Global Analyses of Polarized DIS & SIDIS from Small-x Evolution

SPIN 2023

Matthew D. Sievert
NM STATE

9/29/2023

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Collaborators

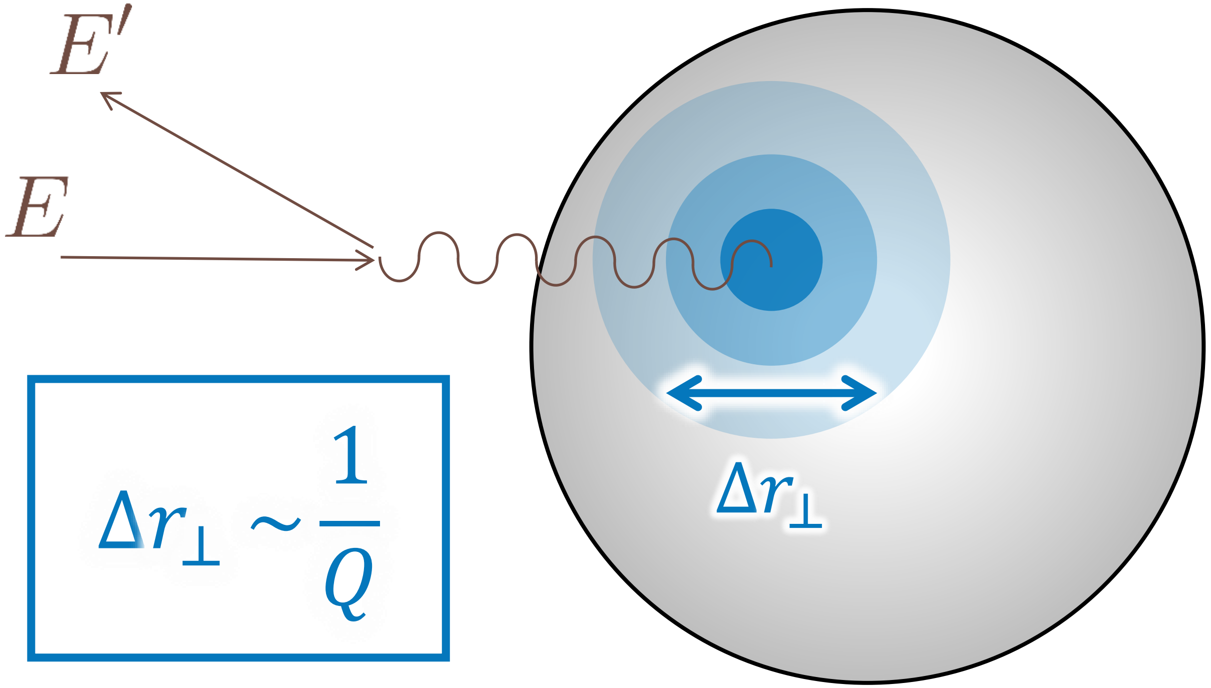
- Wally Melnitchouk (JAM)
- Nobuo Sato (JAM)
- Yuri Kovchegov (SURGE)
- Dan Pitonyak (SURGE)

- **Andrey Tarasov (SURGE: PD)**
- **Yossathorn Tawabur (SURGE: PD)**
- **Daniel Adamiak (SURGE: PD)**

- **Nick Baldonado (SURGE: GA)**

Image Resolution:

$$Q^2 = 4\,E\,E' \,\sin^2\frac{\theta}{2}$$



$$\Delta r_\perp \sim \frac{1}{Q}$$

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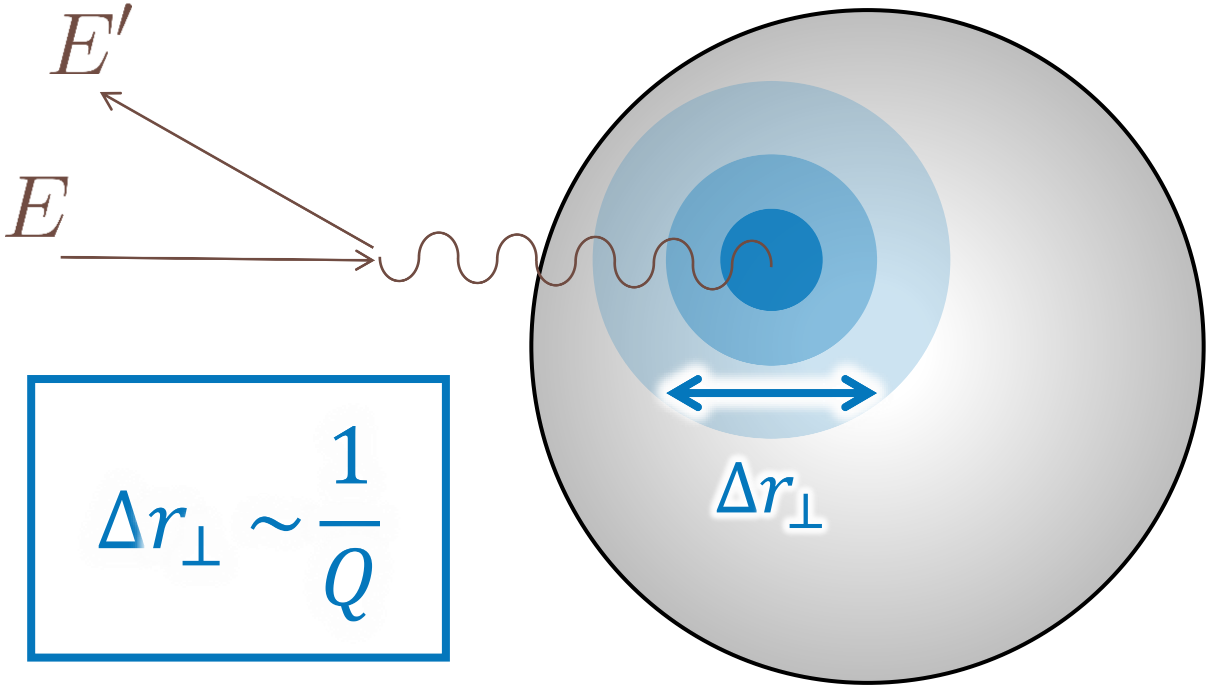
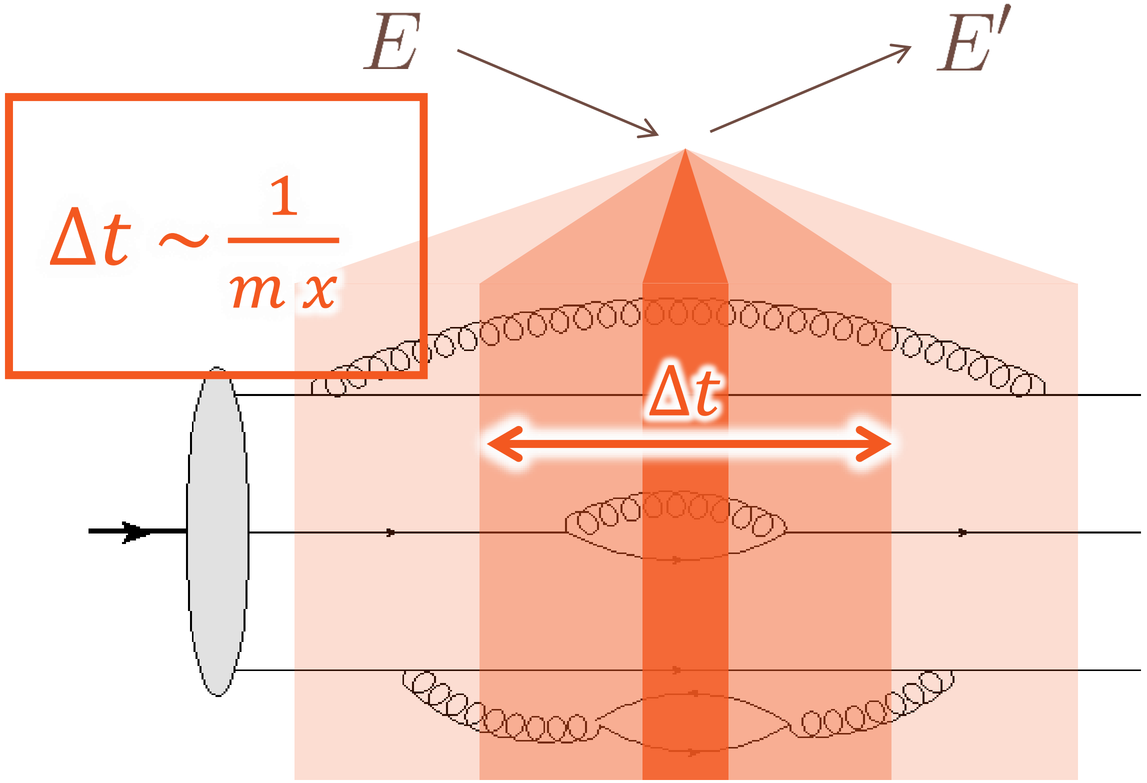


$$\Delta r_\perp \sim \frac{1}{Q}$$

Exposure Time:

$$x = \frac{Q^2}{2m(E - E')}$$



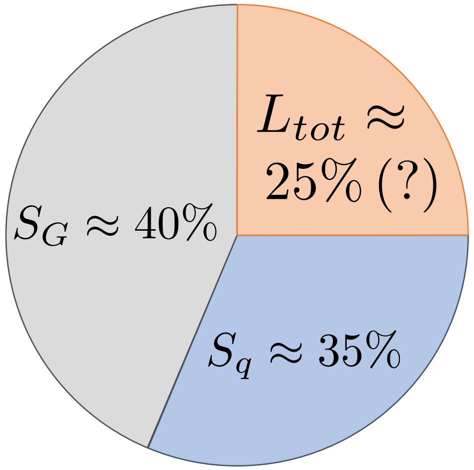
$$\Delta t \sim \frac{1}{m\,x}$$

The Proton Spin Budget

Jaffe-Manohar Spin Sum Rule:

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

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



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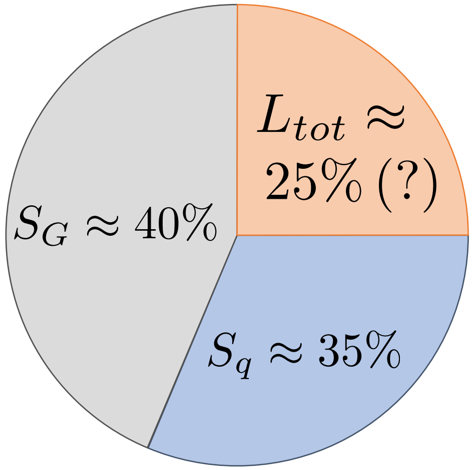

- <u>Quark Polarization:</u>

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

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

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

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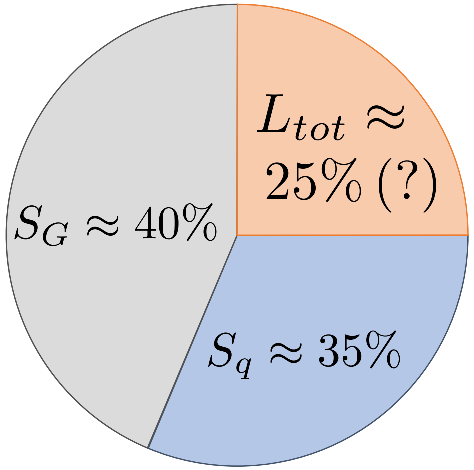

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➢ Nonlocal generalization of the **axial vector current** $j_5^\mu = \bar{\psi} \, \gamma^\mu \gamma^5 \psi$

- <u>Gluon Polarization:</u>

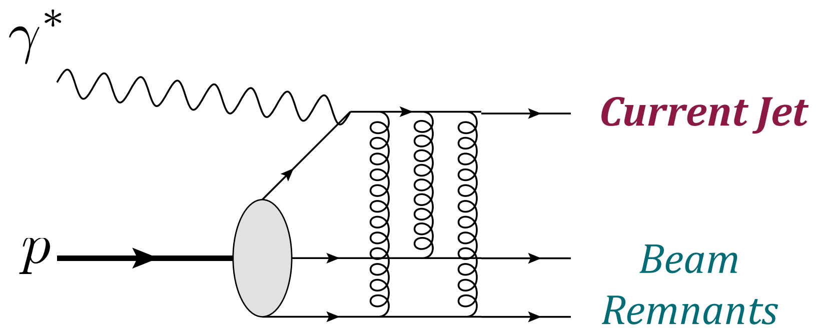
$$S_G(Q^2) = \int_0^1 dx \, \Delta G(x, Q^2)$$

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

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

Dipole Degrees of Freedom at Small x

"Knockout" DIS at Large x:



- At **large x**, DIS resembles a **knockout** process in which a quark is ejected from the proton.

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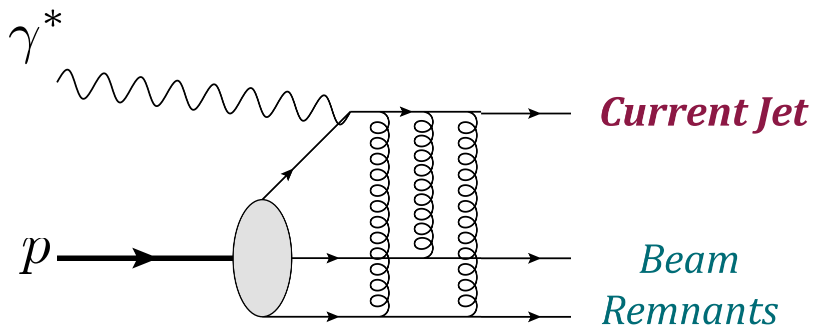

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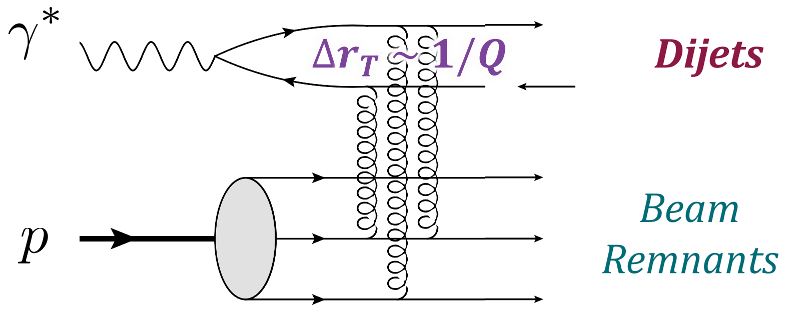

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- At **small x**, DIS resembles a **hadronic scattering** process of a $q\ \bar{q}$ dipole on the target

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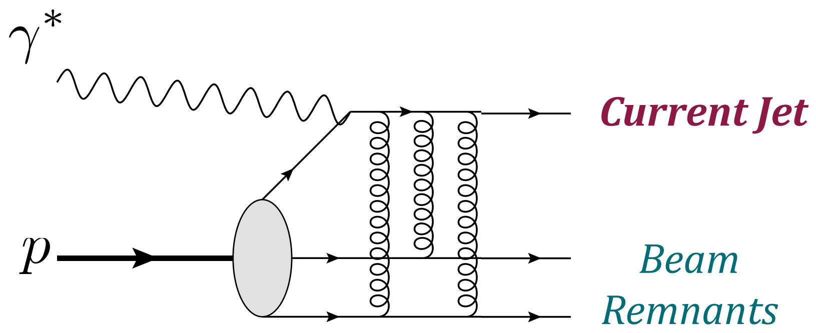

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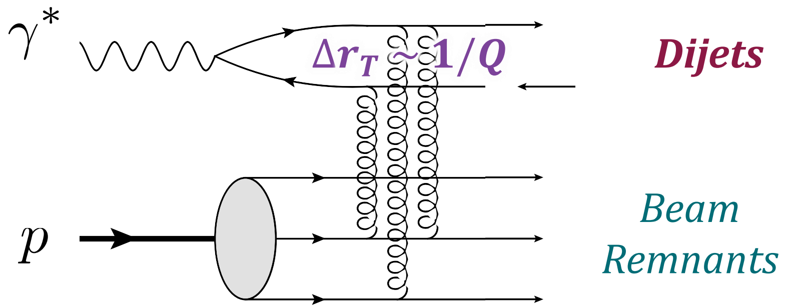
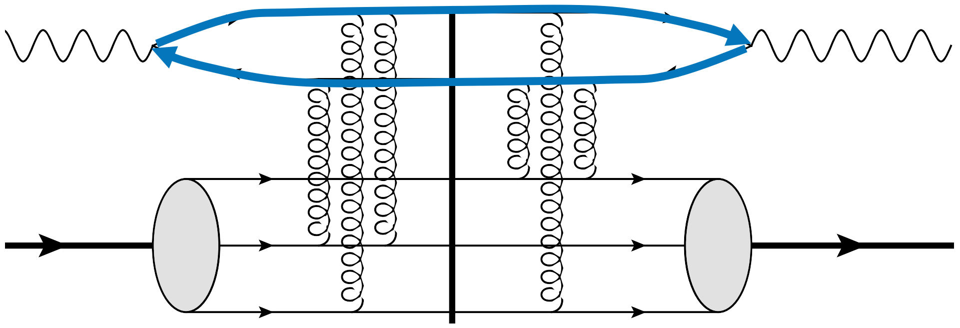


- At **large x**, DIS resembles a **knockout** process in which a quark is ejected from the proton.

- At **small x**, DIS resembles a **hadronic scattering** process of a $q\ \bar{q}$ dipole on the target

$$\left\langle \mathrm{tr}\left[V_{x_\perp} V_{y_\perp}^\dagger\right]\right\rangle$$

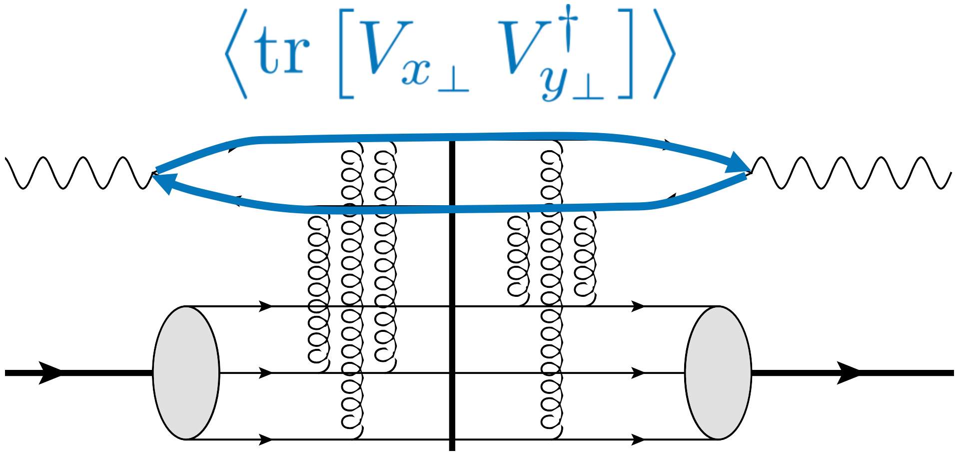


➢ **Wilson lines**: **Boosted, coherent** scattering in a background field

$$V = \mathcal{P} \exp\left[ig \int dz_\mu A^\mu(z)\right]$$

Spin at Small x versus Large x

- The **leading-power** dipole scattering is **spin-independent**
  - ➢ It is **not the ordinary eikonal Wilson lines** that describe polarized physics at small x!



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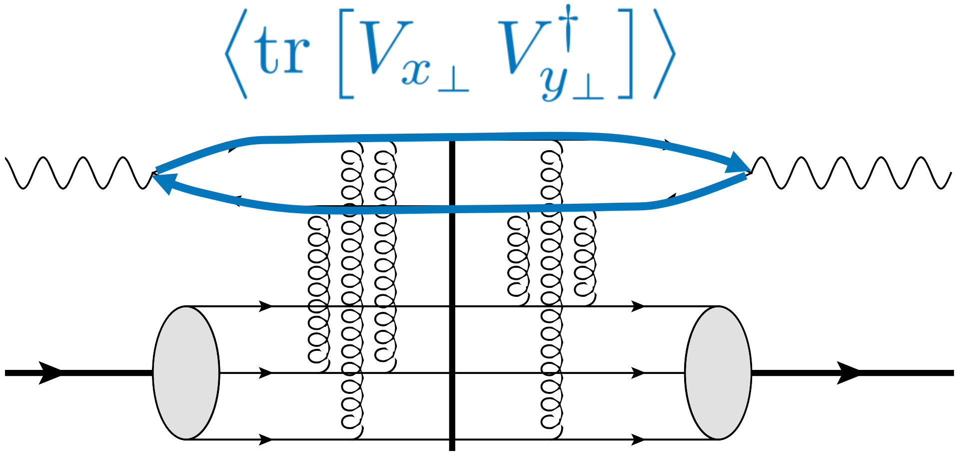
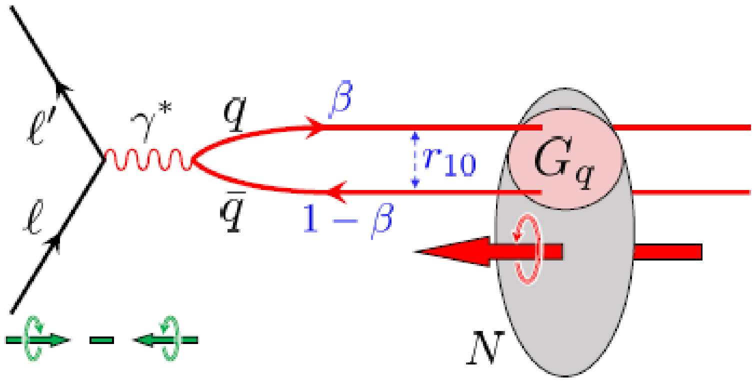
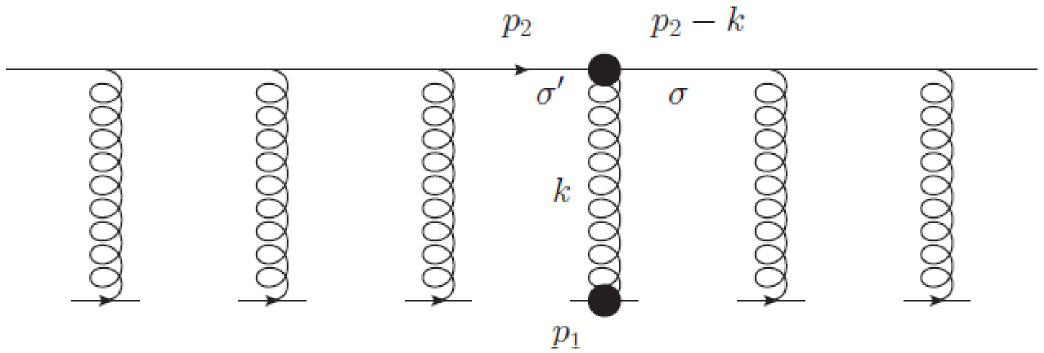


- **Spin at small x** selects on **different, sub-eikonal** dynamics than unpolarized observables
  - ➢ Spin observables are sensitive to **novel small-x physics**
  - ➢ **Useful for gluon saturation**, but **broader** than saturation alone

Small x: "Dipole" DIS



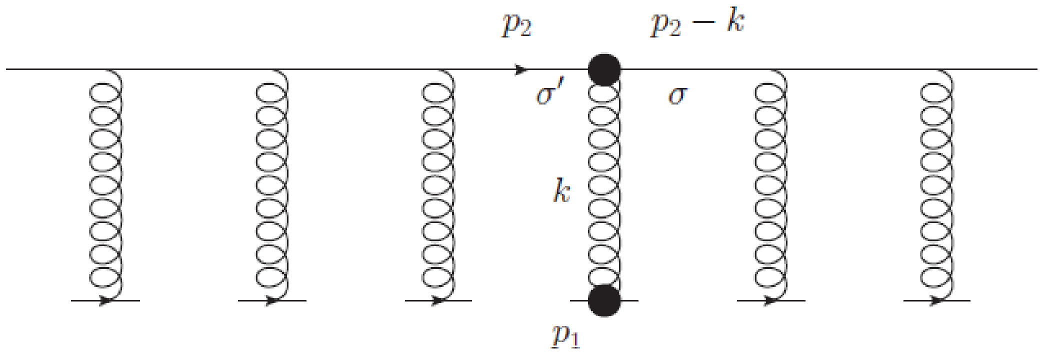


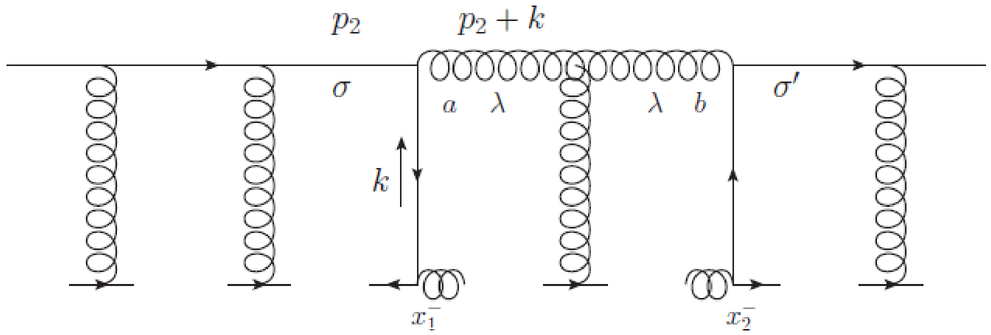
*See, e.g., Kovchegov, Pitonyak, MS: JHEP **01** (2016), Phys. Rev. **D95** (2017), Phys.Rev.Lett. **118** (2017)*

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

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

Building Blocks: Polarized Wilson Lines





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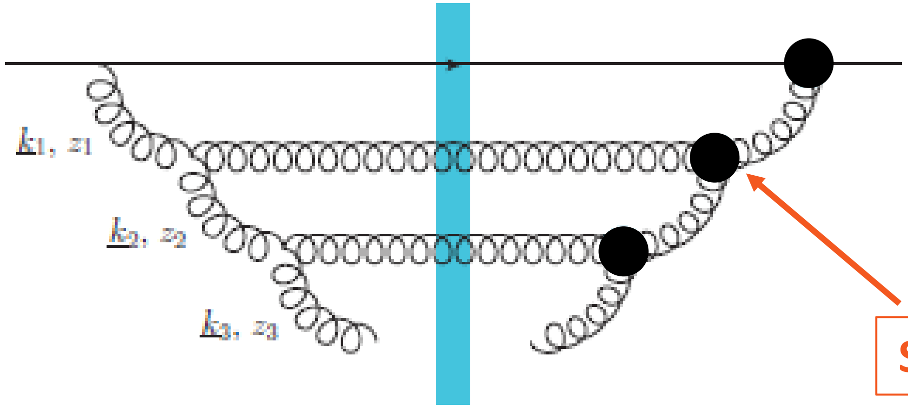
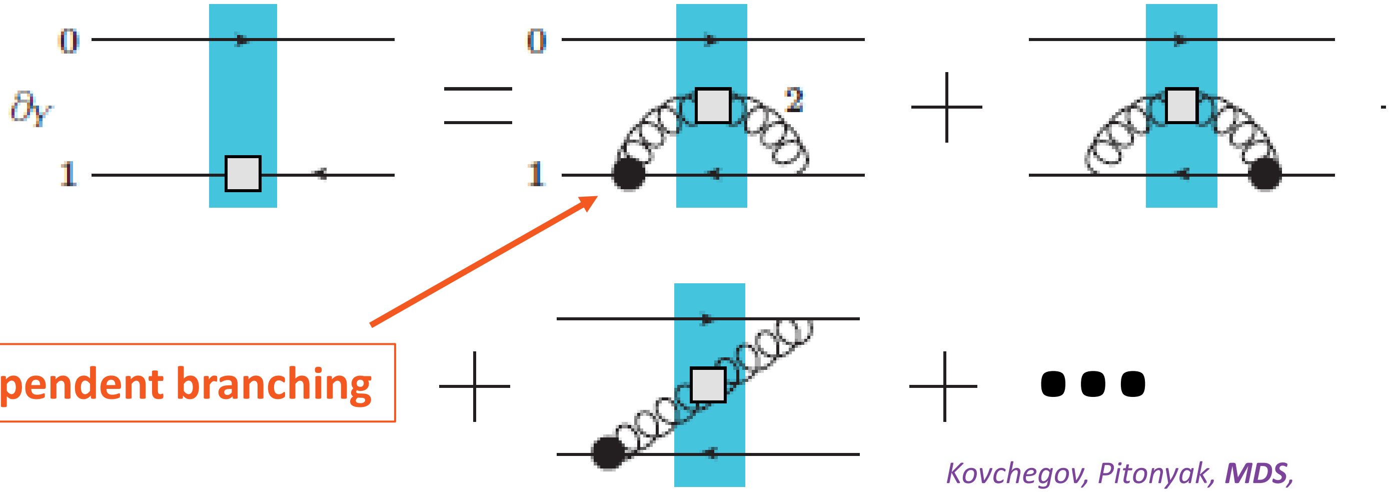
$$- \frac{g^2 \, p_1^+}{s} \int\limits_{-\infty}^{\infty} dx_1^- \int\limits_{x_1^-}^{\infty} dx_2^- \;\; V_{\underline{x}}[+\infty, x_2^-] \, t^b \, \psi_\beta(x_2^-, \underline{x}) \, U_{\underline{x}}^{ba}[x_2^-, x_1^-] \left[\frac{1}{2} \gamma^+ \gamma^5 \right]_{\alpha\beta} \bar{\psi}_\alpha(x_1^-,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

Flavor-changing Wilson line

Since m=0 in Bjorken kinematics: Quark helicity conservation



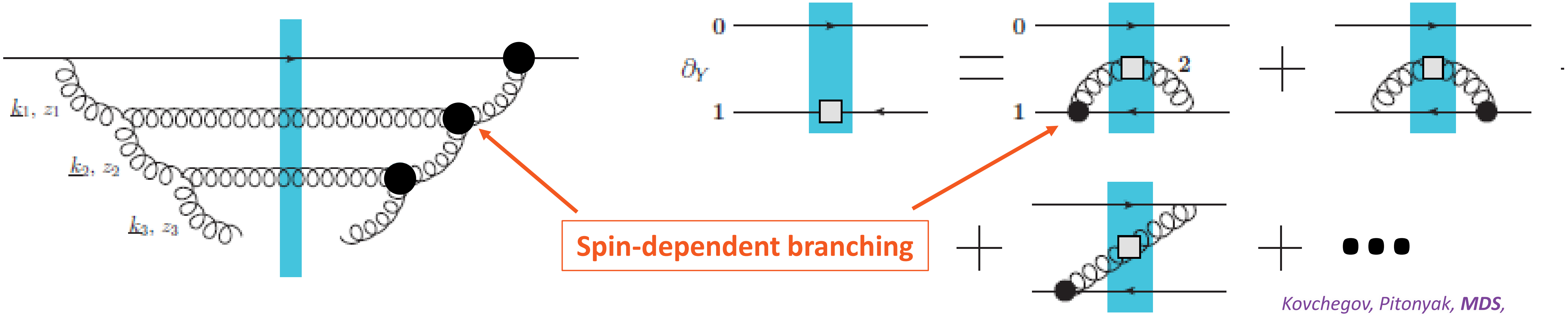
Spin-dependent branching



*Kovchegov, Pitonyak, **MDS**,*
*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)*



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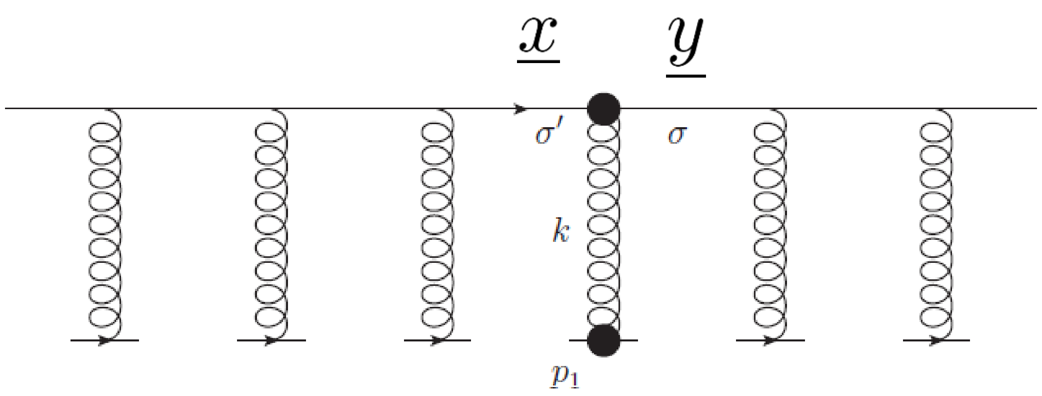
- **Suppressed** by the **coupling** α_s but **enhanced** by the **phase space** $\ln \frac{1}{x}$
  - Resummation leads to **quantum evolution of spin at small x**
  - Analogous to **BFKL evolution** for unpolarized gluons *(leading log accuracy)*

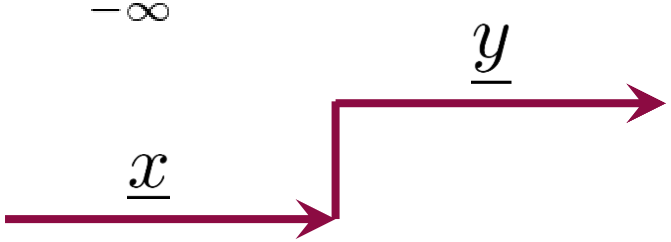


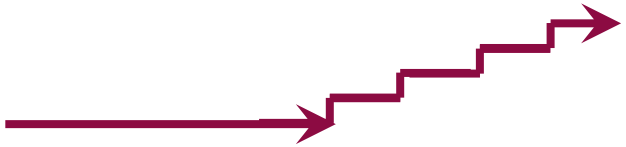
*F. Cougoulic, Y. Kovchegov, A. Tarasov, Y. Tawabutr, JHEP **07** (2022)*

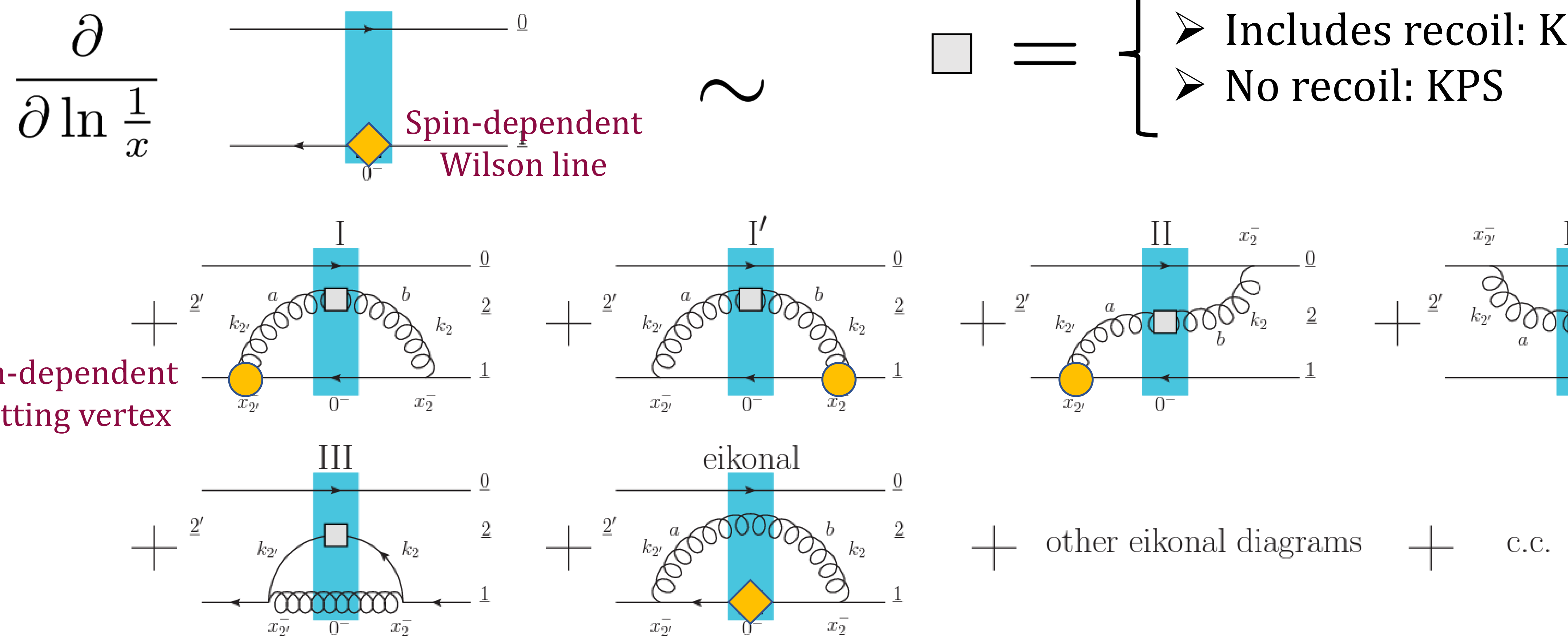
- **Spin-independent** sub-eikonal operator contributes to evolution
- **New contribution** not previously included in dipole helicity evolution

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

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







$\square$ =

- Includes recoil: KPS-CTT
- No recoil: KPS

- <u>Large Nc</u>: Gluon dipoles only
- <u>Large Nc+Nf</u>: Quark + Gluon dipoles

Method of Infrared Evolution Equations

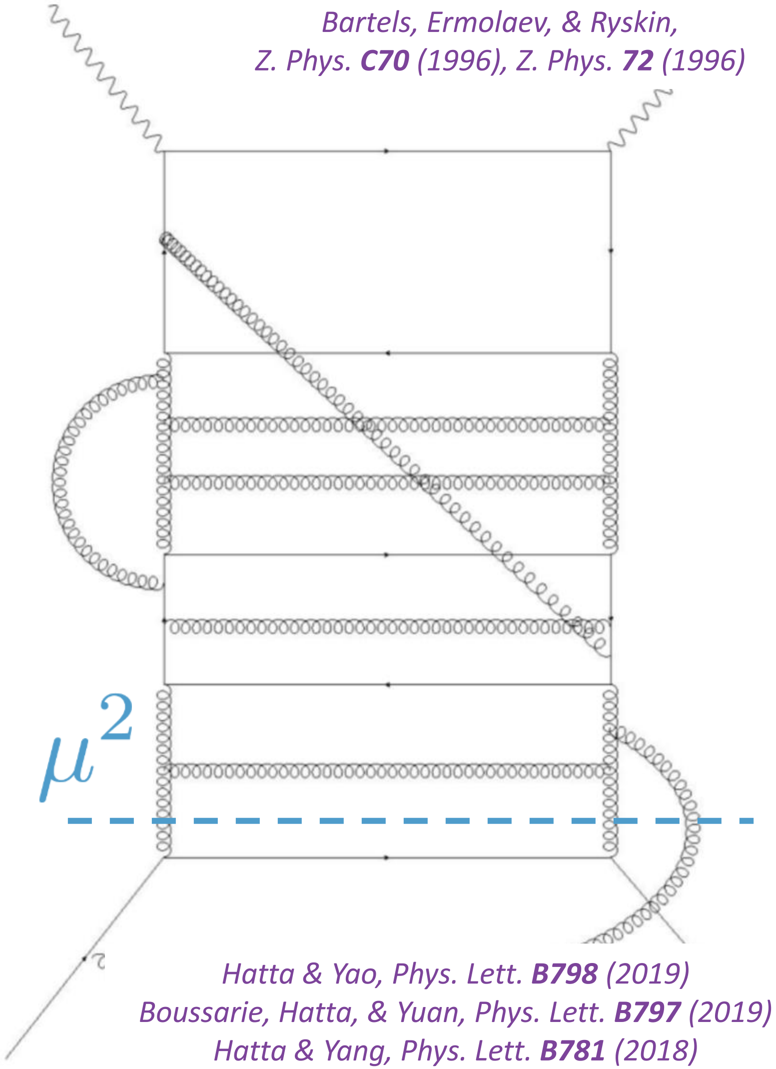
- Missing recoil term **brings small-x asymptotics into agreement** with other calculations using infrared evolution equations (beyond 2 loops)

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

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

Asymptotically as $x \to 0$

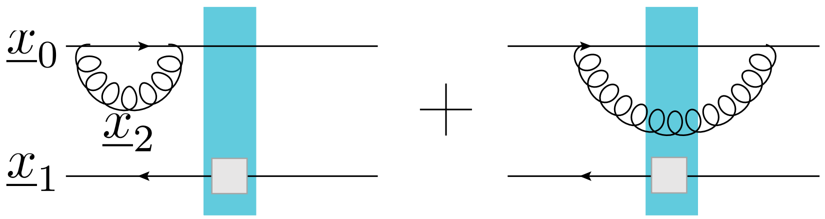
Bartels, Ermolaev, & Ryskin, Z. Phys. **C70** (1996), Z. Phys. **72** (1996)



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)

Beyond Color Transparency and Into the UV

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



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

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

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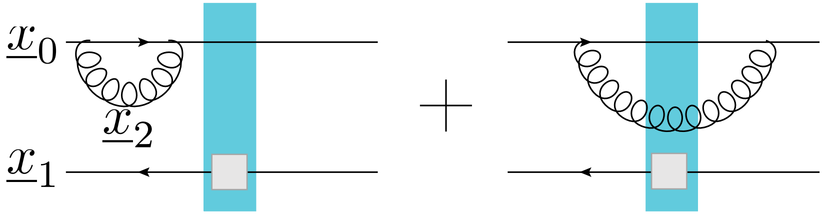

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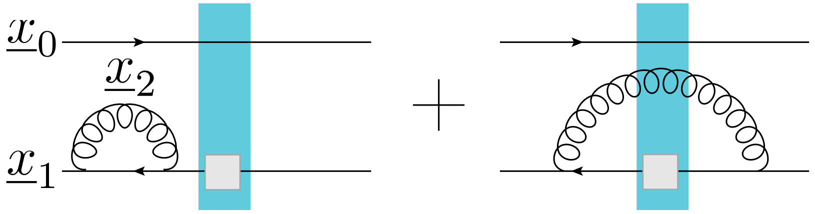
Cancels when $x_2 \to x_0$

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



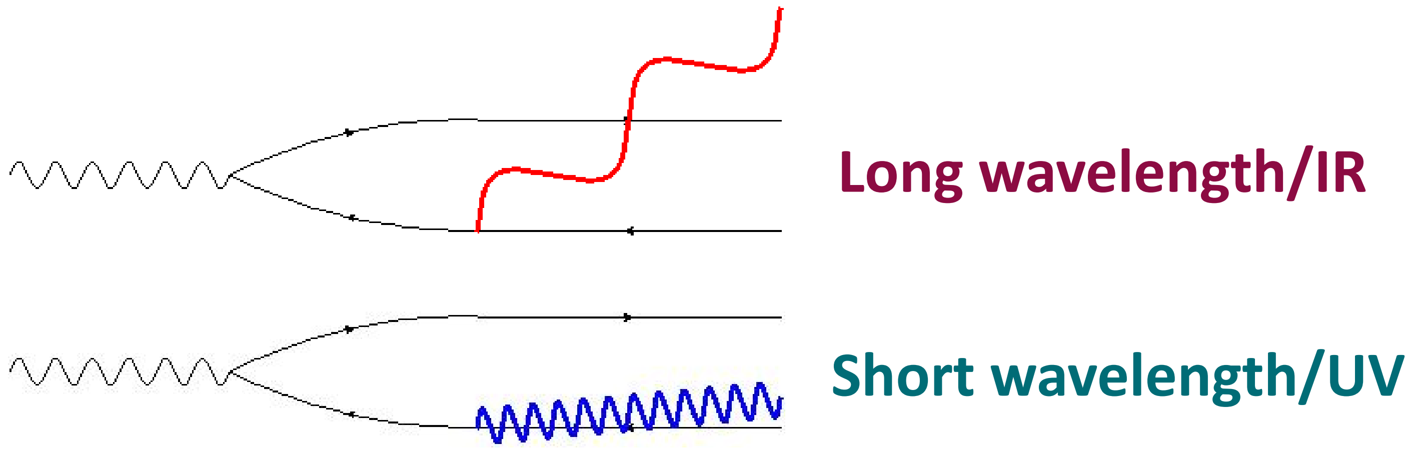
$$\frac{\alpha_s N_c}{2\pi^2} \int\limits_{\Lambda^2/s}^{z} \frac{dz'}{z'} \int \frac{d^2 x_2}{x_{21}^2} \times \left[\frac{1}{N_c^2} \left\langle \mathrm{tr}\left[V_2 V_1^{pol\,\dagger} \right] \mathrm{tr}\left[V_0 V_2^{\dagger} \right] \right\rangle_{(z's)} - \frac{1}{N_c} \left\langle \mathrm{tr}\left[V_0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

Does NOT cancel when $x_2 \to x_1$

Double-Logarithmic Evolution at Small x

Longitudinal + transverse logarithmic phase space

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



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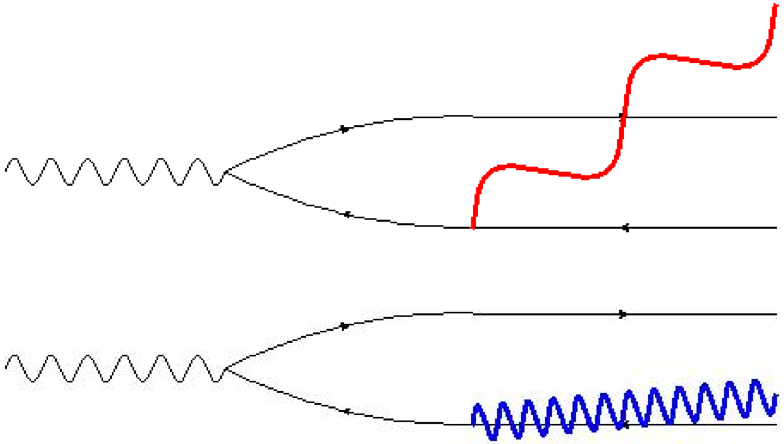

Long wavelength/IR

Short wavelength/UV

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

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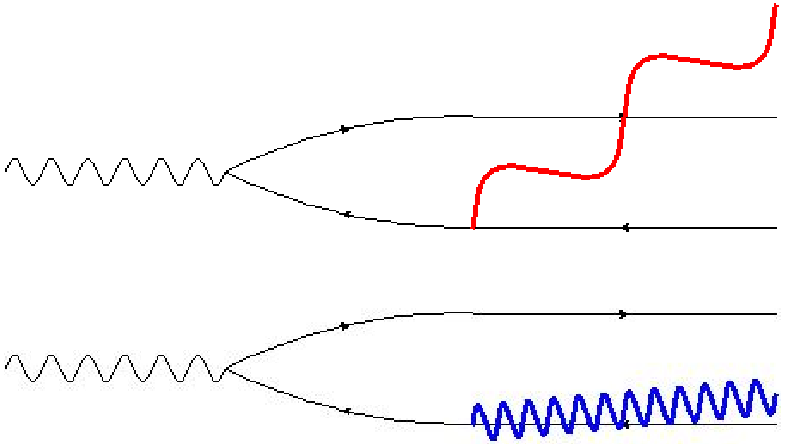

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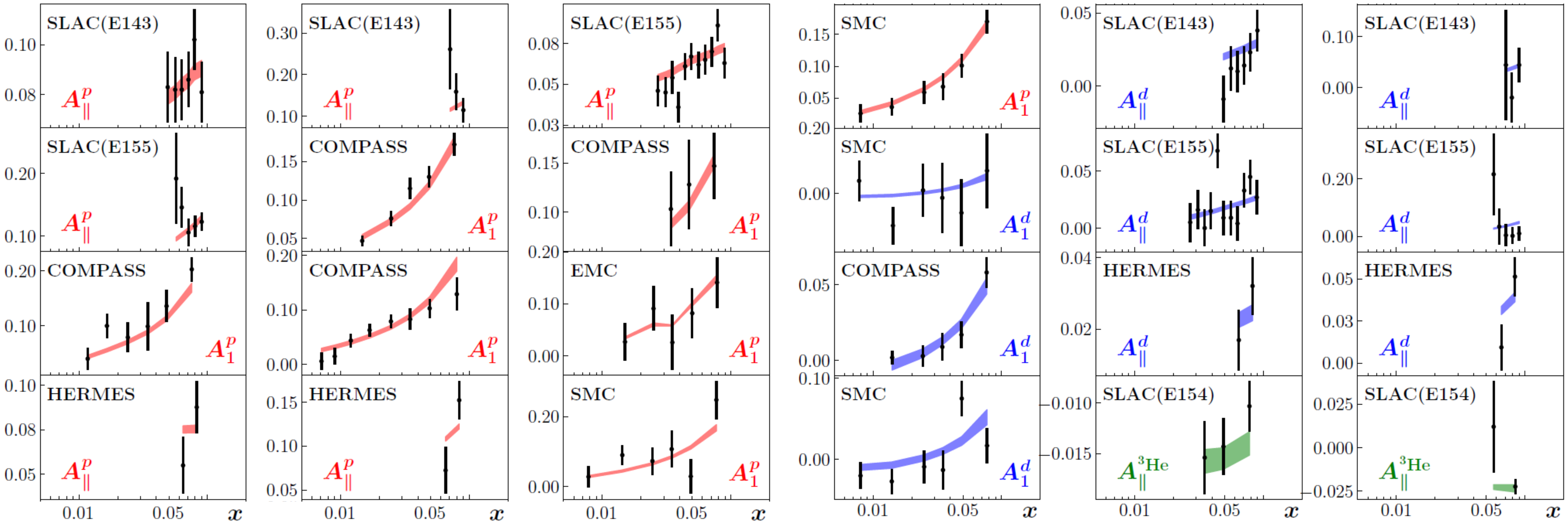
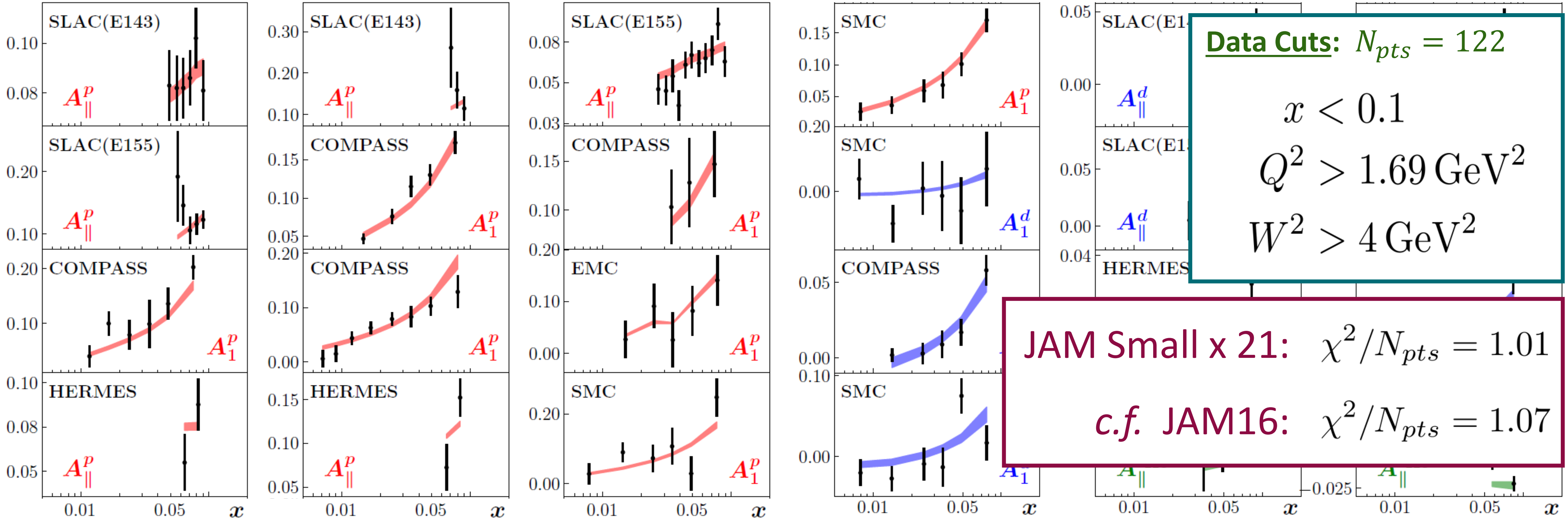
- **Polarized (KPS) evolution:**
  - **No transparency of spin**: dominance of **collinear transverse logs**
  - **Double-logarithmic** evolution: $\alpha_s \ln^2\frac{1}{x} \sim O(1)$
  - Sensitive to **lifetime ordering** (c.f. NLO BFKL), less sensitive to saturation



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

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

First Global Analysis Using KPS Evolution



Data Cuts: $N_{pts} = 122$

$x < 0.1$

$Q^2 > 1.69\,\text{GeV}^2$

$W^2 > 4\,\text{GeV}^2$

JAM Small x 21: $\chi^2/N_{pts} = 1.01$

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

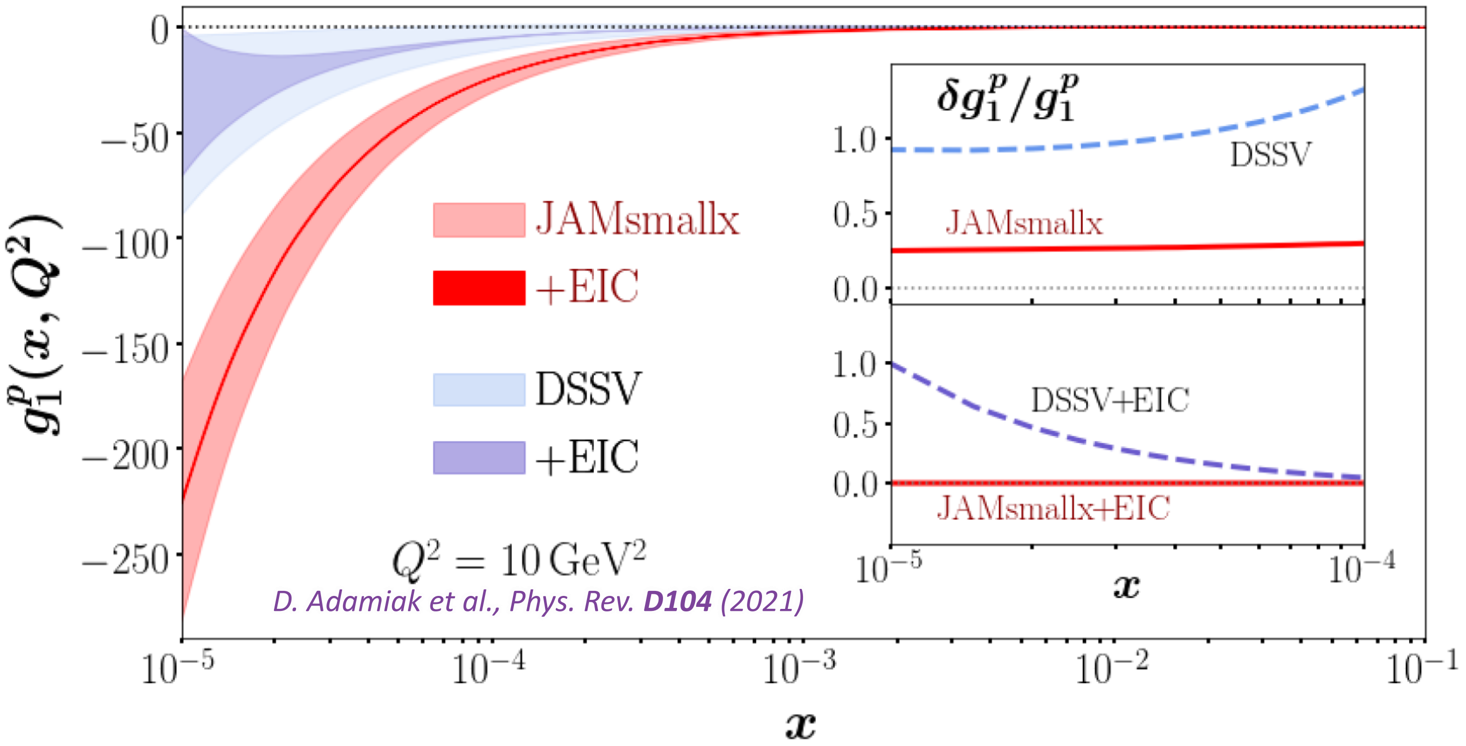
- **Global analysis of polarized DIS** at small x using KPS formalism

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

- **Bayesian analysis** performed using JAM architecture

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

- **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



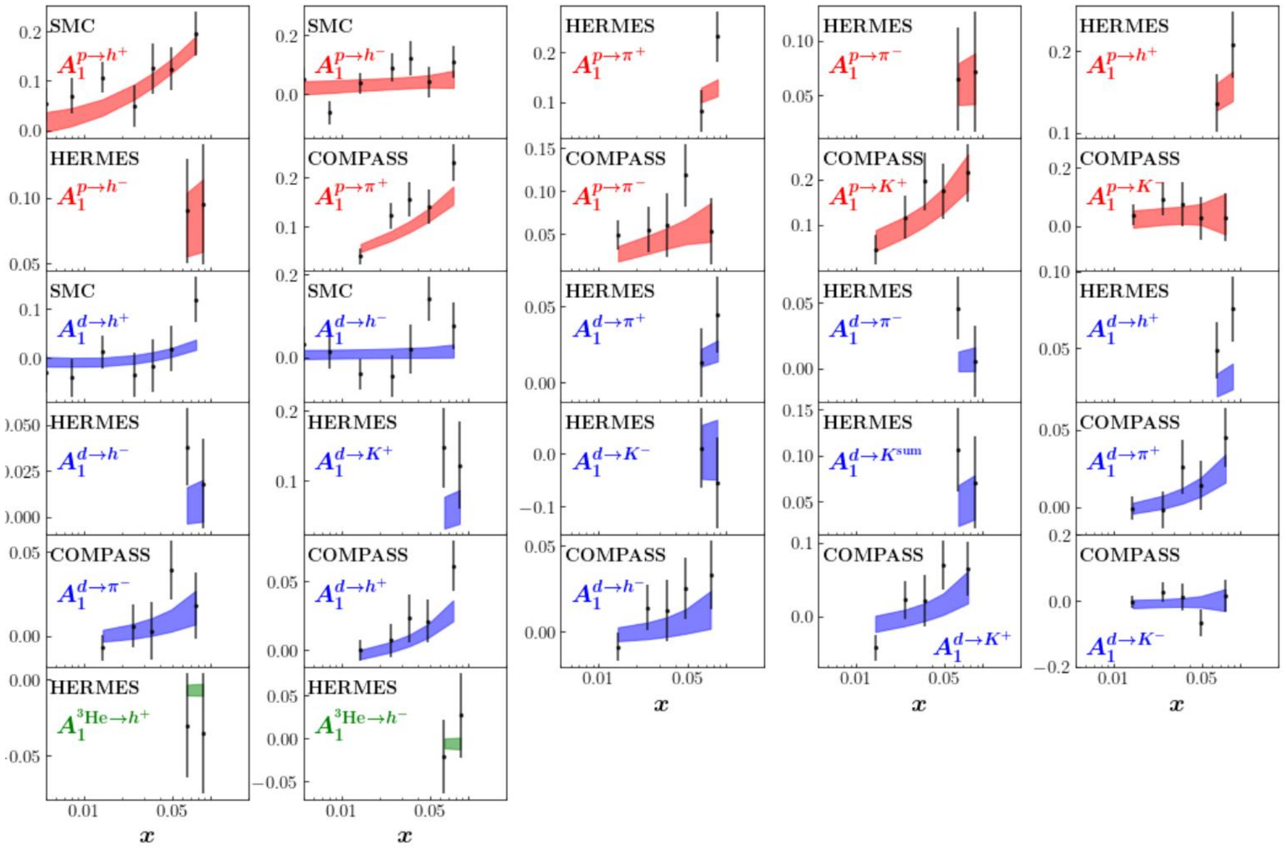
- The procedure **cannot describe everything**
  - ➢ Fails for **too-large x** (as expected)
  - ➢ Equally good $\frac{\chi^2}{N_{pts}} \sim 1$ for $0.05 \leq x \leq 0.20$

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)*

D. Adamiak et al., arXiv: 2308.07461



- <u>**New, updated JAM Small x fit:**</u>
  - ➢ DIS + SIDIS data
  - ➢ Improved KPS-CTT evolution
  - ➢ Large $N_c + N_f$ limit

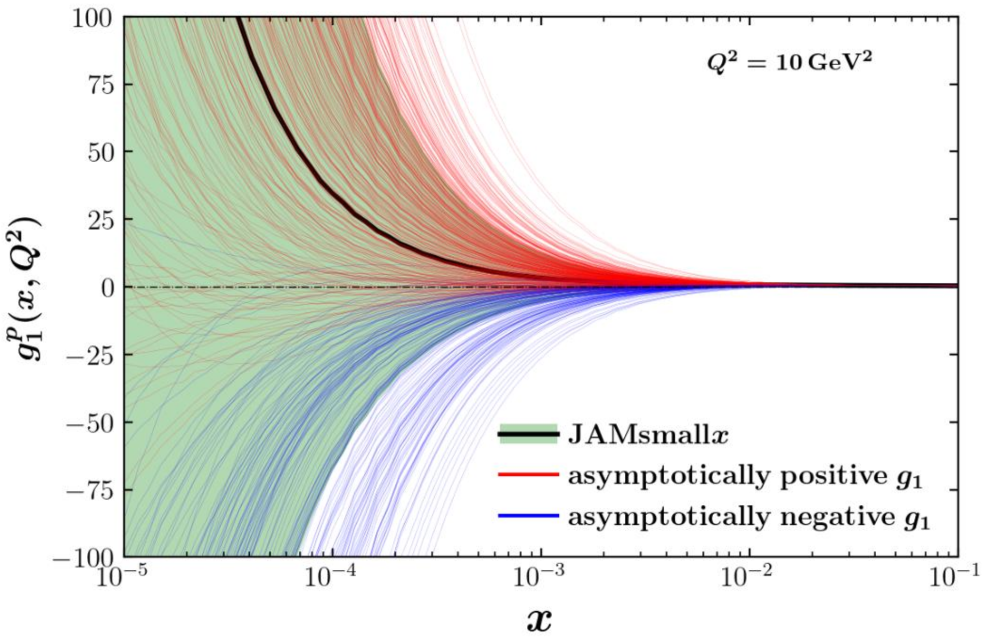
<u>**Data Cuts:**</u> $N_{pts} = 226$

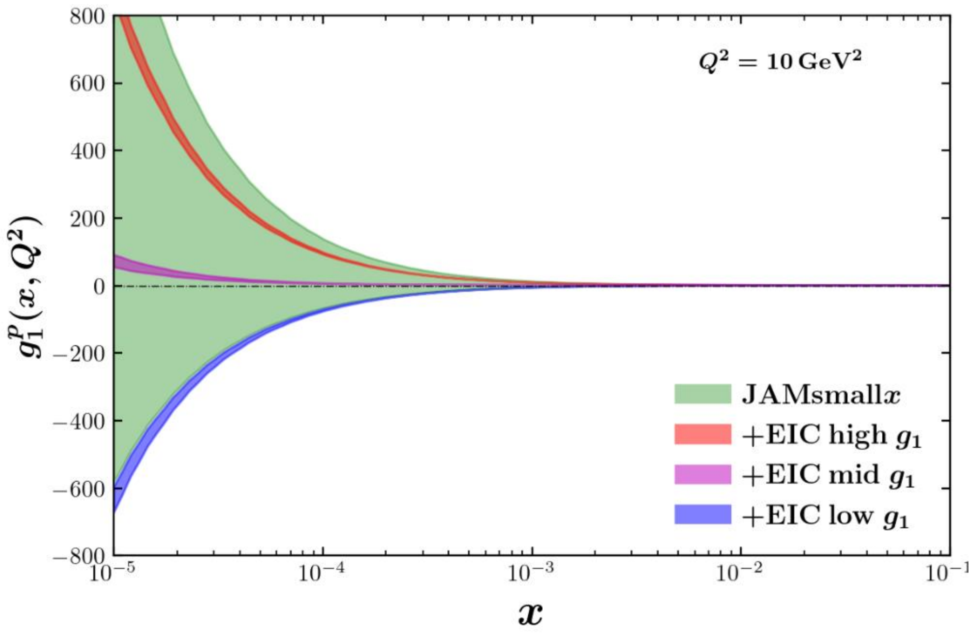
$$x < 0.1$$
$$Q^2 > 1.69\,\text{GeV}^2$$
$$0.4 \lesssim z \lesssim 0.6$$

❖ New evolution + large N_f = **several new dipole functions** included in fit

JAM Small x 23: $\chi^2/N_{pts} = 1.03$

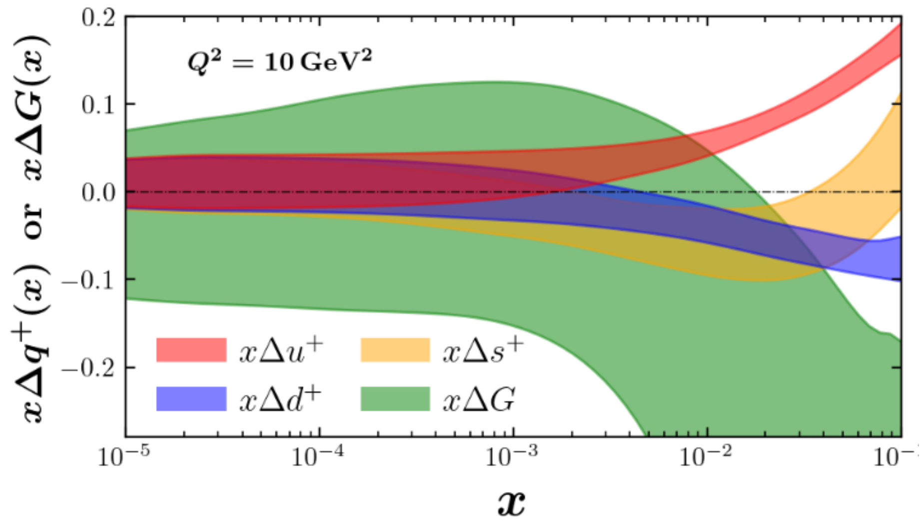
New Global Analysis

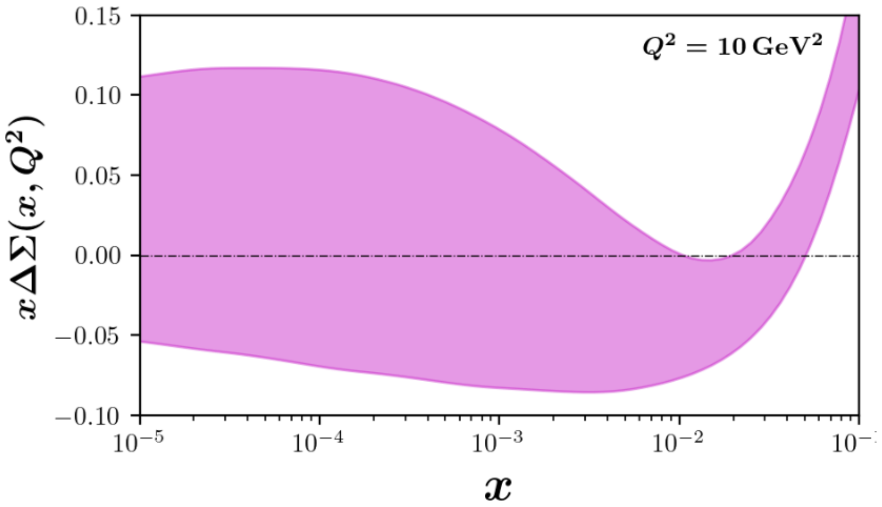




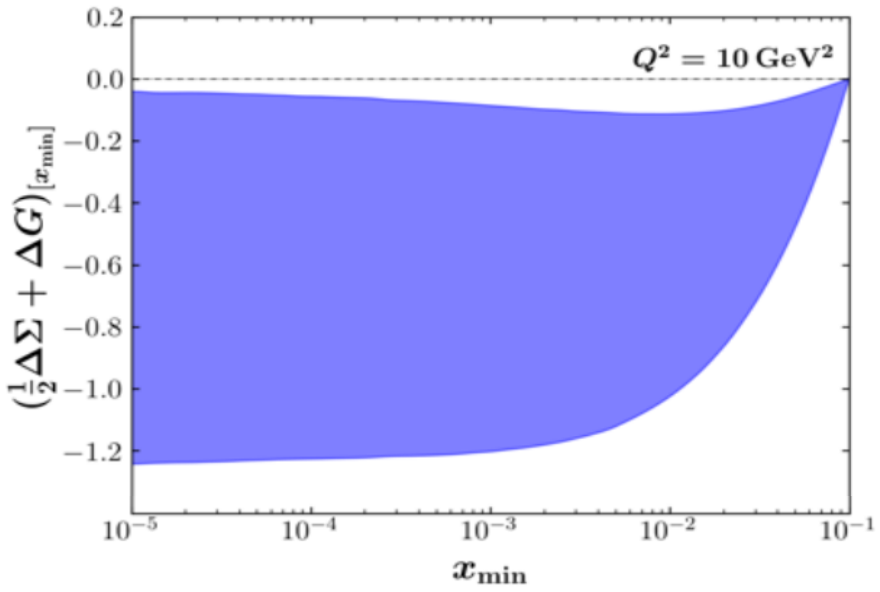
- Small-x evolution drives a definite **curvature of $g_1(x)$** -- but the **sign is unconstrained** from current data for a few new amplitudes

➢ **Need some kind of additional input:** smaller-x data, theory of small-x hadron production in polarized pp, or controlled matching to large x





- ➢ Small-x signs of most distributions span zero due to a few poorly-constrained amplitudes
- ➢ Preference for negative spin contribution from small x?
- ➢ **Stay tuned!**



Parting Comment: The Roots of Spin are Chiral

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

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

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

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

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

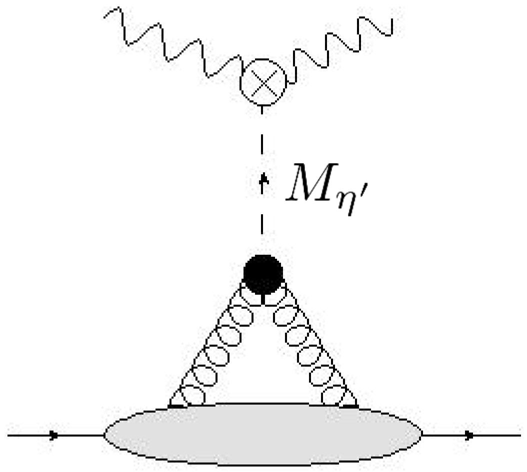
$$\Delta\Sigma(Q^2) = \sum_q \int_0^1 dx\, (\Delta q + \Delta\bar{q})(x, Q^2) = \frac{1}{p^+} \sum_q \langle pS_L|\bar{\psi}(0)\frac{\gamma^+\gamma^5}{2}\psi(0)|pS_L\rangle \sim \frac{\langle j_5^+\rangle}{p^+}$$

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

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

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

$$\ell^\mu = p'^\mu - p^\mu$$



- 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)*

- Does collinear factorization capture **all** the contributions to g_1^p?

Conclusions

- Spin at small x lies at the intersection of multiple frontiers in hadronic structure:
  - ➢ Longitudinal coherence
  - ➢ Sub-eikonal degrees of freedom (spin)
  - ➢ High density / saturation

- Theory and phenomenology of spin at small x is developing rapidly!

Small x: "Dipole" DIS