2022 RHIC/AGS ANNUAL USERS' MEETING

From RHIC to EIC

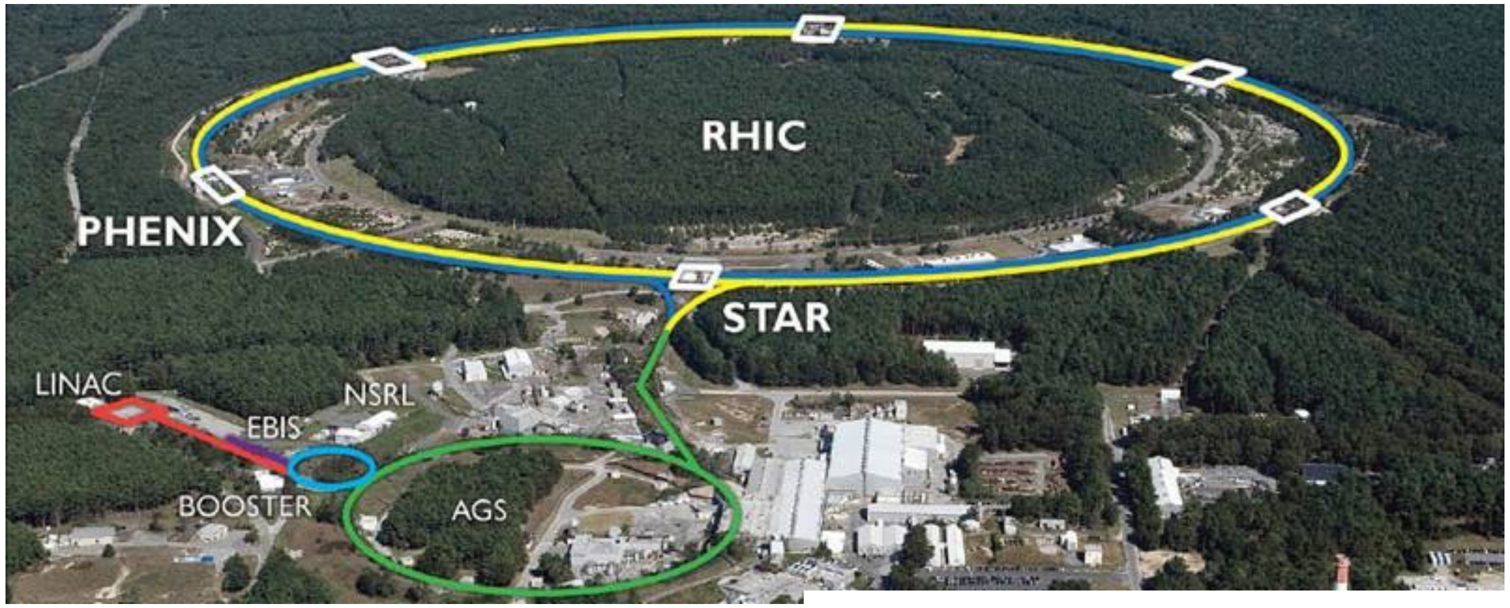
At the QCD Frontiers

Hosted by Brookhaven National Laboratory
June 7–10, 2022

“Cold‘’ QCD from RHIC to EIC

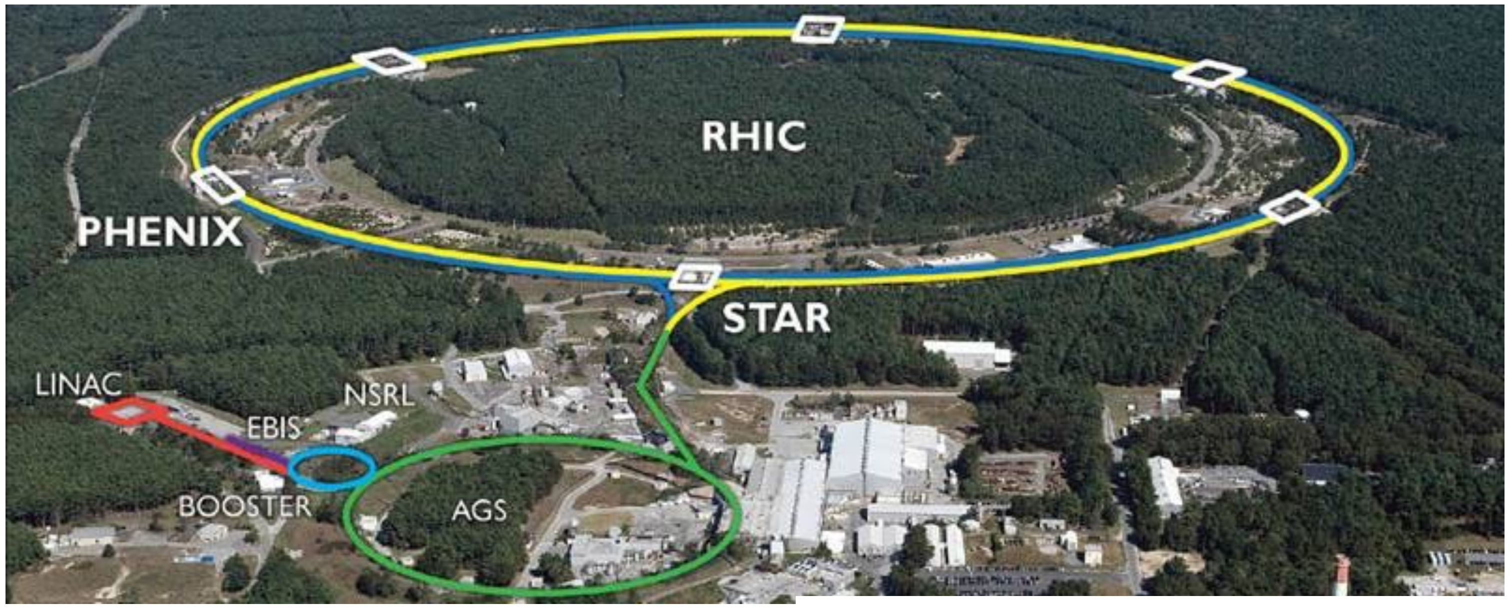
Alexei Prokudin

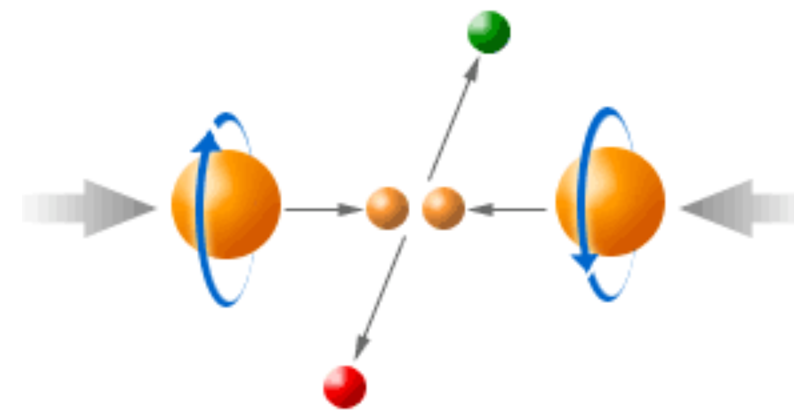
FROM RHIC TO THE EIC



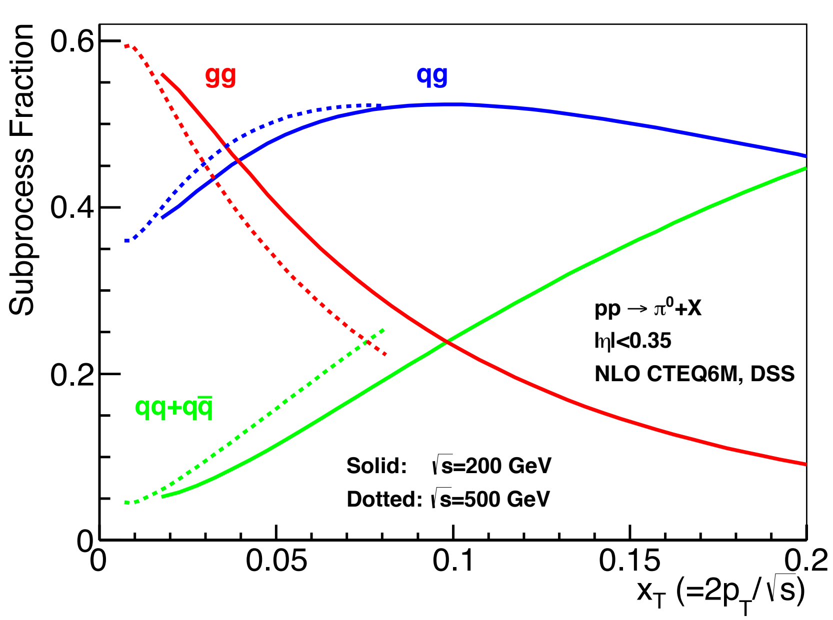
- RHIC is the only collider dedicated to heavy ion research and the only polarized proton collider for transformative studies of extreme states of nuclear matter and the origin of the proton spin.
- Highly polarized, ~60%, with proton beams at $\sqrt{s}$ energy 62.4, 200, 500, 510 GeV.
- All ion beams from protons to heavy nuclei such as gold, lead, and uranium at 100 GeV per nucleon.
- Two major detectors, STAR and PHENIX.

FROM RHIC TO THE EIC





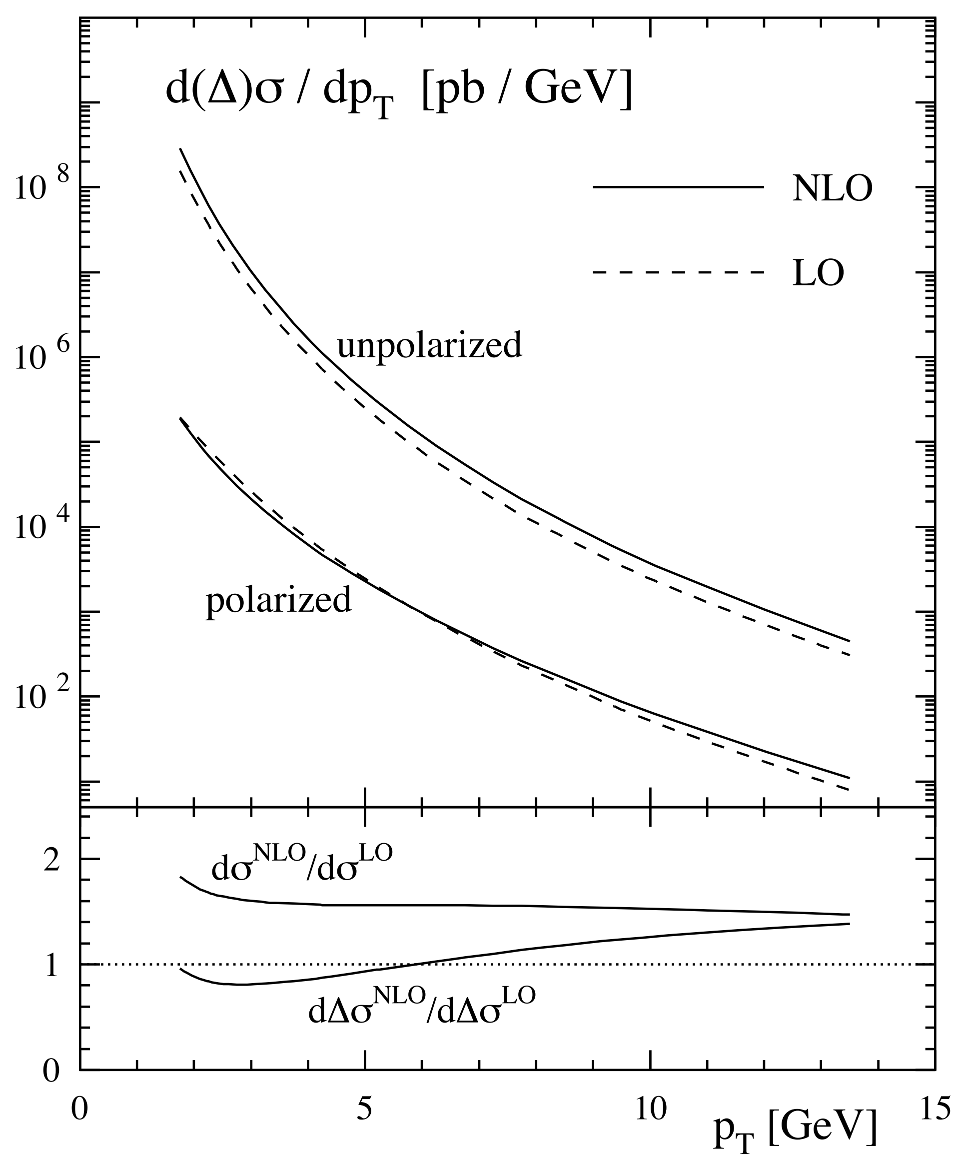
- RHIC is very significant for cold QCD studies.
- Polarized proton-proton collisions with various final states: hadrons, jets, di-lepton pairs, photons etc, give access to the internal (spin) structure.
- The initial states have complicated color structure, making the interpretation nontrivial.



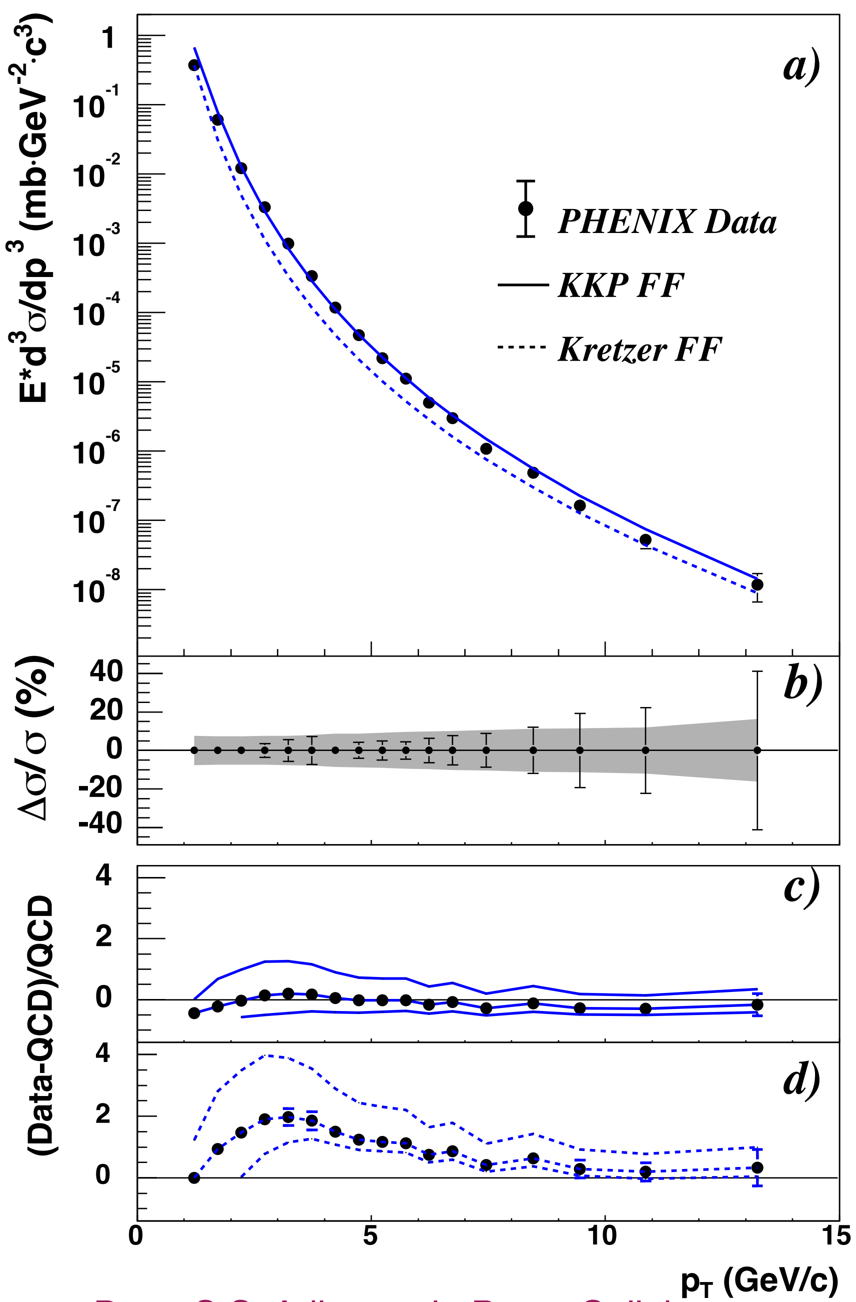
FROM RHIC TO THE EIC

The interpretation of RHIC data is the triumph of perturbative QCD.
Agreement with pQCD over 8 orders of magnitude!

$$pp \to \pi^0 X$$



Prediction: Jager, Schaefer, Stratmann, Vogelsang, *Phys.Rev.D* 67 (2003) 054005

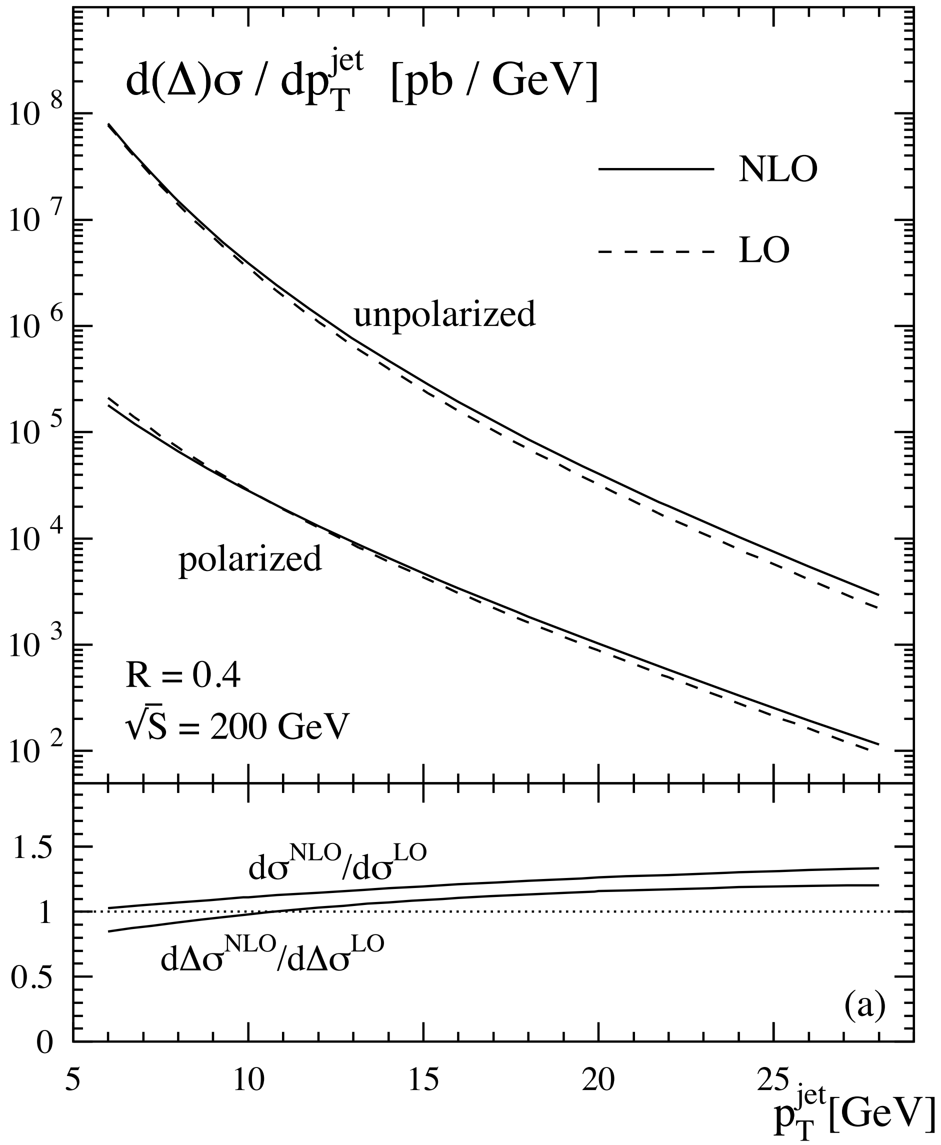


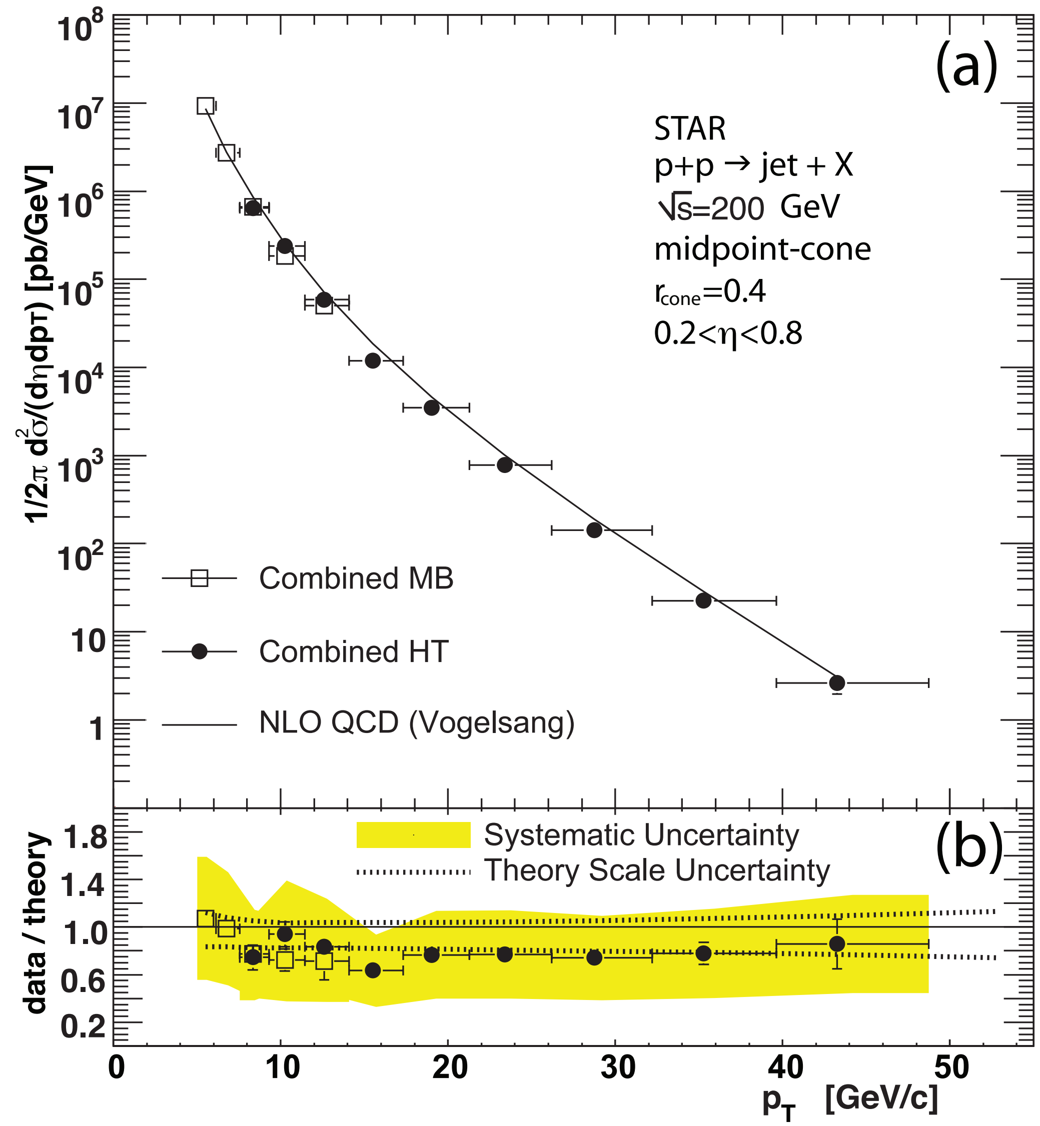
Data: S.S. Adler et al., PHENIX Collab., Phys. Rev. Lett. **91** (2003) 241803

FROM RHIC TO THE EIC

Agreement with pQCD over 8 orders of magnitude!

$$pp \to jet\ X$$

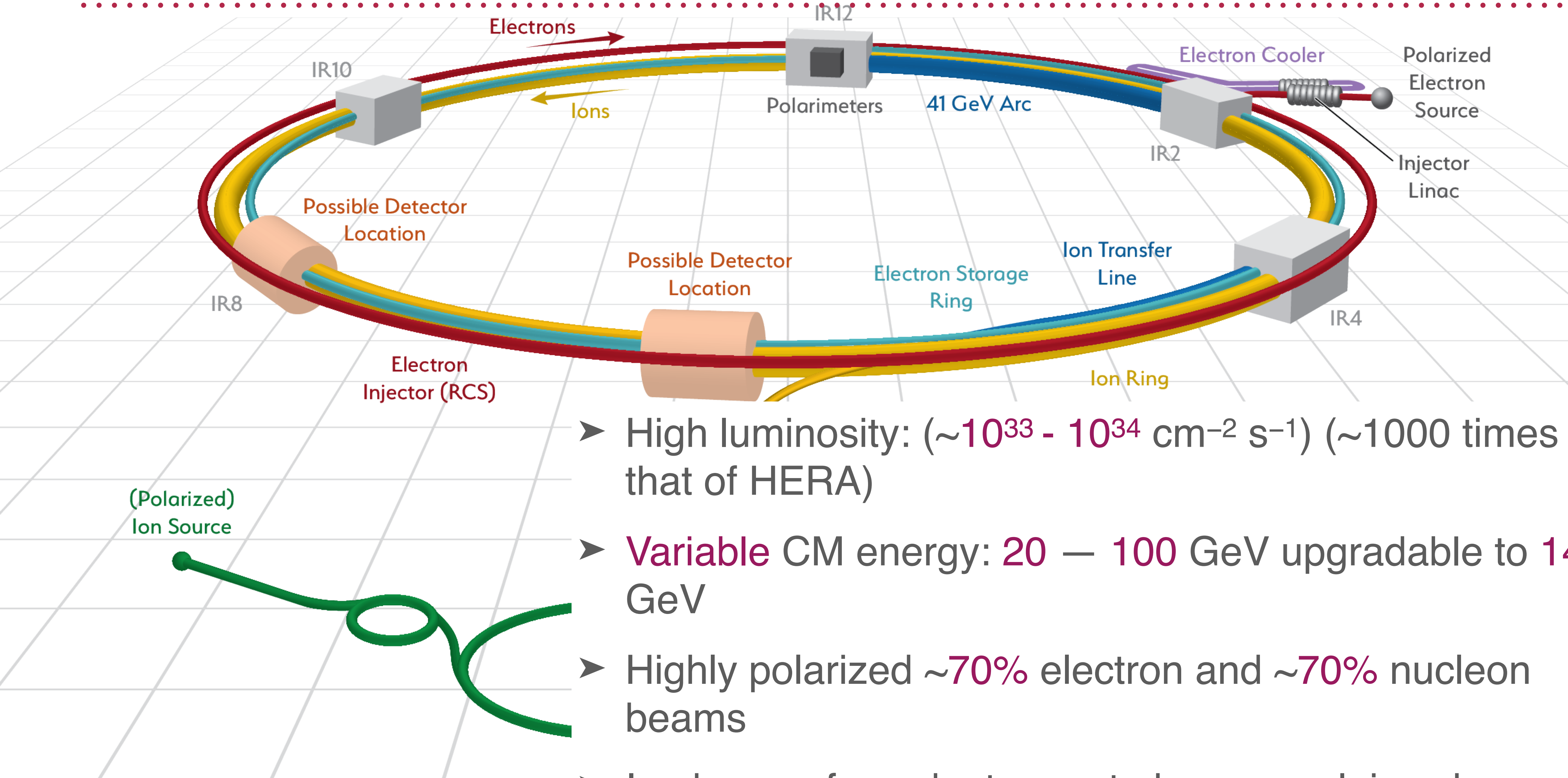




Prediction: Jager, Stratmann, Vogelsang, *Phys.Rev.D* 70 (2004) 034010

Data: B.I. Abelev et al., STAR Collab., Phys.Rev.Lett. 97 (2006) 252001

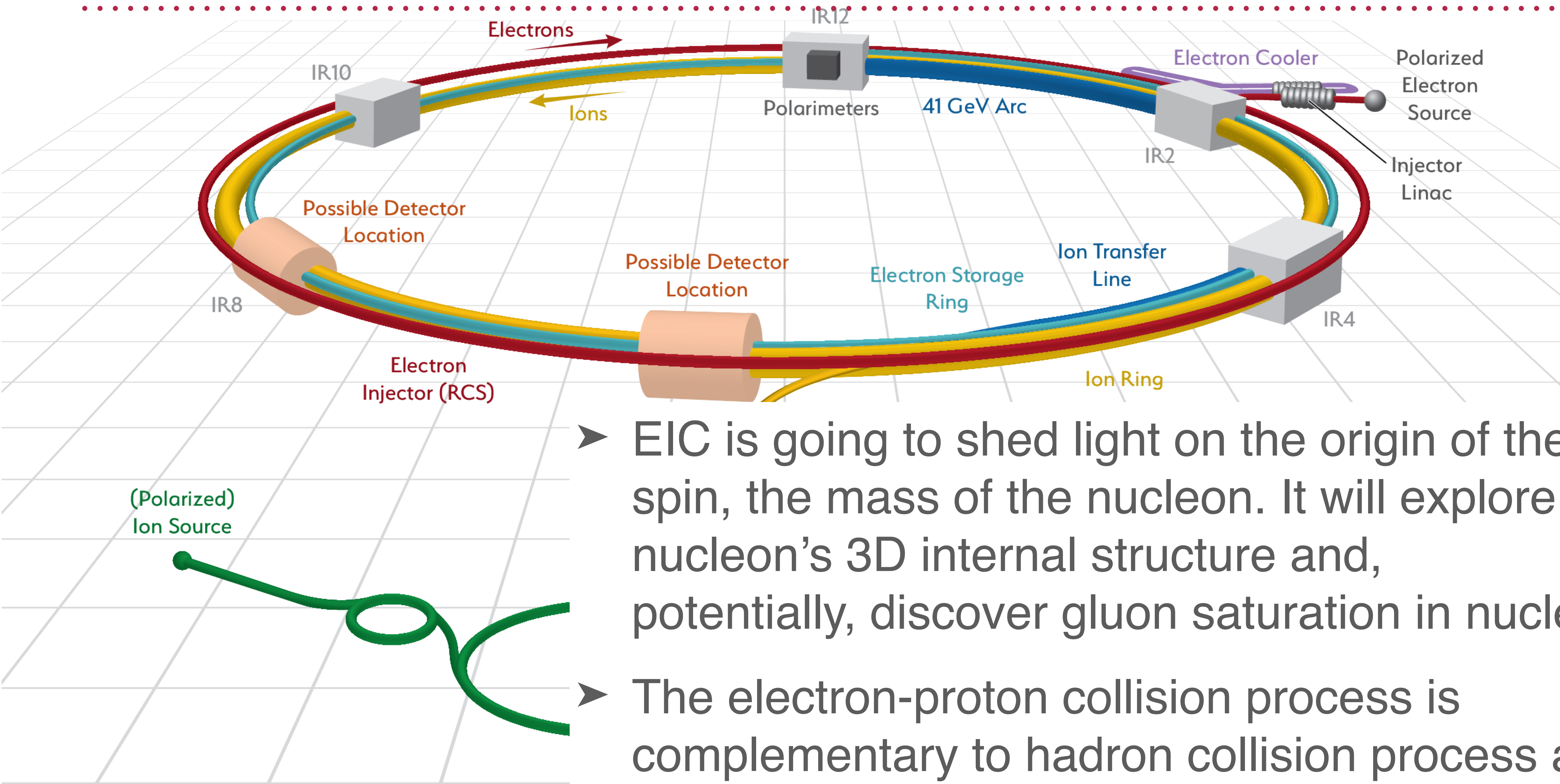
THE ELECTRON-ION COLLIDER @ BNL



White Paper (2012)
Accardi et al, arXiv:1212:1701

- High luminosity: (~10^{33} - 10^{34} cm^{-2} s^{-1}) (~1000 times that of HERA)
- Variable CM energy: 20 — 100 GeV upgradable to 140 GeV
- Highly polarized ~70% electron and ~70% nucleon beams
- Ion beams from deuterons to heavy nuclei such as gold, lead, or uranium
- Possibility of more than one interaction region (none of the major facilities operates with one detector only - important for discovery potential)

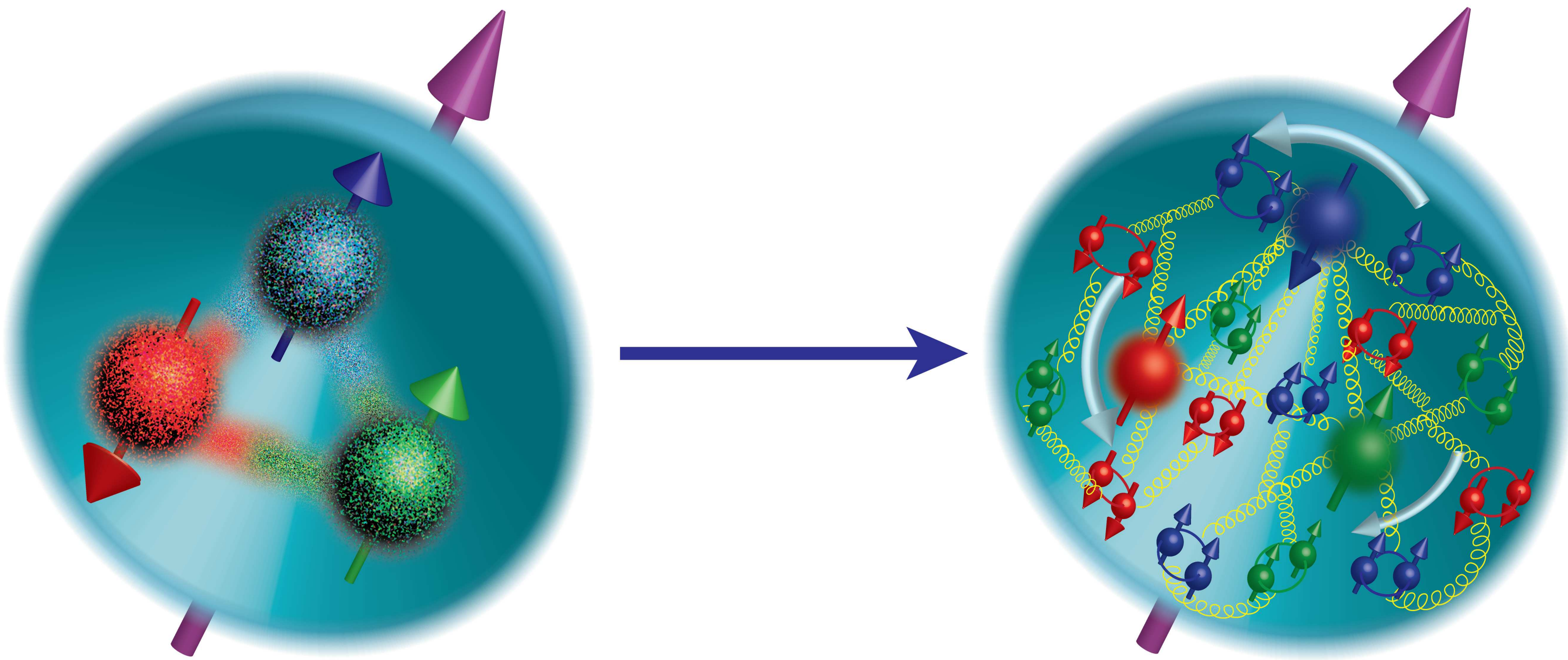
THE ELECTRON-ION COLLIDER @ BNL



White Paper (2012)
Accardi et al, arXiv:1212:1701

- EIC is going to shed light on the origin of the spin, the mass of the nucleon. It will explore nucleon's 3D internal structure and, potentially, discover gluon saturation in nuclei.
- The electron-proton collision process is complementary to hadron collision process at RHIC.
- Relatively simpler initial states allow for more straightforward interpretation of the data.

EVOLUTION OF OUR UNDERSTANDING OF THE SPIN STRUCTURE



1980' - the spin of the nucleon is due to the valence quarks

Modern concept: valence quarks, sea quarks, and gluons together with orbital angular momentum are contributing

COLLINEAR SPIN STRUCTURE

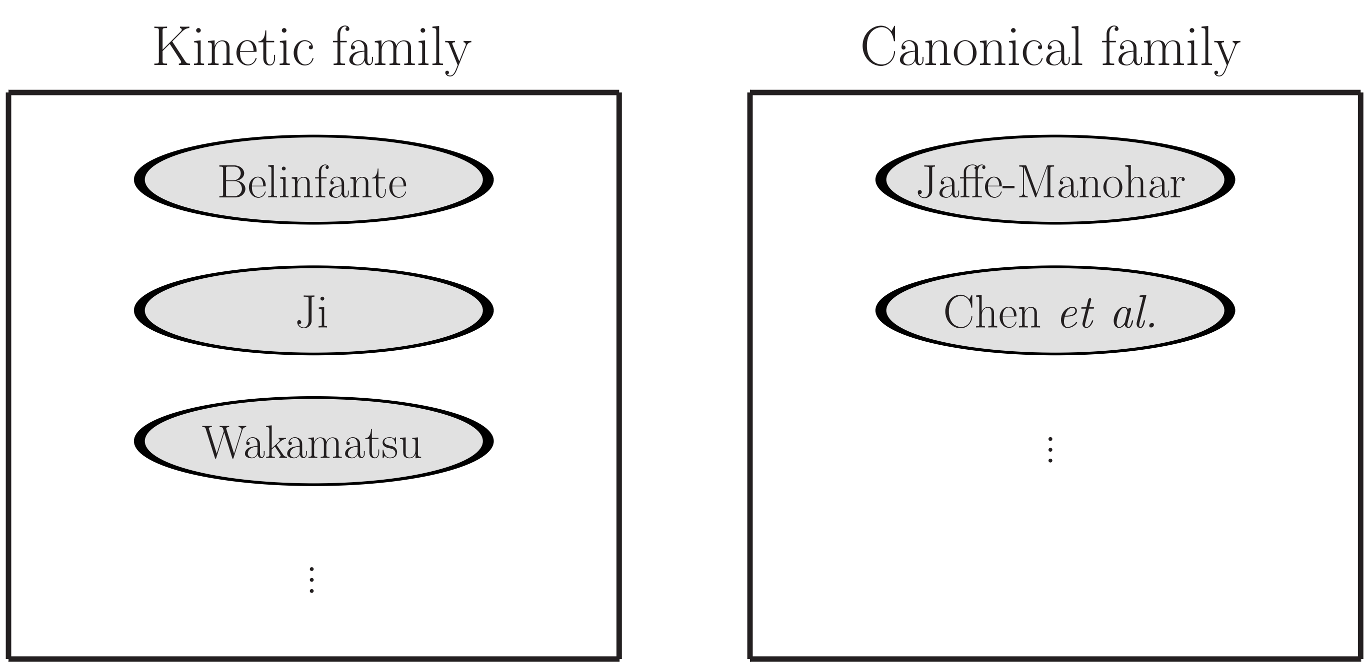
COLLINEAR SPIN STRUCTURE

Spin-1/2 nucleon can be described by three collinear parton distribution functions (pdf)

N \ q	U	L	T	
U	f_1			unpolarized pdf
L		g_1		helicity pdf
T			h_1	transversity pdf

SPIN DECOMPOSITION

- The nucleon is a composite system. The spin is carried by its constituents: quarks, anti-quarks and gluons and the angular momentum generated by their motion.
- The nucleon at rest has spin 1/2, however its decomposition in terms of spin and orbital contributions associated with quarks and gluons is not unique.
- There are two types of decompositions of the proton spin operator: kinetic (also known as mechanical) and canonical. These two types differ by how the OAM operator is split into the quark and gluon contributions. They share the same quark spin operator.



R. L. Jaffe and A. Manohar, Nucl. Phys. B337, 509 (1990)
S. Bashinsky and R. L. Jaffe, Nucl. Phys. B 536 (1998)
X. Ji, Phys. Rev. Lett. 78 (1997)
X. -S. Chen, X. -F. Lu, W. -M. Sun, F. Wang and T. Goldman, Phys. Rev. Lett. 100 (2008)
M. Wakamatsu, Phys. Rev. D 83 (2011)
Y. Hatta, Phys. Rev. D 84 (2011)
E. Leader and C. Lorce, Phys.Rept. 541, 163 (2014)
C. Lorcé and B. Pasquini, JHEP 09 (2013)
C. Lorcé and B. Pasquini, Phys. Rev. D 84, (2011)
C. Lorcé, B. Pasquini, X. Xiong and F. Yuan, Phys. Rev. D 85, (2012)
L. Adhikari and M. Burkard, Phys.Rev.D 94 (2016)

- Kinetic family is related to Generalized Parton Distributions, while canonical in light cone gauge is related to collinear helicity distribution functions

LONGITUDINAL SPIN

When the proton or the neutron are polarized, quarks and gluons are polarized as well. Helicity distribution functions: number of quarks/gluons with spin parallel to the nucleon momentum minus the number of quarks/gluons with the spin opposite to the nucleon momentum

$$\Delta f(x,Q^2) = g_1(x,Q^2) \equiv f^+(x,Q^2) - f^-(x,Q^2)$$

The relevant spin decomposition is by Jaffe and Manohar

R. L. Jaffe and A. Manohar, Nucl. Phys. B337, 509 (1990)

$$\frac{1}{2} = S_q + \mathcal{L}_q + S_g + \mathcal{L}_g$$

Related to measured observables:

Quark spin contribution

$$S_q = \frac{1}{2}\int_0^1 \Delta\Sigma(x,Q^2)dx \equiv \frac{1}{2}\int_0^1 (\Delta u + \Delta\bar{u} + \Delta d + \Delta\bar{d} + \Delta s + \Delta\bar{s})(x,Q^2)dx$$

Gluon spin contribution

$$S_g = \int_0^1 \Delta g(x,Q^2)dx$$

Difficult to measure in experiment:

$$\mathcal{L}_q + \mathcal{L}_g$$

quark and gluon orbital angular momenta (OAM) via twist-3 GPDs, Wigner functions

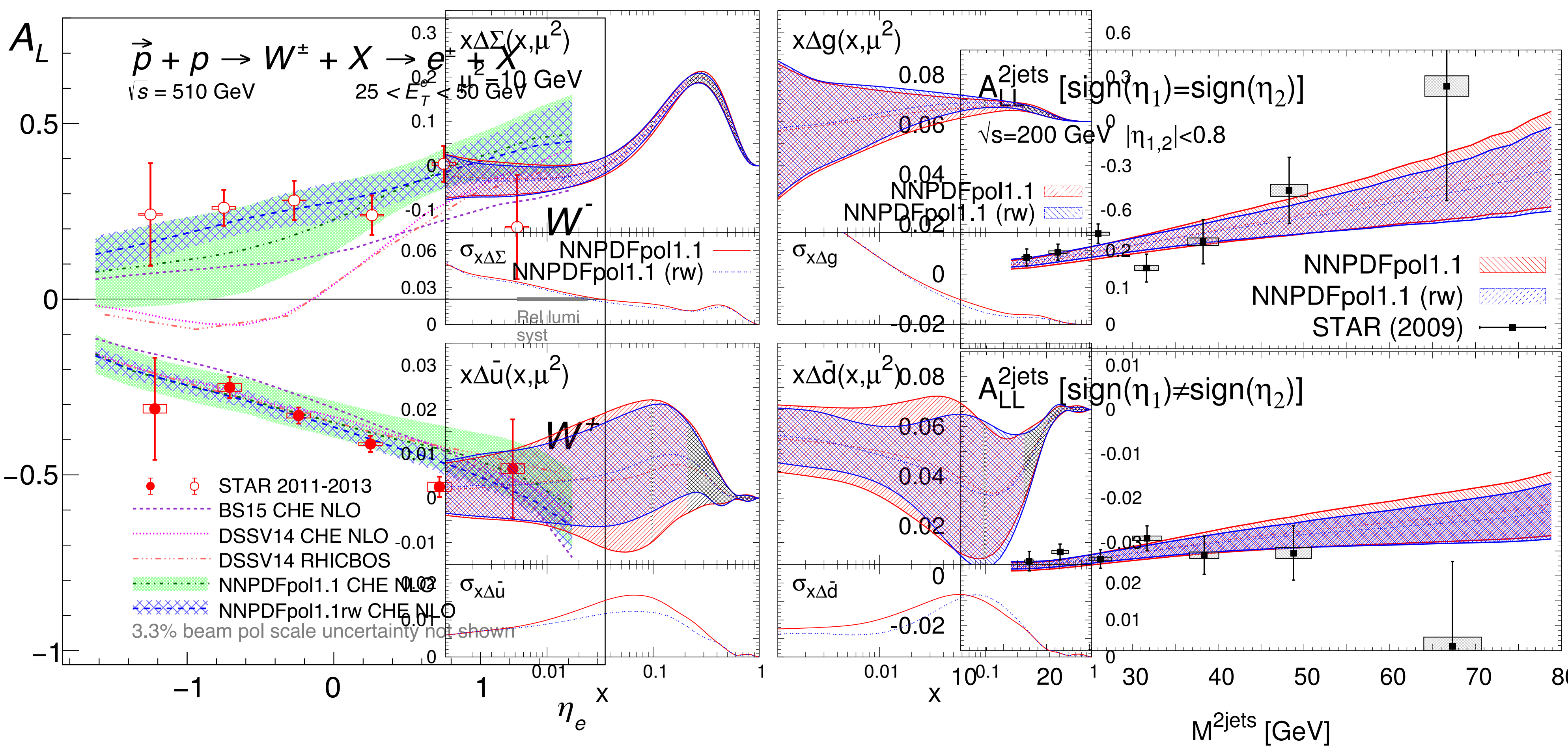
D.V. Kiptily, M.V. Polyakov, Eur. Phys. J. C 37 (2004
A. Courtoy, G. R. Goldstein, J. O. Gonzalez Hernandez, S. Liuti, A. Rajan, PLB 731 (2014)
Y. Hatta, Phys. Lett. B 708 (2012);
Y. Hatta, S. Yoshida, J. High Energy Phys. 1210 (2012

LONGITUDINAL SPIN

- Global QCD analyses are performed to extract helicity pdfs:

  DSSV: D. de Florian, R. Sassot, M. Stratmann and W. Vogelsang, Phys. Rev. Lett. 113 (2014)
  NNPDFpol: E. R. Nocera, R. D. Ball, S. Forte, G. Ridolfi, J. Rojo, Nucl. Phys. B 887 (2014)
  JAM: J. J. Ethier, N. Sato, W. Melnitchouk, Phys. Rev. Lett. 119 (13) (2017)

- At present around $25\ \%$ of the spin is attributed to quarks and anti-quarks.
- The evidence for non-zero gluon contribution, around $30\ \%$, is mainly due to RHIC spin program E. R. Nocera, Impact of Recent RHIC Data on Helicity-Dependent Parton Distribution Functions (2017). arXiv:1702.05077.



J. Adam et al, STAR Collab., *Phys.Rev.D* 99 (2019) 5, 051102 L. Adamczyk et al, STAR Collab., *Phys.Rev.D* 95 (2017) 7, 071103

LONGITUDINAL SPIN

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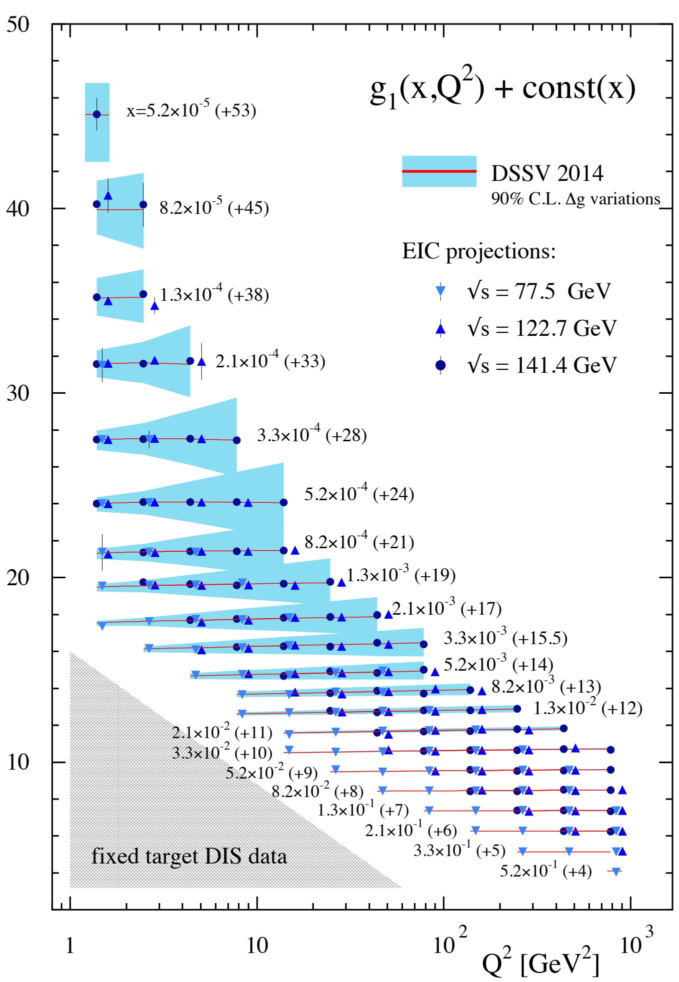
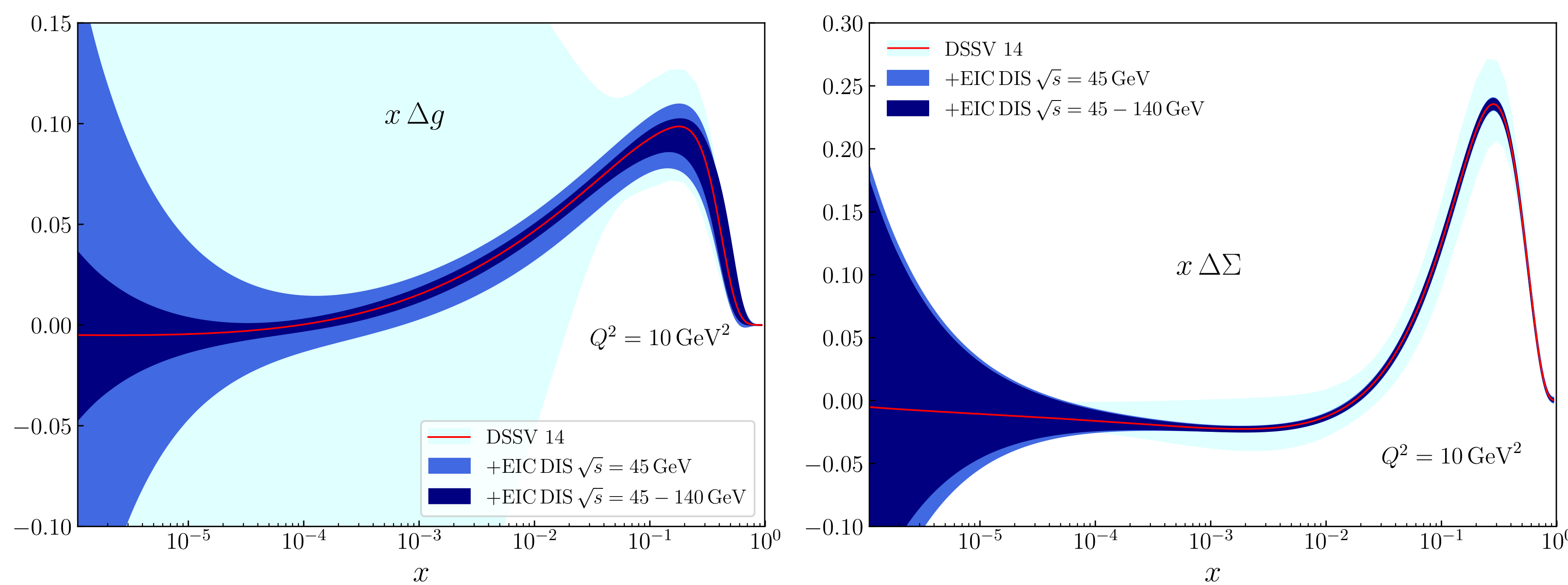
The impact of the EIC on determination of the quark and gluon contributions



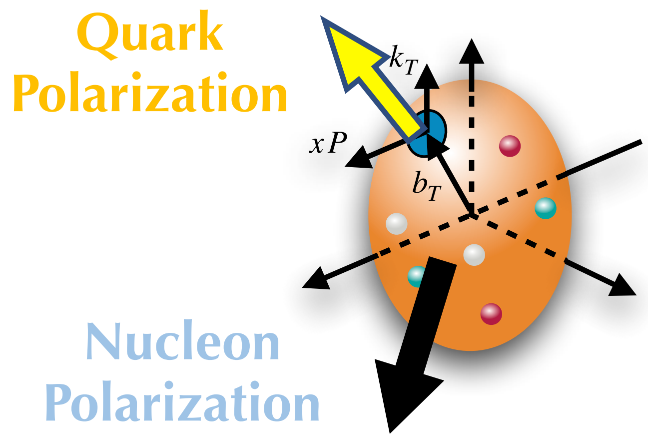


Yellow Report (2021) arXiv:2103.05419

Aschenauer , Sassot, Stratmann, Phys.Rev.D 92 (2015)

BEYOND THE COLLINEAR PICTURE

Our understanding of the nucleon evolves: SPIN



Nucleon emerges as a strongly interacting, relativistic bound state of quarks and gluons

TMDs

		Quark Polarization		
		Unpolarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
Nucleon Polarization	U	$f_1(x,k_T^2)$ *Unpolarized*		$h_1^\perp(x,k_T^2)$ - *Boer-Mulders*
	L		$g_1(x,k_T^2)$ - *Helicity*	$h_{1L}^\perp(x,k_T^2)$ - *Kozinian-Mulders, "worm" gear*
	T	$f_{1T}^\perp(x,k_T^2)$ - *Sivers*	$g_{1T}(x,k_T^2)$ - *Kozinian-Mulders, "worm" gear*	$h_1(x,k_T^2)$ - *Transversity* $h_{1T}^\perp(x,k_T^2)$ - *Pretzelosity*

GPDs

		Quark Polarization		
		Unpolarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
Nucleon Polarization	U	H		$\mathcal{E}_T$
	L		$\tilde{H}$	
	T	E		$H_T,\ \tilde{H}_T$

Many TMDs and GPDs cannot exist without OAM.

Examples: TMD Sivers function $f_{1T}^\perp$ and GPD E

Generalized Parton Distributions

LONGITUDINAL SPIN

Studies of DVCS process were highly motivated by Ji decomposition

$$\frac{1}{2} = S_q + L_q + J_g$$

X. Ji, Phys. Rev. Lett. 78 (1997) 610

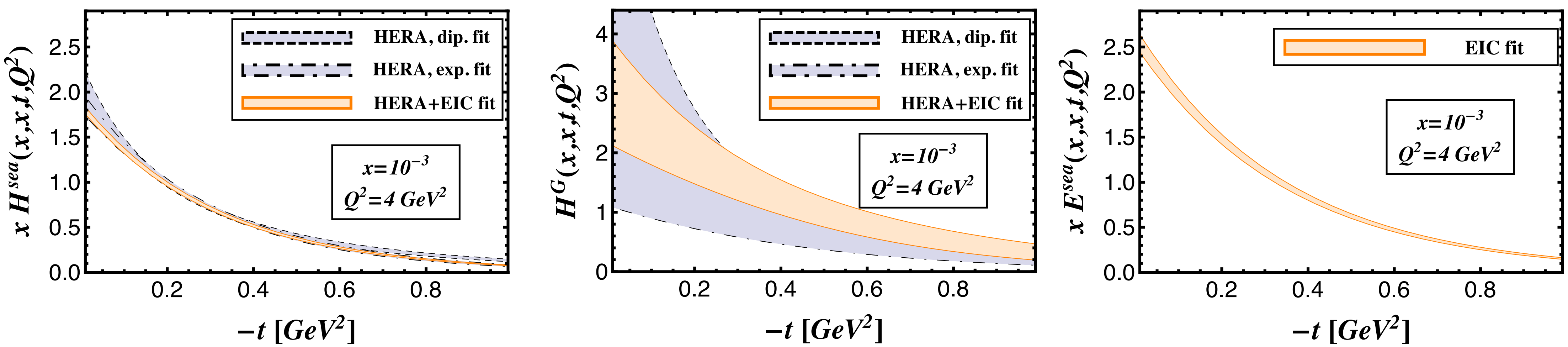
Related to twist-2 GPDs:

$$J_q \equiv S_q + L_q = \frac{1}{2}\int_0^1 \Delta\Sigma(x,Q^2)dx + L_q = \frac{1}{2}\int_{-1}^1 dx x\left(H^q(x,\xi=0,t=0) + E^q(x,\xi=0,t=0)\right)$$

$$J_g = \frac{1}{2}\int_{-1}^1 dx x\left(H^g(x,\xi=0,t=0) + E^g(x,\xi=0,t=0)\right)$$

These quantities can be computed also in lattice simulations

The impact of the EIC on determination of the sea-quark and gluon contributions

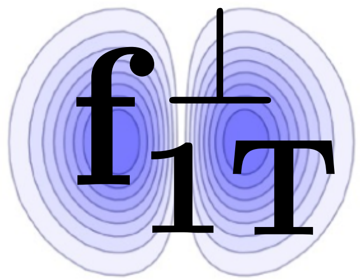


E. Aschenauer, S. Fazio, K. Kumericki, D. Mueller, JHEP 09 (2013) 093

Transverse Momentum Dependent distributions, and transverse Spin

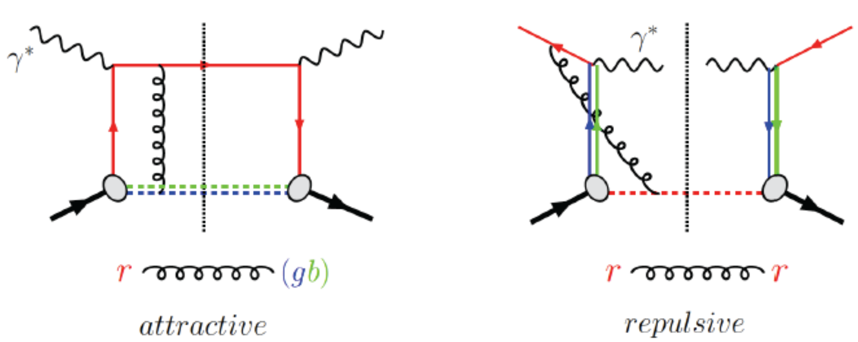
POLARIZED TMD FUNCTIONS

Sivers function $\mathbf{f_{1T}^{\perp}}$

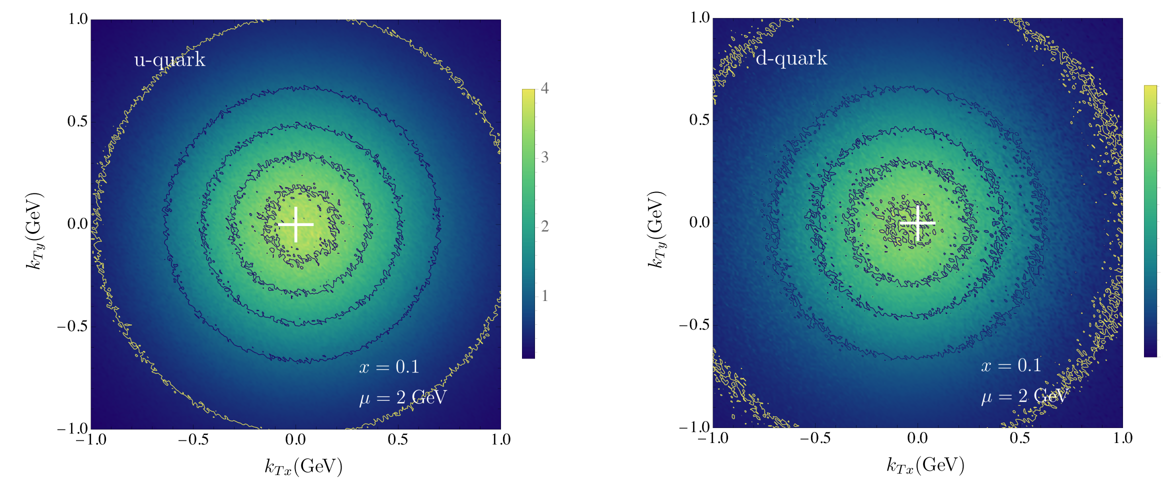


- Describes unpolarized quarks inside of transversely polarized nucleon and is related to the twist-3 Qiu-Sterman matrix element (multi-parton correlation)
- Encodes the correlation of the orbital motion with the spin
- Sign change of Sivers function is fundamental consequence of QCD

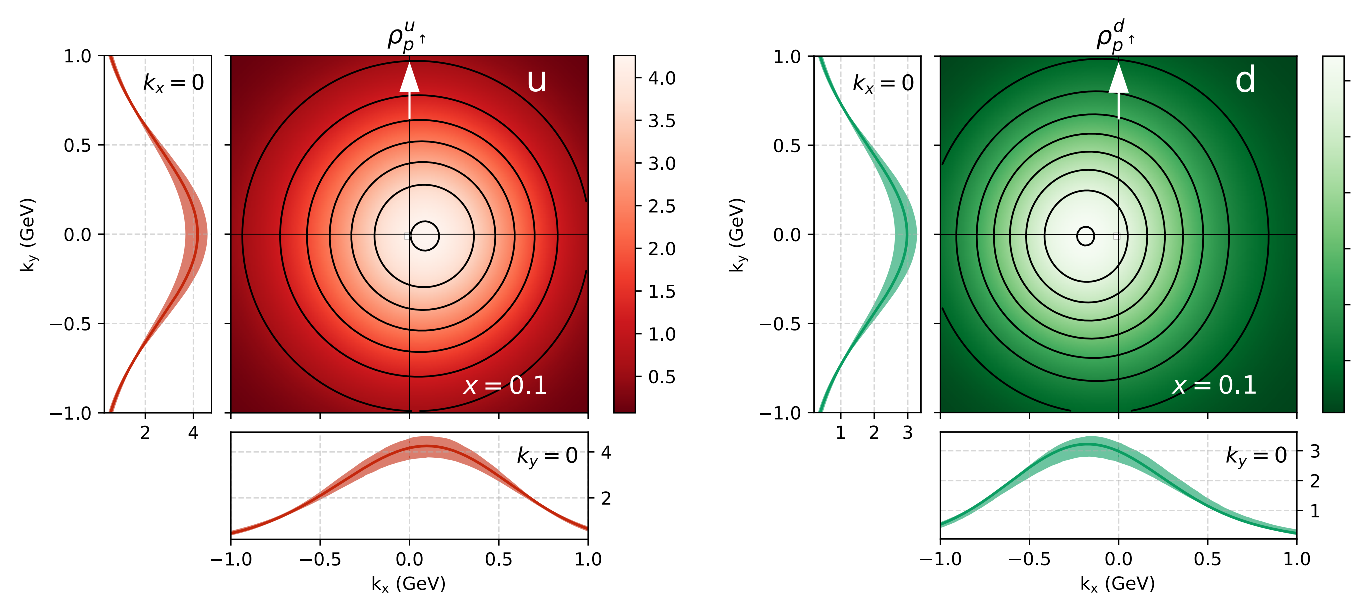
Brodsky, Hwang, Schmidt (2002), Collins (2002)



$$f_{1T}^{\perp SIDIS} = -f_{1T}^{\perp DY}$$



M. Bury, A. Prokudin, A. Vladimirov, Phys.Rev.Lett. 126 (2021)



A. Bacchetta, F. Delcarro, C. Pisano, M. Radici (2020)

THE SIVERS FUNCTION

$$\mu^2 \frac{dF(x,b;\mu,\zeta)}{d\mu^2} = \frac{\gamma_F(\mu,\zeta)}{2} F(x,b;\mu,\zeta),$$

$$\zeta \frac{dF(x,b;\mu,\zeta)}{d\zeta} = -\mathcal{D}(b,\mu) F(x,b;\mu,\zeta),$$

Collins-Soper Equations

μ = renormalization scale

ζ = Collins-Soper parameter

Scimemi, Vladimirov (18), (20)

Vladimirov (20)

- Remarkably simple solution in the zeta-prescription

$$F(x,b;\mu,\zeta) = \left(\frac{\zeta}{\zeta_\mu(b)}\right)^{-\mathcal{D}(b,\mu)} F(x,b)$$

DATA SELECTION

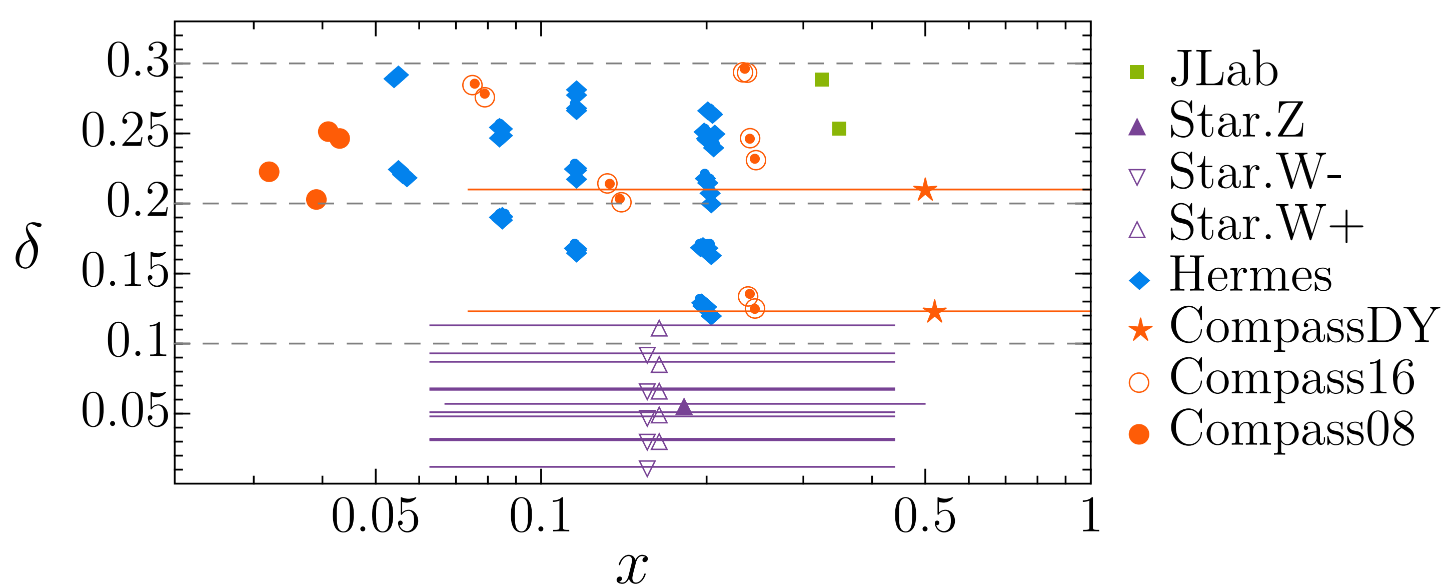
Bury, Prokudin, Vladimirov (2021)

Dataset name	Ref.	Reaction	# Points
Compass08	[36]	$d^\uparrow + \gamma^* \to \pi^+$	1 / 9
		$d^\uparrow + \gamma^* \to \pi^-$	1 / 9
		$d^\uparrow + \gamma^* \to K^+$	1 / 9
		$d^\uparrow + \gamma^* \to K^-$	1 / 9
Compass16	[39]	$p^\uparrow + \gamma^* \to h^+$	5 / 40
		$p^\uparrow + \gamma^* \to h^-$	5 / 40
Hermes	[35]	$p^\uparrow + \gamma^* \to \pi^+$	11 / 64
		$p^\uparrow + \gamma^* \to \pi^-$	11 / 64
		$p^\uparrow + \gamma^* \to K^+$	12 / 64
		$p^\uparrow + \gamma^* \to K^-$	12 / 64
JLab	[41, 42]	${}^3He^\uparrow + \gamma^* \to \pi^+$	1 / 4
		${}^3He^\uparrow + \gamma^* \to \pi^-$	1 / 4
		${}^3He^\uparrow + \gamma^* \to K^+$	1 / 4
		${}^3He^\uparrow + \gamma^* \to K^-$	0 / 4
SIDIS total			63
CompassDY	[40]	$\pi^- + d^\uparrow \to \gamma^*$	2 / 3
Star.W+	[43]	$p^\uparrow + p \to W^+$	5 / 5
Star.W-		$p^\uparrow + p \to W^-$	5 / 5
Star.Z		$p^\uparrow + p \to \gamma^*/Z$	1 / 1
DY total			13
Total			76

- Only P_T dependence used to avoid double counting
- Data selection compatible with TMD factorization requirement

$$\delta = \frac{|P_{hT}|}{zQ}(\text{in SIDIS}), \qquad \delta = \frac{|q_T|}{Q}(\text{in DY}).$$

$$\langle Q \rangle > 2\ \text{GeV} \qquad \text{and} \qquad \delta < 0.3$$



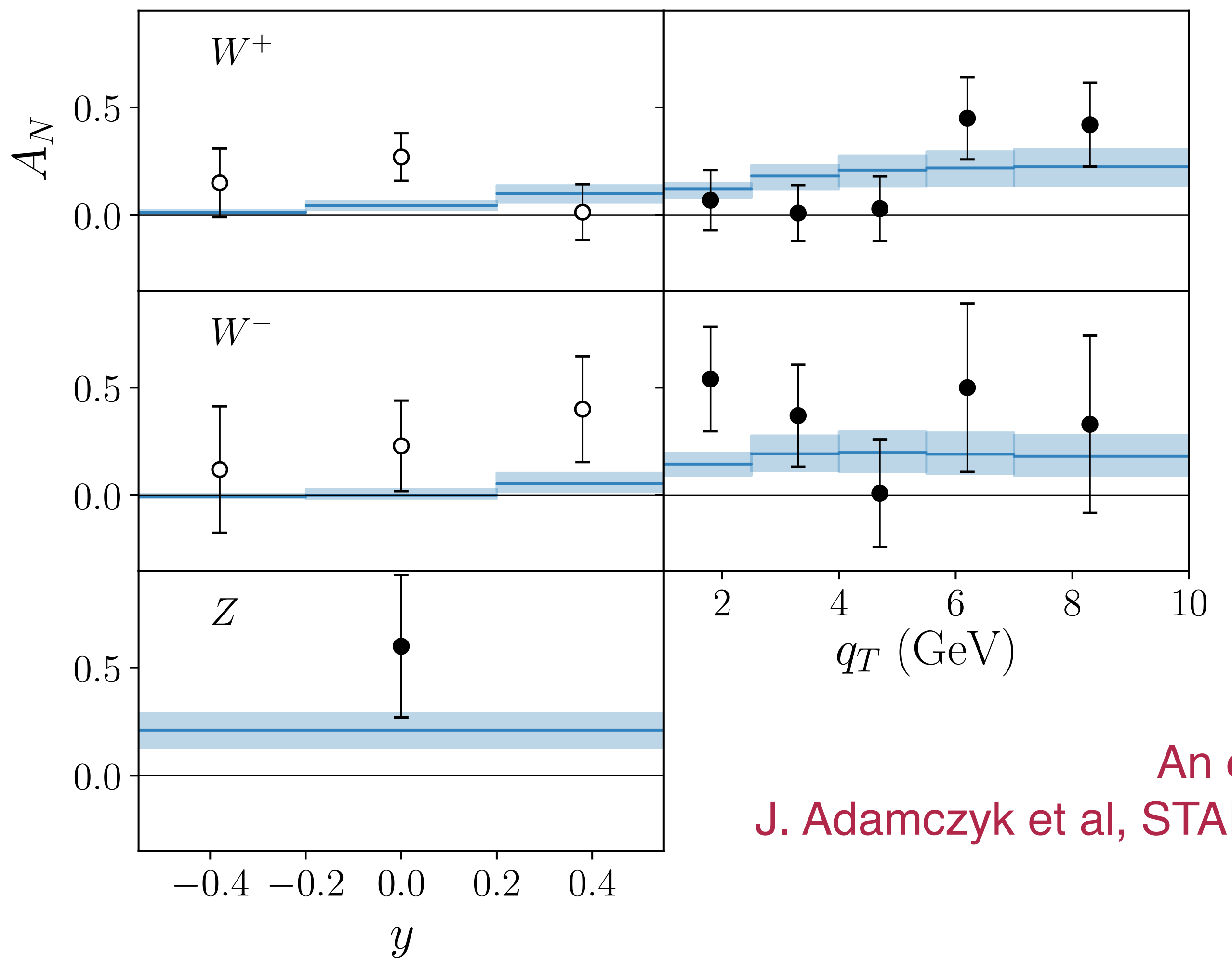
FIT RESULTS

Bury, Prokudin, Vladimirov (2021)

- Replica method using Artemide framework
- Errors both from the data and the uncertainty due to unpolarized TMD

Name	χ^2/N_{pt}[SIDIS]	χ^2/N_{pt}[DY]	χ^2/N_{pt}[total]
SIDIS at N^{3}LO	$0.87^{+0.13}_{+0.03}$	$1.23^{+0.50}_{-0.24}$ no fit	$0.93^{+0.16}_{+0.01}$
SIDIS+DY at N^{3}LO	$0.88^{+0.15}_{+0.04}$	$0.90^{+0.31}_{+0.00}$	$0.88^{+0.15}_{+0.05}$

- No tension between SIDIS and DY data — universality

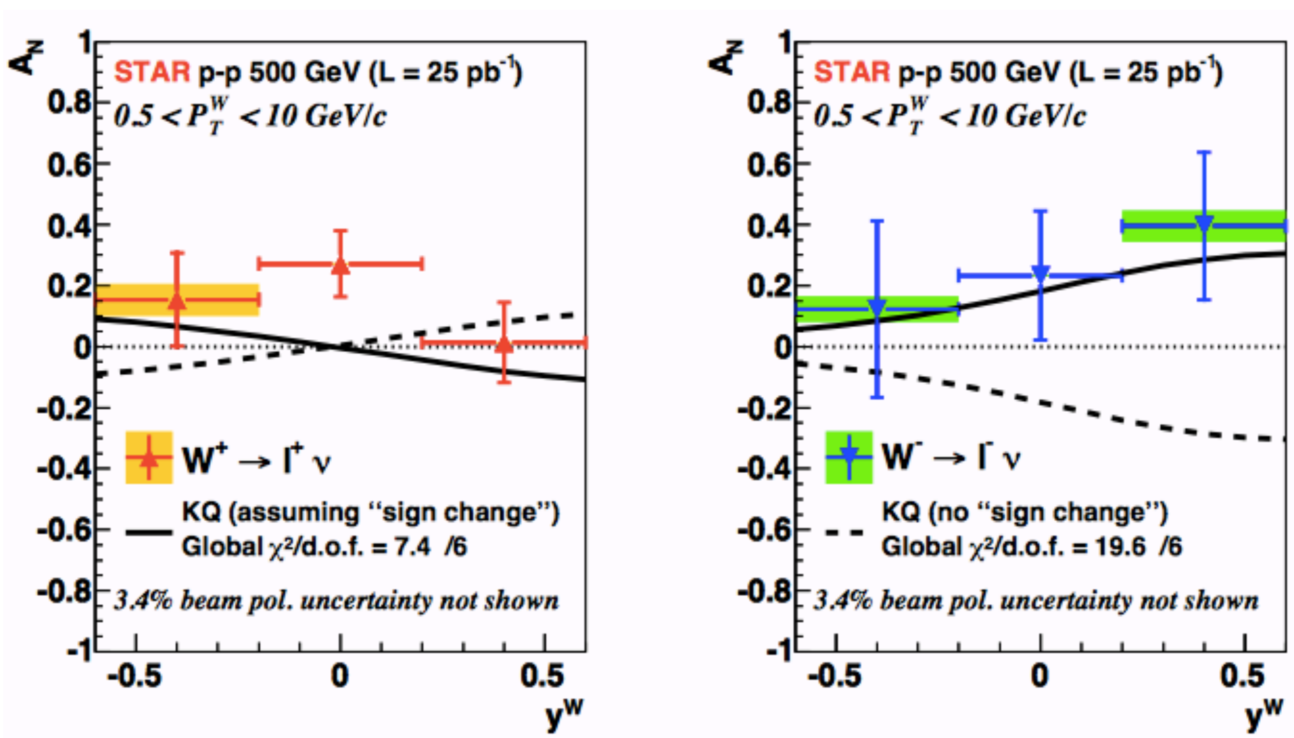


An example of data description:
J. Adamczyk et al, STAR Collab. Phys.Rev.Lett. 116 (2016) 13, 132301

SIGN CHANGE

Leading order analysis favors the sign change:

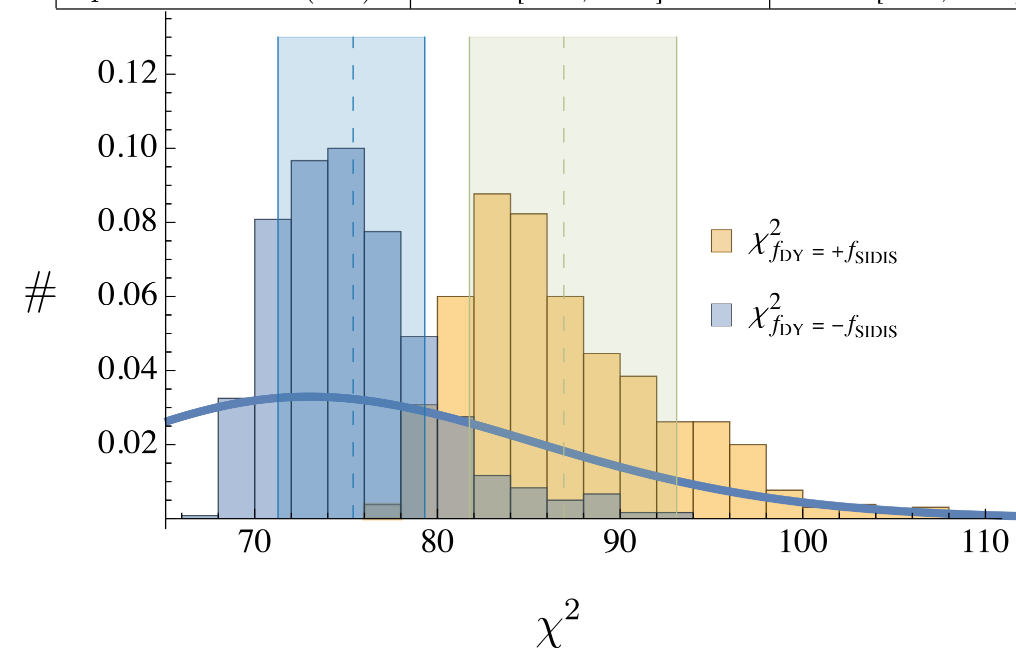
STAR Collab. Phys. Rev. Lett. 116, 132301 (2016)



KQ → Kang, Qiu `09

N3LO analysis allows the same sign (with a considerable tension):

	$f_{1T\,[DY]}^{\perp} = -f_{1T\,[SIDIS]}^{\perp}$	$f_{1T\,[DY]}^{\perp} = +f_{1T\,[SIDIS]}^{\perp}$
χ^2/N_{pt}	$0.88^{+0.16}_{+0.06}$	$1.00^{+0.22}_{+0.08}$
p-value (CF)	0.74	0.44
p-value 68%CI	[0.60, 0.34]	[0.28, 0.08]
p-value 68%CI (SIDIS)	[0.67, 0.42]	[0.53, 0.11]
p-value 68%CI (DY)	[0.56, 0.17]	[0.68, 0.02]



Bury, Prokudin, Vladimirov (2020)

- Large contribution from antiquark Sivers functions to DY makes it possible to describe the data without the sign change albeit some tension of SIDIS with DY.

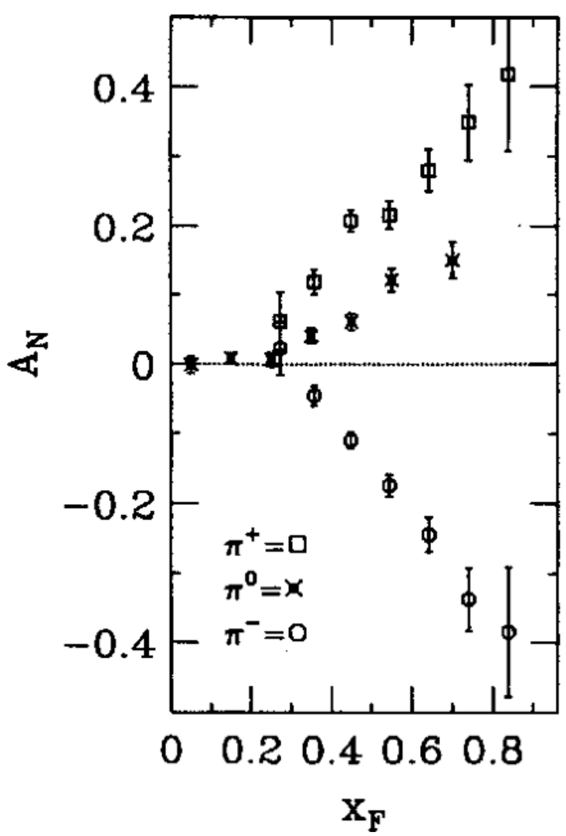
$$f_{1T}^{\perp sea} \to -f_{1T}^{\perp sea}$$

- Can combined SIDIS data (from JLab and future EIC) and DY establish the sign change?

CHALLENGE OF QCD: UNDERSTANDING SPIN ASYMMETRIES

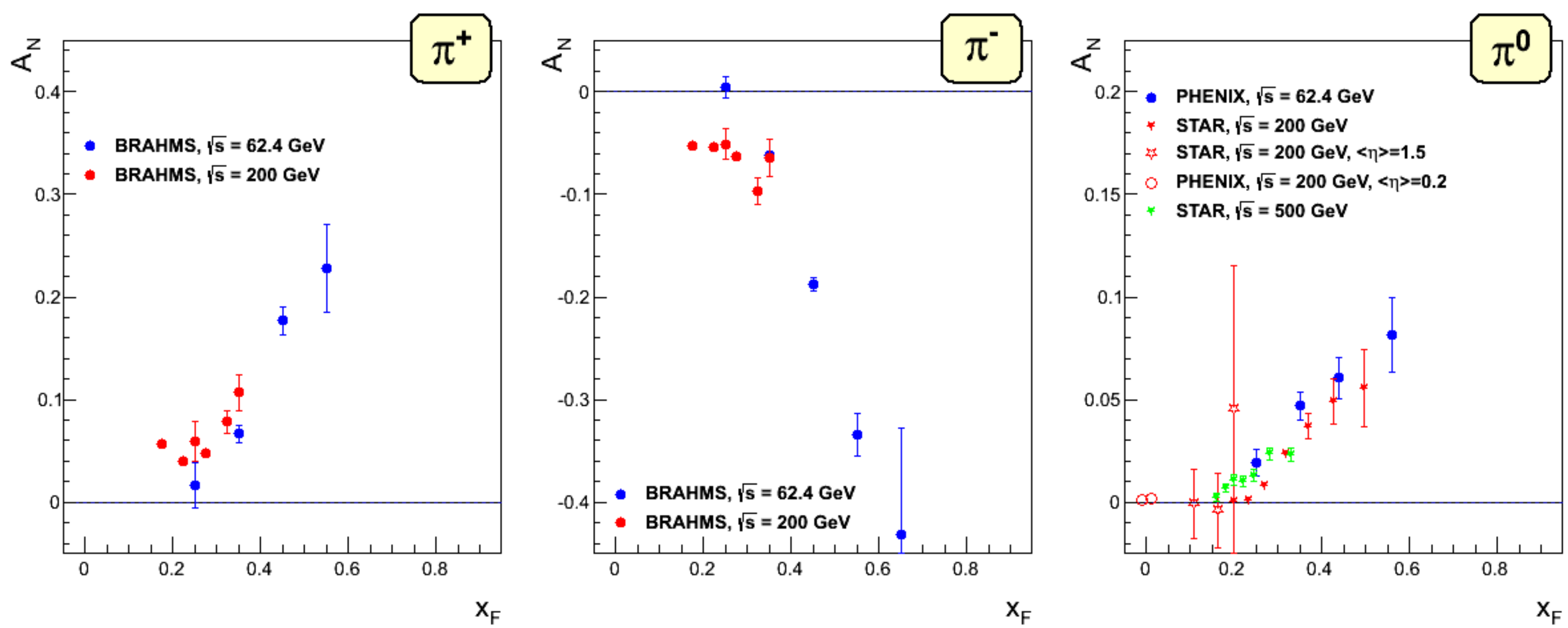
Asymmetry survives with growing collision energy

RHIC: STAR, BRAHMS, PHENIX



Fermilab experiment E704 (1991)

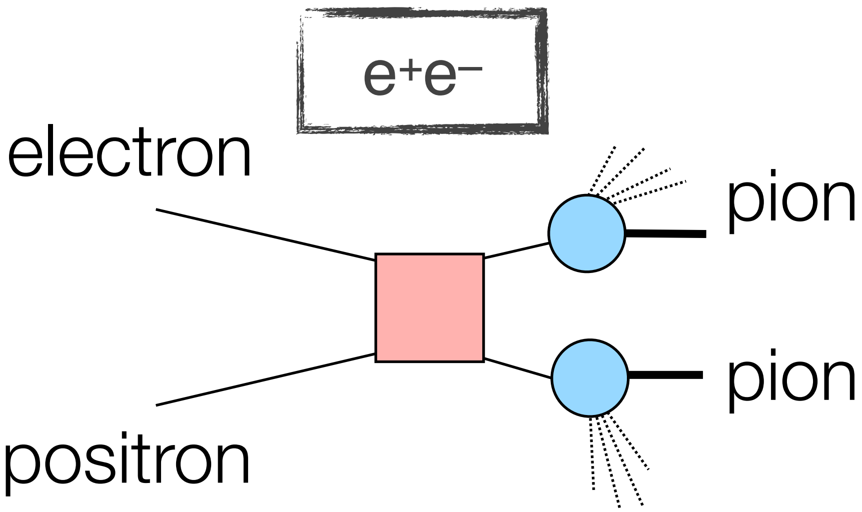
$$\sqrt{s} \simeq 19 \text{ (GeV)}$$



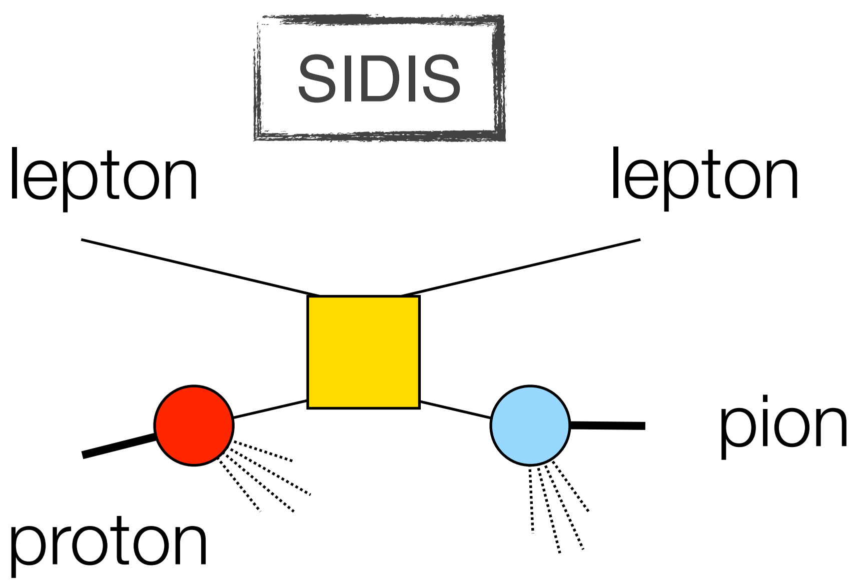
"The RHIC SPIN Program: Achievements and Future Opportunities", Aschenauer et al (15)

UNIVERSAL GLOBAL FIT 2020

Cammarota, Gamberg, Kang, Miller, Pitonyak, Prokudin, Rogers, Sato (2020)

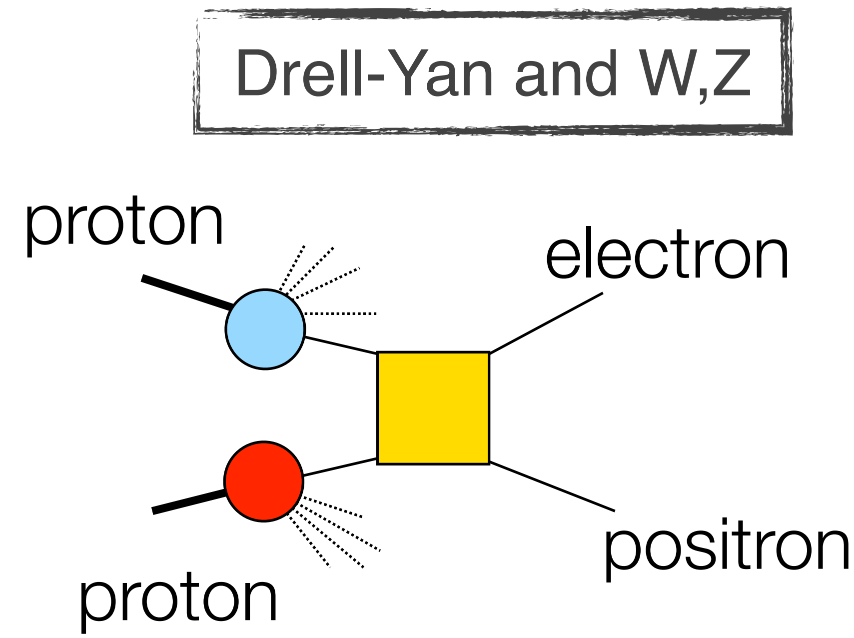


Collins asymmetries
BELLE, BaBar, BESIII data

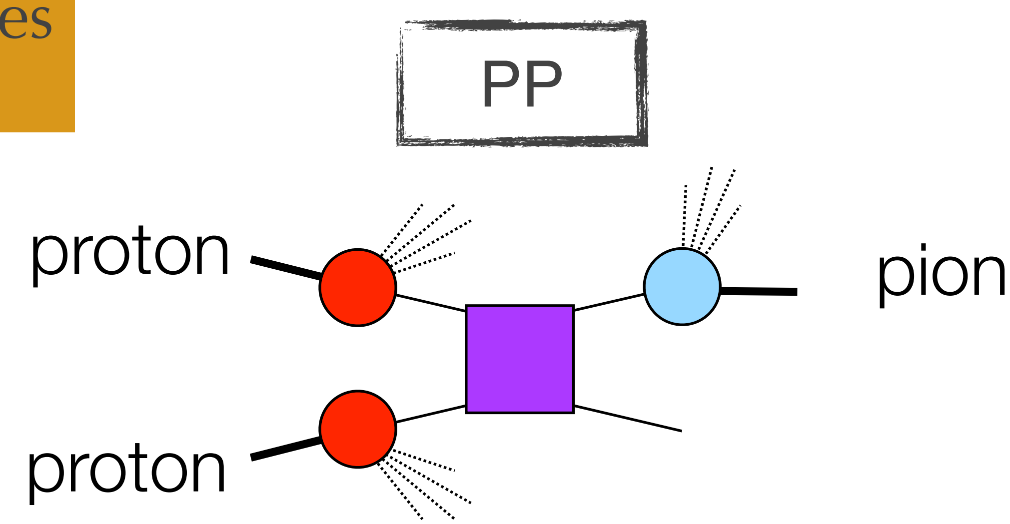


Sivers, Collins asymmetries
COMPASS, HERMES, JLab data

To demonstrate the common origin of SSAs in various processes, we will combine all available data and extract a universal set of non perturbative functions that describes all of them



Sivers asymmetries
COMPASS, STAR data



A_N asymmetry
STAR, PHENIX, BRAHMS data

UNIVERSAL GLOBAL FIT 2020

Cammarota, Gamberg, Kang, Miller, Pitonyak, Prokudin, Rogers, Sato (2020)

Observable	Reactions	Non-Perturbative Function(s)	$\chi^2/N_{\text{pts.}}$
$A_{\text{SIDIS}}^{\text{Siv}}$	$e+(p,d)^{\uparrow}\to e+(\pi^+,\pi^-,\pi^0)+X$	$f_{1T}^{\perp}(x,k_T^2)$	$150.0/126 = 1.19$
$A_{\text{SIDIS}}^{\text{Col}}$	$e+(p,d)^{\uparrow}\to e+(\pi^+,\pi^-,\pi^0)+X$	$h_1(x,k_T^2), H_1^{\perp}(z,z^2p_\perp^2)$	$111.3/126 = 0.88$
$A_{\text{SIA}}^{\text{Col}}$	$e^+ + e^- \to \pi^+\pi^-(UC,UL)+X$	$H_1^{\perp}(z,z^2p_\perp^2)$	$154.5/176 = 0.88$
$A_{\text{DY}}^{\text{Siv}}$	$\pi^- + p^{\uparrow}\to \mu^+\mu^- + X$	$f_{1T}^{\perp}(x,k_T^2)$	$5.96/12 = 0.50$
$A_{\text{DY}}^{\text{Siv}}$	$p^{\uparrow}+p\to (W^+,W^-,Z)+X$	$f_{1T}^{\perp}(x,k_T^2)$	$31.8/17 = 1.87$
A_N^h	$p^{\uparrow}+p\to(\pi^+,\pi^-,\pi^0)+X$	$h_1(x), F_{FT}(x,x)=\frac{1}{\pi}f_{1T}^{\perp(1)}(x), H_1^{\perp(1)}(z)$	$66.5/60 = 1.11$

- Just 3 polarized functions to describe *all data for four different processes.*
- We concluded that spin phenomena have the same origin: multi-parton correlations

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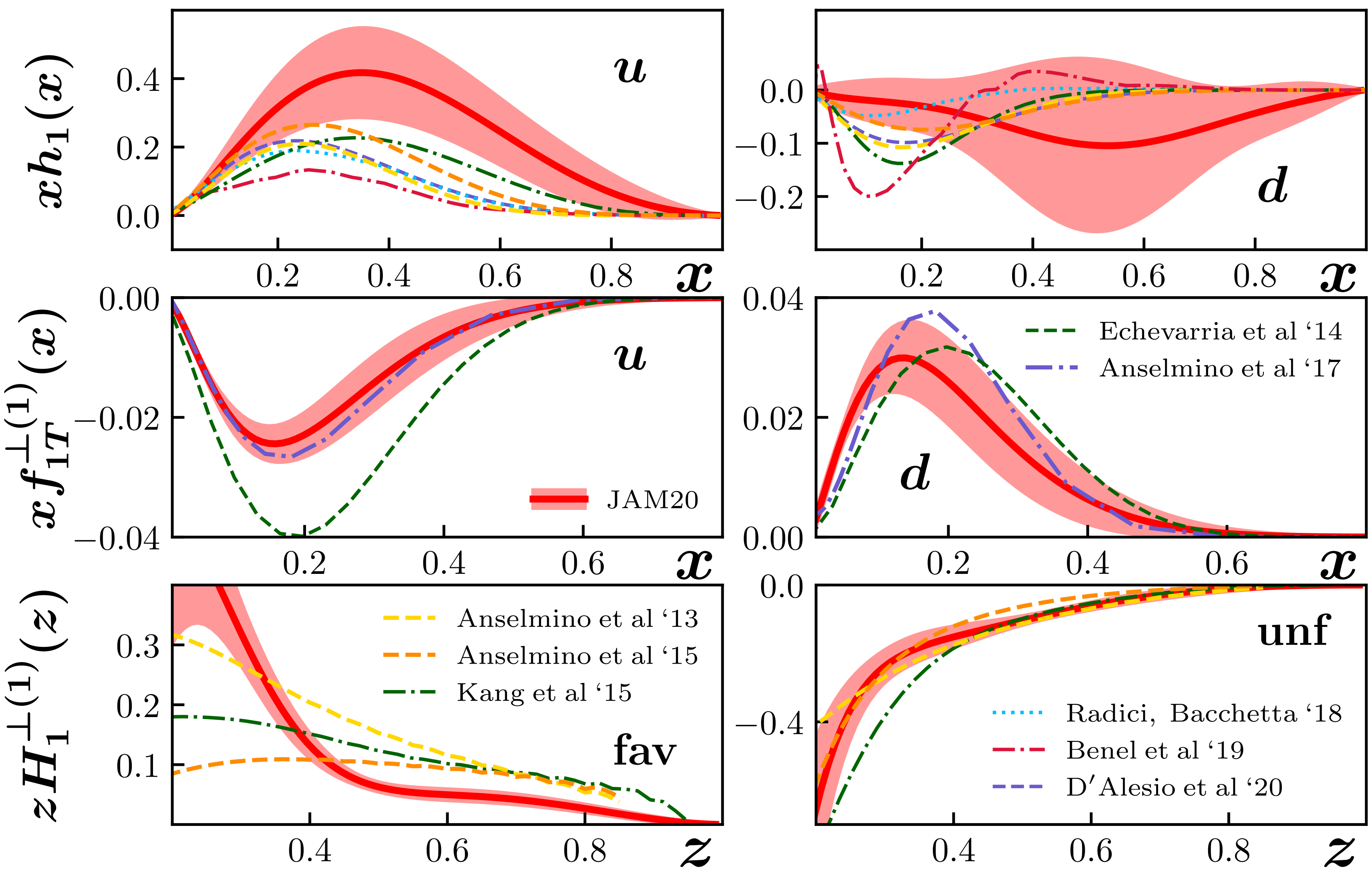
Cammarota, Gamberg, Kang, Miller, Pitonyak, Prokudin, Rogers, Sato Phys.Rev.D 102 (2020) 5, 05400 (2020)



Transversity

$h_1(x)$

Sivers

$f_{1T}^{\perp(1)}(x)$

Collins FF

$H_1^{\perp(1)}(z)$

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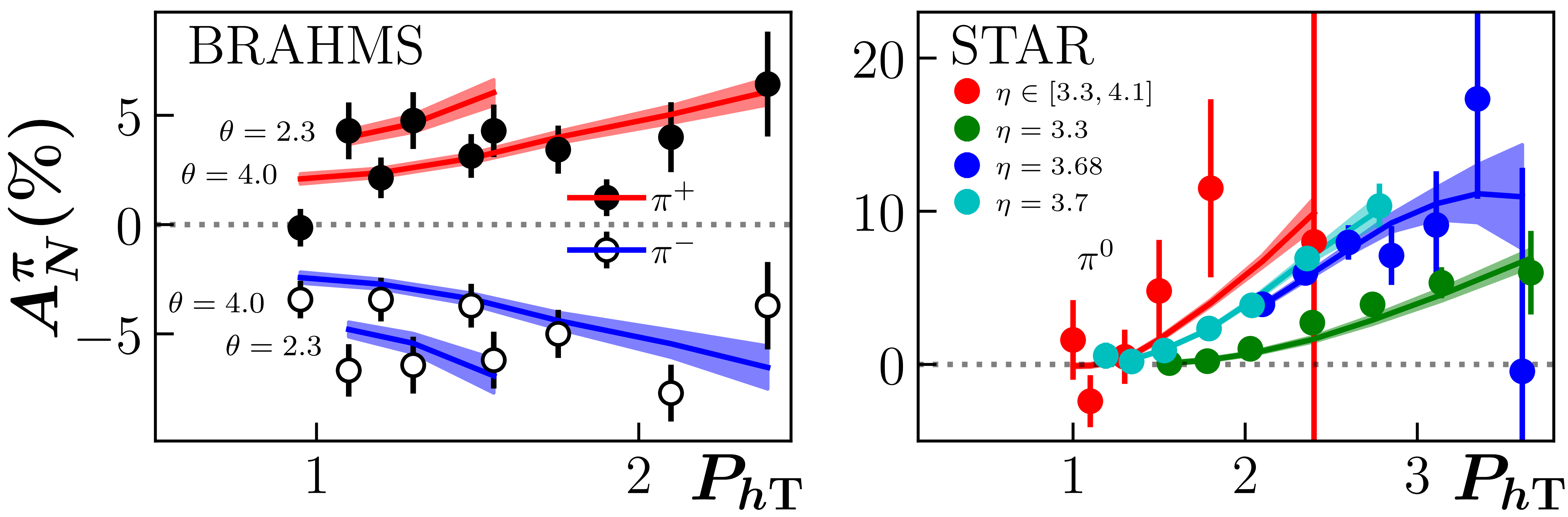
proton-proton A_N



$$\frac{\chi^2}{npoints} = \frac{66.5}{60} = 1.11$$

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Cammarota, Gamberg, Kang, Miller, Pitonyak, Prokudin, Rogers, Sato (2020)

$$\frac{E_h d\sigma^{Frag}(S_P)}{d^3\vec{P}_h} = -\frac{4\alpha_s^2 M_h}{S}\,\epsilon^{P'PP_hS_P}\sum_i\sum_{a,b,c}\int_0^1\frac{dz}{z^3}\int_0^1 dx'\int_0^1 dx\,\delta(\hat{s}+\hat{t}+\hat{u})$$
$$\times\frac{1}{\hat{s}\,(-x'\hat{t}-x\hat{u})}h_1^a(x)\,f_1^b(x')\left\{\left[H_1^{\perp(1),\pi/c}(z)-z\frac{dH_1^{\perp(1),\pi/c}(z)}{dz}\right]S_{H_1^\perp}^i+\frac{1}{z}H^{\pi/c}(z)\,S_H^i\right.$$
$$\left.+\frac{2}{z}\int_z^\infty\frac{dz_1}{z_1^2}\frac{1}{\left(\frac{1}{z}-\frac{1}{z_1}\right)^2}\hat{H}_{FU}^{\pi/c,\Im}(z,z_1)\,S_{\hat{H}_{FU}}^i\right\},$$

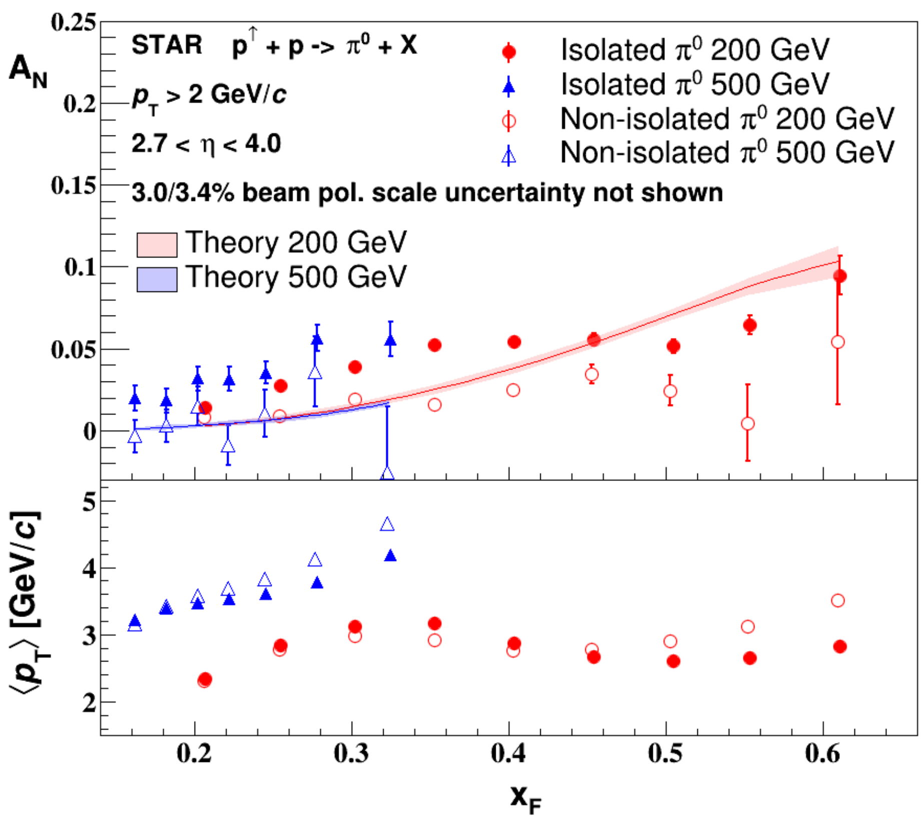
Integration over **x** for transversity, conservation of momenta in *ab→cd:*

$$\int_{x_{min}}^1\frac{dx}{x} \qquad\qquad x_{min} = -(U/z)/(T/z+S)$$

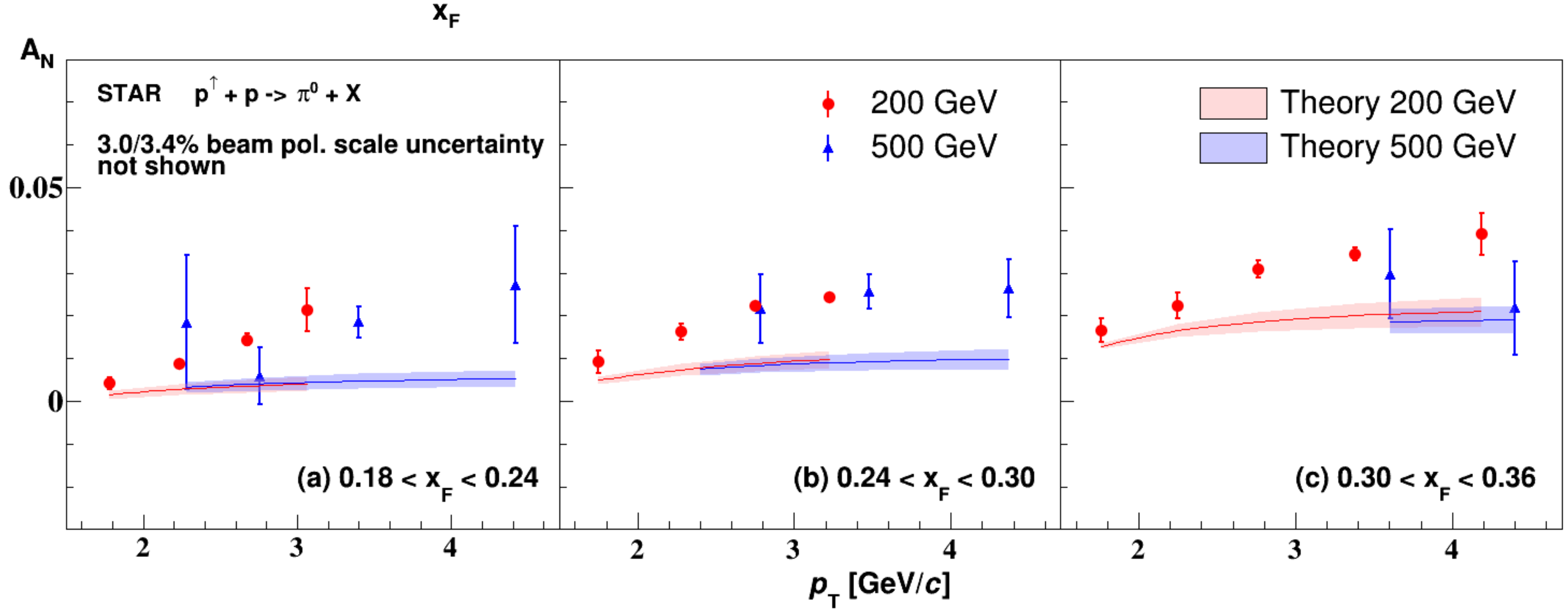
RHIC data is sensitive to high-x behavior of transversity quark-gluon channel is dominant contribution for large x_F

PREDICTIONS VS DATA

Cammarota, Gamberg, Kang, Miller, Pitonyak, Prokudin, Rogers, Sato (2020)



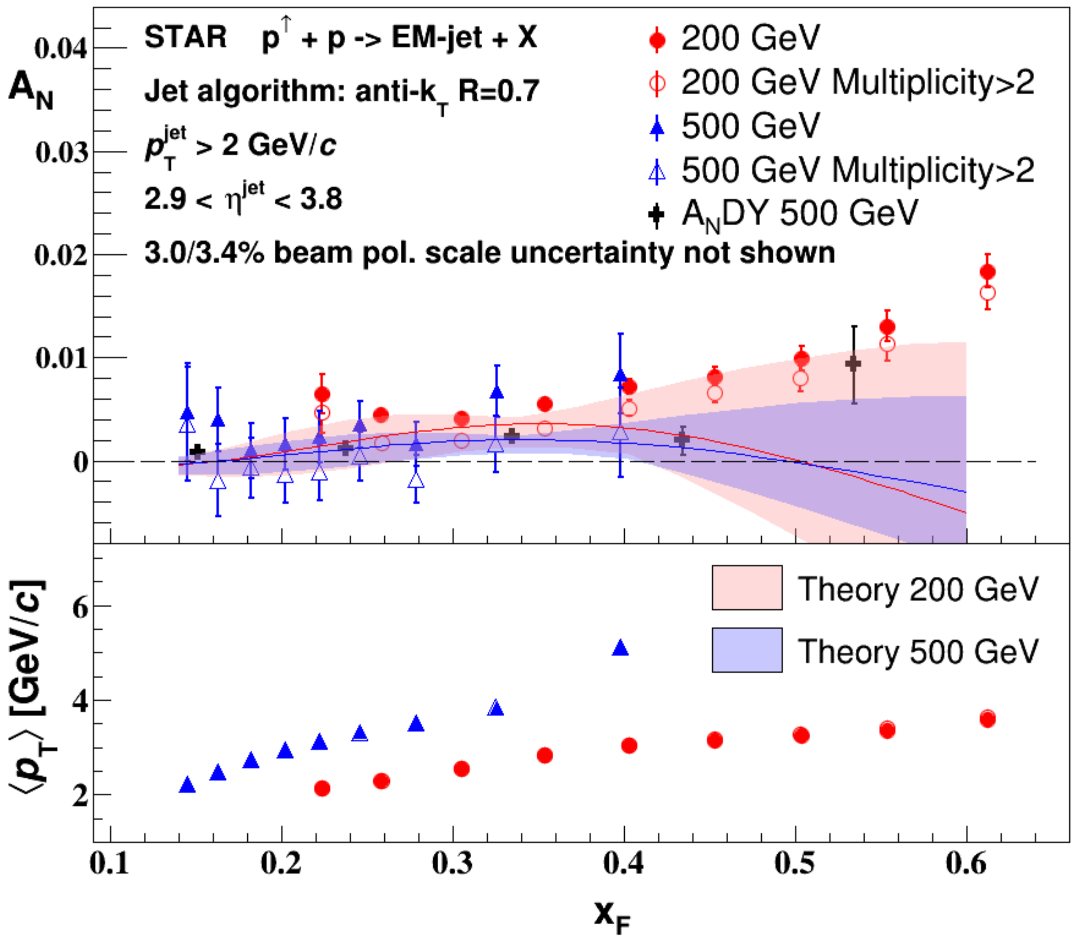
- Predictions are closer to non-isolated π^0 sample, $z_{em} = E_{\pi^0}/E_{jet} < 0.9$
- Analysis of the new data in progress
- Same shape, but difficulty with P_T dependence



J. Adam et al, STAR Collab., Phys.Rev.D 103 (2021) 9, 092009

PREDICTIONS VS DATA

L. Gamberg, Z.-B. Kang, and A. Prokudin, Phys. Rev. Lett. 110, 232301 (2013)



- Jet A_N is generated by Sivers effect
- The data will constraint large-x behavior of Sivers functions

Predictions vs the data:
J. Adam et al, STAR Collab., Phys.Rev.D 103 (2021) 9, 092009

TRANSVERSITY

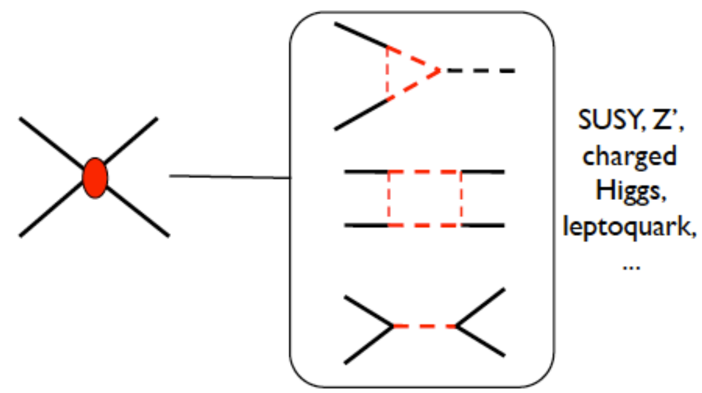
➤ The only source of information on tensor charge of the nucleon

$$\delta q \equiv g_T^q = \int_0^1 dx \ \left[h_1^q(x,Q^2) - h_1^{\bar{q}}(x,Q^2)\right]$$

➤ Tensor couplings, not present in the SM Lagrangian, could be the footprints of new physics at higher scales

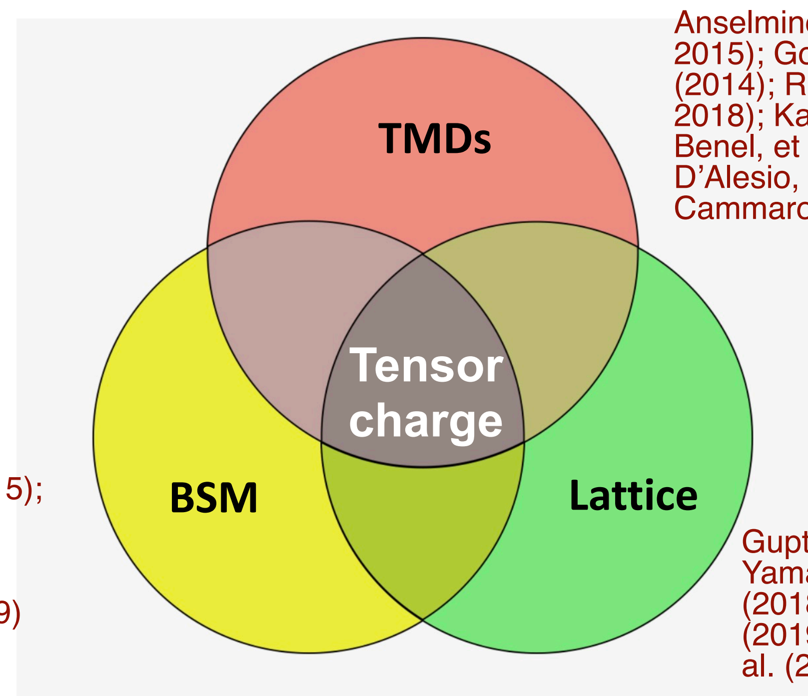
Bhattacharya et al, PRD 85 (12)
Pattie et al., P.R. C88 (13)

$\varepsilon_T \, g_T \approx M_W^2 / M_{BSM}^2$



➤ Tensor charge is extensively studied on the lattice

Gupta et al, (18), Alexandrou et al., (19)



Anselmino, et al. (2013, 2015); Goldstein, et al. (2014); Radici, et al. (2013, 2018); Kang, et al. (2016); Benel, et al. (2019); D'Alesio, et al. (2020); Cammarota, et al. (2020)

Courtoy, et al. (2015); Yamanaka, et al. (2017); Liu, et al. (2018); Gonzalez-Alonso, et al. (2019)

Gupta, et al. (2018); Yamanaka, et al. (2018); Hasan, et al. (2019); Alexandrou, et al. (2019)

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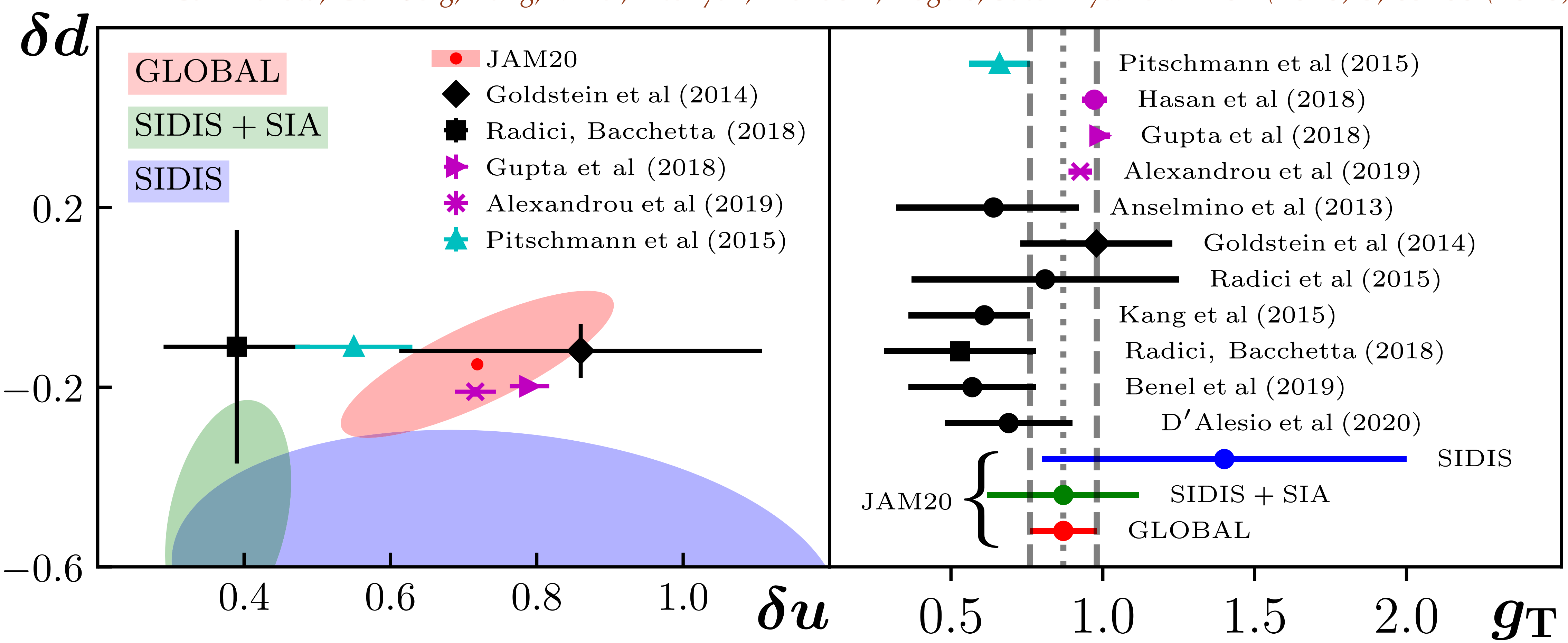


- Tensor charge from up and down quarks is constrained and compatible with lattice results

- Isovector tensor charge $g_T = \delta u - \delta d$
  $g_T = 0.87 \pm 0.11$ compatible with lattice results

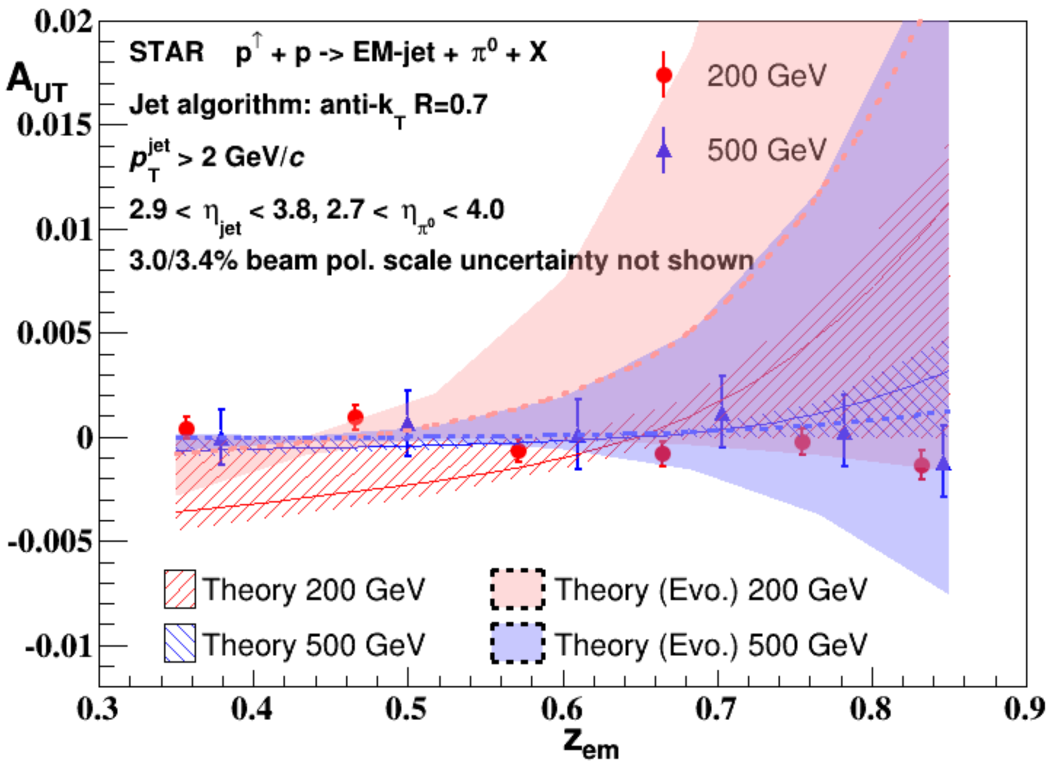
<u>δu and δd Q^2=4 GeV^2</u>

δu= 0.72 $\pm$ 0.19

δd= -0.15 $\pm$ 0.16

PREDICTIONS VS DATA

Z.-B. Kang, A. Prokudin, F. Ringer, and F. Yuan,
Phys. Lett. B 774, 635 (2017)



- π^0 in Jet A_{UT} is generated by transversity and Collins FF
- The data will constraint large-z behavior of Collins FF

Predictions vs the data:
J. Adam et al, STAR Collab., Phys.Rev.D 103 (2021) 9, 092009

CONCLUSIONS

- RHIC and EIC play a transformative role in our understanding of the (spin) structure of the nucleon.
- There is still potential and need for more data from RHIC before EIC construction begins
- The EIC will become the leading nuclear physics facility and both experimental and theoretical communities are working hard towards realization of its potential to the fullest

DATA DRIVEN SCIENCE