First Analysis of World Polarized DIS Data in the Small-x Dipole Formalism

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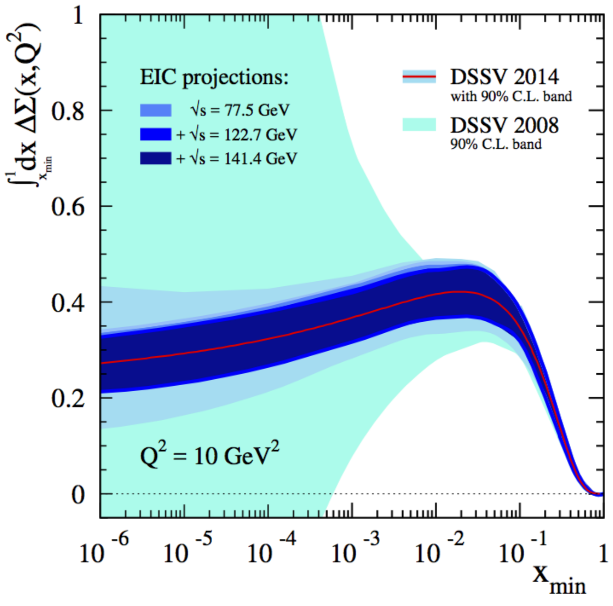
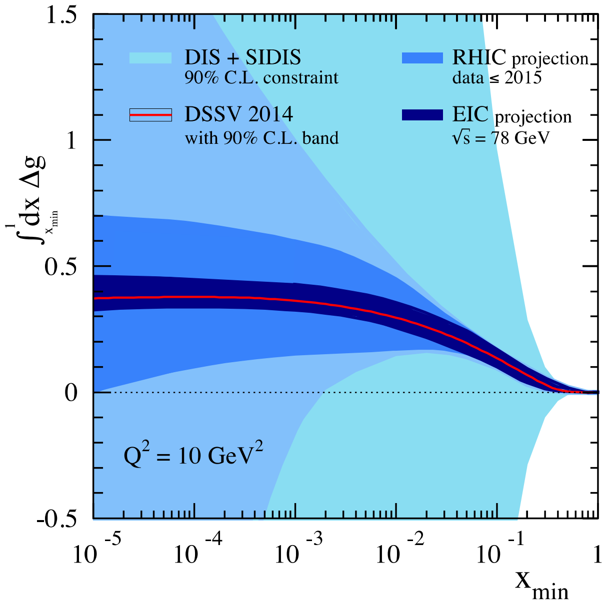
$$\Delta q^+ \equiv q + \bar{q}$$

$$\Delta\Sigma(Q^2) = \sum_q \int_0^1 dx\, \Delta q^+(x, Q^2)$$

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

Aschenauer et al., Phys. Rev. **D92** (2015) no. 9 094030





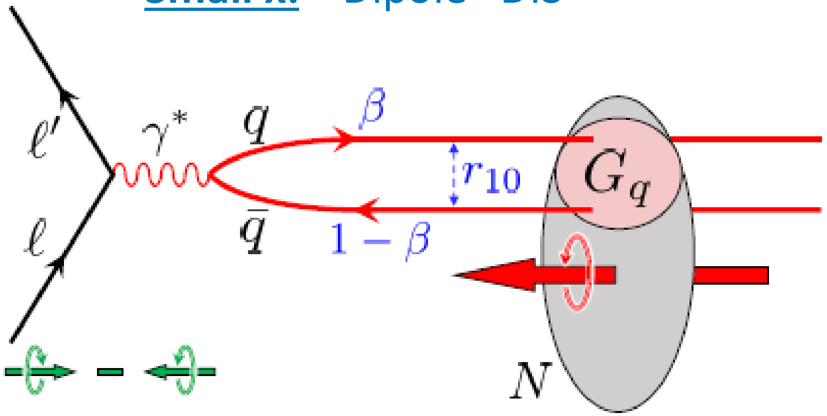
- Determination of the partonic origin of proton spin **requires extrapolation to x=0**
- Extractions based on **DGLAP** are **not predictive of the x dependence**
  - Inevitable that the **uncertainty blows up** once **data constraints run out**
  - Controlled extrapolation to x=0 **requires a theory** which **predicts spin at small x**

Spin at Small x: Beyond the Eikonal Framework

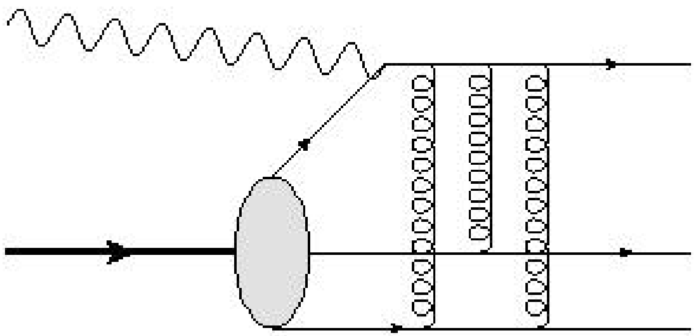
$$\Delta q^+(x,Q^2) = \frac{N_c}{2\pi^3}\int\limits_{\Lambda^2/s}^{1}\frac{d\beta}{\beta}\int\limits_{1/\beta s}^{r^2_{max}}\frac{dr^2_{10}}{r^2_{10}}\,G_q(r^2_{10},\beta s),$$

$s = Q^2/x$

$$r^2_{max} = \min\{1/\Lambda^2, 1/(\beta Q^2)\}$$

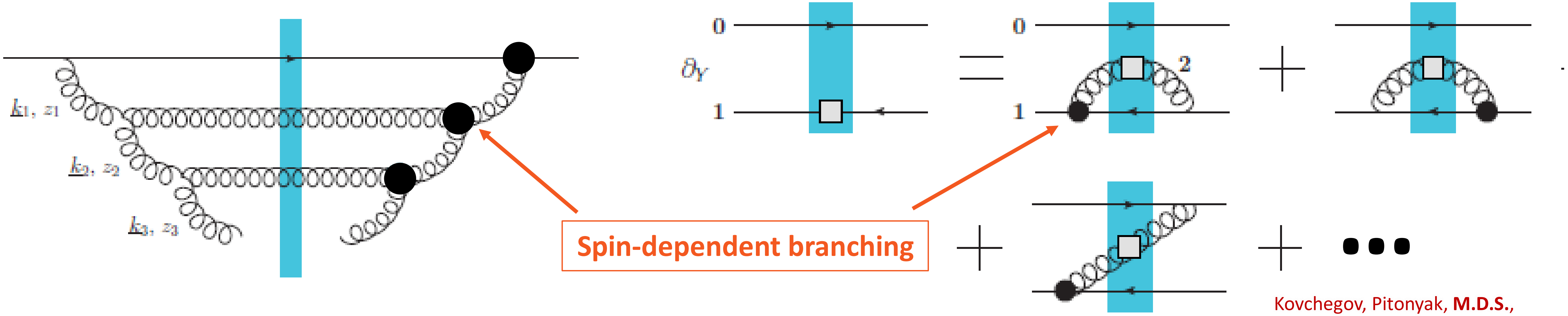


- At **large x**, DIS is dominated by a **"Knockout" process**
  - ➢ At **small x**, the leading channel is a **"dipole" process**



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

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



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**

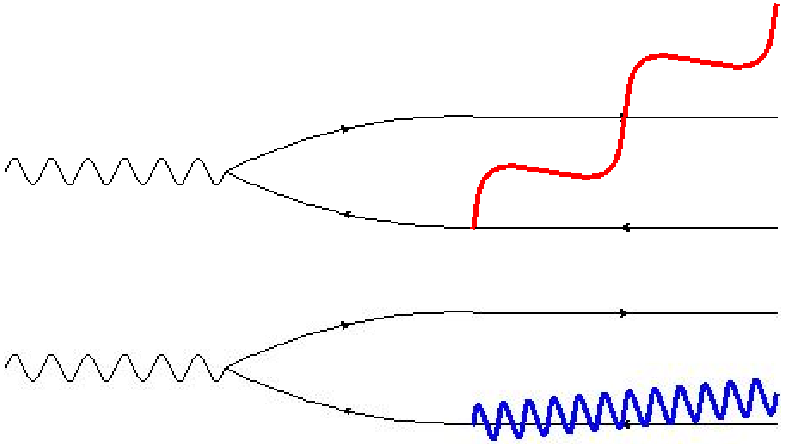
See also Bartels, Ermolaev, Ryskin, Z. Phys. **C70** (1996)

- **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

Polarized vs. Unpolarized Small-x Evolution

Longitudinal + transverse
logarithmic phase space

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



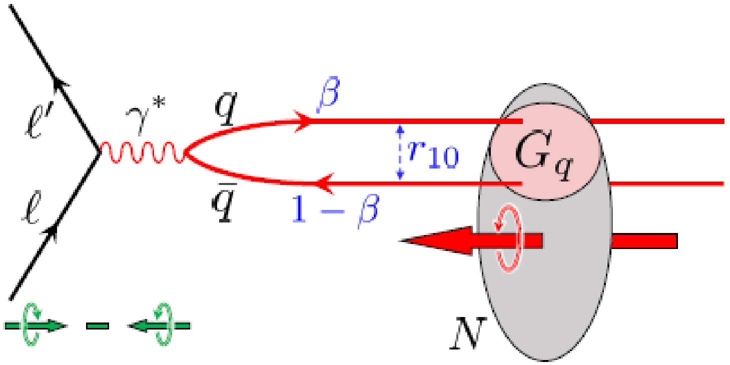
Long wavelength/IR

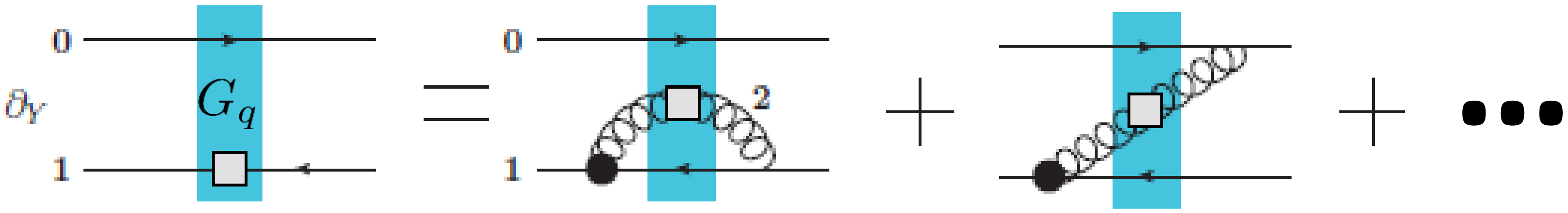
Short wavelength/UV

- **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 **UV 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

The KPS Evolution Equations





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

$$\eta = \sqrt{\frac{\alpha_s N_c}{2\pi}}\ln\frac{\beta s}{\Lambda^2}, \qquad s_{10} = \sqrt{\frac{\alpha_s N_c}{2\pi}}\ln\frac{1}{r_{10}^2\Lambda^2},$$

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

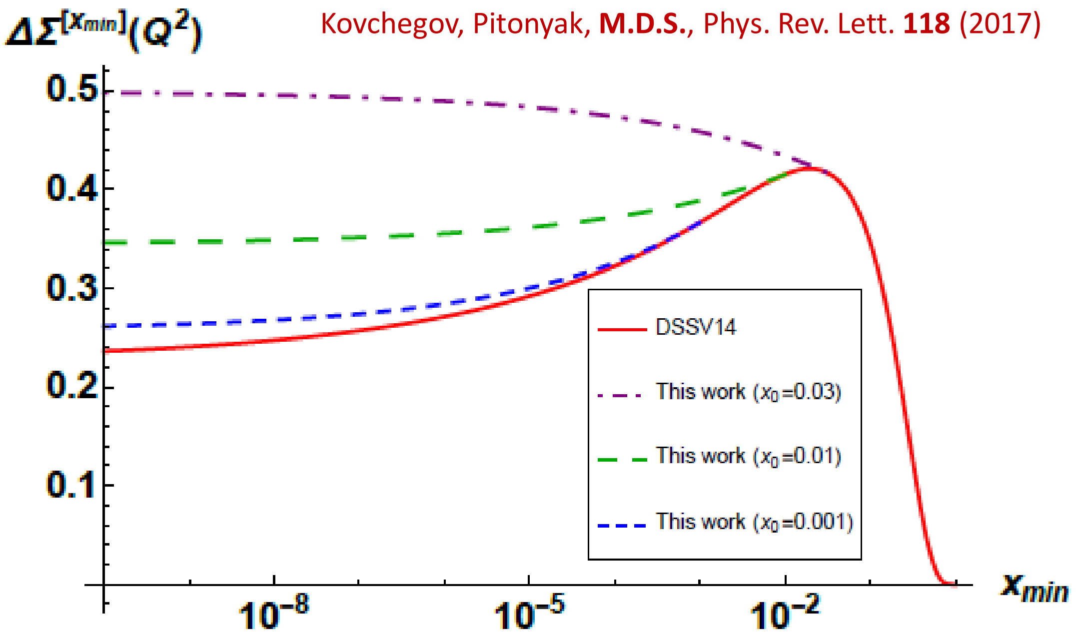
$$s_{32}^{\min} = \max\{s_{10}\,,\ s_{21} - \eta' + \eta''\}$$

- **Double-logarithmic evolution** equations written with logarithmic variables η, s_{10}
- Infinite tower of operators only **closes in certain limits (<u>large-N_c</u>** or large-<u>N_c&N_f</u>)
- Auxiliary **“neighbor dipole” function Γ** necessary to enforce lifetime ordering

The Ambition: Bayesian Global Analysis of Polarized DIS

- **Previous estimates:**
  - **Potentially substantial contribution** to the proton spin from small-x quarks
  - **Exploratory methods**: instantaneous transition from large-x fit (DSSV) to power-law asymptotics of KPS evolution

Kovchegov, Pitonyak, **M.D.S.**, Phys. Rev. Lett. **118** (2017)



- **This work:**
  - **JAM Bayesian analysis** code N. Sato et al., Phys. Rev. **D93** (2016)
  - **Global analysis** of world polarized DIS data (SLAC, EMC, SMC, COMPASS, HERMES)
  - **Proton, "neutron"** (d, ³He) targets
  - **Inclusive DIS** only
    - Avoid complication of fragmentation

$$A_1 \approx \frac{g_1}{F_1}$$

$$A_{||} \propto A_1$$

Data Cuts: $N_{pts} = 122$

$$x < 0.1$$

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

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

The Approach

1. Parameterize an **initial condition** for the polarized dipole amplitude at **large $x > x_0$**
   - Generalized form of Born approximation
   - **Frozen initial condition** at $x > x_0$

$$G_q^{(0)}(s_{10}, \eta) = a_q\, \eta + b_q\, s_{10} + c_q$$

2. **Solve KPS eqns. numerically** for $x < x_0$ to determine g_1 structure function

$$\Delta q^+(x, Q^2) = \frac{1}{\alpha_s \pi^2} \int\limits_0^{\eta_{\max}} d\eta \int\limits_{s_{10}^{\min}}^{\eta} ds_{10}\, G_q(s_{10}, \eta)$$

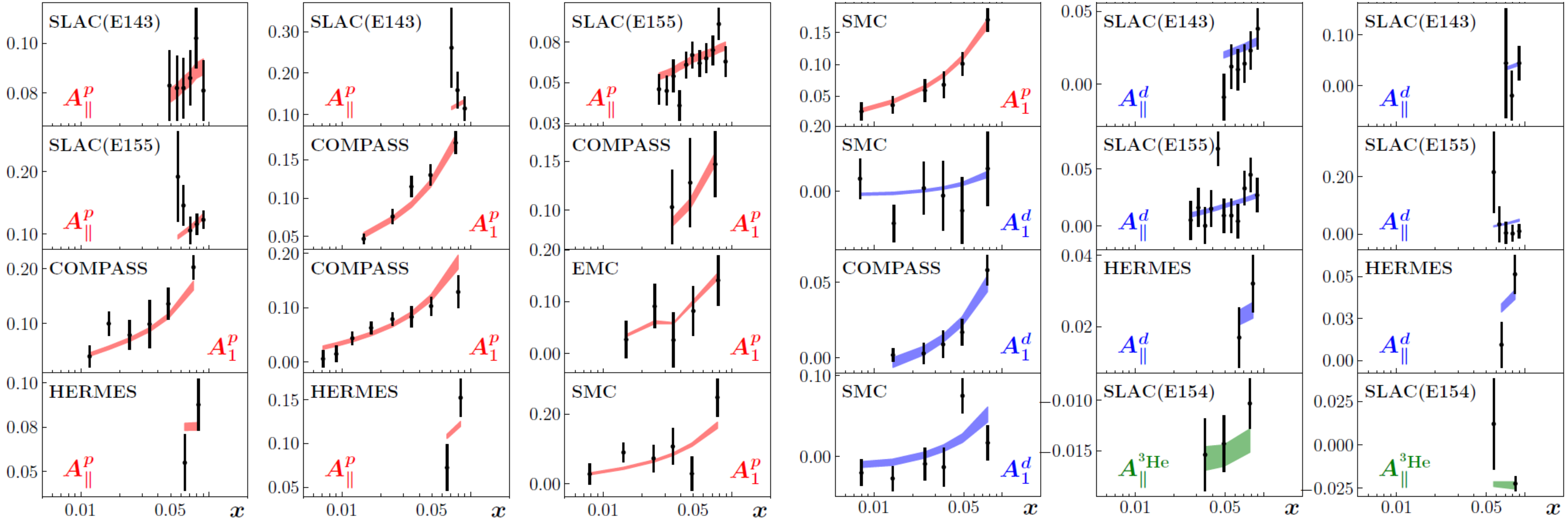
3. **Compute spin asymmetries** $A_1, A_\parallel$ and compare with experimental data
   - F_1 taken from **previous JAM fits**

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

4. **Scan parameter space** using Bayesian inference with JAM Monte Carlo framework
   - **6 parameters** scanned (a, b, c for p, n) **+ x_0, Λ**

$$A_1 \approx \frac{g_1}{F_1} \qquad A_\parallel \propto A_1$$

The KPS Formalism is Able to Describe World Data



- **Nontrivial test:** **purely small-x theory** is able to describe the world DIS data
  - ➢ Most constraining: a **few data points below x = 0.01**

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

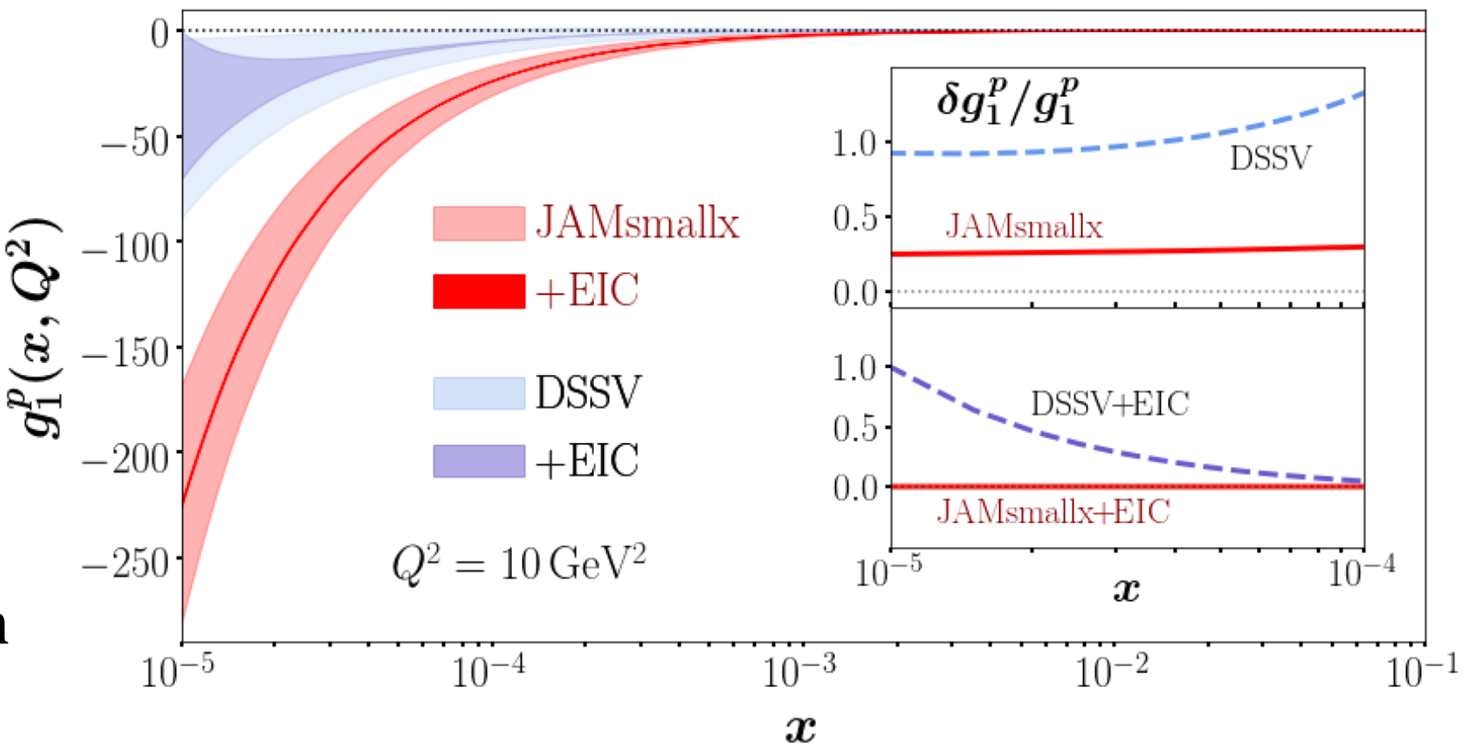
c.f. JAM16: $\chi^2/N_{pts} = 1.07$

Results: Prediction of Stronger Negative g1

- **Structure function g_1** determined down to **low x**

- **Large, negative g_1** is a robust prediction of the analysis
  - Data requires that the **dominant term** be **negative**
  - **Predictive power** at small x: controlled error in extrapolation

- The procedure **cannot describe everything**
  - Fails for **too-large x** (as expected)
  - $\frac{\chi^2}{DOF} = 5.66$ for $x_0 = 0.3$



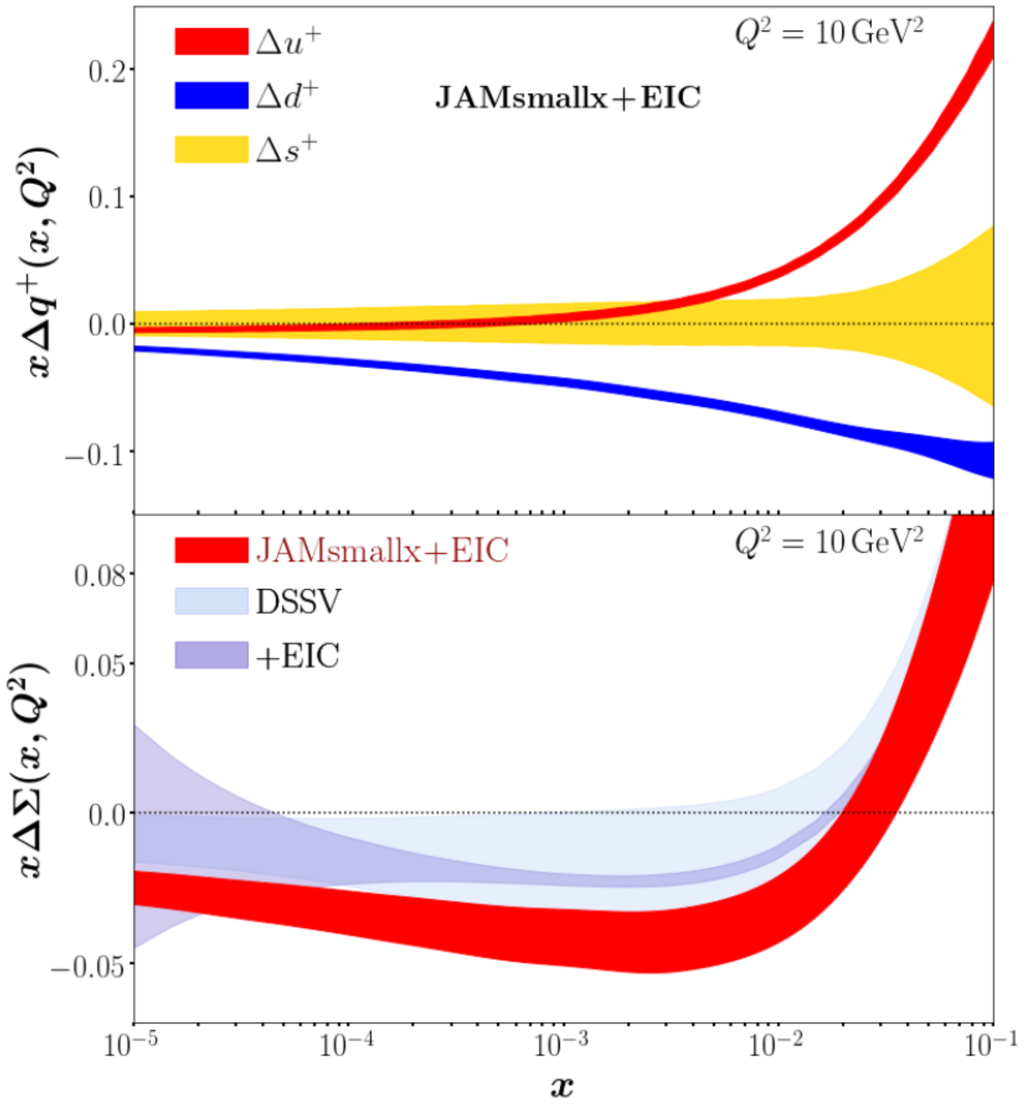
Error band: Bayesian 1σ confidence level

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

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

EIC Projections and Flavor Separation from A_{PV}

- Inclusive DIS on the proton, "neutron" alone are **not sufficient** for (u, d, s) **flavor decomposition**
- Instead of SIDIS, an alternative the **parity-violating asymmetry A_{PV}** $(\gamma/Z$ interference)
- We estimate the **impact of EIC data**
  - ➢ $100\ fb^{-1}$; $(A_{\parallel}, A_{PV})$; $(p, d, {}^{3}\mathrm{He})$
- **Constraints** of high-precision data on **polarized PDFs**
  - ➢ Big improvement in the **unmeasured region**



Future Outlook

- Proof of principle for a **global analysis** based on **small-x helicity evolution**
  - **Consistent with existing DIS data**
  - Extrapolation with **predictive power at small x**

- Significant room for **theory improvements**
  - **Single-logarithmic corrections**
    - Running coupling
  - **Large-N_c&N_f limit**
    - Modification of evolution equations
    - Qualitatively new features

Y. Kovchegov, Y. Tawabutr, JHEP **08** (2020)

- Further phenomenology: **SIDIS**