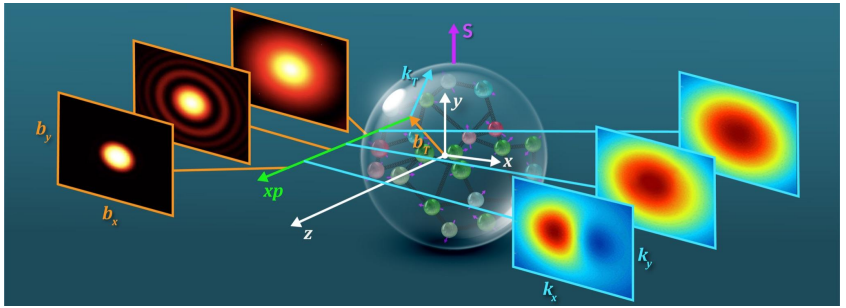
Updates from the JAM collaboration

Yiyu Zhou

Motivations

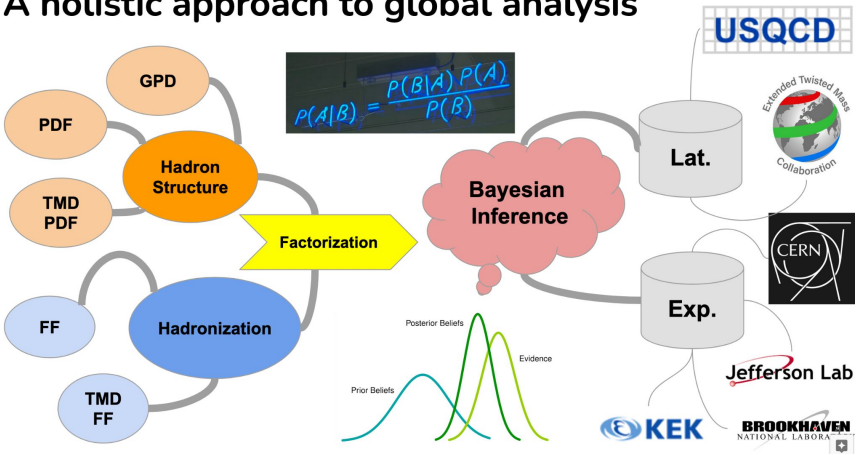


- **WHAT?: Synthesis of 3D tomography/nuclear imaging** - quantum correlation functions (QCFs)
  - hadron structure (PDFs, TMDs, GPDs, …)
  - hadronization (FFs, TMDFFs)

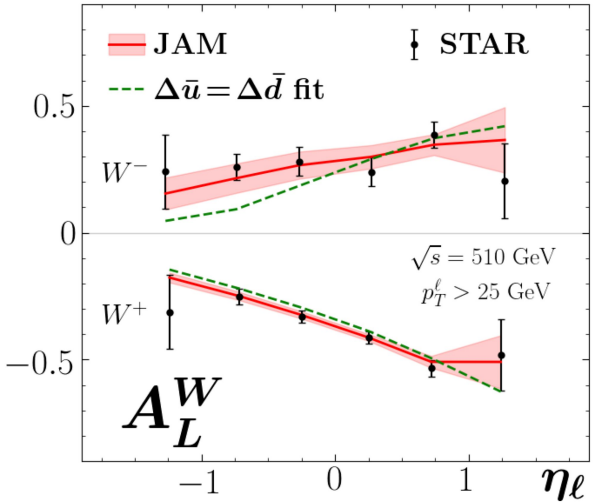
- **HOW?: Data (EXP), Factorization (THY/LQCD), Inference (CS)**
  - test of universality & theory predictive power
  - significant computing and data analysis
  - systematic improvements (resummation, evolution, HO calculations)
  - synergy with lattice QCD (Bayesian priors)

- **WHY?: Opportunities**
  - origin of proton spin
  - quark and gluon tomography
  - structure of proton sea (strangeness, antimatter asymmetry)
  - origin of nuclear EMC effect
  - …

A holistic approach to global analysis

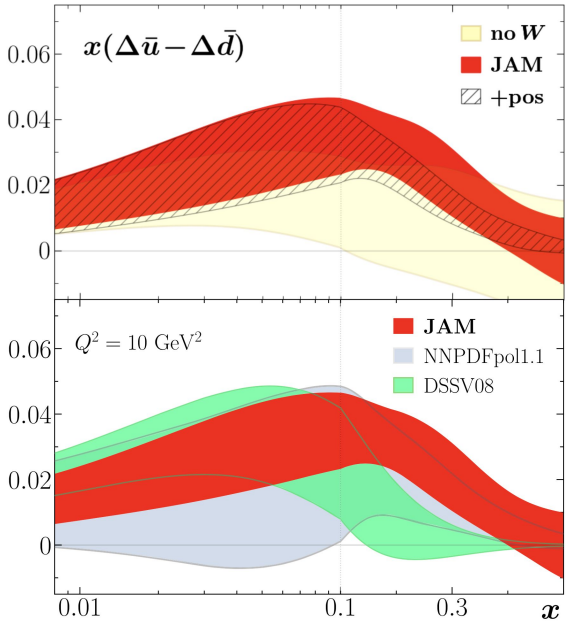


Polarized-antimatter asymmetry



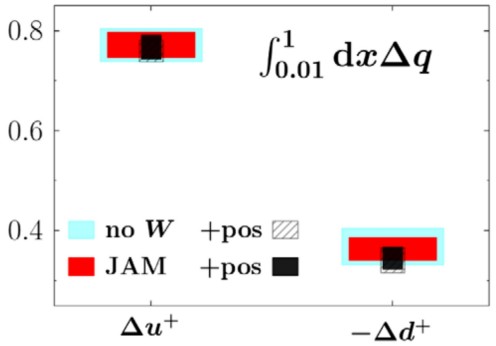
$$A_L^{W^+} \propto \frac{\Delta\bar{d}(x_1)u(x_2) - \Delta u(x_1)\bar{d}(x_2)}{\bar{d}(x_1)u(x_2) + u(x_1)\bar{d}(x_2)},$$

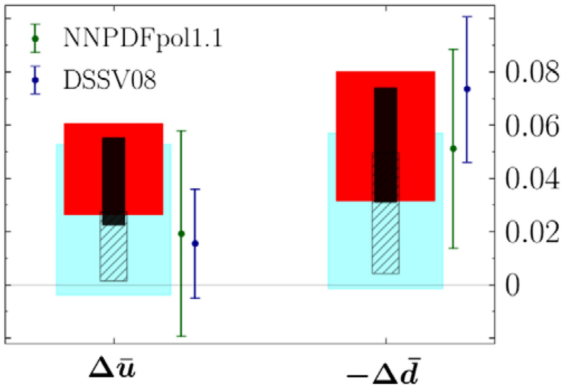
$$A_L^{W^-} \propto \frac{\Delta\bar{u}(x_1)d(x_2) - \Delta d(x_1)\bar{u}(x_2)}{\bar{u}(x_1)d(x_2) + d(x_1)\bar{u}(x_2)},$$



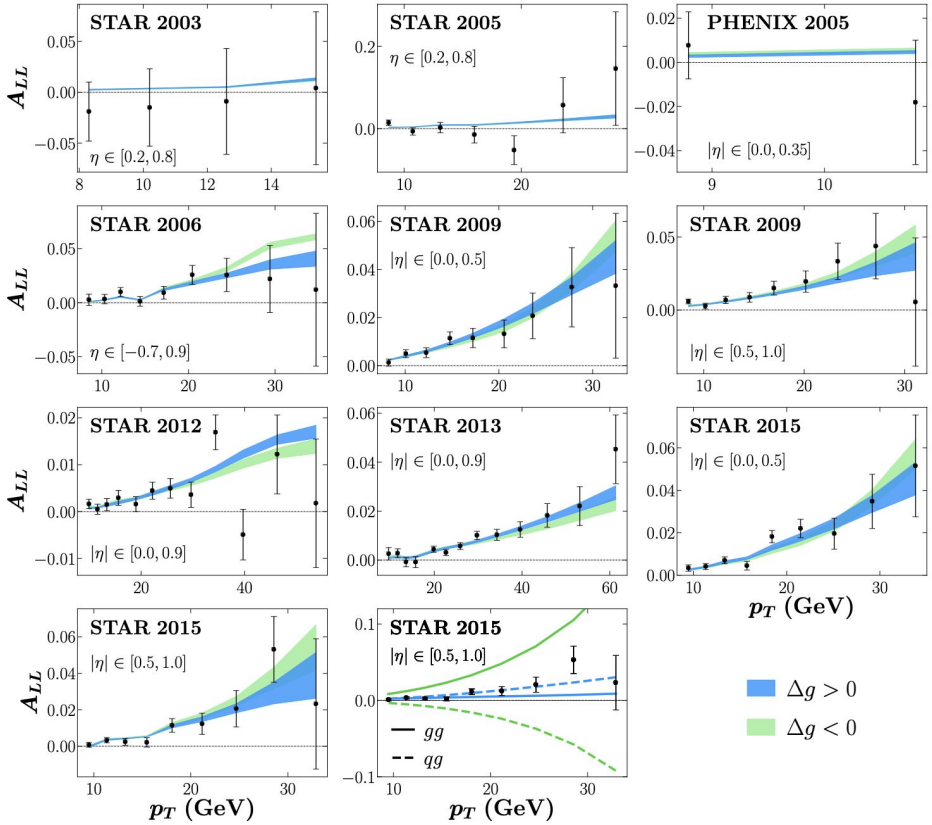
- First global analysis to include latest STAR W-production data
- Most precise phenomenological extraction of *dbar-ubar* asymmetry to date

Cocuzza, Melnitchouk, Metz, Sato (PRD)



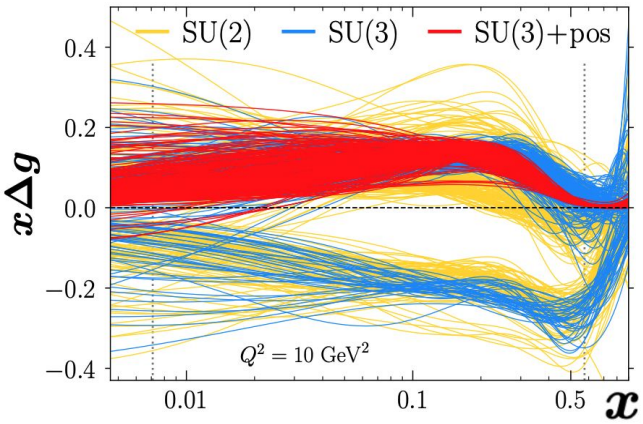


Gluon helicity distribution



$$A_{LL}^{\text{jet}} \sim (\Delta g)^2 + (\Delta q)\Delta g + \cdots$$

Zhou, Sato, Melnitchouk (PRD)



Both solutions describes the data equally well.

Positivity constraints + data are incompatible with the negative solution in terms of χ^2.

Gluon helicity distribution

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

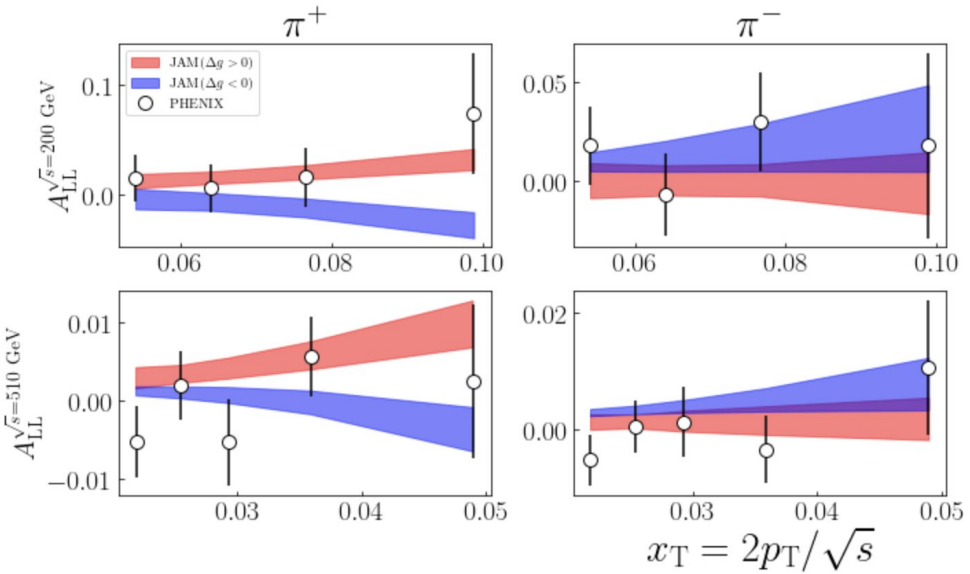
PHENIX Collaboration • U.A. Acharya (Georgia State U.) et al. (Apr 6, 2020)

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]



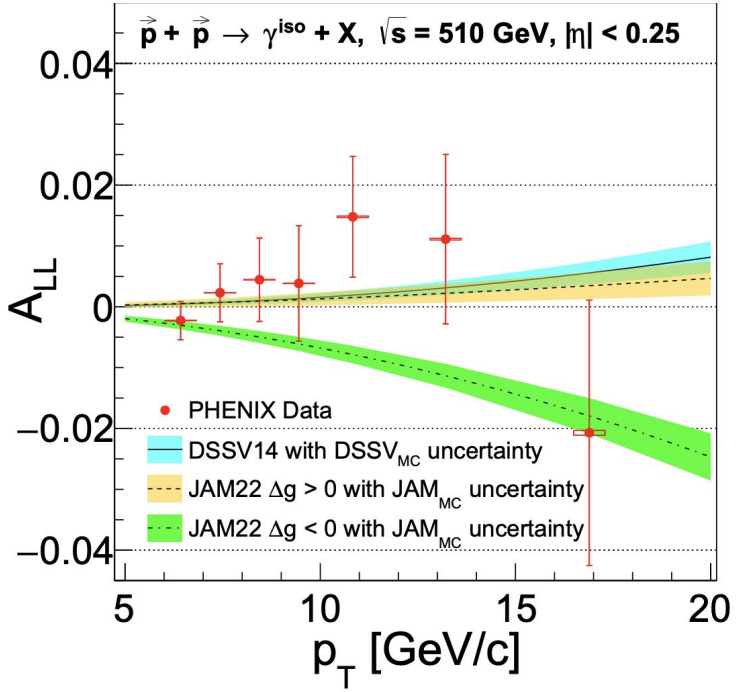
The PHENIX experiment at the Relativistic Heavy Ion Collider has measured the longitudinal double spin asymmetries, A_{LL}, for charged pions at midrapidity ($|\eta| < 0.35$) in longitudinally polarized p+p collisions at $\sqrt{s} = 510$ GeV. These measurements are sensitive to the gluon spin contribution 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.

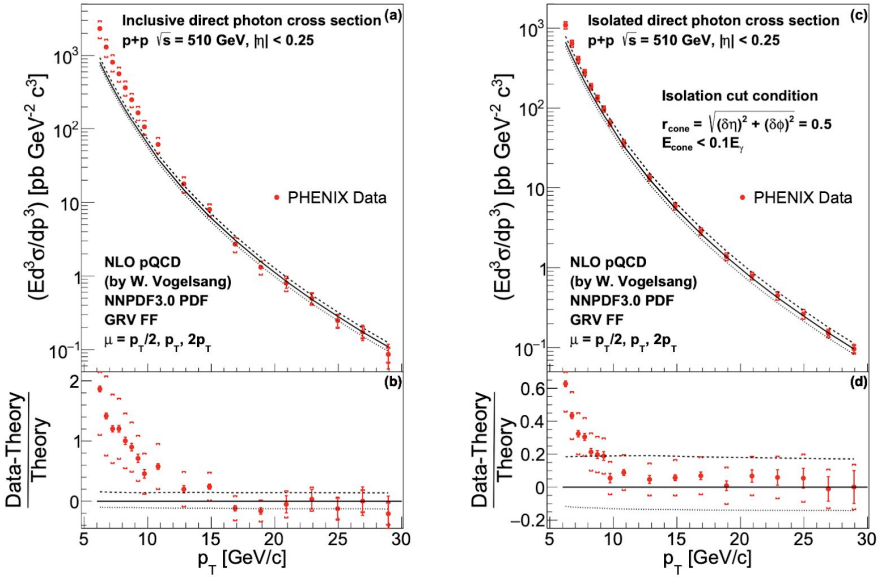
Gluon helicity distribution

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.

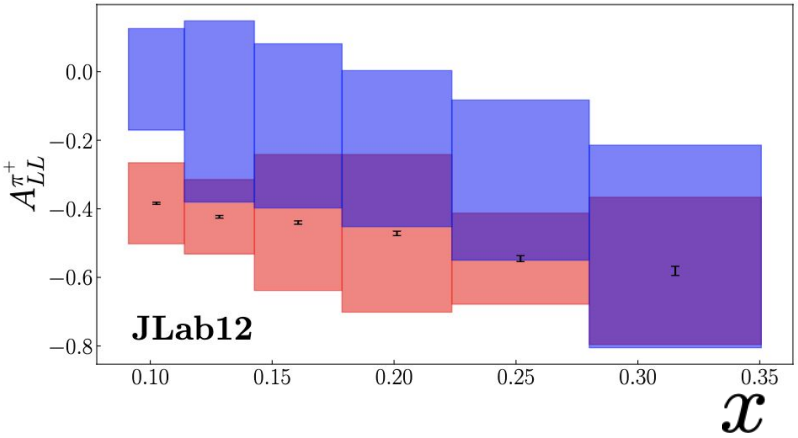
Projects at Jefferson Lab

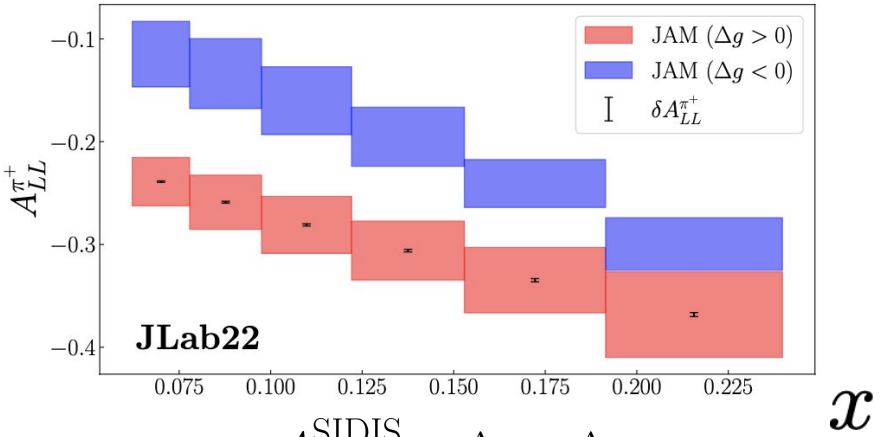
$$e(\ell) + N(P) \rightarrow e(\ell') + h(P_h) + X$$

$$\mathcal{L} = 86 \text{ fb}^{-1}$$

10 days of data taking

Whitehill, Zhou, Sato, Melnitchouk (PRD)



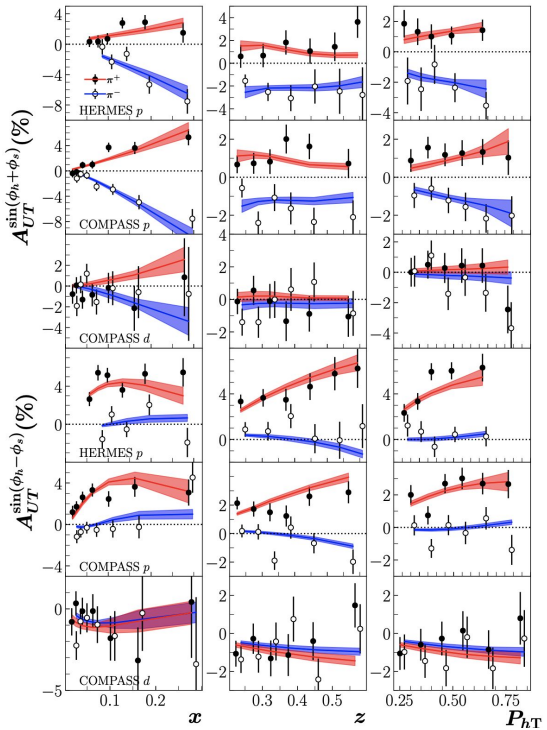


$$A_{LL}^{\text{SIDIS}} \sim \Delta g + \Delta q + \cdots$$

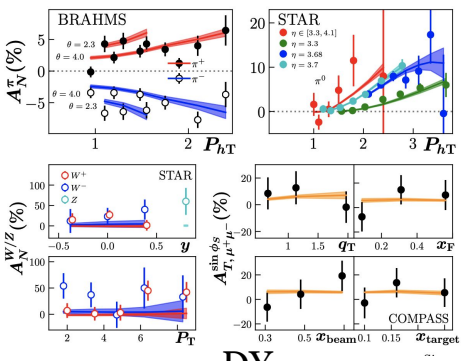
JLab 22 upgrade has the potential to discriminate the sign of gluon using DSAs in SIDIS

Global analysis of tensor charge (TMD+CT3)

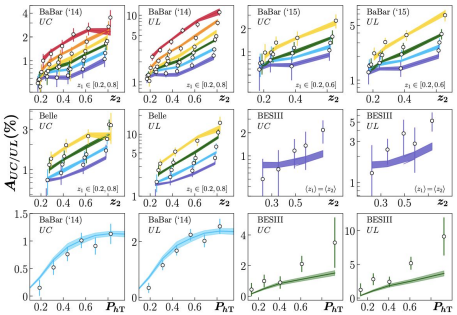
pp



SIDIS

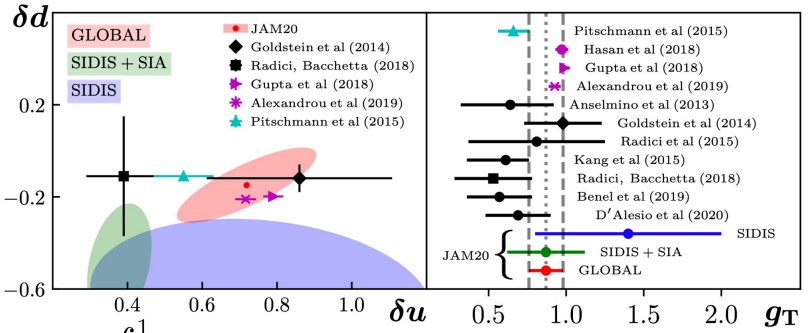


DY



SIA

[Cammarota, et al. (PRD)]



$$\delta q = \int_0^1 (h_1^q(x) - h_1^{\bar{q}}(x))\mathrm{d}x \qquad g_T = \delta u - \delta d$$

- 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.
- Extracted flavor-dependent transversity in good agreement with LQCD.

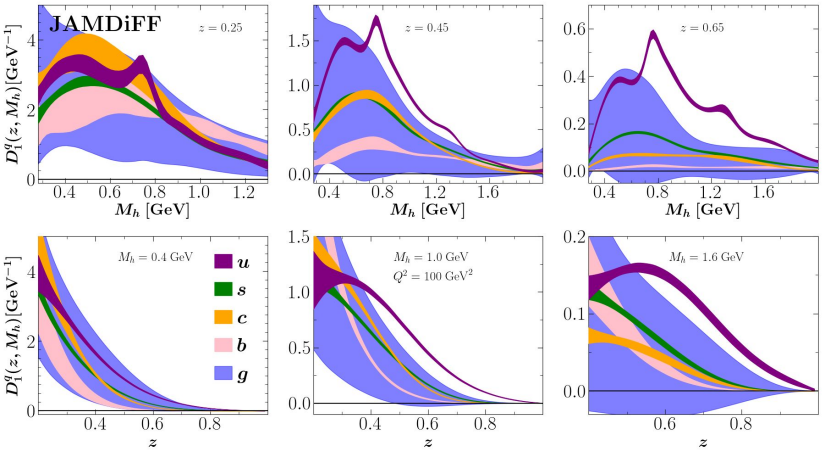
Global analysis of tensor charge (dihadron)

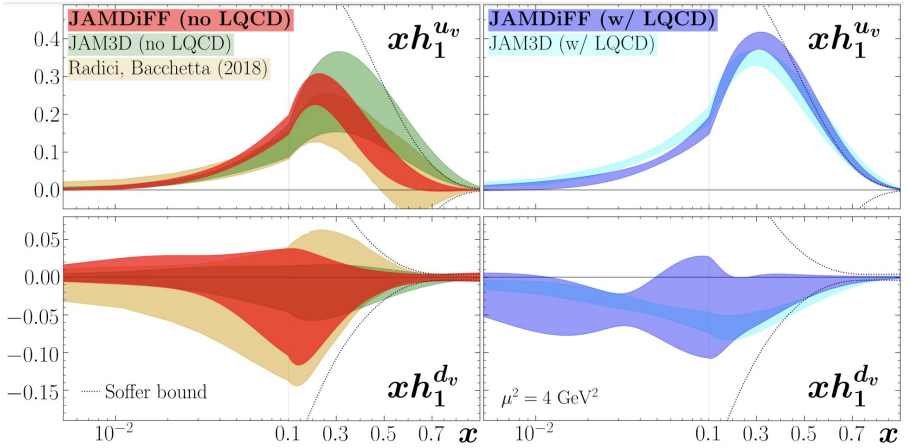
Transversity distributions and tensor charges of the nucleon: extraction from dihadron production and their universal nature

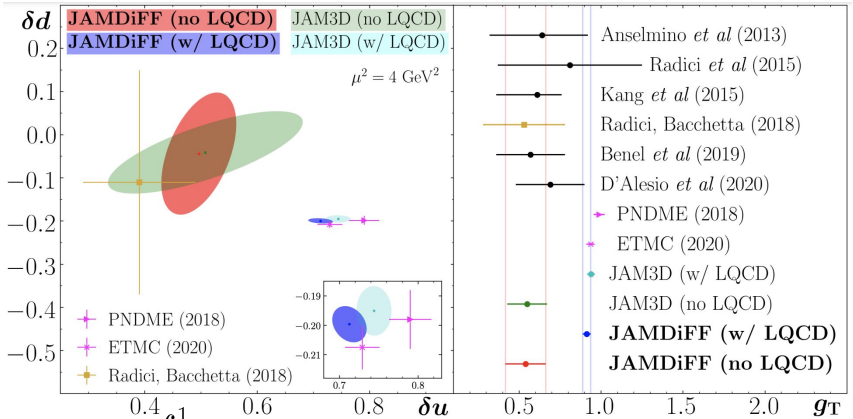
C. Cocuzza,[1] A. Metz,[1] D. Pitonyak,[2] A. Prokudin,[3,4] N. Sato,[4] and R. Seidl[5]

PRELIMINARY

Experiment	$N_{\rm dat}$	$\chi^2_{\rm red}$ no LQCD	$\chi^2_{\rm red}$ w/ LQCD
Belle (cross section)	1094	1.05	1.06
Belle (Artru-Collins)	183	0.78	0.78
HERMES	12	1.09	1.12
COMPASS (p)	26	0.75	1.25
COMPASS (D)	26	0.74	0.78
STAR (2015)	24	1.83	1.59
STAR (2018)	106	1.06	1.18
ETMC δu	1	—	0.55
ETMC δd	1	—	1.10
PNDME δu	1	—	8.20
PNDME δd	1	—	0.03
Total	1475	**1.02**	**1.05**

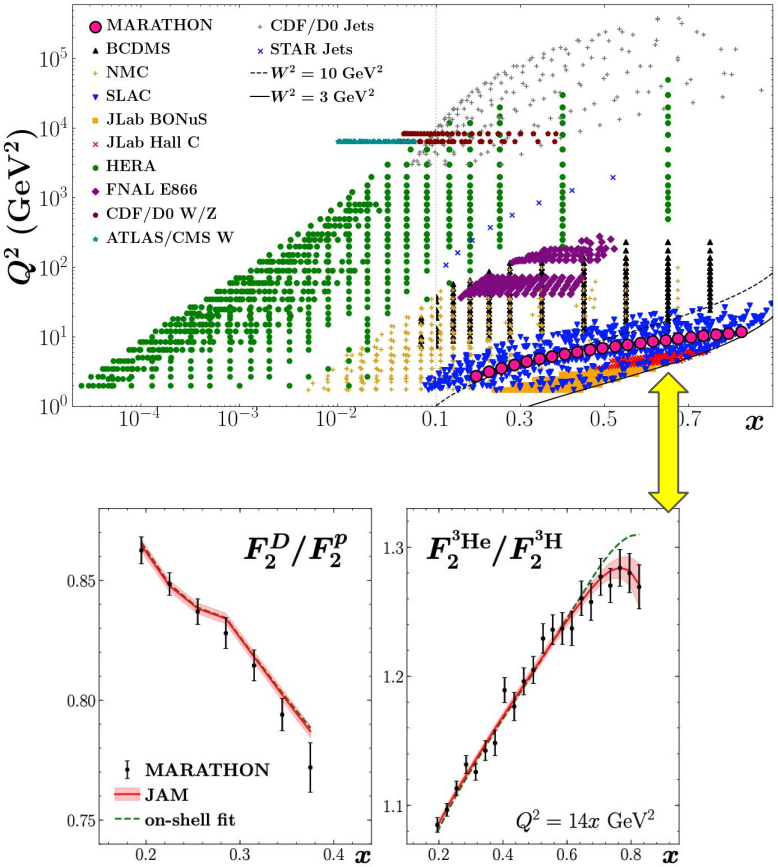




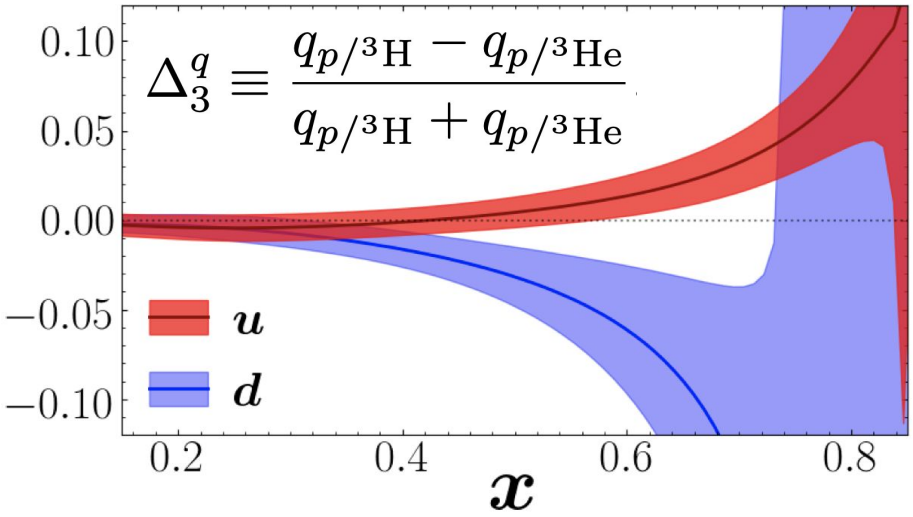


$$\delta q = \int_0^1 (h_1^q(x) - h_1^{\overline{q}}(x))\mathrm{d}x \qquad g_T = \delta u - \delta d$$

Isovector EMC effects from MARATHON data

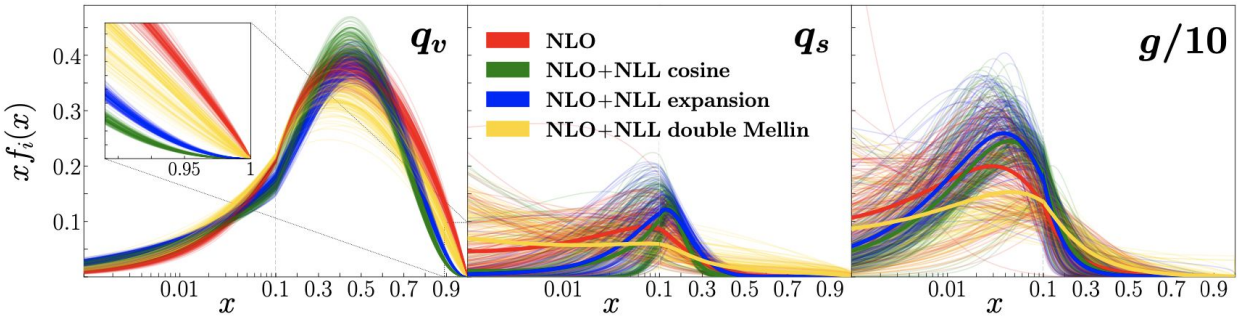


Cocuzza, Keppel, Liu, et al. (PRL)

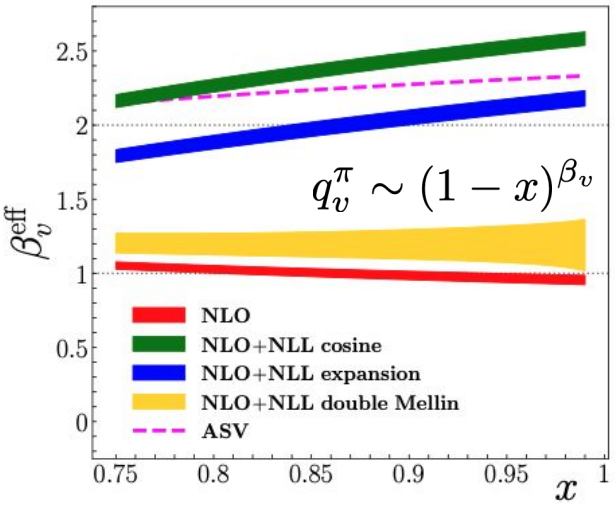


- Global analysis including latest collider W/Z data and MARATHON d/p, helium, tritium DIS data
- Evidence of different medium modifications for u and d quarks
- Naive modeling of nuclear PDFs, *e.g.*, $u/p/A$ = $d/n/A$ is disfavored

Pion structure

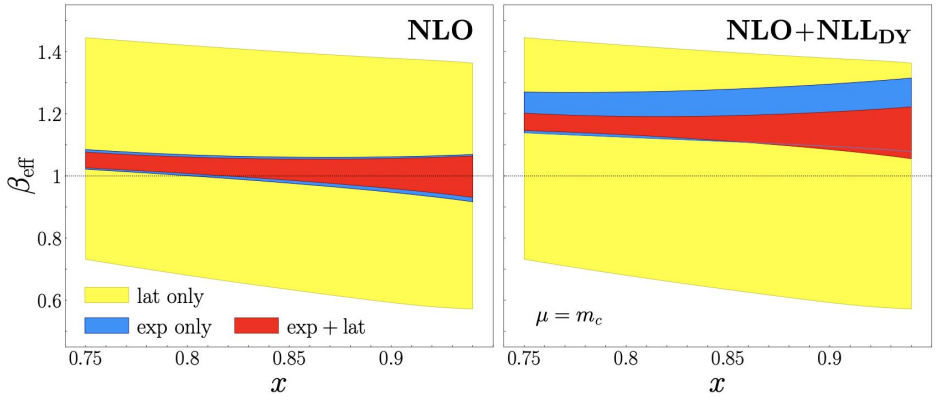


Barry, Ji, Melnitchouk, Sato (PRL)



- Improved pQCD framework indicates large x pion PDF is closer to 1 despite QCD model calculations
- Results are also stable after the inclusion LQCD Ioffe time distributions

Barry, et al. (PRD) - JAM & HadStruct



Pion vs proton TMDs

Barry, et al. (arXiv)

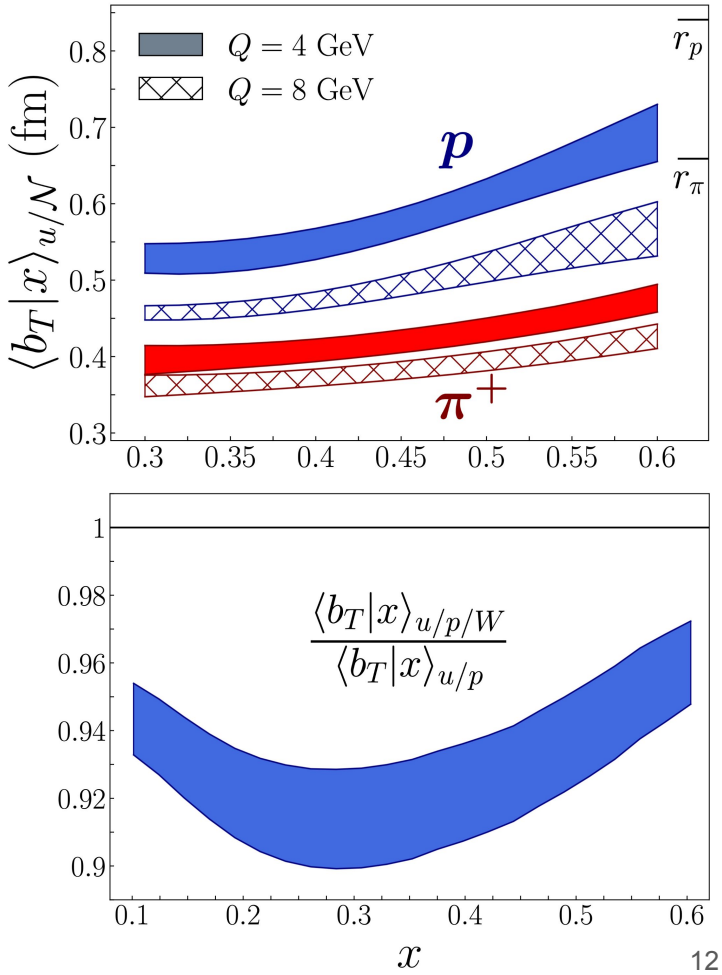
$$\tilde{f}_{q/\mathcal{N}}(x, b_T) = \int \frac{\mathrm{d}b^-}{4\pi} e^{-ixP^+b^-} \mathrm{Tr}\left[\langle \mathcal{N} \,|\, \bar{\psi}_q(b)\gamma^+ \mathcal{W}(b,0)\psi_q(0) \,|\, \mathcal{N}\rangle\right],$$

$$b \equiv (b^-, 0^+, \boldsymbol{b}_T)$$

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

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

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



Summary

- Extract the most precise and data-driven collinear unpolarized/helicity/transversity PDFs.
- Fit simultaneously:
  - Collinear and TMD distributions
  - Initial and final state distributions
  - Nucleon and nuclear distributions
- Wide range of data included from existing and future facilities, as well as LQCD.

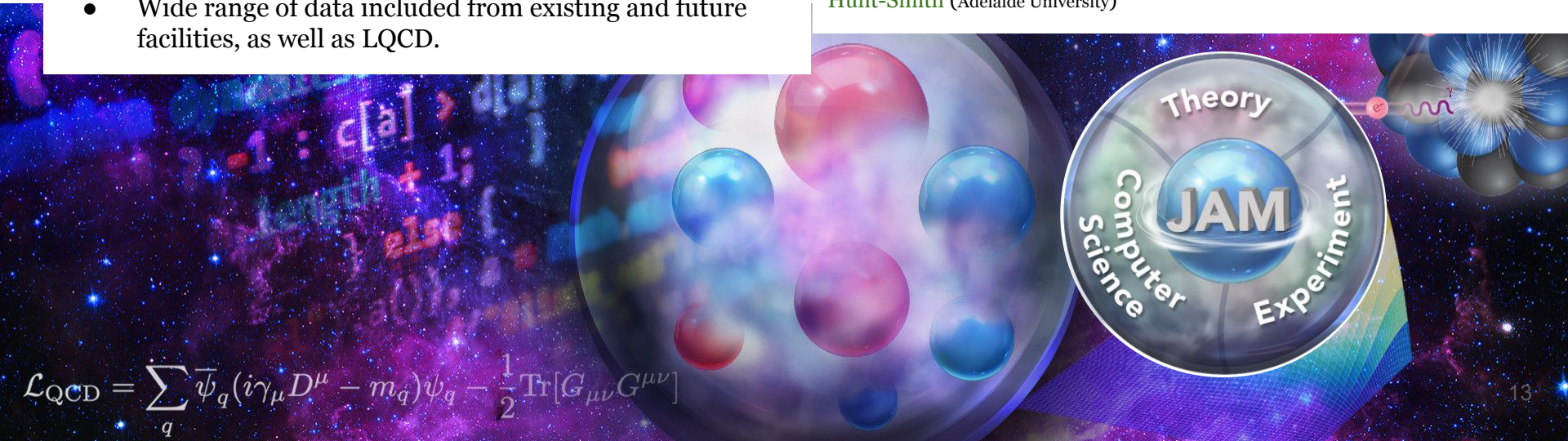
JAM collaboration

Staff / Faculty

W. Melnitchouk (JLab), N. Sato(JLab), T. Rogers (ODU/JLab), A. Prokudin (PSU), D. Pitonyak (LVC), L. Gamberg (PSU), Z. Kang (UCLA), J. Qiu (JLab), A. Accardi (Hampton/JLab), A. Metz (Temple), C.-R. Ji (NCSU), M. Constantinou (Temple), F. Steffens (Bonn), Y. Kovchegov (OSU), M. Sievert (NMSU), I. Cloet (ANL)

Students / Postdocs

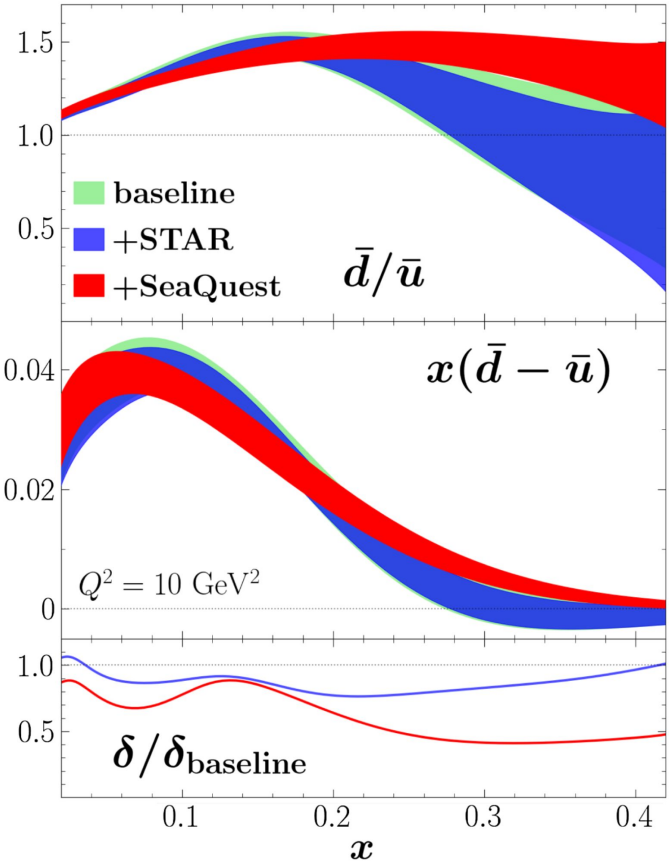
C. Cocuzza (Temple), Y. Zhou (South China Normal University), P. Barry (JLab), E. Moffat (ANL), D. Adamiak (OSU), A. Freese (WU), T. Anderson (William & Mary), R. Whitehill (Wichita State University), N. Hunt-Smith (Adelaide University)

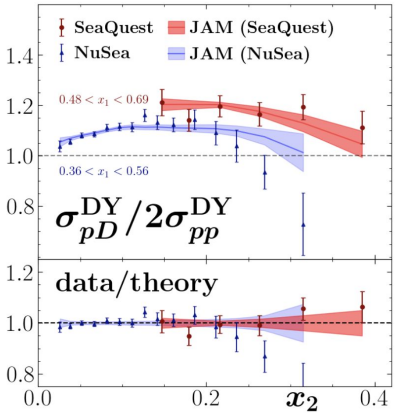


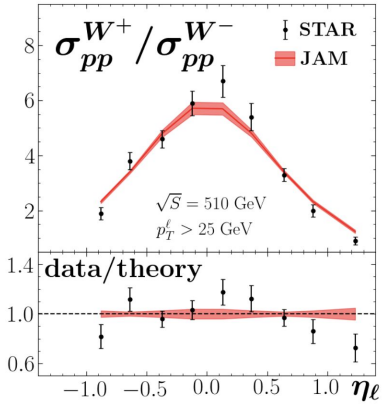
Backup

Antimatter asymmetry

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

Positivity and renormalization of parton densities

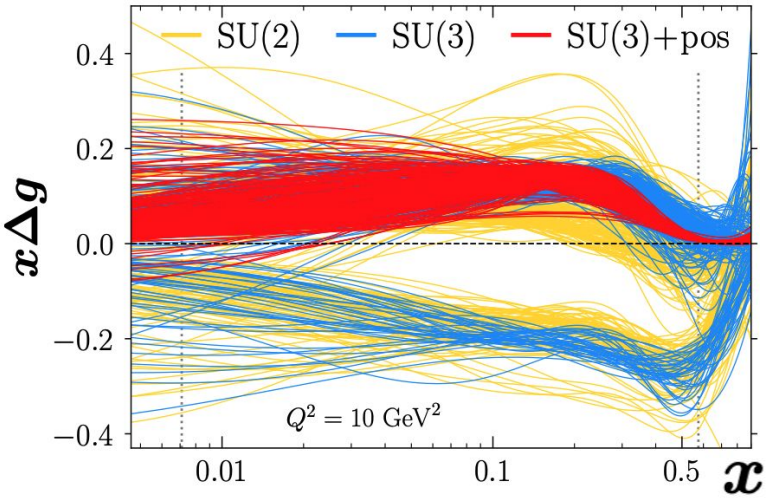
John Collins, Ted C. Rogers, and Nobuo Sato
Phys. Rev. D **105**, 076010 – Published 14 April 2022

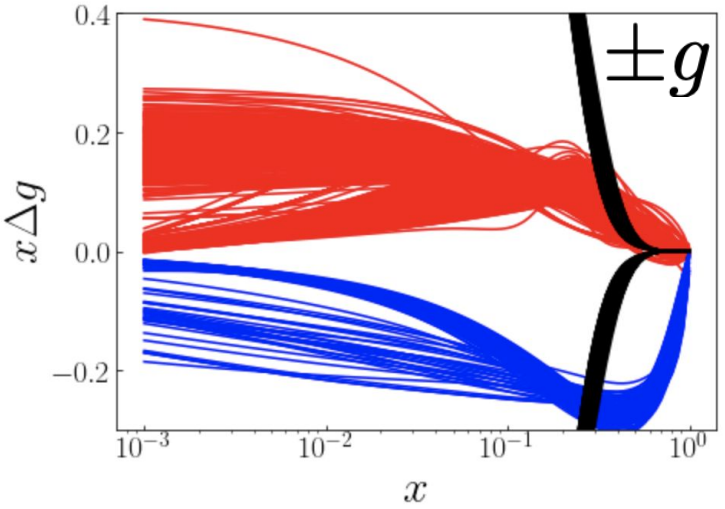
Formally PDFs can be **negative**

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

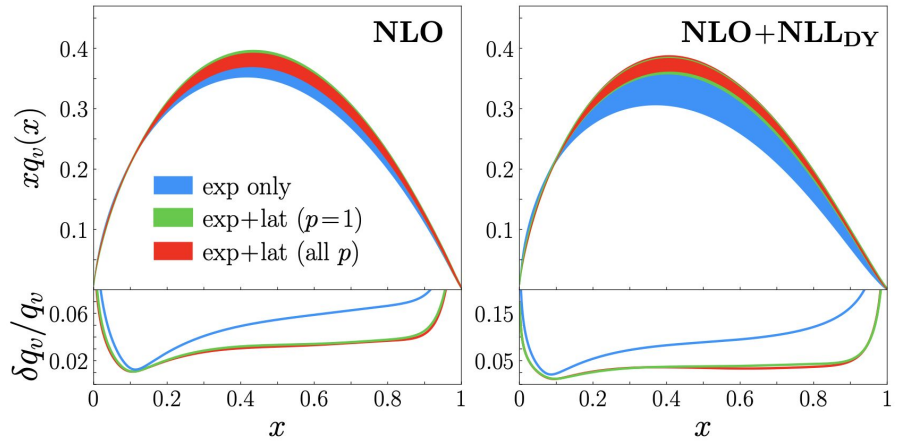
Y. Zhou, N. Sato, and W. Melnitchouk (Jefferson Lab Angular Momentum (JAM) Collaboration)
Phys. Rev. D **105**, 074022 – Published 25 April 2022

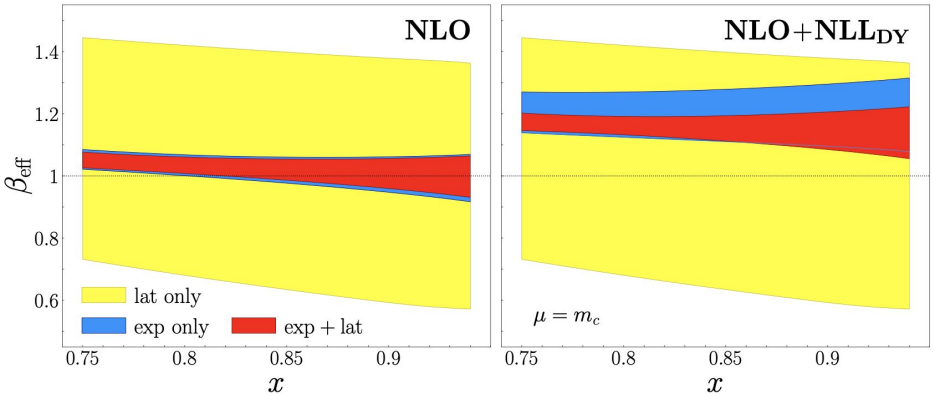
Sign of gluon helicity cannot be ruled out uniquely by current data





Synergies with LQCD - *pion structure*





- LQCD can aid hadron structure studies in cases where constraints from experiments are limited - *“lattice priors”*
- Theory Center has expertise from JAM & HadStruc and has started collaborative research work