Small-x Helicity Global Analysis: Now With Polarized pp Data

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SURGE COLLABORATION

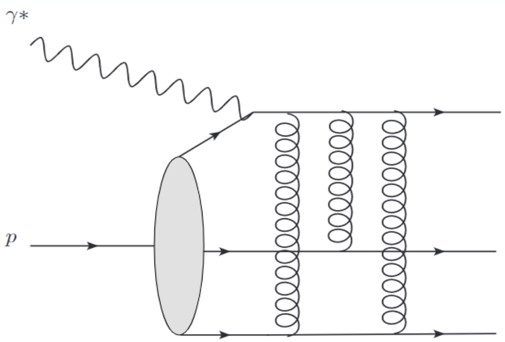
Proton Spin Puzzle and Small-x

- Proton Spin ≡ ½, Experimental Measurement of spin coming from partons ≠ ½
- Jaffe-Manohar sum rule [1]: $S_q + L_q + S_G + L_G = \frac{1}{2}$

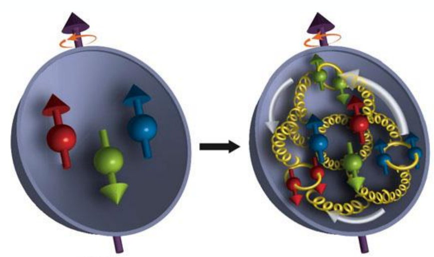
$$S_q(Q^2) = \frac{1}{2}\int_0^1 dx\, \Delta\Sigma(x, Q^2), \quad S_G(Q^2) = \int_0^1 dx\, \Delta G(x, Q^2)$$

- Experimental data only exists for a range of values $x \in [x_{min}, 1]$

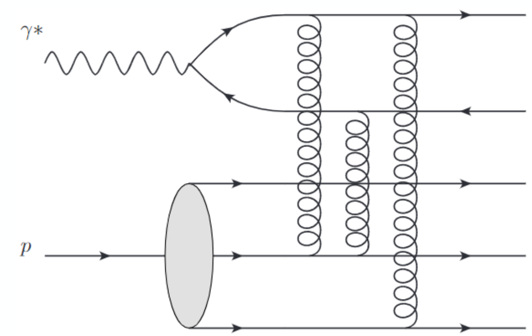
"Knockout" DIS at Large-x



$$x = \frac{Q^2}{s + Q^2} \sim \frac{Q^2}{E_{CM}^2} \sim \frac{1}{m\,\Delta t_{Ioffe}}$$



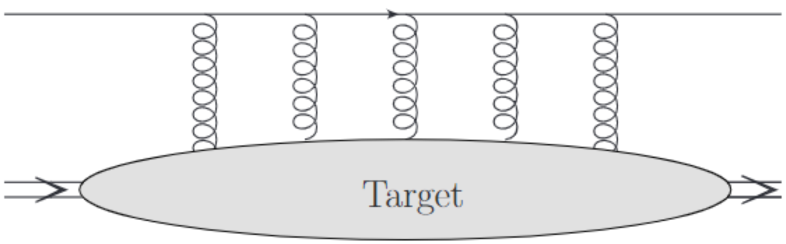
"Dipole" DIS at Small-x



At small-x and with large Ioffe time our degrees of freedom change from quarks and gluons to eikonal Wilson Lines, and the proton appears very dense and frozen.

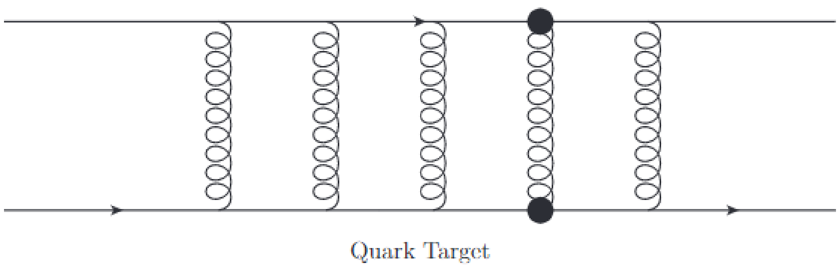
Sub-Eikonal Corrections and Double Logs

Unpolarized Wilson Line

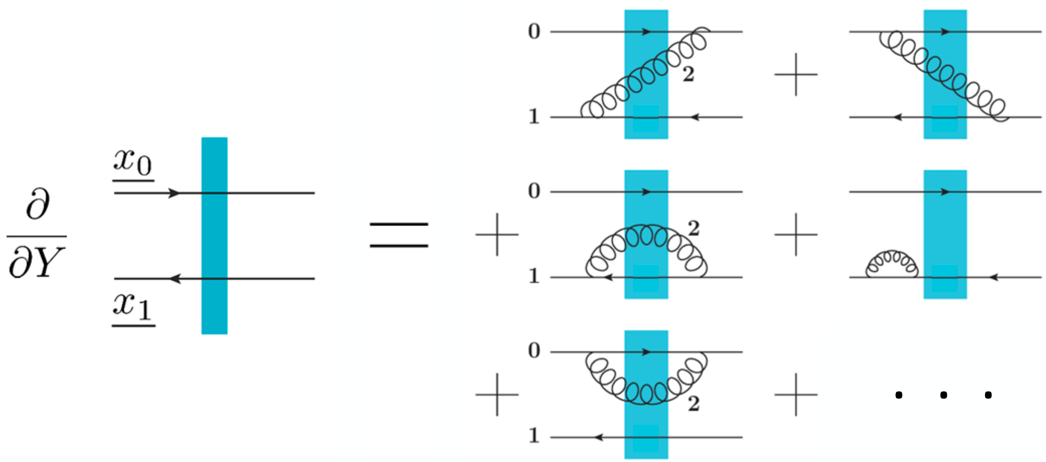


$$V_{\underline{0}} = \mathcal{P} \exp\left[ig \int_{-\infty}^{+\infty} dx^- A^+(x^+ = 0, x^-, \underline{x}_0) \right]$$

Polarized Wilson Line



$$\left(V_{\underline{x}}^{pol}\right)^g \propto \int_{-\infty}^{\infty} dx^-\, V_{\underline{x}}[+\infty, x^-] F^{12}(x^-, \underline{x}) V_{\underline{x}}[x^-, -\infty]$$



Radiative Corrections

Small-x Evolution

Unpolarized evolution: $\alpha_s \ln \frac{1}{x} \sim 1$

Polarized evolution: $\alpha_s \ln^2 \frac{1}{x} \sim 1$

KPS-CTT Evolution and Helicity Distribution

KPS-CTT = Kovchegov-Pitonyak-Sievert-Cougoulic-Tarasov-Tawabutr

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

$$G_{10}^{i}(zs) \equiv \frac{1}{2N_c} \left\langle\!\!\left\langle \mathrm{tr}\left[V_{\underline{0}}^{\dagger} V_{\underline{1}}^{i\,\mathrm{G}[2]} + \left(V_{\underline{1}}^{i\,\mathrm{G}[2]}\right)^{\dagger} V_{\underline{0}}\right] \right\rangle\!\!\right\rangle(zs)$$

$$\cdots$$

Polarized dipole amplitudes are various combinations of polarized and unpolarized Wilson lines [2-4].

$$\left.\begin{aligned}
Q_f(x_{10}^2, zs) &\sim \boxed{Q_f^{(0)}(x_{10}^2, zs)} + \iint \left[2\tilde{G} + \tilde{\Gamma} + Q_f - \bar{\Gamma}_f + 2\Gamma_2 + 2G_2\right] + \iint \left[Q_f + 2G_2\right] \\
\bar{\Gamma}_f(x_{10}^2, x_{21}^2, z's) &\sim \boxed{Q_f^{(0)}(x_{10}^2, z's)} + \iint \left[2\tilde{G} + 2\tilde{\Gamma} + Q_f - \bar{\Gamma}_f + 2\Gamma_2 + 2G_2\right] + \iint \left[Q_f + 2G_2\right] \\
\tilde{G}(x_{10}^2, zs) &\sim \boxed{\tilde{G}^{(0)}(x_{10}^2, zs)} + \iint \left[3\tilde{G} + \tilde{\Gamma} + 2G_2 + \Gamma_2 - \bar{\Gamma}_f\right] - \iint \left[Q_f + 2G_2\right] \\
\tilde{\Gamma}(x_{10}^2, x_{21}^2, z's) &\sim \boxed{\tilde{G}^{(0)}(x_{10}^2, z's)} + \iint \left[3\tilde{G} + \tilde{\Gamma} + 2G_2 + \Gamma_2 - \bar{\Gamma}_f\right] - \iint \left[Q_f + 2G_2\right] \\
G_2(x_{10}^2, zs) &\sim \boxed{G_2^{(0)}(x_{10}^2, zs)} + \iint \left[\tilde{G} + 2G_2\right] \\
\Gamma_2(x_{10}^2, x_{21}^2, z's) &\sim \boxed{G_2^{(0)}(x_{10}^2, z's)} + \iint \left[\tilde{G} + 2G_2\right]
\end{aligned}\right\}$$

(Large-N_c&N_f)

$$\Delta G \propto G_2$$

$$\Delta\Sigma \propto -\int\int \left[Q_f + 2G_2\right]$$

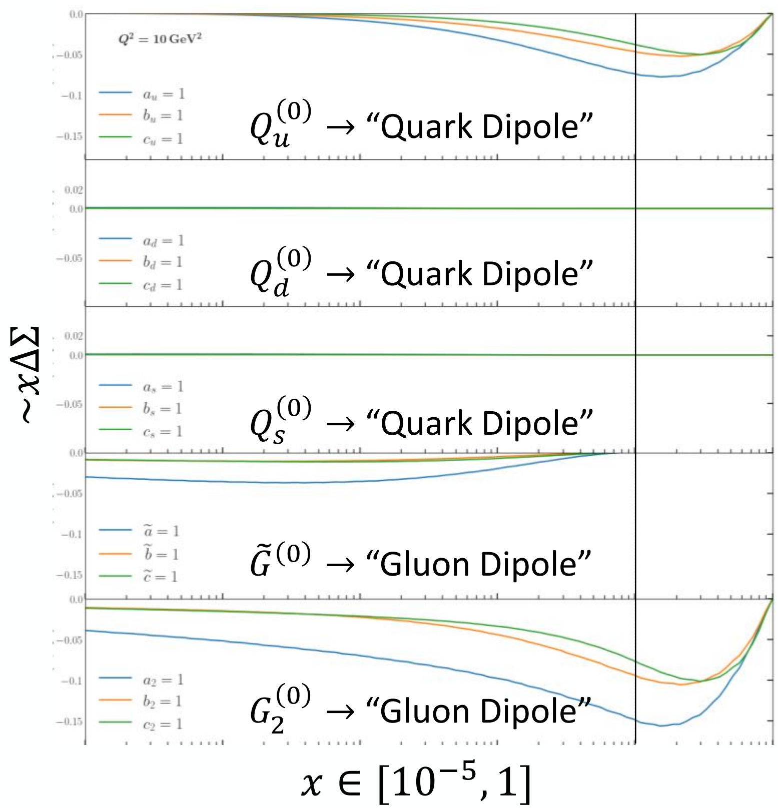
$$\Delta q_f^{NS} \propto \int\int \left[G_f^{NS}\right]$$

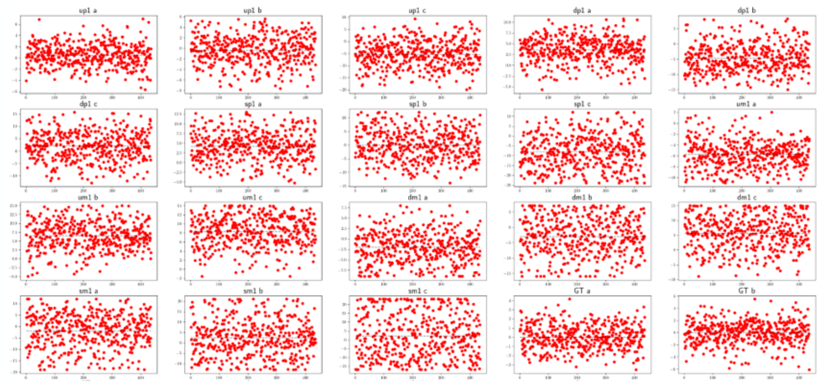
$$A_{\parallel}^{DIS} \propto A_1 \propto g_1^p \propto -\int\int \left[Q_f + 2G_2\right]$$

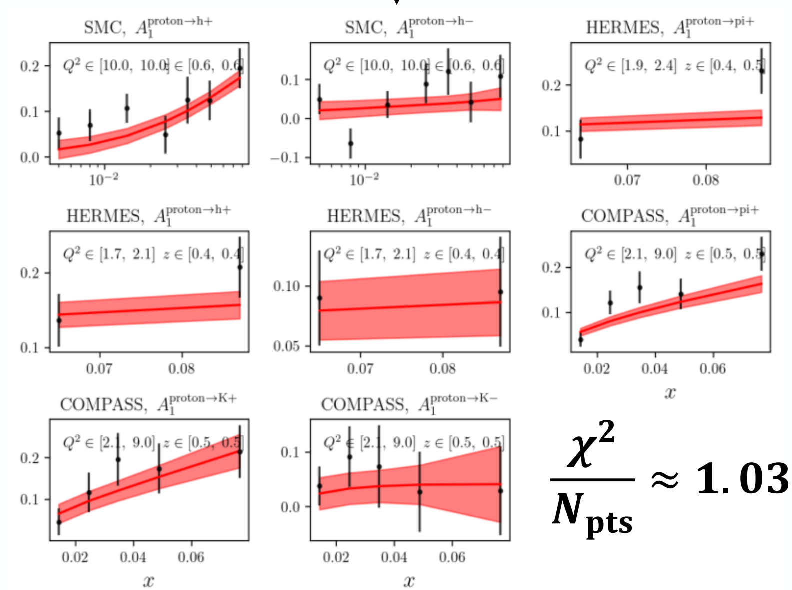
$Q_f^{(0)}, \tilde{G}^{(0)}, G_2^{(0)}, G_f^{NS\,(0)}$ $(x \approx 0.1)$	➜	**KPS-CTT [5]**	➜	$\Delta G, \Delta\Sigma, \Delta q_f^{NS}, g_1$ $(x \ll 0.1)$

Global Analysis: Bayesian-MC Analysis

$$\boxed{G^{(0)} \approx a\eta + b s_{10} + c}$$





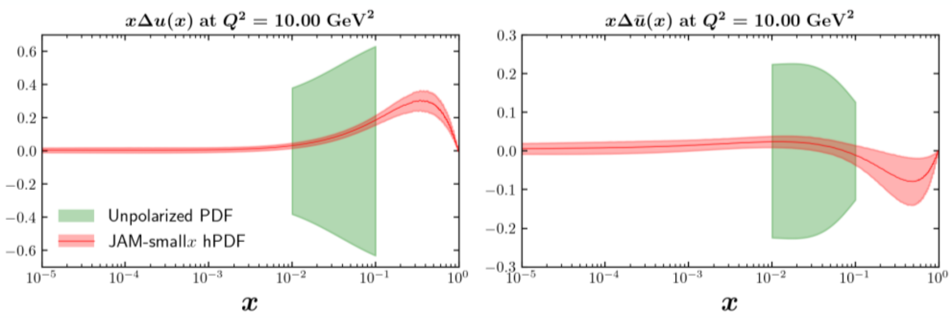


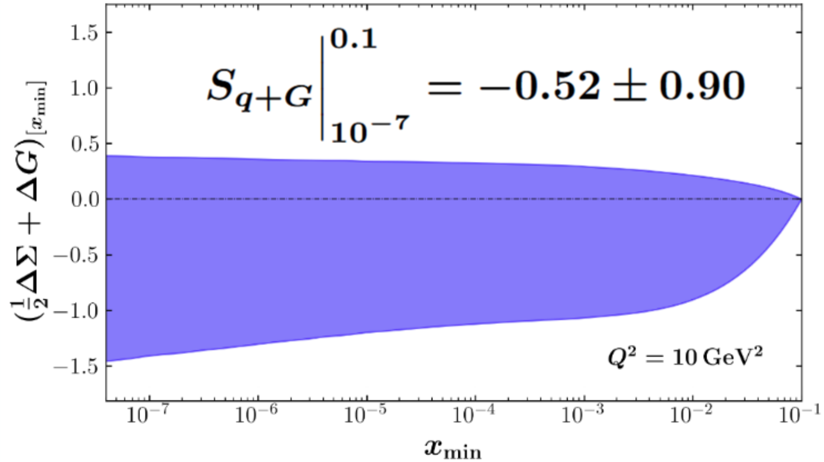
$$\frac{\chi^2}{N_{\mathrm{pts}}} \approx 1.03$$

- Compute Full Evolution from any parameter.
- Chi-squared optimization for DIS and SIDIS data.

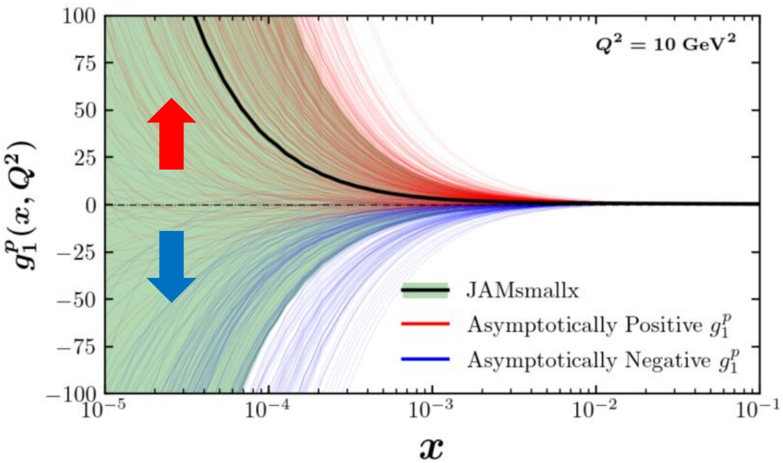
Global Analysis: Success and Setback with SIDIS

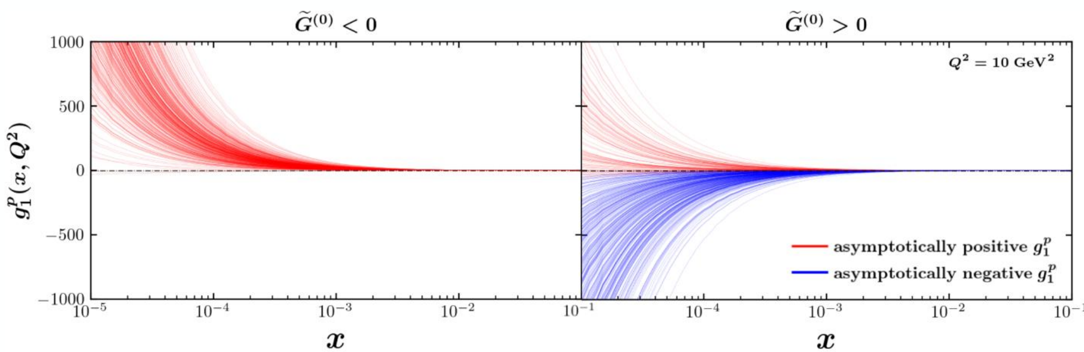
SIDIS data improves the first analysis [6] and allows us to separate quark flavor hPDFs, Δq_f, from $\Delta\Sigma$.





$$\lim_{x\to 0} g_1^p \sim \lim_{x\to 0} \Delta\Sigma \sim \lim_{x\to 0} \Delta G \sim \left(\frac{1}{x}\right)^{\alpha_h}$$

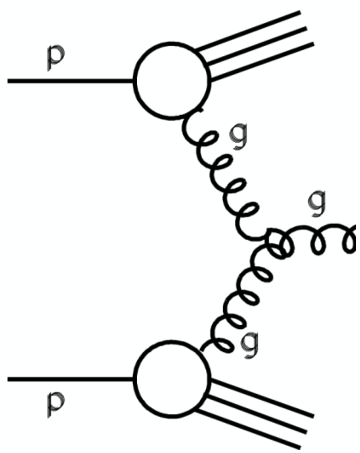




Asymptotic bimodality is caused by the insensitivity of DIS and SIDIS data to **gluon dominated dipole amplitudes** [7].

Global Analysis with pp Data

Polarized proton-proton collisions allow for gluon-gluon interactions and thus can be more sensitive to the gluon dominated polarized dipole amplitudes.



(Picture from CERN)

The polarized pp data available is A_{LL}^{jet}, with jet cross-section [8]:

$$\frac{d\Delta\sigma^{pp\to\text{jet}X}}{d^2p_T^{\text{jet}}\,d\eta^{\text{jet}}} = \frac{1}{\pi S}\int_{x_g^{P,\min}}^{1}\frac{dx_g^P}{x_g^P}\Delta f_g^P(x_g^P,\mu_F)\int_{x_g^{T,\min}}^{1}\frac{dx_g^T}{x_g^T}\Delta f_g^T(x_g^T,\mu_F)$$
$$\times\int_{z_g^{\min}}^{1}\frac{dz_g}{z_g^2}\frac{d\Delta\hat{\sigma}_{gg}^{g}(\lambda,\hat{s},\hat{p_T},\hat{\eta},\mu_F,\mu_F',\mu_R)}{vdvdw}\mathcal{J}_g\left(z_g,\frac{R\,p_T^{\text{jet}}}{\mu_F'},\mu_R\right)$$

DLA Accuracy: Only the leading order term in the jet function $\mathcal{J}_g$ preserves the resummation parameter $\alpha_s\ln^2(\frac{1}{x})$: $\boldsymbol{\mathcal{J}_g \equiv \delta(1-z_g)}$

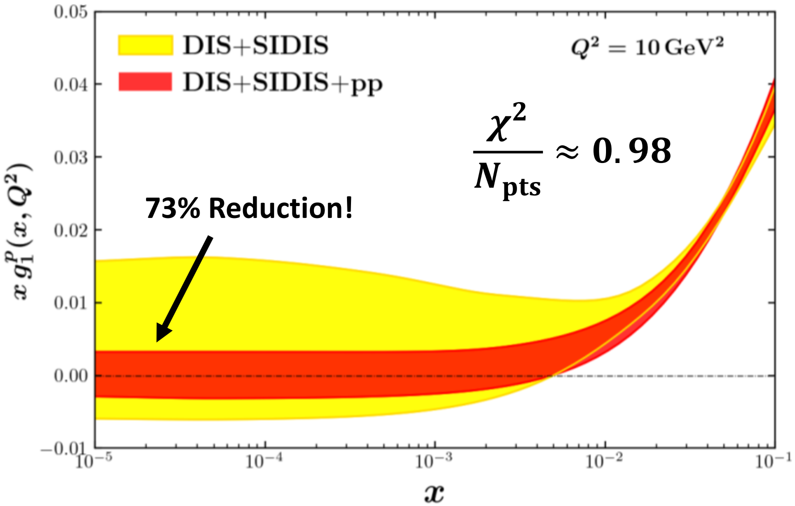
The small-x cross-section **in the pure-gluon limit**:

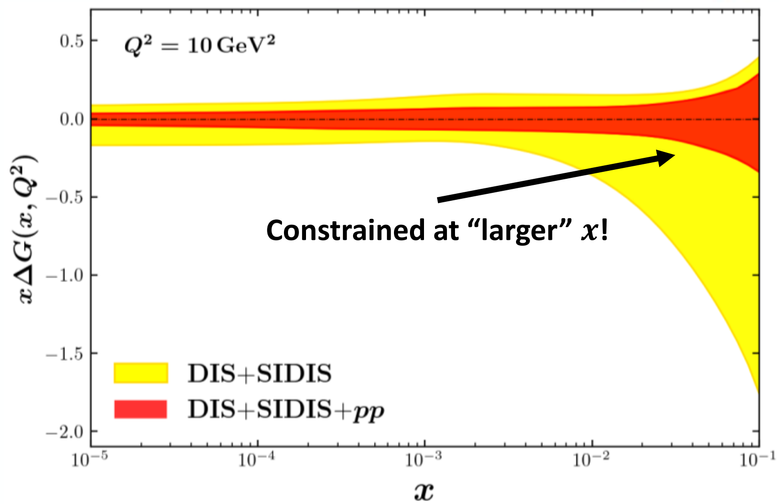
$$\frac{\mathrm{d}\Delta\sigma^{pp\to\text{jet}X}}{\mathrm{d}^2p_T\mathrm{d}y} = \frac{8\,C_F}{\pi^3}\frac{1}{s\,p_T^2}\int_0^\infty \mathrm{d}x_\perp\frac{1}{\alpha_s(1/x_\perp^2)}x_\perp J_0(p_T\,x_\perp)$$
$$\times\left[2\,G_{2,P}\nabla_\perp^2\widetilde{G}_T + 2\,(\nabla_\perp^2\widetilde{G}_P)G_{2,T} + \frac{\partial}{\partial x_\perp}\widetilde{G}_P\frac{\partial}{\partial x_\perp}\widetilde{G}_T + 2\,\frac{\partial}{\partial x_\perp}G_{2,P}\frac{\partial}{\partial x_\perp}\widetilde{G}_T + 2\,\frac{\partial}{\partial x_\perp}\widetilde{G}_P\frac{\partial}{\partial x_\perp}G_{2,T}\right]$$

$$\left(x_{T,P}\approx\frac{p_T}{\sqrt{s}}e^{\pm y}<0.1\right)$$

Influence of pp Data

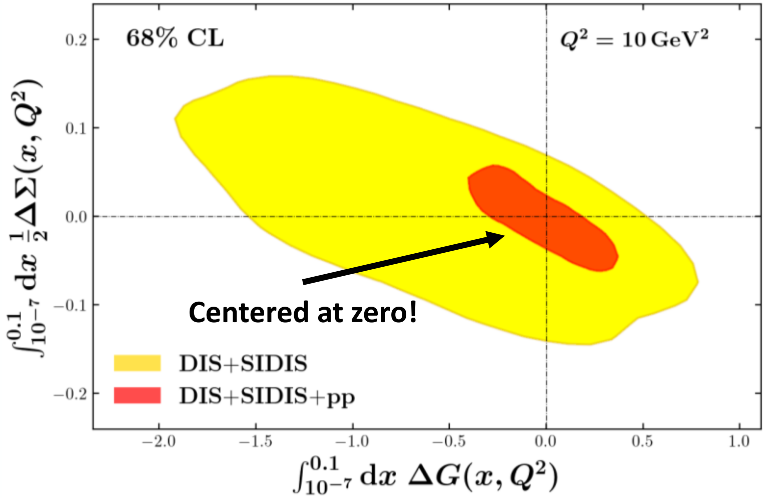
$$\Delta G(x,Q^2) = \frac{2N_c}{\alpha_s(Q^2)\pi^2} G_2(s_{10},\eta)\Big|^{s_{10}=\sqrt{\frac{N_c}{2\pi}}\ln\frac{Q^2}{\Lambda^2}}_{\eta=\sqrt{\frac{N_c}{2\pi}}\ln\frac{Q^2}{x\Lambda^2}}$$





DIS+SIDIS: $$S_{q+G}\Big|_{10^{-7}}^{0.1} = -0.52 \pm 0.90$$

DIS+SIDIS+pp: $$S_{q+G}\Big|_{10^{-7}}^{0.1} = -0.04 \pm 0.23$$

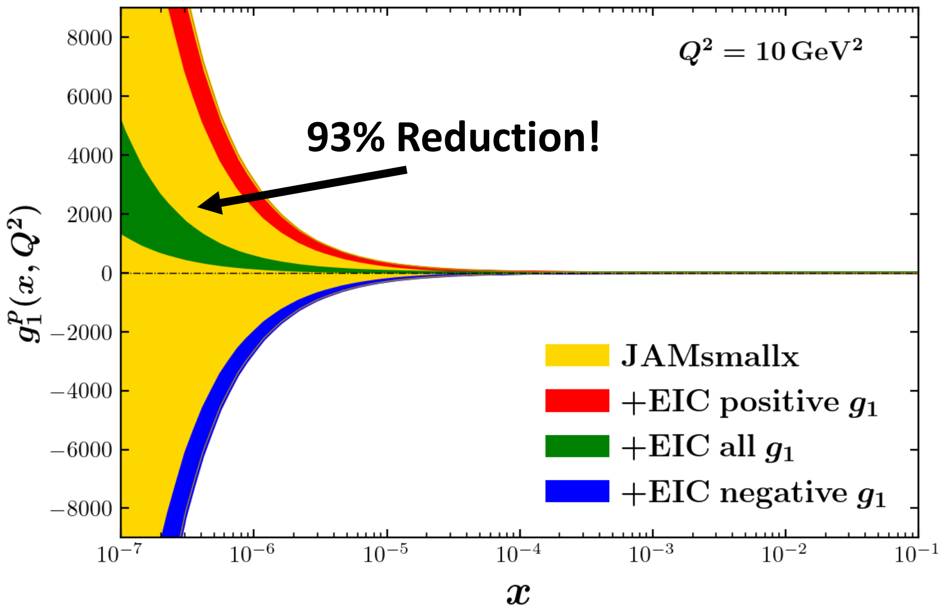


Uncertainty spans zero → Bimodality persists

EIC Impact Study

EIC Pseudo data: Create data points with EIC-consistent uncertainties/kinematics [10] using small-x theory input.

- $10^{-4} < x < 10^{-1}$, $1.69\ \mathrm{GeV}^2 < Q^2 < 50\ \mathrm{GeV}^2$
- Proton DIS: $\sqrt{s} = \{29, 45\ , 63, 141\}$ GeV, L = $100\ \mathrm{fb}^{-1}$
- Deuteron/^{3}He DIS: $\sqrt{s} = \{29, 66, 89\}$ GeV, L = $10\ \mathrm{fb}^{-1}$
- 2% point-to-point systematic uncertainty



Final Thoughts

- Small-x helicity global analysis is successful and **not degraded** with the inclusion of polarized pp data.
- pp data drastically reduces uncertainty, especially for larger-x gluon hPDFs.
- Asymptotic bimodality persists → Can be broken with smaller-x data ($x \approx 10^{-4}$).
- Net quark and gluon spin <u>now consistent with zero:</u>
  - How will this be affected by re-introducing quarks?
  - Quark and gluon OAM contributions?

Interested? Check arXiv soon!
(also I'm available for a postdoc position!)

☺

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Extras

Cuts on Data

- We fit to all available DIS and SIDIS data within the kinematic ranges $5 \times 10^{-3} < x < 0.1$ and $1.69\ \mathrm{GeV}^2 < Q^2 < 10.4\ \mathrm{GeV}^2$
- This leaves a total of 240 data points in the JAM database.

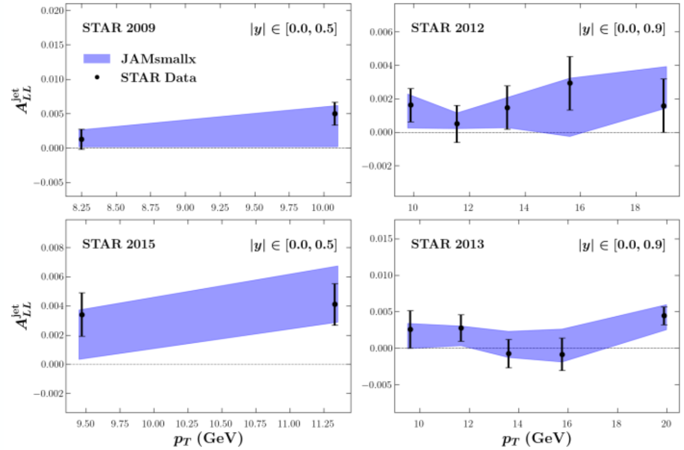

TABLE I. Summary of polarized DIS data included in the fit, separated into A_1 (left) and $A_{\parallel}$ (right), along with the χ^2/N_{pts} for each data set.

Data set (A_1)	Target	N_{pts}	χ^2/N_{pts}
COMPASS [120]	p	5	0.77
COMPASS [121]	p	17	0.93
COMPASS [122]	d	5	0.34
EMC [123]	p	5	0.23
HERMES [124]	n	2	1.11
SLAC (E142) [125]	^{3}He	1	1.47
SMC [126, 127]	p	6	1.26
	p	6	0.43
	d	6	0.65
	d	6	2.13
Total		59	0.90

Data set ($A_{\parallel}$)	Target	N_{pts}	χ^2/N_{pts}
HERMES [128]	p	4	1.47
	d	4	1.00
SLAC (E143) [129]	p	9	0.55
	d	9	1.01
SLAC (E154) [130]	^{3}He	5	0.69
SLAC(E155) [131]	p	16	1.07
	d	16	1.57
Total		63	1.10

TABLE II. Summary of the polarized SIDIS data on A_1^h included in the fit, along with the χ^2/N_{pts} for each data set.

Dataset (A_1^h)	Target	Tagged Hadron	N_{pts}	χ^2/N_{pts}
COMPASS [132]	d	π^+	5	0.63
	d	π^-	5	0.83
	d	h^+	5	1.01
	d	h^-	5	1.02
	d	K^+	5	1.60
	d	K^-	5	0.71
COMPASS [133]	p	π^+	5	1.94
	p	π^-	5	1.18
	p	K^+	5	0.46
	p	K^-	5	0.23
HERMES [134]	^{3}He	h^+	2	0.55
	^{3}He	h^-	2	0.29
HERMES [135]	p	π^+	2	2.75
	p	π^-	2	0.00
	p	h^+	2	1.25
	p	h^-	2	0.19
	d	π^+	2	0.58
	d	π^-	2	1.23
	d	h^+	2	3.03
	d	h^-	2	1.24
	d	K^+	2	0.82
	d	K^-	2	0.25
	d	$K^+ + K^-$	2	0.36
SMC [136]	p	h^+	7	1.22
	p	h^-	7	1.41
	d	h^+	7	0.84
	d	h^-	7	1.52
Total			104	1.04

TABLE III. Summary of polarized pp data on $A_{\mathrm{LL}}^{\mathrm{jet}}$ included in the fit along with the χ^2/N_{pts} for each data set.

Data set ($A_{\mathrm{LL}}^{\mathrm{jet}}$)	N_{pts}	χ^2/N_{pts}
STAR [137]	2	0.60
STAR [138]	5	0.30
STAR [139]	2	0.55
STAR [140]	5	0.24
Total	14	0.36

Extras

EIC impact: DGLAP extrapolation vs KPS-CTT prediction

- EIC pseudodata can break the bimodality, predicting a specific sign as $x \to 0$.
- Uncertainties in the extrapolation region are much smaller using small-x helicity than those using DGLAP evolution.