THE 2ND WORKSHOP ON JETS FOR 3D IMAGING AT EIC

Recent RHIC-Spin Results with Jets and Prospects with STAR Forward Upgrade

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SPIN PHYSICS PROGRAM AT RHIC WITH JETS

RHIC spin program goal:

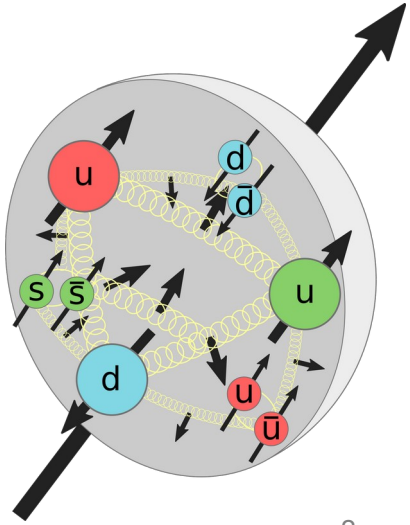
- Delineate the **spin structure of the proton** in terms of quarks and gluons and study the role of spin in QCD

Tool:

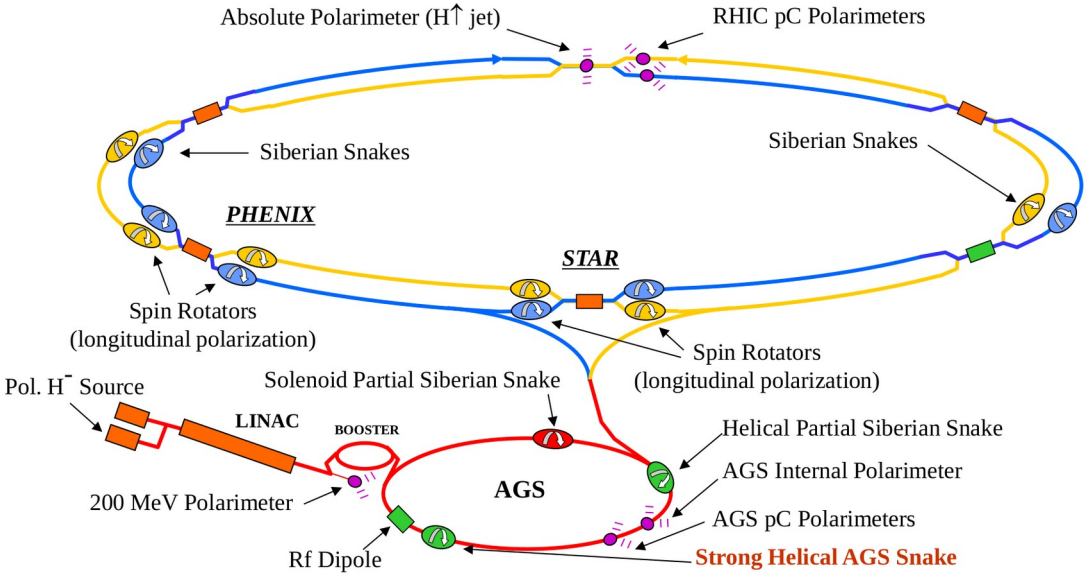
- **Strong interactions** in polarized proton-proton collisions (complementary with DIS measurements)

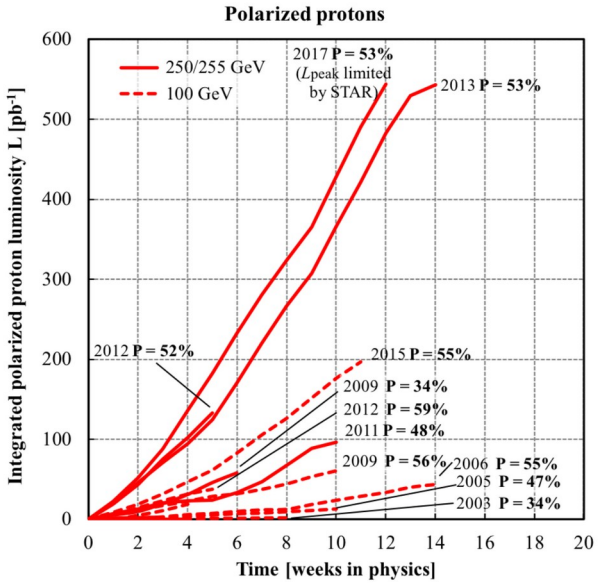
Jets as a probe to address questions about **proton spin structure** in the **collinear** and **transverse** momentum dependent frameworks:

1. **Gluon helicity** distribution: inclusive jet and dijet A_{LL}
2. **Quark Collins effect (transversity + Collins FF)**: A_{UT} of hadrons in jets
3. **Quark and Gluon Sivers' function**: Asymmetry of the tilt of dijet opening angle forward jet A_N



RHIC – POLARIZED PROTON COLLIDER





- Polarized protons √s = 62, 200, 500 GeV
- Transverse and longitudinal polarization
- Alternating spin configurations bunch by bunch and fill by fill
- The only polarized high-energy proton-proton collider

Hard scattering processes with control of systematic effects

SOLENOIDAL TRACKER AT RHIC

Time Projection Chamber + Magnetic Field $\Delta\varphi = 2\pi$, $|\eta| < 1$, 0.5 T
PID, tracking, vertex reconstruction

Electromagnetic Calorimeter $\Delta\varphi = 2\pi$, $-1 < \eta < 2$
Barrel ($|\eta| < 1$) and Endcap ($1 < \eta < 2$)
- Energy measurement, trigger

Time of Flight Barrel $\Delta\varphi = 2\pi$, $|\eta| < 1$
- Particle Identification

Forward Meson Spectrometer $\Delta\varphi = 2\pi$, $2.6 < \eta < 4$
- Energy measurement, trigger

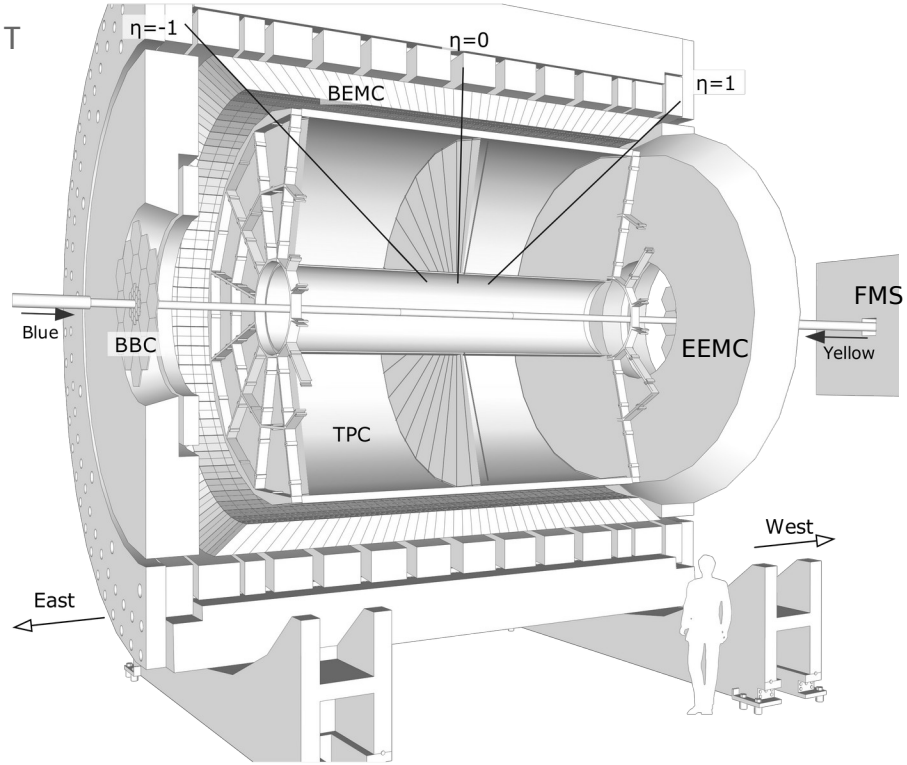
Beam-Beam Counter
Vertex Position Detector
Zero Degree Calorimeter
- Relative luminosity and Minimum Bias trigger

Roman Pots

Characteristics
- Large acceptance (PID and calorimetry)
- Good detector for jets

Upgrades: iTPC, EPD, ETOF, **Fwd Upgrade**

Focusing mostly on **STAR** in this talk



CURRENT JET RECONSTRUCTION AT STAR

See also talk by
Raghav Kunnawalkam Elayavalli

Anti-kT algorithm via FastJet

Cacciari, Salam, Soyez, Eur. Phys. J. C 72, 1896 (2012), Cacciari, Salam, Soyez, JHEP 04, 063 (2008)

- Less sensitive to underlying event and pile-up effects
- R = 0.6 at 200 GeV
- R = 0.5 at 500 GeV

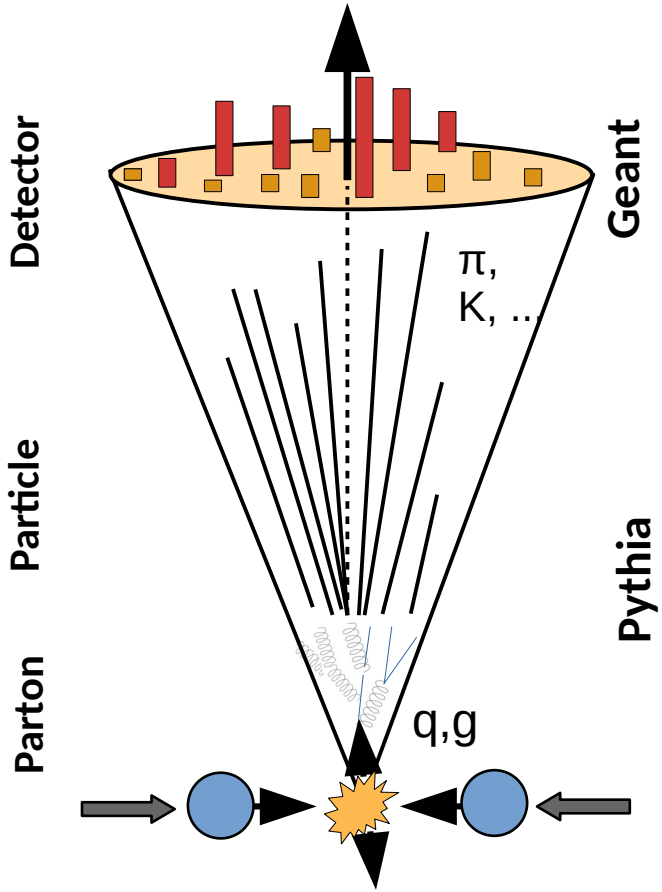
PYTHIA (Perugia12 + STAR tune) + GEANT + Zero-bias events for embedding

Jets reconstructed at **three levels**:

- **Detector level:** detector response to stable particles (takes into consideration finite detector acceptance, efficiency and resolution effects)
- **Particle level:** complete set of stable color-neutral particles produced in the event
- **Parton level:** hard-scattered partons from Pythia event
  - Initial-state and final-state radiation associated with the process included
  - No partons from beam remnants and multiple parton interactions

Jet momentum resolution ~ 18%

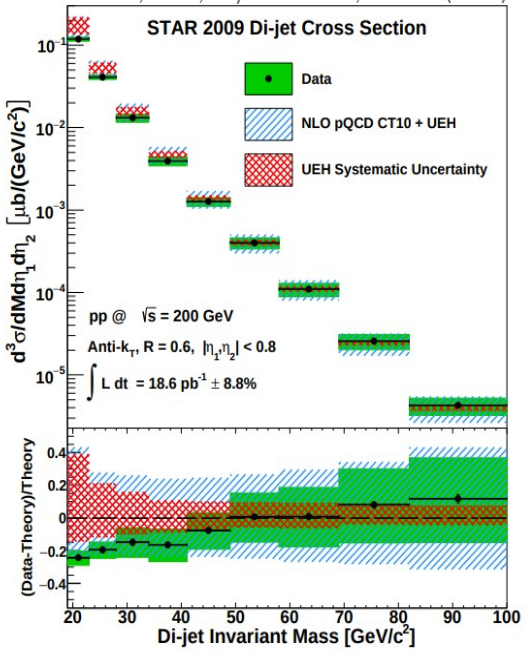
UE correction based on off-axis cone method, ALICE, PRD 91 (2015), 112012



JET CROSS SECTIONS

Dijets

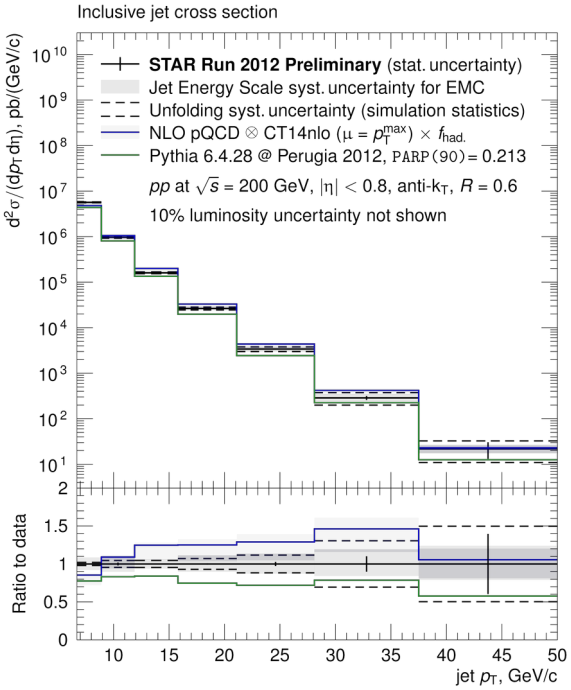
Data: Phys. Rev. D 95 (2017) 71103
Theory: D. de Florian, et al., Nucl. Phys. B 539, 455 (1999)
H. L. Lai, et al., Phys. Rev. D 82, 074024 (2010)



- MC-driven UE correction

Inclusive jets at 200 GeV

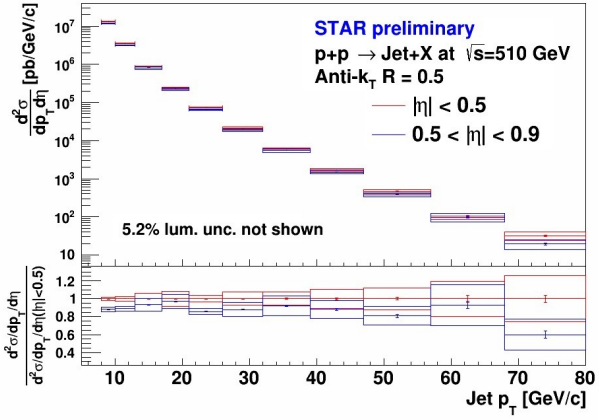
Data: D. Kalinkin (STAR), DIS21



- Off-axis UE correction

Inclusive jets at 510 GeV

Data: Z. Chang (STAR), DNP20



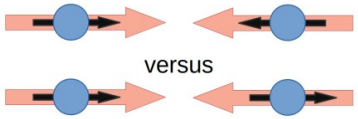
- Off-axis UE correction

Cross-section measurements support the **NLO pQCD** interpretation of spin asymmetries from RHIC

GLUON HELICITY

ACCESS TO ΔG

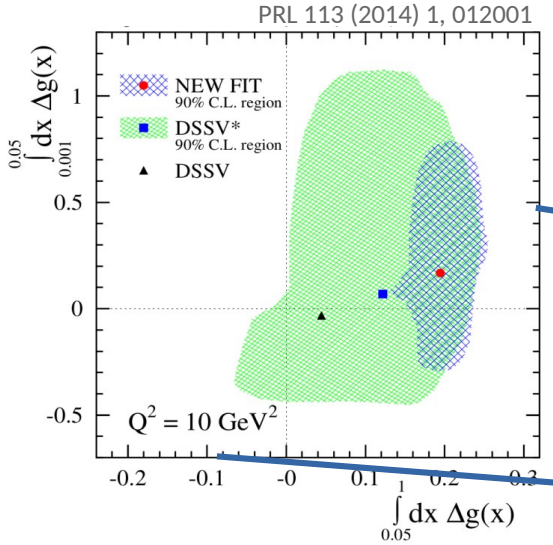
$$\vec{p} + \vec{p} \rightarrow \text{jet/dijet} + X$$



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

LO for illustration

- At RHIC energies: sensitivity to qg and gg – Access to **Δg(x)/g(x)**
- Cross-section measurement to support the NLO pQCD interpretation of asymmetries



STAR inclusive jet A_{LL} from 2009 data at √s = 200 GeV PRL 115 (2015) 9, 092002
Included in global pQCD analysis provided evidence for **positive gluon polarization for x > 0.05 at Q^2 = 10 GeV**

Low-x range

Extend sensitivity to smaller x:

Forward rapidity $x_g \propto \exp(-\eta)$

√s = 510 GeV data $x_g \propto 1/\sqrt{(s)}$

High-x range

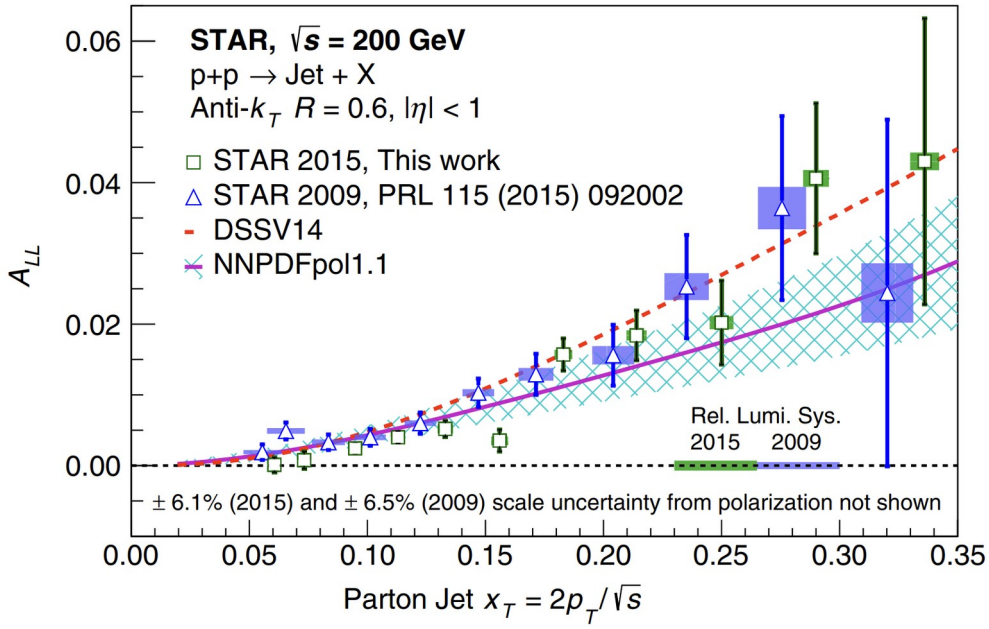
Further precision from:

- Jet and neutral pion probes
- Complementary probes (dijets)

INCLUSIVE JETS AT 200 GEV

New result on jet and dijet A_{LL} from STAR from 2015 data

STAR, Phys. Rev. D 103, L091103 (2021)

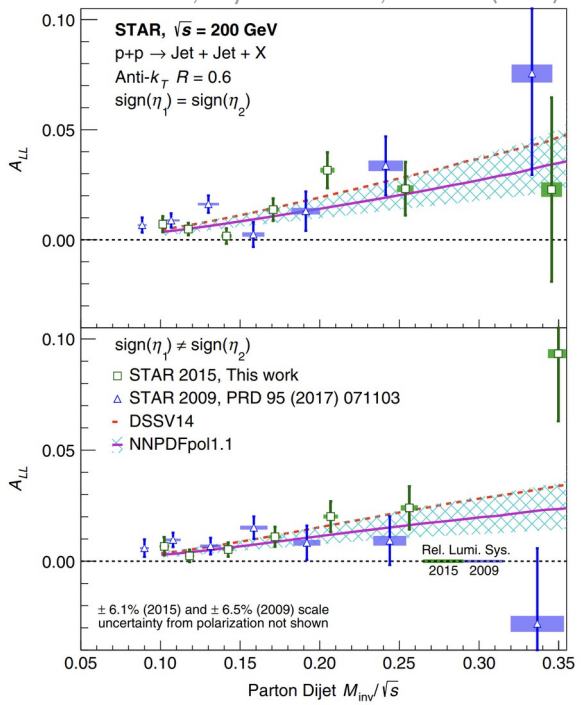


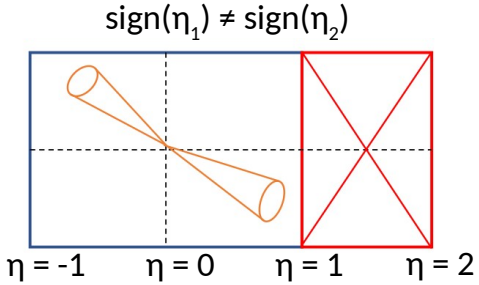
- Consistent with 2009 data, which provided first evidence for **positive gluon polarization for x > 0.05**
- Twice larger figure-of-merit (LP^4) with improved systematics
- Will significantly reduce uncertainty on **Δg(x) for x > 0.05** once included in global fits

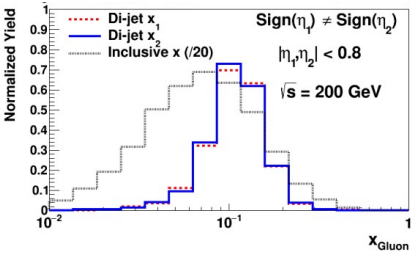
The most precise dataset likely to conclude the 200 GeV longitudinal spin program with jets

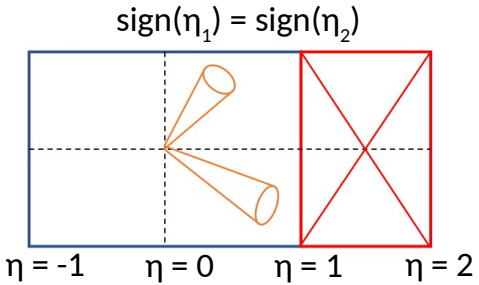
DIJETS AT 200 GEV

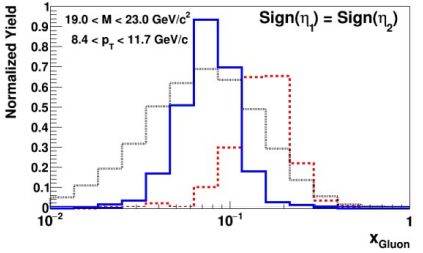
STAR, Phys. Rev. D 103, L091103 (2021)









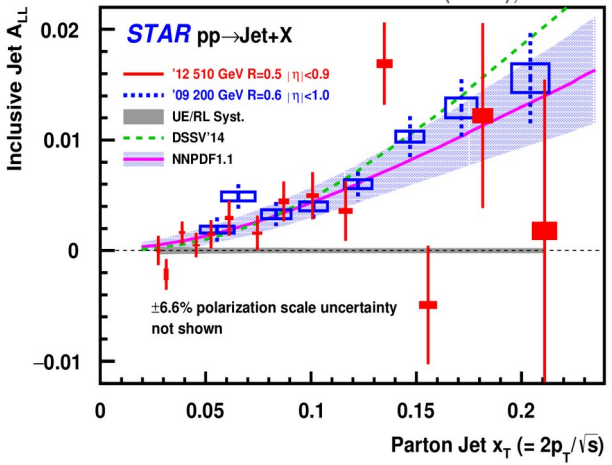


Dijets give stricter constraints to underlying **partonic kinematics**

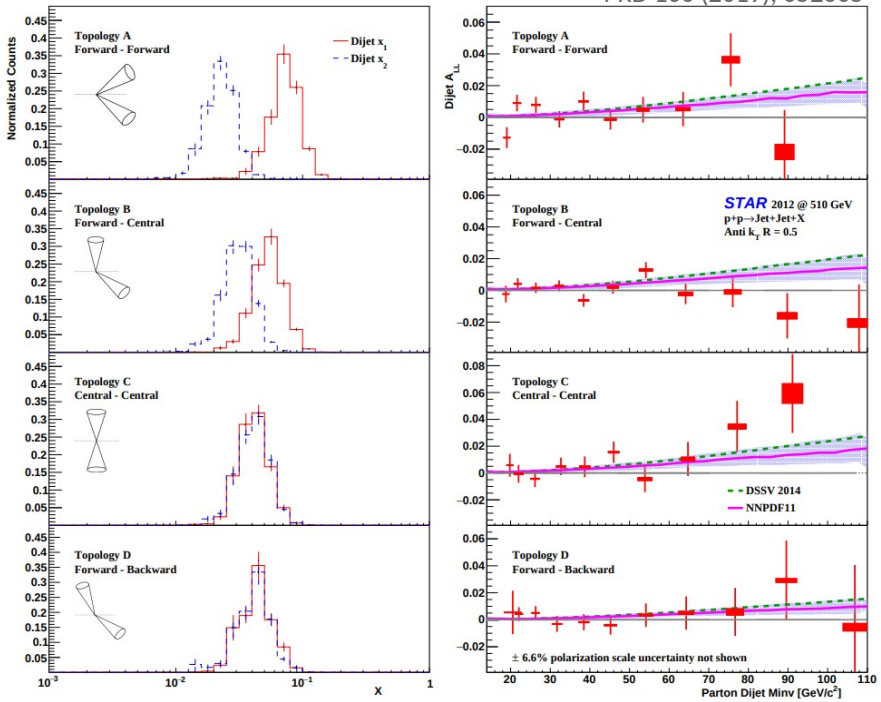
- Better constraints on **functional form of Δg(x) - narrow ranges** of initial state partonic momentum tested
- More-forward production - **lower x** (down to 0.01 with STAR Endcap PRD 98 (2018), 032011)

INCLUSIVE JETS AND DIJETS AT 510 GEV

PRD 100 (2019), 052005



PRD 100 (2019), 052005

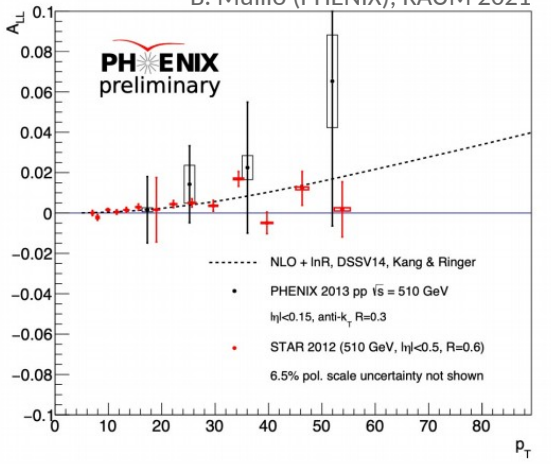


- **Higher √s pushes sensitivity to lower x** (down to ~ 0.004 with STAR Endcap dijets at 510 GeV)
  - Consistent results from both energies and both experiments
- Further precision with jet A_{LL} from Run 2013 data at 510 GeV (x 3.5 statistics w.r.t. Run 2012) and Run 2015 with EEMC

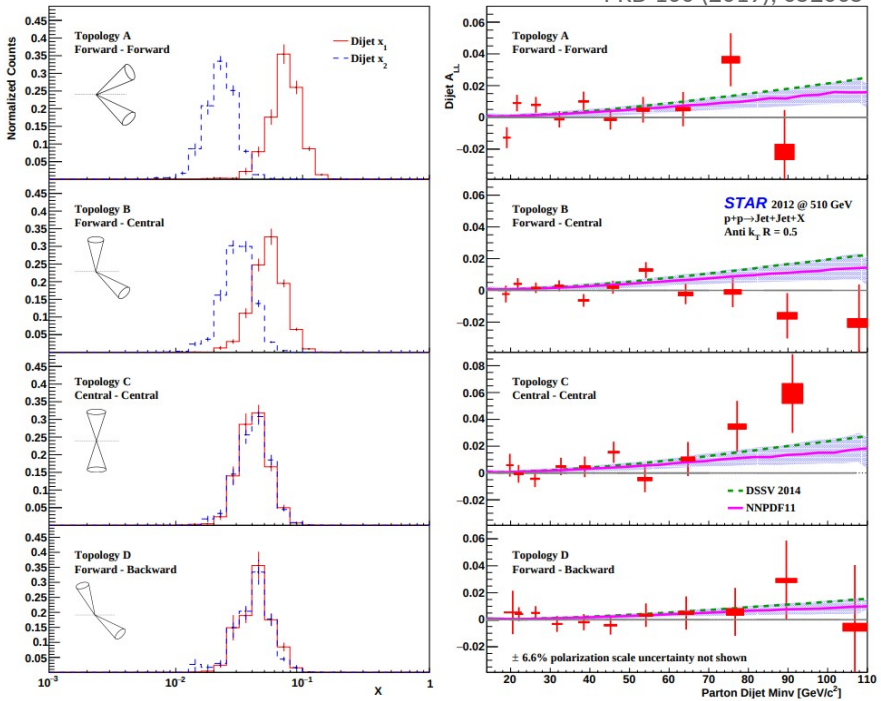
RHIC concluded the data taking with longitudinally polarized protons in 2015
The data are anticipated to provide the most precise insights in Δg(x) well into the future

INCLUSIVE JETS AND DIJETS AT 510 GEV

B. Mulilo (PHENIX), RAUM 2021



PRD 100 (2019), 052005



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SIVERS FUNCTION

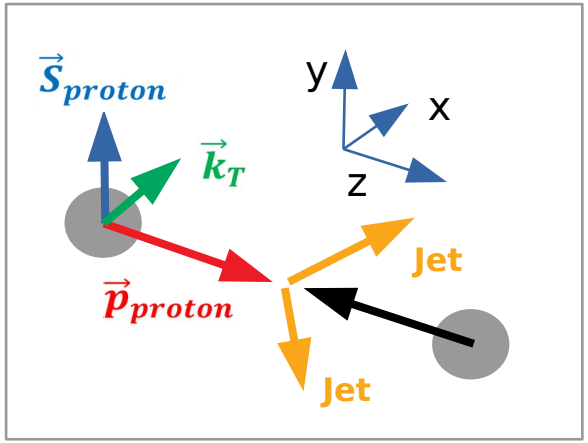
SIVERS FUNCTION WITH DIJETS

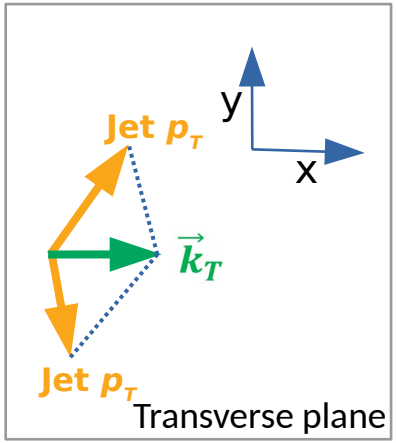
Sivers function - describes correlation between parton's **transverse momentum** inside the proton with proton **transverse spin** (initial state TMD)

Search for a non-zero correlation between proton spin and parton k_T

$$\langle \vec{S}_{proton} \cdot (\vec{p}_{proton} \times \vec{k}_T) \rangle \neq 0$$

Non-zero k_T leads to spin-dependent **tilt of dijet opening angle** in transverse plate

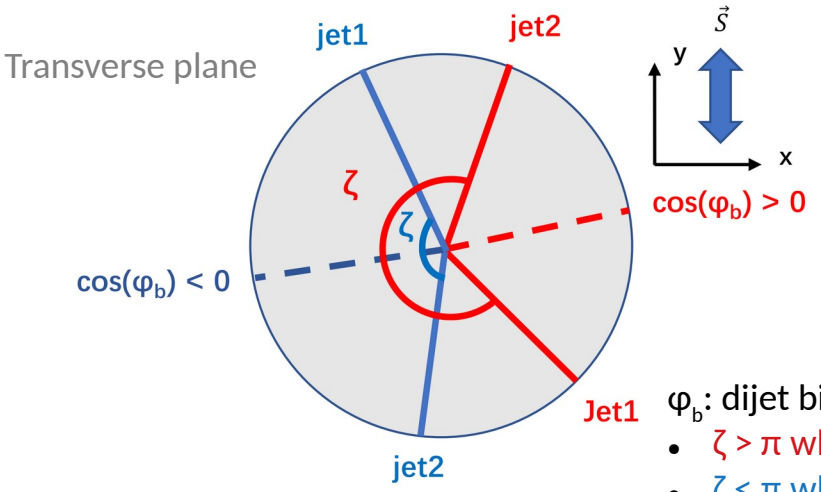




- Net partonic k_T must average to zero → u and d contributions expected to be opposite in sign and different in magnitude
- Explore the Sivers function at a higher Q^2 scale ($Q^2 > 160$ GeV^2) than SIDIS

SIVERS FUNCTION WITH DIJETS

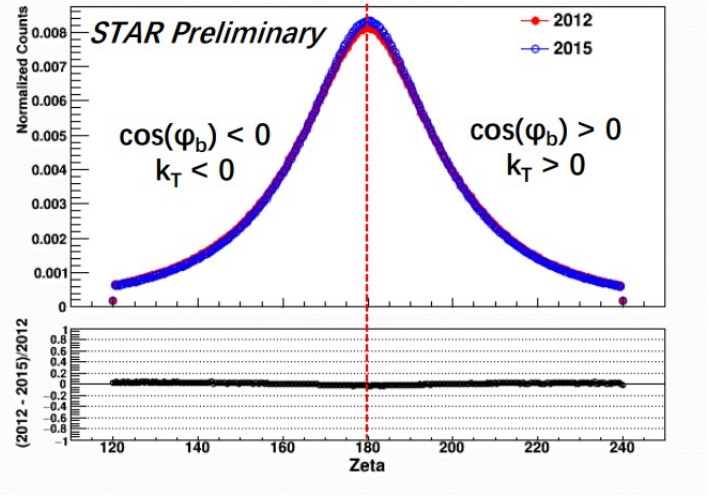
Observable to probe the Sivers effect:**The signed dijet opening angle ζ**



φ_b: dijet bisector angle

- $\zeta > \pi$ when $\cos(\varphi_b) > 0$
- $\zeta < \pi$ when $\cos(\varphi_b) < 0$

H. Liu et. al (STAR), BNL Nuclear Physics Seminar 2020



Asymmetry of the spin-dependent centroid shift of ζ

$$\Delta\zeta = \frac{\langle\zeta\rangle^{+} - \langle\zeta\rangle^{-}}{P}$$

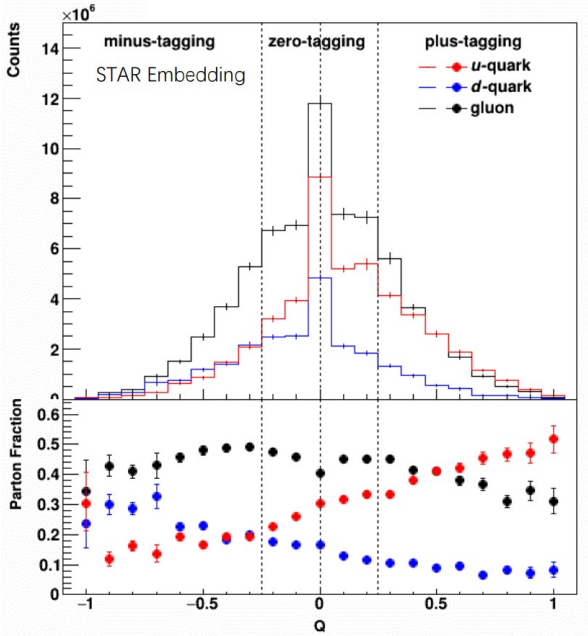
+/- : spin up and down
P: Polarization

Pioneering measurement at STAR Phys. Rev. Lett. 99 142003 (2007):

- the result was found to be consistent with zero within dominant statistical uncertainties

SIVERS FUNCTION WITH DIJETS

Jet "taging": Samples enhancing contribution of u or d quarks (jets sorted by their net charge)

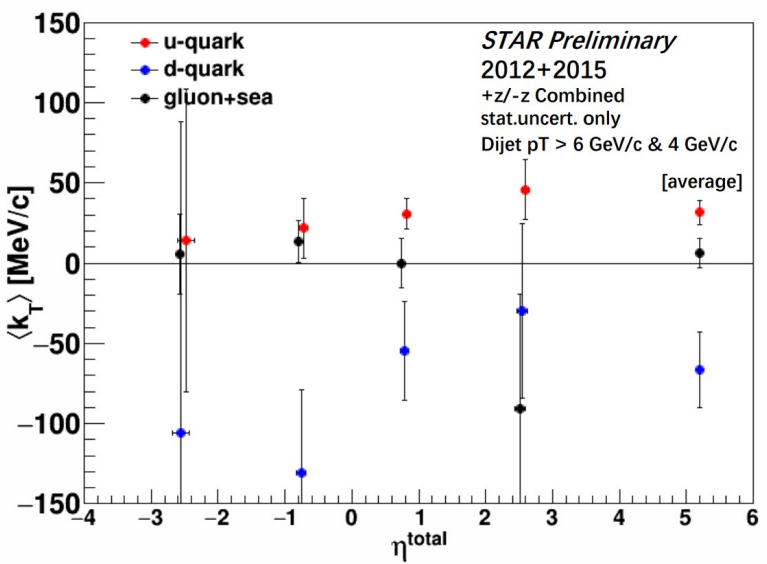


$$Q = \sum_{\substack{\text{tracks} \\ (p_T > 0.8\ \text{GeV})}} \frac{|p|_{\text{track}}}{|p|_{\text{jet}}} q_{\text{track}}$$

Plus tagging (Q ≥ 0.25)
- enhances u

Minus tagging (Q ≤ -0.25)
- enhances d

H. Liu et. al (STAR), BNL Nuclear Physics Seminar 2020



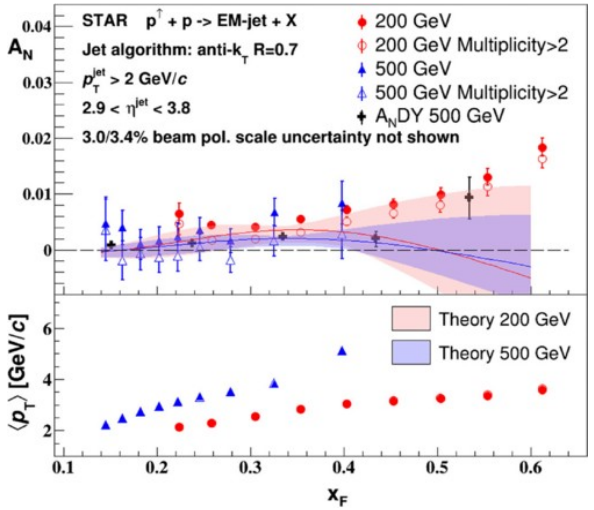
- Conversion of the asymmetry to the k_T results based on purely kinematic model
- Further unfolded for the k_T of individual partons

- Suggests clear flavor dependence: d opposite in sign, twice as large as average k_T for u quarks
- Constrain of the quark Sivers function at a high Q^2 scale (> 160 GeV^2)

SIVERS FUNCTION WITH FORWARD EM-JETS

Forward EM jets A_N with FMS

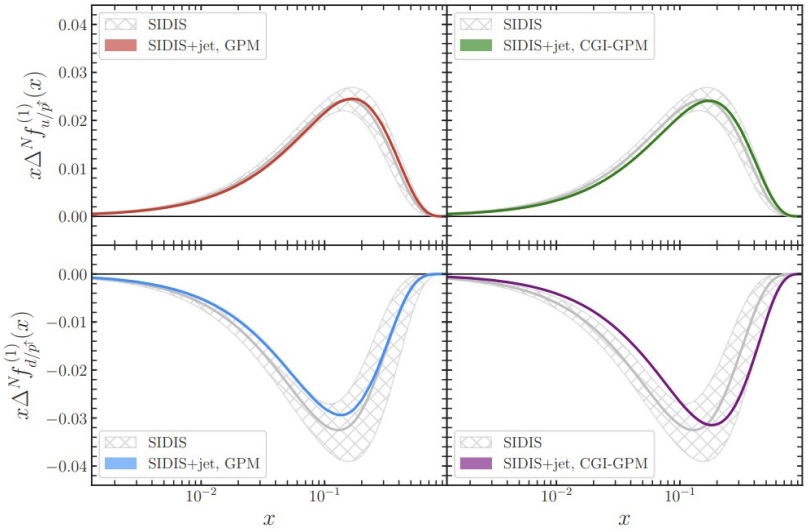
STAR, PRD 103 (2021) 92009



Theory: L. Gamberg, Z. Kang, A. Prokudin, PRL 110 23, 232301 (2013)

Impact of forward EM jets A_N on u and d Sivers function

M.Boglione, et al., Phys. Lett. B 815 (2021) 136135

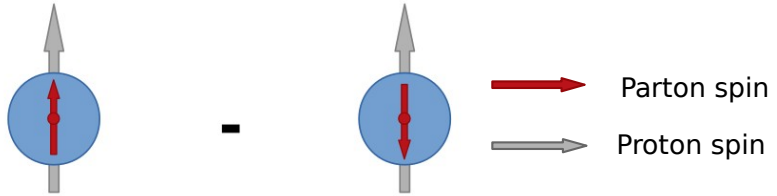


- Measured **small** A_N for EM-jets with weak dependence on the center-of-mass energy (A_NDY and STAR)
- Inclusive EM-jet A_N sensitive to the Sivers function via the twist-3 correlators
- Reduces uncertainty of quark Sivers function extracted from SIDIS

TRANSVERSITY AND COLLINS FF

TRANSVERSITY AND COLLINS FF

Transversity - Net density of quarks with spin aligned with the transversely polarized nucleon (leading twist)

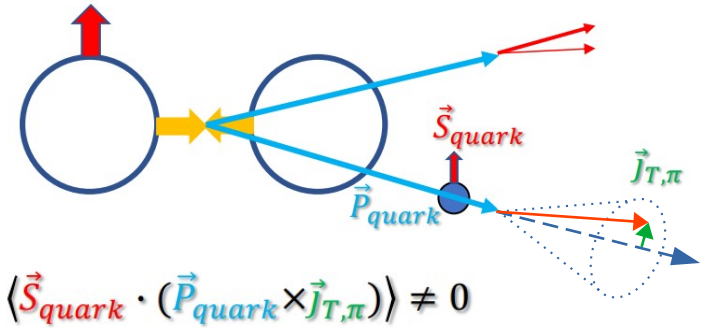


One way to access it at RHIC: A_{UT} asymmetry of spin-dependent modulation of hadrons in jets

Collins function (TMD FF) - Correlation of transverse spin of fragmenting quark and transverse momentum kick given to fragmentation hadron

Transversity Collins FF

$$A_{UT}^{\sin(\phi_S-\phi_H)} \propto \frac{\sum_{a,b,c} h_1^a(x_1,\mu) f_b(x_2,\mu) \Delta\sigma_{ab\to c} H_{1,h/c}^{\perp}(z, j_T, Q)}{\sum_{a,b,c} f_a(x_2,\mu) f_b(x_2,\mu) \sigma_{ab\to c} D_{1,h/c}(z, j_T, Q)}$$

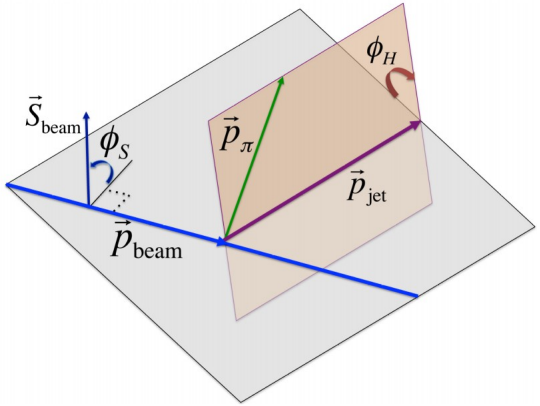


- z - fraction of the jet momentum carried by the hadron
- j_T - component of the hadron momentum that is transverse to the jet axis

- Transversity probed with the jet p_T and η dependence
- Collins TMD sensitive to the hadron j_T and z dependence

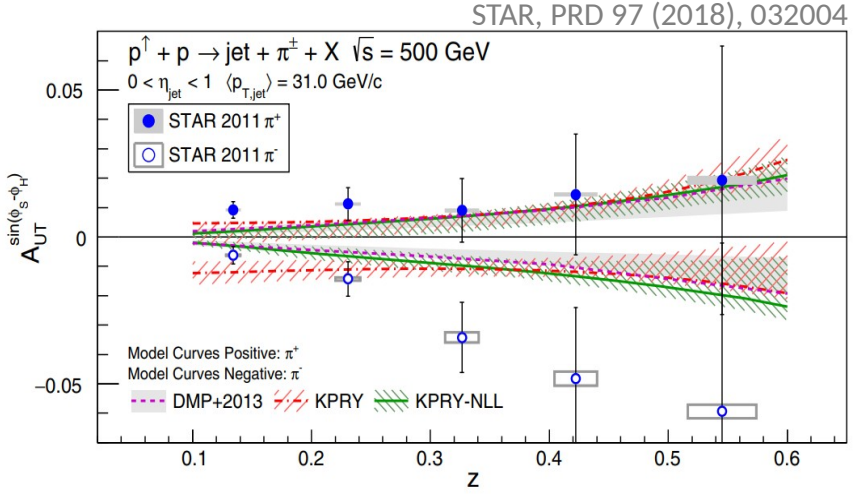
COLLINS ASYMMETRY

PRD 97 (2018), 032004



$$d\sigma^{\uparrow}(\phi_S,\phi_H) - d\sigma^{\downarrow}(\phi_S,\phi_H)$$
$$\sim d\Delta\sigma_0 \sin(\phi_S)$$
$$+d\Delta\sigma_1^{-} \sin(\phi_S - \phi_H) + d\Delta\sigma_1^{+} \sin(\phi_S + \phi_H)$$
$$+d\Delta\sigma_2^{-} \sin(\phi_S - 2\phi_H) + d\Delta\sigma_2^{+} \sin(\phi_S + 2\phi_H)$$

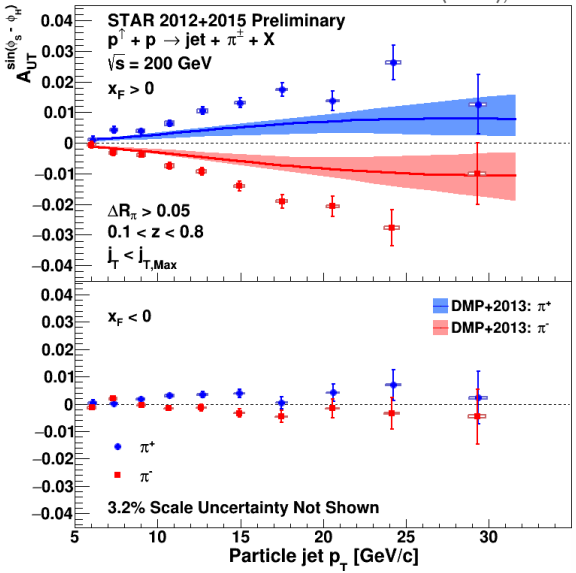
STAR, PRD 97 (2018), 032004



- First measurement at 500 GeV PRD 97 (2018), 032004 reasonably described by calculations combining transversity from SIDIS with the Collins FF from e+e-
- D'Alesio, Murgia & Pisano, PLB 773 (2017), 300
- Kang, Prokudin, Ringer, Yuan, PLB 774 (2017), 635, w/ & w/o evolution

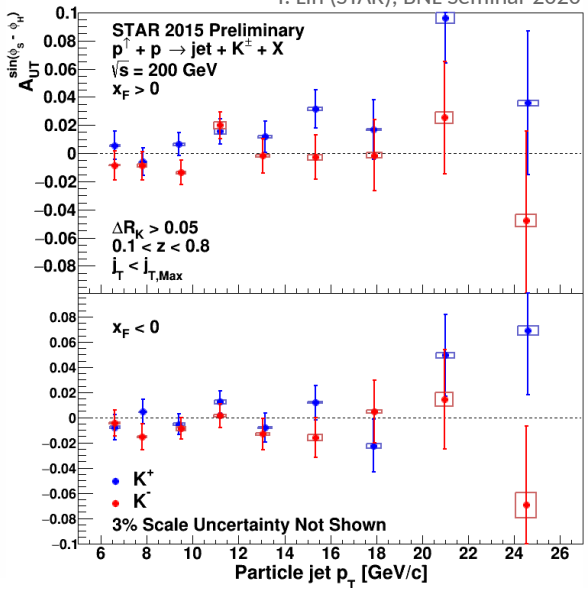
COLLINS ASYMMETRY

T. Lin (STAR), DIS21



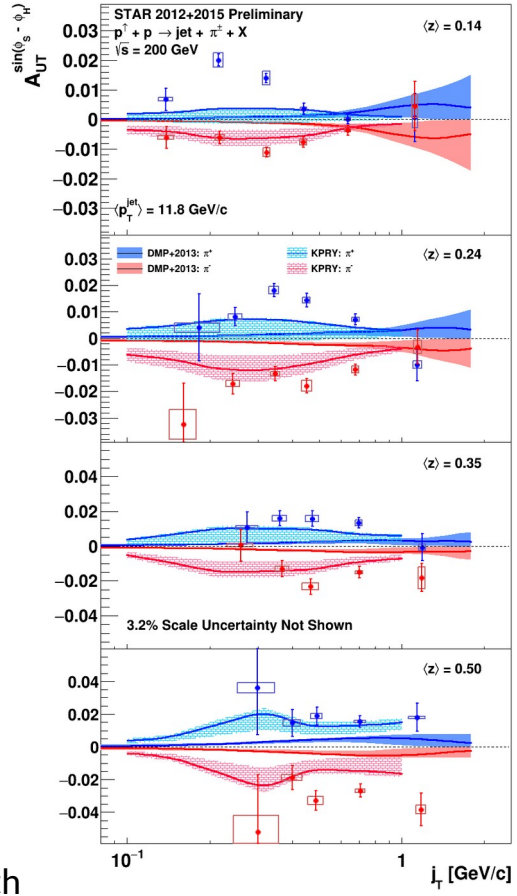
π with 2012 + 2015 STAR data

T. Lin (STAR), BNL Seminar 2020



K with 2012 + 2015 STAR data

T. Lin (STAR), DIS21



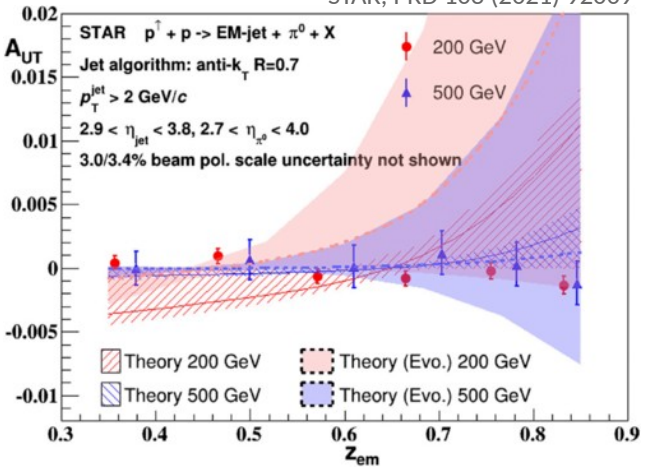
π with 2012 + 2015 STAR data

- Significant Collins asymmetries with π from 200 GeV data (2012 + 2015)
- Peak of A_{UT} distribution for π moves higher as z increases
- First measurement for K (2015 data): A_{UT} for K^+ consistent with π^+ and for K^- with zero within currently large statistical uncertainties

COLLINS ASYMMETRY WITH FORWARD EM-JETS

π^0 in EM jets A_{UT}

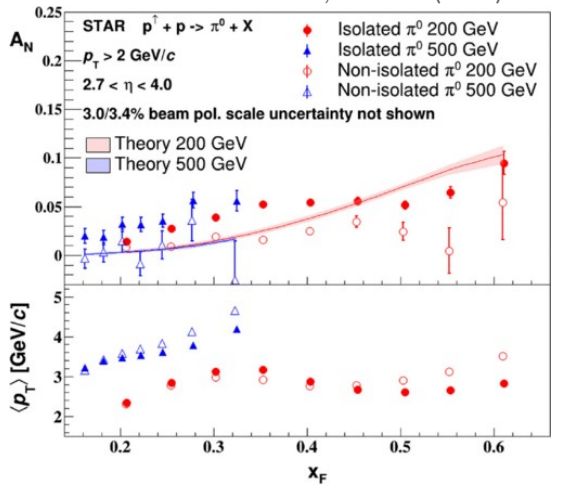
STAR, PRD 103 (2021) 92009



Theory curves : Z. Kang, et al. PLB 774, 635 (2017)

π^0 A_N

STAR, PRD 103 (2021) 92009

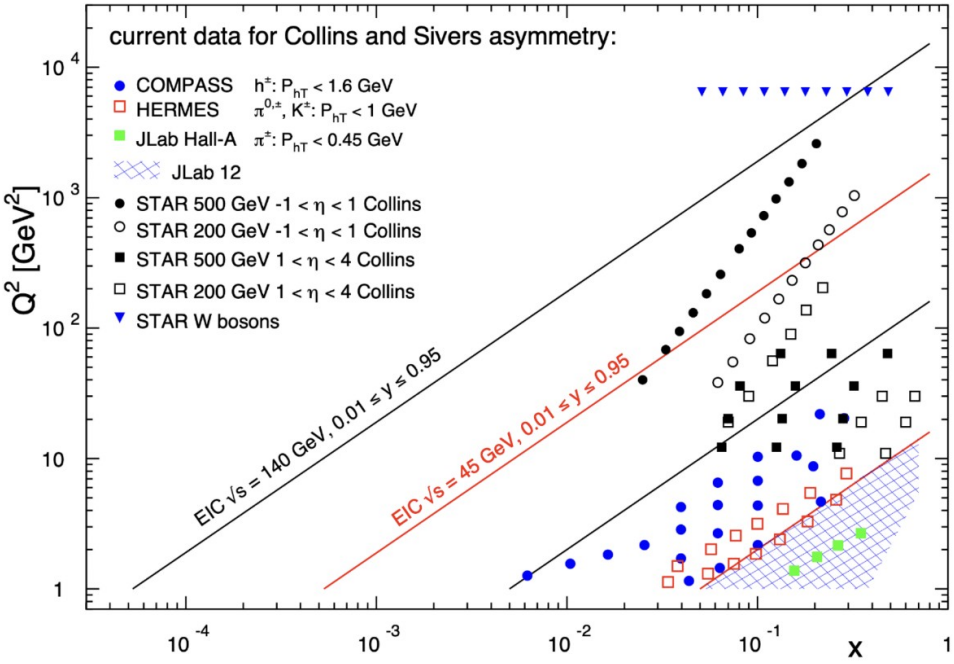


Theory curves: J. Cammarota et al. PRD 102, 054002 (2020)

Can the Collins and Sivers signals we see at mid-rapidity explain large forward A_N?

- Measured **small** A_N for Collins asymmetry for π^0 within EM jets with weak dependence on the center-of-mass energy
- A_N for non-isolated π^0 and higher-multiplicity EM jets lower (description of A_N beyond pQCD $2 \rightarrow 2$ process)

OVERLAP WITH KINEMATIC REACH OF EIC



Sivers and Collins effect at √s = 200 and 500 GeV

→ Study factorization breaking effects for TMD observables in hadronic collisions

→ Important input to study evolution of TMDs and essential kinematic overlap in x-Q^2 with future EIC

- Forward jet and charged hadron capabilities at STAR in **Run 2022**
- Increased statistics in mid-rapidity → STAR and sPHENIX in pp (2022 STAR, 2024) and pA (**2024**) runs

Fixed-target DIS, RHIC-spin, and EIC are truly complementary

FUTURE PLANS AT RHIC

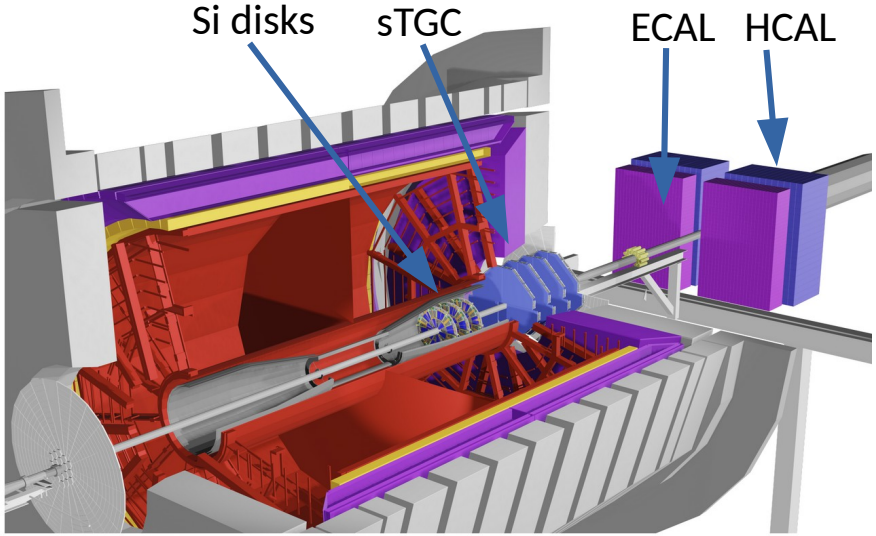
RUN 2022

Program with $p^{\uparrow}p^{\uparrow}$ at 510 GeV with STAR forward upgrade and enhanced PID at mid-η

Forward jet capability and **charge-sign discrimination**: charged-particle tracking (p_T and sign)

- **Tracking:** Si disks + small Thin Gap Chambers (FST + FTT)
- **Calorimetry:** hadronic and electromagnetic (ECAL + HCAL)

Access to **highly asymmetric partonic collisions**: high x-quark and low-x gluon interactions



Forward rapidity 2.5 < η < 4

TMD measurements at high x

- Sivers through tagged jets, direct photon
- Transversity at high x + Collins/IFF
- Diffractive processes

Midrapidity -1.5 < η < 1.5

Improved statistical precision and the extended acceptance with iTPC

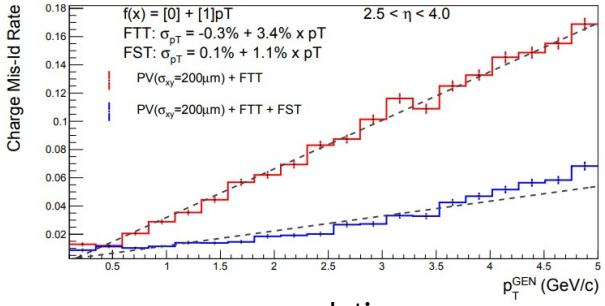
- Sivers measurements with dijet and W/Z
- Transversity + Collins/IFF
- Unpolarized W/Z cross section

FORWARD JETS

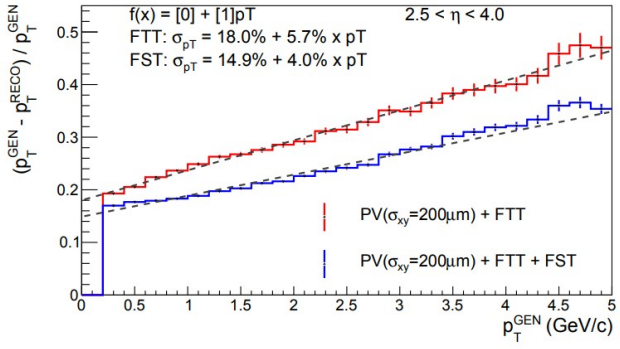
STAR forward upgrade capabilities with **jets and charged hadrons**

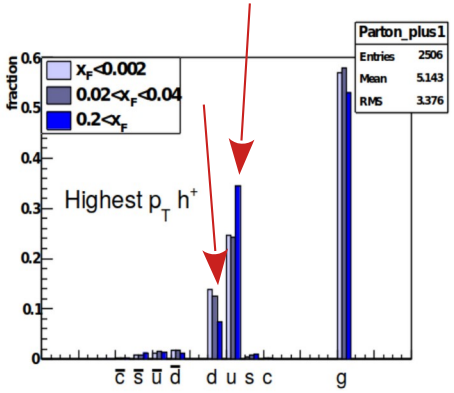
- Study forward **Sivers, Collins** and **Diffractive** processes:
  → charged-hadron enhanced jets (Twist-3 formalism), h in jet Collins asymmetry, diffractive processes with rapidity gaps

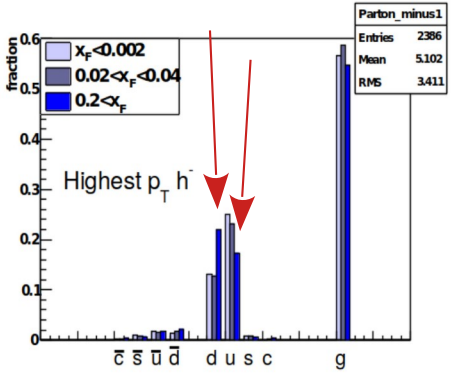
Charge mis-identification rate



p_T resolution





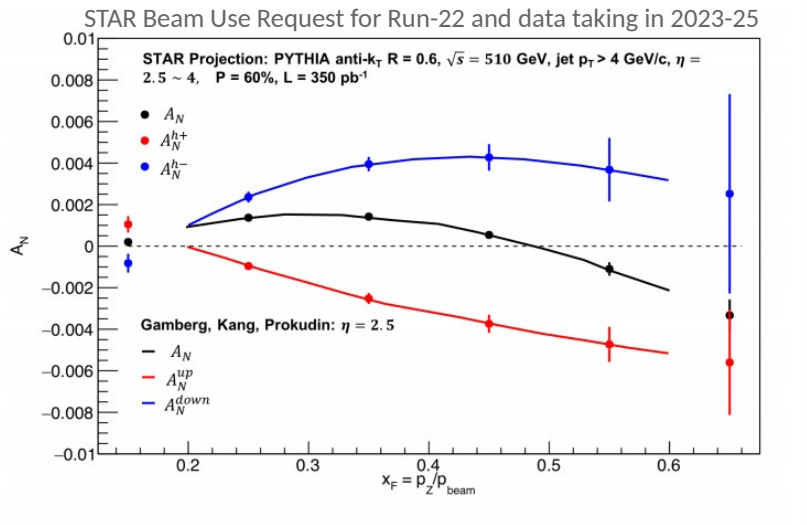


- At forward rapidity u/d quarks enhanced for positively/negatively charged leading hadrons for $x_F > 0.2$
- Very good charge separation power and p_T resolution at Forward Rapidity with FTT and FST

Plots: STAR Beam Use Request for Run-22 and data taking in 2023-25

SIVERS FUNCTION WITH FORWARD JETS

1. Access through the relation with ETQS correlation function (Twist-3 formalism)
→ **A_N for charged-hadron enhanced jets**



- A_N for full jet reconstruction, combined with charge-sign tagging of a hadron fragment with z > 0.5 at 510 GeV
- Overlaid on the theory curves as calculated by the ETQS function, which is based on the SIDIS Sivers functions by Gambert et al.
- Up to 10 σ separation between plus-tagged and minus-tagged jet A_N

2. Direct access to Sivers function with forward dijets
→ **Spin dependent dijet opening angle**

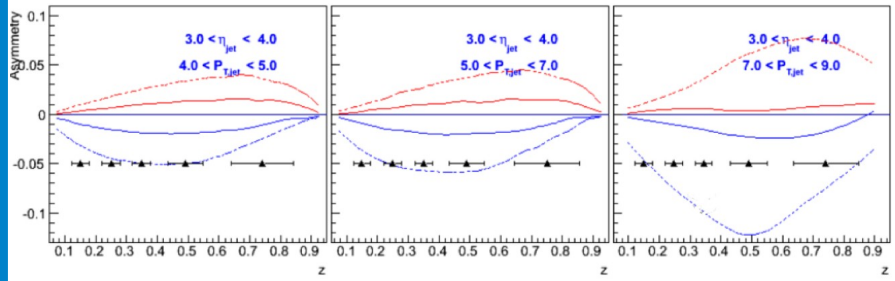
- Mid-rapidity STAR covers $|\eta_1 + \eta_2| < 3$, with forward upgrade access to $|\eta_1 + \eta_2| \sim 6$
- Probing high x-quark and low-x gluon interactions region

COLLINS AND TRANSVERSITY WITH FORWARD JETS

Plots: STAR Beam Use Request for Run-22 and data taking in 2023-25

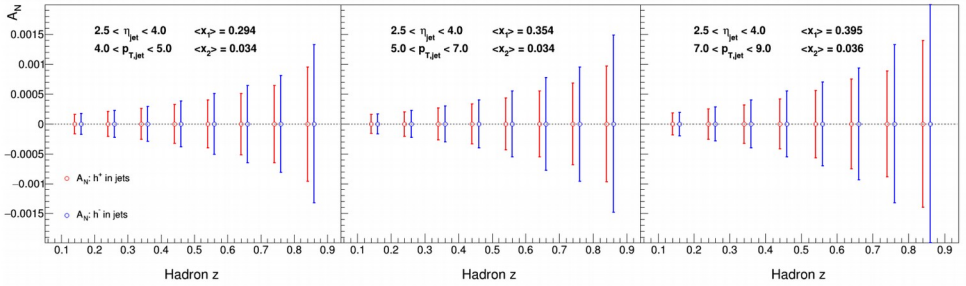
→ A_{UT} for charged-hadron in jets

Torino extraction (full lines), Soffer bound (dashed lines)



zoom

Pythia: $p^{\uparrow} + p \rightarrow jet + h^{\pm} + X$, 510 GeV



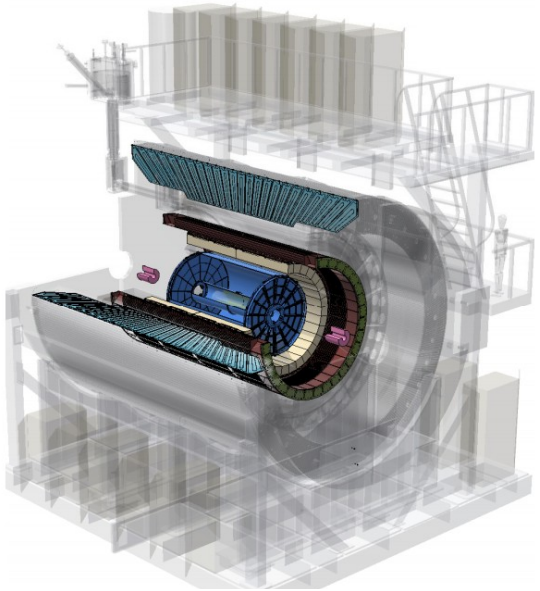
- Extending Collins asymmetry measurements to forward rapidities: direct access to **transversity** in the **region 0.3 < x < 0.5**
  - Probing transvesity in valence region → nucleon tensor charge
- Only charged hadrons considered (no PID), proxy for pions
  - h+: dilution by protons (10-14%) and by kaons (12-13%)
  - h-: ~ 78% purity according to PYTHIA6
- Simultaneous measurements with similar uncertainties of the “Collins-like” asymmetries to access **linearly polarized gluons in transversely polarized protons** down to x ~ 0.005

SPIN PHYSICS WITH SPHENIX AND STAR

Program with $p^{\uparrow}p^{\uparrow}$, $p^{\uparrow}$Au at 200 GeV (sPHENIX + STAR) in 2024: Complementary to each other in the future RHIC measurements

Together with Run 2022:
- Overlap in kinematic coverage with EIC
- Establishing the validity and limits of factorization and universality

See talk by Megan Connors, Jet physics with sPHENIX



Cold QCD opportunities with **sPHENIX**

→ Utilizing the **jet, heavy flavor** and **direct photon** strengths of the sPHENIX **barrel** to probe
- Sivers and Collins effect and
- Nuclear PDFs and FF in **midrapidity**

Capabilities of **STAR** with forward upgrade

- Allows exploration of **low-x → gluon saturation**
  - Opportunity for di-$h^{\pm}$, photon-jet, photon-hadron and dijet correlation measurements in pp and pA
- Nuclear effects in the initial and final state
- Combination of Run 22 results with similar data taken at 200 GeV

SUMMARY

RHIC - critical and complementary role in resolving the spin structure of the proton

RHIC-spin program with jets has provided unique insight into:

- **Polarized gluon distribution**
- Evidence for the positive gluon polarization for x > 0.05

- **Sivers' function**
  Observation of non-zero Sivers effect in dijets
  - 2017 with higher √s and more forward regions from 2022/2024
- **Transversity** through the **Collins and IFF asymmetry**
  Non-zero asymmetries at mid-rapidity that are sensitive to quark-transversity at hard scales
  - 2017 (x 12 more data at 510 GeV) and much higher statistics and better PID in mid-rapidity in 2022/2024

Ongoing STAR upgrades will provide unique physics opportunities with jets in:

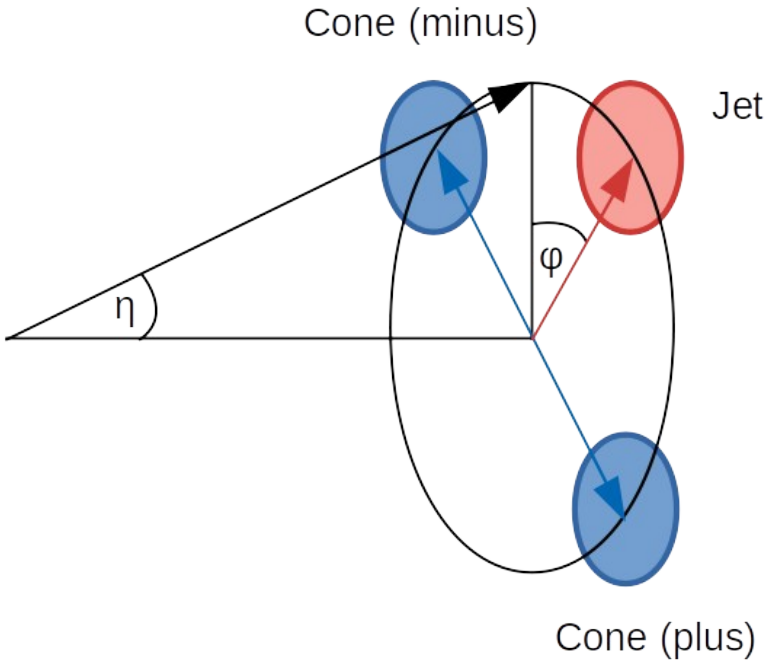
- Constraining tensor charge through **transversity at high x**
- Understanding the origin on **large forward A_N**
- Testing **TMD evolution**
- Probing the non-linear gluon effects and nuclear effects in the initial and final state

BACKUP

UNDERLYING EVENT CORRECTION

Introduced in A_{LL} analysis based on 510 GeV 2012 data analysis STAR, PRD 100 (2019), 052005

- Jet-by-jet underlying event correction using off-axis cone method ALICE, PRD 91 (2015), 112012



Off-axis cones at ± π/2 away in φ and at the same η

$$dp_T = \frac{1}{2}(\sigma_{\text{plus}} + \sigma_{\text{minus}}) \times A_{\text{jet}}$$

σ - energy density, *A* – jet area

Example UE correction values for 2015 data:
p_T = 6 – 7.1 GeV/c: avarage UE dp_T ~ 1 GeV/c
p_T = 26.8 – 31.6 GeV/c: avarage UE dp_T ~ 0.7 GeV/c