Recent updates from JAM and beyond

Nobuo Sato

May. 22, 2023

QCD Evolution Workshop 2023

Jefferson Lab

WHAT?: Synthesis of 3D tomography/nuclear imaging - quantum correlation functions (QCFs)

- hadron structure (PDFs, TMDs, GPDs, ...)
- hadronization (FFs, TMDFFs)

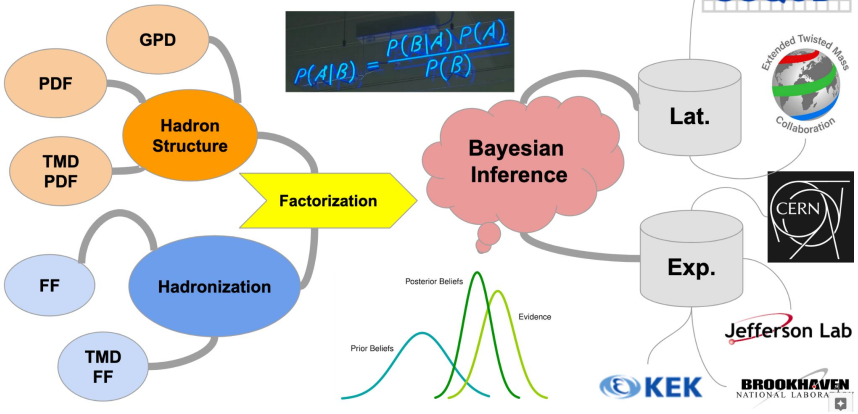
HOW?: Data (EXP), Factorization (THY/LQCD), Inference (CS)
test of universality & theory predictive power

- significant computing and data analysis
- systematic improvements (resummation, evolution, HO calculations)
- synergy with lattice QCD (Bayesian priors)

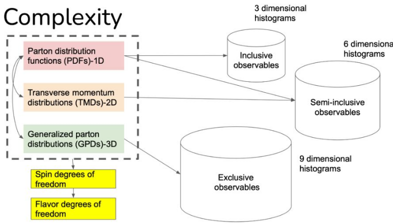
WHY?: QCD emergent phenomena

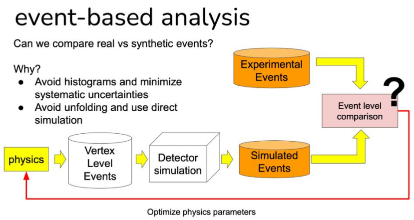
- origin of proton spin
- quark and gluon tomography
- structure of proton sea (strangeness, antimatter asymmetry)
- origin of nuclear EMC effect
- small-*x* phenomena
- precision EW physics (Weinberg angle)
- …

A holistic approach to global analysis



Integrated theory & experimental analysis





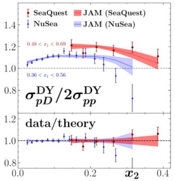
QuantOm Collaboration

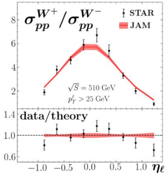
Argonne NATIONAL LABORATORY | Jefferson Lab | VT

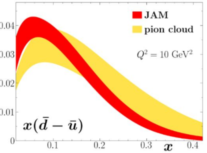
Supported by DOE SciDAC 5

Quick summary

Antimatter asymmetry

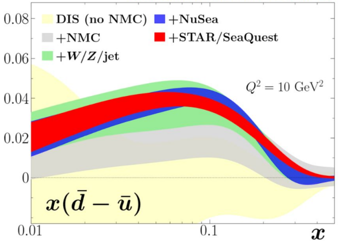






$(\bar d - \bar u)(x) = \left[\left(f_{n\pi^+} + f_{\Delta^0\pi^+} - f_{\Delta^{++}\pi^-}\right) \otimes \bar q_v^\pi\right](x),$

Cocuzza, Melnitchouk, Metz, Sato (PRD)



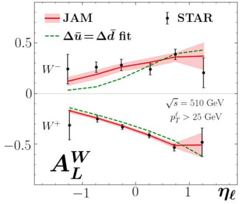
- First global analysis to include latest SeaQuest and STAR data
- Most precise phenomenological extraction of *dbar-ubar* asymmetry to date
- Quantitative test of the pion-cloud model

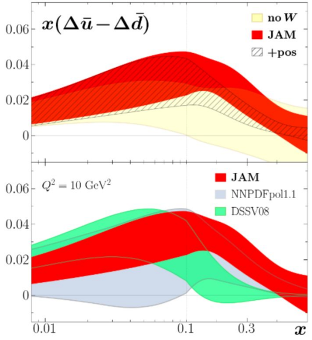
6

Polarized antimatter asymmetry

Cocuzza, Melnitchouk, Metz, Sato (PRD)

process	$N_{\rm dat}$	$\chi^2/N_{\rm dat}$
polarized		
inclusive DIS	365	0.93
inclusive jets	83	0.81
SIDIS (π^+, π^-)	64	0.93
SIDIS (K^+, K^-)	57	0.36
STAR $W^\pm$	12	0.53
PHENIX $W^\pm/Z$	6	0.63
total	**587**	**0.85**
unpolarized		
inclusive DIS	3908	1.11
inclusive jets	198	1.11
Drell-Yan	205	1.19
W/Z production	153	0.99
total	**4464**	**1.11**
SIA $(\pi^\pm)$	231	0.85
SIA $(K^\pm)$	213	0.49
total	**5495**	**1.05**



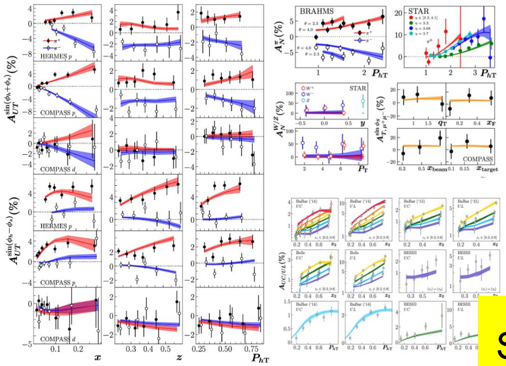


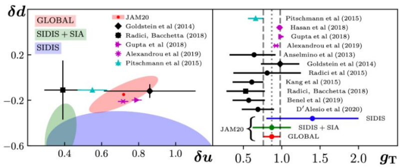
- First simultaneous extraction of unpolarized and helicity PDFs and FFs in global analysis with inclusion of RHIC spin *W+/-* data
- Most precise phenomenological extraction of polarized *dbar-ubar* asymmetry to date

17

Global analysis of SSAs (TMD+CT3 framework)

Cammarota, et al (PRD)





- Exploratory study for a global analysis of all single-spin asymmetries from *ep*, *e+e-* add *pp* reactions using the parton model TMD with collinear twist-3 framework.

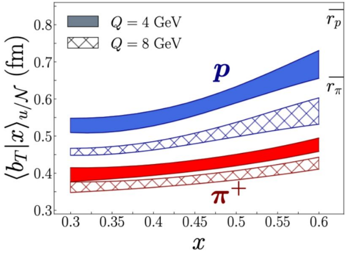
See talk by D. Pitonyak

Pion vs proton TMDs

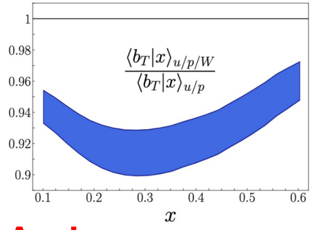
$$\tilde f_{q/\mathcal{N}}(x, b_T) = \int \frac{db^-}{4\pi} e^{-ixP^+b^-} \mathrm{Tr}\left[\langle \mathcal{N} \,|\, \bar\psi_q(b)\gamma^+ \mathcal{W}(b,0)\psi_q(0)\,|\,\mathcal{N}\rangle\right], \quad b \equiv (b^-, 0^+, \boldsymbol{b}_T),$$

$$\tilde f_{q/\mathcal{N}}(b_T|x; Q, Q^2) \equiv \frac{\tilde f_{q/\mathcal{N}}(x, b_T; Q, Q^2)}{\int d^2\boldsymbol{b}_T\, \tilde f_{q/\mathcal{N}}(x, b_T; Q, Q^2)}$$

$$\langle b_T|x\rangle_{q/\mathcal{N}} = \int d^2\boldsymbol{b}_T\, b_T\, \tilde f_{q/\mathcal{N}}(b_T|x; Q, Q^2)$$



- TMDs in b space characterises the strength of qqb correlations
- We observe a clear difference between protons and pions
- We observe a clear EMC effect in coordinate space



See talk by P Barry

And many more…

42

Updates on gluon helicity

Positivity and renormalization of parton densities

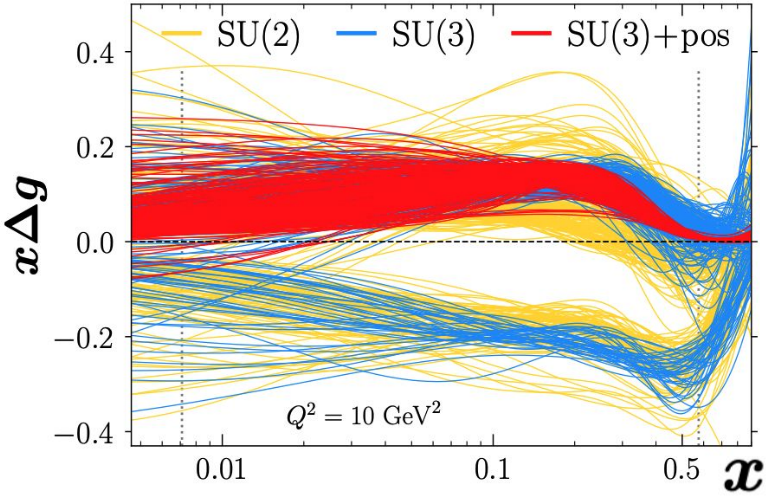
John Collins, Ted C. Rogers, and Nobuo Sato
Phys. Rev. D **105**, 076010 – Published 14 April 2022

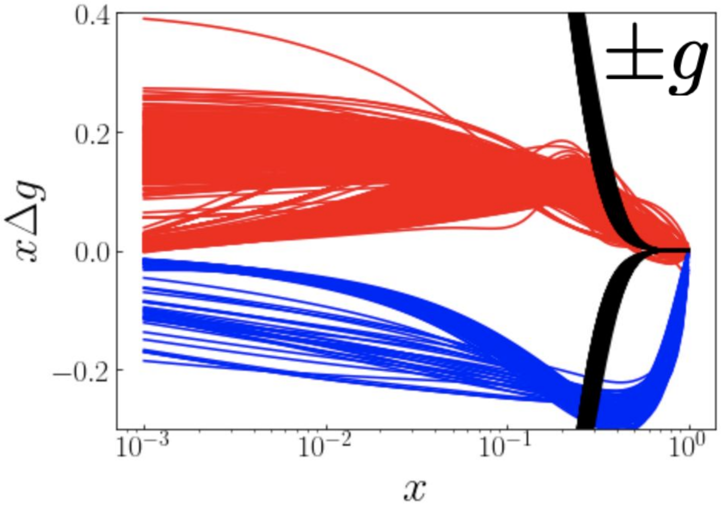
Formally pdfs can be **negative**

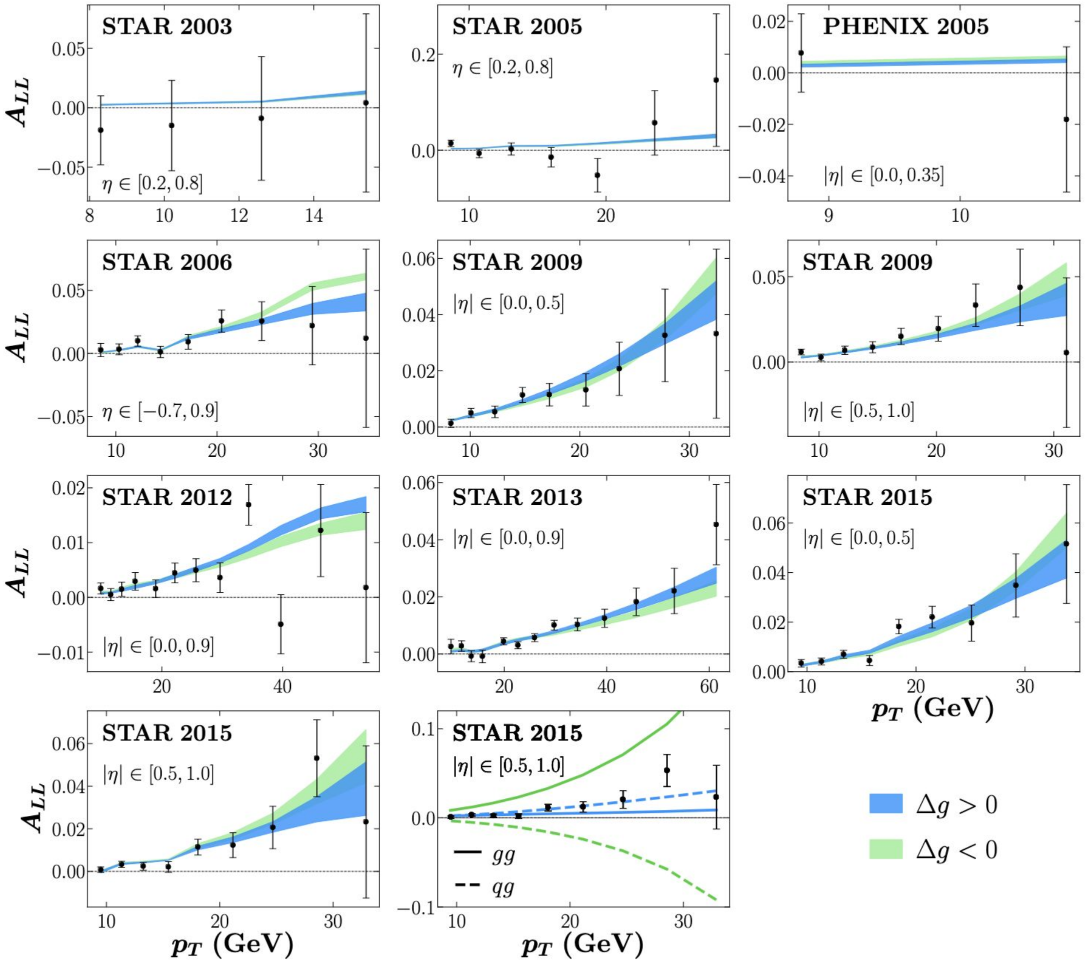
How well do we know the gluon polarization in the proton?

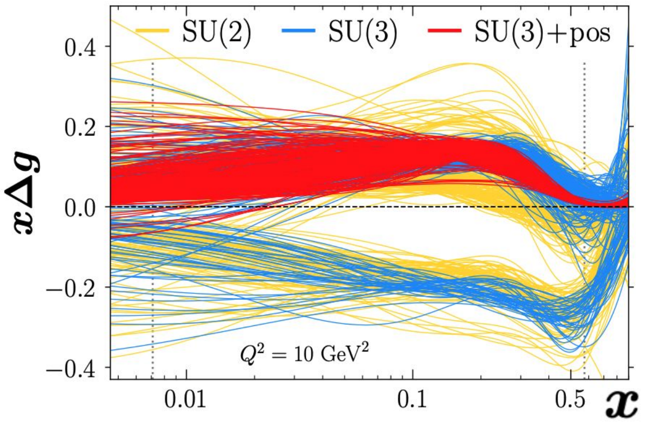
Y. Zhou, N. Sato, and W. Melnitchouk (Jefferson Lab Angular Momentum (JAM) Collaboration)
Phys. Rev. D **105**, 074022 – Published 25 April 2022

Sign of gluon helicity is cannot be ruled out uniquely by current data









Both solutions describes the data pretty well

Positivity constraints + data are incompatible in terms of chi2

Measurement of charged pion double spin asymmetries at midrapidity in longitudinally polarized $p+p$ collisions at $\sqrt{s}$ = 510 GeV

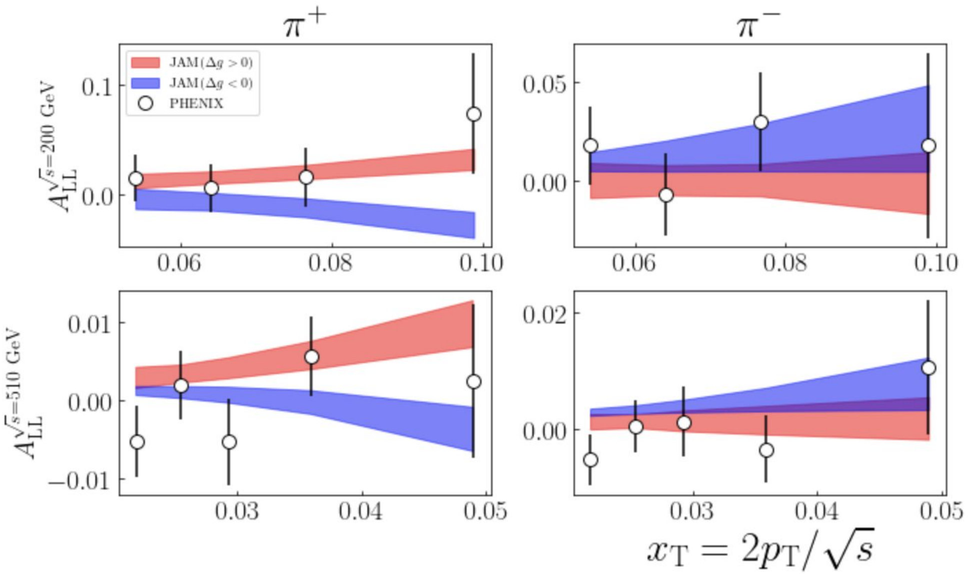
PHENIX Collaboration • U.A. Acharya (Georgia State U.) et al. (Apr 6, 2020)

Published in: *Phys.Rev.D* 102 (2020) 3, 032001 • e-Print: 2004.02681 [hep-ex]

Charged-pion cross sections and double-helicity asymmetries in polarized p+p collisions at $\sqrt{s}$=200 GeV

PHENIX Collaboration • A. Adare (Colorado U.) et al. (Sep 5, 2014)

Published in: *Phys.Rev.D* 91 (2015) 3, 032001 • e-Print: 1409.1907 [hep-ex]

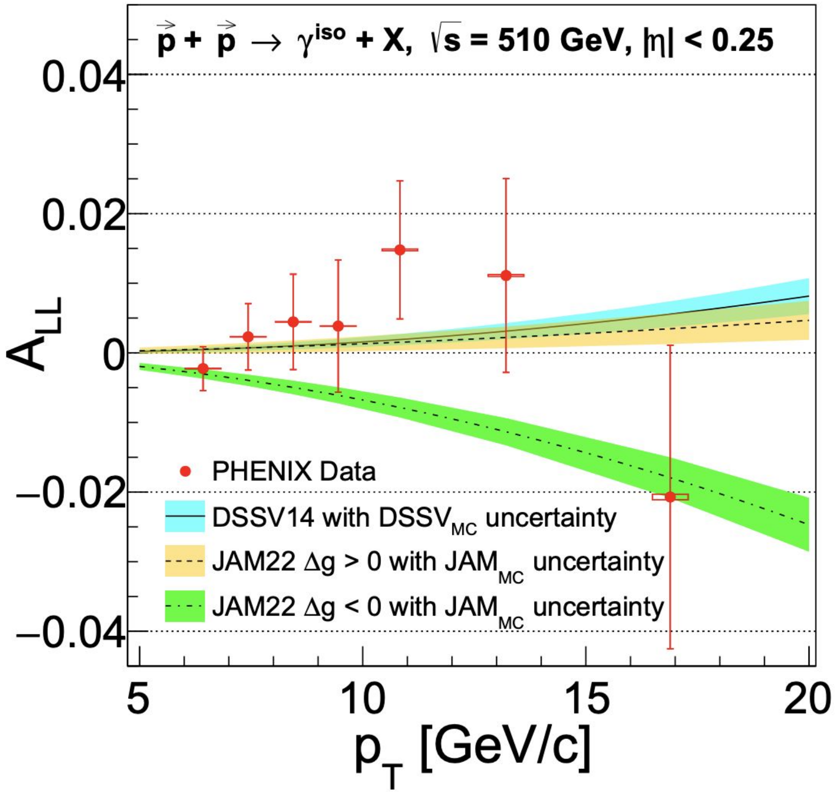


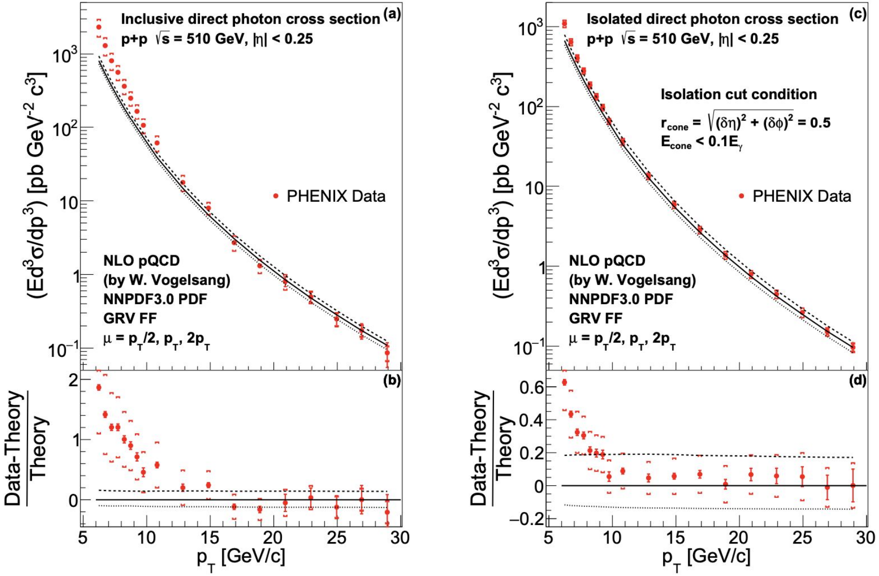
The PHENIX experiment at the Relativistic Heavy Ion Collider has measured the longitudinal double spin asymmetries, A_{LL}, for charged pions at midrapidity ($|\eta| < 0.35$) in longitudinally polarized p+p collisions at $\sqrt{s} = 510$ GeV. These measurements are sensitive to the gluon spin contribution to the total spin of the proton in the parton momentum fraction x range between 0.04 and 0.09. One can infer the sign of the gluon polarization from the ordering of pion asymmetries with charge alone. The asymmetries are found to be consistent with global quantum-chromodynamics fits of deep-inelastic scattering and data at $\sqrt{s} = 200$ GeV, which show a nonzero positive contribution of gluon spin to the proton spin.

Measurement of Direct-Photon Cross Section and Double-Helicity Asymmetry at $\sqrt{s} = 510$ GeV in $\vec{p} + \vec{p}$ Collisions

PHENIX Collaboration • U. Acharya (Georgia State U., Atlanta) et al. (Feb 16, 2022)

e-Print: 2202.08158 [hep-ex]





The two dashed curves in Fig. 2 come from the global analysis of the JAM Collaboration [15, 16]. They found there are two distinct sets of solutions for the polarized gluon PDF, Δg, which differ in sign. Even though the solutions with $\Delta g < 0$ violate the positivity assumption, $|\Delta g| < g$, all previous data cannot exclude those solutions due to the mixed contributions from quark-gluon and gluon-gluon interactions. However, the direct-photon A_{LL} comes mainly from the quark-gluon interactions and has $\chi^2 = 4.7$ and 12.6 for 7 data points for the $\Delta g > 0$ and $\Delta g < 0$ solutions, respectively, with the difference of 7.9 between χ^2 values implying that the negative solution is disfavored at more than 2.8σ level.

Constraints from LQCD

LQCD data

Matching into LC pdfs

$$\widetilde{\mathfrak{M}}(\nu, z^2)\langle x_g\rangle_{\mu^2} = \widetilde{\mathcal{I}}_p(\nu, \mu^2) - \frac{\alpha_s N_c}{2\pi}\int_0^1 \mathrm{d}u\, \widetilde{\mathcal{I}}_p(u\nu, \mu^2)\Bigg\{ \ln\left(z^2\mu^2\frac{e^{2\gamma_E}}{4}\right) \left(\left[\frac{2u^2}{\bar{u}} + 4u\bar{u}\right]_+ - \left(\frac{1}{2} + \frac{4}{3}\frac{\langle x_S\rangle_{\mu^2}}{\langle x_g\rangle_{\mu^2}}\right)\delta(\bar{u})\right) + 4\left[\frac{u+\ln(1-u)}{\bar{u}}\right]_+ - \left(\frac{1}{\bar{u}} - \bar{u}\right)_+ - \frac{1}{2}\delta(\bar{u}) + 2\bar{u}u\Bigg\} - \frac{\alpha_s C_F}{2\pi}\int_0^1 \mathrm{d}u\, \widetilde{\mathcal{I}}_S(u\nu, \mu^2)\left\{ \ln\left(z^2\mu^2\frac{e^{2\gamma_E}}{4}\right)\widetilde{\mathcal{B}}_{gq}(u) + 2\bar{u}u\right\} + \mathcal{O}(\Lambda^2_{\mathrm{QCD}}z^2)\,,$$

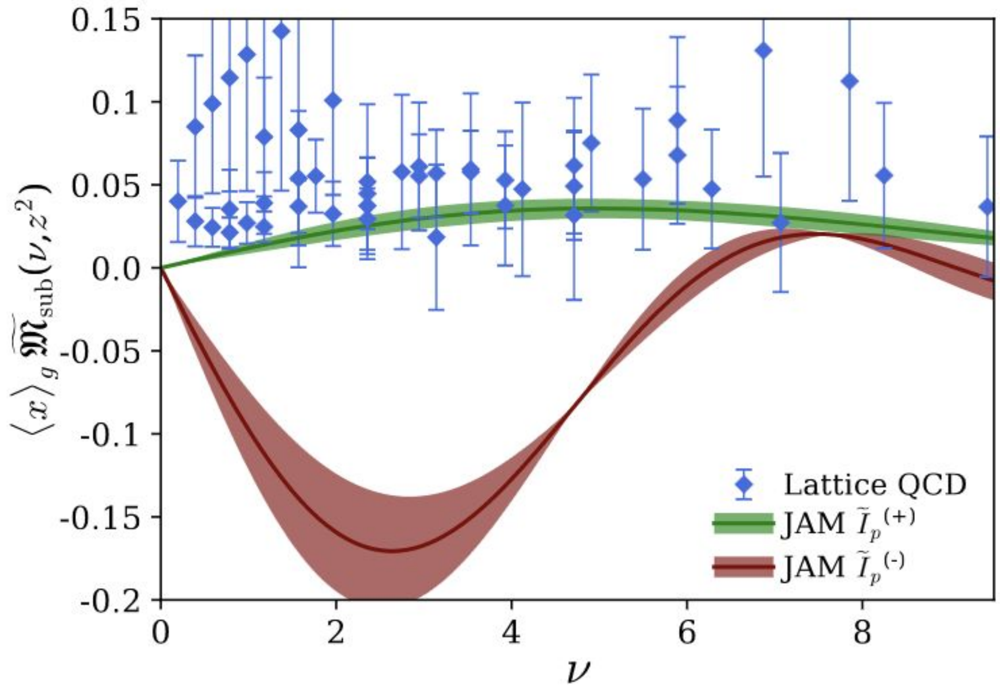
$$\widetilde{\mathcal{I}}_p(\nu) = \frac{i}{2}\int_{-1}^1 \mathrm{d}x\, e^{-ix\nu}\, x\,\Delta g(x)\,.$$

Balitsky, Morris, Radyushkin ‘22

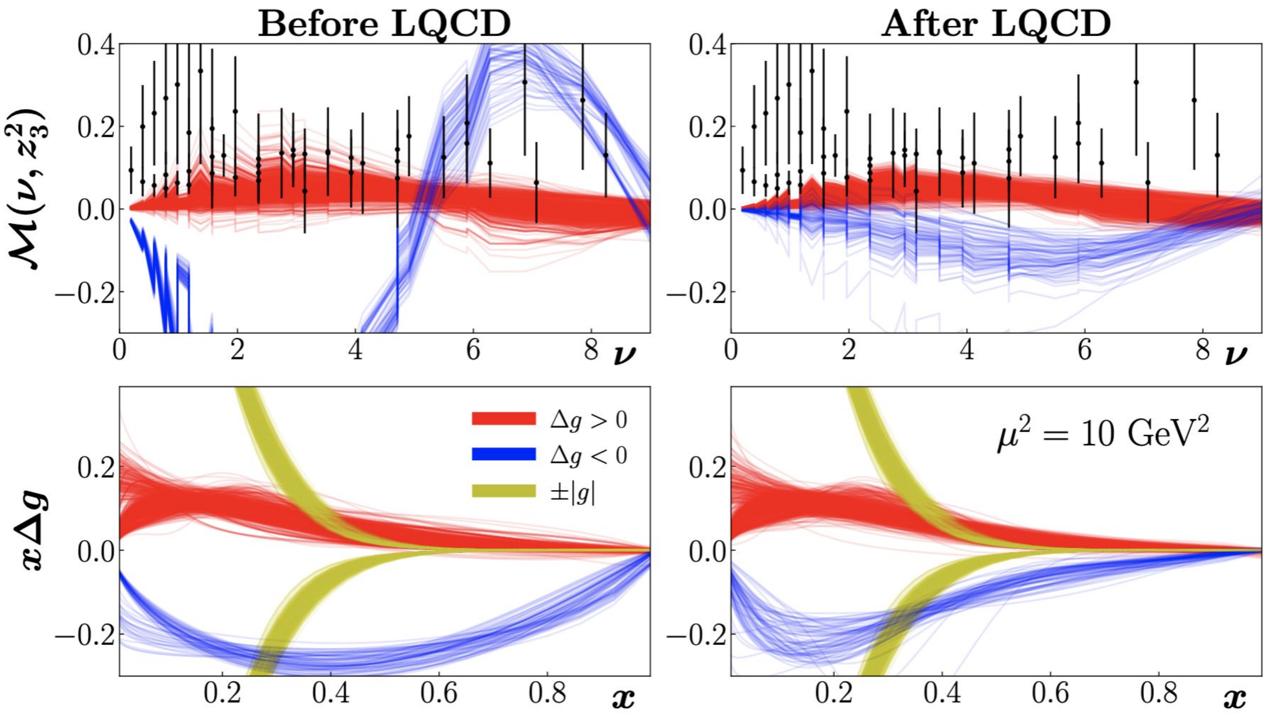
Toward the determination of the gluon helicity distribution in the nucleon from lattice quantum chromodynamics

HadStruc Collaboration • Colin Egerer (Jefferson Lab) et al. (Jul 18, 2022)

Published in: *Phys.Rev.D* 106 (2022) 9, 094511 • e-Print: 2207.08733 [hep-lat]



> Negative delta g is clearly disfavored by LQCD…

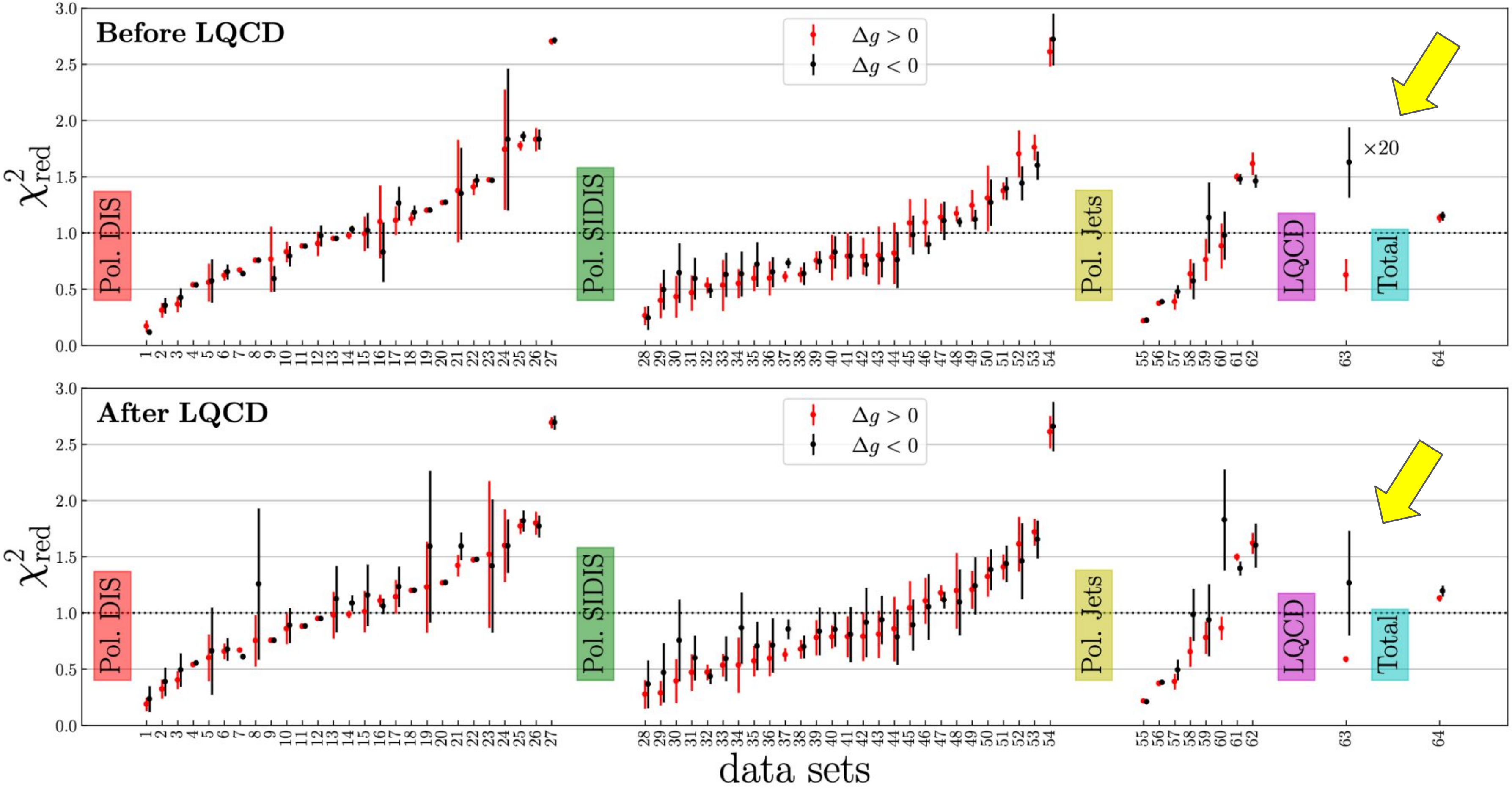


> The error bars are just the sqrt of the cov matrix diagonal entries - correlation terms weakens the constraints

> LQCD data does not remove entirely the negative solutions

> It tends to push towards positivity bounds

Karpie et al, JAM+HadStruc colab (in preparation)

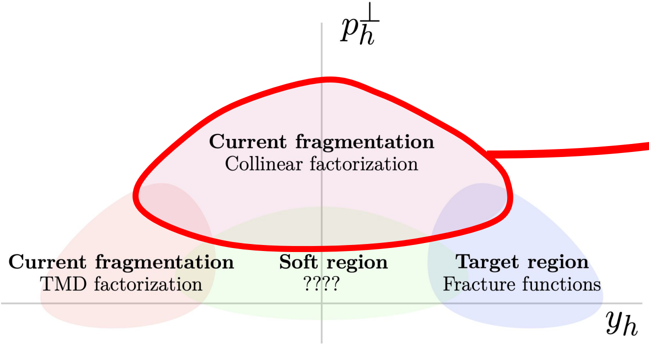


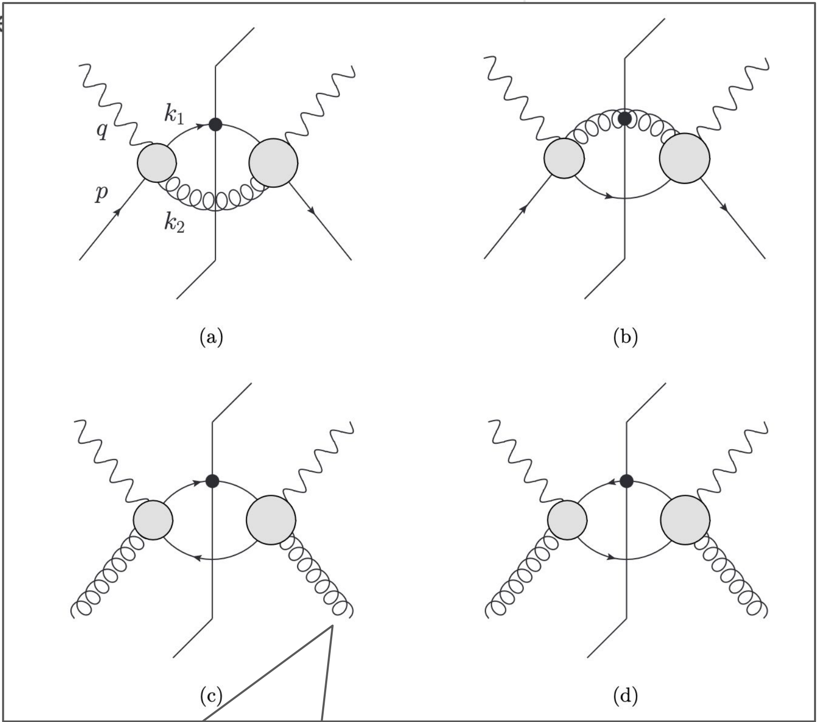
Before LQCD
After LQCD
$\Delta g > 0$
$\Delta g < 0$
$\chi^2_{\rm red}$
Pol. DIS
Pol. SIDIS
Pol. Jets
LQCD
Total
×20
data sets

Accessing gluon polarization with high-P_T hadrons in SIDIS

Jefferson Lab Angular Momentum (JAM) Collaboration • R.M. Whitehill (Wichita State U.) et al. (Oct 21, 2022)

Published in: *Phys.Rev.D* 107 (2023) 3, 034033 • e-Print: 2210.12295 [he





$$4P_h^0 E' \frac{d\sigma_h}{d^3\boldsymbol{\ell}' d^3\boldsymbol{P}_h} = \sum_{ij} \int_x^1 \frac{d\xi}{\xi} \int_z^1 \frac{d\zeta}{\zeta^2} \left(4k_1^0 E' \frac{d\hat{\sigma}_{ij}}{d^3\boldsymbol{\ell}' d^3\boldsymbol{k}_1} \right) f_{i/N}(\xi)\, D_{h/j}(\zeta),$$

$$4P_h^0 E' \frac{d\Delta\sigma_h}{d^3\boldsymbol{\ell}' d^3\boldsymbol{P}_h} = \sum_{ij} \int_x^1 \frac{d\xi}{\xi} \int_z^1 \frac{d\zeta}{\zeta^2} \left(4k_1^0 E' \frac{d\Delta\hat{\sigma}_{ij}}{d^3\boldsymbol{\ell}' d^3\boldsymbol{k}_1} \right) \Delta f_{i/N}(\xi)\, D_{h/j}(\zeta),$$

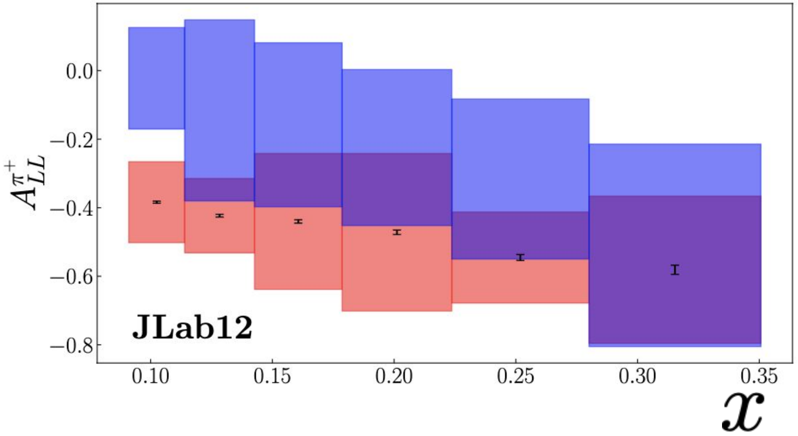
Opportunity to access gluon helicity

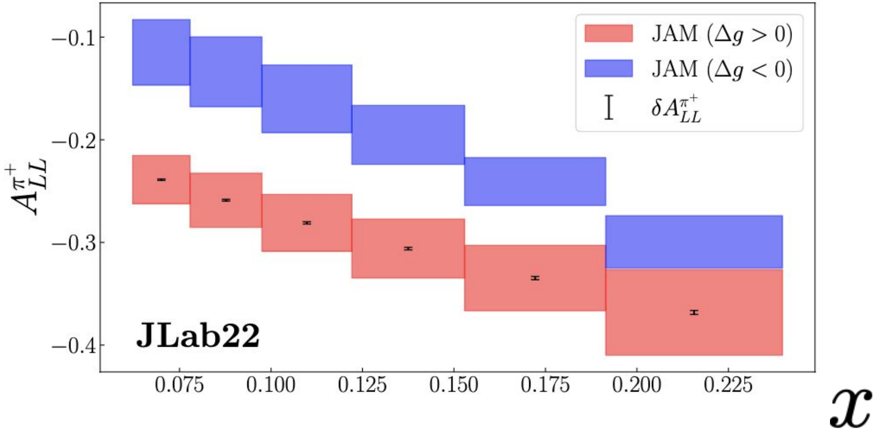
Projects at Jefferson Lab

$$d\mathcal{L}/dt = 5 \times 10^{38}/\mathrm{cm}^2/s$$

$$\mathcal{L} = 8.64 \times 10^6 \mathrm{fb}^{-1}$$

200 days of data taking





JLab 22 upgrade has the potential to discriminate the sign of delta using DSAs in SIDIS

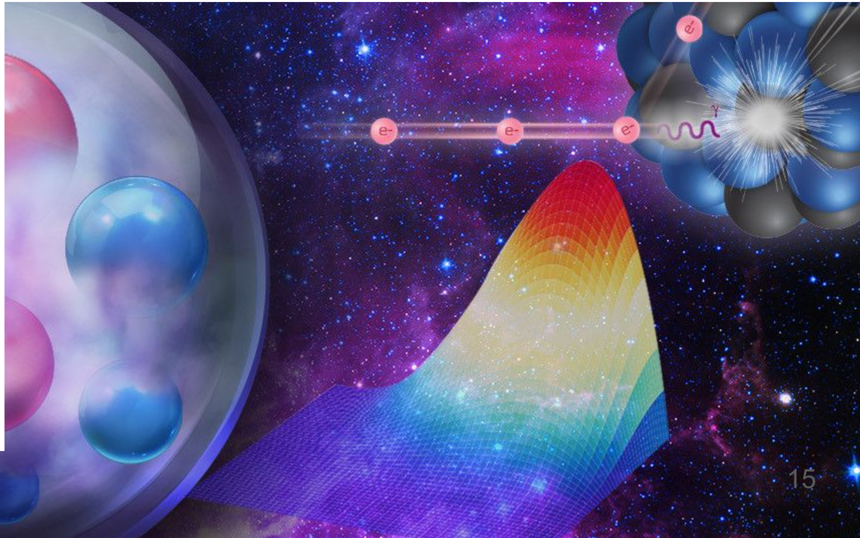
Outlook

Summary

- Sign of gluon helicity is still elusive in phenomenology.
- Synergies with LQCD is growing and providing hints to determine the sign of gluon helicity.
- DSAs in high pT SIDIS at JLab 22 GeV has the potential to resolve this on a comparable time scale as the EIC.

Future

- Integrate RHIC data into JAM analysis -> validate further the presence of two gluon helicity pdfs
- Need to develop fully (Si)DIS theory from small to large x
- Fully develop Large pT program at low energies -> (see talk by J. Cammarota in connection with QED)



$$\mathcal{L}_{QCD} = \sum_q \bar{\psi}_q (i\gamma_\mu D^\mu - m_q)\psi_q - \frac{1}{2}\mathrm{Tr}[G_{\mu\nu}G^{\mu\nu}]$$