Updates from JAM on gluon helicity PDF

Nobuo Sato

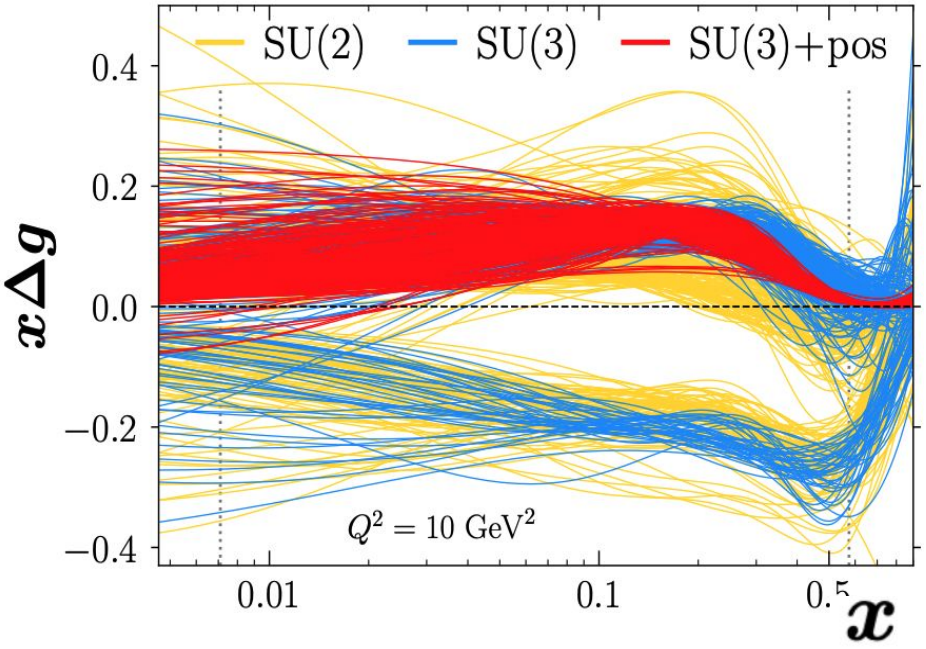
Zhou, NS, Melnitchouk ‘22
Karpie, Whitehill, Melnitchouk, Monahan, Orginos, Qiu, Richards, NS, Zafeiropoulos ‘23
Hunt-Smith, Cocuzza, Melnitchouk, NS, Thomas, White ‘24

QCD evolution,
Pavia IT May 24 2024

Jefferson Lab

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

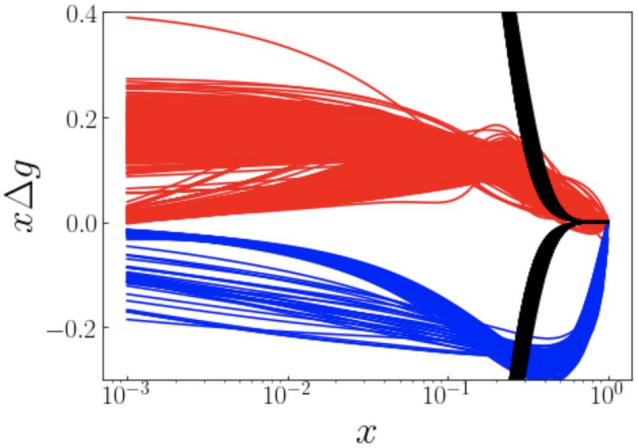
Y. Zhou, N. Sato, and W. Melnitchouk (Jefferson Lab Angular Momentum (JAM) Collaboration)
Phys. Rev. D **105**, 074022 – Published 25 April 2022

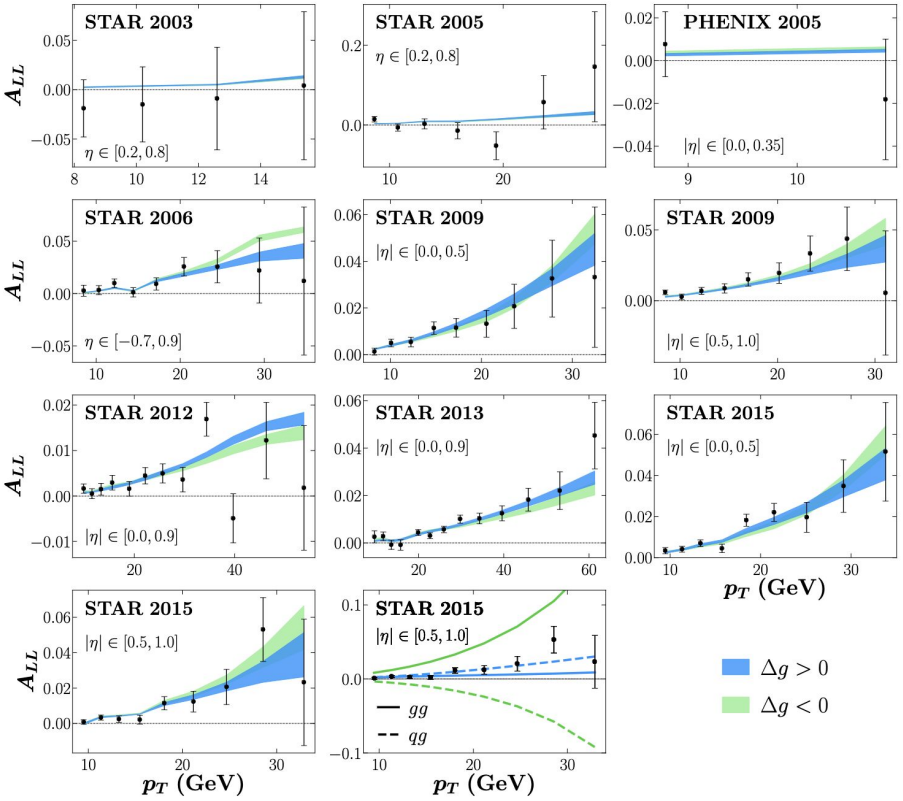


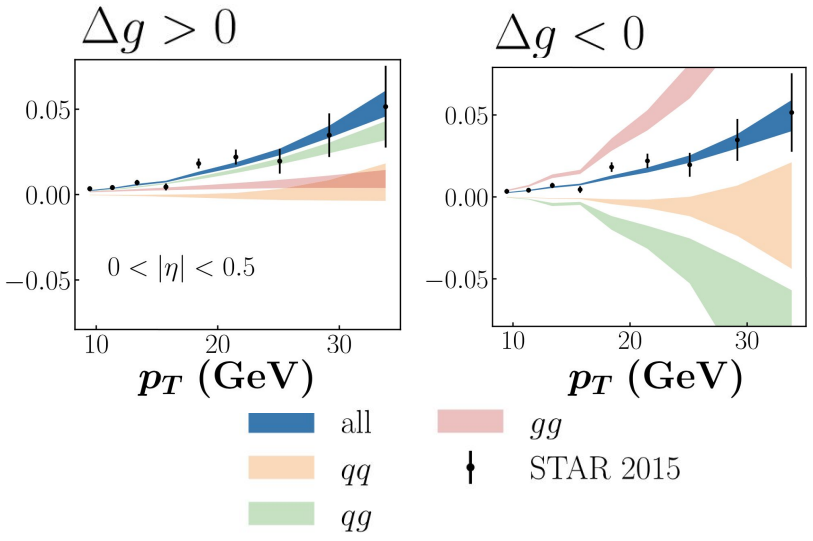
$$|\Delta g| < g$$

pdf positivity constraint

- Sign of gluon-hpdf is not uniquely determined by existing experimental data
  (DIS W^2 > 10 GeV^2)
- PDF positivity constraints + data strongly disfavors negative g-hpdf
- Negative g-hpdf violates significantly pdf positivity constraint
- PDF positivity is not a strict requirement in QCD







$$A_{LL}^{\text{jet}}(p_T, y) \propto a_{gg}[\Delta g \otimes \Delta g] + \sum_q a_{qg}[\Delta q \otimes \Delta g] + \sum_{q,q'} a_{qq'}[\Delta q \otimes \Delta q'] + \mathcal{O}(\alpha_s),$$

$|A_{LL}| < 1$ ✓

g-hpdf enters quadratically, and different subchannels contribute with different signs and strengths

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

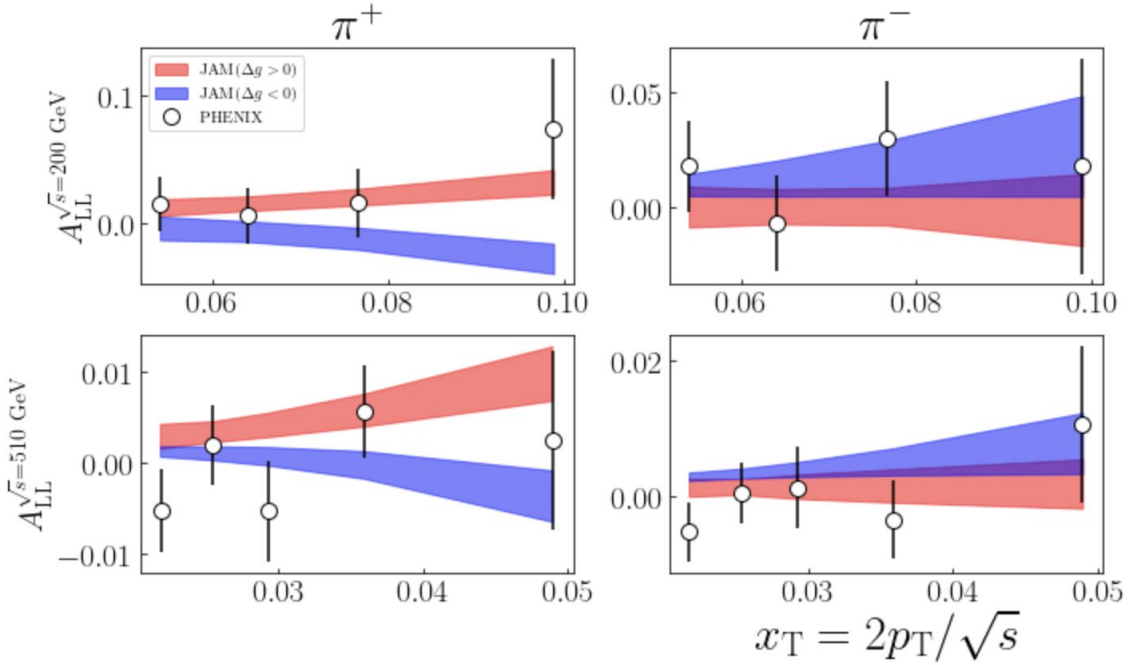
PHENIX Collaboration • U.A. Acharya (Georgia State U.) et al. (Apr 6, 2020)

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]

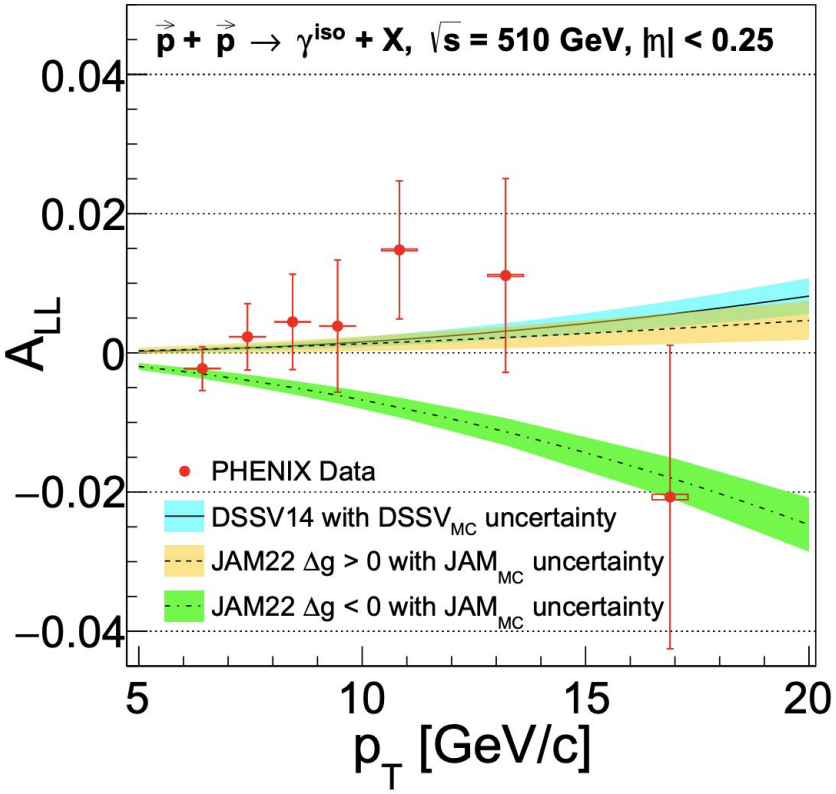


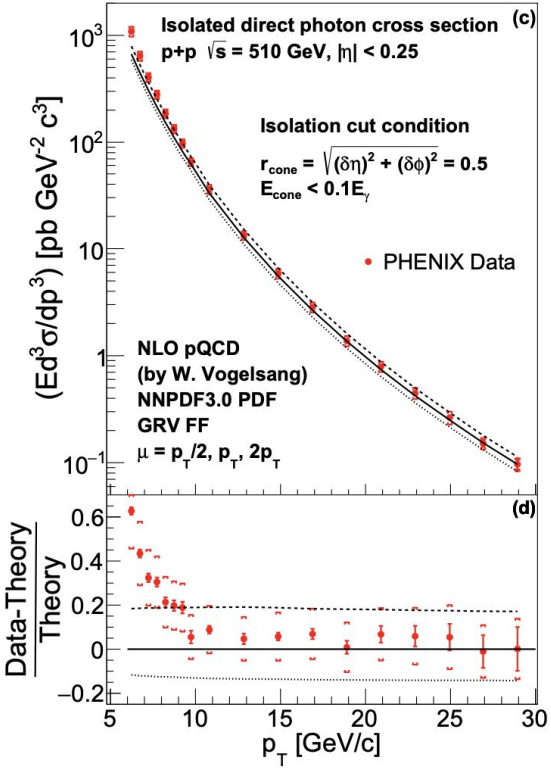
- PHENIX collaboration stated that the gluon spin contribution is positive
- The two solutions for g-hpdf found by JAM describe the data equally well

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]





- PHENIX collaboration stated that negative g-hpdf is disfavored by more than 2.8 σ
- However, only last 3 high-pT A_LL points are well described in pQCD (see denominator of A_LL)

Gluon helicity from global analysis of experimental data and lattice QCD loffe time distributions

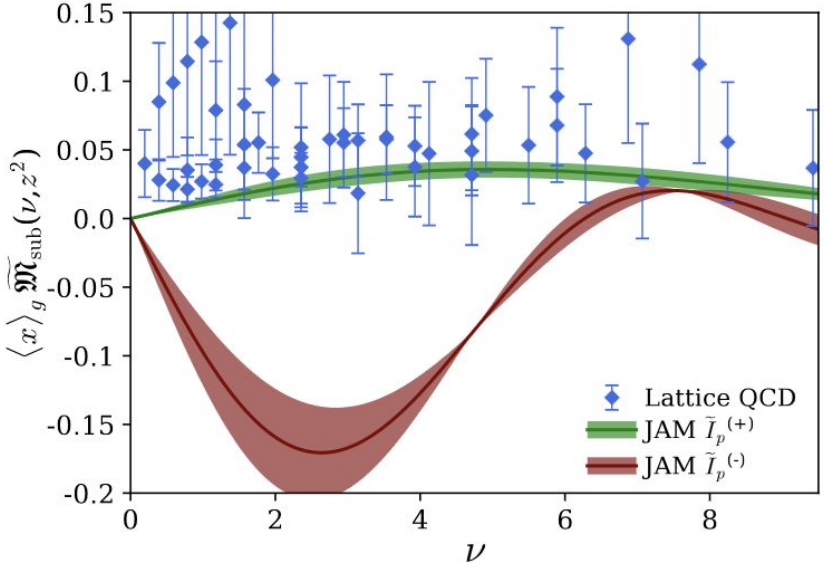
J. Karpie, R. M. Whitehill, W. Melnitchouk, C. Monahan, K. Orginos, J.-W. Qiu, D. G. Richards, N. Sato, and S. Zafeiropoulos (Jefferson Lab Angular Momentum and HadStruc Collaborations)

Phys. Rev. D **109**, 036031 – Published 27 February 2024

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]

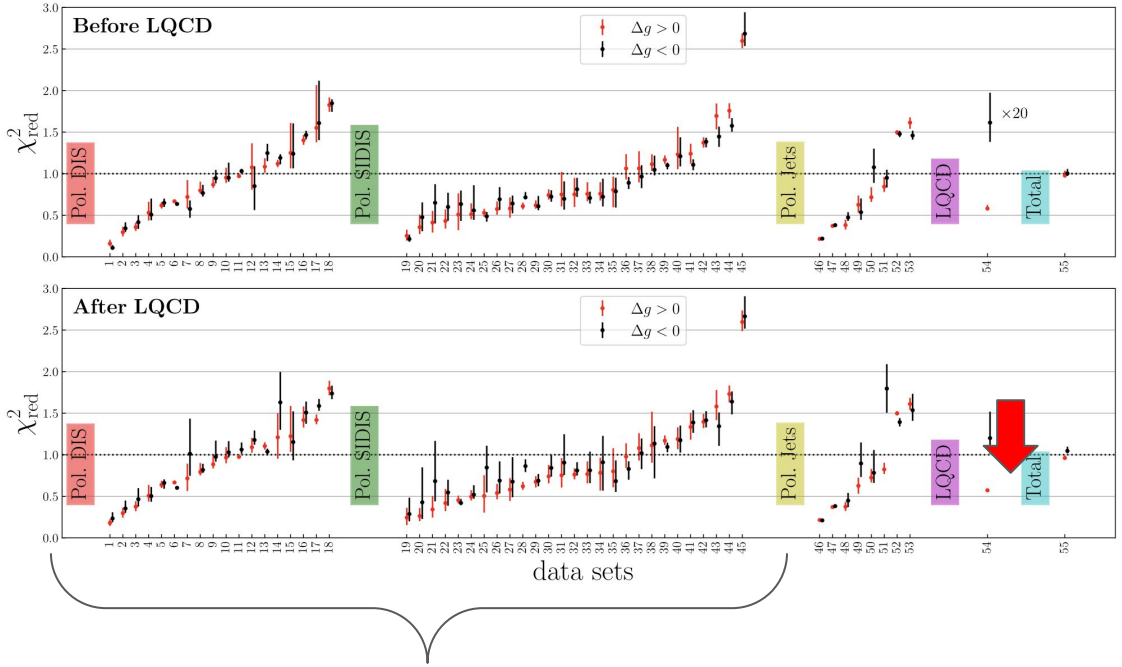


$$\widetilde{M}^{\mu\nu;\alpha\beta}(p,z) = \langle p|F^{\mu\nu}(0)W(0;z)\widetilde{F}^{\alpha\beta}(z)|p\rangle$$

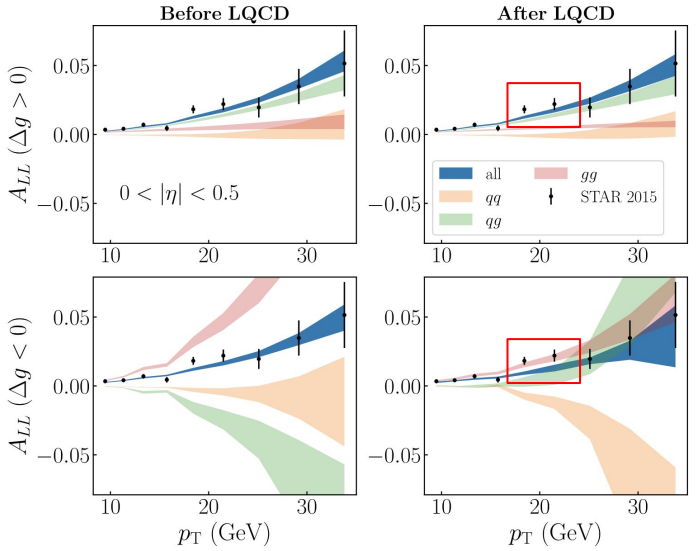
$$\widetilde{\mathfrak{M}}(\nu,z^2) = \frac{\widetilde{M}_{00}(p,z)/p_0 p_3 Z_L(z_3/a)}{M_{00}(p=0,z)/m^2}$$

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

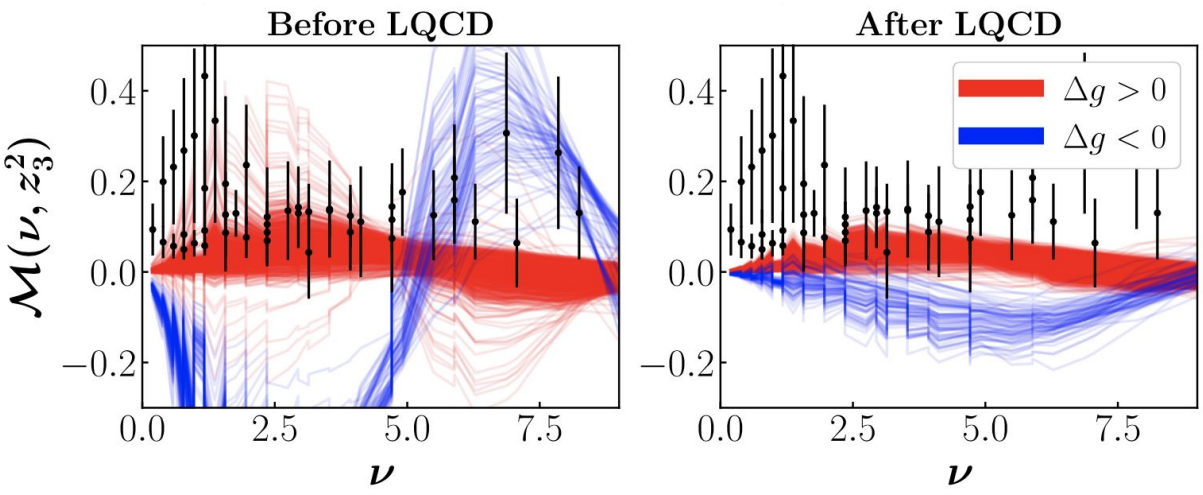
$$\widetilde{\mathcal{I}}_p(\nu) = \frac{i}{2}\int_{-1}^{1}\mathrm{d}x\,e^{-ix\nu}\,x\,\Delta g(x)\,.$$

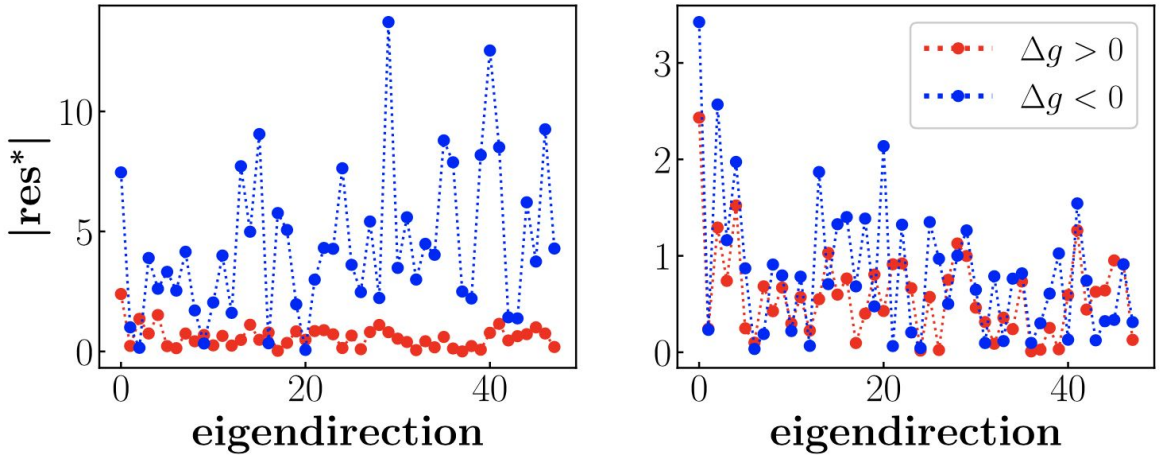


DIS W^2>10 GeV^2



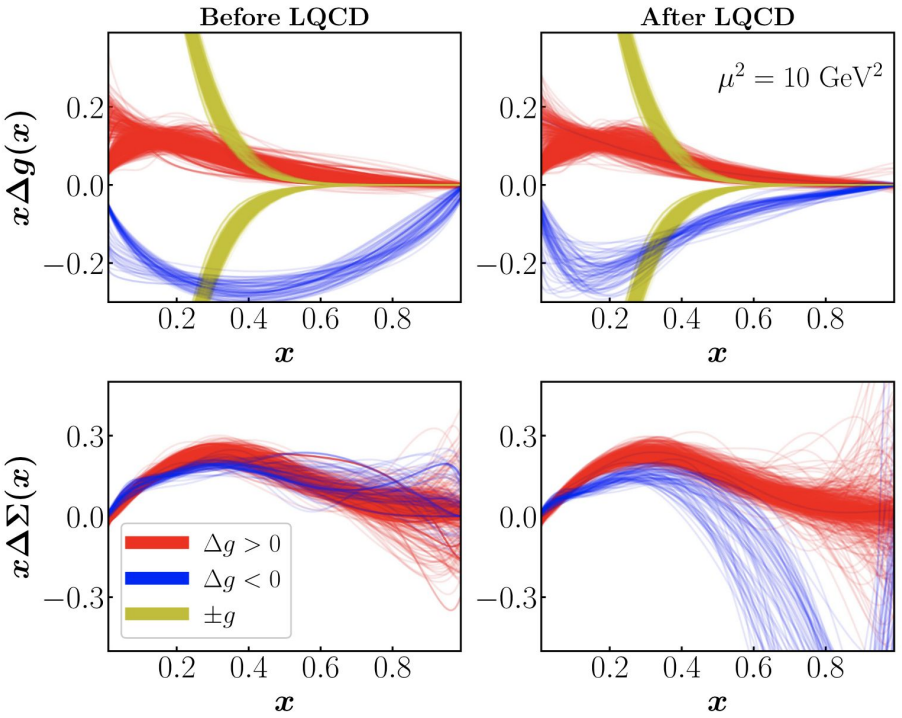
- Good description of global data after inclusion of LQCD for both solutions for g-hpdf
- On the basis of χ^2, LQCD cannot discriminate fully the sign of g-hpdf



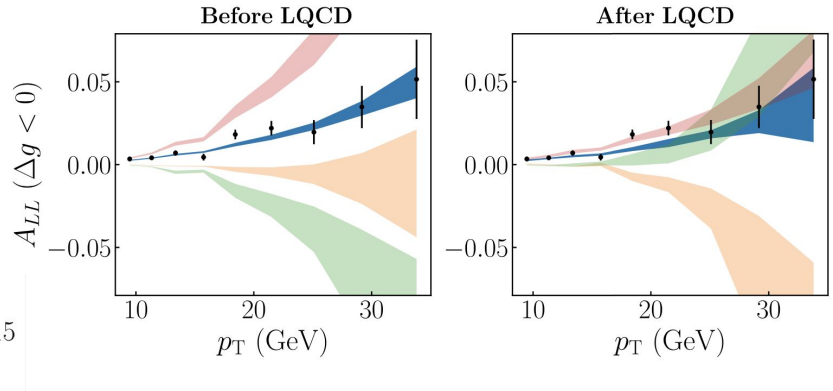


$$\chi^2 = (\boldsymbol{d}-\boldsymbol{t})^T \boldsymbol{\Sigma}^{-1} (\boldsymbol{d}-\boldsymbol{t})$$
$$= (\boldsymbol{d}-\boldsymbol{t})^T \boldsymbol{U}\boldsymbol{D}^{-1}\boldsymbol{U}^T (\boldsymbol{d}-\boldsymbol{t})$$
$$= \sum_i \mathrm{res}_i^{*2}.$$

- PCA projections of residuals reveal strong correlations between LQCD data points
- The correlations prevent determination of g-hpdf sign



- LQCD distorts significantly the negative g-hpdf at higher x > 0.3
- Note that both solutions violate pdf positivity bounds for x > 0.3
- Before inclusion of LQCD data, singlet-hpdf were stable for both solutions
- Inclusion of LQCD data forces the quark singlet-hpdf to become negative at x > 0.4 for the negative g-hpdf



On the resolution of the sign of gluon polarization in the proton

N. T. Hunt-Smith,[1] C. Cocuzza,[2] W. Melnitchouk,[3] N. Sato,[3] A. W. Thomas,[1] and M. J. White[1]

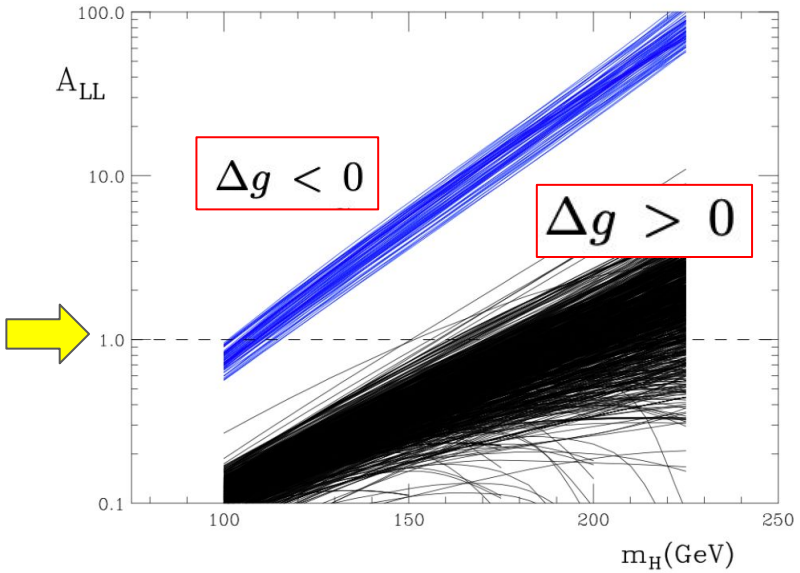
[1] *CSSM and ARC Centre of Excellence for Dark Matter Particle Physics, Department of Physics, University of Adelaide, Adelaide 5005, Australia*
[2] *Department of Physics, William and Mary, Williamsburg, Virginia 23185, USA*
[3] *Jefferson Lab, Newport News, Virginia 23606, USA*

JAM Collaboration

(Dated: March 14, 2024)

Higgs production at RHIC and the positivity of the gluon helicity distribution

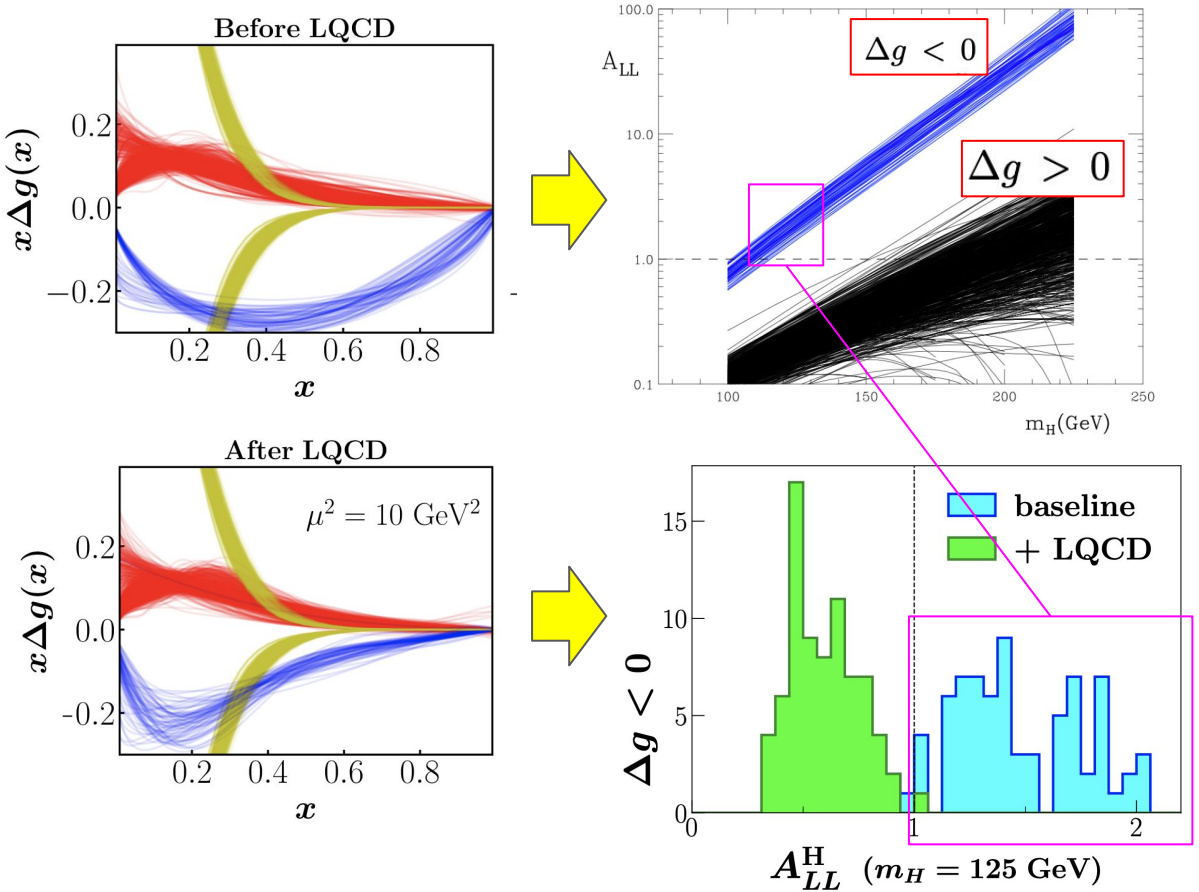
Daniel de Florian[a], Stefano Forte[b], Werner Vogelsang[c]



- Higgs A_LL is directly sensitive to g-hpdf squared at LO
- Calculations of A_LL(H) with negative g-hpdf can lead to unphysical results **(using non-LQCD based analysis)**

$$A_{LL}^{\mathrm{H}}(\tau) = \frac{[\Delta g \otimes \Delta g]}{[g \otimes g]} + \mathcal{O}(\alpha_s),$$

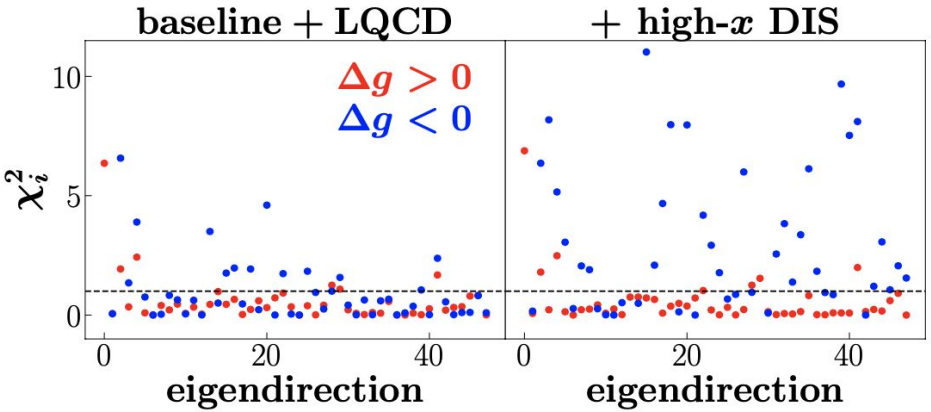
Can Higgs A_LL fully discriminate negative g-hpdf?



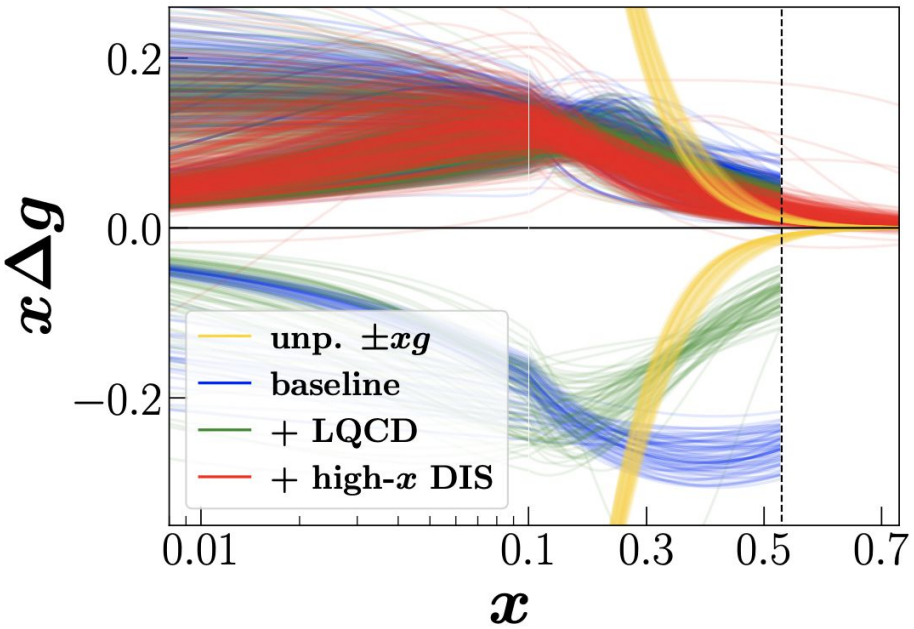
Negative g-hpdf with LQCD constraints still admits a physical Higgs A_LL

	$\chi^2_{\rm red}(\Delta g > 0)$			$\chi^2_{\rm red}(\Delta g < 0)$			N
Reaction	baseline	+ LQCD	+ high-x DIS	baseline	+ LQCD	+ high-x DIS	
Polarized							
Inclusive DIS	0.95	0.96	1.21	0.98	1.12	1.25	1735*
SIDIS	0.85	0.84	1.08	0.84	0.96	1.11	231
Inclusive jets	0.84	0.89	0.90	0.88	1.10	1.44	83
Inclusive $W^{\pm}/Z$	0.60	0.60	0.99	0.83	0.84	1.32	18
Total	**0.89**	**0.90**	**1.18**	**0.92**	**1.06**	**1.24**	**2067**
Unpolarized							
Inclusive DIS	1.17	1.17	1.17	1.18	1.18	1.19	3908
SIDIS	0.99	0.99	1.04	0.99	0.99	1.02	1490
Inclusive jets	1.28	1.28	1.30	1.29	1.29	1.30	198
Drell-Yan	1.21	1.21	1.21	1.24	1.24	1.24	205
Inclusive $W^{\pm}/Z$	1.01	1.01	1.01	1.03	1.03	1.04	153
Total	**1.14**	**1.14**	**1.14**	**1.15**	**1.15**	**1.15**	**5954**
SIA	0.86	0.86	0.89	0.90	0.90	0.92	564
LQCD	—	0.57	0.58	—	1.18	3.92	48
Total	**1.08**	**1.10**	**1.13**	**1.10**	**1.12**	**1.17**	**8633**

1370 additional data points for pol DIS (+ high-x DIS)

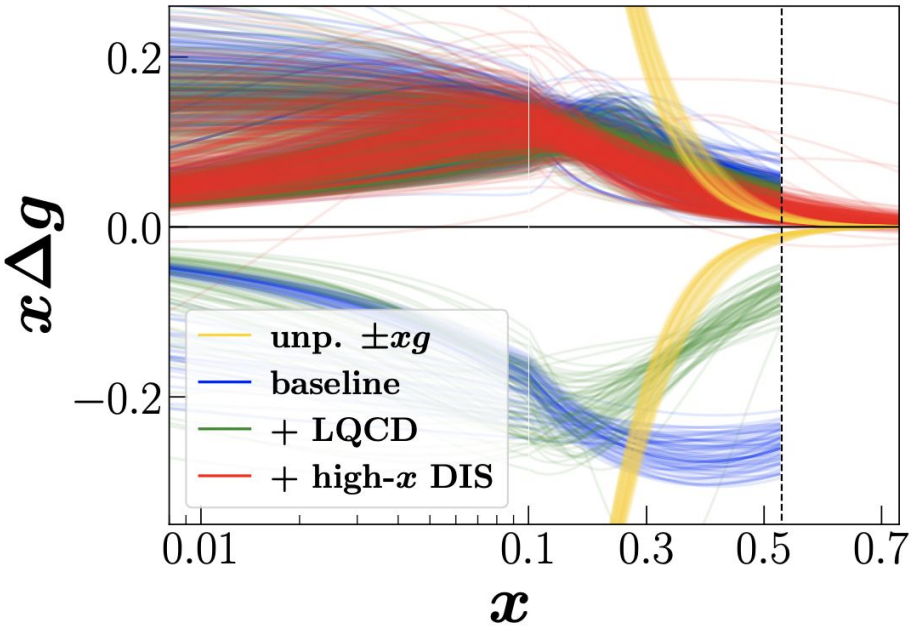


- With inclusion of high-x DIS DSAs, LQCD data strongly disfavor negative g-hpdf solution
- Combined DSA from jet and high-x DIS with LQCD allows us to discriminate the sign of g-hpdf for the first time!



Summary & outlook

- For the first time, we were able to discriminate the sign of g-hpdf using data-driven approach
- Constraints from LQCD along with DSAs from jets and DIS at large-x were crucial to achieve the resolution of g-hpdf sign
- Inclusion of LQCD is becoming increasingly important in global analysis
- Experimental constraints at large x on gluon - hpdf are still scarce, and more data needed to reach precision similar to unpolarized gluon density (EIC - small x, JLab 12/22 - high x)



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

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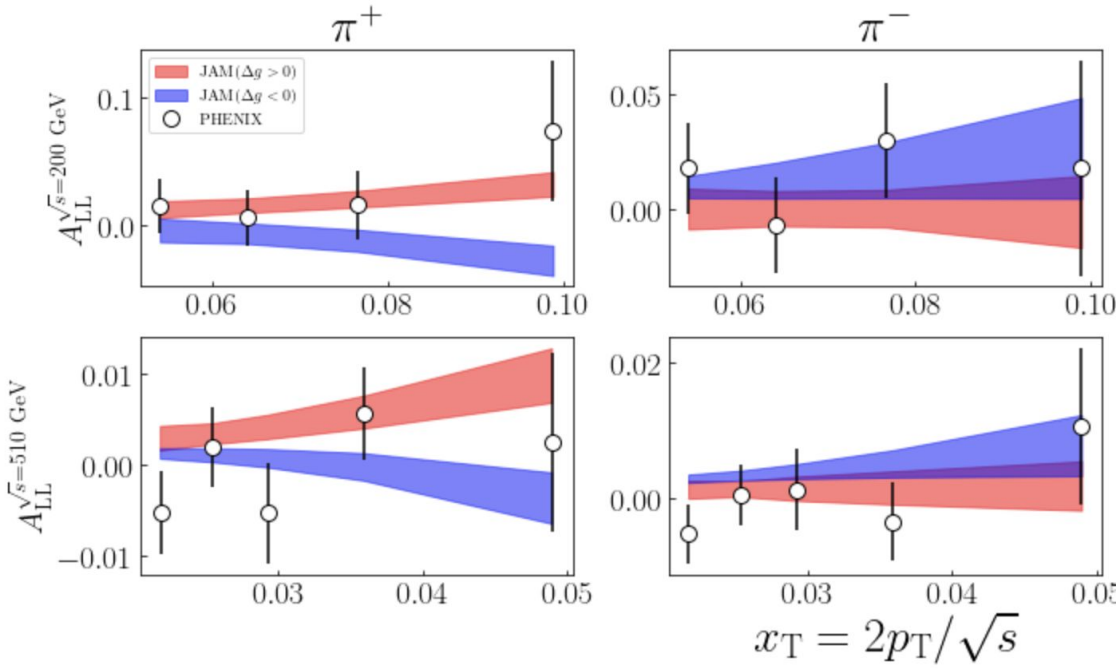
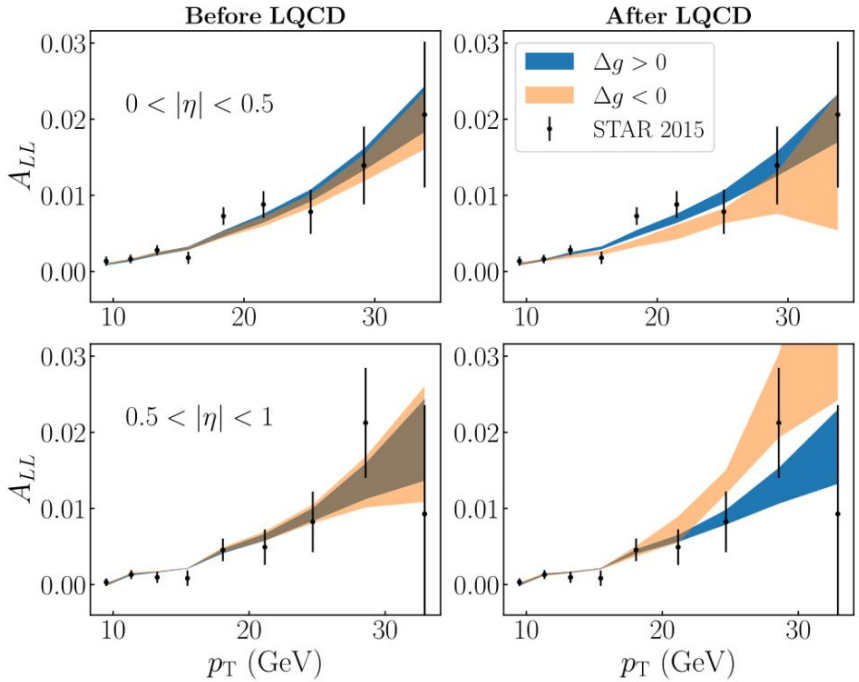
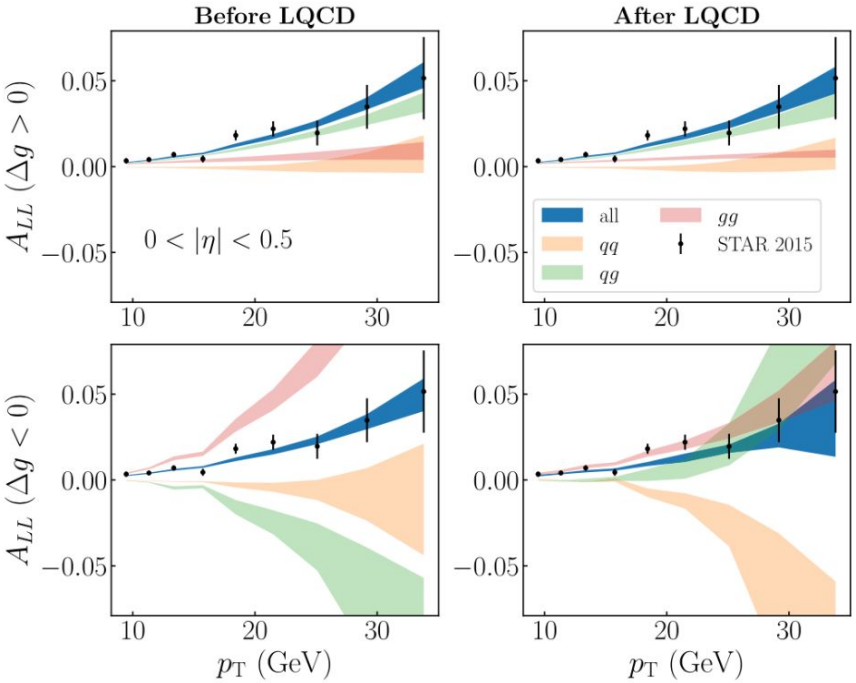
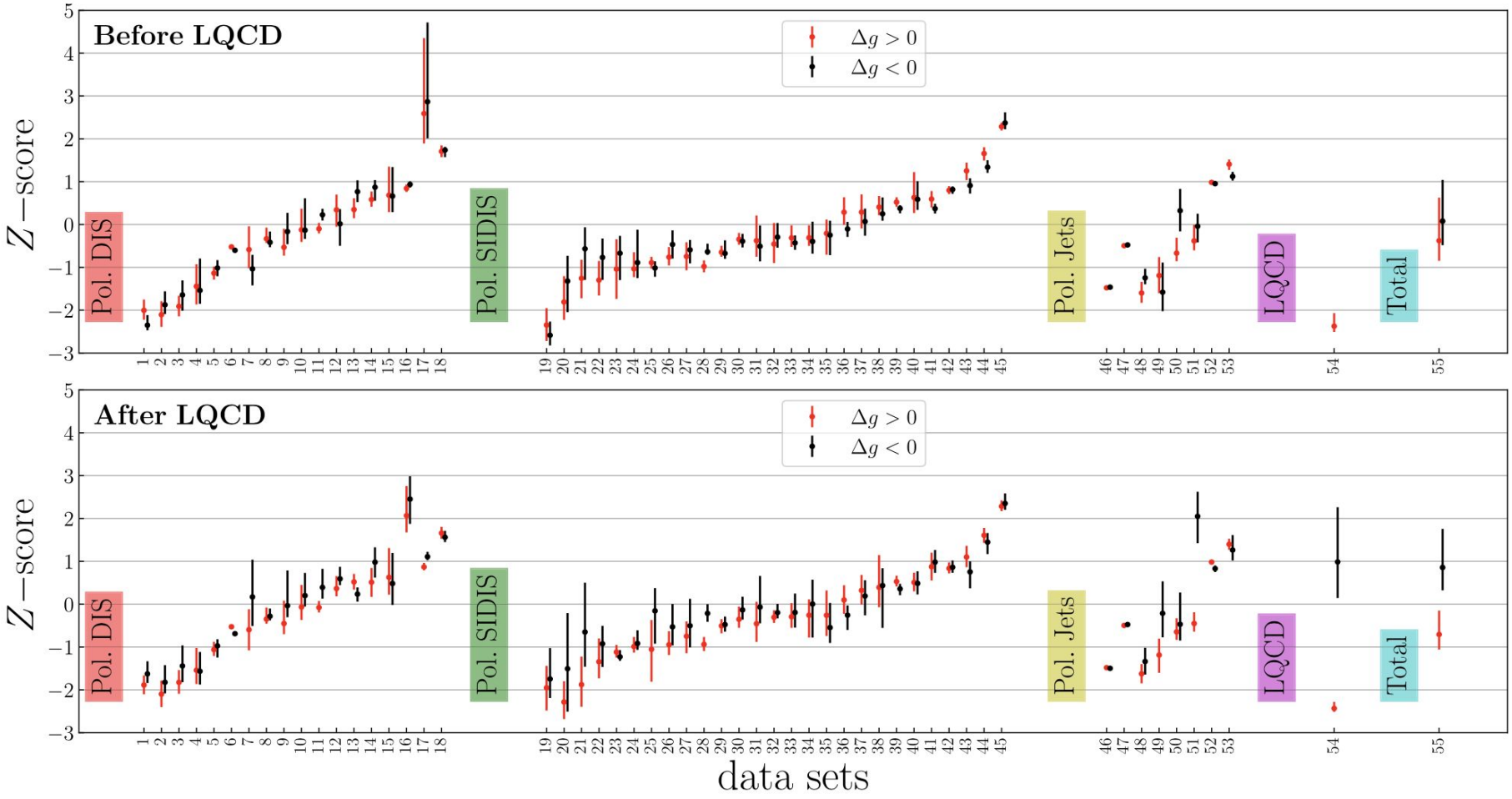


The PHENIX experiment at the Relativistic Heavy Ion Collider has measured the longitudinal double spin asymmetries, A_{LL}, for charged pions at midrapidity ($|\eta| < 0.35$) in longitudinally polarized p+p collisions at $\sqrt{s} = 510$ GeV. These measurements are sensitive to the gluon spin contribution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


Before LQCD
After LQCD
$0 < |\eta| < 0.5$
$0.5 < |\eta| < 1$
A_{LL}
$\Delta g > 0$
$\Delta g < 0$
STAR 2015
p_T (GeV)


Before LQCD
After LQCD
A_{LL} ($\Delta g > 0$)
A_{LL} ($\Delta g < 0$)
$0 < |\eta| < 0.5$
all
qq
qg
gg
STAR 2015
p_T (GeV)


Before LQCD
After LQCD
$\Delta g > 0$
$\Delta g < 0$
Z−score
Pol. DIS
Pol. SIDIS
Pol. Jets
LQCD
Total
data sets