The 226th HENPIC Roundtable Discussions

中国高能核物理网络论坛

HIGH ENERGY NUCLEAR PHYSICS IN CHINA

Spin experiments at RHIC

-- nucleon spin structures and polarized fragmentation functions

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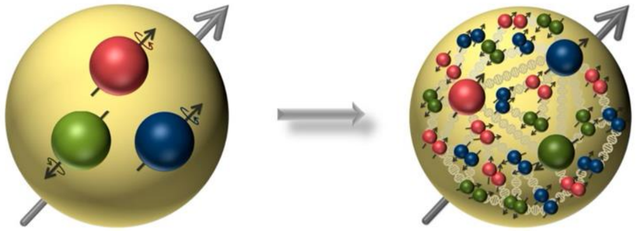
Motivation of RHIC spin



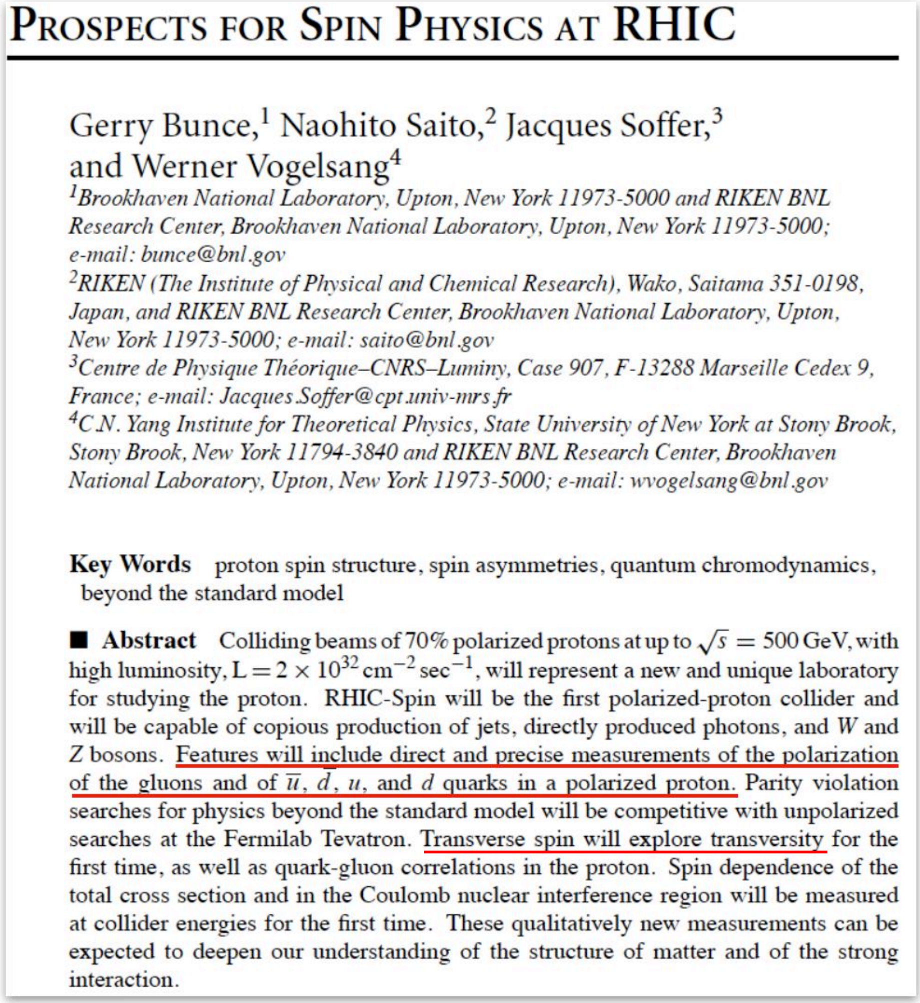
To understand proton spin structure

If gluons really carry the bulk of nucleon's spin, why not use polarized proton? (*known by then to be predominantly made of gluons!*)

Why $\Delta\Sigma$ (quark + anti-quark's spin) small? Are quark and antiquark spins anti-aligned? Polarized p+p at high energy, through W+/- production could address this

A severe need for investigations of the surprising transverse spin effects was naturally possible and needed with the proposed polarized p+p collider…

Prospects for RHIC Spin Physics in 2000



Prospects for Spin Physics at RHIC

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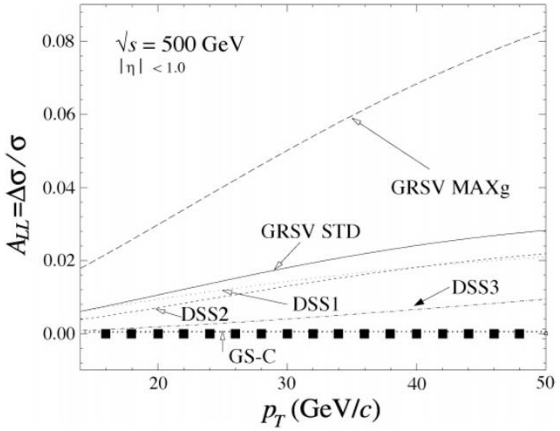
Key Words proton spin structure, spin asymmetries, quantum chromodynamics, beyond the standard model

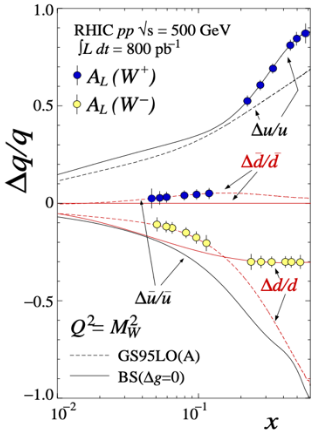
■ **Abstract** Colliding beams of 70% polarized protons at up to $\sqrt{s} = 500$ GeV, with high luminosity, $L = 2 \times 10^{32}\,\mathrm{cm^{-2}\,sec^{-1}}$, will represent a new and unique laboratory for studying the proton. RHIC-Spin will be the first polarized-proton collider and will be capable 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

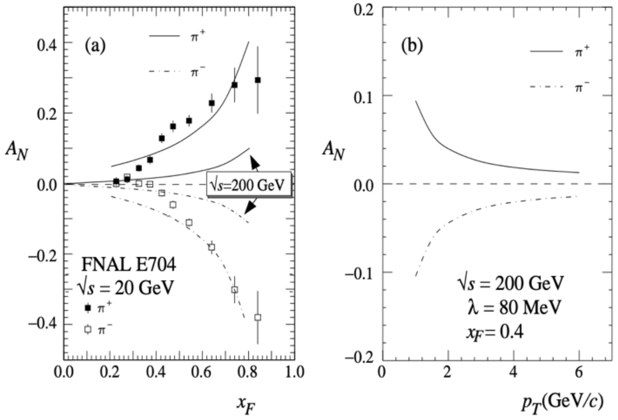
Jet production



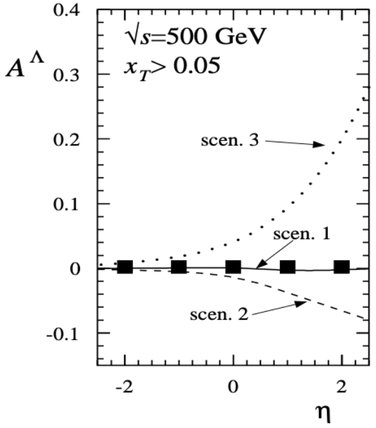
$W^{\pm}$ production



Transverse SSA

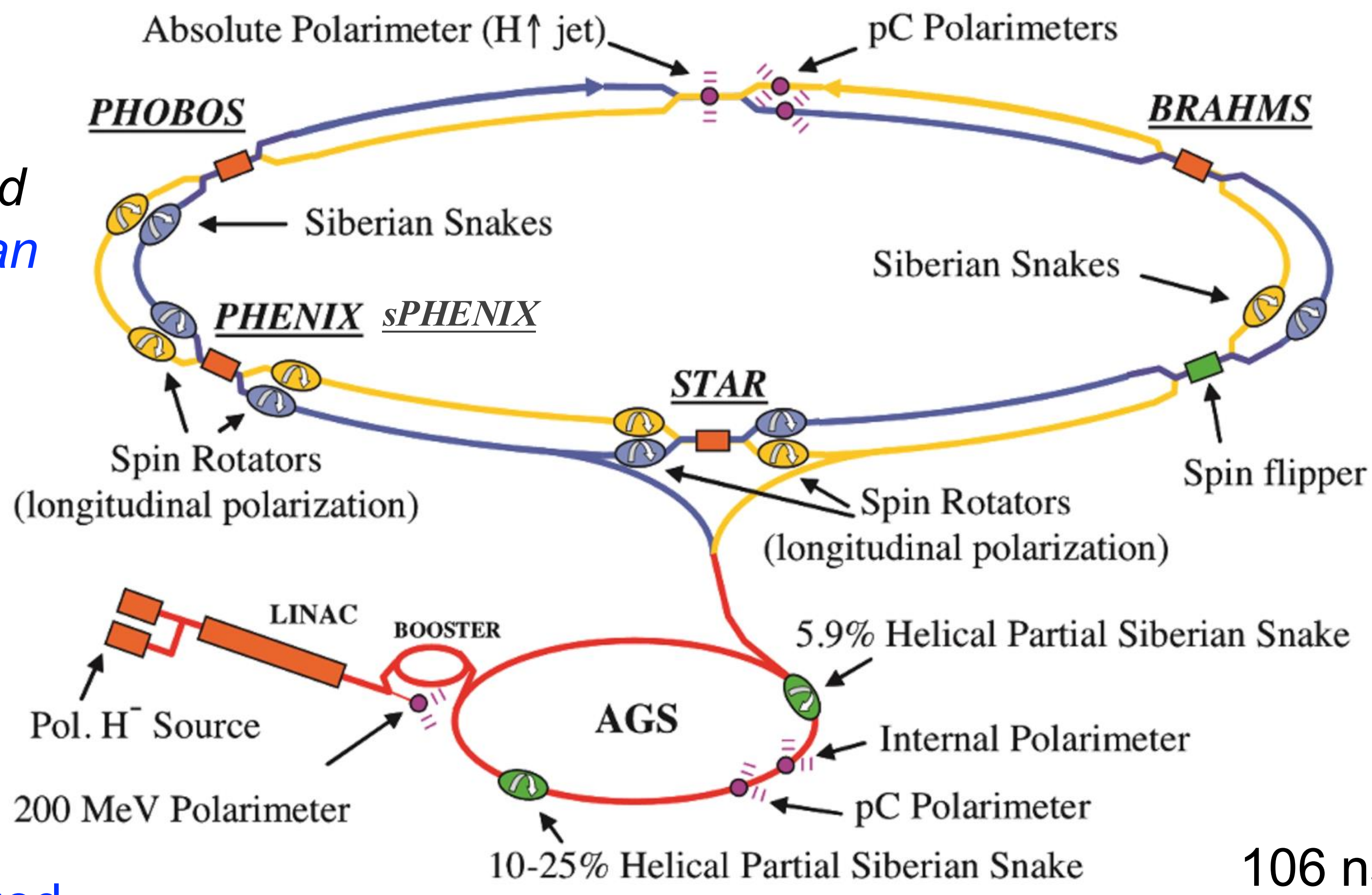


Lambda spin transfer



Polarized RHIC

Accelerate polarized protons with Siberian Snakes

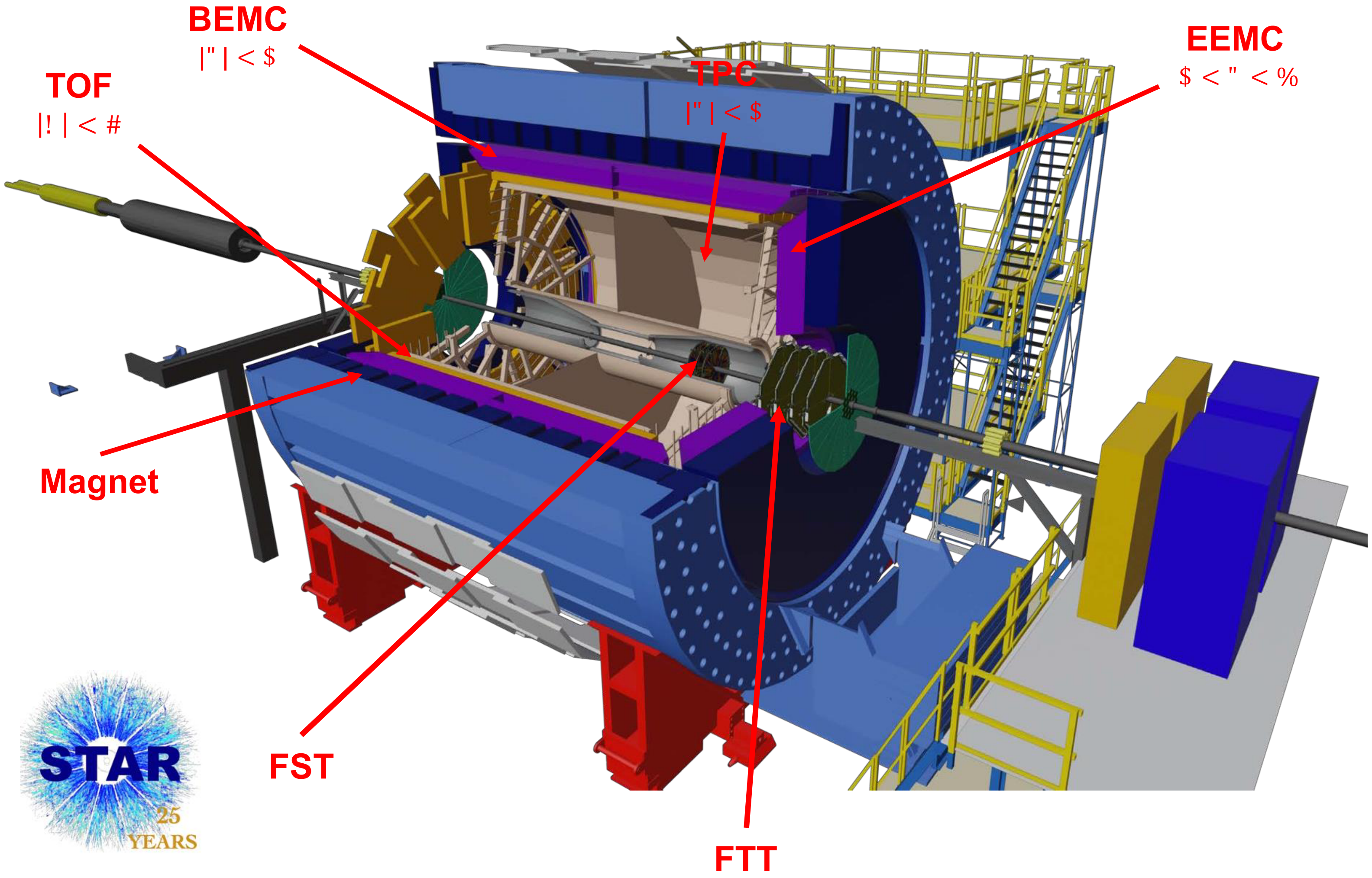


Manipulate spin direction with spin rotator

High current polarized proton source

106 ns bunch crossing with pre-determined spin directions

STAR detector overview



Time Projection Chamber
- charged track momentum msmt
- particle identification dE/dx,
- vertex reconstruction
- coverage $|\eta| < 1$

Time of Flight detector
- particle identification
- coverage $|\eta| < 1$

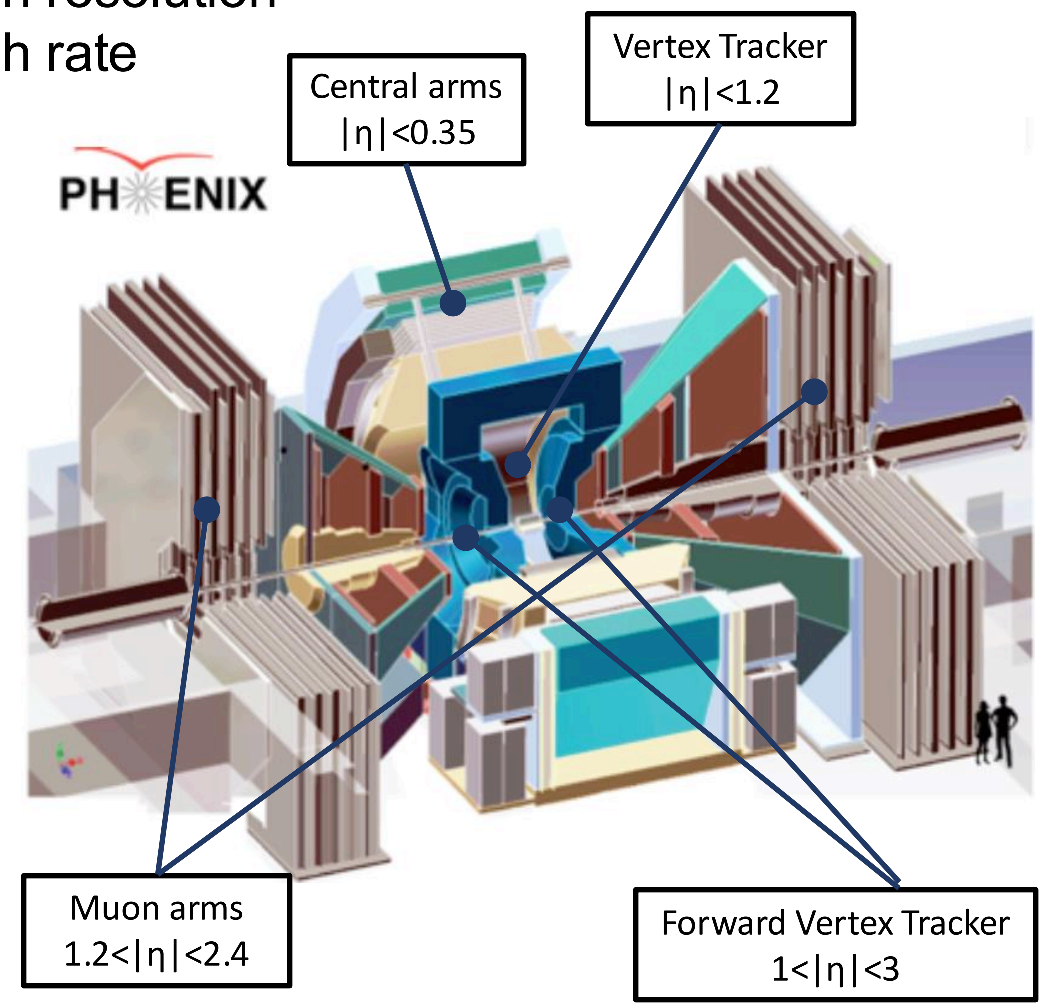
Barrel and Endcap E.M. Cal.
- towers and Shower Maximum Det.
- neutral EM energy measurement,
- trigger (towers, patches of towers)
- coverage $|\eta| < 1$ and $1 < \eta < 2$

Only running detector at RHIC in 2017-2022

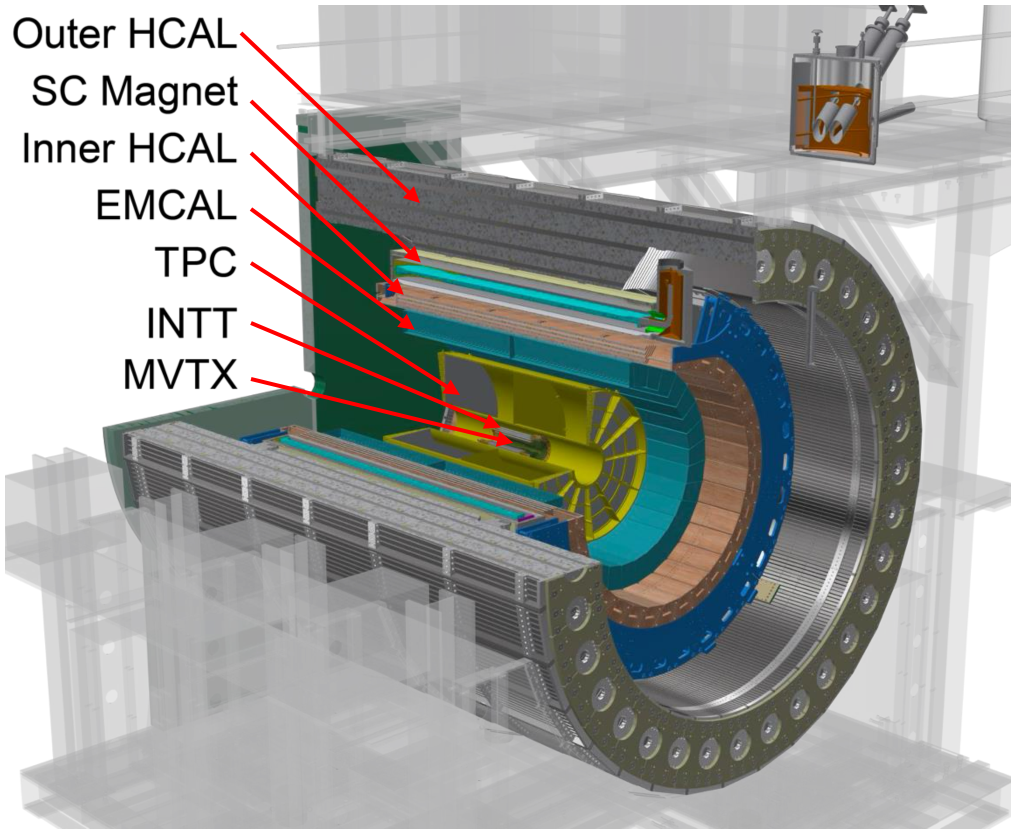
PHENIX and sPHENIX Detector Overview

High resolution
High rate

Running till 2016

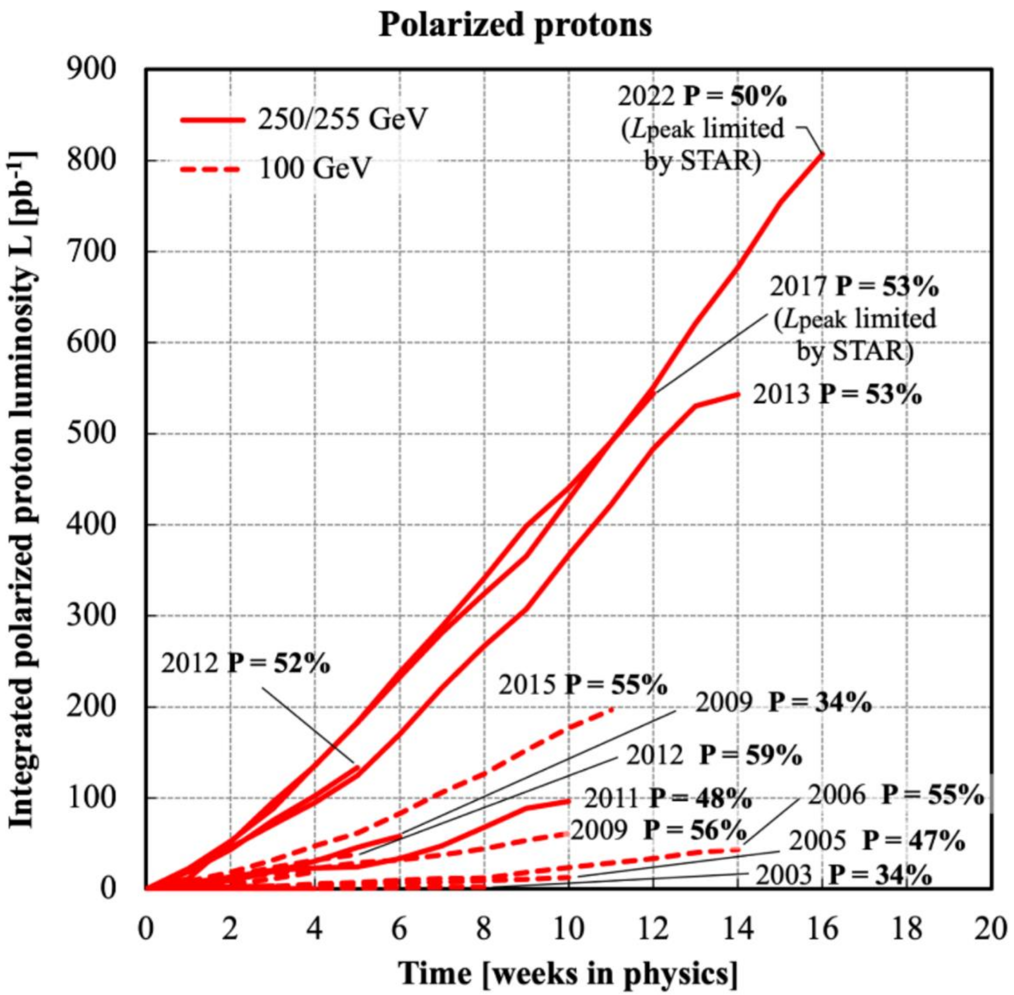


Operation: 2023-2025



- High rate
- Large acceptance
- Excellent resolution
- HCal and EMCal

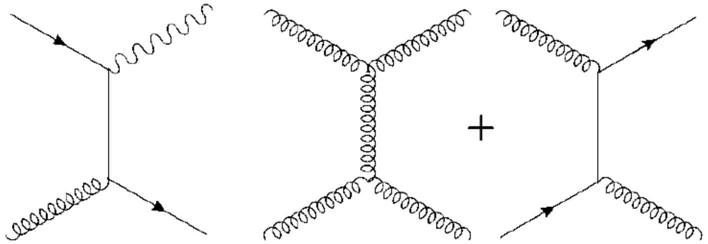
RHIC spin data accumulation



	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	52	53
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	52	53
	2017	510	350	55
	2022	508	400	52
	2024	200	164	55

by STAR

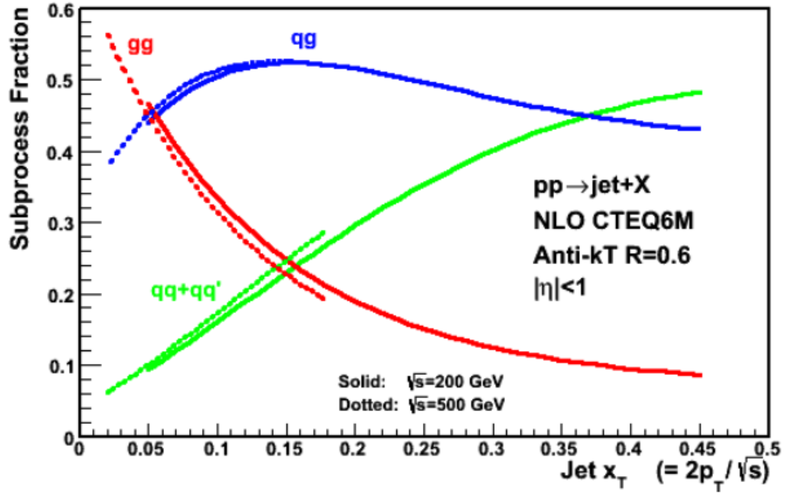
Probe gluon polarization



QCD Compton scattering

Quark-gluon, gluon-gluon elastic scattering

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

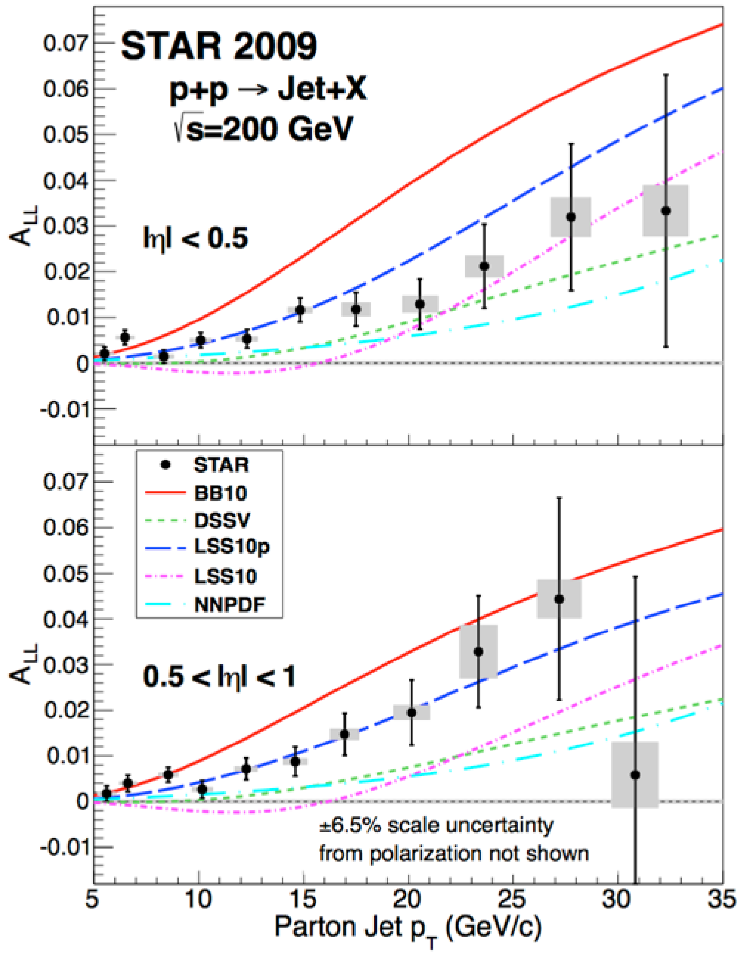


Measured double-spin asymmetry:

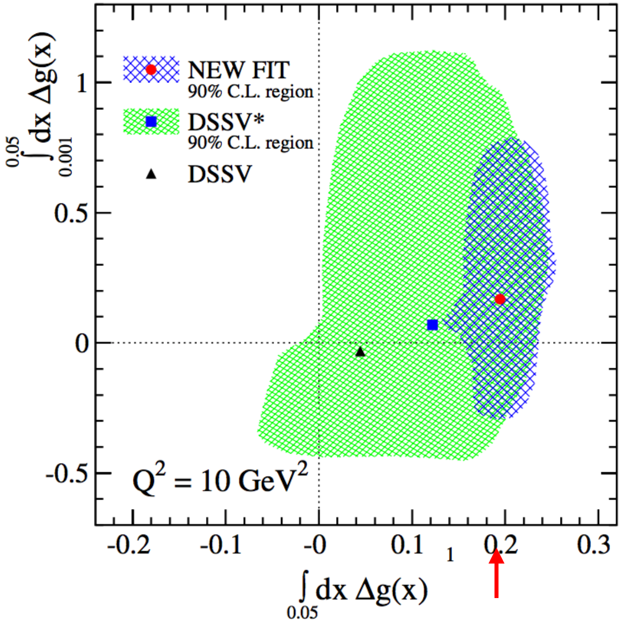
$$A_{LL} = \frac{\sigma^{\uparrow\uparrow} - \sigma^{\uparrow\downarrow}}{\sigma^{\uparrow\uparrow} + \sigma^{\uparrow\downarrow}} \propto \overbrace{\frac{\Delta f_1}{f_1} \otimes \frac{\Delta f_2}{f_2}}^{\text{probed}} \otimes \overbrace{\hat{a}_{LL} \otimes D_f^h}^{\text{inputs}}$$

Yes, gluon spin does contribute!

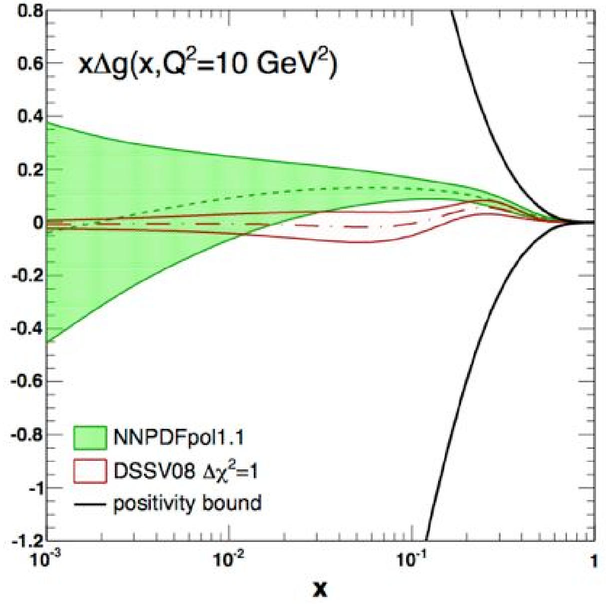
STAR, PRL115 (2015) 092002



DSSV, PRL113 (2014) 012001



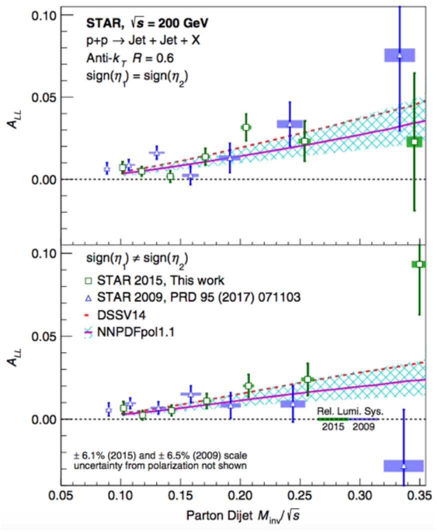
NNPDF, NPB887 (2014) 276



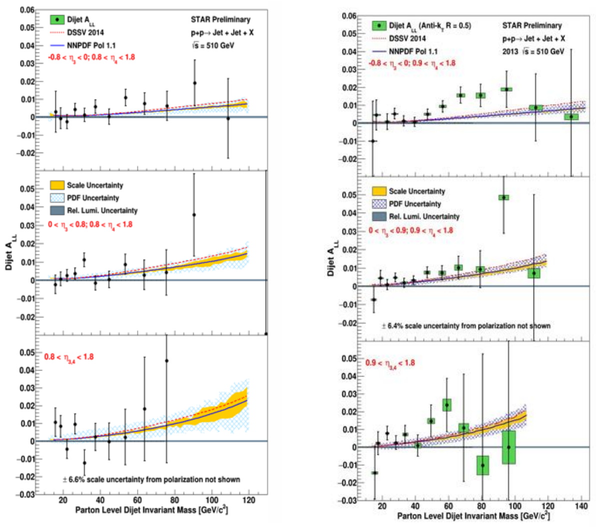
- **First evidence** of non-zero contributions from gluon spin at $Q^2 \sim 10\ GeV^2$

A big wave of precision results

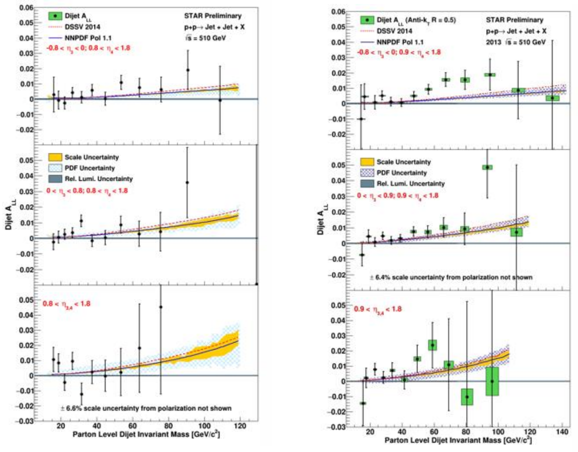
STAR, PRD 105, 092011 (2022)



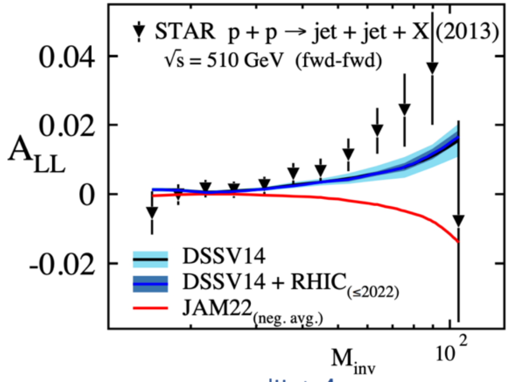
STAR, PRD 103, L091103 (2021)



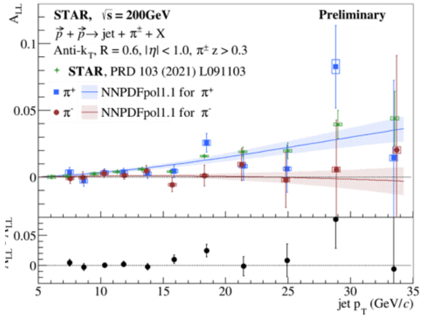
STAR di-jet preliminary results



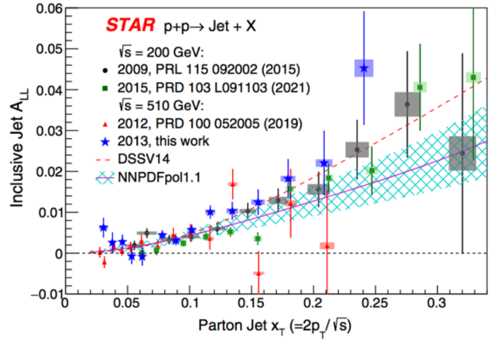
STAR, PRD 105, 092011 (2022)



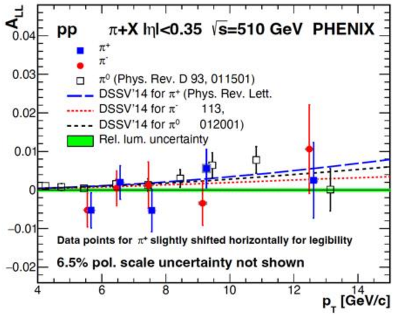
dijet A_{LL}



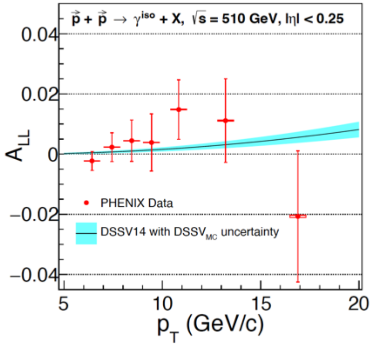
π tagged jet A_{LL}



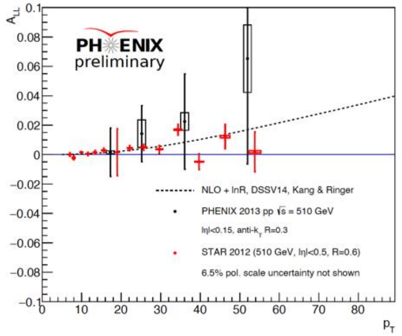
PHENIX, PRD 102, 032001 (2020)



PHENIX, PRL130, 251901 (2023)



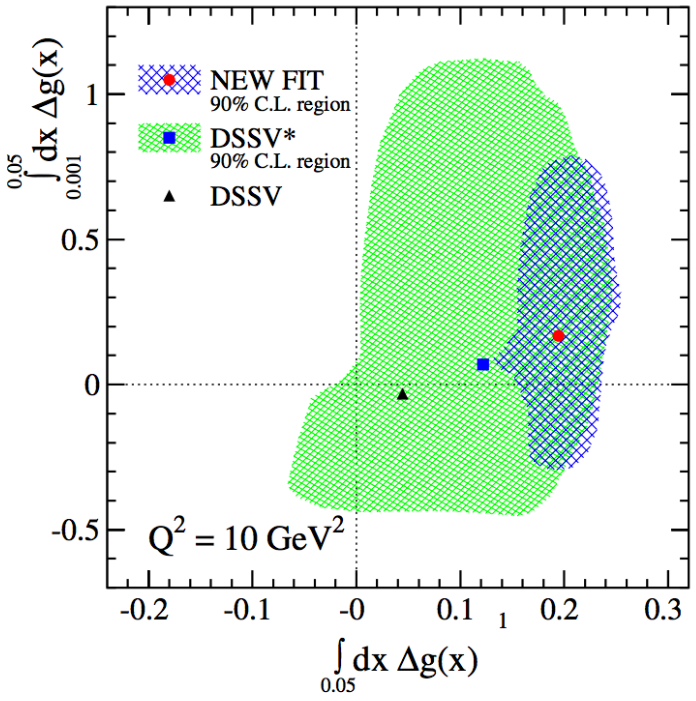
PHENIX preliminary



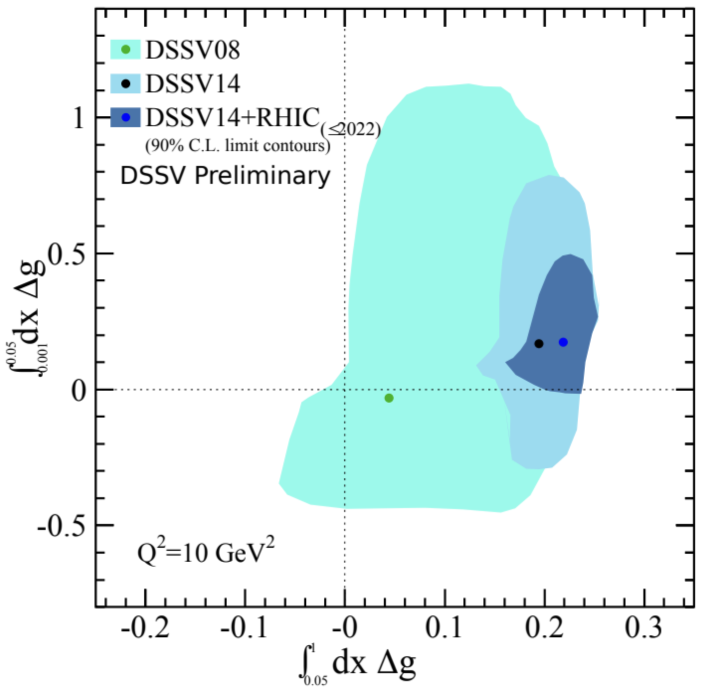
Longitudinal data taking concluded at RHIC, PHENIX and STAR released the full statistics results.

Gluon polarization from RHIC spin

DSSV, PRL113 (2014) 012001



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



DSSV14 + RHIC (≤2022):

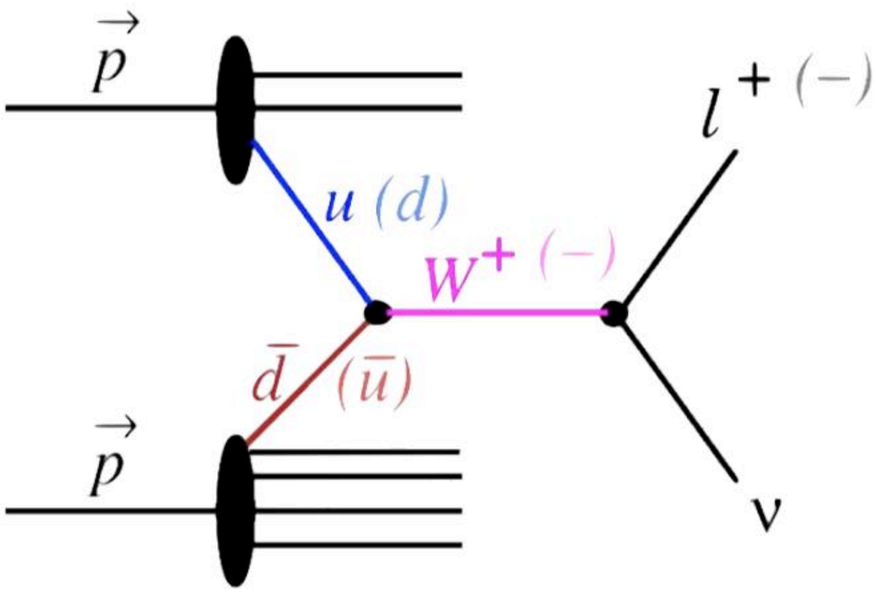
- $\Delta G = \int_{0.05}^{1} \Delta g(x)dx = 0.22^{+0.03}_{-0.06}$
- $\Delta G = \int_{0.001}^{0.05} \Delta g(x)dx = 0.17^{+0.33}_{-0.17}$

– Gluon spin contribute ~40% of proton spin

Flavor separation with W boson

Elegant way to study proton spin-flavor structure:

- W boson selects quarks/antiquarks with specific helicity.
- W bosons are measured via leptonic decay.

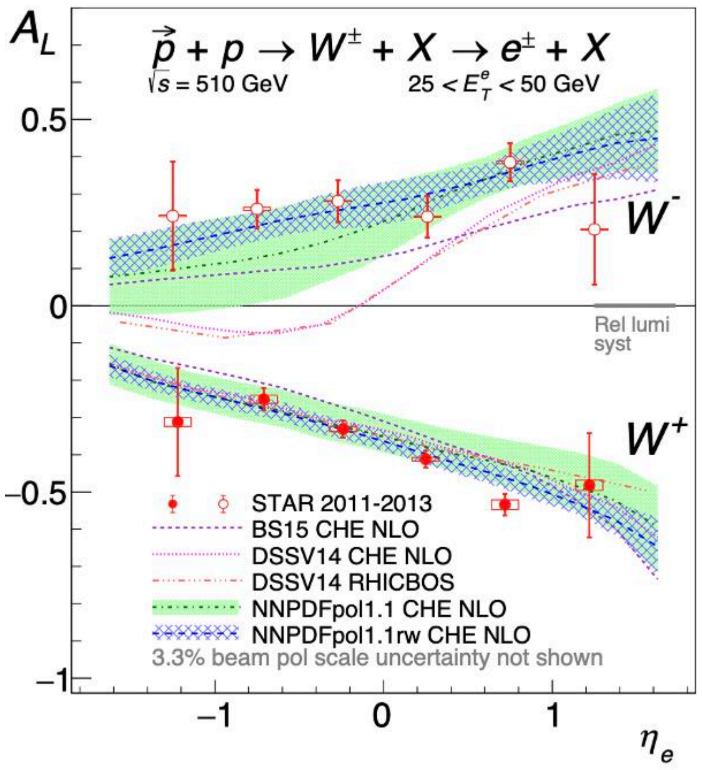


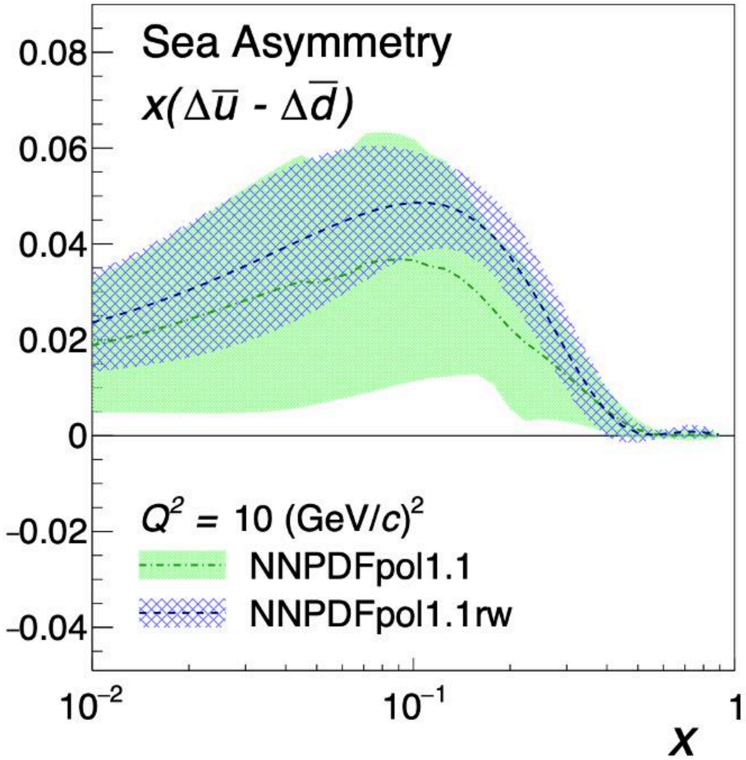
Parity violating single-spin asymmetry:

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

Impact of W results

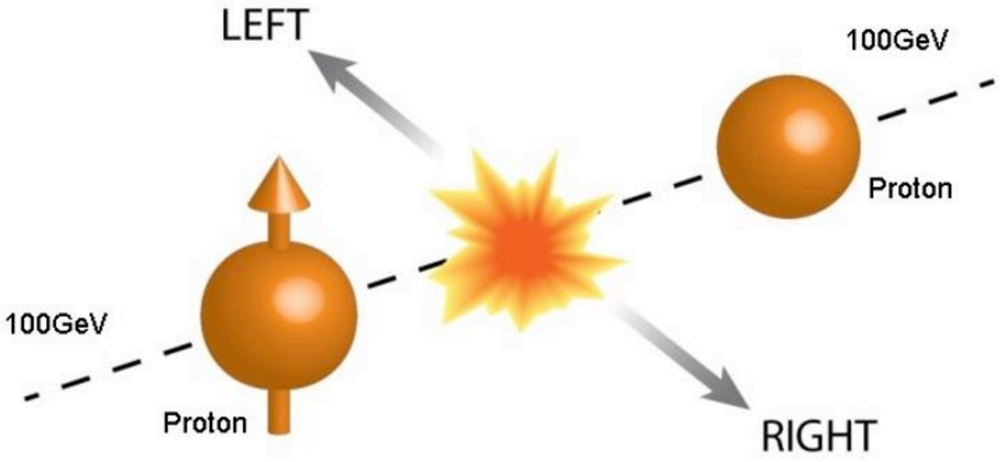
STAR, PRD99, 051102 (2019)





- Now we know: $\Delta\bar{u} > 0$ and $\Delta\bar{d} < 0$
- The flavor asymmetry $\Delta\bar{u} - \Delta\bar{d}$ similar size but opposite sign to the unpolarized case.
- *TMD W* A_L is ongoing.

Another longstanding spin puzzle



Transverse single spin asymmetry:

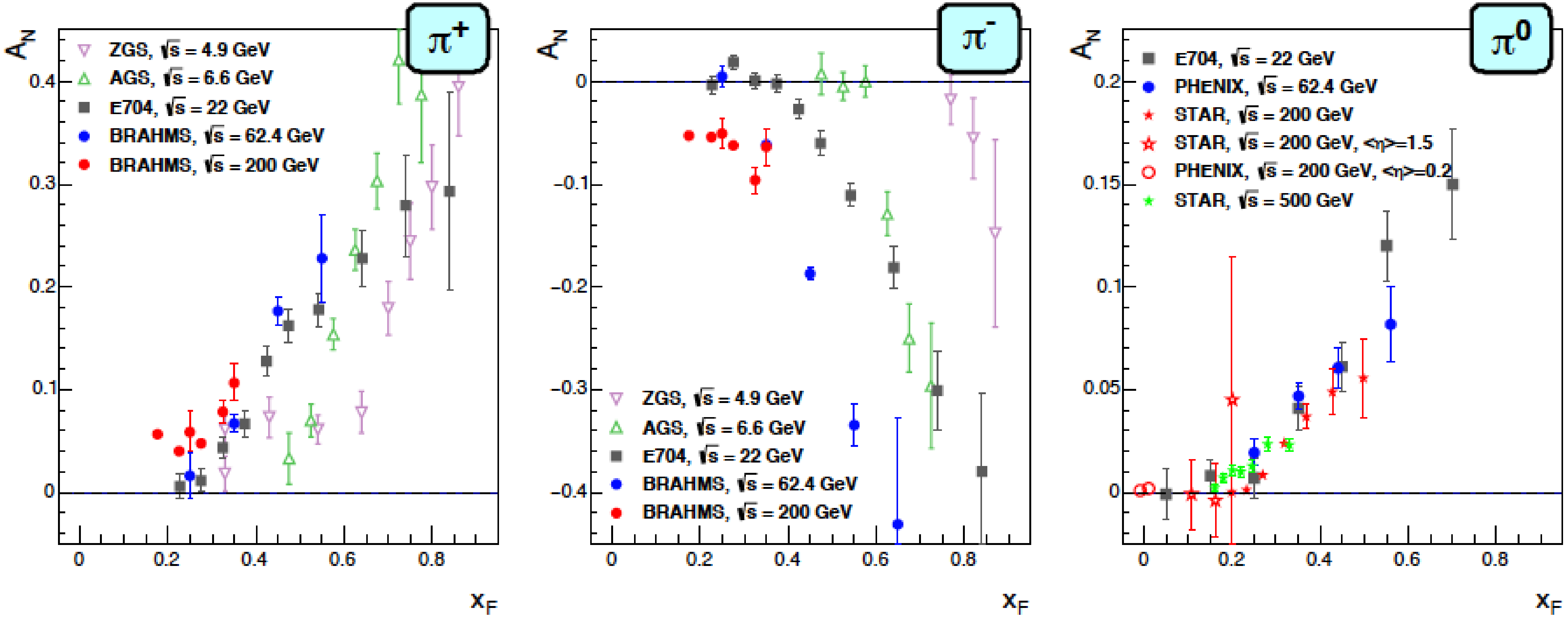
$$A_N = \frac{N_L - N_R}{N_L + N_R}$$

Transverse spin effect expected to be small at high energies…

--- but FNAL came with a big surprise: it is very large!

Remains mystery after 40+ years

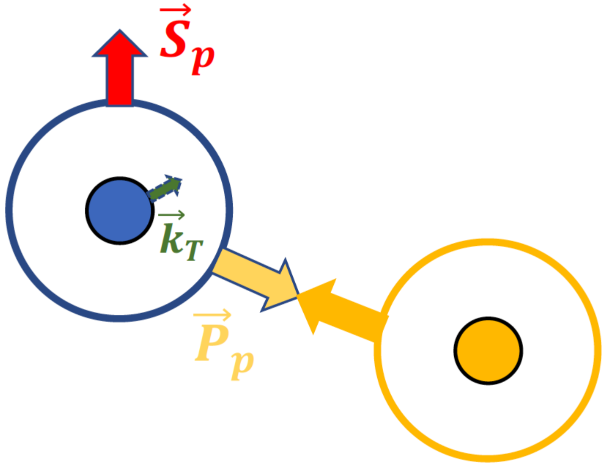
RHIC Cold QCD plan, arXiv: 1602.03922



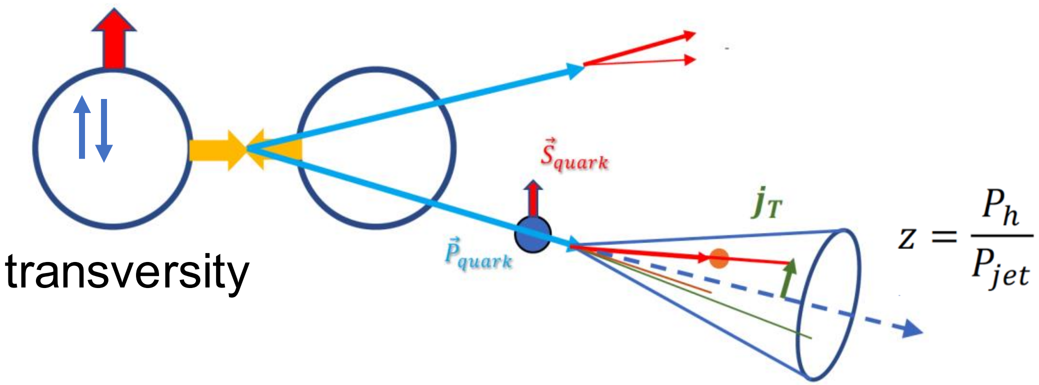
Large asymmetry over a very wide range (√s: 4.9 GeV to 500 GeV)

Possible origins

Sivers effect



Collins effect



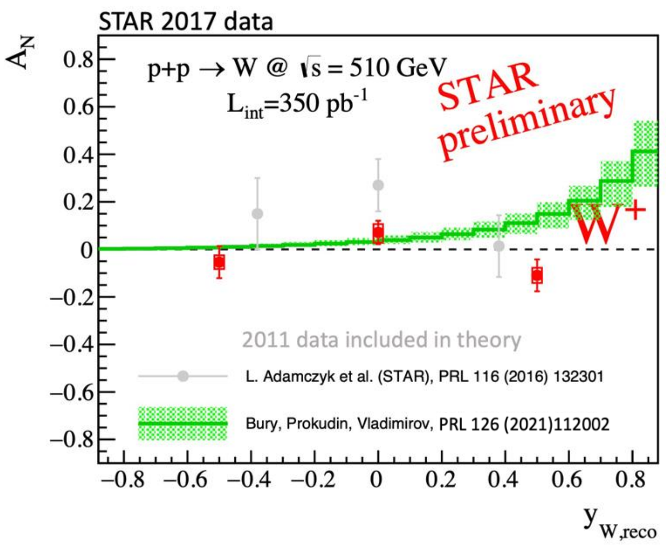
Due to transverse motion of quarks in the nucleon: initial state effect

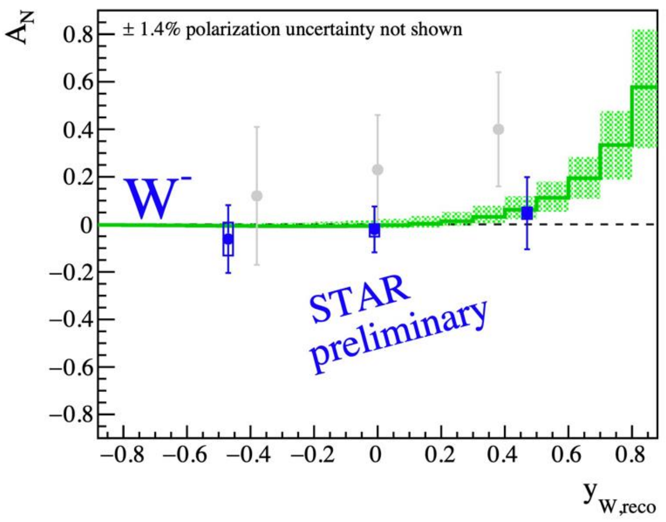
Asymmetry in the fragmentation hadrons: final state effect

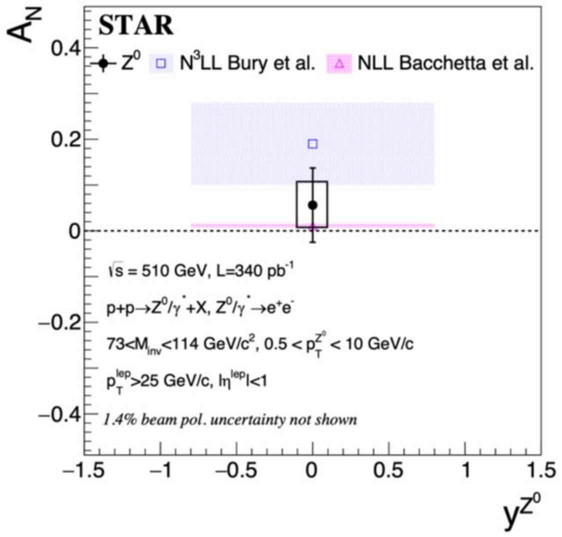
Weak bosons A_N – Sivers

- Universality test of Sivers function: sign-change from DIS to DY/W/Z

PLB 854 (2024) 138715



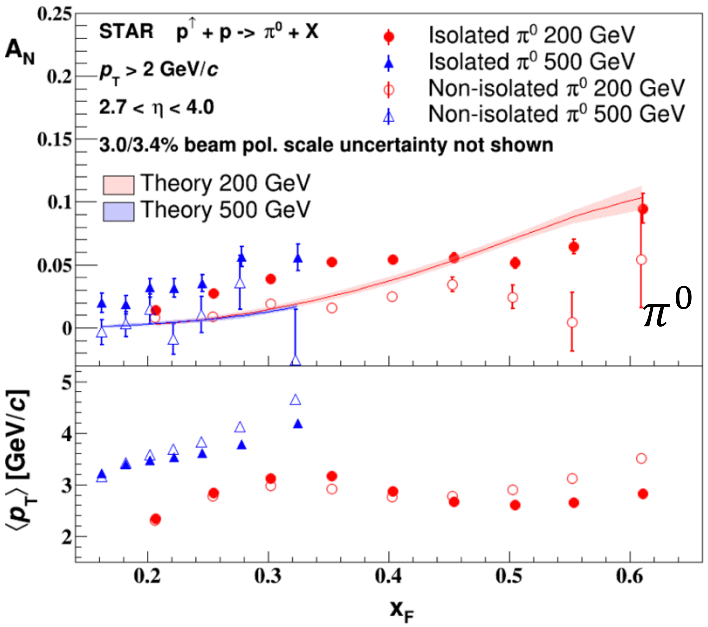


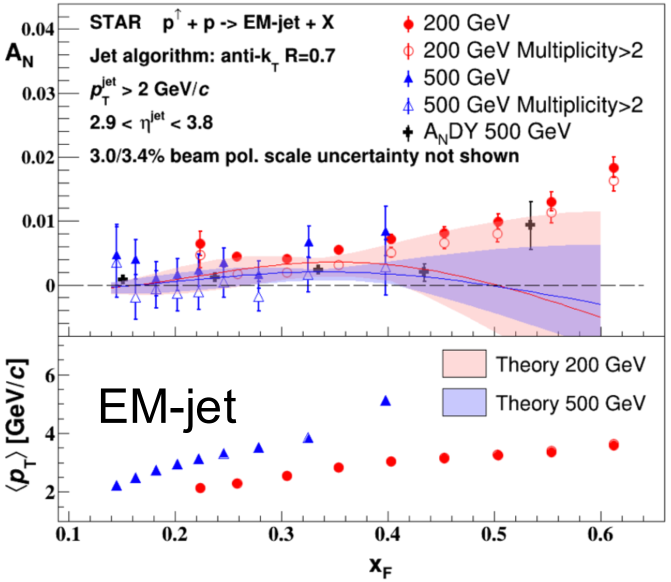


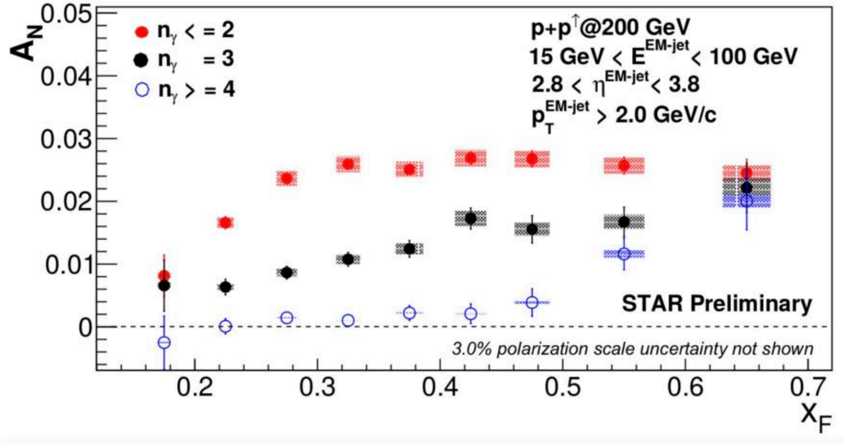
- Theoretical (PRL126,112002): extraction includes SIDIS, DY and 2011 STAR data with N3LO and NNLO accuracy of the TMD evolution *assuming sign-change*
- STAR preliminary with 2017 data with much improved precision, expect big impact in Sivers function at high-x in next global TMD fit

Forward A_N π^0, EM-jet

STAR, PRD 103, 092009 (2021)



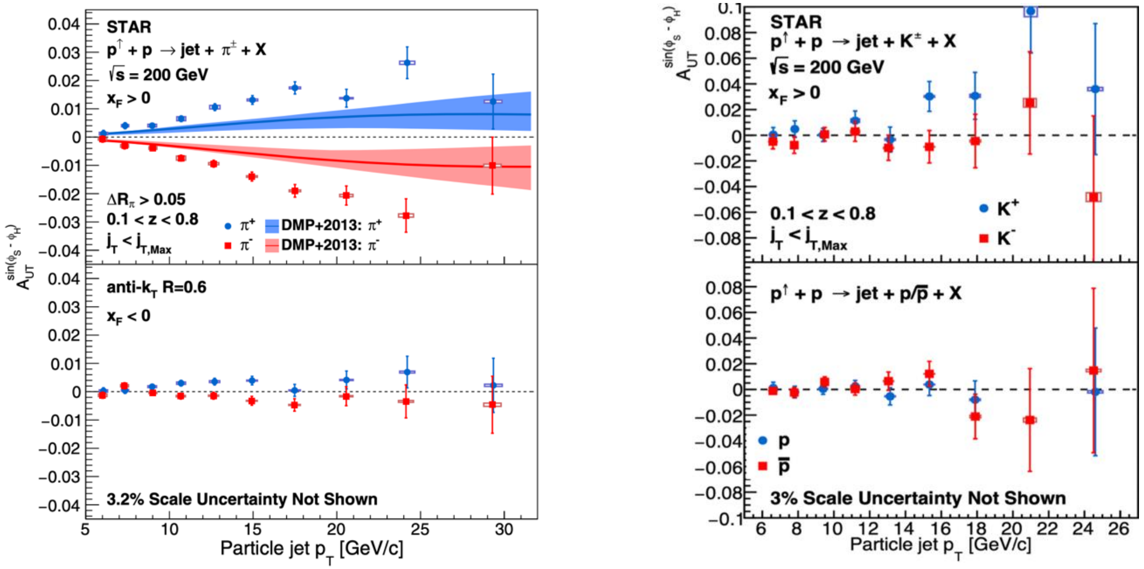




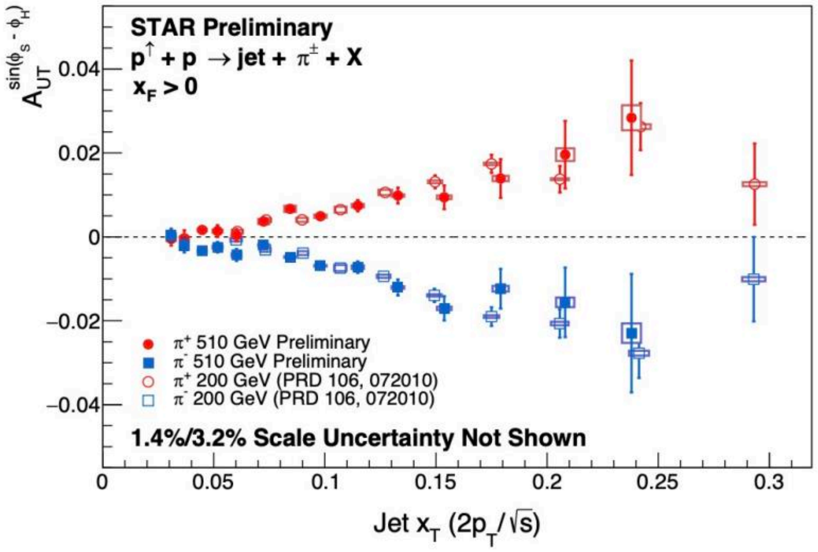
- A_N with forward EM-jets and π^0 in 200/500 GeV pp collisions
- Decreasing A_N as ”jet-ness” increasing (high multiplicity)
- Run2022 and 2024: improved statistic for various objects using Forward Upgrades

Hadron in Jet A_N – Transversity + Collins

STAR, PRD 106 (2022), 072010

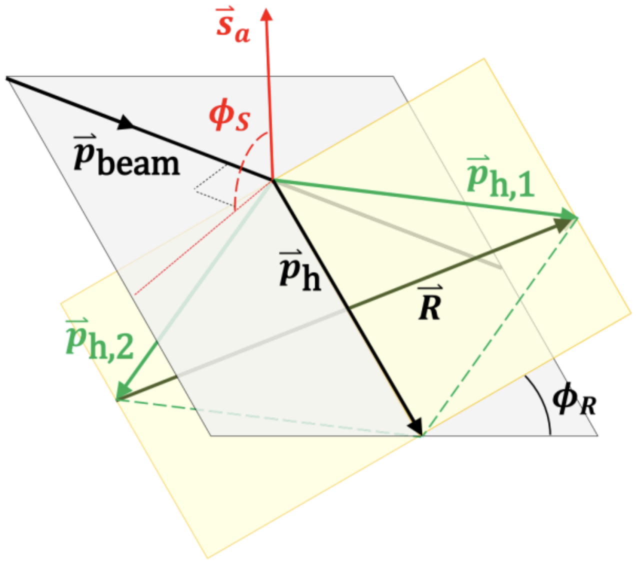


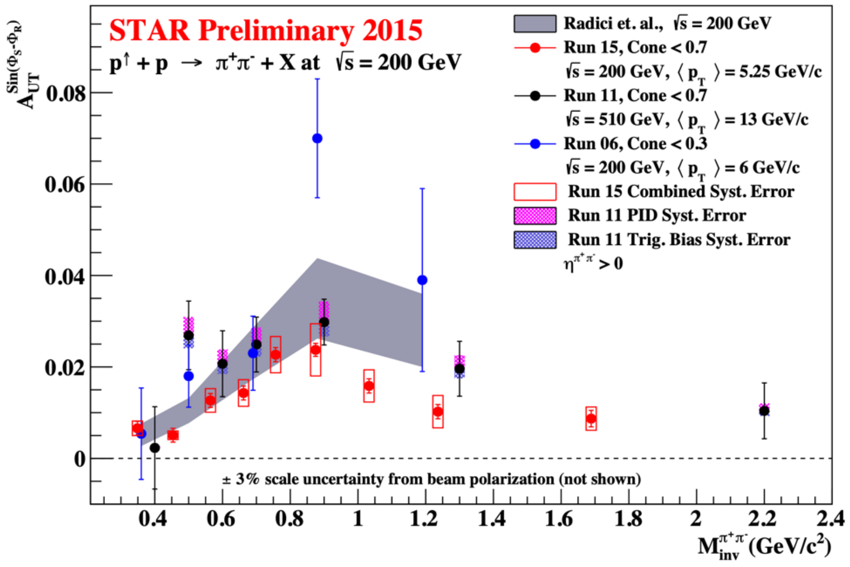
STAR, SPIN2023



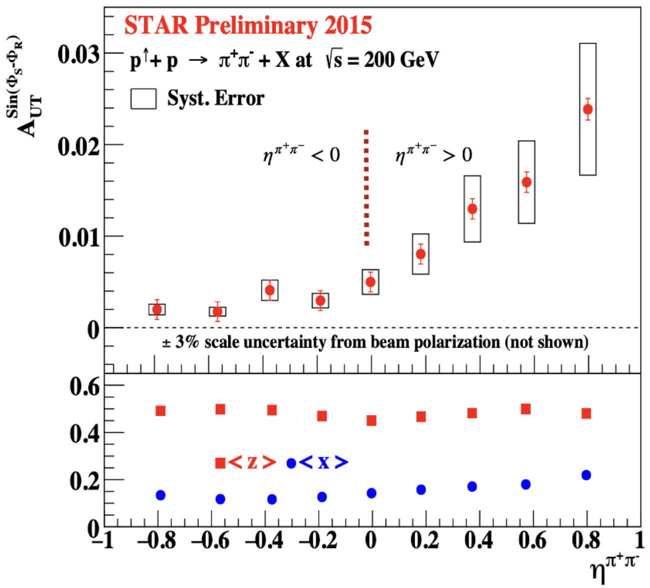
- Significant Collins asymmetries have been observed in 200 and 500 GeV
- New results show weak energy dependence and provide important constraints on the scale evolution for Collins asymmetry

Di-hadron correlations – Transversity + IFF



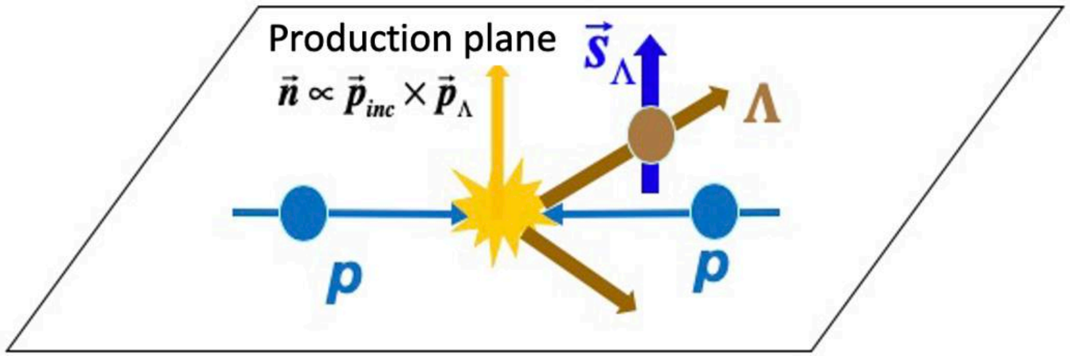


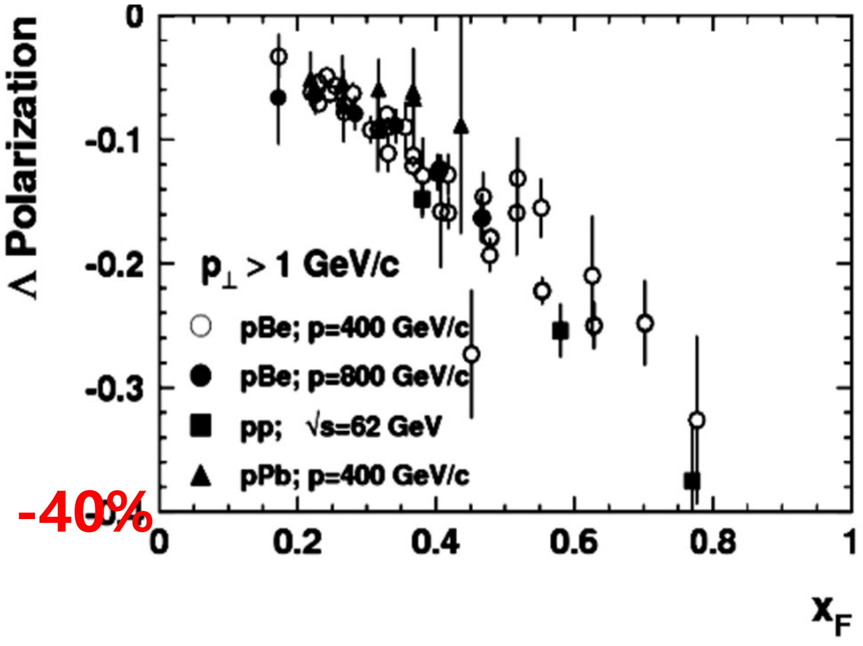
$A_{UT} \sim h_1 \otimes H_1^{\sphericalangle}$



- 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.

One more longstanding spin puzzle …





Polarization of particles produced in unpolarized hadron scattering

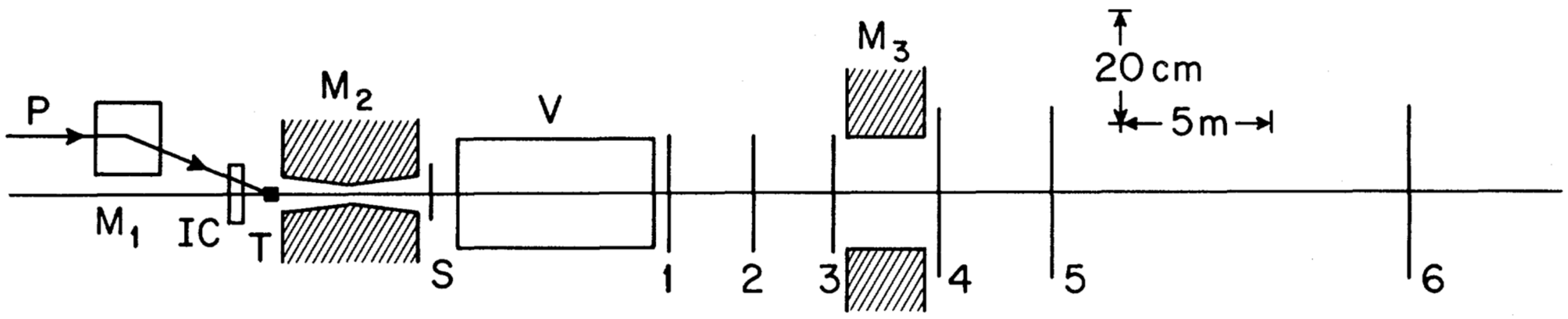
was expected to be small

--- but a big surprise from experiment: it is very large!

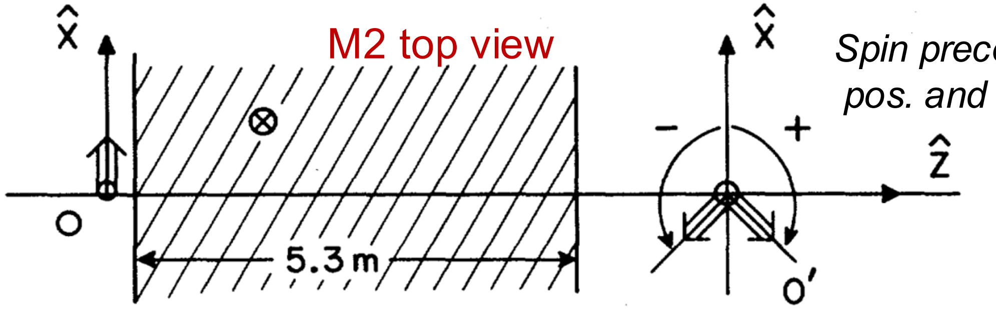
The measurement in 1976

G. Bunce et al. PRL36, 1113 (1976)

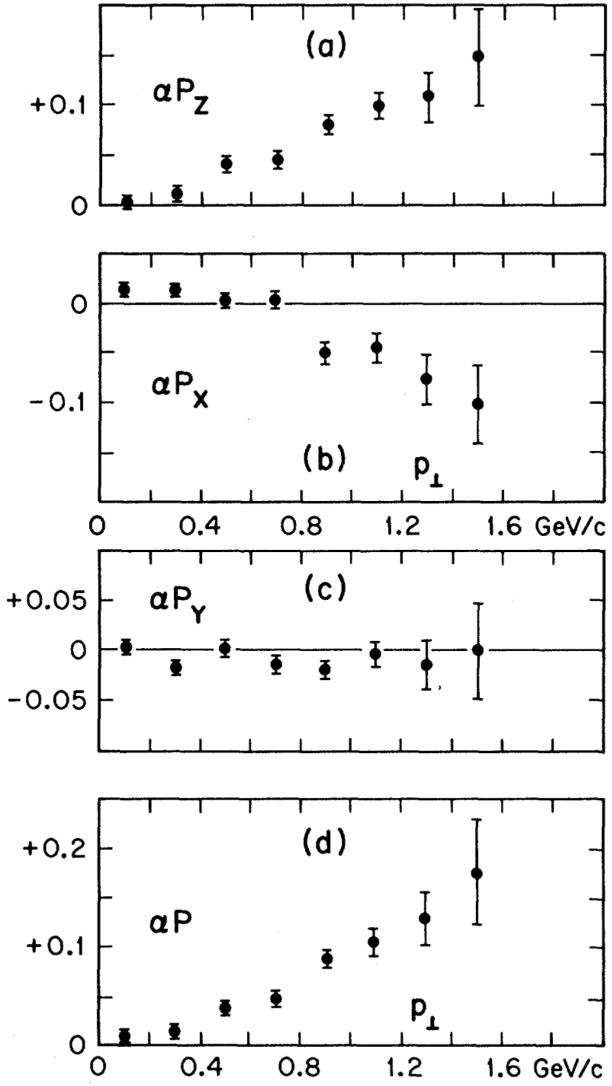
300 GeV <u>unpolarized</u> proton on <u>unpolarized</u> Beryllium target



- Scattering angles determined by incoming beam angle
- Recorded Lambda decay after 5.3m collimator inside sweeping magnet M2
- *10%* level polarization observed; increasing vs. p_T



Spin precession for pos. and neg. M2 polarity



10%

Follow-up measurements

incomplete list

Heller et al., Phys. Lett. B68 480 (1977)	24 GeV proton + Platinum at CERN
Heller et al., Phys. Rev. Lett. 41, 607 (1978)	400 GeV proton + Beryllium at Fermilab (different hyperon)
Erhan et al., Phys. Lett B82, 301 (1979)	$\sqrt{s}$ = 53, 62 GeV proton + proton at CERN (ISR)
Lomanno et al., Phys. Rev. Lett. 43, 1905 (1979)	28.5 GeV proton + Iridium at BNL (AGS)
Heller et al., Phys. Rev. Lett. 51, 2025 (1983)	400 GeV proton + Beryllium/Copper/Lead at Fermilab
Abe et al., Phys. Rev. Lett. 50, 1102 (1983)	12 GeV proton + Tungsten at KEK
Aleev et al., Z. Phys. C 36, 27 (1987)	~40 GeV neutron + Carbon/Aluminum/Copper
Lundberg et al., Phys. Rev. D 40, 3557 (1989)	400 GeV proton + Beryllium at Fermilab (higher pT)
Ramberg et al., Phys. Lett. B 338, 403 (1994)	800 GeV proton + Beryllium at Fermilab
Fanti et al., Eur. Phys. J. C 6 265 (1999)	450 GeV proton + Beryllium at CERN (SPS-NA48)
Abt et al., Phys. Lett. B 638, 415 (2006)	920 GeV proton + Carbon/Tungsten at DESY (HERA-B)
Aad et al., Phys. Rev. D 91, 032004 (2015)	$\sqrt{s}$ = 7 TeV proton + proton at CERN (ATLAS)
Abt et al., JHEP09, 082 (2024)	2.5 TeV proton + Neon at CERN (LHCb-SMOG)

Features of lambda “spontaneous(?)” polarization

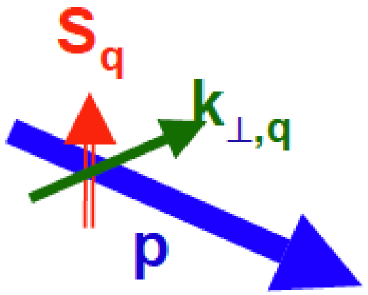
- Lambda transverse polarization is significant.
- Anti-lambda is not polarized.
- Polarization is (almost) independent of beam energy.
- Feynman-x and transverse momentum dependence scales with energy.
- Weak target-mass dependence: pA $\approx$ pp, parton level reaction.

Non-perturbative effects at Initial and Final States

Partonic scattering (pQCD) cannot explain the large polarization.

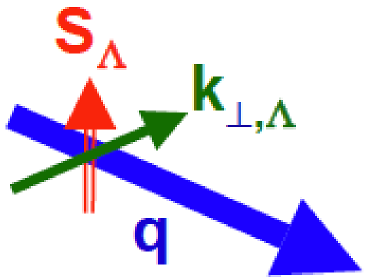
Then, must be non-pQCD effects from *initial state and/or final state.*

Parton distributions



$\longleftarrow \vec{S}\cdot(\vec{p}\times\vec{k}_\perp) \longrightarrow$

Parton fragmentations



Can not distinguish in pp;

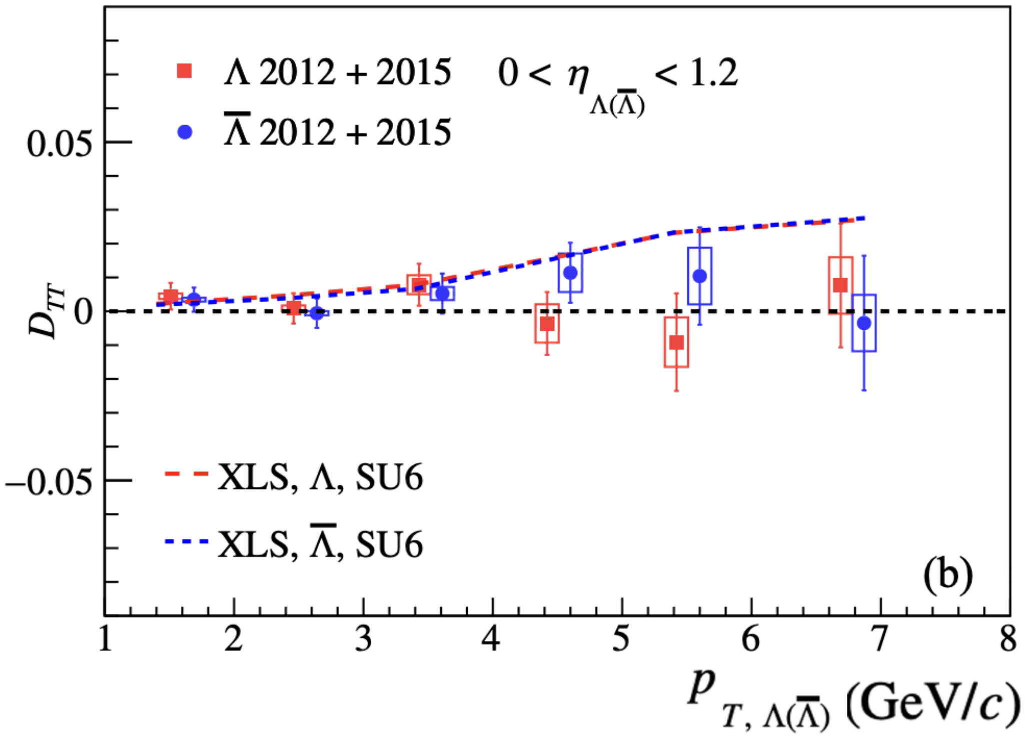
ep and e^+e^- can separate.

- Spin transfer from initial state: parton is polarized in polarized proton — Helicity/Transversity

  parton is polarized in unpolarized proton — Boer-Mulders
- Polarization arising at final state: parton is unpolarized but fragmenting into polarized hadron. — Polarizing FFs

Lambda transverse spin transfer – Transversity + pFFs

STAR, PRD109, 012004 (2024)



The results are consistent with model calculations within uncertainties.

Transverse spin transfer:

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

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

Transversity PDF

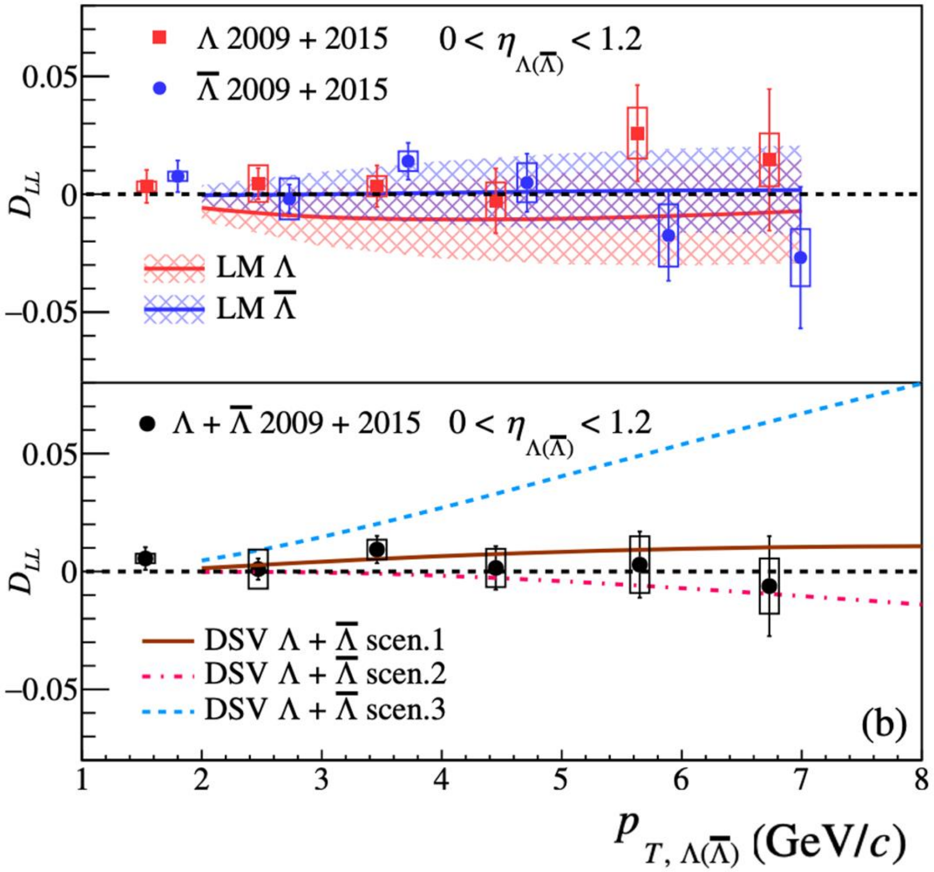
Transversity FF

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

Strange quarks polarization via Lambda spin transfer

STAR, PRD109, 012004 (2024)



Spin transfer:

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

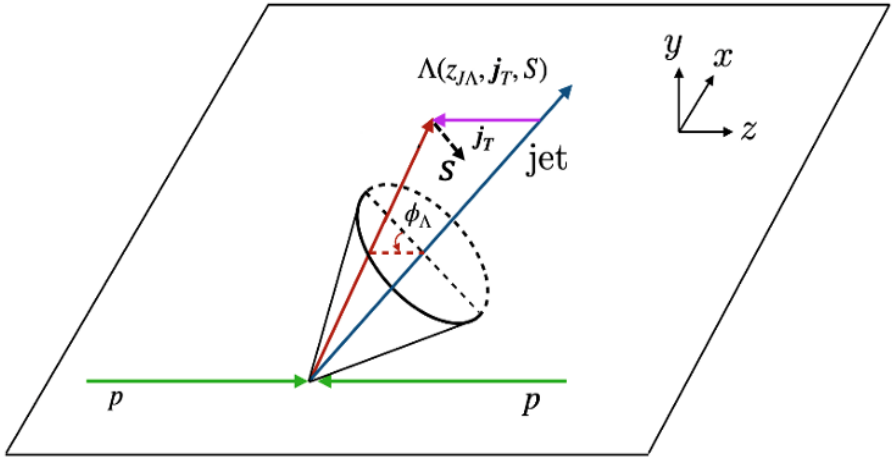
$$d\Delta\sigma^{\Lambda} = \sum \int dx_a dx_b dz \underbrace{\Delta f_a(x_a)}_{\text{Polarized PDFs}} f_b(x_b) \Delta\sigma(ab \to cd) \underbrace{\Delta D^{\Lambda}}_{\text{Polarized FFs}}(z)$$

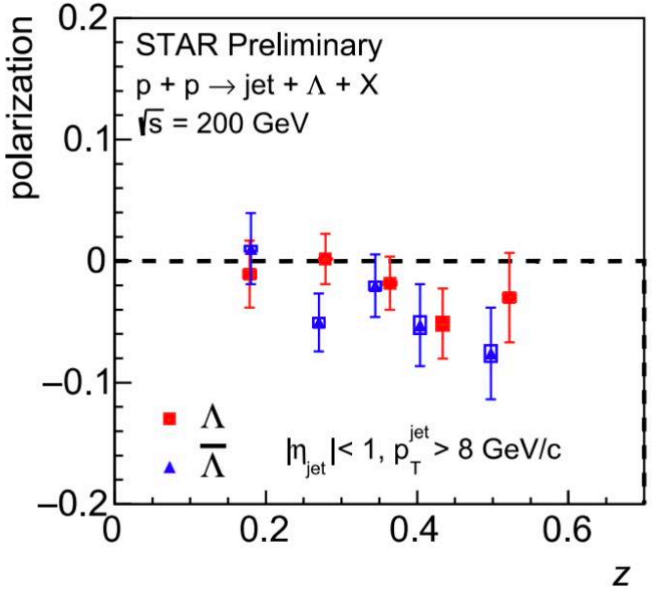
Access polarized FFs and PDFs of strange quarks

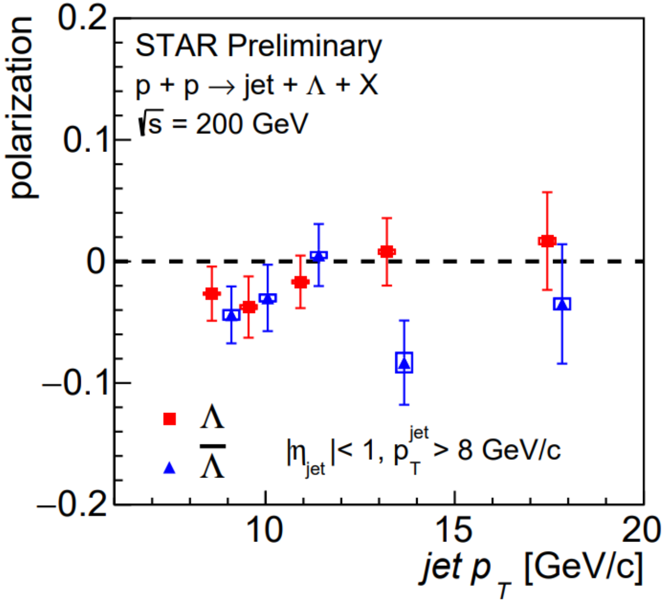
- Final state polarization accessible via weak decay
- Lambda's spin is expected to be carried mostly by its constituent strange quark

Polarizing fragmentation function

Taoya Gao, SPIN2023, arXiv:2402.01168







Access polarizing fragmentation functions (FF) via polarization of Lambda-in-jet

- Indication of negative transverse polarization at large z and low jet p_T

Summary

RHIC spin operation concluded last year.

RHIC has been making significant contributions to three poorly constrained pieces of the spin puzzle

- **Gluon polarization** $\Delta G > 0$
- **Flavor-separated quark and anti-quark polarizations** $\Delta\bar{u} > \Delta\bar{d}$
- **Transverse** program in progress: existing data being published/analyzed, **stay tuned**

** Rich physics of spin in heavy ion at RHIC not covered.*

Outlook

- Successful RHIC spin operation in 2022 and 2024 with STAR forward upgrade and new sPHENIX (2024).
- Studies of final state spin effects, intersecting with heavy-ion physics, are being extended to the LHC.
- Next generation spin experiments: polarized Electron Ion Collider (EicC/US-EIC), polarized HIAF, LHC, NICA, etc.

Thank you for your attention!