Overview of RHIC Spin Program

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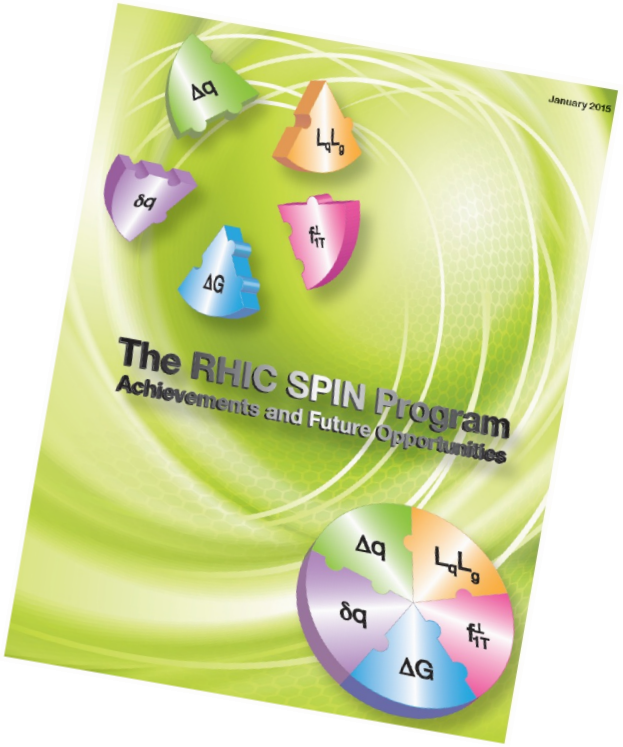
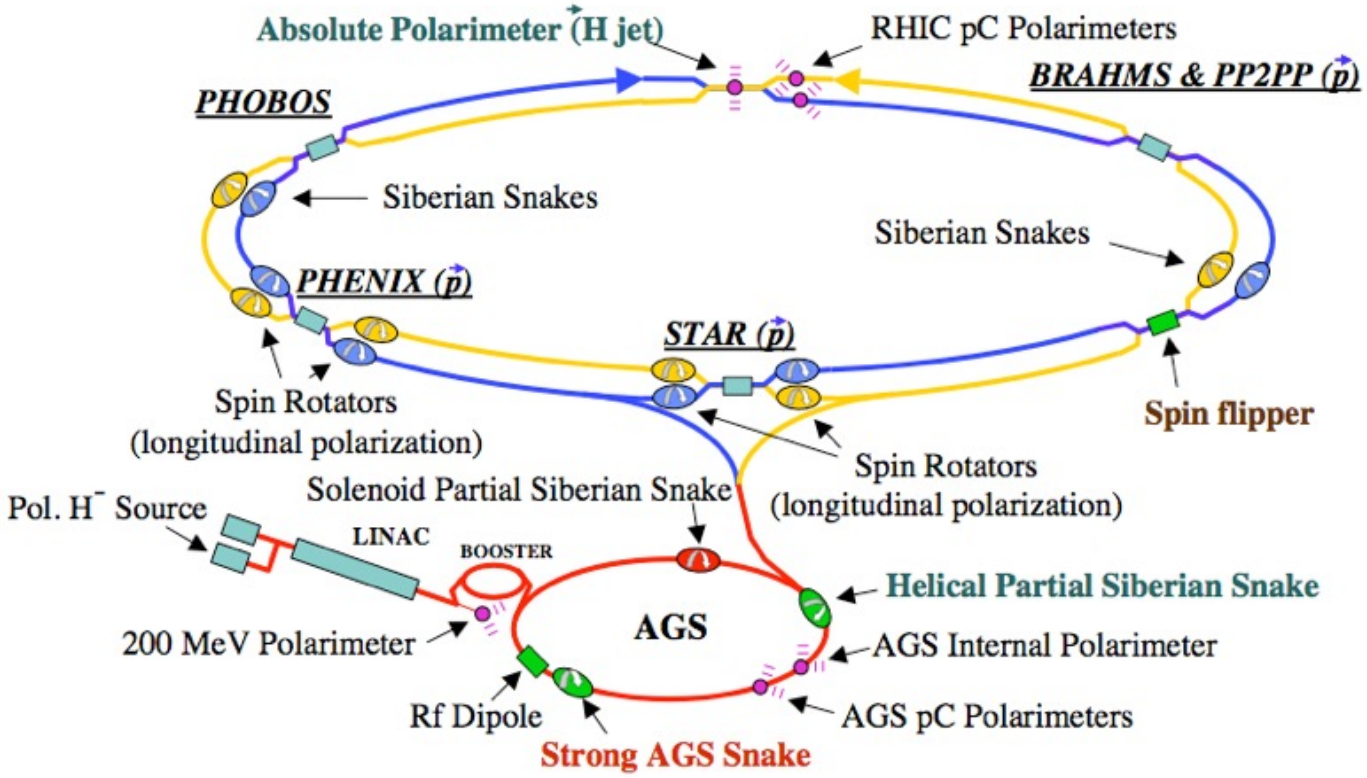
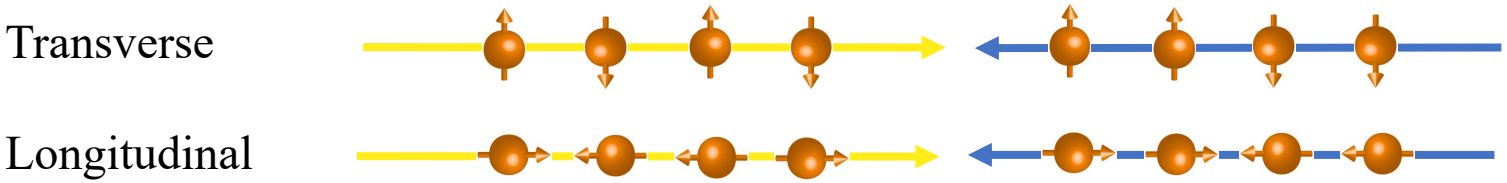
Outline

- RHIC, polarized proton-proton collider
  - STAR and PHENIX
- Unique physics opportunities at RHIC and selected recent results
  - Helicity structure of proton: gluons and quarks
  - Studies on transverse dimensions
  - *Measurement with unpolarized beam*
- Outlook and Summary

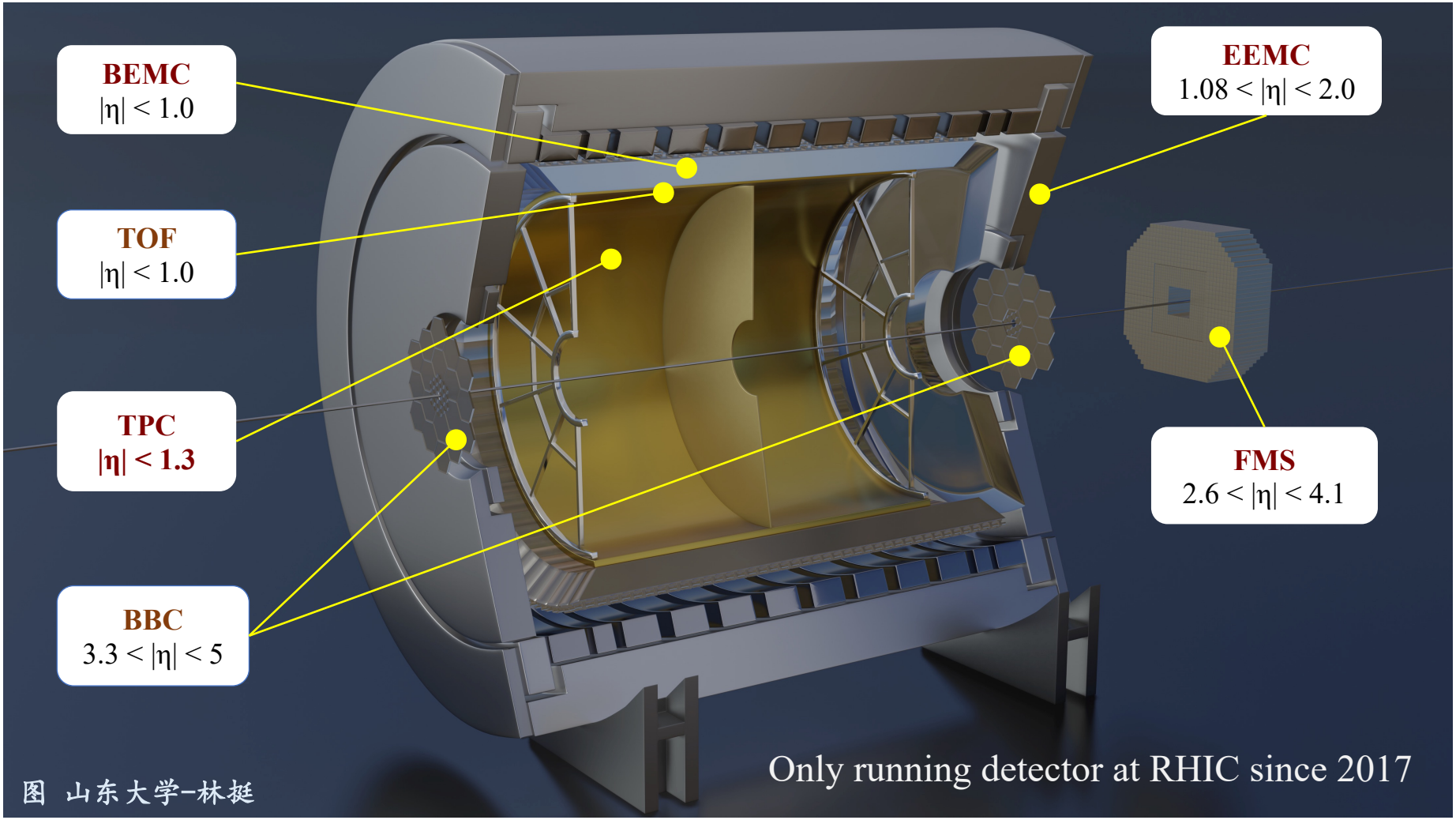


RHIC – Polarized Proton-Proton Collider

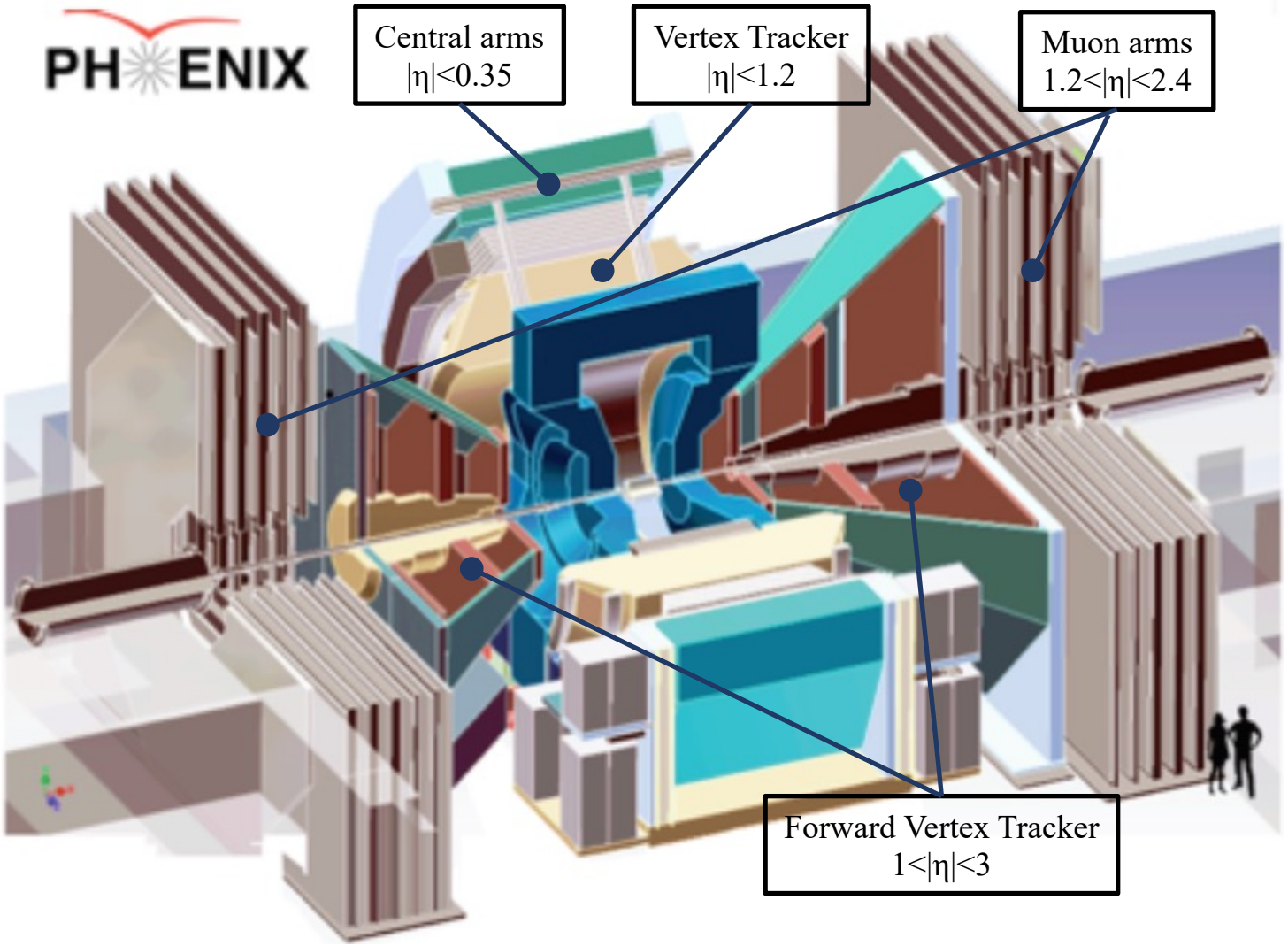




STAR Detector Overview

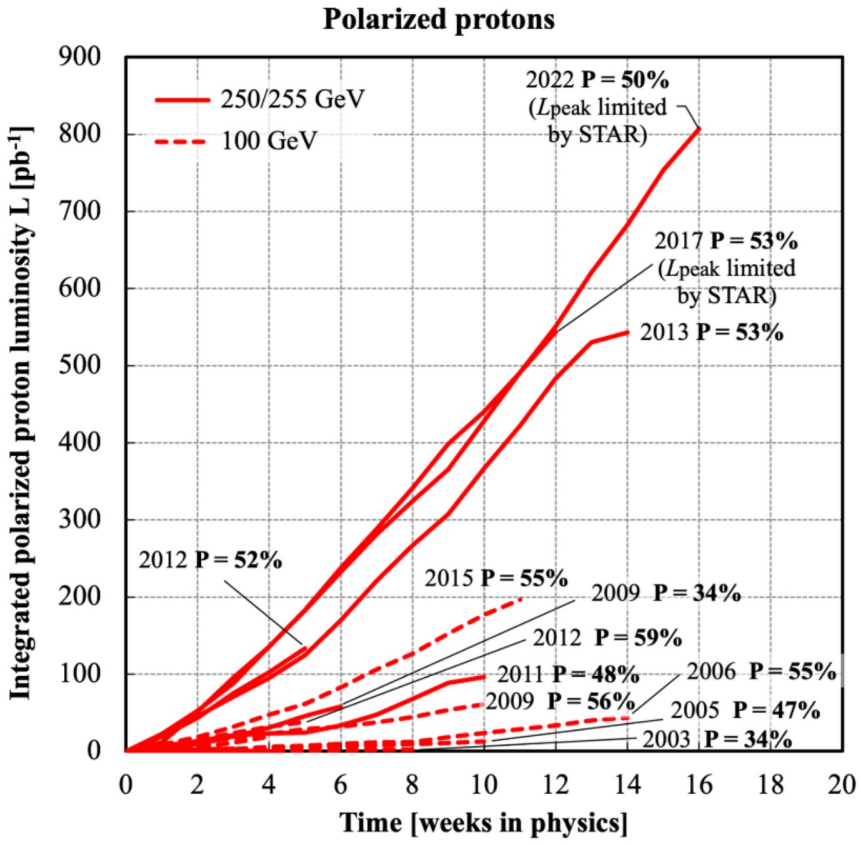


PHENIX Detector Overview



Up through 2016, next stage – sPHENIX

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	510	800	50

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 relied on polarized DIS
  - Total quark spin contributions pined down pretty well
  - Flavor separation was accessible via semi-inclusive DIS but has to reply on Fragmentation Functions; additional uncertainty introduced
  - No direct access to gluon

Prospects for RHIC Spin Physics in 2000

PROSPECTS FOR SPIN PHYSICS AT RHIC

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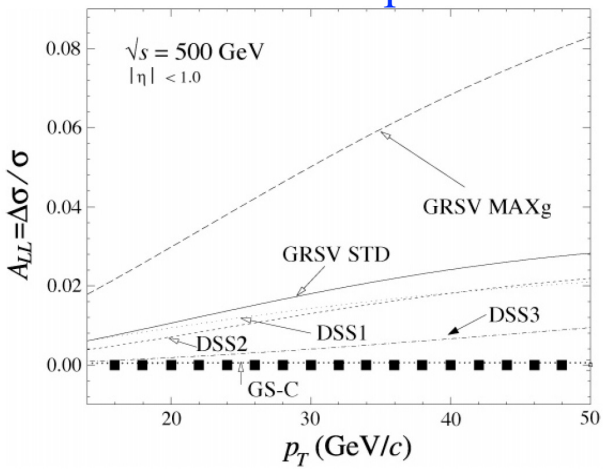
Key Words proton spin structure, spin asymmetries, quantum chromodynamics, beyond the standard model

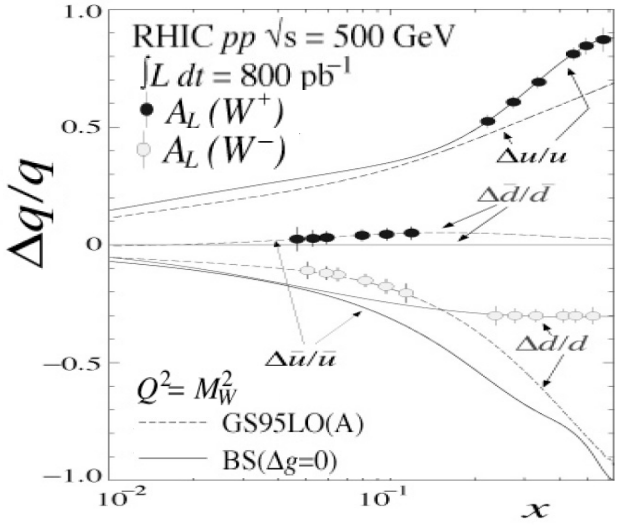
■ **Abstract** Colliding beams of 70% polarized protons at up to $\sqrt{s} = 500$ GeV, with high luminosity, $L = 2 \times 10^{32}\,cm^{-2}\,sec^{-1}$, will represent a new and unique laboratory for studying the proton. RHIC-Spin will be the first polarized-proton collider and will be capable of copious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

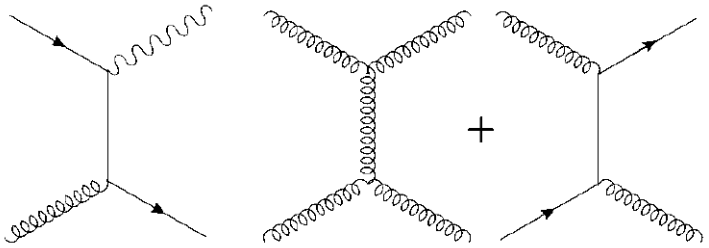
Jet production



$W^{\pm}$ production



Probe Gluon Polarization via Hadron/Jet/prompt-photon

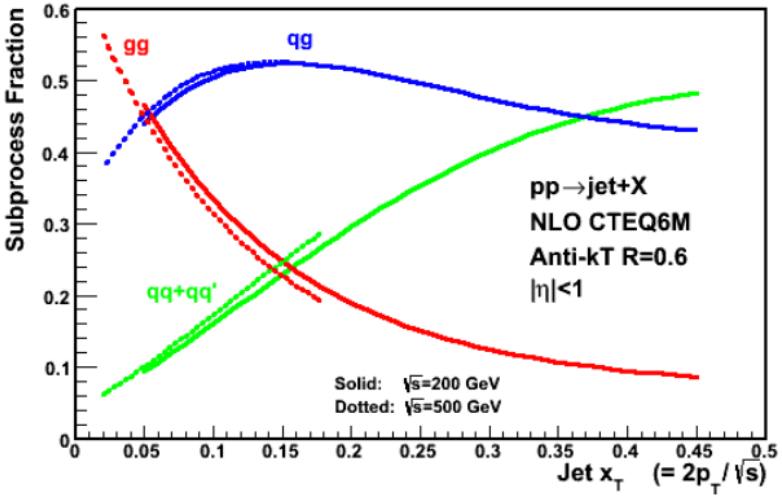


Quark gluon Compton scattering

Quark-gluon, gluon-gluon elastic scattering

Double-spin asymmetry:

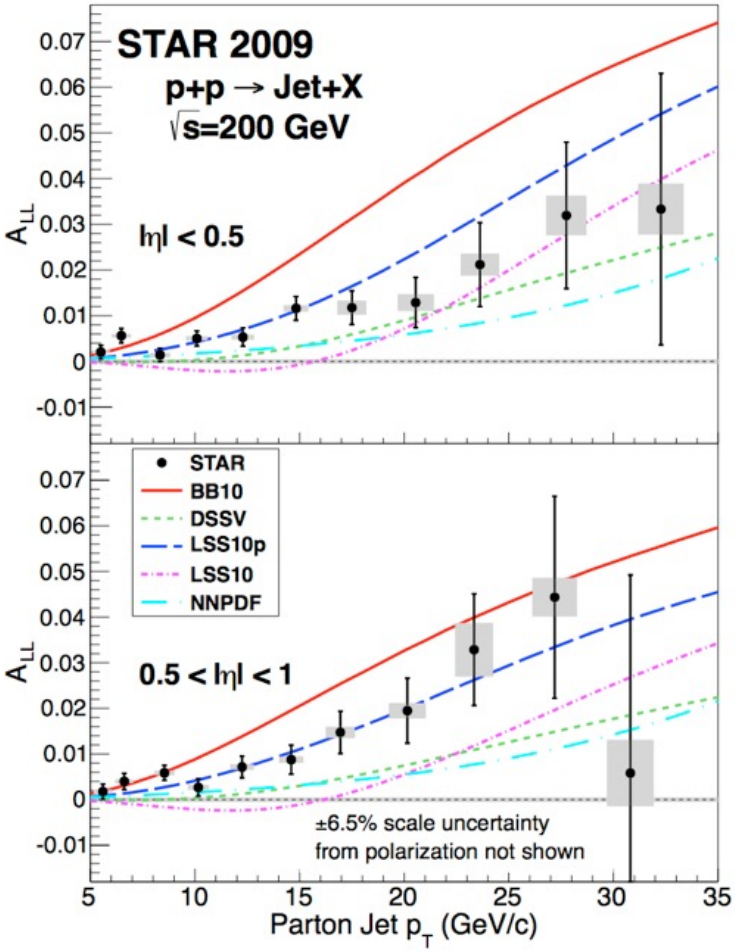
$$A_{LL} = \frac{\sigma^{\uparrow\uparrow} - \sigma^{\uparrow\downarrow}}{\sigma^{\uparrow\uparrow} + \sigma^{\uparrow\downarrow}} \propto \overbrace{\frac{\Delta f_1}{f_1} \otimes \frac{\Delta f_2}{f_2}}^{\text{probed}} \otimes \overbrace{\hat{a}_{LL} \otimes D_f^h}^{\text{inputs}}$$



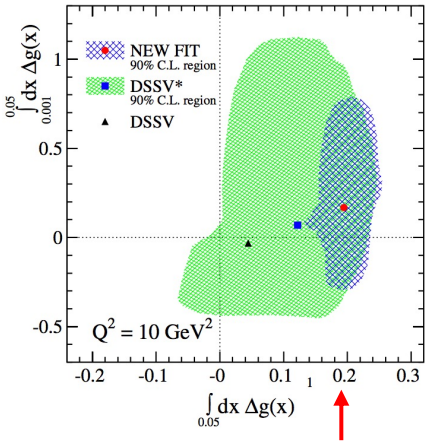
- Abundant yields of π^0 and jets at RHIC
- Sub-processes directly sensitive to gluon
- $x_{g,q} \sim p_T^{\pi^0,\text{jets}} / \sqrt{s} \bullet e^{-\eta}$
- Constrain gluon helicity-dependent PDFs

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

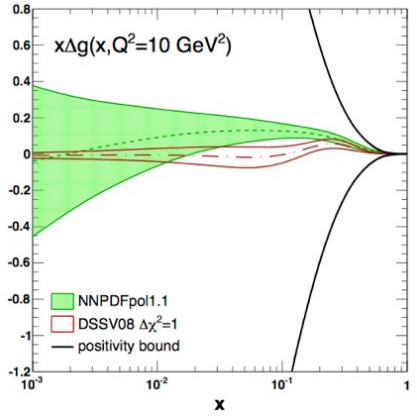
PRL115 (2015) 092002



PRL113 (2014) 012001



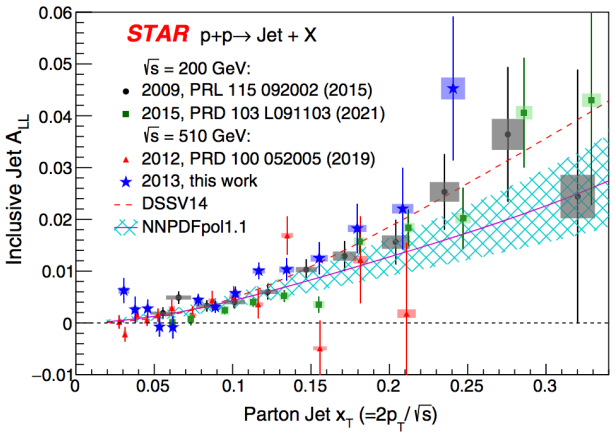
Nucl. Phys. B887 (2014) 276



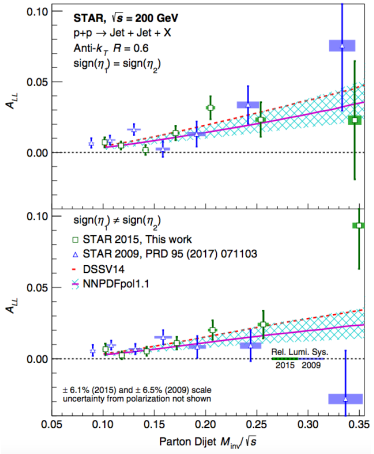
- First evidence of non-zero contributions from gluon spin at $Q^2 \sim 10$ GeV^2
  - STAR inclusive jets and PHENIX π^0
- Drive the constraints on ΔG

Inclusive-jet/di-jet/hadrons/direct-photon A_{LL} Results

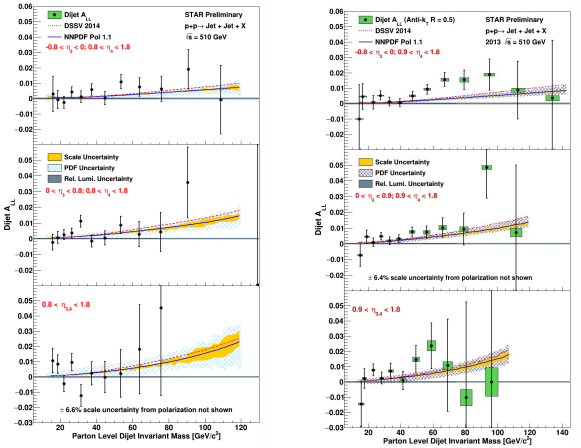
STAR, PRD 105, 092011 (2022)



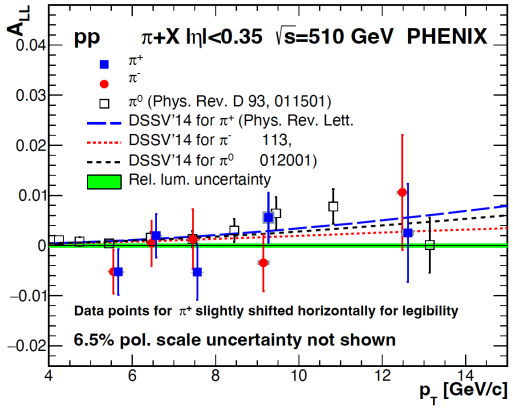
STAR, PRD 103 (2021) L091103



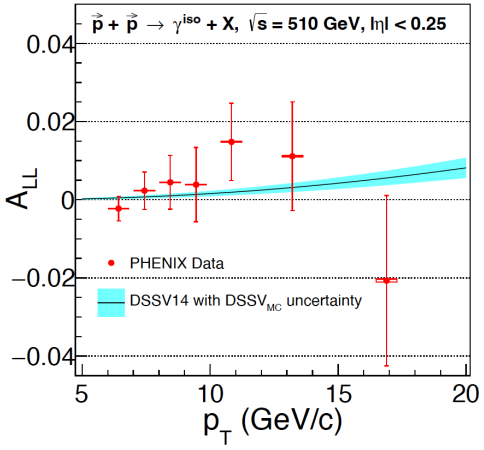
STAR di-jet preliminary results



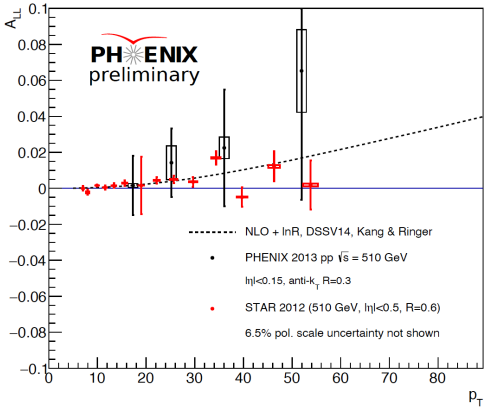
PHENIX, PRD 102, 032001 (2020)



PHENIX, arXiv:2202.08158

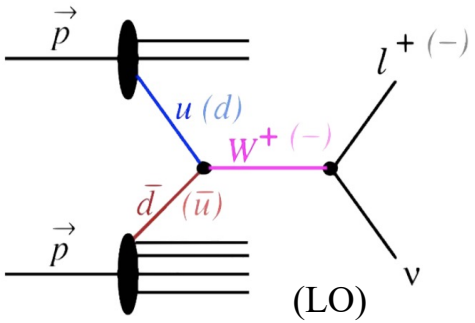


PHENIX preliminary



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

Probe sea quark polarization via W boson

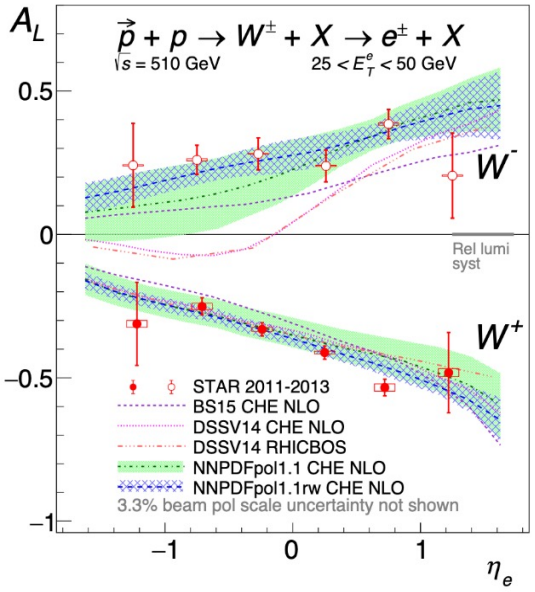


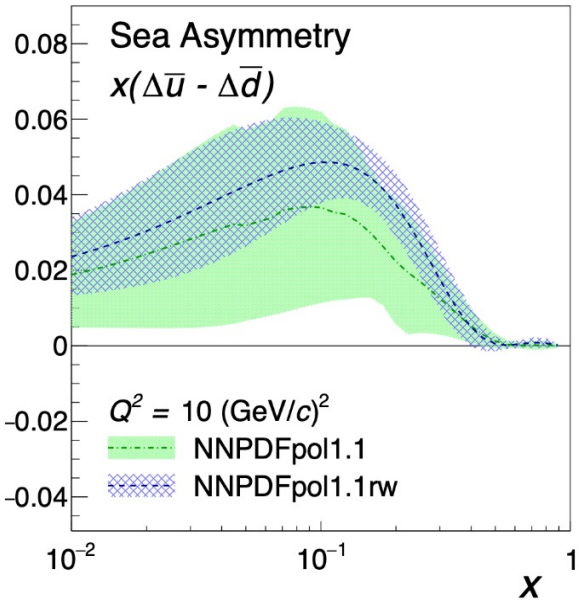
(LO)

Single-spin asymmetry:

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

PRD 99 (2019) 5, 051102

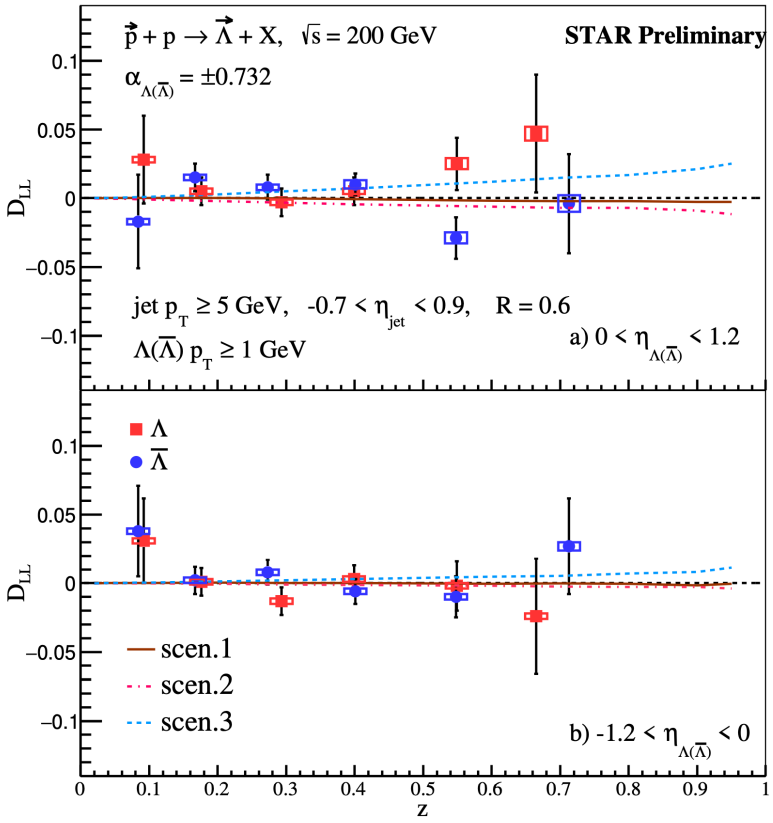




- W bosons production sensitive to flavor, spin, charge simultaneously; powerful tool to probe sea quark polarization
- Both STAR and PHENIX have concluded the W A_L measurements
- First experimental observation of a flavor-asymmetry between anti-up and anti-down polarizations, opposite to the unpolarized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

Strange quarks polarization via Lambda spin transfer

Yi Yu (SDU) SPIN2021



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

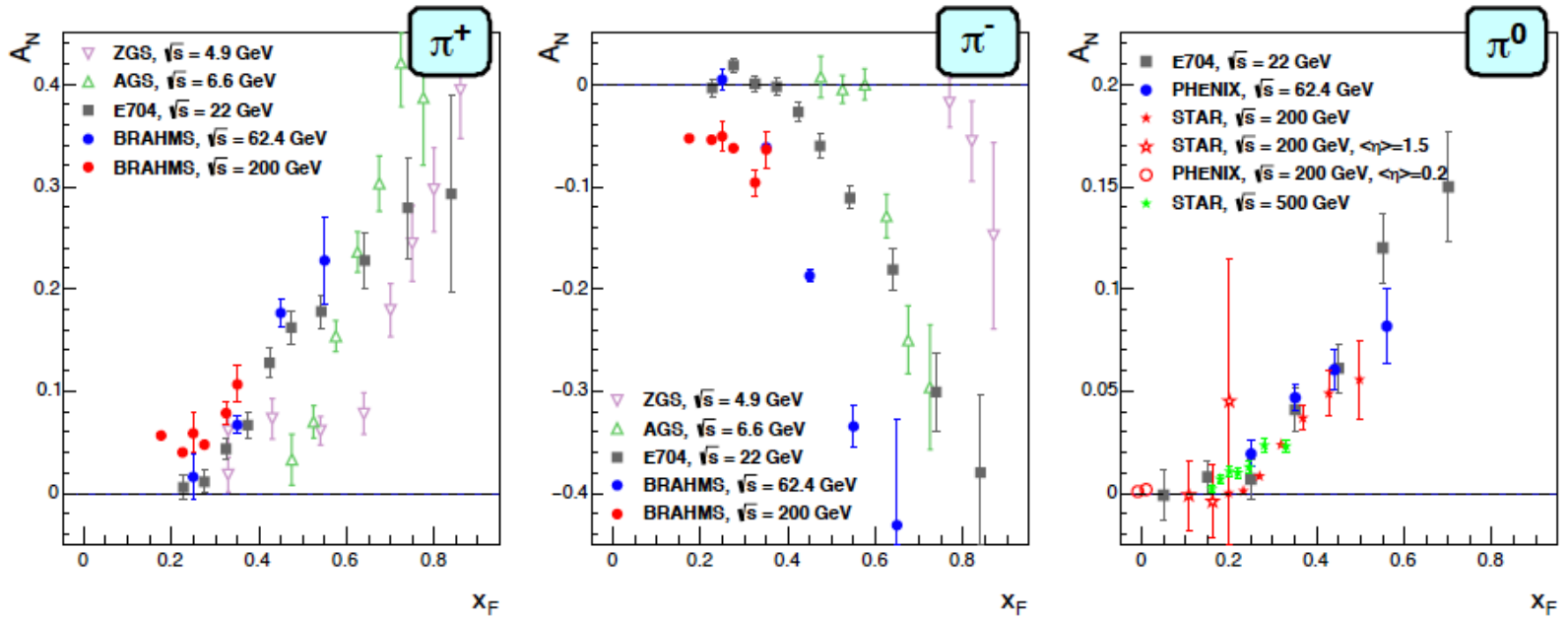
Spin transfer:

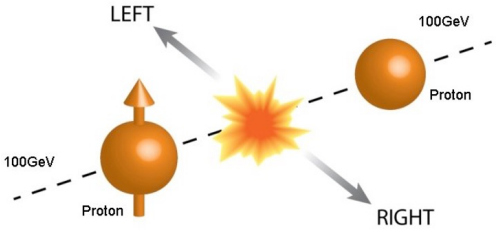
$$D_{LL}^{\Lambda} \equiv \frac{d\sigma(p^+p \to \Lambda^+X) - d\sigma(p^+p \to \Lambda^-X)}{d\sigma(p^+p \to \Lambda^+X) + d\sigma(p^+p \to \Lambda^-X)} = \frac{d\Delta\sigma^{\Lambda}}{d\sigma^{\Lambda}}$$

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

Polarized PDFs *Polarized FFs*

Forward A_N – remains mystery



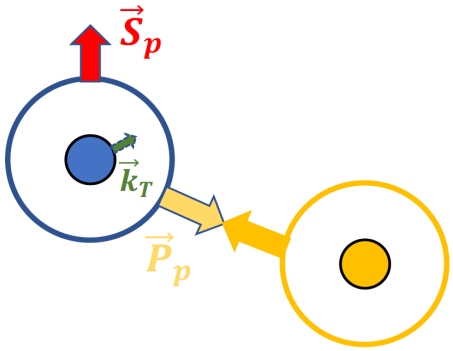


$$A_N = \frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}}$$

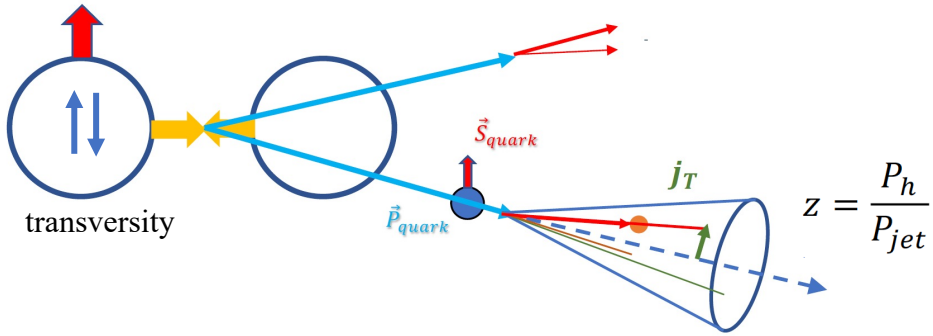
- Surprisingly large transverse single-spin asymmetries (pQCD predicts ~0)
- Nearly independent of √s over a very wide range (√s: 4.9 GeV to 500 GeV).
- TMDs and colinear Twist-3 frameworks developed to explain A_N origin
  - Qiu-Sterman functions, Sivers effect, Collins effect, etc.

Transverse single-spin asymmetries at RHIC

Sivers effect



Collins effect

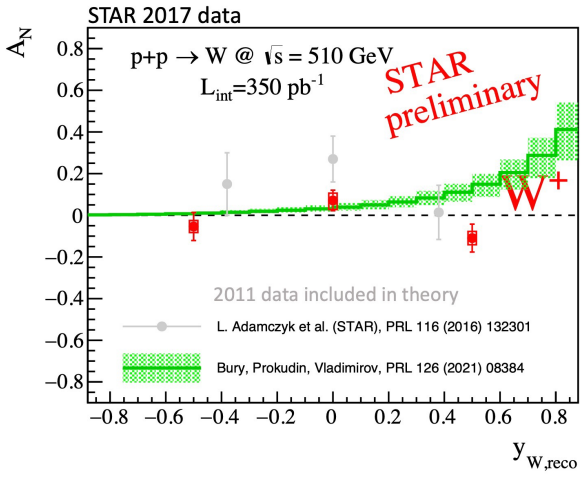


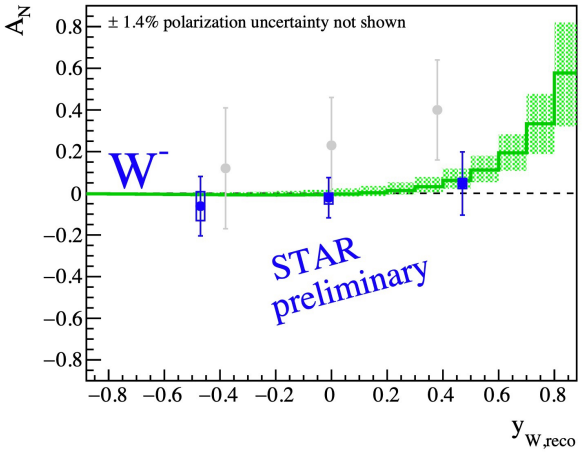
Sivers: Correlations between initial-state parton transverse momentum with proton's spin and momentum; process dependent.

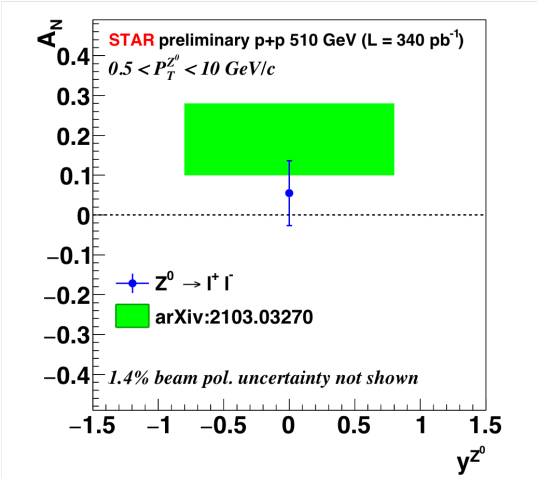
Collins: Correlations between the polarization of a scattered quark and the momentum of a hadron fragment transverse to the scattered quark direction.

Transversity: transverse polarization of partons inside transversely polarized proton.

Weak bosons A_N – Sivers



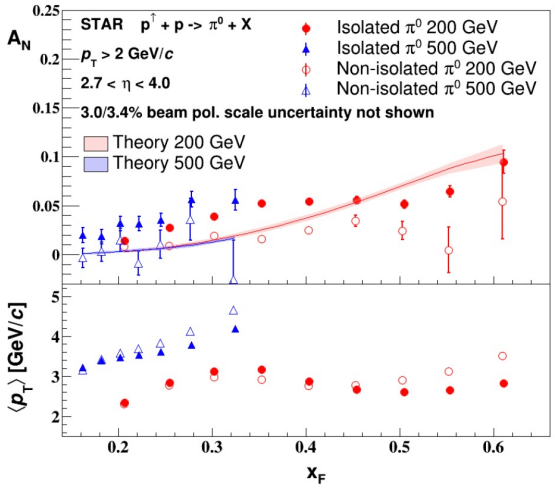


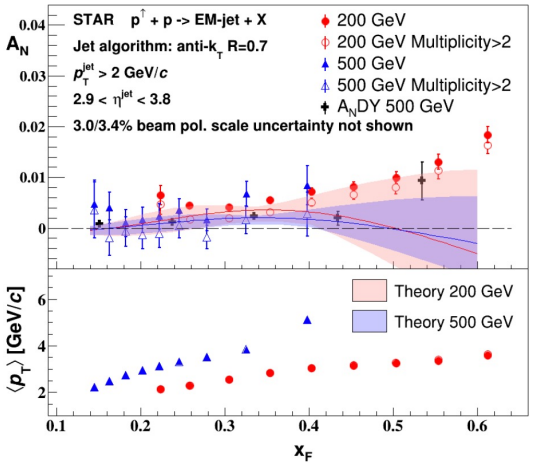


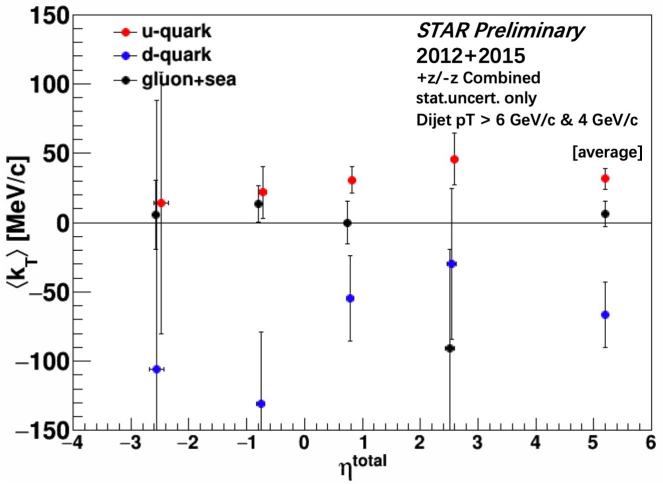
- Clean access to Sivers effect without fragmentation contribution.
- STAR data prefer to Sivers function sign change between SIDIS and DY
- Theoretical (PRL126,08384): extraction includes SIDIS, DY and 2011 STAR data with N3LO and NNLO accuracy of the TMD evolution assuming sign-change.
- STAR 2022 will further improve the precision.

π^0, EM-jet, Di-jet A_N – Sivers

STAR, PRD 103 (2021) 9, 092009







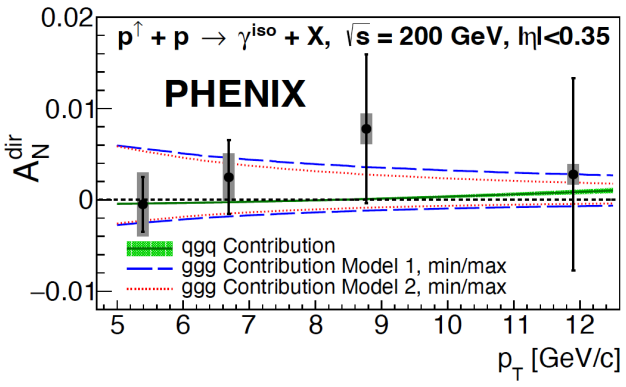
- A_N measured with forward EM-jets and π^0 in 200/500 GeV pp collisions
- High multiplicity EM-jets ($n_\gamma > 2$) and non-isolated π (w/ nearby γ) tend to generate smaller A_N.
- No significant collision energy dependence observed.

Provide significant constraints for the quark Sivers functions

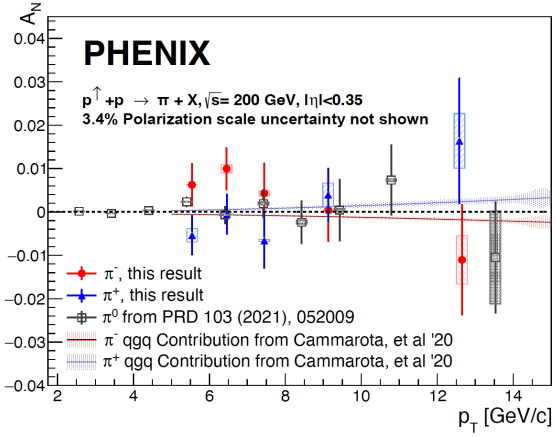
M.Boglione et.al., PLB 815, 136135 (2021)

A_N at PHENIX – Sivers

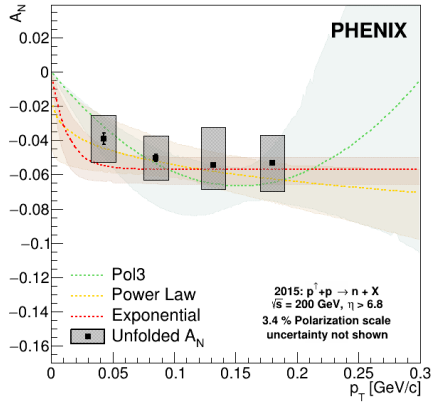
PHENIX, PRL127, 162001 (2021)



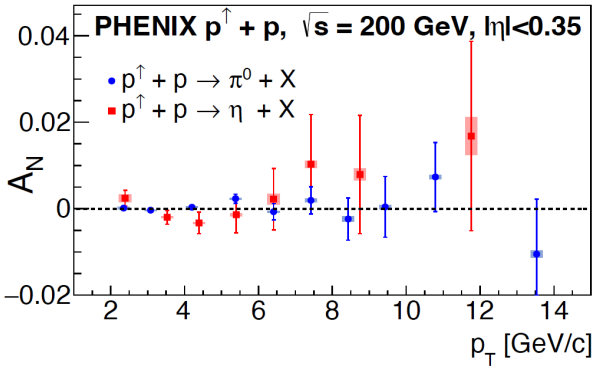
PHENIX, PRD105, 032003 (2022)



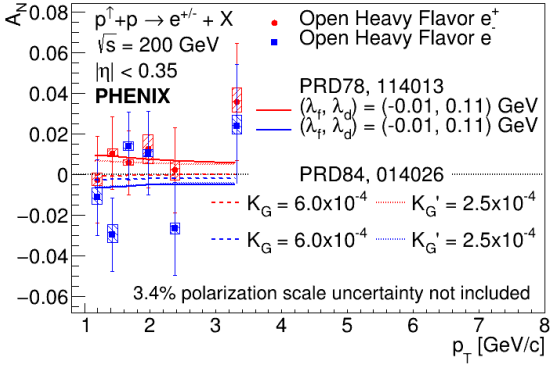
PHENIX, PRD103, 032007 (2021)



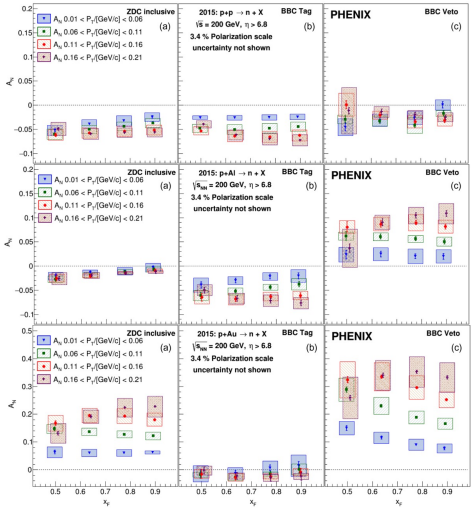
PHENIX, PRD103, 052009 (2021)



PHENIX, arXiv:2204.12899



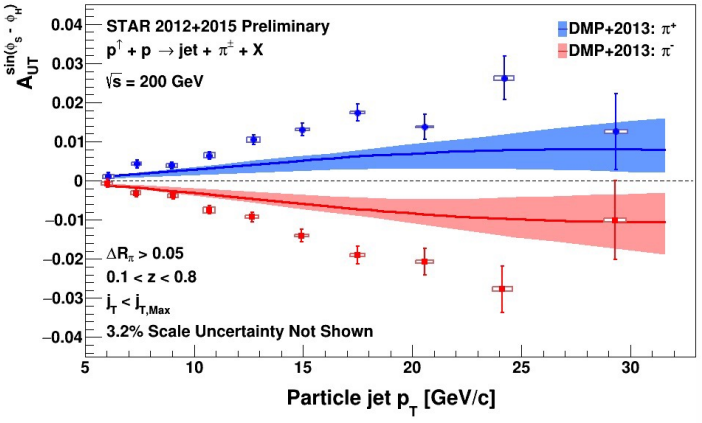
PHENIX, PRD105, 032004 (2022)

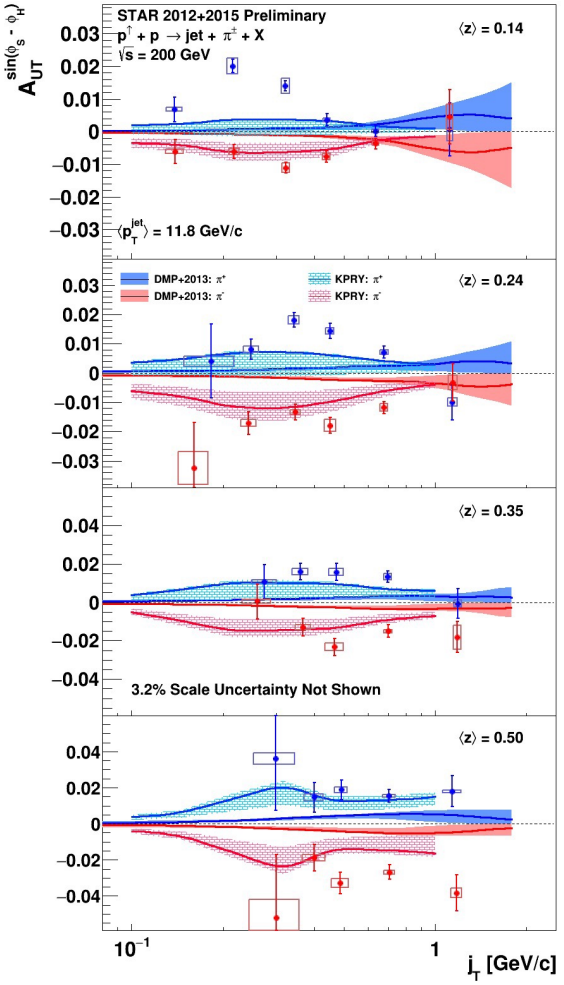


- PHENIX recently published a lot of A_N results
- Important inputs for Sivers' functions extraction

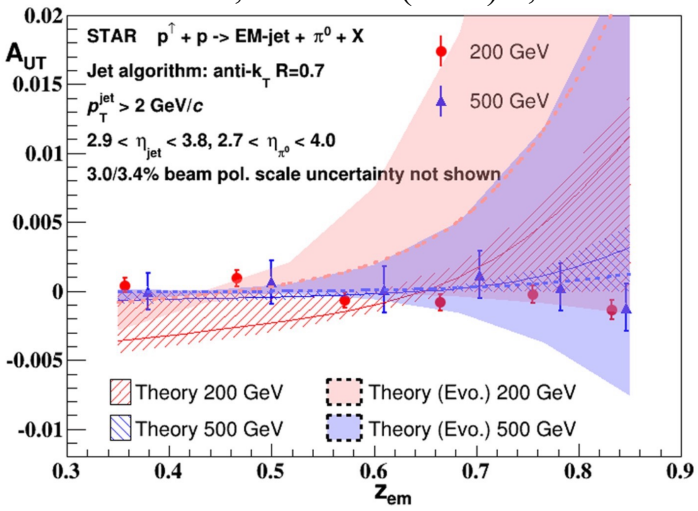
Hadron in Jet A_N – Transversity + Collins

STAR, arXiv:2205.11800, submitted to PRD





STAR, PRD 103 (2021) 9, 092009

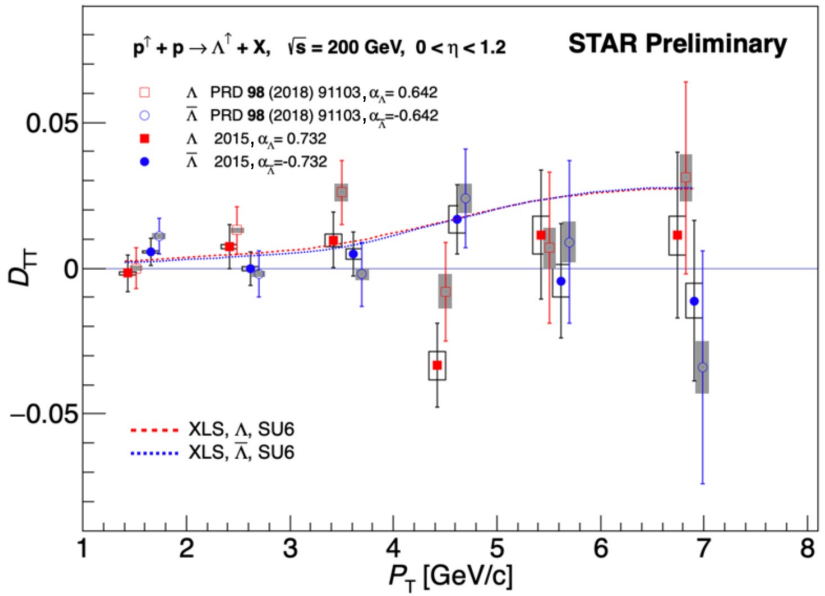


- Transversity is probed most directly in the jet p_T dependence
- Collins TMD FF is sensitive to the (j_T,z) dependence

Lambda transverse spin transfer – Transversity + FF

Lambda transverse spin transfer can provide connection to the transversity PDF and FF of strangeness.

Yike Xu (SDU) DIS2021

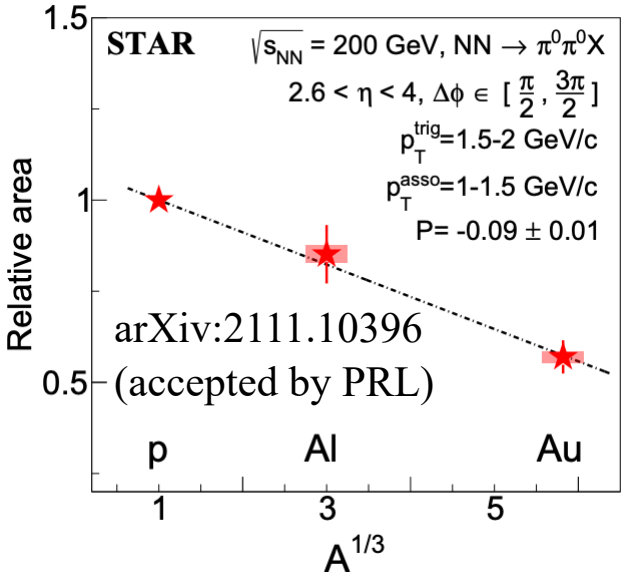


Transverse spin transfer: $D_{TT}^{\Lambda} \equiv \frac{\sigma^{(p^\uparrow p \to \Lambda^\uparrow X)} - \sigma^{(p^\uparrow p \to \Lambda^\downarrow X)}}{\sigma^{(p^\uparrow p \to \Lambda^\uparrow X)} + \sigma^{(p^\uparrow p \to \Lambda^\downarrow X)}} = \frac{d\delta\sigma^{\Lambda}}{d\sigma^{\Lambda}}$

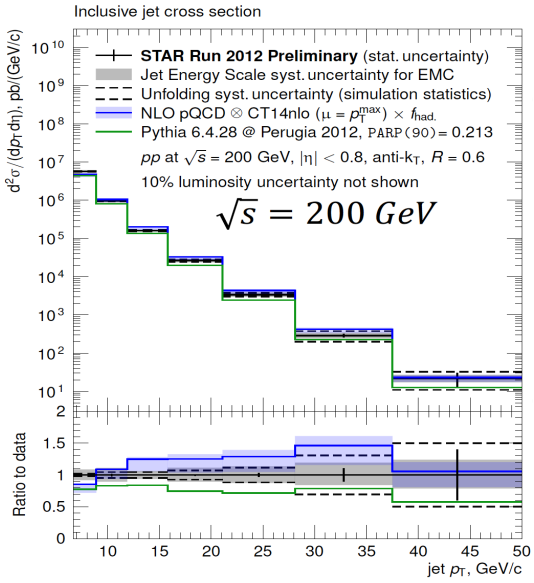
$$d\delta\sigma^{\Lambda} = \sum_{abcd} \int dx_a\, dx_b dz \underbrace{\delta f_a(x_a)}_{\text{Transversity PDF}} f_b(x_b) \delta\sigma^{(a^\uparrow b \to c^\uparrow d)} \underbrace{\delta D_c^{\Lambda}(z)}_{\text{Transversity FF}}$$

Measurements with unpolarized beam

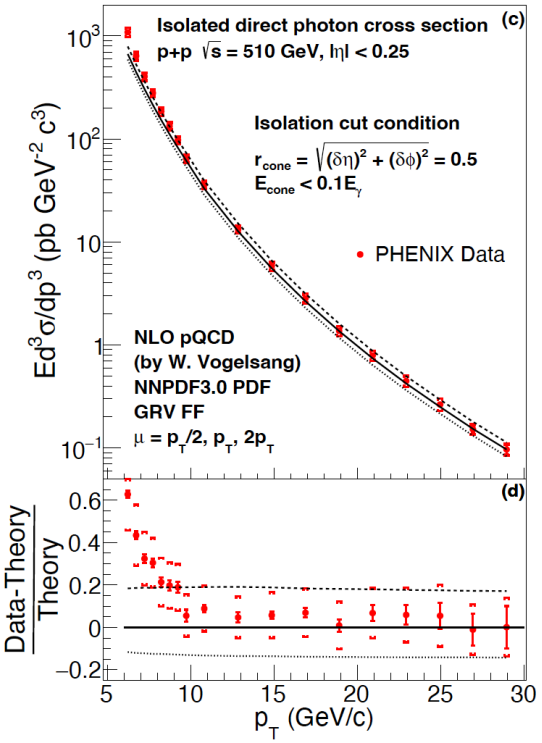
Nonlinear gluon effects



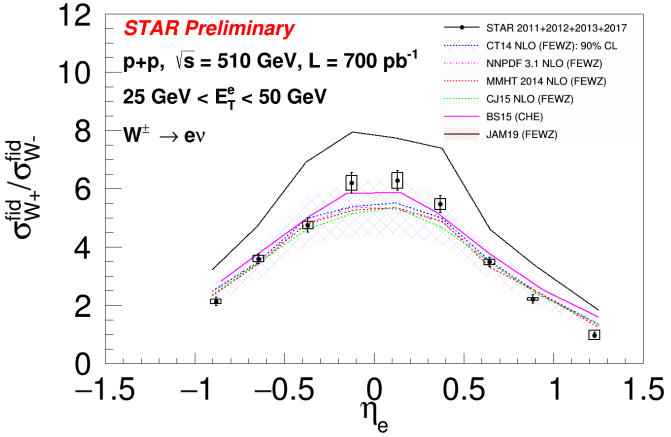
Gluon PDF with Jet/direct-photon cross section

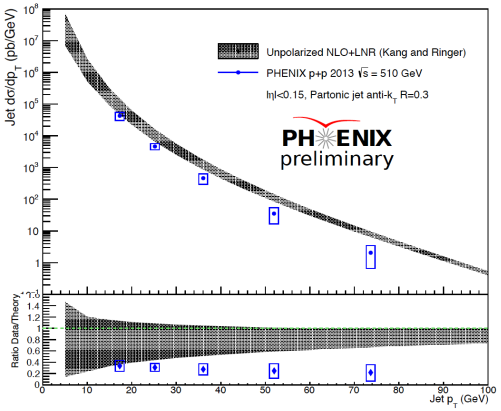


arXiv:2202.08158



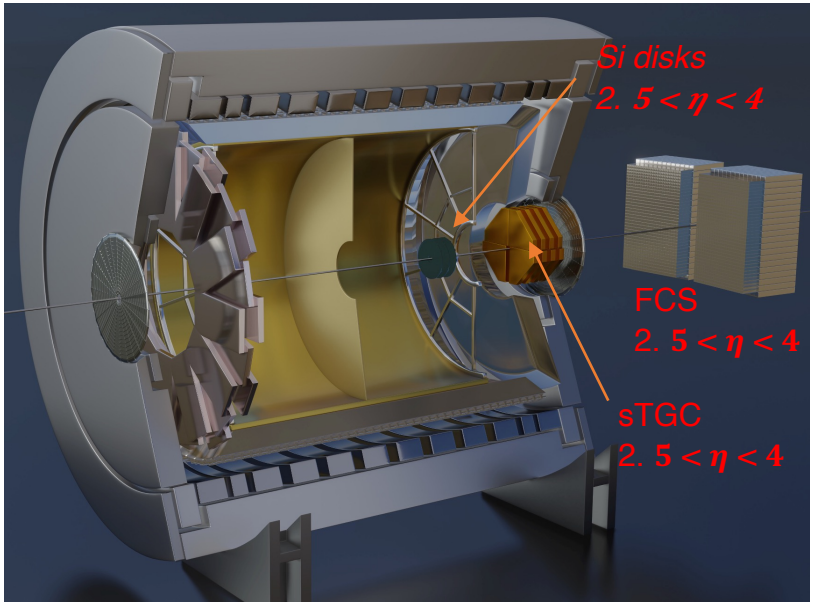
$\bar{d}/\bar{u}$ with W x-sec ratio



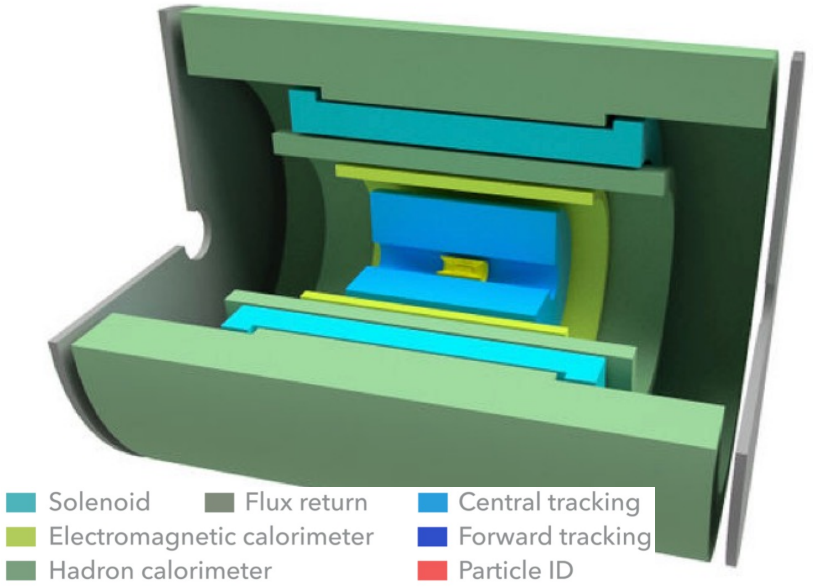


Outlook

STAR w/ forward upgrade



sPHENIX



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

$\sqrt{s}$ (GeV)	Species	Luminosity	Year	
510	$p^{\uparrow}+p^{\uparrow}$	400 pb^{-1}	2022	STAR on disk already
200	$p^{\uparrow}+p^{\uparrow}$	235 pb^{-1}	2024	STAR & sPHENIX
200	$p^{\uparrow}+Au$	1.3 pb^{-1}	2024	STAR & sPHENIX

Summary

- RHIC is 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!