Overview: Spin Working Group

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NM STATE

SURGE 2023
Collaboration Meeting

6/28/2023

Outline

- **Goals of the SURGE Collaboration**

- **Spin at Small x**
  - Is power-suppressed
  - Couples to new quantum numbers
  - Evolves quickly at small x
  - Is rooted in chiral symmetry

- **Conversations from the Spin Working Group**
  - Goals
  - Timeline
  - Talks

Goals of the SURGE Collaboration

As written in the SURGE proposal:

- **Identify observables that are sensitive to gluon saturation** in polarized and unpolarized proton-nucleus collisions pA, ultraperipheral heavy ion and pA collisions, in DIS off polarized protons or light nuclei ep, and in DIS off heavy nuclei eA.

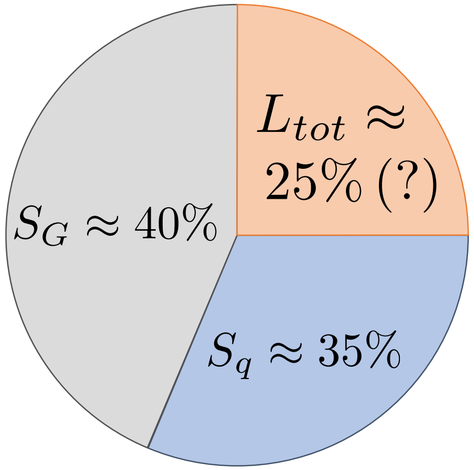
- **Provide robust end-to-end calculations** minimizing known uncertainties for **each of these observables with an ambitious goal of <10% accuracy**, sufficient for unambiguous characterization of the gluon dominated small x regime in protons and nuclei.

- Incorporate results in a **novel global analysis framework** for data-theory comparisons that can be systematically improved to cleanly establish evidence for a universal gluon saturation regime in QCD.

- Explore the **larger implications** of the ideas and techniques developed during the project and their interdisciplinary connections.

Jaffe-Manohar Spin Sum Rule: $$\frac{1}{2} = S_q + S_G + L_q + L_G$$

Jaffe and Manohar, Nucl. Phys. ***B337*** *509 (1990)*



- Quark Polarization:

$$S_q(Q^2) = \frac{1}{2} \sum_{f,\bar{f}} \int_0^1 dx\, \Delta q_f(x, Q^2)$$

$$\Delta q(x, Q^2) = \int \frac{dr^-}{2\pi} e^{ixp^+r^-} \left\langle pS_L \middle| \bar{\psi}(0)\, \mathcal{U}[0,r]\, \frac{\gamma^+\gamma^5}{2}\, \psi(r) \middle| pS_L \right\rangle$$

➢ Nonlocal generalization of the **axial vector current** $j_5^\mu = \bar{\psi}\,\gamma^\mu \gamma^5 \psi$

- Gluon Polarization:

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

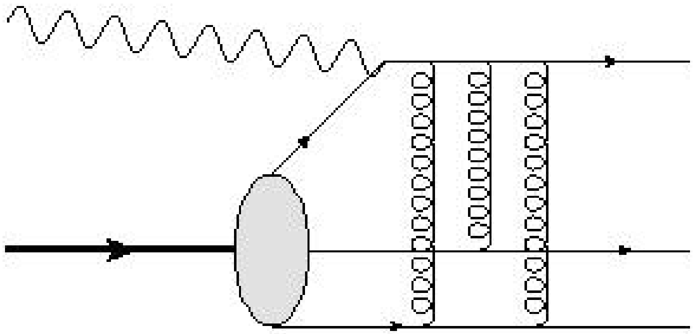
$$\Delta G(x, Q^2) = \frac{-2i}{xp^+} \int \frac{dr^-}{2\pi} e^{ixp^+r^-} \left\langle pS_L \middle| \epsilon_T^{ij}\, \mathrm{tr}\left[F^{+i}(0)\, \mathcal{U}[0,r]\, F^{+j}(r)\, \mathcal{U}'[r,0]\right] \middle| pS_L \right\rangle$$

➢ Circular **azimuthal correlation** of gluon field strengths

Spin at Small x versus Large x

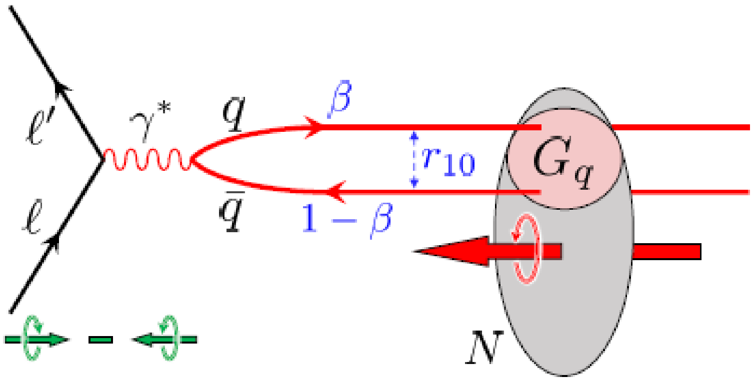
- At **large x**, DIS is dominated by a **"Knockout" process**
  - At **small x**, the leading channel is a **"dipole" process**

c.f) **Large x:** "Knockout" DIS

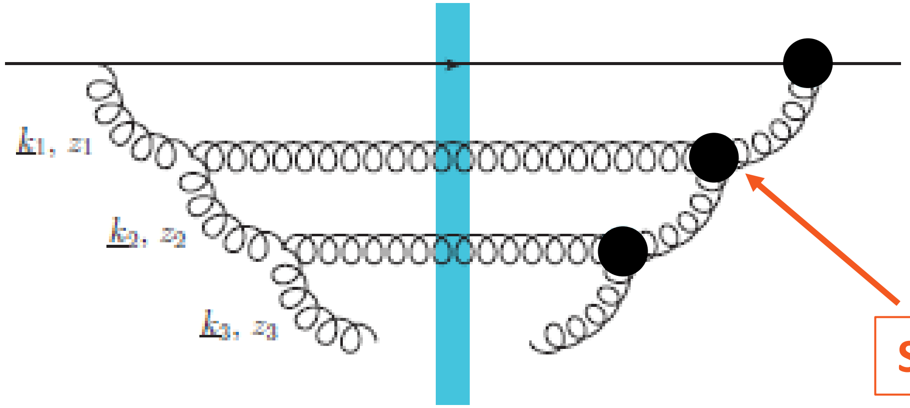


- **Leading-power** dipole scattering is **spin-independent**
  - Pure eikonal **Wilson lines** (gluons)

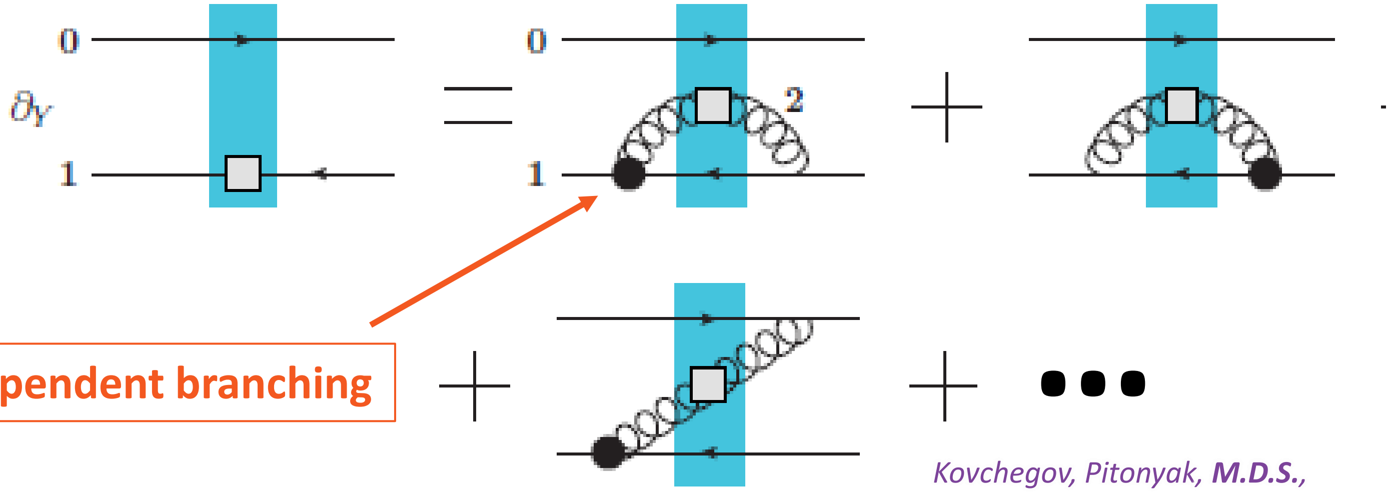
Small x: "Dipole" DIS



- **Spin at small x** selects on **different, sub-eikonal** dynamics
  - Spin observables are sensitive to **novel small-x physics**



Spin-dependent branching

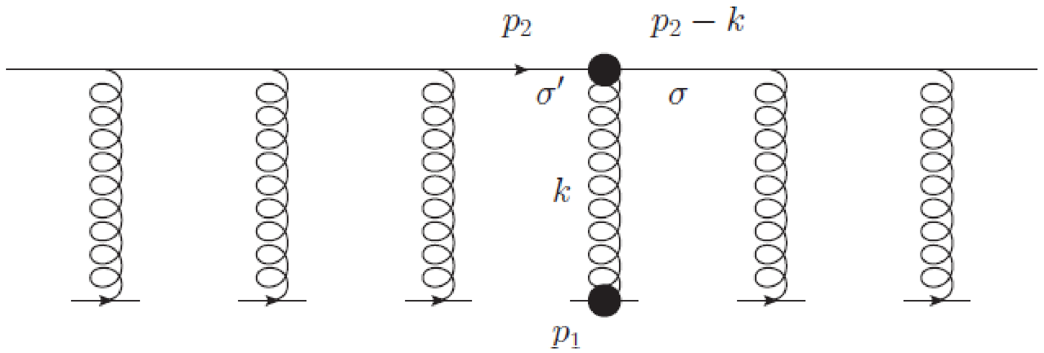


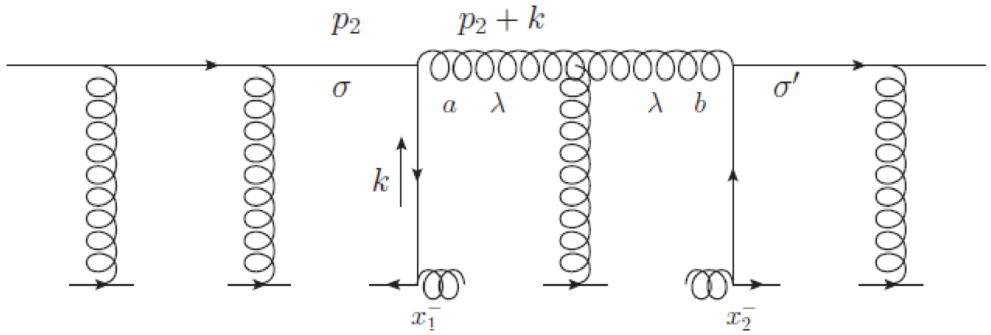
*Kovchegov, Pitonyak, **M.D.S.**,*
*JHEP **1601** (2016), Phys. Rev. **D95** (2017)*

- **Spin information** from the valence sector (large x) is **transmitted to small x** by **spin-dependent branching**

*Also G. Chirilli, JHEP **1901** (2019)*

- **Suppressed** by the **coupling** α_s but **enhanced** by the **phase space** $\ln \frac{1}{x}$
  - ➢ Resummation leads to **quantum evolution of spin at small x**
  - ➢ Analogous to **BFKL evolution** for unpolarized gluons *(leading log accuracy)*





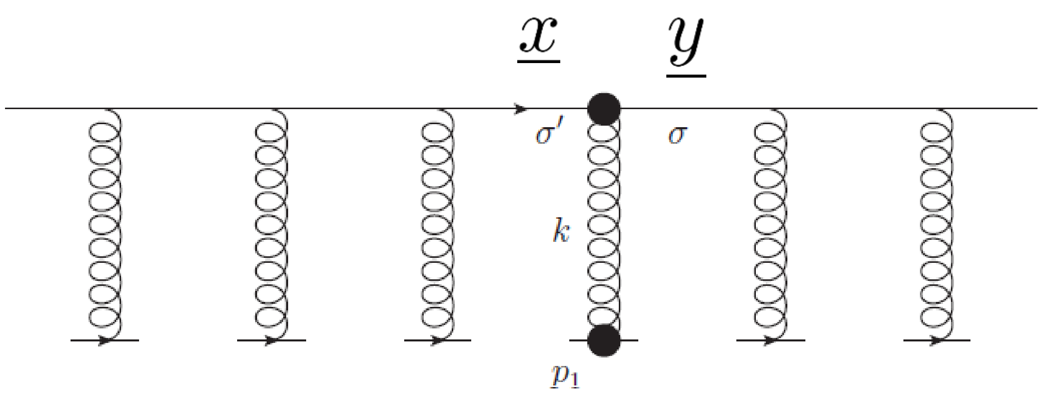
QCD Stern-Gerlach: $\gamma \, \vec{S} \cdot \vec{B}$

$$V_{\underline{x}}^{pol} = \frac{igp_1^+}{s} \int^{\infty} dx^- \, V_{\underline{x}}[+\infty, x^-] \, F^{12}(x^-, \underline{x}) \, V_{\underline{x}}[x^-, -\infty]$$

$$- \frac{g^2 \, p_1^+}{s} \int_{-\infty}^{\infty} dx_1^- \int_{x_1^-}^{\infty} dx_2^- \;\; V_{\underline{x}}[+\infty, x_2^-] \, t^b \, \psi_\beta(x_2^-, \underline{x}) \, U_{\underline{x}}^{ba}[x_2^-, x_1^-] \left[\frac{1}{2} \gamma^+ \gamma^5 \right]_{\alpha\beta} \bar{\psi}_\alpha(x_1^-, \underline{x}) \, t^a \, V_{\underline{x}}[x_1^-, -\infty].$$

Flavor-changing Wilson line

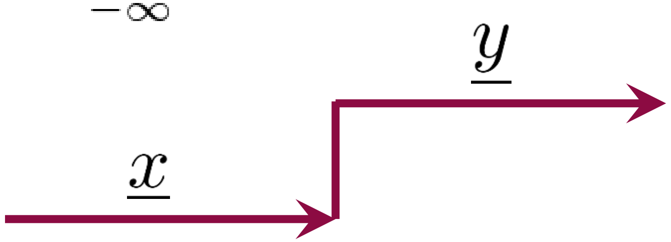
Since m=0 in Bjorken kinematics: Quark helicity conservation

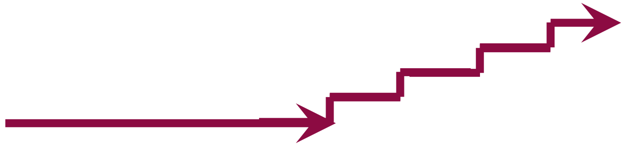


- **Spin-independent** sub-eikonal operator contributes to evolution
- **New contribution** not previously included in dipole helicity evolution

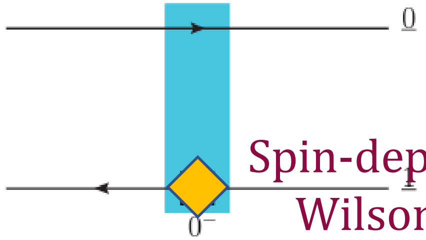
Jump displacement in transverse position: $\underline{\nabla}\delta^2(\underline{x}-\underline{y})$

$$V^{\mathrm{G}[2]}_{\underline{x},\underline{y}} = -\frac{i\,P^+}{s}\int\limits_{-\infty}^{\infty} dz^- d^2 z\; V_{\underline{x}}[\infty, z^-]\,\delta^2(\underline{x}-\underline{z})\,\overleftarrow{D}^i(z^-,\underline{z})\,D^i(z^-,\underline{z})\,V_{\underline{y}}[z^-,-\infty]\,\delta^2(\underline{y}-\underline{z}),$$





$$\frac{\partial}{\partial \ln \frac{1}{x}}$$

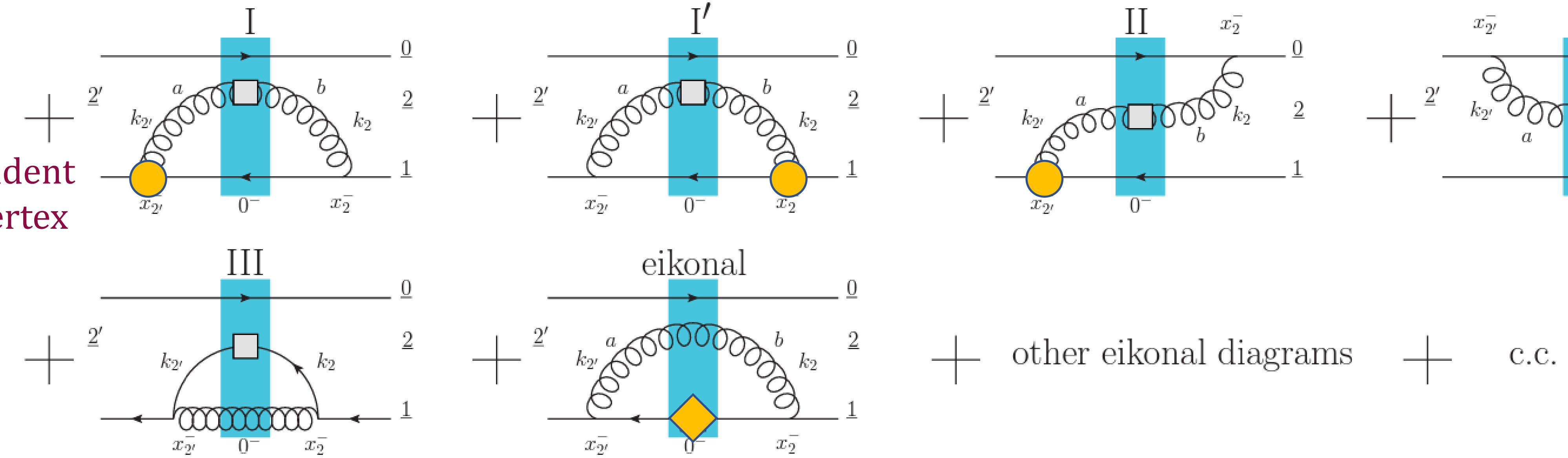


Spin-dependent Wilson line

$\sim$

$\square =$
- Includes recoil: KPS-CTT
- No recoil: KPS

Spin-dependent splitting vertex



- Large Nc: Gluon dipoles only
- Large Nc+Nf: Quark + Gluon dipoles

Method of Infrared Evolution Equations

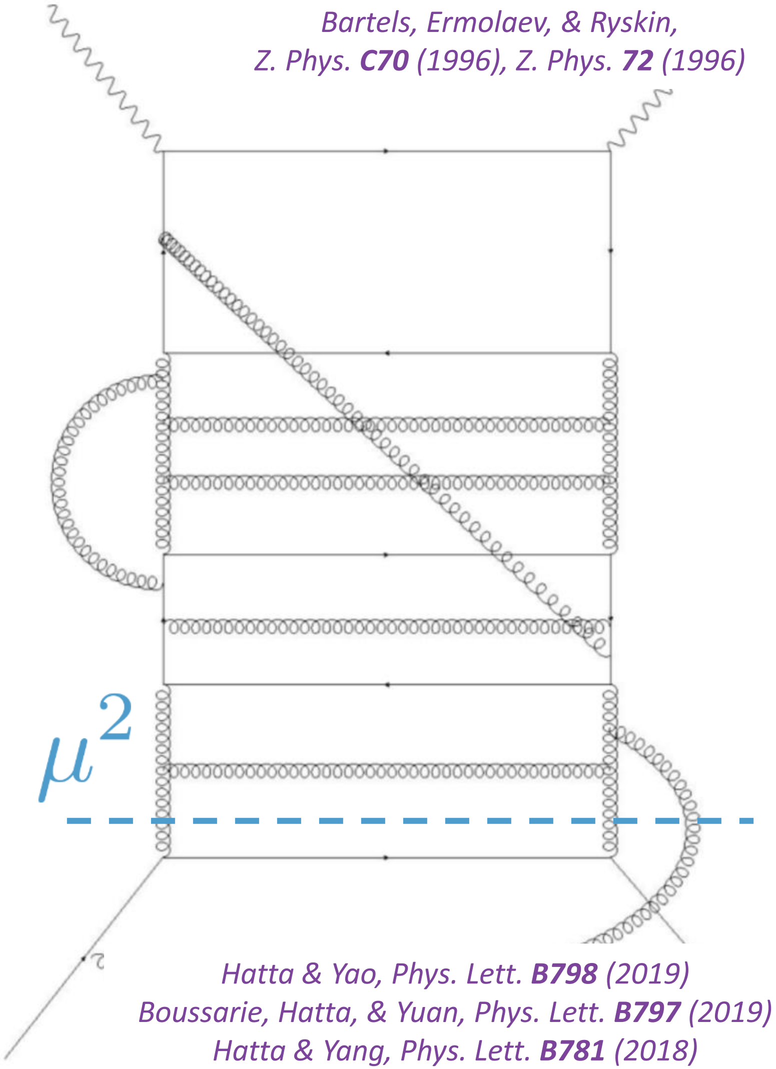
- Missing recoil term **brings small-x asymptotics into agreement** with other calculations using infrared evolution equations

- Based on identifying and resuming **double logarithms of the infrared cutoff**, capturing both types of logs $\ln\frac{Q^2}{\mu^2}$ and $\ln\frac{1}{x}$.

$$\left.\begin{matrix}\Delta\Sigma(x,Q^2)\\ \Delta G(x,Q^2)\\ g_1(x,Q^2)\end{matrix}\right\} \sim \left(\frac{1}{x}\right)^{3.66\sqrt{\frac{\alpha_s N_c}{2\pi}}}$$

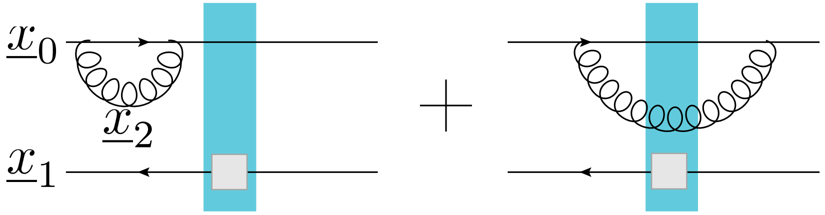
Asymptotically as $x \to 0$

Bartels, Ermolaev, & Ryskin, Z. Phys. ***C70*** *(1996), Z. Phys.* ***72*** *(1996)*



Hatta & Yao, Phys. Lett. ***B798*** *(2019)*
Boussarie, Hatta, & Yuan, Phys. Lett. ***B797*** *(2019)*
Hatta & Yang, Phys. Lett. ***B781*** *(2018)*
Hatta et al., Phys. Rev. ***D95*** *(2017)*

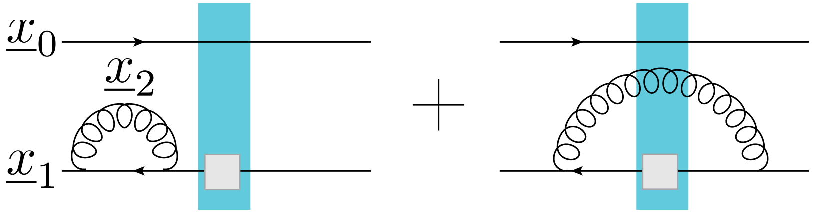
- Ladder emissions from the **unpolarized Wilson line** possess **color transparency** at short distances



$$\frac{\alpha_s N_c}{2\pi^2} \int\limits_{\frac{\Lambda^2}{s}}^{z} \frac{dz'}{z'} \int \frac{d^2 x_2}{x_{20}^2} \times \underline{\left[\frac{1}{N_c^2} \left\langle \mathrm{tr}\left[V_2 V_1^{pol\,\dagger} \right] \mathrm{tr}\left[V_0 V_2^{\dagger} \right] \right\rangle_{(z's)} - \frac{1}{N_c} \left\langle \mathrm{tr}\left[V_0 V_1^{pol\,\dagger} \right] \right\rangle_{(z's)} \right]}$$

Cancels when $\underline{x}_2 \to \underline{x}_0$

- But for ladder emissions from the **polarized Wilson line**, color transparency is **violated by spin**



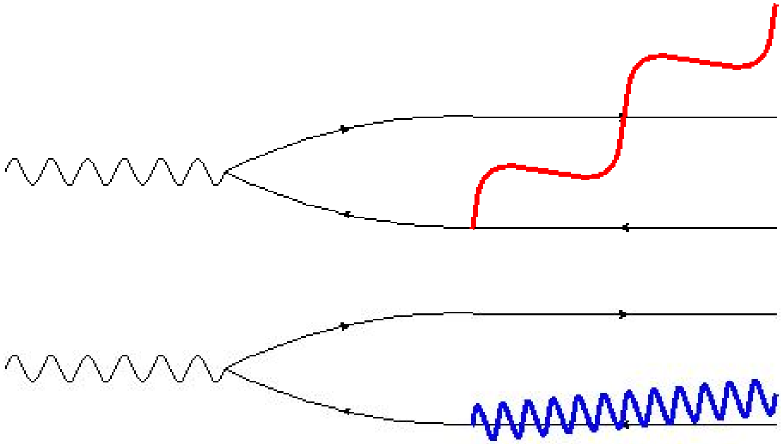
$$\frac{\alpha_s N_c}{2\pi^2} \int\limits_{\frac{\Lambda^2}{s}}^{z} \frac{dz'}{z'} \int \frac{d^2 x_2}{x_{21}^2} \times \underline{\left[\frac{1}{N_c^2} \left\langle \mathrm{tr}\left[V_2 V_1^{pol\,\dagger} \right] \mathrm{tr}\left[V_0 V_2^{\dagger} \right] \right\rangle_{(z's)} - \frac{1}{N_c} \left\langle \mathrm{tr}\left[V_0 V_1^{pol\,\dagger} \right] \right\rangle_{(z's)} \right]}$$

Does NOT cancel when $\underline{x}_2 \to \underline{x}_1$

Double-Logarithmic Evolution at Small x

Longitudinal + transverse logarithmic phase space

$$dP \sim \alpha_s \frac{dx}{x} \frac{d^2k}{k_T^2}$$



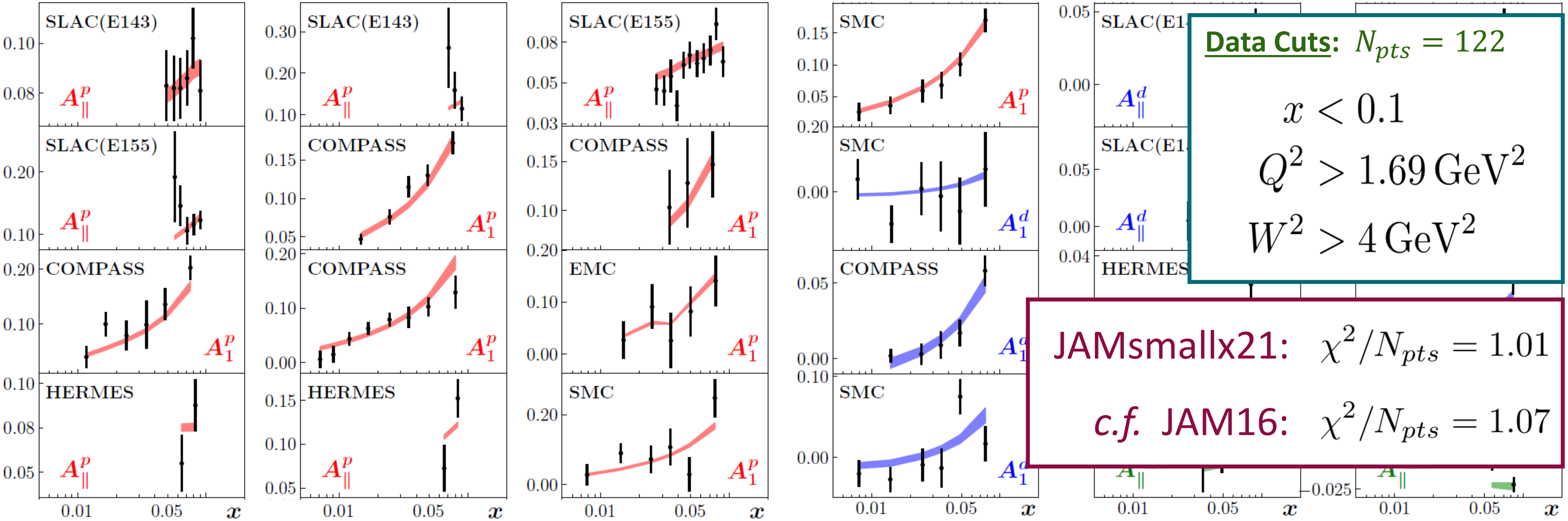
Long wavelength/IR

Short wavelength/UV

- **Unpolarized (BFKL) evolution:**
  - **Transverse logs cancel** (neutrality in the IR, transparency in the UV)
  - Only **longitudinal** phase space is logarithmic: $\alpha_s \ln\frac{1}{x} \sim O(1)$

- **Polarized (KPS) evolution:**
  - **No transparency of spin**: dominance of **collinear transverse logs**
  - **Double-logarithmic** evolution: $\alpha_s \ln^2\frac{1}{x} \sim O(1)$
  - Sensitive to **lifetime ordering** (c.f. NLO BFKL), less sensitive to saturation

First Global Analysis Using KPS Evolution



Data Cuts: $N_{pts} = 122$

$$x < 0.1$$
$$Q^2 > 1.69\,\mathrm{GeV}^2$$
$$W^2 > 4\,\mathrm{GeV}^2$$

JAMsmallx21: $\chi^2/N_{pts} = 1.01$

c.f. JAM16: $\chi^2/N_{pts} = 1.07$

- **Global analysis of polarized DIS** at small x using KPS formalism

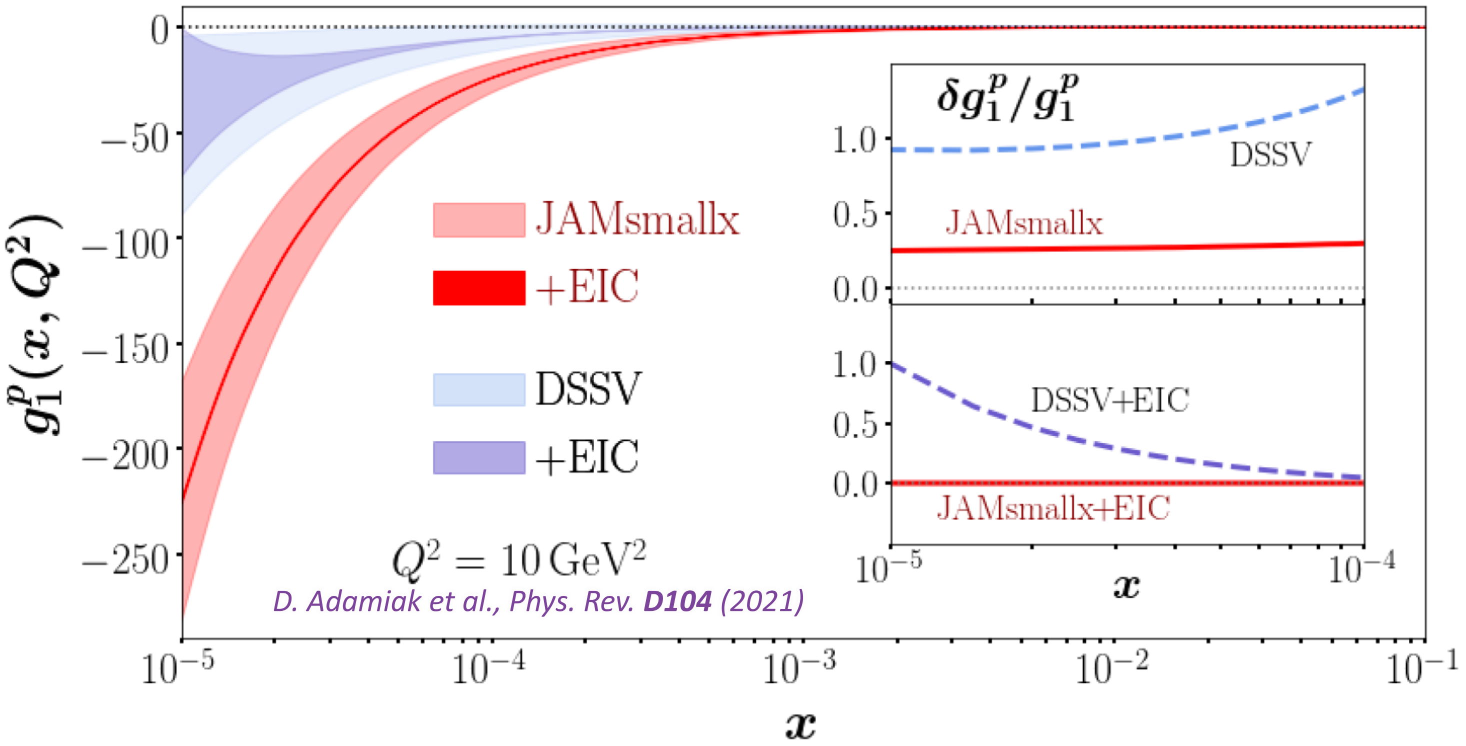
  D. Adamiak et al., Phys. Rev. ***D104*** *(2021)*

- **Bayesian analysis** performed using JAM architecture

  N. Sato et al., Phys. Rev. ***D93*** *(2016)*

First Global Analysis Using KPS Evolution

- **Structure function g_1** determined down to **low x**
- Analysis prefers **large, negative g_1** at small x
- **Predictive power** at small x: controlled error in extrapolation



- The procedure **cannot describe everything**
  - Fails for **too-large x** (as expected)
  - Equally good $\frac{\chi^2}{N_{pts}} \sim 1$ for $0.05 \le x \le 0.20$

Error band: Bayesian 1σ confidence level

Statistical impact of **EIC data** (thin red band)

DSSV: de Florian et al., Phys. Rev. Lett. ***113*** *(2014), Phys. Rev.* ***D100*** *(2019)*

The Roots of Spin are Chiral

- **Helicity** shares an intimate connection with the **axial vector current**

Jaffe and Manohar, Nucl. Phys. ***B337*** *509 (1990)*

A. Tarasov, R. Venugopalan,
Phys. Rev. ***D100*** *(2019),* ***D102*** *(2020),* ***D105*** *(2022)*

$$\Delta q(x, Q^2) = \int \frac{dr^-}{2\pi} e^{ixp^+ r^-} \left\langle pS_L \middle| \bar{\psi}(0)\, \mathcal{U}[0, r]\, \frac{\gamma^+\gamma^5}{2}\, \psi(r) \middle| pS_L \right\rangle$$

- The **total quark helicity** leads to a **local matrix element** of the **axial vector current**.

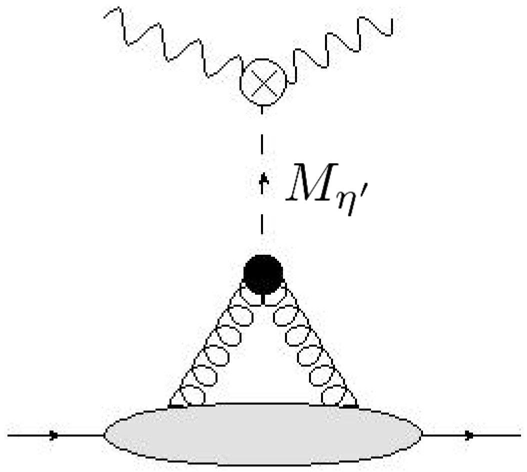
$$\Delta\Sigma(Q^2) = \sum_q \int_0^1 dx\, (\Delta q + \Delta\bar{q})(x, Q^2) = \frac{1}{p^+} \sum_q \langle pS_L | \bar{\psi}(0) \frac{\gamma^+\gamma^5}{2} \psi(0) | pS_L \rangle \sim \frac{\langle j_5^+ \rangle}{p^+}$$

- Opens the door to nonperturbative contributions from the **axial anomaly**

$$\partial_\mu j_5^\mu = \frac{\alpha_s N_f}{2\pi} \mathrm{tr}\left(F_{\mu\nu} \tilde{F}^{\mu\nu} \right)$$

$$\langle p' S_L | j_5^\mu | p S_L \rangle = \frac{1}{4\pi^2} \frac{\ell^\mu}{\ell^2} \int \frac{d^4 k}{(2\pi)^4} \, \mathrm{tr} F_{\alpha\beta}(k) \tilde{F}^{\alpha\beta}(-k-\ell)$$

$$\ell^\mu = p'^{\,\mu} - p^\mu$$



- Singularities in $\frac{1}{t}$ appear in the forward limit, **beyond those captured by collinear factorization**

*S. Bhattacharya, Y. Hatta, W. Vogelsang, Phys. Rev. **D107** (2023), arxiv: 2305.09431*

- This pole can be interpreted as the **exchange of a scalar η' meson**, coupled to gluon helicity: $g\,\phi_{\eta'} F\,\tilde{F}$.

*A. Tarasov, R. Venugopalan, Phys. Rev. **D100** (2019), **D102** (2020), **D105** (2022)*

- Appears to make a **finite contribution to helicity PDF** (forward matrix element)

Goals of the Spin Working Group

Spin Working Group Goals Articulated in the Proposal:

- Refinement of helicity global analyses

	Yes	Not Yet	
CTT Recoil Operator Correction	X		
Large Nc+Nf Evolution	X		
Running Coupling	X		
hMV Initial Conditions		X	
Nonlinear Saturation Corrections		X	Derived
Interface with Unpolarized Dipole Fits		X	
Include Polarized SIDIS Data	X		
Include Polarized pp Data		X	Work in Progress
Orbital Angular Momentum		X	Work in Progress

Spin Working Group Goals Articulated in the Proposal:

- ❖ Contributions of the Chiral Anomaly

	Yes	Not Yet	
Resolve Conceptual Issues		X	Work in Progress
Calculation of (More) Observables		X	Work in Progress
Integrate into Analysis Framework		X	

Spin Timeline from the Proposal

- **Year 1:**
  - Update the **helicity dependent MV model** (Kovchegov)
  - **Implement new developments** and **begin inclusion of SIDIS and polarized p+p collisions data into small-x helicity fits** at large-Nc&Nf (Kovchegov, Pitonyak, Sievert)
  - Include **running coupling corrections** into large-Nc & Nf helicity evolution phenomenology (Kovchegov, Pitonyak, Sievert)
  - **Begin determination of axial anomaly** contribution to **g1 and SIDIS** (Venugopalan, Hatta)

- **Year 2:**
  - **Finalize inclusion of SIDIS and polarized p+p collision data into small-x helicity fits** at large-Nc&Nf with running coupling, **interfacing it with the hMV model** (Kovchegov, Pitonyak, Sievert)
  - **Finalize determination of axial anomaly contribution to g1, g2 and SIDIS** (Venugopalan, Hatta)

Spin WG Talks at this Collaboration Meeting

Wednesday, June 28

2:20 PM — **Anomaly zero modes and sub-eikonal corrections at small-x**
Speaker: Andrey Tarasov (North Carolina State University)

Thursday, June 29

11:40 AM — **Global analysis of polarized DIS + SIDIS at small x**
Speaker: Daniel Adamiak

1:30 PM — **Status report on particle production in polarized p+p**
Speaker: Ming Li (North Carolina State University)

1:50 PM — **Disambiguation of bimodal solutions for g_1(x)**
Speaker: Nicholas Baldonado

2:10 PM — **Updates on OAM at small x**
Speaker: Brandon Manley (Ohio State University)

Friday, June 30

1:55 PM — **Chiral and trace anomalies in DVCS**
Speaker: Yoshitaka Hatta (BNL)

2:15 PM — **Analytic solution of the large-Nc helicity evolution**
Speaker: Jeremy Borden (Ohio State University)