Updates from JAM on gluon helicity PDF

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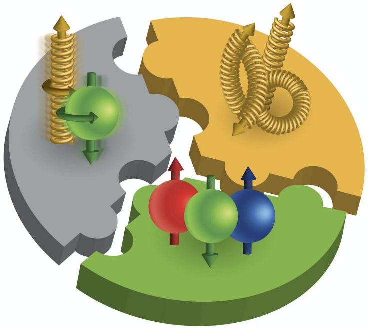
Zhou, Sato & Melnitchouk: 2201.02075
Whitehill, Zhou, Sato & Melnitchouk: 2210.12295
Karpie, Whitehill, Melnitchouk, Monahan, Orginos, Qiu, Richards, Sato & Zafeiropoulos: 2310.18179
Hunt-Smith, Cocuzza, Melnitchouk, Sato, Thomas & White: 2403.08117

Proton spin decomposition

What is the decomposition of the proton spin?

- current extraction of ΔΣ is around 0.3 (contribution from quarks)
- spin can be extracted from parton distribution functions (PDFs)
- orbital angular momentum can be extracted from GPDs

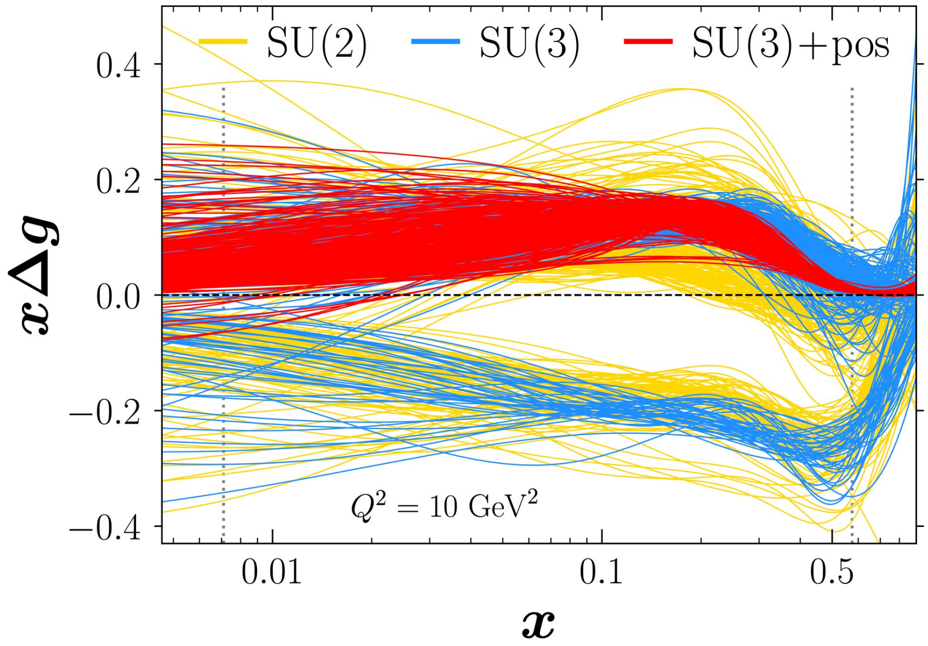


$$\frac{1}{2} = \underset{\underset{\mathbf{0.15}}{\downarrow}}{\boxed{\frac{1}{2}\Delta\Sigma}} + \underset{\underset{\mathbf{?}}{\downarrow}}{\boxed{\Delta G}} + L_{q+g}$$

Jaffe & Manohar: 1990

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

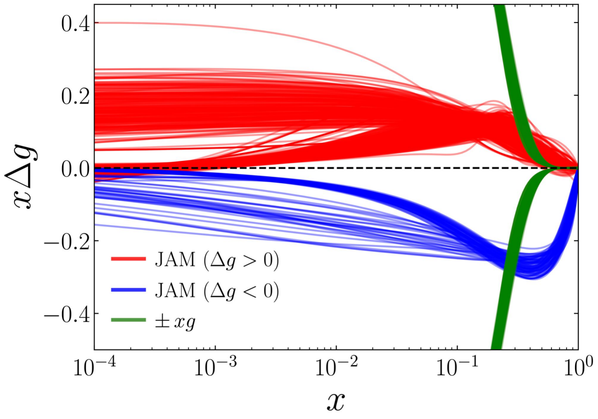
Y. Zhou, N. Sato, and W. Melnitchouk (Jefferson Lab Angular Momentum (JAM) Collaboration)
Phys. Rev. D **105**, 074022 – Published 25 April 2022

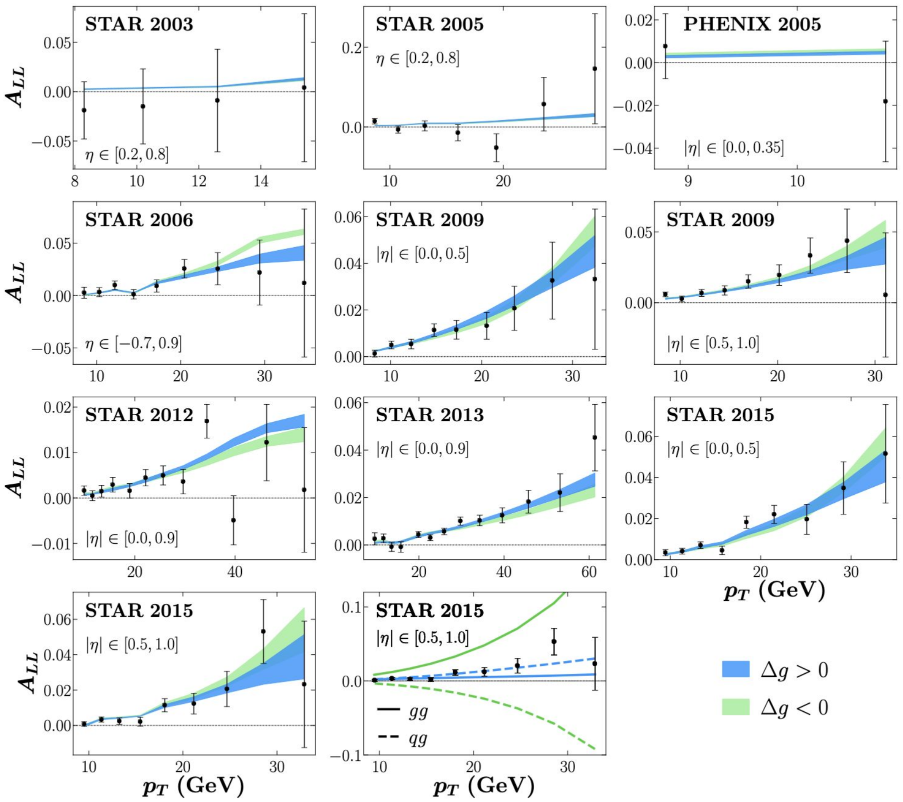


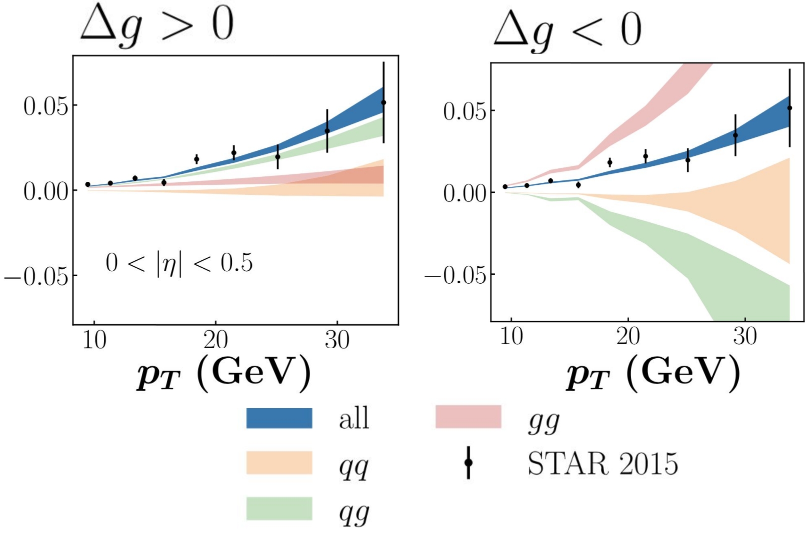
$$|\Delta g| \leq g$$

PDF positivity constraint

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







$|A_{LL}| < 1$ ✓

$$A_{LL}^{\rm jet}(p_T, y) \;\propto\; a_{gg}[\Delta g \otimes \Delta g] + \sum_q a_{qg}[\Delta q \otimes \Delta g]$$

$$+ \sum_{q,q'} a_{qq'}[\Delta q \otimes \Delta q'] \;+\; \mathcal{O}(\alpha_s),$$

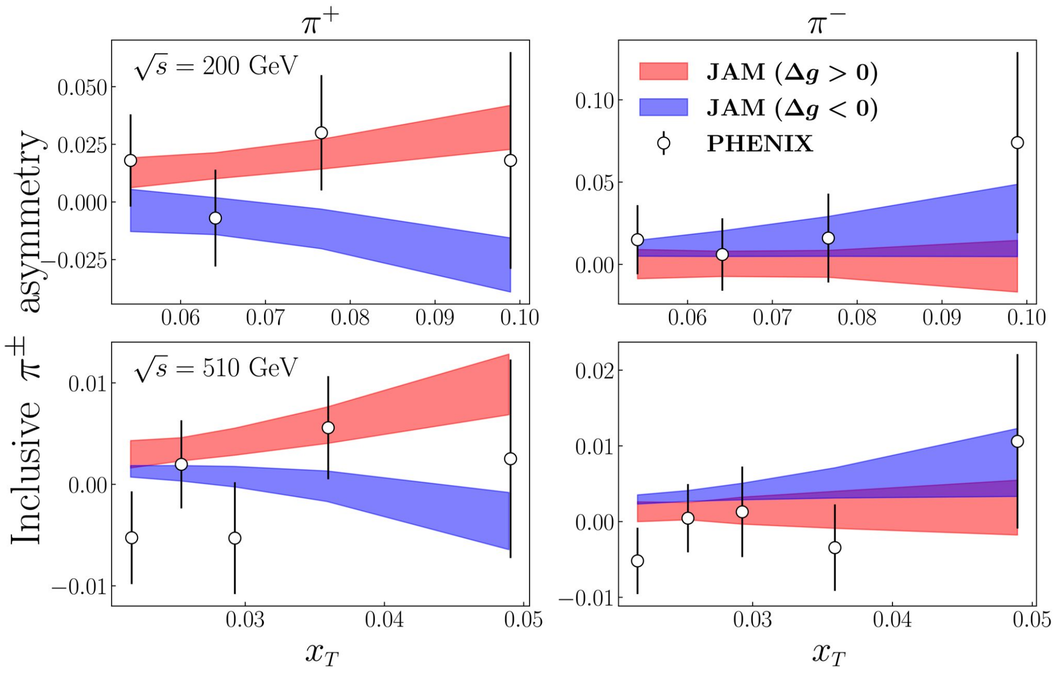
Δg enters quadratically, and different channels contribute with different signs and magnitudes

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

A. Adare *et al.* (PHENIX Collaboration)
Phys. Rev. D **91**, 032001 – Published 2 February 2015

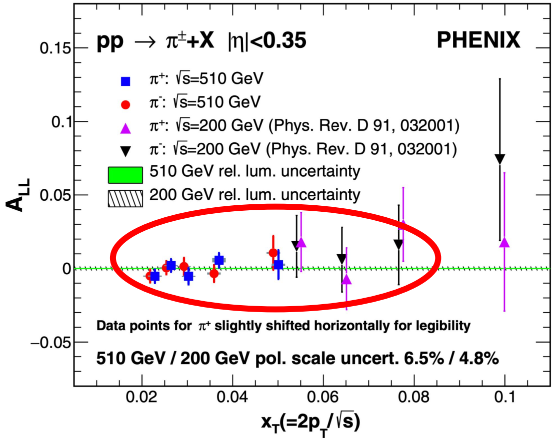
Measurement of charged pion double spin asymmetries at midrapidity in longitudinally polarized $p + p$ collisions at $\sqrt{s} = 510\ \text{GeV}$

U. Acharya *et al.* (PHENIX Collaboration)
Phys. Rev. D **102**, 032001 – Published 5 August 2020



- PHENIX collaboration stated that the ordering of π^+, π^0 and π^- asymmetries can help discriminate Δg solutions

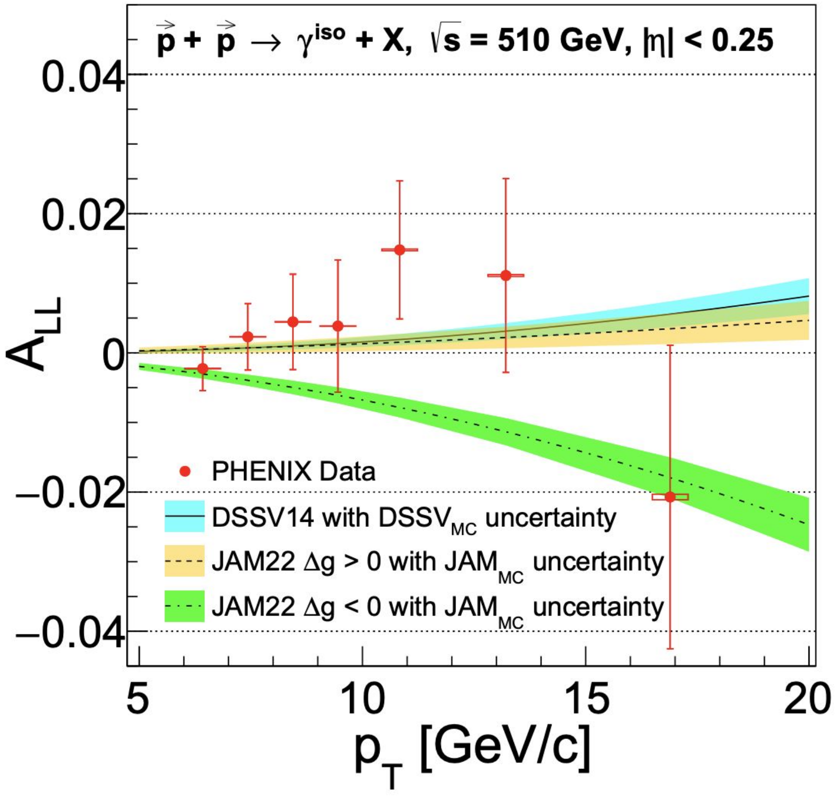
- The two solutions for Δg found by JAM describe the data equally well



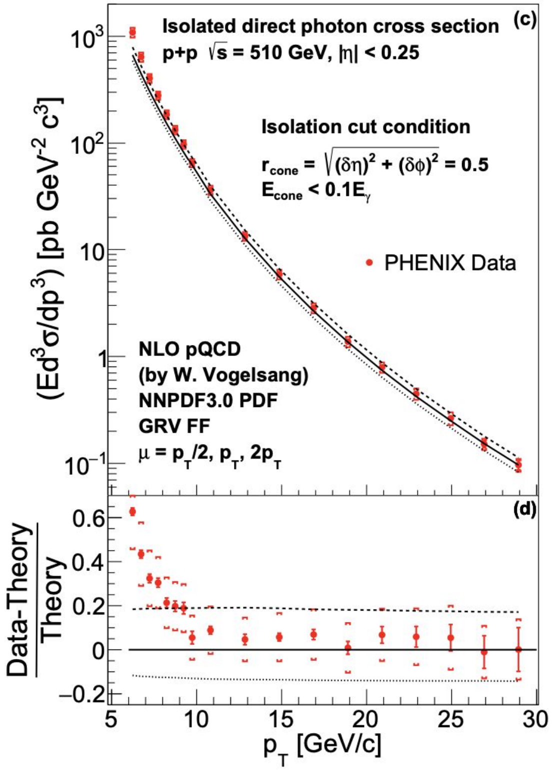
PHENIX: 1409.1907, 2004.02681

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

N. J. Abdulameer *et al.* (PHENIX Collaboration)
Phys. Rev. Lett. **130**, 251901 – Published 21 June 2023



PHENIX: 2202.08158



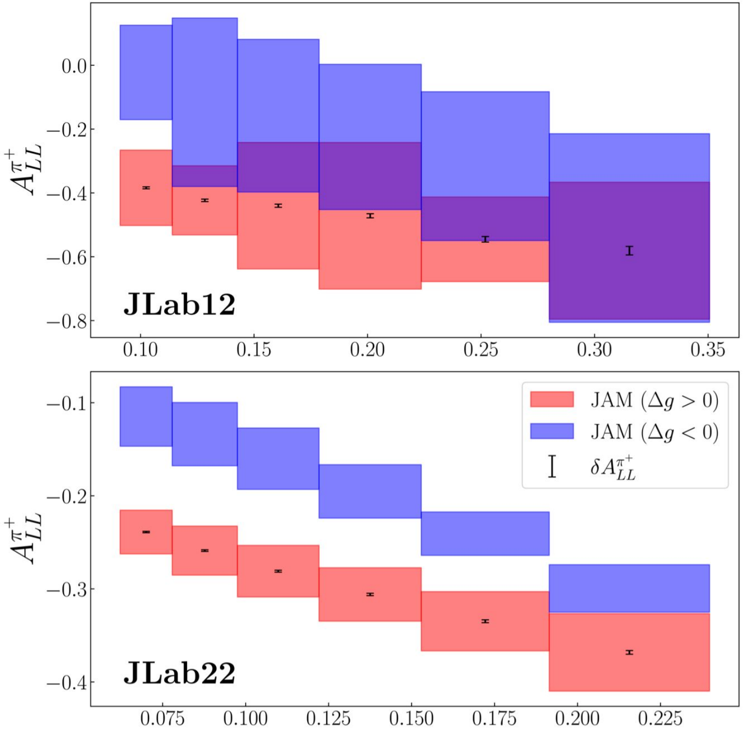
- PHENIX collaboration stated that negative Δg is disfavored by more than 2.8σ

- However, only last 3 high-p_T A_{LL} points are well described in pQCD (see denominator of A_{LL})

Accessing gluon polarization with high-P_T hadrons in SIDIS

R. M. Whitehill, Yiyu Zhou, N. Sato, and W. Melnitchouk (Jefferson Lab Angular Momentum (JAM) Collaboration)
Phys. Rev. D **107**, 034033 – Published 27 February 2023

SIDIS with large p_T: $e(\ell) + N(P) \rightarrow e(\ell') + h(P_h) + X$



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

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

Gluon helicity from global analysis of experimental data and lattice QCD Ioffe 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)

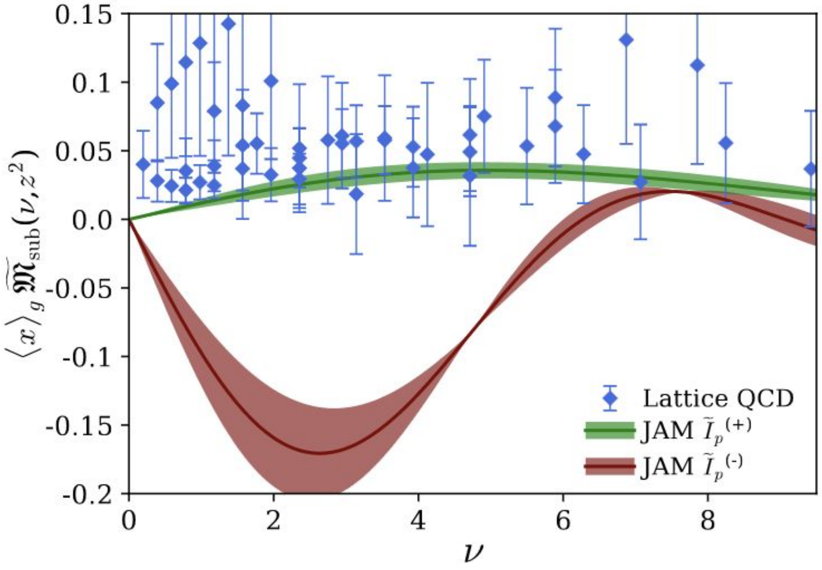
Phys. Rev. D **109**, 036031 – Published 27 February 2024

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

Colin Egerer, Bálint Joó, Joseph Karpie, Nikhil Karthik, Tanjib Khan, Christopher J. Monahan, Wayne Morris, Kostas Orginos, Anatoly Radyushkin, David G. Richards, Eloy Romero, Raza Sabbir Sufian, and Savvas Zafeiropoulos (HadStruc Collaboration)
Phys. Rev. D **106**, 094511 – Published 28 November 2022

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

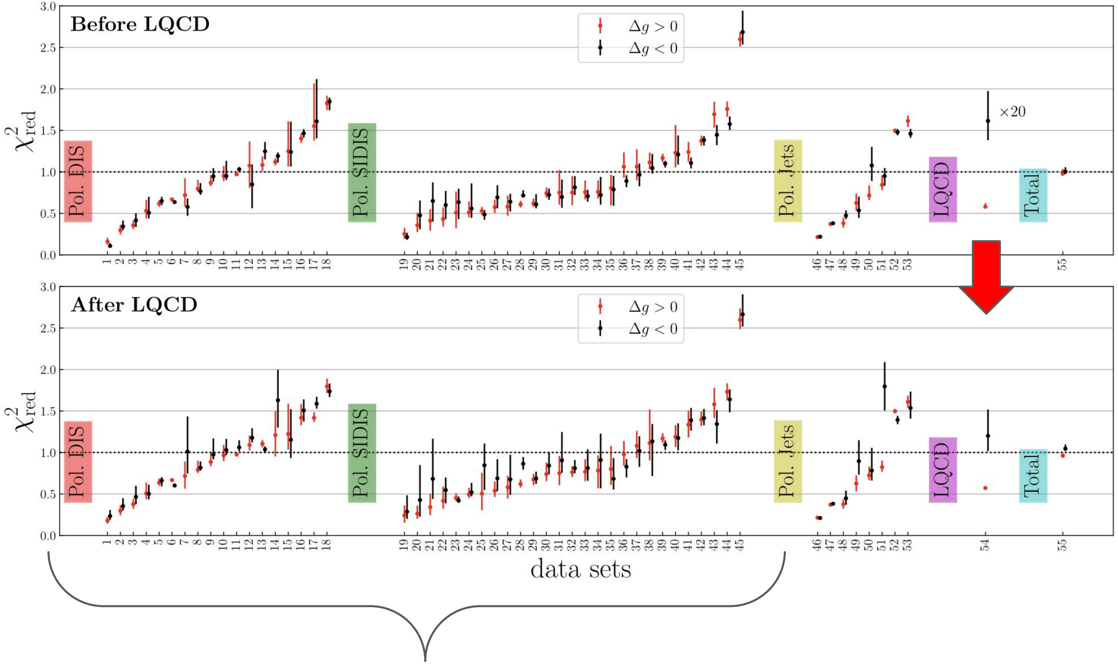
$$\widetilde{\mathfrak{M}}(\nu,z^2) = \frac{\widetilde{M}_{00}(p,z)/p_0p_3Z_L(z_3/a)}{M_{00}(p=0,z)/m^2}$$



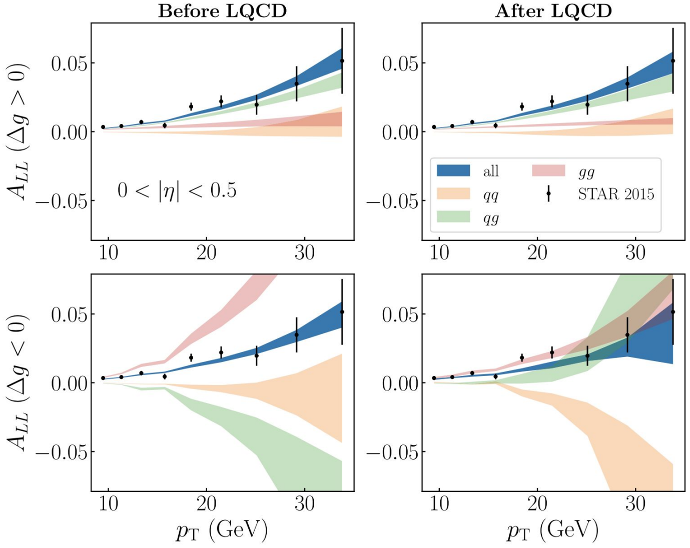
$$\begin{aligned}\widetilde{\mathfrak{M}}(\nu,z^2)\langle x_g\rangle_{\mu^2} = \boxed{\widetilde{\mathcal{I}}_p(\nu,\mu^2)} - \frac{\alpha_s N_c}{2\pi}\int_0^1 \mathrm{d}u\,\widetilde{\mathcal{I}}_p(u\nu,\mu^2)\Bigg\{\ln\left(z^2\mu^2\frac{e^{2\gamma_E}}{4}\right)\\ \left(\left[\frac{2u^2}{\bar{u}}+4u\bar{u}\right]_+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

$$\boxed{\mathcal{I}_{\Delta g}(\nu,\mu^2) = \int_0^1 \mathrm{d}x\, x\,\sin(x\nu)\Delta g(x,\mu^2)}$$

Egerer et al: 2207.08733

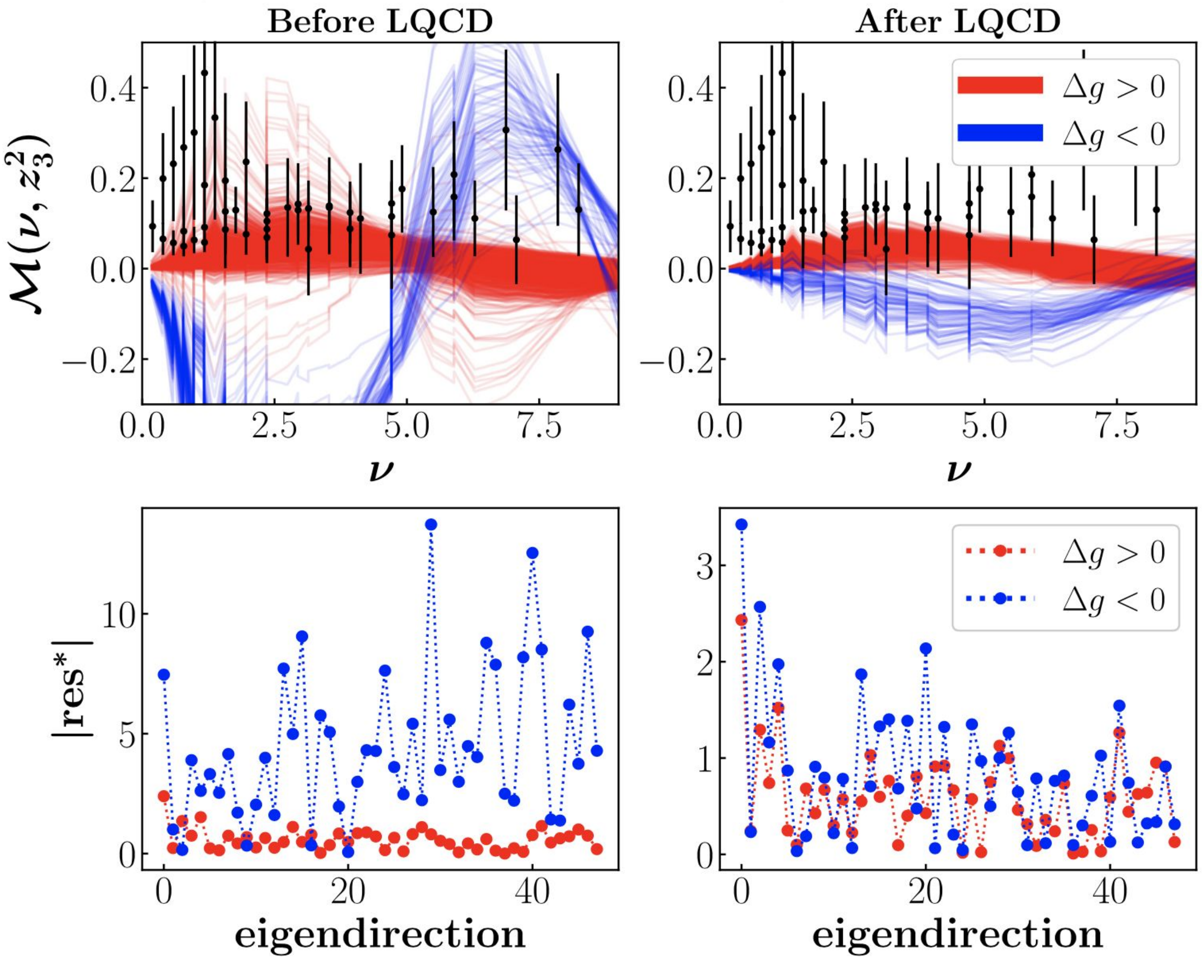


DIS $W^2 > 10$ GeV²



- Good description of global data after inclusion of LQCD for both solutions for Δg

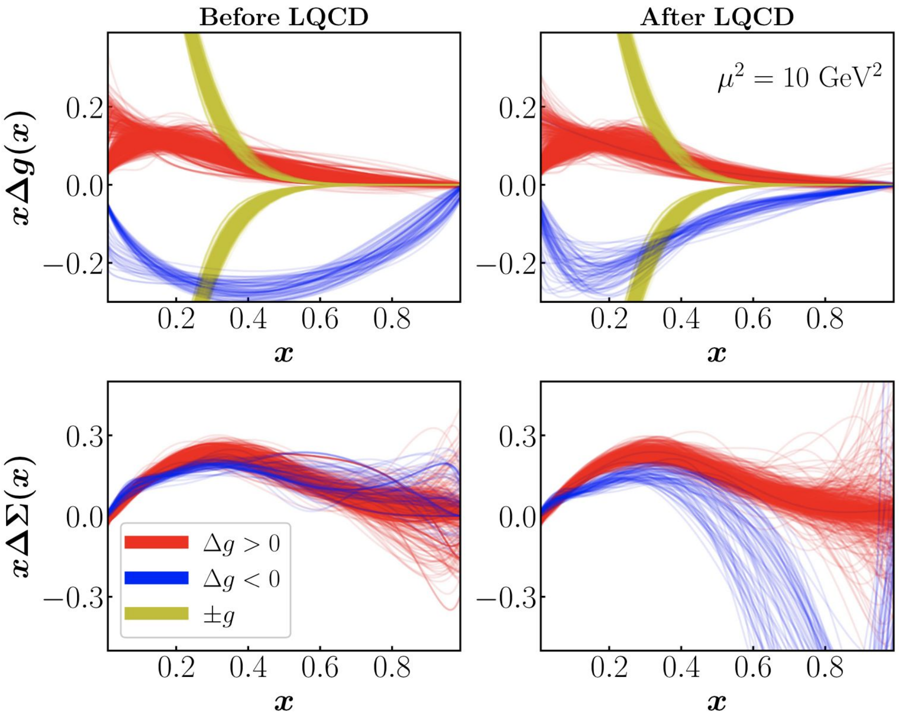
- On the basis of χ^2, LQCD cannot discriminate fully the sign of Δg



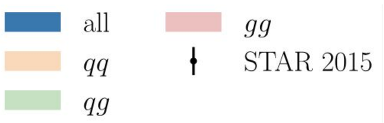
$$
\begin{aligned}
\chi^2 &= (\boldsymbol{d}-\boldsymbol{t})^T \boldsymbol{\Sigma}^{-1} (\boldsymbol{d}-\boldsymbol{t}) \\
&= (\boldsymbol{d}-\boldsymbol{t})^T \boldsymbol{U}\boldsymbol{D}^{-1}\boldsymbol{U}^T (\boldsymbol{d}-\boldsymbol{t}) \\
&= \sum_i \mathrm{res}_i^{*2}.
\end{aligned}
$$

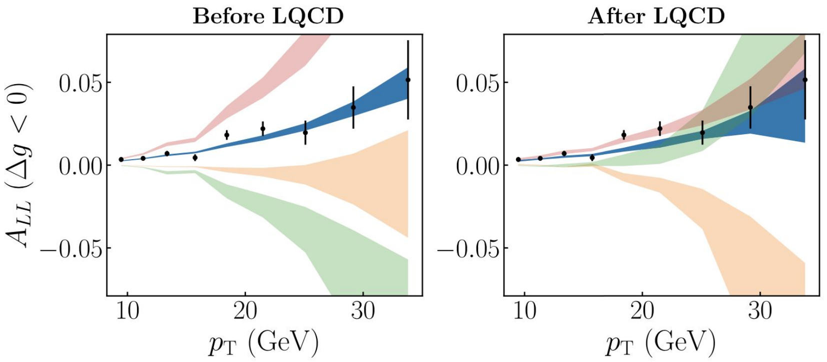
- Projections of residuals reveal strong correlations between LQCD data points

- The correlations prevent determination of sign of Δg



- LQCD distorts significantly the negative Δg at $x > 0.3$
- Note that both solutions violate PDF positivity bounds in $x > 0.3$
- Before inclusion of LQCD data, $\Delta\Sigma$ were stable for both solutions
- Inclusion of LQCD data forces the $\Delta\Sigma$ to become negative at $x > 0.4$ for the negative gluon solution





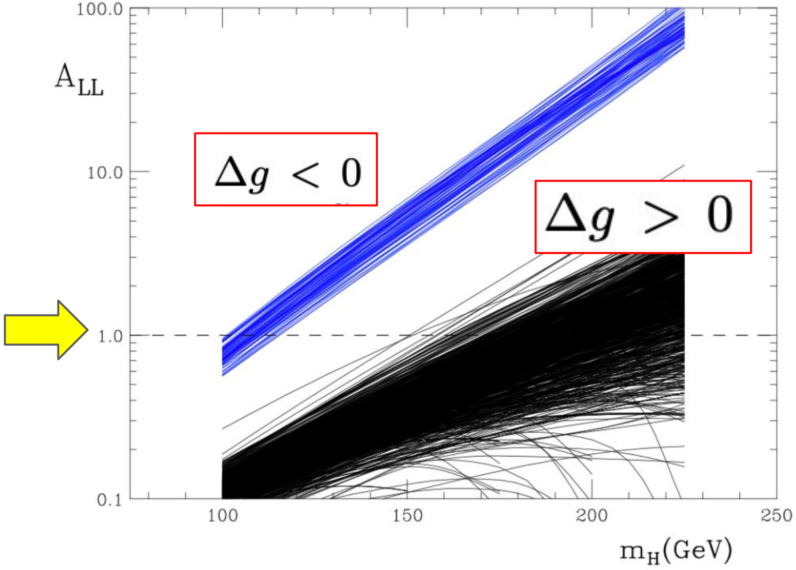
New Data-Driven Constraints on the Sign of Gluon Polarization in the Proton

N. T. Hunt-Smith, C. Cocuzza, W. Melnitchouk, N. Sato, A. W. Thomas, and M. J. White (JAM Collaboration-Spin PDF Analysis Group)

Phys. Rev. Lett. **133**, 161901 – Published 16 October 2024

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

Daniel de Florian, Stefano Forte, and Werner Vogelsang
Phys. Rev. D **109**, 074007 – Published 10 April 2024

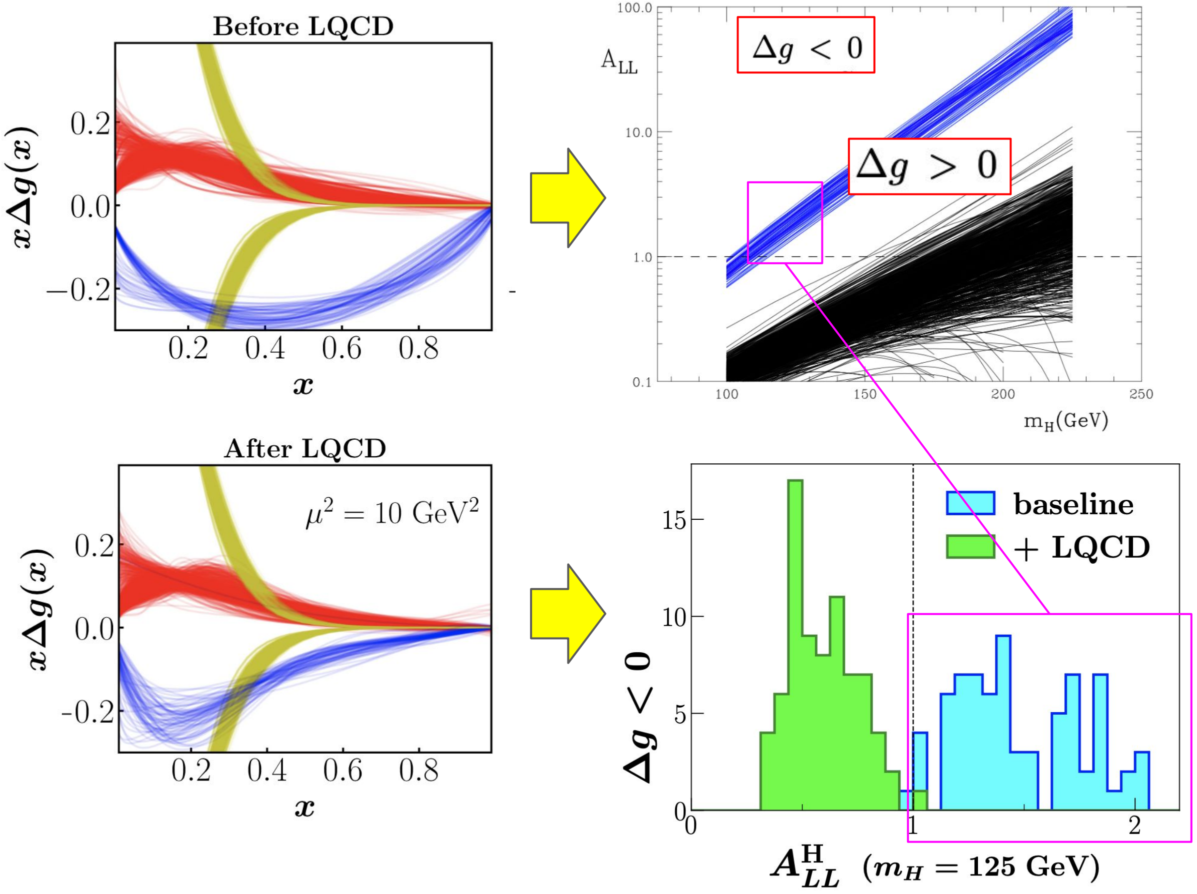


- Higgs A_{LL} is directly sensitive to Δg squared at LO
- Calculations of A_{LL} (Higgs) with negative Δg can lead to unphysical results **(using non-LQCD based analysis)**

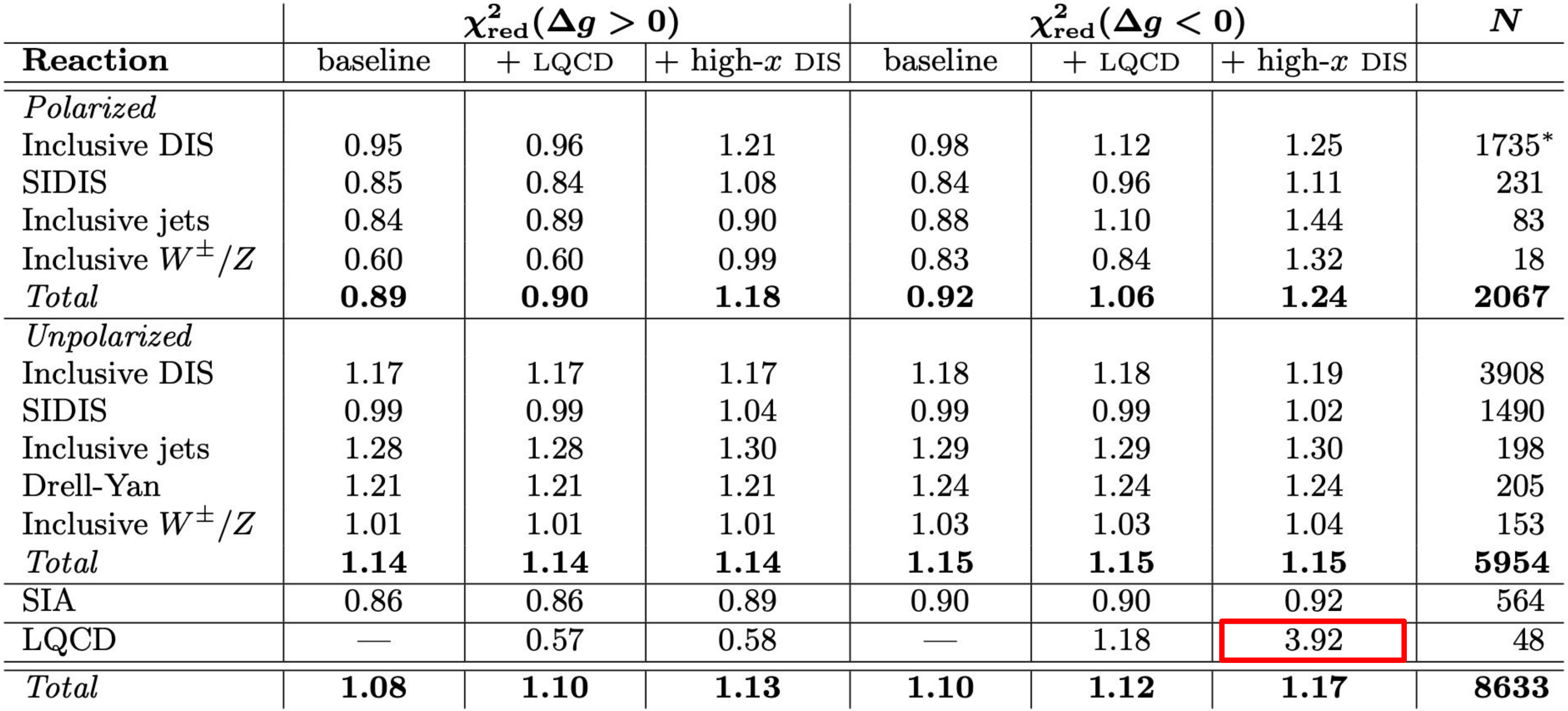
$$A^{\mathrm{H}}_{LL}(\tau) = \frac{[\Delta g \otimes \Delta g]}{[g \otimes g]} + \mathcal{O}(\alpha_s),$$

De Florian, Forte & Vogelsang: 2401.10814

Can Higgs A_{LL} fully discriminate negative Δg?

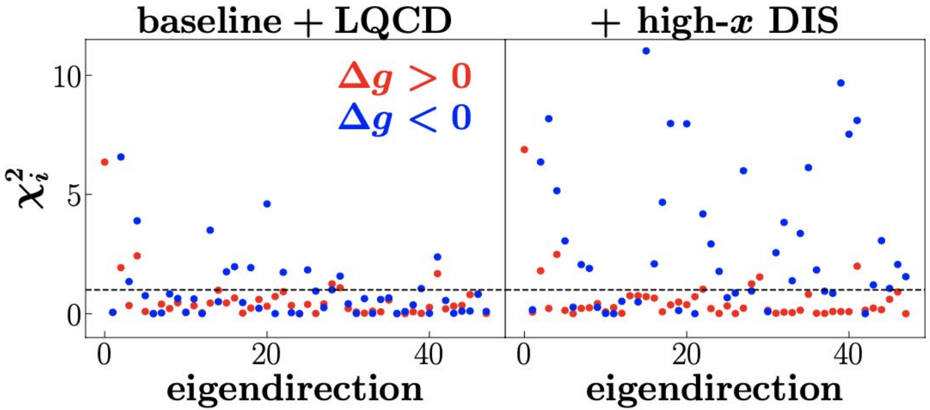


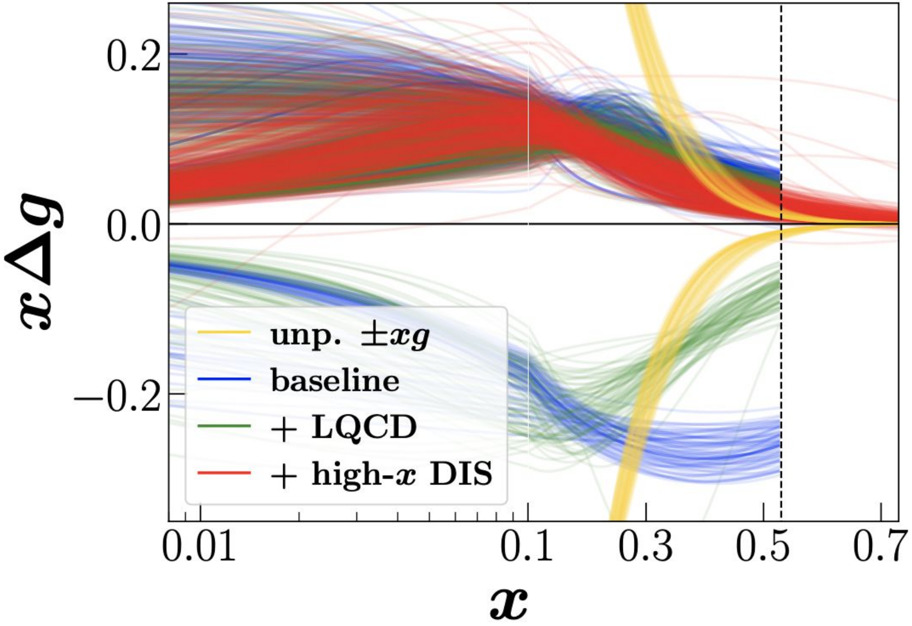
Negative Δg with LQCD constraints still admits a physical Higgs A_{LL}



	$\chi^2_{\rm red}(\Delta g > 0)$			$\chi^2_{\rm red}(\Delta g < 0)$			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 Δg solution

- Combined DSA from jet and high-x DIS with LQCD allows us to discriminate the sign of Δg for the first time!

Summary & outlook

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