The Spin / Cold QCD Physics Program at STAR

Completing the RHIC program
Looking ahead to an EIC

Scott Wissink, Indiana University
for the STAR Collaboration

STAR

Supported in part by
U.S. DEPARTMENT OF ENERGY
Office of Science

Experimental landscape: Run opportunities are clear

Run 22: 16 weeks p+p at $\sqrt{s}$ = 510 GeV, expect $\mathcal{L}$ = 450 pb^{-1}

- **'Last chance' to study observables unique to this energy, *e.g., W, Z's***
- **Substantial increase to data taken at midrapidity in Run 17 (~350 pb^{-1})**
- **Crucial to take new data with forward upgrades at this energy**

Run 24: 11 weeks p+p (240 pb^{-1}), 11 weeks p+Au (1.3 pb^{-1}), 200 GeV

- **Essential to combine Run 22 results with similar data taken at 200 GeV**
- **Exploit new opportunities enabled by forward upgrade, iTPC, eTOF**

All the above data to be taken with transversely polarized p beams

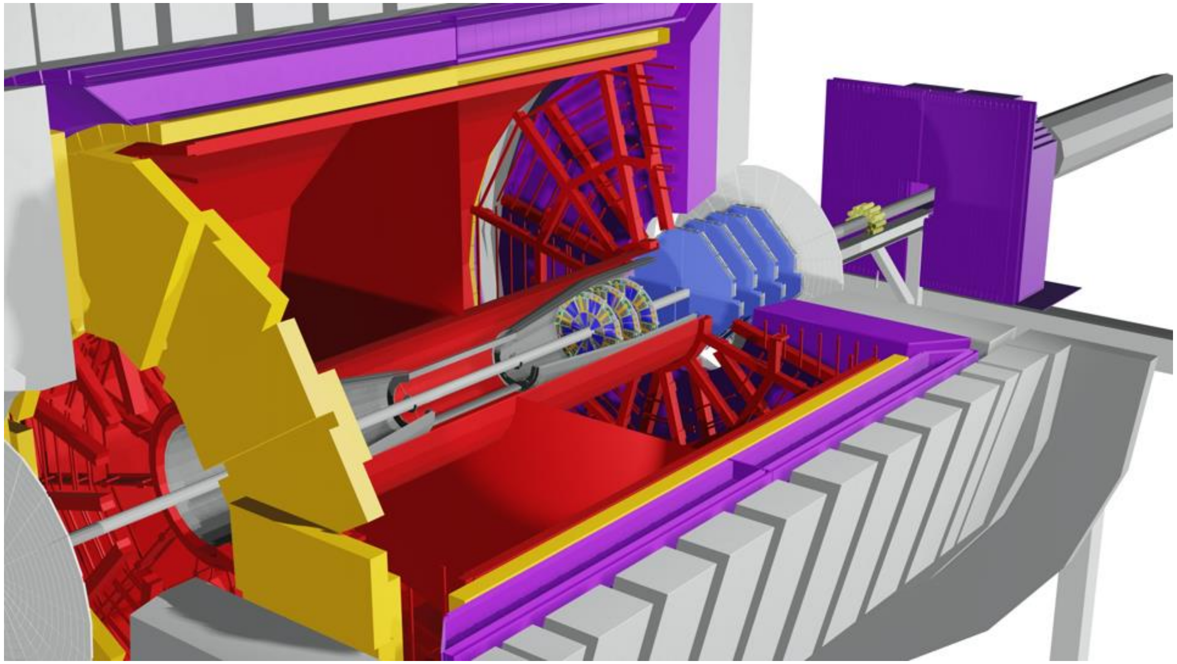
EIC in 2030:

- **Demands that we take the most critical data to finish the RHIC mission**
- **But to realize full potential of EIC, information is needed that can only be obtained from hadronic studies – complementarity of probes**

Experimental landscape: Recent, ongoing upgrades

Suite of new forward detectors will provide charged-particle tracking *(p_T* and sign) via 3 Si μ-strip and 4 smallstrip TGC planes, electromagnetic and hadronic calorimetry over range $2.5 < \eta < 4$

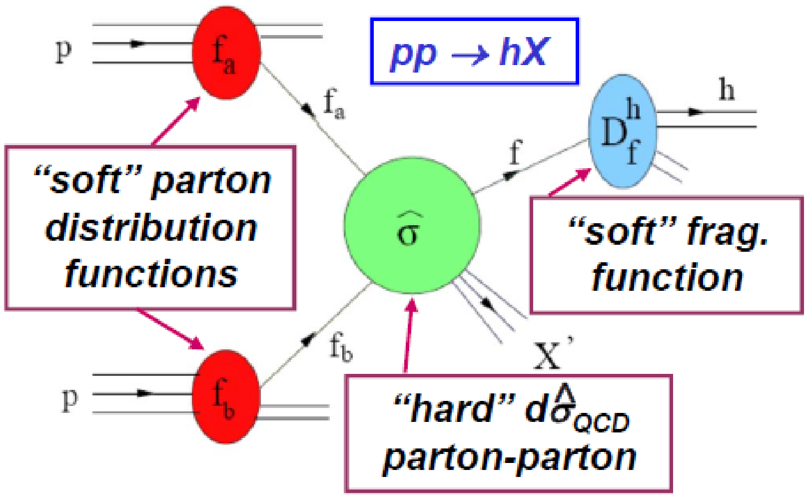
Also have iTPC, eTOF at midrapidity, and EPD



Does much more than 'just' extend kinematic reach! For dijet, correlation studies, provides unique access to *highly asymmetric* partonic collisions.

→ Dominated by interactions of high-*x* (largely valence, polarized) quarks with (abundant) low-*x* gluons, enriching data samples in *q-g* subprocess

Extracting struct. functions: physics behind the physics



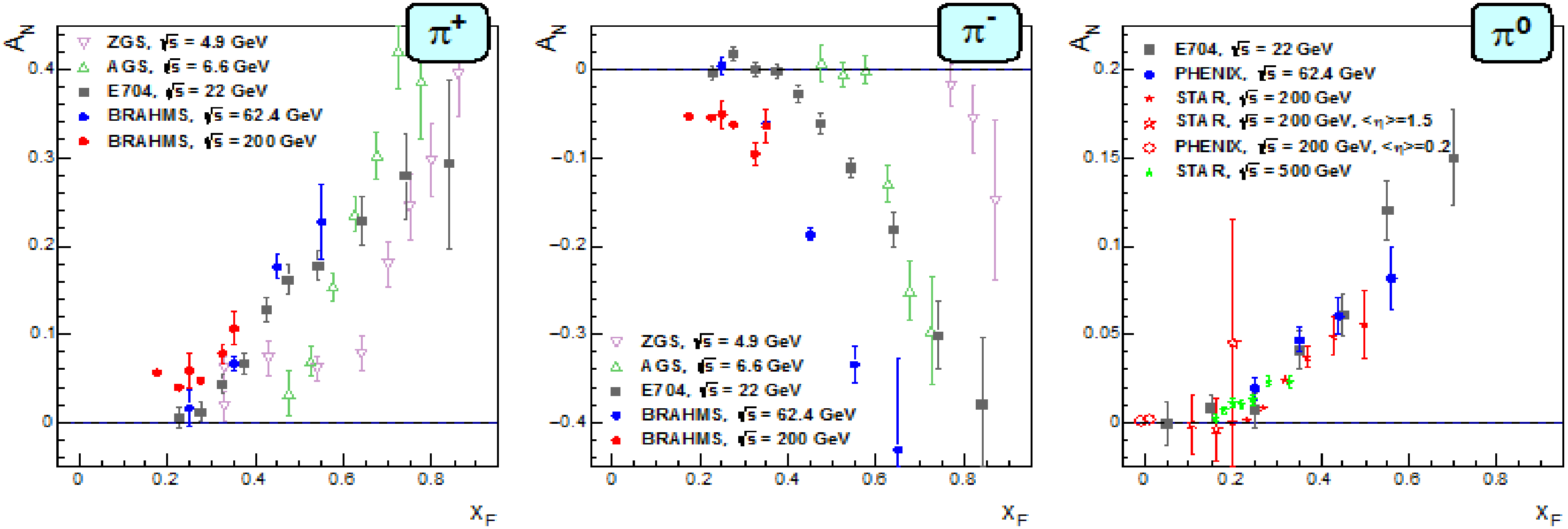
$$\frac{\sum_{a,b,c} \Delta f_a \otimes \Delta f_b \otimes d\hat{\sigma}^{f_a f_b \to f_c X} \cdot \hat{a}_{LL}^{f_a f_b \to f_c X} \otimes D_{f_c}^h}{\sum_{a,b,c} f_a \otimes f_b \otimes d\hat{\sigma}^{f_a f_b \to f_c X} \otimes D_{f_c}^h}$$

Take data at high $\sqrt{s}$ so QCD is weak, can be treated perturbatively – but several critical issues remain.

- At what level does this 'decoupling' of soft physics (structure functions) from hard physics (interactions) break down? Evidence for factorization breaking?
- To what extent are the parton distributions extracted from data dependent on the nature of the probe used? Are they truly intrinsic, so universality works?
- How does the information revealed about these functions depend on the energy, or Q^2 / distance scale, at which they are probed? How do they evolve?

Must explore these questions experimentally in order to interpret new data!

Need new theoretical tools, driven by data



Surprisingly large transverse single-spin (left/right) asymmetries in inclusive pion production – very similar behavior for $\sqrt{s}$ = 5-200 GeV!

→ *A seemingly simple phenomenon not consistent with LO pQCD*

Two ways to proceed:

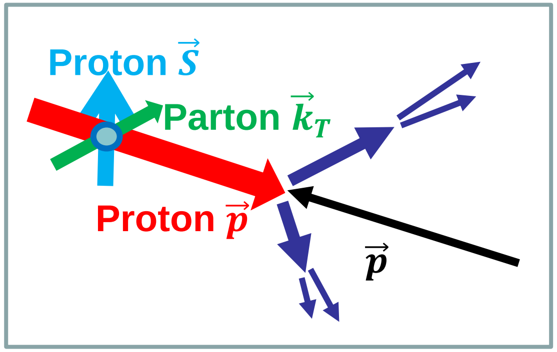
- **Transverse-momentum-dependent PDFs – work in leading twist, but allow for non-collinear interactions due to partonic k_T**
- **Incorporate higher-twist terms, *e.g.,* soft gluon radiation, collinear**

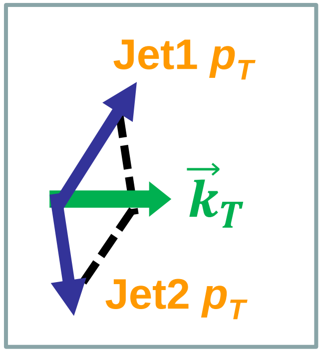
Both frameworks allow for 'new' effects in initial and/or final states

Sivers Function: TMD's in initial state

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

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

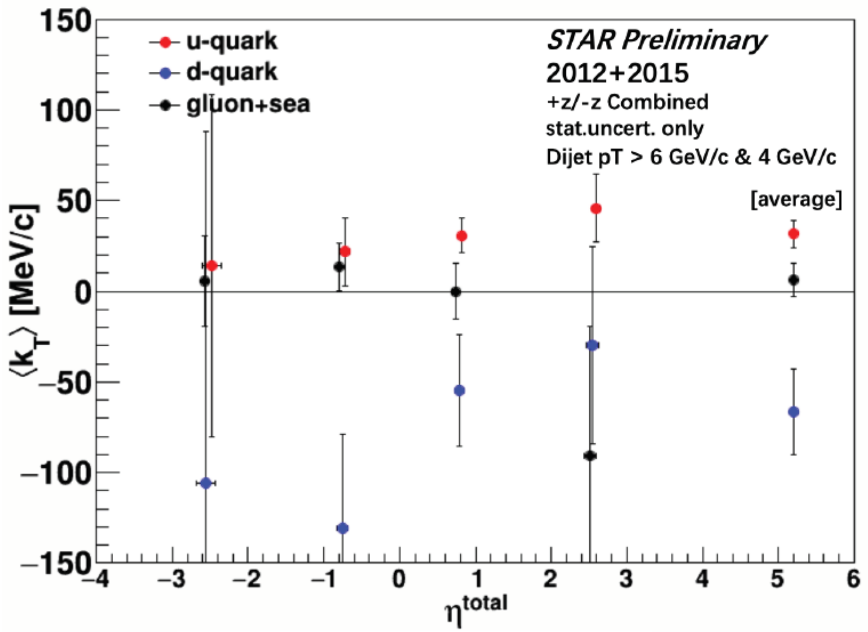




Non-zero k_T leads to spin-dependent 'tilt' of dijet opening angle

Expect no effect on average – must sort jets by their net charge → yields samples enhanced in *u* or *d* quarks

First observation of effect in dijets!

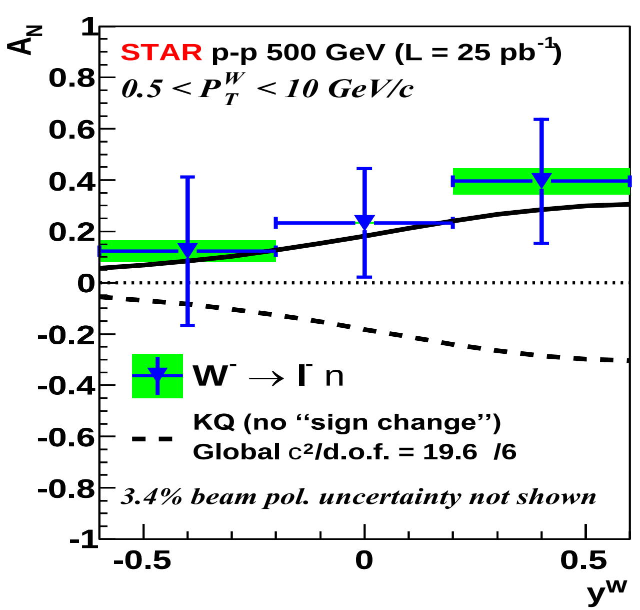


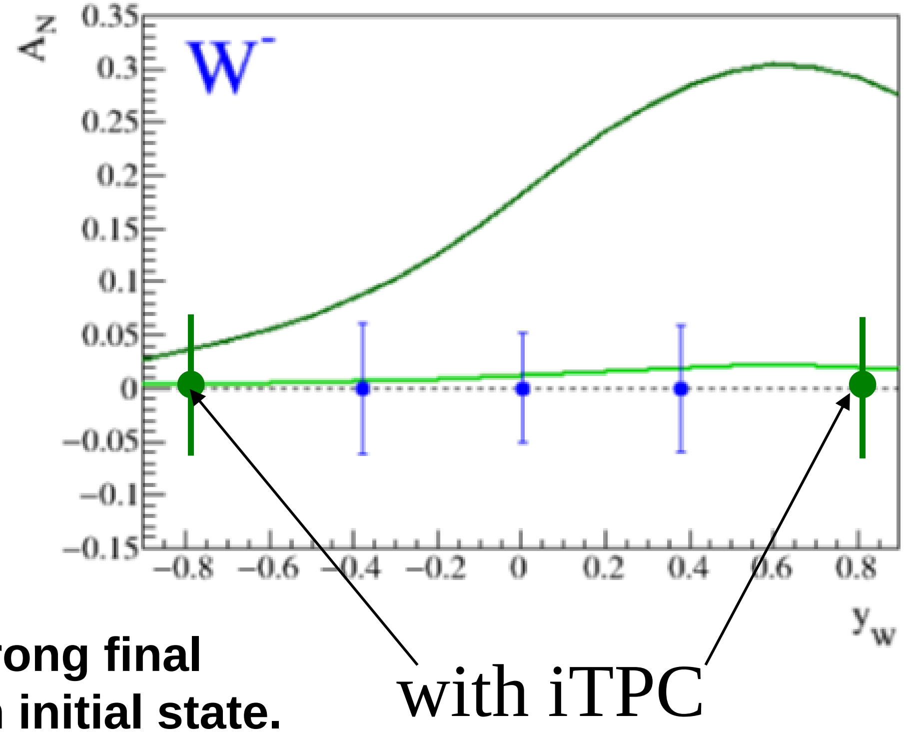
Suggests clear flavor dependence, with *d* opposite in sign, twice as large as average k_T for *u* quarks

→ Need data at 510 GeV to study *x*-dependence, also at higher $\eta^{tot} = \eta_3+\eta_4$ using new forward detectors

Sivers effect for weak boson production

A spin-dependent k_T will lead to asymmetries in other reaction channels as well





For W, Z production, Drell-Yan, no strong final state interactions. For SIDIS, none in initial state.

→ Expect a *<u>change in sign</u>* between these processes, as effects should be repulsive for ISI but attractive for FSI – test of gauge invariance in QCD.

A fundamental structure function: transversity

A leading-twist function, like the unpolarized and helicity distributions

→ **Net transverse polarization of quarks in a transversely polarized proton**

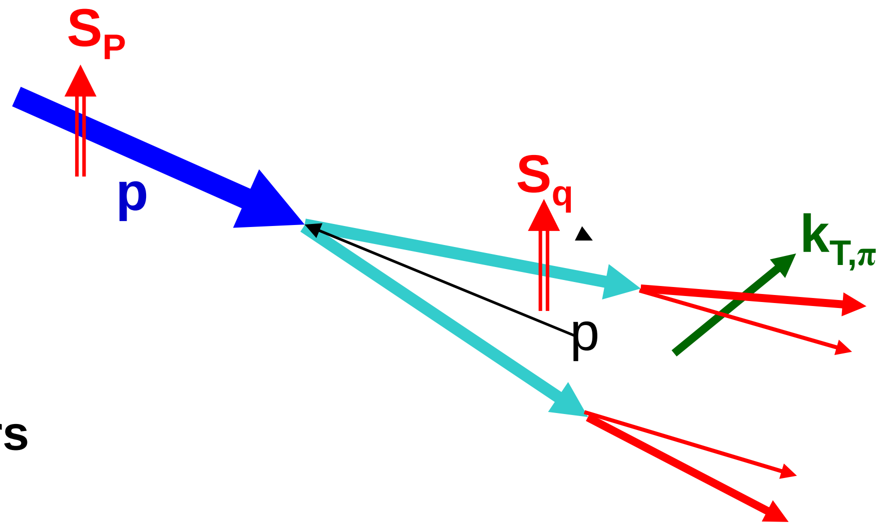
→ **Integration (in *x*) over valence region yields nucleon "tensor charge"**

- **Calculable on lattice, *ab initio* QCD calc's can be compared to exp't**
- **Sets sensitivity scale of low-energy BSM exp'ts with tensor couplings**

→ **Chiral-odd – must be accessed via a second chiral-odd function**

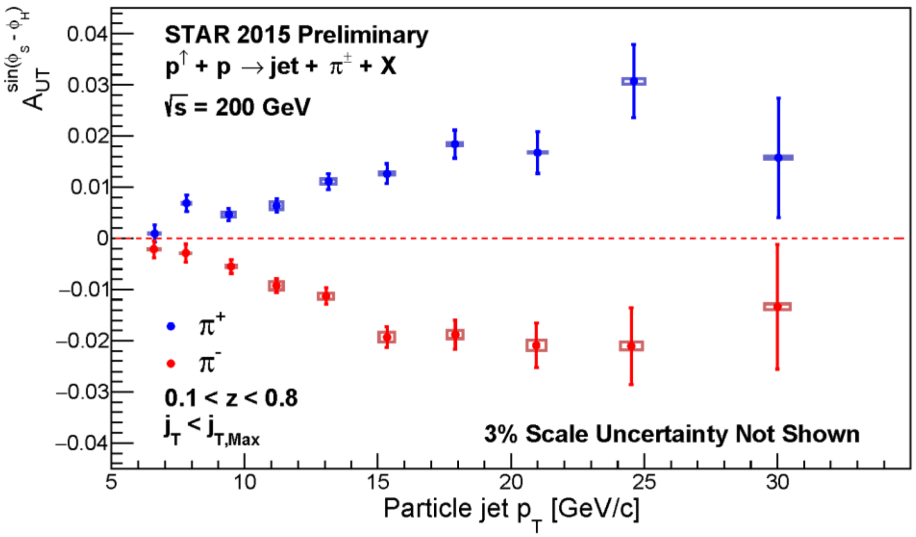
One option: *Collins function*, a left/right asymmetry in fragmentation process – a TMD process acting in the final state.

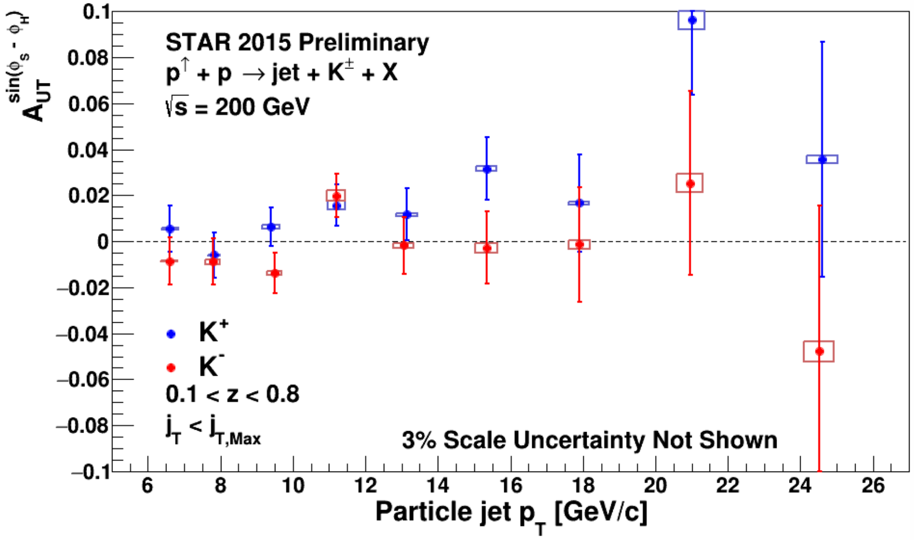
Measure azimuthal distribution of pions, *e.g.*, about the jet thrust axis, over broad range of jet (p_T , η), pion (j_T , z) parameters



Can also probe di-hadron correlations in jets, IFF's

STAR well-suited for Collins / IFF measurements!



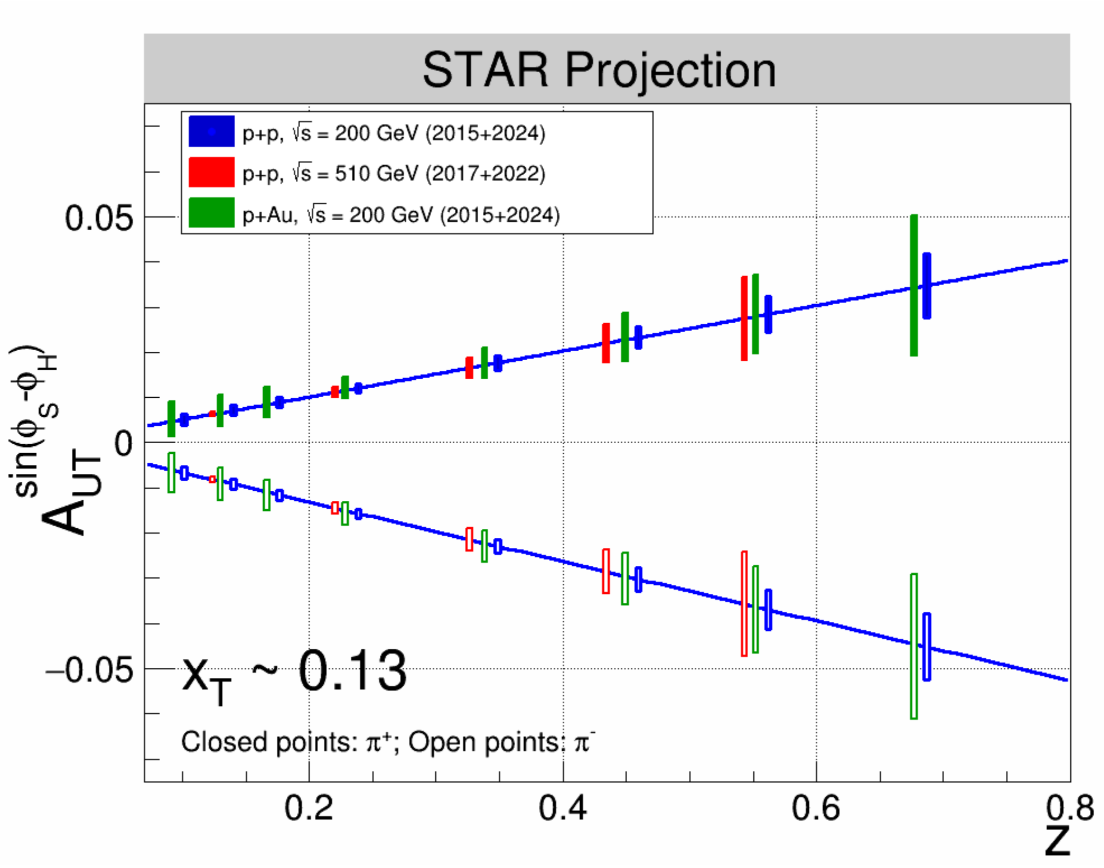


Hermetic coverage at mid-rapidity *essential* for these "particles within jet" measurements – need precise, unbiased determination of jet thrust axis.

For clean physics interpretation, also need good PID → iTPC will increase FOM by providing better dE/dx resolution, separating pions, kaons, protons

- **While π^+ / π^- are ~symmetric, K^+ A_{UT} is larger than π^+, but $K^- \approx 0$**
- **Much higher statistics and better PID available in Runs 22, 24**

STAR well-suited for Collins measurements (cont'd)

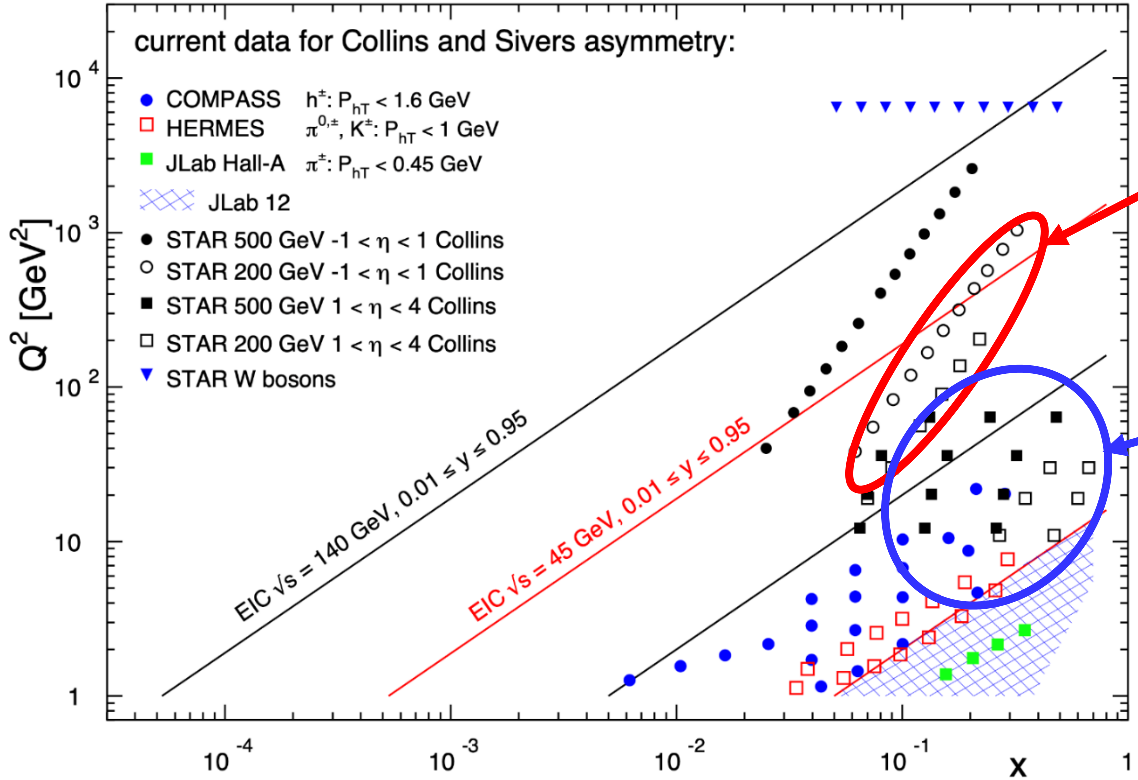


Precision measurements of Collins effect for pions at $\sqrt{s}$ = 200 and 500 GeV

→ Will provide important constraints on evolution of TMDs, plus essential kinematic overlap in *x*-*Q*^{2} space with future EIC

Also: can perform similar studies in p+Au collisions, explore propagation and hadronization of polarized quark in nuclear matter

Extensive overlap with kinematic reach of EIC



Full particle ID: $\pi^{+/-}$, $K^{+/-}$ in 200 and 510 GeV

Unidentified hadrons: $h^{+/-}$ in 200 and 510 GeV

Collins and Sivers x-Q^2 coverage for 510 and 200 GeV

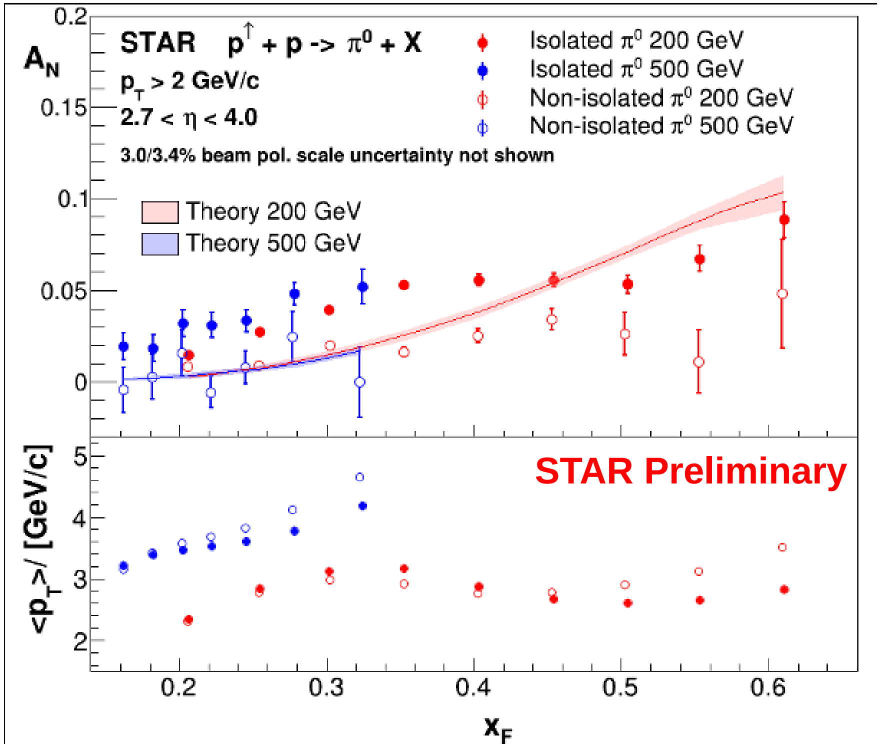
- Forward acceptance with the iTPC comes with full PID
  - Precision measurements as at mid-rapidity, but limited to x <~ 0.2
  - Only a limited Q^2 lever arm between 200 GeV eta=0 and 200 GeV iTPC
- Forward acceptance with the Forward Upgrade only samples $h^{+/-}$
  - Coverage focuses on high x where there are no SIDIS measurements

Impact of the Forward Upgrade: pion A_N

New results on the measurement that started it all: forward pion A_N

→ Transverse asymmetries for π^0 are *larger* if pion is isolated, rather than surrounded by other photons

→ Clue towards understanding the dynamics of the phenomena



But similar measurements taken with upgrades will be much richer:

- ❑ **Enable measurements of $h^{+/-}$ (no PID) in addition to neutral pions**
- ❑ **Isolate particle of interest from nearby charged particles, not just γ's**
- ❑ **Full jet and Collins asymmetries, for both charged and neutral particles**
- ❑ **Can also detect protons in Roman pots, 'tag' diffractive event sample**

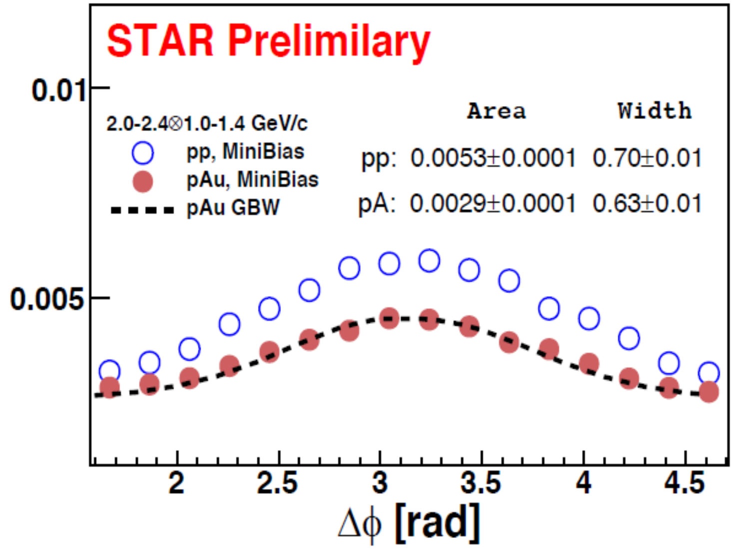
Gluon saturation: forward di-hadrons in p+p and p+Au

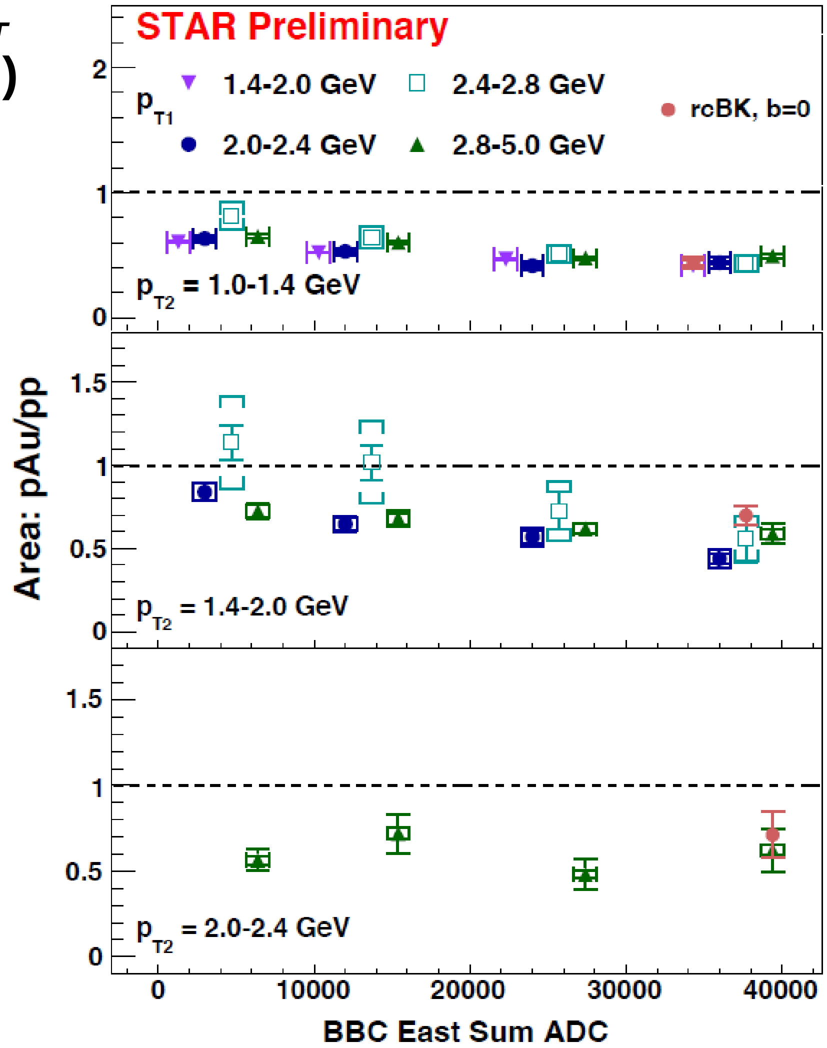
Detect two π^0s in FMS: trigger on high p_T (*q* in proton), study lower p_T (*g* in p or Au)

→ **Selection enhanced in low-*x* gluons from the 'target' – saturation region!**

→ **Area of away-side peak suppressed in p+Au, width and 'pedestal' the same**

→ **Suppression grows with increased event activity – first hint of CGC?**





Summary and Outlook

Looking forward (pun intended) to many exciting, high impact results from p+p running at 510 GeV in Run 22, p+p and p+Au at 200 GeV in Run 24

- ✓ High sampled luminosity, with forward upgrade and enhanced PID at mid-η
- ✓ Wide range in *x* (0.005 – 0.5) covered by combining data at two energies
  → Overlapping regions (same *x*, different Q^2) enable tests of evolution
- ✓ Precise, high statistics data in kinematic regions that overlap with those of EIC
  → Enables critical experimental studies of factorization breaking, universality in transverse spin phenomena, nuclear PDFs, fragmentation functions
- ✓ Allows exploration of low-*x*, non-linear gluon dynamics → onset of saturation?

More broadly: data from these runs will not only address specific, crucial questions on nucleon and nuclear structure, but offer fundamental insights towards our understanding of QCD that will be essential while designing experiments that will maximize the scientific output of the EIC.

Back-up