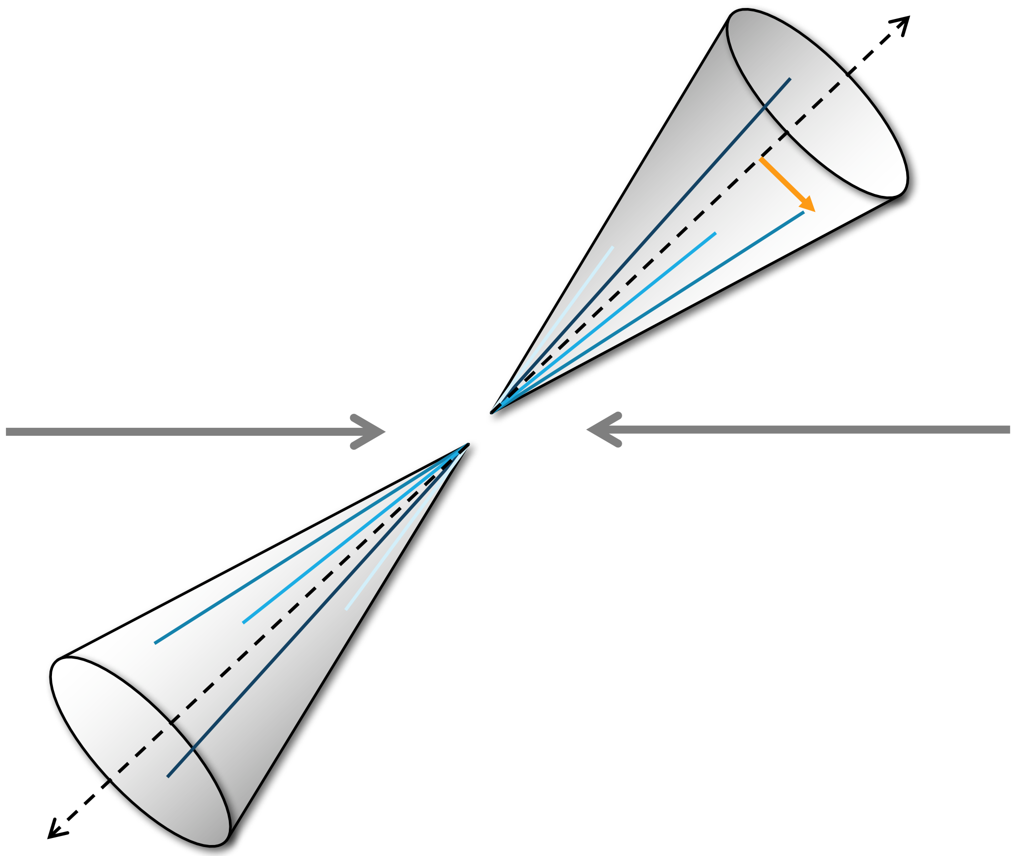
Using Jets to access TMDs in proton-proton collisions



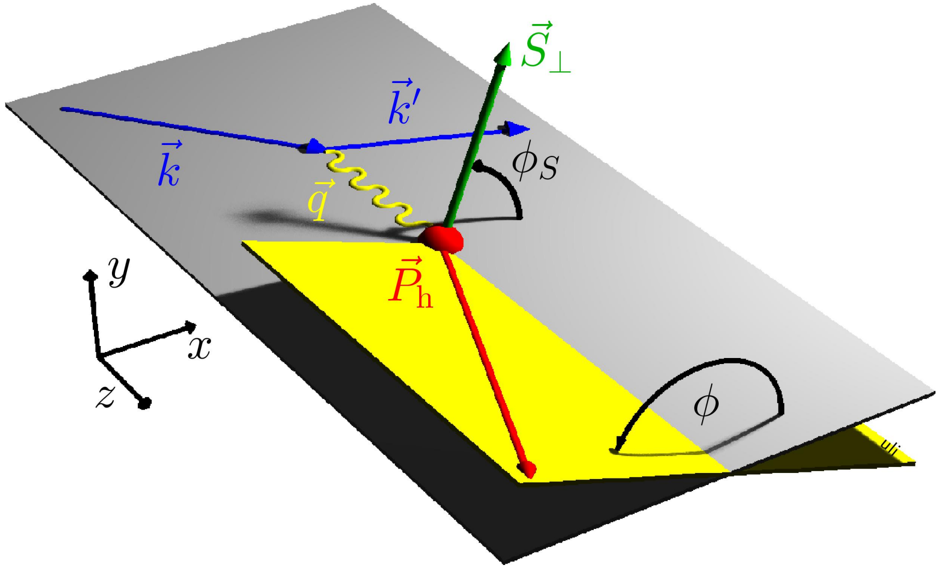
Renee Fatemi

University of Kentucky

Why Jets?

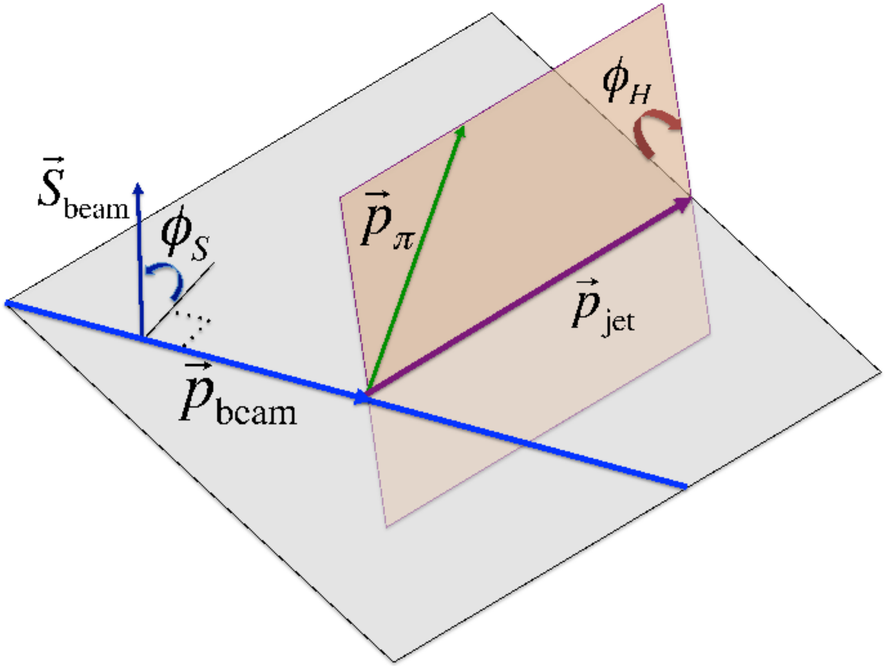
- TMD's have long been studied in semi-inclusive lepton-proton collisions where only the scattered lepton and the momentum of your chosen hadron is reconstructed.

- In the case of l+p scattering it is possible to explicitly reconstruct x, P_T^H and Q^2.



Why Jets?

- In proton-proton collisions must use jet P_T as proxy for momentum transfer Q.
- The hadron momentum (j_T) is measured with respect to jet axis.
- Initial parton momentum cannot be reconstructed, unless dijets are identified, and even then only at leading order.



Why Jets?

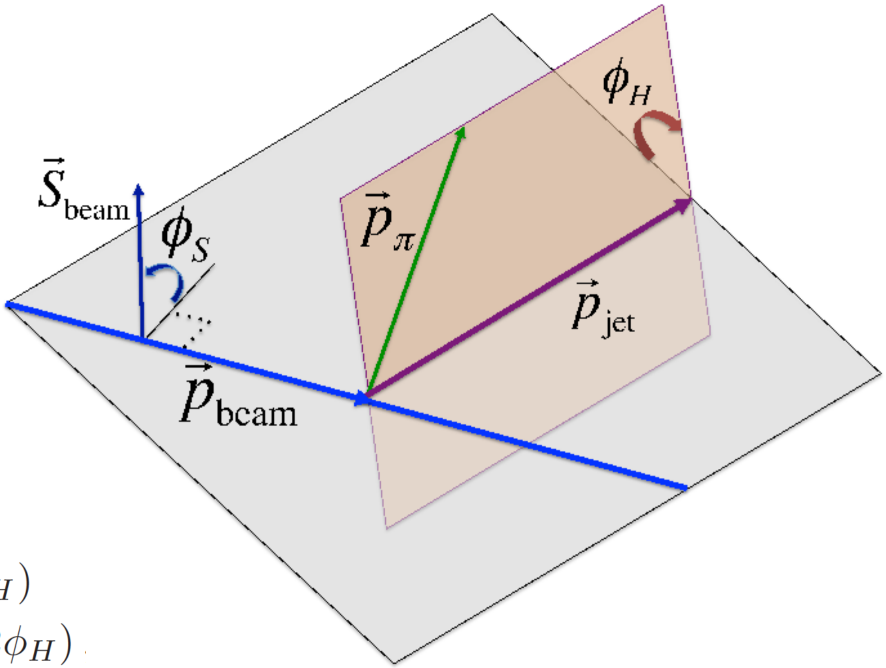
- Access TMDs via modulation of transverse single spin asymmetries.

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

- Spin dependent terms:

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

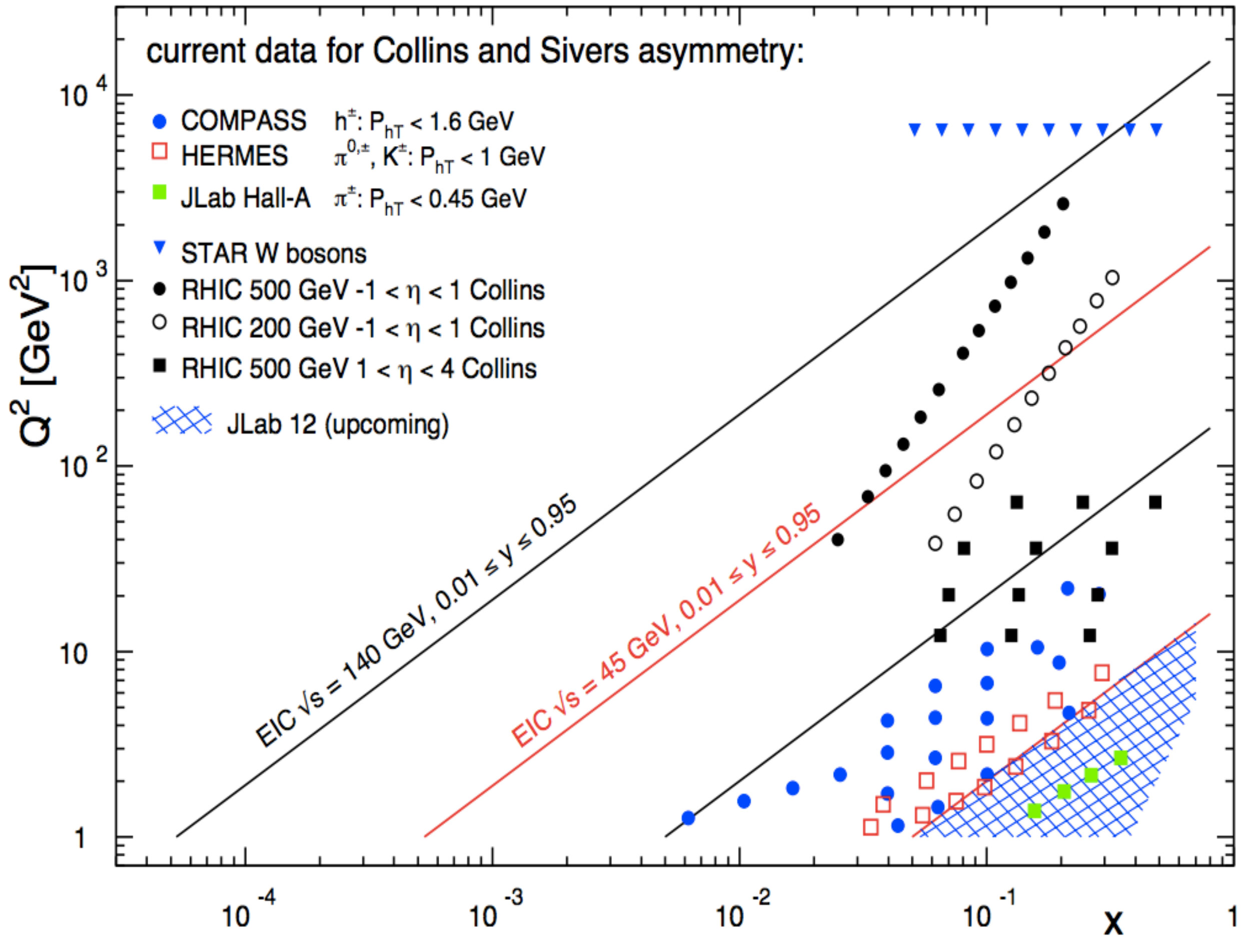
- dΔ**σ** include PDFs and FF



Why p+p?

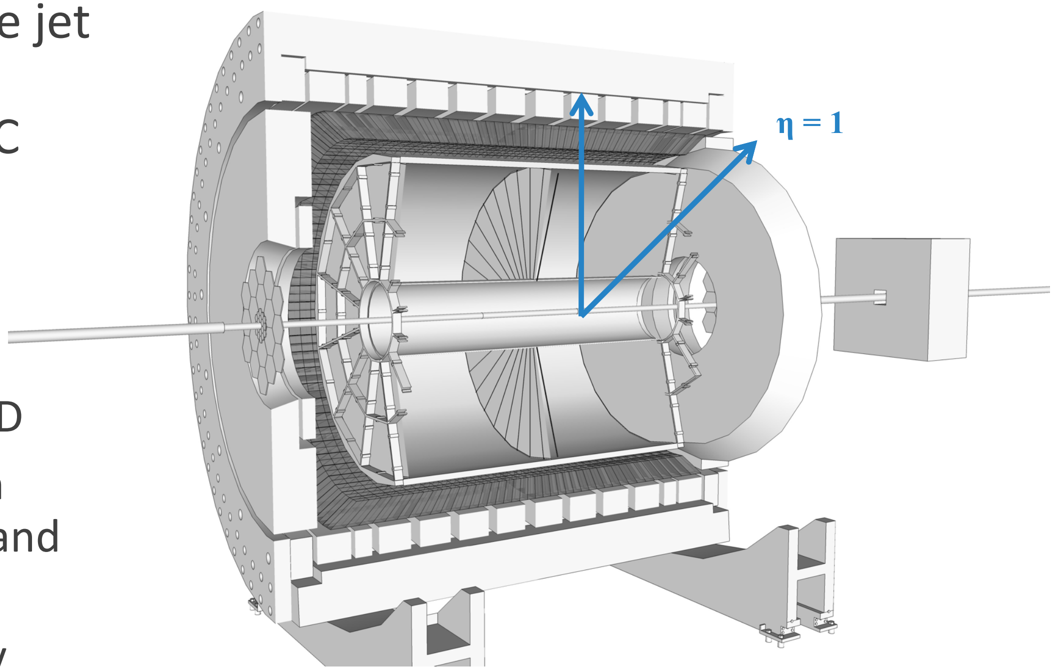
- ***Gluons!***
  - One of the driving motivations behind an EIC is the study of gluons. Strong interactions access gluons directly and are ideally suited for studying observables like *Gluon Fragmentation Functions* and *Gluon Linear Polarization*.
- ***Factorization*** and ***Universality***
  - Separate intrinsic properties of hadrons from interaction dependent dynamics
  - Ideally we need precision measurements from both SIDIS and pp to make meaningful comparisons.
  - Push the theoretical envelop
- ***Evolution***
  - TMD evolution is area of active theoretical research! Unlike in the k_T integrated case there are non-perturbative factors that can only be constrained by experimental measurements.
  - Proton colliders routinely access higher Q^2 than fixed target experiments (as well as some running scenarios for an EIC).

Current and Projected TMD Data



Jet Measurements at STAR

- STAR is uniquely suited to make jet TMD measurements in the era preceeding the turn-on of an EIC
- Classic collider detector
  - Full azimuthal coverage at mid-rapidity
  - TPC provides charged hadron PID
  - Long standing jet reconstruction program in both cross-sections and polarized observables.
  - Nearly complete EM calorimetry coverage out to η = 4.

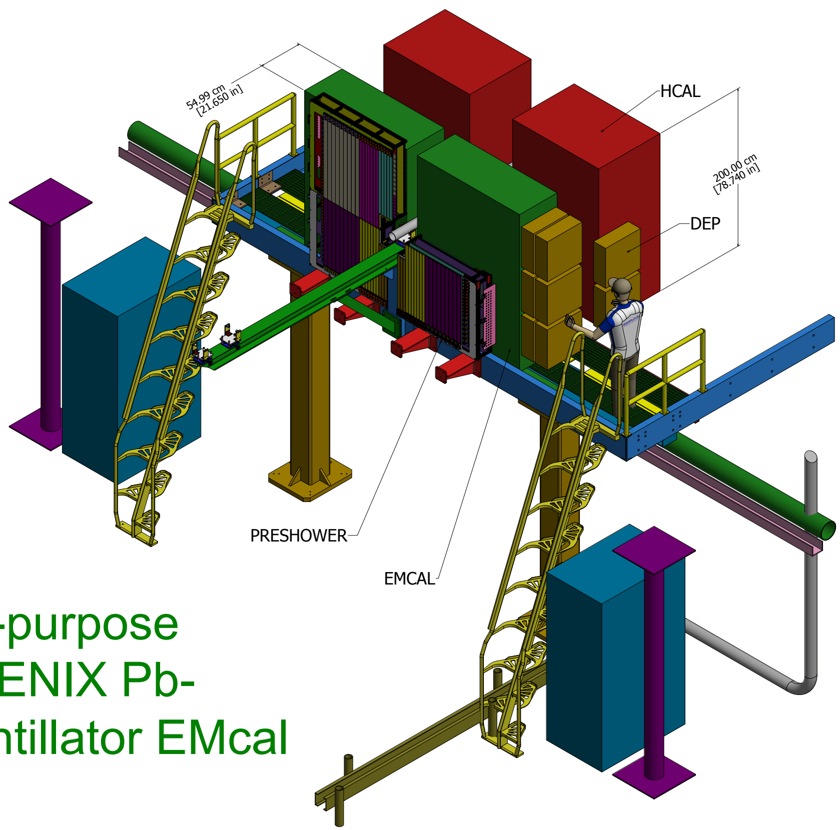


- ***Relatively inexpensive upgrades would build on existing strengths at mid-rapidity by extending jet reconstruction and charge sign identification into forward region***.

STAR Forward Calorimeter + Tracking Upgrade

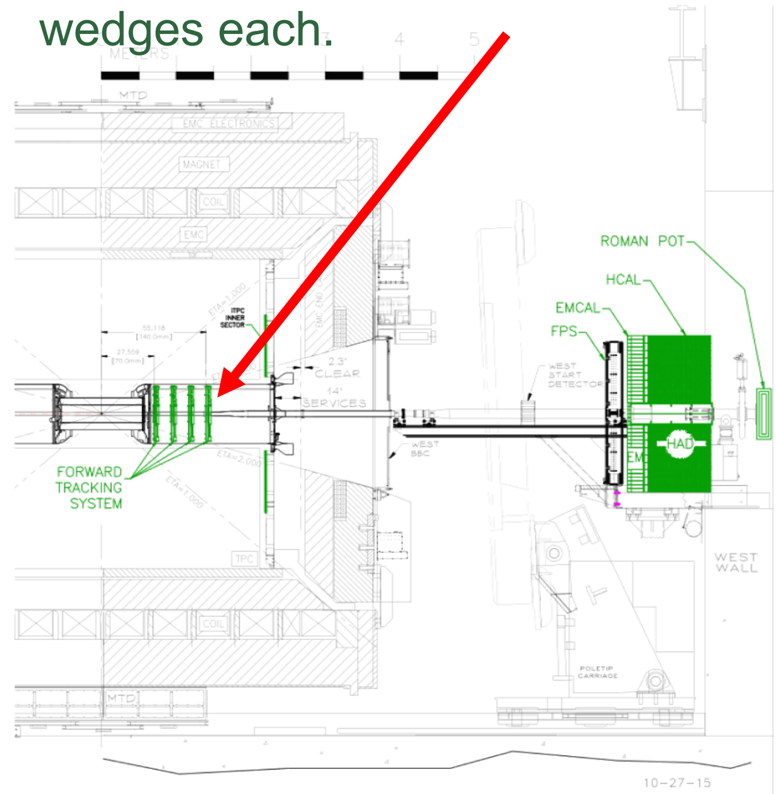
Install in forward region $2.3 > \eta > 4.0$

4-interaction length thick Pb-scintillator plate HCAL



Re-purpose PHENIX Pb-scintillator EMcal

Four planes of silicon strip detectors comprised of 12 wedges each.



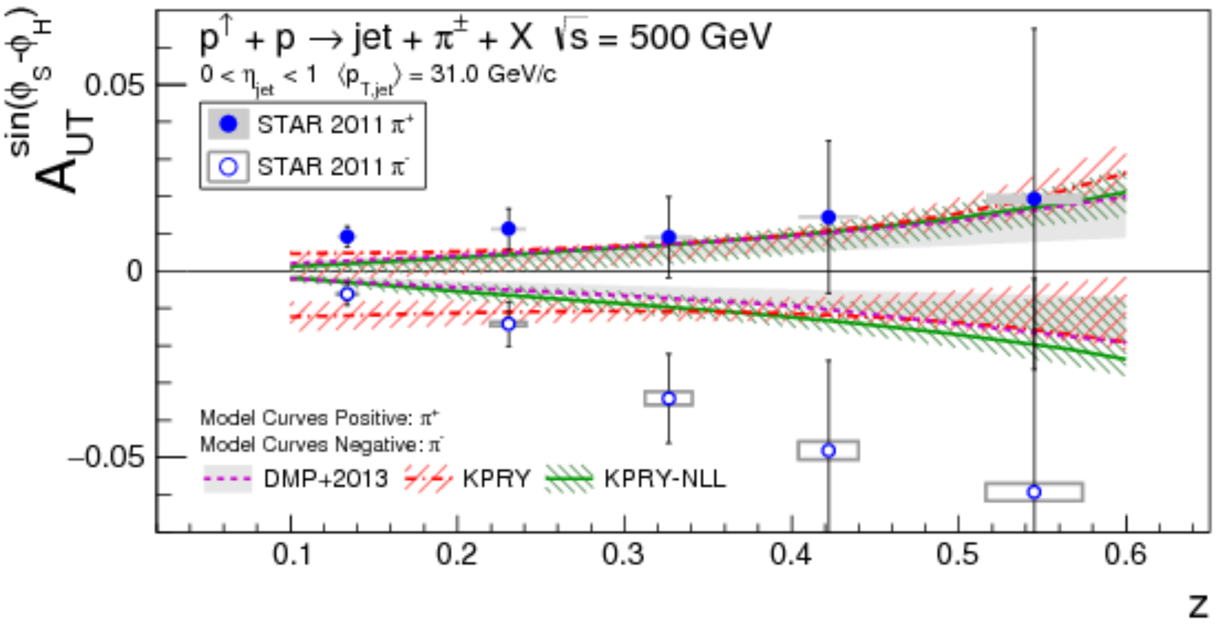
Designed to provide charge-sign & vertex determination.

Timelines & TMDs

** twist-3 related to TMDs via ETQS eq.*

YEAR	TMD	OBSERVABLE	SPECIES + √s
2017	Sea Quark Sivers, Transversity & Collins FF Gluon linear polarization Gluon + Quark Sivers* Gluon FF GPD E_G	A_N for W, Z and DY A_{UT} in jets A_{UT} in jets A_{UT} in jets Hadrons in jets A_{UT} for J/Ψ in UPC	$P^{\uparrow}P$ 500 GeV
2018-20	*iTPC and Forward*	*Upgrade installation*	Beam Energy Scan
2021	Hi/low x Transversity & Collins Precision Sea Quark Sivers?	A_{UT} in jets A_N for W, Z and DY	$P^{\uparrow}P$ 500 GeV
2022	*sPHENIX*	*installation*	
2023	Transversity & Collins FF Gluon linear polarization Gluon + Quark Sivers* Gluon FF	A_{UT} in jets A_{UT} in jets A_{UT} in jets Hadrons in jets	$P^{\uparrow}P$ 200 GeV
2023	A-Dependence of TMDs	A_{UT} /Hadrons in jets	$P^{\uparrow}A$ 200 GeV

Collins $A_{UT}^{\sin(\Phi_S-\Phi_H)}$ Mid-rapidity Jets



STAR : *arXiv:**1708.07080***

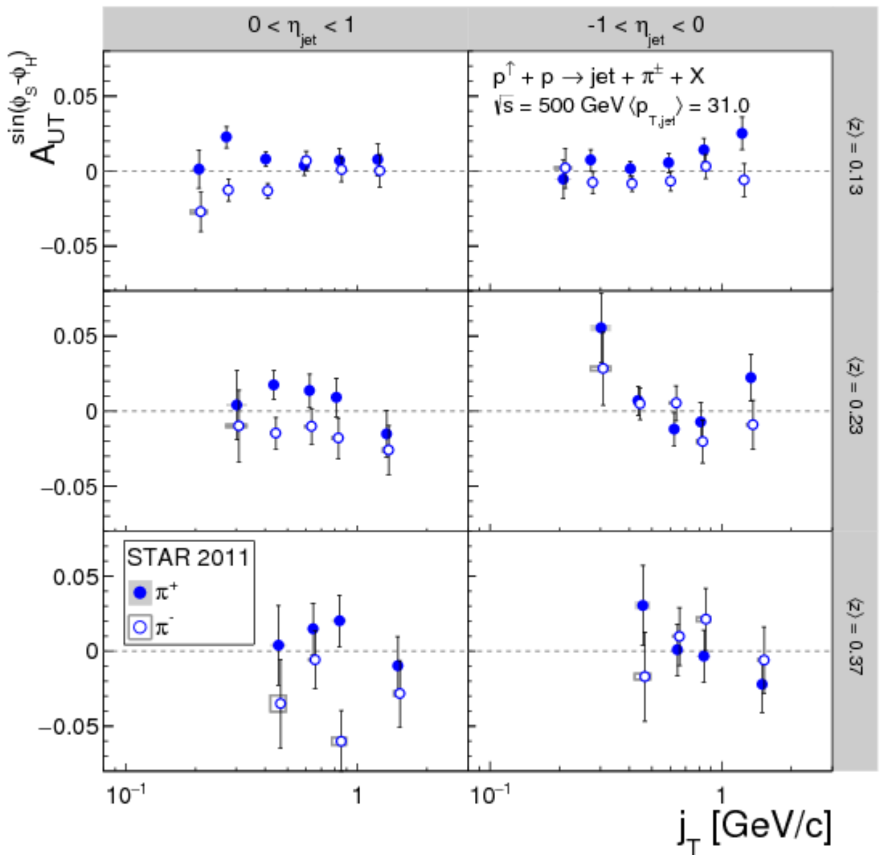
Theory :

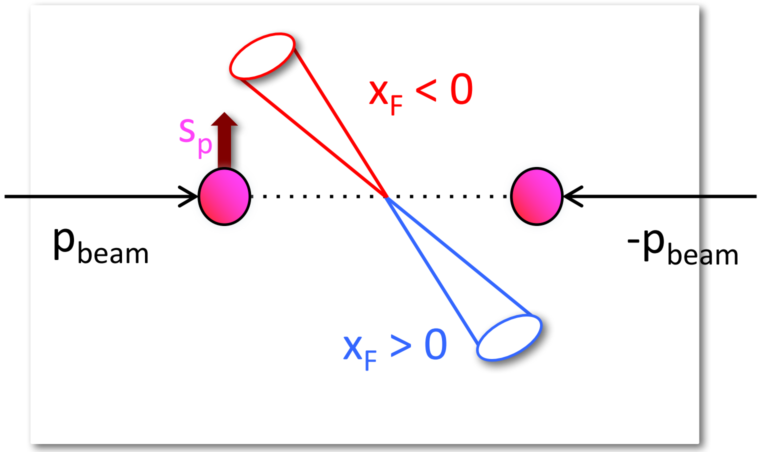
U. D'Alesio, F. Murgia, and C. Pisano, Phys.Lett. B773 (2017) 300-306

Z.-B. Kang, A. Prokudin, F. Ringer, and F. Yuan, arXiv:1707.00913

- First signature of Collins effect in p+p!
- Excellent agreement with calculations based on SIDIS and e+e- data. ***Implies universality holds for Collins FF and factorization-breaking effects are small!***
- Agreement holds for more precise 200 GeV data.

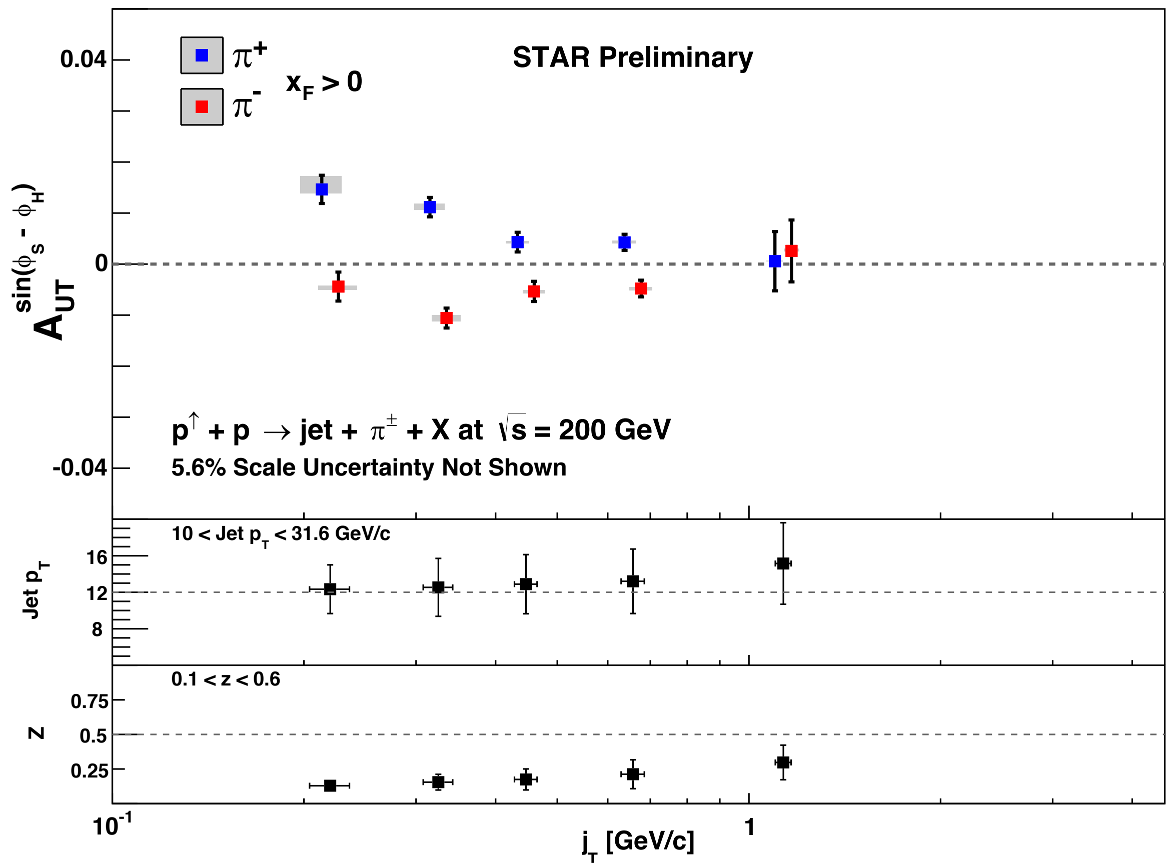
Collins $A_{UT}^{\sin(\Phi_S-\Phi_H)}$ Mid-rapidity jets





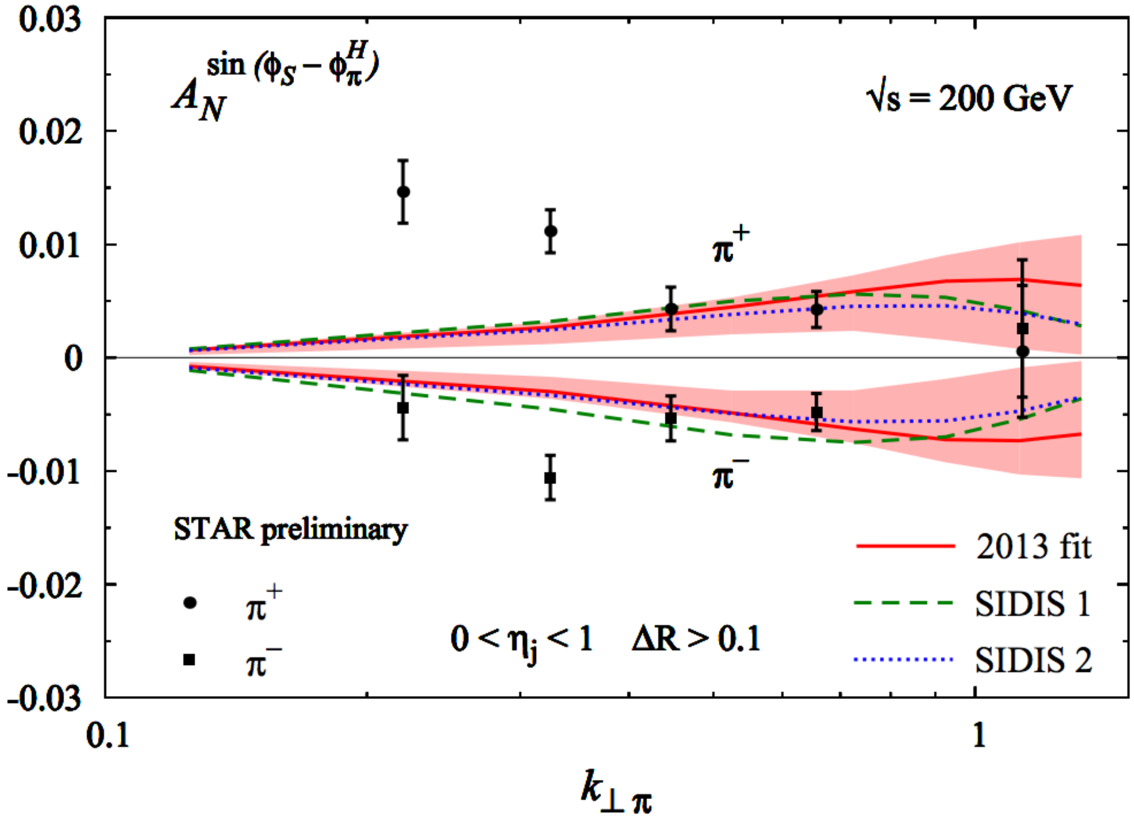
- Interesting j_T dependence shows fall-off at higher values
- Paper also includes mult-variable binning in p_T and z.

Collins $A_{UT}^{\sin(\Phi_s - \Phi_H)}$ vs. j_T at 200 GeV (xF>0)



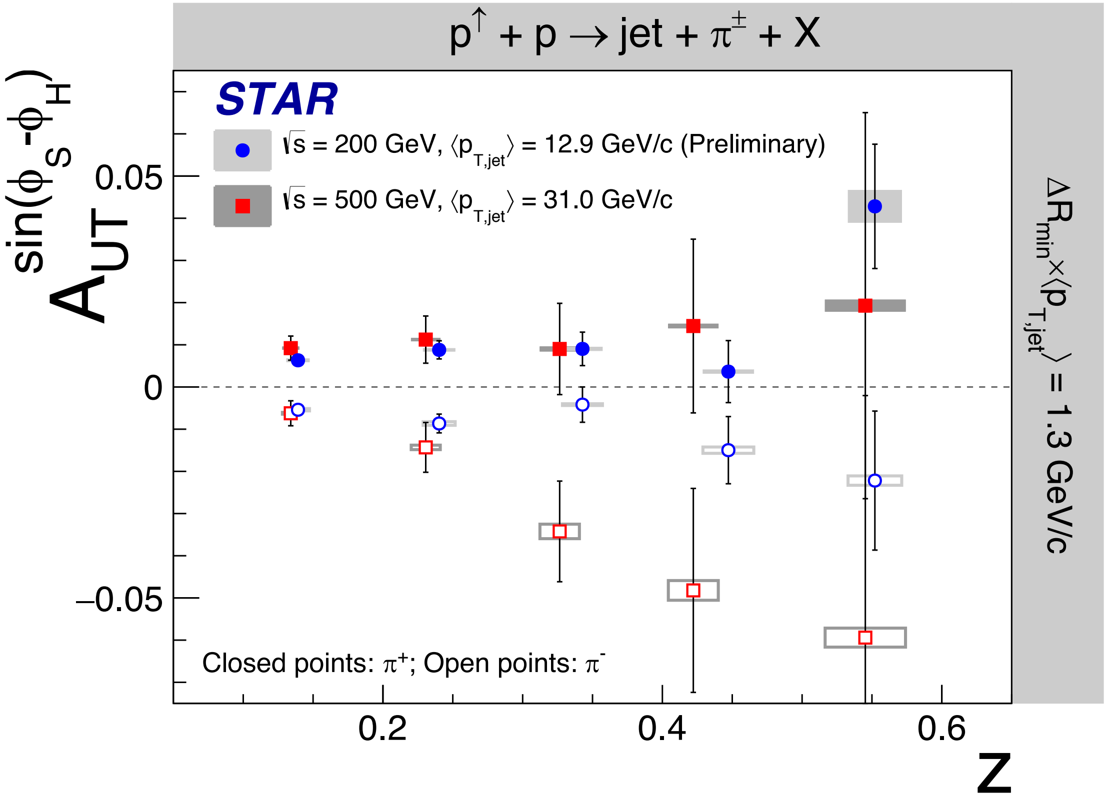
- General shape is preserved and clearer in 200 GeV data.
- Maximum is shifting down. Note that average jet p_T is ~ 12 GeV compared to 31 in 500 GeV data.
- Final results will be differential in z as well.

Collins $A_{UT}^{\sin(\Phi_s - \Phi_H)}$ vs. j_T at 200 GeV (xF>0)



- Same data now compared with curves from *U. D'Alesio, F. Murgia, and C. Pisano, Phys.Lett. B773 (2017) 300-306*
- Good agreement at high j_T ($k_\perp$). Need to explore low J_T region both theoretically and experimentally.

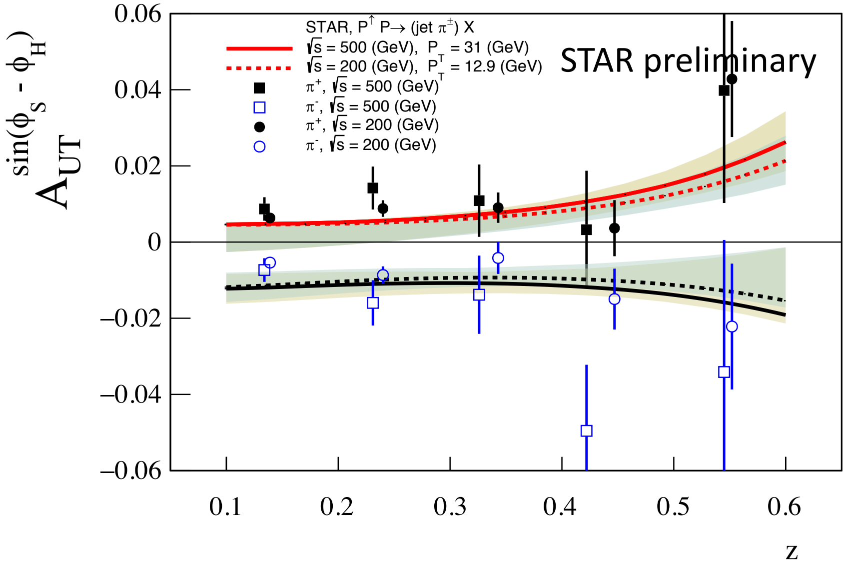
Collins Evolution: 200-> 500 GeV

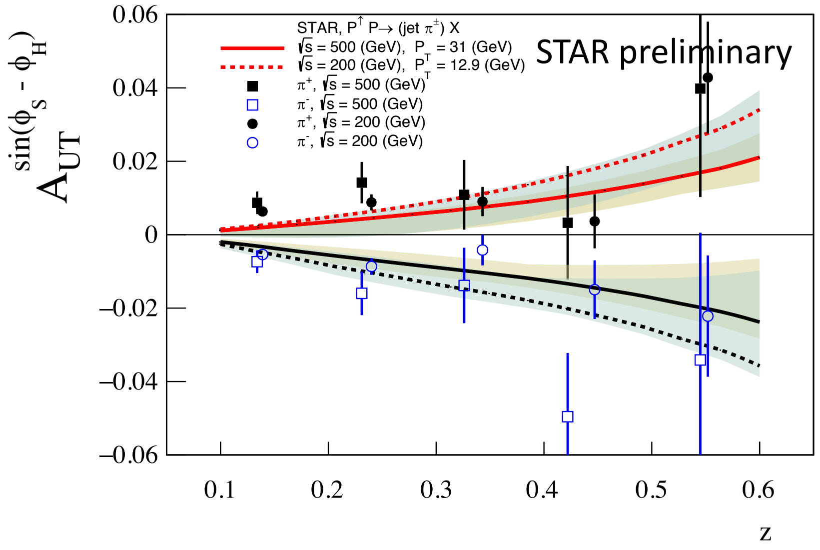


- Apply cuts to ensure same quark fraction and average hadron J_T.
- Excellent agreement between 200 and 500 GeV for π+ … π- not as strong.
- Need more statistics in 500 GeV to match precision of 200 GeV.

Collins Evolution: 200-> 500 GeV

STAR data compared to calculations by Z.-B. Kang, A. Prokudin, F. Ringer, and F. Yuan, (arXiv:1707.00913) without and with evolution.

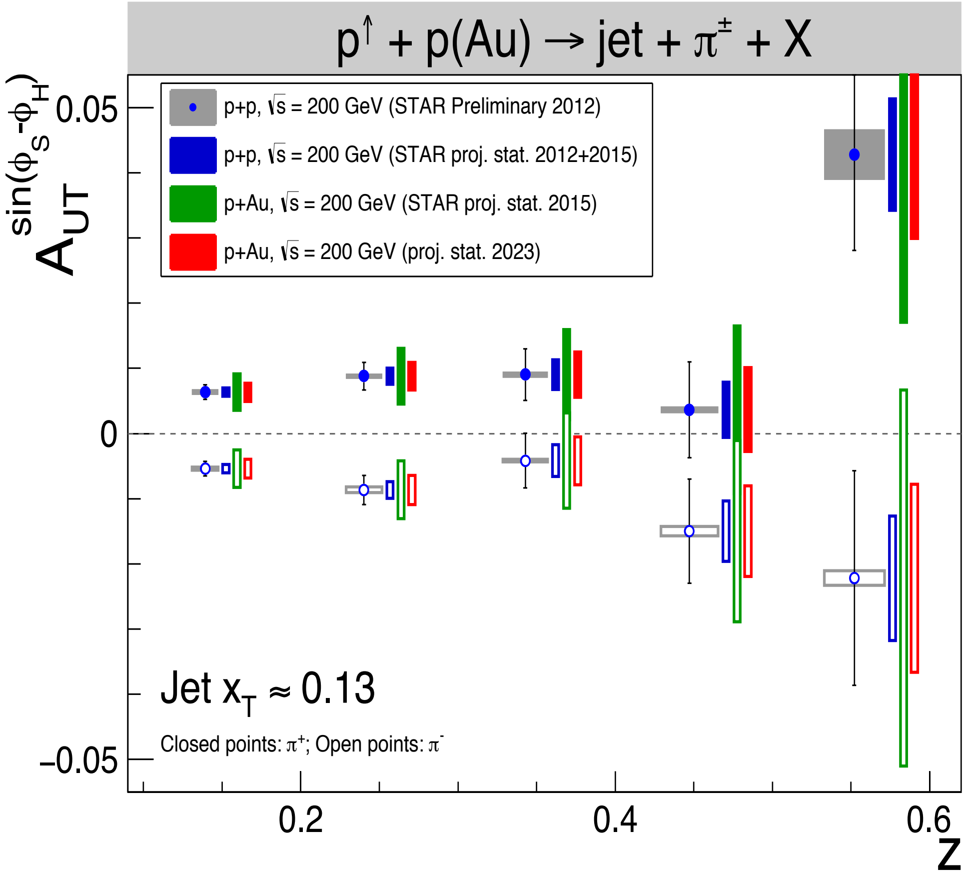




At the current level of precision the data implies universality holds for p+p collisions and TMD Evolution effects are small. Need more data!

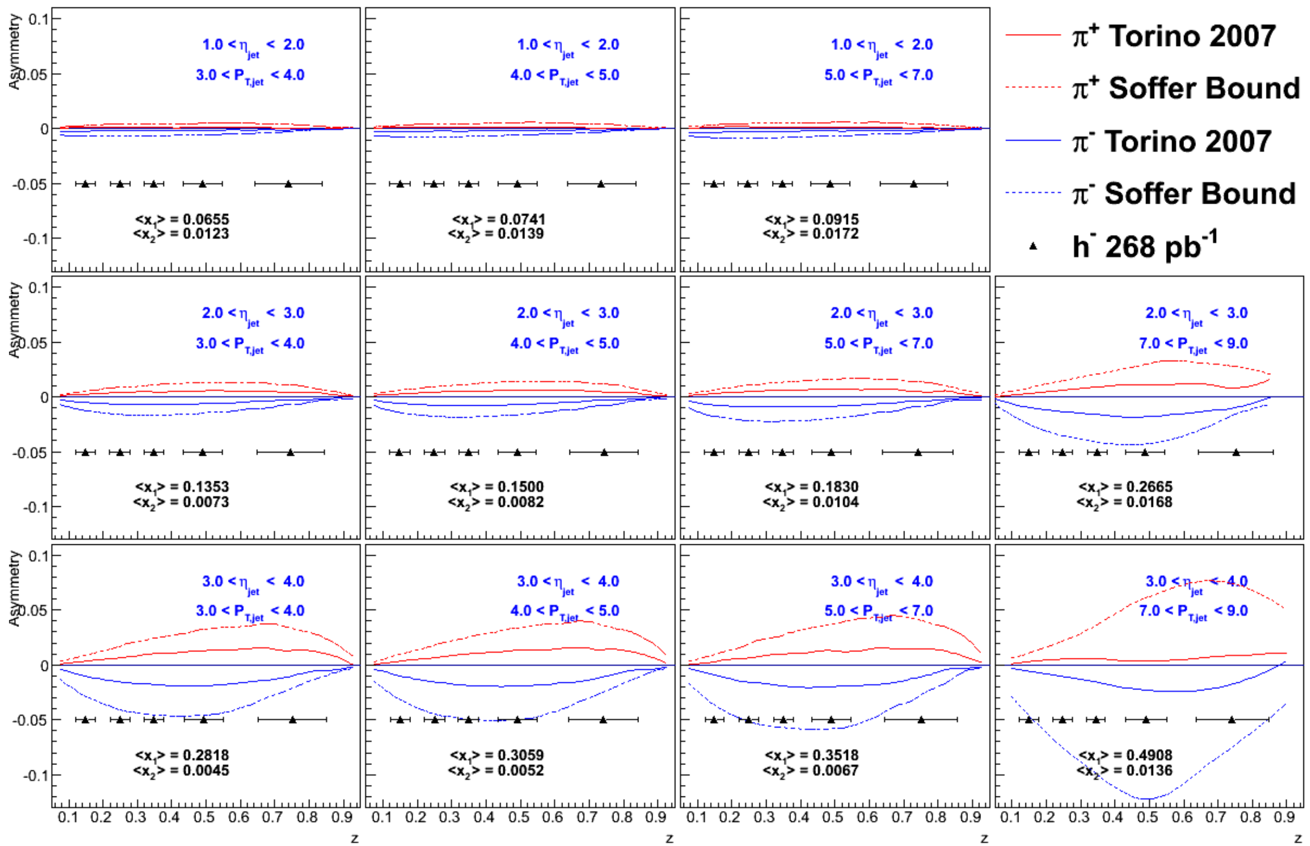
Fragmentation Properties in Nuclei

- What happens if we repeat this analysis but instead of p+p we collide p+A?
- First dataset collected on p+Au in 2015.
- Running in 2023 will permit the study of A-dependence.
- Analogous to EMC effect but in spin dependent proton collisions!

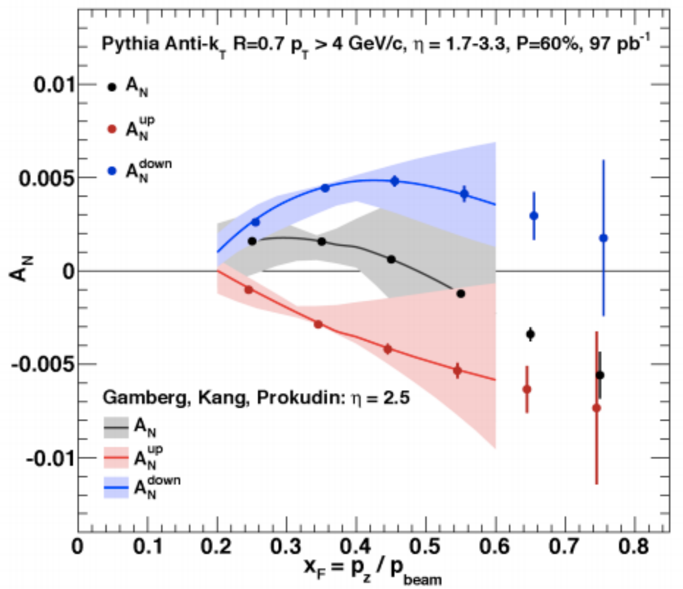


A_{UT} of Charged Hadrons in Forward Jets

- Mid-rapidity jet A_{UT} samples an x range of 0.2-0.3.
- STAR could push sensitivity to higher (> 0.3) and lower x (~10^{-3}) at **high Q^2** by reconstructing jets and charged hadrons (h^+/h^-) in the forward direction.
- Pion purity for h-(h+) estimated to by 87(78)%. Pbar highly surpressed in forward region.

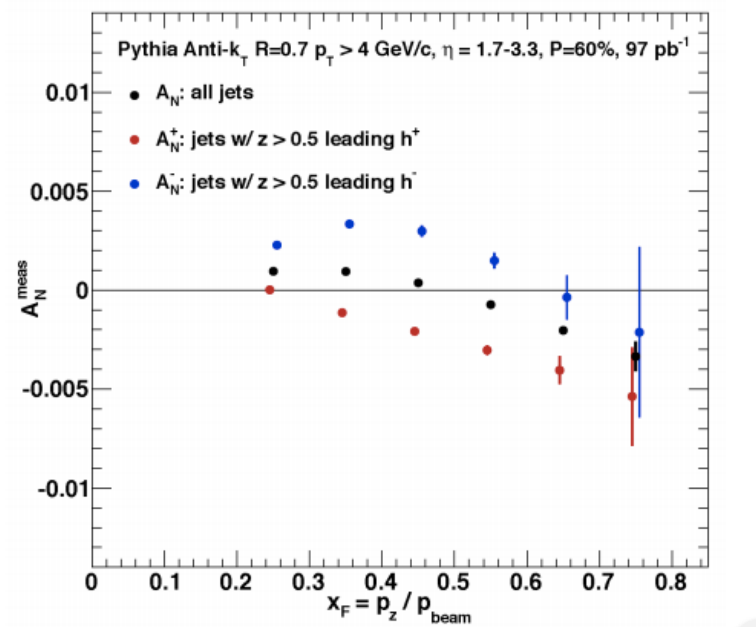


A_{UT} of Forward Jets with high z hadrons



Jet A_{UT} is sensitive to twist-3 “Sivers-like” correlators, which are expected to be opposite sign for u and d quarks.

No PID in forward region, only charged sign separation for h+/h-.



- Tests connection between twist-3 and TMDs via ETQS relationship
- Facilitates interpretation of the small inclusive jet A_{UT} measured by AnDY.

Gluon Fragmentation Functions

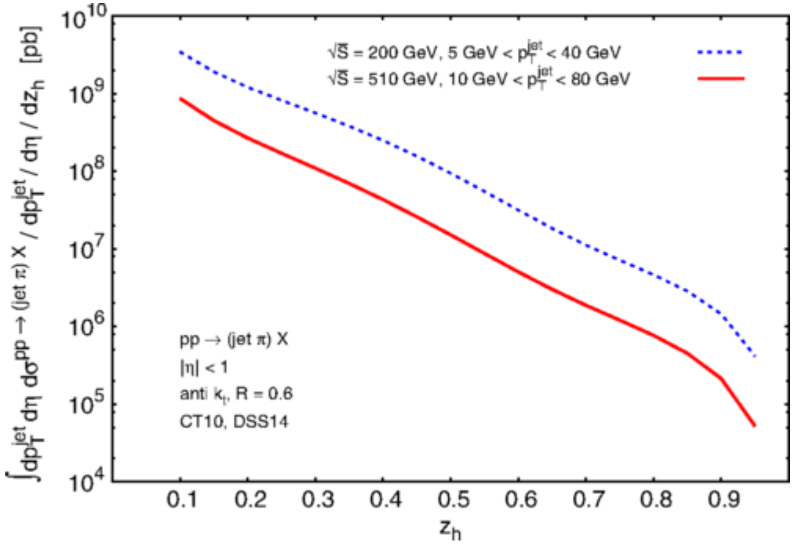
Recent work by Kaufmann, Mukherjee & Vogelsang show that cross-sections of hadrons in jets:

$$\frac{d\sigma^{pp\to jet+X}}{dp_T^{jet}\, d\eta^{jet}\, dz_h}$$

differential in $z_h = p_T^H / p_T^{JET}$ may be used to access universal FF in proton-proton collisions.

This new observable is sensitive to ***GLUON FF*** which are particularly difficult to extract from traditional e+e- scattering measurements.

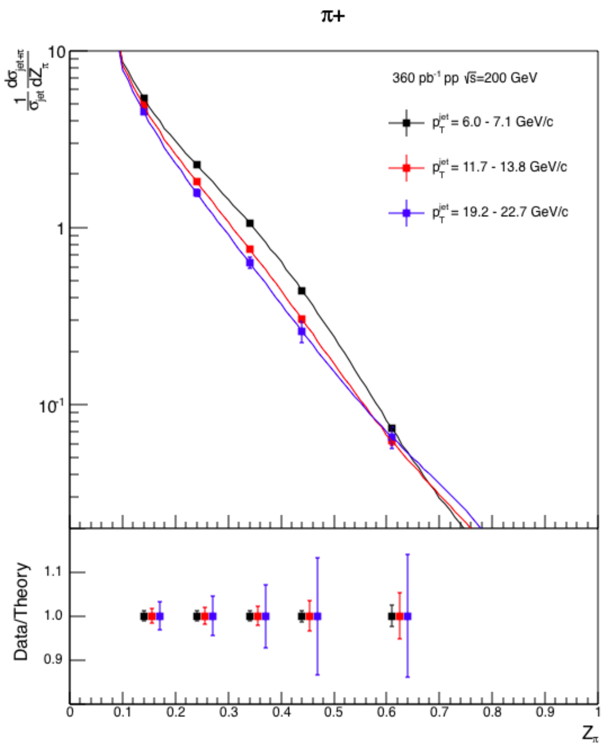
Phys. Rev. D 92, 054015 (2015)

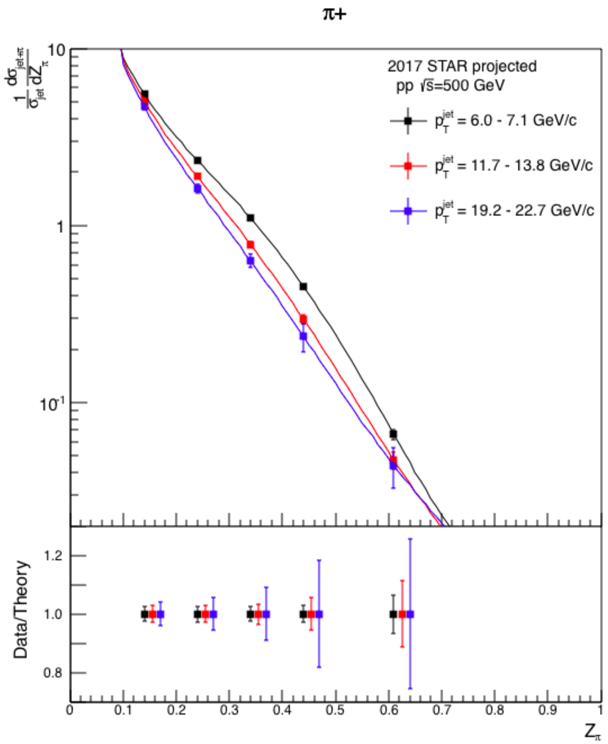


STAR can contribute by measuring this at both 200 and 500 GeV. Complimentary to analysis at the LHC.

Gluon Fragmentation Functions

Projected measurements for π+ in mid-rapidity jets at 200 and 500 GeV





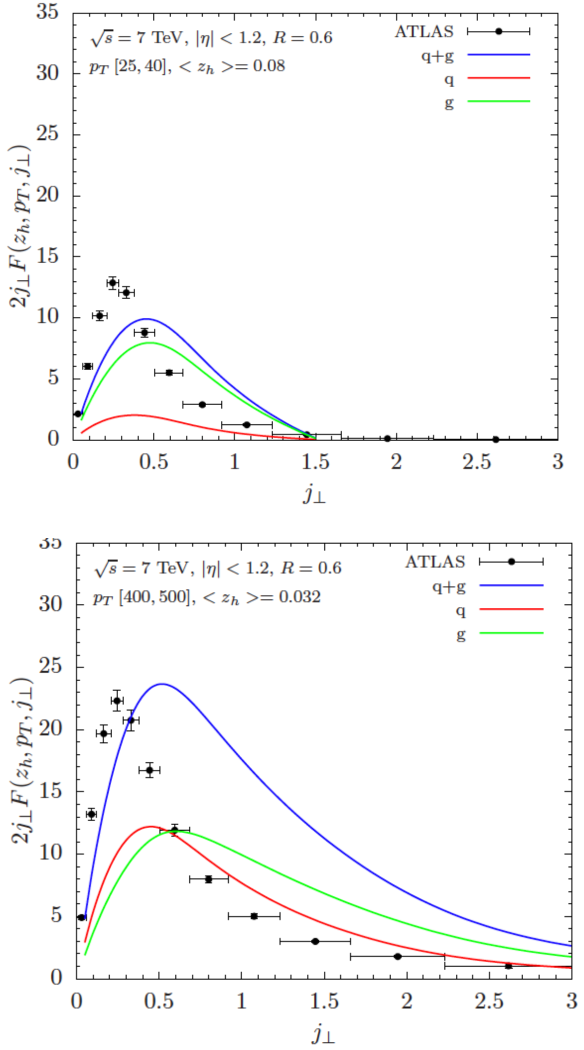
Curves are from Kaufmann et al using DSSV14 FF and PDF.

Gluon TMD FF

arXiv:1705.08443v1

Recent work by Kang, Liu, Ringer and Xing defined a universal TMD FF:

$$F\left(z_h, j_T; p_T, \eta, R\right) = \frac{\dfrac{d\sigma^{pp\to jet+X}}{dp_T^{jet}\, d\eta^{jet}\, d^2 j_T\, dz_h}}{\dfrac{d\sigma^{pp\to jet+X}}{dp_T^{jet}\, d\eta^{jet}}}$$



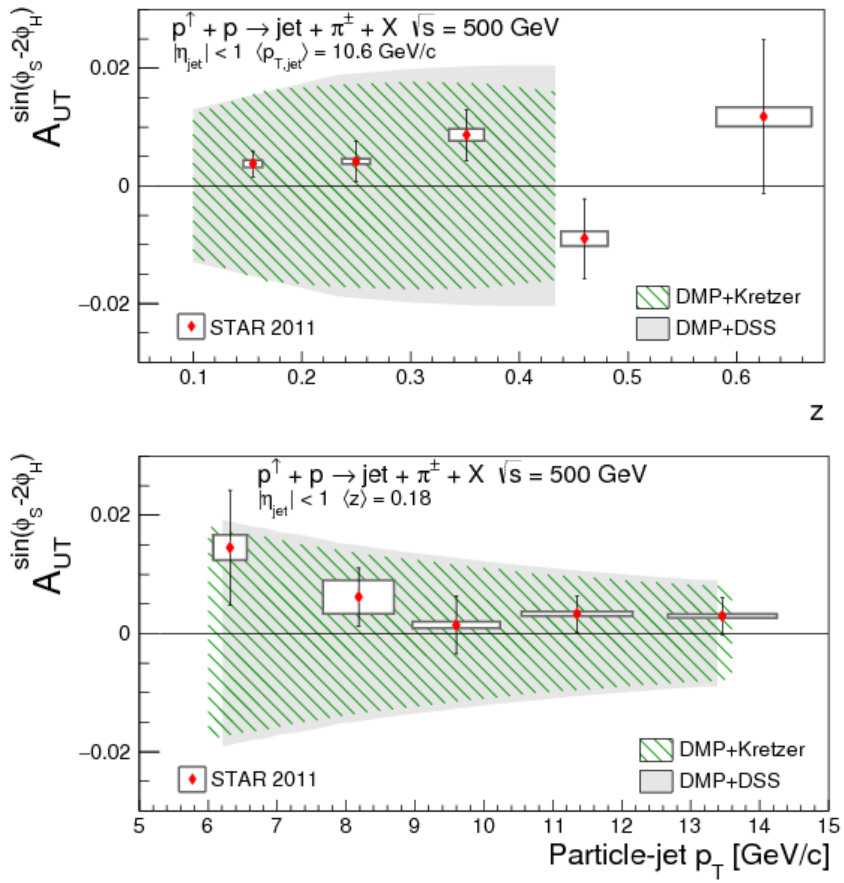
Similar to collinear case it is especially sensitive to the **GLUON** TMD FF, which is at this time virtually unconstrained.

Unlike in SIDIS, the TMDFF's accessed in pp do not depend on the TMDPDFs!

Gluon Linear Polarization

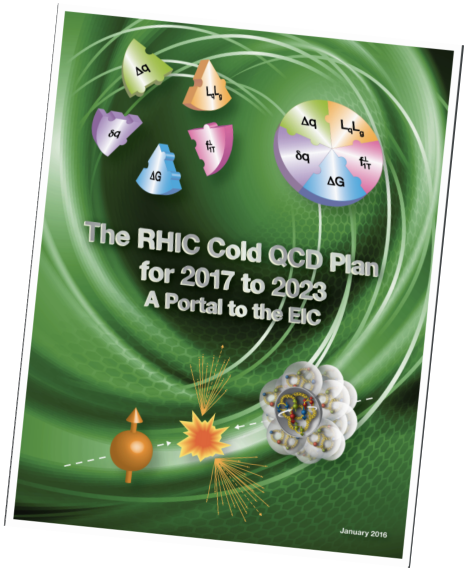
- $\sin(\Phi_S - 2\Phi_H)$ modulation in jet A_{UT} is sensitive to gluon linear polarization signal.
- First measurement - completely unconstrained! Possible cause of the ridge in pp/pA? *Phys.Rev. D94 no.1, 014030, arXiv:1708.08625*
- Shaded bands represent maximal predictions from *U. D'Alesio, F. Murgia, and C. Pisano, arXiv:1707.00914* utilizing Kretzer and DSS fragmentation functions.

arXiv:1708.07080



Wrap-up

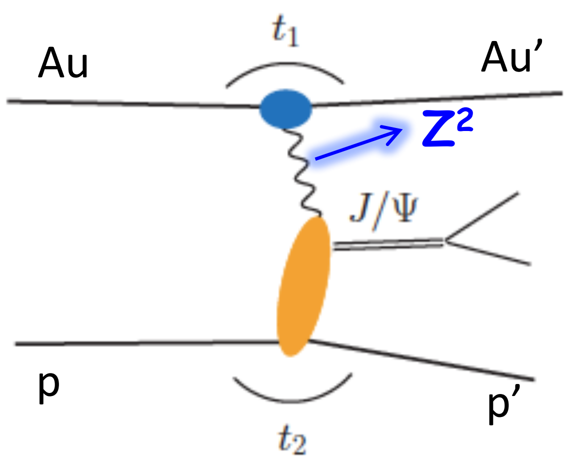
- As recommended by the Long Range Plan, we should utilize the existing RHIC infrastructure to continue to explore the structure of the proton and cold nuclear matter.
  - Complete the measurements best done at a pp/pA collider, such as Gluon FF and Gluon linear polarization.
  - Pursue measurements that will allow us to optimize and enhance the EIC program, for example tests of Universality and Factorization and TMD evolution.
  - Keep the cold QCD community strong and engaged as we move towards an EIC.

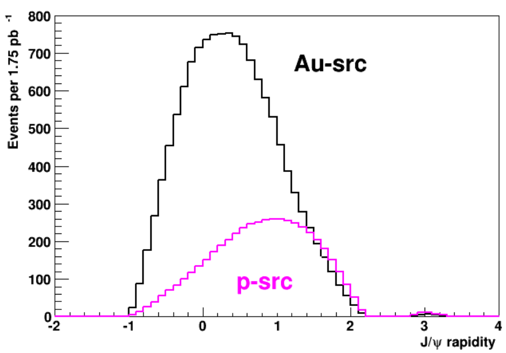


- The RHIC Spin and cold QCD community has developed a plan to complete the RHIC mission. arXiv: 1602.03922

Back up

Generalized Parton Distributions





- RHIC can access the GPD E function for gluons via measurements of **A_{UT}** of **J/ψ** in ultra-peripheral collisions
- A significant asymmetry would be the **FIRST** sign of a non-zero GPD E_g.
- GPD E_g is sensitive to spin-orbit correlations and provides input on **angular momentum** component of the spin puzzle.
- DETECTOR: EMCals to reconstruct mid-rapidity J/ψ and Roman pots to reconstruct elastically scattered proton