Recent Highlights from the STAR Cold-QCD Physics Program

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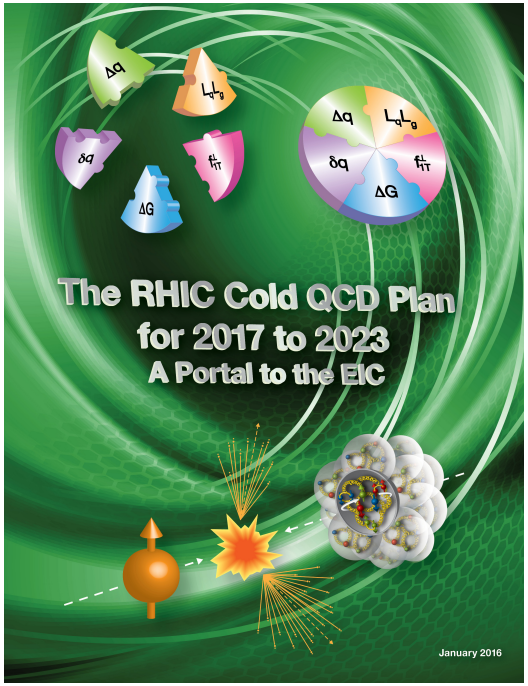
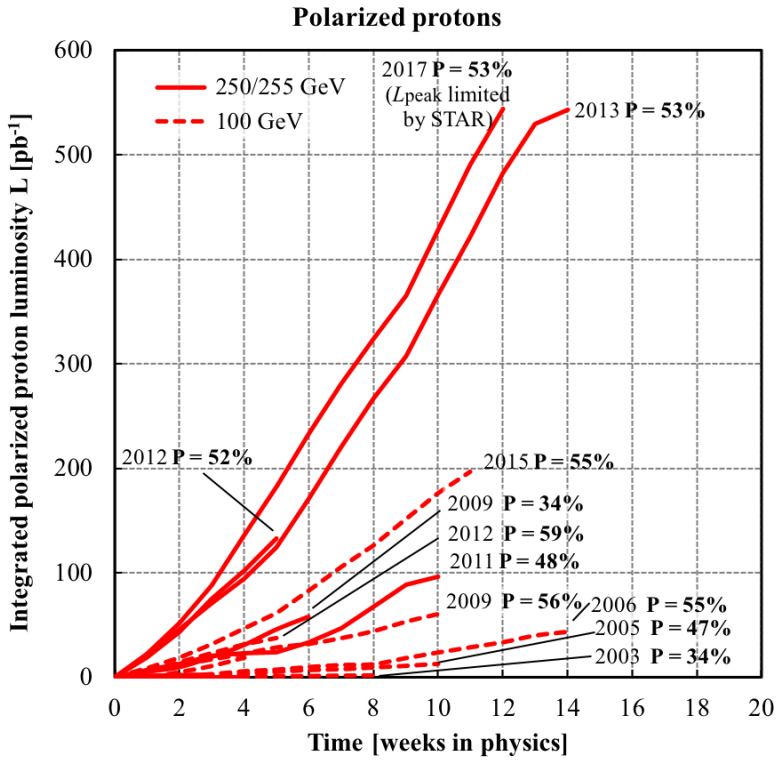
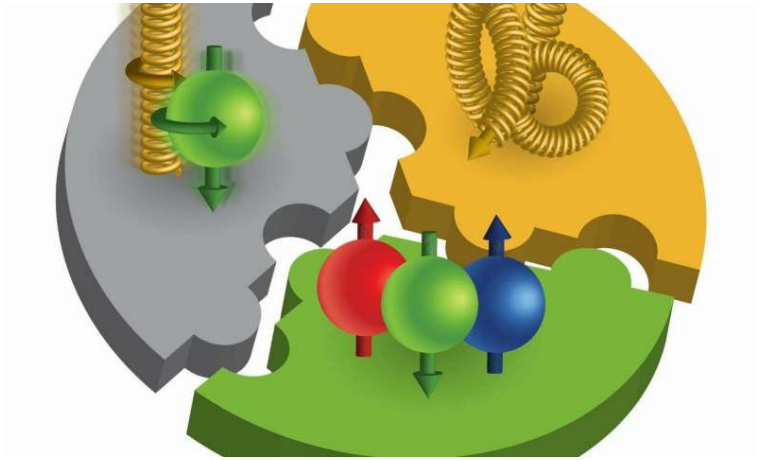
Introduction

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

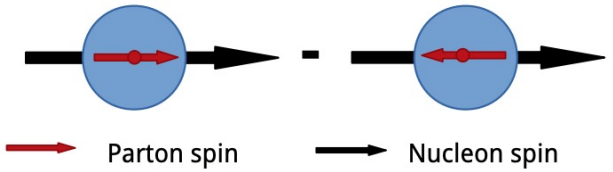
Proton spin (Jaffe-Manohar sum rule)

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

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

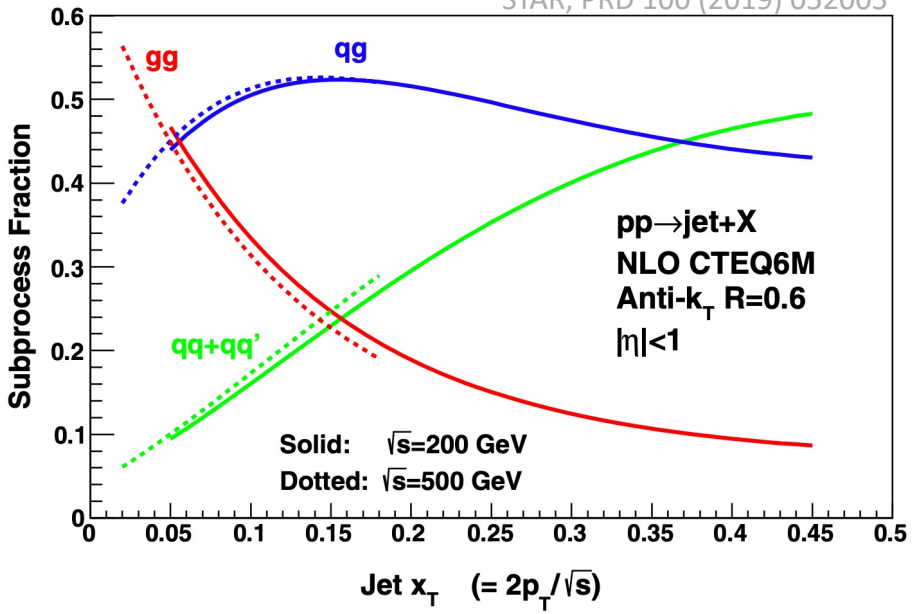
$$\Delta G = \int_0^1 \Delta g(x, Q^2) dx$$

Measurements



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

STAR, PRD 100 (2019) 052005

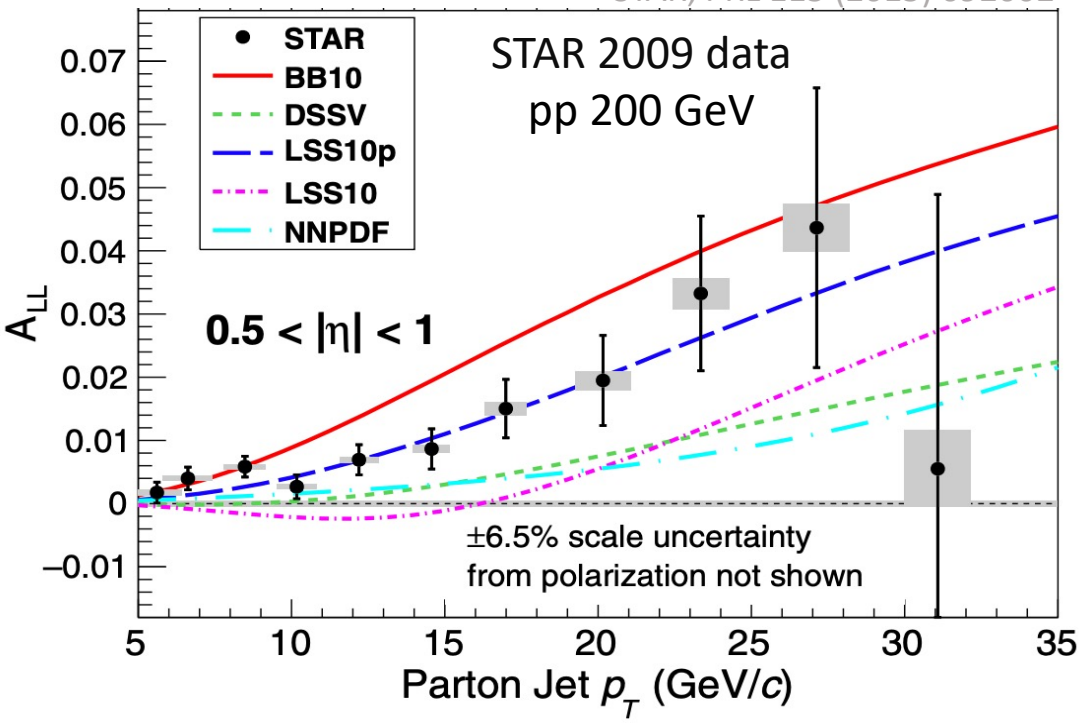


How to access ΔG at RHIC?

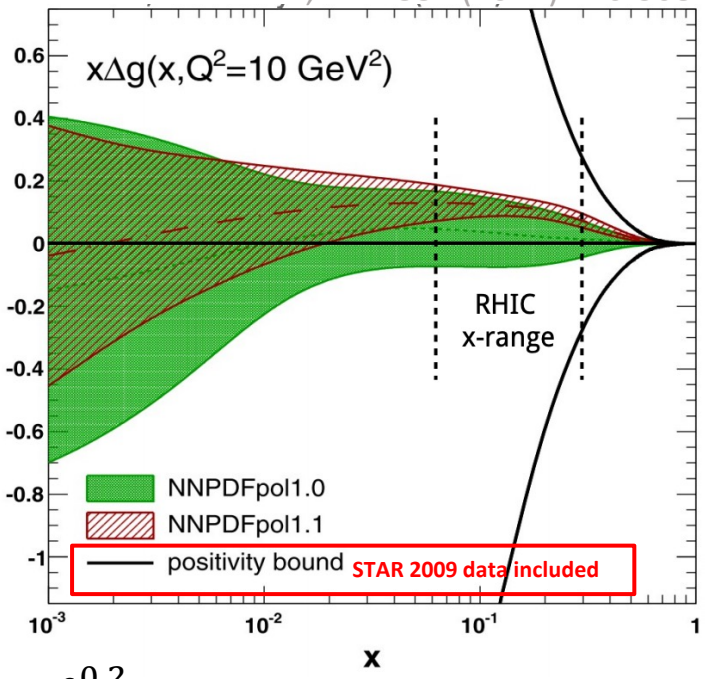
- Midrapidity jet production at RHIC is dominated by qg and gg scatterings at low x_T
- The qg and gg scattering cross sections are sensitive to the helicities of the gluon

Evidence of positive ΔG

STAR, PRL 115 (2015) 092002



NNPDF, NPB 887 (2014) 276-308



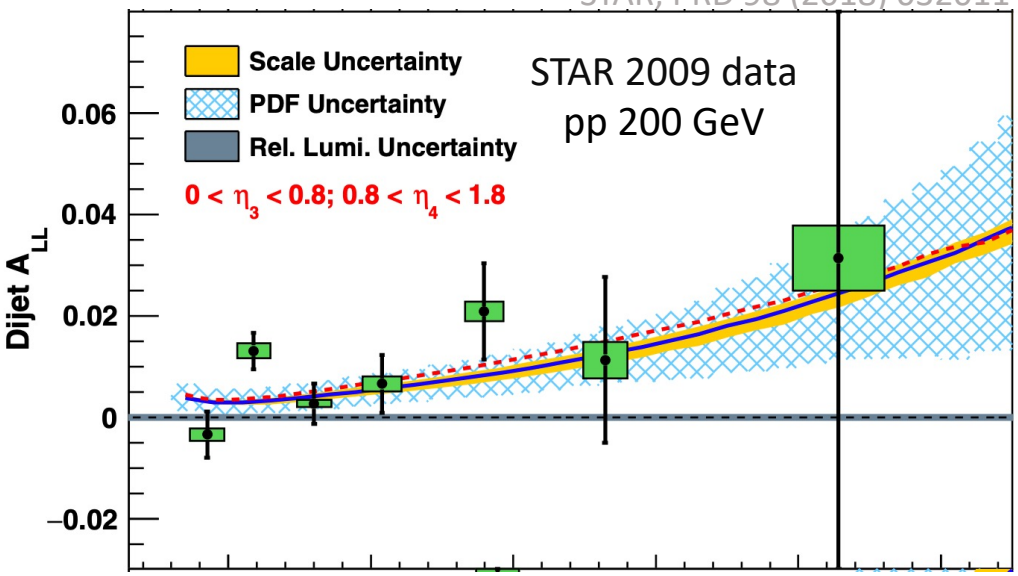
$$\int_{0.05}^{0.2} \Delta g(x, Q^2) dx = 0.17 \pm 0.6$$

at Q^2=10 GeV^2

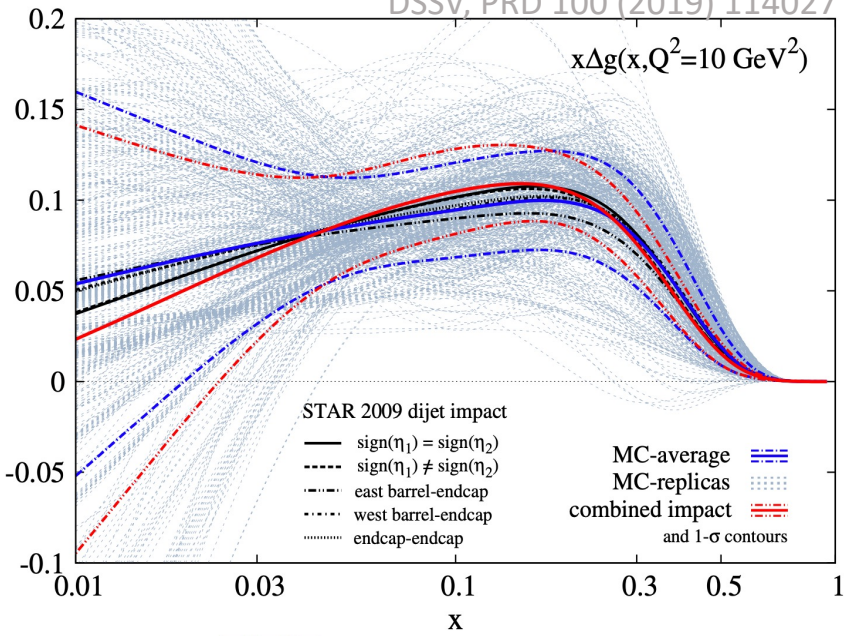
- Evidence of positive gluon polarization at 0.05 < x < 0.2
- These data are included in NNPDF and DSSV fits: help constrain gluon polarization at intermediate x

Impact of di-jet data

STAR, PRD 98 (2018) 032011



DSSV, PRD 100 (2019) 114027



STAR data not included

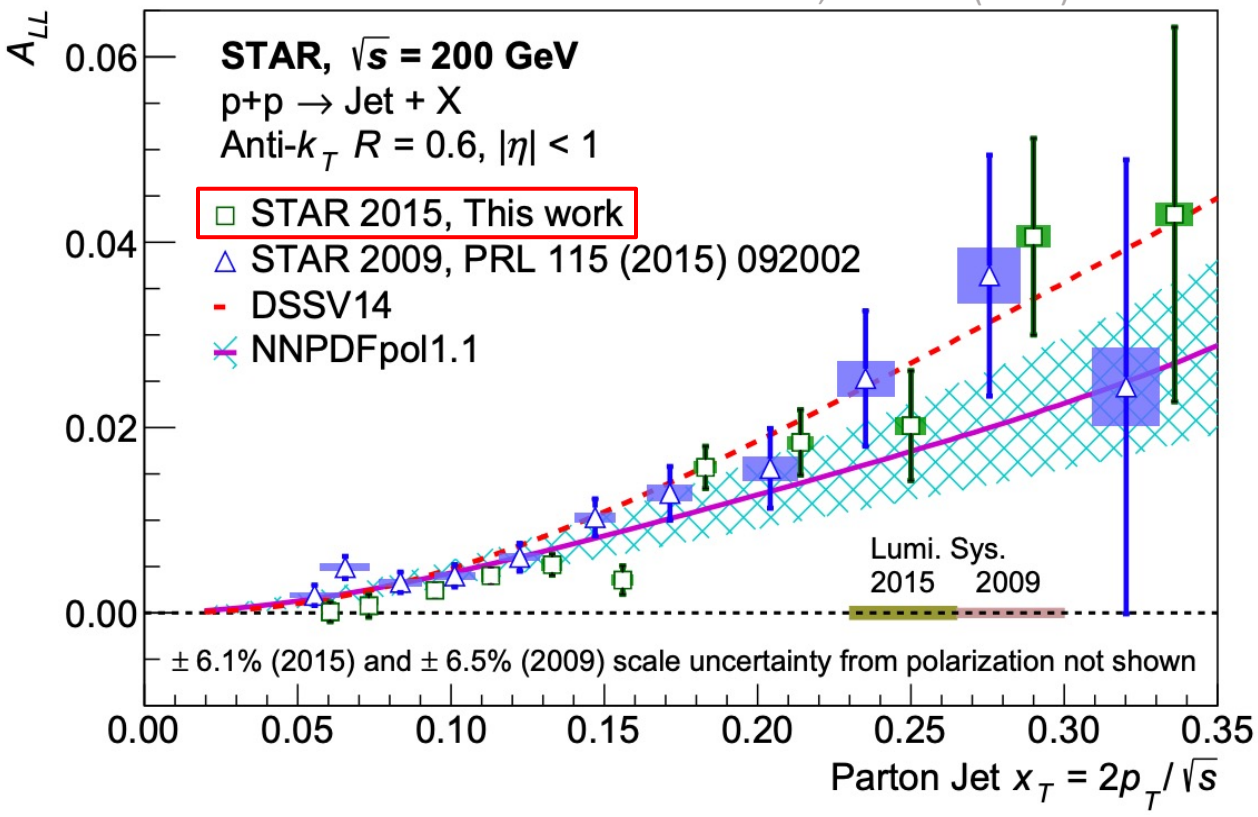
STAR data included

- 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!

STAR, PRD 103 (2021) L091103

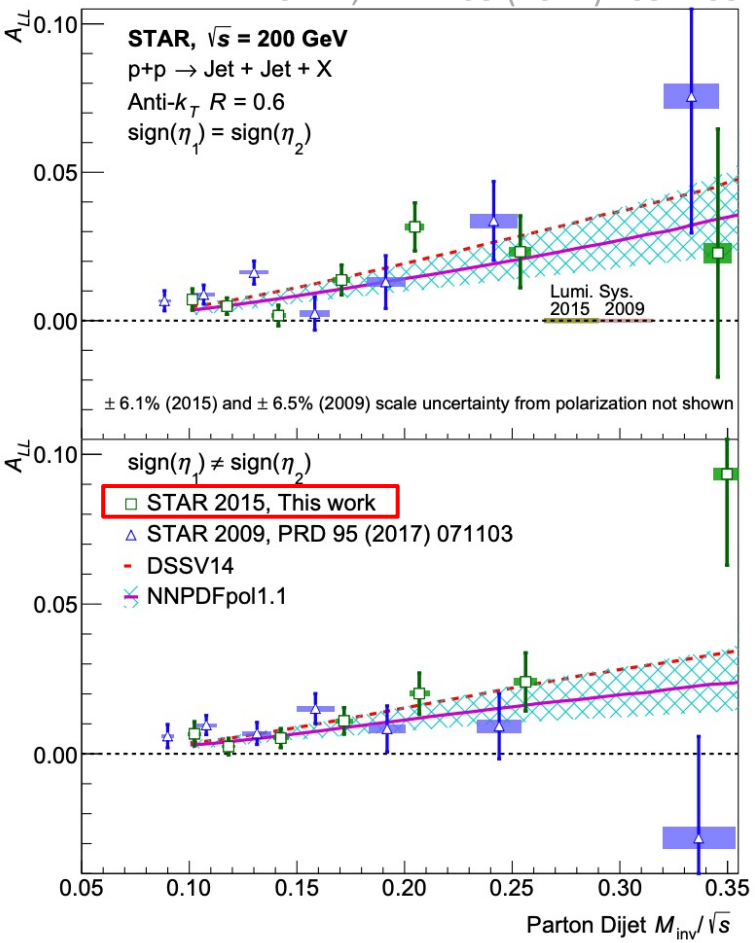


- Largest 200 GeV longitudinally polarized pp dataset; improved both statistical and systematic uncertainties
- This result can reduce the uncertainty of gluon polarization for $x_T > 0.05$ if included in global fits

Di-jet A_{LL} at 200 GeV

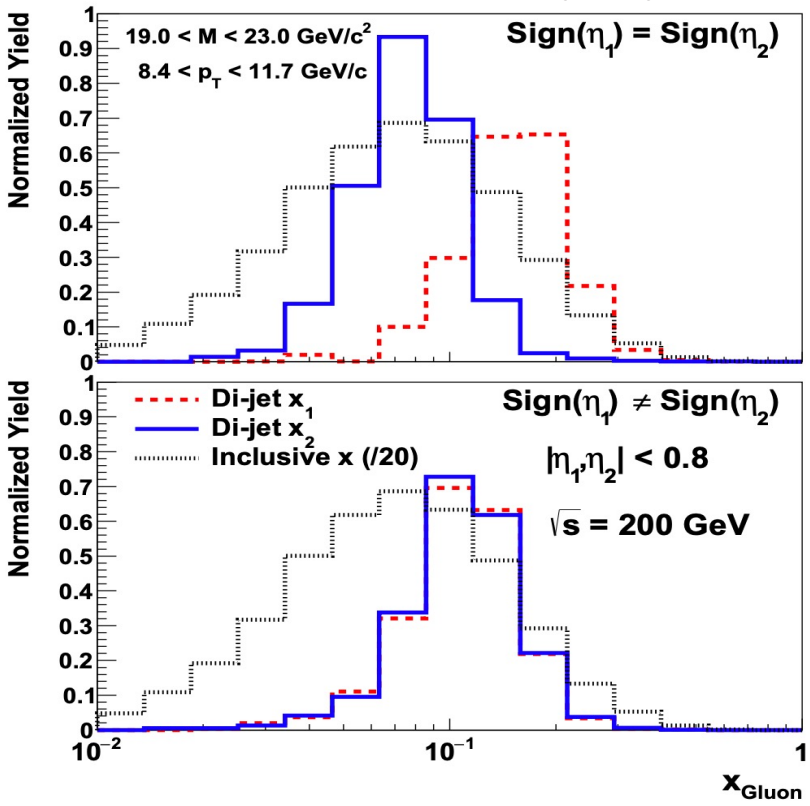
Newly published results!

STAR, PRD 103 (2021) L091103



Two different η topology bins

STAR, PRD 95 (2017) 071103

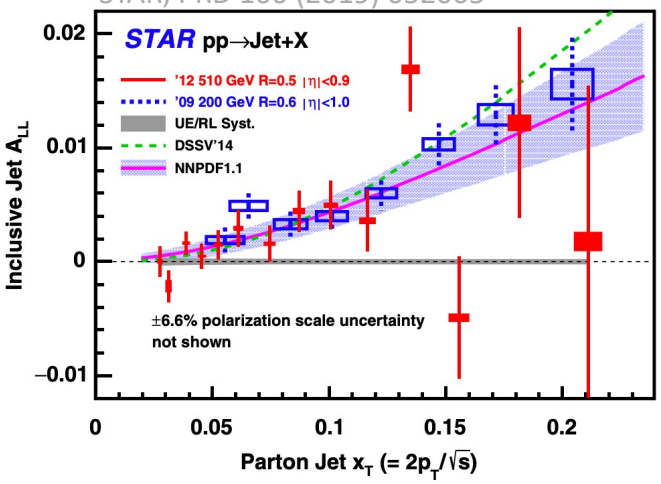


$$x_1 = \frac{p_{T1e^{\eta 1}} + p_{T2e^{\eta 2}}}{\sqrt{s}}; x_2 = \frac{p_{T1e^{-\eta 1}} + p_{T2e^{-\eta 2}}}{\sqrt{s}}$$

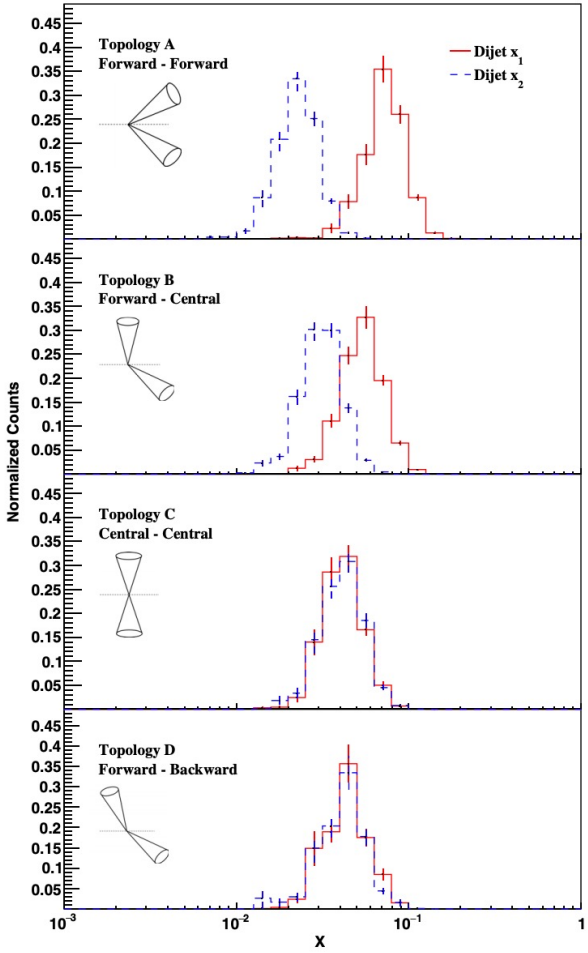
Di-jets: Much narrower ranges of initial state partonic momentum fraction tested; different topologies enhance sensitivity of the data to selected x;

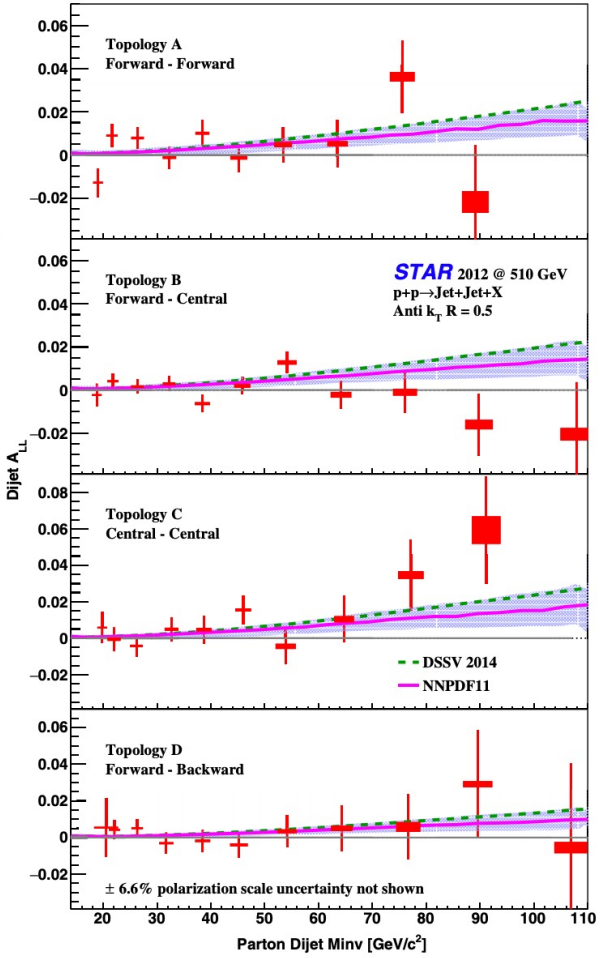
Inclusive jets and di-jets A_{LL} at 510 GeV

STAR, PRD 100 (2019) 052005



Four different η topology bins





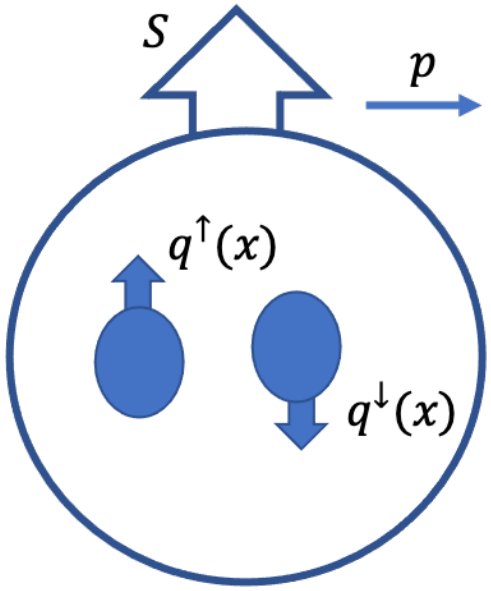
Measurement of jet and di-jet A_{LL} at 510 GeV with 2012 data:

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

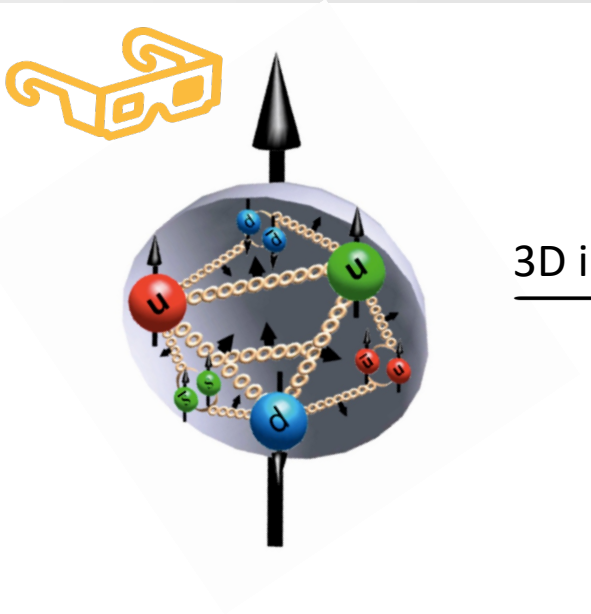
$|\cos\theta^*| = \tanh(|\eta_1 - \eta_2|)/2$

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

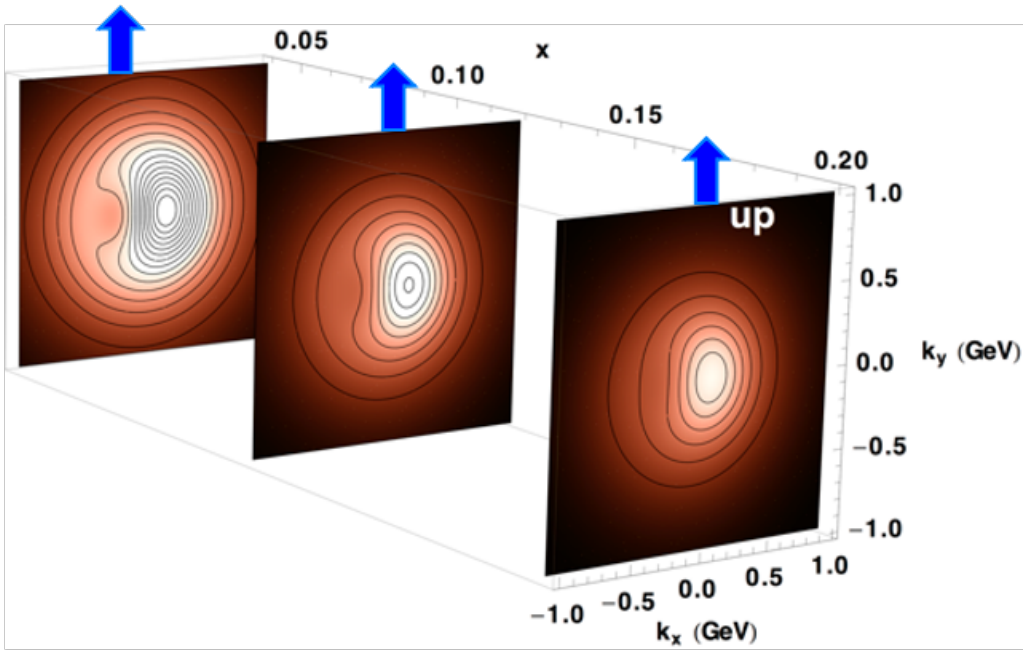
Transversely polarized Beam: Proton 3D Structure



Transverse structure of the proton



3D image

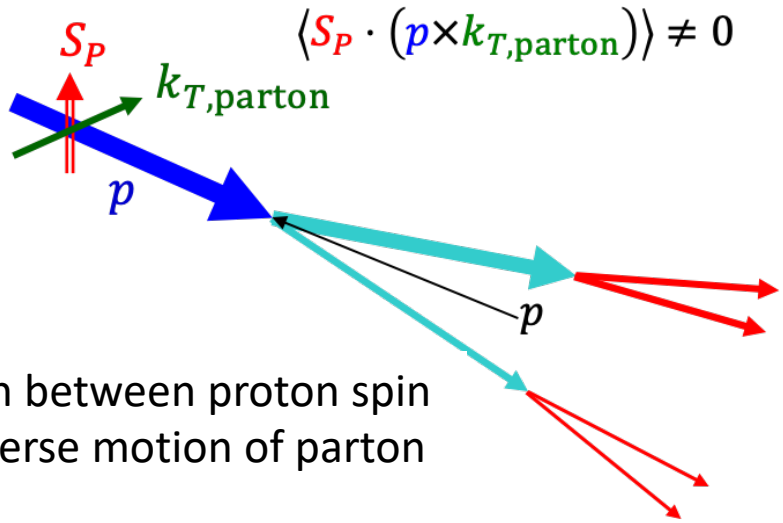


- Transverse momentum dependent PDFs (TMDs, f (x , k_T)) → 3D structure of the proton
- Access to two types of TMDs
  - Initial state effect from PDFs → **Sivers function**
  - Final state effect from fragmentation → **Collins function**
- Measurement: Transverse single spin asymmetry (TSSA)

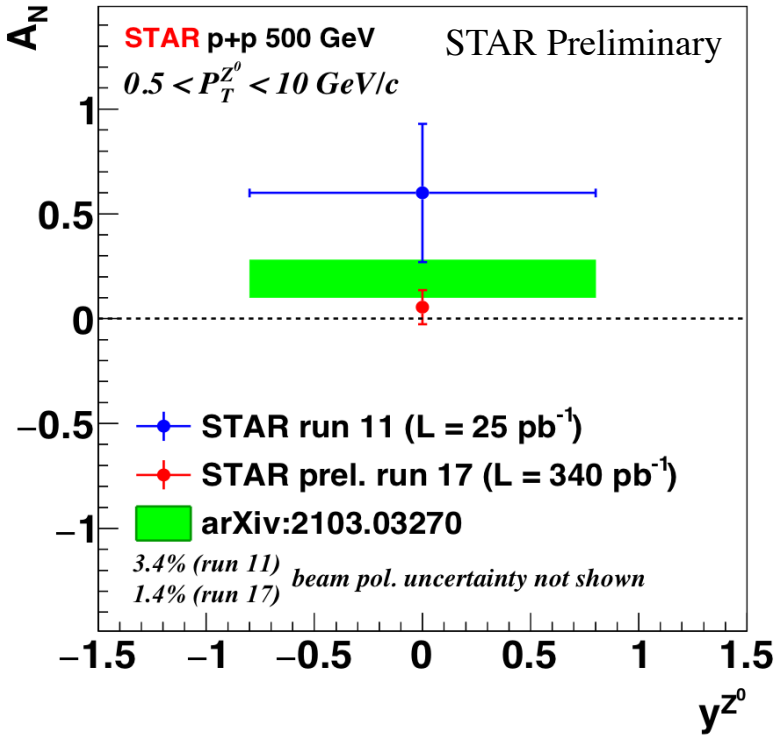
$$A_N = \frac{d\sigma^{\uparrow} - d\sigma^{\downarrow}}{d\sigma^{\uparrow} + d\sigma^{\downarrow}}$$

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

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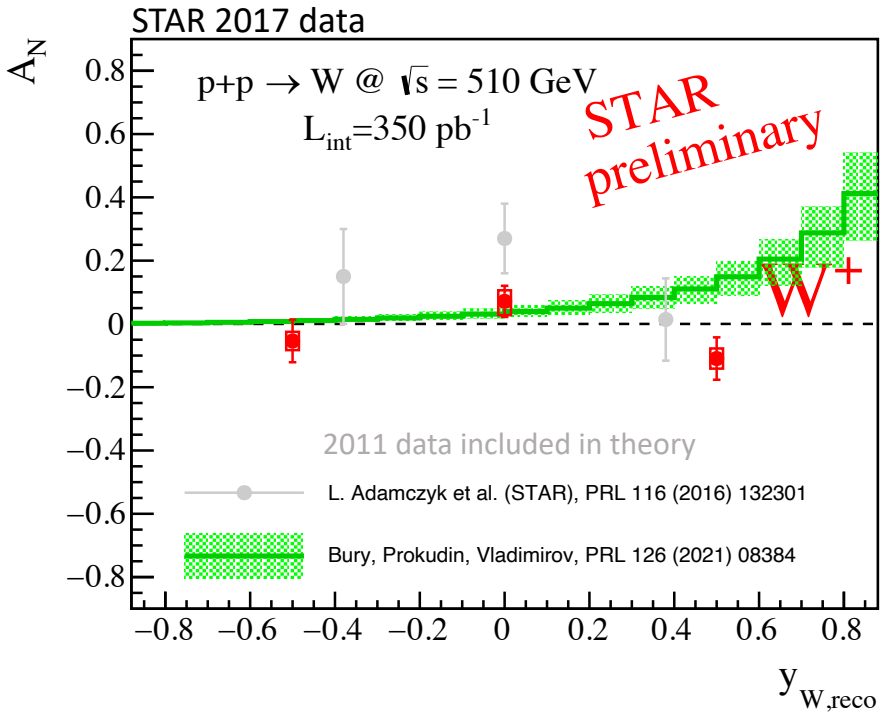

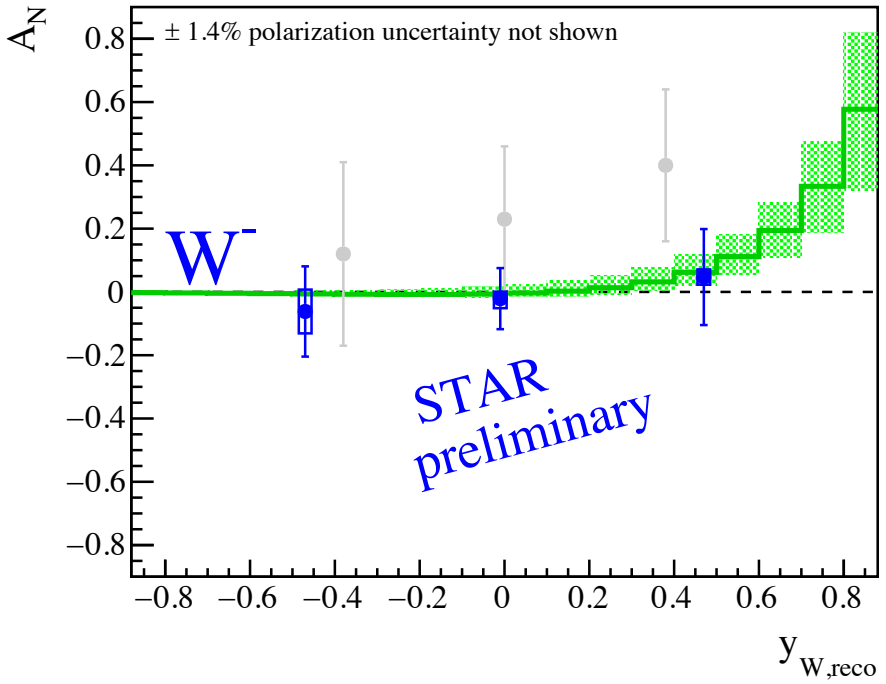

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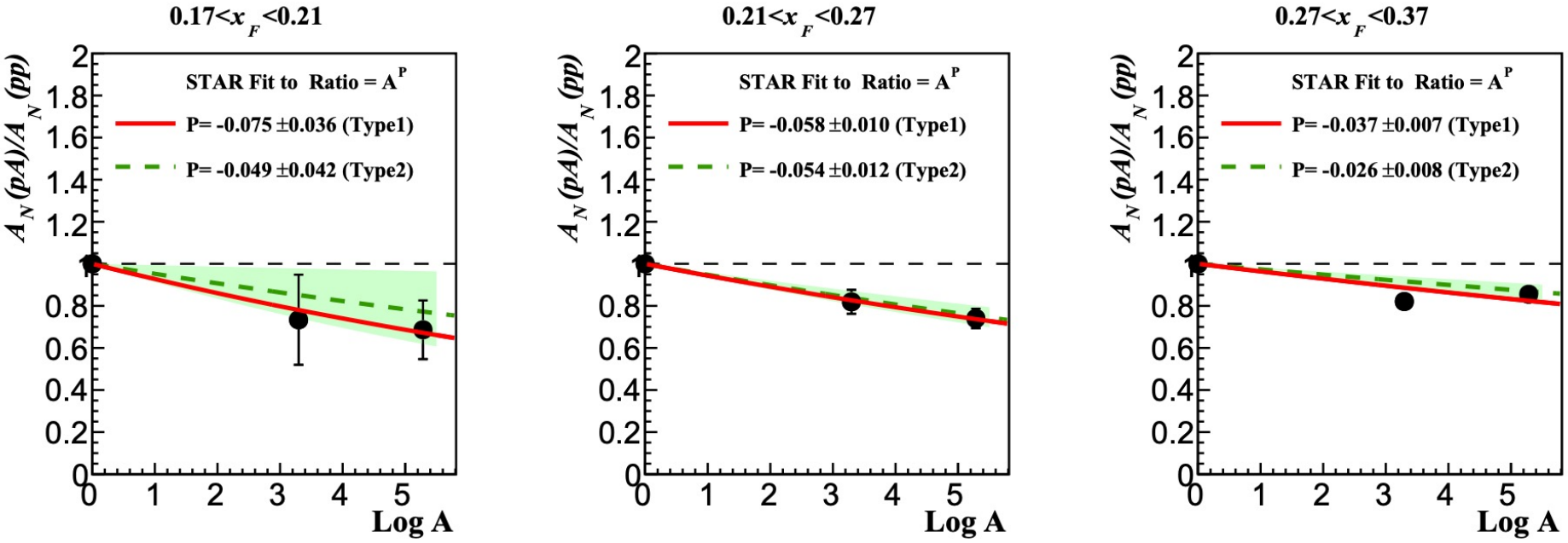
A dependence of π^0 A_N

STAR, PRD103 (2021) 072005



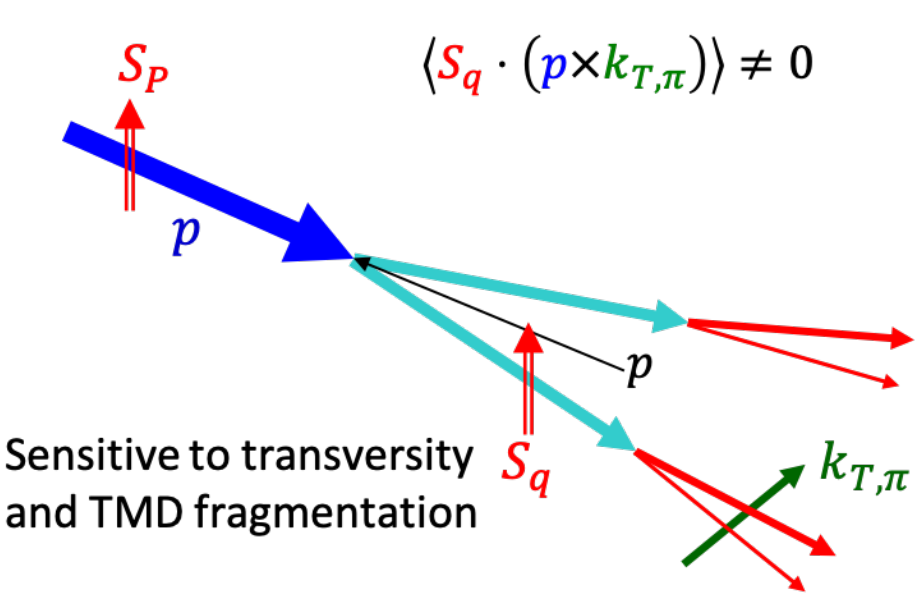
Type1: correlated uncertainties in the ratio; Type2: without correlated uncertainties

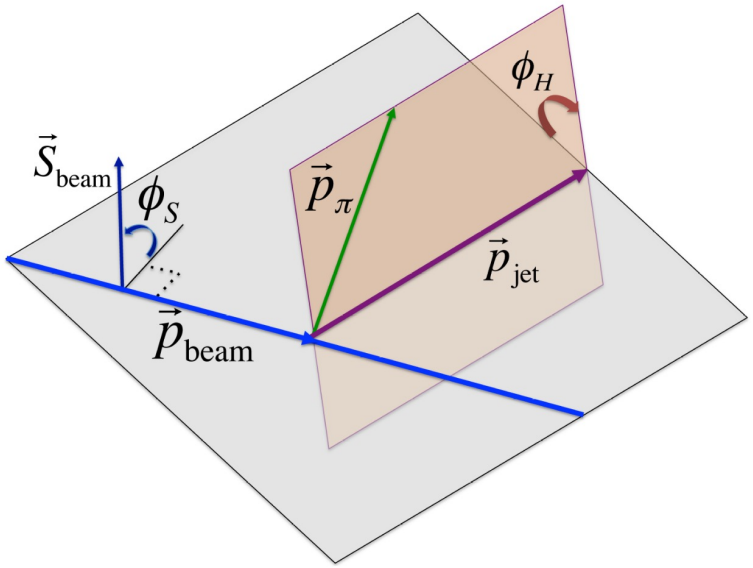
$$x^F = \frac{E_L^{\pi^0}}{E^{beam}}$$

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 logA in each x_F bin are measured
- Suppression of A_N in pA to A_N in pp collisions is observed

Collins asymmetry



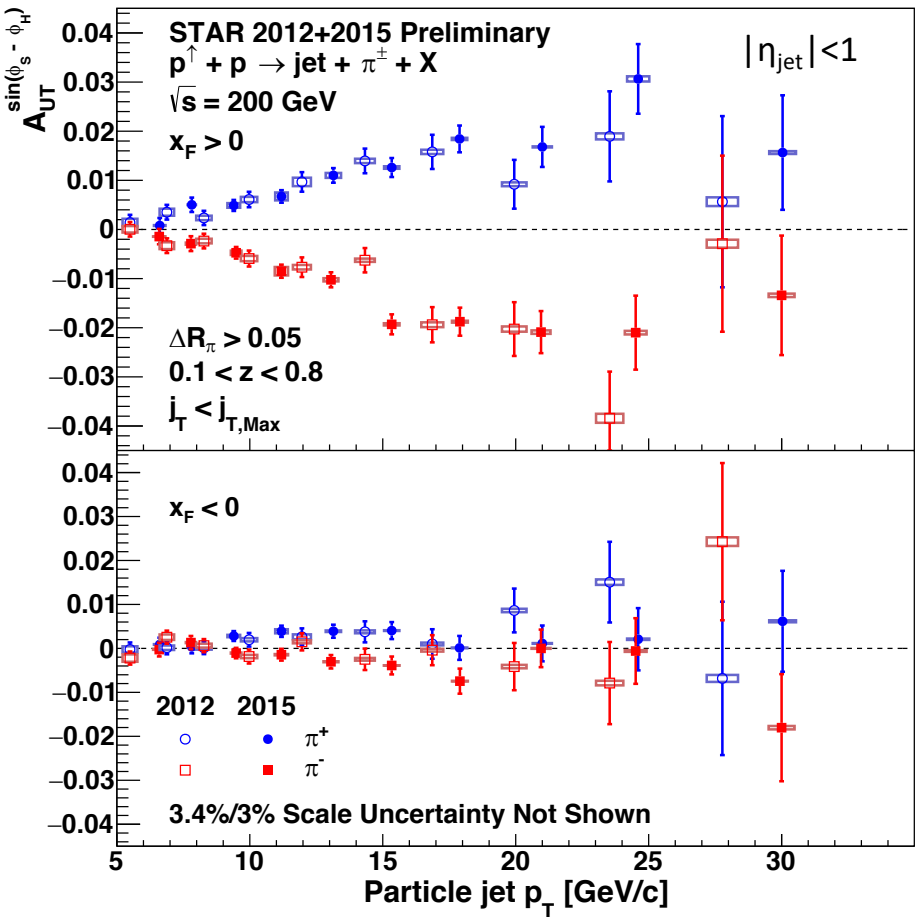


$$A_{UT}^{\sin(\phi)} \sin(\phi) = \frac{\sigma^{\uparrow}(\phi) - \sigma^{\downarrow}(\phi)}{\sigma^{\uparrow}(\phi) + \sigma^{\downarrow}(\phi)}$$

$$\phi = \phi^s - \phi^H$$

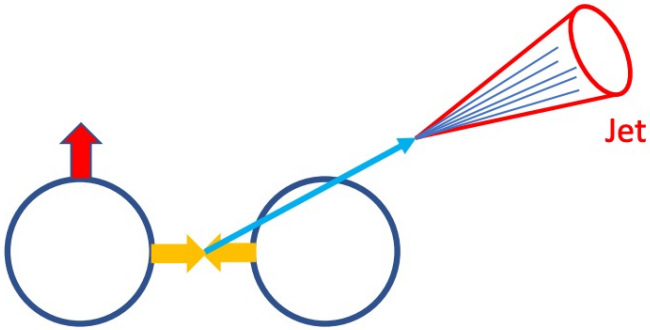
Collins asymmetry indicates the azimuthal asymmetry of a hadron originating from the fragmentation of a transversely polarized quark

Collins asymmetry for $\pi^{\pm}$ in jets



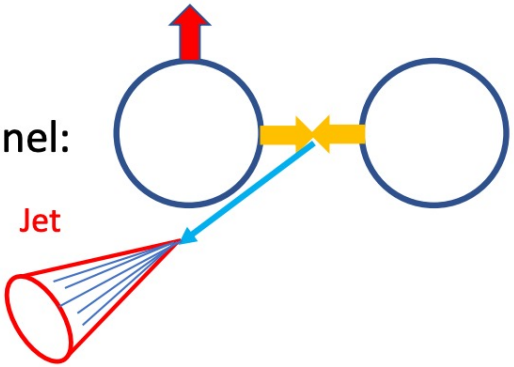
Top panel:

$x^F > 0$



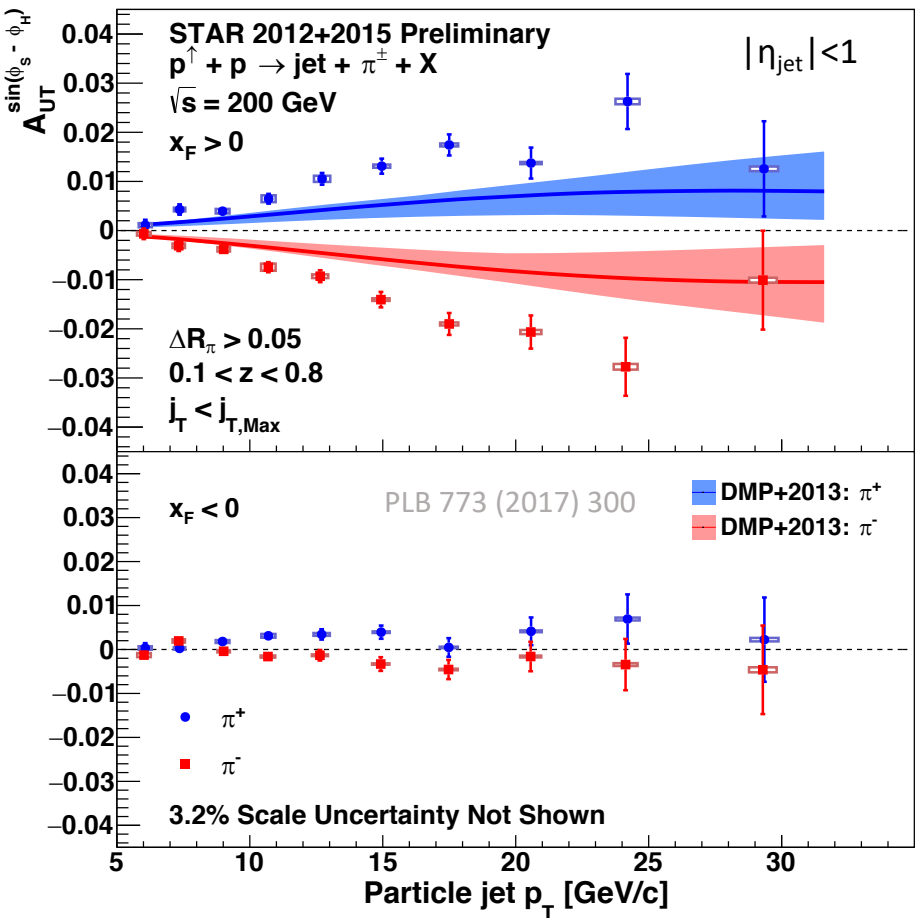
Bottom panel:

$x^F < 0$



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

Collins asymmetry for $\pi^{\pm}$ in jets



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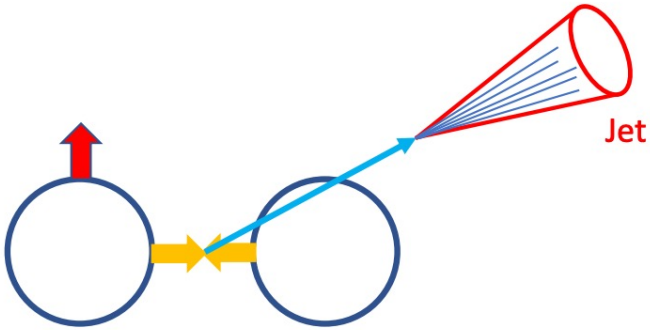

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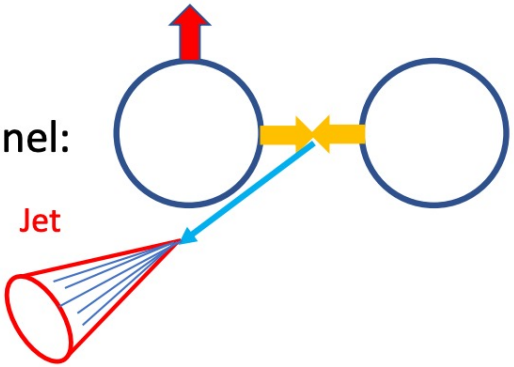


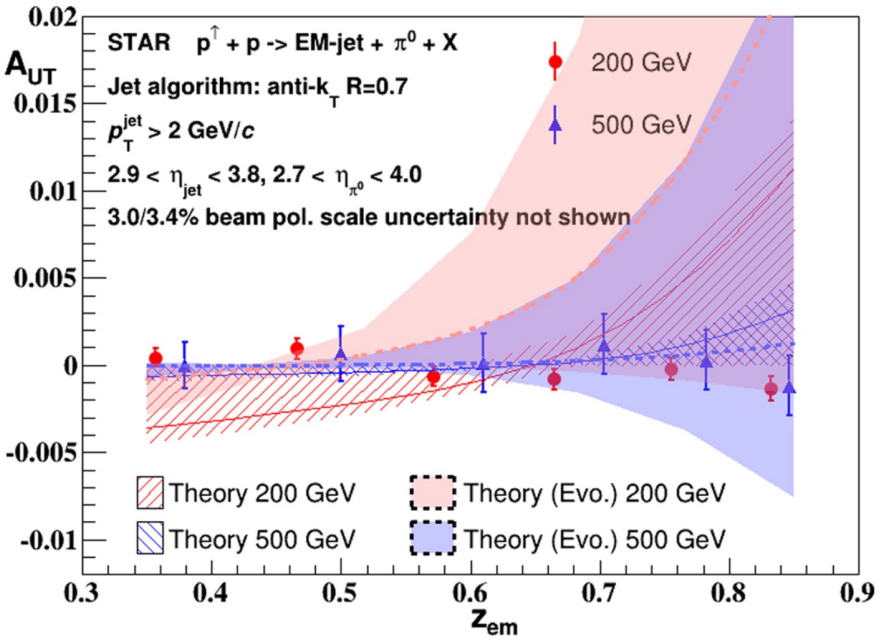
- Collins asymmetries of $\pi^{\pm}$ are measured
- Combined results will help constrain theoretical calculations

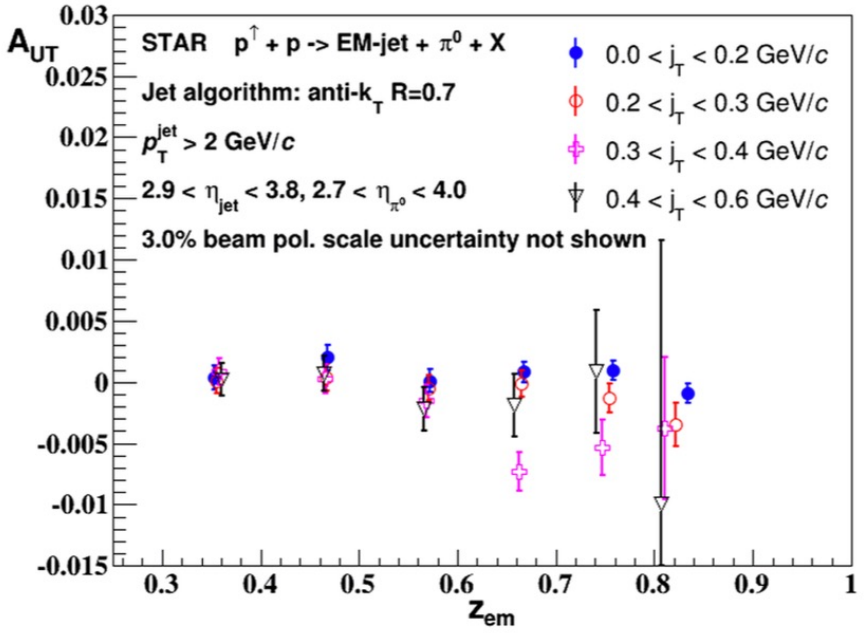
Collins asymmetry for π^0 in jets

Newly published results!

Forward π^0: $2.7 < \eta < 4.0$

STAR, PRD 103 (2021) 092009





$z_{em} = \frac{E_{\pi^0}}{E_{jet}}$, 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 √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 → precise measurement to investigate Sivers effect
- Collins asymmetry for $\pi^{\pm}$ and π^0 → 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)