TMDs from RHIC to EIC

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Not covered:
inclusive hadron A_N
IFF → Anselm

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Why p+p to access TMDs

Complementarity:

QCD has two concepts, which lay its foundation: factorization and universality

→ To tests these concepts and separate interaction dependent phenomena from intrinsic nuclear properties different complementary probes are critical

Probes: high precision data from ep, pp, e+e-

Gluons:

One of the driving motivations behind an EIC is the study of gluons. Strong interactions access gluons directly (qg & gg) and are well suited for studying TMD observables like Gluon Fragmentation Functions and Gluon Linear Polarization.

DIS: F_L, tag PGF (di-jets, heavy flavor)

Evolution:

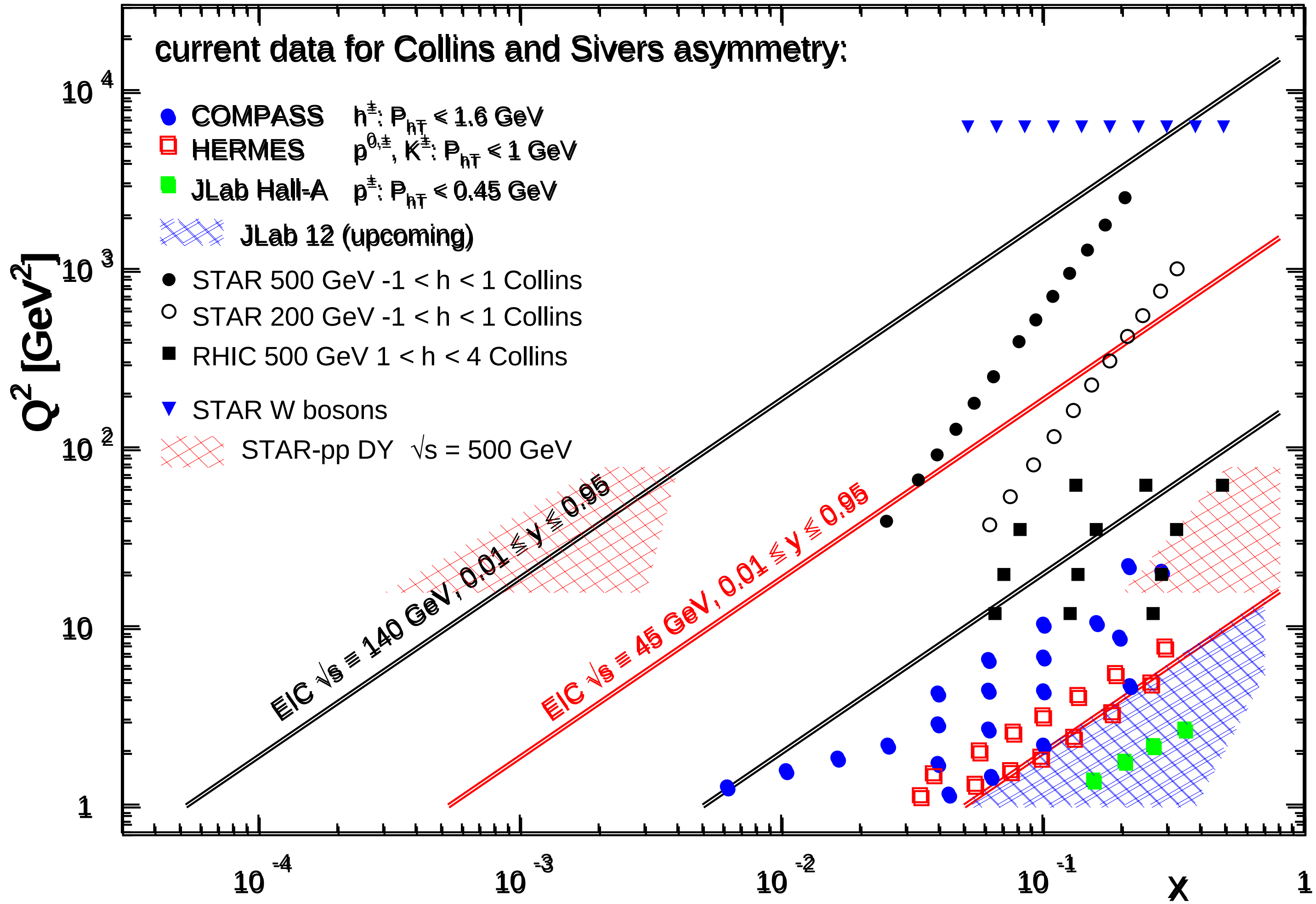
TMD evolution is area of active theoretical research!

→ Proton colliders routinely access higher Q^2 and p_t than fixed target experiments (as well as some running scenarios for an EIC).

→ Provides insights into the size of observables we want to measure at an EIC.

Hadron collider data critical to fully realize the scientific promise of the EIC and lay the groundwork for the EIC, both scientifically and by refining the experimental requirements

TMDs at RHIC



Till today TMDs came only from fixed target data → high x @ low Q^2

need to establish concept at high Q^2 and wide range in x

polarised pp at RHIC

RHIC unique kinematics: from low to high x at high Q^2

only way to access gluon TMDs before an EIC

The objectives for TMDs

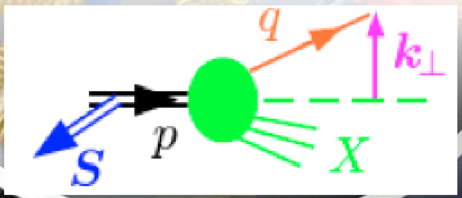
- Constrain TMDs over a wide x and Q^2 range (valence, sea-quarks & gluons)
  - → need 2 scale processes (DY, W, Z^0, Di-jet, $h^\pm$ in jet)
  - → different √s → different p_t at the same x_t → evolution
  - → Test non-universality of TMDs ← → SIDIS
- observables as transversity can be accessed also in collinear observables (IFF)
  - → test of TMD factorization & universality
- observables purely sensitive (1-scale (π^0/γ/jet)) to the TWIST-3 formalism
  - → different √s → evolution

Initial State

- A_N for $W^{+/-}$, Z^0, DY
  - → Sivers
- A_N for jets
  - → g-Sivers in Twist-3
- direct photons
  - → q-Sivers in Twist-3

related through

$$-\int d^2k_\perp \frac{|k_\perp^2|}{M} f_{1T}^{\perp q}(x,k_\perp^2)|_{SIDIS} = T_{q,F}(x,x)$$

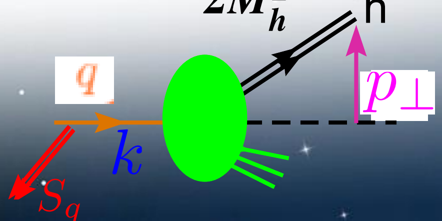


Final State

- A_{UT} $\pi^{+/-}\pi^0$ **azimuthal distribution in jets**
  - → Transversity x Collins
- A_{UT} in dihadron production
  - → Transversity x Interference FF
- A_N for π+/- and π^0
  - → Novel Twist-3 FF Mechanisms

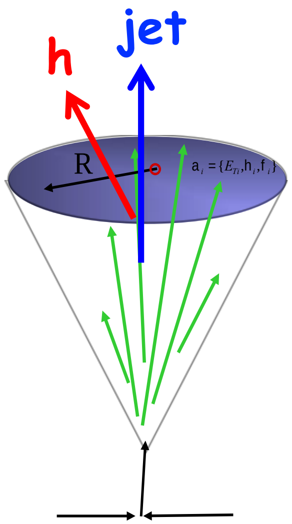
related through

$$\hat{H}(z) = z^2 \int d^2\vec{k}_\perp \frac{\vec{k}_\perp^2}{2M_h^2} H_1^\perp(z, z^2, \vec{k}_\perp^2)$$



A GoldeN Observable: "Hadrons in Jet"

Observable: Hadron distribution inside jet



- Study a hadron distribution inside a fully reconstructed jet

$$F(z,p_t)=\frac{d\sigma^h}{dydp_t dz}/\frac{d\sigma}{dydp_t}\qquad f(z,p_t,j_t)=\frac{d\sigma^h}{dydp_t dz dj_t}/\frac{d\sigma}{dydp_t}\qquad z=\frac{p_t^h}{p_t^{jet}}$$

W. Vogelsang et al. arXiv:1506.01415

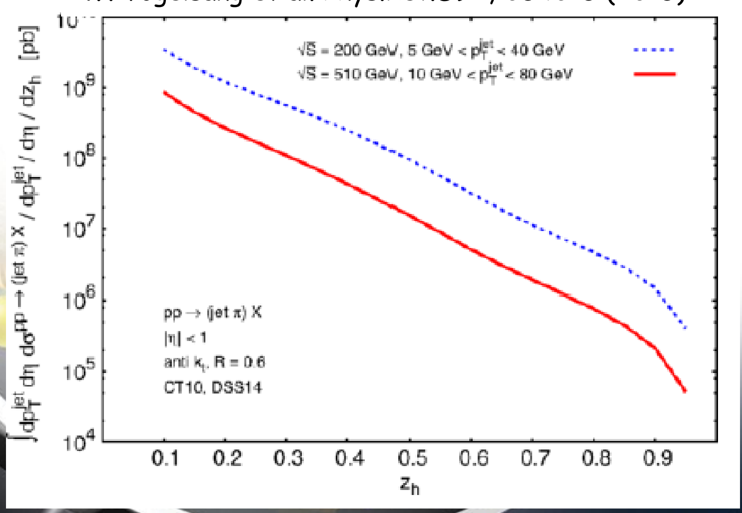
j_t: hadron transverse momentum with respect to the jet direction

- The 1[st] observable is collinear, while the 2[nd] observable is a TMD

Cross section for hadrons in jet

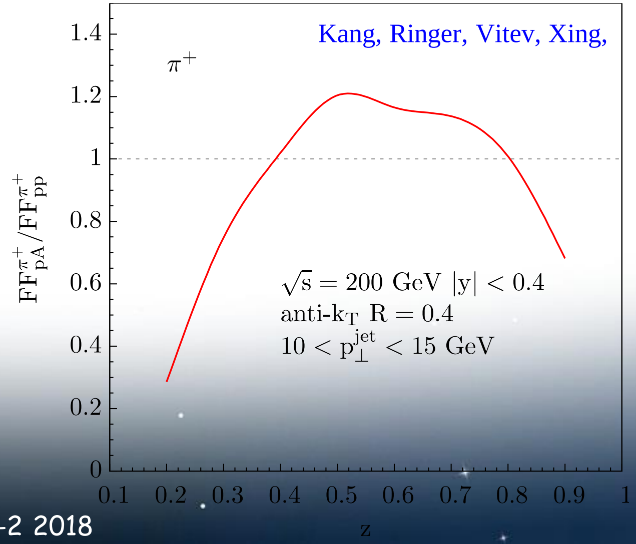
- High sensitivity to Gluon FF
- Unique to pp

W. Vogelsang et al. Phys.Rev.D92, 054015 (2015)



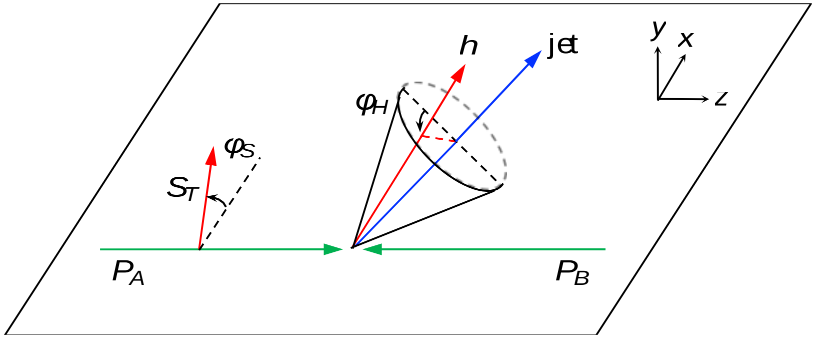
Nuclear dependence of FFs

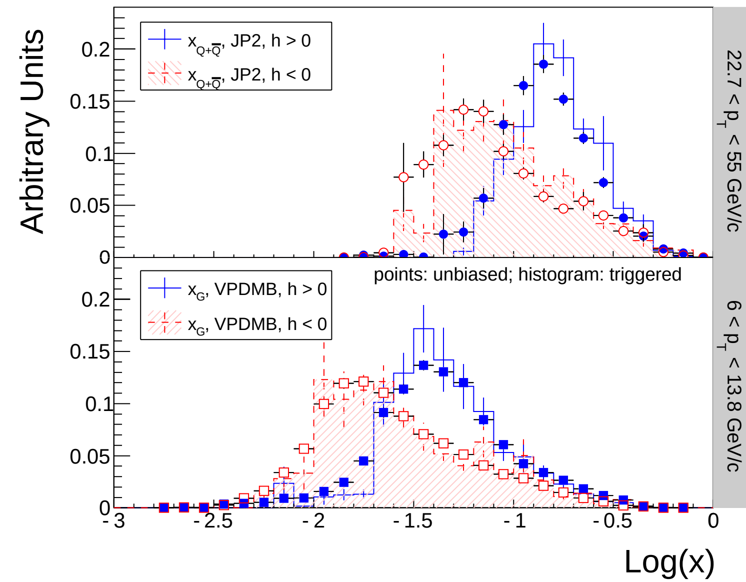
- Seems to follow the feature of p+Pb at LHC
- Will see how energy loss picture will compare



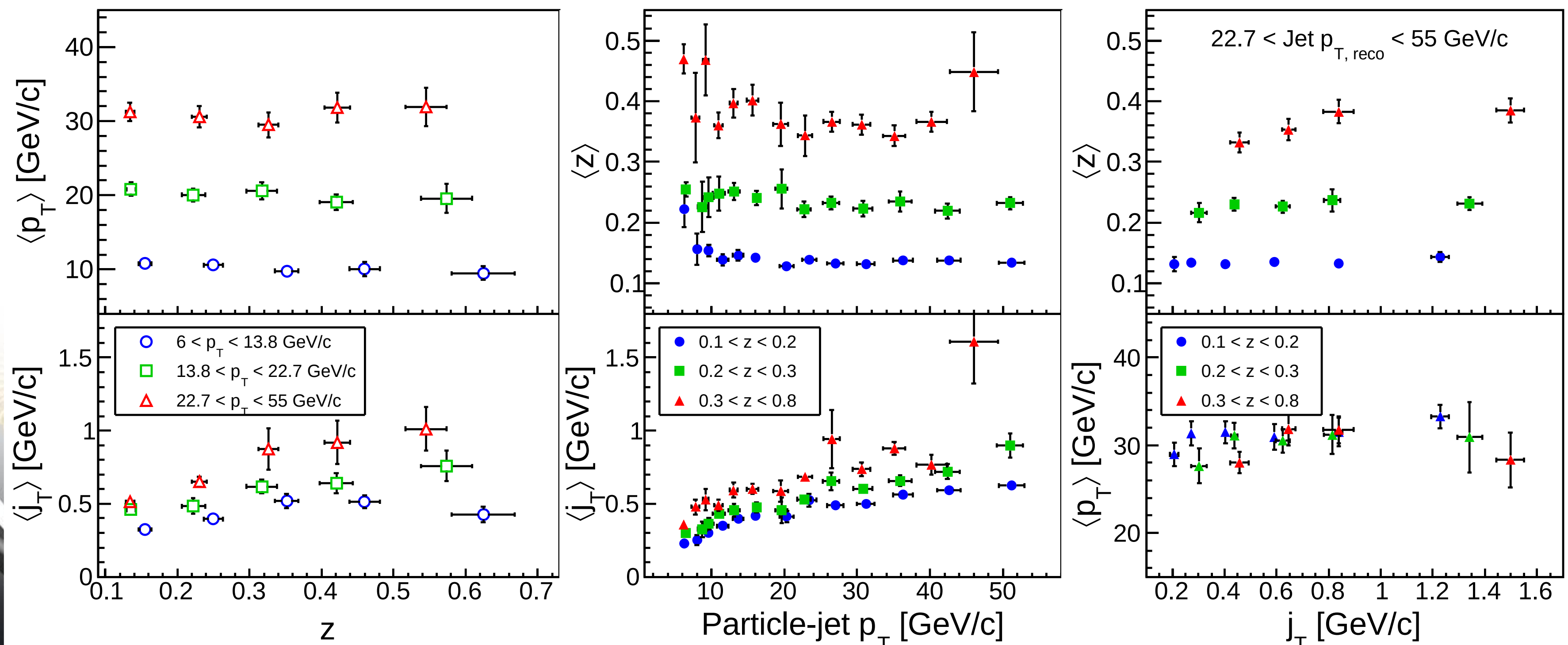
Jets to access Transversity x Collins

Kinematics for hadrons in a jet:





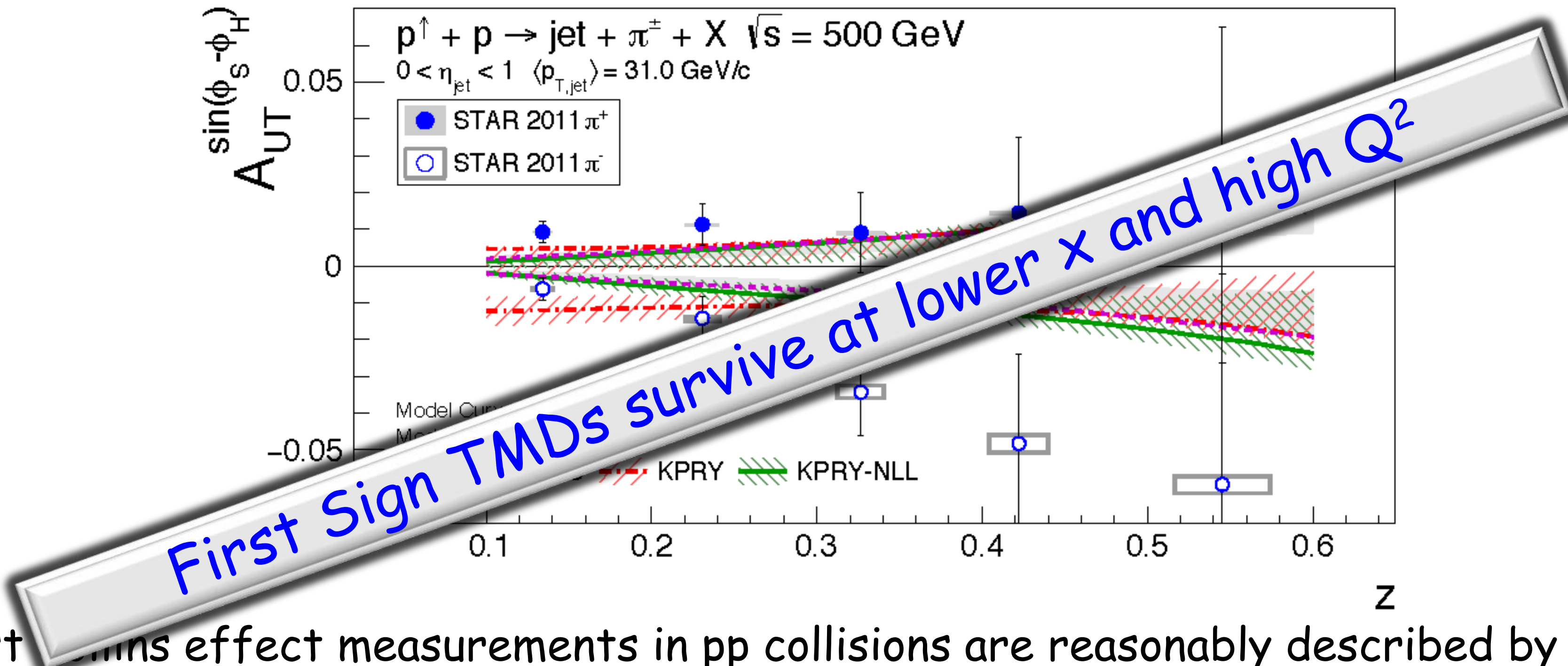
jets: anti-k_t with R=0.5
PRD97 (2018), 032004



Jets to access Transversity x Collins

$$A_{UT}^{\rho^\pm} \approx \frac{h_1^{q_1}(x_1,k_T) f_{q_2}(x_2,k_T)\hat{s}_{UT}(\hat{s},\hat{t},\hat{u}) DD_{q_1}^{\rho^\pm}(z,j_T)}{f_{q_1}(x_1,k_T) f_{q_2}(x_2,k_T)\hat{s}_{UU} D_{q_1}^{\rho^\pm}(z,j_T)}$$

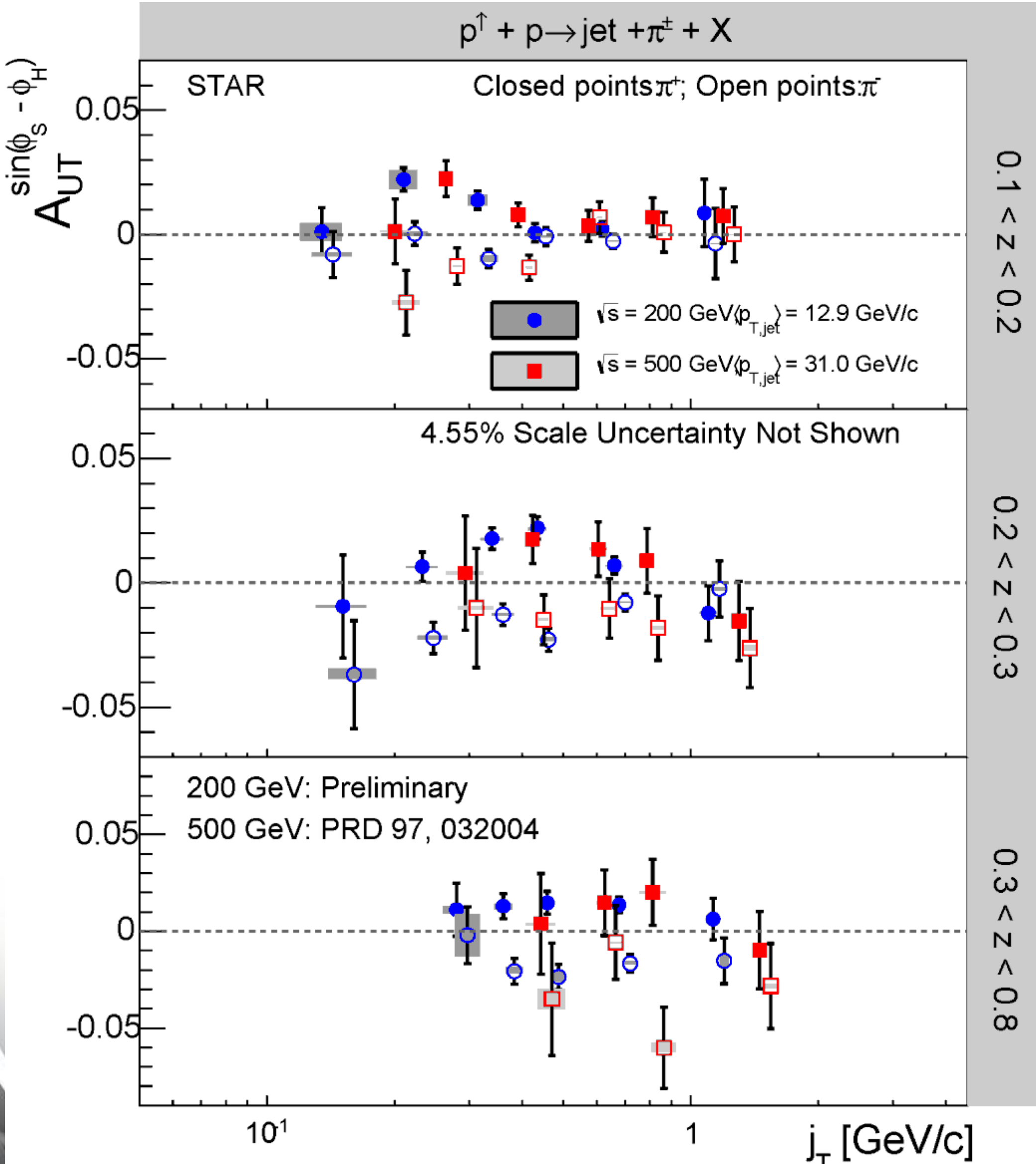
STAR arXiv:1708.07080
DMP: PLB 773, 300 (2017)
KPRY: PLB 774, 635 (2017)



First Collins effect measurements in pp collisions are reasonably described by two recent calculations that convolute the transversity distribution from SIDIS with the Collins FF from *e+e-* collisions

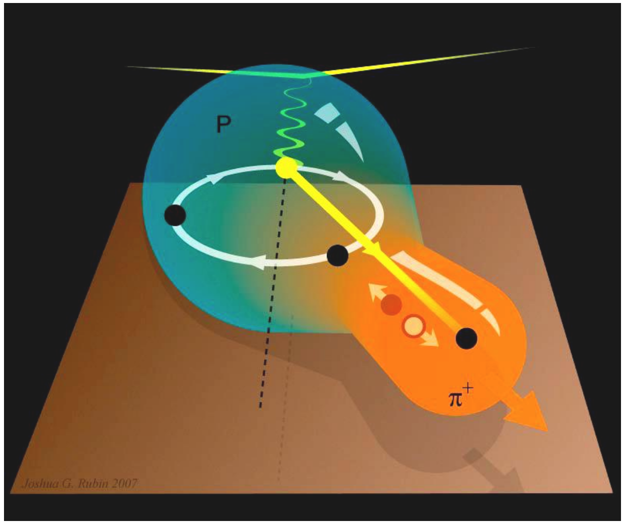
- Tests the predicted **universality of the Collins FF**
  - Kang et al, JHEP 11, 068 (2017)
- TMD evolution effects appear to be small

Collins effect vs jT in separate z-bins

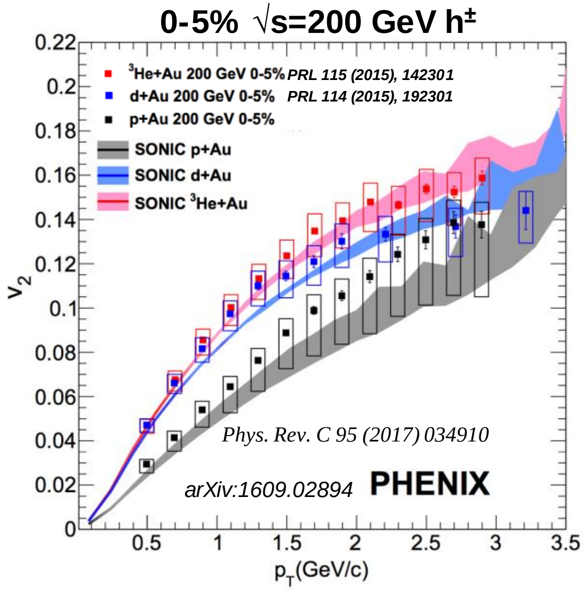


- 500 GeV pp results hinted the A_{UT} peak shifts to higher j_T as z increases
  - 2017 data factor 14 more statistics
- New preliminary **200 GeV pp results provide confirming evidence**

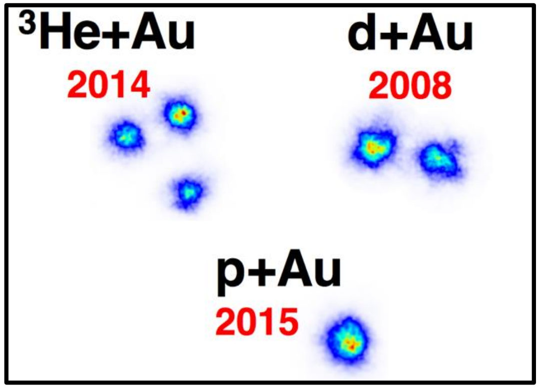
What Do We Know about Gluon TMDs



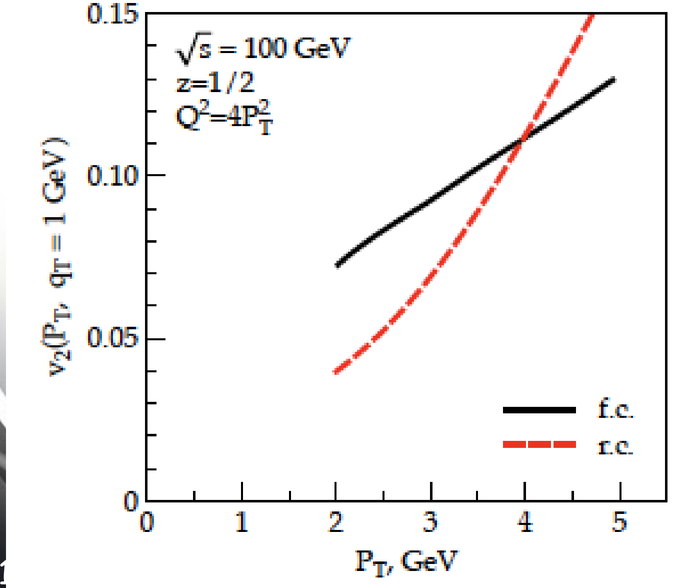
TMDs and "QGP" in small systems



Collective flow signatures seen even in the smallest systems and at the lowest RHIC energies



TMD formalism in DIS predicts a distribution for linearly polarized gluons in an unpolarized target. This is reflected in cos(2φ) asymmetries in dijet production



Study azimuthal anisotropy as a function of the rapidity dis-balance of the jets

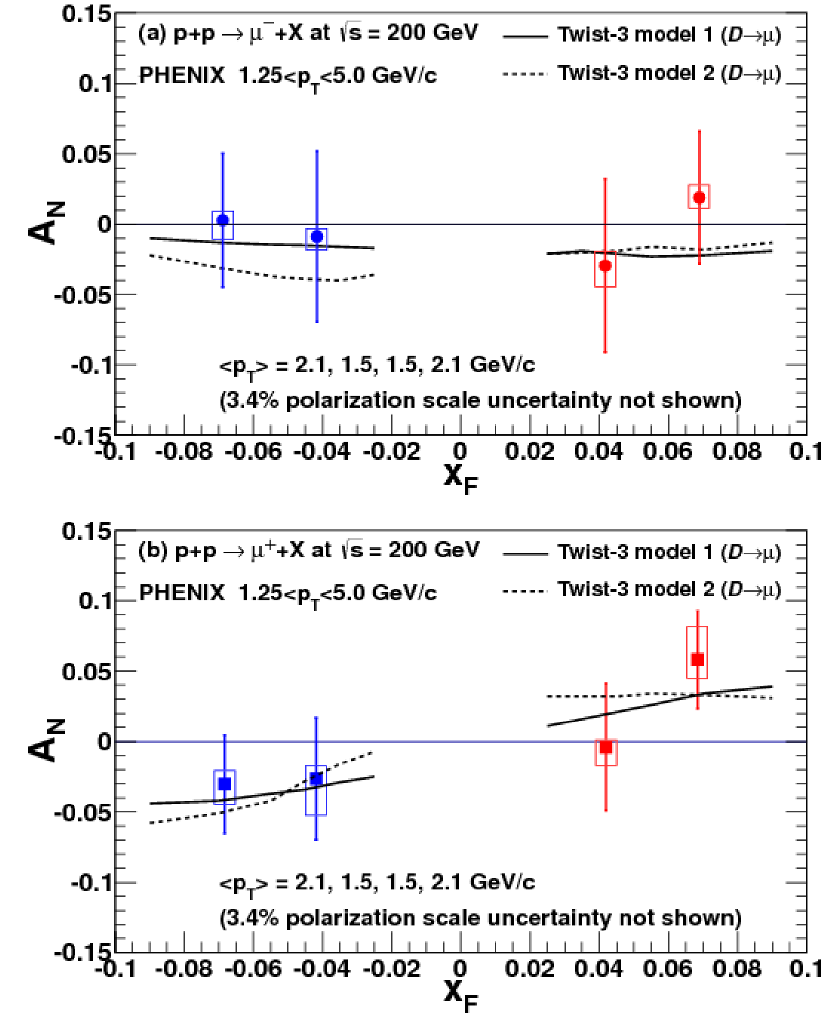
→ Process sensitive to unpolarized and linearly polarized gluon distribution

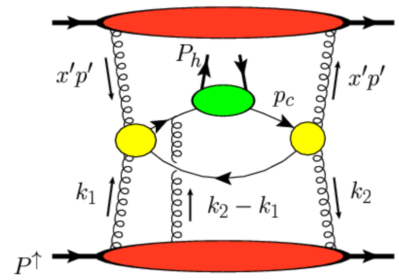
$$xG_{ww}^{ij} = \frac{1}{2}\delta^{ij} xG^{(1)} - \frac{1}{2}\left(\delta^{ij} - \frac{2k^i k^j}{k^2}\right) xh_\perp^{(1)}$$

Phys.Rev. D94 (2016) no.1, 014030
Phys.Rev.Lett. 115 (2015) no.25,252301
Phys.Rev. D91 (2015) no.7, 074006
Phys.Lett. B743 (2015) 134-137

Sensitivity to Gluon "TMDs"

Phys.Rev. D95 (2017) 112001

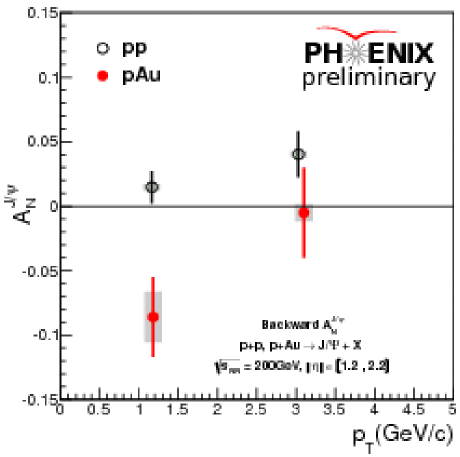


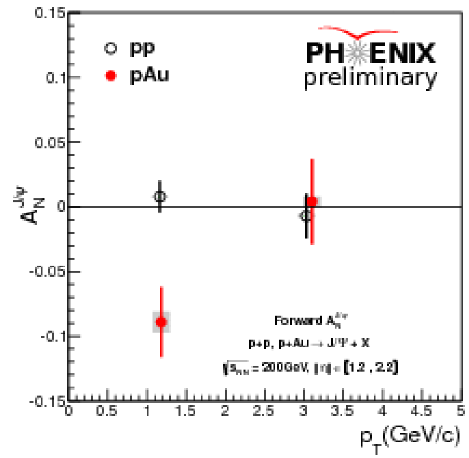


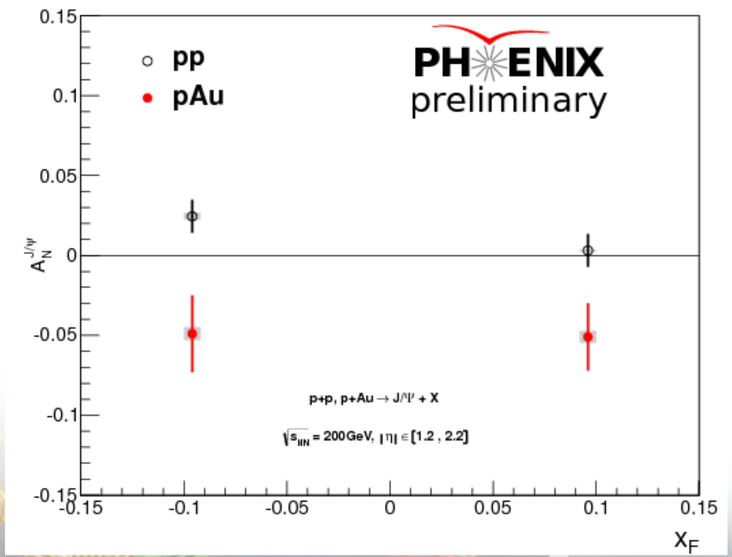
- Heavy flavor asymmetries most sensitive to Twist-3 counterpart of Gluon Sivers and tri-gluon correlator,
- no final state effects expected due to heavy quark mass
- Both contributions poorly known

Model calculations from: Koike et.al. Phys.Rev. D84 (2011) 014026

Sensitivity to Gluon "TMDs"

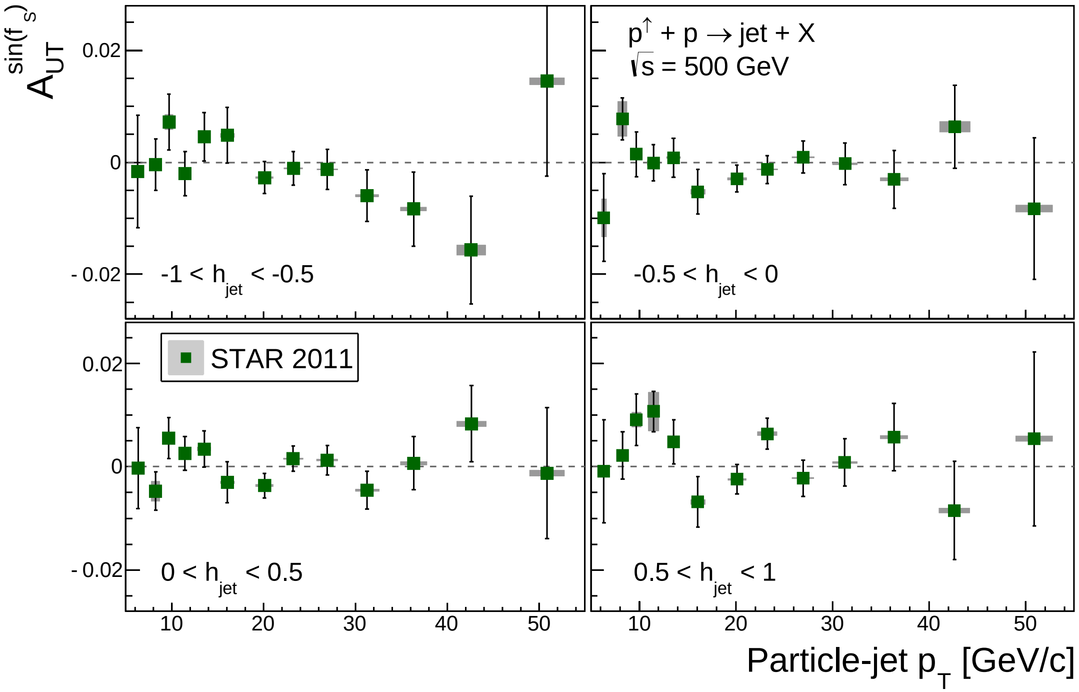


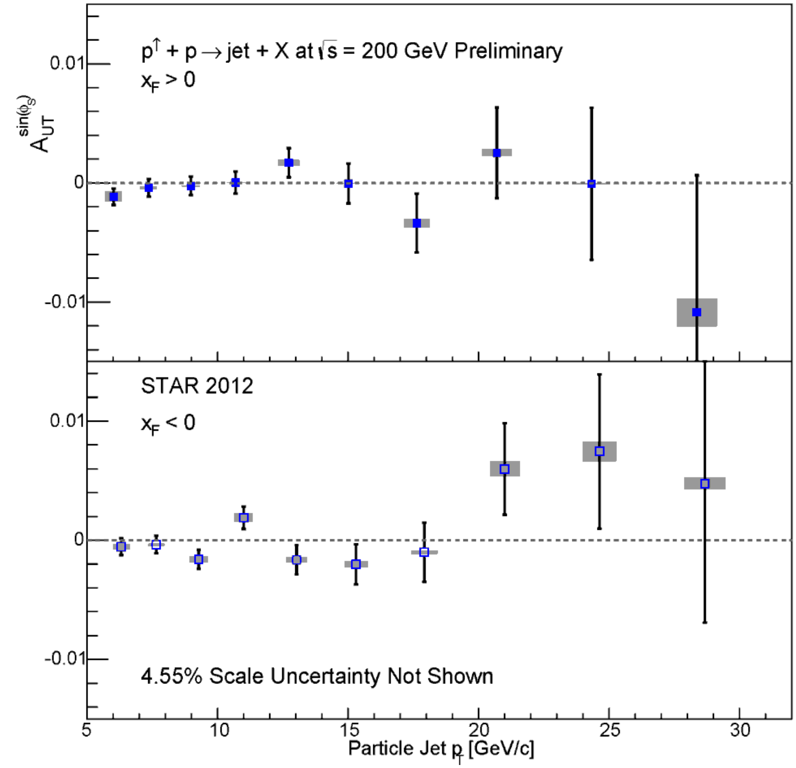


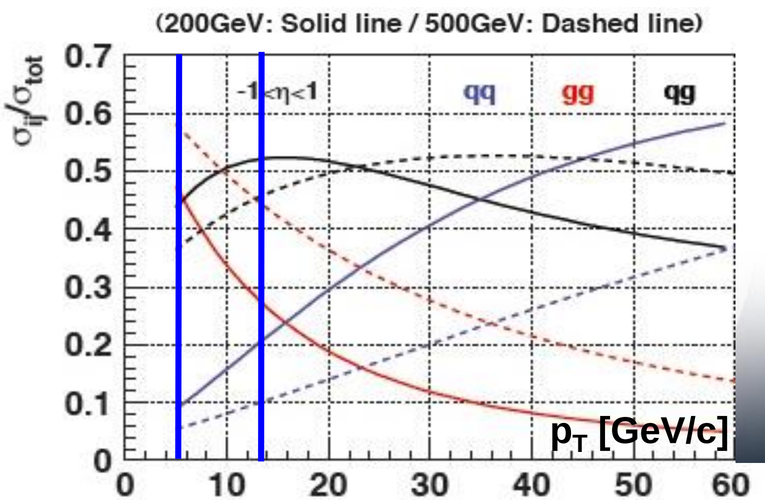


- Surprising nonzero J/Psi A_Ns seen in pAu collisions while pp Asymmetries are mostly consistent with zero
- Nonzero effect only visible at the lowest available P_t
- Diffractive effects as cause not very likely due to coincidence with hard collision trigger
- pAl data is being analyzed

"Twist-3 Sivers" through Inclusive Jets



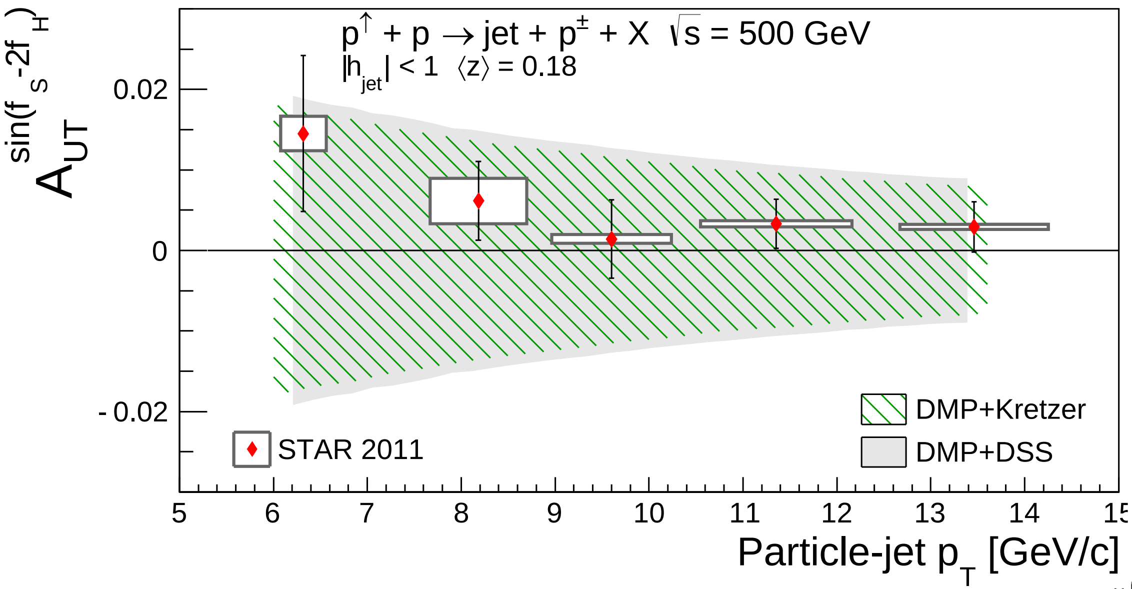




No sign of sizable azimuthal asymmetry in jet production at $\sqrt{s}$ = 500 GeV & 200 GeV

Consistent with expectation from inclusive jets, di-jets, and neutral pions at $\sqrt{s}$ = 200 GeV

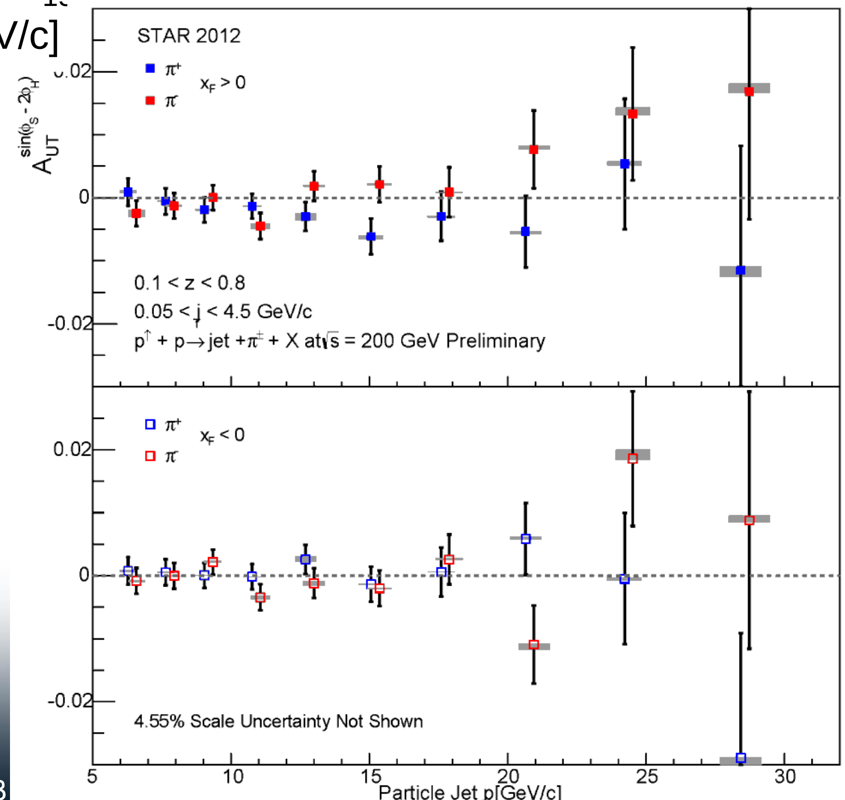
Collins like Effect



Until now, Collins-like asymmetries completely unconstrained

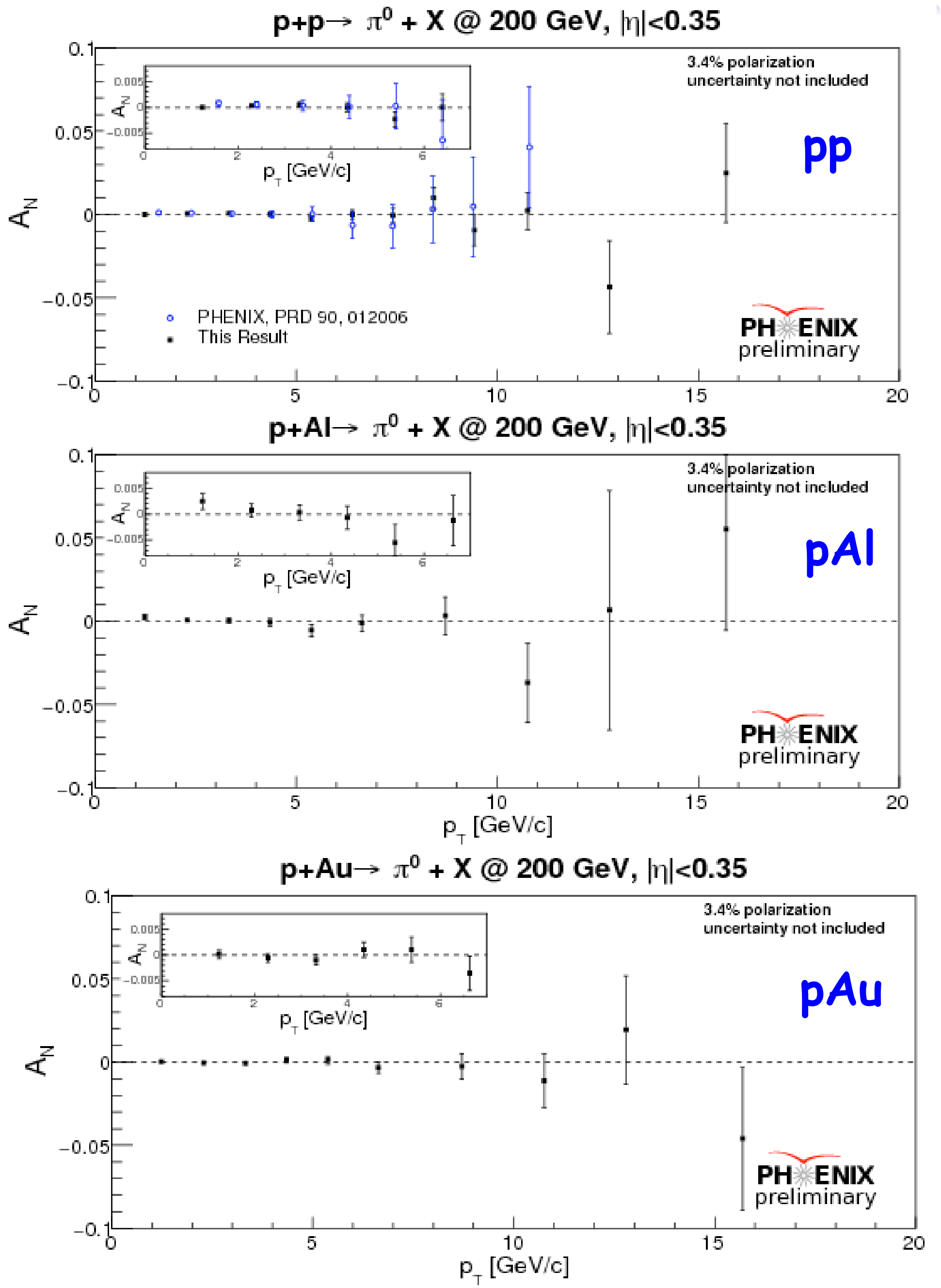
World's first ever limit *on linearly polarized gluons in a polarized proton*

Shaded bands represent maximal predictions from D'Alesio, Murgia, andPisano, arXiv:1707.00914 utilizing Kretzer and DSS FF



New preliminary results from 200 GeV pp collisions will provide much stronger limits

Sensitivity to Gluon "TMDs"

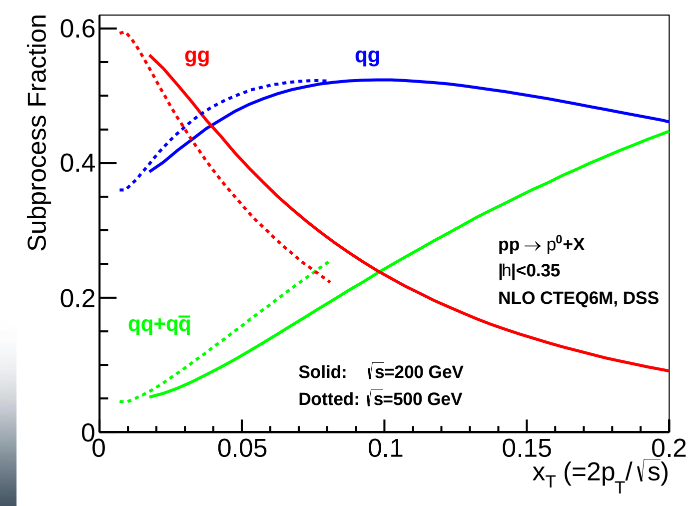


pp:

- Improved results from 2015!
- Consistent with 0
  to $3\sim10^{-4}$ precision level at low p_T
- constrain of gluon Sivers effect
  Anselmino et al, PRD 74 (2006), 094011
  D'Alesio et al, JHEP 1509 (2015), 119

pA:

high precision test of nuclear effects



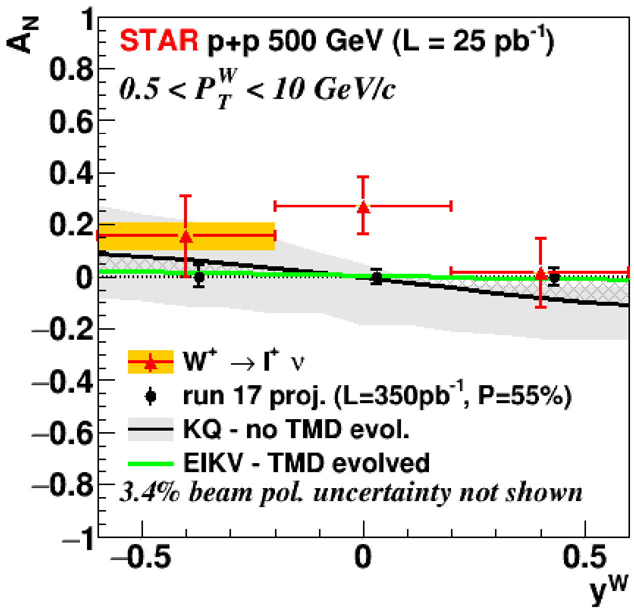
What Will Come

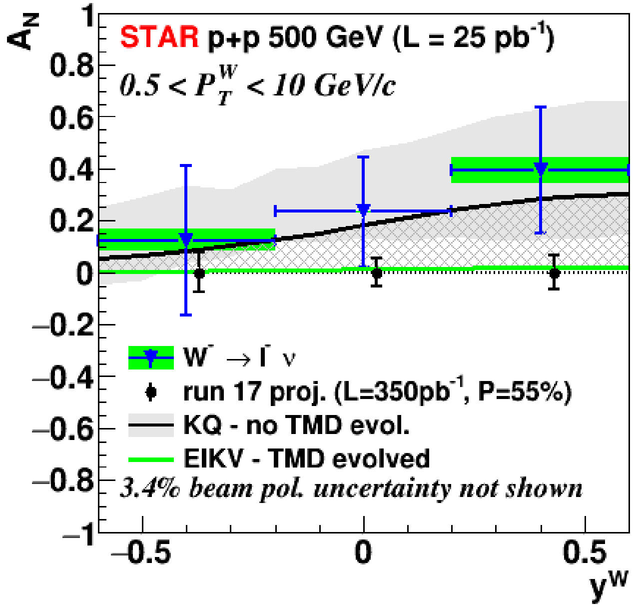
to

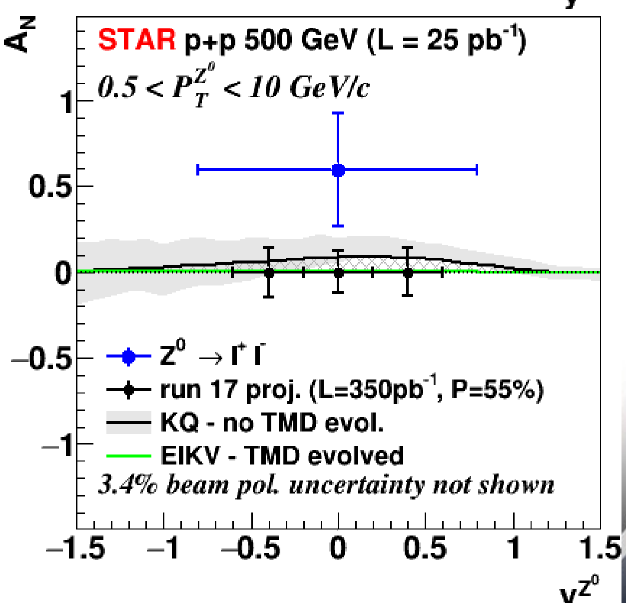
RUN-17: A goldmine for TMDs@STAR

Collected:

350 pb^{-1} → 14 times Run-11 for $-1 < \eta < 1.8$ → A_N $W^{+/-}$ & Z^0, Collins, ……







Will provide data to constrain

→ TMD evolution,

→ sea-quark Sivers fct

→ through rapidity distribution → neg. η

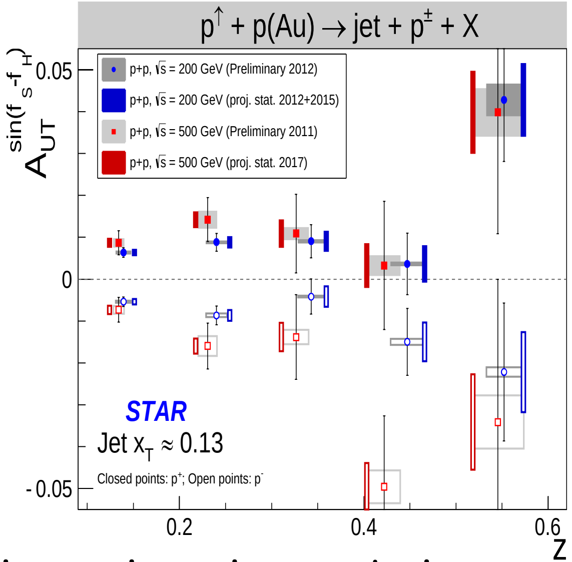
→ test of Sivers fct. non-universality

→ Z^0 very clean channel no corrections

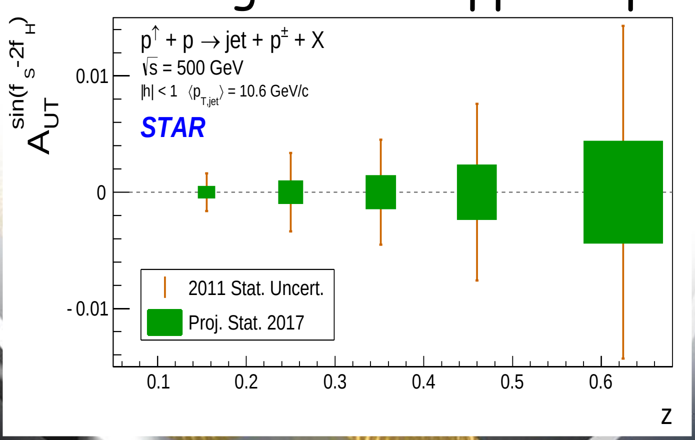
Mid-rapidity observables

At 500 GeV in 2017:

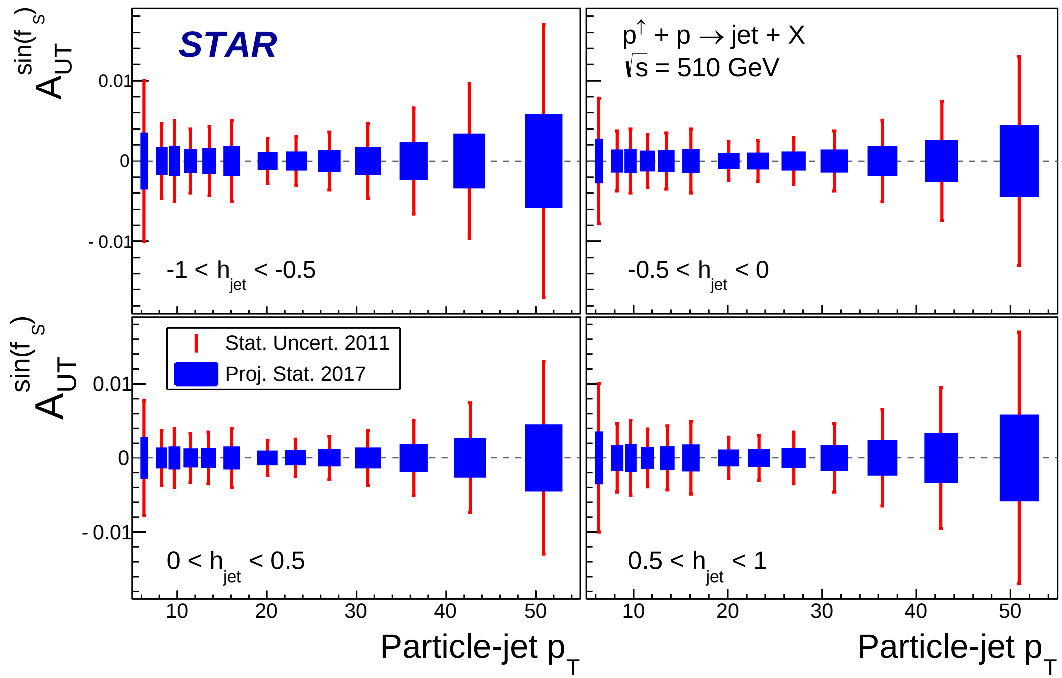
Transversity x Collins



linearly polarised gluons
→ could be an explanation for the ridge seen in pp and pA



Sivers function through TWIST-3:



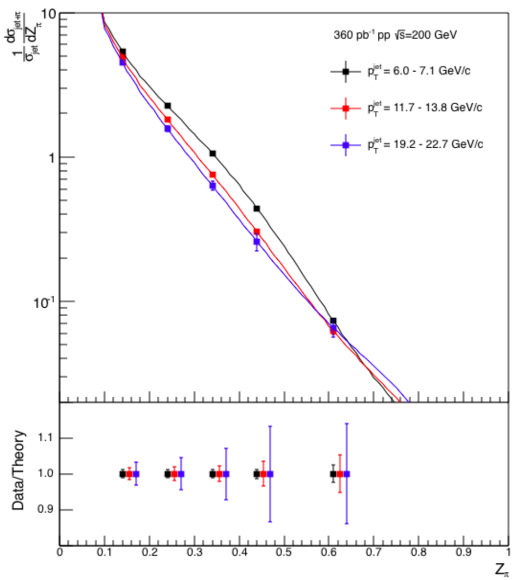
To have high precision data at different √s
→ constrain TMD evolution
→ fixed x and Q^2 → p_T different

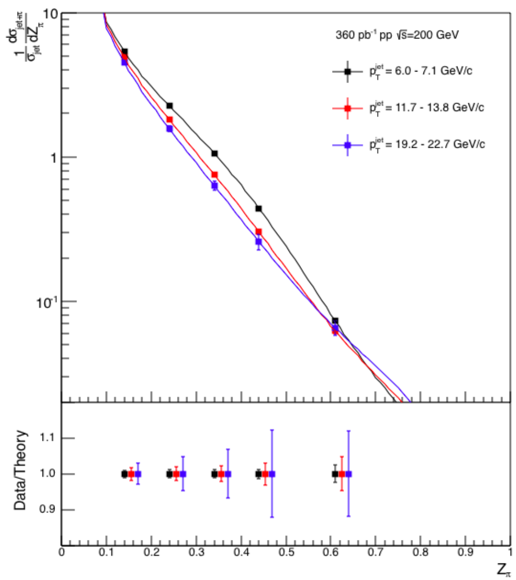
Fragmentation Functions in pp and pA

Observable: hadron in jet

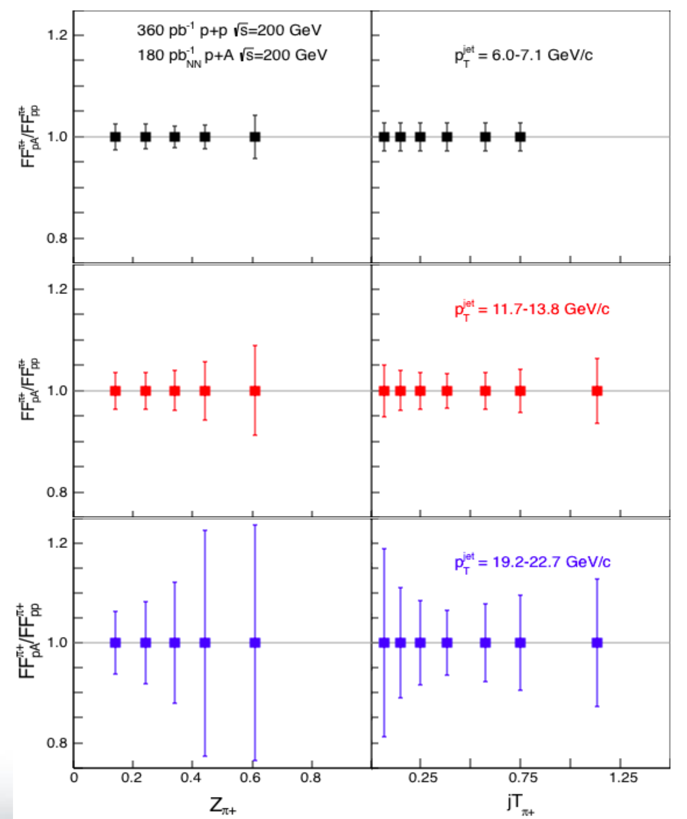
→ pp best way to measure gluon PDFs → direct access through qg and gg scattering

p+p: $\pi+$ $\pi-$

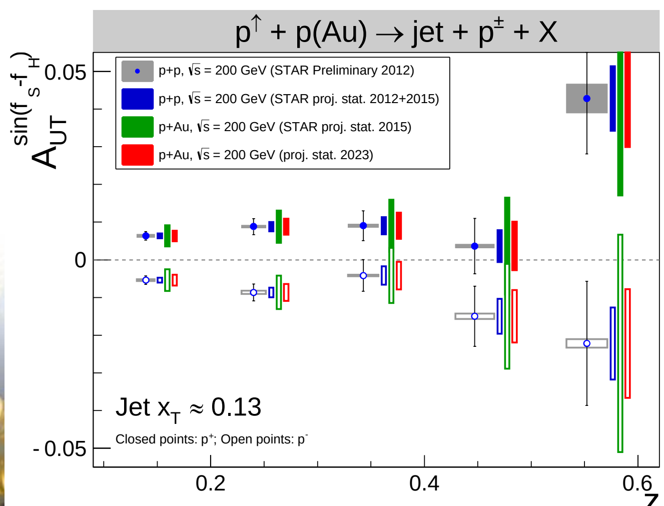




fragmentation functions in p+A/p+p at $|\eta| < 0.4$

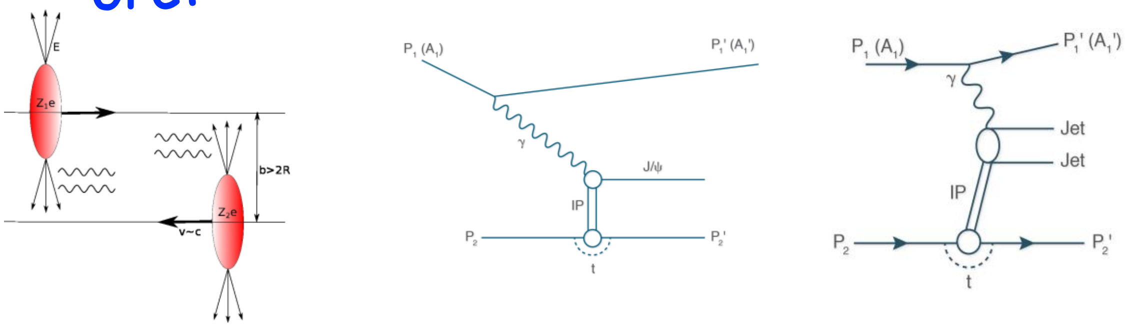


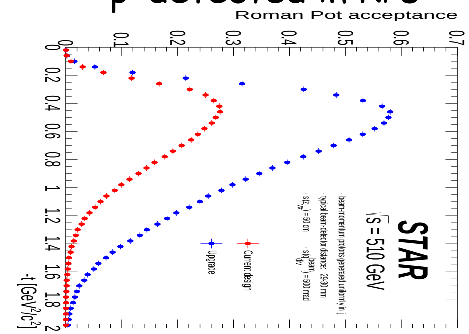
only at RHIC: measure nuclear effects for polarized FF → nCollins



GPD E_g and Wigner Functions

UPC:



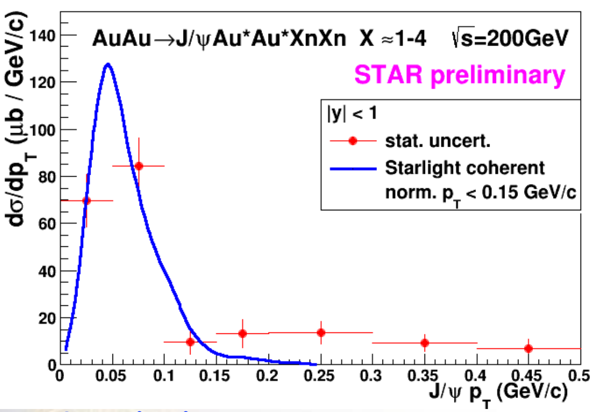


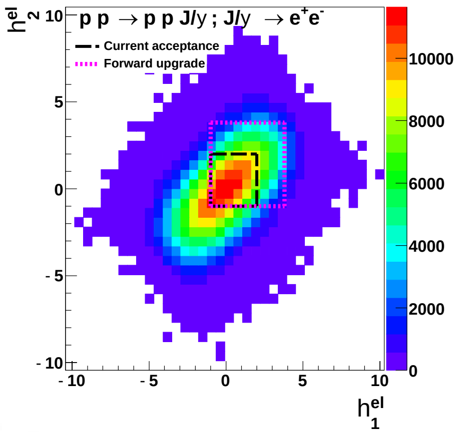
world wide only access to GPD E for gluons
→ J/Ψ production in p↑Au / p↑p UPC

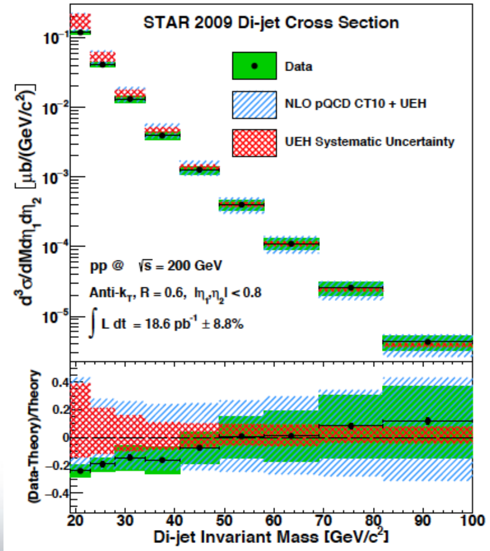
Access to Wigner functions
→ Diffractive di-jets in UPC

$$A_{UT}(t,t) \sim \frac{\sqrt{t_0 - t}}{m_p}\frac{\text{Im}(E^*H)}{|H|} \qquad t = \frac{M^2_{J/\Psi}}{s}$$

STAR di-jets results (-1 < η < 1.5):
Phys.Rev. D95 (2017), 071103
& arXiv:1805.09742







Statistics:
2017 p↑+p 400 pb^{-1}
→ 1k J/Ψs
→ δA_{UT}: +/-0.2 in 3 t-bins
Run-15 pA: ~300 J/Ψ

Expect 8000 diffractive di-jets in UPC in 700 pb^{-1} in 2021

2021+ : Forward Upgrade

Objective:

unique program addressing several fundamental questions in QCD

→ essential to

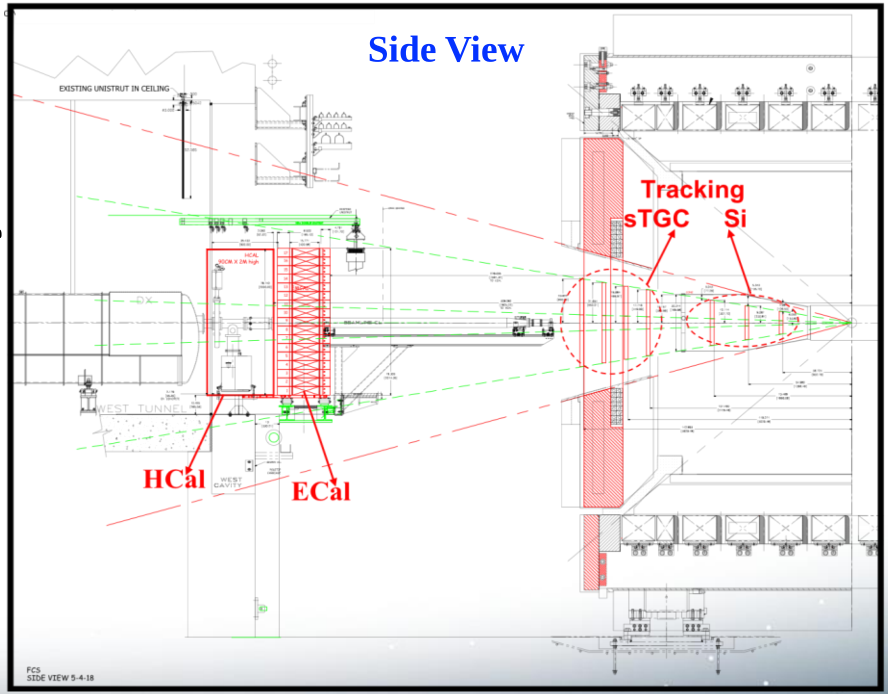
- the mission of the RHIC physics program in cold and hot QCD
- fully realize the scientific promise of the EIC
  - lay the groundwork for the EIC, both scientifically and by refining exp. requirements
  - Test EIC detector technologies under real conditions, i.e SiPMs

Scientific goals:

p+p:
3-dim. characterization of the proton in momentum and spatial coordinates

p+A
Nature of initial state and hadronization in nuclear collisions
Onset and A-dependence of saturation

A+A
Longitudinal medium characterization
Precision flow measurements via long range correlations

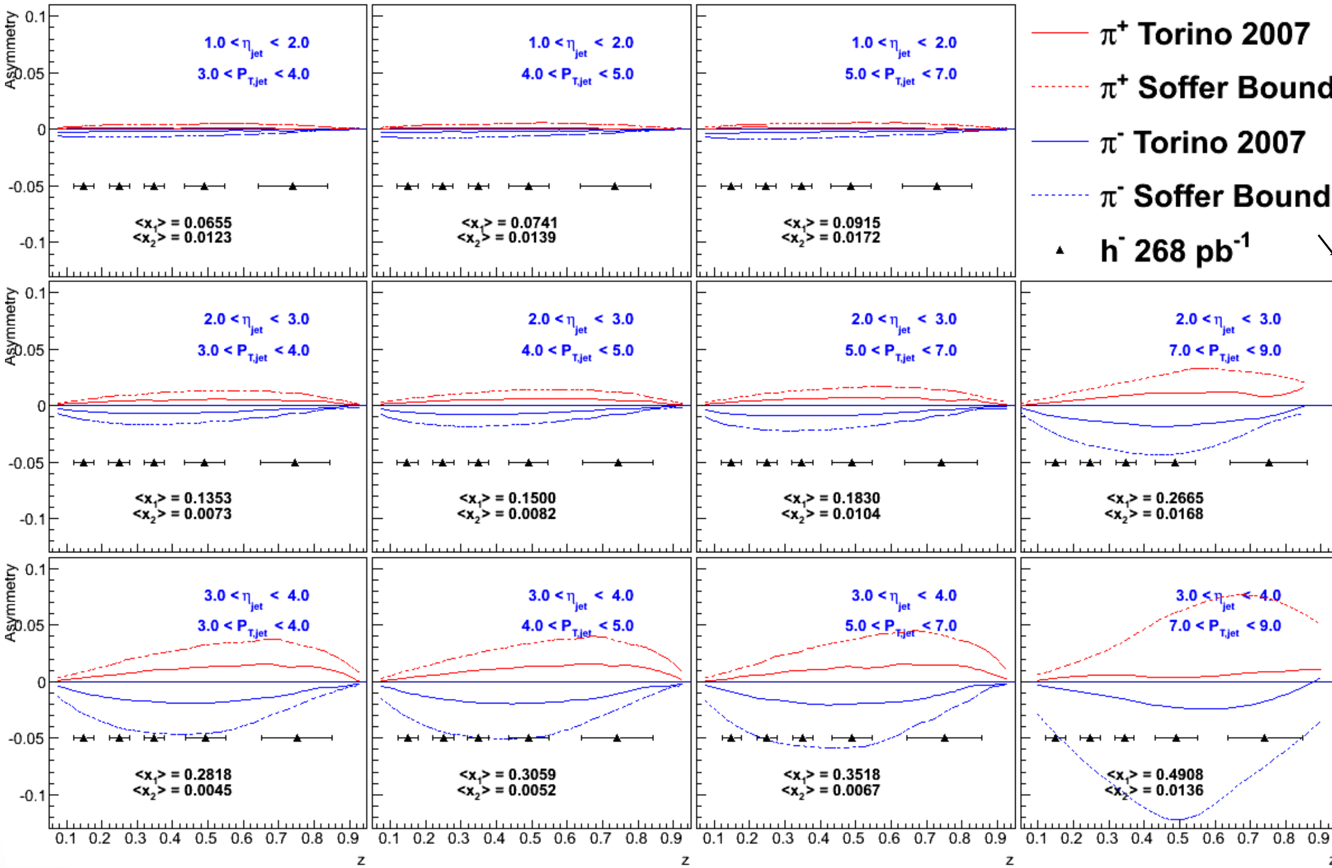


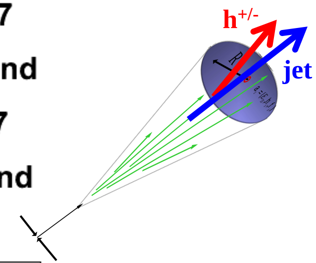
Upgrade includes:

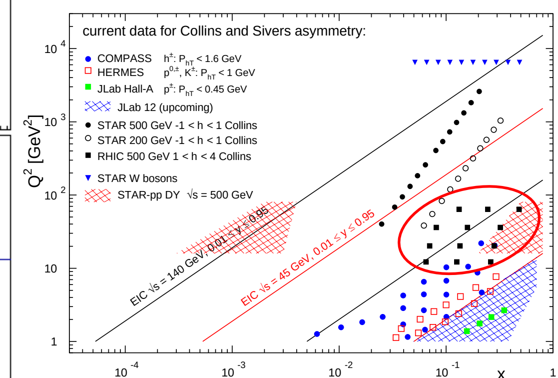
Forward Calorimeter System: EM and Hadronic
Forward Tracking System: Si + sTGCs

Forward rapidity pp Physics

Transversity x Collins FF through hadron in jet

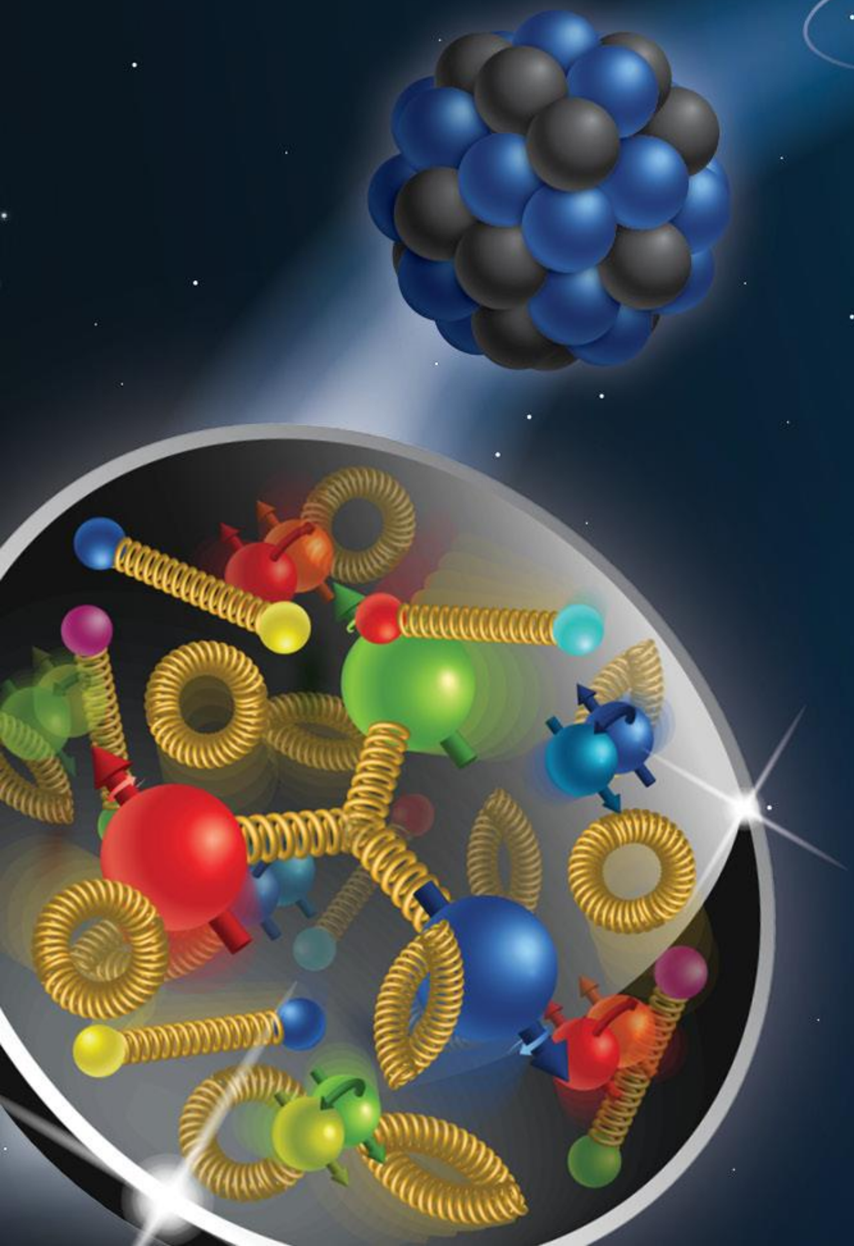






500 GeV: access high x (0.05 – 0.5) at high Q^2 (10 – 100 GeV^2)

very strong constrain for tensor charge $\delta q^a = \int_0^1 \left[\delta q^a(x) - \delta\bar{q}^a(x)\right] dx$



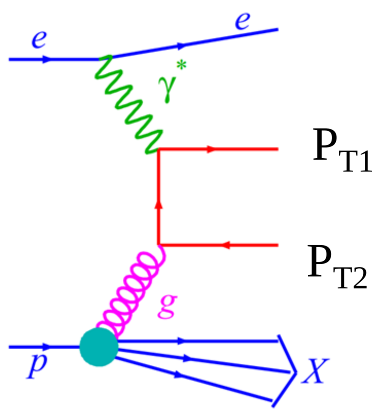
Constraining the Gluon Sivers function at a future EIC

L. Zheng, E.C. Aschenauer, J.H. Lee,
Bo-Wen Xiao, and Zhong-Bao Yin

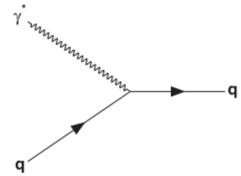
arXiv:1805.05290, Phys. Rev. D 98, 034011 (2018)

Accessing gluon Sivers at EIC

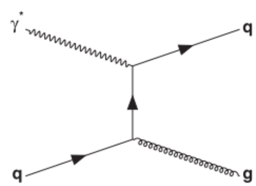
Photon-gluon fusion (PGF)

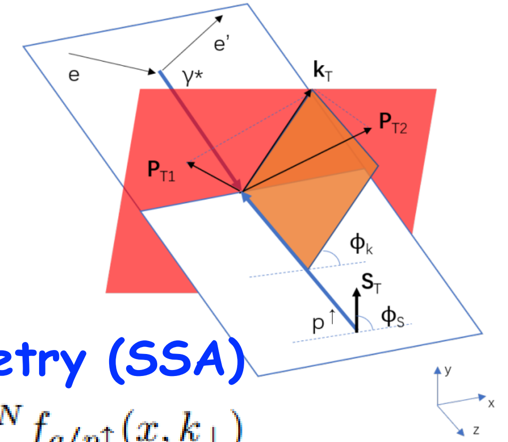


Leading order DIS (LODIS)



QCD compton (QCDC)





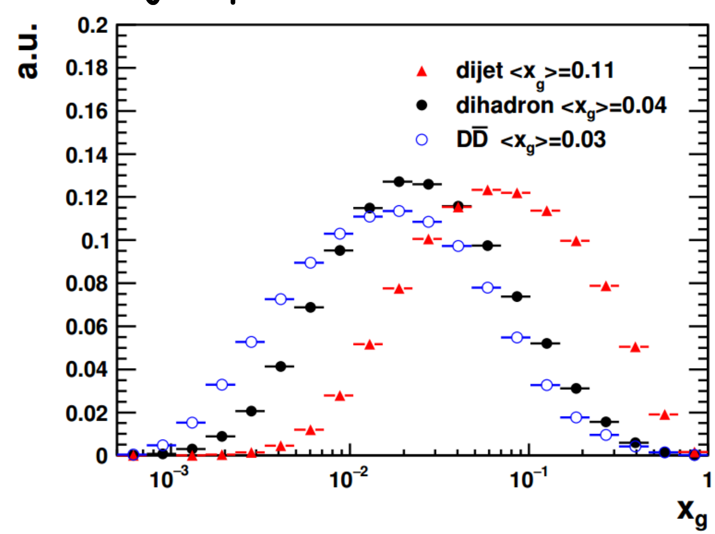
Single Spin Asymmetry (SSA)

$$A_{UT} = \frac{d\sigma^{\uparrow} - d\sigma^{\downarrow}}{d\sigma^{\uparrow} + d\sigma^{\downarrow}} \propto \frac{\Delta^N f_{g/p^{\uparrow}}(x, k_{\perp})}{f_1^g(x_g, k_{\perp})}$$

- Tag signal process PGF
- Vector sum of p_{T1} and p_{T2} reconstruct the gluon k_T in $\gamma^* p$ c.m.s frame.
- Design kinematic cuts to suppress the quark contributions.

Final state observables

1. Open charm
2. Charged hadron pair
3. Dijet pair



Back-to-back limit:

$P_T' = |\mathbf{P}_T^{h1} - \mathbf{P}_T^{h2}|/2$

$k_T' = |\mathbf{P}_T^{h1} + \mathbf{P}_T^{h2}|$

$k_T' << P_T'$

Event weighting method

PYTHIA event generator

Beam energy

Partonic flavor, kinematic info

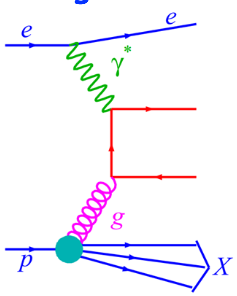
hadronization

Weighting events in a final state observable

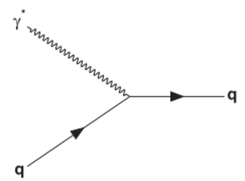
$$A_{UT} = R_g \frac{\Sigma_i^{N_g} w_i}{N_g} + R_q \frac{\Sigma_i^{N_q} w_i}{N_q}$$

SSA in final state observable

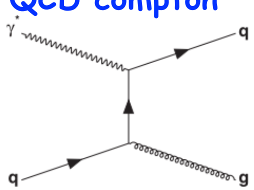
Photon-gluon fusion



Leading order DIS



QCD compton



Sivers weight event-by-event（signal, background）

$$w = \frac{\Delta^N f_{a/p^\uparrow}(x, k_\perp, Q^2)}{2 f_{a/p}(x, k_\perp, Q^2)}.$$

Inputs to the model calculation

$$\Delta^N f_{a/p^\uparrow}(x,k_\perp) = 2\mathcal{N}_a(x) f_{a/p}(x,k_\perp) h(k_\perp)$$

$$w = \frac{\Delta^N f_{a/p^\uparrow}(x,k_\perp,Q^2)}{2 f_{a/p}(x,k_\perp,Q^2)}.$$

$$A_{UT} = R_g \frac{\Sigma_i^{N_g} w_i}{N_g} + R_q \frac{\Sigma_i^{N_q} w_i}{N_q}$$

Quark Sivers: u and d quarks

JHEP 04(2017) Anselmino et. al.

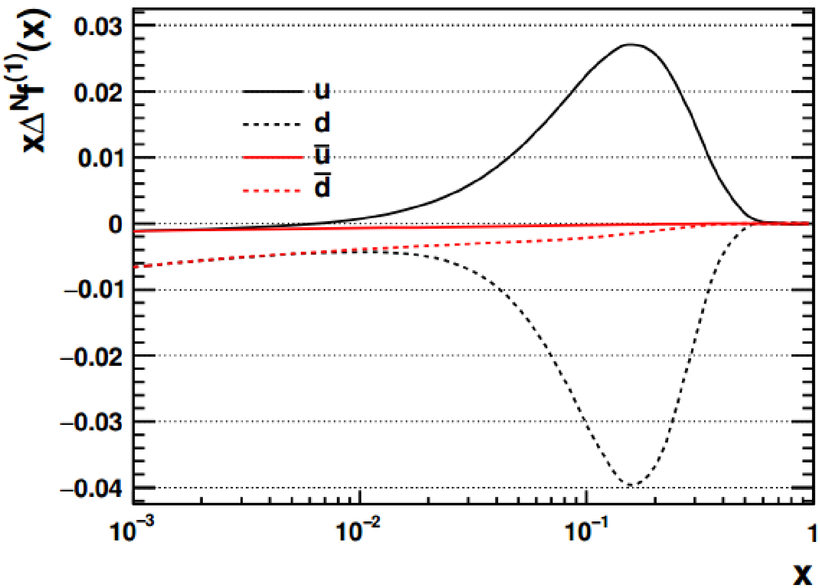
Gluon Sivers:

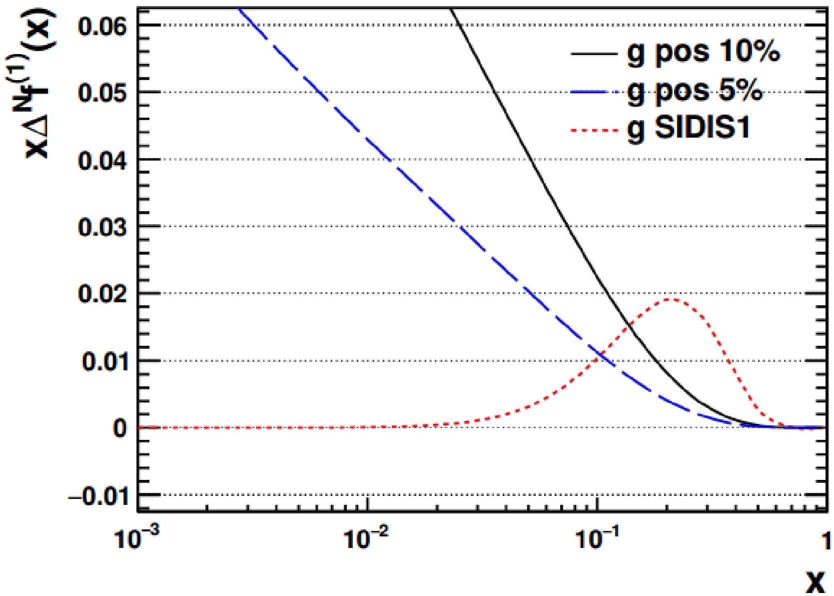
u, d + Kretzer FF (SIDIS1)

JHEP 09 (2015) 119 D' Alesio et. al.

Positivity bound ansatz:

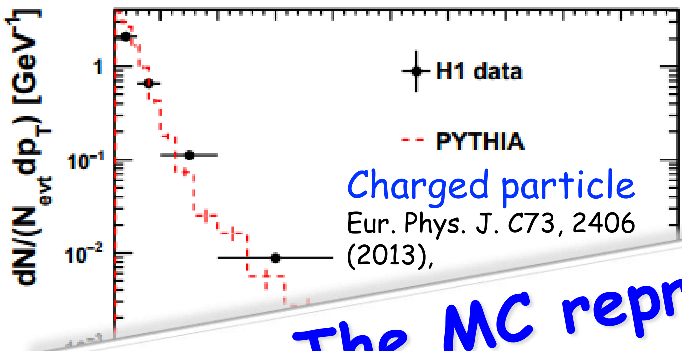
$$f_{1T}^{\perp g} = -\frac{2\sigma M_p}{k_\perp^2 + \sigma^2} f_g(x,k_\perp), \quad \sigma = 0.8$$

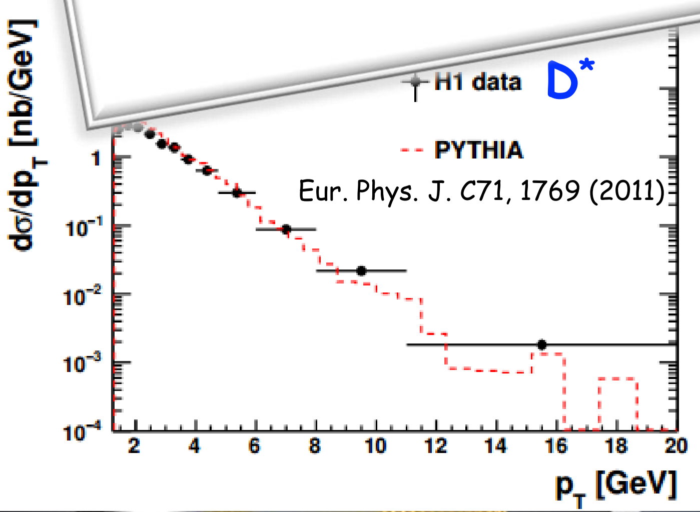




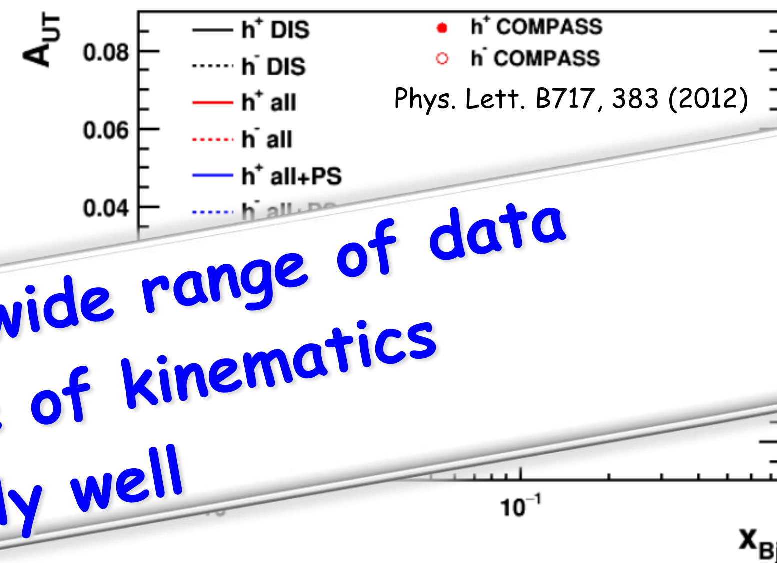
MC: Comparing to existing Data

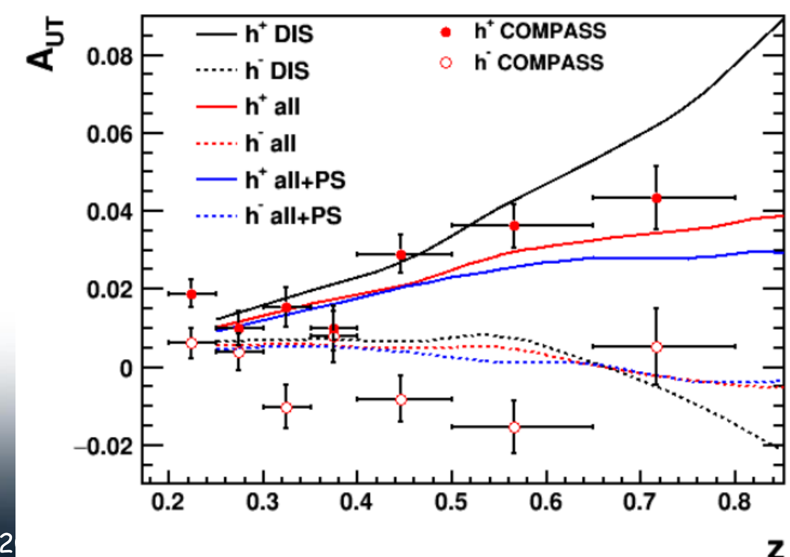
Unpolarized Data from H1:
Ep: 27.6 GeV x 920 GeV
$5<Q^2<10$, $0.0005<x_{Bj}<0.002$
p_T^*, η^* defined in gamma-hadron center of mass frame





Polarized Data (Sivers) from COMPASS
160 GeV μ beam on fixed target
$0.1<y<0.9$, $Q^2>1$, $W>5$

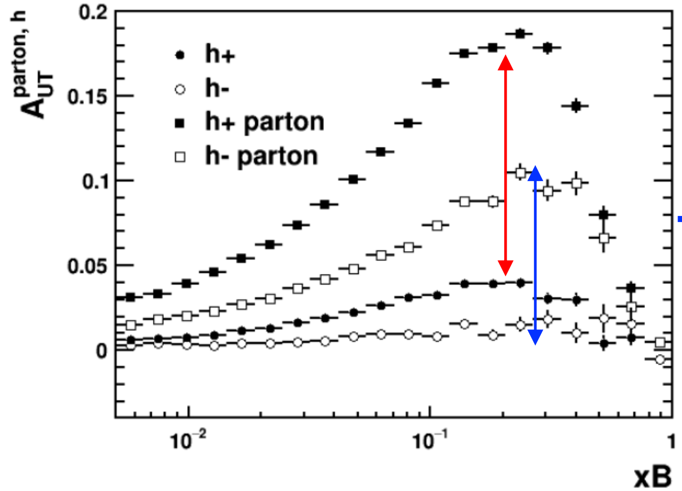




The MC reproduces a wide range of data over a wide range of kinematics extremely well

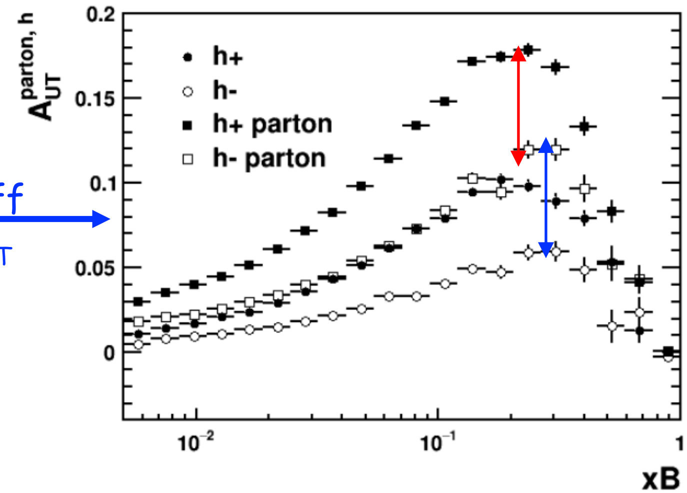
Dilution of parton level asymmetry

Full simulation



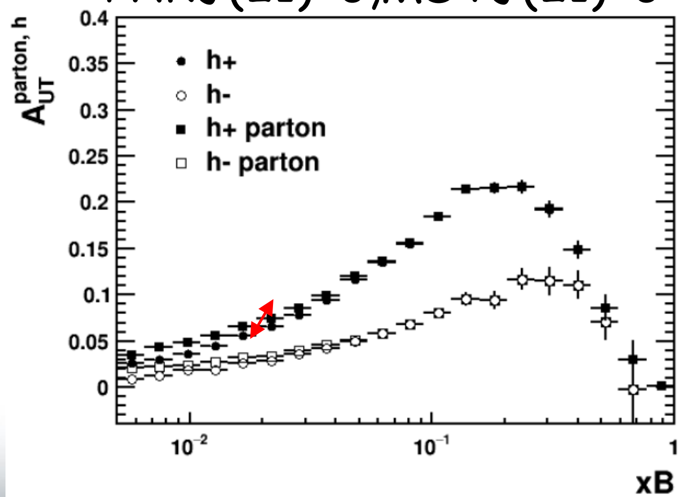
Turn off frag p_T

PARJ(21)=0



Turn off decay of resonances

PARJ(21)=0,MSTJ(21)=0



Fragmentation momenta smearing and resonance decay contribution accounts for the parton to hadron level asymmetry dilution at COMPASS energy.

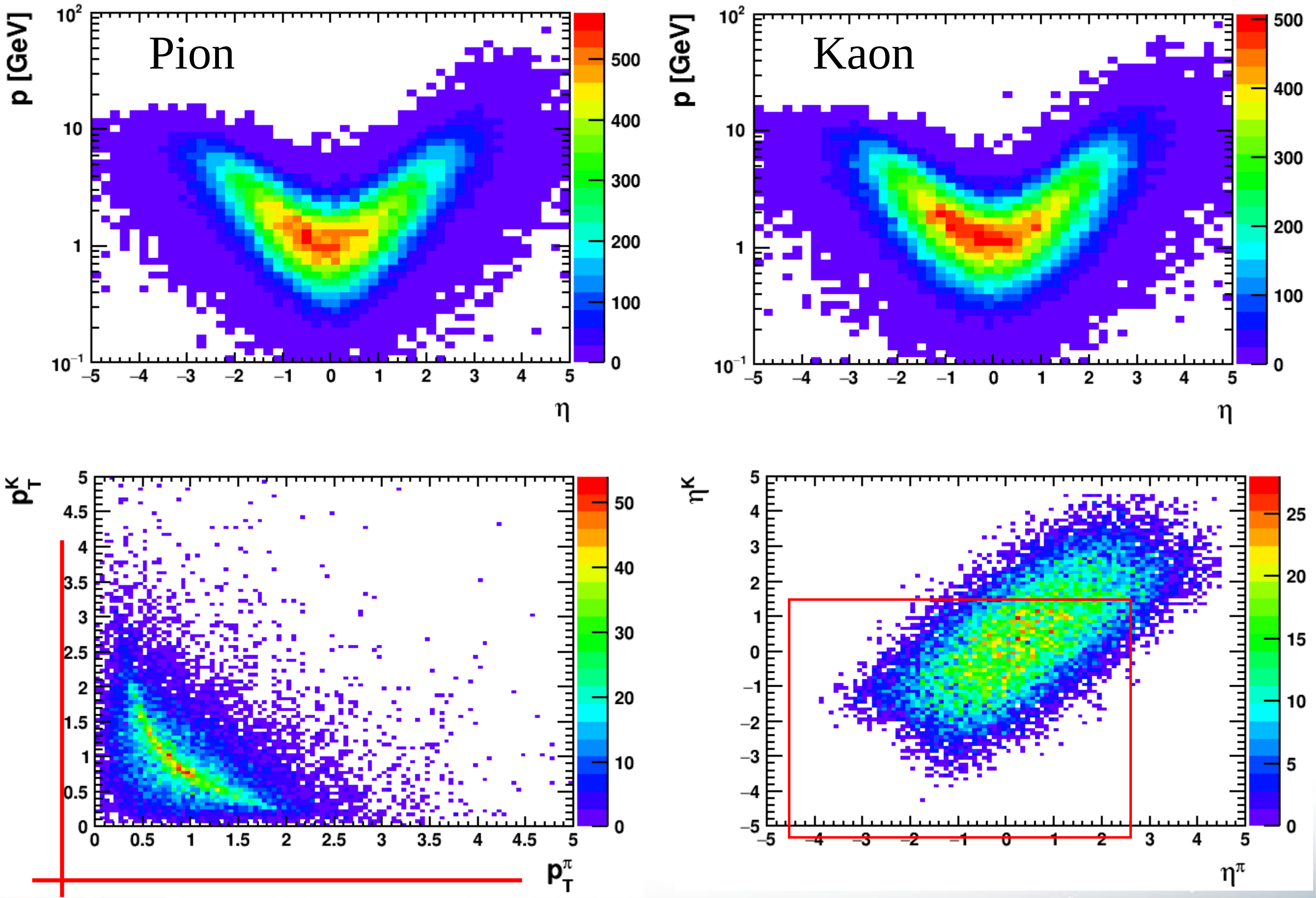
Gluon-Sivers: D-Mesons

Branching ratio: 3.9%

$$D^0(c\bar{u}) \rightarrow \pi^+(u\bar{d})K^-(s\bar{u})$$

$$\bar{D}^0(\bar{c}u) \rightarrow \pi^-(\bar{u}d)K^+(u\bar{s})$$

- Acceptance for PID is assumed to be $|\eta|<3.5$
- Decay products from D mesons are mostly less than 10 GeV in mid-rapidity.
- Decay products $p_T>0.2$ GeV.

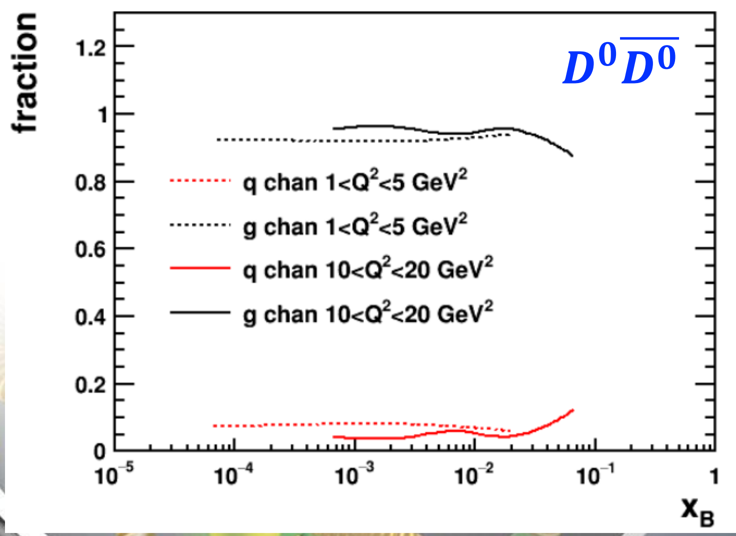


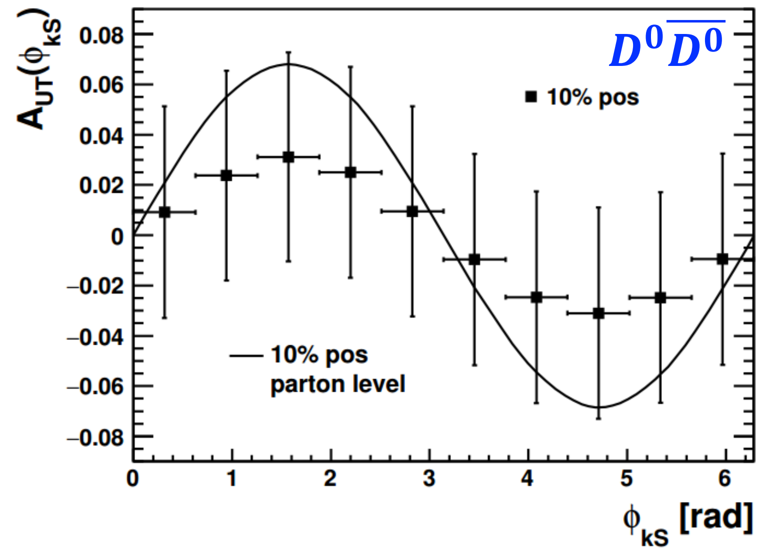
Gluon-Sivers: Open Charm

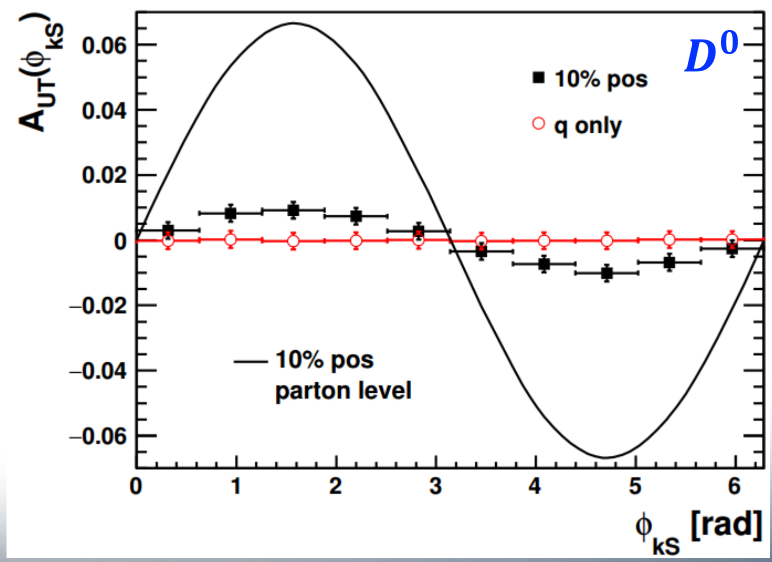
Assumptions on D^0 reconstruction:

D->K + pi (3.9%)
Acceptance: $|\eta|^{pi/K}$<3.5
$p_T^{pi/K}$>0.2 GeV, p_T^{D}>0.7 GeV, z^D>0.1
$\int Ldt = 10\ fb^{-1}$

- Sensitive to gluon kinematics
- D^0-pair statistically challenging
- 10% positivity can be distinguished in single D^0 probe



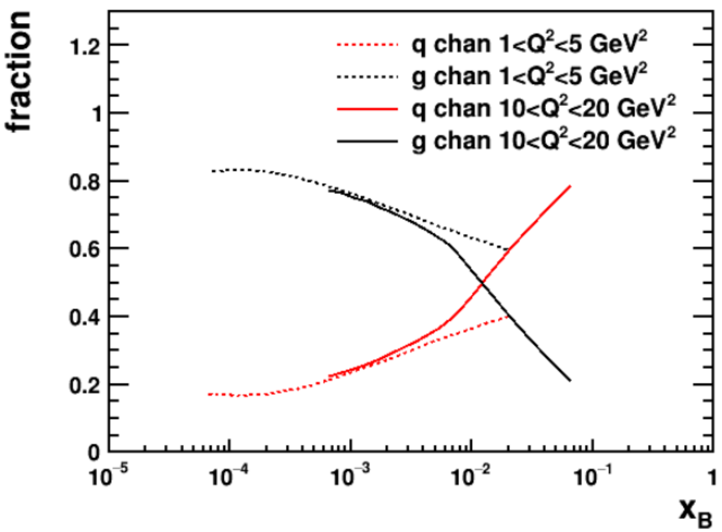


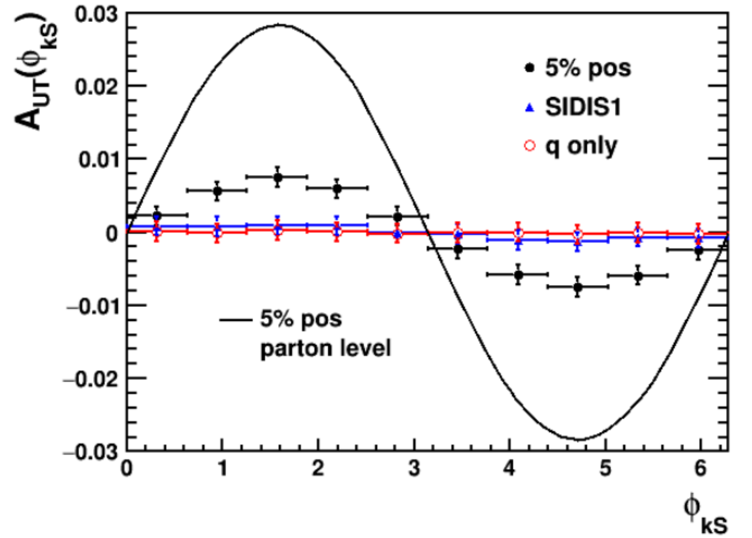


Gluon-Sivers: Di-Hadrons

Assumptions on h-Pair reconstruction:
Pairs of π,K,p
Acceptance: $|\eta|^{h1h2}<4.5$
$p_T>1.4$ GeV, $z_h>0.1$
Back-to-Back limit: $k_T'<0.7p_T'$
$\int Ldt = 10\ fb^{-1}$

- Gluon initiated process account for a large fraction of events at small x_B
- Parton asymmetry dilution larger than open charm
- Statistically more favored than open charm, resolve 5% positivity bound gluon Sivers size

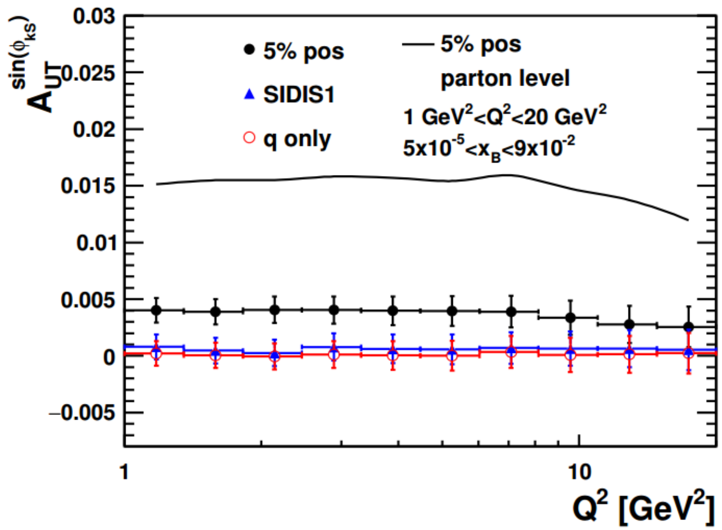




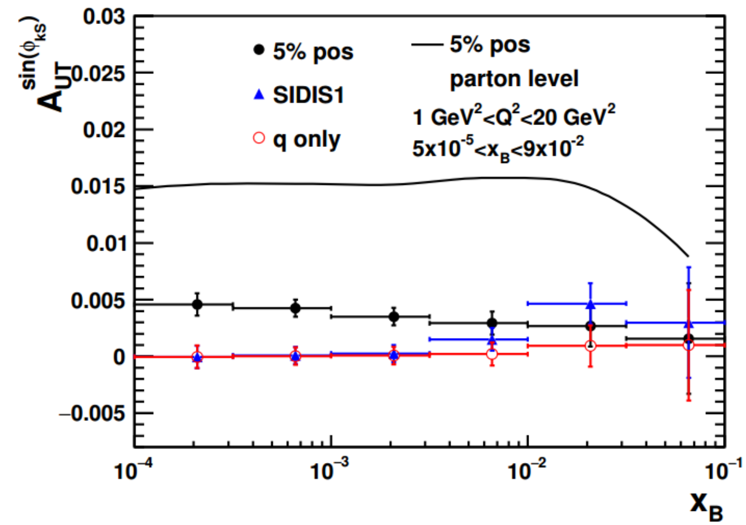
Gluon-Sivers: Di-Hadrons

Single out the asymmetry amplitude

$$A_{UT}^{\sin(\phi_{kS})} = \frac{\int d\phi_{kS}(d\sigma^{\uparrow} - d\sigma^{\downarrow})\sin(\phi_{kS})}{\int d\phi_{kS}(d\sigma^{\uparrow} + d\sigma^{\downarrow})}$$



- Asymmetry size dependence on x_B, Q^2 can be identified with 5% positivity bound
- No significant Q^2 trend as missing TMD evolution.
- x_B sensitive to the x dependence of input Sivers function

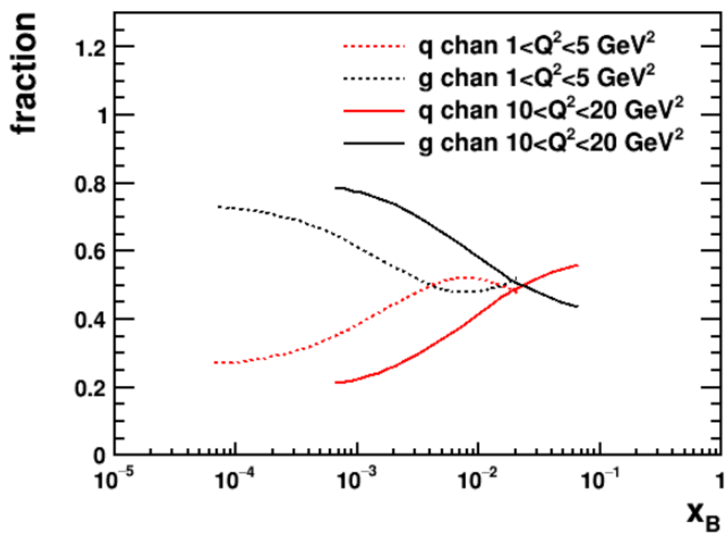


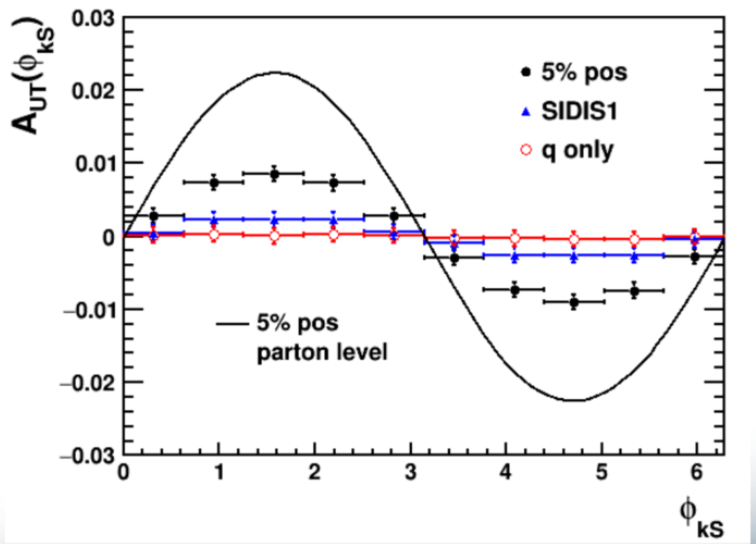
Gluon-Sivers: Di-Jets

Assumptions on di-jet reconstruction:

Anti-k_T, R=1
jet constituents:
p_T>250 MeV, $\pi/K/p/\gamma$, $|\eta|$<4.5
p_T^{jet1}>4.5 GeV, p_T^{jet2}>4 GeV
$\int L dt$ = 10 fb^{-1}

- Gluon initiated process dominant at small x_B
- Stronger correlation between final state observable to parton level kinematics
- Resolution down to 5% positivity bound gluon Sivers size

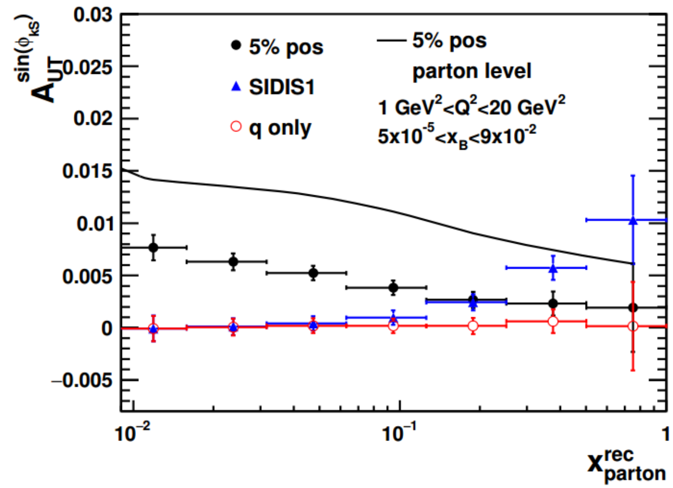


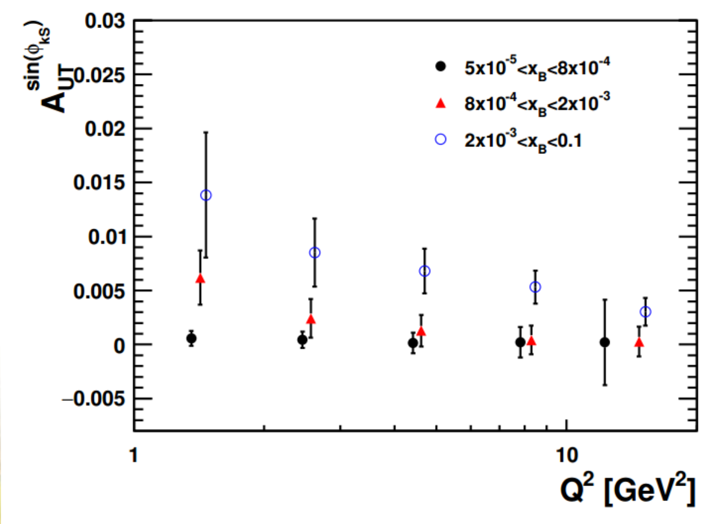


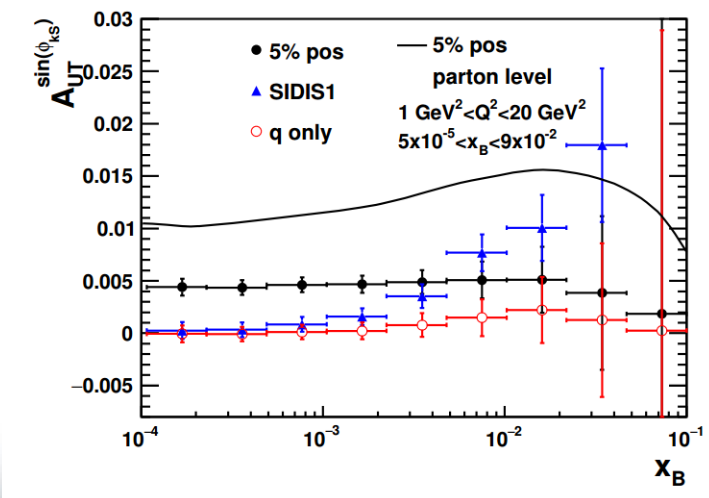
Gluon-Sivers: Di-Jets

- Strong correlation of jet momentum to its mother parton
- Direct handle on parton kinematics put stronger constraint such as x_{parton}
- Large statistics allow to explore SSA in multidimensional analysis.

$$x_{parton}^{rec} = (p_T^{jet1} e^{-\eta^{jet1}} + p_T^{jet2} e^{-\eta^{jet2}})/W.$$

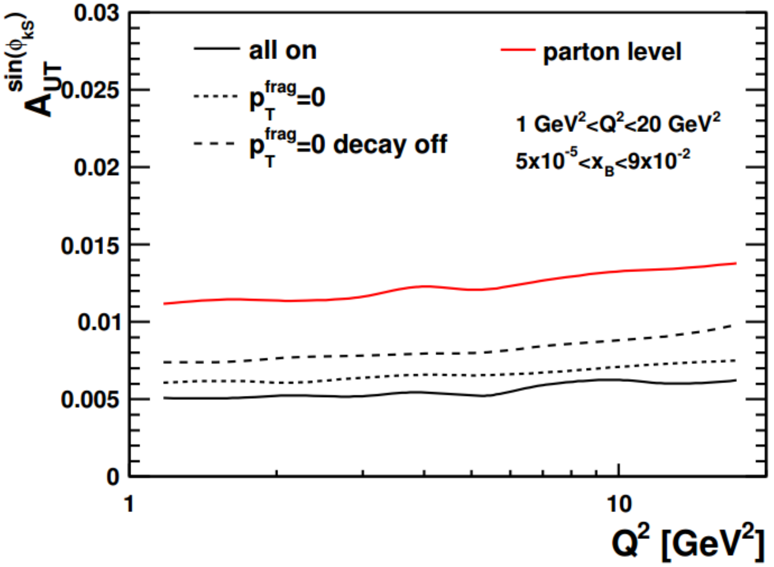


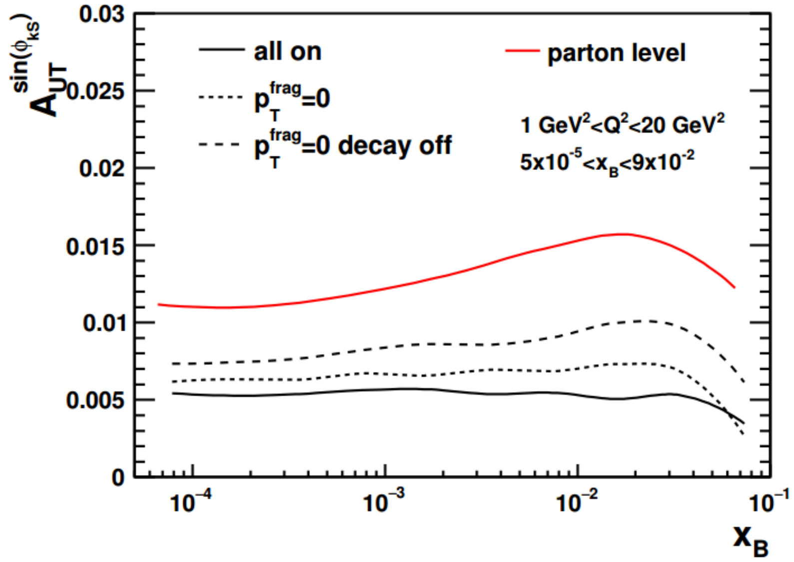


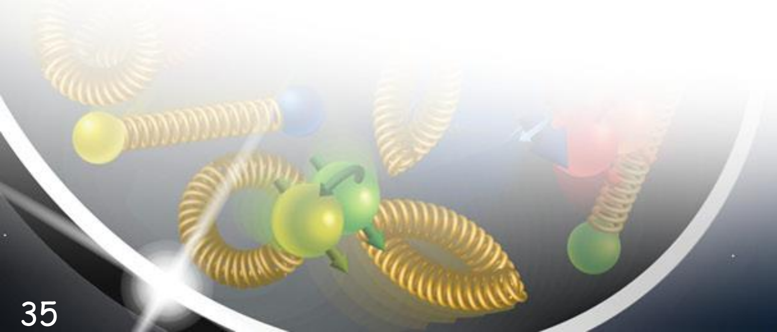


Dilution of parton level asymmetry: Di-jets

- Hadron fragmentation momentum smearing and resonance decay are important
- Other smearing effects in dijet processes → parton radiation





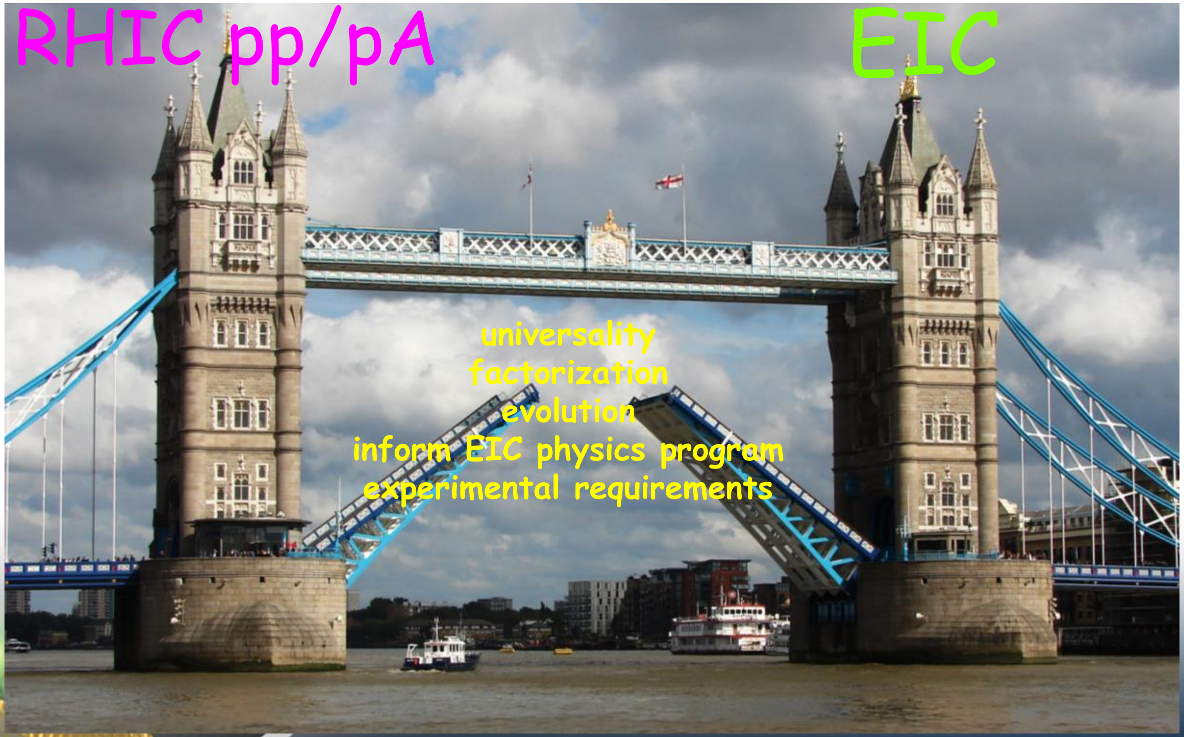


Summary

Unique RHIC forward and midrapidity pp/pA/AA program addressing several fundamental questions in QCD

Hadron-Hadron collider data are crucial to test all aspects of TMDs

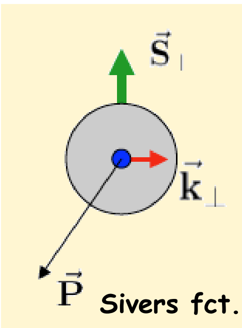
Gluon TMDs at EIC good example that it is critical to confront ideas with measurement reality




BACK UP

Initial State: TMDs vs. Twist-3

TMD

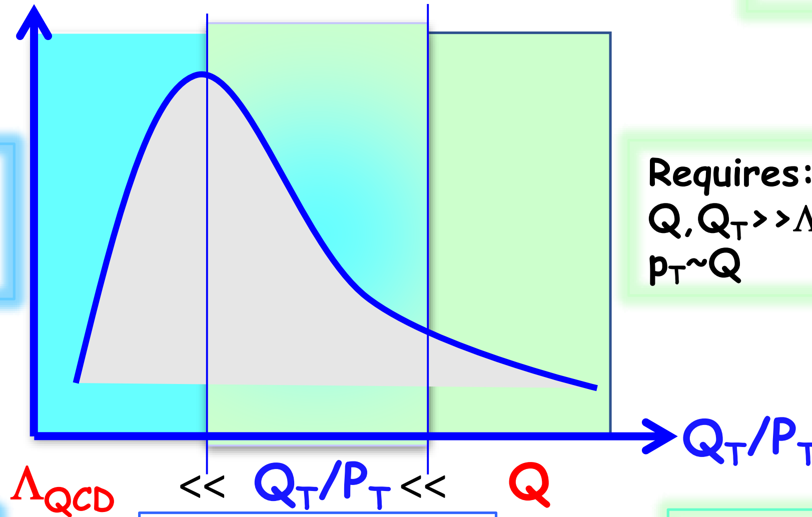


Requires:
$Q >> Q_T >= \Lambda_{QCD}$
$Q >> p_T$

Require 2 scales
Q^2 and p_t

2 scale observables in pp/pA
DY, W/Z-production

Provides access
to full transverse
momentum dynamics k_T



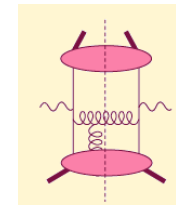
Intermediate Q_T
$Q >> Q_T/p_T >> \Lambda_{QCD}$

related through

$$-\int d^2k_\perp \frac{|k_\perp^2|}{M} f_{1T}^{\perp q}(x,k_\perp^2)|_{SIDIS} = T_{q,F}(x,x)$$

Twist-3

Requires:
$Q, Q_T >> \Lambda_{QCD}$
$p_T \sim Q$



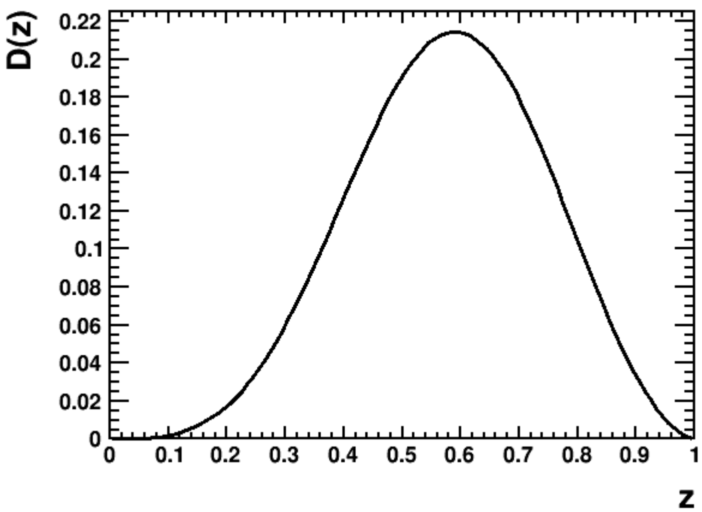
Efremov, Teryaev;
Qiu, Sterman
or
Twist-3 FF

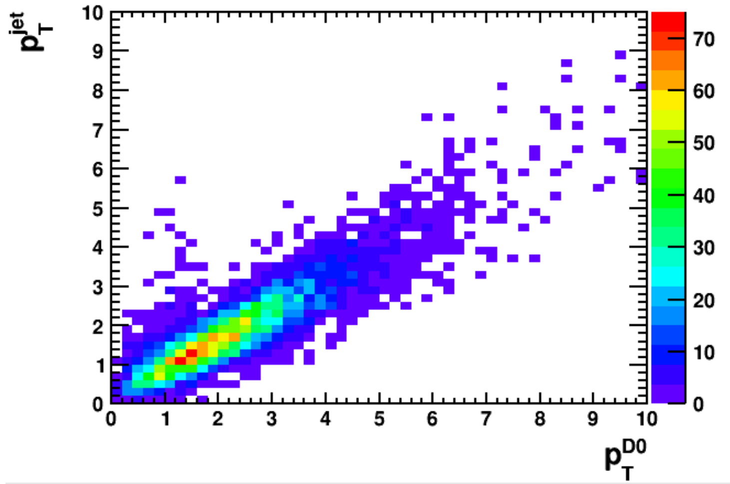
Need only 1 scale
Q^2 or p_t
But
should be of reasonable size

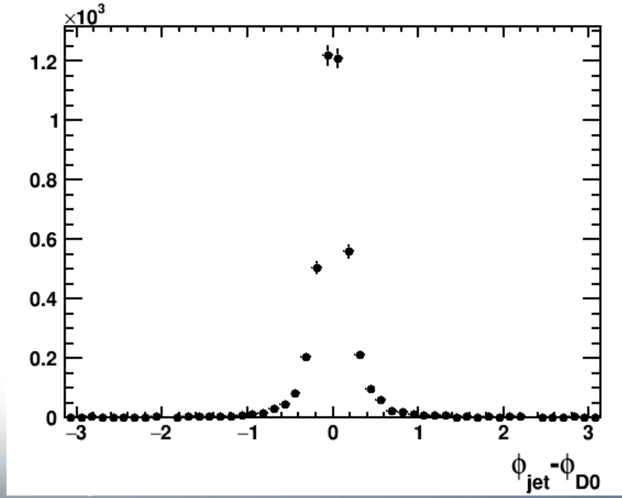
framework for pp observables
$A_N(\pi^0/\gamma/jet)$

Provides access
to average transverse
momentum $\langle k_T \rangle$

D^0 as charm quark proxy



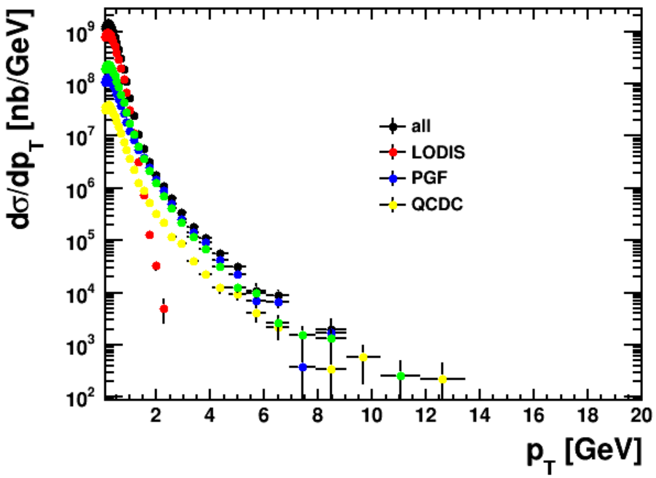


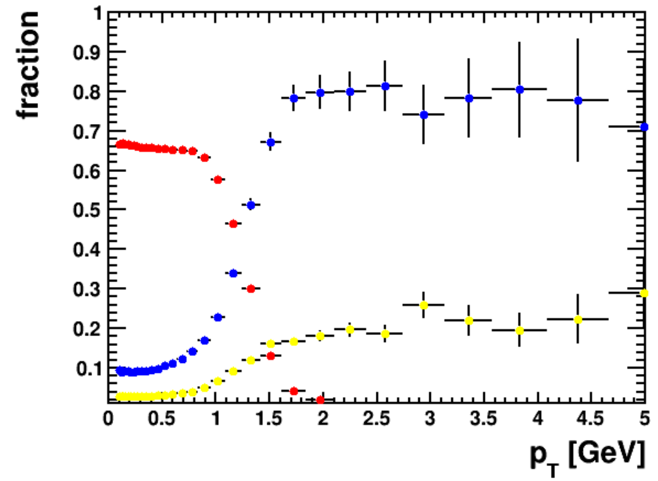


D meson takes a large fraction of the charm quark energy, serves as a proxy to the charm jet information.

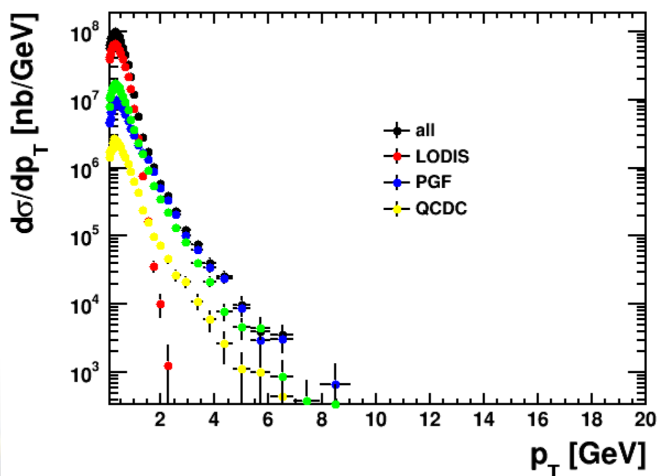
Charged hadron vs kaon spectrum

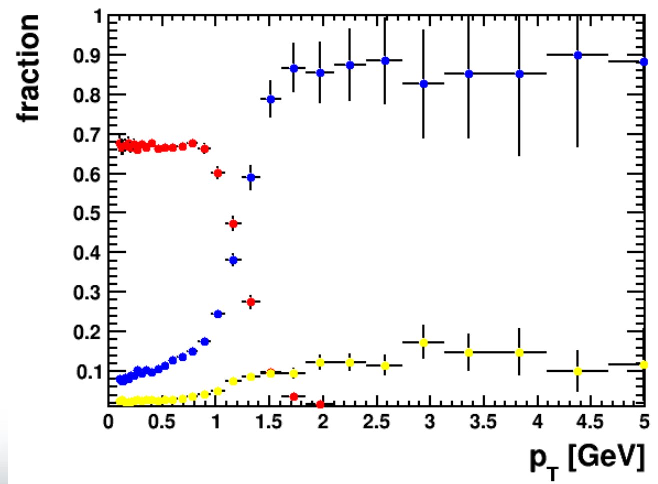
Charged hadron



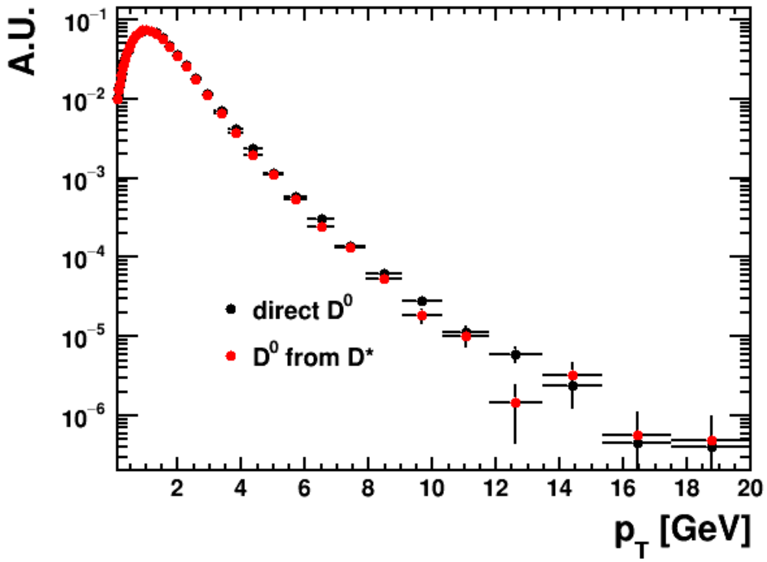


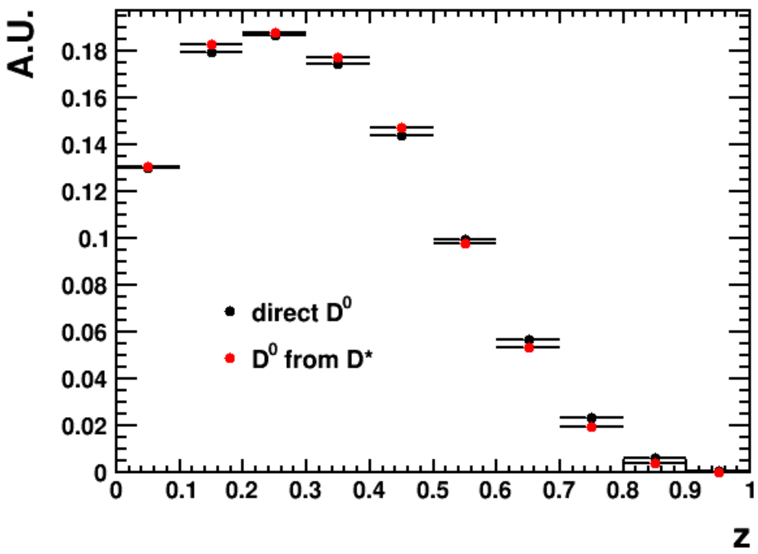
Charged Kaon





D^0 feed-down from D^*



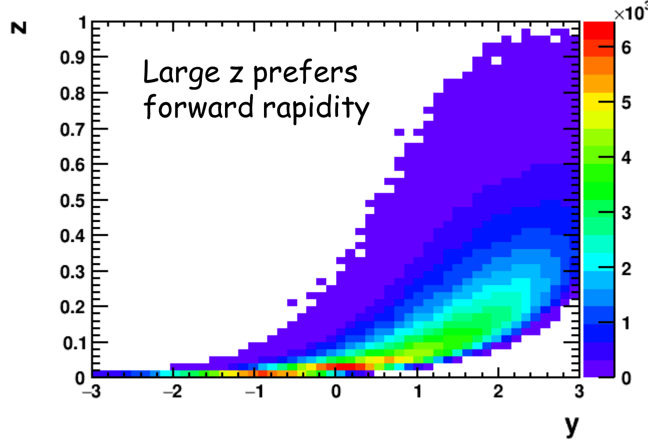


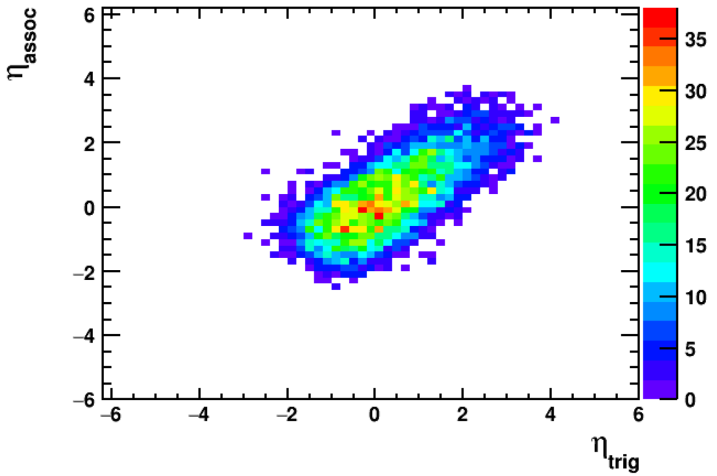
D^0 from D^* decay similar to the directly generated D^0s, therefore all D^0s are analyzed.

Di-hadron pair selection

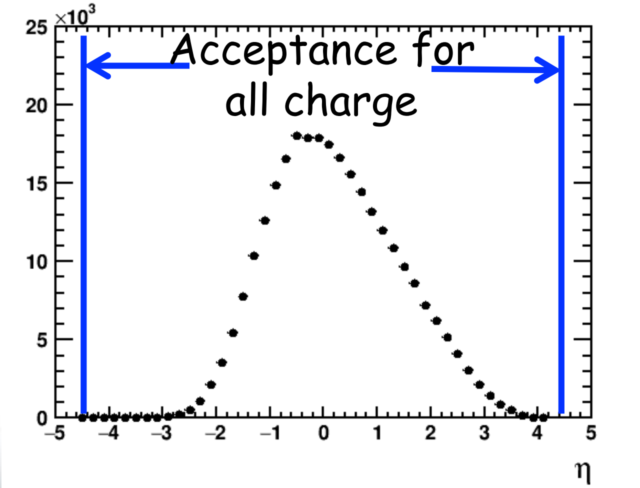
Assumptions on h-Pair reconstruction:

Pairs of π,K,p
Acceptance: $|\eta|^{h1h2}<4.5$
$p_T>1.4$ GeV, $z_h>0.1$
Back-to-Back limit: $k_T'<0.7p_T'$
$\int Ldt = 10\ fb^{-1}$





Hadron pair distribution



Summary

- Gluon Sivers function and other TMDs is an ingredient of complete 3D imaging of nucleon.
- It can be uniquely accessible and constrained in a wide kinematic range at EIC.
- Dihadron and dijet methods are more statistically favored compared to the open charm production.
- Different probes are complementary to each other at EIC.