Highlights from STAR experiment on hadron structure

Jinlong Zhang (Shandong University)

for the STAR Collaboration

June 25-28, 2023

Supported in part by:

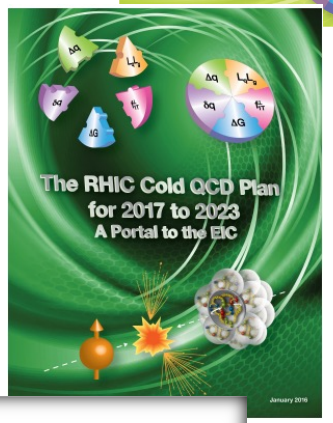
U.S. DEPARTMENT OF ENERGY | Office of Science

Outline

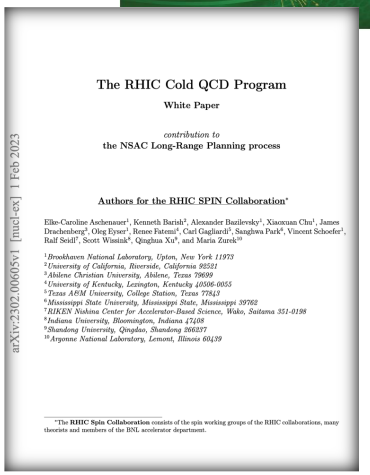
- RHIC, polarized proton-proton collider
  - **STAR cold QCD program** (this talk)
  - PHENIX/sPHENIX (see B Ujvari's and G Nukazuka's talks)
- Unique physics opportunities and selected STAR recent results
  - Helicity structure of proton: gluons and quarks
  - Studies on transverse dimensions
  - Measurement with unpolarized beam
- Outlook and Summary

arXiv: 1501.01220

arXiv:1602.03922



arXiv:2302.00605

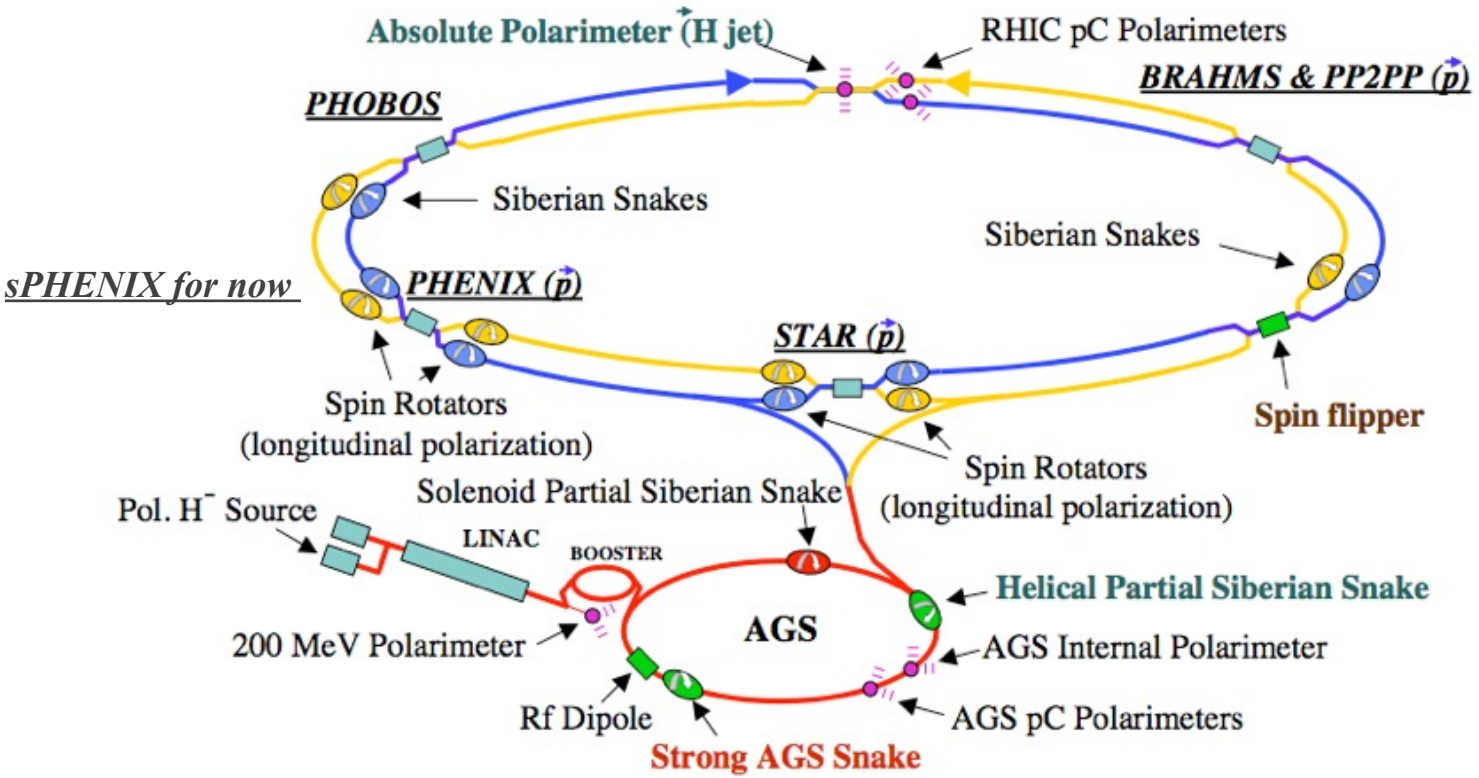

The RHIC Cold QCD Program

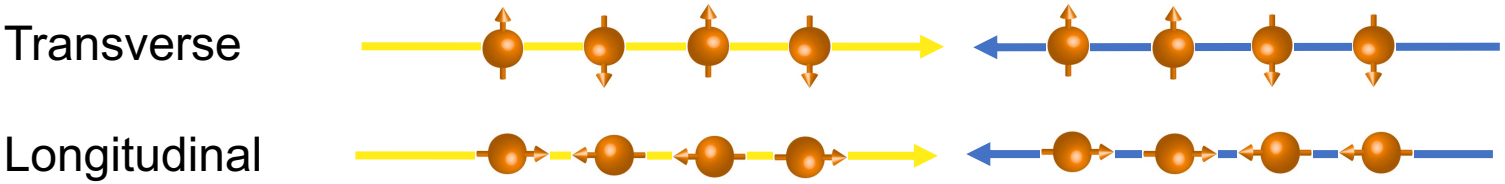
White Paper

contribution to
the NSAC Long-Range Planning process

Authors for the RHIC SPIN Collaboration*

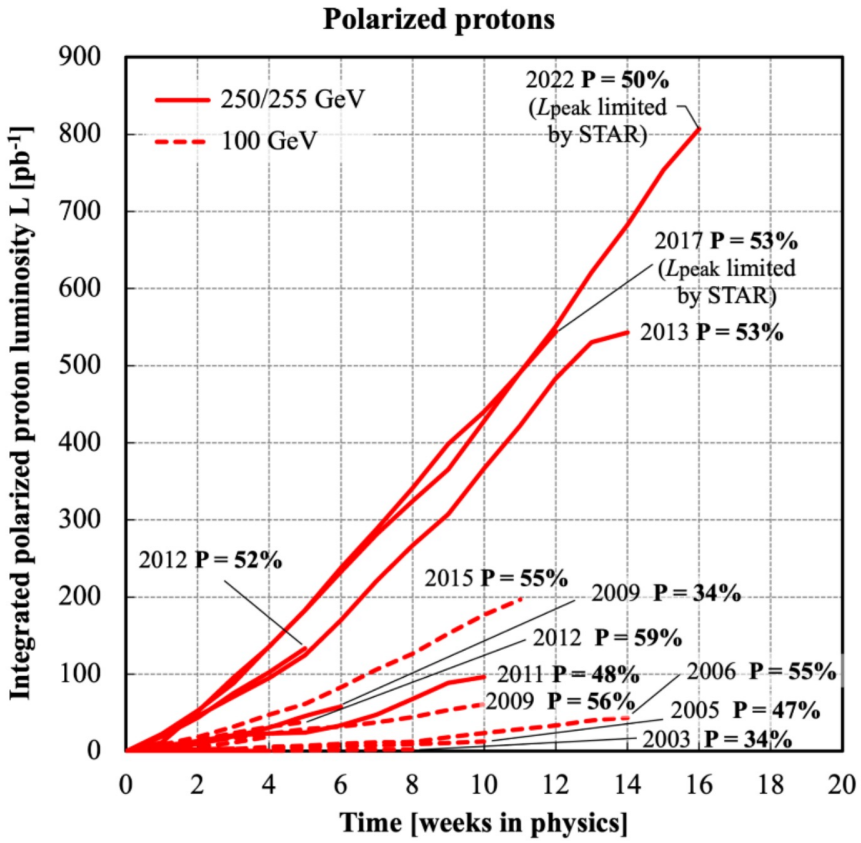
RHIC – Polarized Proton-Proton Collider





Next stage: Electron-ion Collider (e-Ring + RHIC)

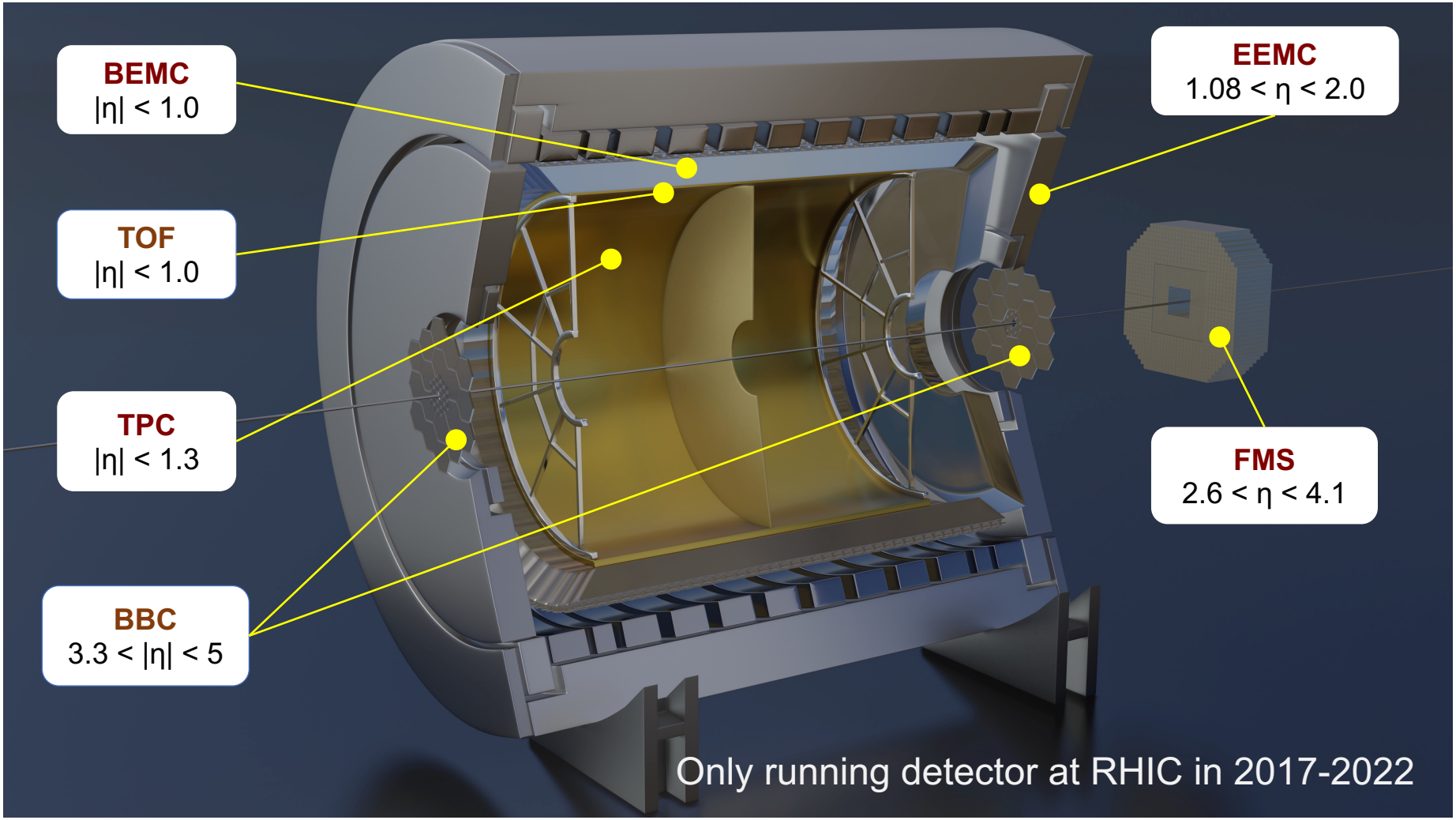
Polarized *p+p* data accumulation at RHIC



	Year	√s (GeV)	L (pb^{-1})	<P> (%)
Long.	2006	62.4	--	48
		200	6.8	57
	2009	200	25	38
		500	10	55
	2011	500	12	48
	2012	510	82	56
	2013	510	256	56
	2015	200	50	60
Trans.	2006	62.4	0.2	48
		200	8.5	57
	2008	200	7.8	45
	2011	500	25	55
	2012	200	22	60
	2015	200	50	60
	2017	510	356	55
	2022	508	400	50

STAR

STAR Detector Overview



Proton spin structure

$$< S_p > = \frac{1}{2} = \frac{1}{2}\Delta\Sigma \qquad < S_p > = \frac{1}{2} = \frac{1}{2}\,\Delta\Sigma + \Delta G + L_q + L_g$$

Jaffe-Manohar 1990

- High-energy spin structure is much more interesting (complicated) than the quark-model
- Before RHIC, mostly rely on polarized DIS
  - Total quark spin contributions pined down pretty well
  - Flavor separation was accessible via semi-inclusive DIS but has to rely on Fragmentation Functions; additional uncertainty introduced
  - No direct access to gluon

Prospects for RHIC Spin Physics in 2000

PROSPECTS FOR SPIN PHYSICS AT RHIC

Gerry Bunce,[1] Naohito Saito,[2] Jacques Soffer,[3] and Werner Vogelsang[4]

[1]*Brookhaven National Laboratory, Upton, New York 11973-5000 and RIKEN BNL Research Center, Brookhaven National Laboratory, Upton, New York 11973-5000; e-mail: bunce@bnl.gov*

[2]*RIKEN (The Institute of Physical and Chemical Research), Wako, Saitama 351-0198, Japan, and RIKEN BNL Research Center, Brookhaven National Laboratory, Upton, New York 11973-5000; e-mail: saito@bnl.gov*

[3]*Centre de Physique Théorique–CNRS–Luminy, Case 907, F-13288 Marseille Cedex 9, France; e-mail: Jacques.Soffer@cpt.univ-mrs.fr*

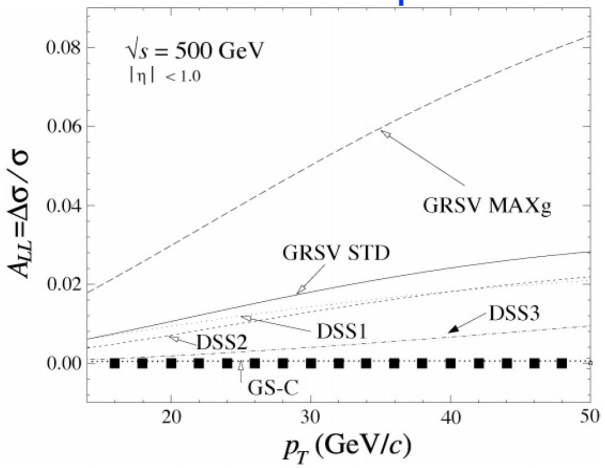
[4]*C.N. Yang Institute for Theoretical Physics, State University of New York at Stony Brook, Stony Brook, New York 11794-3840 and RIKEN BNL Research Center, Brookhaven National Laboratory, Upton, New York 11973-5000; e-mail: wvogelsang@bnl.gov*

Key Words proton spin structure, spin asymmetries, quantum chromodynamics, beyond the standard model

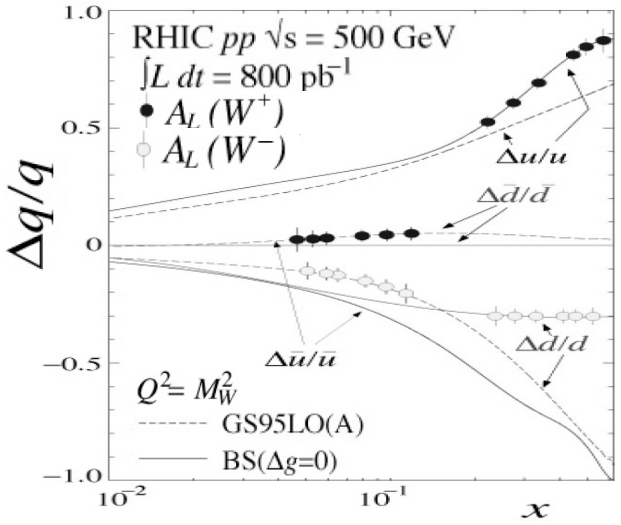
■ **Abstract** Colliding beams of 70% polarized protons at up to $\sqrt{s} = 500$ GeV, with high luminosity, $L = 2 \times 10^{32}\,cm^{-2}\,sec^{-1}$, will represent a new and unique laboratory for studying the proton. RHIC-Spin will be the first polarized-proton collider and will be capable of copious production of jets, directly produced photons, and W and Z bosons. Features will include direct and precise measurements of the polarization of the gluons and of $\bar{u}$, $\bar{d}$, u, and d quarks in a polarized proton. Parity violation searches for physics beyond the standard model will be competitive with unpolarized searches at the Fermilab Tevatron. Transverse spin will explore transversity for the first time, as well as quark-gluon correlations in the proton. Spin dependence of the total cross section and in the Coulomb nuclear interference region will be measured at collider energies for the first time. These qualitatively new measurements can be expected to deepen our understanding of the structure of matter and of the strong interaction.

Annu. Rev. Nucl. Part. Sci. 2000. 50:525

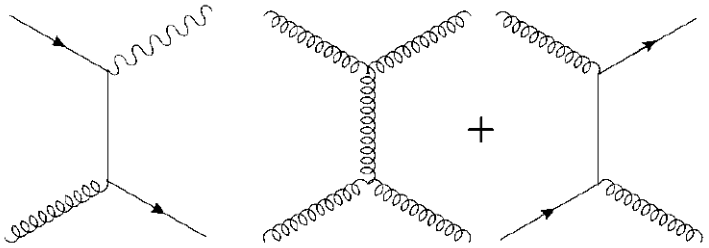
Jet production



$W^{\pm}$ production



Probe Gluon Polarization via Hadron/Jet/prompt-photon

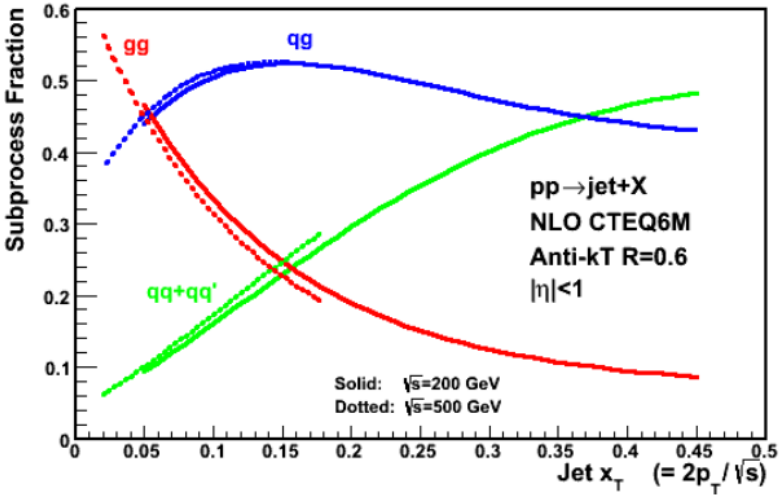


Quark gluon Compton scattering

Quark-gluon, gluon-gluon elastic scattering

Double-spin asymmetry:

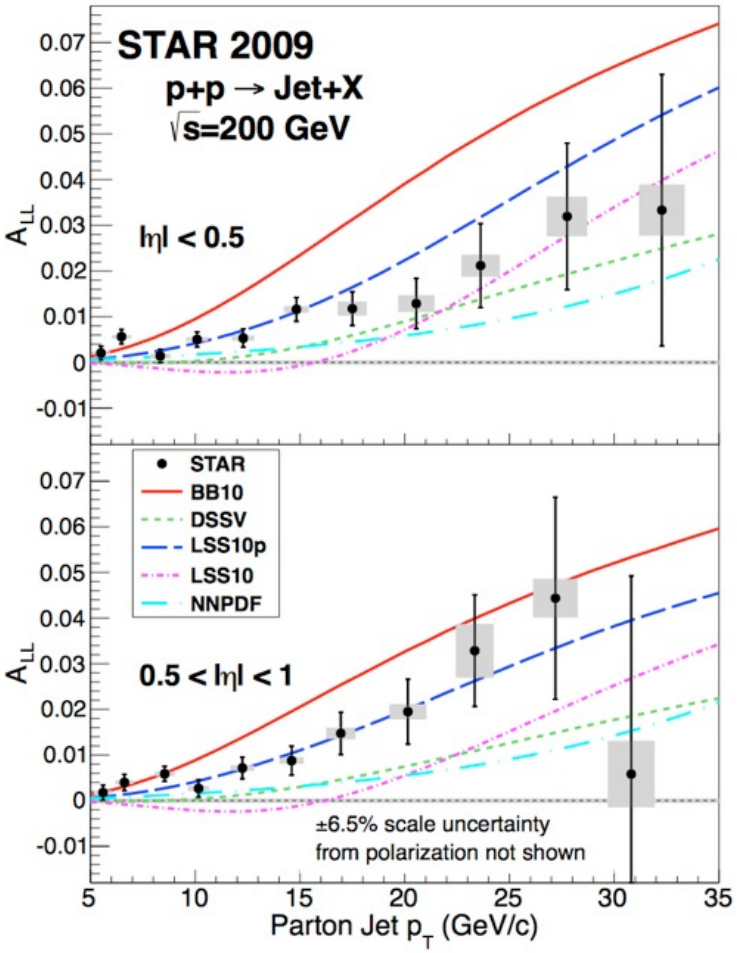
$$A_{LL} = \frac{\sigma^{\uparrow\uparrow} - \sigma^{\uparrow\downarrow}}{\sigma^{\uparrow\uparrow} + \sigma^{\uparrow\downarrow}} \propto \overbrace{\frac{\Delta f_1}{f_1} \otimes \frac{\Delta f_2}{f_2}}^{\text{probed}} \otimes \overbrace{\hat{a}_{LL} \otimes D_f^h}^{\text{inputs}}$$



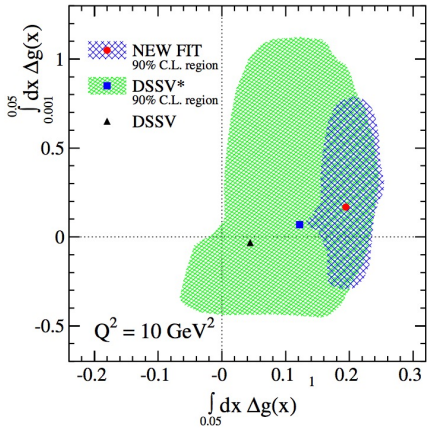
- Abundant yields of π^0 and jets at RHIC
- Sub-processes directly sensitive to gluon
- $x_{g,q} \sim p_T^{\pi^0,\text{jets}} / \sqrt{s} \cdot e^{-\eta}$
- Constrain gluon helicity-dependent PDFs

Inclusive Jet A_{LL}: first non-zero ΔG

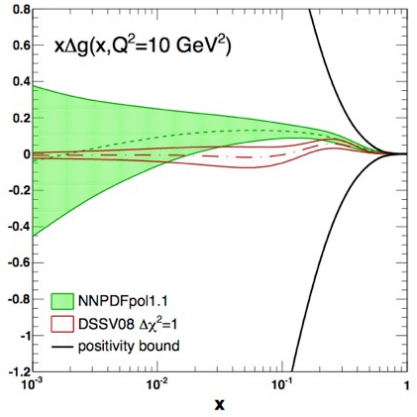
STAR, PRL115, 092002 (2015)



DSSV
PRL113, 012001 (2014)



NNPDF
Nucl. Phys. B887, 276 (2014)

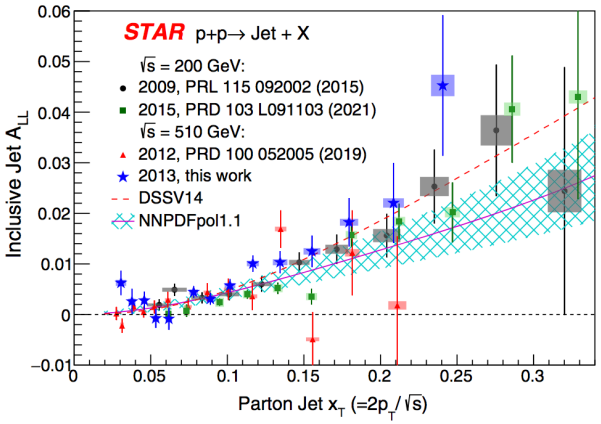


- First evidence of non-zero contributions from gluon spin at Q^2~10 GeV^2
  - STAR inclusive jets and PHENIX π^0
- Drive the constraints on ΔG

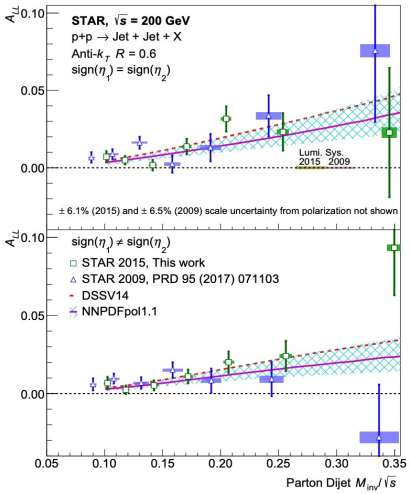
Full statistics jet/dijet A_{LL} results from STAR

Longitudinal data taking concluded , STAR released the full statistics results.

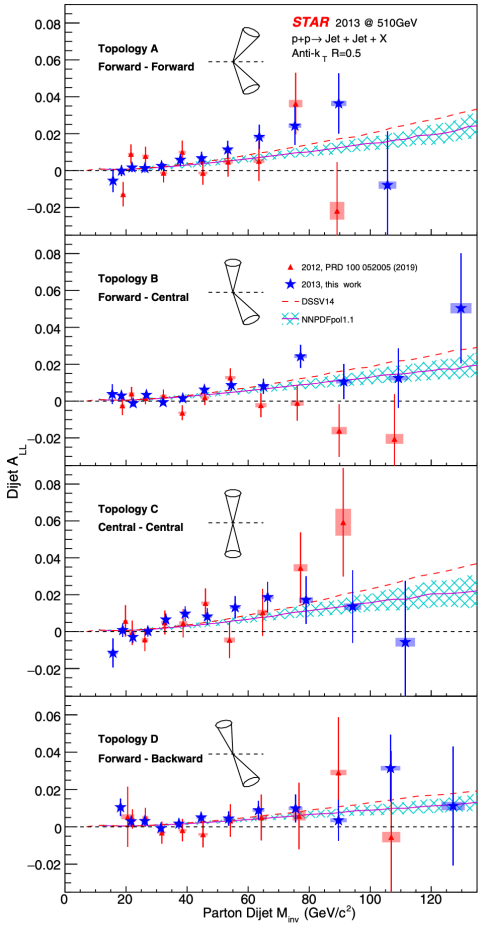
STAR, PRD 105, 092011 (2022)
Inclusive Jet A_{LL}



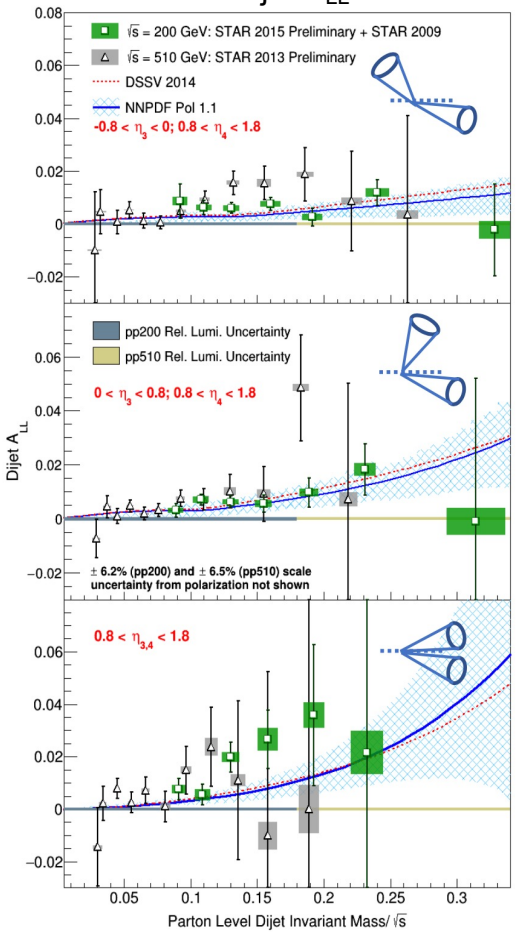
STAR, PRD 103 (2021) L091103
Dijet A_{LL}



STAR, PRD 105, 092011 (2022)
Dijet A_{LL}

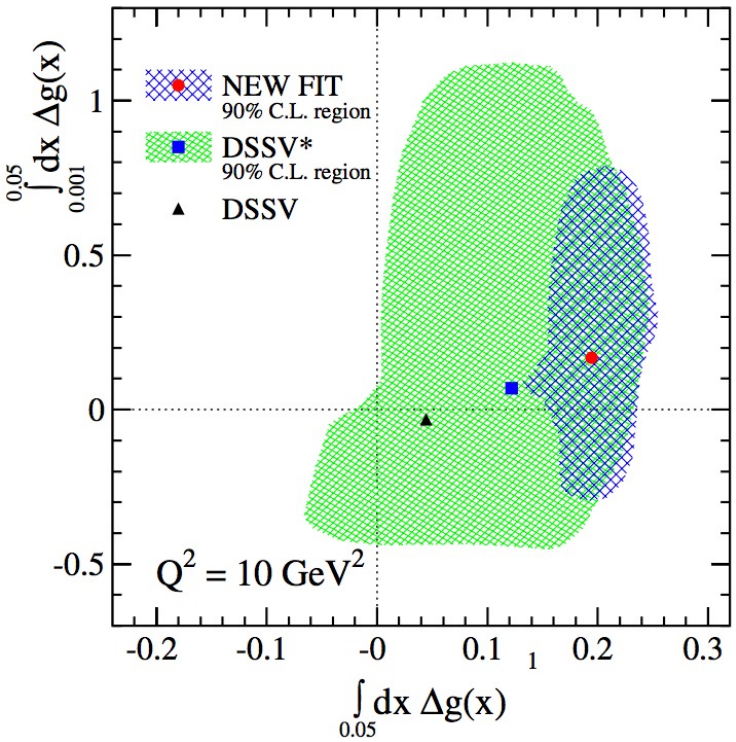


STAR preliminary
Dijet A_{LL}

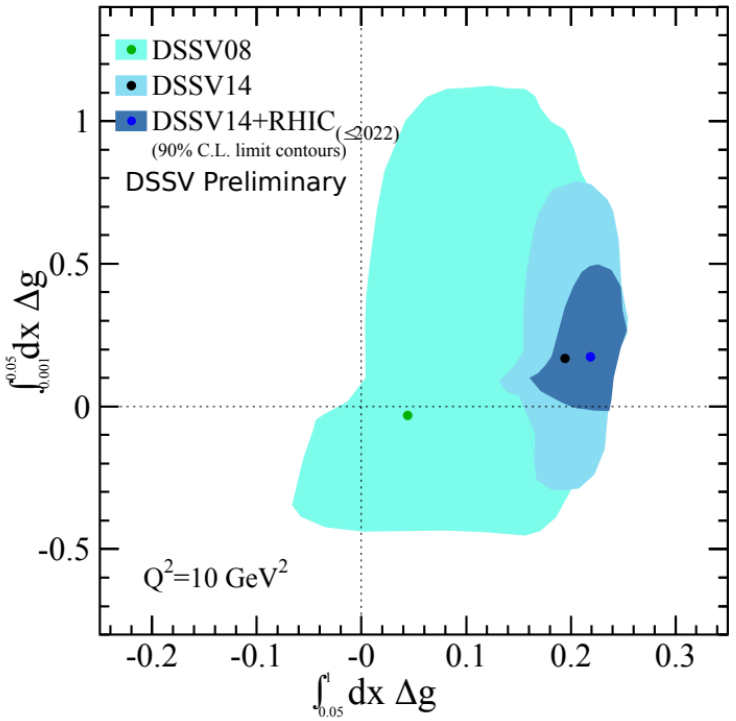


Impact on gluon polarization ΔG

PRL113 (2014) 012001



The RHIC Cold QCD Program, White Paper, arXiv:2302.00605



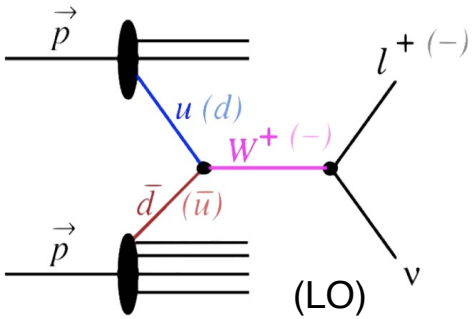
DSSV14:

- $\Delta G = \int_{0.05}^{1} \Delta g(x) dx = 0.20^{+0.06}_{-0.07}$
- $\Delta G = \int_{0.001}^{0.05} \Delta g(x) dx = 0.15^{+0.65}_{-0.45}$

DSSV14 + RHIC (≤2022):

- $\Delta G = \int_{0.05}^{1} \Delta g(x) dx = 0.22^{+0.03}_{-0.06}$
- $\Delta G = \int_{0.001}^{0.05} \Delta g(x) dx = 0.17^{+0.33}_{-0.17}$

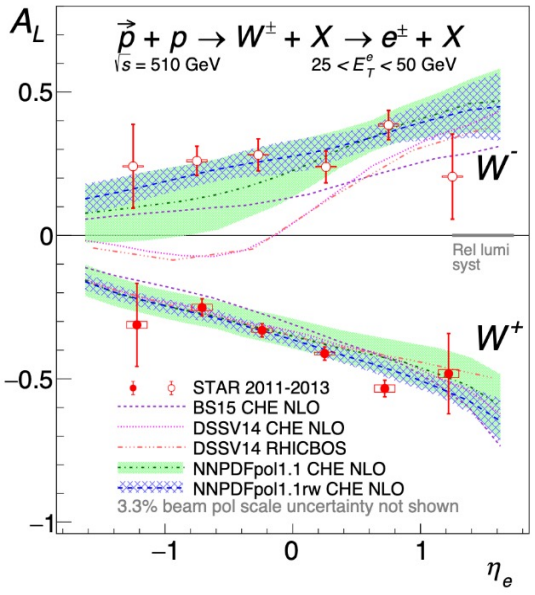
Probe sea quark polarization via W boson

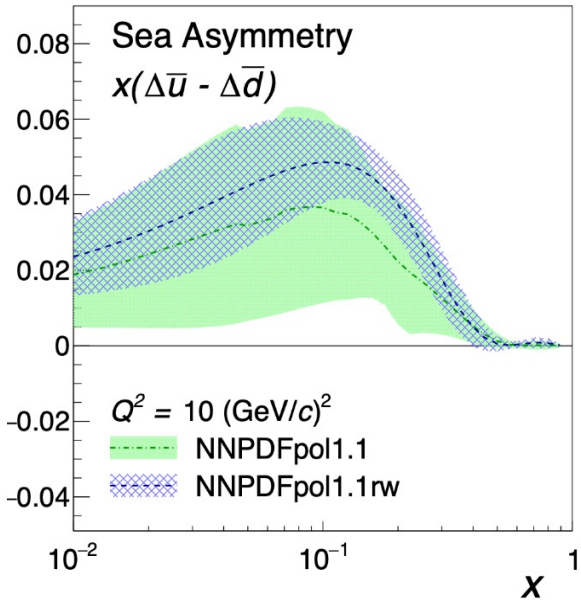


Single-spin asymmetry:

$$A_L = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-}$$

STAR, PRD 99, 051102 (2019)

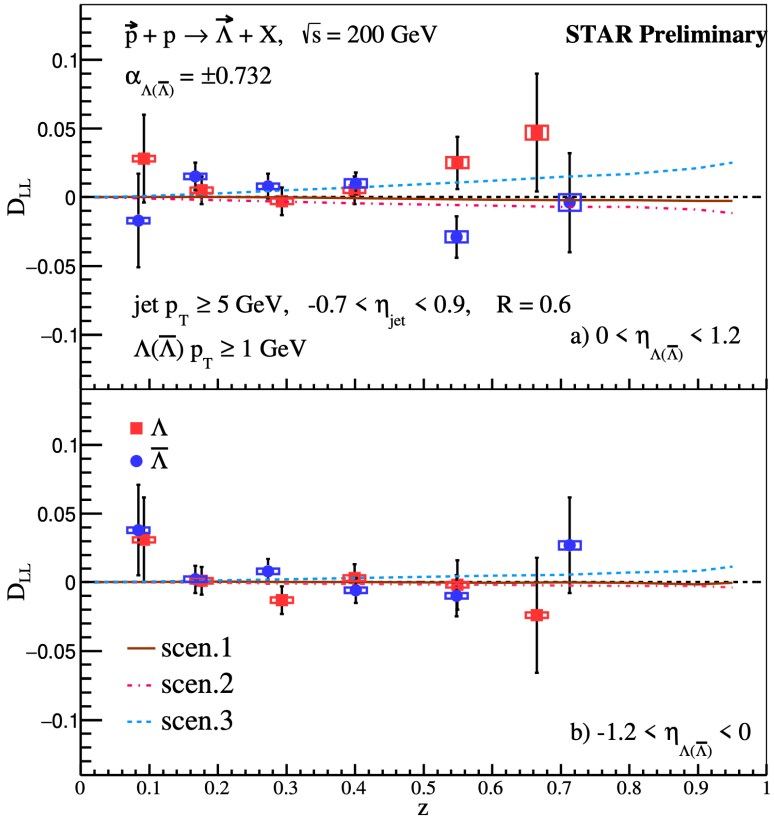




- W bosons production sensitive to flavor, spin, charge simultaneously; powerful tool to probe sea quark polarization
- STAR concluded the W A_L measurements
- First experimental observation of a flavor-asymmetry between anti-up and anti-down polarizations, opposite to the unpolarized distributions.

Strange quarks polarization via Lambda spin transfer

STAR, DIS2021



The results are in agreement with model calculations within uncertainties.

- Lambda hyperon spin transfer can access polarized fragmentation functions (FF) and the helicity distributions (PDF) of strange quarks
  - Final state polarization accessible via weak decay
  - Lambda's spin is expected to be carried mostly by its constituent strange quark

Spin transfer:

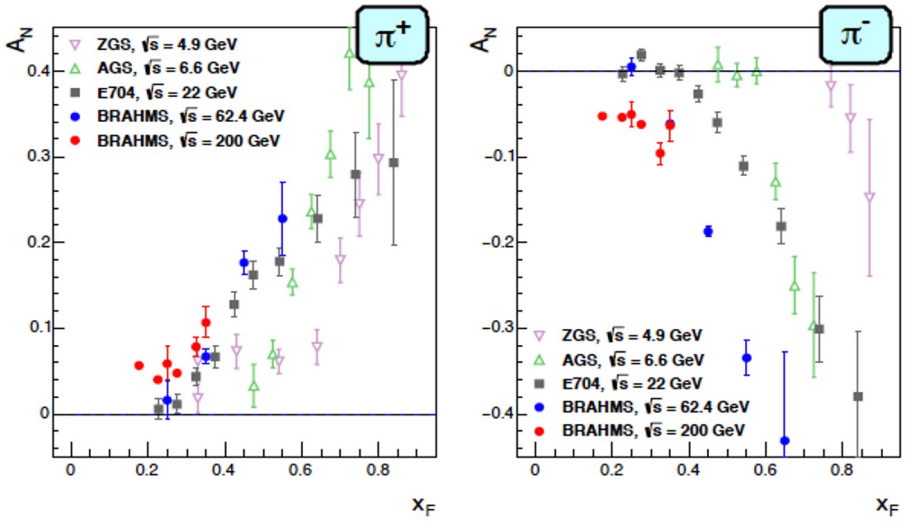
$$D_{LL}^{\Lambda} \equiv \frac{d\sigma(p^+p \to \Lambda^+X) - d\sigma(p^+p \to \Lambda^-X)}{d\sigma(p^+p \to \Lambda^+X) + d\sigma(p^+p \to \Lambda^-X)} = \frac{d\Delta\sigma^{\Lambda}}{d\sigma^{\Lambda}}$$

$$d\Delta\sigma^{\Lambda} = \sum \int dx_a dx_b dz \Delta f_a(x_a) f_b(x_b) \Delta\sigma(ab \to cd) \Delta D^{\Lambda}(z)$$

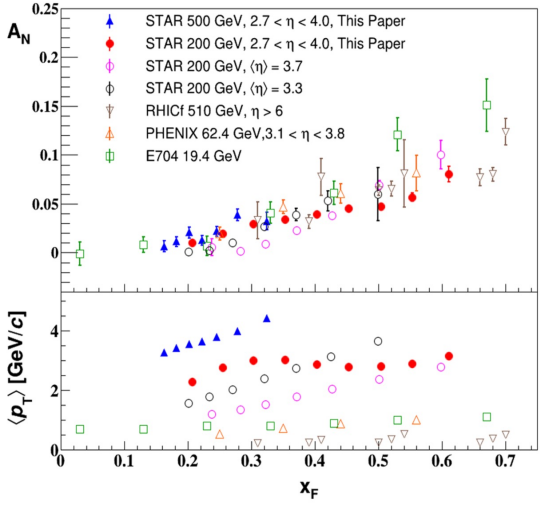
Polarized PDFs *Polarized FFs*

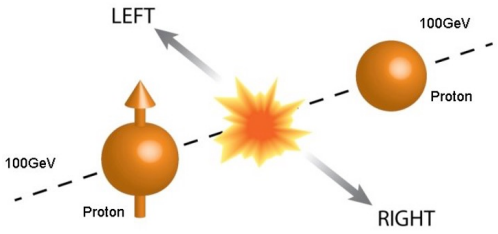
Forward A_N – remains mystery after 40+ years

arXiv: 1602.03922



STAR, PRD 103, 092009 (2021)



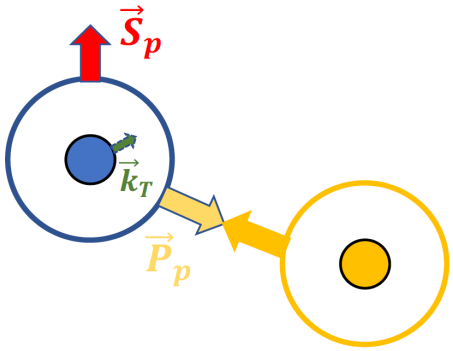


$$A_N = \frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}}$$

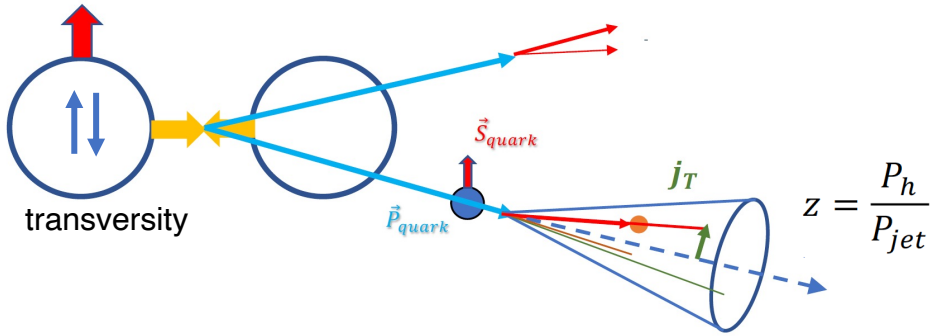
- Surprisingly large transverse single-spin asymmetries (pQCD predicts ~0)
- Nearly independent of √s over a very wide range (√s: 4.9 GeV to 500 GeV)
- TMDs and colinear Twist-3 frameworks developed to explain A_N origin
  - Qiu-Sterman functions, Sivers effect, Collins effect, etc

Transverse single-spin asymmetries at RHIC

Sivers effect



Collins effect



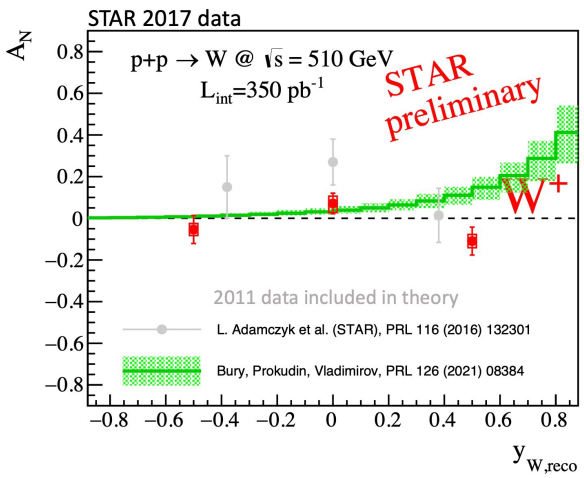
Sivers: Correlations between *initial-state* parton transverse momentum with proton's spin and momentum; process dependent

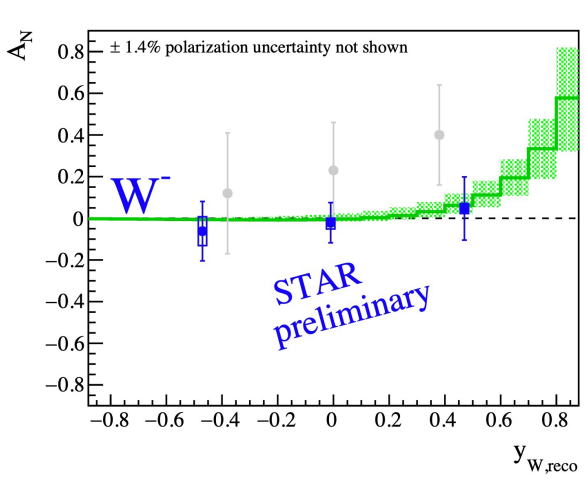
Collins: Correlations between the polarization of a scattered quark and the momentum of a hadron fragment transverse to the scattered quark direction

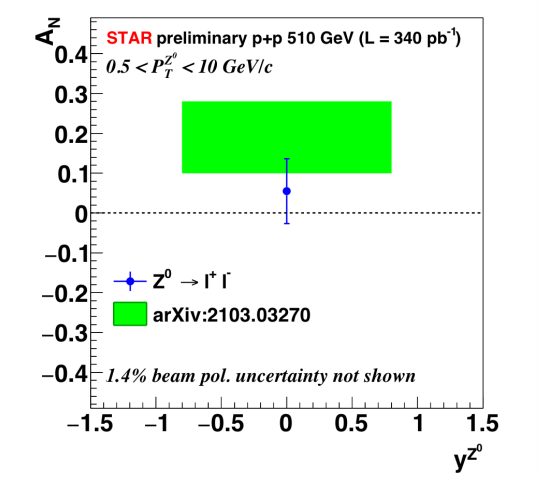
Transversity: transverse polarization of partons inside transversely polarized proton

Weak bosons A_N – Sivers

- Universality test of Sivers function: sign-change from DIS to DY/W/Z
- Clean access to Sivers effect without fragmentation contribution



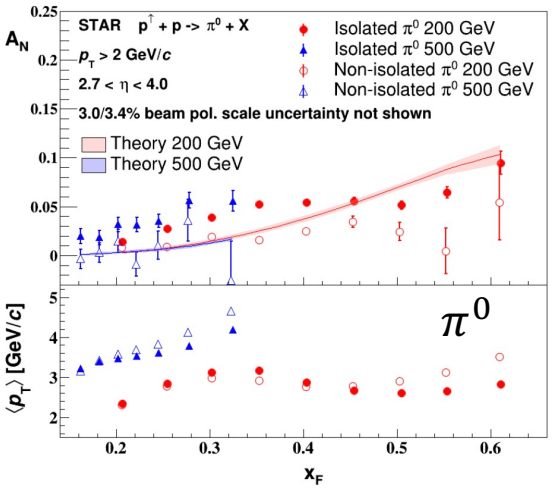


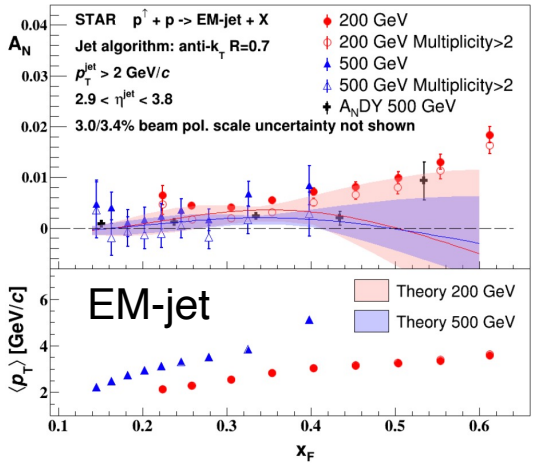


- Theoretical (PRL126,08384): extraction includes SIDIS, DY and 2011 STAR data with N3LO and NNLO accuracy of the TMD evolution *assuming sign-change*
- STAR preliminary with 2017 data with much improved precision, expect big impact in Sivers function at high-x in next global TMD fit

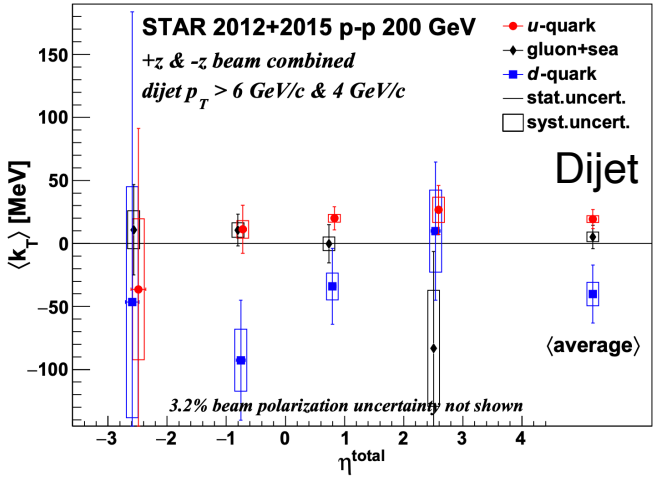
π^0, EM-jet, dijet A_N – Sivers

STAR, PRD 103, 092009 (2021)





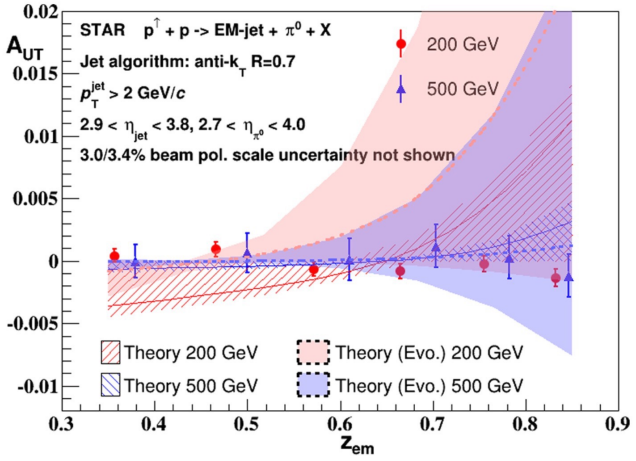
arXiv: 2305.10359



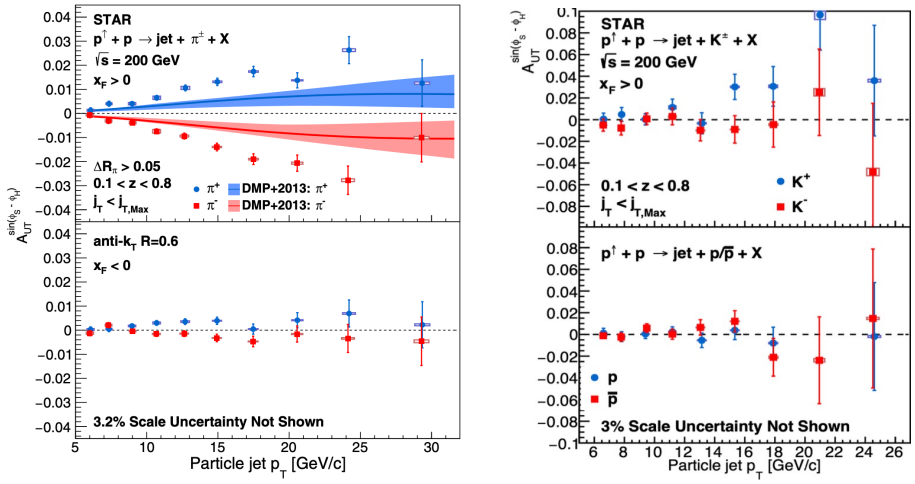
- A_N measured with forward EM-jets, dijet and π^0 in 200/500 GeV pp collisions
- High multiplicity EM-jets ($n_\gamma > 2$) and non-isolated π^0 (w/ nearby γ) tend to generate smaller A_N
- First observation of non-zero Sivers asymmetries in dijet production in polarized *p+p* collisions
- No significant collision energy dependence observed

Hadron in Jet A_N – Transversity + Collins

STAR, PRD 103 (2021) , 092009

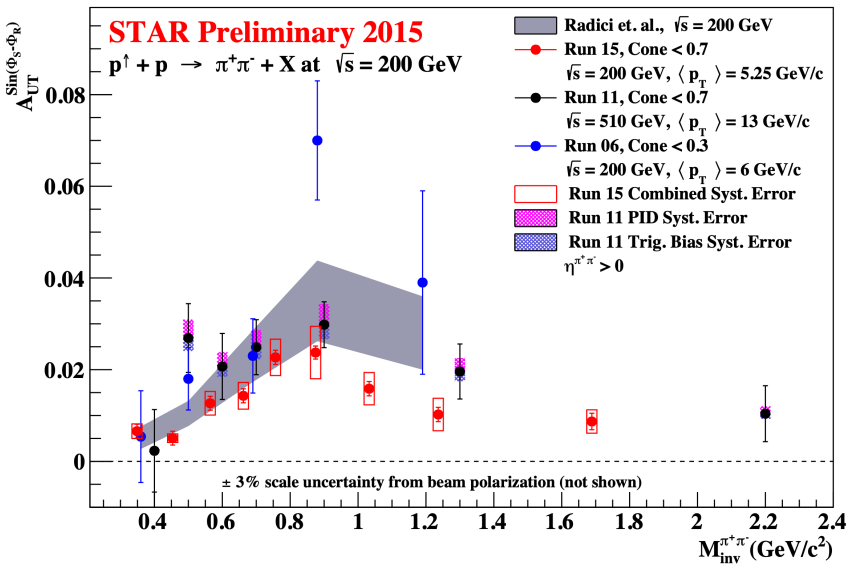


STAR, PRD 106 (2022), 072010

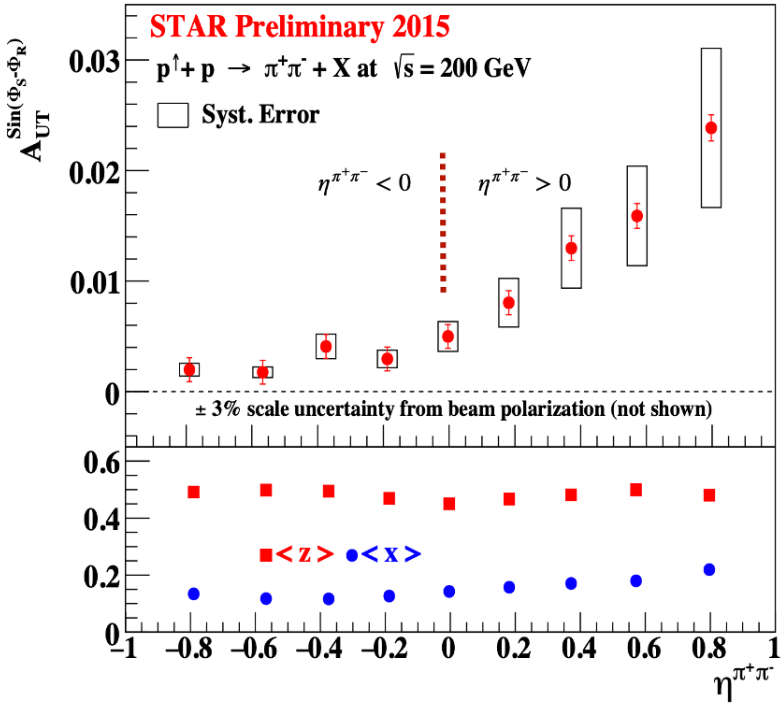


- Transversity is probed most directly in the jet p_T dependence
- Collins TMD FF is sensitive to the (j_T,z) dependence
- Significant Collins asymmetries have been observed in 200 GeV measurement
- Discrepancy with theoretical predictions

Di-hadron correlations – Transversity + IFF



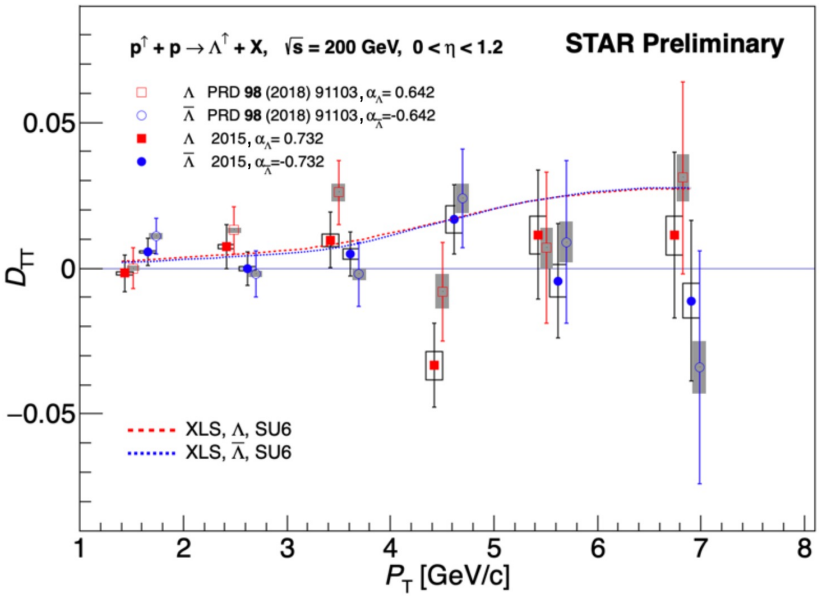
$A_{UT} \sim h_1 \otimes H_1^{\sphericalangle}$



- Spin dependent di-hadron correlations from *p+p* probe collinear quark transversity couple to the interference fragmentation function
- A_{UT} is enhanced around $M_{inv}^{\pi^+\pi^-} \sim 0.8$ GeV, consistent with the previous measurement
- Significant A_{UT} in the forward region, where is h_1 expected to be sizable.

Lambda transverse spin transfer – Transversity + FF

STAR, DIS2021



The results are consistent with model calculations within uncertainties.

- Lambda hyperon spin transfer can access transversity fragmentation functions (FF) and transversity distributions (PDF) of strange quarks
  - Final state polarization accessible via weak decay
  - Lambda's spin is expected to be carried mostly by its constituent strange quark

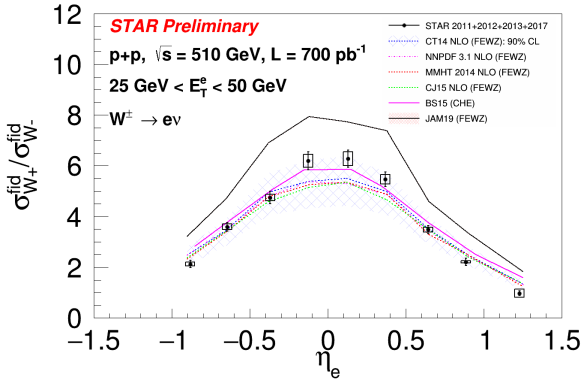
Transverse spin transfer:

$$D_{TT}^{\Lambda} \equiv \frac{\sigma^{(p^\uparrow p \to \Lambda^\uparrow X)} - \sigma^{(p^\uparrow p \to \Lambda^\downarrow X)}}{\sigma^{(p^\uparrow p \to \Lambda^\uparrow X)} + \sigma^{(p^\uparrow p \to \Lambda^\downarrow X)}} = \frac{d\delta\sigma^{\Lambda}}{d\sigma^{\Lambda}}$$

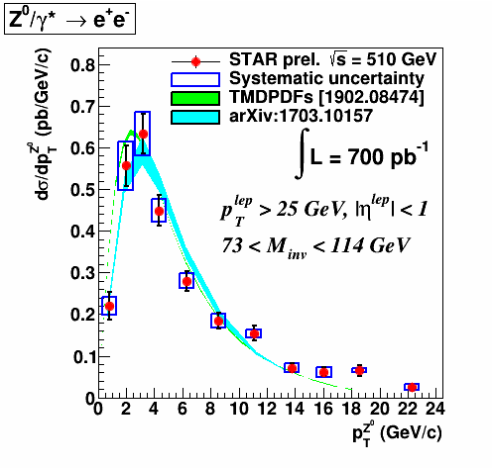
$$d\delta\sigma^{\Lambda} = \sum_{abcd} \int dx_a\, dx_b\, dz \underbrace{\delta f_a(x_a)}_{\text{Transversity PDF}} f_b(x_b) \delta\sigma^{(a^\uparrow b \to c^\uparrow d)} \underbrace{\delta D_c^{\Lambda}(z)}_{\text{Transversity FF}}$$

Measurements with unpolarized beam

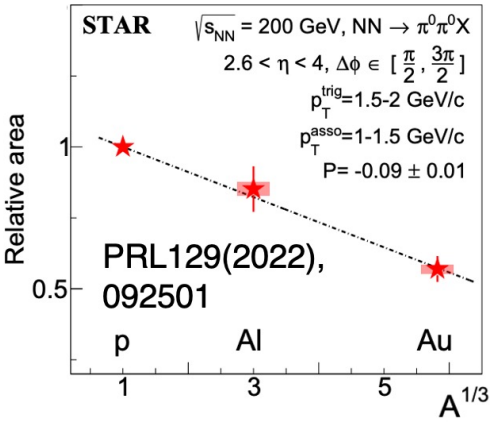
- $\bar{d}/\bar{u}$ with $W^{\pm}$ cross section ratio



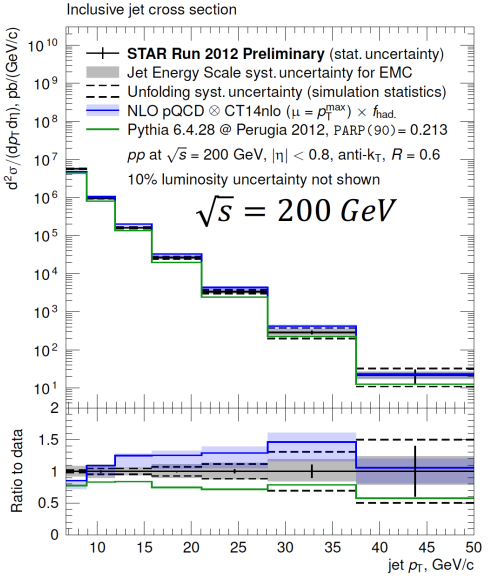
- Differential Z^0 cross section



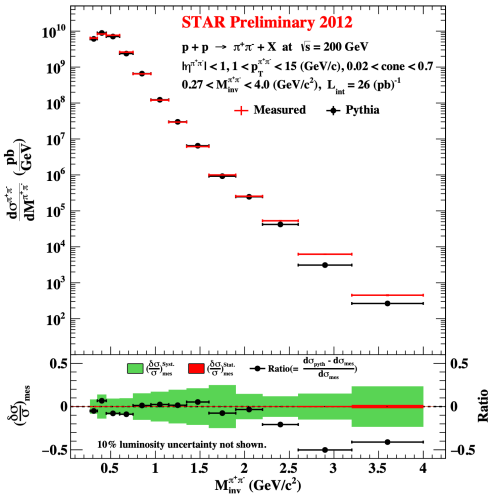
- Nonlinear gluon effects via *A*-dependent di-π^0 correlation



- Gluon PDF with Jet cross section

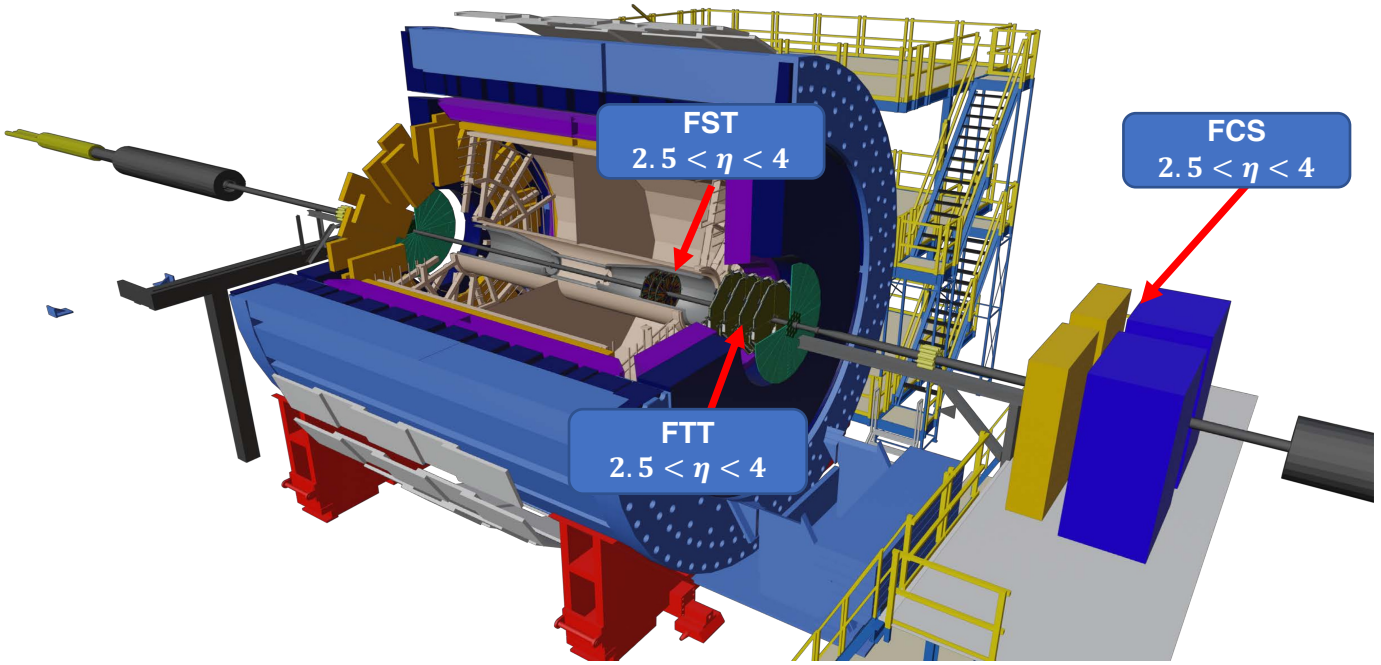


- FF Di-hadron cross section



Rich physics with unpolarized beam

STAR forward upgrade



- Successful STAR run 2022 with forward upgrade
- Last transverse spin run in 2024 before EIC

$\sqrt{s}$ (GeV)	Species	Luminosity	Year	
508	$p^{\uparrow} + p^{\uparrow}$	400 pb^{-1}	2022	on disk already
200	$p^{\uparrow} + p^{\uparrow}$	235 pb^{-1}	2024	
200	$p^{\uparrow} + Au$	1.3 pb^{-1}	2024	STAR BUR 2022

Summary

- RHIC is a unique machine for studying proton spin structure, 1D and 3D
- Featured measurements of gluon and sea quark helicity dependent PDFs (mostly) concluded; successfully.
  - Non-zero gluon polarization: $\Delta G > 0$
  - symmetry breaking in the polarized sea: $\Delta\bar{u} > \Delta\bar{d}$
- Transverse program in progress
  - Existing data being published/analyzed and more data in 2024
  - Important constraints for TMD PDFs / FFs

Thank you for your attention!