Physics Opportunities at an Electron-Ion Collider (POETIC) XI
FIU, February 26, 2025

Gluon polarization in the proton from JAM global QCD analysis

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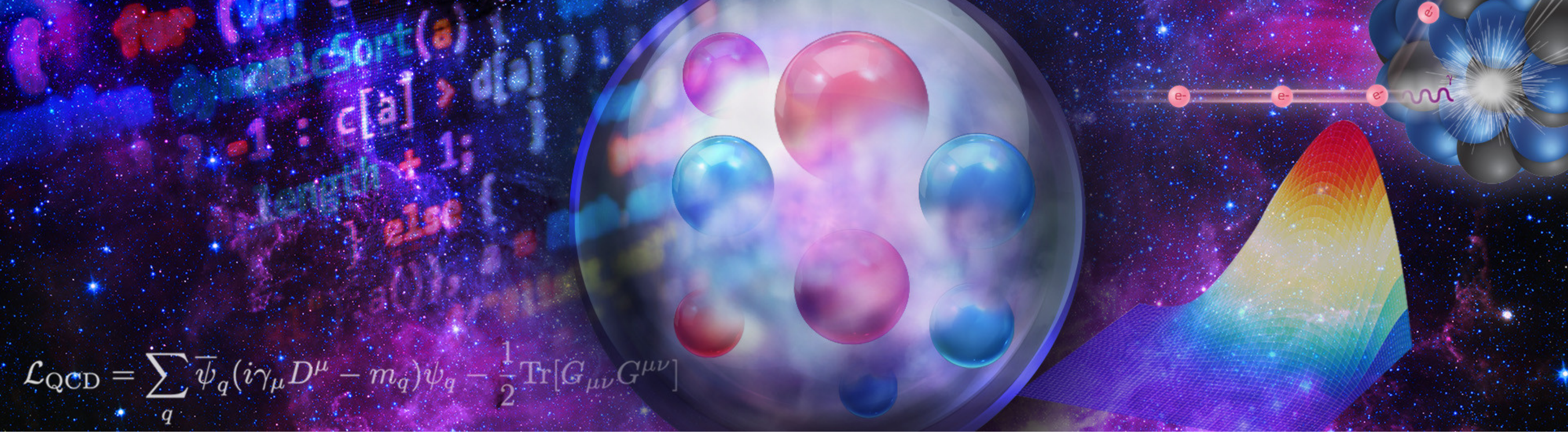
Jefferson Lab

http://www.jlab.org/jam



- Jefferson Lab Angular Momentum (JAM) collaboration — an enterprise involving theorists, experimentalists, and computer scientists using QCD to study internal structure of hadrons

  → analyze data using modern Monte Carlo techniques & uncertainty quantification to simultaneously extract various quantum correlation functions
  - — parton distribution functions (PDFs)
  - — fragmentation functions (FFs)
  - — transverse momentum dependent (TMD) distributions
  - — generalized parton distributions (GPDs)

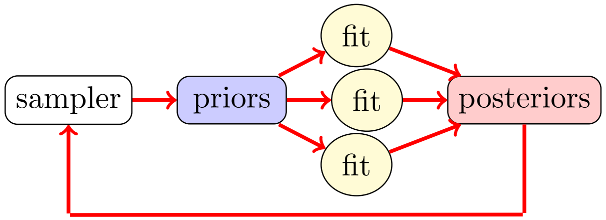
  Theory / Computer Science / Experiment — JAM

  http://www.jlab.org/jam

  → inclusion of lattice data (where necessary) and ML algorithms to potentially expand reach and efficacy of JAM analyses and understanding of hadron structure in QCD

JAM global QCD analysis

- Theoretical framework
  - — collinear / TMD factorization
  - — iterative Monte Carlo
  - — data resampling
  - — Bayesian sampling of parameter space



- Choice of parametrization, $e.g.$, for PDFs

$$f(x) = N\, x^{\alpha}(1-x)^{\beta}\, P(x)$$

polynomial, neural net, ...

$\longrightarrow$ iterate until convergence (posteriors = priors)

- Extraction of QCFs is challenging because typically there exist multiple solutions — "inverse problem"

$\longrightarrow$ QCFs are not directly measured, but inferred from observables involving convolutions with other functions

$\longrightarrow$ reliable uncertainty quantification is essential

JAM analysis groups

Unpolarized PDFs (and FFs)

Global QCD analysis and dark photons
N. T. Hunt-Smith, W. Melnitchouk, N. Sato, A. W. Thomas, X. G. Wang, M. J. White
JHEP **09**, 096 (2023), *arXiv:2302.11126 [hep-ph]*

Bayesian Monte Carlo extraction of the sea asymmetry with SeaQuest and STAR data
C. Cocuzza, W. Melntichouk, A. Metz, N. Sato
Phys. Rev. D **104**, 074031 (2021), *arXiv:2109.00677 [hep-ph]*

Simultaneous Monte Carlo analysis of parton densities and fragmentation functions
E. Moffat, W. Melnitchouk, T. C. Rogers, N. Sato
Phys. Rev. D **104**, 016015 (2021), *arXiv:2101.04664 [hep-ph]*

Isovector EMC effect from global QCD analysis with MARATHON data
C. Cocuzza, C. E. Keppel, H. Liu, W. Melnitchouk, A. Metz, N. Sato, A. W. Thomas
Phys. Rev. Lett. **127**, 242001 (2021), *arXiv:2104.06946 [hep-ph]*

Strange quark suppression from a simultaneous Monte Carlo analysis of parton distributions an
N. Sato, C. Andres, J.J. Ethier, W. Melnitchouk
Phys. Rev. D **101**, 074020 (2020), *arXiv:1905.03788 [hep-ph]*

First Monte Carlo analysis of fragmentation functions from e^+e^- annihilation
N. Sato, J. J. Ethier, M. Hirai, S. Kumano, W. Melnitchouk
Phys. Rev. D **94**, 114004 (2016), *arXiv:1609.00899 [hep-ph]*

Helicity PDFs

On the resolution of the sign of gluon polarization in the proton
N. T. Hunt-Smith, C. Cocuzza, W. Melnitchouk, N. Sato, A. W. Thomas, M. J. White
arXiv:2403.08117 [hep-ph]

Accessing gluon polarization with high-PT hadrons in SIDIS
R. M. Whitehill, Y. Zhou, N. Sato, W. Melnitchouk
Phys. Rev. D **107**, 034033 (2023), *arXiv:2210.12295 [hep-ph]*

Polarized antimatter in the proton from global QCD analysis
C. Cocuzza, W. Melnitchouk, A. Metz, N. Sato
Phys. Rev. D **106**, L031502 (2022), *arXiv:2202.03372 [hep-ph]*

How well do we know the gluon polarization in the proton?
Y. Zhou, N. Sato, W. Melnitchouk
Phys. Rev. D **105**, 074022 (2022), *arXiv:2201.02075 [hep-ph]*

First simultaneous extraction of spin-dependent parton distributions and fragmentation functio
J. J. Ethier, N. Sato, W. Melnitchouk
Phys. Rev. Lett. **119**, 132001 (2017), *arXiv:1705.05889 [hep-ph]*

Iterative Monte Carlo analysis of spin-dependent parton distributions
N. Sato, W. Melnitchouk, S. E. Kuhn, J. J. Ethier, A. Accardi
Phys. Rev. D **93**, 074005 (2016), *arXiv:1601.07782 [hep-ph]*

Small-x PDFs

Global analysis of polarized DIS and SIDIS data with improved small-x helicity evolution
D. Adamiak, N. Baldonado, Y. V. Kovchegov, W. Melnitchouk, D. Pitonyak, N. Sato, M. D. Sievert, A. Tarasov, Y. Tawabutr
Phys. Rev. D **108**, 114007 (2023), *arXiv:2308.07461 [hep-ph]*

First analysis of world polarized DIS data with small-x helicity evolution
D. Adamiak, Y. V. Kovchegov, W. Melnitchouk, D. Pitonyak, N. Sato, M. D. Sievert
Phys. Rev. D **104**, L031501 (2021), *arXiv:2102.06159 [hep-ph]*

JAM analysis groups

Transversity PDFs

First simultaneous global QCD analysis of dihadron fragmentation functions and transversity parton distribution functions
C. Cocuzza, A. Metz, D. Pitonyak, A. Prokudin, N. Sato, R. Seidl
Phys. Rev. D **109**, 034024 (2024), *arXiv:2308.14857 [hep-ph]*

Transversity distributions and tensor charges of the nucleon
C. Cocuzza, A. Metz, D. Pitonyak, A. Prokudin, N. Sato, R. Seidl
Phys. Rev. Lett. **132**, 091901 (2024), *arXiv:2306.12998 [hep-ph]*

First Monte Carlo global analysis of nucleon transversity with lattice QCD constraints
H.-W. Lin, W. Melnitchouk, A. Prokudin, N. Sato, H. Shows
Phys. Rev. Lett. **120**, 152502 (2018), *arXiv:1710.09858 [hep-ph]*

Pion distributions

Tomography of pions and protons via transverse momentum dependent distributions
P. C. Barry, L. Gamberg, W. Melnitchouk, E. Moffat, D. Pitonyak, A. Prokudin, N. Sato
Phys. Rev. D **108**, L091504 (2023), *arXiv:2302.01192 [hep-ph]*

Towards the three-dimensional parton structure of the pion: Integrating transverse momentum d
N. Y. Cao, P. C. Barry, N. Sato, W. Melnitchouk
Phys. Rev. D **103**, 114014 (2021), *arXiv:2103.02159 [hep-ph]*

Complementarity of experimental and lattice QCD data on pion parton distributions
P. C. Barry, C. Egerer, J. Karpie, W. Melnitchouk, C. Monahan, K. Orginos, Jian-Wei Qiu, D. Richards, N. Sato, R. S. Sufian, S. Zafeiropoulos
Phys. Rev. D **105**, 114051 (2022), *arXiv:2204.00543 [hep-ph]*

Global QCD analysis of pion parton distributions with threshold resummation
P. C. Barry, C.-R. Ji, N. Sato, W. Melnitchouk
Phys. Rev. Lett. **127**, 232001 (2021), *arXiv:2108.05822 [hep-ph]*

First Monte Carlo global QCD analysis of pion parton distributions
P. C. Barry, N. Sato, W. Melnitchouk, C.-R. Ji
Phys. Rev. Lett. **121**, 152001 (2018), *arXiv:1804.01965 [hep-ph]*

TMDs

Updated QCD global analysis of single transverse-spin asymmetries: Extracting $\tilde{H}$*, and lattice QCD*
L. Gamberg, M. Malda, J. A. Miller, D. Pitonyak, A. Prokudin, N. Sato
Phys. Rev. D **106**, 034014 (2022), *arXiv:2205.00999 [hep-ph]*

Origin of single transverse-spin asymmetries in high-energy collisions
J. Cammarota, L. Gamberg, Z.-B. Kang, J.A. Miller, D. Pitonyak, A. Prokudin, T.C. Rogers, N. Sa
Phys. Rev. D **102**, 054002 (2020), *arXiv:2002.08384 [hep-ph]*

New tool for kinematic regime estimation in semi-inclusive deep-inelastic scattering
M. Boglione, M. Diefenthaler, S. Dolan, L. Gamberg, W. Melnitchouk, D. Pitonyak, A. Prokudin, N. Sato, Z. Scalyer
JHEP **04** (2022) 084, *arXiv:2201.12197 [hep-ph]*

GPDs

Shedding light on shadow generalized parton distributions
E. Moffat, A. Freese, I. Cloët, T. Donohoe, L. Gamberg, W. Melnitchouk, A. Metz, A. Prokudin, N. Sato
Phys. Rev. D **108**, 036027 (2023), *arXiv:2303.12006 [hep-ph]*

Where does the spin of the proton come from?

- Proton spin crisis (1988) — total spin $\Delta\Sigma$ carried by quarks and antiquarks consistent with zero!

- Global experimental program in polarized lepton-nucleon & pp scattering
  $\longrightarrow$ more refined picture, in which $\Delta\Sigma \sim 0.3$, and evidence that spin carried by gluons ΔG is positive

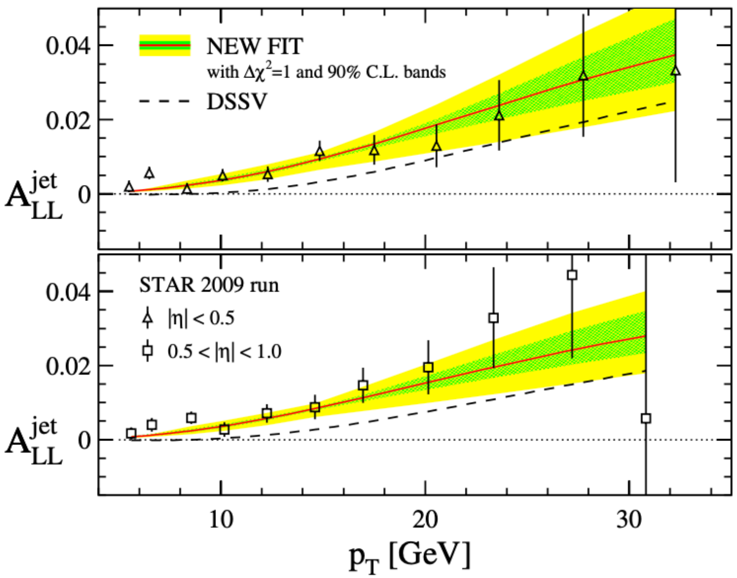
$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L$$

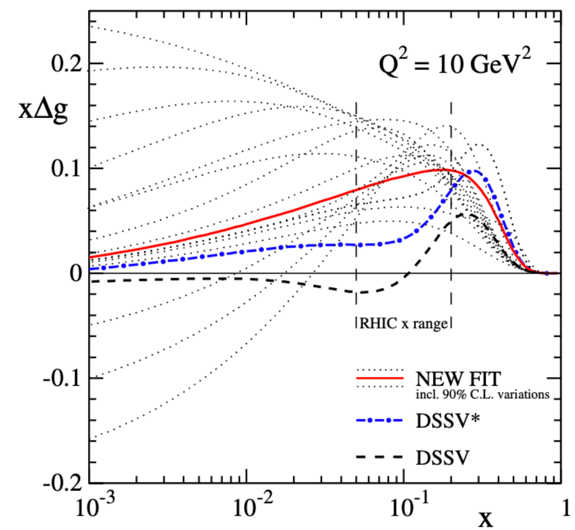
quark helicity (~ 30%) → $\Delta\Sigma$; gluon helicity (positive?) → ΔG; orbital angular momentum (largely unknown) → L

- Quest to unravel spin decomposition continues!
  $\longrightarrow$ address fundamental questions about origin of spin, gauge and scheme dependence of individual contributions

Where does the spin of the proton come from?

- First quantitative indication for nonzero gluon helicity from DSSV global QCD analysis (2014), using RHIC jet data in addition to DIS & SIDIS





de Florian, Sassot, Stratmann, Vogelsang
PRL ***113****, 012001 (2014)*

- Double longitudinal polarization asymmetry for jet production is, to lowest order in α_S, sensitive to polarized gluon PDF

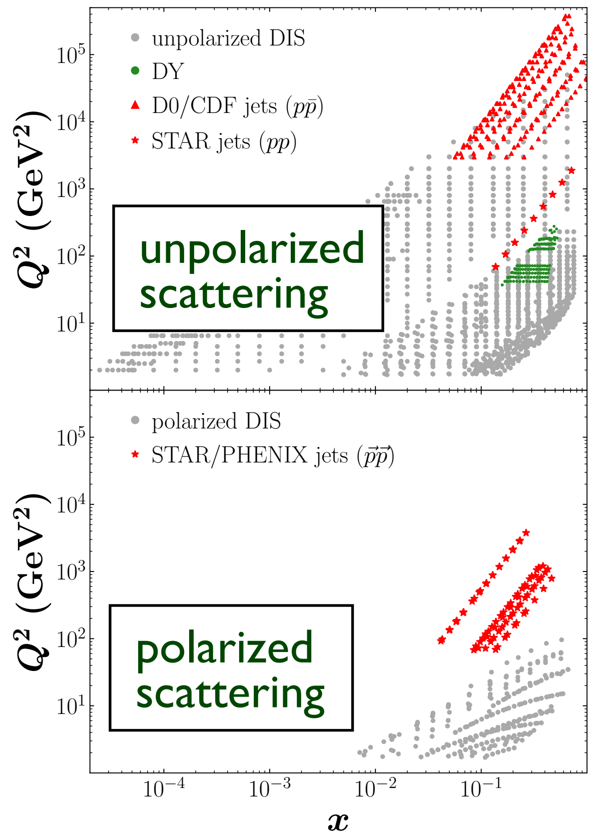
$$A_{LL}^{\rm jet} \sim a_{gg}[\Delta g \otimes \Delta g] + \sum_q a_{qg}[\Delta q \otimes \Delta g] + \sum_{q,q'} a_{qq'}[\Delta q \otimes \Delta q'] + \mathcal{O}(\alpha_s)$$

quadratic in Δg

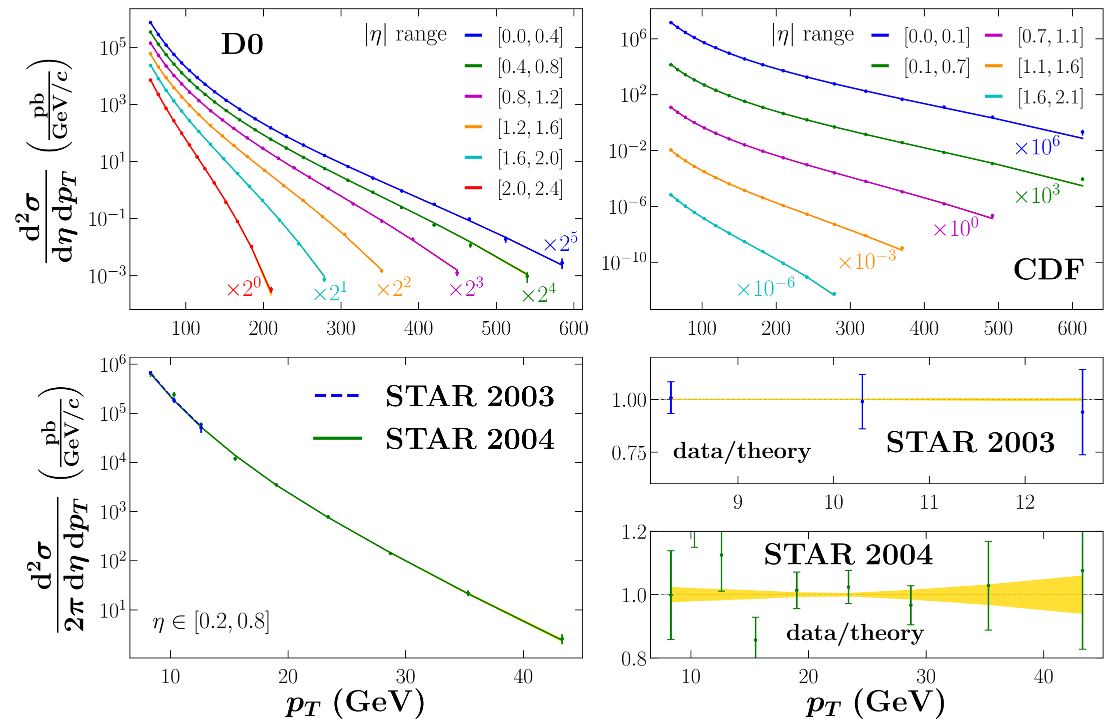
JAM simultaneous global analysis

- JAM collaboration re-examined global data in simultaneous analysis (including jets in polarized *and* unpolarized collisions from RHIC / FNAL), to understand role of theoretical assumptions on extracted PDFs

kinematics



unpolarized jet cross sections

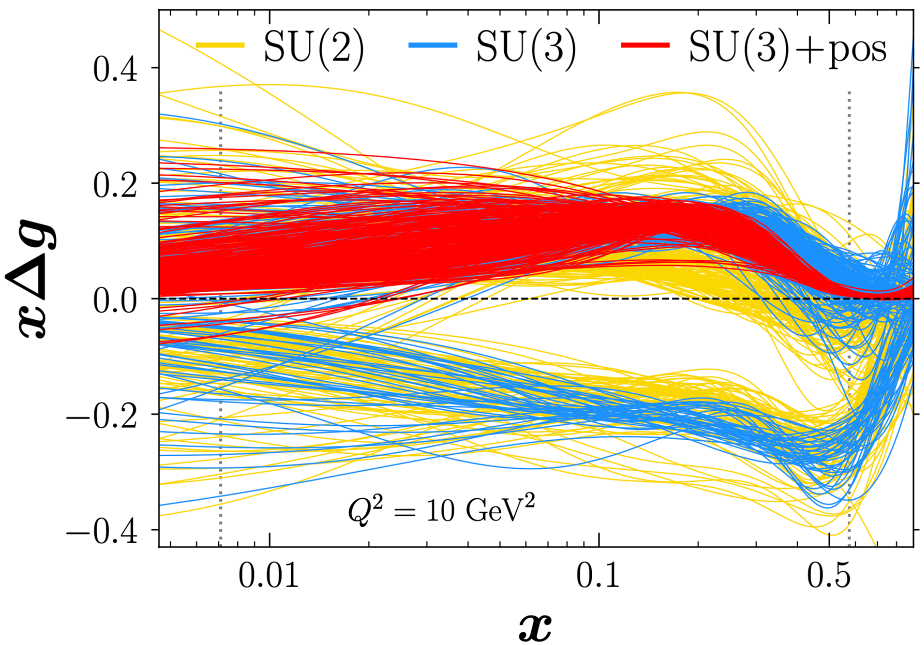


Zhou, Sato, WM, PRD ***105***, *074022 (2022)*

⟶ good description of unpolarized jet data over large p_T range for $p_T \gtrsim 8$ GeV

JAM simultaneous global analysis

- Extracted helicity PDFs depend on theoretical assumptions, such as SU(3) flavor symmetry and PDF positivity



*Zhou, Sato, WM, PRD **105**, 074022 (2022)*

SU(2):

$$\int_0^1 dx\,[\Delta u^+ - \Delta d^+](x, Q^2) = g_A$$ ✓

SU(3):

$$\int_0^1 dx\,[\Delta u^+ + \Delta d^+ - 2\Delta s^+](x, Q^2) = a_8$$?

PDF positivity:

$$|\Delta f_i(x, Q^2)| \leq f_i(x, Q^2)$$ ✗

JAM simultaneous global analysis

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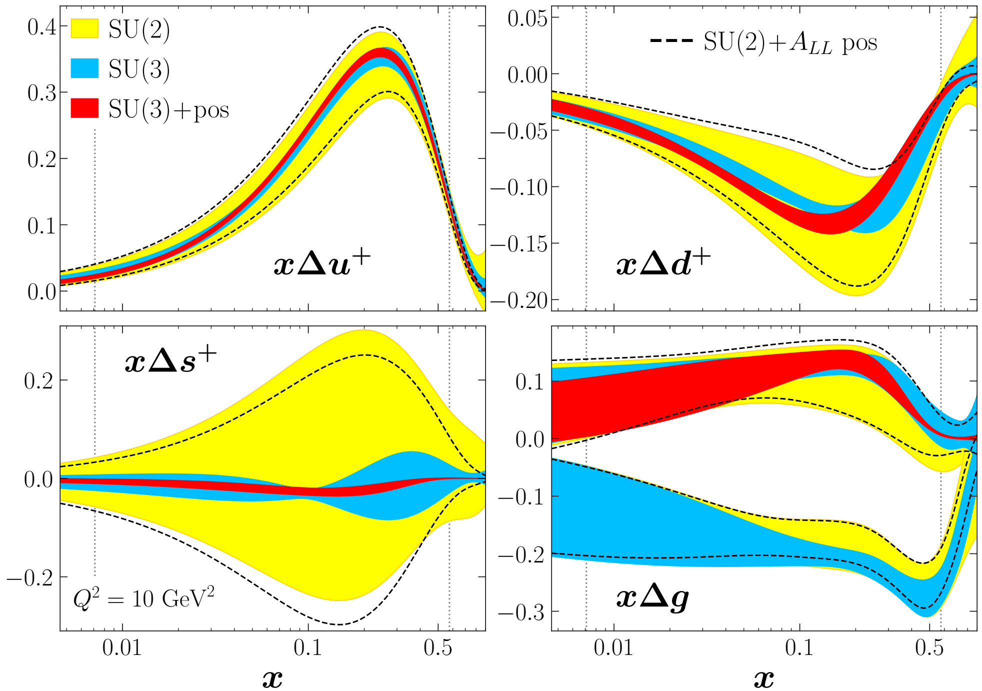

Zhou, Sato, WM, PRD ***105****, 074022 (2022)*

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PDF positivity:

$$|\Delta f_i(x,Q^2)| \le f_i(x,Q^2)$$ ×

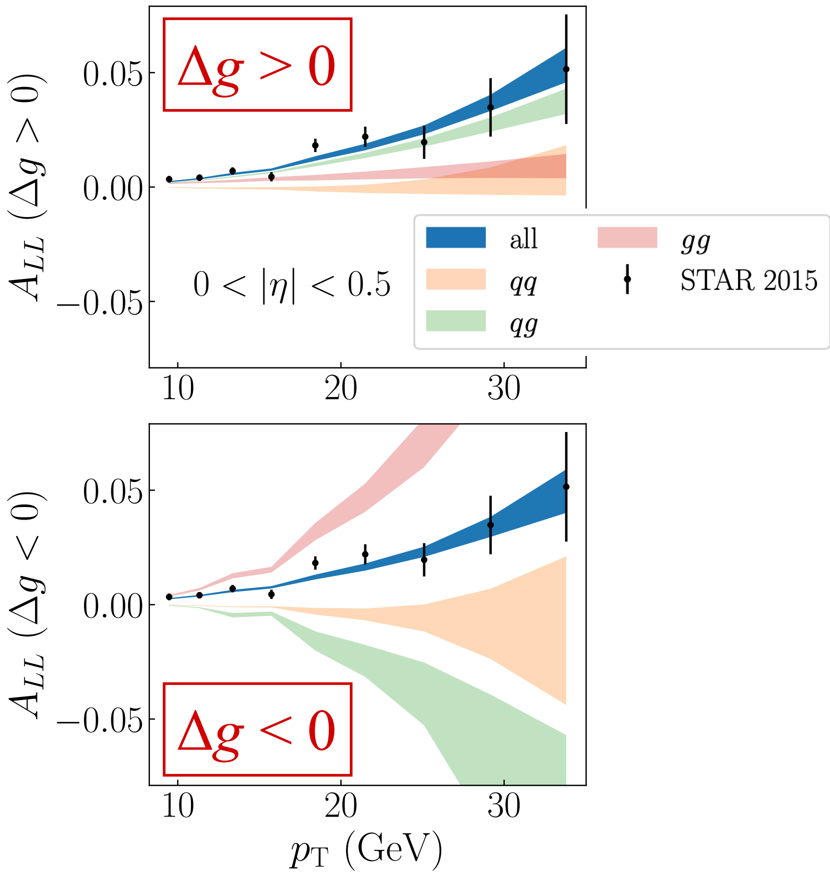
⟶ large uncertainties on Δs, without assuming SU(3) flavor symmetry

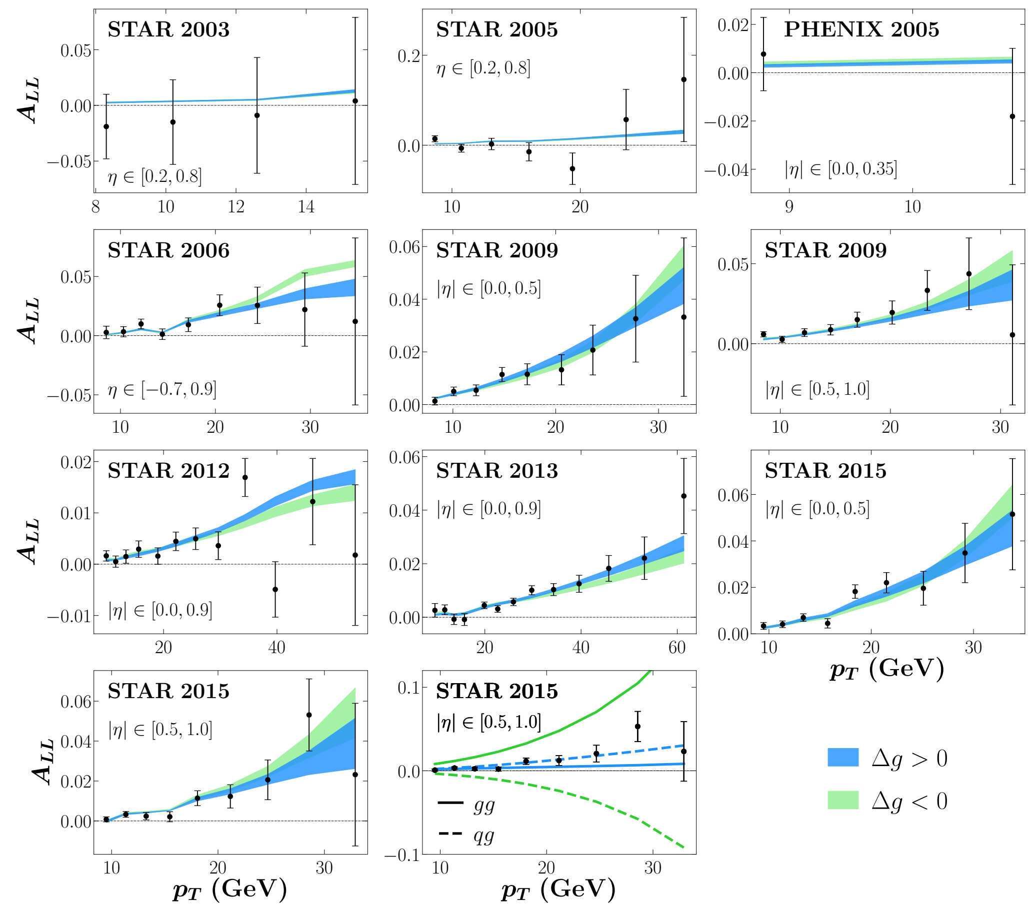
⟶ positive and negative Δg solutions possible, without assuming positivity of (unpolarized) PDFs

… not a necessary constraint beyond leading order in α_s

JAM simultaneous global analysis

Double longitudinal polarization asymmetry for inclusive jet production



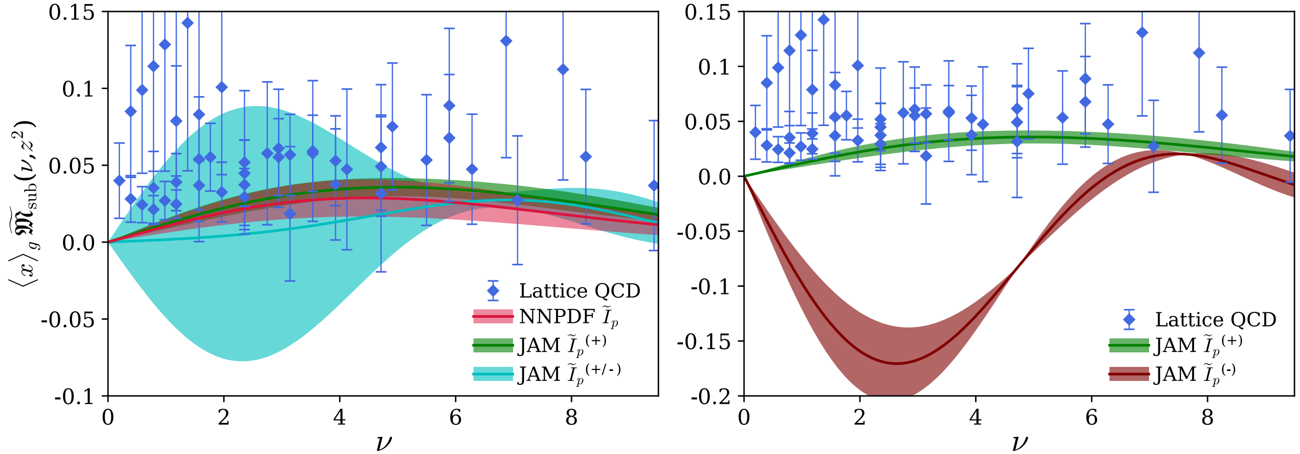


→ significant cancellations between (positive) $\Delta g \otimes \Delta g$ and (negative) $\Delta q \otimes \Delta g$ terms

→ positive and negative Δg solutions describe jet data equally well

JAM + lattice QCD data

- Lattice QCD calculations of Ioffe-time pseudo-distributions are sensitive to gluon polarization



Egerer et al. [HadStruc]
*PRD **106**, 094511 (2022)*

⟶ lattice matrix element $\widetilde{\mathfrak{M}}(\nu, z^2)$ depends on Ioffe-time distribution

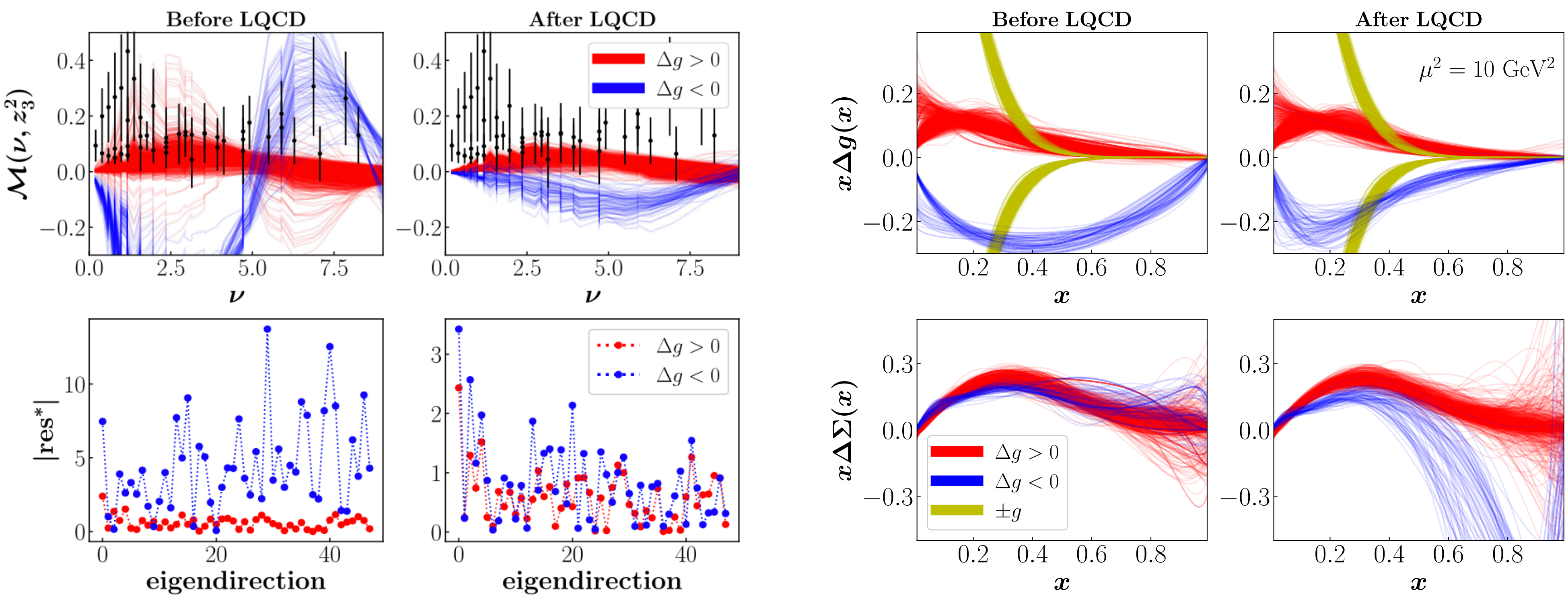
$$\widetilde{\mathcal{I}}_p(\nu) = \frac{i}{2} \int_{-1}^{1} \mathrm{d}x \, e^{-ix\nu} \, x \, \Delta g(x) \, .$$

⟶ appears to favors positive gluon polarization, but …
… need to fit experimental + lattice data simultaneously

JAM + lattice QCD data

- Lattice QCD calculations of Ioffe-time pseudo-distributions are sensitive to gluon polarization

*Karpie et al., PRD **109**, 036031 (2024)*



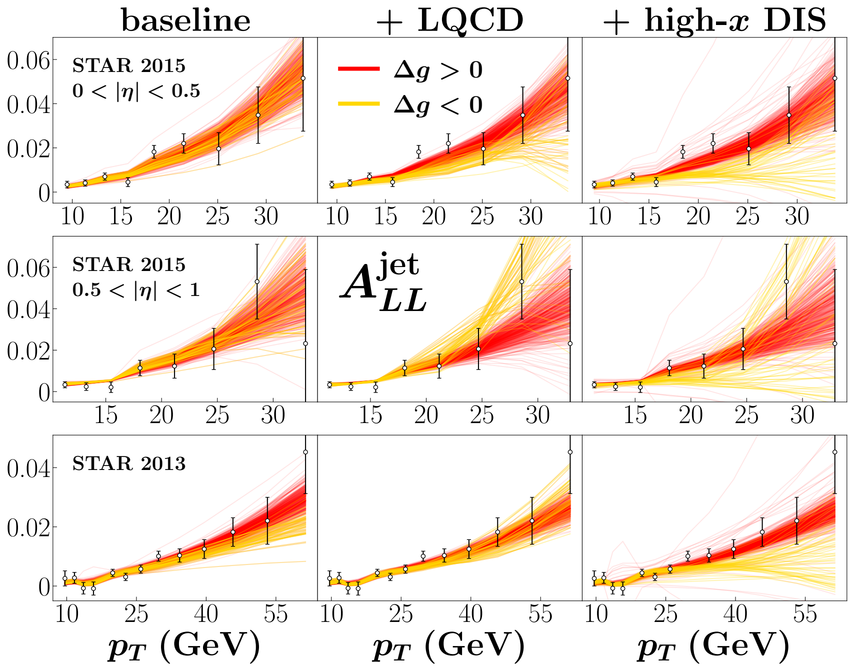
→ good description of data after inclusion of LQCD for both Δg solutions

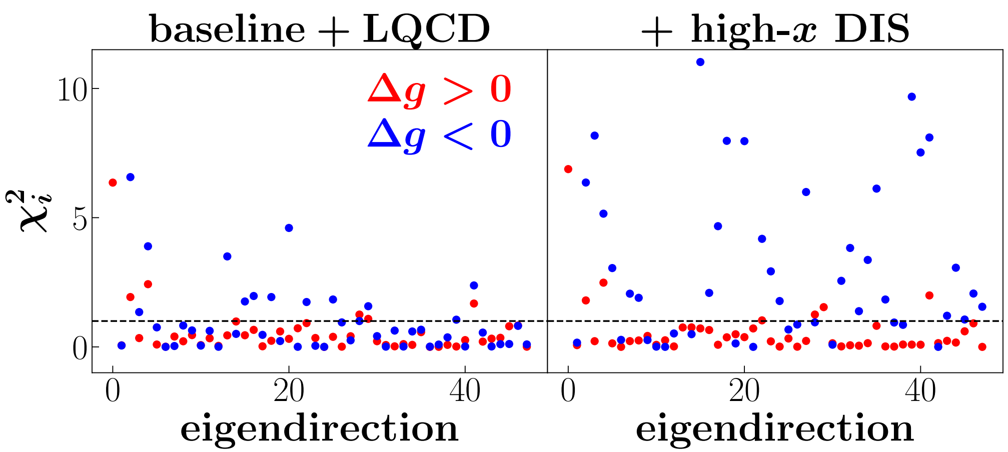
→ from χ^2 alone, LQCD cannot discriminate sign of Δg

→ but … negative Δg gives rise to negative $\Delta\Sigma$ at large x

JAM + lattice QCD + high-x data

- Lower W^2 cut from 10 GeV^2 to 4 GeV^2 to include high-x region



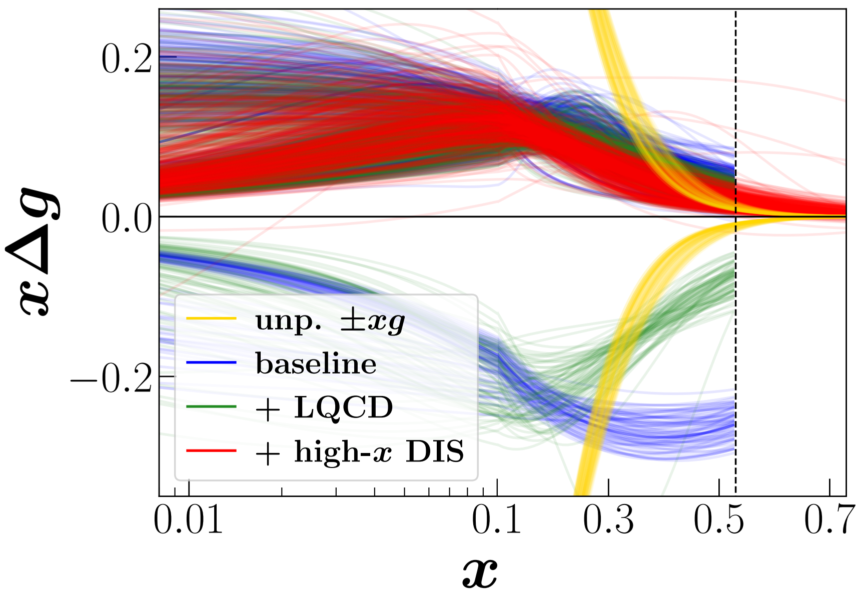


Hunt-Smith et al., PRL ***133****, 161901 (2024)*

⟶ including high-x DIS data (CLAS, Hall A, SANE), LQCD strongly disfavors negative $\Delta\Sigma$ solutions at $x > 0.5$

JAM + lattice QCD + high-x data

- Lower W^2 cut from 10 GeV^2 to 4 GeV^2 to include high-x region



Reaction	$\chi^2_{\rm red}(\Delta g > 0)$ Baseline	+LQCD	+ high-x DIS	$\chi^2_{\rm red}(\Delta g < 0)$ Baseline	+LQCD	+ high-x DIS	N
Polarized	0.89	0.90	1.18	0.92	1.06	1.24	2067
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
Jets	0.84	0.89	0.90	0.88	1.10	1.44	83
$W^\pm/Z$	0.60	0.60	0.99	0.83	0.84	1.32	18
Unpolarized	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

Hunt-Smith et al., PRL ***133****, 161901 (2024)*

→ including high-x DIS data (CLAS, Hall A, SANE), LQCD strongly disfavors negative $\Delta\Sigma$ solutions at $x > 0.5$

→ in data-driven approach, $\Delta g < 0$ can be ruled out only with inclusion of polarized jet, lattice, and high-x DIS data!

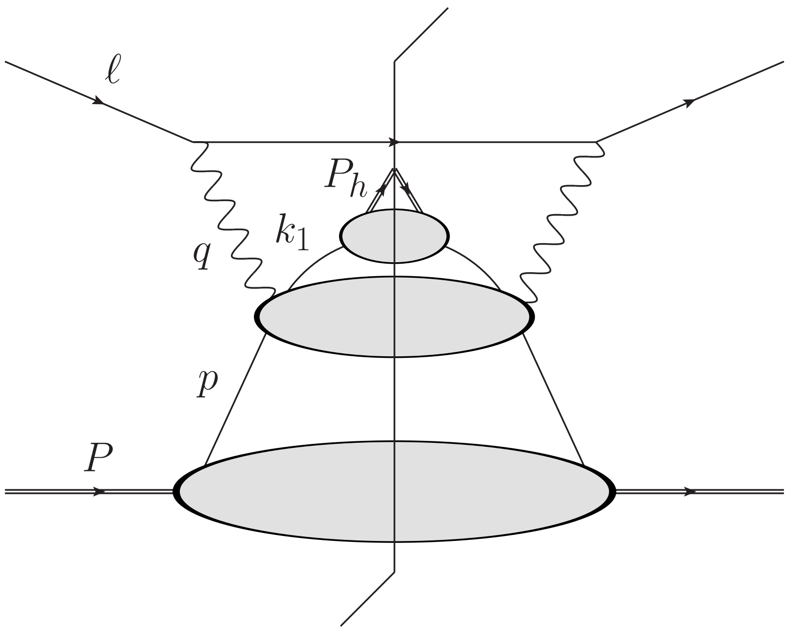
High P_T hadrons in polarized SIDIS

- Is there an observable linear in Δg where gluon contribution not suppressed relative to quark?

  $\longrightarrow$ polarized lepton-nucleon semi-inclusive DIS, with production of hadrons in final state with large transverse momentum P_T

differential cross section

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



partonic cross section

$$4k_1^0 E' \frac{\mathrm{d}\hat{\sigma}_{ij}}{\mathrm{d}^3\boldsymbol{\ell}'\mathrm{d}^3\boldsymbol{k}_1} = \frac{2\alpha^2}{\hat{s}Q^4} L_{\mu\nu}\widehat{W}_{ij}^{\mu\nu}.$$

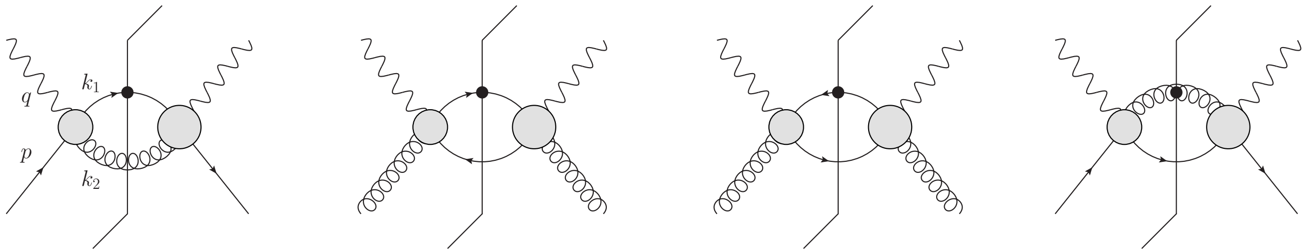
*Whitehill, Zhou, Sato, WM, PRD **107**, 034033 (2023)*

hard factors $\mathcal{H}$

$$L_{\mu\nu}\widehat{W}^{\mu\nu} = \int \mathrm{d}\Pi \mathcal{H}_{ij} \qquad \int \mathrm{d}\Pi = 2\pi\delta_+(k_2^2) = \frac{2\pi\hat{x}}{Q^2}\delta\left((1-\hat{x})(1-\hat{z}) - \frac{\hat{x}\,\hat{z}\,q_T^2}{Q^2}\right)$$

High P_T hadrons in polarized SIDIS

Hard scattering diagrams



⟶ partonic cross sections

unpolarized

$$\frac{d\mathcal{H}^{U}_{qq}}{d\hat{x}\,dy\,d\hat{z}\,dP_{hT}^2} = \frac{64\pi\alpha_s^2}{3\hat{x}(1-\hat{x})y^2Q_1^2}\left[(1+\hat{x}^2\hat{z}^2)(1+\bar{y}^2)Q^4 + 8\hat{x}^2\hat{z}^2\bar{y}Q^2q_T^2 + \hat{x}^2\hat{z}^2(1+\bar{y}^2)q_T^4\right]$$

$$\frac{d\mathcal{H}^{U}_{qg}}{d\hat{x}\,dy\,d\hat{z}\,dP_{hT}^2} = \frac{64\pi\alpha_s^2}{3(1-\hat{x})y^2Q_2^2}\Big[\big((2+\hat{x}^2\hat{z}^2)(1+\bar{y}^2) - 4\hat{x}\,\hat{z}\,\bar{y} - 2\hat{x}y^2(1-\hat{x}(1-\hat{z}))\big)Q^4 + 2\hat{x}\,\hat{z}(4\hat{x}\,\hat{z}\,\bar{y} + \hat{x}y^2 - 1 - \bar{y}^2)Q^2q_T^2 + \hat{x}^2\hat{z}^2(1+\bar{y}^2)q_T^4\Big],$$

$$\frac{d\mathcal{H}^{U}_{gq}}{d\hat{x}\,dy\,d\hat{z}\,dP_{hT}^2} = \frac{8\pi\alpha_s^2Q^2}{\hat{x}y^2Q_1^2Q_2^2}\Big[\big((1+2\hat{x}^2\hat{z}^2)(1+\bar{y}^2) + 2\hat{x}^2y^2(1-\hat{z}) - 4\hat{x}\,\hat{z}\,\bar{y} - 2\hat{x}y^2\big)Q^4 + 2\hat{x}\,\hat{z}(8\hat{x}\,\hat{z}\,\bar{y} + \hat{x}y^2 - 1 - \bar{y}^2)Q^2q_T^2 + 2\hat{x}^2\hat{z}^2(1+\bar{y}^2)q_T^4\Big],$$

polarized

$$\frac{d\mathcal{H}^{P}_{qq}}{d\hat{x}\,dy\,d\hat{z}\,dP_{hT}^2} = -\frac{64\pi\alpha_s^2(2-y)}{3\hat{x}(1-\hat{x})yQ_1^2}\left[(1+\hat{x}^2\hat{z}^2)Q^4 - \hat{x}^2\hat{z}^2q_T^4\right],$$

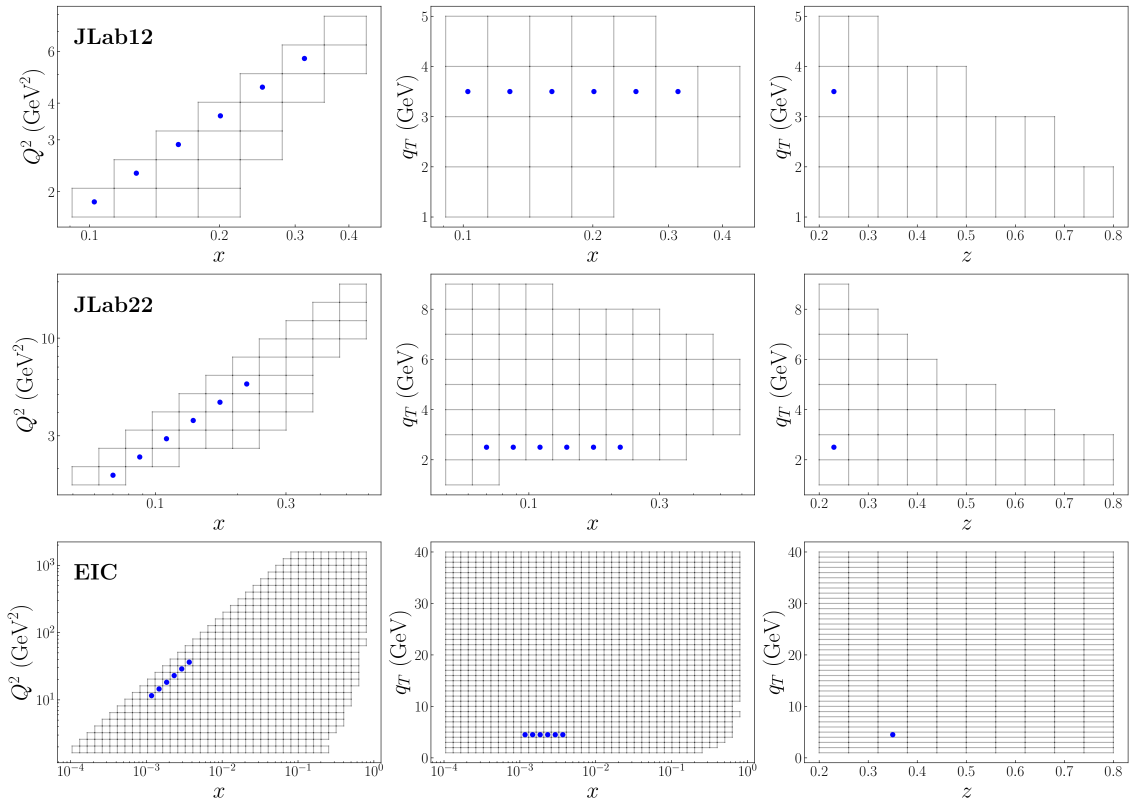
$$\frac{d\mathcal{H}^{P}_{qg}}{d\hat{x}\,dy\,d\hat{z}\,dP_{hT}^2} = -\frac{64\pi\alpha_s^2\hat{x}(2-y)}{3(1-\hat{x})yQ_2^2}\left[(2+\hat{x}\hat{z}^2 - 2\hat{x}\,\hat{z})Q^4 + 2\hat{z}(1-\hat{x})Q^2q_T^2 - \hat{x}\hat{z}^2q_T^4\right],$$

$$\frac{d\mathcal{H}^{P}_{gq}}{d\hat{x}\,dy\,d\hat{z}\,dP_{hT}^2} = \frac{8\pi\alpha_s^2(2-y)Q^2}{\hat{x}yQ_1^2Q_2^2}\left[(2\hat{x}^2\hat{z}^2 - 2\hat{x}^2\hat{z} + 2\hat{x} - 1)Q^4 + 2\hat{x}\,\hat{z}(1-\hat{x})Q^2q_T^2 - 2\hat{x}^2\hat{z}^2q_T^4\right]$$

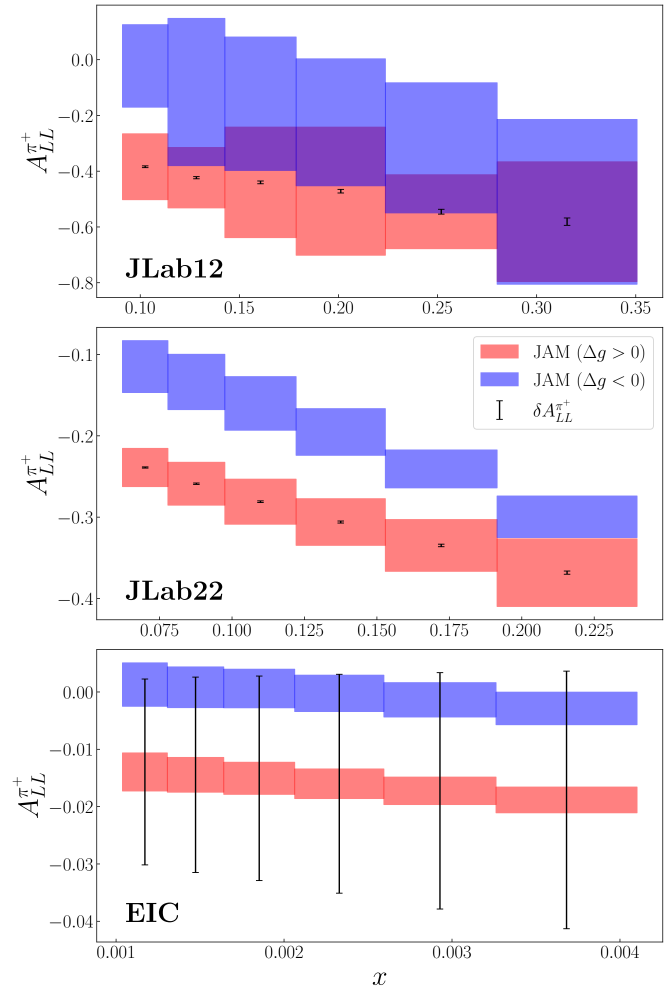
*Whitehill, Zhou, Sato, WM, PRD **107**, 034033 (2023)*

High P_T hadrons in polarized SIDIS

Expected kinematic bins at current and future facilities



Whitehill, Zhou, Sato, WM
PRD ***107****, 034033 (2023)*



<u>JLab uncertainties</u>

luminosity $d\mathcal{L}/dt = 10^{-35}$ cm^{-2} s^{-1}

10 days $\longrightarrow$ integrated luminosity ≈ 86 fb^{-1}

relative uncertainty $\dfrac{\delta A_{LL}}{A_{LL}} \sim \dfrac{1}{\sqrt{\mathcal{L}}}$

<u>EIC uncertainties</u>

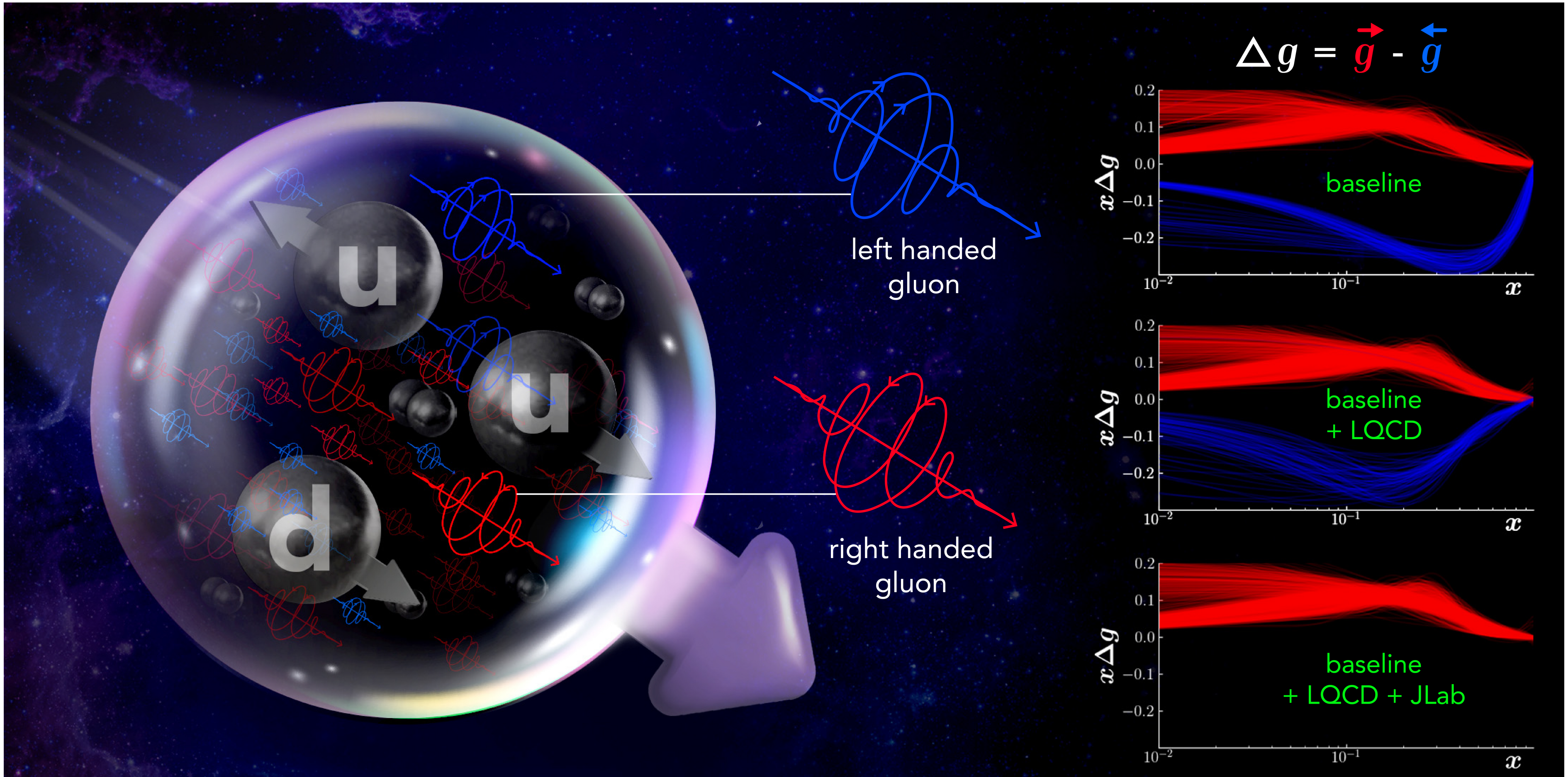
assume integrated luminosity ≈ 10 fb^{-1}

$\longrightarrow$ benefit from higher $\mathcal{L}$

Summary

- Global QCD analysis of world's polarized data, including jet production in polarized pp collisions, gives <u>positive Δg</u> *without* assumptions about PDF positivity <u>only</u> when combined with *lattice* QCD and *high-x* DIS data

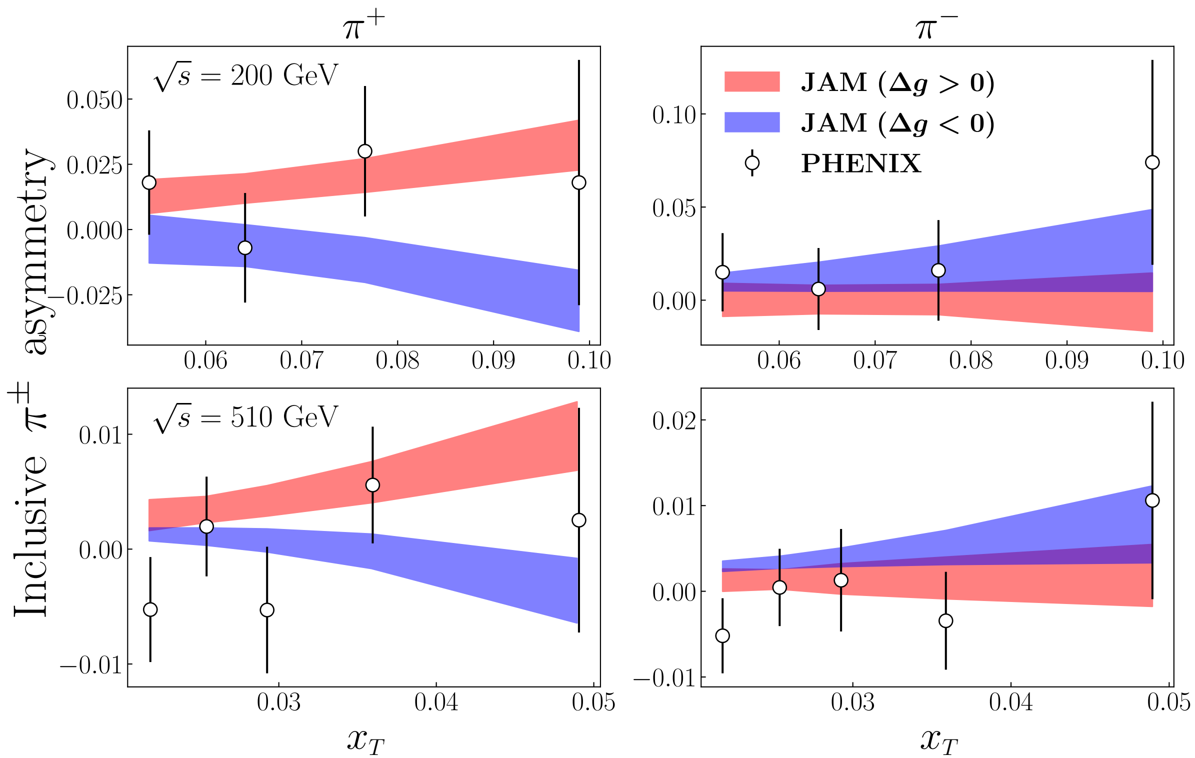
- Future data on SIDIS at high P_T may remove need for lattice constraints



Hunt-Smith et al. [JAM collaboration], Phys. Rev. Lett. 133, 161901 (2024)

Other experimental constraints?

- Pion production in polarized pp collisions



PHENIX

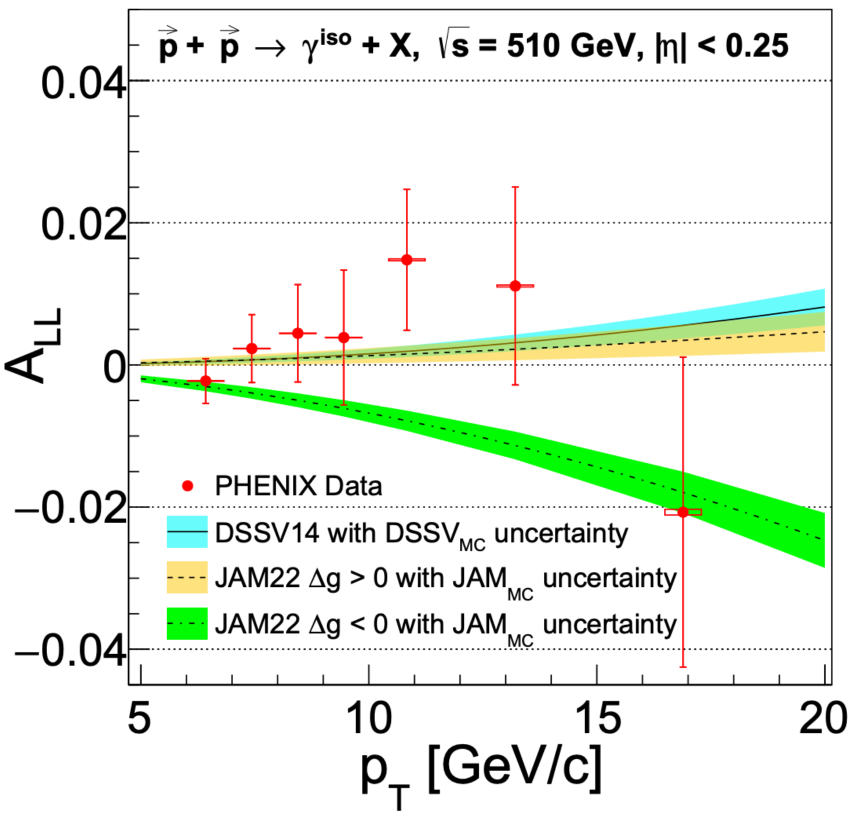
Adare et al., Phys. Rev. D ***91****, 032001 (2015)*

Acharya et al., Phys. Rev. D ***102****, 032001 (2020)*

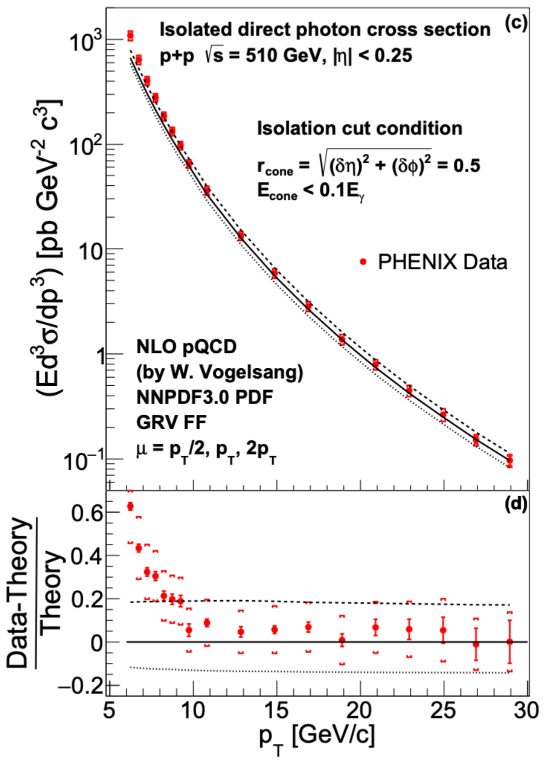
⟶ both $\Delta g > 0$ and $\Delta g < 0$ solutions describe pion production data in polarized pp collisions

Other experimental constraints?

■ Direct-photon production in polarized *pp* collisions



PHENIX
Acharya et al.,
PRL ***130****, 251901 (2023)*



→ only 3 highest-p_T data points for unpolarized cross section are well described in pQCD

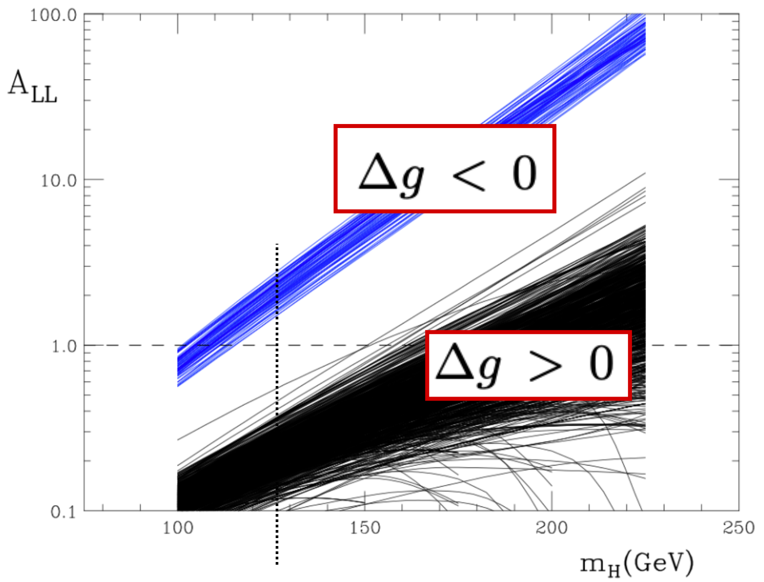
→ cannot unambiguously rule out $\Delta g < 0$ solution

Other experimental constraints?

- Higgs production in polarized *pp* collisions at RHIC?

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

⟶ Higgs asymmetry must be < 1
… rules out large positivity violations
(“baseline” analysis)



*de Florian, Forte, Vogelsang, PRD **109**, 074007 (2024)*

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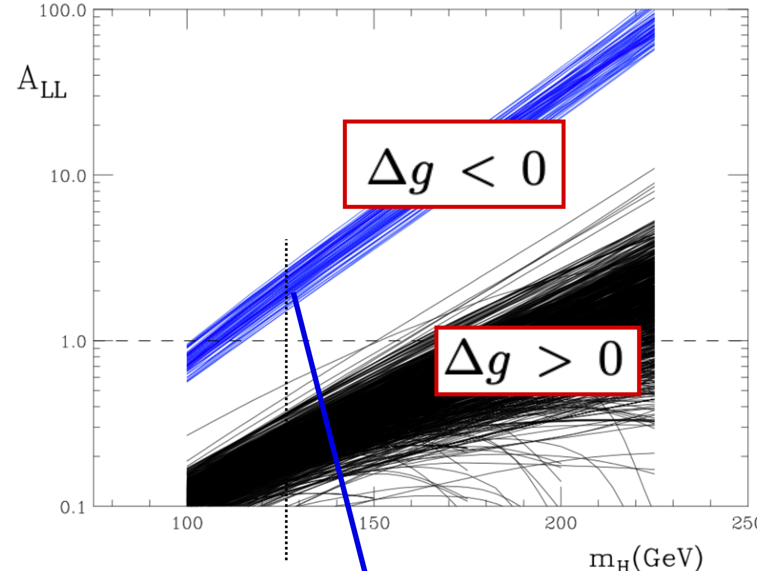
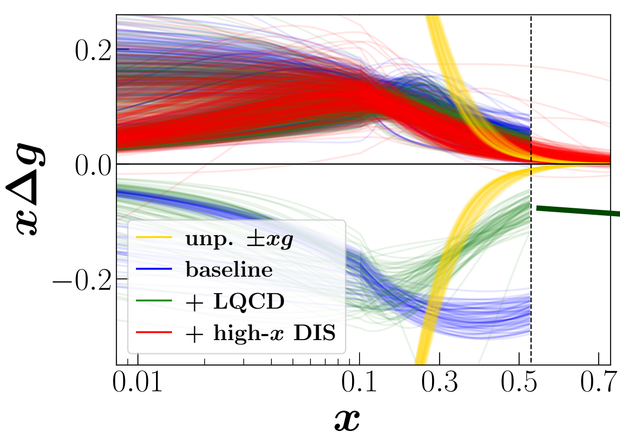
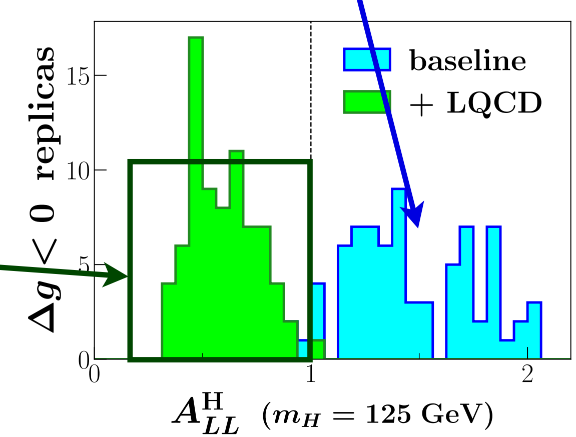


de Florian, Forte, Vogelsang, PRD ***109****, 074007 (2024)*

→ but… does <u>not</u> rule out $\Delta g < 0$ solution with lattice QCD constraint





Hunt-Smith et al., PRL ***133****, 161901 (2024)*

Can $\overline{\mathrm{MS}}$ parton distributions be negative?

Alessandro Candido, Stefano Forte and Felix Hekhorn

Tif Lab, Dipartimento di Fisica, Università di Milano and INFN, Sezione di Milano, Via Celoria 16, I-20133 Milano, Italy

JHEP ***11*** *(2020) 129*

→ argue "No"

but…

PHYSICAL REVIEW D **105,** 076010 (2022)

Positivity and renormalization of parton densities

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There have been recent debates about whether $\overline{\mathrm{MS}}$ parton densities exactly obey positivity bounds (including the Soffer bound) and whether the bounds should be applied as a constraint on global fits to parton densities and on nonperturbative calculations. A recent paper [Candido *et al.*, Can $\overline{\mathrm{MS}}$ parton distributions be negative?, J. High Energy Phys. 11 (2020) 129] appears to provide a proof of positivity in contradiction with earlier work by other authors. We examine their derivation and find that its primary failure is in the apparently uncontroversial statement that bare parton density (or distribution) function (pdfs) are always positive. We show that under the conditions used in the derivation, that statement fails. This is associated with the use of dimensional regularization for both UV divergences (space-time dimension $n < 4$) and for collinear divergences, with $n > 4$. Collinear divergences appear in massless partonic quantities convoluted with bare pdfs, in the approach used by these and other authors, which we call "track B." Divergent UV contributions are regulated and are positive when $n < 4$, but can and often do become negative after analytic continuation to $n > 4$. We explore ramifications of this idea and provide some elementary calculations in a model QFT that show how this situation can generically arise in reality. We examine the connection with the origin of the track B method. Our examination pinpoints considerable difficulties with track B that render it either wrong or highly problematic and explain that a different approach, which appears in some literature and that we call track A, does not suffer from this set of problems. The issue of positivity highlights that track-B methods can lead to wrong results of phenomenological importance. From our analysis we identify the restricted situations in which positivity tends to be violated.

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JHEP ***11*** *(2020) 129*

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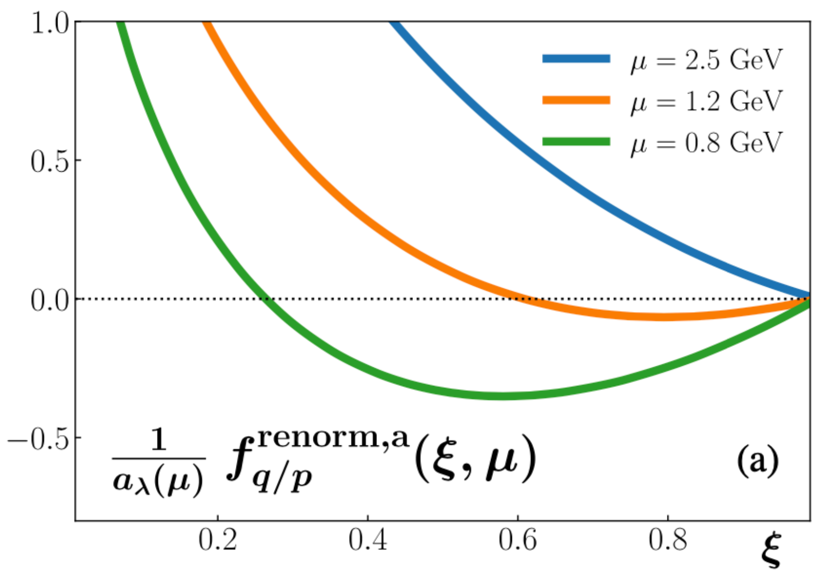
PHYSICAL REVIEW D **105,** 076010 (2022)



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