_1}$$

$$\underset{\substack{\downarrow \\ \text{polarized dipole} \\ \text{amplitude}}}{G_q(s_{10}, \eta)} = \underset{\substack{\downarrow \\ \text{flavor dependent} \\ \text{initial condition}}}{G_q^{(0)}(s_{10}, \eta)} + \underbrace{\int\limits_{s_{10}}^{\eta} d\eta' \int\limits_{s_{10}}^{\eta'} ds_{21} \left[\Gamma_q(s_{10}, s_{21}, \eta') + 3 G_q(s_{21}, \eta') \right]}_{\text{flavor } \textit{independent} \text{ evolution}}$$

↓

fit to the data: $a_q \eta + b_q s_{10} + c_q$

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polarized dipole amplitude

flavor dependent initial condition

fit to the data: $a_q\eta + b_q s_{10} + c_q$

N.B.: Only using DIS data does *not* allow for a flavor separation of the helicity PDFs unless one assumes SU(3) symmetry of the sea and uses constraints from the octet axial charge a_8 . We do not utilize this constraint and instead extract only g_1^p and g_1^n.

$$G_p^{(0)}(s_{10},\eta) = a_p\,\eta + b_p\,s_{10} + c_p$$

$$G_n^{(0)}(s_{10},\eta) = a_n\,\eta + b_n\,s_{10} + c_n$$

- The KPS evolution equations must start at some low value of $x = x_0$. We fit the world polarized DIS data (proton, deuteron, and ^{3}He targets) using a cut of $x < x_0$ on the data

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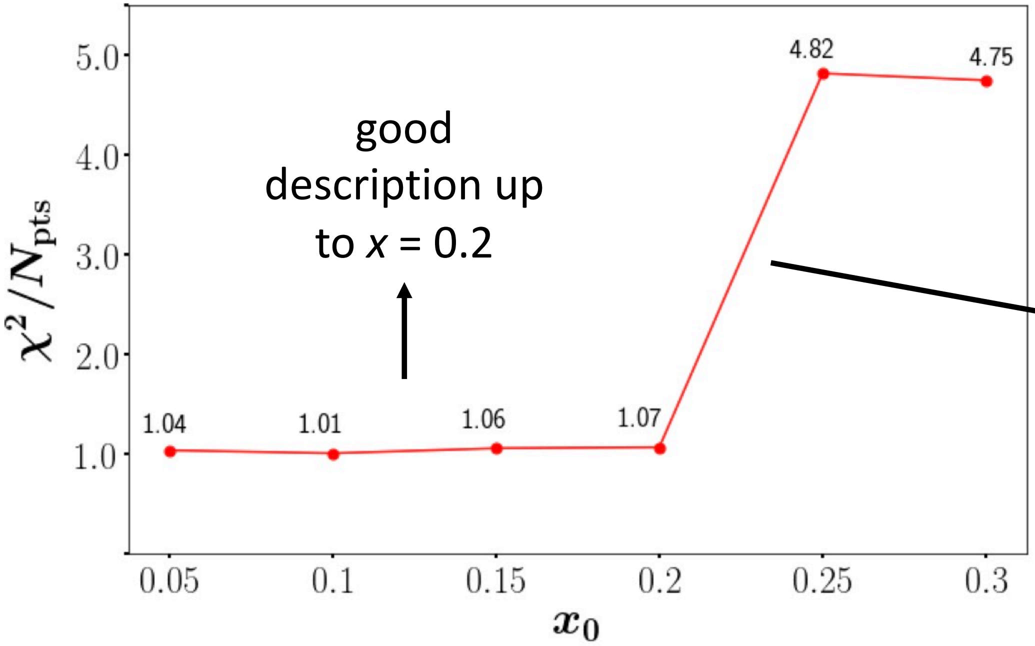
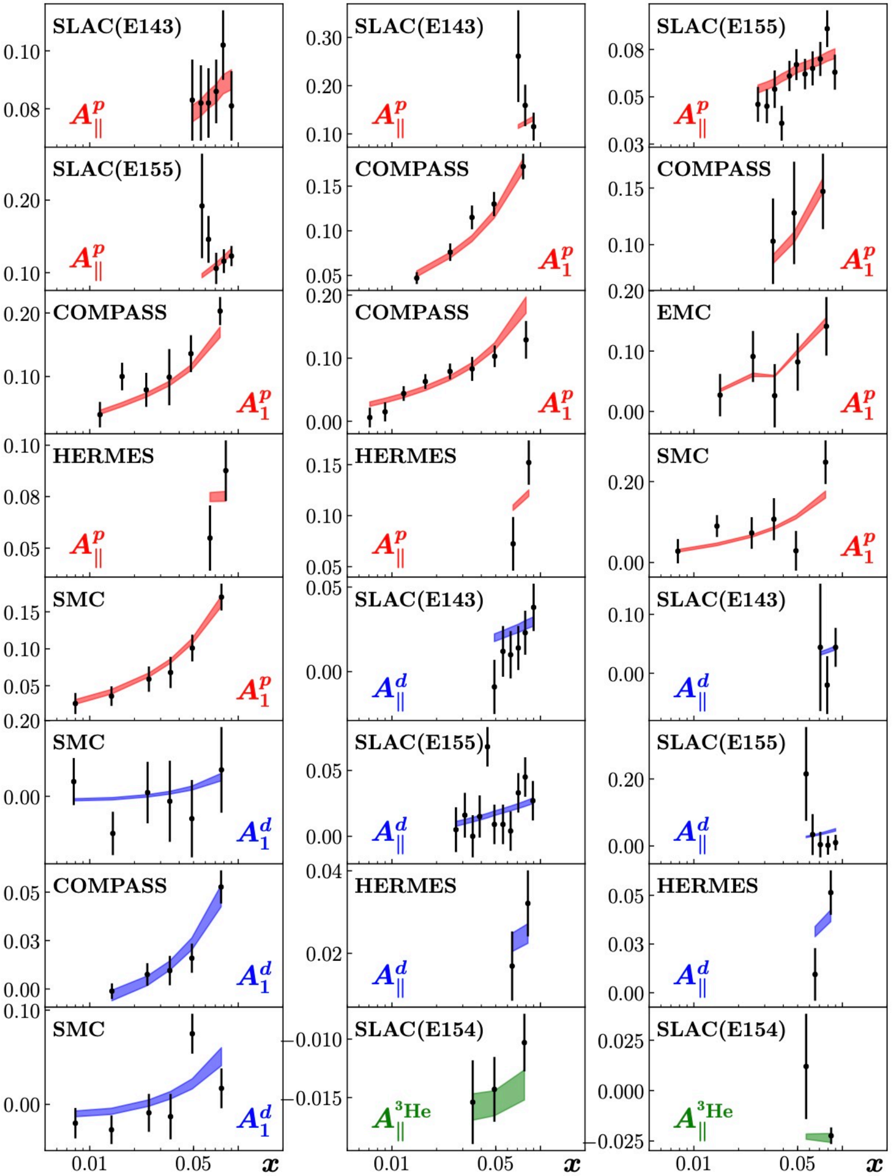


good description up to x = 0.2

breakdown of the framework at x > 0.2

- The results on the next slides are for $x_0 = 0.1$ (122 data points). The fits were preformed within the Jefferson Lab Angular Momentum (JAM) Collaboration Monte Carlo framework – refer to as JAMsmallx

$\chi^2/N_{\text{pts}} = 1.01$



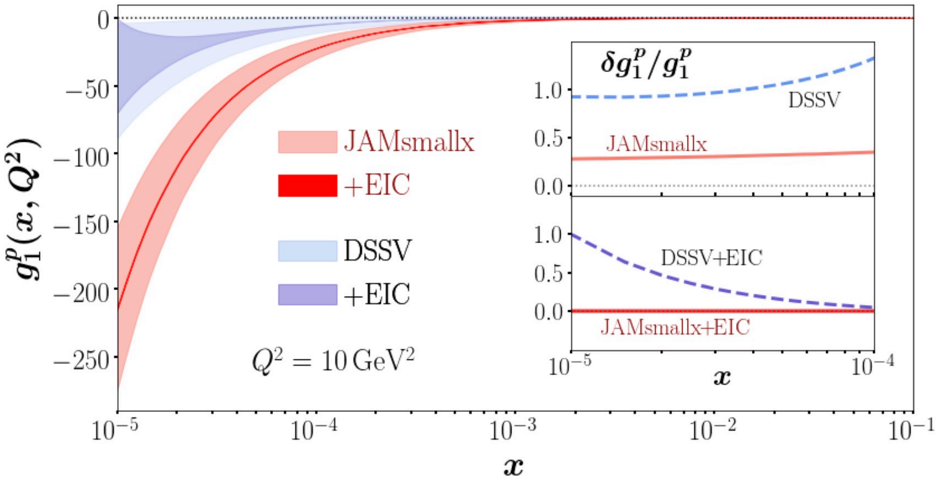
$$G_p^{(0)}(s_{10}, \eta) = a_p\,\eta + b_p\,s_{10} + c_p$$

$$G_n^{(0)}(s_{10}, \eta) = a_n\,\eta + b_n\,s_{10} + c_n$$

$a_p = -1.33 \pm 0.30$ $a_n = -2.47 \pm 0.65$

$b_p = 0.49 \pm 0.44$ $b_n = 3.03 \pm 1.01$

$c_p = 2.24 \pm 0.16$ $c_n = 0.30 \pm 0.36$



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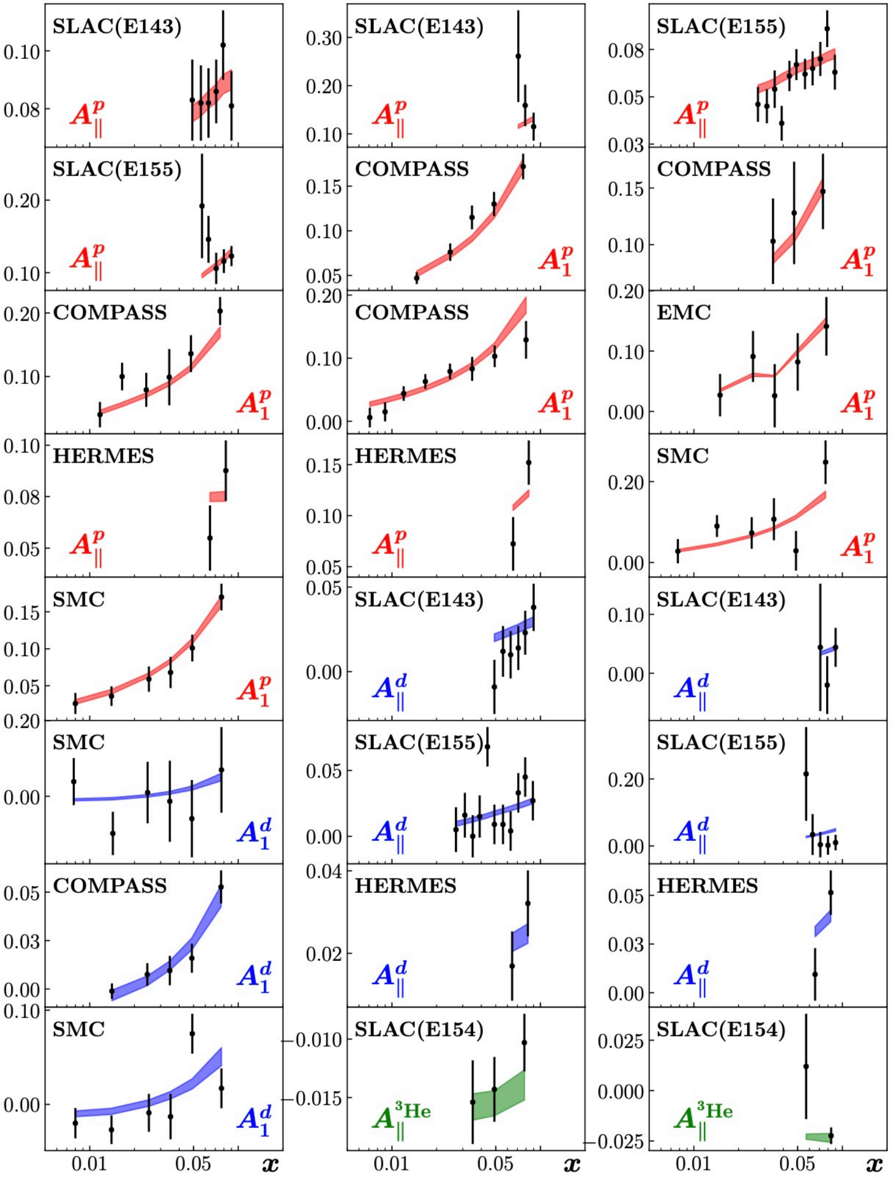

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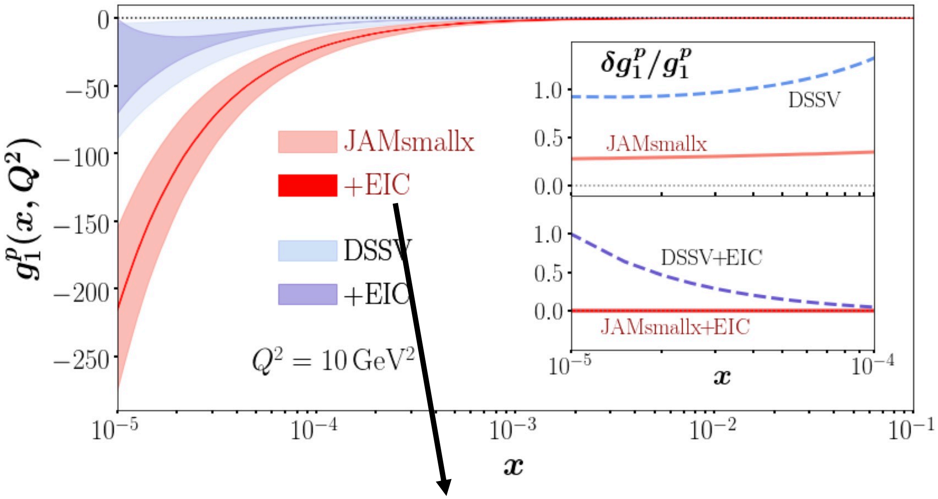
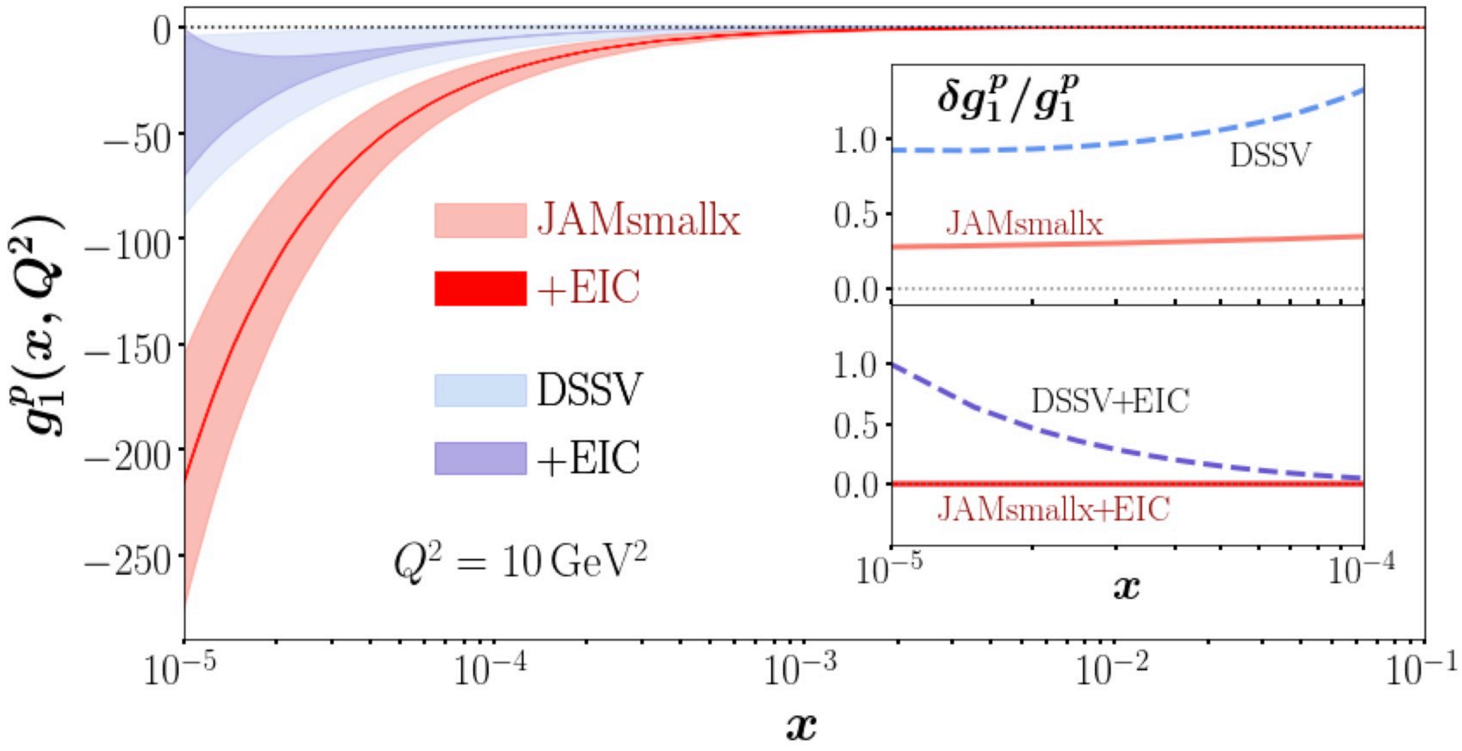
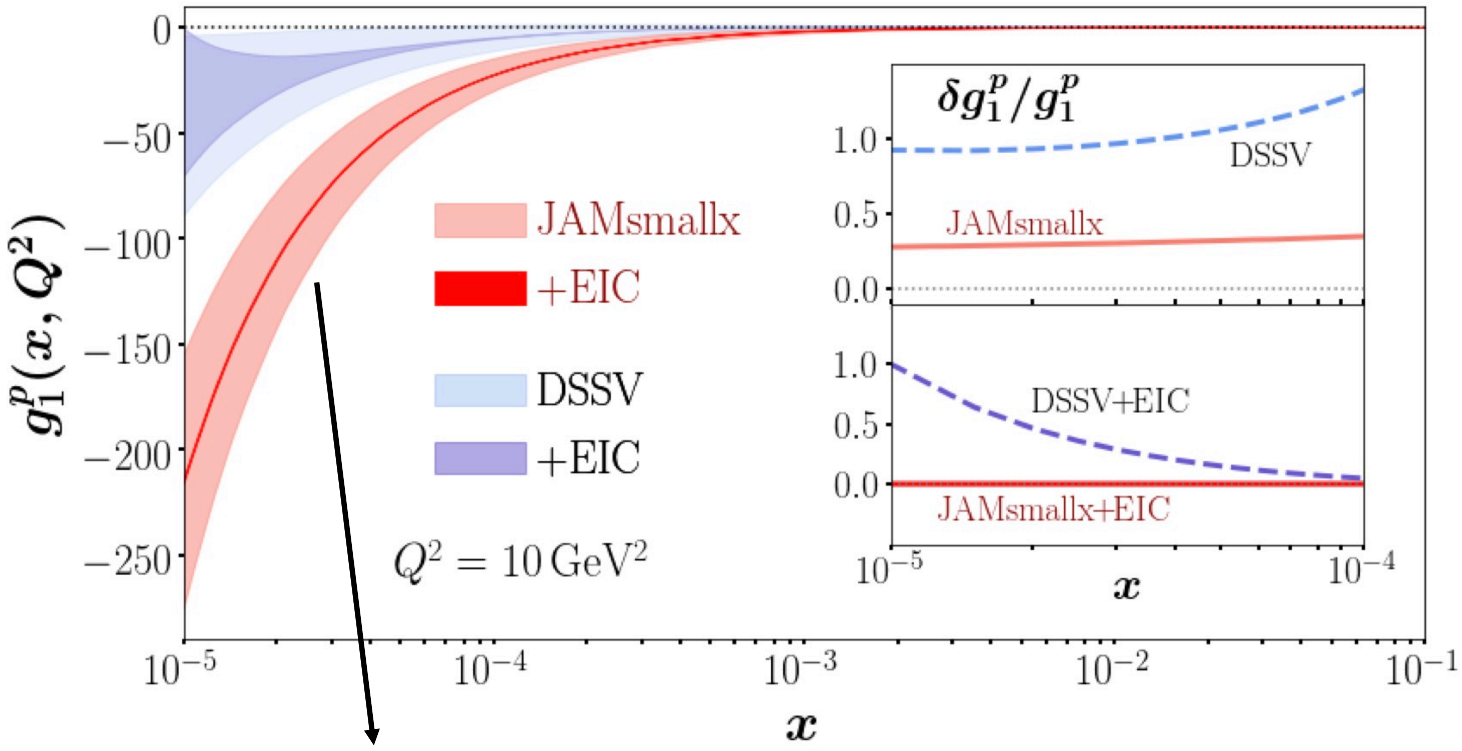
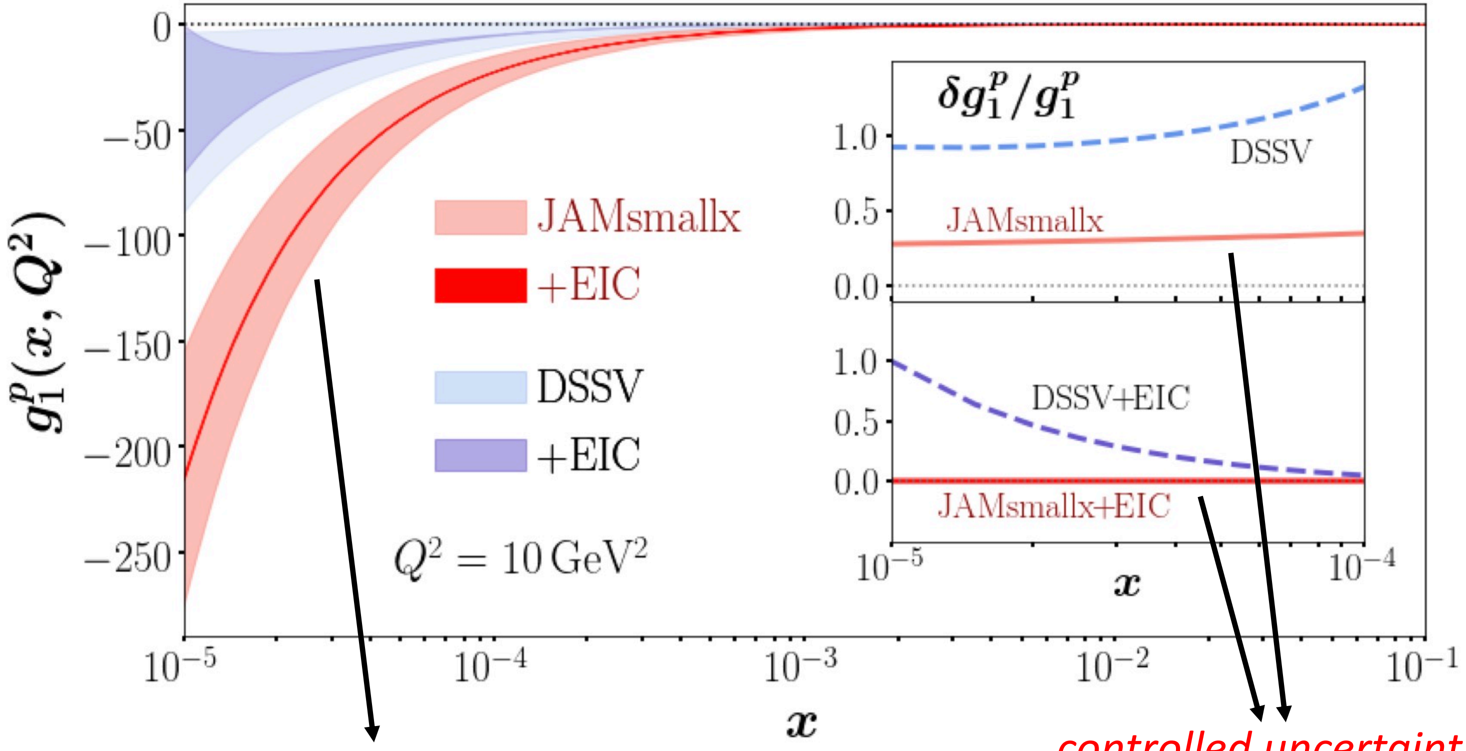


included EIC pseudo-data for DIS and PVDIS (1096 total data points)


$g_1^p(x, Q^2)$
0
−50
−100
−150
−200
−250
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
x
JAMsmallx
+EIC
DSSV
+EIC
$Q^2 = 10\,\mathrm{GeV}^2$
$\delta g_1^p / g_1^p$
1.0
0.5
0.0
DSSV
JAMsmallx
1.0
0.5
0.0
DSSV+EIC
JAMsmallx+EIC
10^{-5}
10^{-4}
x



prediction that, based on current DIS data, g_1^p goes negative at small *x*



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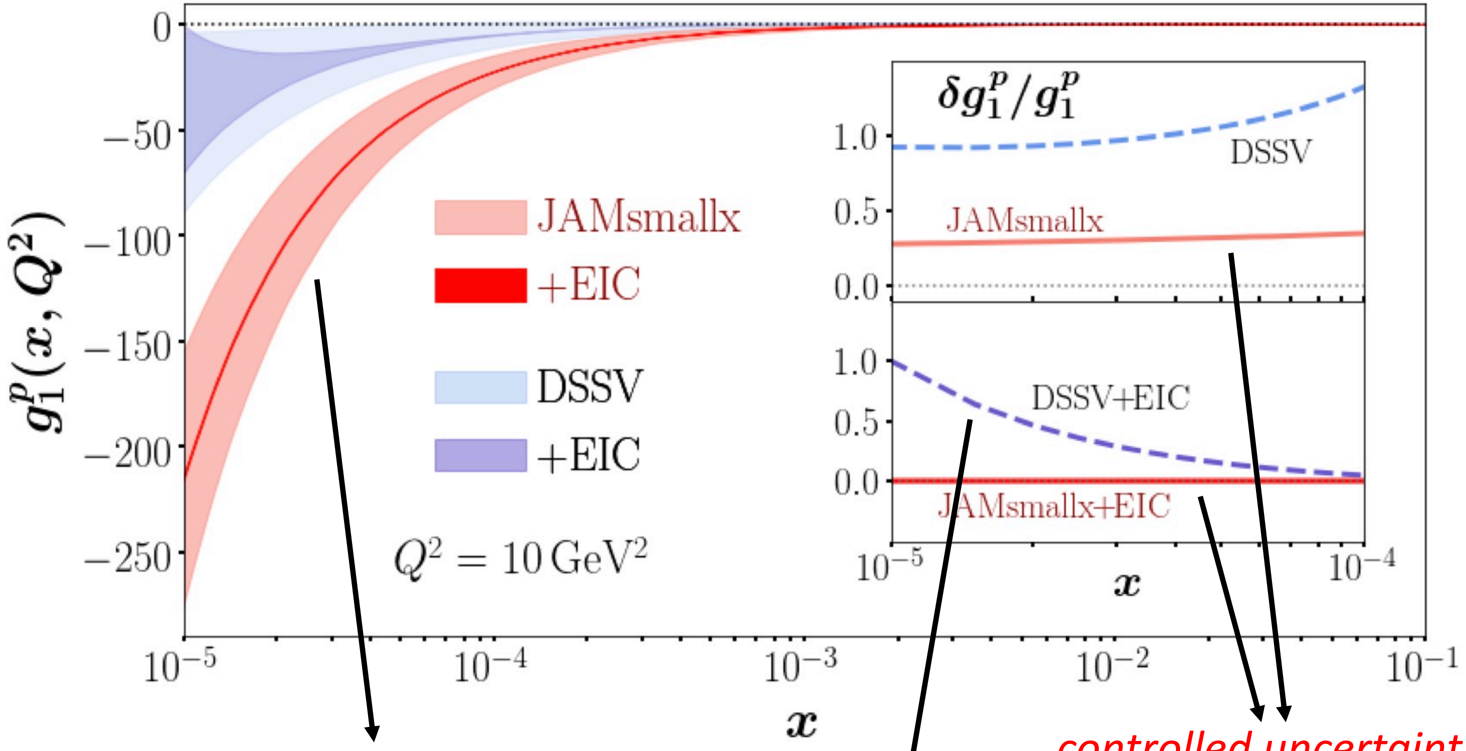
controlled uncertainties as one calculates beyond the measured region of *x*



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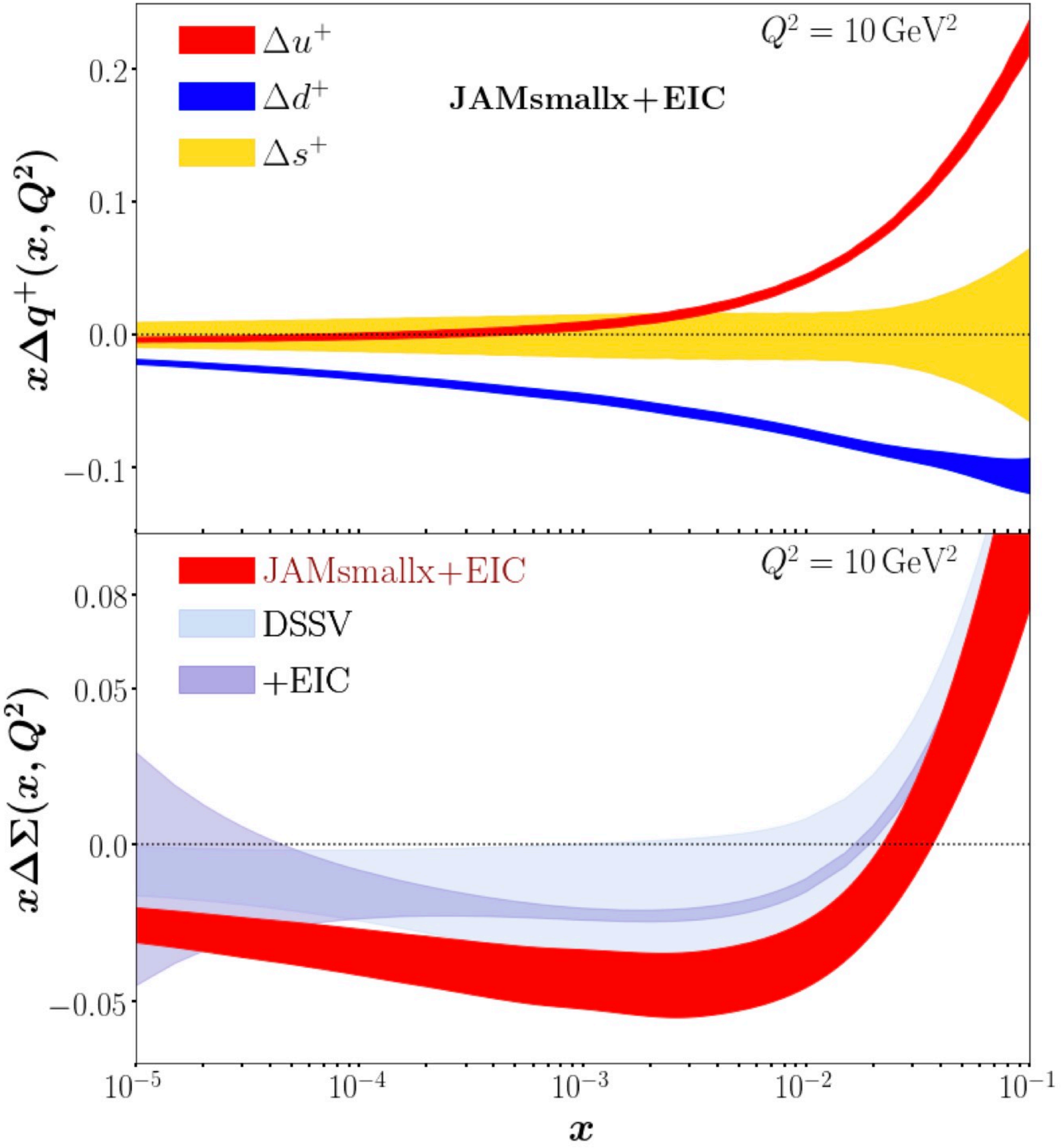
controlled uncertainties as one calculates beyond the measured region of *x*

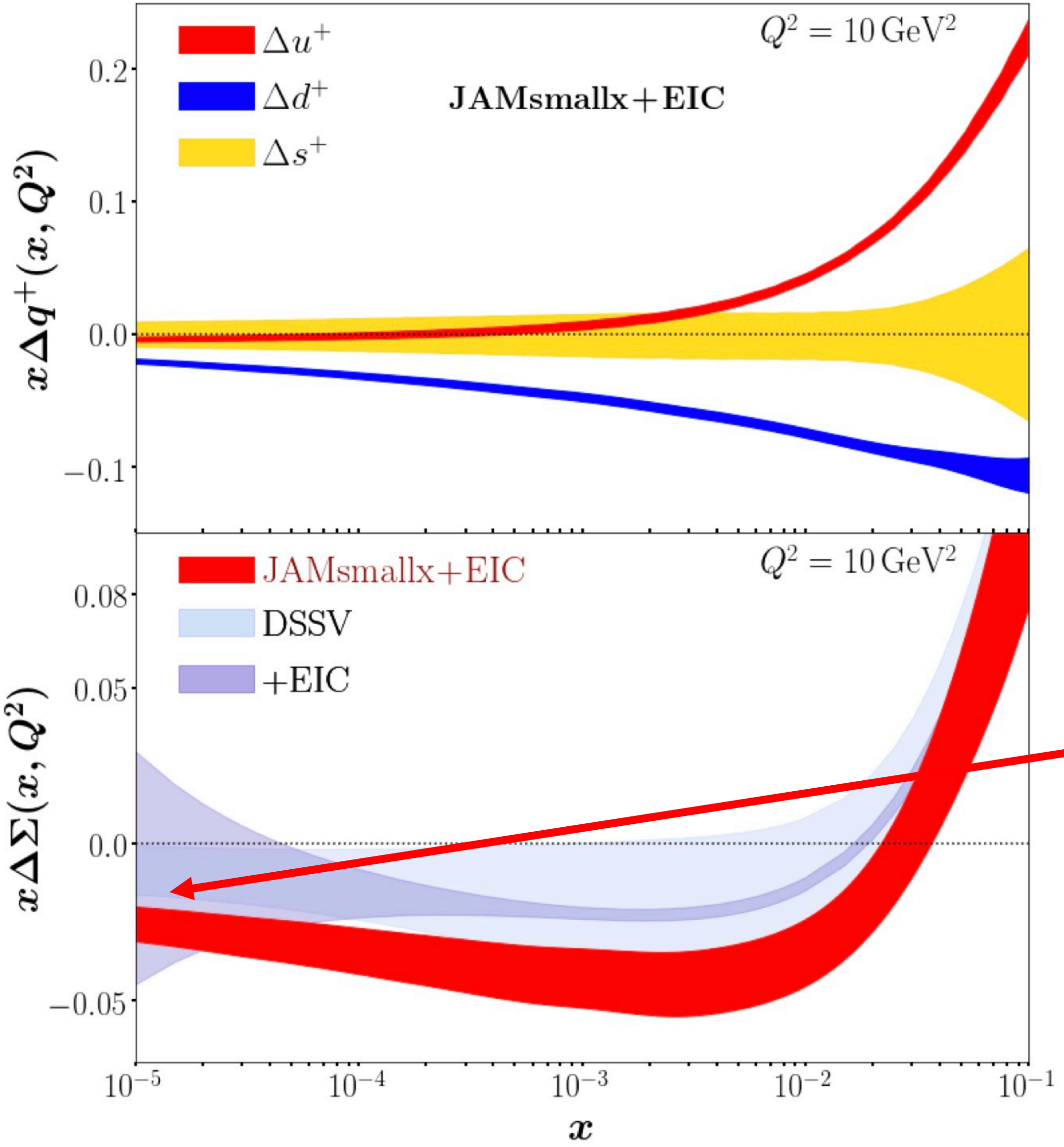
fits using DGLAP evolution *extrapolate* into the unmeasured region of *x* – uncertainties still “blow up” *even including EIC data*

- An opportunity presented by the EIC that can allow us to obtain a flavor separation using only DIS data is a measurement of parity-violating DIS (PVDIS)

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

- As a proof of principle that we can extract $\Delta u^+, \Delta d^+, \Delta s^+$ with our JAM-smallx framework, we fit EIC pseudo-data for PVDIS (and DIS) along with the current experimental DIS data


Δu^+
Δd^+
Δs^+
JAMsmallx+EIC
$Q^2 = 10\,\mathrm{GeV}^2$
0.2
0.1
0.0
−0.1
$x\Delta q^+(x, Q^2)$
JAMsmallx+EIC
DSSV
+EIC
$Q^2 = 10\,\mathrm{GeV}^2$
0.08
0.05
0.0
−0.05
$x\Delta\Sigma(x, Q^2)$
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
x



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

KPS evolution allows for S_q (and S_g) to be calculated with precision down to very small *x* values, beyond what the EIC will reach

A Possible Path to Resolving the Spin Puzzle

$$\frac{1}{2} = S_q + \mathcal{L}_q + S_g + \mathcal{L}_g$$

$$S_q\Big|_{\text{large}\,x} = \frac{1}{2}\int_{0.001}^{1} dx\,\Delta\Sigma(x,Q^2) \approx 0.18$$

$$S_g\Big|_{\text{large}\,x} = \int_{0.05}^{1} dx\,\Delta g(x,Q^2) \approx 0.20$$

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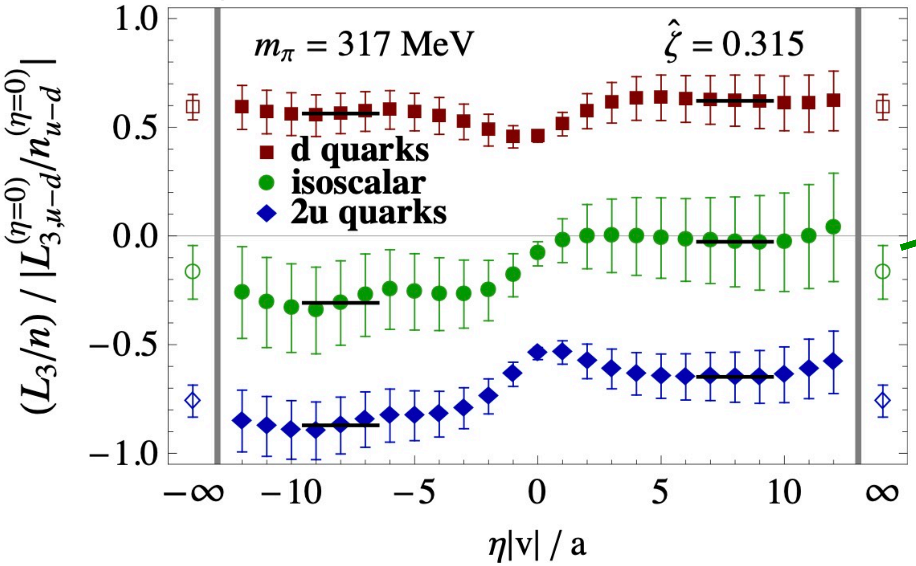
$$\mathcal{L}_q + \mathcal{L}_g = \text{whatever is left ???}$$

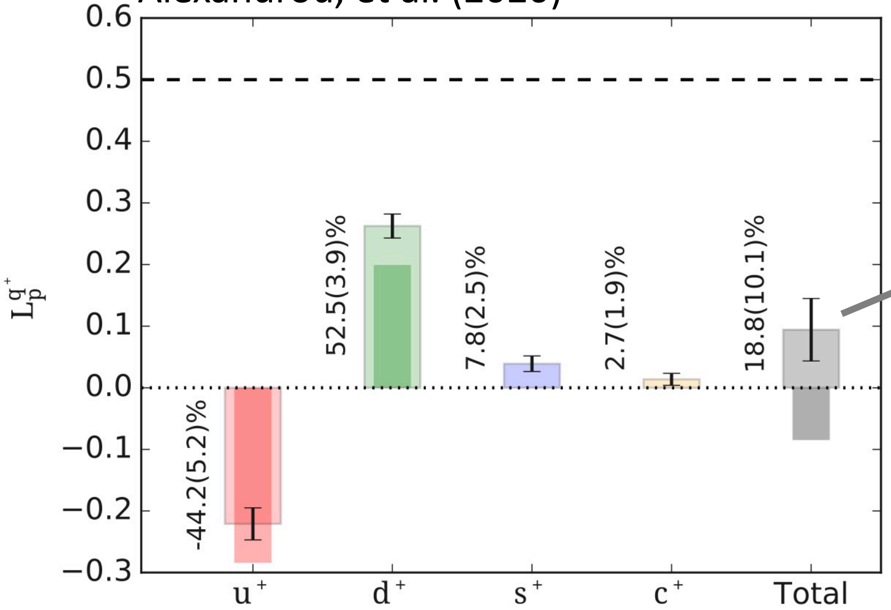
Engelhardt, et al. (2020)



Jaffe-Manohar OAM from u+d quarks

(no disconnected diagrams; not at the physical point)

Alexandrou, et al. (2020)



Ji OAM from all quarks

(includes disconnected diagrams; at the physical point)

- Using similar techniques as those used to derive small-*x* helicity evolution, one can show at small *x* (Hatta and Yang (2018); Kovchegov (2019))

$$\mathcal{L}_q(x,Q^2) = -\Delta\Sigma(x,Q^2)$$

➡ small *x* contribution to $S_q + \mathcal{L}_q$ is given by

$$(S_q + \mathcal{L}_q)\big|_{\mathrm{small}\,x} = -\frac{1}{2}\int_0^{x_{max}} dx\,\Delta\Sigma(x,Q^2)$$

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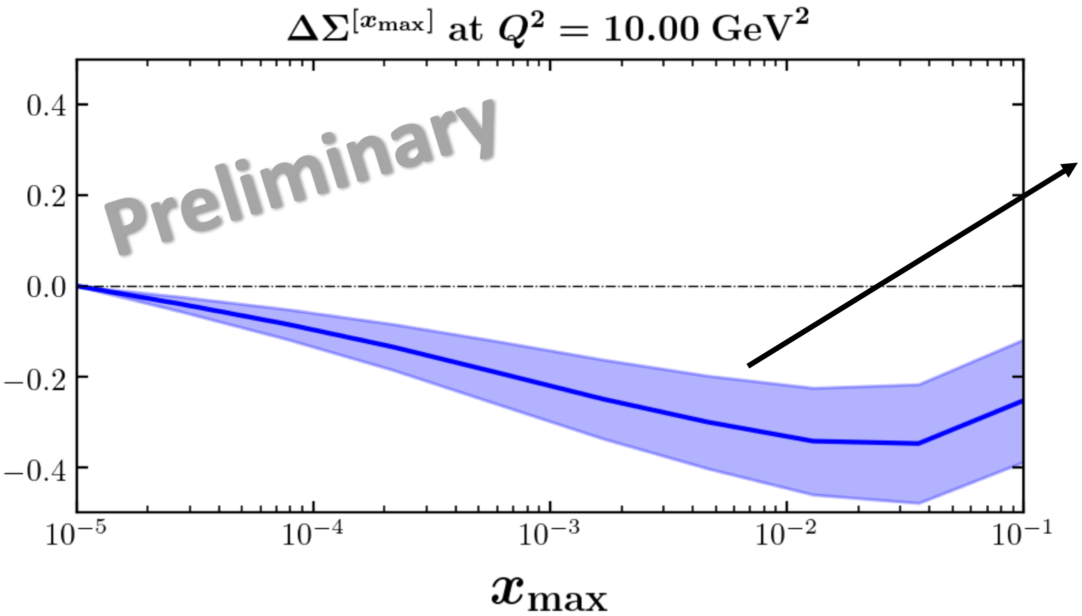
$$\mathcal{L}_q(x,Q^2) = -\Delta\Sigma(x,Q^2)$$

➡ small x contribution to $S_q + \mathcal{L}_q$ is given by

$$(S_q + \mathcal{L}_q)\big|_{\mathrm{small}\,x} = -\frac{1}{2}\int_{10^{-5}}^{x_{max}} dx\,\Delta\Sigma(x,Q^2)$$



PRELIMINARY result from JAMsmall*x* fit of polarized DIS+SIDIS data

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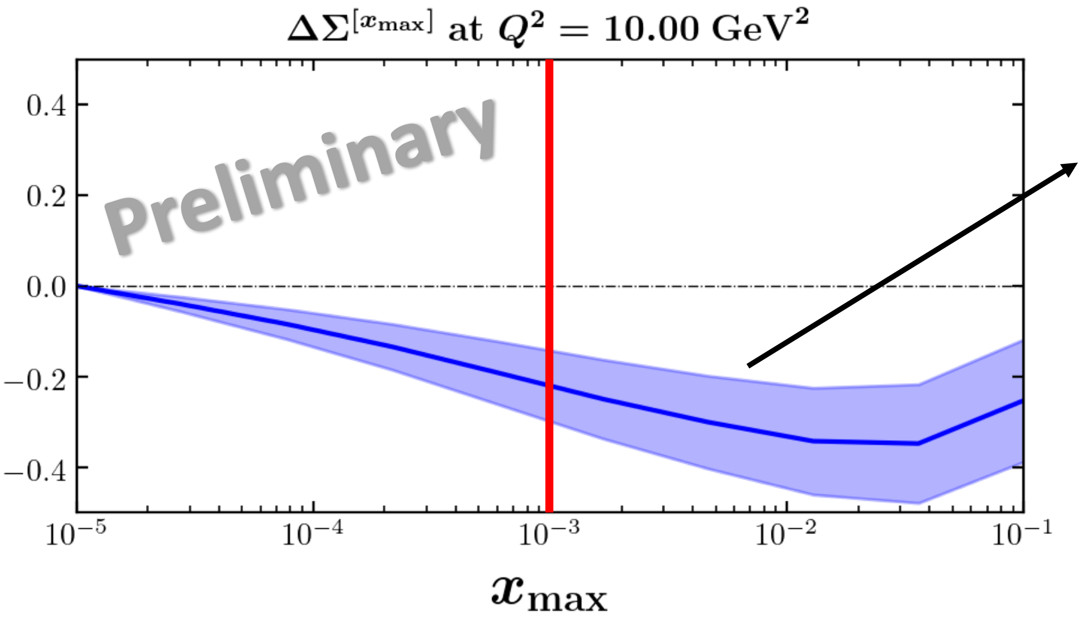
$$(S_q + \mathcal{L}_q)\big|_{\text{small}\, x} = -\frac{1}{2}\int_{10^{-5}}^{10^{-3}} dx\, \Delta\Sigma(x, Q^2) \approx 0.1$$



PRELIMINARY result from JAMsmall*x* fit of polarized DIS+SIDIS data

$$\frac{1}{2} = S_q + \mathcal{L}_q + S_g + \mathcal{L}_g$$

$$S_q\big|_{\text{large}\,x} = \frac{1}{2}\int_{0.001}^{1} dx\,\Delta\Sigma(x,Q^2) \approx 0.18$$

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$$(S_q + \mathcal{L}_q)\big|_{\text{small}\,x} = -\frac{1}{2}\int_{10^{-5}}^{10^{-3}} dx\,\Delta\Sigma(x,Q^2) \approx 0.1$$

Recall $S_q \gg S_g$ at small x

Also, $\mathcal{L}_g(x,Q^2) \ll \Delta g(x,Q^2)$ at small x (Kovchegov (2019))

$$\frac{1}{2} = S_q + \mathcal{L}_q + S_g + \mathcal{L}_g$$

$$\left.\begin{aligned} S_q\big|_{\text{large}\,x} &= \frac{1}{2}\int_{0.001}^{1} dx\,\Delta\Sigma(x,Q^2) \approx 0.18 \\ S_g\big|_{\text{large}\,x} &= \int_{0.05}^{1} dx\,\Delta g(x,Q^2) \approx 0.20 \\ (S_q+\mathcal{L}_q)\big|_{\text{small}\,x} &= -\frac{1}{2}\int_{10^{-5}}^{10^{-3}} dx\,\Delta\Sigma(x,Q^2) \approx 0.1 \end{aligned}\right\} \mathbf{0.48}$$

Recall $S_q \gg S_g$ at small x

Also, $\mathcal{L}_g \approx 0$ at small x

$$\frac{1}{2} = S_q + \mathcal{L}_q + S_g + \mathcal{L}_g$$

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Recall $S_q \gg S_g$ at small x

Also, $\mathcal{L}_g \approx 0$ at small x

If quark and gluon (Jaffe-Manohar) OAM is negligible at large *x*, small-*x* partons may give the remainder of the proton spin

Summary and Outlook

- We have shown the JAMsmallx framework, utilizing KPS evolution, can fit the world polarized DIS data at $x < 0.1$, with significantly reduced uncertainties (compared to "standard" DGLAP fits) as one extends into the unmeasured (small-x) region

- We are working on including polarized SIDIS data to perform a flavor separation and make a genuine prediction for the spin carried by quarks at small x. Also polarized proton-proton collisions will be explored (access to $\Delta g(x)$).

- Additional future updates will also include single-log corrections (Kovchegov, Tarasov, Tawabutr (2021)) and using solutions for the large-N_c & -N_f KPS evolution equations (Kovchegov and Tawabutr (2020))

KPS evolution provides a controlled way to extend helicity PDFs down to very small *x* and will be a crucial ingredient to resolve the proton spin puzzle, especially once EIC data is available