JAM-small x Helicity Phenomenology

Daniel Adamiak [1]
Yu. Kovchegov [1] W. Melnitchouk [2] D. Pitonyak[3] N. Sato [2]
M. Sievert [4]

[1]Department of Physics, The Ohio State University

[2]Jefferson Lab

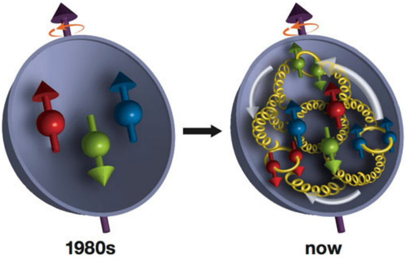
[3]Lebanon Valley College

[4]New Mexico State University

DIS 2021

OCGtools: processing OCG's ...

Proton Spin Problem



Spin Sum Rule

Jaffe-Manohar Spin Sum Rule:

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

Spin Sum Rule

Jaffe-Manohar Spin Sum Rule:

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

$\boldsymbol{S_q}(S_G)$ is the total spin of the quarks (Gluons)

Spin Sum Rule

Jaffe-Manohar Spin Sum Rule:

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

$\boldsymbol{S_q}(S_G)$ is the total spin of the quarks (Gluons)
$L_q(L_G)$ is the total orbital angular momentum of the quarks (gluons)

Spin Sum Rule

Jaffe-Manohar Spin Sum Rule:

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

$\boldsymbol{S_q}(S_G)$ is the total spin of the quarks (Gluons)
$L_q(L_G)$ is the total orbital angular momentum of the quarks (gluons)

Existing experiments can only measure a finite portion of $\boldsymbol{S_q}$, finding it accounts for only 30% of the proton spin.

Spin Sum Rule

Jaffe-Manohar Spin Sum Rule:

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

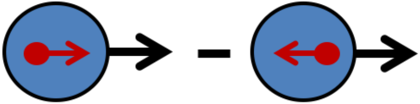
$\boldsymbol{S_q}(S_G)$ is the total spin of the quarks (Gluons)
$L_q(L_G)$ is the total orbital angular momentum of the quarks (gluons)

Existing experiments can only measure a finite portion of $\boldsymbol{S_q}$, finding it accounts for only 30% of the proton spin.

We can calculate (most) of $\boldsymbol{S_q}$

Helicity Parton Distribution Functions

$$S_q(Q^2) = \frac{1}{2} \int_0^1 dx \sum_q (\Delta q(x, Q^2) + \Delta \bar{q}(x, Q^2))$$

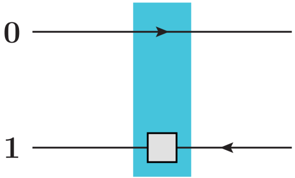
$\Delta q =$ 

- Q^2 resolution at which we probe the proton
- $x \propto \frac{1}{s}$, we need theory to find the dependence of

Calculating Helicity Distributions

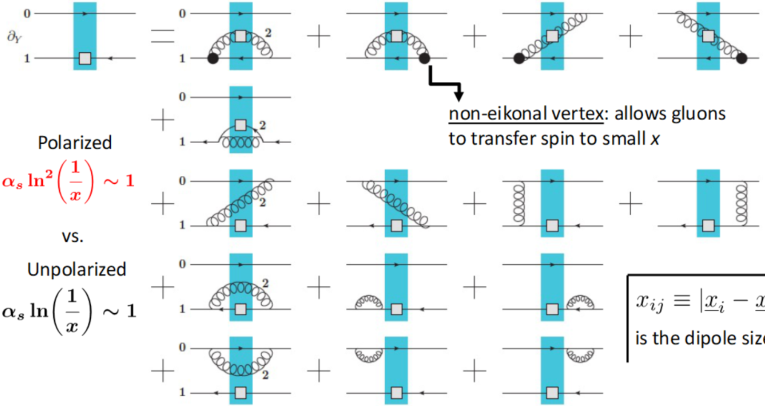
Helicity distributions are computed from the polarized dipole amplitude

$$\Delta q(x, Q^2) + \Delta \bar{q}(x, Q^2) = \frac{N_c}{2\pi^3} \int\limits_0^{\ln \frac{Q^2}{x\Lambda^2}} d\eta \int\limits_{\max\left\{0,\ \ln \frac{1}{x}\right\}}^{\eta} ds_{10}\ G_q(s_{10}, \eta)$$

$G =$ 

- Rapidity, $\eta = \ln \frac{zs}{\Lambda^2}$, $z =$ momentum fraction of quark
- Log of transverse momentum, $s_{10} = \ln \frac{1}{x_{10}^2 \Lambda^2}$, x_{10} separation between quarks

Small-x helicity (KPS) evolution involves the "polarized dipole amplitude" (Kovchegov, Pitonyak, Sievert: JHEP 1601 (2016), PRL 118 (2017), PRD 95 (2017), PLB 772 (2017), JHEP 1710 (2017); Kovchegov & Sievert PRD 99 (2019);Kovchegov & Cougoulic PRD 100 (2019))



$x_{ij} \equiv |\underline{x}_i - \underline{x}_j|$

is the dipole size

KPS Evolution

Evolution of polarized dipole amplitude closes in the large N_c limit:

$$G_q(s_{10}, \eta) = G_q^{(0)}(s_{10}, \eta) + \frac{\alpha_s N_c}{2\pi} \int_{s_{10}}^{\eta} d\eta' \int_{s_{10}}^{\eta'} ds_{21} \left[\Gamma_q(s_{10}, s_{21}, \eta') + 3 G_q(s_{21}, \eta')\right.$$

KPS Evolution

Evolution of polarized dipole amplitude closes in the large N_c limit:

$$G_q(s_{10}, \eta) = G_q^{(0)}(s_{10}, \eta) + \frac{\alpha_s N_c}{2\pi} \int_{s_{10}}^{\eta} d\eta' \int_{s_{10}}^{\eta'} ds_{21} \left[\Gamma_q(s_{10}, s_{21}, \eta') + 3G_q(s_{21}, \eta')\right.$$

- $G_q^{(0)}(s_{10}, \eta)$ is a flavour dependent initial condition that is fit to data.
- $G_q^{(0)}(s_{10}, \eta) = a_q \ \eta + b_q \ s_{10} + c_q$

KPS Evolution

Evolution of polarized dipole amplitude closes in the large N_c limit:

$$G_q(s_{10}, \eta) = G_q^{(0)}(s_{10}, \eta) + \frac{\alpha_s N_c}{2\pi} \int\limits_{s_{10}}^{\eta} d\eta' \int\limits_{s_{10}}^{\eta'} ds_{21} \left[\Gamma_q(s_{10}, s_{21}, \eta') + 3 G_q(s_{21}, \eta')\right.$$

- $G_q^{(0)}(s_{10}, \eta)$ is a flavour dependent initial condition that is fit to data.
- $G_q^{(0)}(s_{10}, \eta) = a_q\ \eta + b_q\ s_{10} + c_q$
- $\Gamma_q(s_{10}, s_{21}, \eta')$ is an auxiliary function which obeys a separate integral equation that mixes with G.

Mid-talk recap

$$S_q(Q^2) = \frac{1}{2}\int_0^1 dx \ \sum_q (\Delta q(x, Q^2) + \Delta\bar{q}(x, Q^2))$$

Mid-talk recap

$$S_q(Q^2) = \frac{1}{2}\int_0^1 dx \ \sum_q (\Delta q(x, Q^2) + \Delta\bar{q}(x, Q^2))$$

$$\uparrow$$

$$\Delta q(x, Q^2) + \Delta\bar{q}(x, Q^2) = \frac{N_c}{2\pi^3}\int d\eta \int ds_{10} \ G_q(s_{10}, \eta)$$

Mid-talk recap

$$S_q(Q^2) = \frac{1}{2}\int_0^1 dx\ \sum_q (\Delta q(x,Q^2) + \Delta\bar{q}(x,Q^2))$$

$$\uparrow$$

$$\Delta q(x,Q^2) + \Delta\bar{q}(x,Q^2) = \frac{N_c}{2\pi^3}\int d\eta \int ds_{10}\ G_q(s_{10},\eta)$$

$$\uparrow$$

$$G_q(s_{10},\eta) = G_q^{(0)}(s_{10},\eta) + \frac{\alpha_s N_c}{2\pi}\int_{s_{10}}^{\eta} d\eta' \int_{s_{10}}^{\eta'} ds_{21}\left[\Gamma_q(s_{10},s_{21},\eta') + 3G_q(s_{21},\eta')\right]$$

Constraining the initial condition

What enters observables are linear combinations of hPDFS

$$\Delta q^{+} = \Delta q + \Delta \bar{q}$$

Constraining the initial condition

What enters observables are linear combinations of hPDFS

$$\Delta q^{+} = \Delta q + \Delta \bar{q}$$

- Three relevant hPDFs in DIS: $\Delta u^{+}, \Delta d^{+}$ and Δs^{+}

Constraining the initial condition

What enters observables are linear combinations of hPDFS

$$\Delta q^{+} = \Delta q + \Delta \bar{q}$$

- Three relevant hPDFs in DIS: $\Delta u^{+}, \Delta d^{+}$ and Δs^{+}
- Three observables that contain these hPDFs in linearly independent combinations: g_1^p, g_1^n and $g_1^{\gamma Z}$.

Constraining the initial condition

What enters observables are linear combinations of hPDFS

$$\Delta q^{+} = \Delta q + \Delta \bar{q}$$

- Three relevant hPDFs in DIS: $\Delta u^{+}, \Delta d^{+}$ and Δs^{+}
- Three observables that contain these hPDFs in linearly independent combinations: g_1^p, g_1^n and $g_1^{\gamma Z}$.
- Only have data for g_1^p and g_1^n

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

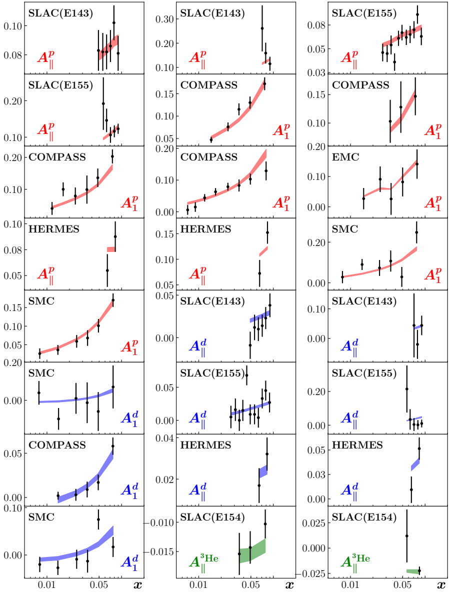
Fitting to data

Observables predicted by our formalism: Double spin asymmetries

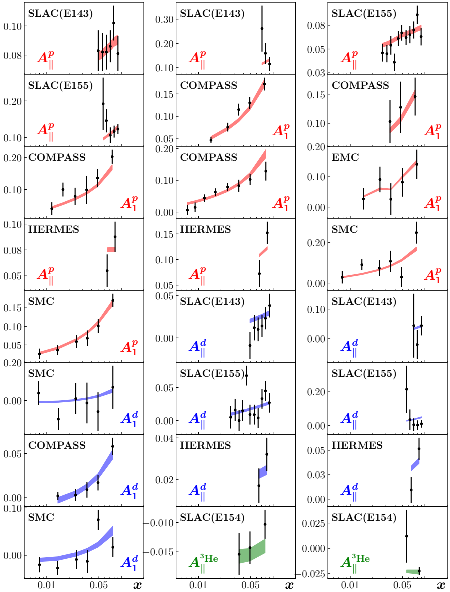
$$A_{||} = \frac{\sigma^{\uparrow\Downarrow} - \sigma^{\uparrow\Uparrow}}{\sigma^{\uparrow\Downarrow} + \sigma^{\uparrow\Uparrow}} \propto A_1 \propto g_1$$

$\uparrow$ ($\downarrow$) is Positive (negative) helicity electron
$\Uparrow$ ($\Downarrow$) is Positive (negative) helicity proton
A_1 is a virtual photoproduction asymmetry

Fitting to data

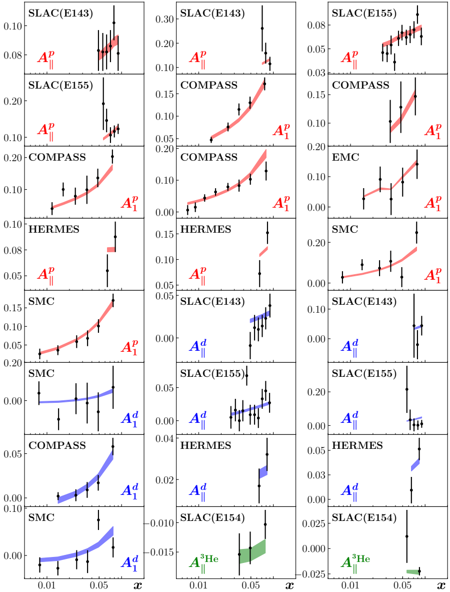


Fitting to data



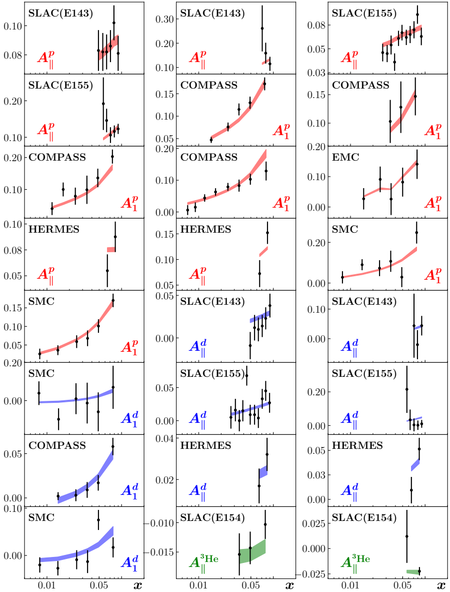
- First fit of small-x theory to polarized data
- With a cut of $x < 0.1$

Fitting to data



- First fit of small-x theory to polarized data
- With a cut of $x < 0.1$
- We re-sum $\alpha_s \ln^2 \frac{1}{x}$, which allows us to reach larger x

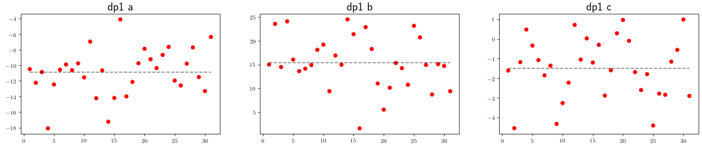
Fitting to data

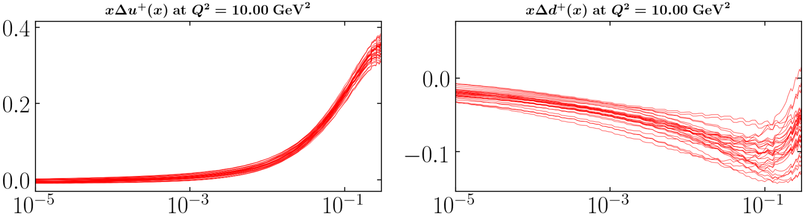


- First fit of small-x theory to polarized data
- With a cut of $x < 0.1$
- We re-sum $\alpha_s \ln^2 \frac{1}{x}$, which allows us to reach larger x
- $\chi^2/npts = 1.01$

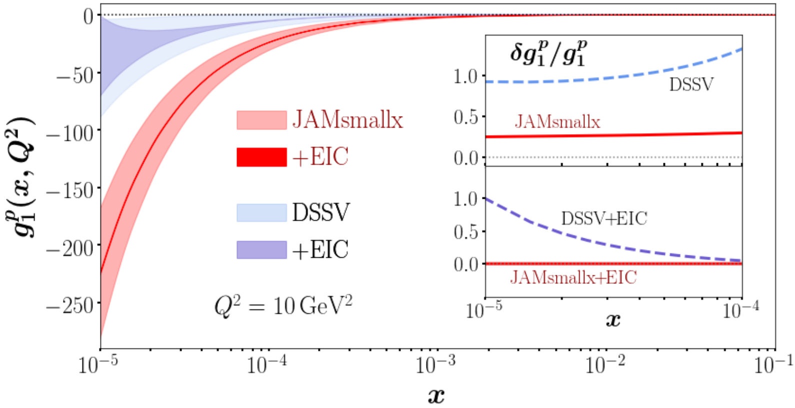
JAM framework

Monte-Carlo generation of parameters that tend towards minimum χ^2





Predictions for Electron Ion Collider

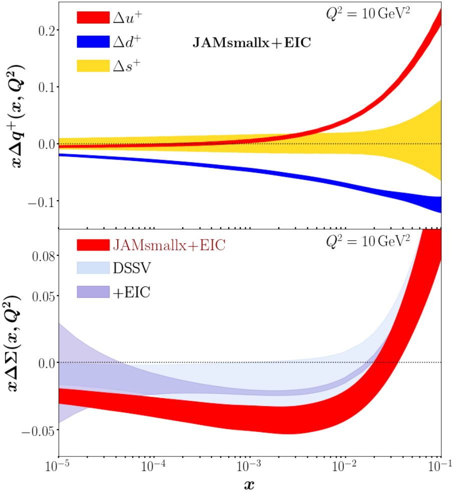


- Predict large negative g_1
- Significant improvement in error from EIC

Helicity PDFs

Preliminary extraction of hPDFs and $\Delta\Sigma = \frac{1}{2}\sum_q \Delta q^+(x, Q^2)$

(assuming $\Delta s^+ = 0$)



Conclusions

- We have a theory that describes the hPDFs in terms of the polarized dipole amplitude
- Performed the first small-x fit to world polarized DIS data
- Predicted g_1 down to $x = 10^{-5}$
- While maintaining control over the uncertainty
- Preliminary extraction of the hPDFs and quark spin contribution

Outlook

- Fit to other measurements (Semi-inclusive DIS) to further constrain the helicity PDFs
- Large N_c & N_f (include quarks into quark evolution)(Kovchegov, Tawabutr, JHEP 08 (2020))
- Include higher-order correction to evolution, such as the single log contribution and running coupling (See Josh's talk: Wednesday 13:45 in the spin session)