The 12th Circum-Pan-Pacific Symposium on High Energy Spin Physics

RHIC spin program

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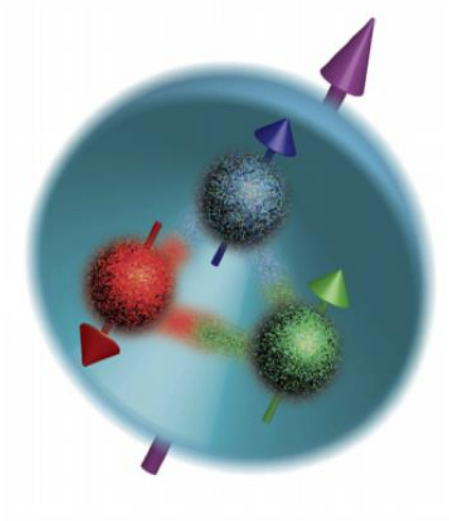
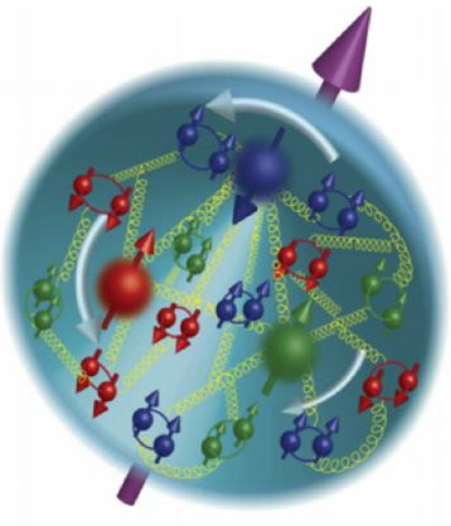
山东大学
SHANDONG UNIVERSITY

Proton spin structure





Jaffe-Manohar 1990

$$< S_p > = \frac{1}{2} = \frac{1}{2}\Delta\Sigma$$

quark spin

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

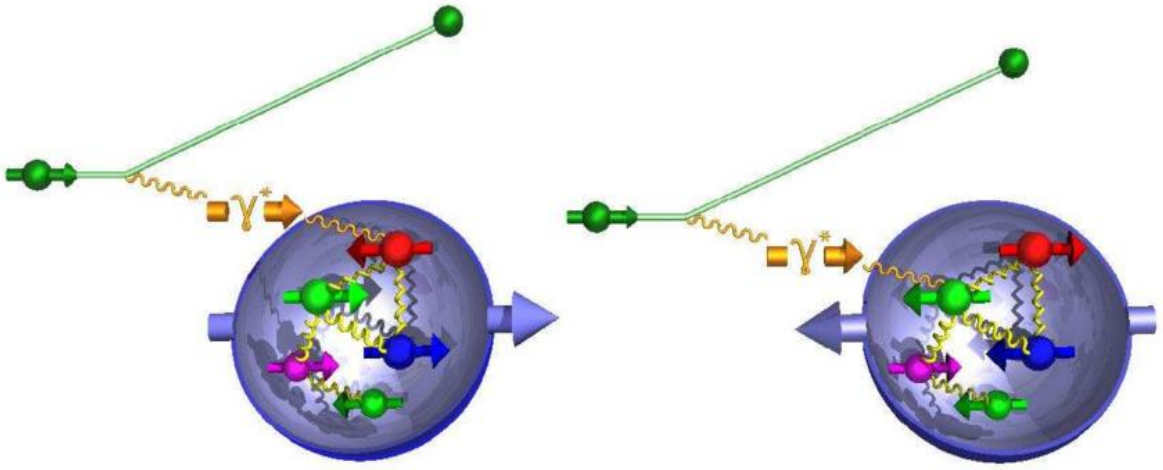
quark spin

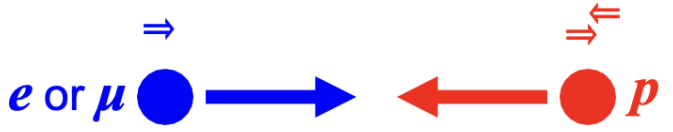
gluon spin

orbital angular momentum

Probe proton spin with polarized DIS

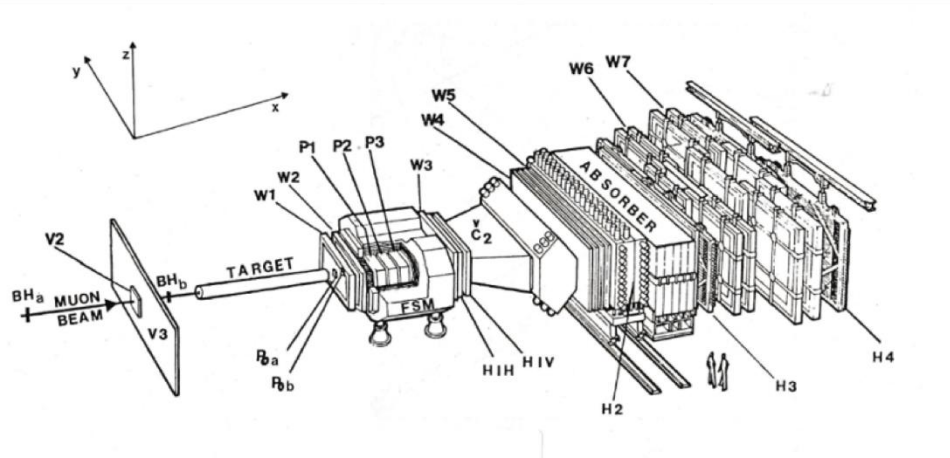
- Measure deep-inelastic scattering with polarized electrons or muons off polarized protons
- Difference in cross section for like vs. unlike helicity beams provides information about spin orientations of the quarks inside the polarized proton





$$A_{\gamma * p} \propto \frac{N^{\uparrow\downarrow} - N^{\uparrow\uparrow}}{N^{\uparrow\downarrow} + N^{\uparrow\uparrow}}$$

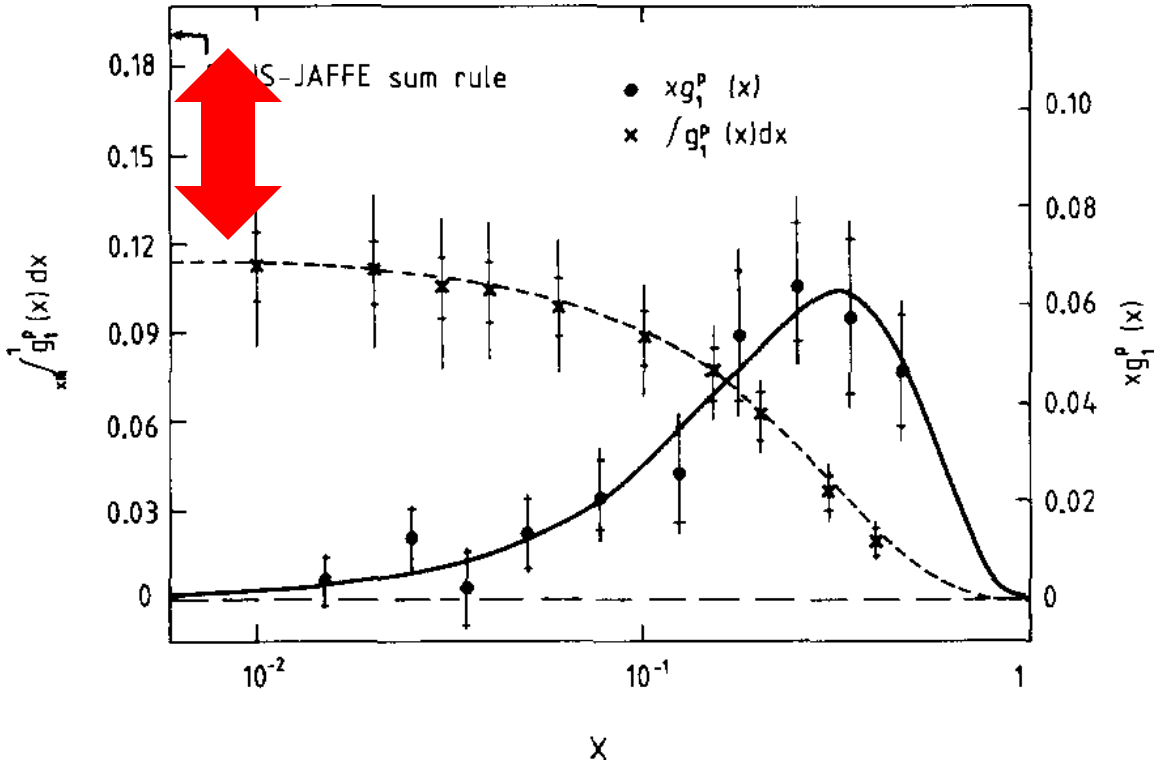
Proton crisis!



European Muon Collaboration at CERN

160 GeV muon beam

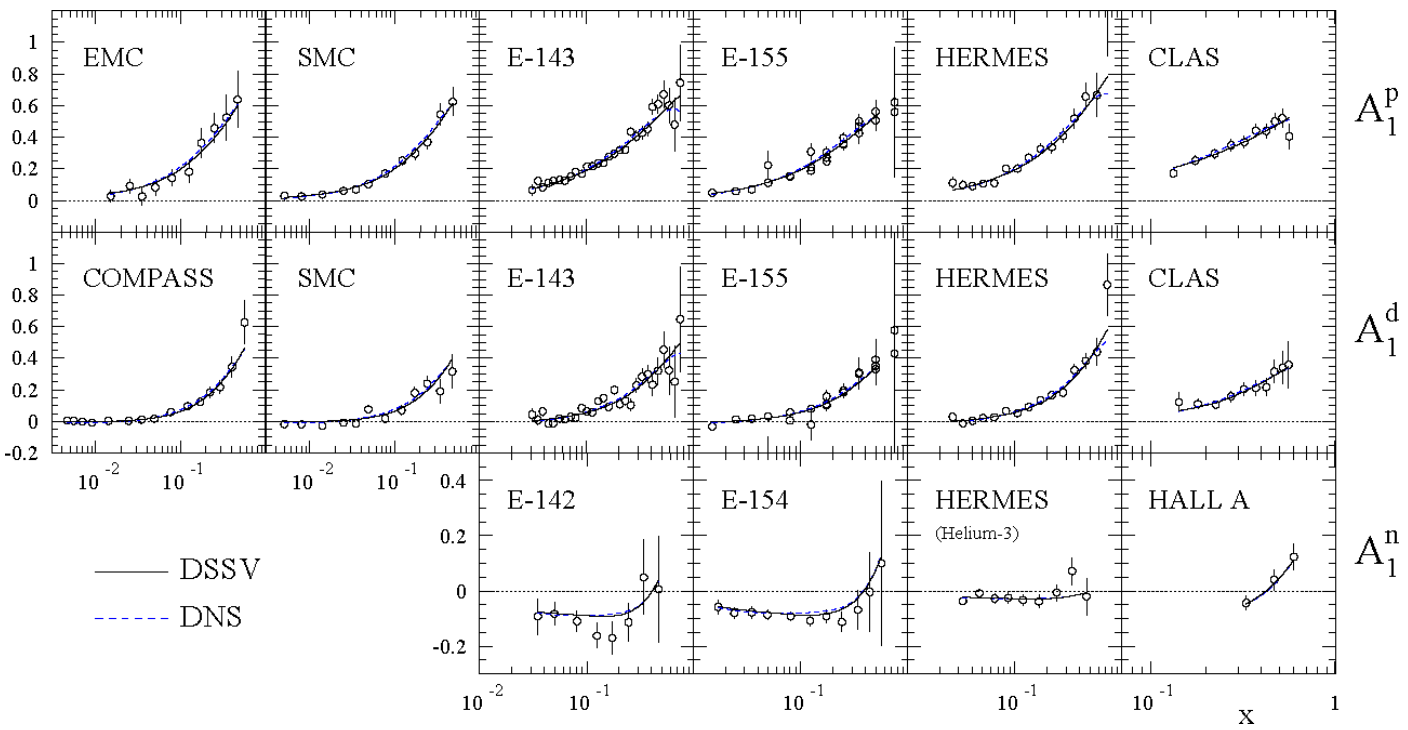
EMC, PLB 206, 364 1988

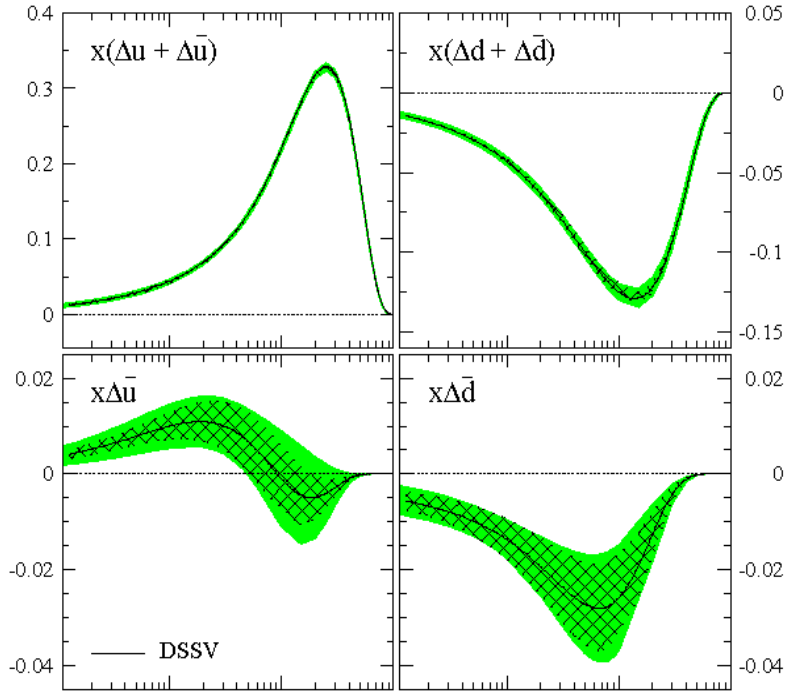


- First measurement over a broad kinematic region was performed by the European Muon Collaboration in the mid-’80s
- Found that quarks contribute only **(14 ± 9 ± 21)%** of the proton spin

Since EMC

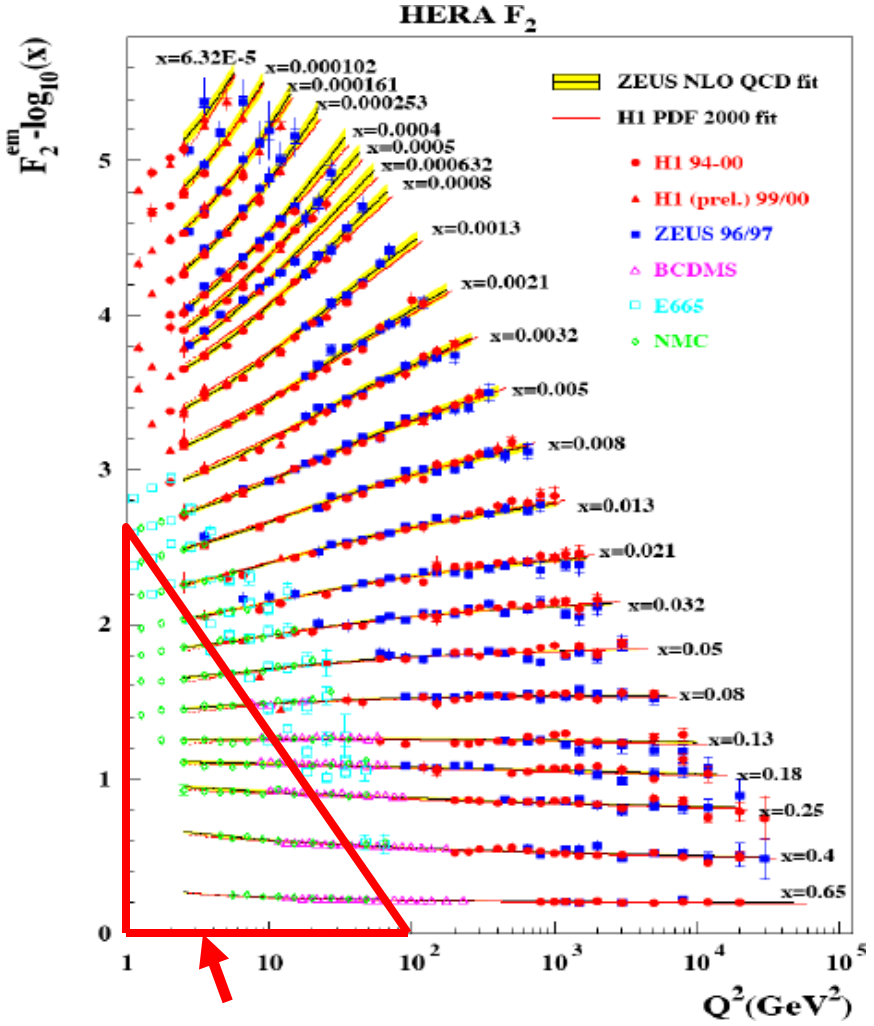
DSSV, PRD 80, 034030 (2009)



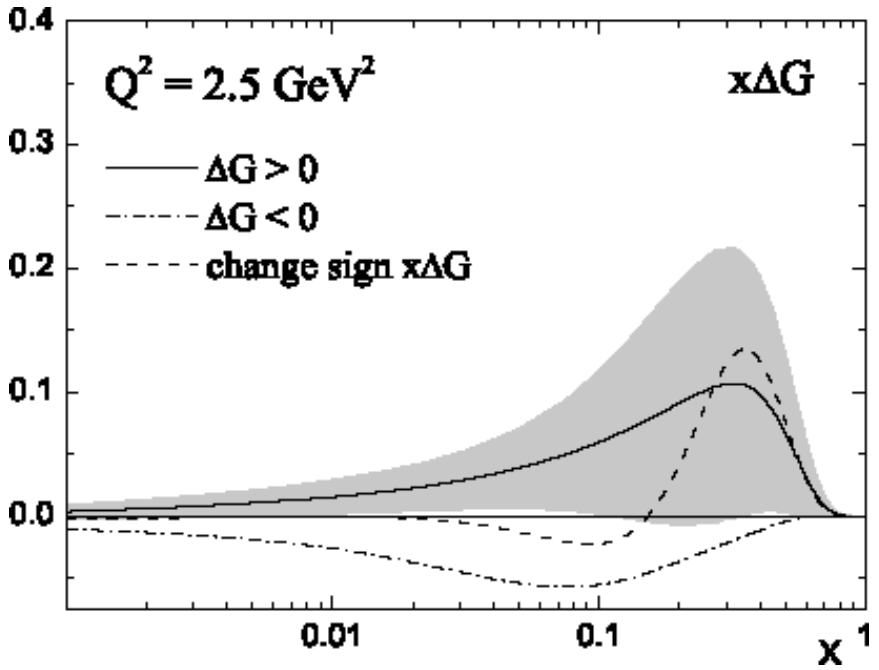


- Many subsequent measurements
- Results are well described by "global analyses" that find best-fit *polarized* PDF
- Polarization of $u + \bar{u}$ and $d + \bar{d}$ quarks well determined
  - Individual u, $\bar{u}$, d, $\bar{d}$ polarizations have much larger uncertainty
- Only **~30% of the proton spin** arises from quarks and antiquarks

What about gluons?



Kinematic region of **fix-target**
Polarized DIS measurements



Three fits of equal quality:

- ΔG = 0.13 ± 0.16
- ΔG ~ 0.006
- ΔG = -0.20 ± 0.41

all at Q^2 = 1 GeV^2

Leader et al, PRD 75, 074027

Motivation of RHIC spin

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 ΔΣ (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

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

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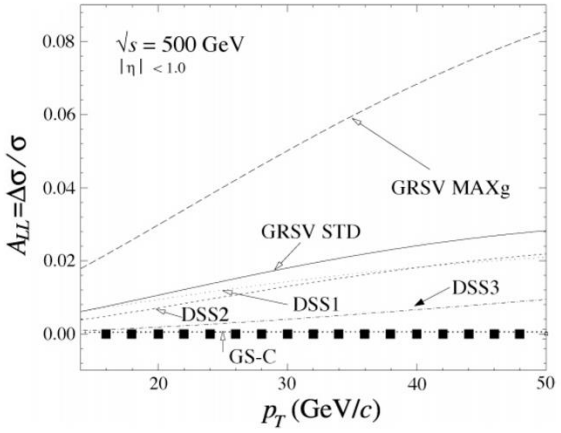
Key Words proton spin structure, spin asymmetries, quantum chromodynamics, beyond the standard model

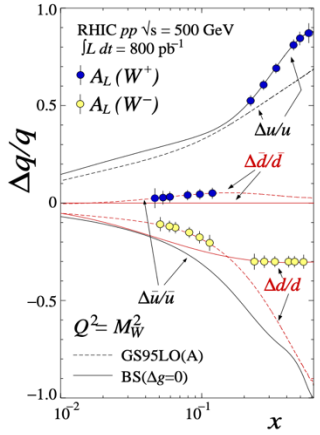
■ **Abstract** Colliding beams of 70% polarized protons at up to $\sqrt{s} = 500$ GeV, with high luminosity, $L = 2 \times 10^{32}\,cm^{-2}\,sec^{-1}$, will represent a new and unique laboratory for studying the proton. RHIC-Spin will be the first polarized-proton collider and will be capable of copious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

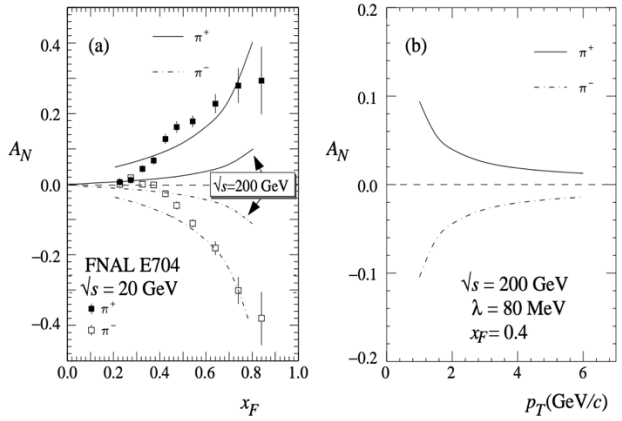
Jet production



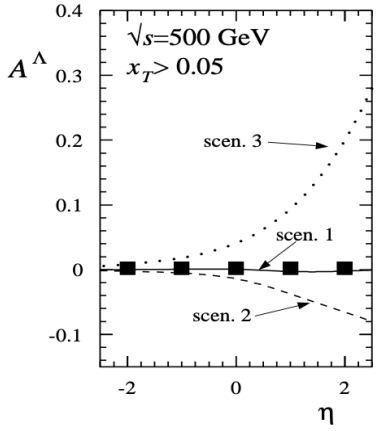
$W^{\pm}$ production



Transverse SSA

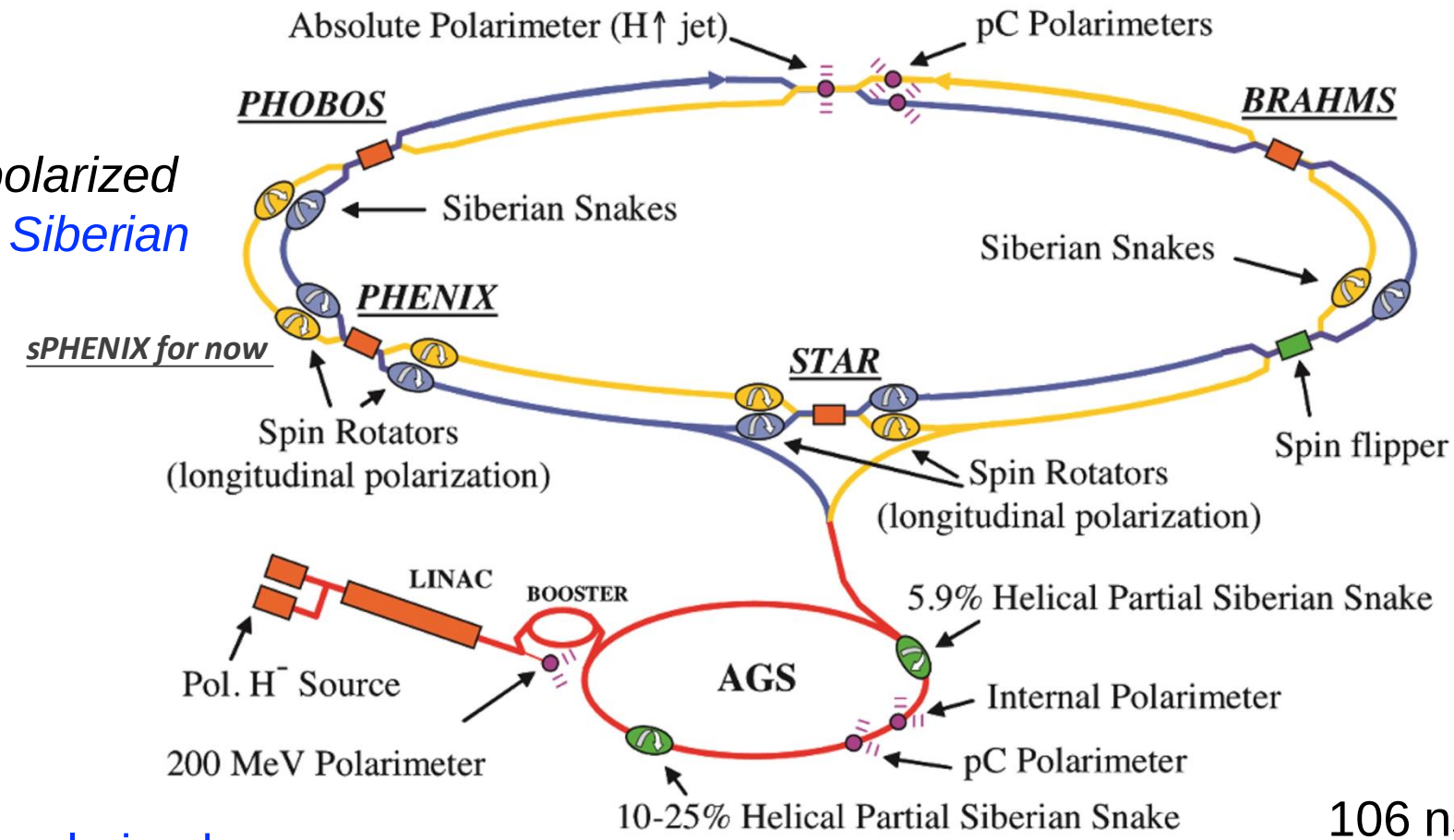


Lambda spin transfer



Polarized RHIC

Accelerate polarized protons with Siberian Snakes

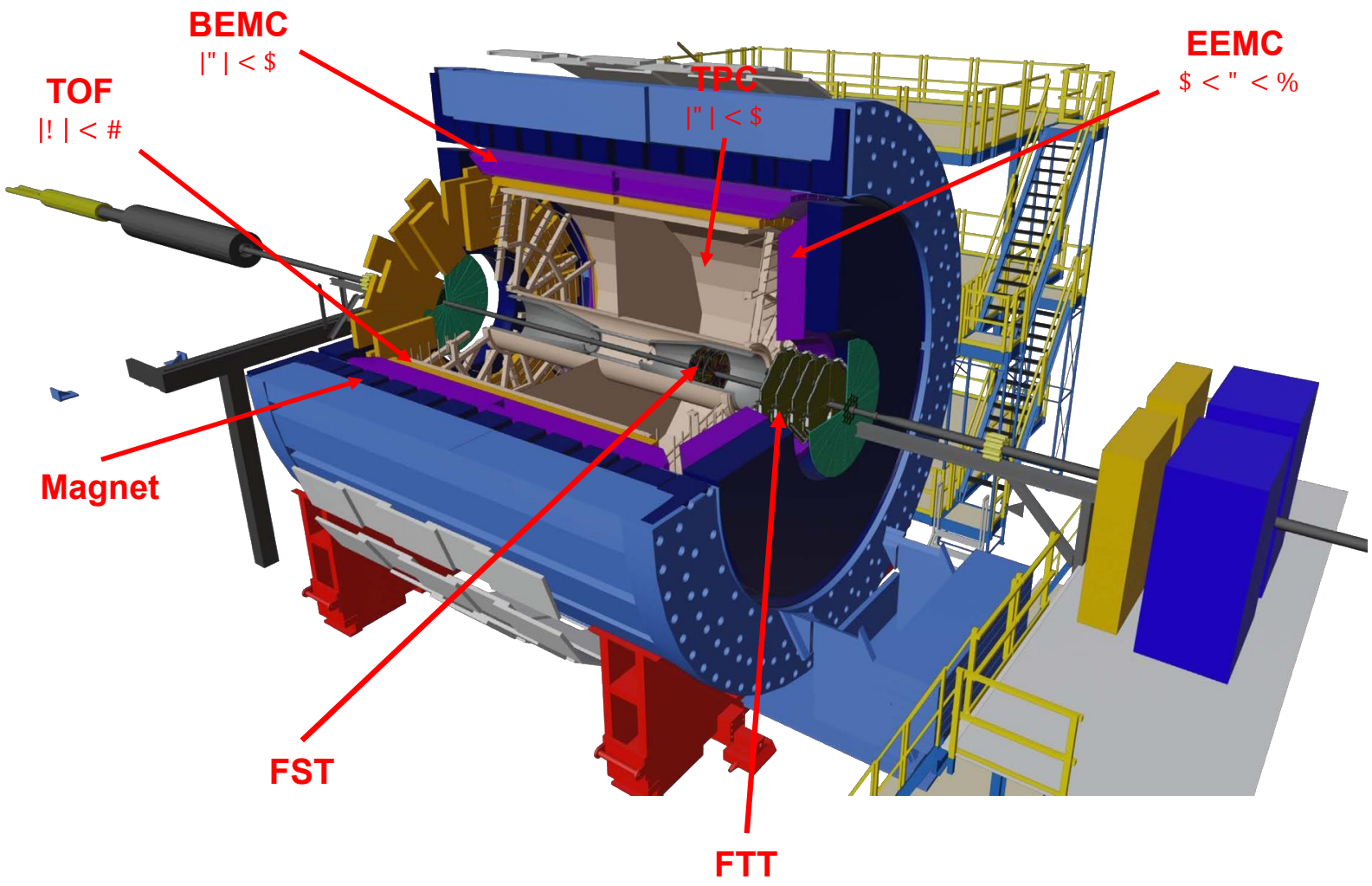


Manipulate spin direction with spin rotator

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 $|\eta| < 1$

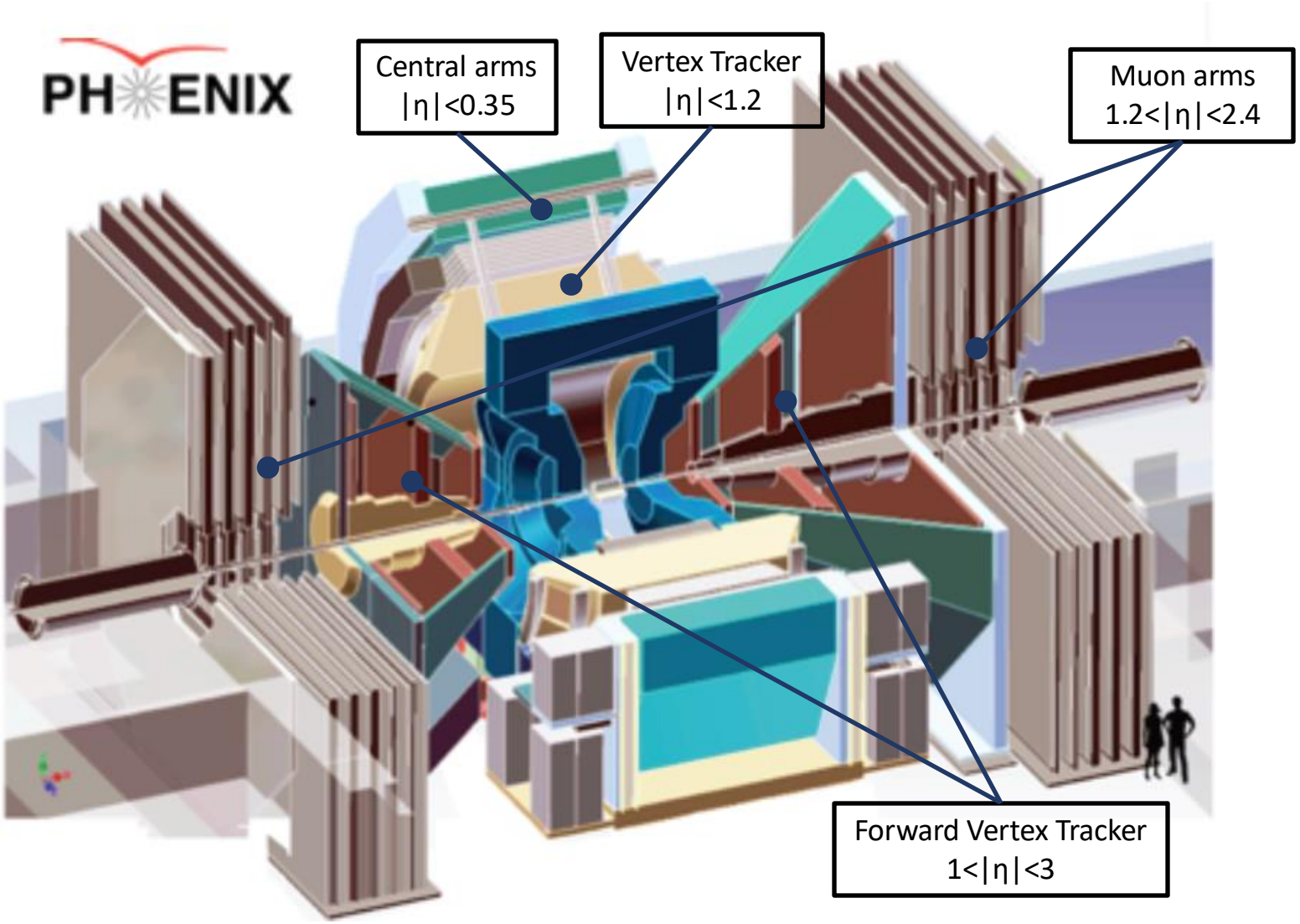
Time of Flight detector
- particle identification
- coverage $|\eta| < 1$

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 Detector Overview

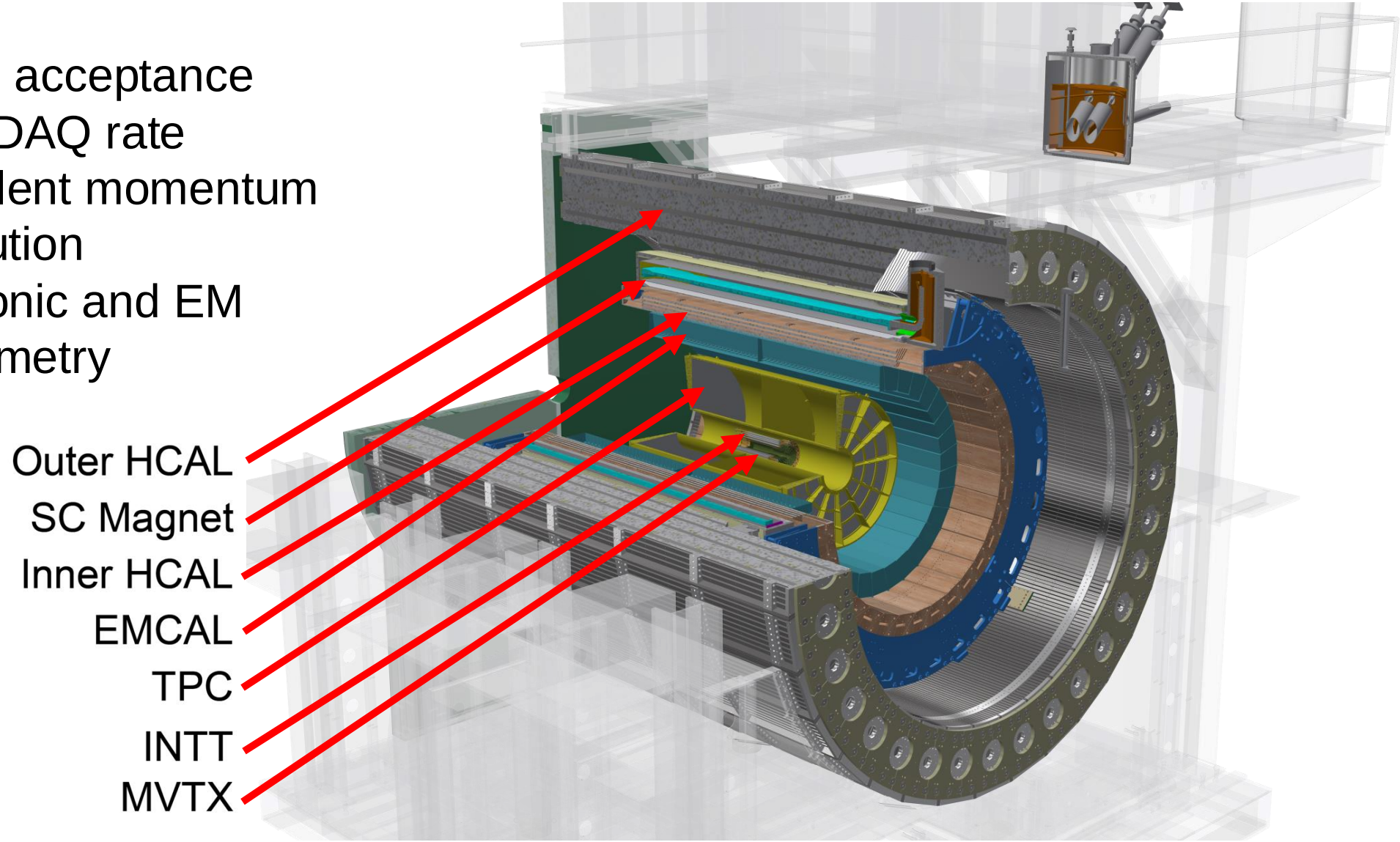
High resolution
High rate



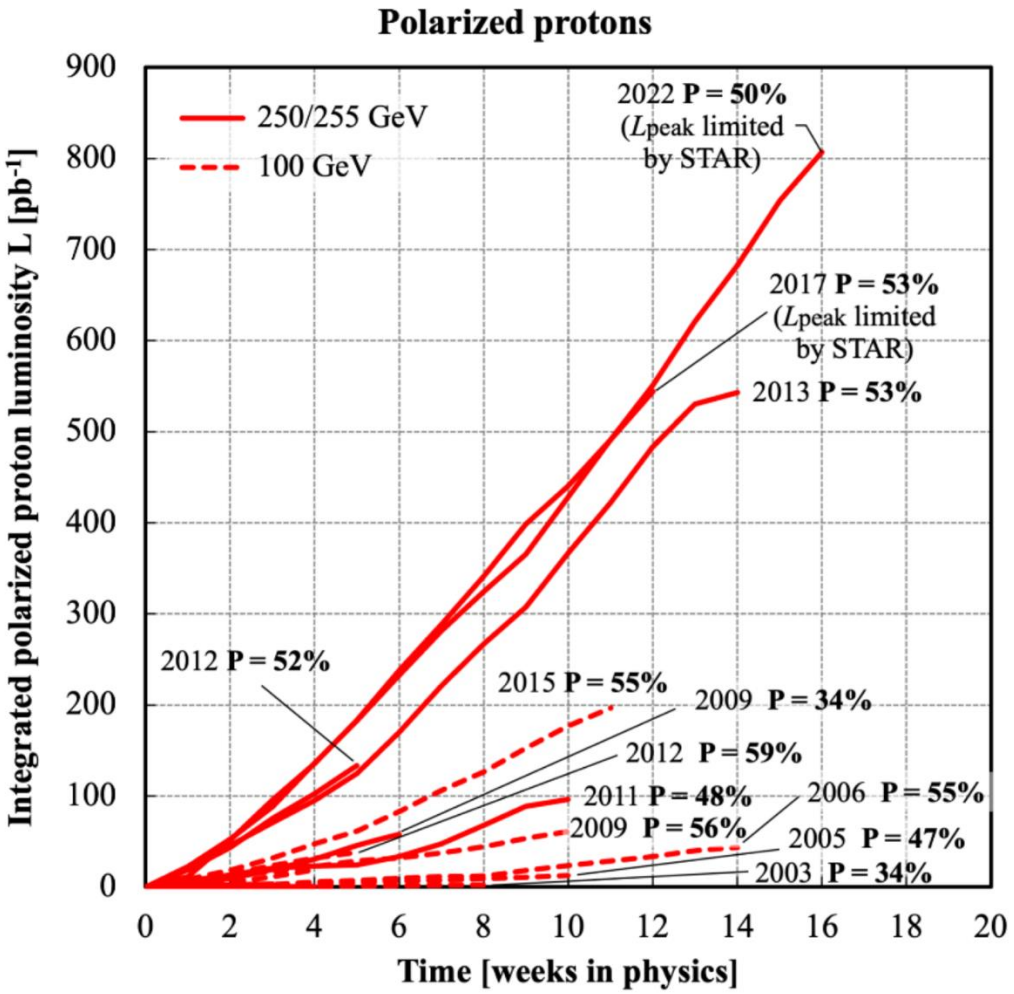
Up through 2016, upgraded to sPHENIX

sPHENIX Detector Overview

- Large acceptance
- High DAQ rate
- Excellent momentum resolution
- Hadronic and EM calorimetry



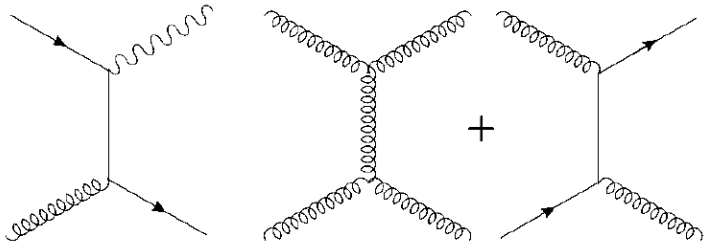
RHIC spin data accumulation



	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

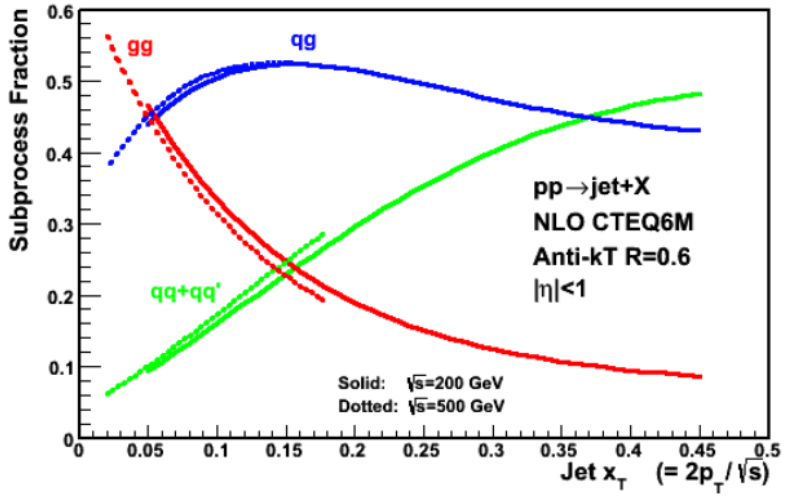
Probe gluon polarization



QCD Compton scattering

Quark-gluon, gluon-gluon elastic scattering

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

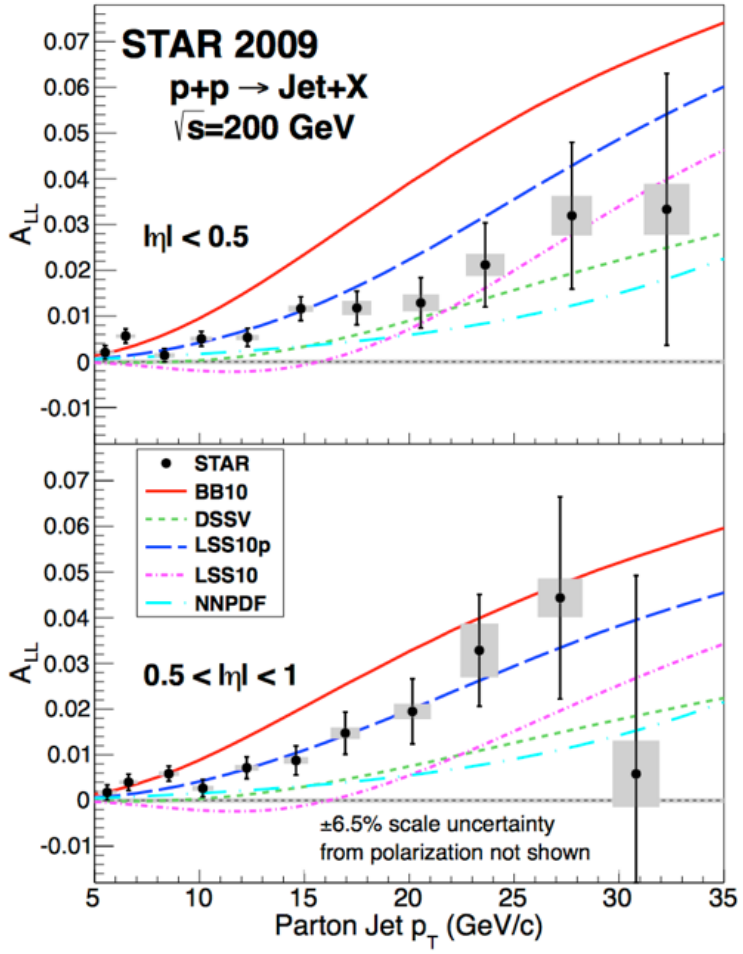


Measured double-spin asymmetry:

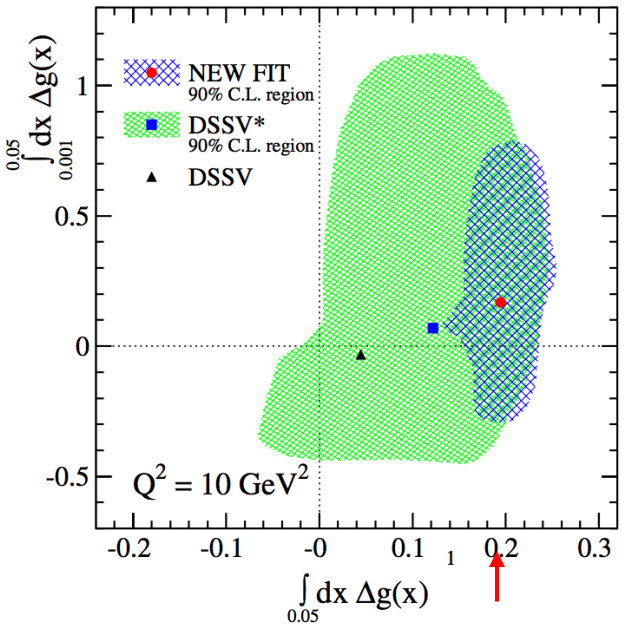
$$A_{LL} = \frac{\sigma^{\uparrow\uparrow} - \sigma^{\uparrow\downarrow}}{\sigma^{\uparrow\uparrow} + \sigma^{\uparrow\downarrow}} \propto \overbrace{\frac{\Delta f_1}{f_1} \otimes \frac{\Delta f_2}{f_2}}^{\text{probed}} \otimes \overbrace{\hat{a}_{LL} \otimes D_f^h}^{\text{inputs}}$$

Yes, gluon spin does contribute!

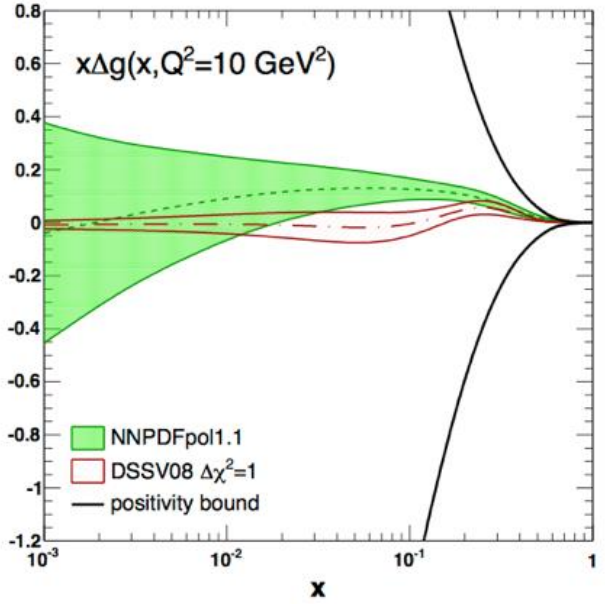
STAR, PRL115 (2015) 092002



DSSV, PRL113 (2014) 012001



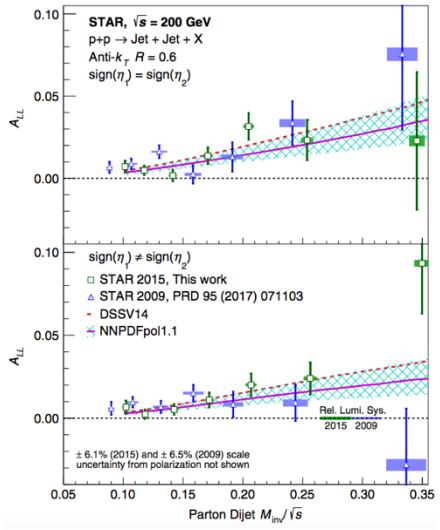
NNPDF, NPB887 (2014) 276



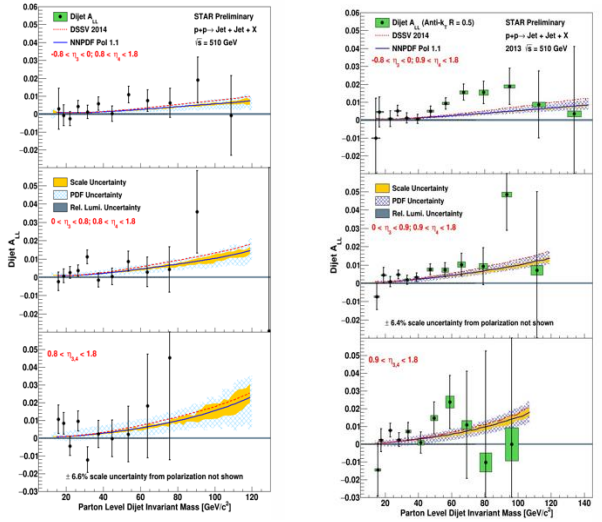
- **First evidence** of non-zero contributions from gluon spin at Q^2~10 GeV^2

A big wave of precision results

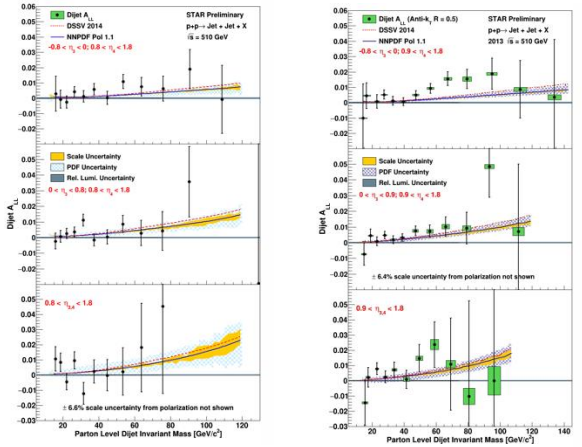
STAR, PRD 105, 092011 (2022)



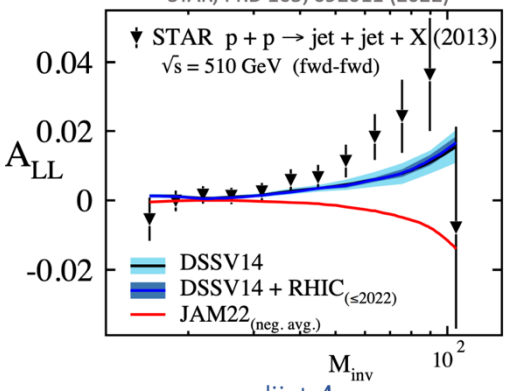
STAR, PRD 103, L091103 (2021)



STAR di-jet preliminary results

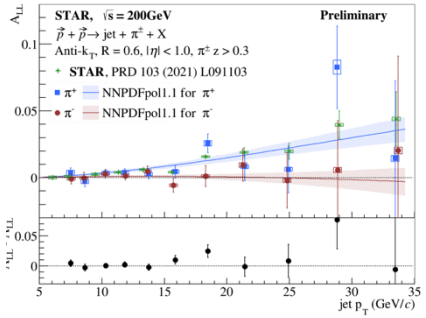


STAR, PRD 105, 092011 (2022)

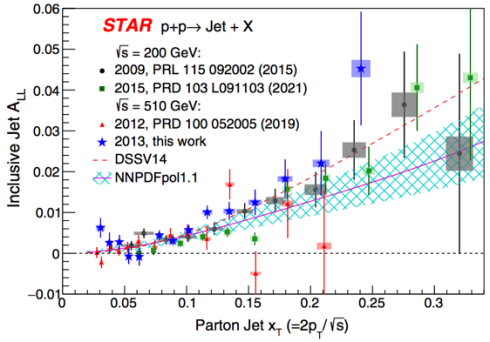


dijet A_{LL}

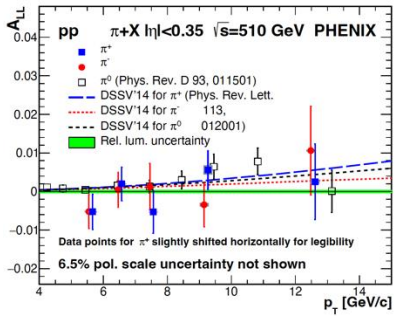
See Yi Yu's talk



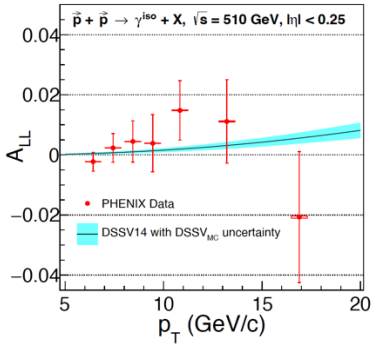
π tagged jet A_{LL}



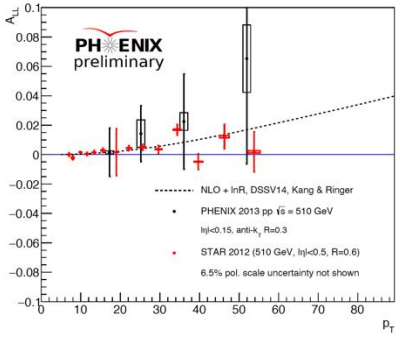
PHENIX, PRD 102, 032001 (2020)



PHENIX, PRL130, 251901 (2023)



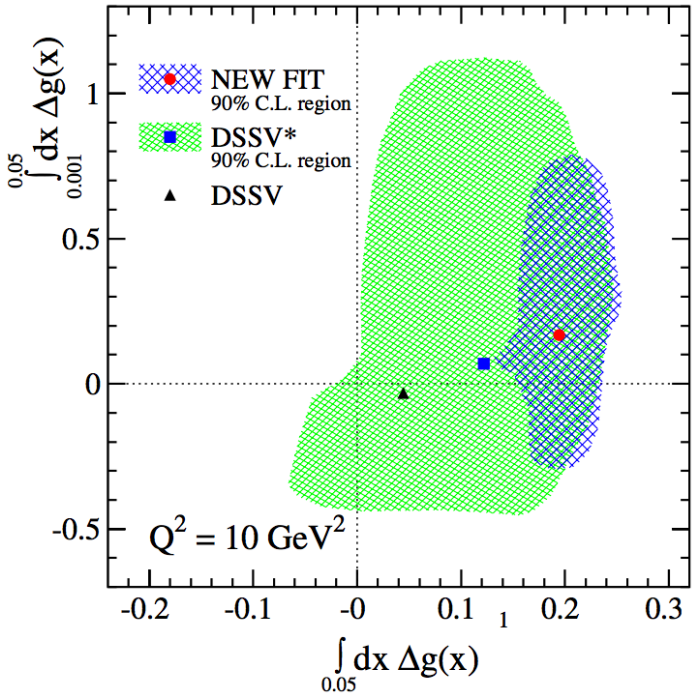
PHENIX preliminary



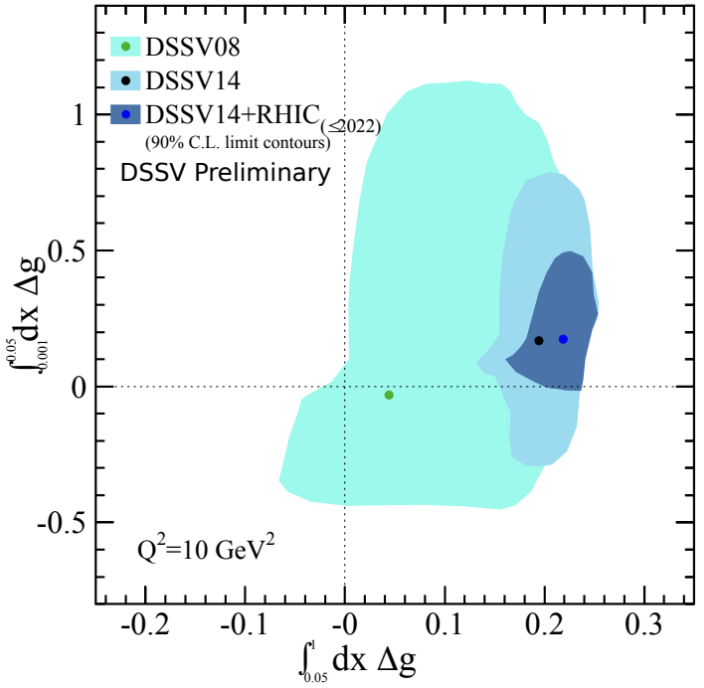
Longitudinal data taking concluded at RHIC, PHENIX and STAR released the full statistics results.

A big wave of precision results

DSSV, PRL113 (2014) 012001



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



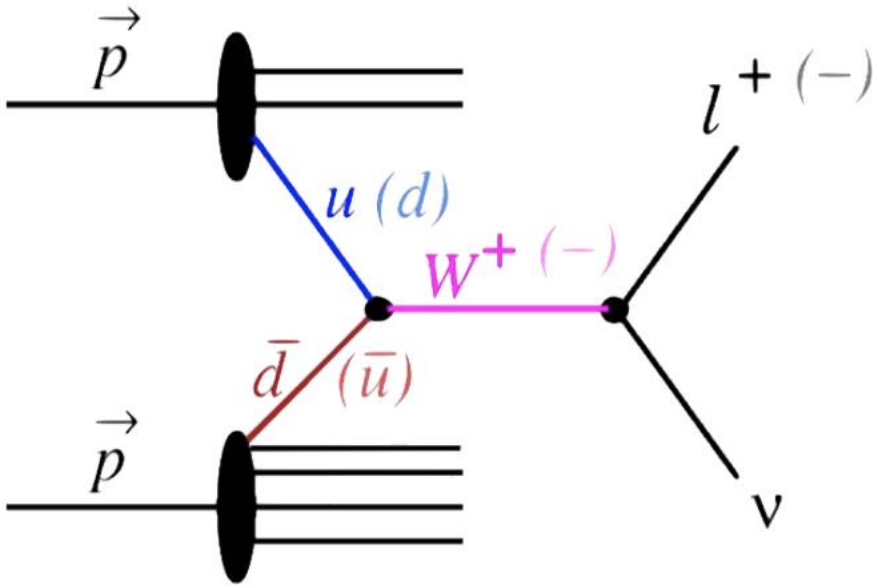
DSSV14 + RHIC (≤2022):

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

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.

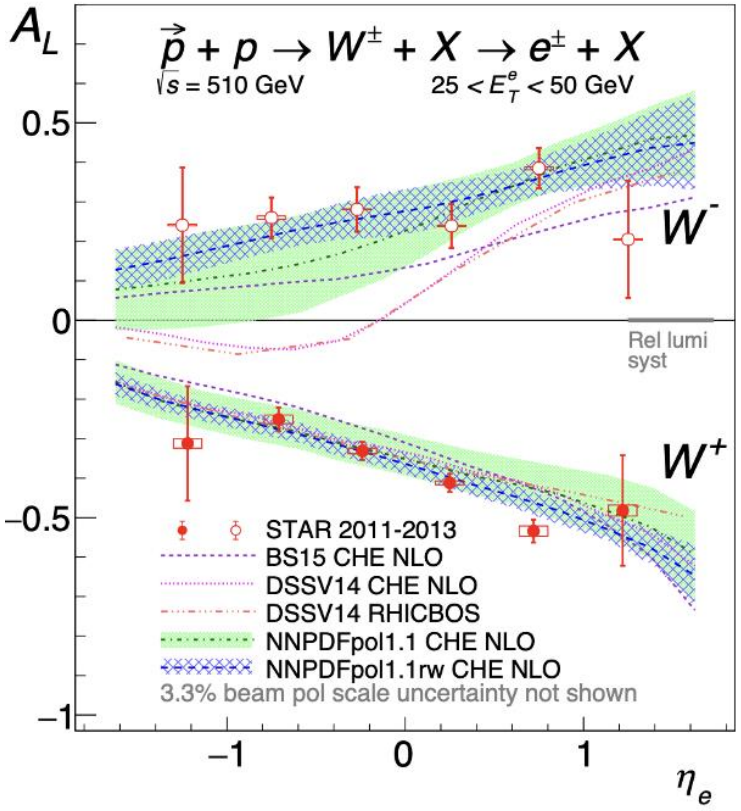


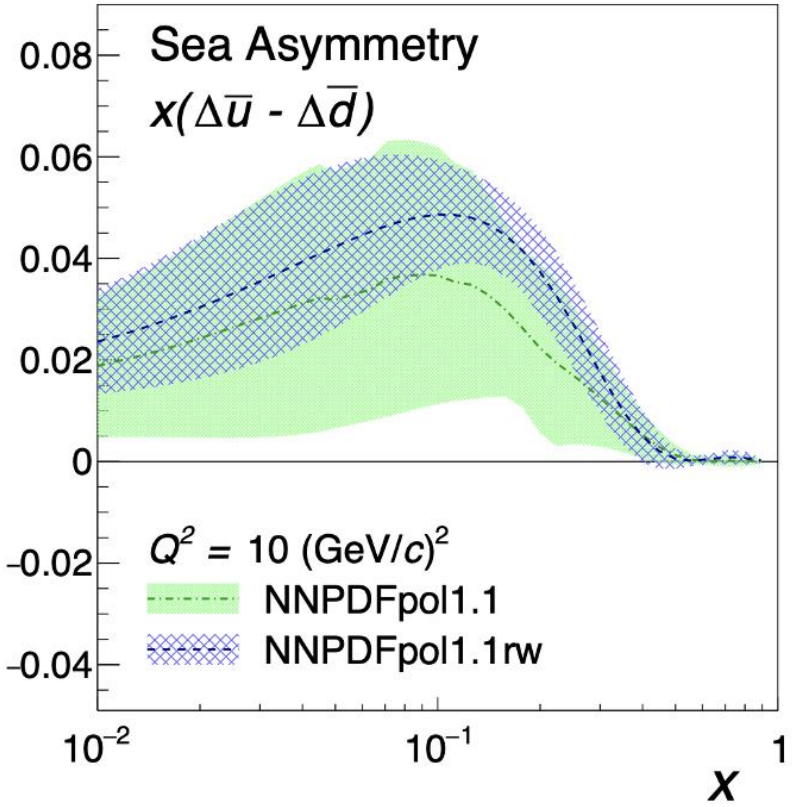
Parity violating single-spin asymmetry:

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

Impact of W results

STAR, PRD99, 051102 (2019)

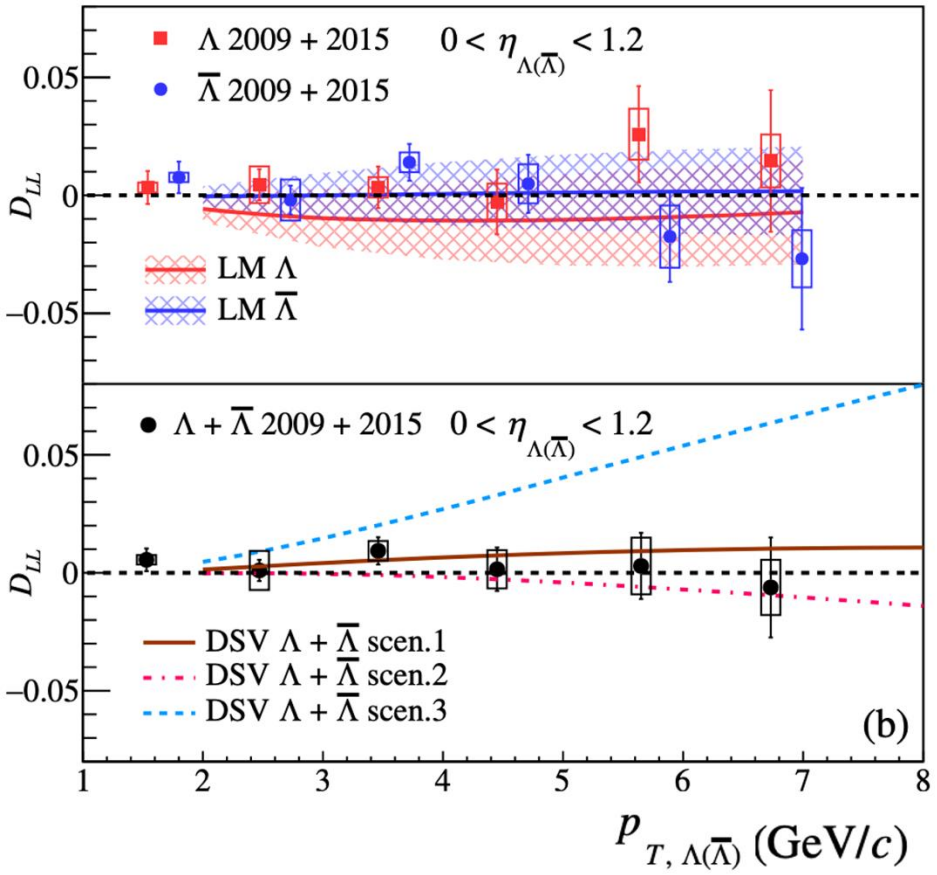




- Now we know: $\Delta\bar{u} > 0$ and $\Delta\bar{d} < 0$
- The flavor asymmetry $\Delta\bar{u} - \Delta\bar{d}$ similar size but opposite sign to the unpolarized case.

Strange quarks polarization via Lambda spin transfer

STAR, PRD109, 012004 (2024)



Spin transfer:

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

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

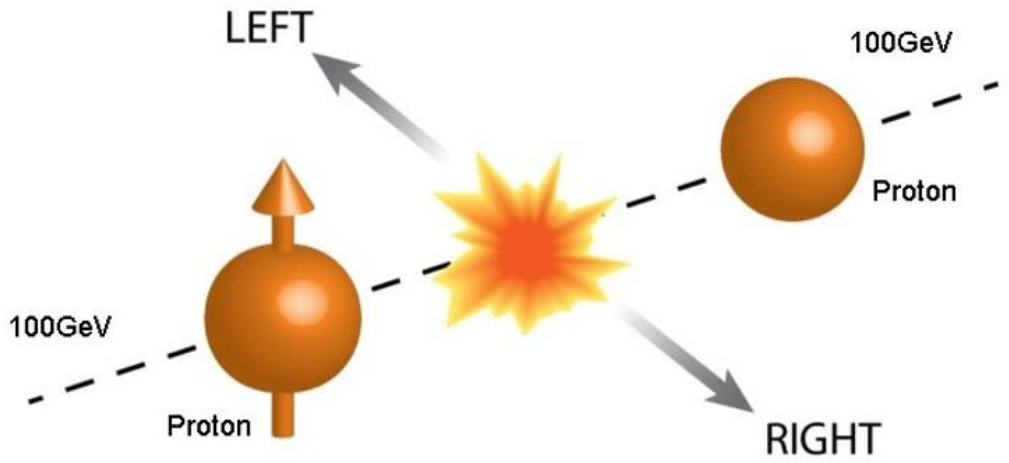
Polarized PDFs *Polarized FFs*

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

See Yi Yu's talk

Another longstanding spin puzzle



Transverse single spin asymmetry:

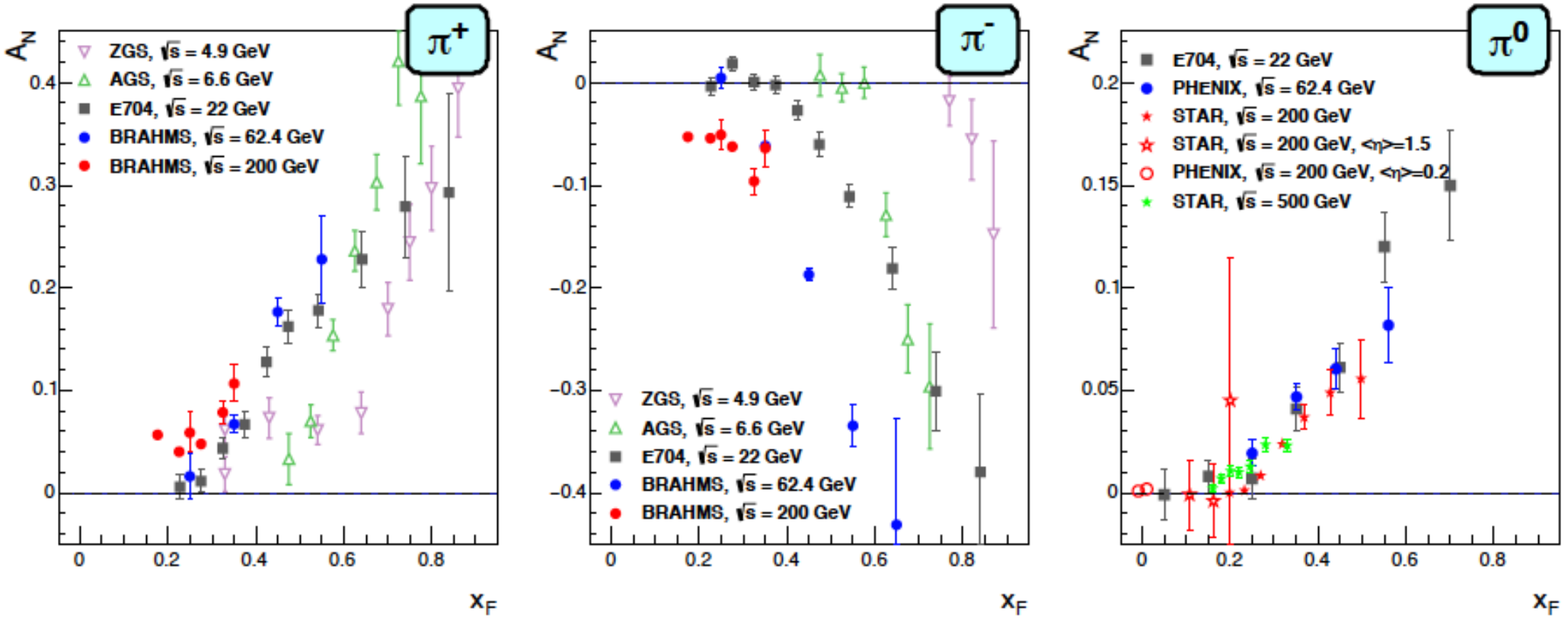
$$A_N = \frac{N_L - N_R}{N_L + N_R}$$

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

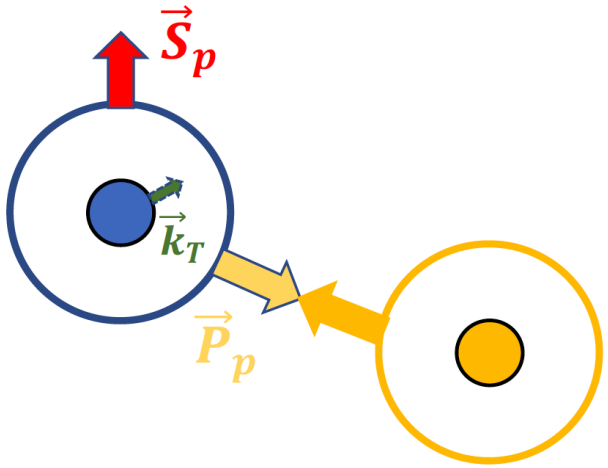
RHIC Cold QCD plan, arXiv: 1602.03922



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

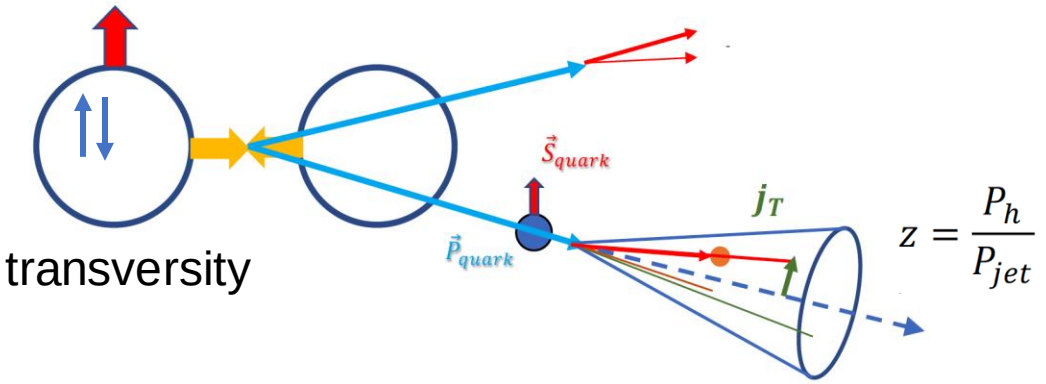
Possible origins

Sivers effect



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

Collins effect

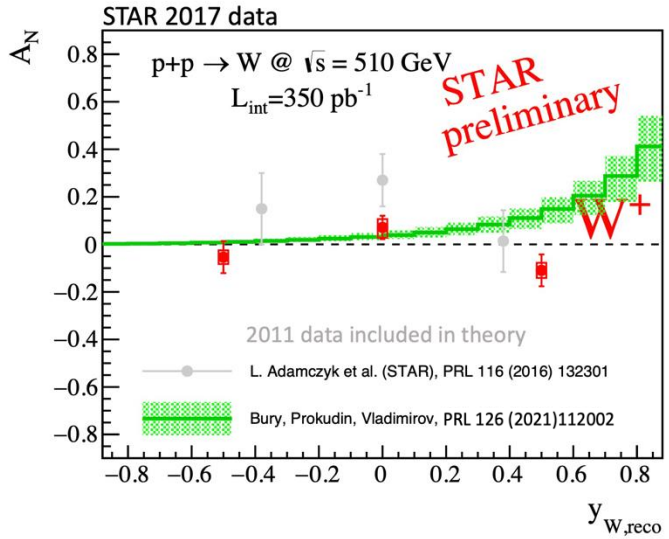


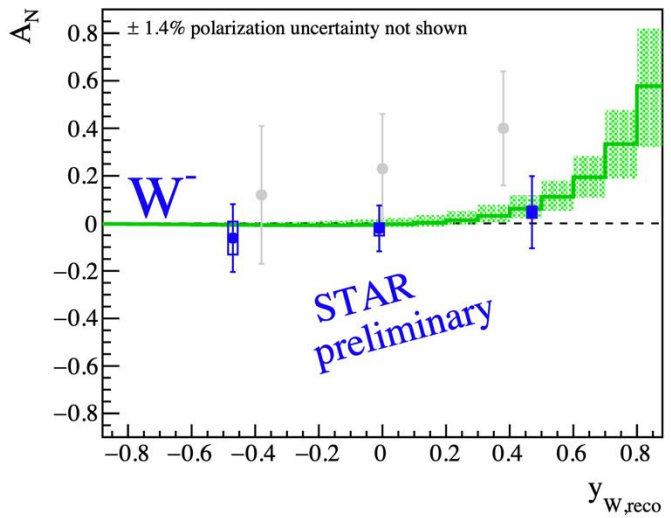
Asymmetry in the fragmentation hadrons: final state effect

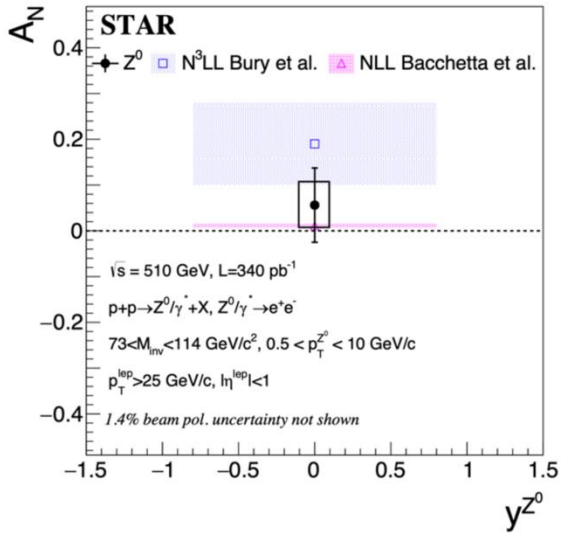
Weak bosons A_N – Sivers

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

PLB 854 (2024) 138715



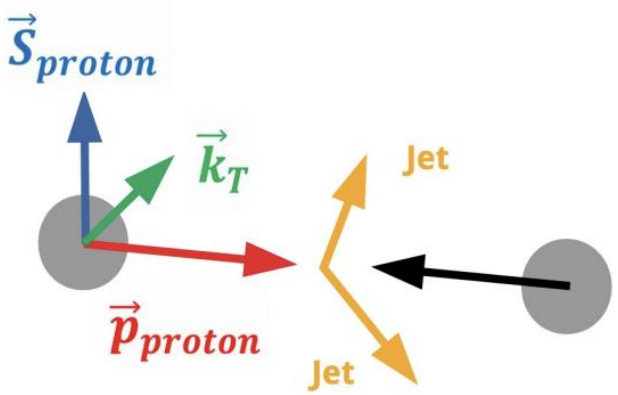


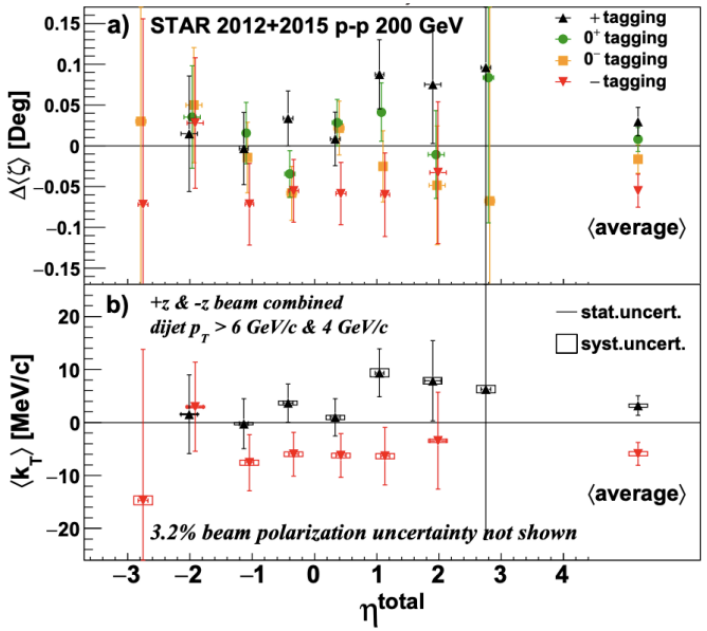


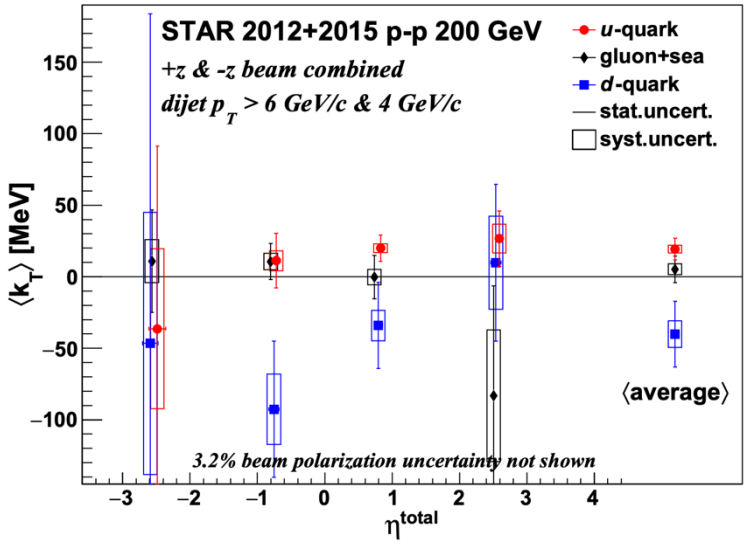
- Theoretical (PRL126,112002): extraction includes SIDIS, DY and 2011 STAR data with N3LO and NNLO accuracy of the TMD evolution *assuming sign-change*
- STAR preliminary with 2017 data with much improved precision, expect big impact in Sivers function at high-x in next global TMD fit

Dijet A_N – Sivers

arXiv: 2305.10359



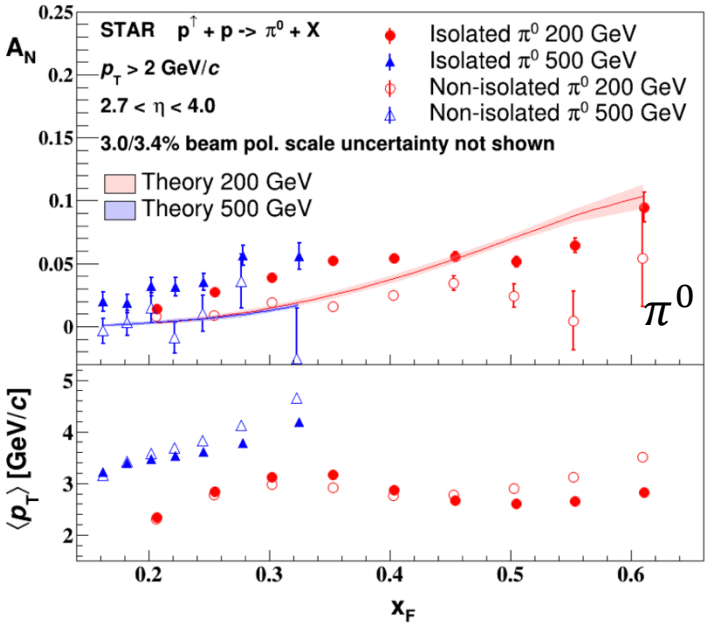


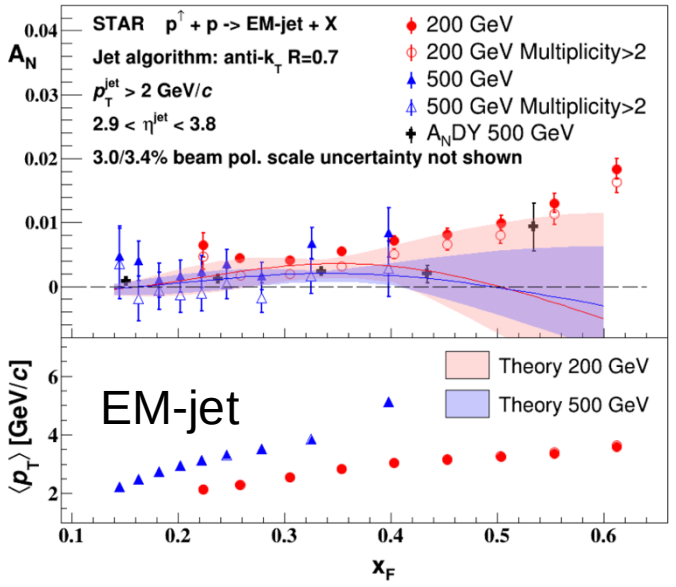


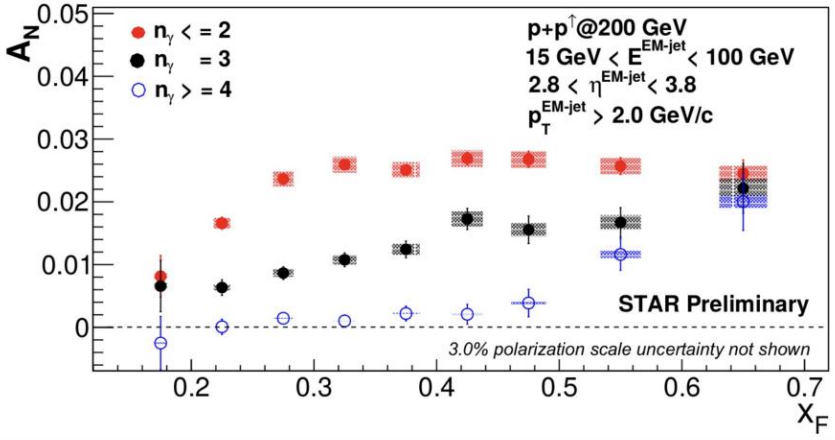
- Spin-dependent dijet opening angle sensitive to Sivers
- First observation of non-zero Sivers asymmetries in dijet production in polarized *p*+*p* collisions

Forward A_N π^0, EM-jet

STAR, PRD 103, 092009 (2021)





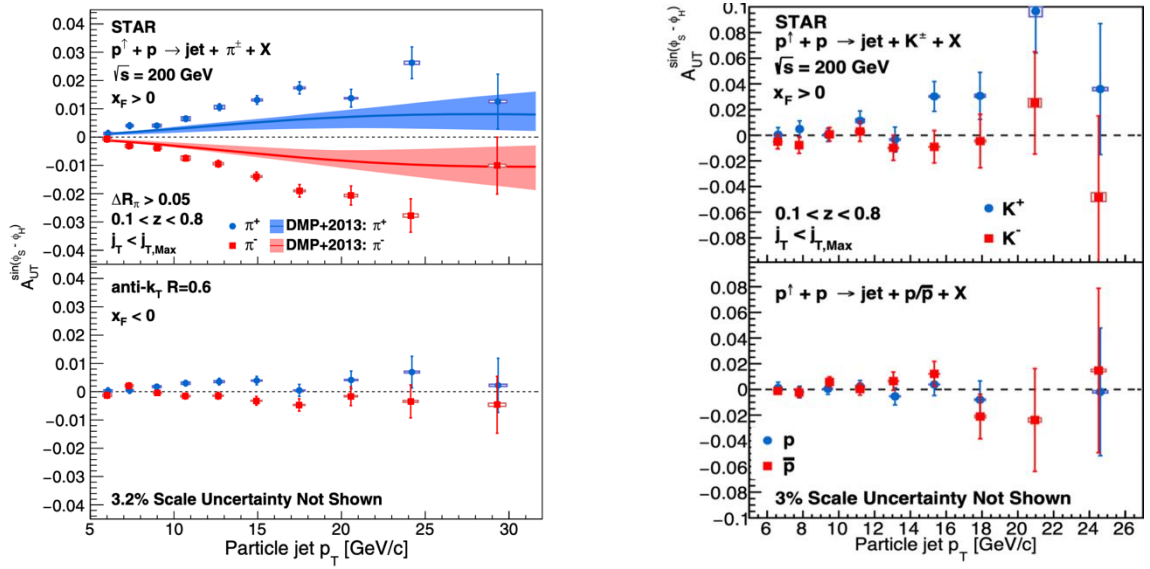


- A_N with forward EM-jets and π^0 in 200/500 GeV pp collisions
- Decreasing A_N as ”jet-ness” increasing (high multiplicity)
- Run2022 and 2024: improved statistic for various objects using Forward Upgrades

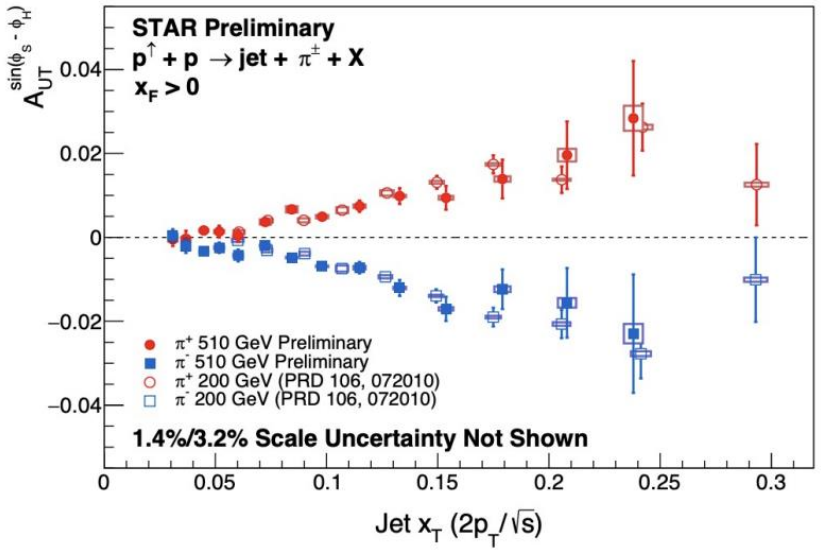
Hadron in Jet A_N – Transversity + Collins

See Yixin Zhang's talk

STAR, PRD 106 (2022), 072010

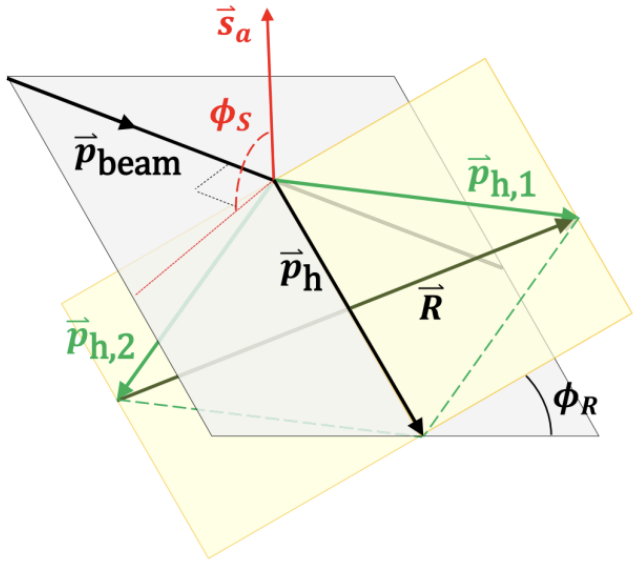


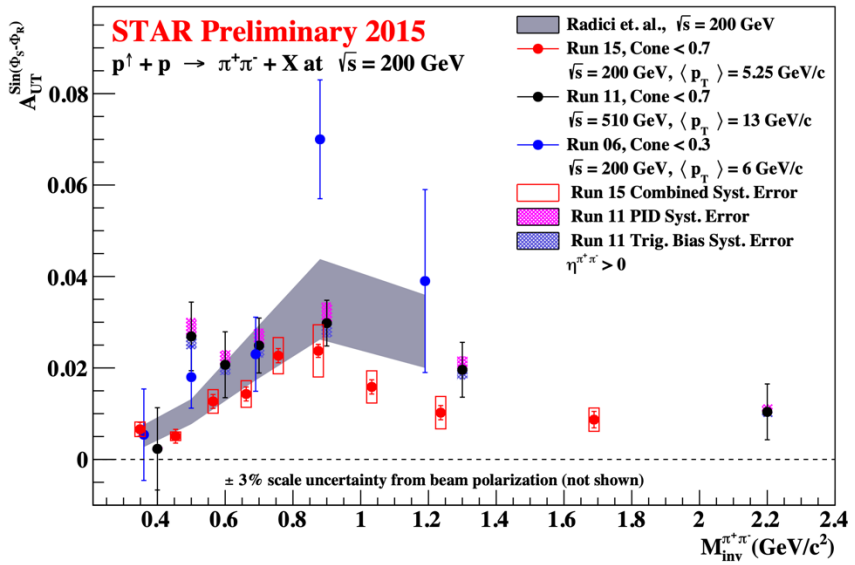
STAR, SPIN2023

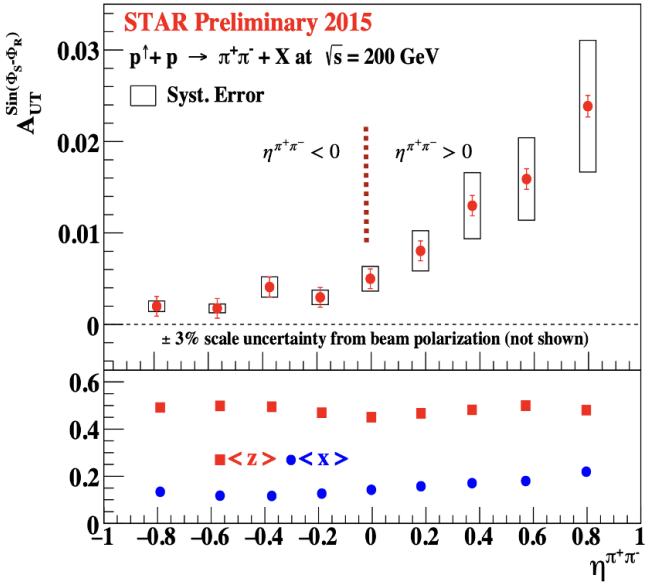


- Significant Collins asymmetries have been observed in 200 and 500 GeV
- New results show weak energy dependence and provide important constraints on the scale evolution for Collins asymmetry

Di-hadron correlations – Transversity + IFF





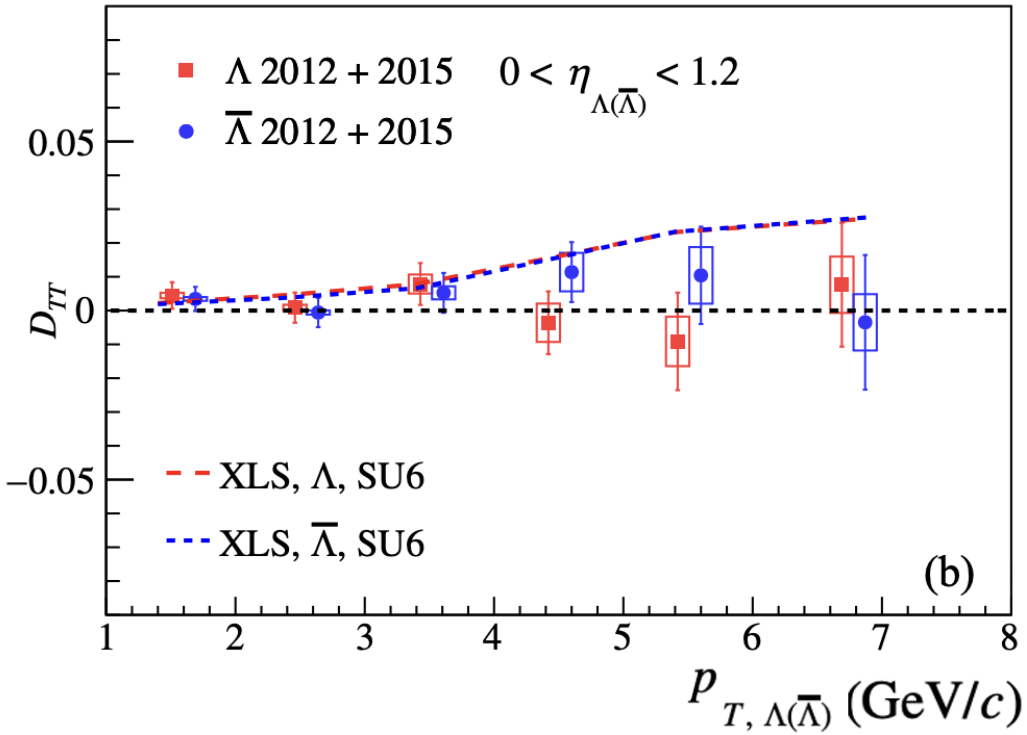


$$A_{UT} \sim h_1 \otimes H_1^{\sphericalangle}$$

- 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.

Lambda transverse spin transfer – Transversity + FFs

STAR, PRD109, 012004 (2024)



The results are consistent with model calculations within uncertainties.

Transverse spin transfer:

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

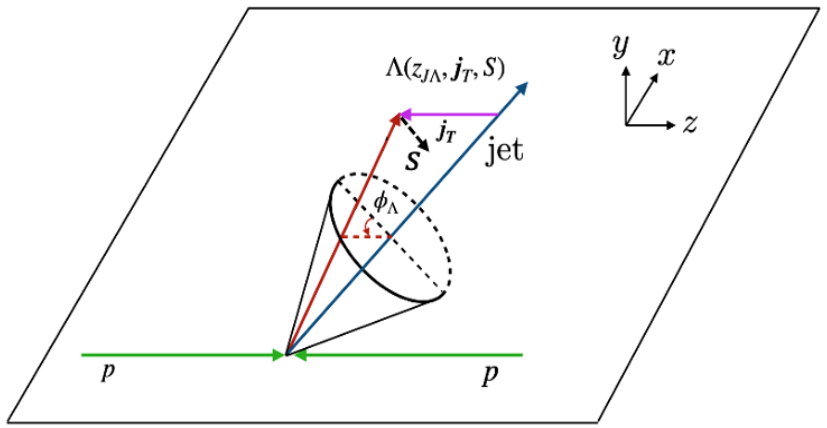
$$d\delta\sigma^{\Lambda} = \sum_{abcd}\int dx_a\, dx_b dz \underbrace{\delta f_a(x_a)}_{\text{Transversity PDF}} f_b(x_b)\, \delta\sigma^{(a^{\uparrow}b\to c^{\uparrow}d)}\, \underbrace{\delta D_c^{\Lambda}(z)}_{\text{Transversity FF}}$$

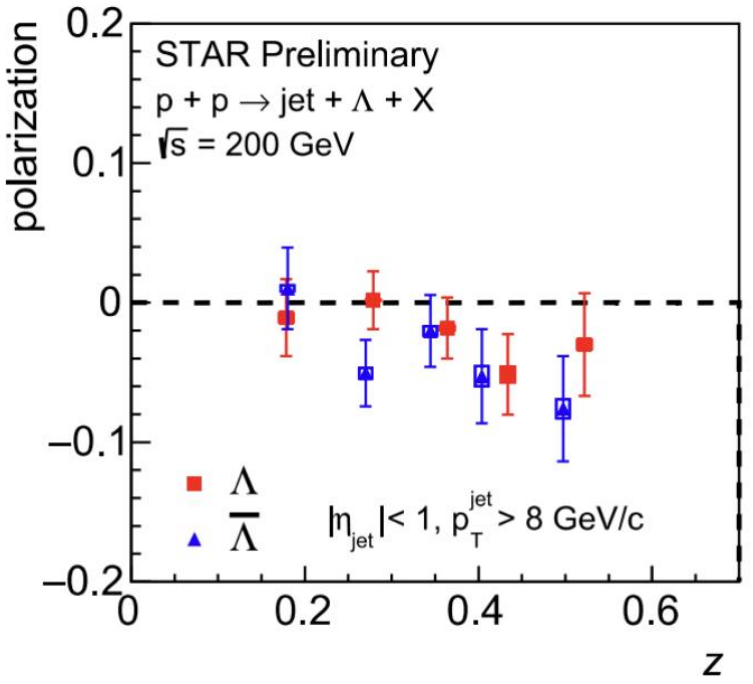
Access transversity fragmentation functions (FF) and transversity distributions (PDF) of strange quarks

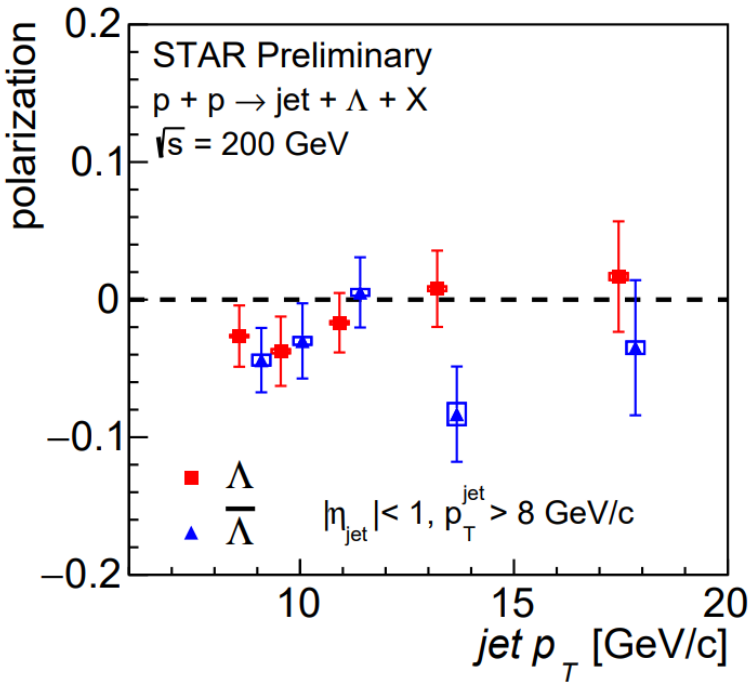
- Final state polarization accessible via weak decay
- Lambda's spin is expected to be carried mostly by its constituent strange quark

Polarizing fragmentation function

arXiv:2402.01168





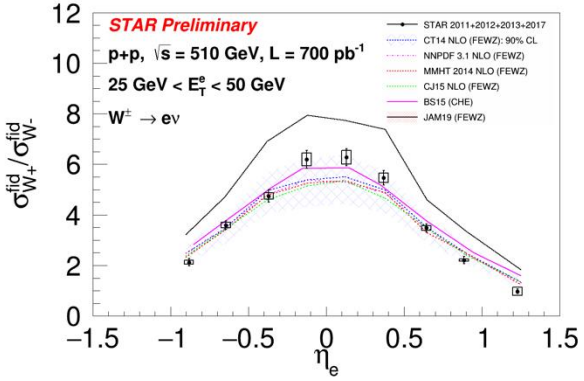


Access polarizing fragmentation functions (FF) via polarization of Lambda-in-jet

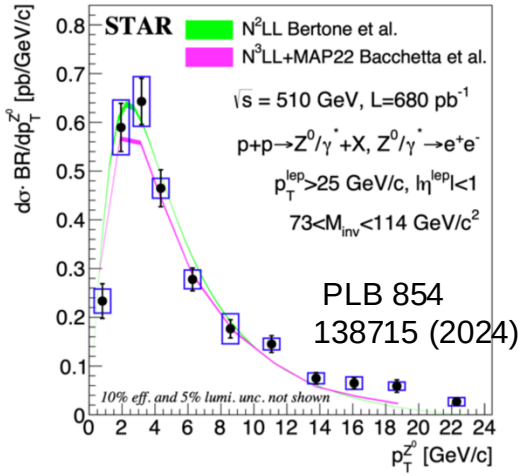
- Indication of negative transverse polarization at large z and low jet p_T

Rich physics with unpolarized beam

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

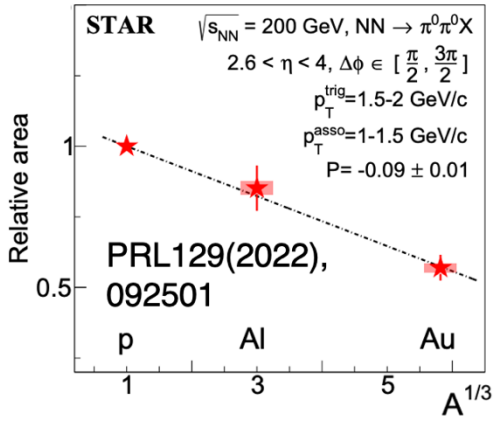


- Differential Z^0 cross section

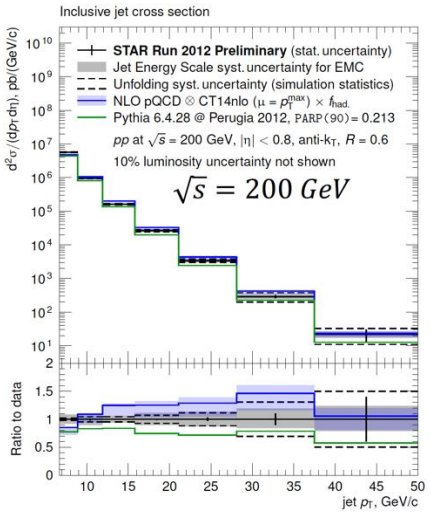


PLB 854
138715 (2024)

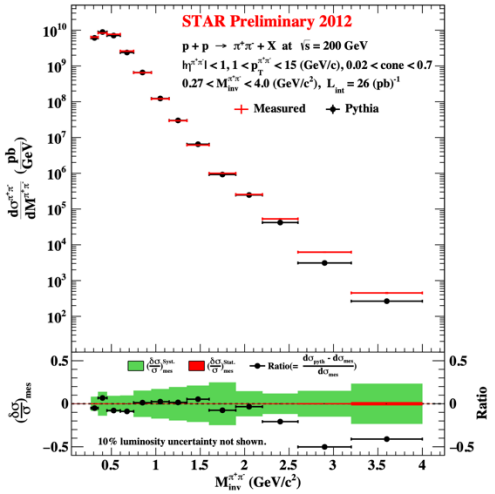
- Nonlinear gluon effects via *A*-dependent di-π^0 correlation



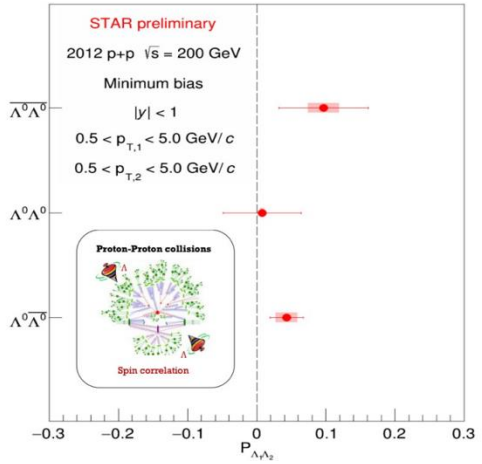
- Gluon PDF with Jet cross section



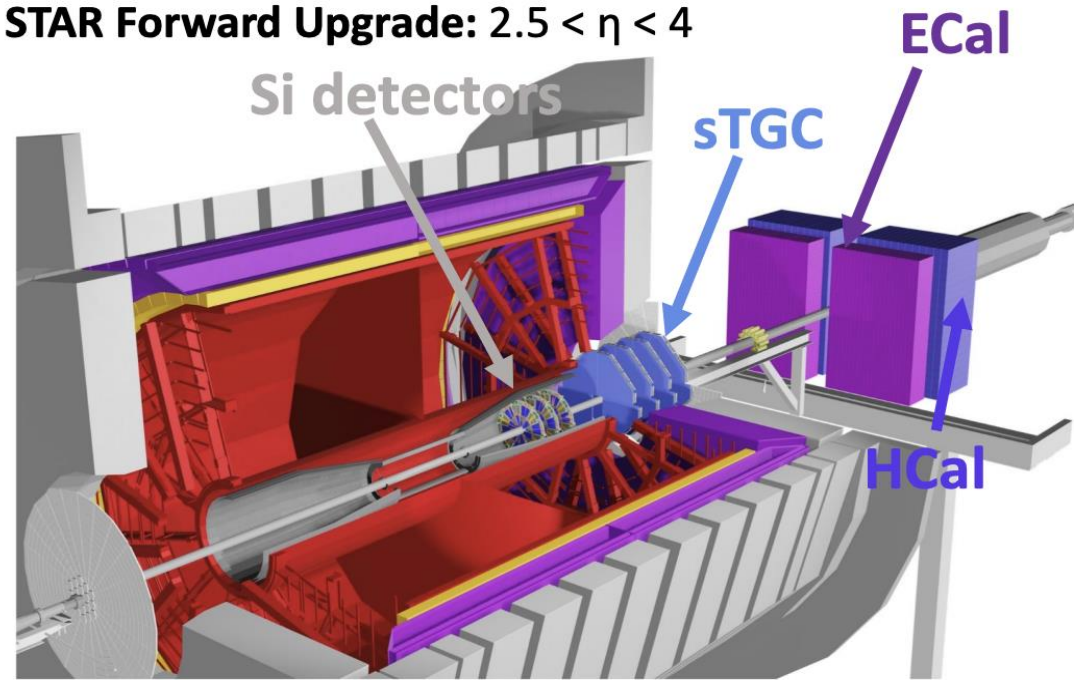
- FF Di-hadron cross section



- Lambda spin correlation



STAR forward upgrade



detector	pp and pA	AA
ECal	~10%/$\sqrt{E}$	~20%/$\sqrt{E}$
HCal	~50%/$\sqrt{E}$+10%	---
Tracking	charge separation photon suppression	0.2<p_T<2 GeV/c with 20-30% 1/p_T

- Successful RHIC spin run in 2022 and 2024 with STAR forward upgrade.

Summary

RHIC spin operation just concluded (Sep 30)

RHIC is 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**

Next generation: polarized Electron Ion Collider

Yuji Goto's talk
Yuxiang Zhao's talk

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Thank you for your attention!