Unveiling the Proton Structure: collinear and TMD observables

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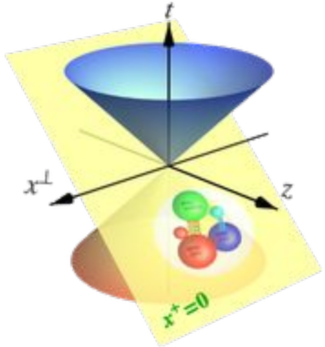


LFQCD Seminar, Mar 5, 2025

Jefferson Lab Angular collaboration (JAM)

Theory

- Alberto Accardi (Christopher Newport University/Jefferson Lab)
- Daniel Adamiak (Jefferson Lab)
- Trey Anderson (William & Mary)
- Patrick Barry (Argonne National Lab)
- Ian Cloet (Argonne National Lab)
- Christopher Cocuzza (William & Mary)
- Adam Freese (Jefferson Lab)
- Leonard Gamberg (Penn State University Berks)
- Chueng-Ryong Ji (North Carolina State University)
- Yuri Kovchegov (Ohio State University)
- Wally Melnitchouk* (Jefferson Lab)
- Andreas Metz (Temple University)
- Eric Moffat (Argonne National Lab)
- Daniel Pitonyak (Lebanon Valley College)
- Alexei Prokudin (Penn State University Berks)
- Jianwei Qiu (Jefferson Lab)
- Nobuo Sato* (Jefferson Lab)
- Matthew Sievert (New Mexico State University)
- Anthony Thomas (University of Adelaide)
- Richard Whitehill (Old Dominion University)
- Yiyu Zhou (Turin)

Lattice QCD

- Martha Constantinou (Temple University)
- Joseph Karpie (Jefferson Lab)
- Kostas Orginos (William & Mary/Jefferson Lab)
- David Richards (Jefferson Lab)
- Savvas Zafeiropoulos (Aix Marseille University)

Experiment

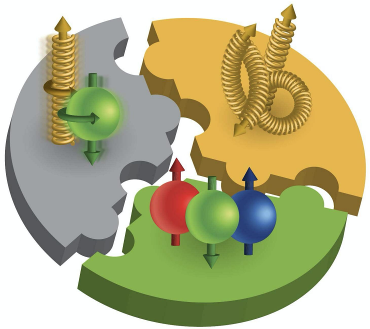
- Harut Avakian (Jefferson Lab)
- Peter Bosted (Jefferson Lab)
- Jianping Chen (Jefferson Lab)
- Markus Diefenthaler (Jefferson Lab)
- Thia Keppel (Jefferson Lab)
- Sebastian Kuhn (Old Dominion University)
- Shujie Li (LBNL)
- Hanjie Liu (University of Massachusetts Amherst)
- Zein-Eddine Meziani (Argonne National Lab)
- Oscar Rondon (University of Virginia)
- Brad Sawatzky (Jefferson Lab)

Past collaborators

- Rabah Abdul Khalek
- Carlota Andres
- Jake Bringewatt
- Nina Cao
- Filippo Delcarro
- Jacob Ethier
- Nicholas Hunt-Smith
- Pedro Jimenez-Delgado

Website: https://www.jlab.org/theory/jam

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

$$\frac{1}{2} = \boxed{\frac{1}{2}\Delta\Sigma} + \boxed{\Delta G} + L_{q+g}$$

0.15

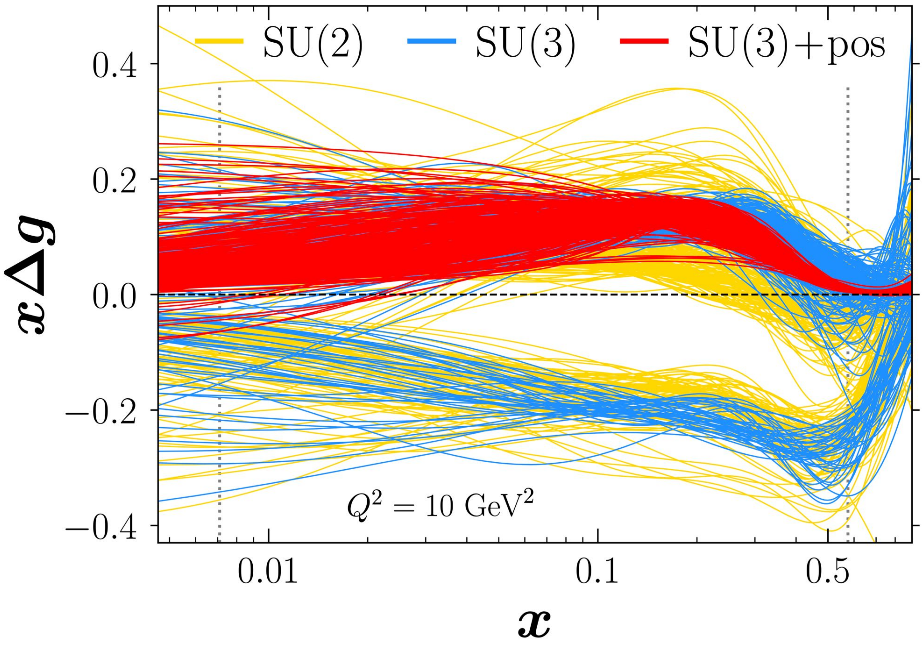
$$\int \mathrm{d}x\, \Delta g = ?$$

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)

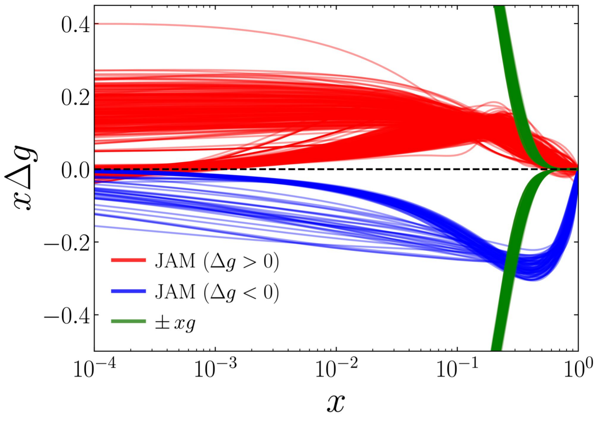
Phys. Rev. D **105**, 074022 – Published 25 April 2022

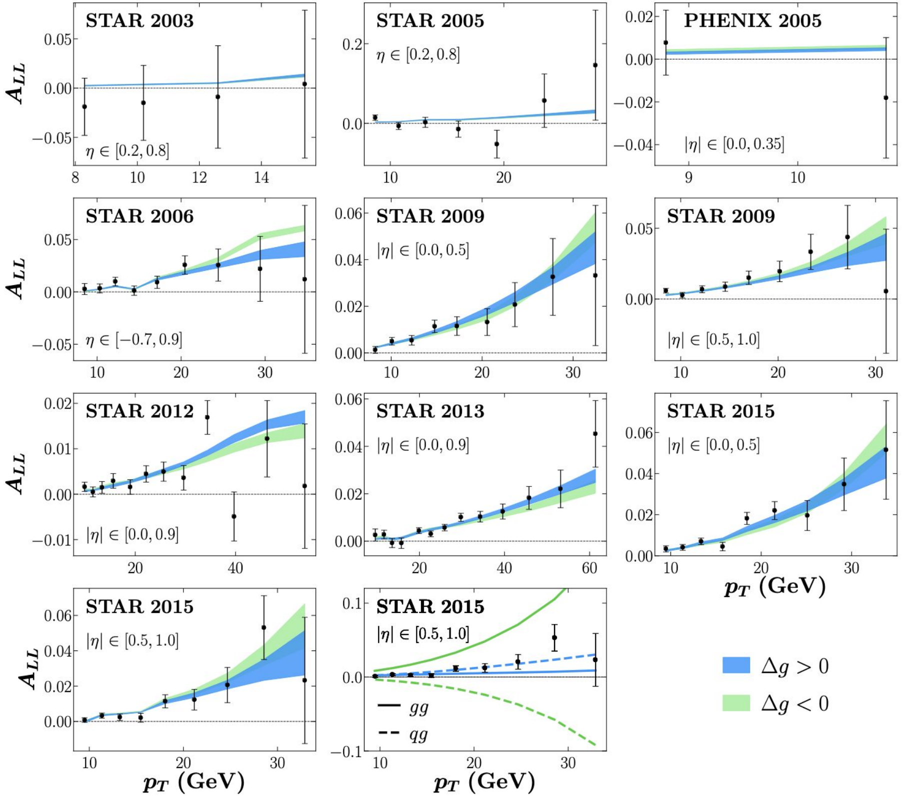


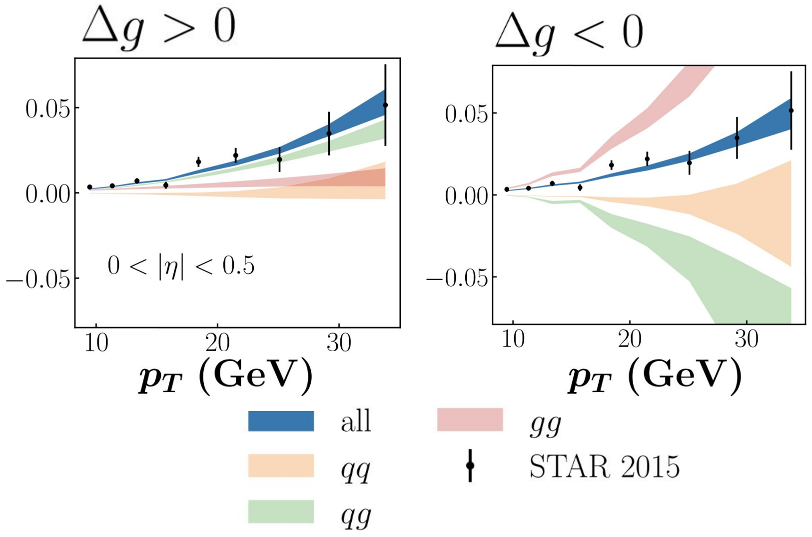
- Sign of Δg is not uniquely determined by existing experimental data (DIS $W^2 > 10$ GeV^2)
- PDF positivity constraints + data strongly disfavors the negative Δg
- Negative Δg violates significantly PDF positivity constraint
- PDF positivity is not a strict requirement in QCD

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

PDF positivity constraint







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

$$|A_{LL}| < 1$$ ✔

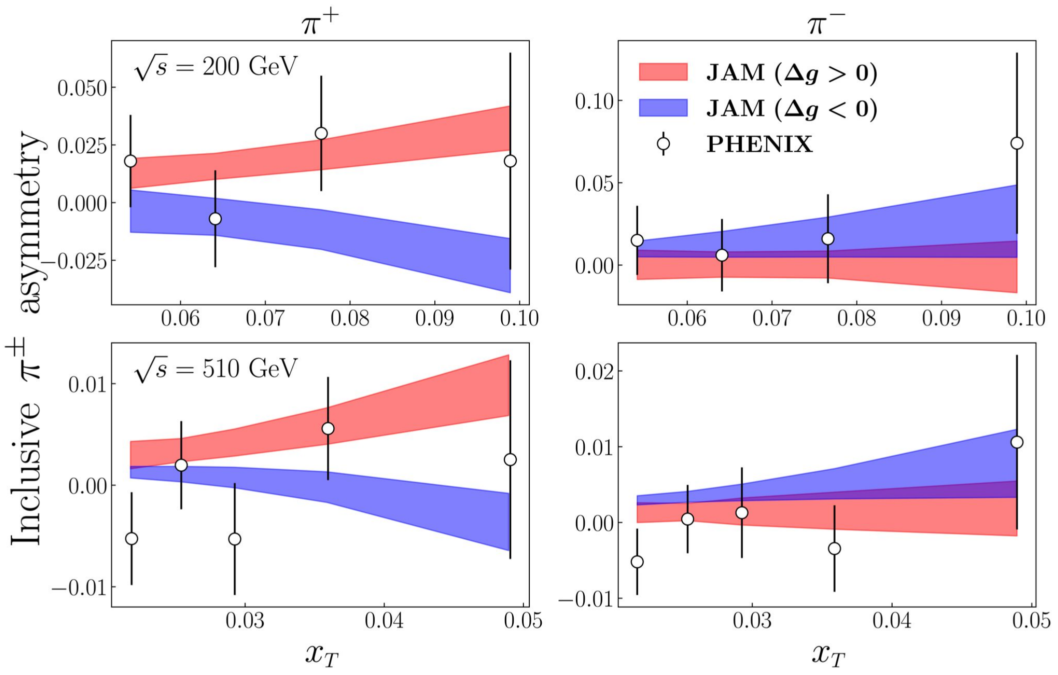
Δg enters quadratically, and different channels contribute with different signs and magnitudes

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

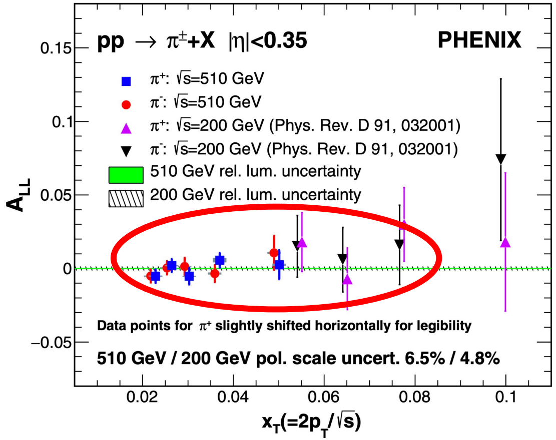
A. Adare *et al.* (PHENIX Collaboration)
Phys. Rev. D **91**, 032001 – Published 2 February 2015

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

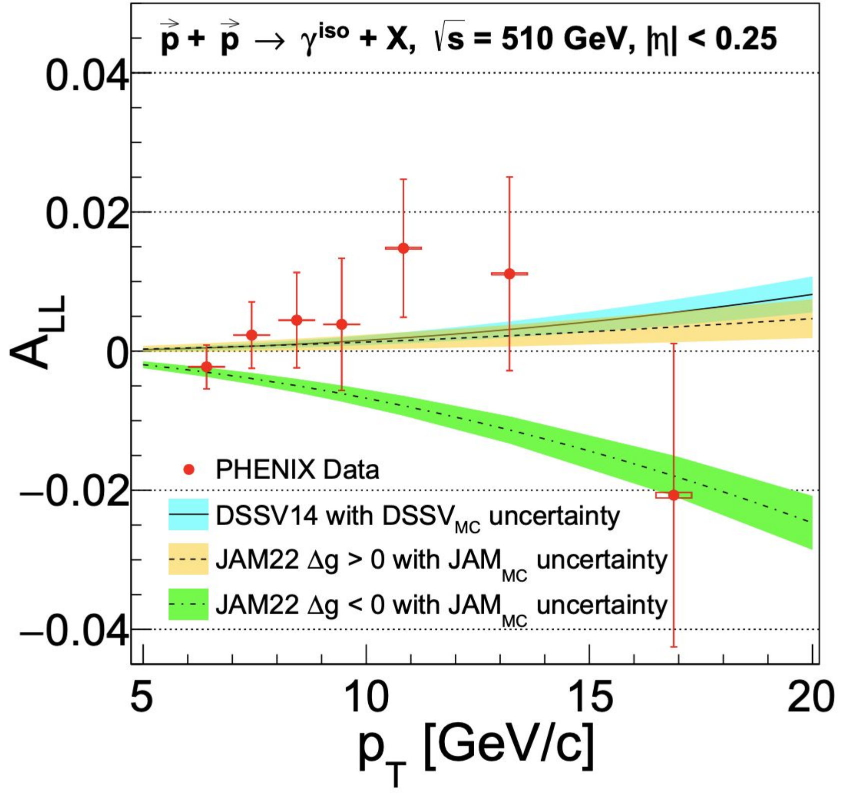


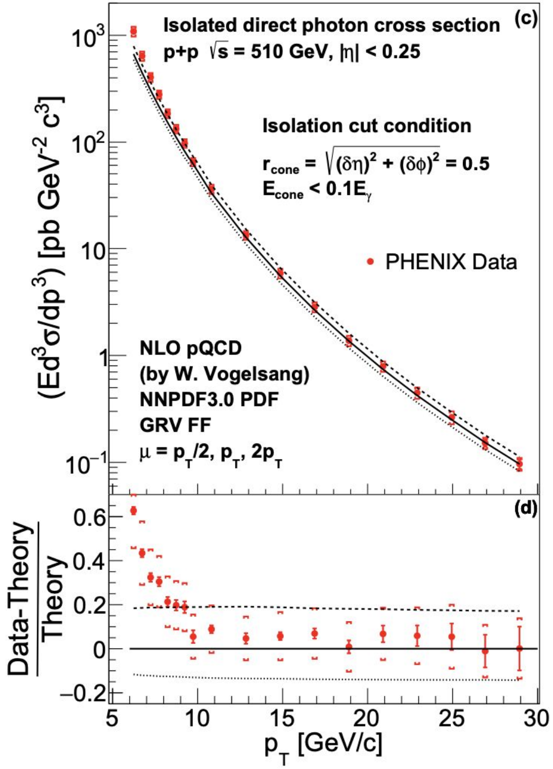
PHENIX: 1409.1907, 2004.02681

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

$$A_{LL} = \frac{\sigma^{++} - \sigma^{+-}}{\sigma^{++} + \sigma^{+-}}$$





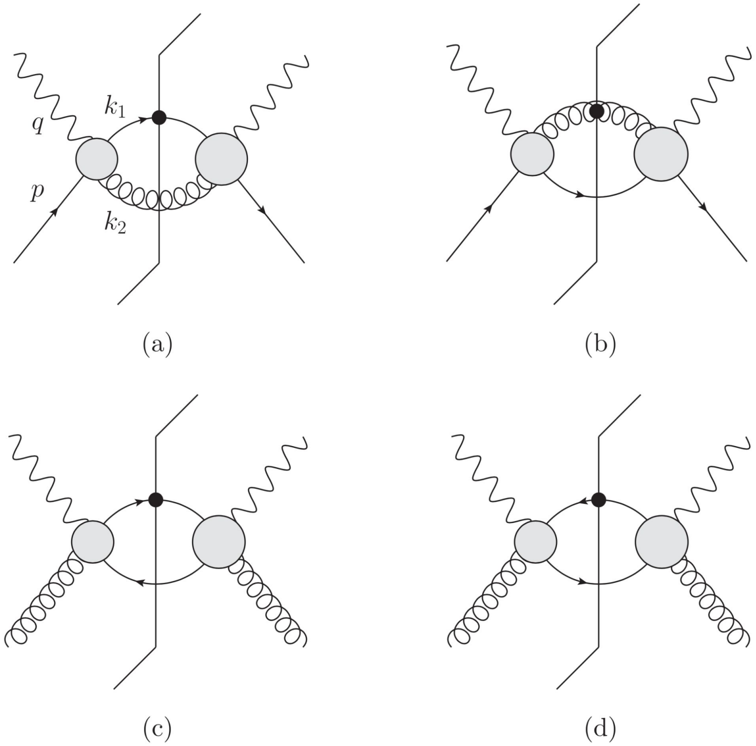
- PHENIX collaboration stated that negative Δg is disfavored by more than 2.8σ
- However, only last 3 high-p_T A_{LL} points are well described in pQCD (see denominator of A_{LL})

PHENIX: 2202.08158

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

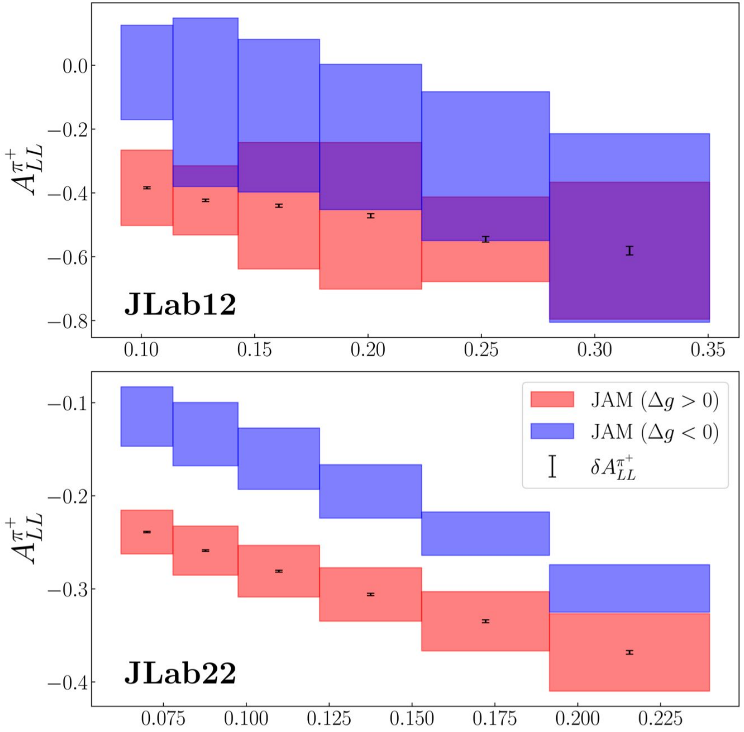
SIDIS with large $p_{h,T}$: $e(\ell) + N(P) \to e(\ell') + h(P_h) + X$



- q_T is required to be comparable to photon virtuality Q
- Δg starts to contribute at LO
- The cross section depends on Δg linearly

$$q_T \equiv \frac{p_{h,T}}{z} \gtrsim Q$$

SIDIS with large $p_{h,T}$: $e(\ell) + N(P) \to e(\ell') + h(P_h) + X$



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

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

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

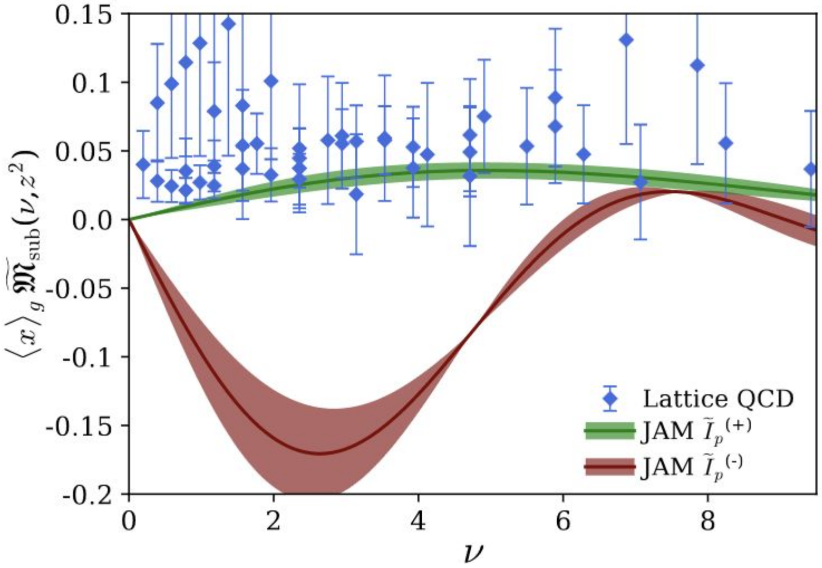
Toward the determination of the gluon helicity distribution in the nucleon from lattice quantum chromodynamics

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

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

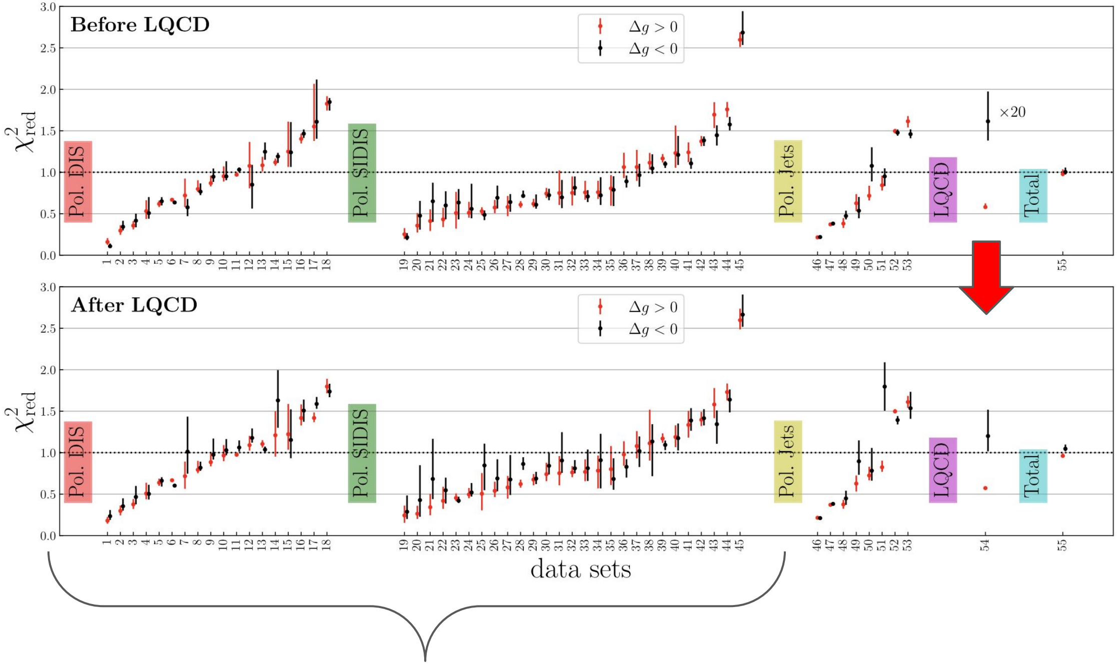
$$\widetilde{\mathfrak{M}}(\nu,z^2) = \frac{\widetilde{M}_{00}(p,z)/p_0p_3Z_L(z_3/a)}{M_{00}(p=0,z)/m^2}$$



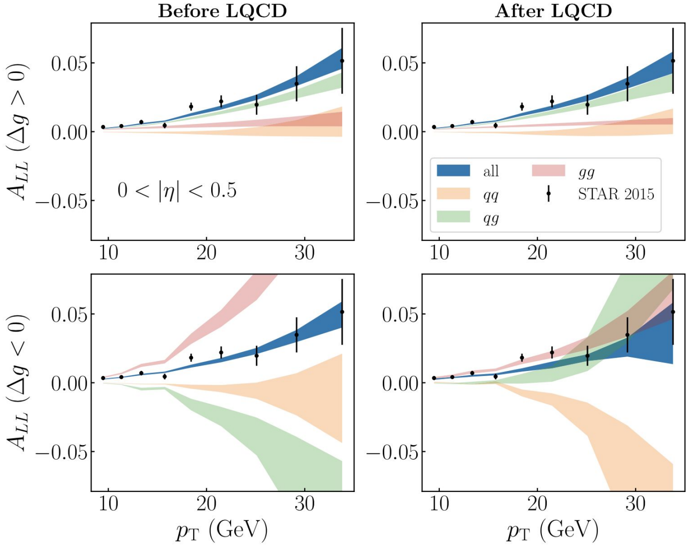
$$\widetilde{\mathfrak{M}}(\nu,z^2)\langle x_g\rangle_{\mu^2} = \widetilde{\mathcal{I}}_p(\nu,\mu^2) - \frac{\alpha_s N_c}{2\pi}\int_0^1 du\,\widetilde{\mathcal{I}}_p(u\nu,\mu^2)\Big\{\ln\Big(z^2\mu^2\frac{e^{2\gamma_E}}{4}\Big)\Big(\Big[\frac{2u^2}{\bar{u}}+4u\bar{u}\Big]_+ - \Big(\frac{1}{2}+\frac{4}{3}\frac{\langle x_S\rangle_{\mu^2}}{\langle x_g\rangle_{\mu^2}}\Big)\delta(\bar{u})\Big) + 4\Big[\frac{u+\ln(1-u)}{\bar{u}}\Big]_+ - \Big(\frac{1}{\bar{u}}-\bar{u}\Big)_+ - \frac{1}{2}\delta(\bar{u}) + 2\bar{u}u\Big\} - \frac{\alpha_s C_F}{2\pi}\int_0^1 du\,\widetilde{\mathcal{I}}_S(u\nu,\mu^2)\Big\{\ln\Big(z^2\mu^2\frac{e^{2\gamma_E}}{4}\Big)\widetilde{\mathcal{B}}_{gq}(u) + 2\bar{u}u\Big\} + \mathcal{O}(\Lambda_{\mathrm{QCD}}^2 z^2),$$

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

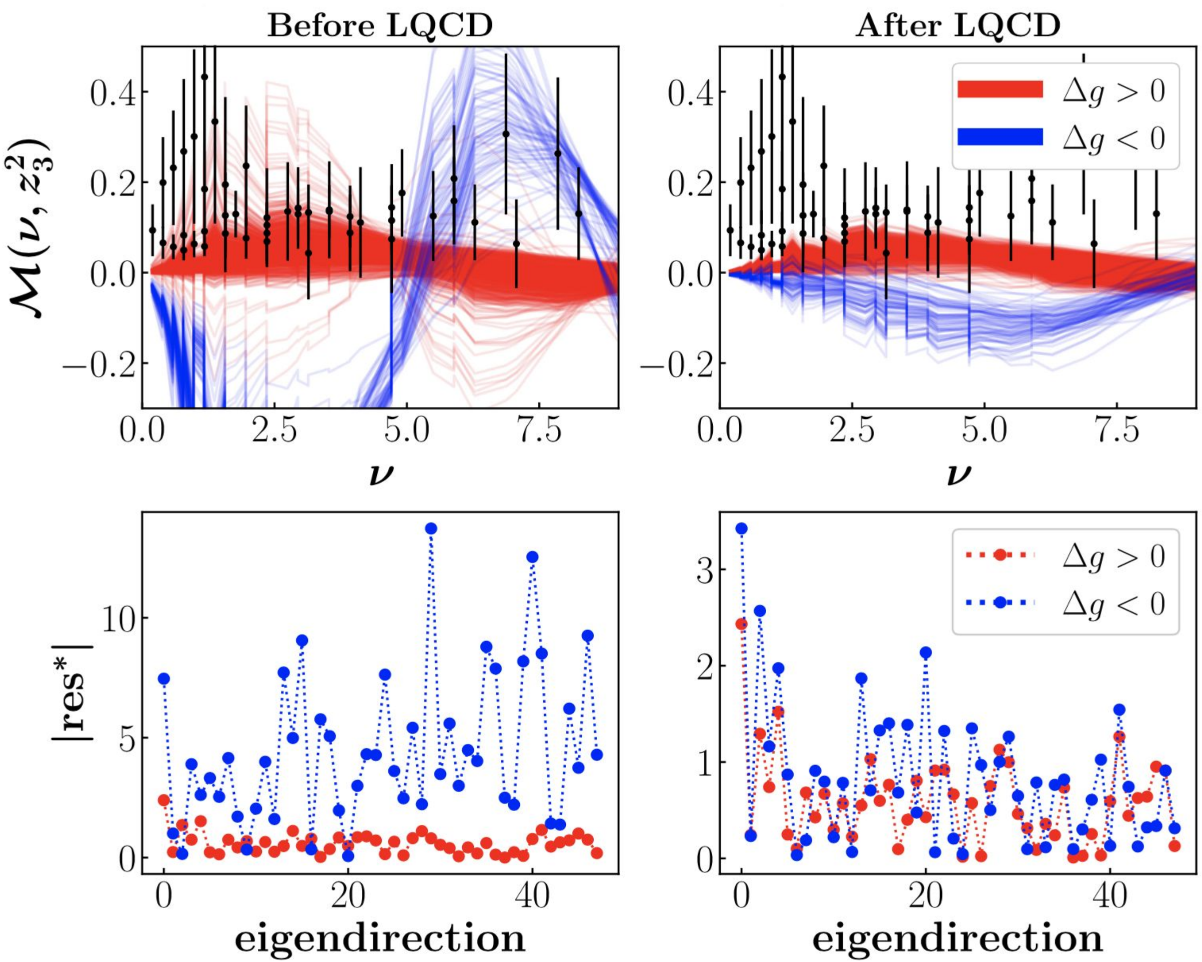
Egerer et al: 2207.08733



DIS $W^2 > 10$ GeV^2

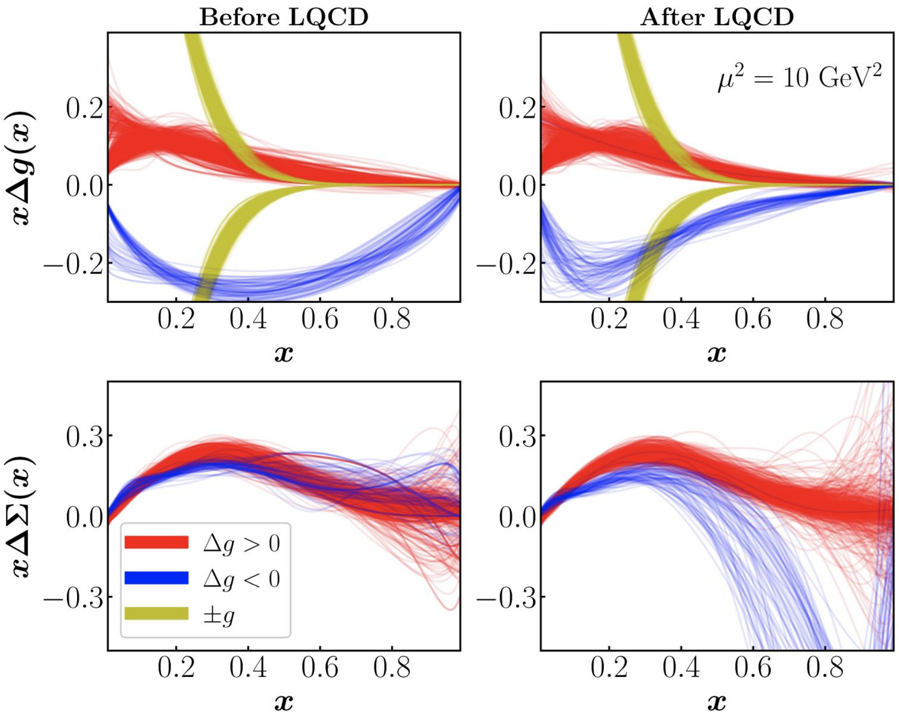


- Good description of global data after inclusion of LQCD for both solutions for Δg
- On the basis of χ^2, LQCD cannot discriminate fully the sign of Δg



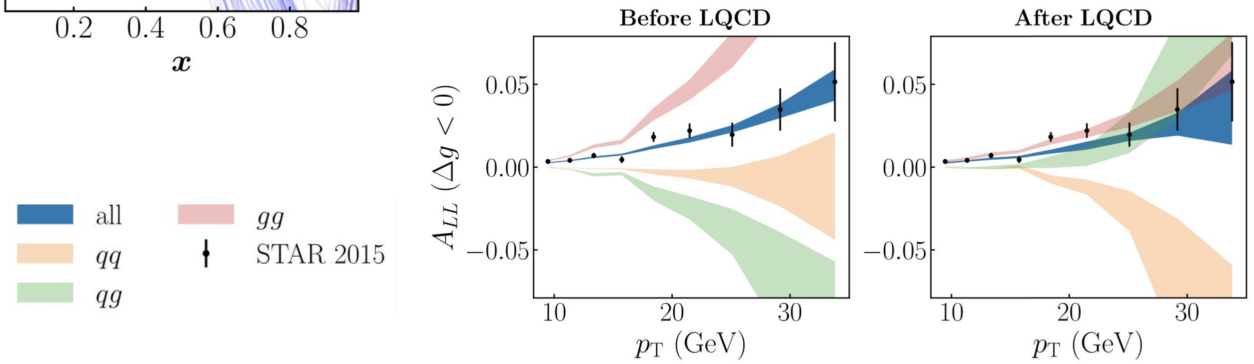
$$
\begin{aligned}
\chi^2 &= (\boldsymbol{d}-\boldsymbol{t})^T \boldsymbol{\Sigma}^{-1} (\boldsymbol{d}-\boldsymbol{t}) \\
&= (\boldsymbol{d}-\boldsymbol{t})^T \boldsymbol{U}\boldsymbol{D}^{-1}\boldsymbol{U}^T (\boldsymbol{d}-\boldsymbol{t}) \\
&= \sum_i \mathrm{res}_i^{*2}.
\end{aligned}
$$

- Projections of residuals reveal strong correlations between LQCD data points
- The correlations prevent determination of sign of Δg



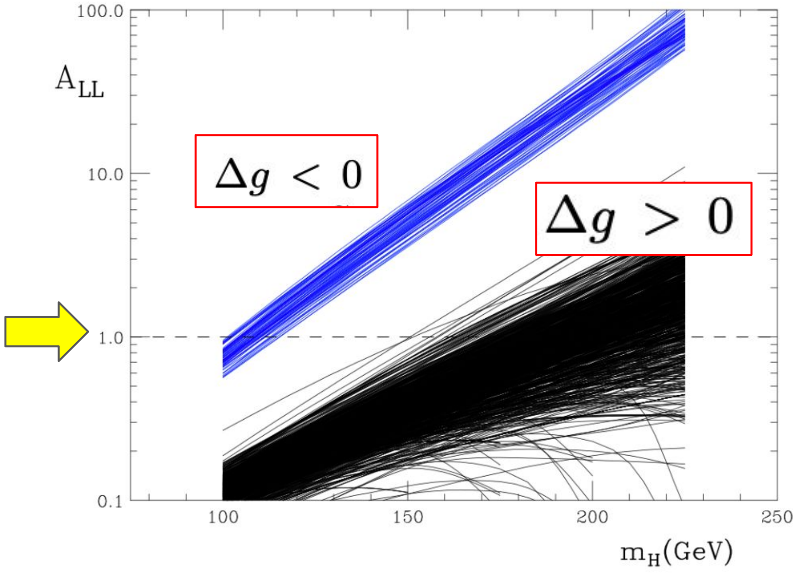
- LQCD distorts significantly the negative Δg at $x > 0.3$
- Note that both solutions violate PDF positivity bounds in $x > 0.3$
- Before inclusion of LQCD data, $\Delta\Sigma$ were stable for both solutions
- Inclusion of LQCD data forces the $\Delta\Sigma$ to become negative at $x > 0.4$ for the negative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

$$\Delta\Sigma = \sum_q (\Delta q + \Delta\bar{q})$$



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

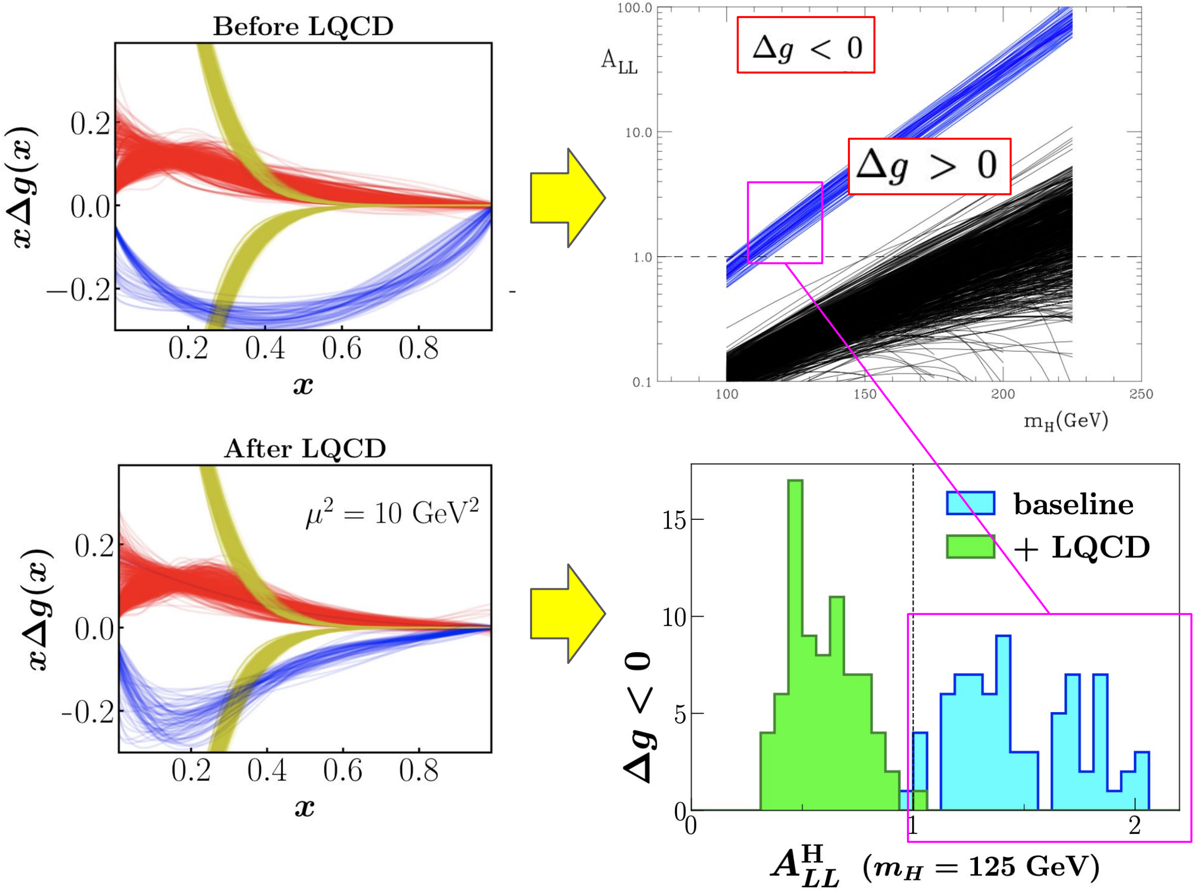


- Higgs A_{LL} is directly sensitive to Δg squared at LO
- Calculations of A_{LL} (Higgs) with negative Δg can lead to unphysical results **(using non-LQCD based analysis)**

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

De Florian, Forte & Vogelsang: 2401.10814

Can Higgs A_{LL} fully discriminate negative Δg?

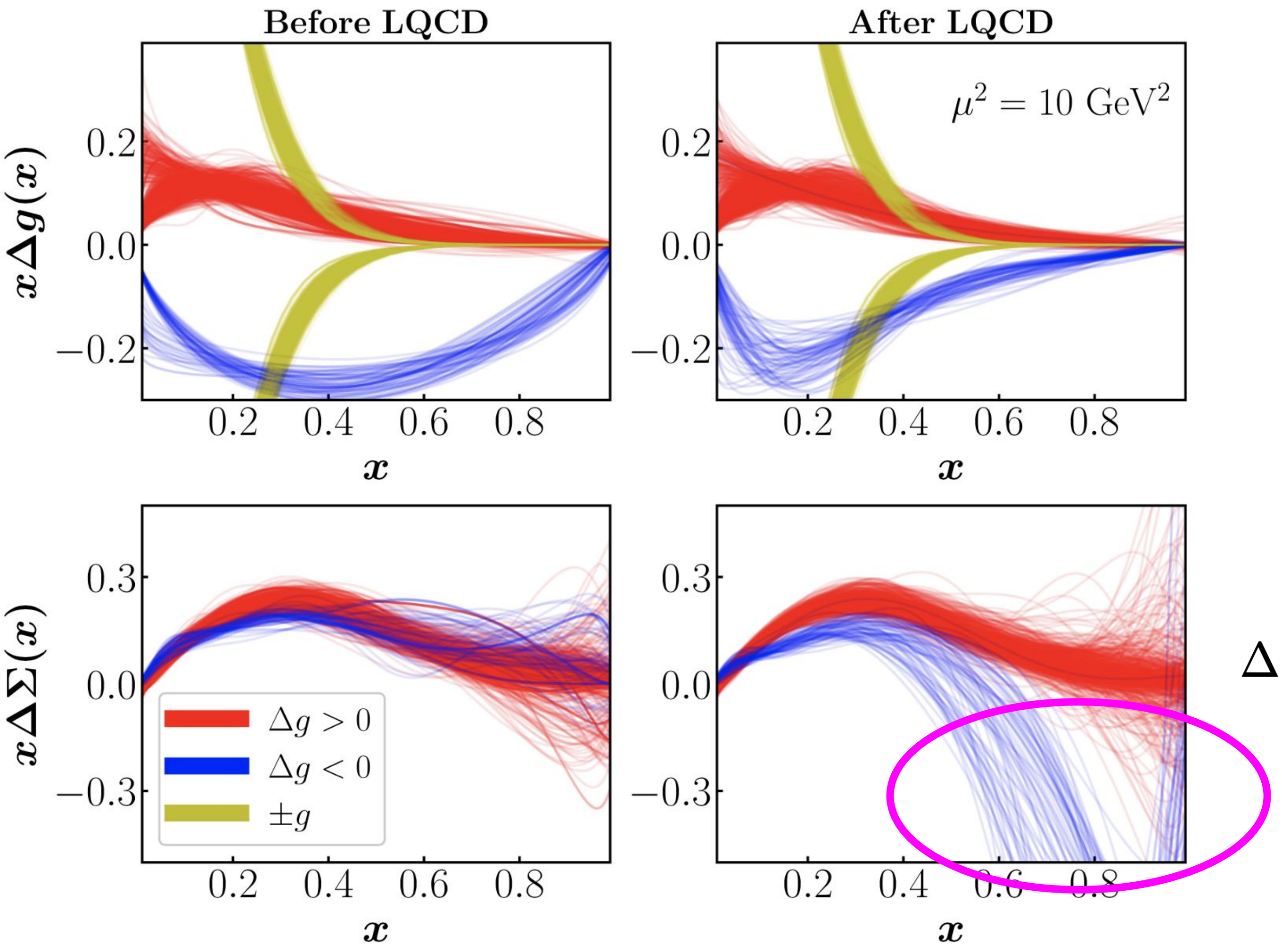


Negative Δg with LQCD constraints still admits a physical Higgs A_{LL}

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)

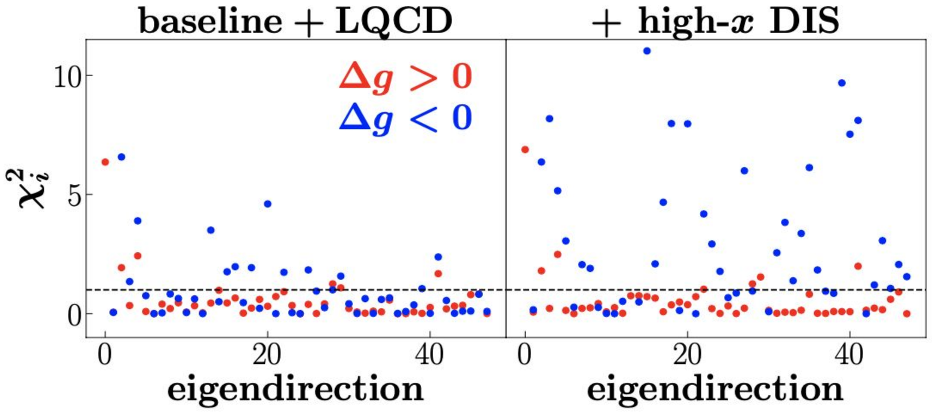
Phys. Rev. Lett. **133**, 161901 – Published 16 October 2024



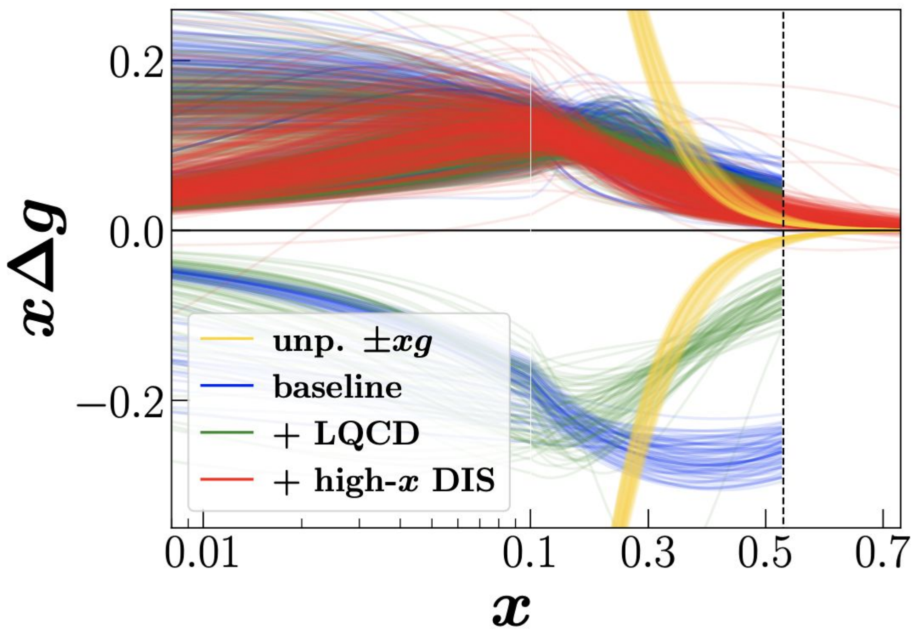
$$\Delta\Sigma = \sum_q (\Delta q + \Delta\bar{q})$$

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



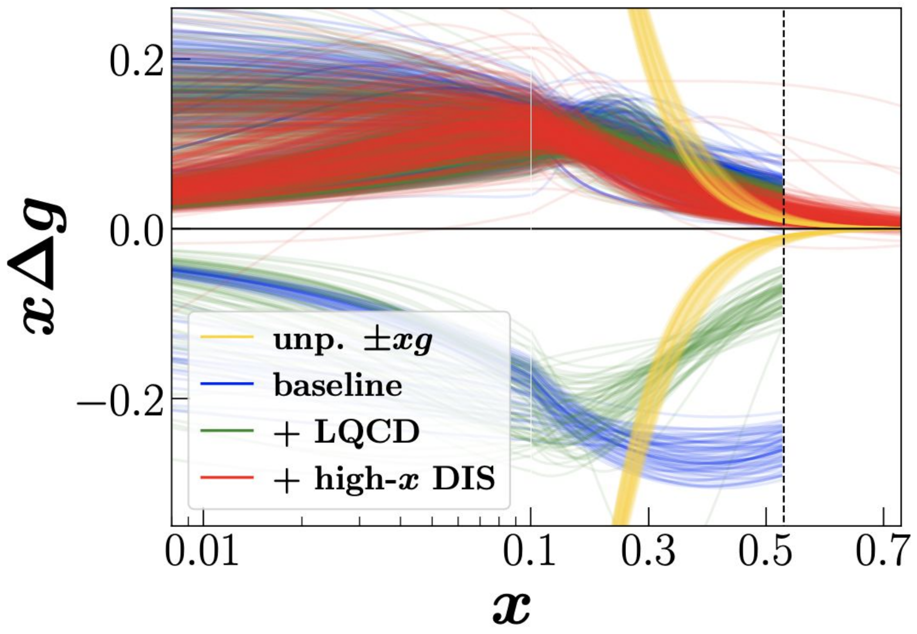
Summary of collinear section

- 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)

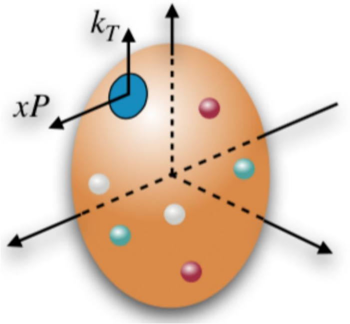


Proton structure in 3D

3D structure in momentum space

TMD (transverse momentum dependent) distributions:

- longitudinal momentum fraction
- transverse momentum k_T



TMD Handbook

A modern introduction to the physics of
Transverse Momentum Dependent distributions

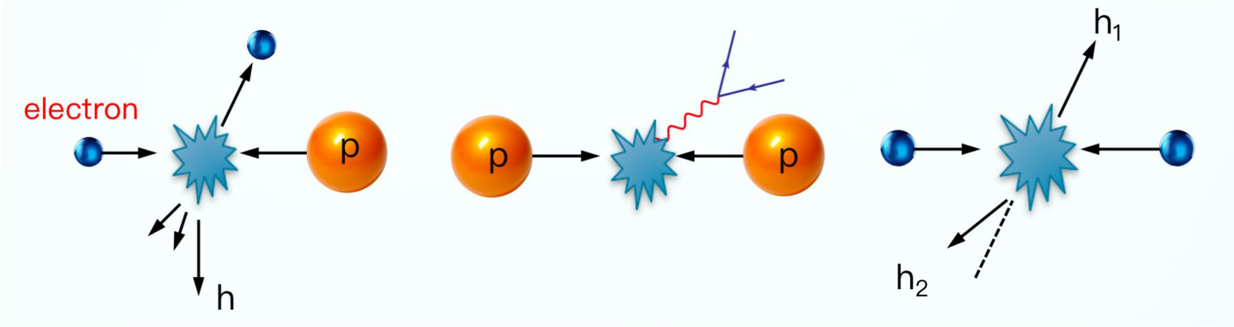
TMD Collaboration

Renaud Boussarie
Matthias Burkardt
Martha Constantinou
William Detmold
Markus Ebert
Michael Engelhardt
Sean Fleming
Leonard Gamberg
Xiangdong Ji
Zhong-Bo Kang
Christopher Lee
Keh-Fei Liu
Simonetta Liuti
Thomas Mehen *
Andreas Metz
John Negele
Daniel Pitonyak
Alexei Prokudin
Jian-Wei Qiu
Abha Rajan
Marc Schlegel
Phiala Shanahan
Peter Schweitzer
Iain W. Stewart *
Andrey Tarasov
Raju Venugopalan
Ivan Vitev
Feng Yuan
Yong Zhao

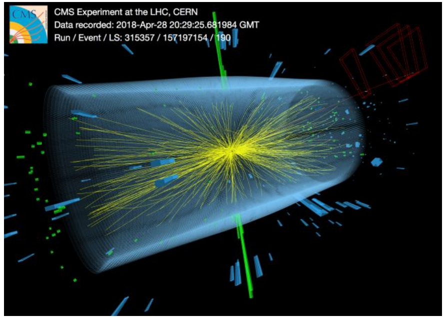
* - Editors

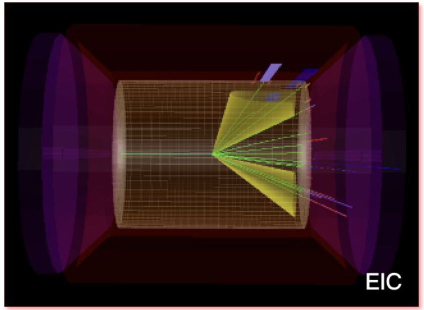
Processes to extract TMDs

- Standard processes: SIDIS, Drell-Yan, e^+e^-



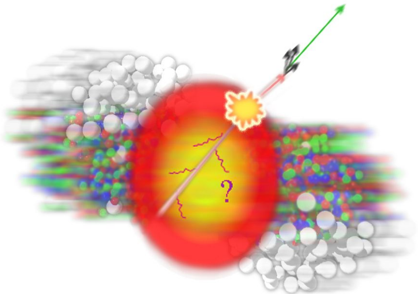
- Focus: using jets for 3D imaging





Why jets?

- Precision probe of QCD
- Explore beyond standard model (BSM) parameters
- Probe quark gluon plasma (QGP)
- ...

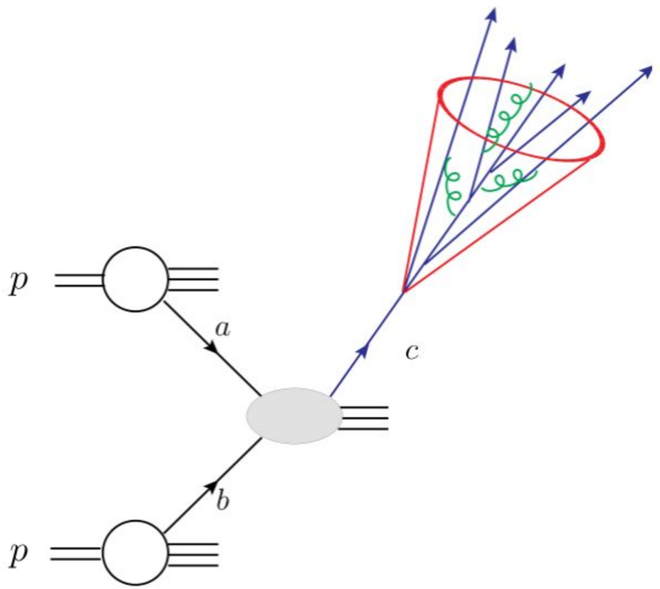


Advantage of jet substructure:

- Clean laboratory for TMD physics: only one TMD function is involved
- Tomography: “scan” the longitudinal momentum fraction z_h distribution

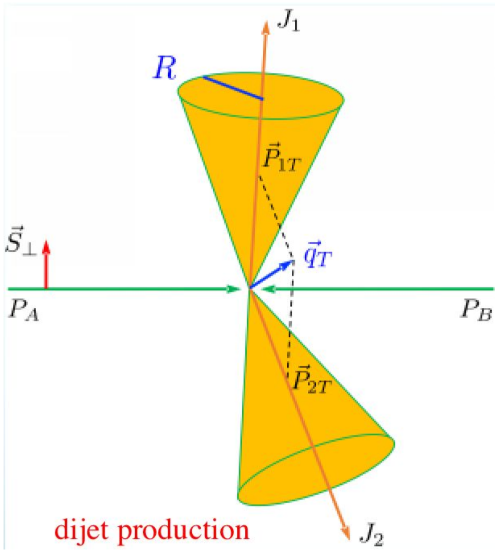
Two types of jet production

Single inclusive: only care about a single jet



Exclusive: a fixed number of final state jets

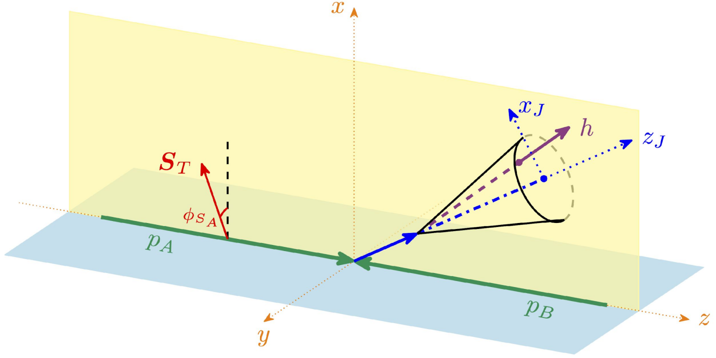
(back-to-back dijet/Z+jet)



Single inclusive jet production

- Collinear PDFs: only one scale p_T is measured.
- TMD FFs: when hadron transverse momentum distribution is measured.

Kang, Ringer & Vitev: 16; Dai, Kim & Leibovich: 16; Kaufmann, Mukherjee & Vogelsang: 15



$$\frac{d\sigma^{pp\to \text{jet}(h)+X}}{dp_T\, d\eta\, dz_h} \propto f_a \otimes f_b \otimes H_{ab\to c} \otimes \mathcal{D}_1^{h/c}(z, z_h, p_T R, \mu),$$

$$\frac{d\sigma^{pp\to \text{jet}(h)+X}}{dp_T\, d\eta\, dz_h\, d^2\boldsymbol{j}_\perp} \propto f_a \otimes f_b \otimes H_{ab\to c} \otimes \mathcal{G}_1^{h/c}(z, z_h, \boldsymbol{j}_\perp, p_T R, \mu, \zeta_J),$$

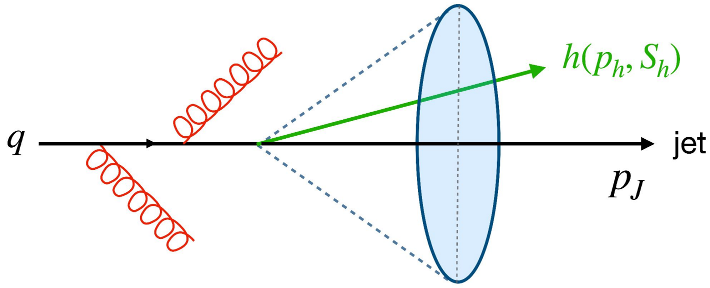
- z_h: large momentum fraction of hadron v.s. jet
- $\boldsymbol{j}_\perp$: hadron transverse momentum w.r.t jet axis

Relation between fragmenting **jet** functions (FJFs) and **standard** fragmentation functions

If you measure only collinear z_h distribution

$$\Delta_{(T)}\mathcal{G}_i^h(z, z_h, p_T R, \mu) = \sum_j \int_{z_h}^1 \frac{dz_h'}{z_h'} \Delta_{(T)}\mathcal{J}_{ij}(z, z_h', p_T R, \mu)\Delta_{(T)}D_{h/j}\left(\frac{z_h}{z_h'}, \mu\right)$$

$$\begin{aligned}\Delta\mathcal{J}_{qq}(z, z_h, p_T R, \mu) &= \delta(1-z)\delta(1-z_h) + \frac{\alpha_s}{2\pi}\Big\{L\Big[\Delta P_{qq}(z)\delta(1-z_h) - \Delta P_{qq}(z_h)\delta(1-z)\Big] \\ &+ \delta(1-z)\left[2C_F(1+z_h^2)\left(\frac{\ln(1-z_h)}{1-z_h}\right)_+ + C_F(1-z_h) + \Delta\mathcal{I}_{qq}^{\text{anti-}k_T}(z_h)\right] \\ &- \delta(1-z_h)\left[2C_F(1+z^2)\left(\frac{\ln(1-z)}{1-z}\right)_+ + C_F(1-z)\right]\Big\}, \qquad (2.43)\end{aligned}$$



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Relation between FJFs and **standard** fragmentation function

$$
\begin{aligned}
\Delta\mathcal{J}_{qq}(z,z_h,p_TR,\mu) = {}& \delta(1-z)\delta(1-z_h) + \frac{\alpha_s}{2\pi}\bigg\{L\Big[\Delta P_{qq}(z)\delta(1-z_h) - \Delta P_{qq}(z_h)\delta(1-z)\Big] \\
&+ \delta(1-z)\bigg[2C_F(1+z_h^2)\left(\frac{\ln(1-z_h)}{1-z_h}\right)_+ + C_F(1-z_h) + \Delta\mathcal{I}_{qq}^{\text{anti-}k_T}(z_h)\bigg] \\
&- \delta(1-z_h)\bigg[2C_F(1+z^2)\left(\frac{\ln(1-z)}{1-z}\right)_+ + C_F(1-z)\bigg]\bigg\}, \qquad (2.43)
\end{aligned}
$$

$$
\begin{aligned}
\Delta\mathcal{J}_{qg}(z,z_h,p_TR,\mu) = {}& \frac{\alpha_s}{2\pi}\bigg\{L\Big[\Delta P_{gq}(z)\delta(1-z_h) - \Delta P_{gq}(z_h)\delta(1-z)\Big] \\
&+ \delta(1-z)\Big[2\Delta P_{gq}(z_h)\ln(1-z_h) - 2C_F(1-z_h) + \Delta\mathcal{I}_{gq}^{\text{anti-}k_T}(z_h)\Big] \\
&- \delta(1-z_h)\Big[2\Delta P_{gq}(z)\ln(1-z) - 2C_F(1-z)\Big]\bigg\}, \qquad (2.44)
\end{aligned}
$$

$$
\begin{aligned}
\Delta\mathcal{J}_{gq}(z,z_h,p_TR,\mu) = {}& \frac{\alpha_s}{2\pi}\bigg\{L\Big[\Delta P_{qg}(z)\delta(1-z_h) - \Delta P_{qg}(z_h)\delta(1-z)\Big] \\
&+ \delta(1-z)\Big[2\Delta P_{qg}(z_h)\ln(1-z_h) + 2T_F(1-z_h) + \Delta\mathcal{I}_{qg}^{\text{anti-}k_T}(z_h)\Big] \\
&- \delta(1-z_h)\Big[2\Delta P_{qg}(z)\ln(1-z) + 2T_F(1-z)\Big]\bigg\}, \qquad (2.45)
\end{aligned}
$$

$$
\begin{aligned}
\Delta\mathcal{J}_{gg}(z,z_h,p_TR,\mu) = {}& \delta(1-z)\delta(1-z_h) + \frac{\alpha_s}{2\pi}\bigg\{L\Big[\Delta P_{gg}(z)\delta(1-z_h) - \Delta P_{gg}(z_h)\delta(1-z)\Big] \\
&+ \delta(1-z)\bigg[4C_A\big(2(1-z_h)^2 + z_h\big)\left(\frac{\ln(1-z_h)}{1-z_h}\right)_+ \\
&\qquad - 4C_A(1-z_h) + \Delta\mathcal{I}_{gg}^{\text{anti-}k_T}(z_h)\bigg] \\
&- \delta(1-z_h)\bigg[4C_A\big(2(1-z)^2 + z\big)\left(\frac{\ln(1-z)}{1-z}\right)_+ - 4C_A(1-z)\bigg]\bigg\}, \qquad (2.46)
\end{aligned}
$$

$$
\begin{aligned}
\Delta_T\mathcal{J}_{qq}(z,z_h,p_TR,\mu) = {}& \delta(1-z)\delta(1-z_h) + \frac{\alpha_s}{2\pi}\bigg\{L\Big[\Delta_T P_{qq}(z)\delta(1-z_h) - \Delta_T P_{qq}(z_h)\delta(1-z)\Big] \\
&+ \delta(1-z)\bigg[4C_F z_h\left(\frac{\ln(1-z_h)}{1-z_h}\right)_+ + \Delta_T\mathcal{I}_{qq}^{\text{anti-}k_T}(z_h)\bigg] \\
&- \delta(1-z_h)\bigg[4C_F z\left(\frac{\ln(1-z)}{1-z}\right)_+\bigg]\bigg\}, \qquad (2.47)
\end{aligned}
$$

$$
\begin{aligned}
\Delta\mathscr{J}_{qq}(z_h,p_TR,\mu) = {}& \delta(1-z_h) + \frac{\alpha_s C_F}{2\pi}\bigg[\delta(1-z_h)\left(\frac{L^2}{2} - \frac{\pi^2}{12}\right) - \Delta P_{qq}(z_h)L \\
&+ 1 - z_h + \Delta\hat{\mathscr{I}}_{qq}^{\text{anti-}k_T}(z_h)\bigg],
\end{aligned}
$$

$$
\Delta\mathscr{J}_{qg}(z_h,p_TR,\mu) = \frac{\alpha_s C_F}{2\pi}\Big[-\Delta P_{gq}(z_h)L - 2(1-z_h) + \Delta\hat{\mathscr{I}}_{qg}^{\text{anti-}k_T}(z_h)\Big],
$$

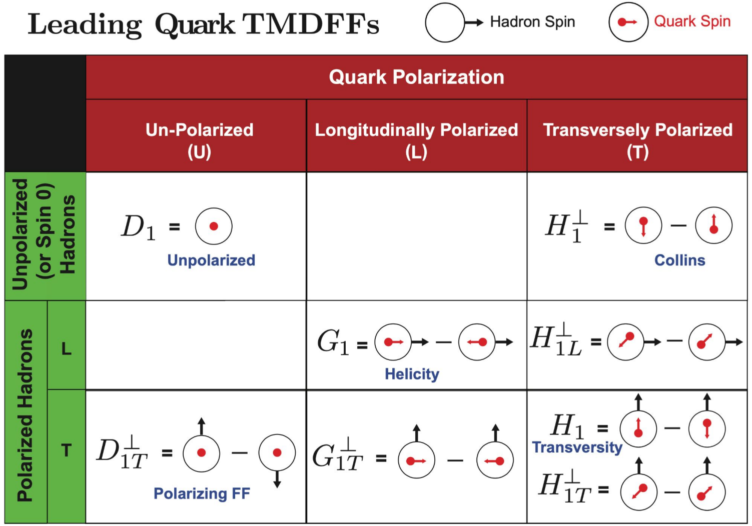
$$
\Delta\mathscr{J}_{gq}(z_h,p_TR,\mu) = \frac{\alpha_s T_F}{2\pi}\Big[-\Delta P_{qg}(z_h)L + 2(1-z_h) + \Delta\hat{\mathscr{I}}_{gq}^{\text{anti-}k_T}(z_h)\Big],
$$

$$
\begin{aligned}
\Delta\mathscr{J}_{gg}(z_h,p_TR,\mu) = {}& \delta(1-z_h) + \frac{\alpha_s C_A}{2\pi}\bigg[\delta(1-z_h)\left(\frac{L^2}{2} - \frac{\pi^2}{12}\right) - \Delta P_{gg}(z_h)L \\
&- 4(1-z_h) + \Delta\hat{\mathscr{I}}_{gg}^{\text{anti-}k_T}(z_h)\bigg],
\end{aligned}
$$

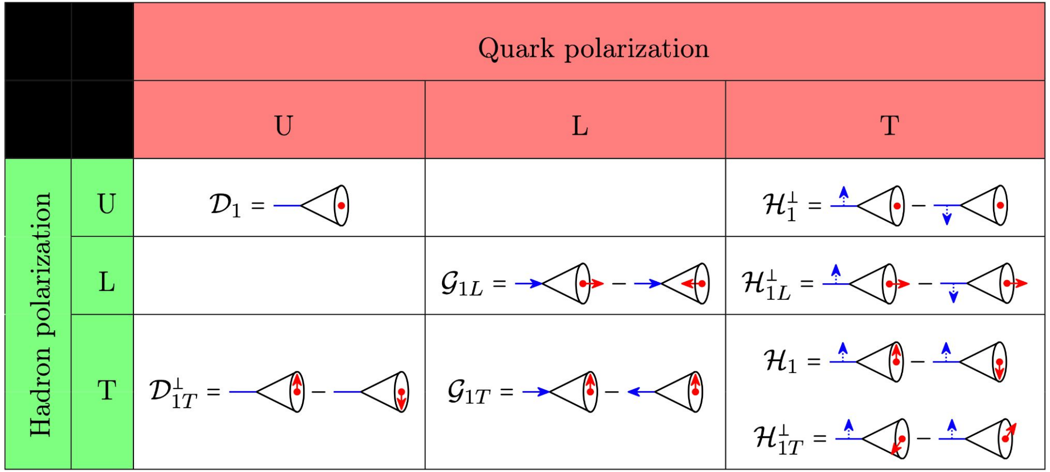
$$
\begin{aligned}
\Delta_T\mathscr{J}_{qq}(z_h,p_TR,\mu) = {}& \delta(1-z_h) + \frac{\alpha_s C_F}{2\pi}\bigg[\delta(1-z_h)\left(\frac{L^2}{2} - \frac{\pi^2}{12}\right) \\
&- \Delta_T P_{qq}(z_h)L + \Delta_T\hat{\mathscr{I}}_{q}^{\text{anti-}k_T}(z_h)\bigg],
\end{aligned}
$$

Relation between **TMD** FFs and **TMD** FJFs

If you measure both z_h and $\boldsymbol{j}_\perp$



TMD handbook, 2304.03302



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How do we connect them?

TMD FJFs

If you measure both z_h and $\boldsymbol{j}_\perp$

$$\mathcal{D}_1(z, z_h, \boldsymbol{j}_\perp) = \hat{H}^U_{c\to i}(z) \int \frac{b\,\mathrm{d}b}{(2\pi)^2} J_0\left(\frac{j_\perp b}{z_h}\right) \widetilde{D}_1^{h/i}(z_h, \boldsymbol{b})$$

Hard splitting & jet formation

Hadron fragmentation & soft correction.

Standard TMD FFs

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ALL coefficients have been computed in our work!

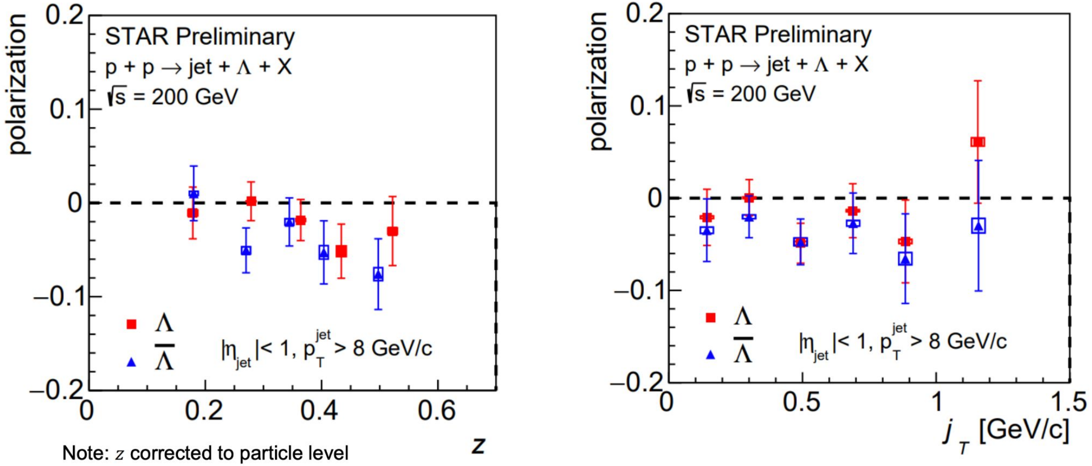
Λ-baryon polarization

STAR, 2023

- Large transverse polarization found for Λ produced in unpolarized hadron scattering

- STAR recent measurement: test of universality of Λ polarized FFs

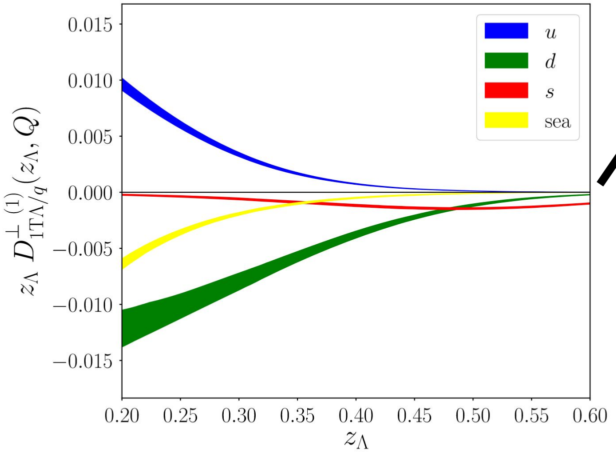
Polarization as a function of z and j_T

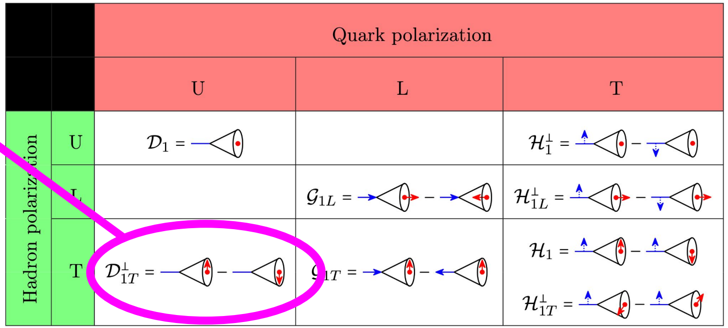


Note: z corrected to particle level

Λ-baryon polarization

$$\mathcal{D}_{1T}^{\perp}(z,z_h,\boldsymbol{j}_\perp)=\hat{H}^U_{c\to i}(z)\int\frac{b^2\,\mathrm{d}b}{(2\pi)^2}\frac{z_\Lambda^2 m_\Lambda^2}{j_\perp}J_1\left(\frac{j_\perp b}{z_\Lambda}\right)\widetilde{D}_1^{\perp,(1)}(z_h,\boldsymbol{b})$$





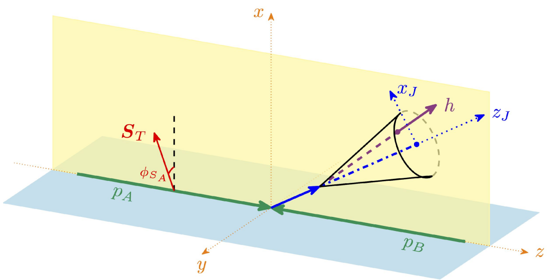
currently in preparation

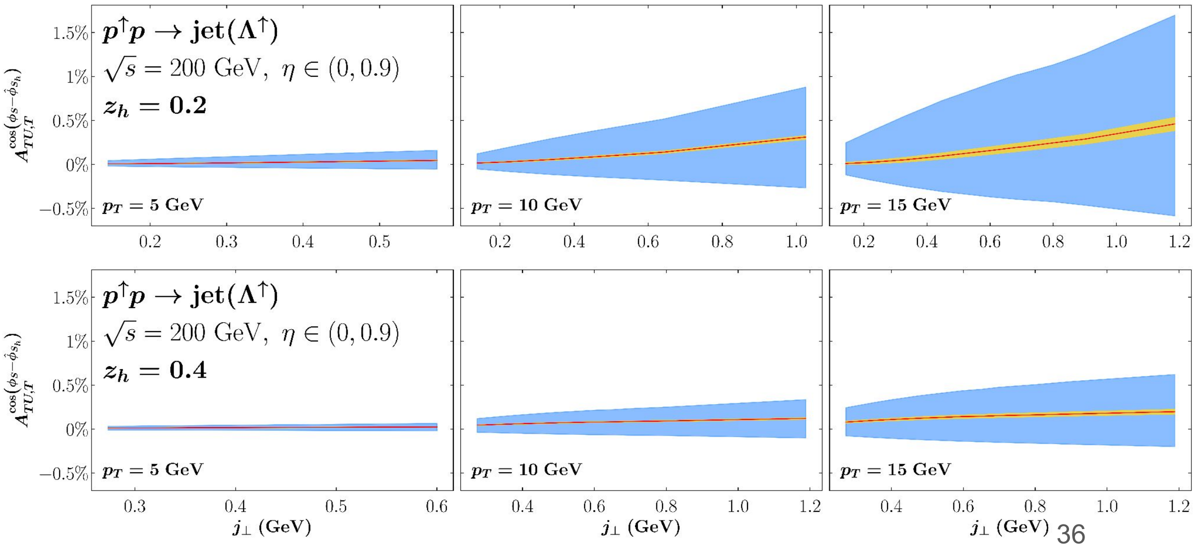
Extracted from BELLE data, 2003.04828

Single inclusive jet production: $pp \to \text{jet}(h)$

- collinear transversity PDFs
- TMD transversely polarized FFs

$$A_{TU,T}(z_h, j_\perp) \equiv \frac{h_1 \otimes f \otimes \mathcal{H}_1 \otimes \Delta_T \hat{\sigma}}{f \otimes f \otimes \mathcal{D}_1 \otimes \hat{\sigma}}$$

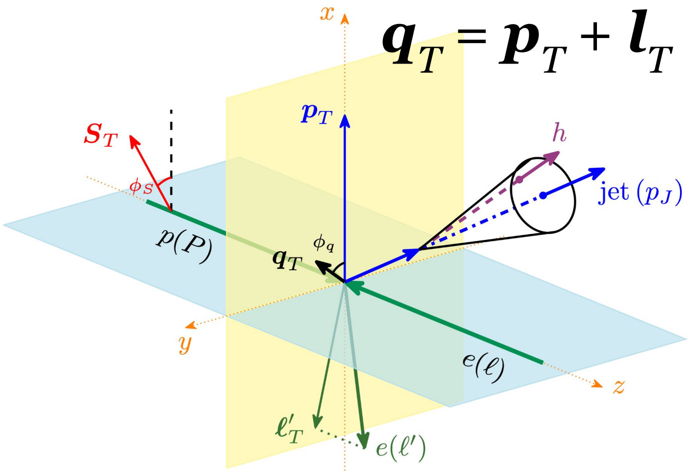




[Kang, Xing, Zhao and **Zhou**, 2311.00672]

Exclusive jet production

- Momentum imbalance $\boldsymbol{q}_T$: sensitive to initial-state TMD distributions
- Hadron $\boldsymbol{j}_\perp$: sensitive to TMD FFs



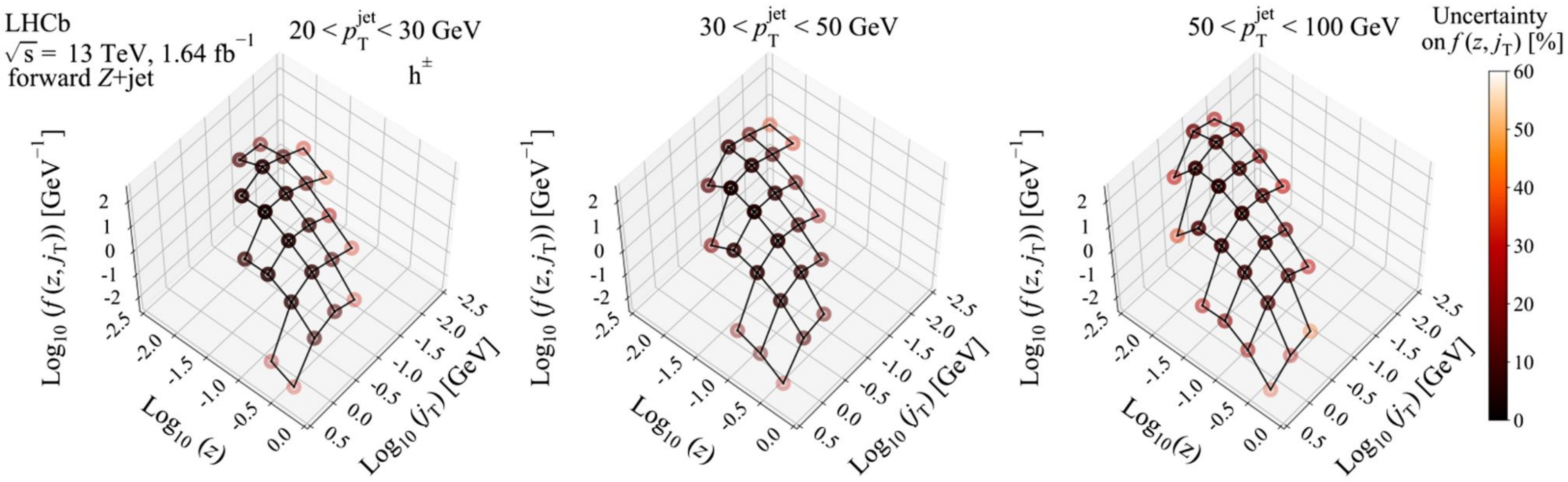
$$\frac{d\sigma_{pp}}{d\mathcal{PS}} = \int \frac{d^2\boldsymbol{b}}{(2\pi)^2} e^{-i\boldsymbol{q}_T\cdot\boldsymbol{b}} \tilde{f}_a^{q/p}(x_a, b)\tilde{f}_b^{q/p}(x_b, b)$$

$$\times \widetilde{S}_{n\bar{n}n_J}(\boldsymbol{b})\widetilde{S}^{cs}_{n_J}(\boldsymbol{b}, R) H_{ab\to cZ}(p_T, m_Z) J_c(p_{JT}R)$$

- Kang, Lee, Shao & Zhao: 2106.15624
- Kang, Lee, Xing, Zhao & Zhou: 2505.XXXX

Exclusive jet production: $pp \to Z + \text{jet}(h)$

- Recent measurement by LHCb (2208.11691)
- First time differential in both z_h and $\boldsymbol{j}_\perp$ (proposed in 1906.07187)



Exclusive jet production: $pp \to Z + \text{jet}(h)$

- JAM fitted FFs (2101.04664, 2202.03372, **Zhou**: in preparation)
- Data included: e^+e^-, SIDIS, polarized SIDIS

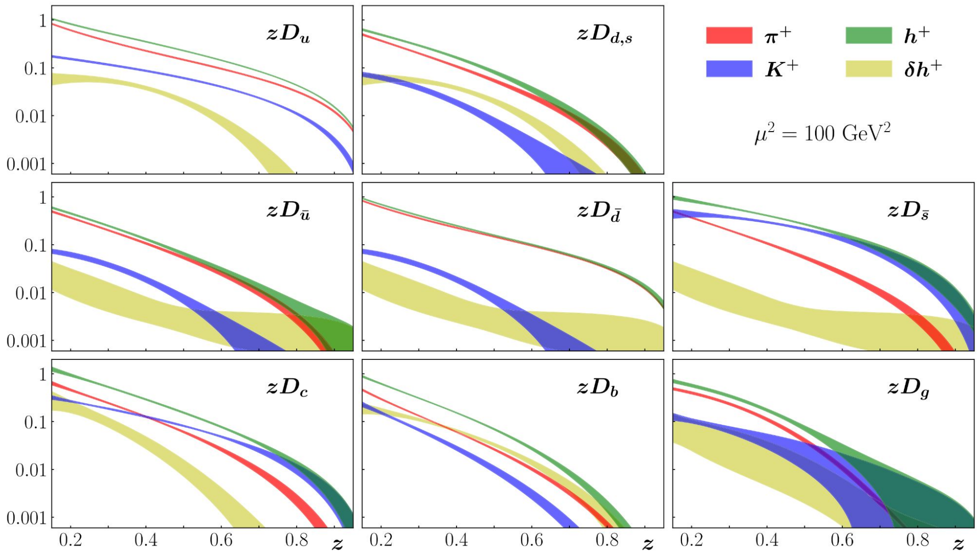
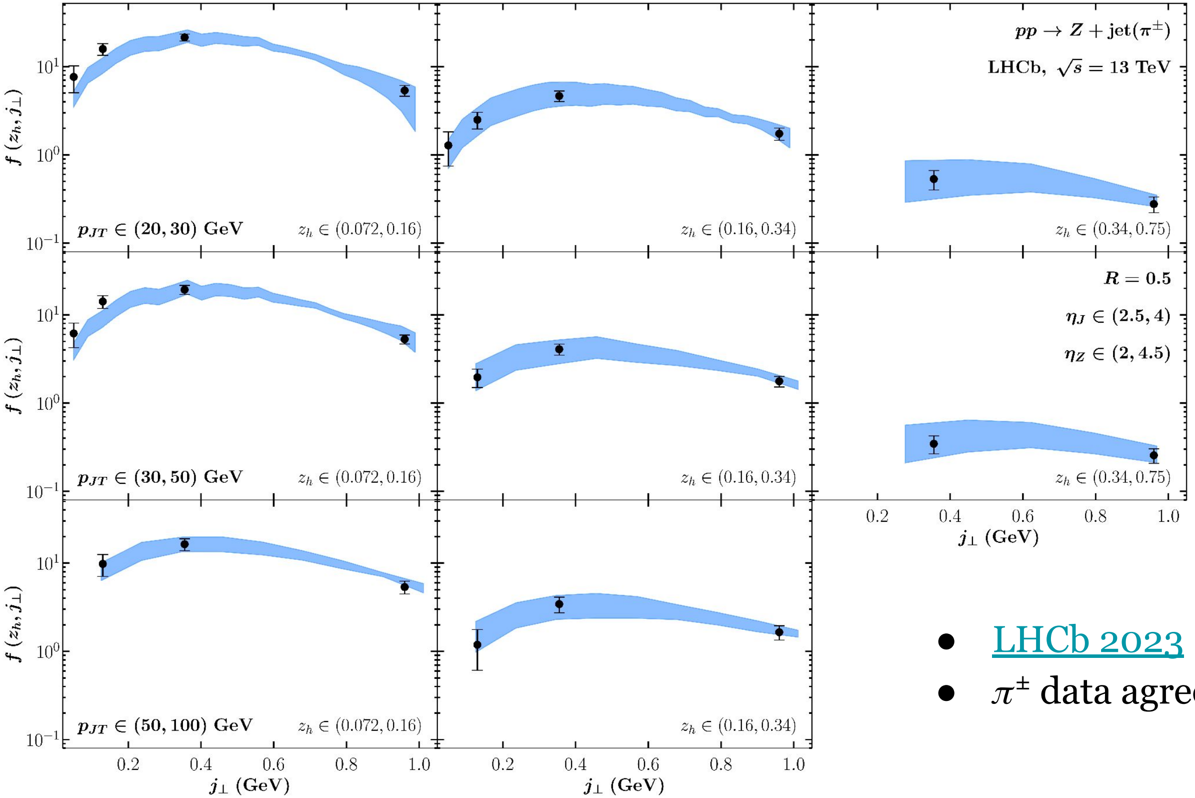


TABLE I. Summary of χ^2 values per number of points $N_{\rm dat}$ for the various datasets used in this analysis.

Process	$N_{\rm dat}$	$\chi^2/N_{\rm dat}$
Polarized		
Inclusive DIS	365	0.95
SIDIS (π^+, π^-)	64	1.05
SIDIS (K^+, K^-)	57	0.42
SIDIS (h^+, h^-)	110	0.95
Inclusive jets	83	0.84
STAR $W^\pm$	12	0.65
PHENIX $W^\pm/Z$	6	0.50
Total	**697**	**0.89**
Unpolarized		
Inclusive DIS	3908	1.17
SIDIS (π^+, π^-)	498	0.94
SIDIS (K^+, K^-)	494	1.31
SIDIS (h^+, h^-)	498	0.71
Inclusive jets	198	1.28
Drell-Yan	205	1.21
W/Z production	153	1.01
Total	**5954**	**1.12**
SIA $(\pi^\pm)$	231	0.91
SIA $(K^\pm)$	213	0.70
SIA $(h^\pm)$	120	1.07
Total	**7215**	**1.08**

Exclusive jet production: $pp \to Z + \text{jet}(\pi^{\pm})$

$\pi^{\pm}$

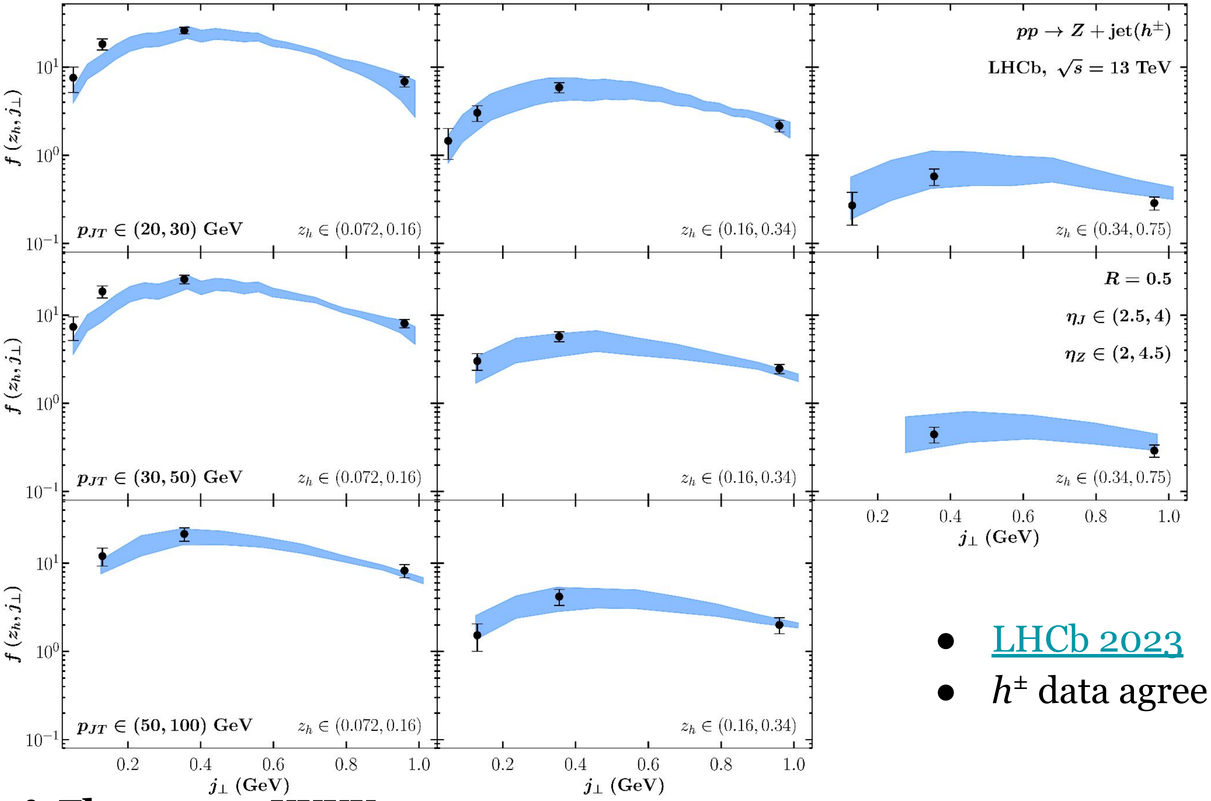


- LHCb 2023
- $\pi^{\pm}$ data agree very well ✓

Kang, Lee, Xing, Zhao & **Zhou**: 2505.XXXX

Exclusive jet production: $pp \to Z + \text{jet}(h^{\pm})$

$h^{\pm}$



- LHCb 2023
- $h^{\pm}$ data agree very well ✓

Kang, Lee, Xing, Zhao & **Zhou**: 2505.XXXX

Exclusive jet production: $p\text{Pb} \to Z + \text{jet}(h)$

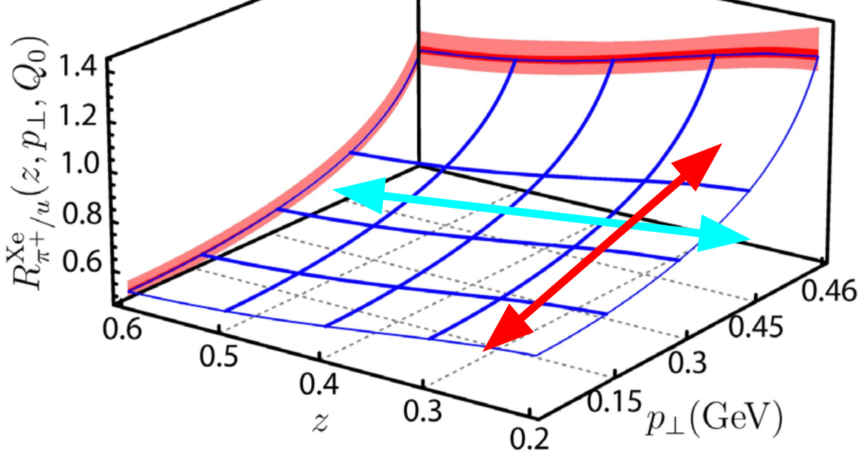
- Nuclear TMD modification extracted in [Alrashed, Anderle, Kang, Terry and Xing, 2107.12401]

- Fitted for TMD PDFs & TMD FFs

$$S_{\rm NP}^{q/A,f}(b, Q_0, \sqrt{\zeta_a}) = \frac{g_2}{2}\ln\left(\frac{b}{b_*}\right)\ln\left(\frac{\sqrt{\zeta_a}}{Q_0}\right) + g_1^{q/A} b^2\,,$$

$$g_1^{q/A} = g_1 + a_N L, \quad L = A^{1/3} - 1$$

$$R^{\rm Xe}_{\pi^+/u} \equiv \frac{D^{\rm Xe}_{\pi^+/u}}{D^{p}_{\pi^+/u}}$$



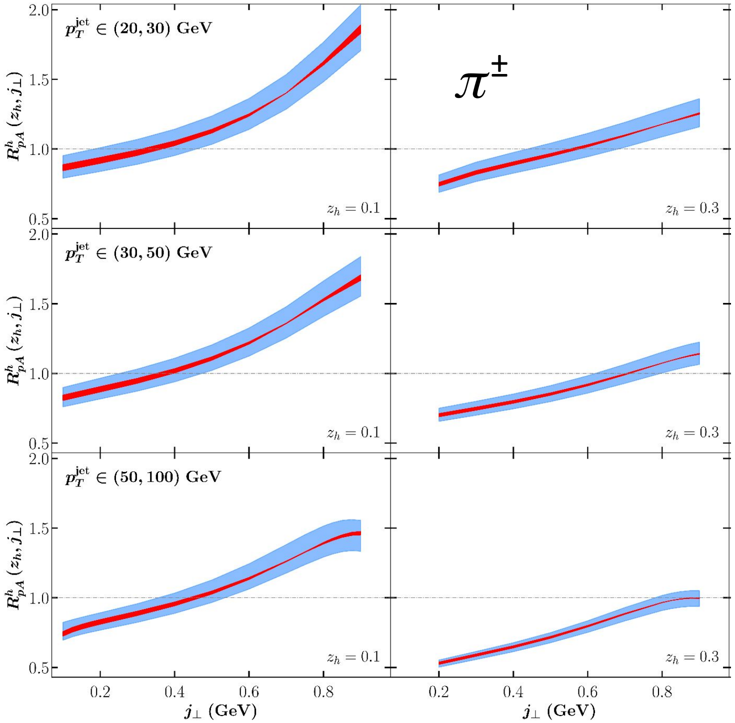
- **Broadening of transverse momentum distribution**
- **Behaviour driven by collinear FFs**

Kang, Lee, Xing, Zhao & **Zhou**: 2403.XXXX

Exclusive jet production: $p\text{Pb} \to Z + \text{jet}(h)$

- Nuclear TMD modification extracted in [Alrashed, Anderle, Kang, Terry and Xing, 2107.12401]
- The reaction is $p\text{Pb} \to Z + \text{jet}(\pi^{\pm})$
- LHC is interested in the observable and is planning to measure it

$$S_{\rm NP}^{q/A,f}(b, Q_0, \sqrt{\zeta_a}) = \frac{g_2}{2} \ln\left(\frac{b}{b_*}\right) \ln\left(\frac{\sqrt{\zeta_a}}{Q_0}\right) + g_1^{q/A} b^2 \,,$$

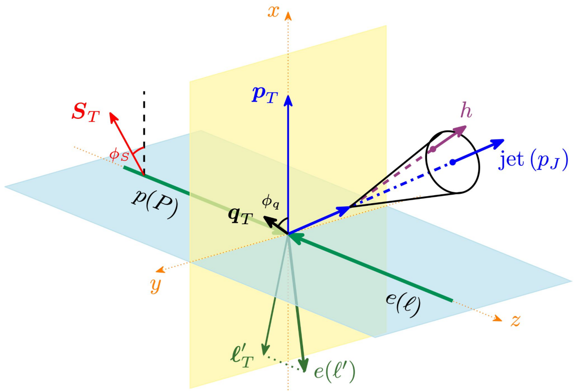


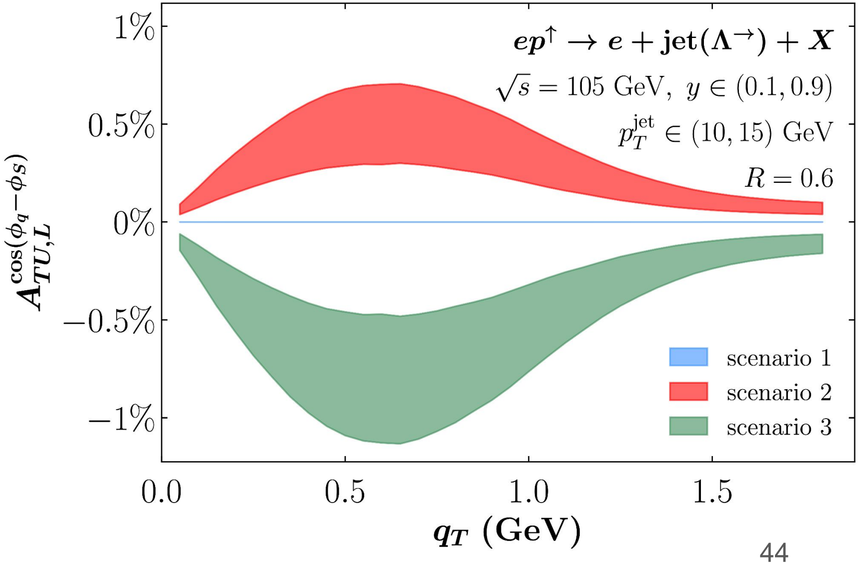
Kang, Lee, Xing, Zhao & **Zhou**: 2505.XXXX

Exclusive jet production: $ep \to e + \text{jet}(h)$

- worm-gear function
- longitudinally polarized FFs

$$A_{TU,L}(z_h, j_\perp) \equiv \frac{\hat{\sigma}_0 H \mathscr{G}_{1L} \widetilde{g}_{1T} \overline{S}_{\text{global}} \overline{S}_{\text{cs}}}{\hat{\sigma}_0 H \mathscr{D}_1 \widetilde{f}_1 \overline{S}_{\text{global}} \overline{S}_{\text{cs}}}$$





Kang, Xing, Zhao and **Zhou**, 2311.00672

Summary of TMD section

- We established relations between **jet** fragmentation functions and **standard** fragmentation functions in all possible polarizations
- We use them to describe experimental data at RHIC and LHC
    - Kaon FFs can be further constrained from LHCb data
    - Λ polarization in jet from STAR can be described by our formalism
- Nuclear TMD corrections can also be studied with our formalism