Recent Results from the STAR Spin Program

Kenneth N. Barish

for the

STAR Collaboration

8th International Conference on Quarks and Nuclear Physics, November 2018 (QNP2018)

UNIVERSITY OF CALIFORNIA UCRIVERSIDE

The Proton Spin Structure (p+p)

Polarization experiments

- **Longitudinal Spin**
  - Gluon polarization
  - Sea quark polarization
  - Longitudinal Spin Transfer
- **Transverse Spin**
  - Sivers effect
  - Collins effect
  - Transversity
  - Transverse Spin Transfer

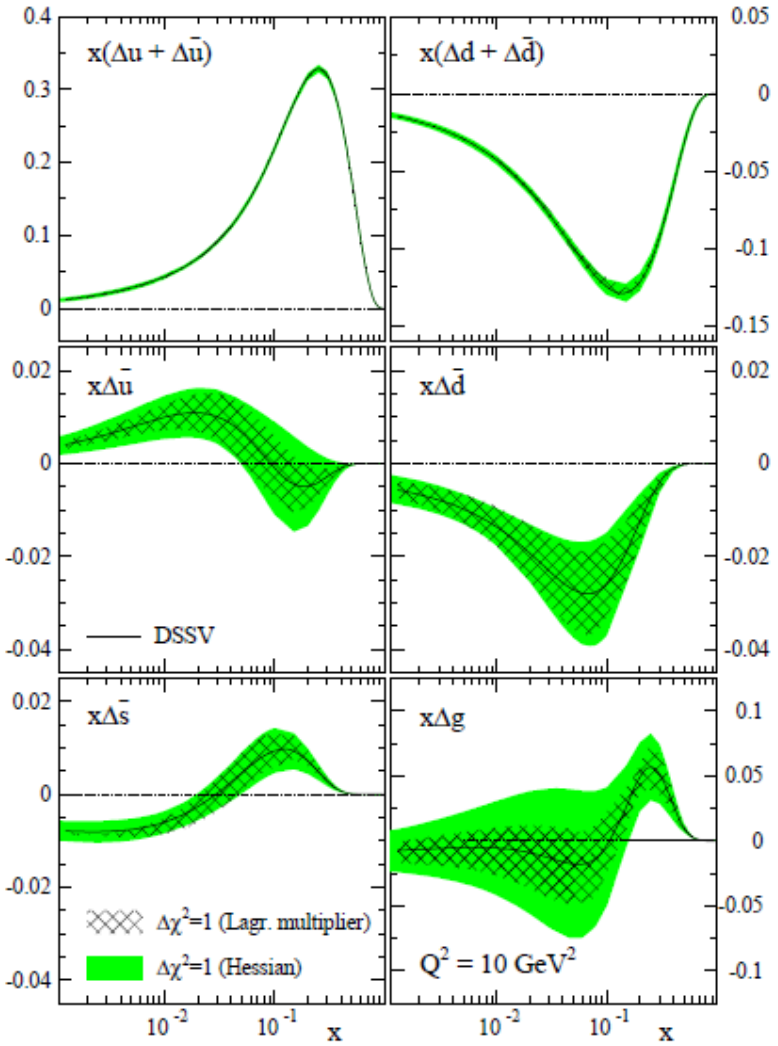
Forward Upgrade

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L$$

gluon spin

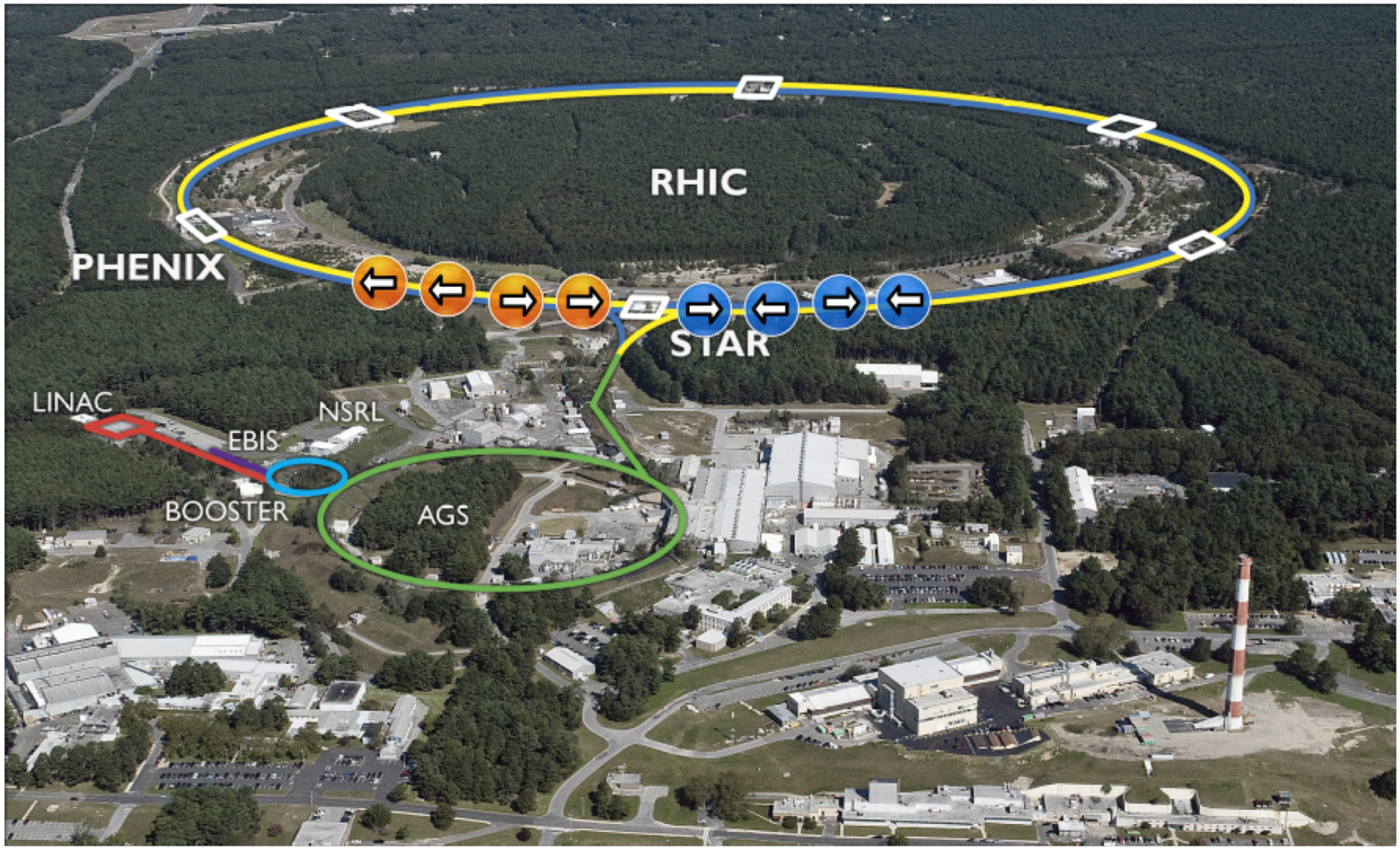
$\frac{1}{2}\Delta\Sigma$: valence + sea quark spin

L: quark & gluon orbital motion



DSSV: PRD80 034030,2009

Relativistic Heavy Ion Collider (RHIC)



Brookhaven National Laboratory
Long Island, NY

- World's **only** polarized synchrotron collider
- Spin state known for **every** proton bunch
- Longitudinally polarized collisions achieved with **Spin Rotators**

Solenoid Tracker at RHIC (STAR)

Forward Rapidity

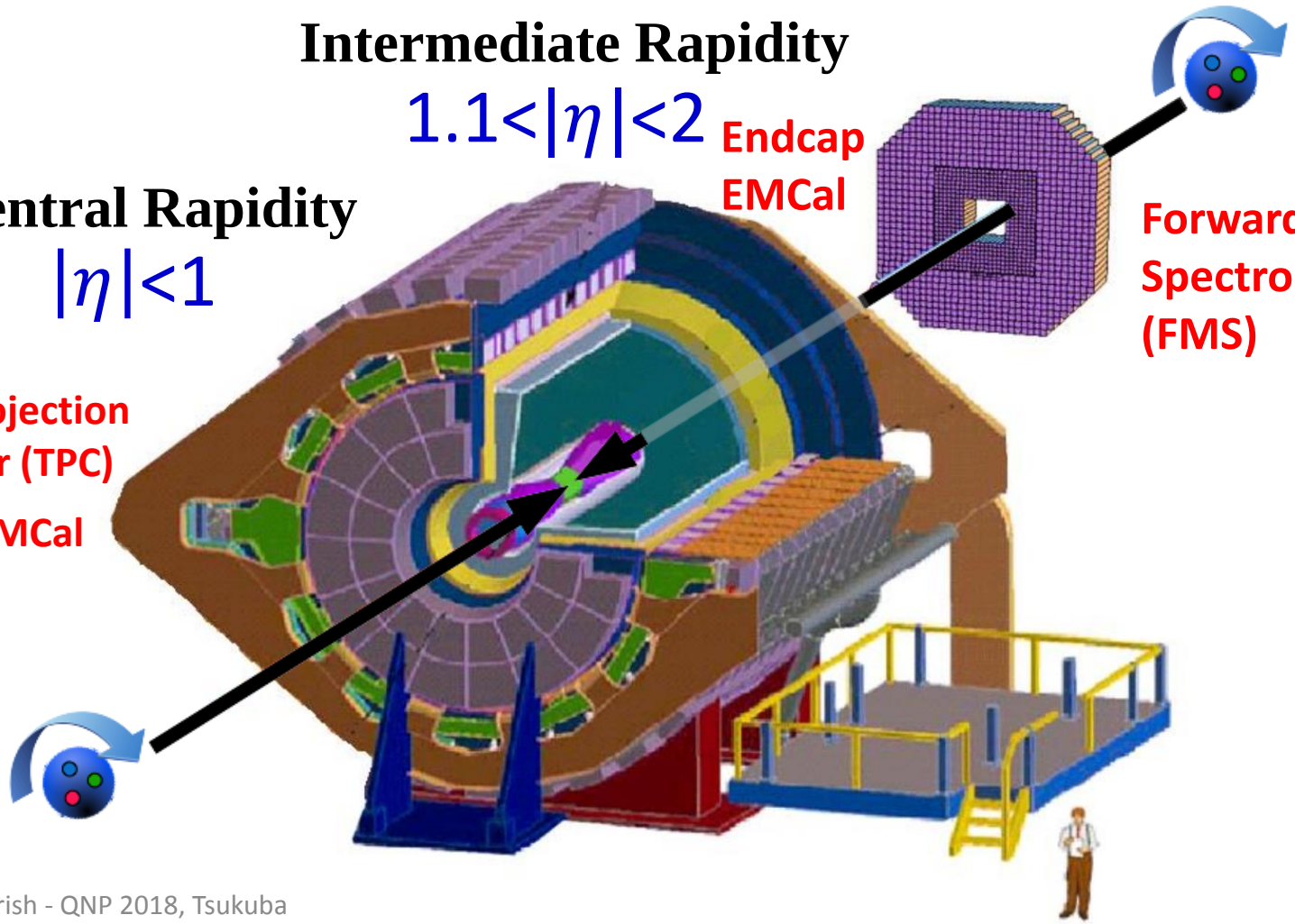
$2.65<|\eta|<3.9$

Intermediate Rapidity

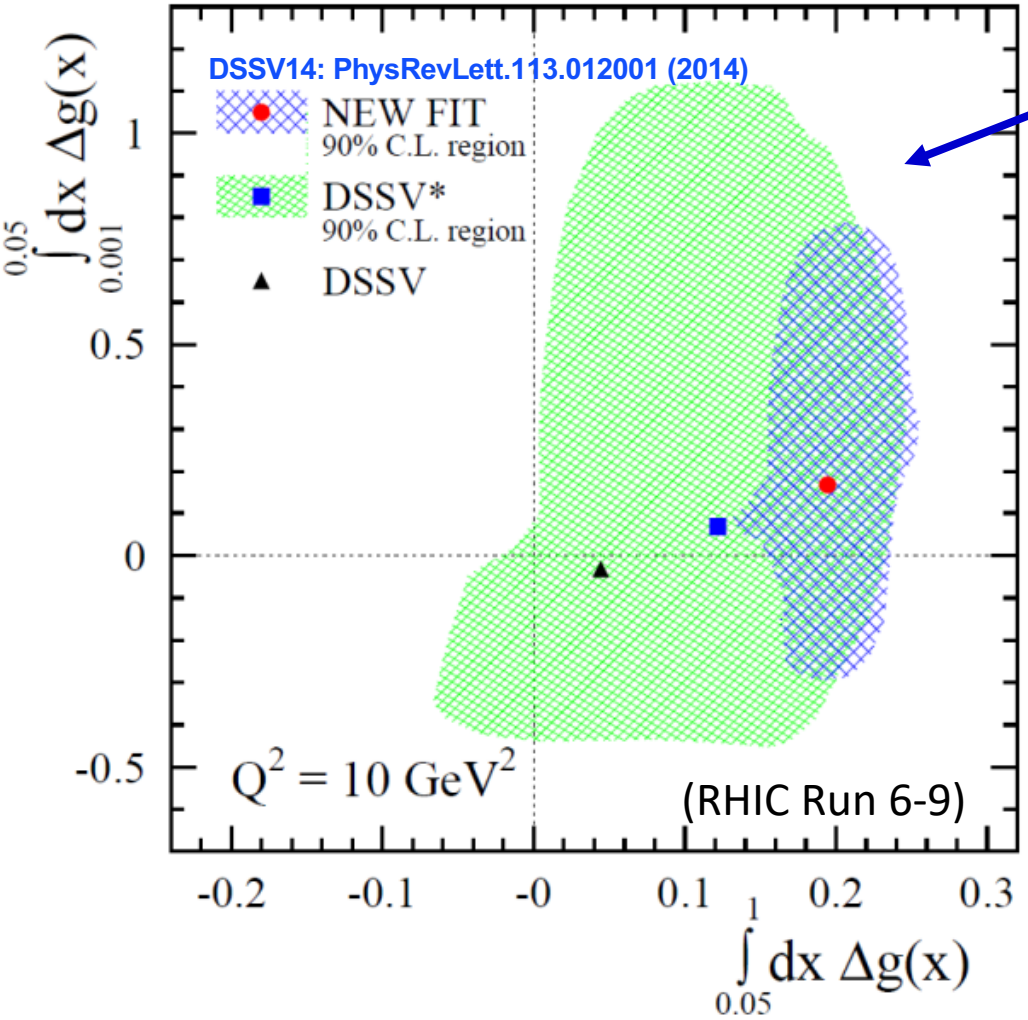
$1.1<|\eta|<2$

Central Rapidity

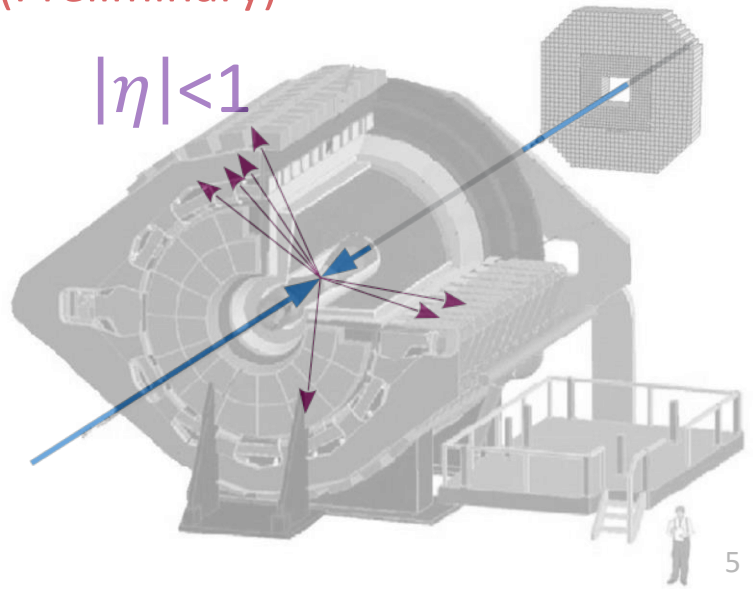
$|\eta|<1$



Gluon Polarization (Central Rapidity)

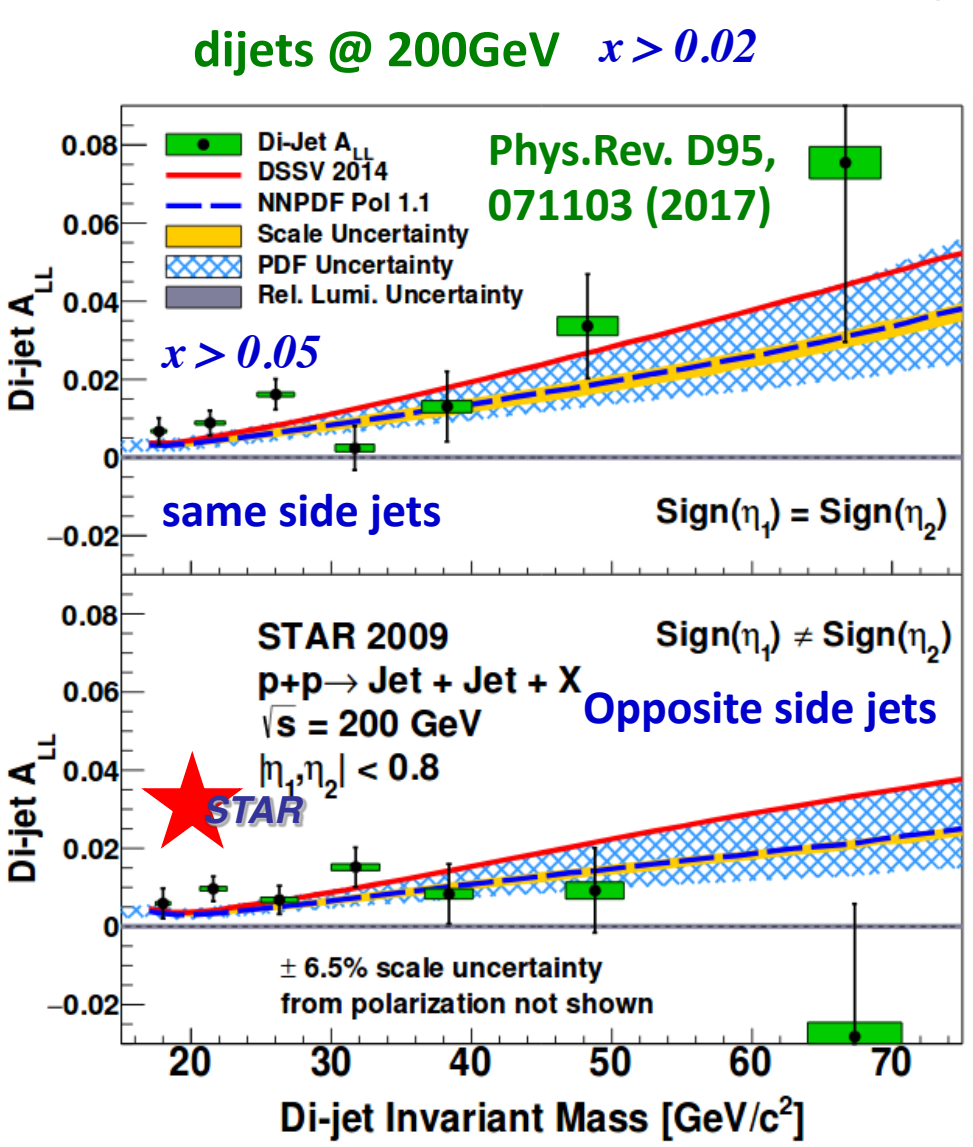


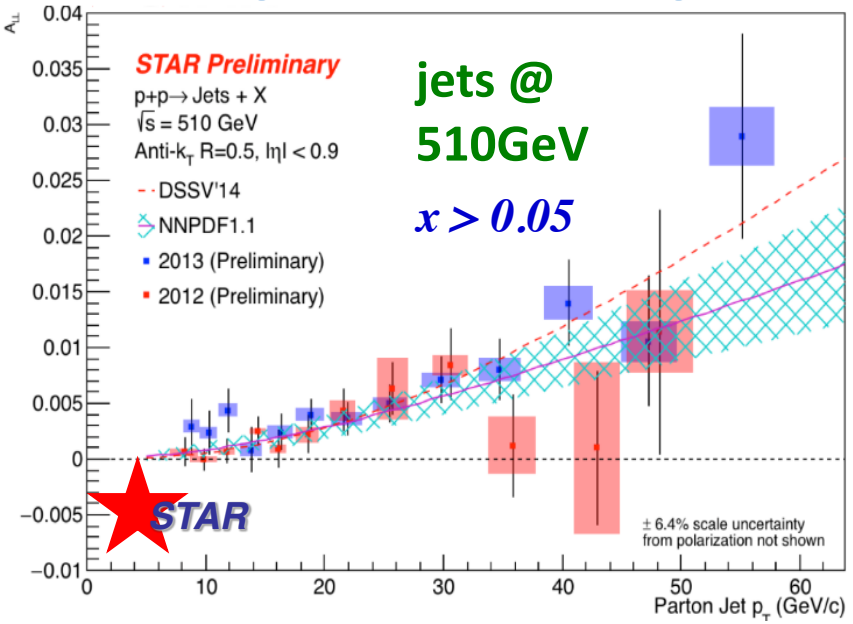
- **Jets at 200 GeV in 2009**
  Phys.Rev.Lett. 115, 092002 (2015).
  ($x > 0.05$)
- **Jets at 510 GeV in 2012 and 2013**
  Int.J.Mod.Phys.Conf.Ser. 40, 1660021 (2016) (Preliminary)
- **Dijets at 200 GeV in 2009**
  Phys.Rev. D95, 071103 (2017)
- **Dijets at 510 GeV in 2012 and 2013**
  (Preliminary)

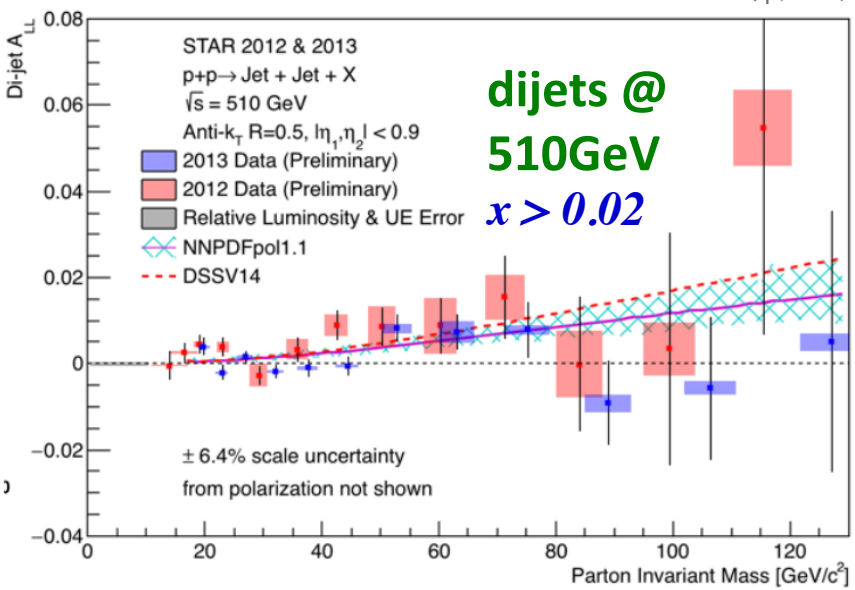


$\int_{0.05}^{1} dx\ \Delta g(x) = 0.20\ ^{+0.06}_{-0.07}$ at 90 % C.L.

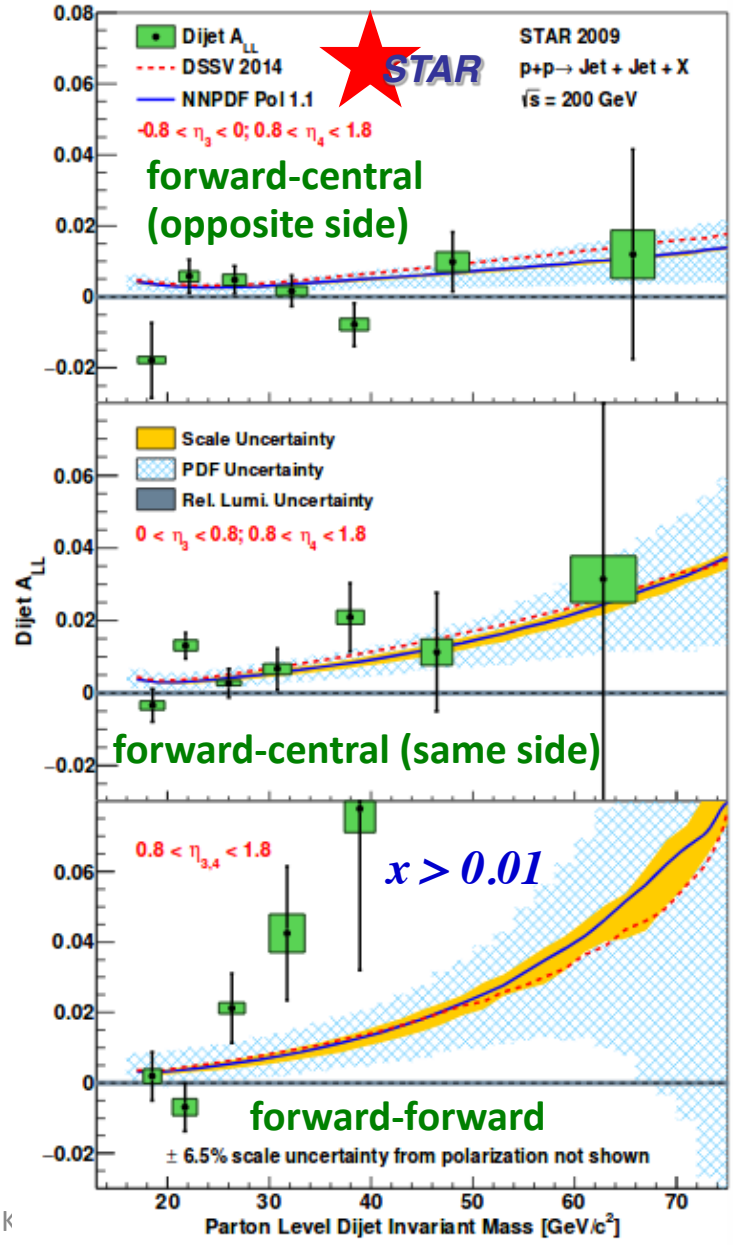
Gluon Polarization (Central jets and dijets)







Gluon Polarization (Intermediate rapidity)



Dijets at 200 GeV in 2009

Phys.Rev. D98, 032011 (2018)

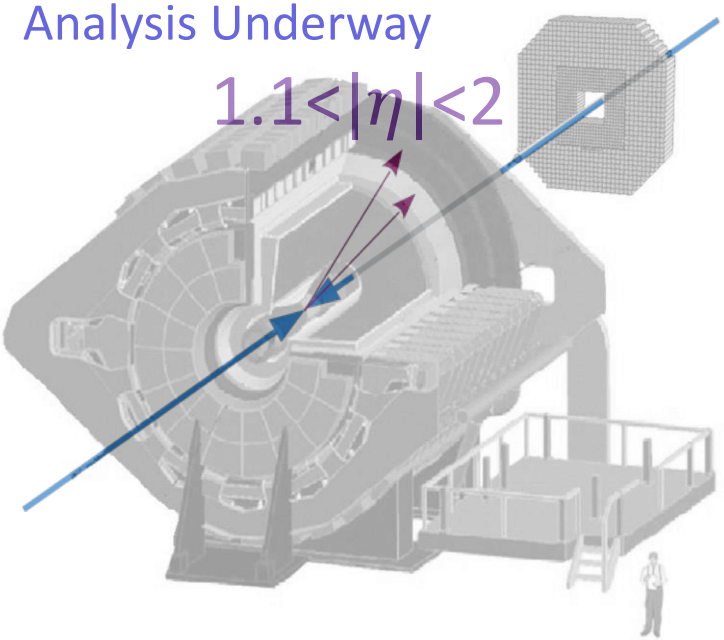
- More-forward production probes lower x, down to 0.01
- Provides tighter constraints to size and especially shape of Δg(x) for x<0.05

Pions at 200 GeV in 2006

- Phys.Rev. D89, 012001 (2014)

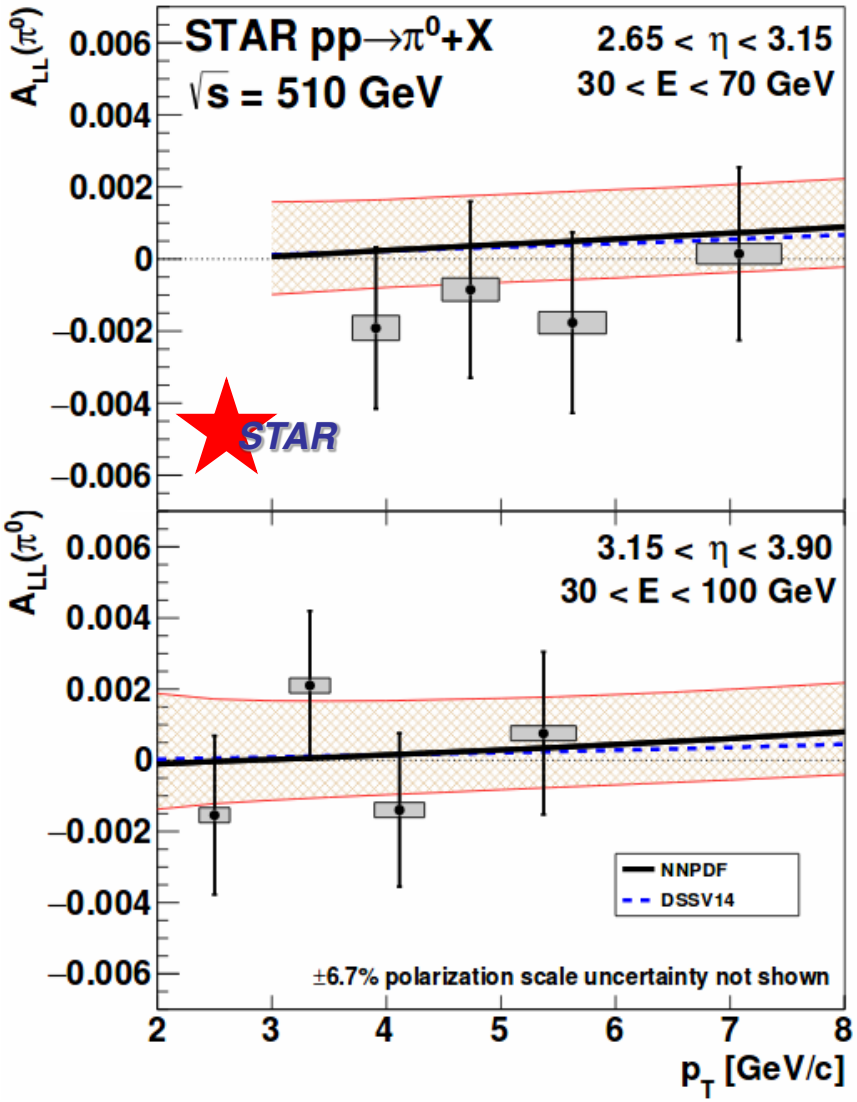
Pions at 510 GeV in 2012 and 2013

- Analysis Underway

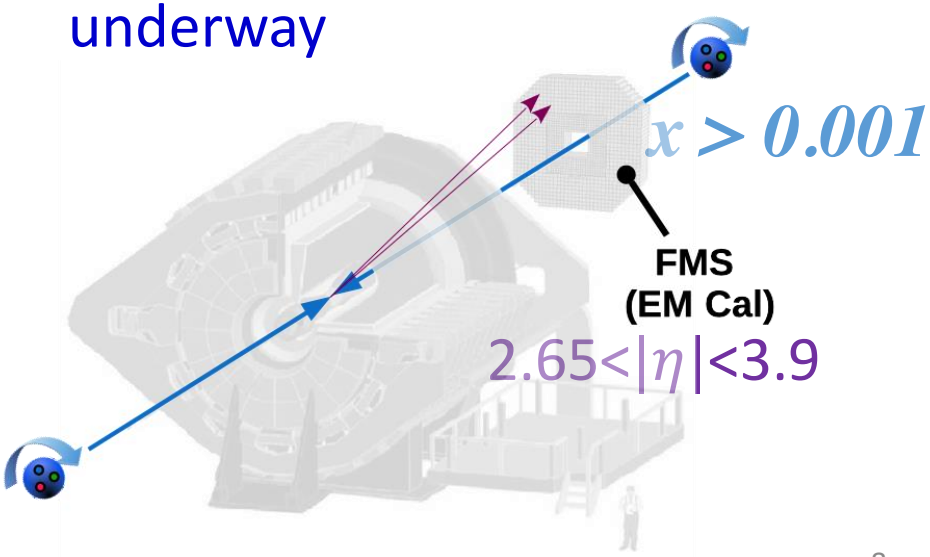


Gluon Polarization (Forward Pions)

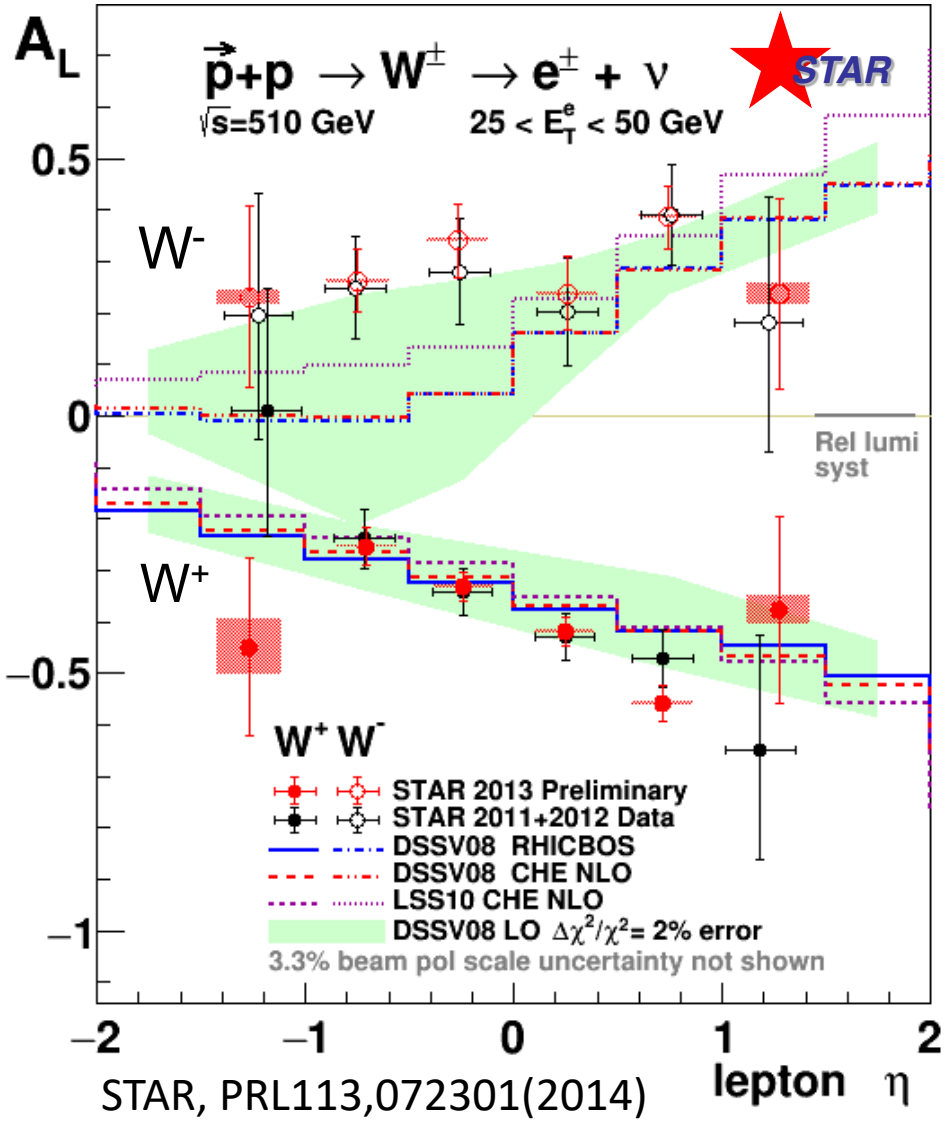
Phys.Rev.D 98, 032013 (2018)



- Pushing farther forward probes x down to 0.001
- Provides constraints to the unexplored low-*x* region, which is *abundant* with soft gluons
- Shown for two pseudorapidity regions
- Analysis for 200 GeV is underway



Sea Quark Polarization (Run 2013 $A_L(W)$)



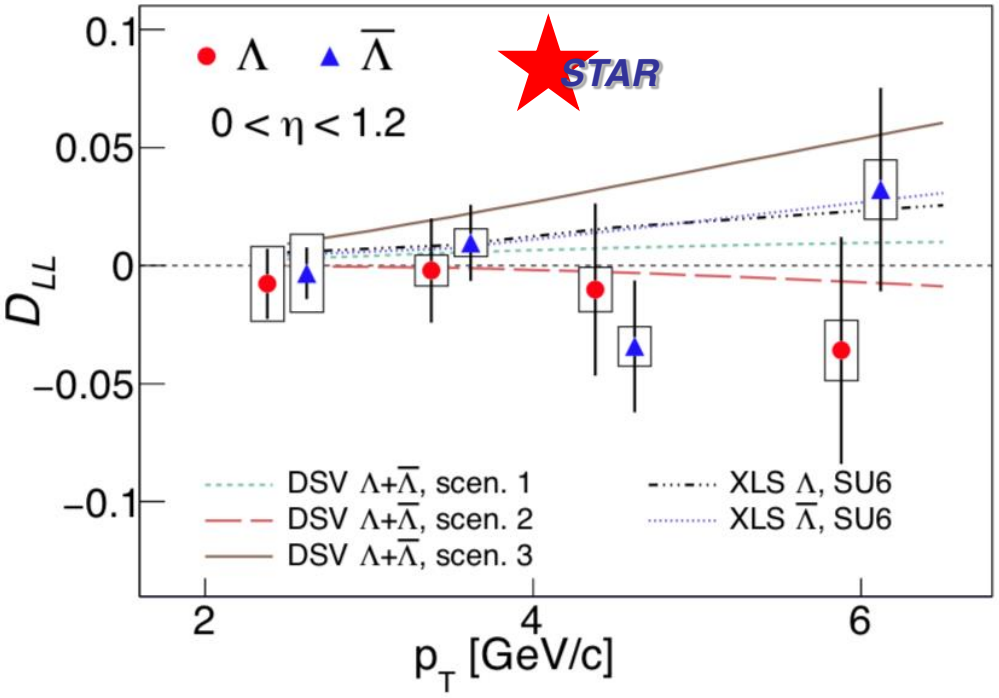
STAR, PRL113,072301(2014)

- STAR 2013 results are the most precise measurements of W A_L so far.
- Provides constraints on sea quark helicity distributions
- A_L results at near-forward rapidity added.
- Consistent with 2011+2012 published results, with 40% uncertainty reduced.
- Paper to be submitted soon
- Clear evidence of flavor asymmetry for polarized sea..

$$\Delta\bar{u} > \Delta\bar{d}$$

Longitudinal spin transfer D_{LL} results

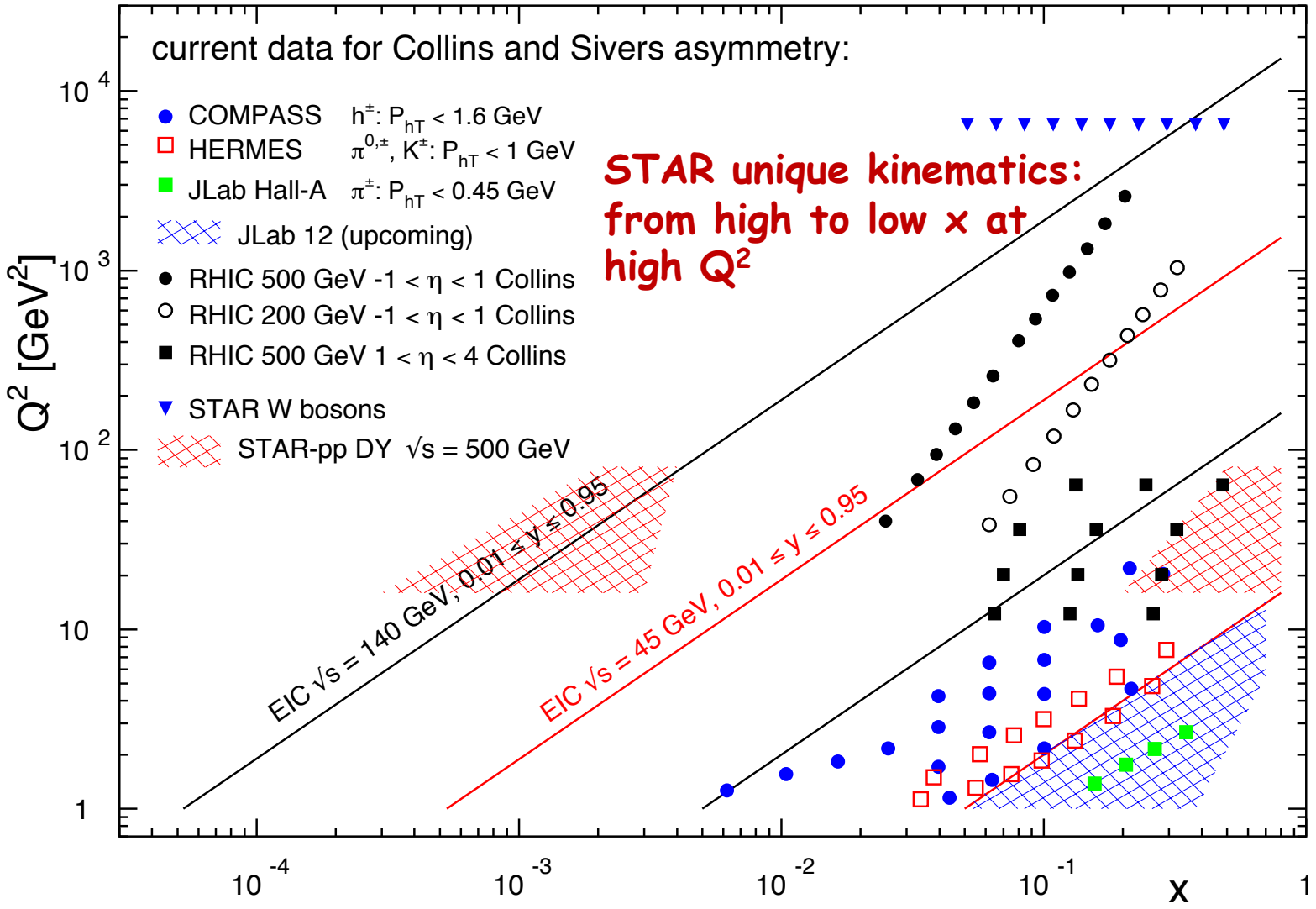
Accepted by PRD, arXiv: 1808.07634



- D.de Florian, M.Stratmann, and W.Vogelsang, PRL81, 530 (1998)
- Q. Xu, Z.T. Liang, E. Sichtermann, PRD 73, 077503 (2006)

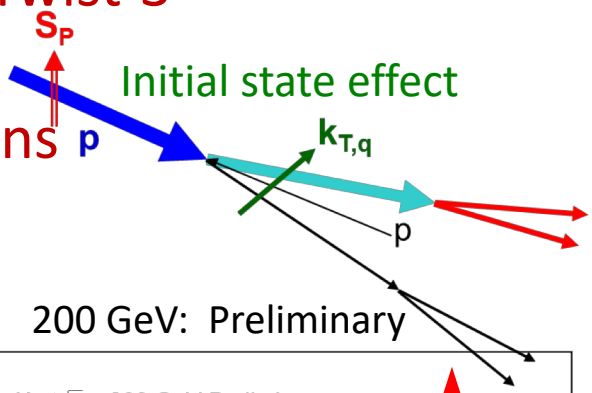
- ✓ **Longitudinal spin transfer D_{LL} provides access to helicity distribution Δf and polarized fragmentation function ΔD**
- ✓ **Improved longitudinal spin transfer from STAR 2009 Data**
- ✓ D_{LL} results are still consistent with zero within the uncertainties.
- ✓ The size of the statistical uncertainties is similar to the spread of different models.

Transverse Momentum PDFs (TMDs)

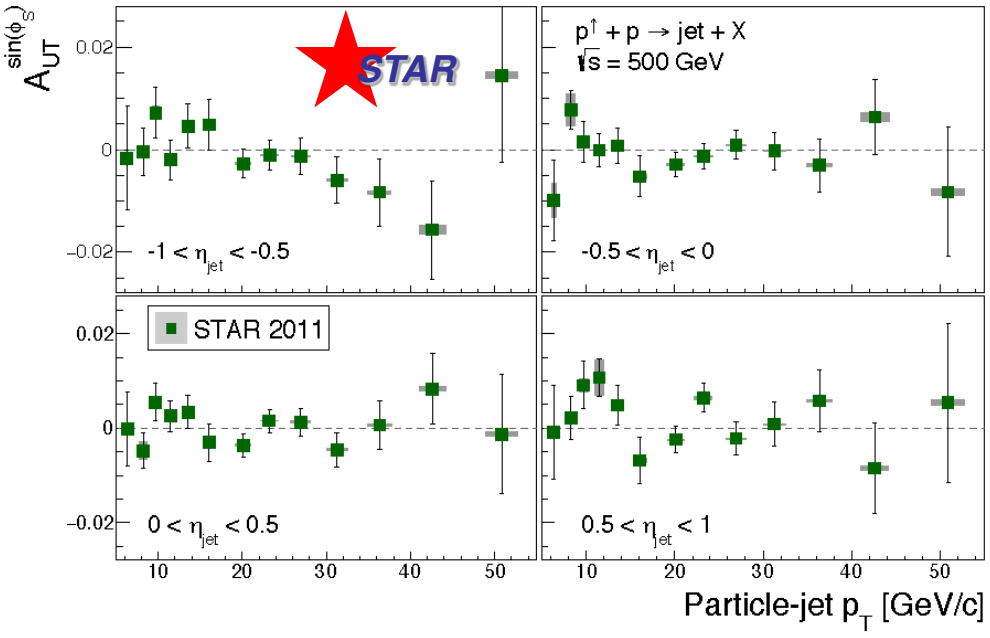


Transverse: Inclusive $A_N(jet)$ Sivers

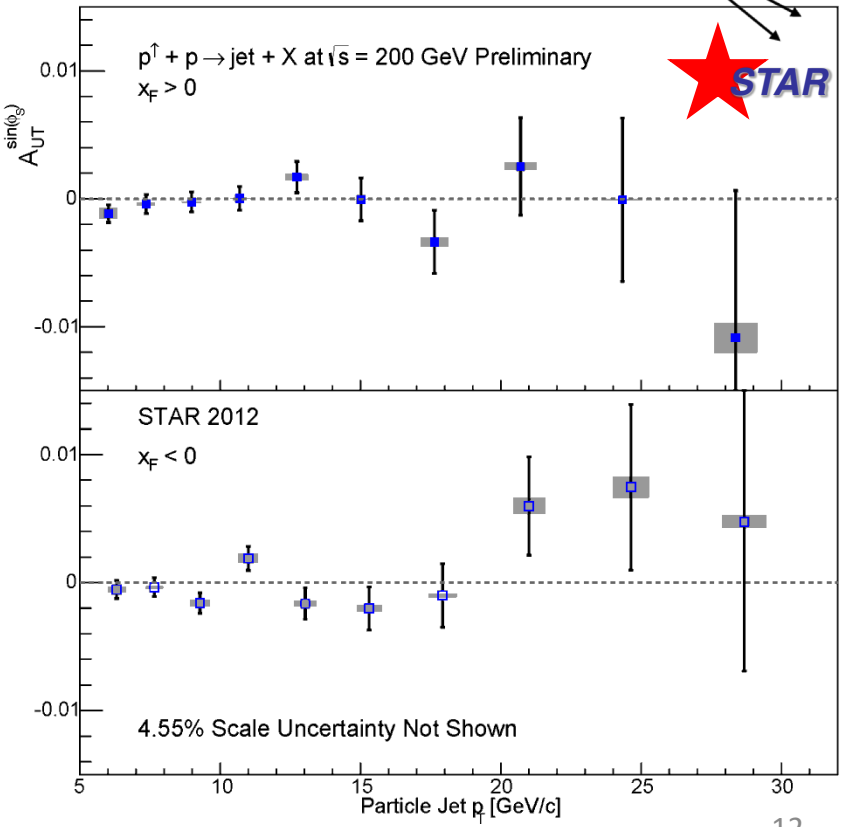
- Sensitive to the **gluon Sivers function** via the Twist-3 relationship $T_{q,F}(x,x) = -\int d^2k_\perp \frac{|k_\perp|^2}{M} f_{1T}^{\perp q}(x,k_\perp^2)|_{SIDIS}$
- New preliminary results in 200 GeV pp collisions
  - Far more precise than 500 GeV results
  - Still consistent with zero



500 GeV: PRD 97, 032004 (2018)



200 GeV: Preliminary



Transverse: Sivers $A_N(W)$

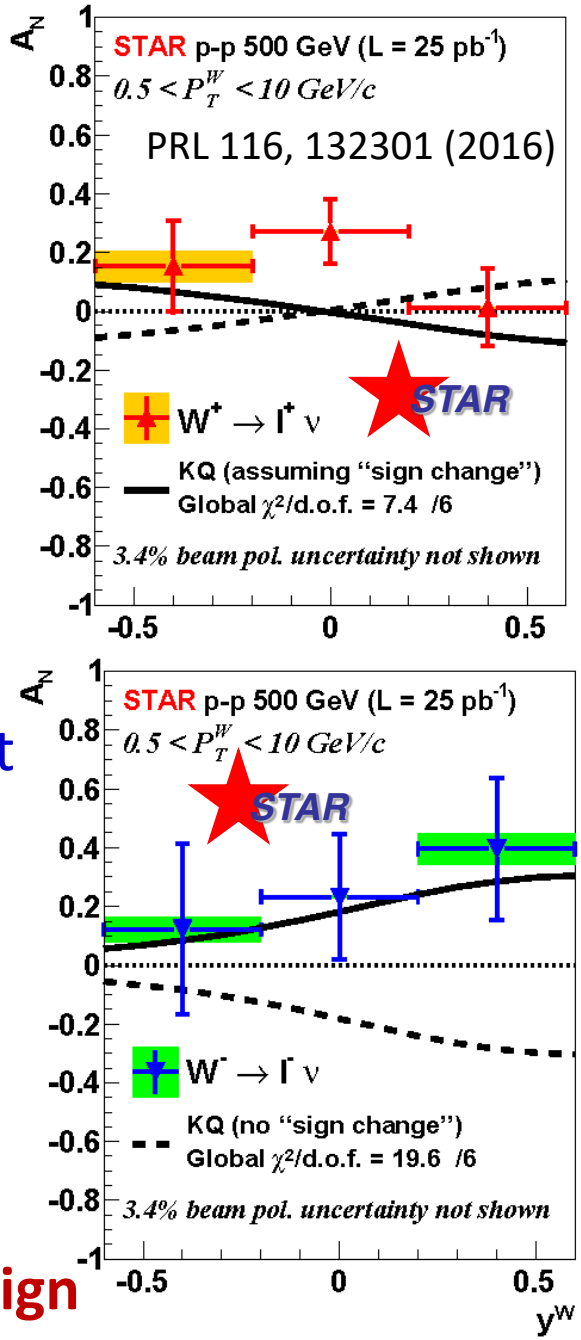
Run 2011: Exploratory $A_N(W)$ @ 500GeV

- W kinematics fully reconstructed
- Favors **sign change** if evolution effects are modest **($Sivers_{DIS} = - Sivers_{Drell\text{-}Yan}$)**

Run 2017: Definitive $A_N(W)$, $A_N(DY)$, $A_N(\gamma)$

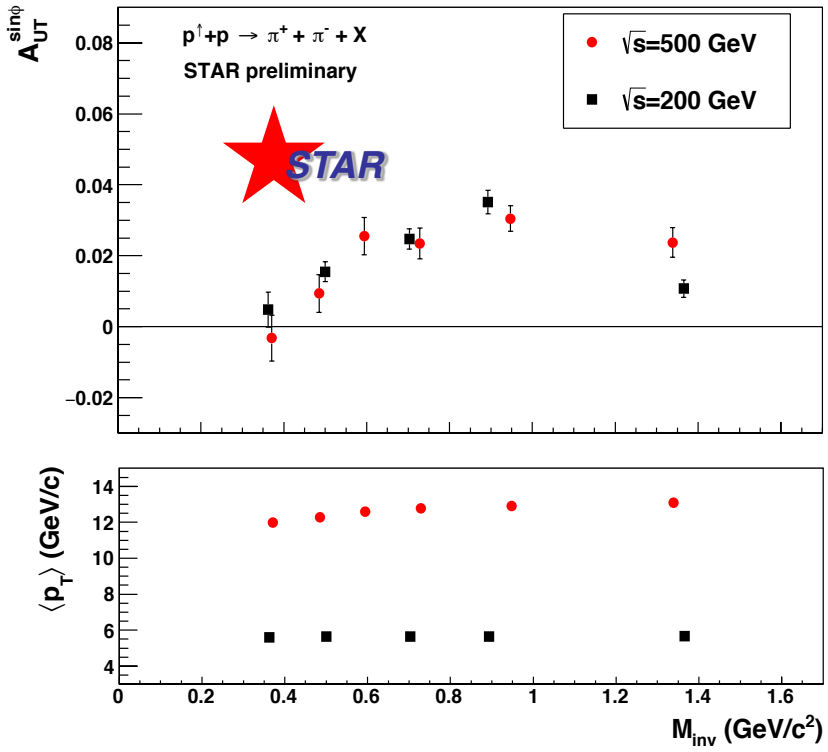
- See the sign change if evolution effects are less than factor of 5
- Probe **anti-quark Sivers function** for the first time
- Directly measure the evolution effects
  - → Access to similar observables at comparable x but different Q^2
  - → W & Z central and Drell-Yan forward
- Currently under analysis

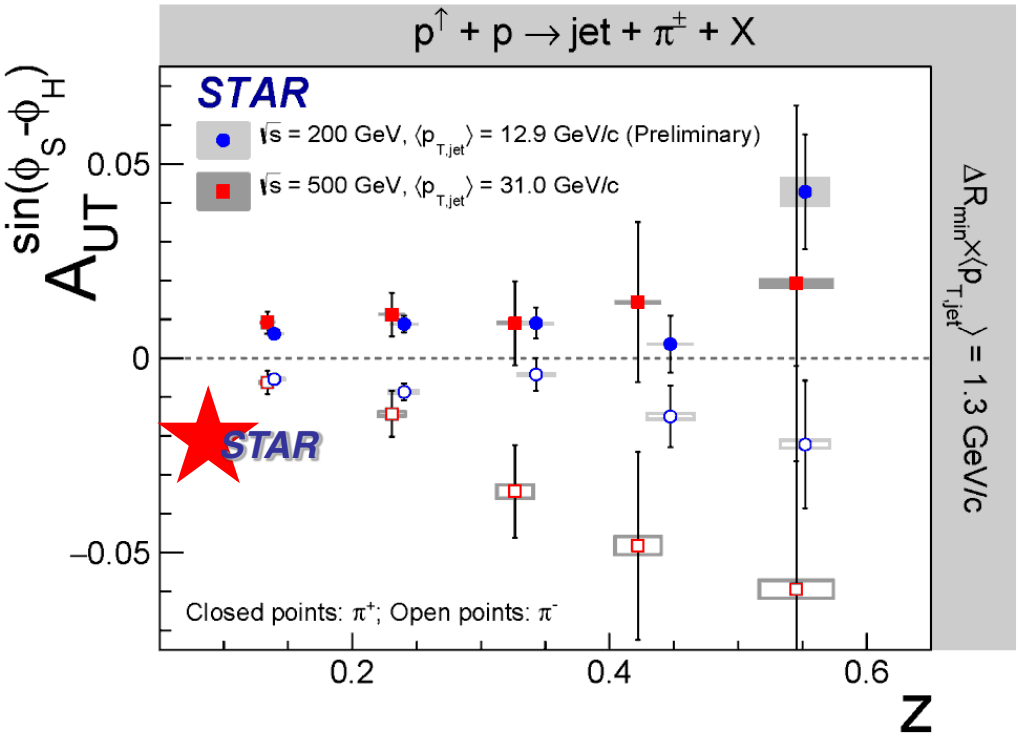
Run 2021 (proposed): Go beyond testing the sign



Transverse: Transversity

Proton momentum →
Proton spin ↑





Significant measurements of transversity convoluted with:

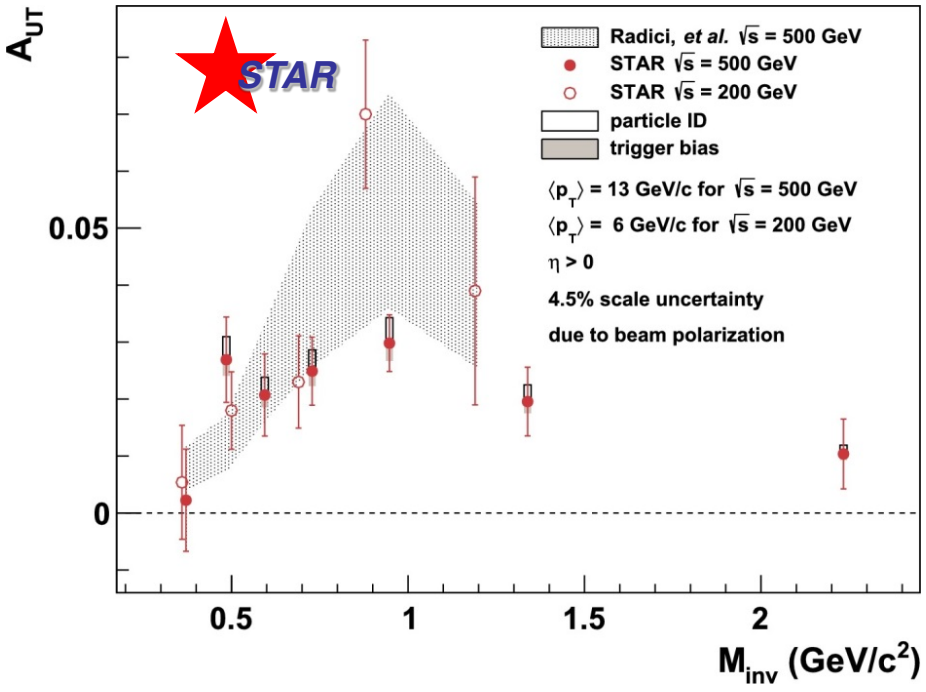
- » Di-hadron interference fragmentation function (IFF)
- » Collins fragmentation function

Both have similar magnitudes in 200 and 500 GeV pp collisions

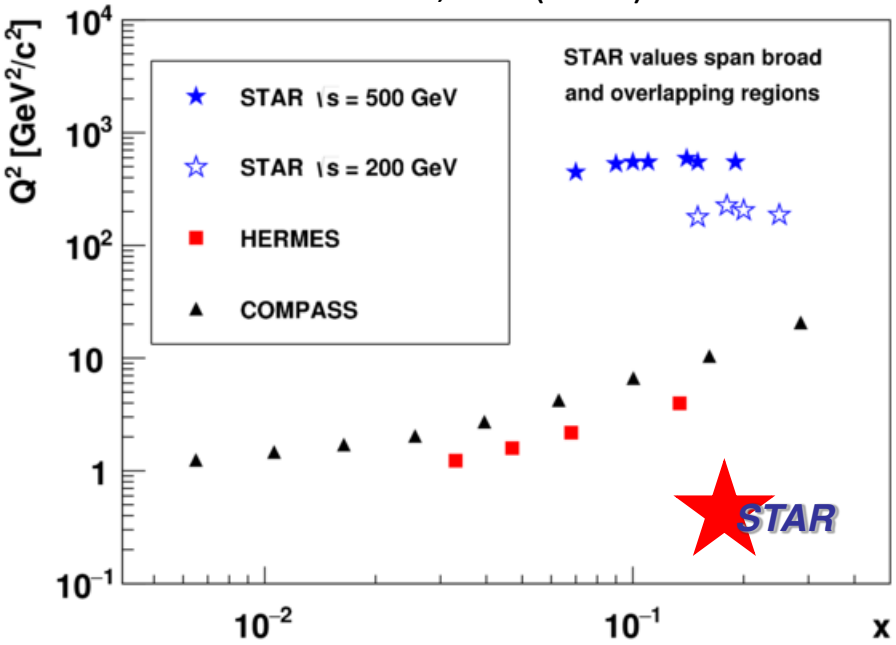
Complementary results that obey different evolution equations

Transverse: IFF Transversity Measurements

PLB 780, 332 (2018)



PLB 780, 332 (2018)



- **STAR measurements provide the first observations of transversity at very high scales**
- ***STAR*** IFF measurements in 200 and 500 GeV pp collisions are well described by recent IFF calculations

Transverse: Collins

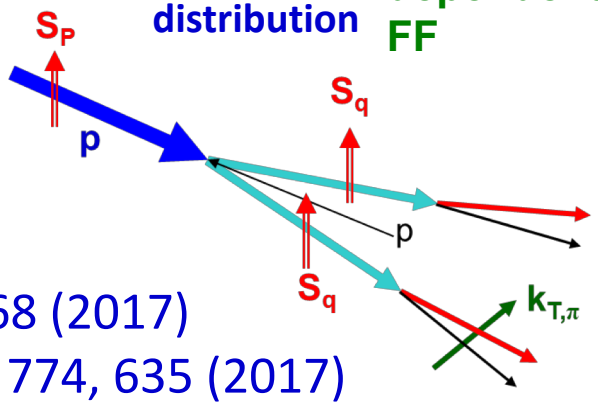
$$\propto \delta q(x) \cdot H_1^{\perp}(z_2, \bar{k}_{\perp}^2)$$

Quark transverse spin distribution

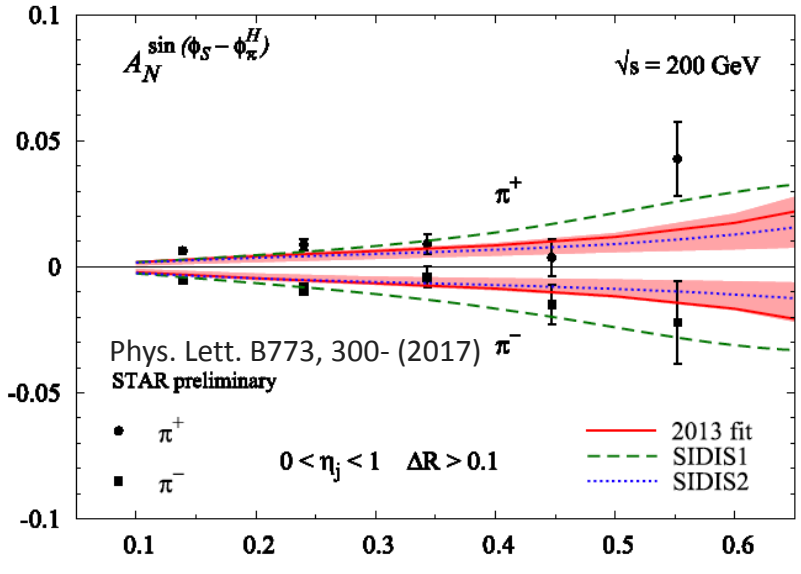
"Collins" spin dependent FF

200 vs. 500 GeV Comparison:

- Evolution: 200 GeV ⟷ 500 GeV factor 3 in Q
- Test of factorization & Universality
  - → compare with transversity from IFF
  - → compare with SIDIS and e+e-
- Inspired a lot of theory work
  - → Proof of factorization: Kang et al. JHEP 1711, 068 (2017)
  - → Asymmetry calculation: Kang et al. Phys.Lett B. 774, 635 (2017)
  - → Universality: D'Alesio et al. Phys.Lett. B773, 300 (2017)

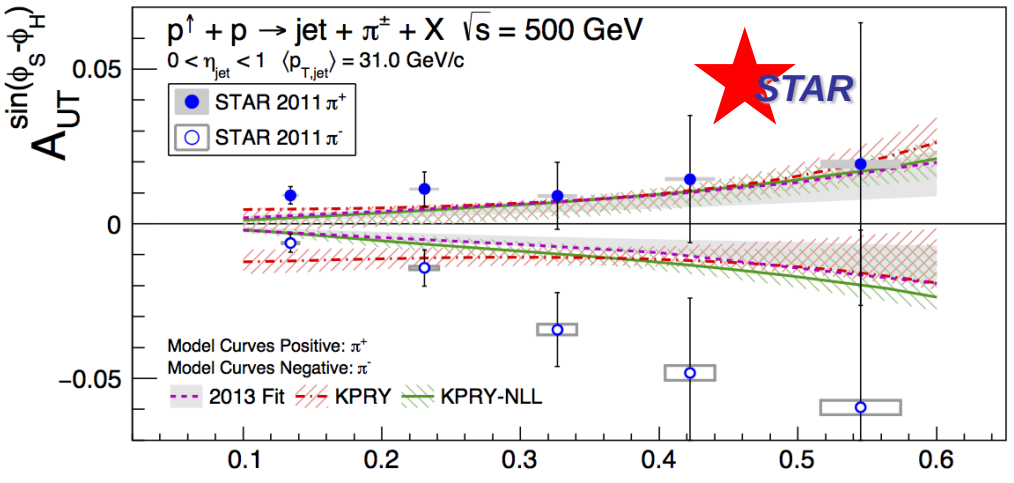


final state effect



$\pi^{\pm}$ azimuthal distribution in jets

STAR: PRD 97, 032004 (2018) (arXiv:1708.07080)

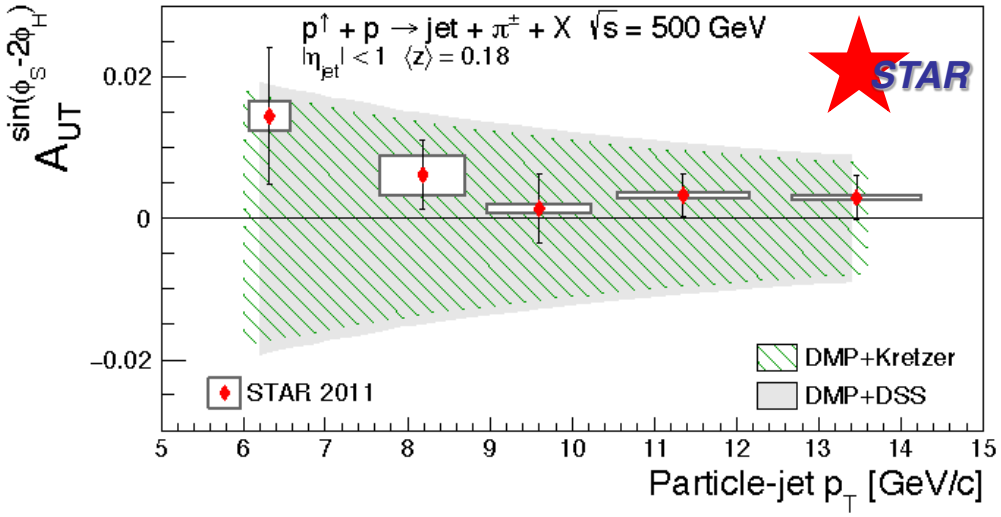


First Sign TMDs survive at low x and high Q^2

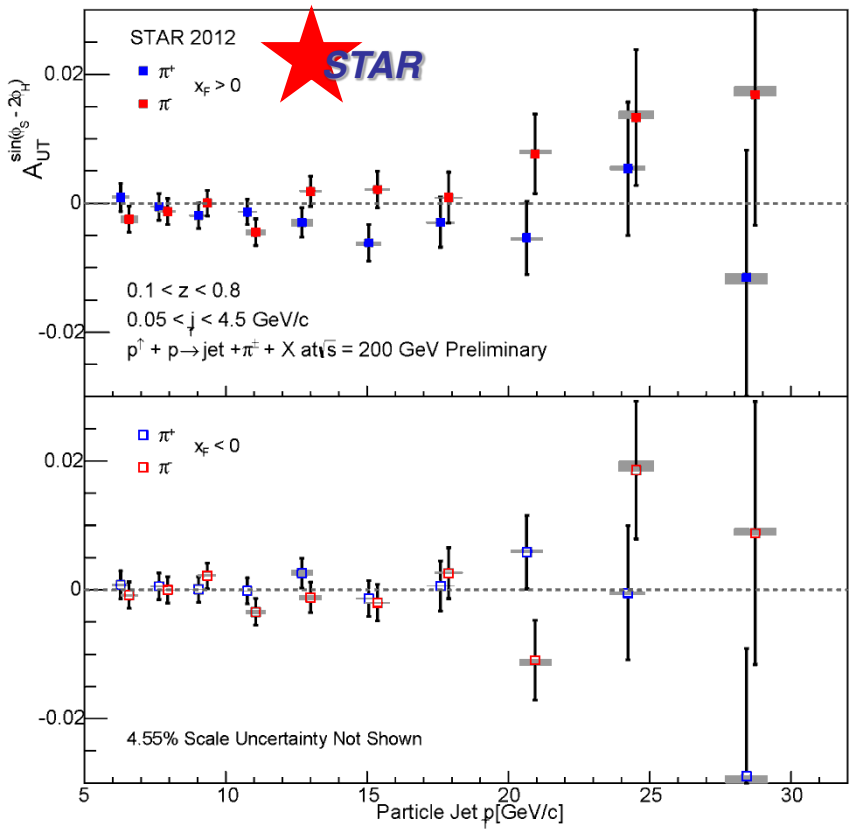
Transverse: "Collins-like" effect

Gluon analog to Collins FF

500 GeV: PRD 97, 032004 (2018)



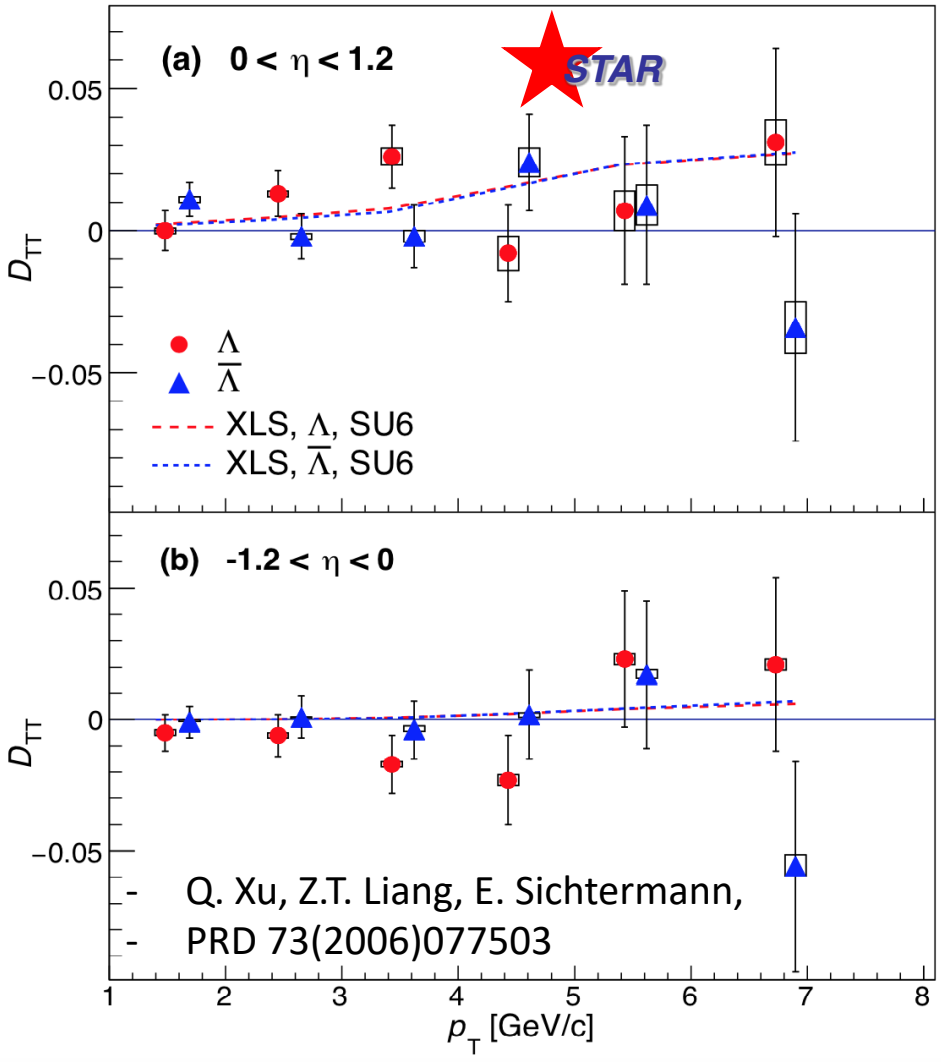
200 GeV: Preliminary



- **World's first ever limit** on linearly polarized gluons in a polarized proton
- **New preliminary results from 200 GeV pp collisions**
  - **Will provide much stronger limits**

Transverse spin transfer D_{TT} results

Accepted by PRD, arXiv: 1808.0800



- ✓ **Transverse spin transfer of hyperons provide access to transversity and transversely polarized fragmentation function**
- ✓ **First transverse spin transfer measurement in p+p collisions at RHIC.**
- ✓ Result:

$\langle p_T \rangle = 6.7$ GeV and $\langle \eta \rangle = 0.5$:

$$D_{TT}(\Lambda) = 0.031 \pm 0.033(stat) \pm 0.008(sys)$$

$$D_{TT}(\bar{\Lambda}) = -0.034 \pm 0.040(stat) \pm 0.009(sys)$$

- ✓ D_{TT} of $\Lambda/\bar{\Lambda}$ are consistent with a model prediction, also consistent with zero within uncertainty.

Physics with STAR in 2021+

Opportunity:

- Unique program addressing several fundamental questions in QCD

Motivation: (The RHIC Cold QCD Plan for 2017 to 2023: A Portal to the EIC (arXiv:1602.03922))

- Central to the mission of the RHIC physics program in cold and hot QCD
- Fully realize the scientific promise of the EIC
  - → Lay the groundwork for the EIC, both scientifically and by refining the experimental requirements
  - → Test EIC detector technologies under real conditions, i.e SiPMs

Take full advantage of STAR's unique capability including upgrades for BES-II:

- Midrapidity program based on existing STAR detector utilizing iTPC, eToF and EPD upgrades (https://drupal.star.bnl.gov/STAR/starnotes/public/sn0669)
- **Forward rapidity program based on upgrade consisting of Hcal + Ecal+ Tracking (Si + sTGCs) at $2.5 < \eta < 4$ (https://drupal.star.bnl.gov/STAR/starnotes/public/sn0648)**

Goal: Complete upgrade for potential polarized pp@500 GeV run in 2021 and the sPHENIX data taking periods

Conclusions

- **STAR results play a central role in expanding the frontier of cold-QCD**

  Recent Publications and Submissions:

  - Improved measurement of the longitudinal spin transfer to Λ and Λ-bar hyperons in polarized proton–proton collisions at √s = 200 GeV accepted by Phys. Rev. D.
  - Transverse spin transfer to Lambda and anti-Lambda hyperons in polarized proton-proton collisions at sqrt(s)=200 GeV accepted by Phys. Rev. D.
  - Longitudinal Double-Spin Asymmetries for Dijet Production at Intermediate Pseudorapidity in Polarized pp Collisions at sqrt(s) = 200 GeV. Phys. Rev. D 98, 032011 (2018)
  - Longitudinal double-spin asymmetries for pi0s in the forward direction for 510 GeV polarized pp collisions. Phys. Rev. D 98, 032013 (2018)
  - Transverse spin-dependent azimuthal correlations of charged pion pairs measured in p+p collisions at sqrt(s)=500 GeV. Phys. Lett. B 780, 332-339 (2018)
  - Azimuthal transverse single-spin asymmetries of inclusive jets and charged pions within jets from polarized-proton collisions at sqrt(s) = 500 GeV. Phys. Rev. D 97, 32004 (2018)
  - Measurement of the cross section and longitudinal double-spin asymmetry for di-jet production in polarized p+p collisions at sqrt(s) = 200 GeV. Phys. Rev. D 95, 71103 (2017)

- ***STAR* has a large body of additional spin data under analysis**

- **The proposed forward upgrade builds upon the strengths of STAR to establish innovative and precision probes**
  - **to address critical questions, now**
  - **to fully realize the scientific promise of the future EIC**

Extra Slides

Gluon Polarization
(Summary of A_{LL} Measurements)

√s (GeV)	RHIC Run	Central Jets	Central Dijets	Interm. Dijets	Interm. Pions	Forward Pions	Forward Dijets
200	2006	Published* x>0.05			Published x>0.01		n/a
200	2009	Published x>0.05	Published x>0.05	Published x>0.01			n/a
200	2015	Underway x>0.05	Underway x>0.05			Underway x>0.0025	n/a
510	2012	Preliminary x>0.02	Preliminary x>0.02	Underway x>0.004	Underway x>0.004	Published x>0.001	n/a
510	2013	Preliminary x>0.02	Preliminary x>0.02	Underway x>0.004	Underway x>0.004	Published x>0.001	n/a
200 & 510	2021+						Future x>0.001

Forward Instrumentation for STAR Upgrade (I)

Detector	pp and pA	AA
ECal	~10%/√E	~20%/√E
HCal	~60%/√E	---
Tracking	charge separation photon suppression	$0.2<p_T<2$ GeV/c with 20-30% $1/p_T$

Calorimeter System

Intensive R&D work on both ECal and HCal as part of STAR and EIC Detector R&D

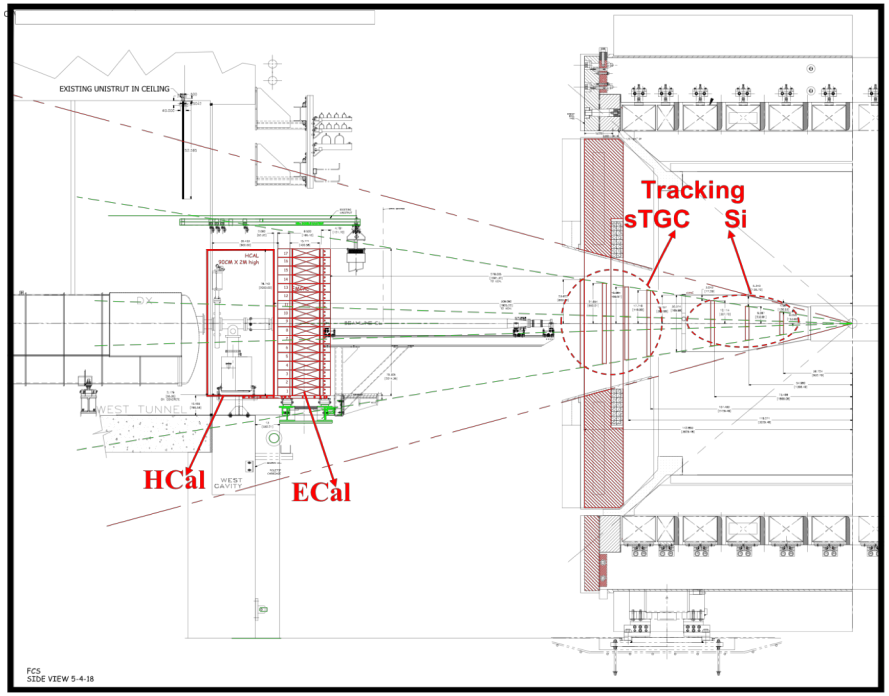
- Beam tests and STAR in situ tests
- System optimized for cost and performance
- Same readout for both calorimeters → cost

ECal Reuse PHENIX PbSC calorimeter with new readout instead of W/ScFi SPACAL

- Significant cost reduction ☺
- Non-compensating calorimeter system ☹

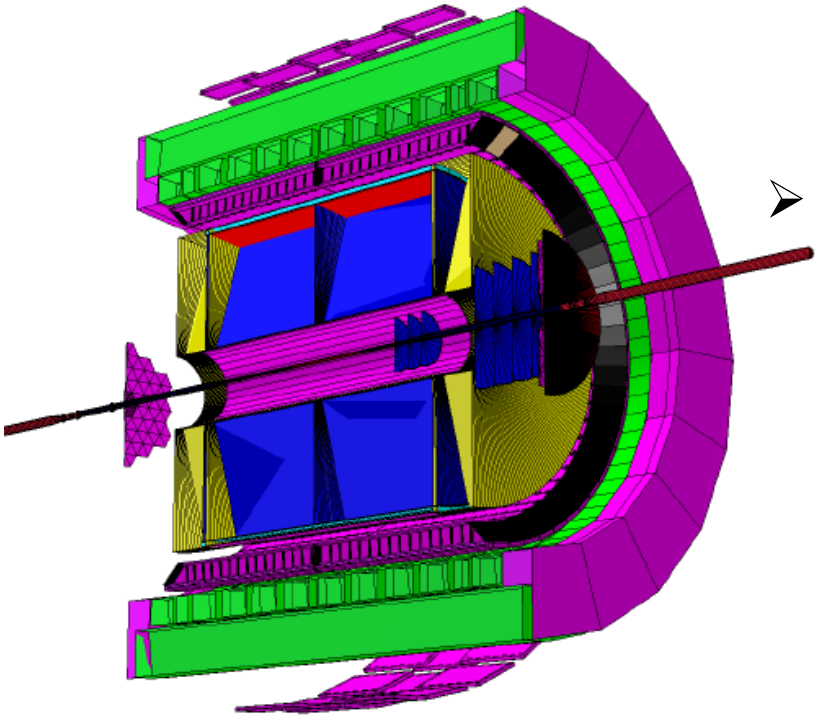
HCal: Sandwich iron-scintillator plate sampling calorimeter.

Side View



Forward Instrumentation for STAR Upgrade (II)

Si + Small-strip Thin Gap Chambers



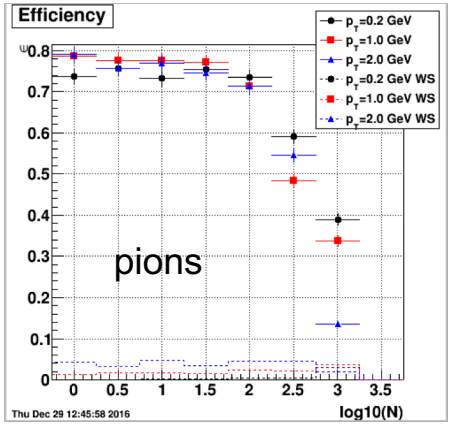
3 Silicon disks + 4 sTGC disks

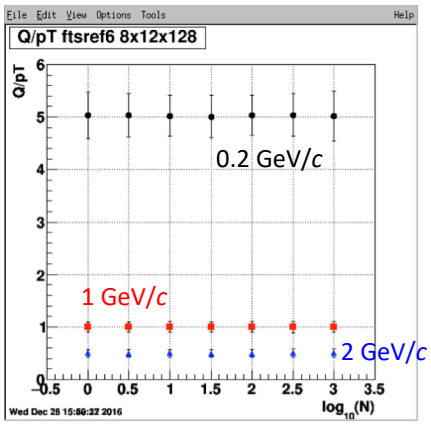
- Si- disks: 140, 160, 187 cm from IP
  - Built on successful experience with STAR IST
  - → Single-sided double-metal mini-strip sensors
  - → Granularity: fine in ϕ and coarse in R
  - → Reuse of the IST cooling system
- sTGC: 270, 300, 330, 360 cm from IP (outside Magnet)
  - → Position resolution: ~100 μm
  - → Material budget: ~0.5% per layer, 2 layers / disk
  - → Readout: reuse current STAR TPC electronics

Momentum resolution:

20-30% for $0.2 < p_T < 2$ GeV/c

track finding efficiency: 80%@100 tr/ev





Summary of Forward pp & pA Measurements

	Year	$\sqrt{s}$ (GeV)	Delivered Luminosity	Scientific Goals	Observable	Required Upgrade
Scheduled RHIC running	2023	$p^{\uparrow}p$ @ 200	300 pb^{-1} 8 weeks	Subprocess driving the large A_N at high x_F and η	A_N for charged hadrons and flavor enhanced jets	Forward instrum. ECal+HCal+Tracking
	2023	$p^{\uparrow}Au$ @ 200	1.8 pb^{-1} 8 weeks	What is the nature of the initial state and hadronization in nuclear collisions Clear signatures for Saturation	R_{pAu} direct photons and DY Dihadrons, γ-jet, h-jet, diffraction	Forward instrum. ECal+Hcal+Tracking
	2023	$p^{\uparrow}Al$ @ 200	12.6 pb^{-1} 8 weeks	A-dependence of nPDF, A-dependence for Saturation	R_{pAl}: direct photons and DY Dihadrons, γ-jet, h-jet, diffraction	Forward instrum. ECal+HCal+Tracking
Potential future running	2021	$p^{\uparrow}p$ @ 510	1.1 fb^{-1} 10 weeks	TMDs at low and high x	A_{UT} for Collins observables, i.e. hadron in jet modulations at $\eta > 1$	Forward instrum. ECal+HCal+Tracking
	2021	$\vec{p}\vec{p}$@ 510	1.1 fb^{-1} 10 weeks	$\Delta g(x)$ at small x	A_{LL} for jets, di-jets, h/γ-jets at $\eta > 1$	Forward instrum. ECal+HCal