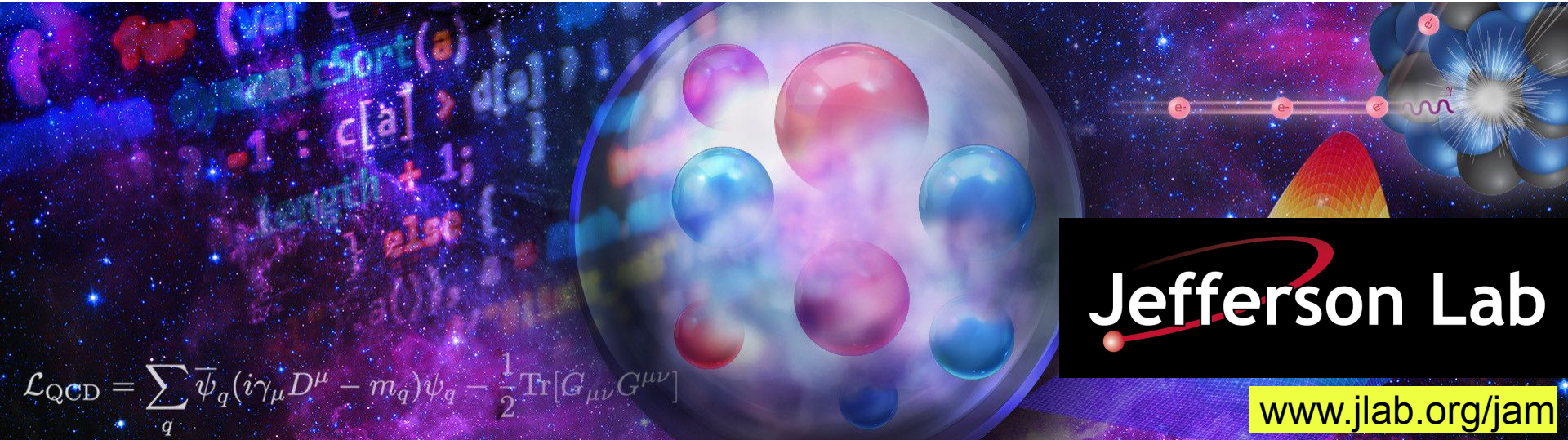
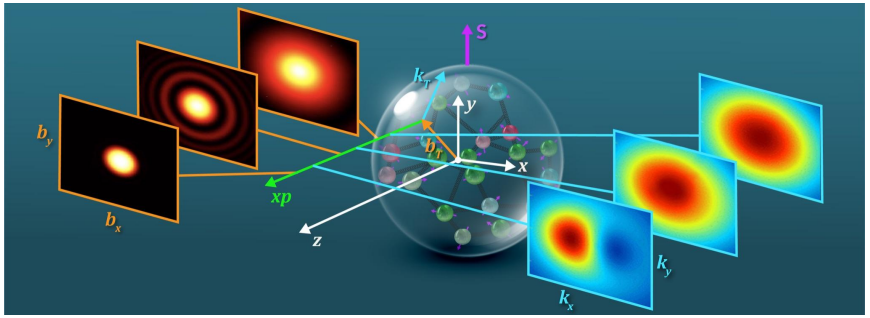
Highlights from JAM

June 26, 2023

Nobuo Sato



Motivations

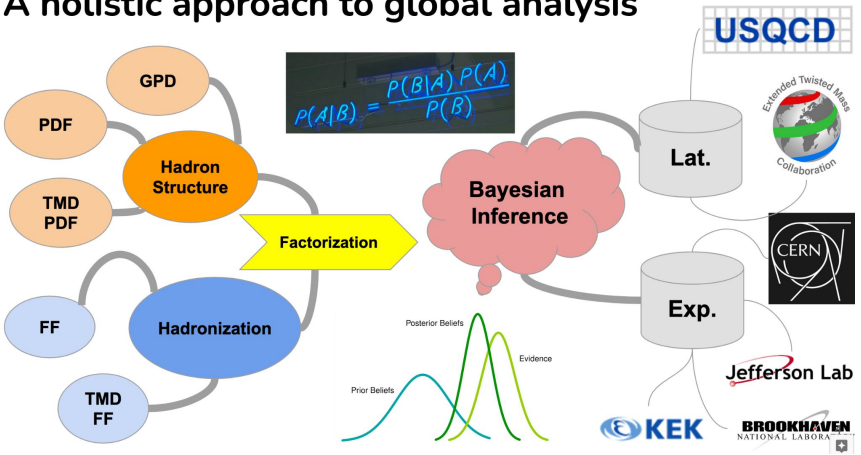


- **WHAT? Synthesis of 3D tomography/nuclear imaging**
  - quantum correlation functions (QCFs)
    - hadron structure (PDFs, TMDs, GPDs, ...)
    - hadronization (FFs, TMDFFs)

- **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
  - small-*x* phenomena
  - precision EW physics (Weinberg angle)
  - …

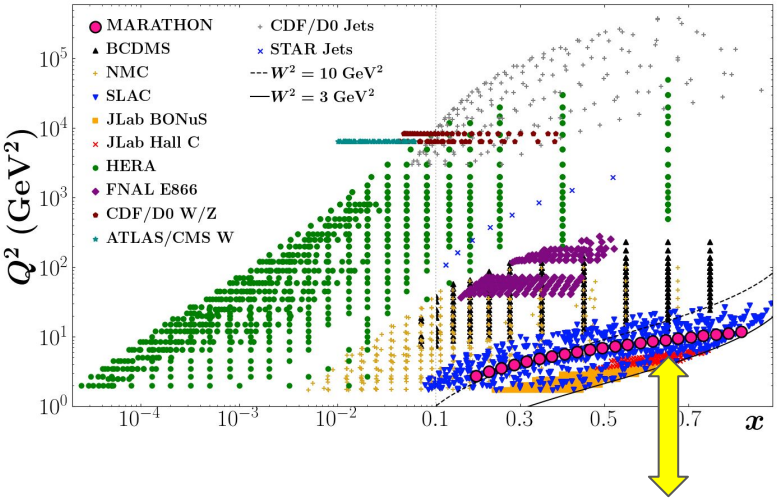
A holistic approach to global analysis

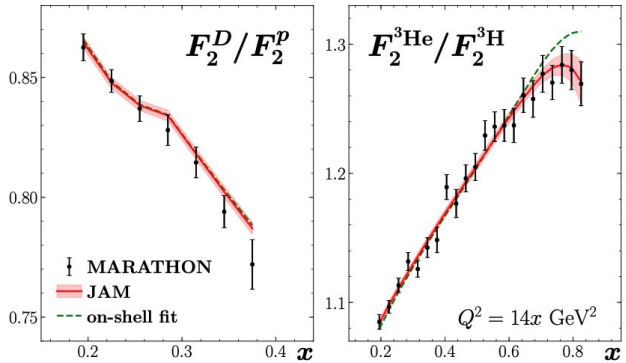


Outline

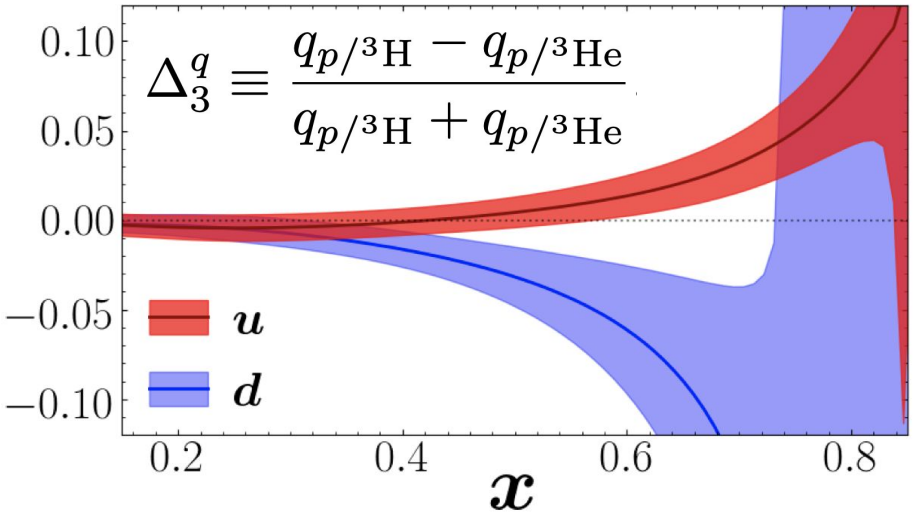
1. Motivations
2. Recent JAM results
3. Summary

Isovector EMC effects from MARATHON data



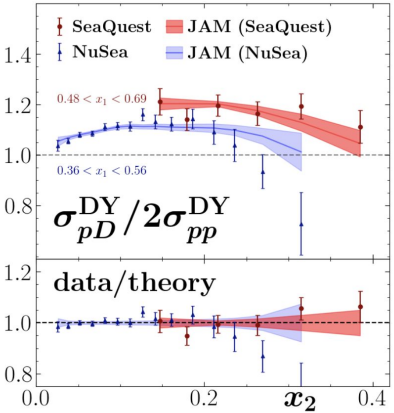


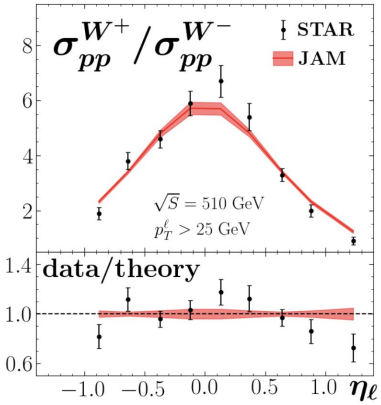
Cocuzza, Melnitchouk, Metz, Sato (PRL)

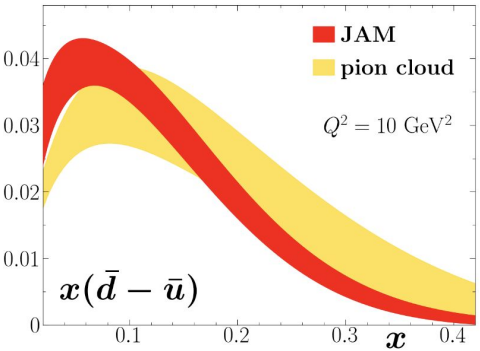


- Global analysis including latest collider *W*/*Z* data and MARATHON *d*/*p*, helium, tritium DIS data
- *Evidence of different medium modifications for u and d quarks*
- *Naive modeling of nuclear PDFs, e.g. u/p/A = d/n/A (violates isospin for non-isoscalar A) is wrong*

Antimatter asymmetry

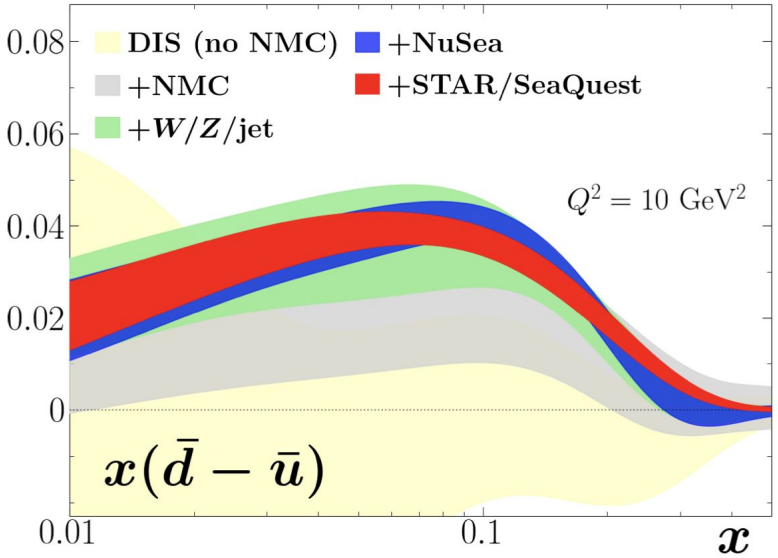






$$(\bar{d} - \bar{u})(x) = \left[\left(f_{n\pi^+} + f_{\Delta^0\pi^+} - f_{\Delta^{++}\pi^-}\right) \otimes \bar{q}_v^{\pi}\right](x),$$

Cocuzza, Melnitchouk, Metz, Sato (PRD)

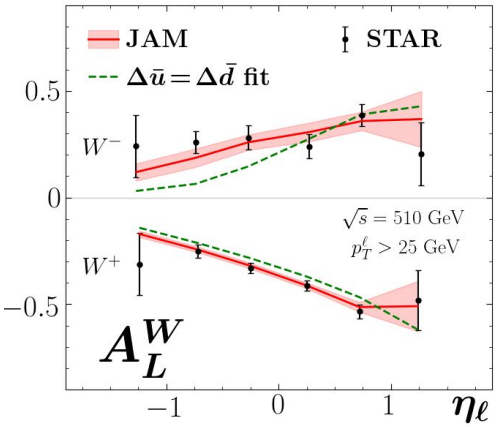


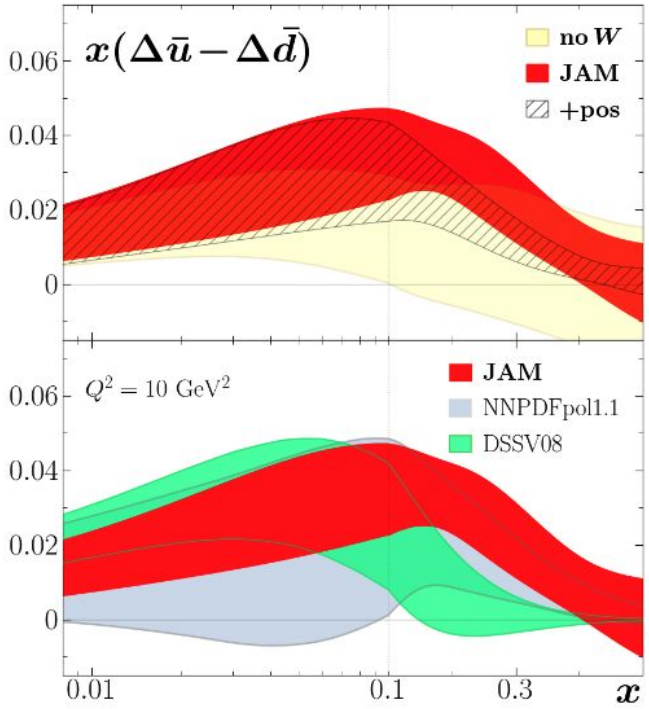
- First global analysis to include latest SeaQuest and STAR data
- Most precise phenomenological extraction of *dbar-ubar* asymmetry to date
- Quantitative test of the pion-cloud model

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**

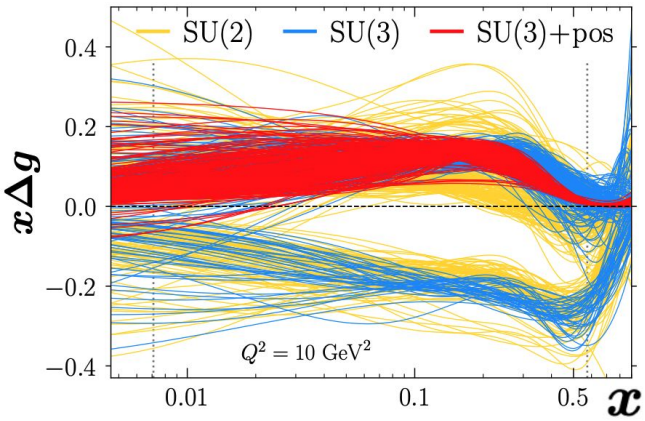


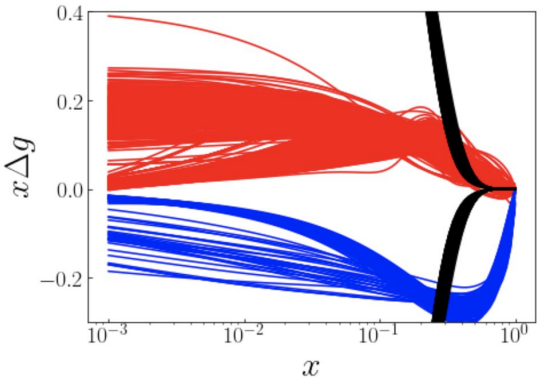


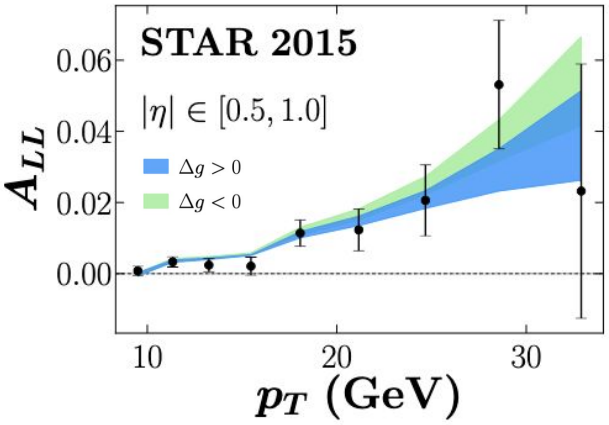
- First simultaneous extraction of unpolarized and helicity PDFs and FFs in global analysis with inclusion of RHIC spin *W+/W-* data
- Most precise phenomenological extraction of polarized *dbar-ubar* asymmetry to date

News on Gluon helicity

Zhou, Melnitchouk, Sato (PRD)

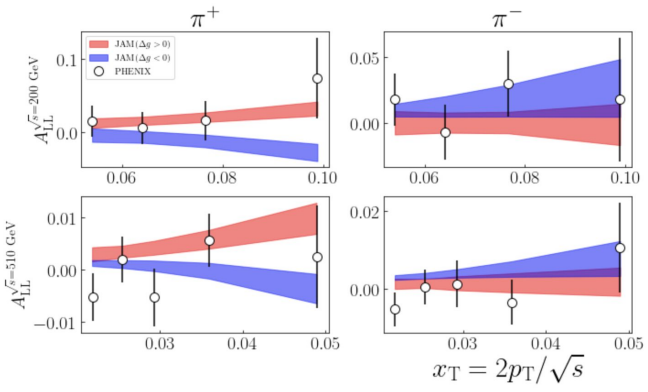


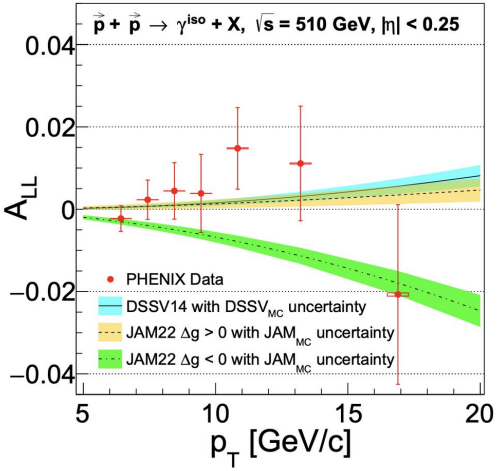




- Inclusion of RHIC polarized jet data allows both positive and negative gluon helicity solutions (in absence of positivity constraints on unpolarized gluon PDF)
- PHENIX has attempted to have empirical confirmation of gluon helicity sign (PRD102.032001, PRD91.032001)

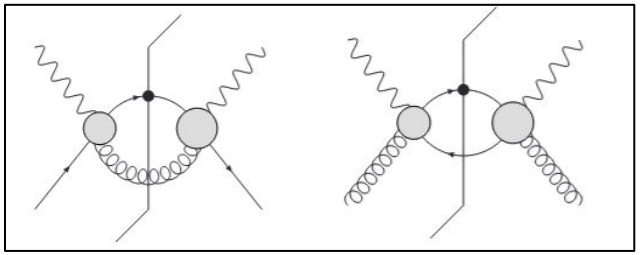
Predictions to other data

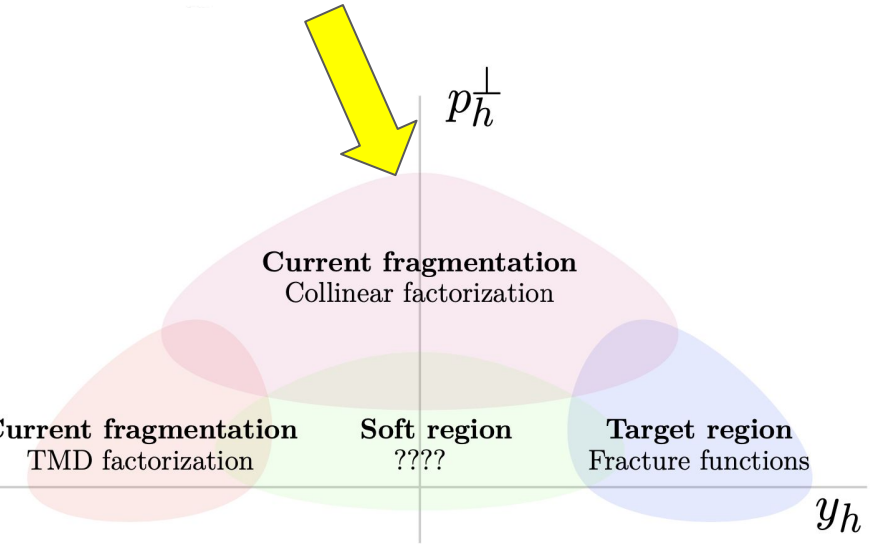


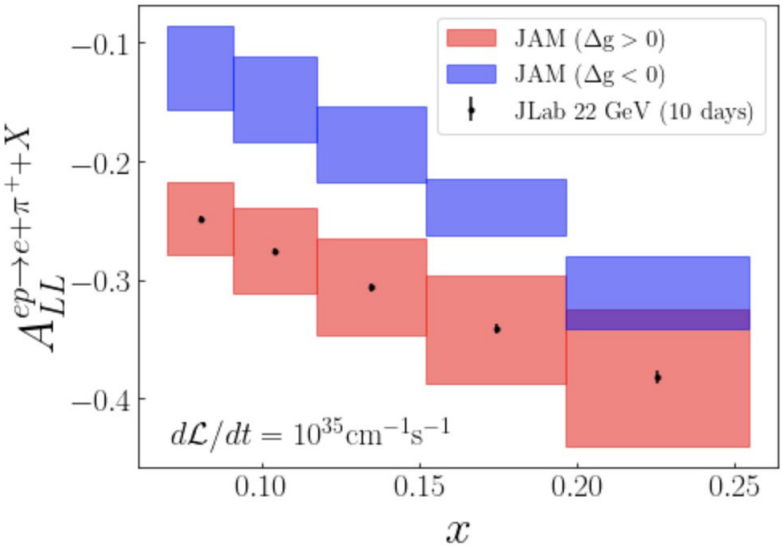


Opportunities at JLab 22 GeV upgrade

Whitehill, Zhou, NS, Melnitchouk (PRD 2023)
JLab 22 GeV white paper https://arxiv.org/abs/2306.09360

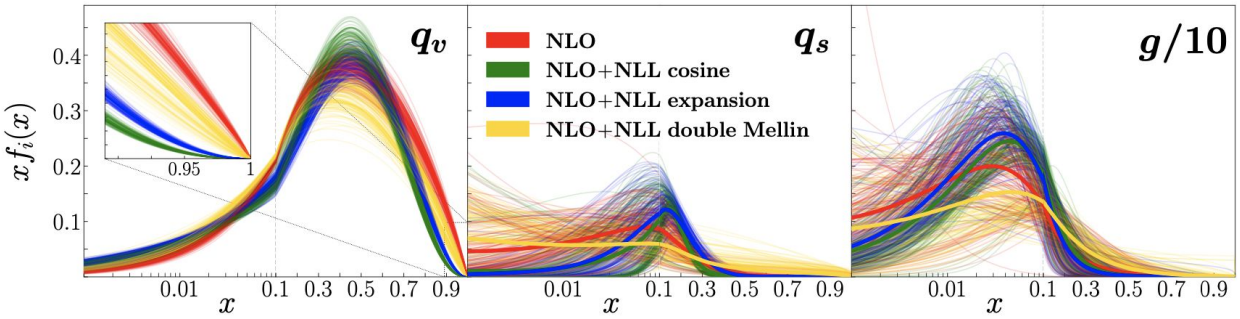




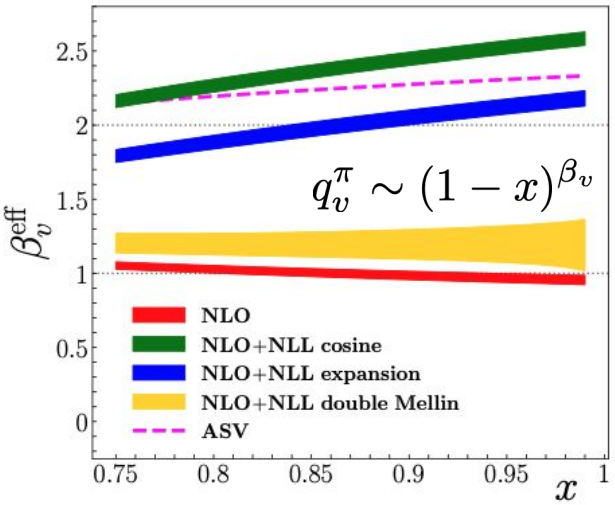


- Hadron production with large transverse momentum has an opportunity to discriminate the sign of gluon polarization
- JLab22 GeV has the potential to measure this observable and establish the sign of gluon helicity at large *x*

Pion structure



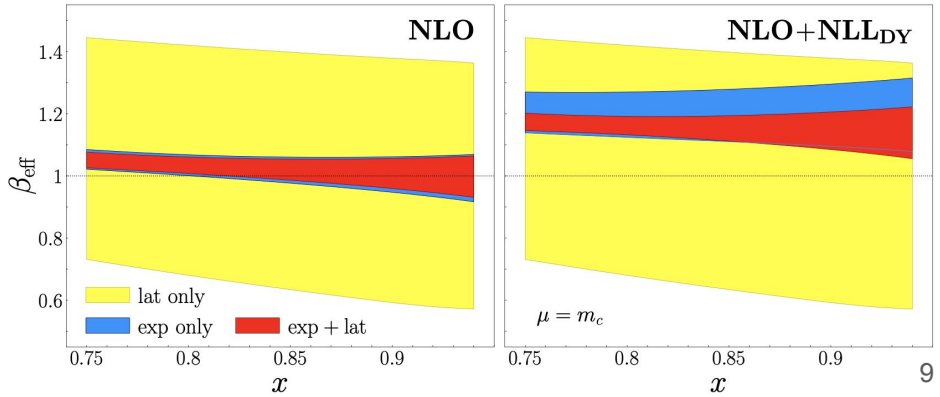
Barry, Ji, Melnitchouk, Sato (PRL 2021)



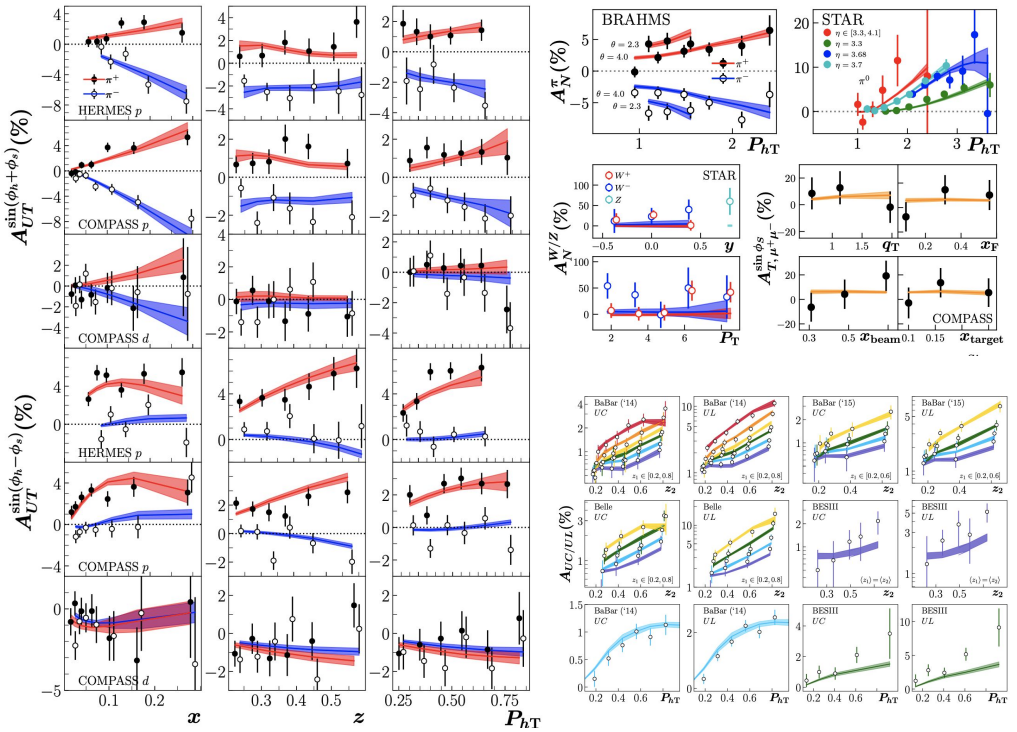
- Improved pQCD framework indicates large *x* pion PDF is closer to 1 despite QCD model calculations
- Results are also stable after the inclusion LQCD Ioffe time distributions

Synergies with LQCD

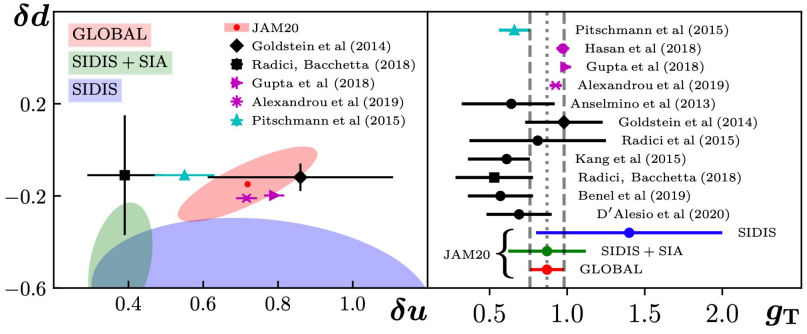
Barry et al. (PRD 2022) - JAM & HadStruct



Global analysis of SSAs (TMD+CT3 framework)



Cammarota et al. (PRD)

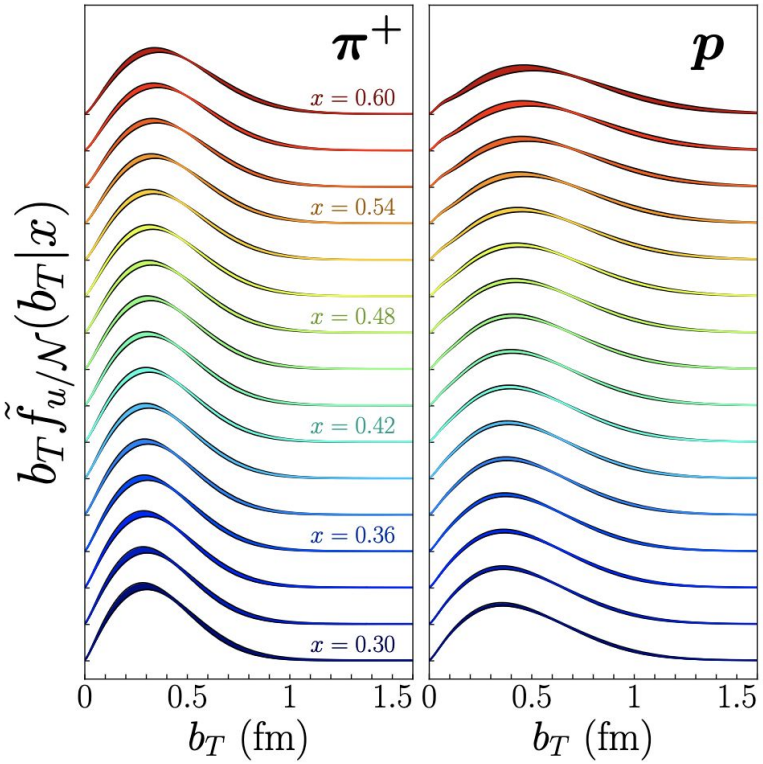


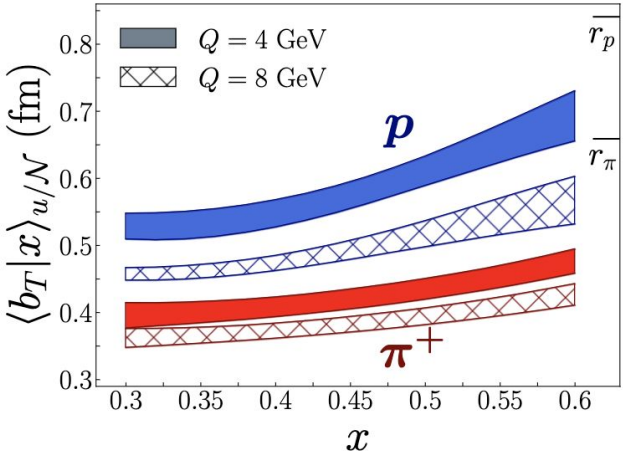
- Exploratory study for a global analysis of all single-spin asymmetries from *ep*, *e+e-* & *pp* reactions using the parton model TMD with collinear twist-3 framework.
- Extracted flavor-dependent transversity in good agreement with LQCD for the first time.

See Metz talks on DiFFs

Pion vs proton TMDs

Barry et al. (2023)



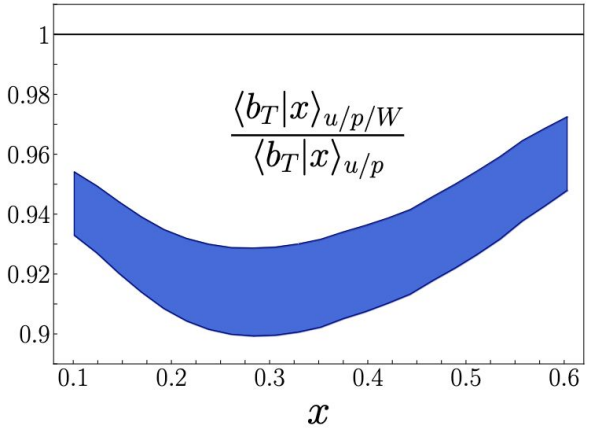


Empirical demonstration that transverse correlation of quark fields are distinguishable between pions and protons

The average transverse separation follows a similar pattern as proton and pion radii

Observation of transverse EMC effect in *W* relative to *p* with maximal impact around *x*=0.3

These results are largely independent of collinear pdf (tested numerically) and they are genuine features of TMDs at large *bT*



Pion vs proton TMDs

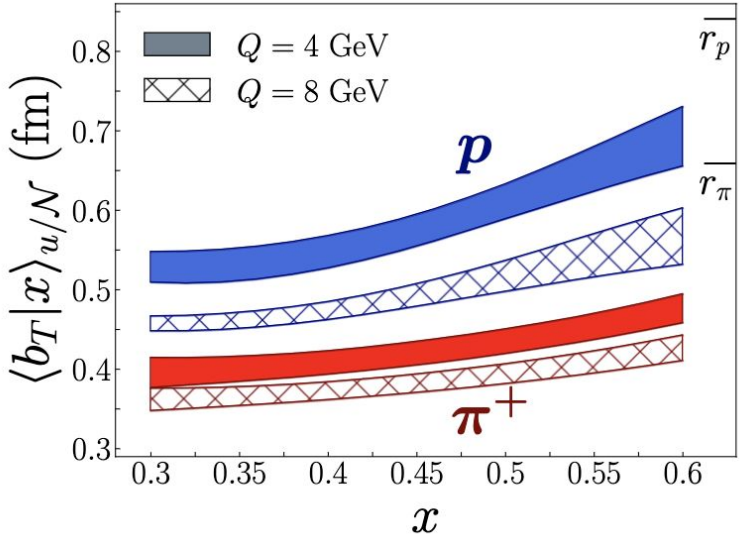
$$\tilde{f}_{q/\mathcal{N}}(x, b_T) = \int \frac{\mathrm{d}b^-}{4\pi} e^{-ixP^+b^-} \mathrm{Tr}\left[\langle \mathcal{N} | \bar{\psi}_q(b)\gamma^+ \mathcal{W}(b,0)\psi_q(0) | \mathcal{N} \rangle\right],$$

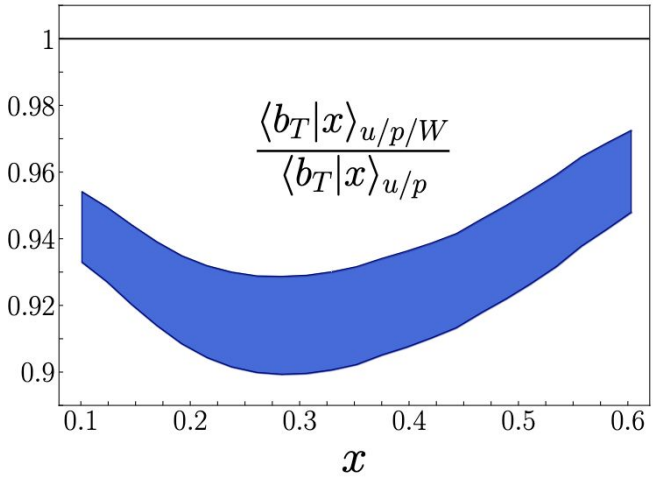
$$b \equiv (b^-, 0^+, \boldsymbol{b}_T),$$

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

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

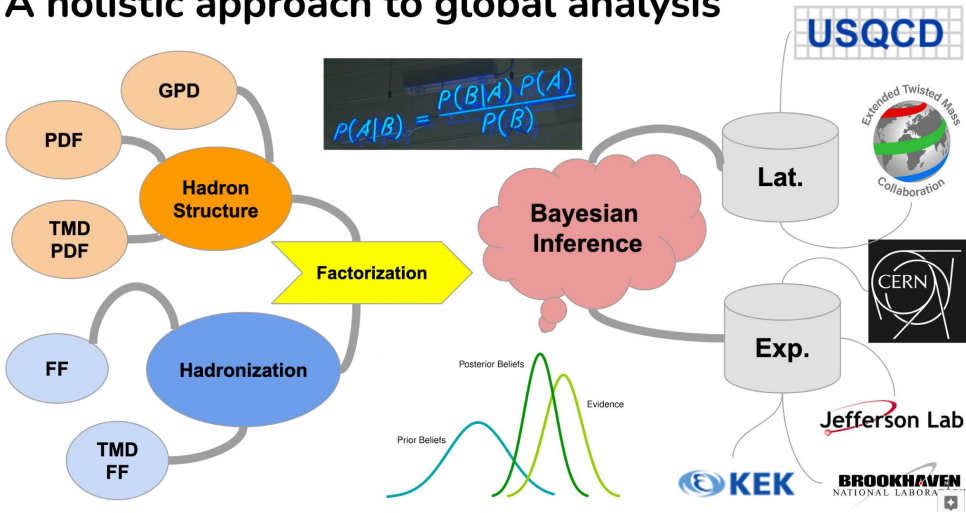
- TMDs in *b* space characterise the strength of quark-antiquark correlations
- Observe a clear difference between protons and pions
- Observe a clear EMC effect in coordinate space

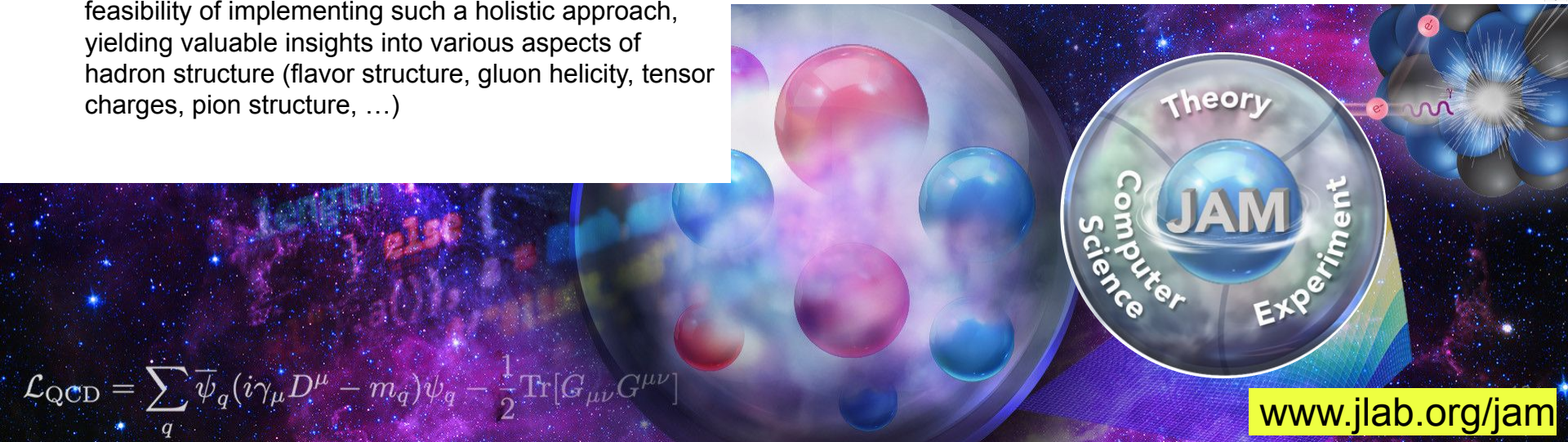




Summary

- Comprehensive and holistic approach to analyzing hadron structure is essential – not only for reliably examining existing data, but also for effectively interpreting results from upcoming experiments
- JAM Collaboration has successfully demonstrated feasibility of implementing such a holistic approach, yielding valuable insights into various aspects of hadron structure (flavor structure, gluon helicity, tensor charges, pion structure, …)





Backup

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

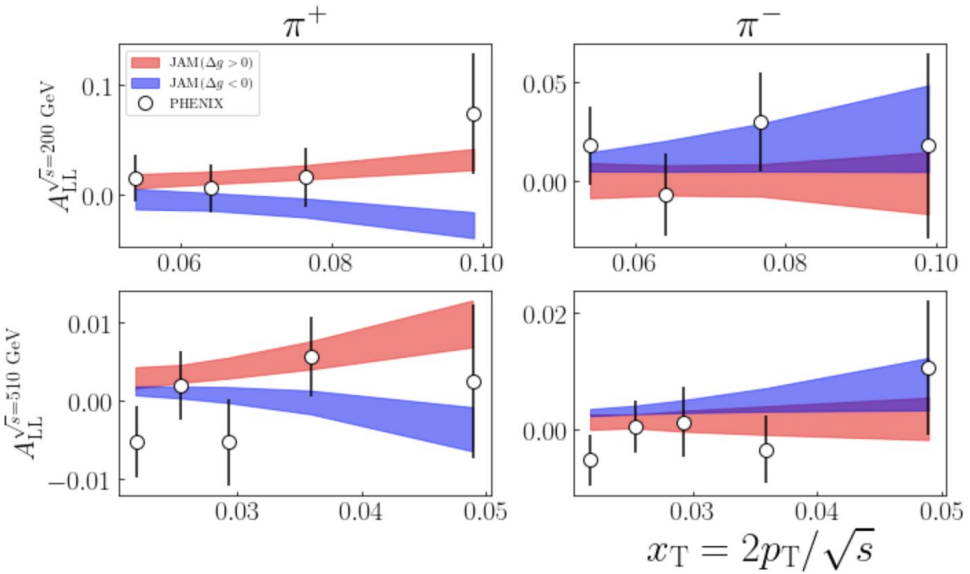
PHENIX Collaboration • U.A. Acharya (Georgia State U.) et al. (Apr 6, 2020)

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]

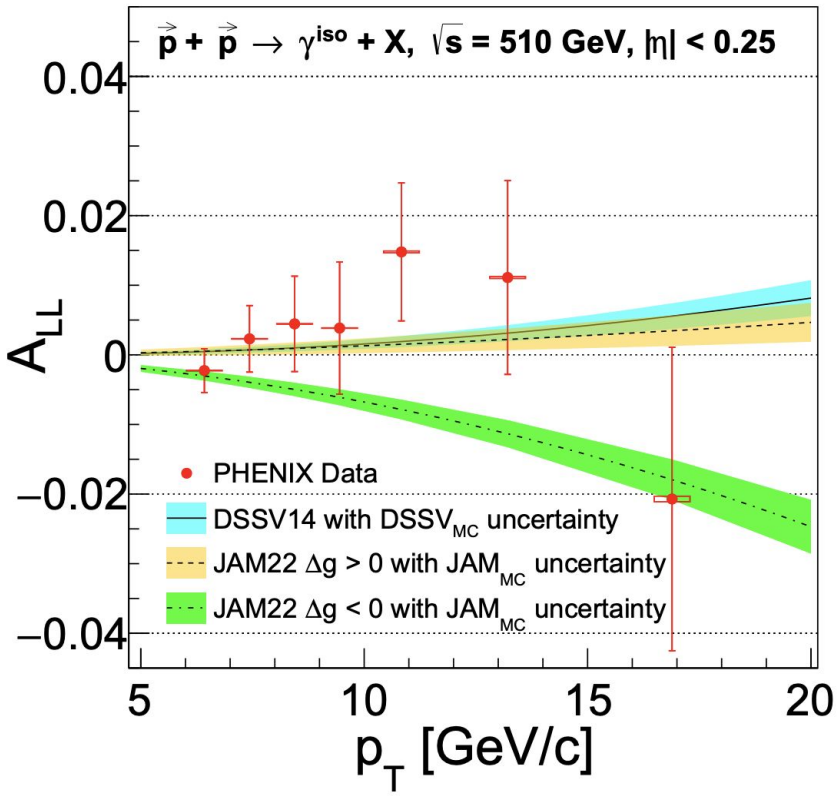


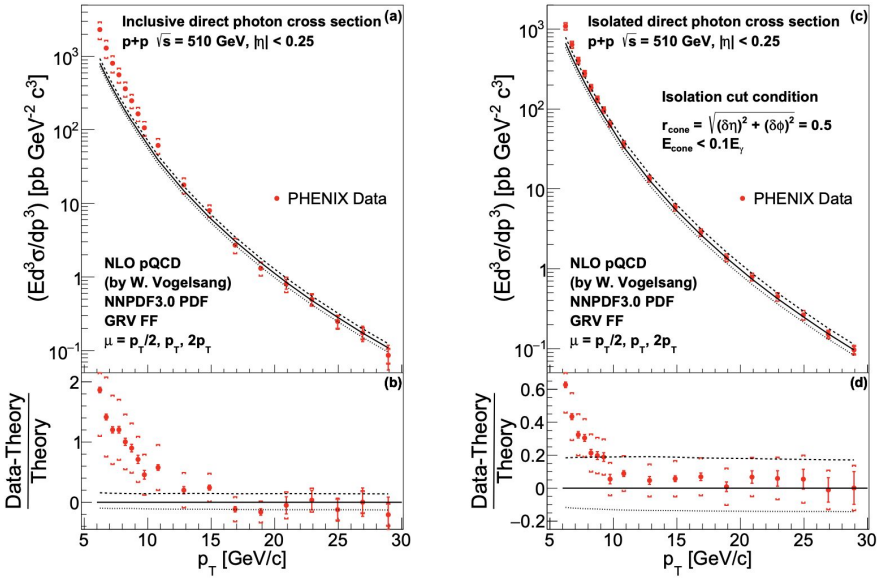
The PHENIX experiment at the Relativistic Heavy Ion Collider has measured the longitudinal double spin asymmetries, A_{LL}, for charged pions at midrapidity ($|\eta| < 0.35$) in longitudinally polarized p+p collisions at $\sqrt{s} = 510$ GeV. These measurements are sensitive to the gluon spin contribution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

Pion vs proton TMDs

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

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- 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