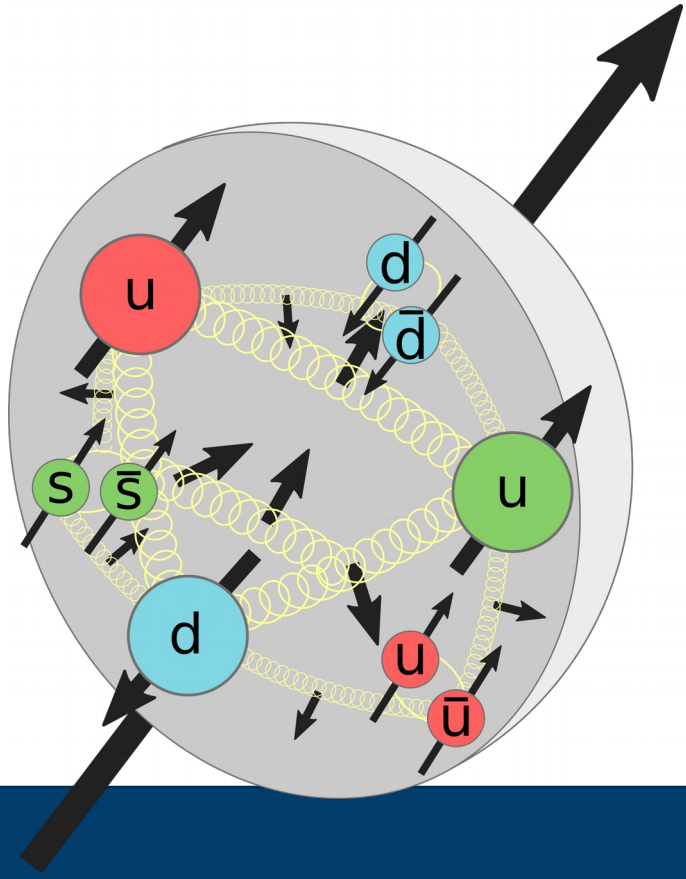


SUMMARY OF SPIN JET MEASUREMENTS FROM RHIC

25 NOV 2020 | MARIA ŻUREK | LAWRENCE BERKELEY NATIONAL LABORATORY

JETS FOR 3D IMAGING AT THE EIC – ONLINE WORKSHOP

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

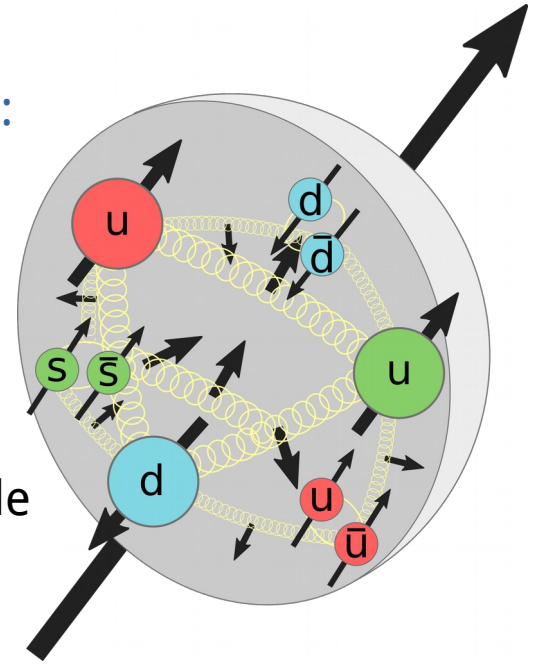
Tool:

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

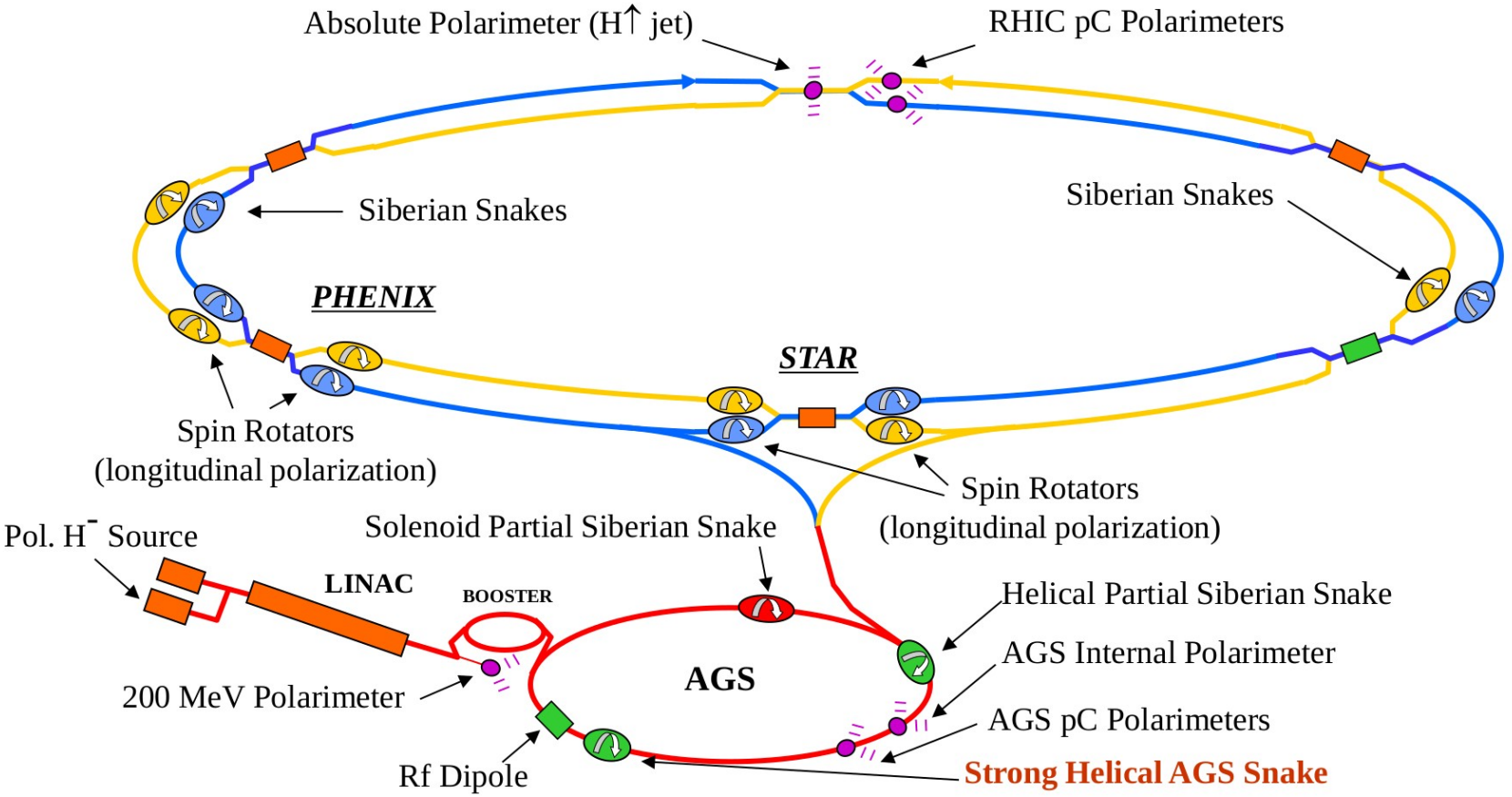
Jets as a probe to address questions about **proton spin structure** in the **collinear** and **transverse** momentum dependent frameworks:

1. **Gluon helicity** distribution: inclusive jet and dijet A_{LL}
2. **Quark transversity** distribution: A_{UT} of hadrons in jets

3. **Collins fragmentation function**: A_{UT} of hadrons in jets
4. **Quark Sivers function**: Asymmetry of the tilt of dijet opening angle



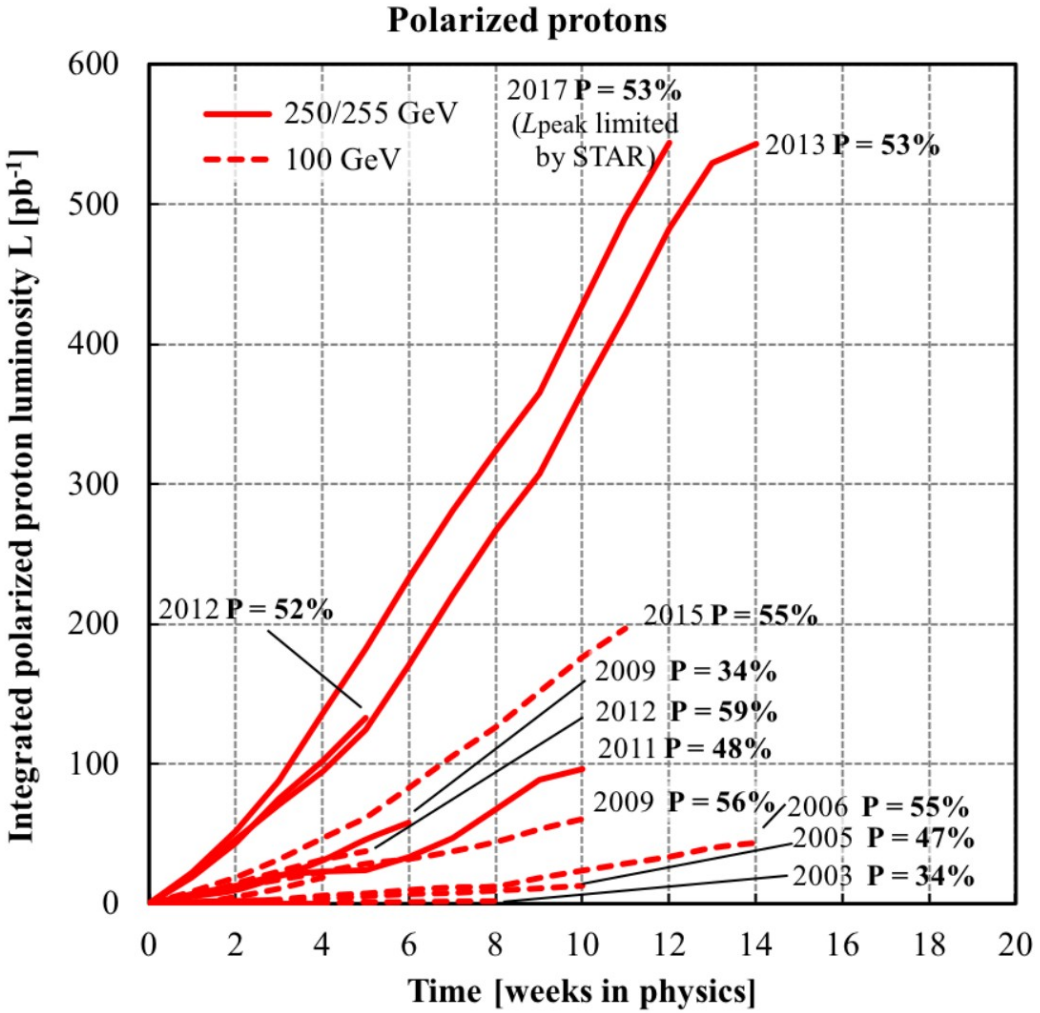
RHIC – POLARIZED PROTON COLLIDER



- 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

RHIC – POLARIZED PROTON COLLIDER



SOLENOIDAL TRACKER AT RHIC

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

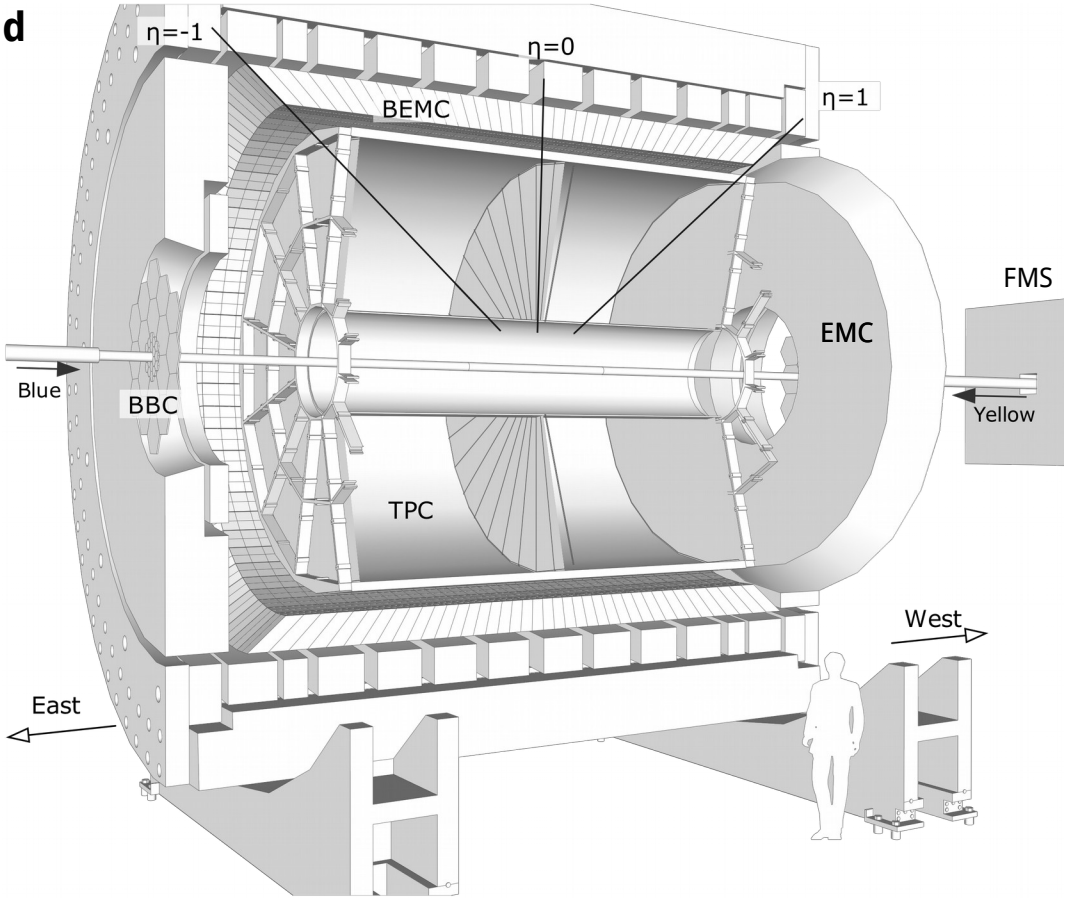
2. Electromagnetic Calorimeter
$\Delta\varphi = 2\pi$, $-1 < \eta < 2$
Barrel ($|\eta| < 1$) and Endcap ($1 < \eta < 2$)
- Energy measurement, trigger

3. Time of Flight Barrel
$\Delta\varphi = 2\pi$, $|\eta| < 1$
- PID

4. 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



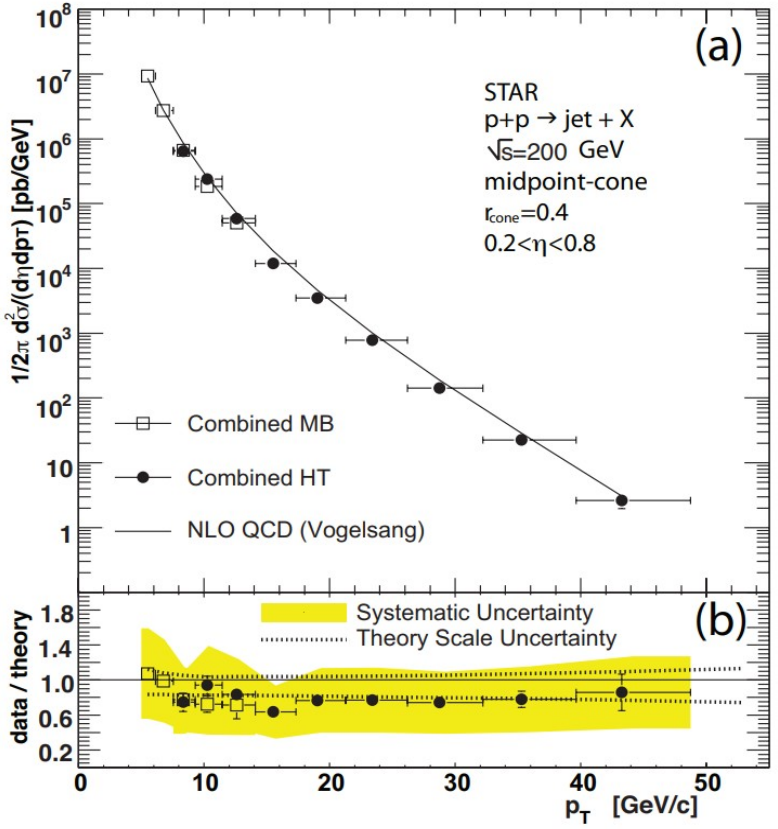
Characteristics
- Large acceptance (PID and calorimetry)
- **Good detector for jets**
- Upgrades: iTPC, EPD, ETOF, Fwd Upgrade

Focusing mostly on **STAR** in this talk. **PHENIX, BRAHMS, pp2pp, ANDY** comparatively little jet capability thus far.

JET CROSS-SECTIONS

Inclusive jet cross section

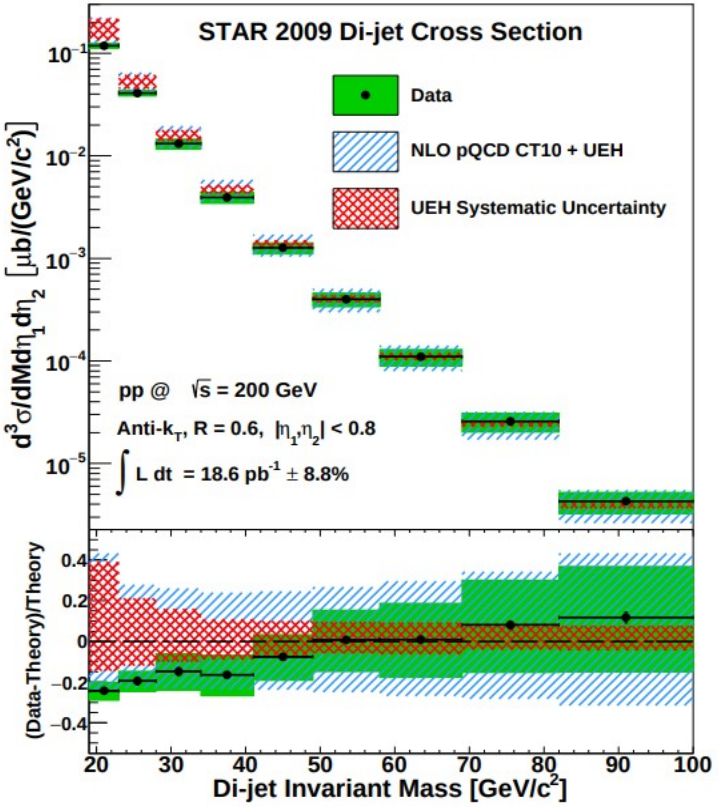
Data: Phys. Rev. Lett. 97 (2006) 252001
Theory: B. Jager et al., Phys. Rev. D 70, 034010 (2004)



- Midpoint cone algorithm
- No UE correction
- Bin-by-bin detector level corrections
- New measurement with improved analysis from STAR in progres

Dijet cross section

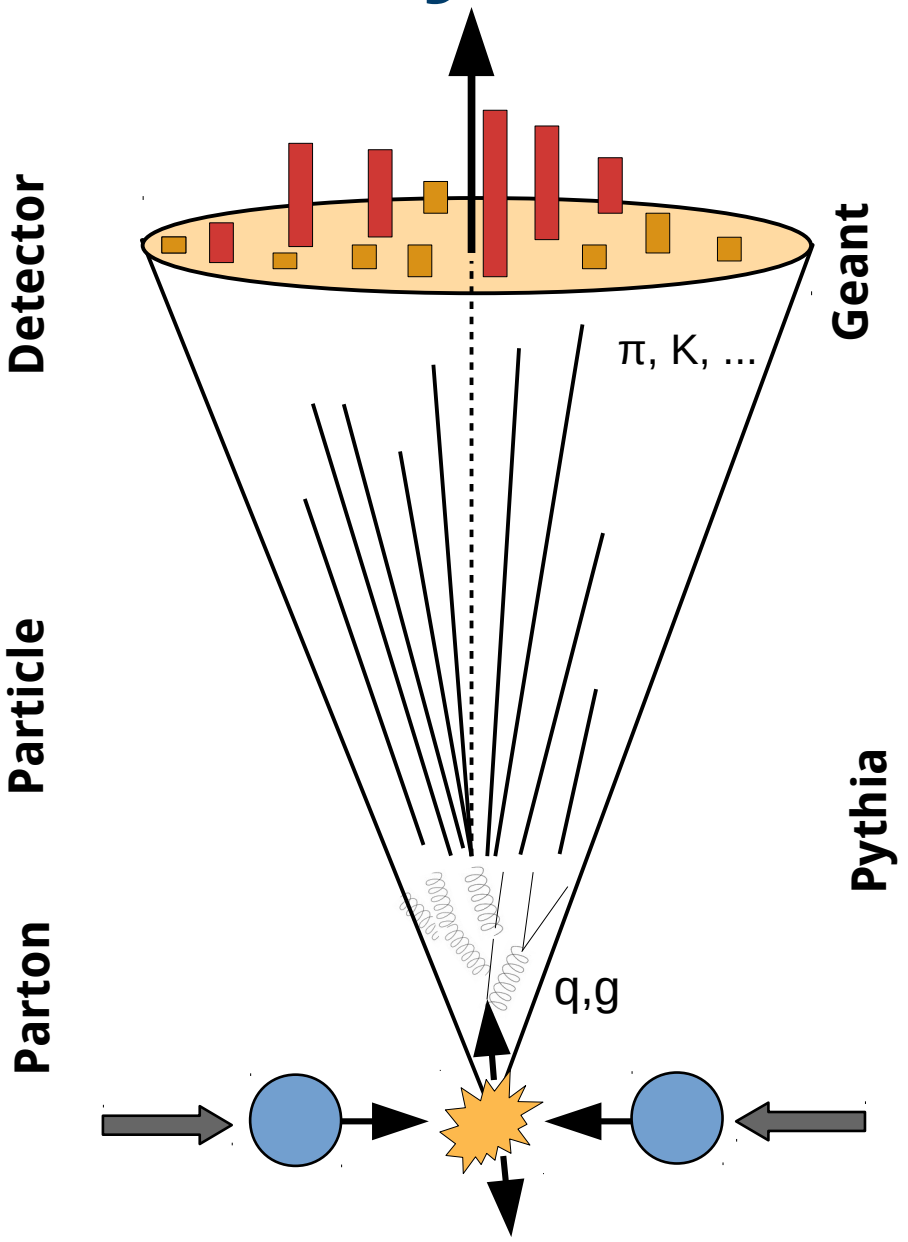
Data: Phys. Rev. D 95 (2017) 71103
Theory: D. de Florian, et al., Nucl. Phys. B 539, 455 (1999)
H. L. Lai, et al., Phys. Rev. D 82, 074024 (2010)



- Anti-k_T algorithm
- MC-driven UE correction
- Detector effects unfolded

Cross-section measurement support the **NLO pQCD** interpretation of asymmetries

CURRENT JET RECONSTRUCTION AT STAR



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 + 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

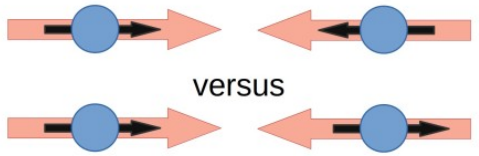
Jet momentum resolution ~ 18%

GLUON HELICITY

HOW TO ACCESS ΔG?

At pp collider: leading order access to gluons → **ΔG/G**

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

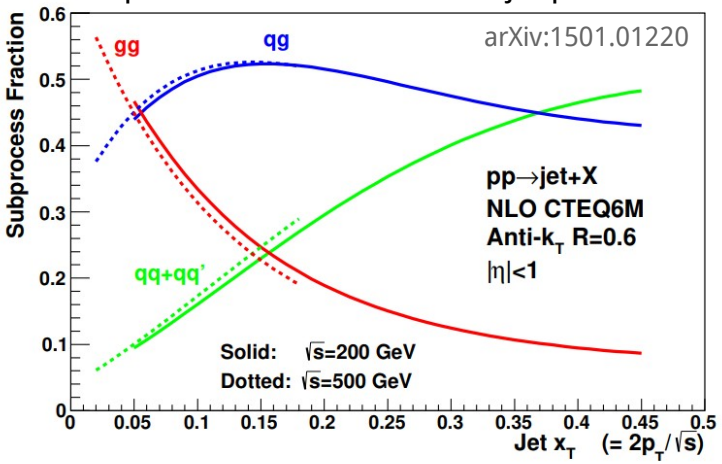


$$A_{LL}=\frac{\sigma_{++}-\sigma_{+-}}{\sigma_{++}+\sigma_{+-}}=\frac{\Sigma\Delta f_a\otimes\Delta f_b\otimes\hat{\sigma}\hat{a_{LL}}}{\Sigma f_a\otimes f_b\otimes\hat{\sigma}}$$

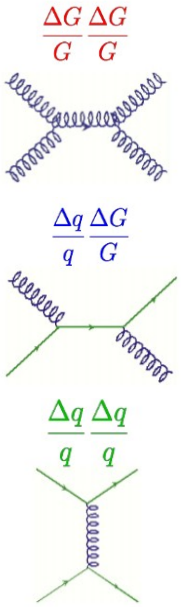
LO for illustration

Which processes dominate at RHIC?

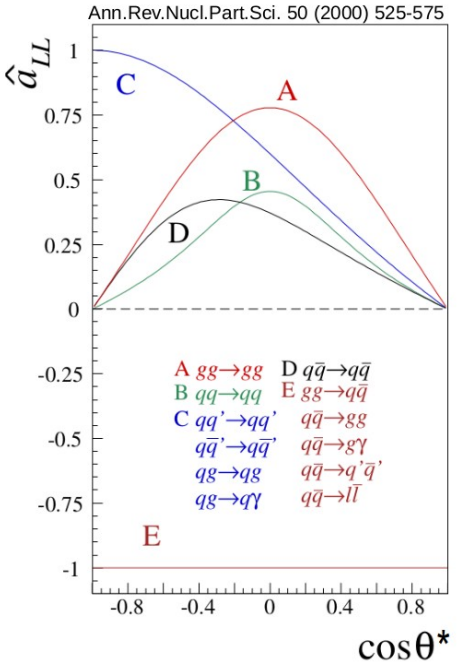
Subprocess fraction in central jet production



Sensitive to qg and gg – Access to **ΔG/G**



What are a_{LL} for these processes?



- Cross-section measurement to support the NLO pQCD interpretation of asymmetries

HOW TO ACCESS ΔG?

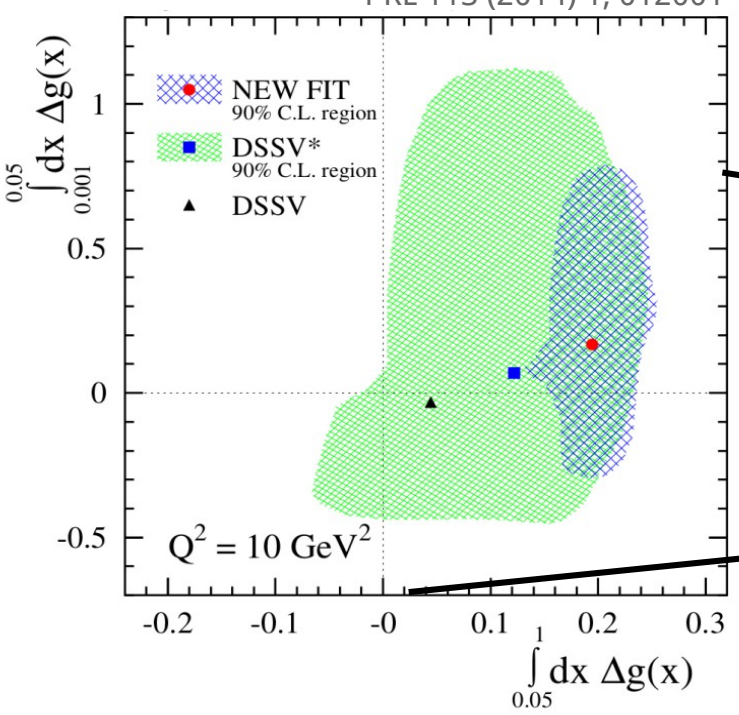
STAR inclusive jet A_{LL} from 2009 data (25 pb^{-1}) at √s = 200 GeV PRL 115 (2015) 9, 092002

- Included in global pQCD analysis provided evidence for **positive gluon polarization for x > 0.05 at Q^2 = 10 GeV**

$$\text{DSSV:} \quad 0.20^{+0.06}_{-0.05}, \quad \text{at } 90\% \text{ C.L. }, x > 0.05 \qquad \text{PRL 113 (2014) 1, 012001}$$

$$\text{NNPDF:} \quad 0.23 \pm 0.07, \quad 0.05 < x < 0.5 \qquad \text{Nucl. Phys. B 887 (2014) 276-308}$$

PRL 113 (2014) 1, 012001



Huge uncertainties outside kinematic reach of existing data

High-x range

Further precision from:

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

Low-x range

Extend sensitivity to smaller x_g:

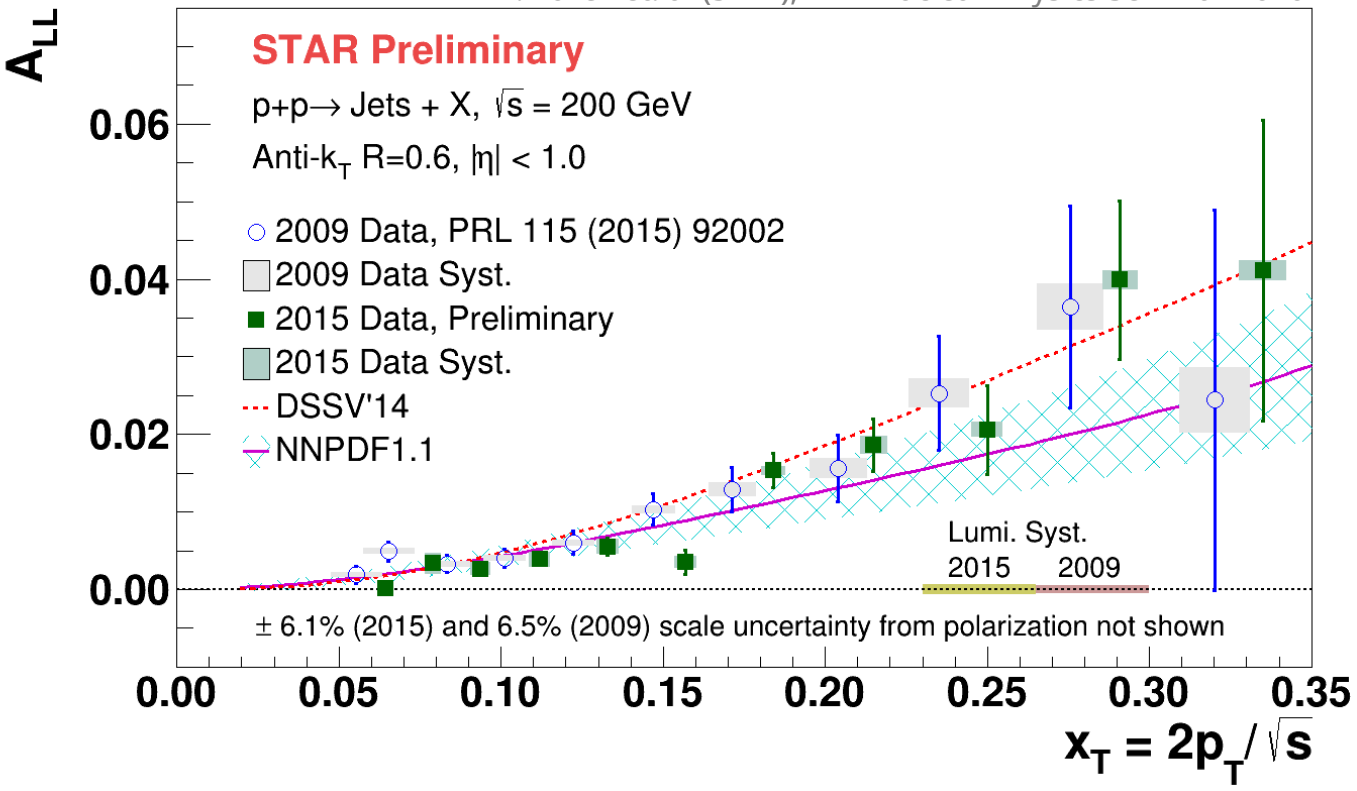
- Forward rapidity $x_g \propto \exp(-\eta)$
- √s = 510 GeV data $x_g \propto 1/\sqrt{(s)}$

INCLUSIVE JETS AT 200 GEV

Towards higher precision at x > 0.05

- The most precise 200 GeV dataset likely to **conclude the 200 GeV longitudinal program with jets.**
- Preliminary result on jet and dijet A_{LL} from STAR from 2015 data.

M. Żurek et. al (STAR), BNL Nuclear Physics Seminar 2020

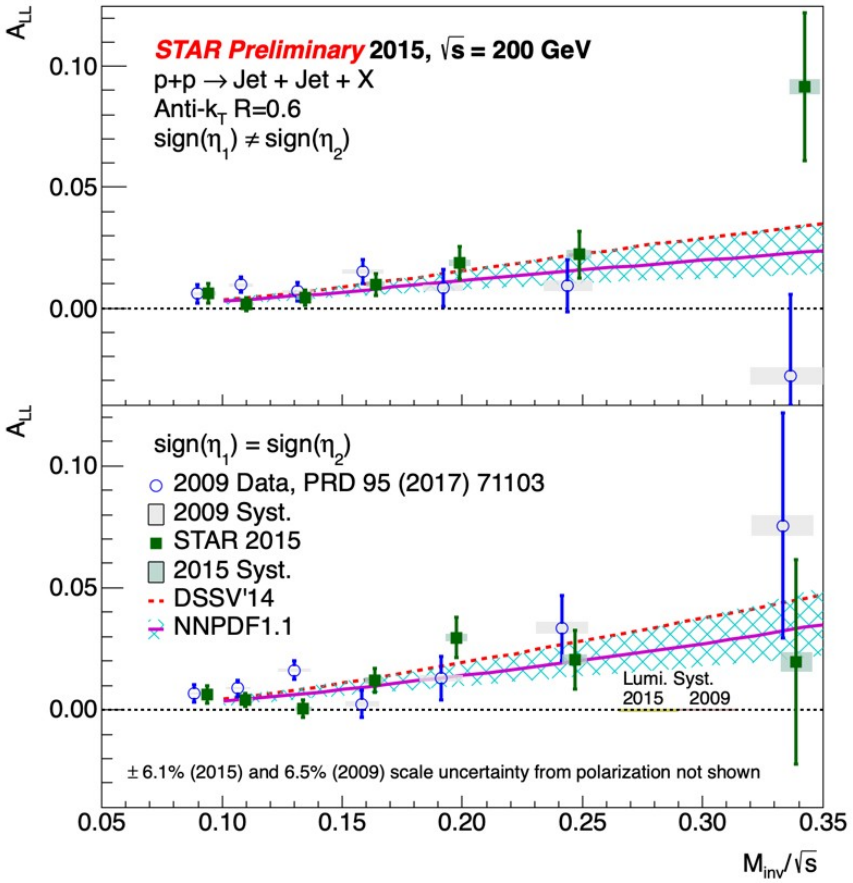


- Consistent with 2009 data, which provided first evidence for positive ΔG for x > 0.05
- Twice larger figure-of-merit ($\mathcal{L}P^4$) with improved systematics
- Will significantly reduce uncertainty on gluon polarization for x > 0.05 once included in global fits

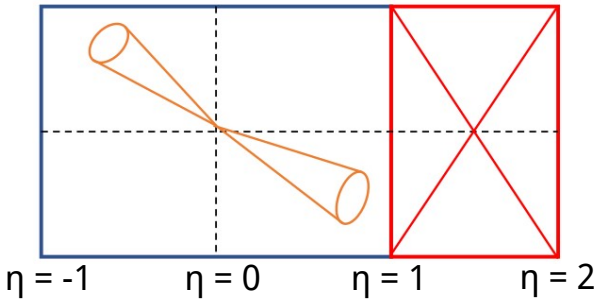
DIJETS AT 200 GEV

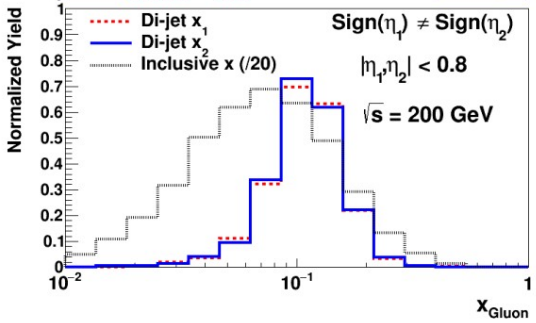
Towards higher precision at x > 0.05

N. Lukow et. al (STAR), RAUM 2020

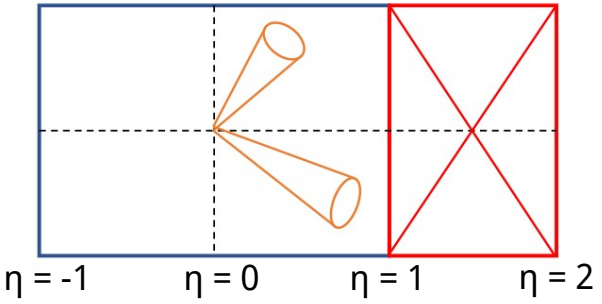


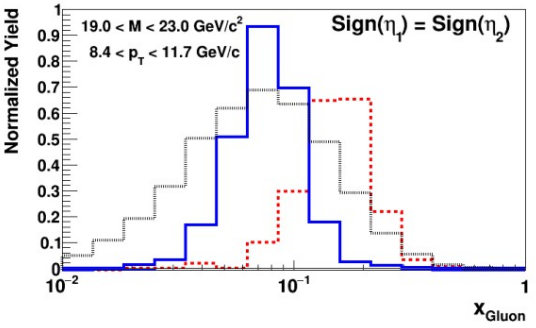
$\text{sign}(\eta_1) \neq \text{sign}(\eta_2)$





$\text{sign}(\eta_1) = \text{sign}(\eta_2)$





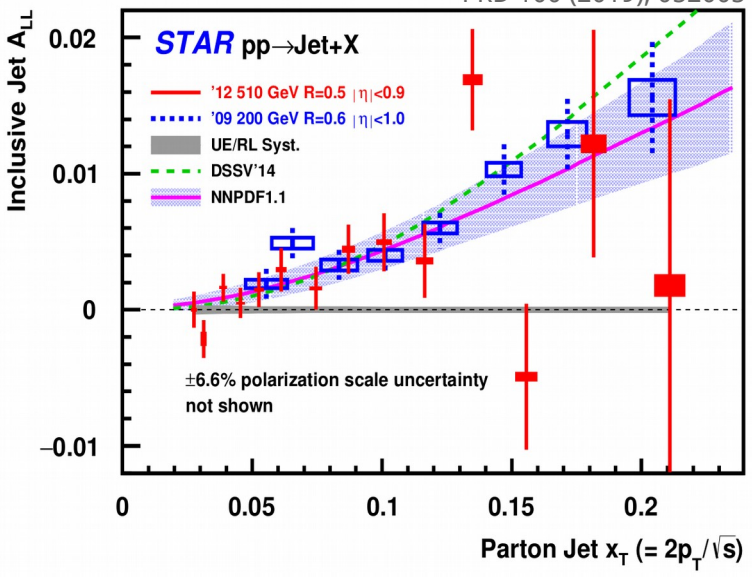
Dijets give stricter constraints to underlying **partonic kinematics**

- May place better constraints on **functional form of ΔG(x)**
- More-forward production - **lower x down to 0.01,** x_2 – likely gluon, x_1 – likely quark
- **Narrow ranges** of initial state partonic momentum tested

JETS AT 510 GEV

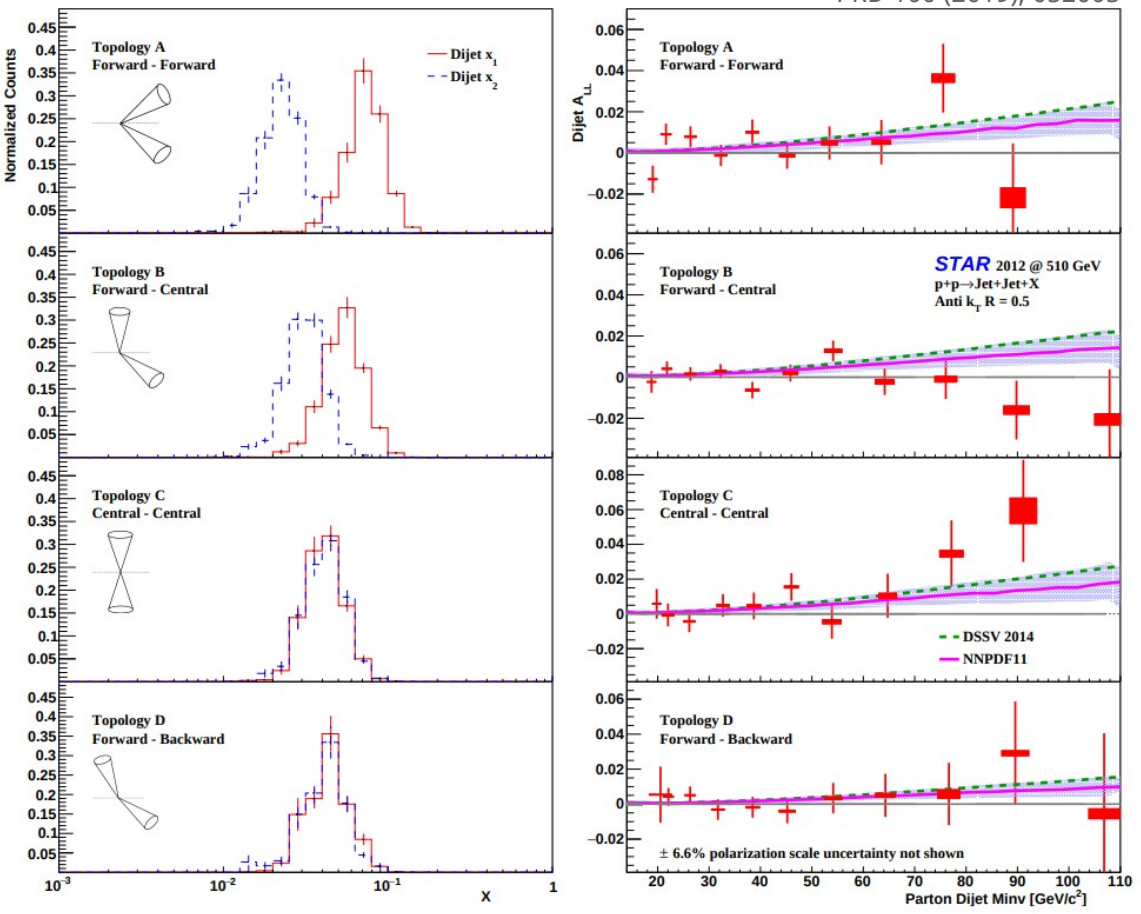
Towards smaller x and complementary probes

PRD 100 (2019), 052005



- **Higher √s pushes sensitivity to lower x > 0.02**
- Consistent results from both energies

PRD 100 (2019), 052005



Further precision: Run 2013 √s = 510 GeV – x 3.2 statistics

TRANSVERSE MOMENTUM DISTRIBUTIONS

SIVERS FUNCTION

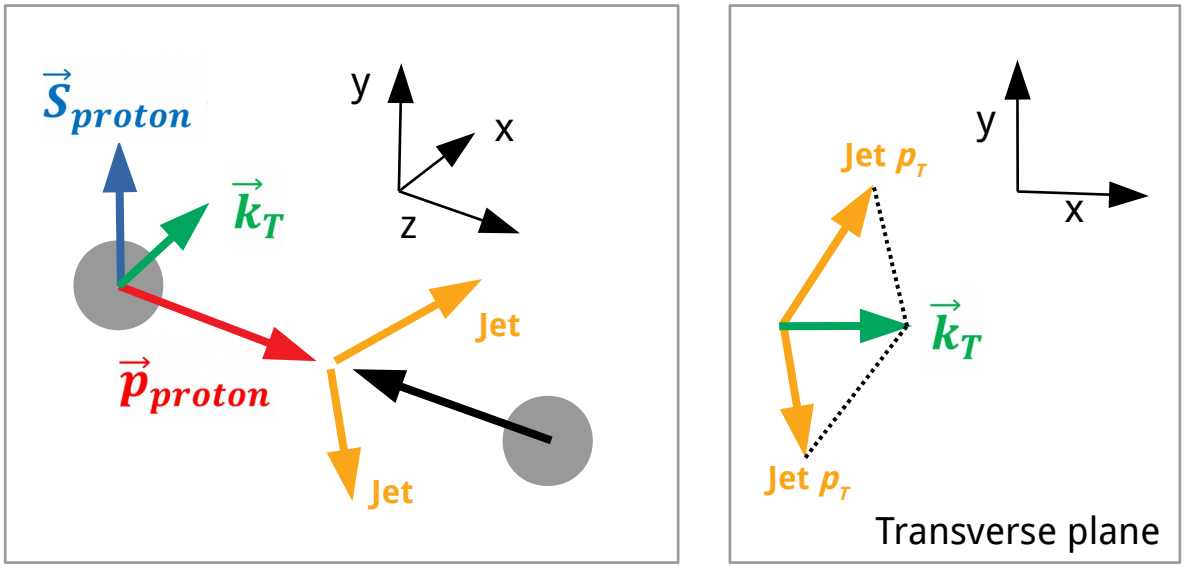
SIVERS FUNCTION WITH JETS

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

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

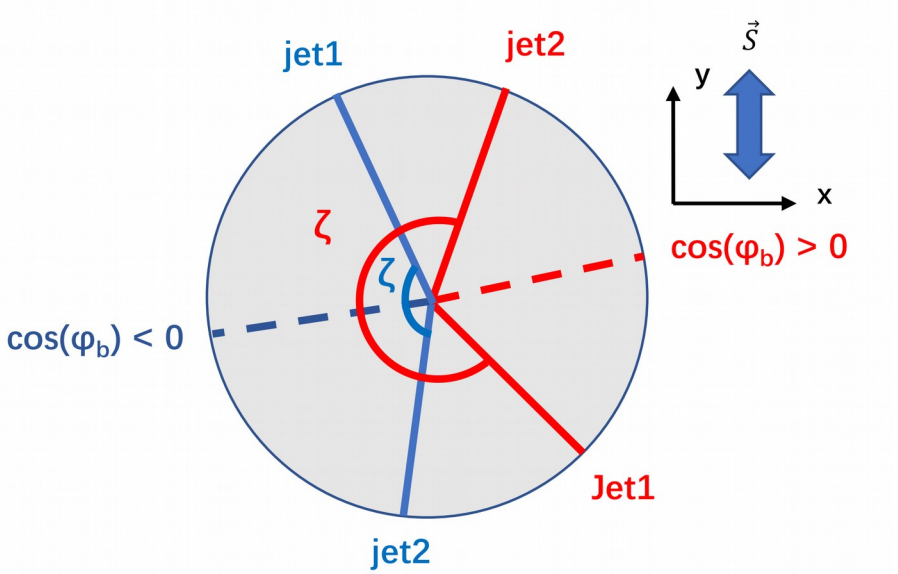
Non-zero k_T leads to spin-dependent **tilt of dijet opening angle** in transverse plate



- 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

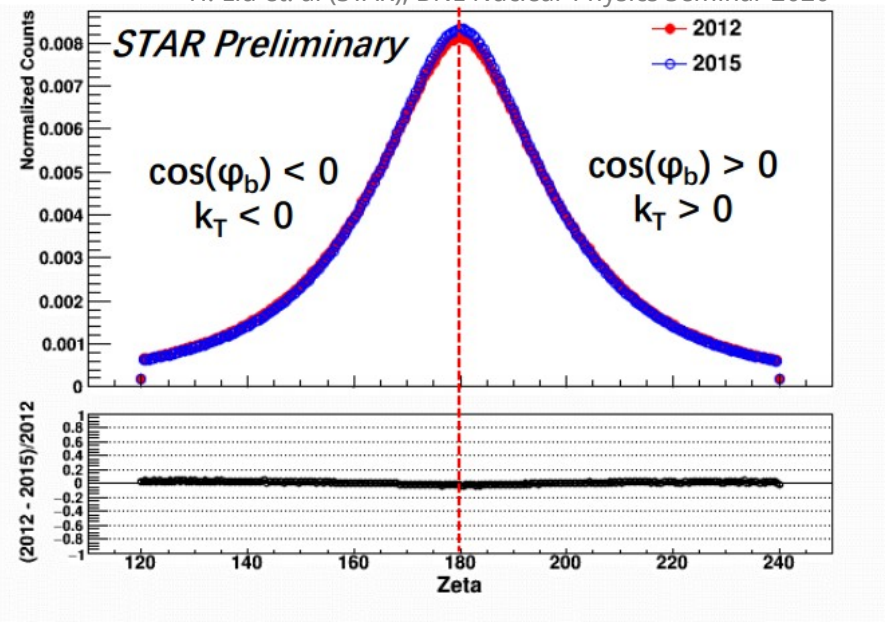
SIVERS FUNCTION WITH JETS

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



Transverse plane

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

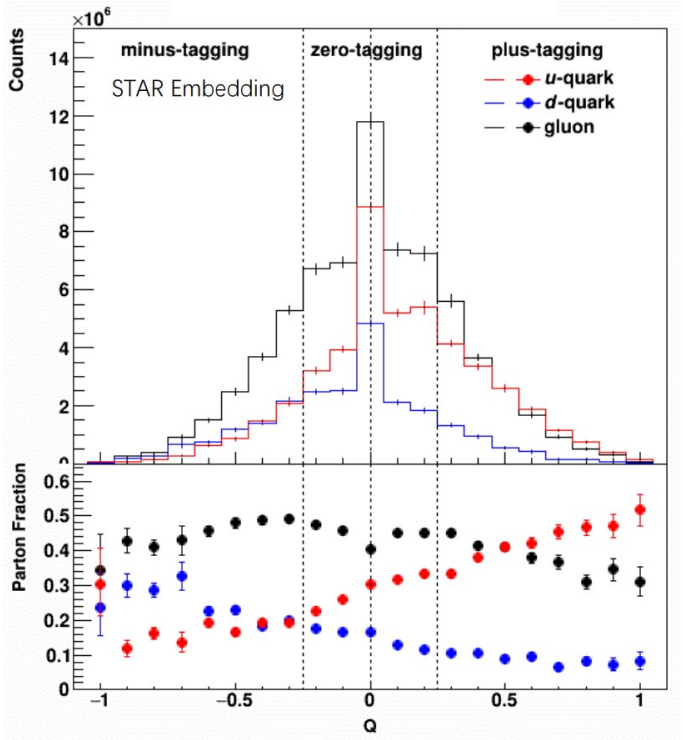
φ_b: dijet bisector angle

- ζ > π when $\cos(\varphi_b) > 0$
- ζ < π when $\cos(\varphi_b) < 0$

Pioneering measurement at STAR Phys. Rev. Lett. 99 142003 (2007): the result was found to be consistent with zero within dominant statistical uncertainties

ASYMMETRY FOR THE DIJET OPENING-ANGLE

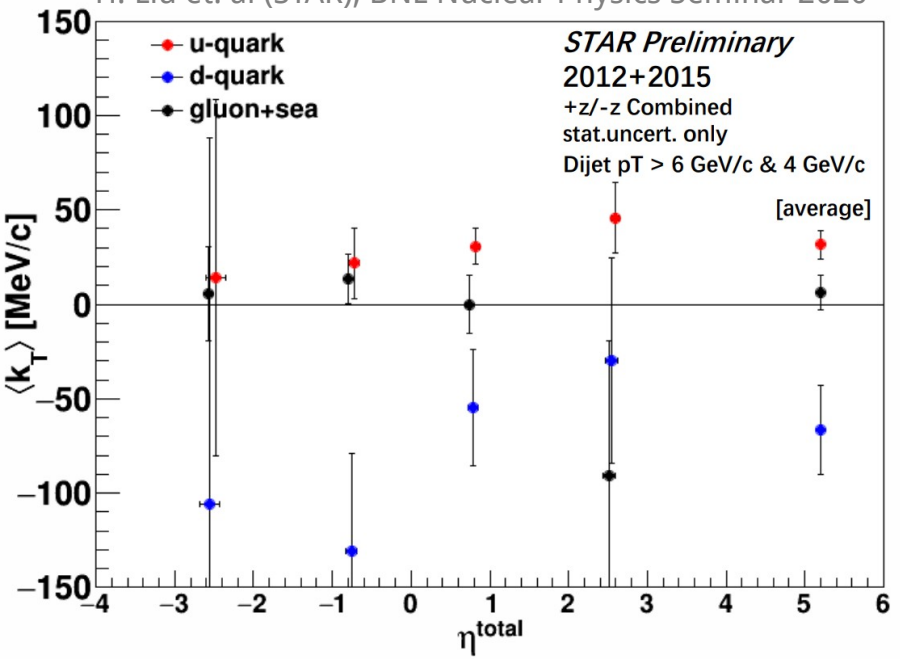
Jet "taging": Samples enhancing contribution of u or d quarks (jets sorted by their net charge)



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

Observation of non-zero Sivers effect in dijets

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



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

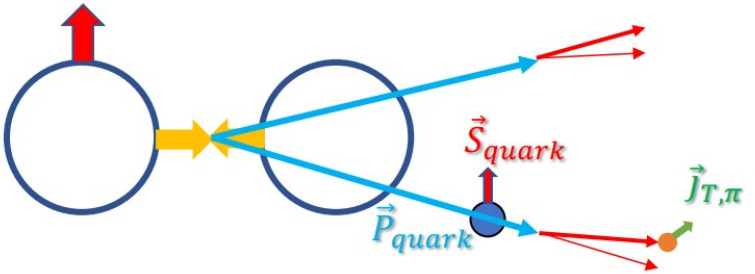
TRANSVERSITY AND COLLINS FUNCTION

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



$$\langle \vec{S}_{quark} \cdot (\vec{P}_{quark} \times \vec{j}_{T,\pi}) \rangle \neq 0$$

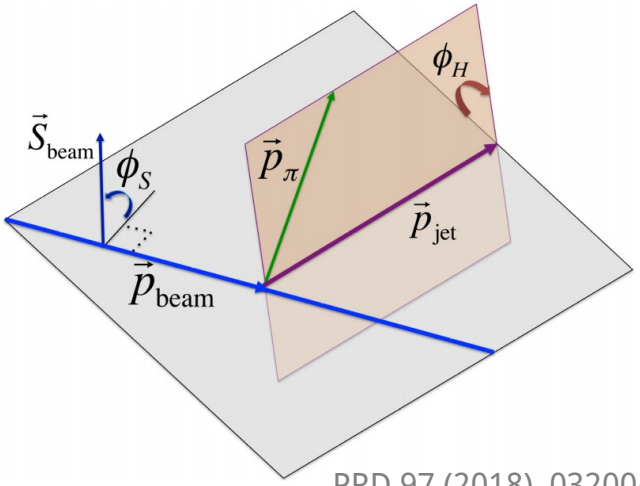
Transversity — Collins FF

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

- 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

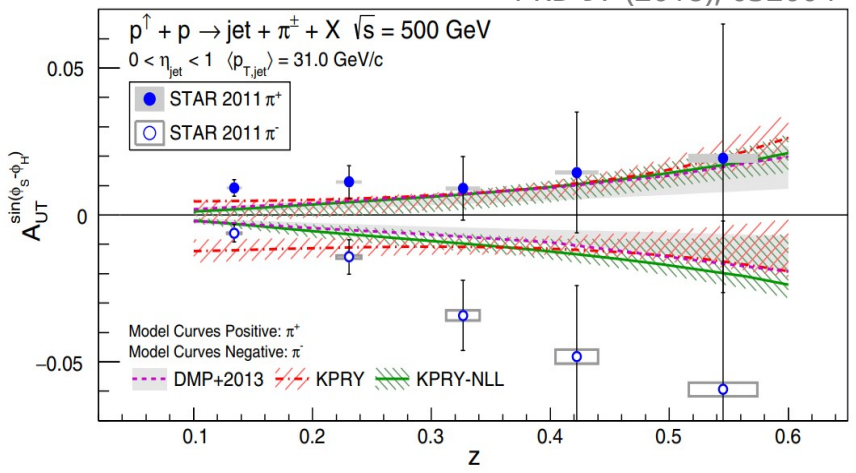
COLLINS ASYMMETRY



PRD 97 (2018), 032004

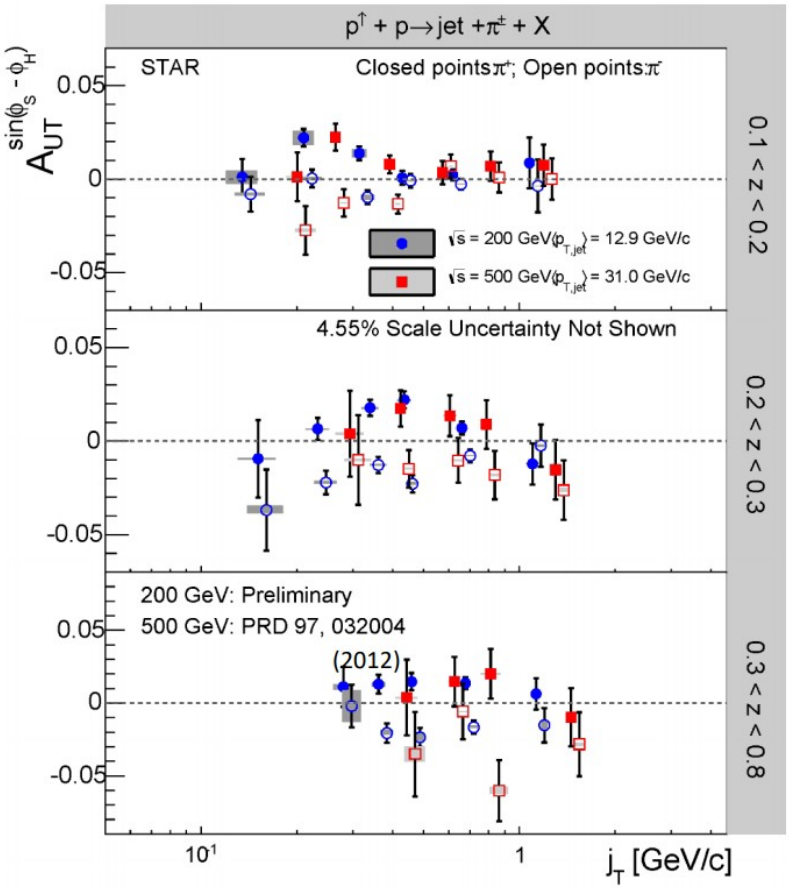
$$d\sigma^{\uparrow}(\phi_S,\phi_H) - d\sigma^{\downarrow}(\phi_S,\phi_H)$$
$$\sim d\Delta\sigma_0 \sin(\phi_S)$$
$$+d\Delta\sigma_1^- \sin(\phi_S-\phi_H) + d\Delta\sigma_1^+ \sin(\phi_S+\phi_H)$$
$$+d\Delta\sigma_2^- \sin(\phi_S-2\phi_H) + d\Delta\sigma_2^+ \sin(\phi_S+2\phi_H)$$

PRD 97 (2018), 032004



D'Alesio, Murgia & Pisano, PLB 773 (2017), 300
Kang, Prokudin, Ringer, Yuan, PLB 774 (2017), 635, w/ & w/o evolution

PRD 97 (2018), 032004
K. Adkins (STAR), SPIN 2014

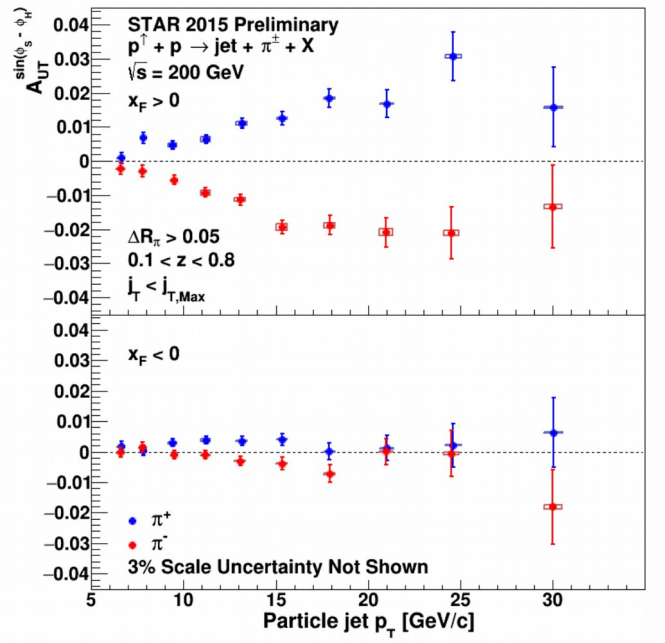


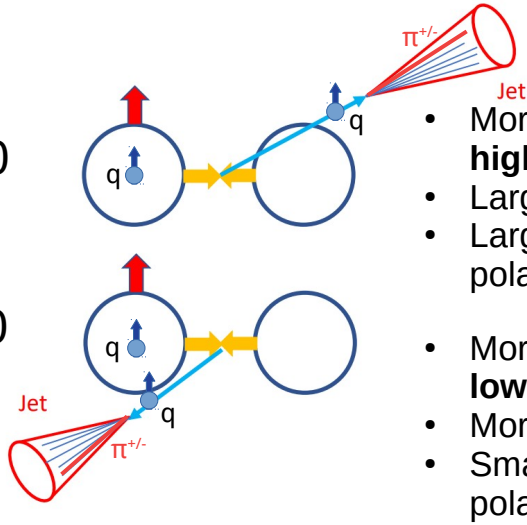
- First measurements reasonably described by calculations combining transversity from SIDIS with the Collins FF from e+e-
- Results hint that the asymmetry peak shifts to higher j_T as z increases

COLLINS ASYMMETRY

STAR preliminary results for the **Collins asymmetry** with 2015 data at 200 GeV

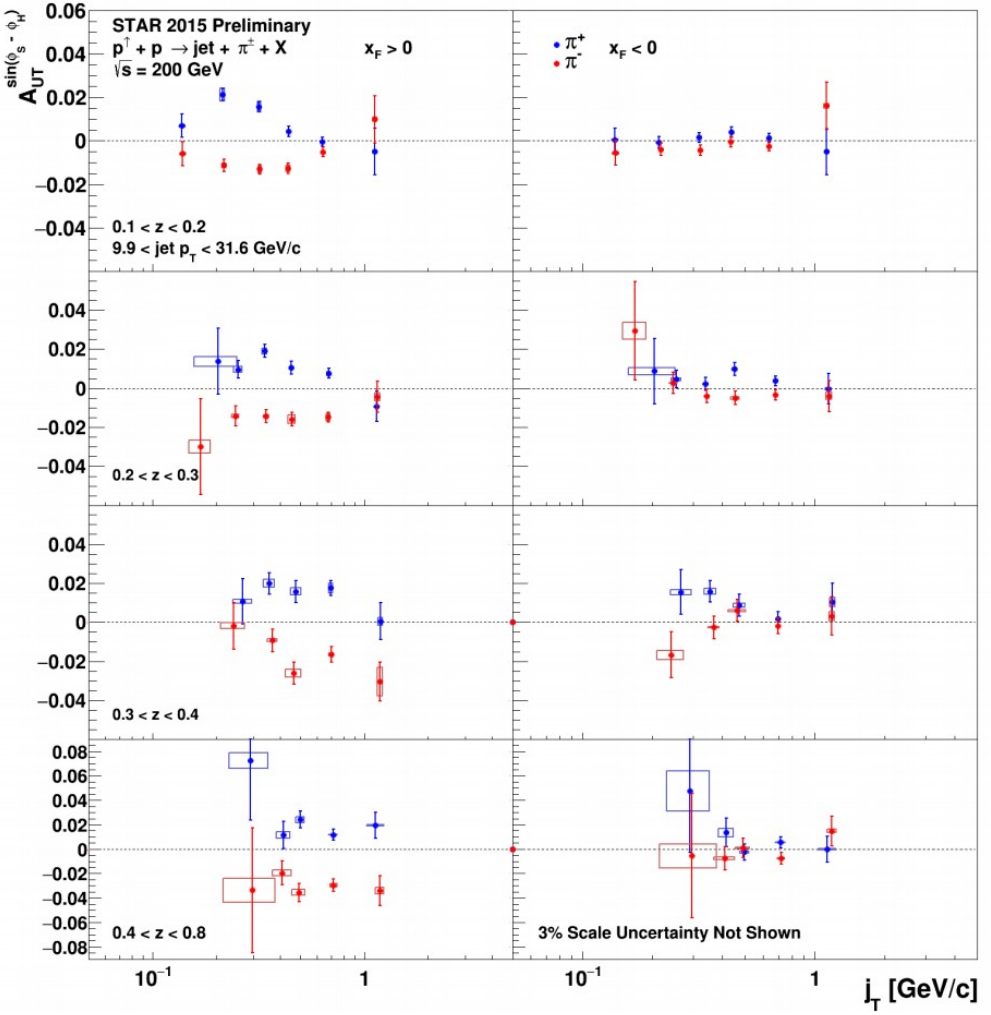
T. Lin et. al (STAR). BNL Nuclear Physics Seminar 2020





- More likely to probe **higher x**
- Larger quark jet fraction
- Larger quark polarization transfer

- More likely to probe **lower x**
- More gluon jets
- Smaller quark polarization transfer



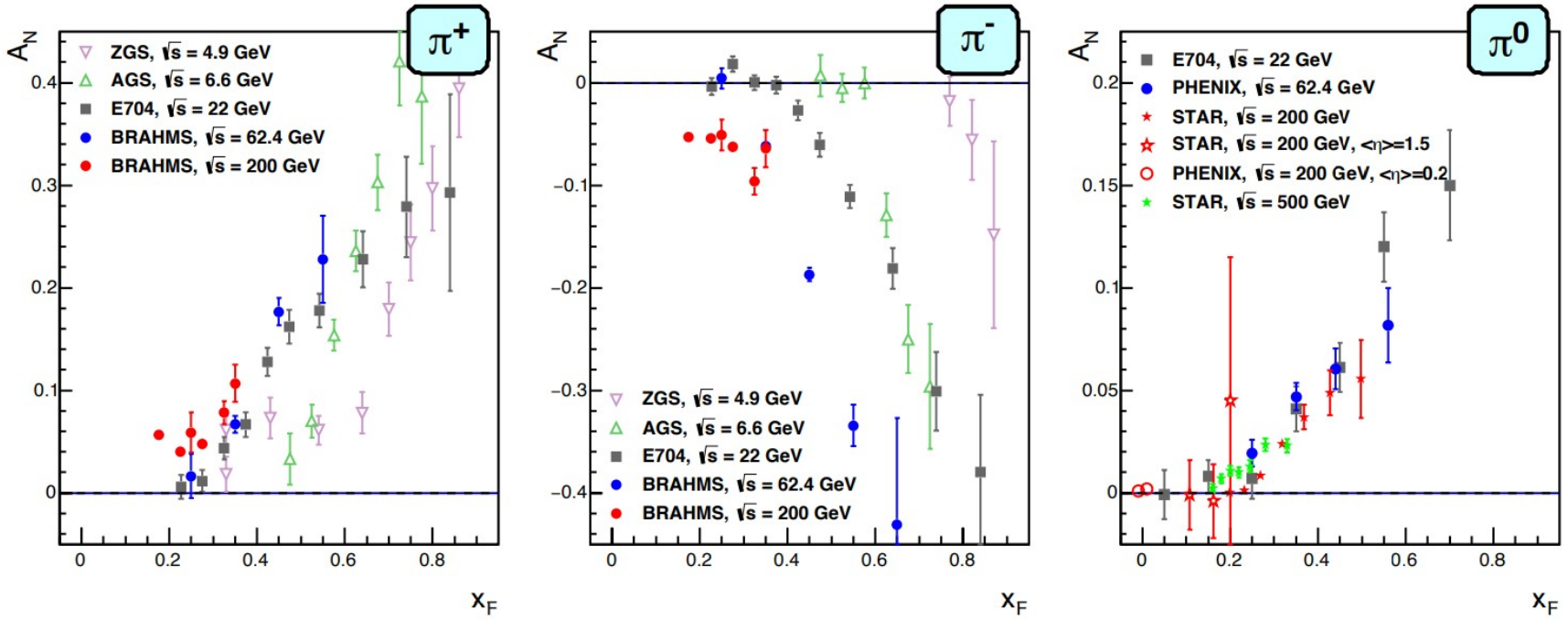
Results consistent with the previous STAR results with smaller statistical and systematic uncertainties

LARGE FORWARD A_N

LARGE FORWARD A_N

Puzzle since E704

arXiv:1602.03922



Large asymmetries nearly independent on √s (especially π^0)

Theoretical formalisms to try to explain these sizable A_N in the QCD framework:

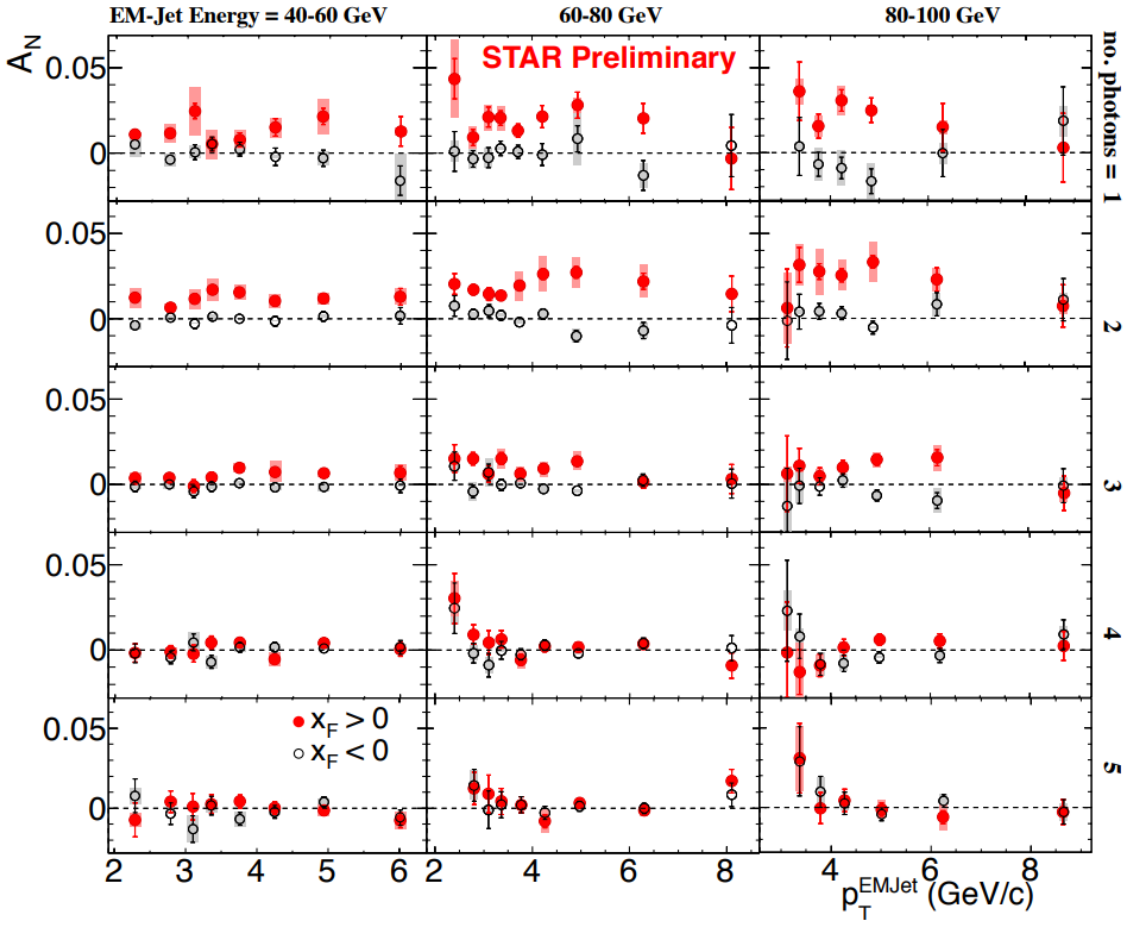
- **Transverse-Momentum-Dependent PDF and FF** (e.g. Sivers, Collins)
- Interpretations within **Twist-3 formalism**:
  - K. Kanazawa, Y. Koike, A. Metz and D. Pitonyak, PRD 89 (2014), 111501(R) – 3-parton collinear FF fit to RHIC data + soft-gluon pole term fixed – good description of π^0 A_N
  - Predictions for π^+ and π^- production asymmetries A_N at the forward rapidities (STAR Fwd Upgrade)

LARGE FORWARD A_N

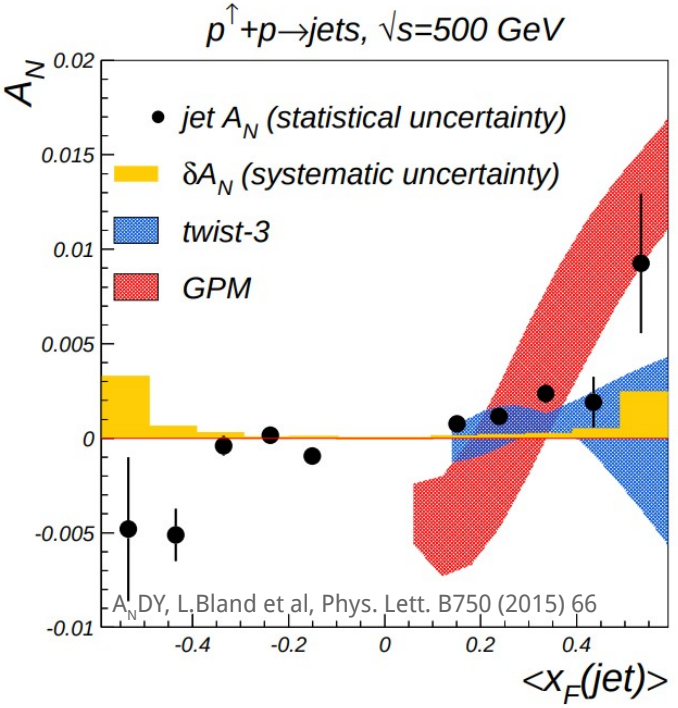
Can the Collins and Sivers signals we see at mid-rapidity explain large forward A_N?

Forward ($2.6 < \eta < 4$) A_N with electromagnetic jets

M. Mondal et al. (STAR), DIS 2014



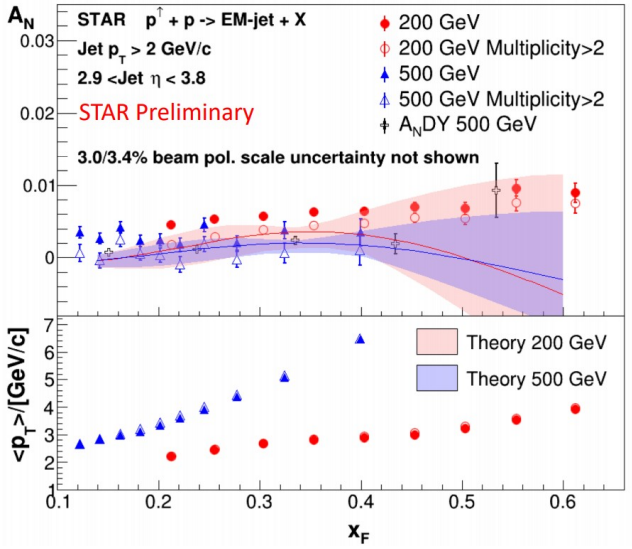
- A_N decreases with EM-jet multiplicity
- Description of A_N beyond pQCD $2 \rightarrow 2$ process: forward measurements with Roman Pots
- A_NDY measured small A_N for jet-like events



FORWARD A_N

STAR: Preliminary results from 2011 (500 GeV) and 2015 (200 GeV) data

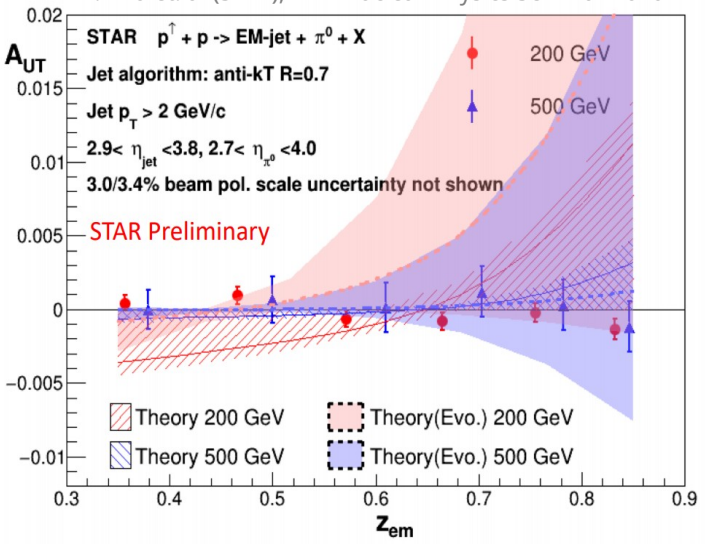
forward EM jets A_N



Theory curves : L. Gamberg, Z. Kang, A. Prokudin, Phys.Rev.Lett. 110 23, 232301 (2013)

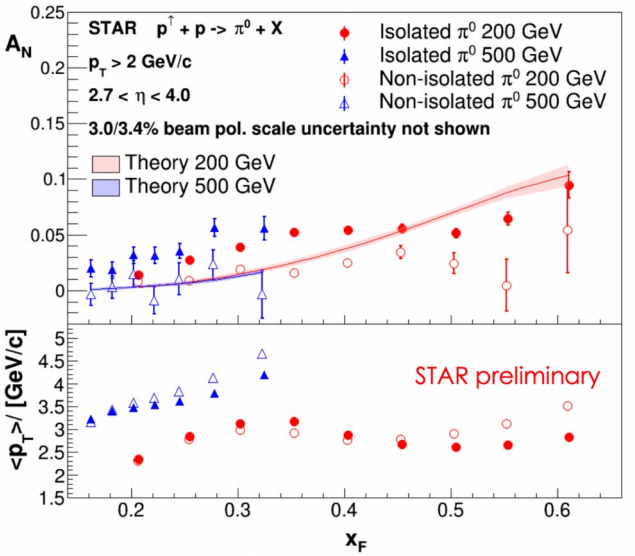
hadrons in EM jets A_{UT}

Z. Zhu et. al (STAR), BNL Nuclear Physics Seminar 2020



Theory curves : Z. Kang, et al. Phys.Lett.B 774, 635 (2017)

π^0 A_N



Theory curves: J. Cammarota et al. arXiv:2002.08384(2020)

- Measured **small** A_N for EM-jets and Collins asymmetry for π^0 within EM jets
- Weak dependence on the center-of-mass energy
- A_N for non-isolated π^0 and higher-multiplicity EM jets lower

With STAR Fwd Upgrade

- Pursue charged-pion enhanced jets (prediction from Twist-3 formalism): Fwd jet and charged ID

OUTLOOK

STAR Forward Upgrade and sPHENIX

STAR Forward Upgrade

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

- **Tracking:** Si disks + small Thin Gap Chambers
- **Calorimetry:** hadronic and electromagnetic

- Access to highly asymmetric partonic collisions: high x-quark and low-x gluon interactions
- Flavor-enhanced jets up to the highest √s at RHIC

sPHENIX

Full azimuthal detector in the central region (Central Barrel)

- Enhanced jet and heavy flavor capabilities

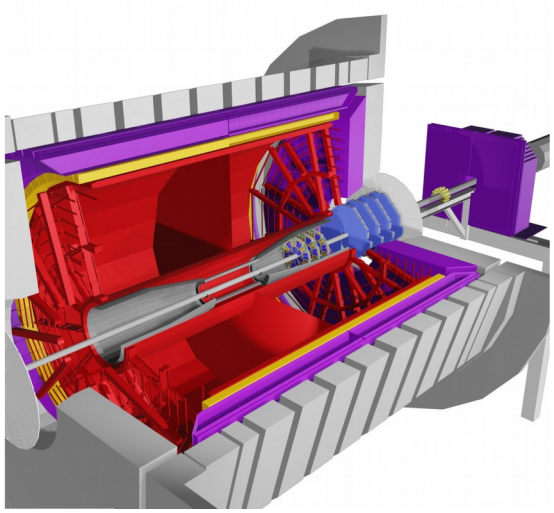
Rich programs planned:

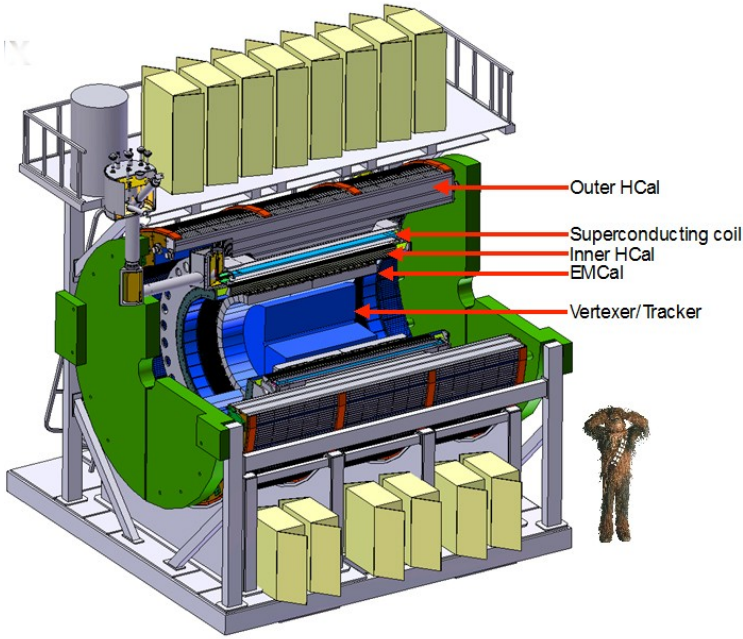
1) 2022 at 510 GeV: $p^{\uparrow}p^{\uparrow}$ (STAR with Fwd upgrade and iTPC)

2) 2024 at 200 GeV: $p^{\uparrow}p^{\uparrow}$, $p^{\uparrow}Au$, $p^{\uparrow}Al$ (STAR + sPHENIX)

Complementary to each other in the future RHIC measurements

PAC Meeting:
https://indico.bnl.gov/event/7881/





SUMMARY

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

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

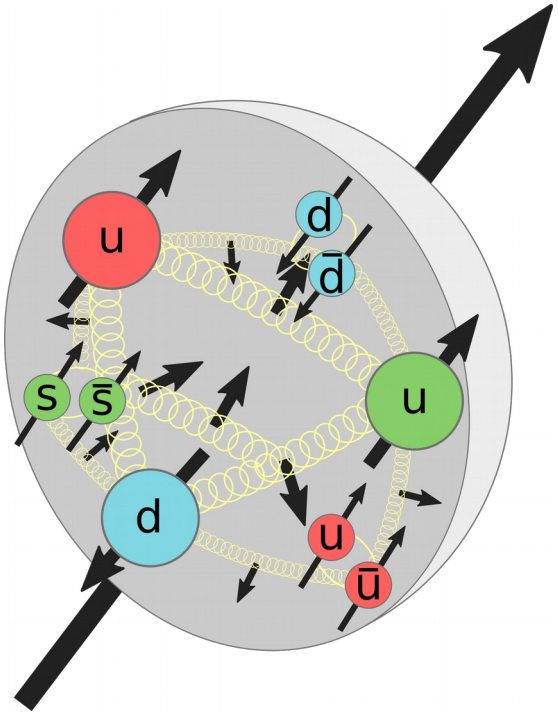
- Constraints on the **polarized gluon distribution**
- Evidence for the positive gluon polarization for x > 0.05

- **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) and much higher statistics and better PID in mid-rapidity in runs 2022/2024

Ongoing 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**

THANK YOU



mariakzurek@lbl.gov

@mariakzurek