

Recent Highlights from the STAR Cold-QCD Physics Program

Xiaoxuan Chu, for the STAR Collaboration

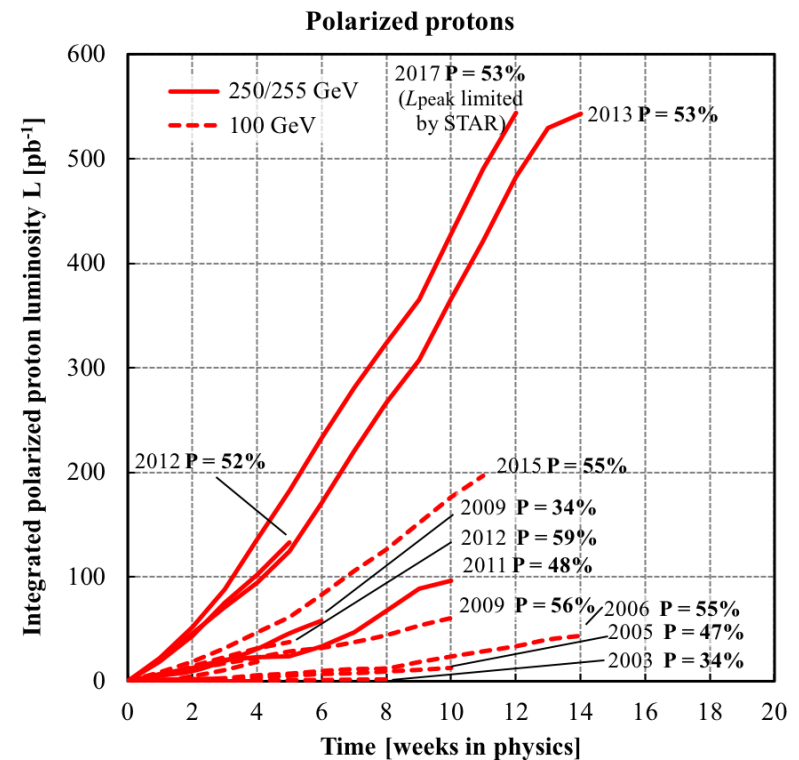
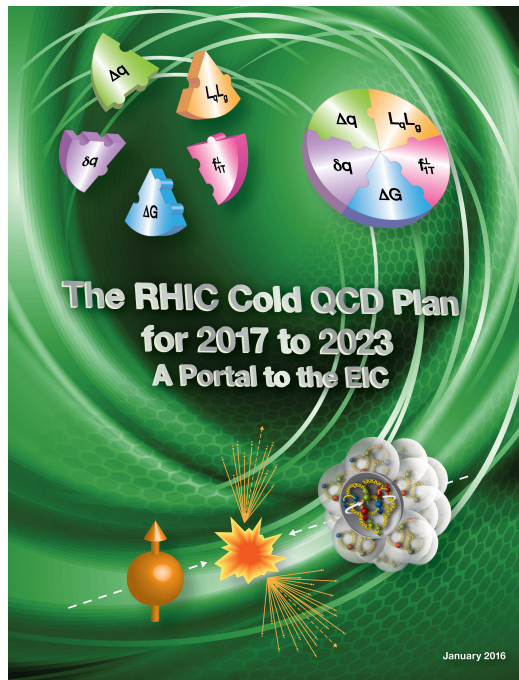
RHIC & AGS Annual Users' Meeting 2021

June 8-11, 2021

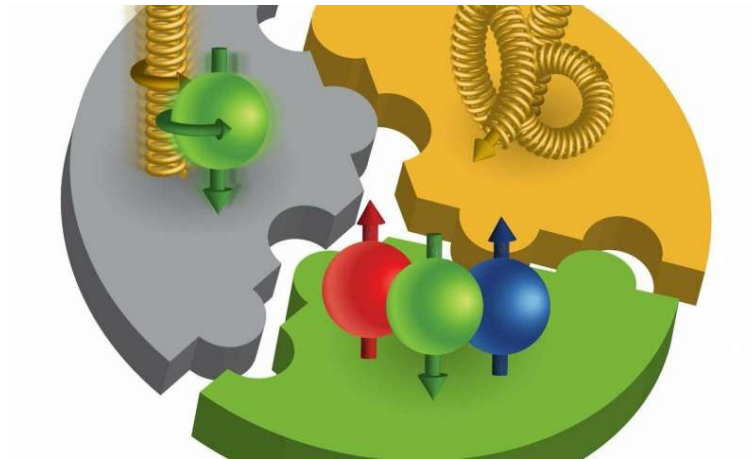


Introduction

The goal of the RHIC Cold QCD program	RHIC dataset
Spin composition of the proton	Longitudinally polarized beam
Multidimensional landscape of proton	Transversely polarized beam
Initial state in nuclear collisions	Unpolarized beam



Longitudinally polarized beam: Gluon polarization



Gluon helicity

Gluon helicity

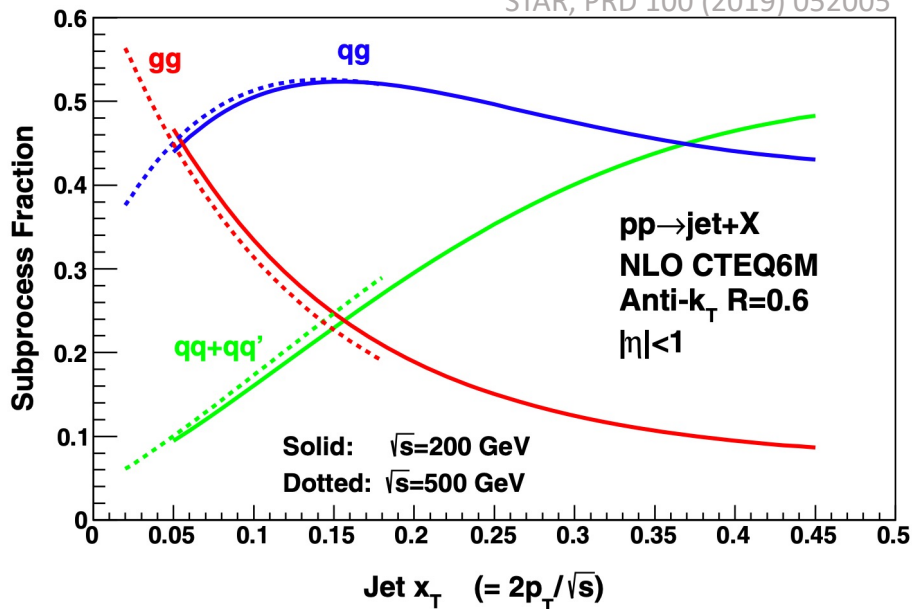
Proton spin (Jaffe-Manohar sum rule)

$$S = \frac{1}{2} = \frac{1}{2} \Delta\Sigma + \Delta G + L_q + L_G$$

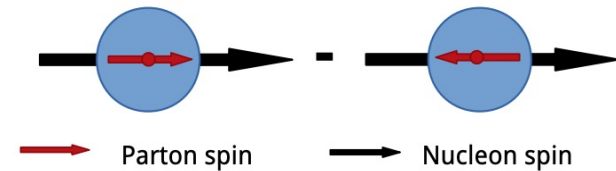
Gluon helicity distribution: $\Delta g(x, Q^2)$

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

STAR, PRD 100 (2019) 052005



Measurements

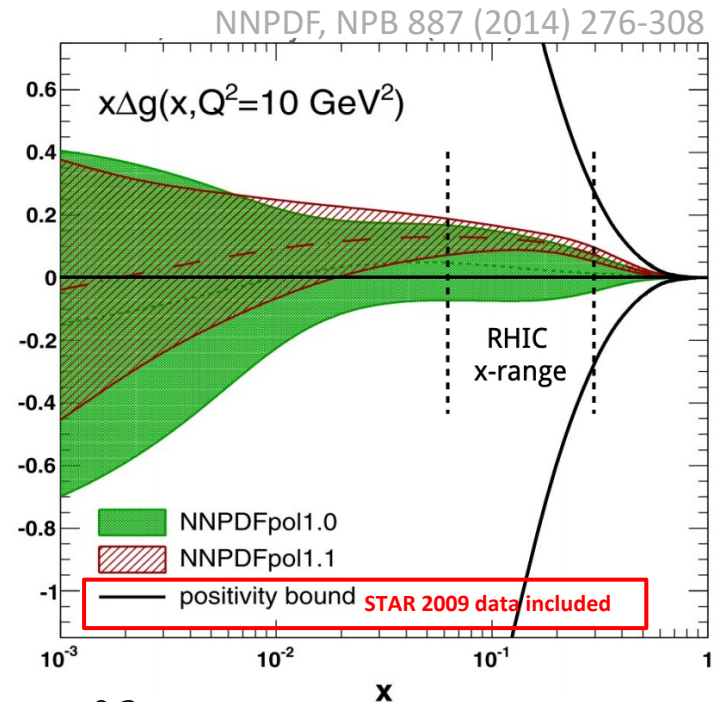
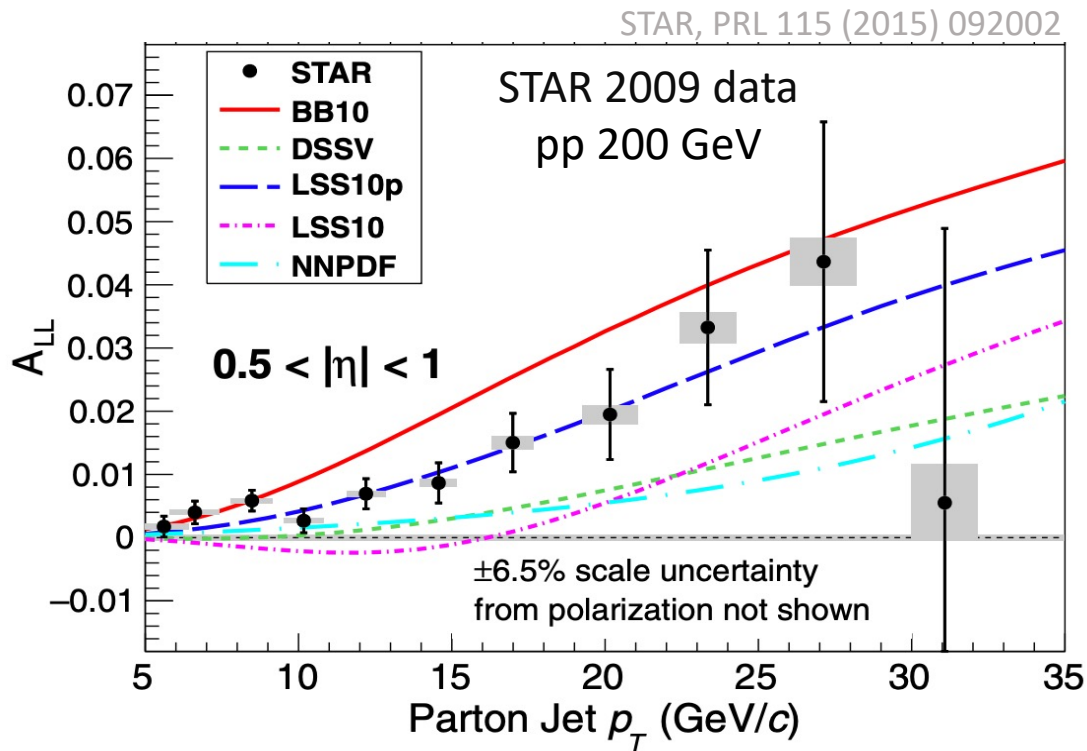


$$A_{LL} = \frac{\sigma_{++} - \sigma_{+-}}{\sigma_{++} + \sigma_{+-}} = \frac{\Sigma \Delta f_a \otimes \Delta f_b \otimes \hat{\sigma} a_{LL}}{\Sigma f_a \otimes f_b \otimes \hat{\sigma}}$$

How to access ΔG at RHIC?

- Midrapidity jet production at RHIC is dominated by qq and gg scatterings at low x_T
- The qq and gg scattering cross sections are sensitive to the helicities of the gluon

Evidence of positive ΔG

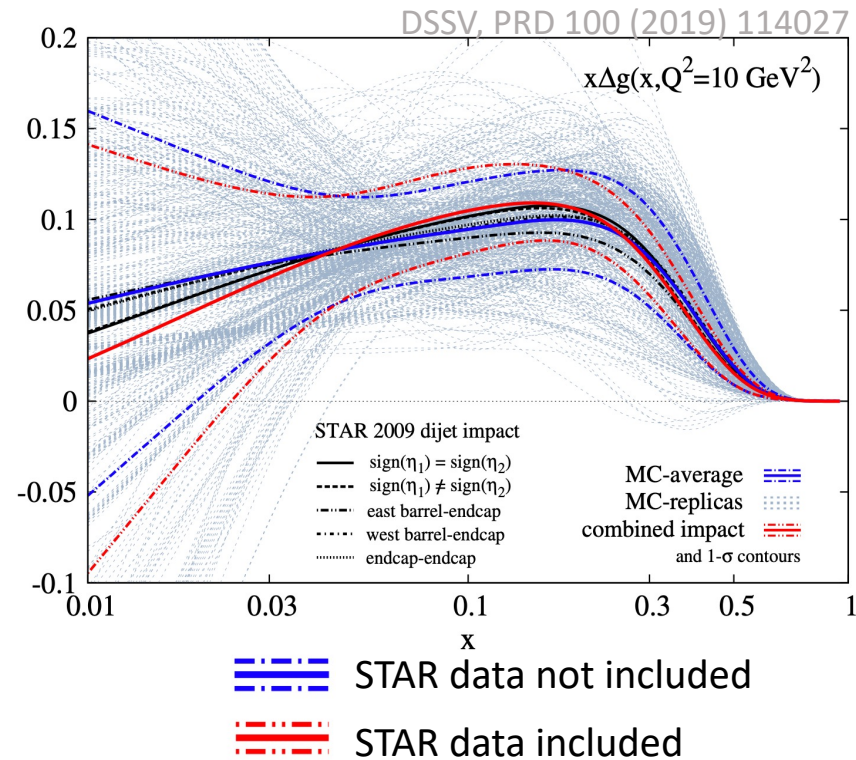
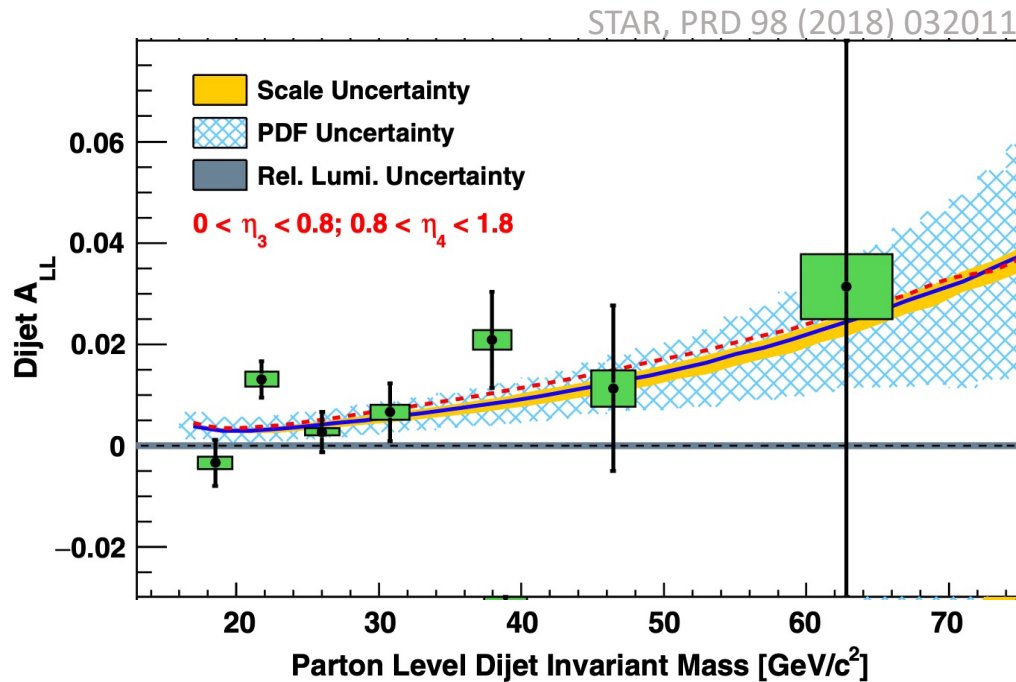


$$\int_{0.05}^{0.2} \Delta g(x, Q^2) dx = 0.17 \pm 0.6$$

at $Q^2=10 \text{ GeV}^2$

- Evidence of positive gluon polarization at $0.05 < x < 0.2$
- These data are included in NNPDF and DSSV fits: help constrain gluon polarization at intermediate x

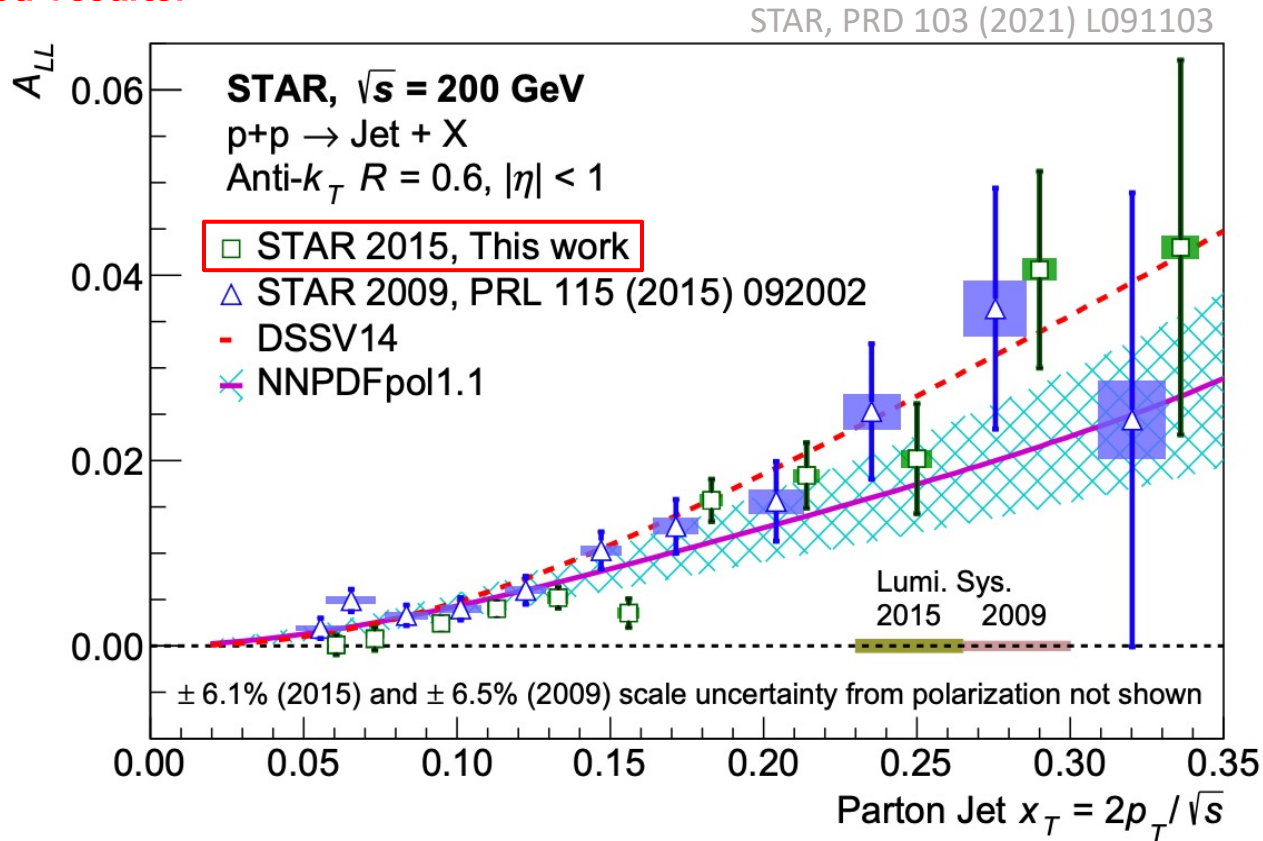
Impact of di-jet data



- STAR 2009 pp 200 GeV di-jet data included in global fit:
 - STAR, PRD 95 (2017) 071103; STAR, PRD 98 (2018) 032011
- Central value of Δg is slightly revised and uncertainty is reduced by including STAR di-jet data

Inclusive jet A_{LL} at 200 GeV

Newly published results!

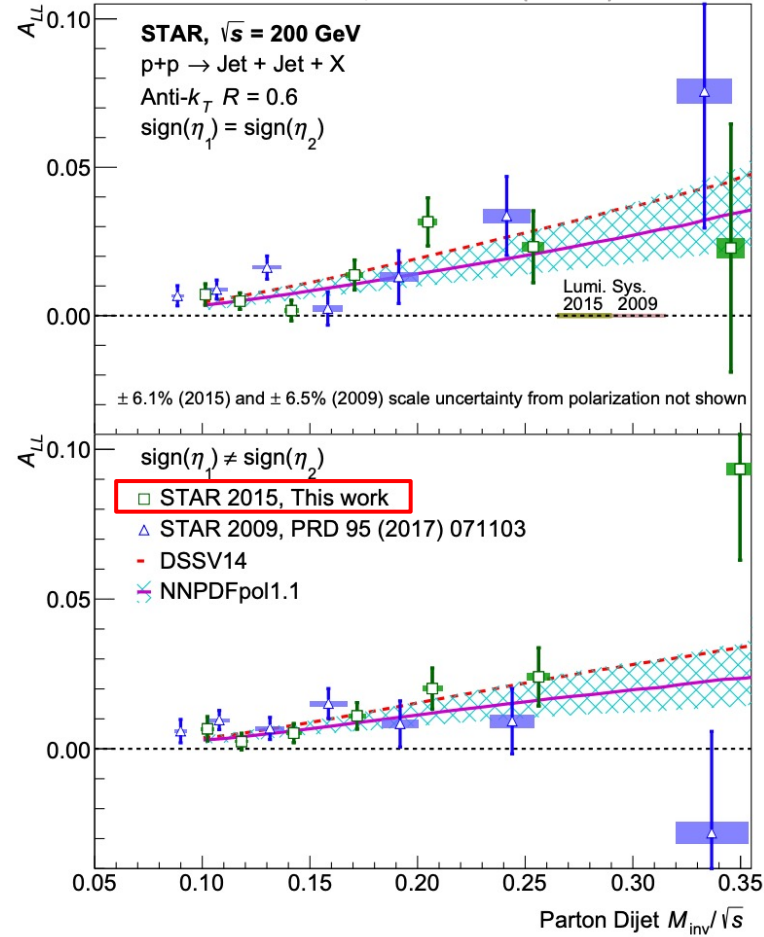


- Largest 200 GeV longitudinally polarized pp dataset; improved both statistical and systematic uncertainties
- This result can reduce the uncertainty of gluon polarization for $x_T > 0.05$ if included in global fits

Di-jet A_{LL} at 200 GeV

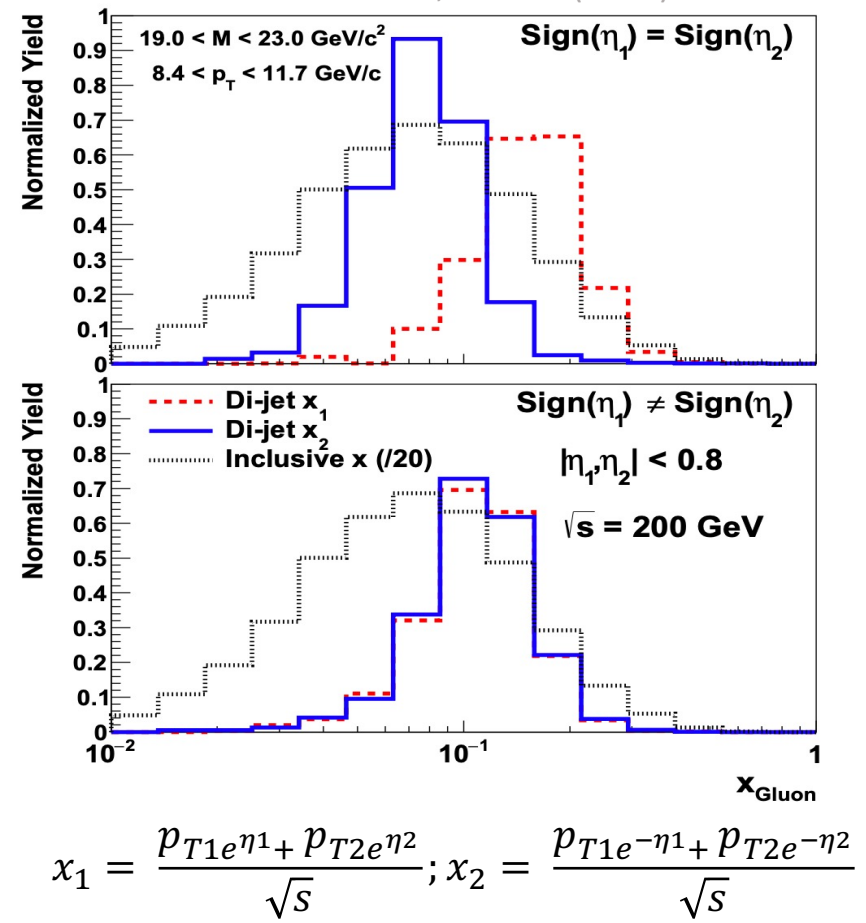
Newly published results!

STAR, PRD 103 (2021) L091103



Two different η topology bins

STAR, PRD 95 (2017) 071103

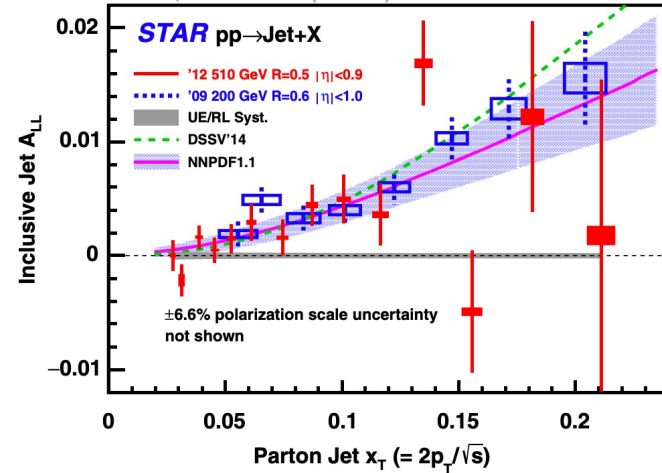


Di-jets: Much narrower ranges of initial state partonic momentum fraction tested; different topologies enhance sensitivity of the data to selected x ;

Inclusive jets and di-jets A_{LL} at 510 GeV

Four different η topology bins

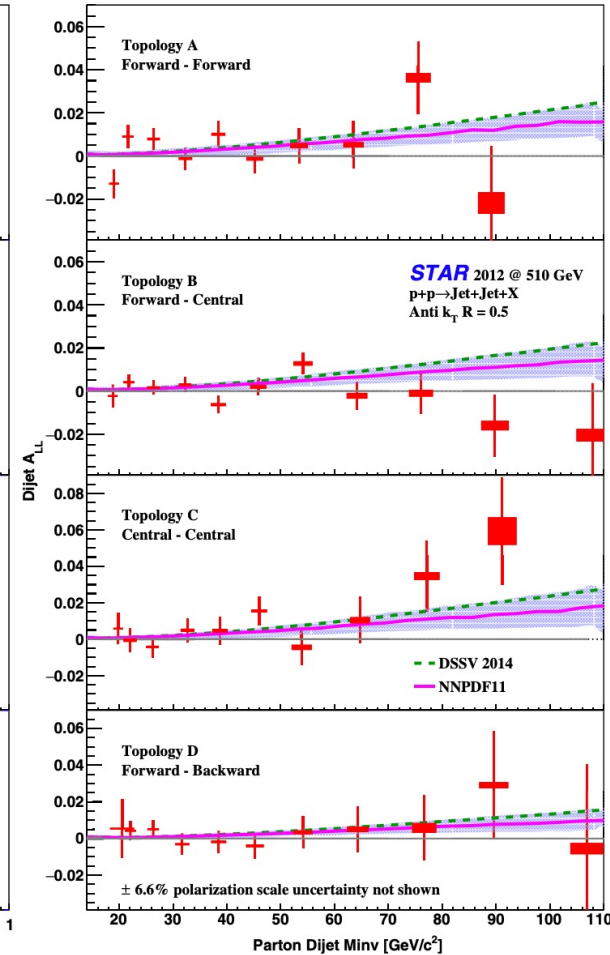
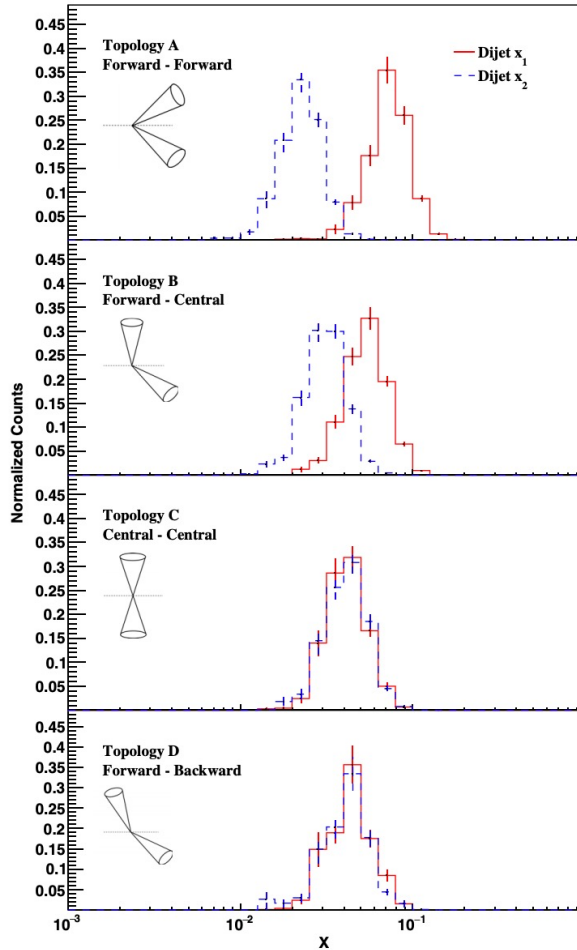
STAR, PRD 100 (2019) 052005



Measurement of jet and di-jet A_{LL} at 510 GeV with 2012 data:

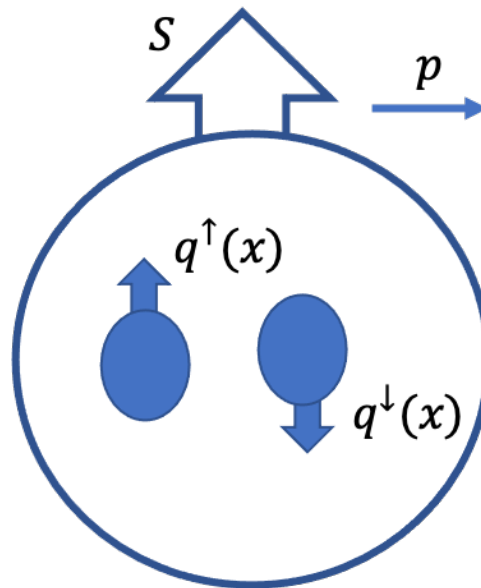
- Higher \sqrt{s} pushes sensitivity to lower x (down to 0.02)
- Consistent results from both energies
- Constrain the shape of Δg

$$|\cos\theta^*| = \tanh(|\eta_1 - \eta_2|)/2$$

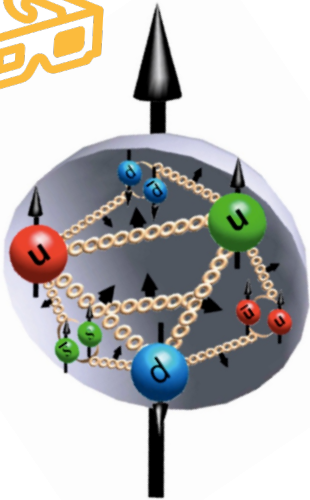


We have concluded the collection of longitudinally polarized data (Run 2013 A_{LL} publication in preparation)

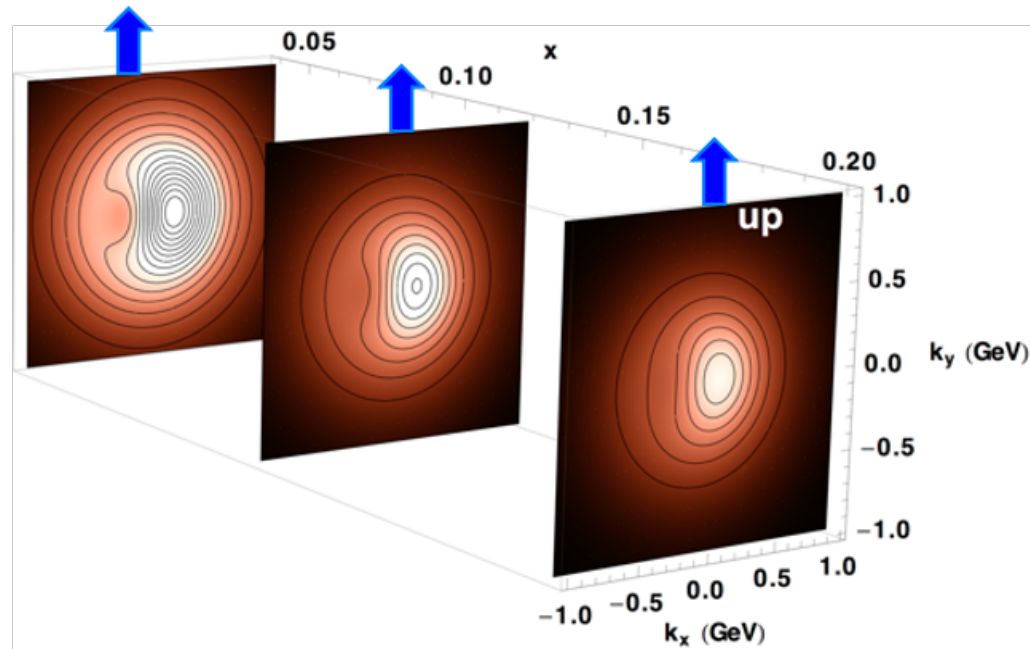
Transversely polarized Beam: Proton 3D Structure



Transverse structure of the proton



3D image
→

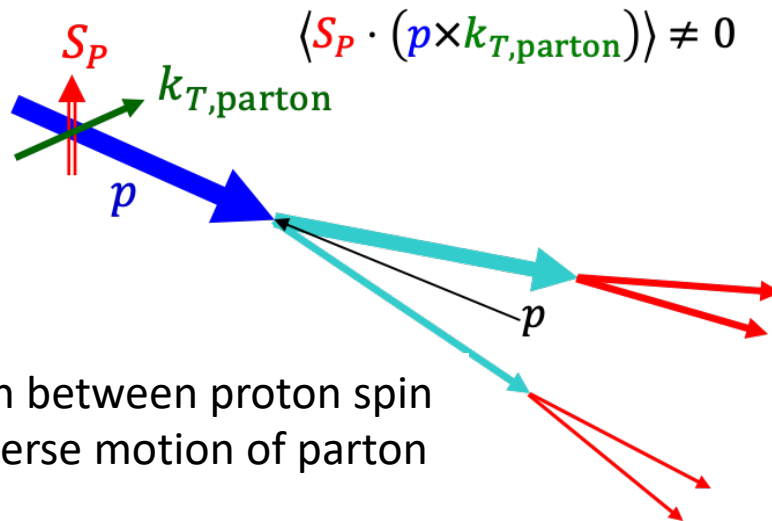


- Transverse momentum dependent PDFs (TMDs, $f(x, k_T)$) → 3D structure of the proton
- Access to two types of TMDs
 - Initial state effect from PDFs → **Sivers function**
 - Final state effect from fragmentation → **Collins function**
- Measurement: Transverse single spin asymmetry (TSSA)

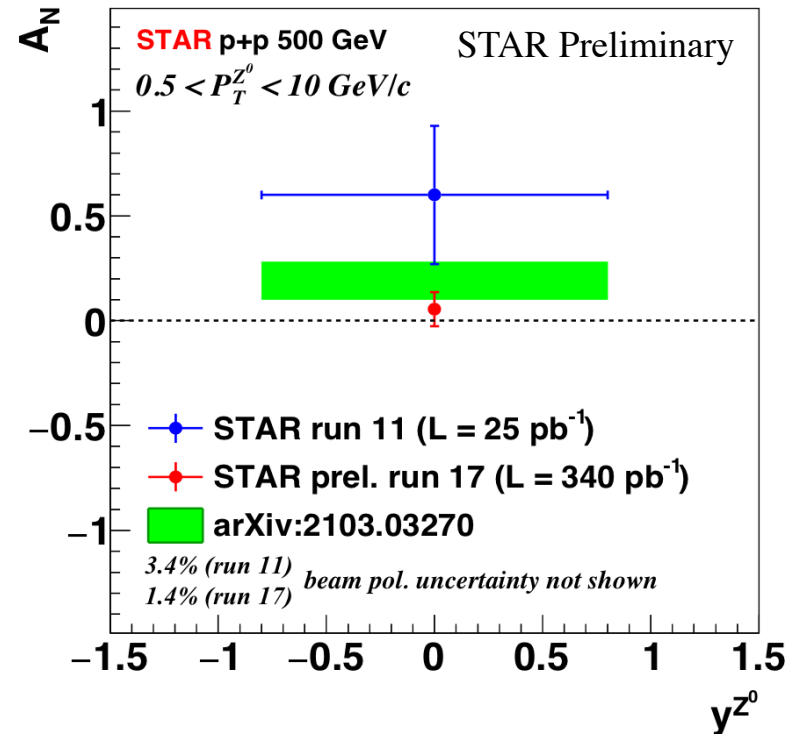
$$A_N = \frac{d\sigma^\uparrow - d\sigma^\downarrow}{d\sigma^\uparrow + d\sigma^\downarrow}$$

A_N for Z and W boson

NEW



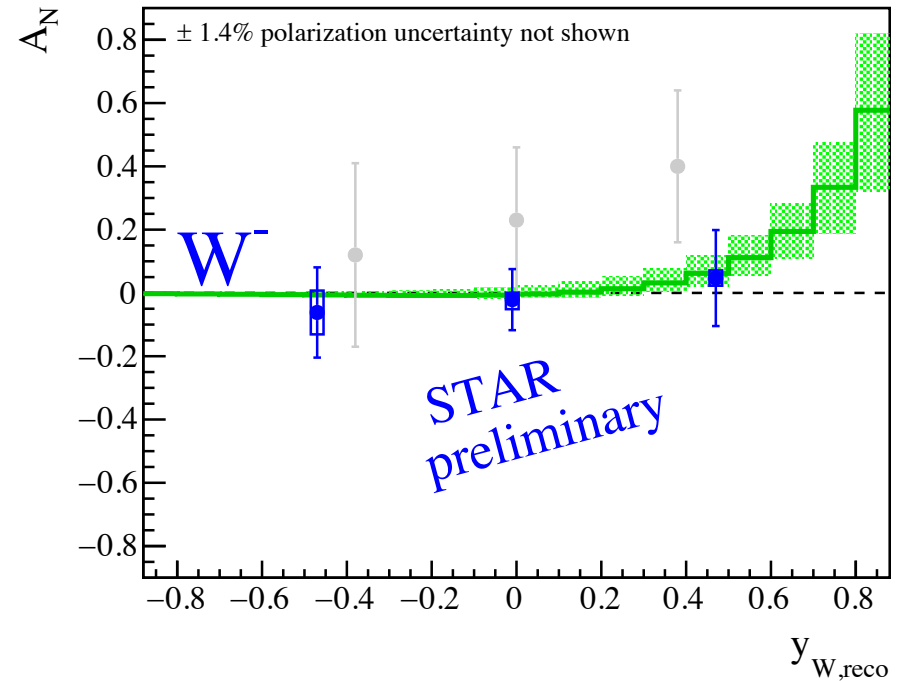
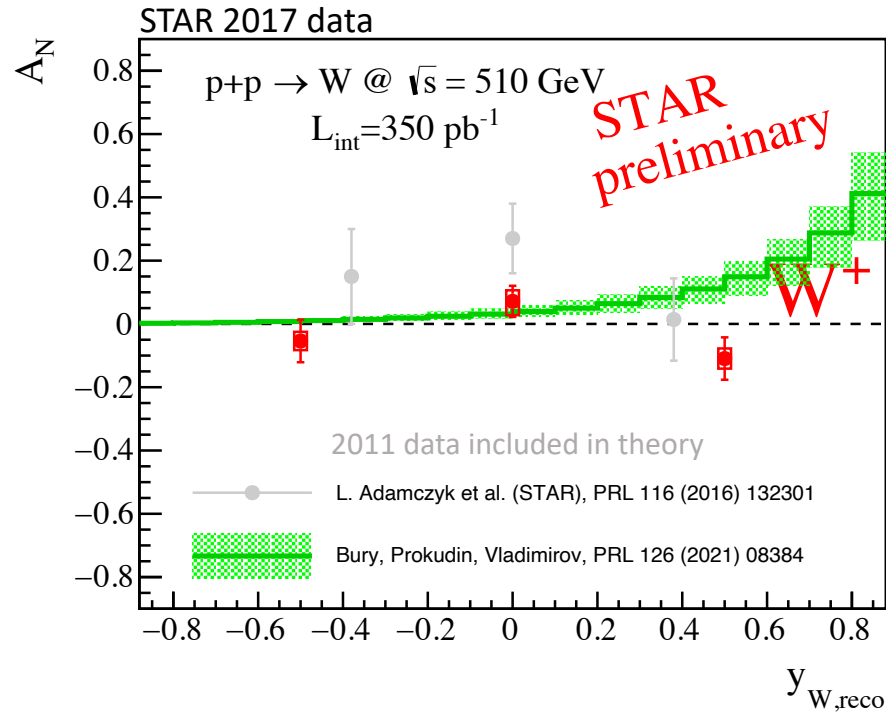
Correlation between proton spin and transverse motion of parton



- Sivers effect: the correlation between the transverse momentum of a parton (k_T) and the transverse spin (S_p) of the proton
- TSSA of weak bosons sensitive to Sivers sign-change and TMD evolution effects
- Improved uncertainties using STAR 2017 data

A_N for Z and W boson

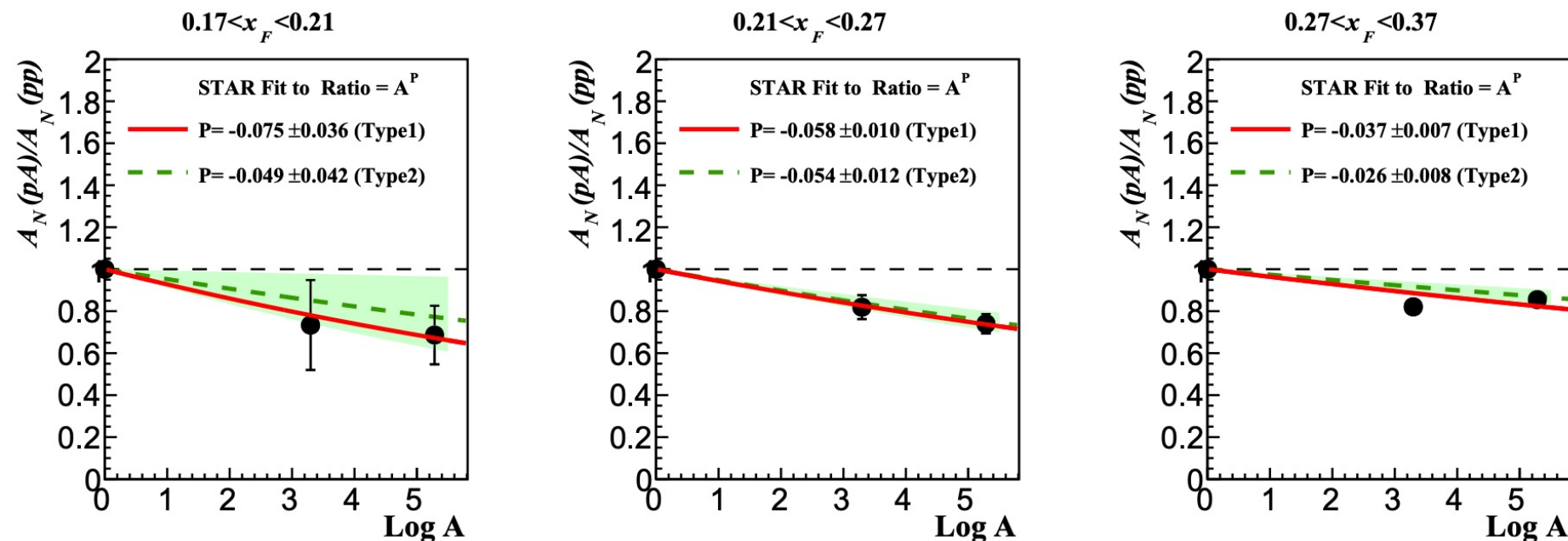
NEW



- Sivers effect: the correlation between the transverse momentum of a parton (\mathbf{k}_T) and the transverse spin (\mathbf{S}_p) of the proton
- TSSA of weak bosons sensitive to Sivers sign-change and TMD evolution effects
- Improved uncertainties using STAR 2017 data

A dependence of π^0 A_N

STAR, PRD103 (2021) 072005



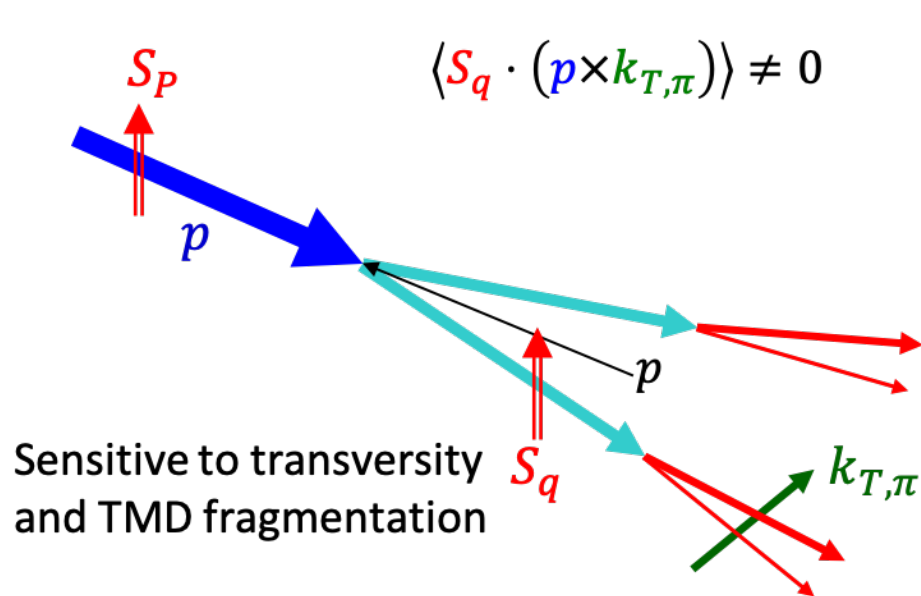
Type1: correlated uncertainties in the ratio; Type2: without correlated uncertainties

$$x^F = \frac{E_L^{\pi^0}}{E_{beam}}$$

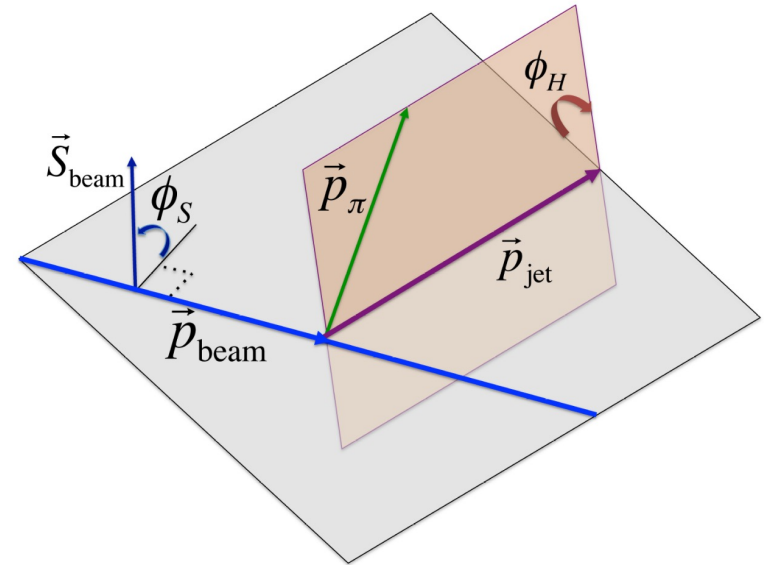
TSSA for forward ($2.7 < \eta < 3.8$) π^0 in pp, pAl and pAu collisions using 2015 data

- Ratios of average A_N values as a function of $\log A$ in each x_F bin are measured
- Suppression of A_N in pA to A_N in pp collisions is observed

Collins asymmetry



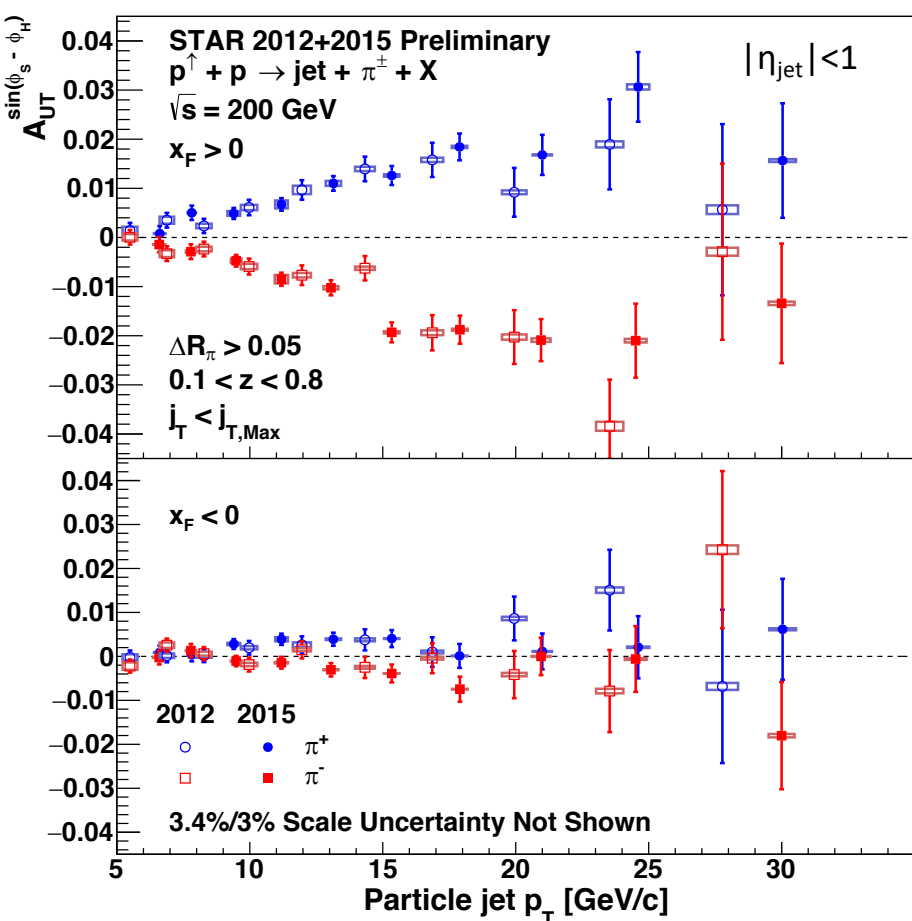
$$A_{UT}^{\sin(\phi)} \sin(\phi) = \frac{\sigma^{\uparrow}(\phi) - \sigma^{\downarrow}(\phi)}{\sigma^{\uparrow}(\phi) + \sigma^{\downarrow}(\phi)}$$



$$\phi = \phi^S - \phi^H$$

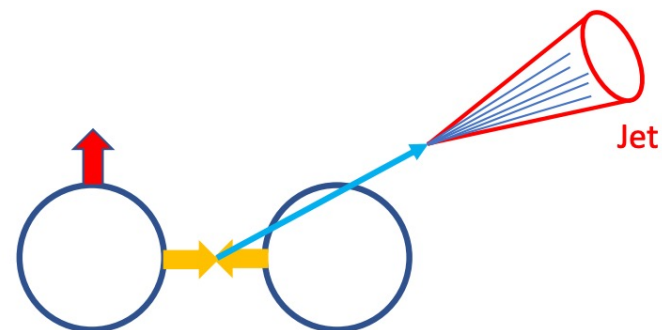
Collins asymmetry indicates the azimuthal asymmetry of a hadron originating from the fragmentation of a transversely polarized quark

Collins asymmetry for π^\pm in jets



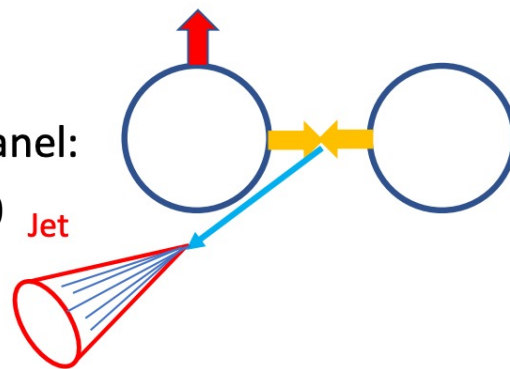
Top panel:

$$x^F > 0$$



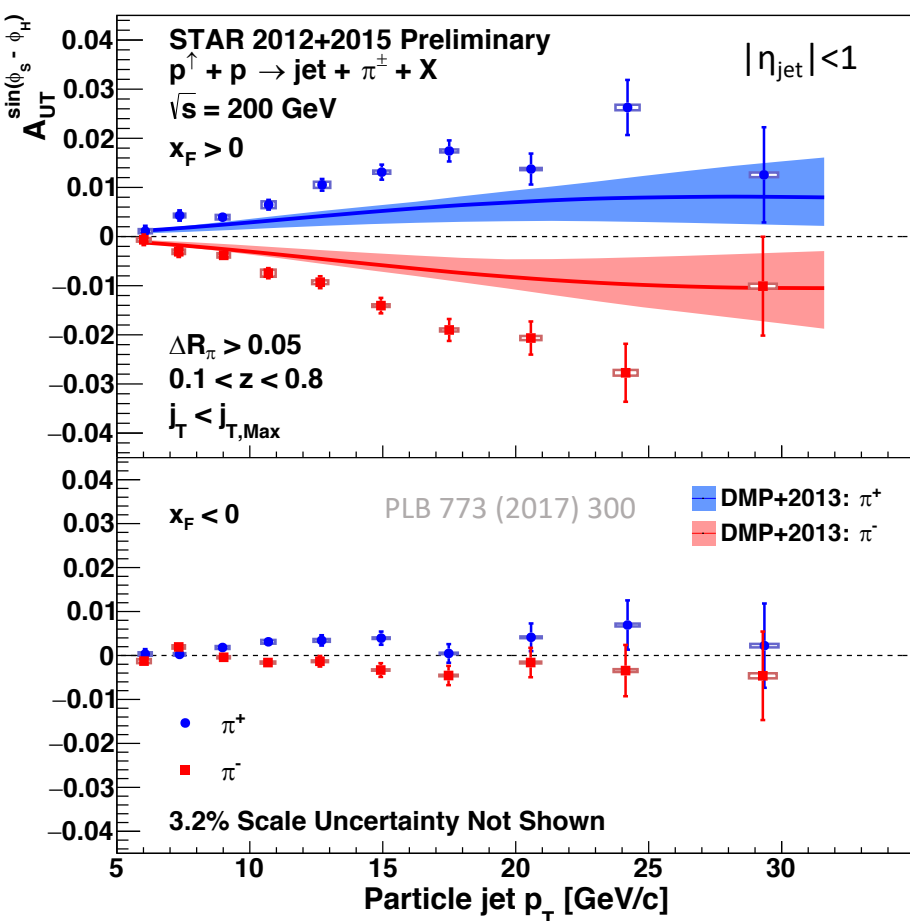
Bottom panel:

$$x^F < 0$$



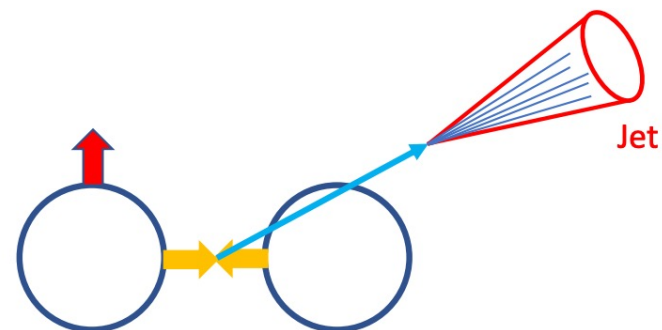
- Collins asymmetries of π^\pm are measured
- Consistent results from 2012 and 2015 data; improved uncertainties using 2015 data

Collins asymmetry for π^\pm in jets



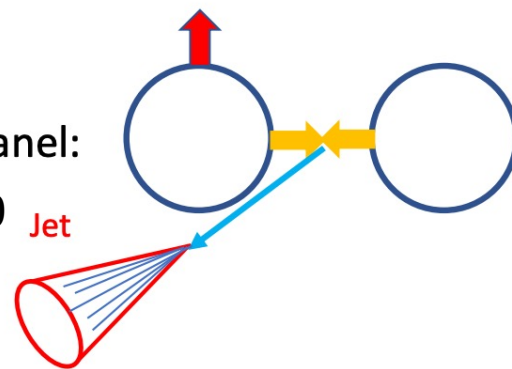
Top panel:

$$x^F > 0$$



Bottom panel:

$$x^F < 0$$



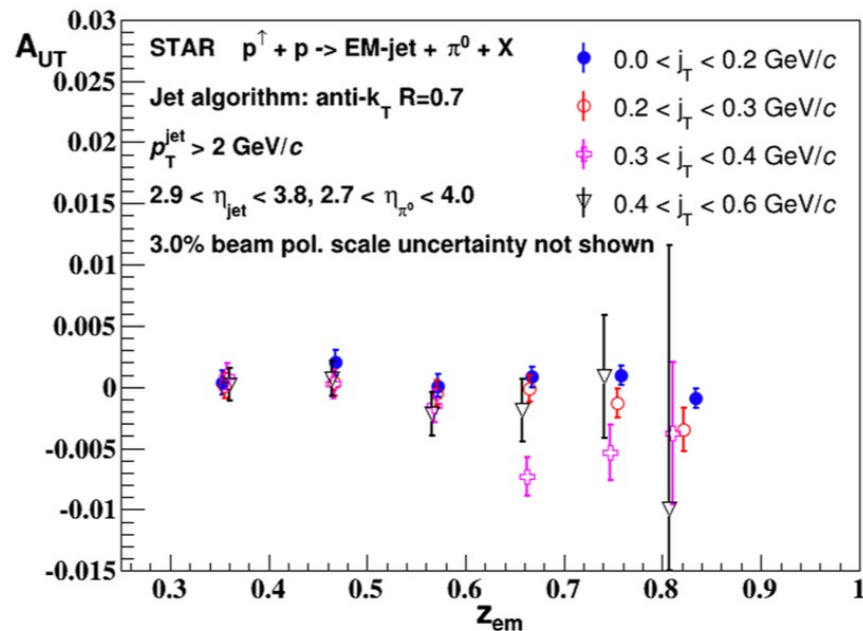
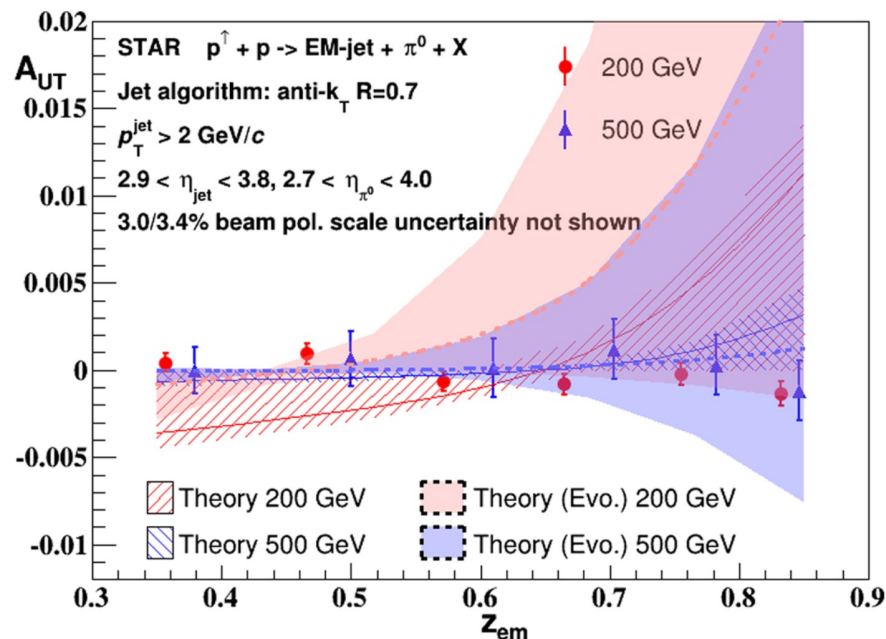
- Collins asymmetries of π^\pm are measured
- Combined results will help constrain theoretical calculations

Collins asymmetry for π^0 in jets

Newly published results!

Forward π^0 : $2.7 < \eta < 4.0$

STAR, PRD 103 (2021) 092009



$$z_{em} = \frac{E_{\pi^0}}{E_{jet}}, \text{ EM-jet reconstructed only by photons and electrons}$$

j_T is E_{π^0} projection perpendicular to jet axis

Cancellation of the Collins effect of the u/d quark; weak j_T dependence is observed

Summary

STAR longitudinal program is completed (Run 2013 A_{LL} publication in preparation)

- Di-jet A_{LL} : test the sensitivity of Δg in selected x region
- Higher \sqrt{s} and more forward rapidity: access to smaller x region

Measurements of TSSA using transversely polarized data probe the transverse spin structure of the proton

- A_N for W and Z boson \rightarrow precise measurement to investigate Sivers effect
- Collins asymmetry for π^\pm and $\pi^0 \rightarrow$ transversity of the proton and TMD fragmentation

Papers published recently: STAR, PRD 103 (2021) L091103; STAR, PRD 103 (2021) 072005; STAR, PRD 103 (2021) 092009

New released results: A_N of W and Z

Results below, not covered by this talk, will be presented by T. Lin:

Scientific goals	Observable	Dataset
Di-jet Sivers effect	Intrinsic k_T of parton	Transversely polarized pp
Non-linear gluon dynamics in nuclei	Forward di-hadron correlation	Unpolarized pp and pA
Sea quark distributions	W^+ / W^- cross-section ratio	Unpolarized pp

(see T. Lin's talk in the next session)