Accessing the gluon Sivers function via Dihadron/Dijet measurements

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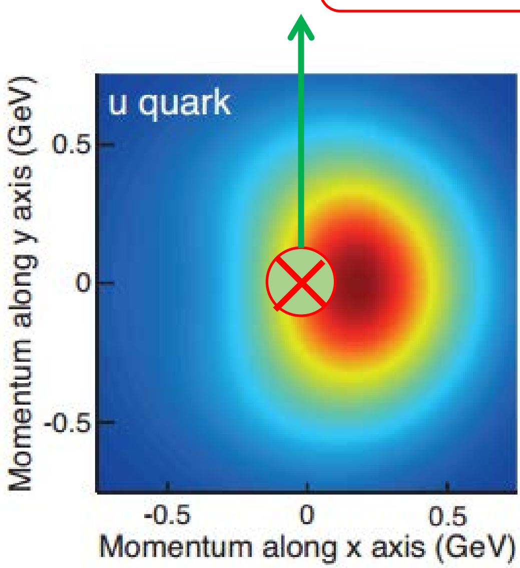
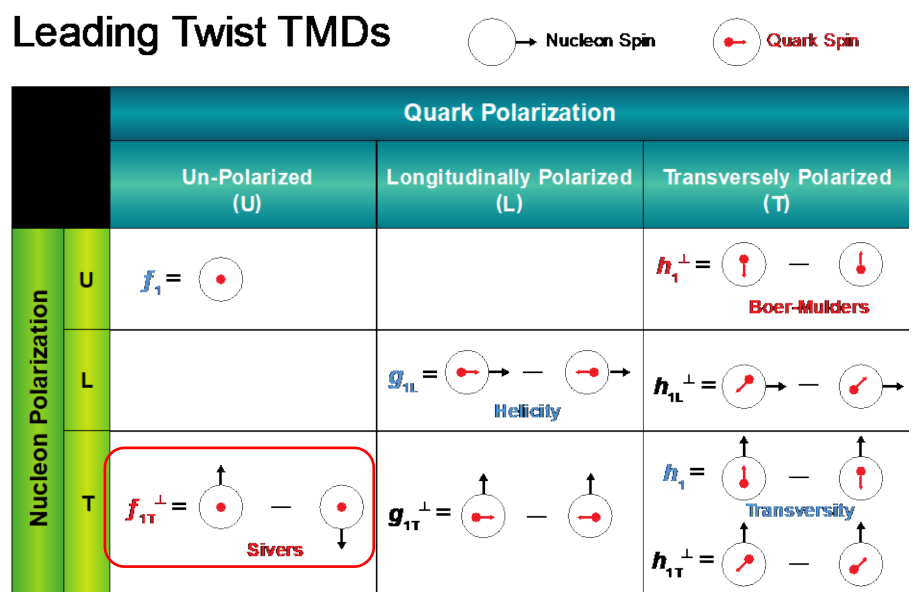
Gluon Sivers function

- EIC: polarized collider to have full access to the nucleon dynamics.
- Transverse Momentum Dependent (TMD) parton distributions provide useful tools to image the nucleon 3D structure in momentum space.
- Sivers function describes the correlation of k_T and S_T.

$$\hat{f}_{a/p^\uparrow}(x,k_\perp) = f_{a/p}(x,k_\perp) + \frac{1}{2}\boxed{\Delta^N f_{a/p^\uparrow}(x,k_\perp)\ \vec{S}\cdot(\hat{\vec{P}}\times\hat{\vec{k}}_\perp)}$$



EIC White paper



Similar for gluons

Two gluon distributions

- Two different gauge invariant gluon definitions
- Weizsacker-Williams (WW) gluon distribution

$$xG_{\mathrm{WW}}(x,k_\perp) = 2\int \frac{d\xi^- d\xi_\perp}{(2\pi)^3 P^+} e^{ixP^+\xi^- - ik_\perp\cdot\xi_\perp} \mathrm{Tr}\langle P|F^{+i}(\xi^-,\xi_\perp)\mathcal{U}^{[+]\dagger}F^{+i}(0)\mathcal{U}^{[+]}|P\rangle$$

- Color dipole gluon distribution

$$xG_{\mathrm{DP}}(x,k_\perp) = 2\int \frac{d\xi^- d\xi_\perp}{(2\pi)^3 P^+} e^{ixP^+\xi^- - ik_\perp\cdot\xi_\perp} \mathrm{Tr}\langle P|F^{+i}(\xi^-,\xi_\perp)\mathcal{U}^{[-]\dagger}F^{+i}(0)\mathcal{U}^{[+]}|P\rangle$$

- Unique opportunity to explore the WW gluon distribution at the EIC

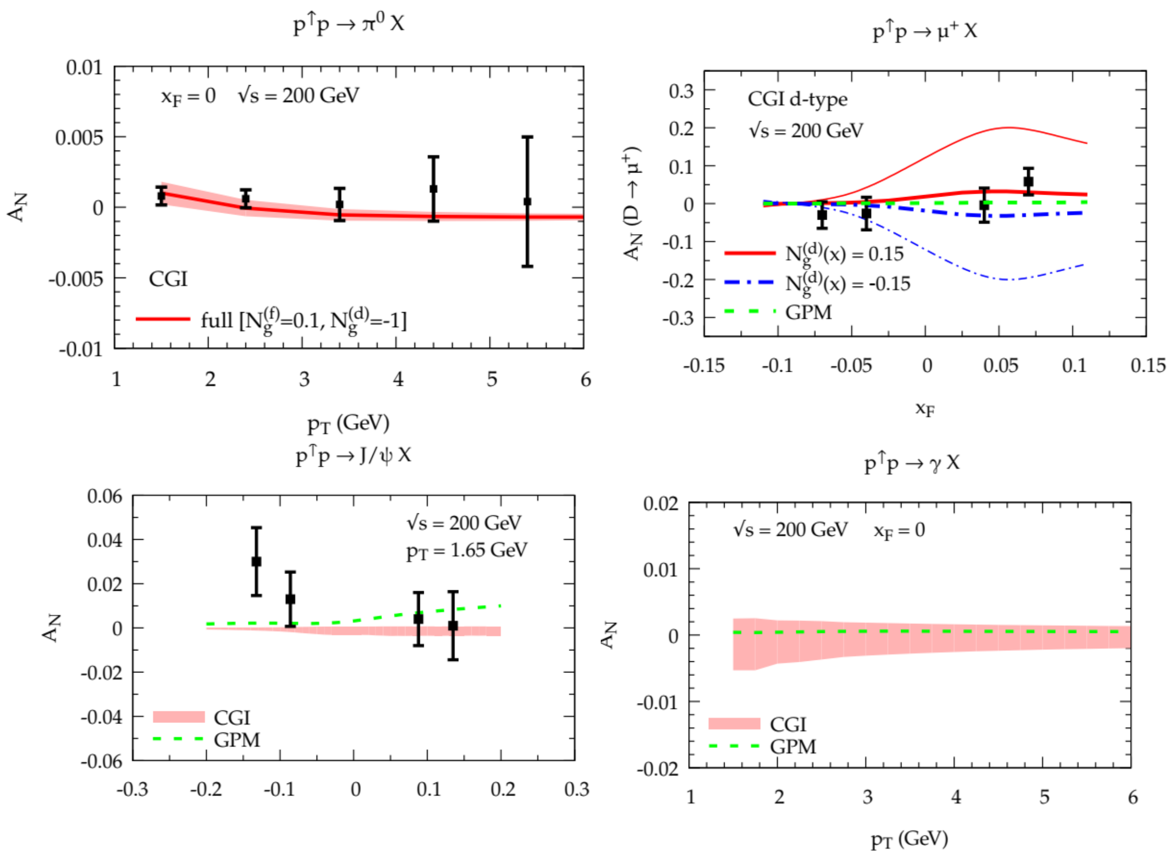
	Inclusive	Single Inc	DIS dijet	γ +jet	dijet in pA
xG_{WW}	$\times$	$\times$	$\surd$	$\times$	$\surd$
xG_{DP}	$\surd$	$\surd$	$\times$	$\surd$	$\surd$

$\times \Rightarrow$ Do Not Appear. $\surd \Rightarrow$ Apppear.

Dominguez, et. al., PRD83, 105005 (2011)

Current understanding to gluon Sivers function

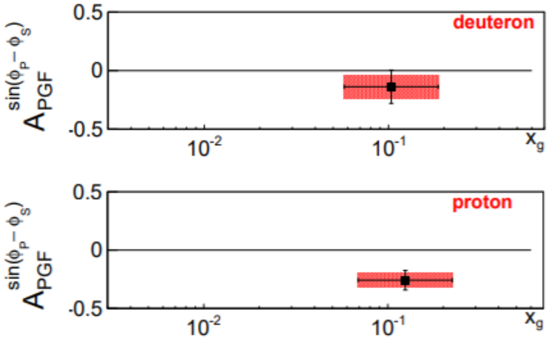
Alesio, et. al., PRD99, 036013 (2019)



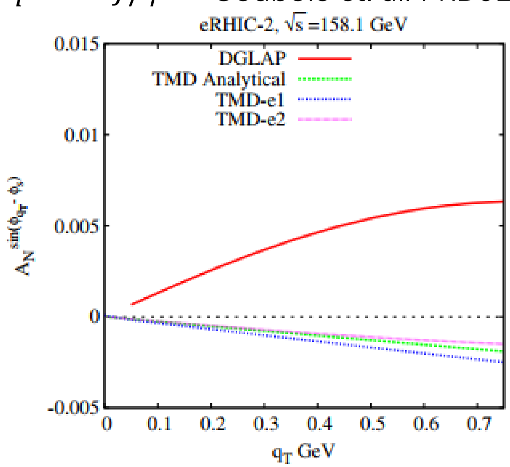
- Fits from π^0 and D, prediction for Jpsi and γ production.
- Effective gluon Sivers from GPM may differ from the actual gluon Sivers in TMD.
- Process dependence explored in this framework.

Current understanding to gluon Sivers function

$ep^{\uparrow} \to e\, h_1 h_2 X$ COMPASS PLB722, 854 (2017)



$ep^{\uparrow} \to e\, J/\psi\, X$ Godbole et. al. PRD91, 014005, (2015)

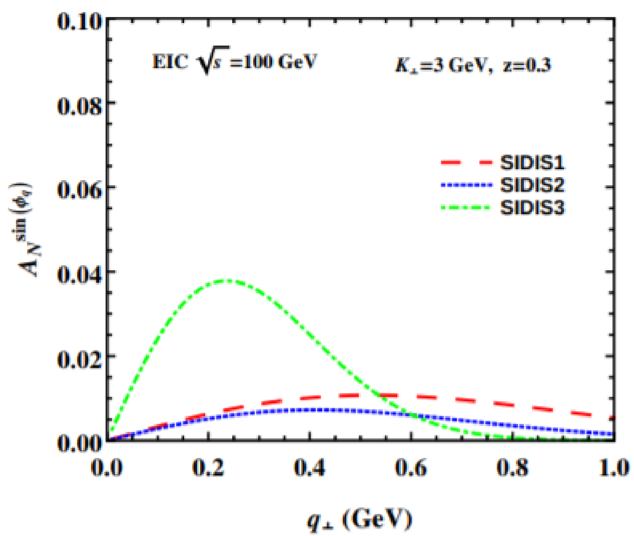


$ep^{\uparrow} \to e\, D\, X$ Yao et. al. PLB790, 361 (2019)

$ep \to e'\pi^0 p'$ Boussarie et. al., arXiv: 1912.08182

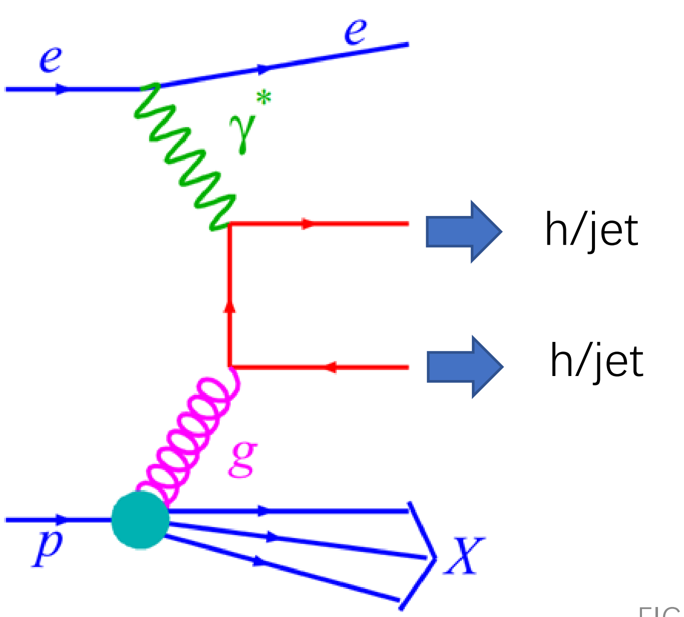
Francesco et. al. PAVIA group, Gluon Sivers on the way

$ep^{\uparrow} \to e\, J/\psi\, jet\, X$ Godbole et. al. PRD101, 054003, (2020)

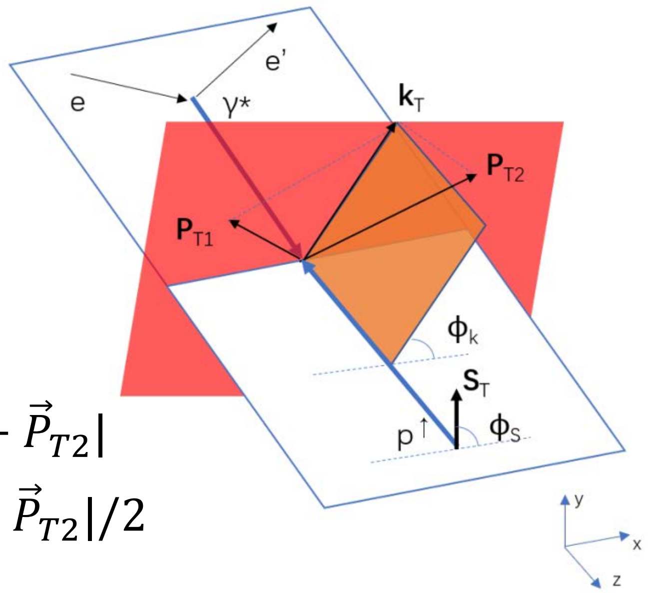


Accessing gluon distribution at the EIC

- Photon-Gluon Fusion (PGF) process as good proxy to the underlying gluon distribution
- Back-to-back dihadron/dijet can map initial gluon kinematics
- Similar ideas applied to eA saturation physics



$$k_T = |\vec{P}_{T1} + \vec{P}_{T2}|$$
$$P_T = |\vec{P}_{T1} - \vec{P}_{T2}|/2$$



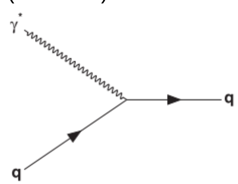
Simulation framework

PYTHIA
event generator

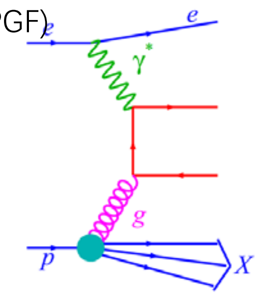
Beam energy

Partonic flavor, kinematic info

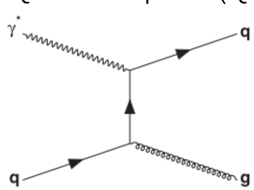
Leading order DIS (LODIS)



Photon-gluon fusion (PGF)



QCD compton (QCDC)



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

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

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

$$\delta A_{UT} = \sqrt{\frac{1}{PN^2} - \frac{A_{UT}^2}{N}}$$

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: Anselmino et. al. JHEP 04, 046 (2017)

u and d quarks

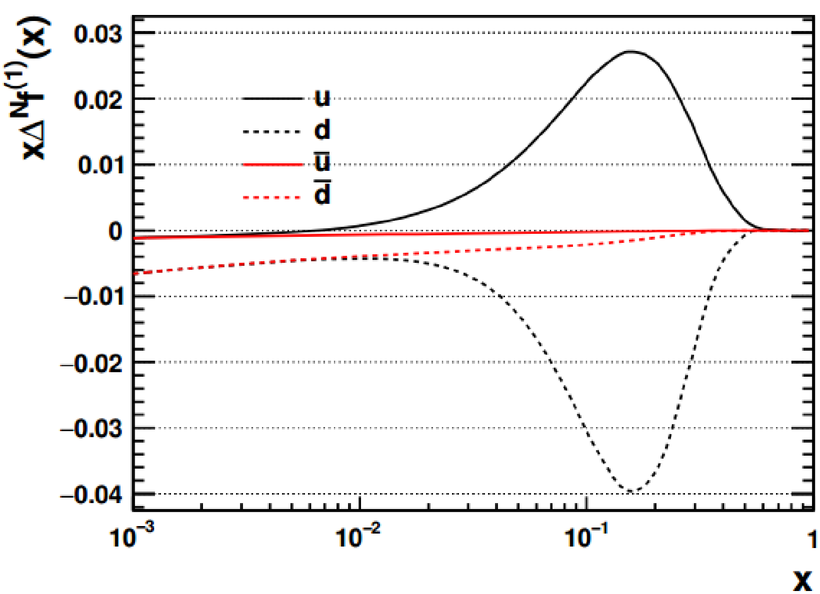
Gluon Sivers:

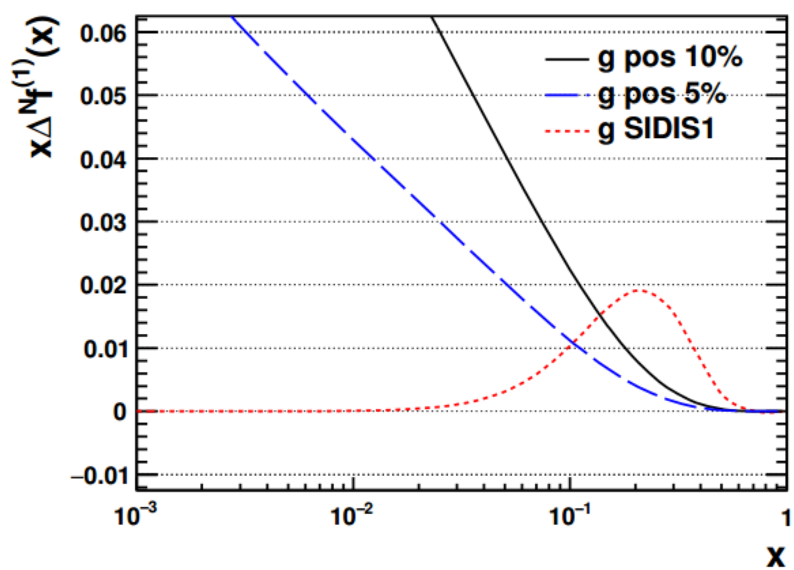
Alesio et. al. JHEP 09, 119 (2015)

(1) GPM fit (g SIDIS1 set)

Anselmino et. al. PRD 70, 074025 (2004)

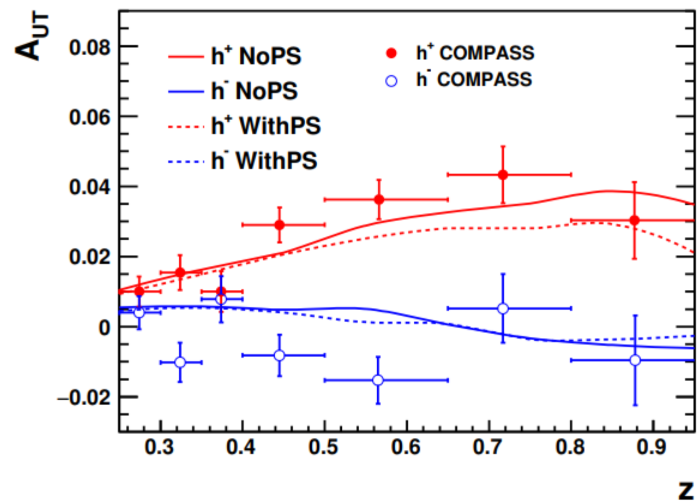
(2) Positivity bound ansatz (g pos set)

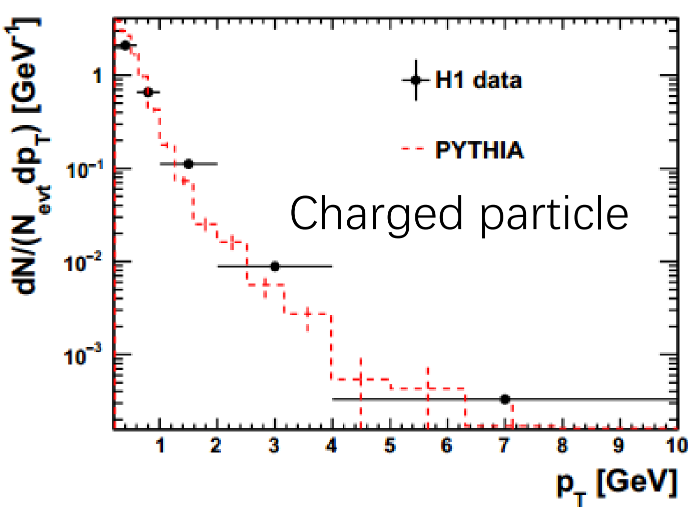


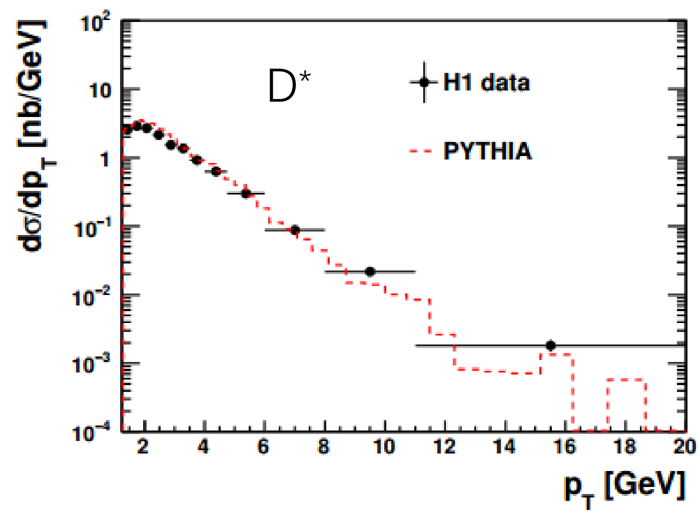


Comparing to experimental data

- The unpolarized data can be described by our tuned PYTHIA
- The quark Sivers data is consistent with event weighted single spin asymmetry



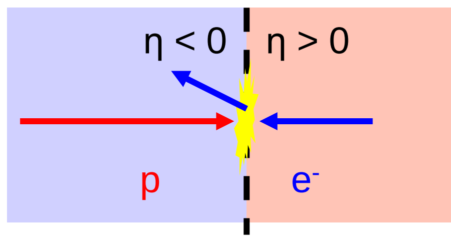




EIC setup for gluon SSA study

Beam configuration
ep$^{\uparrow}$ 20x250 GeV
$\sqrt{s}$=141 GeV
L_{int}=10 fb^{-1}
0.01<y<0.95
1<Q^2<20 GeV^2

Lab frame

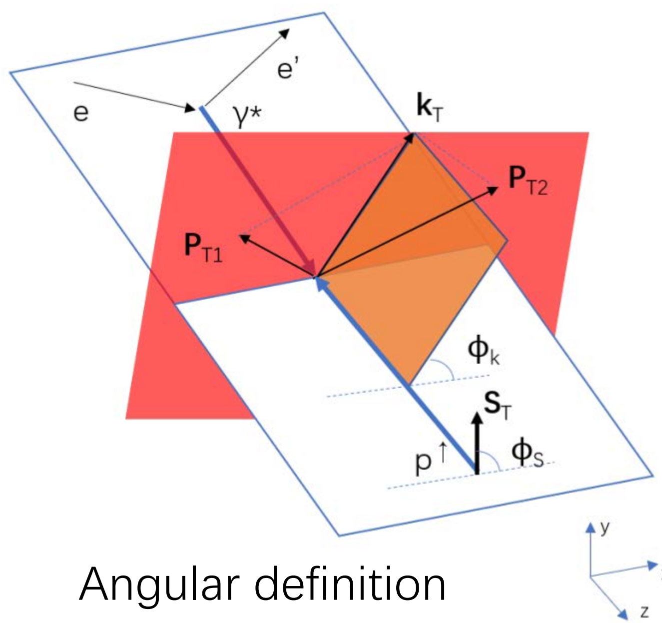


Single Spin Asymmetry (SSA)

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

Final state observables

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



Angular definition

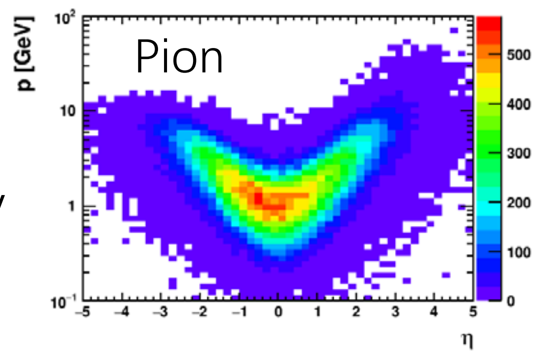
$$\vec{k}_T = \vec{P}_{T1} + \vec{P}_{T2}$$

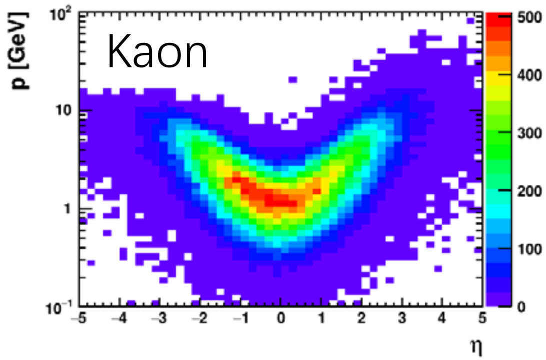
$$P_T = |\vec{P}_{T1} - \vec{P}_{T2}|/2$$

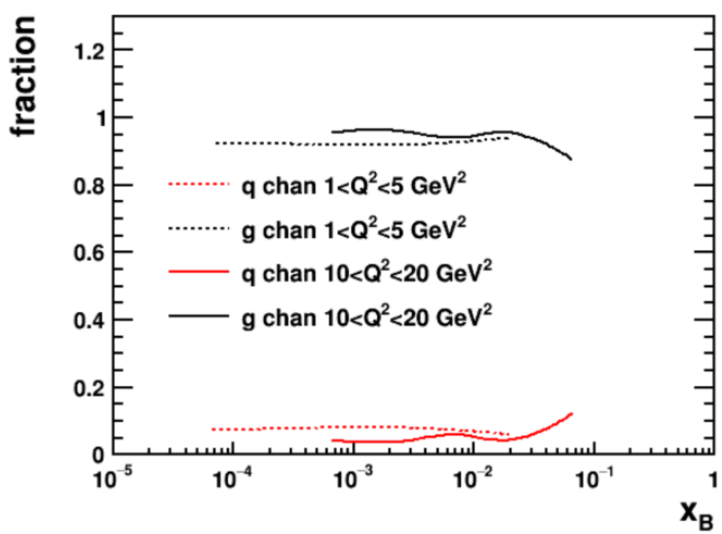
$$\phi_{kS} = \phi_k - \phi_S$$

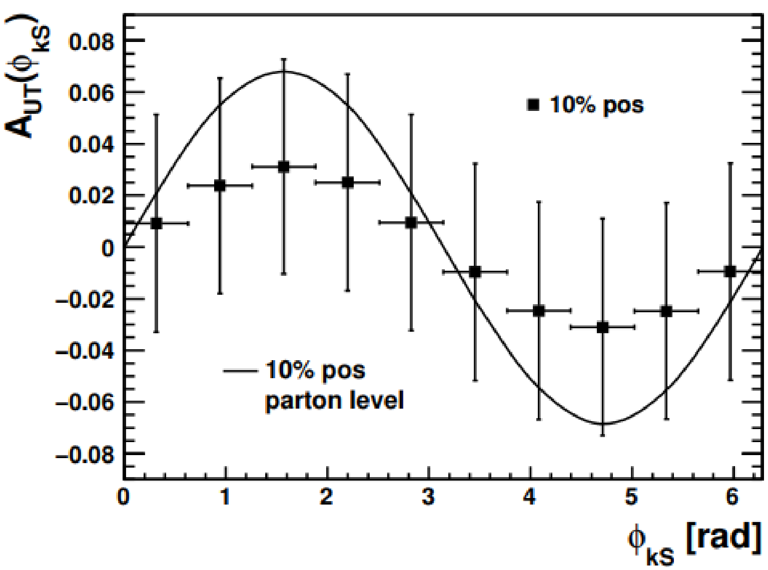
Open charm channel

D^0 cut:
D->K + π (3.9%)
Acceptance $|\eta_{Lab}|^{pi/K}<3.5$
$p_{T\ Lab}^{pi/K}>0.2$ GeV, $p_T^D>0.7$ GeV
$z^D>0.1$
$L_{int} = 10\ fb^{-1}$





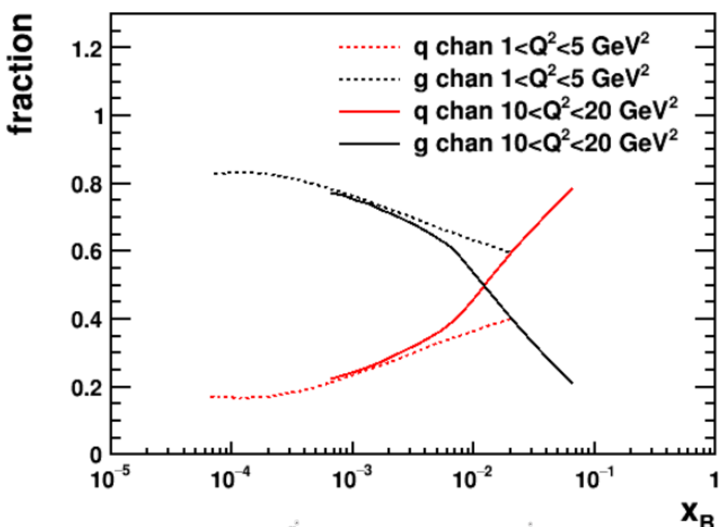


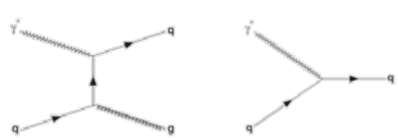


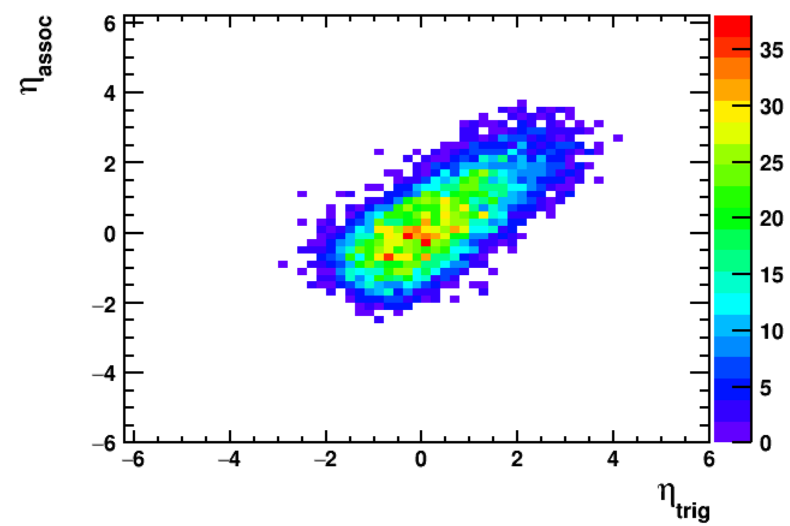
Dihadron channel

Kinematic cuts:
π/K/p
p_T>1.4 GeV, z_h>0.1, $|\eta_{Lab}|$<4.5
Back-to-back limit: k_T< 0.7P_T
L_{int} = 10 fb^{-1}

- Gluon initiated process account for a large fraction of events at small x_B
- Correlated tracks well accepted, experimentally straightforward.





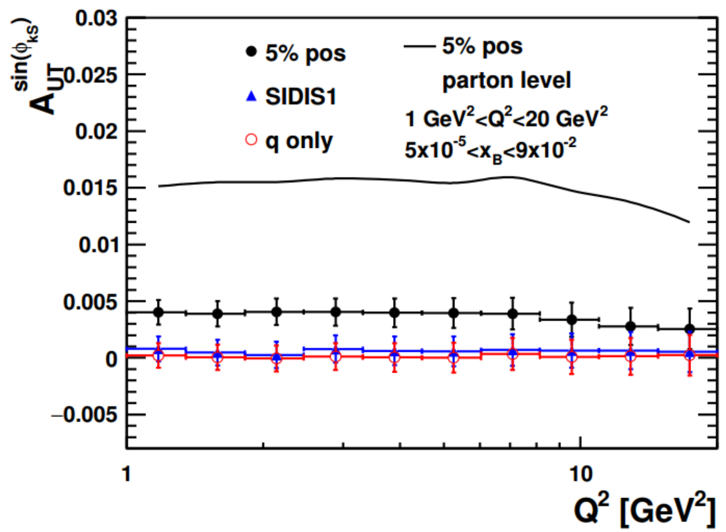


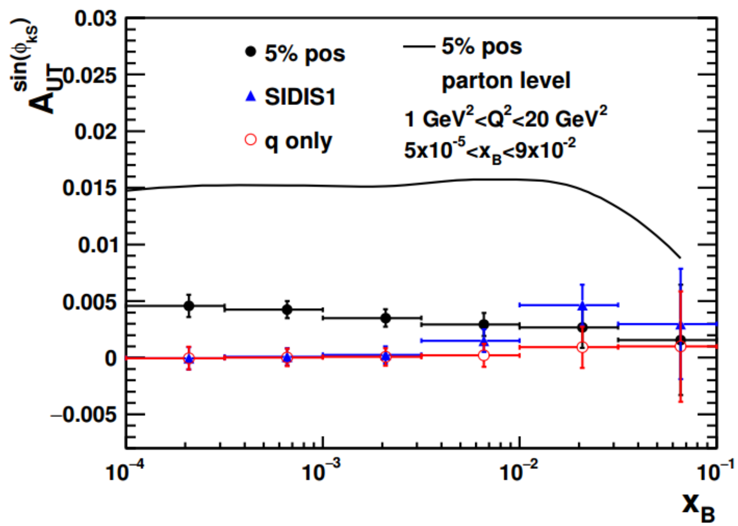
Dihadron channel

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

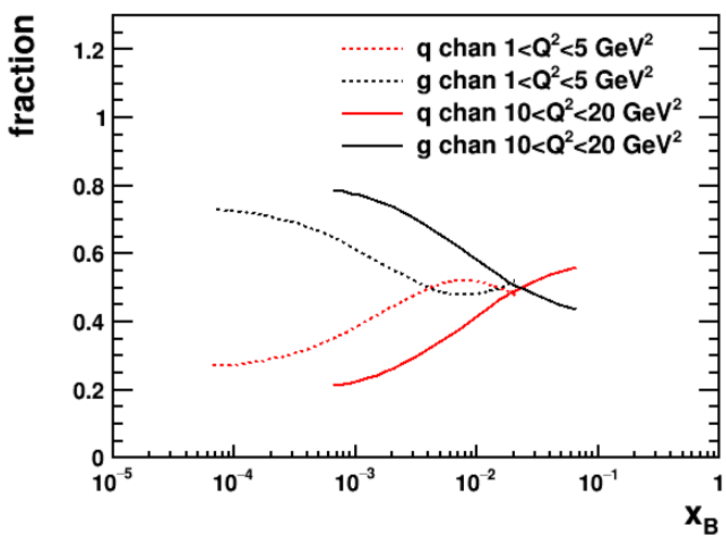


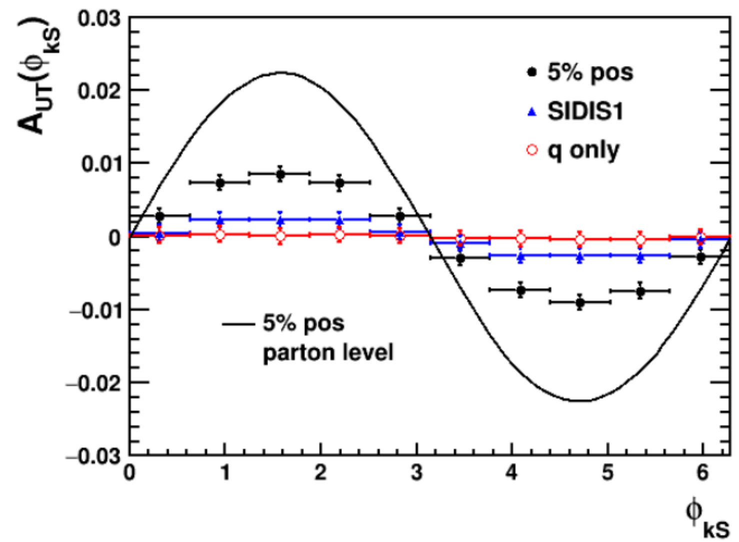


Dijet channel

Anti-k_T, R=1
jet constituent:
$p_{T\ Lab}$>250 MeV, all final state, $|\eta_{Lab}|$<4.5
p_T^{jet1}>4.5 GeV, p_T^{jet2}>4 GeV
L_{int} = 10 fb^{-1}

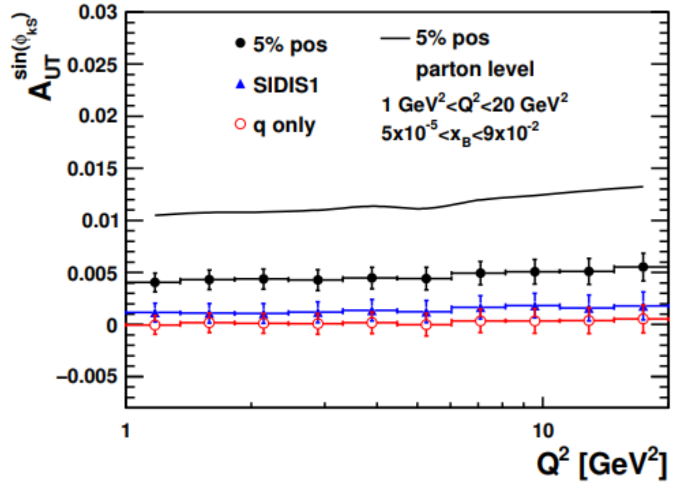
- Subject to the quark background contamination
- Stronger correlation between final state observable to parton level kinematics
- Resolution down to 5% positivity bound gluon Sivers size

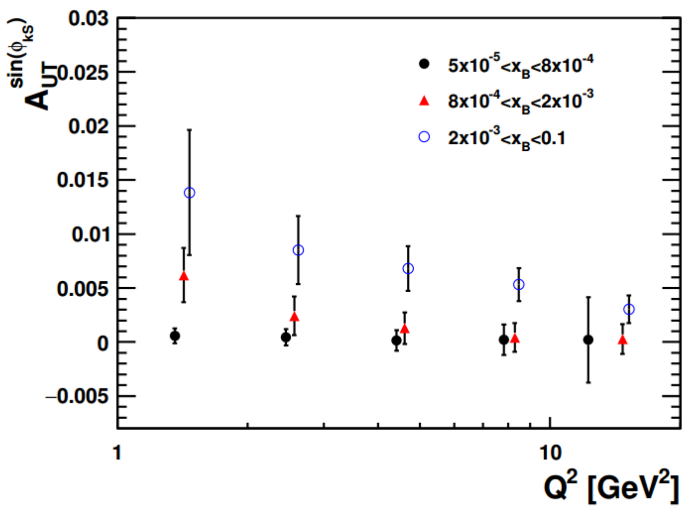


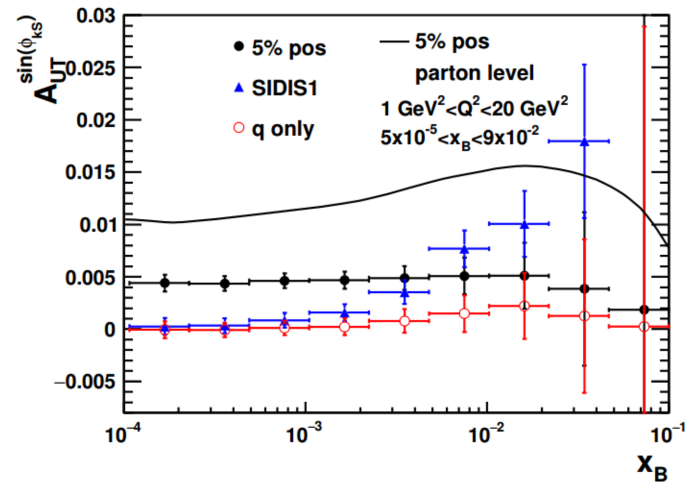


Dijet channel

- Large statistics allow to explore SSA in multidimensional analysis.



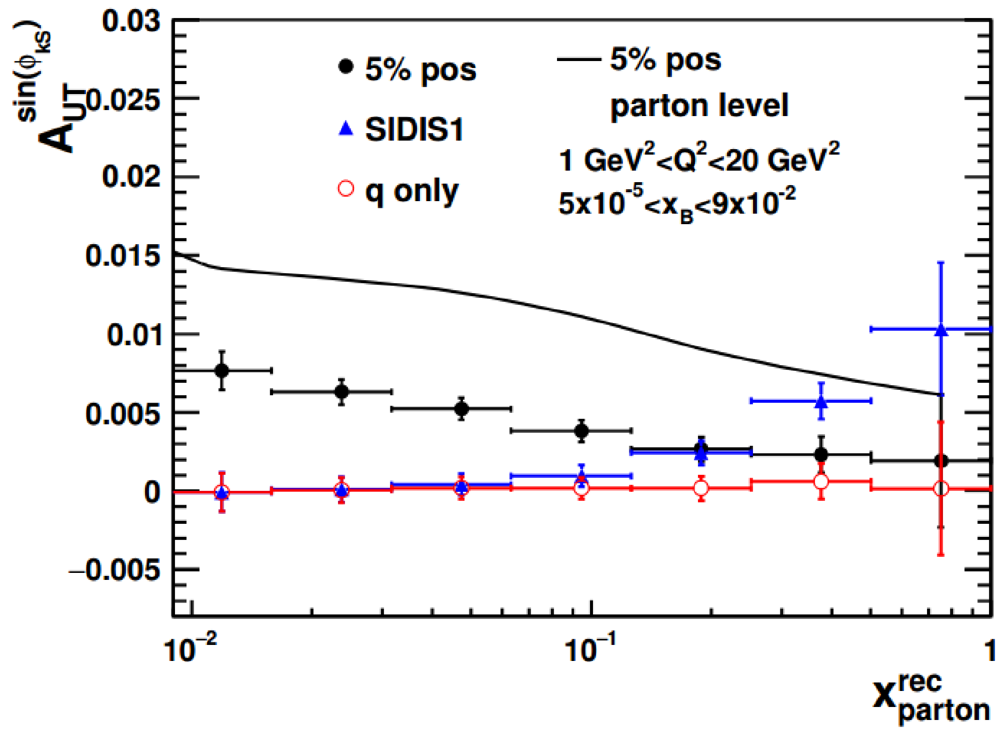




Potential money plot

Dijet is a statistically favored and kinematically clear probe to the gluon Sivers effect

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



Weighing our options

- Sensitive to gluon distribution
- Correlation to parton kinematics
- Statistically hungry

Open charm

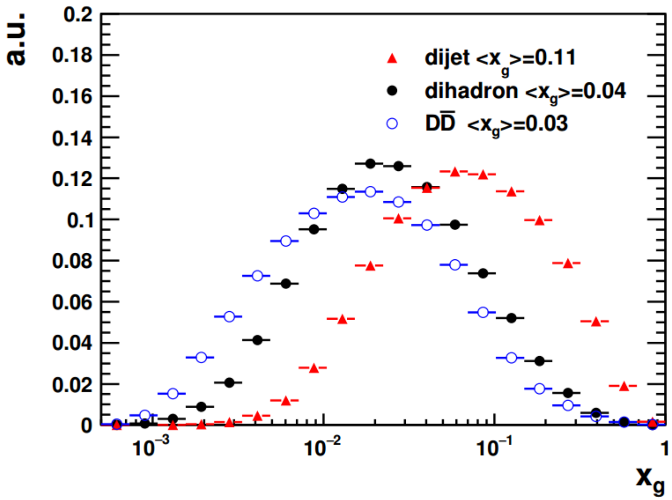
- Experimentally straightforward
- Dilution from parton to hadron

Charged dihadron

- Favored in statistics and kinematics
- Contamination from quark sector

Dijet

Different probes can be complementary in x_g coverage.



Summary

- Gluon Sivers function is an ingredient of 3D nucleon structure which 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.
- Simulation framework with flexible Sivers asymmetry input based on MC events ready for the detector level studies.

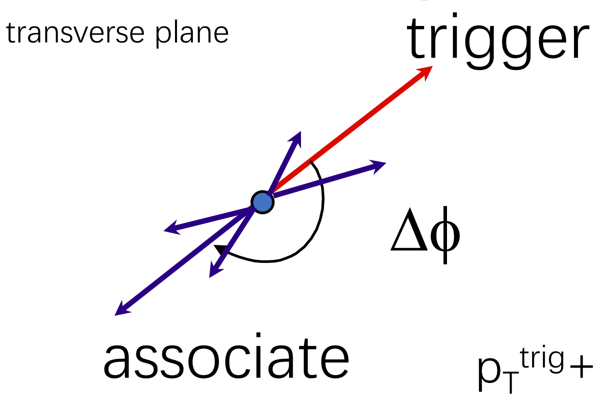
Outlook

- Detector smearing effect to be studied in the current framework. Simple for dihadron but tricky in dijet.
- Utilizing the new jet axis observables to improve the dijet sensitivity to the gluon Sivers effect.

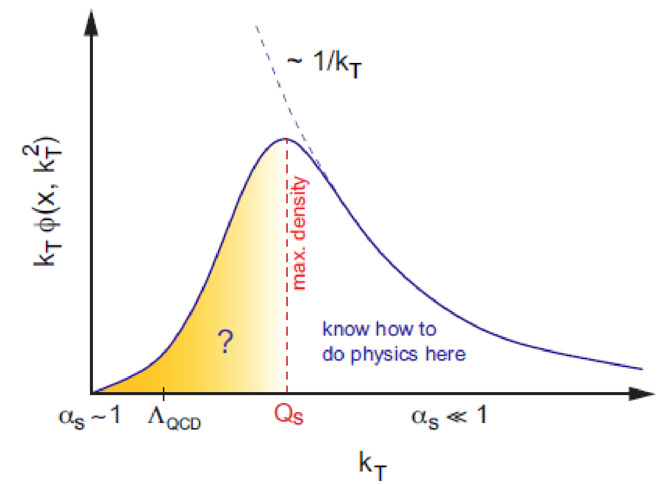

BACKUP

Gluon saturation via dihadron

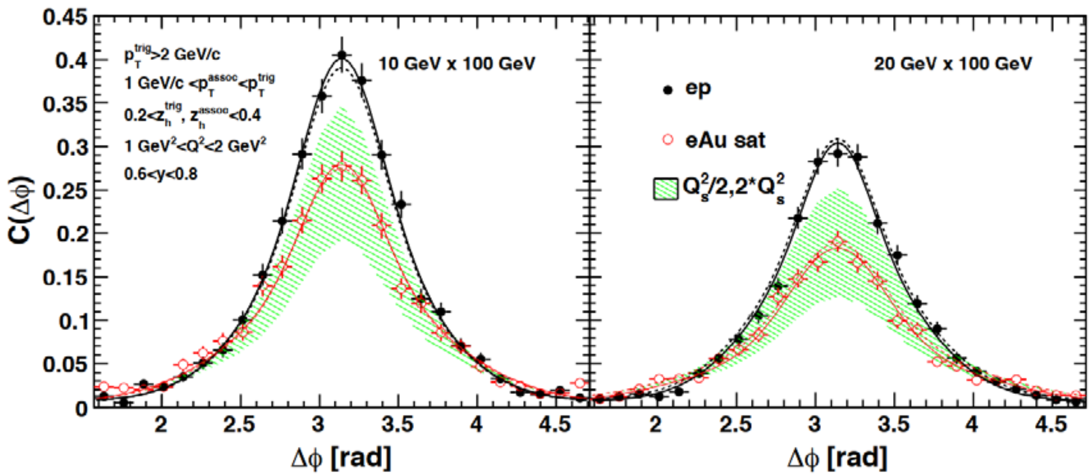
$$C(\Delta\phi) = \frac{N_{pair}(\Delta\phi)}{N_{trig}}$$



$p_T^{trig} + p_T^{asso} \sim Q_s$



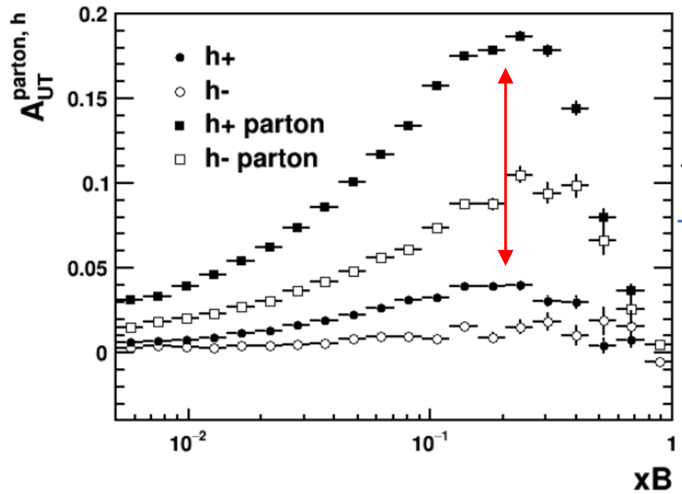
Phys. Rev. D 89, 074037 (2014)



- Back to back hadron pairs decorrelate
- Strong suppression at away side predicted by saturation
- Probe nuclei in k_T space.

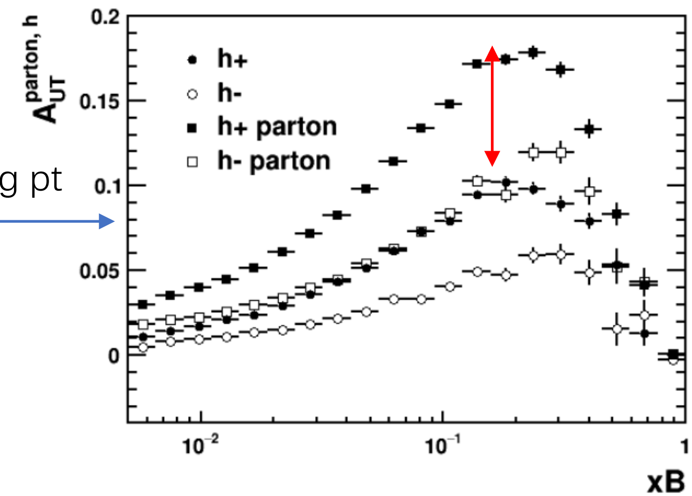
Dilution of parton level asymmetry

all on



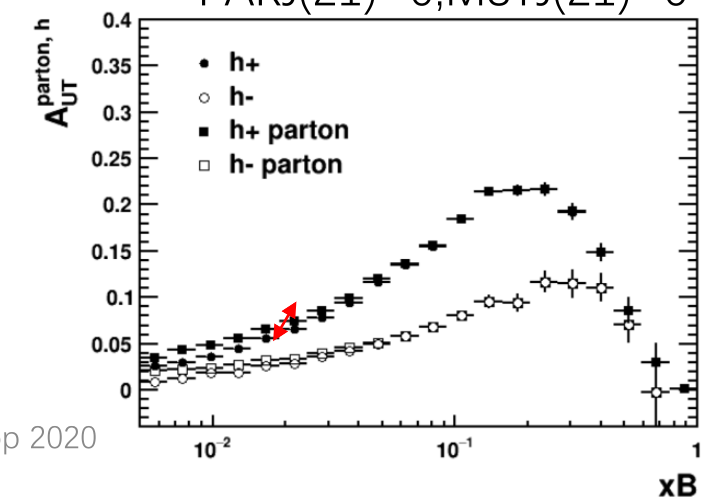
Turn off frag pt

PARJ(21)=0



Turn off decay

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

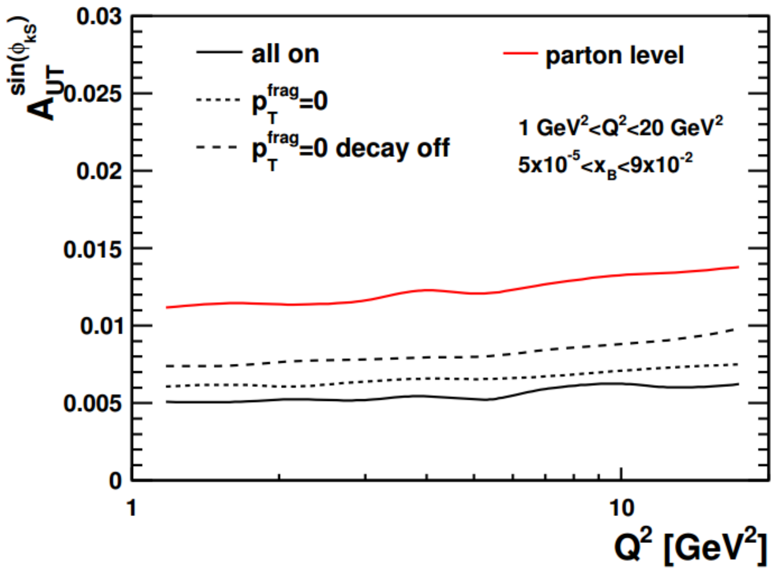


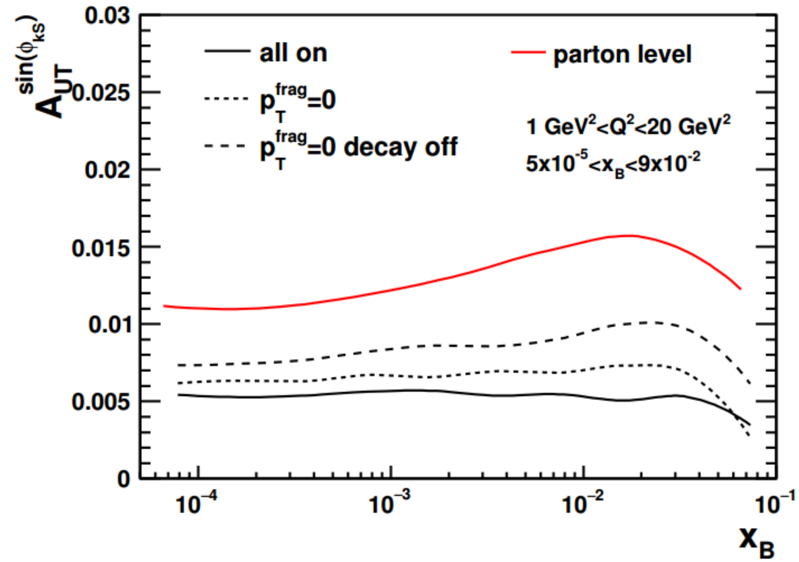
Fragmentation momenta smearing and resonance decay contribution accounts for the parton to hadron level asymmetry dilution at COMPASS energy.

Dilution of parton level asymmetry

Anti-k_T, R=1
jet constituent:
p_T>250 MeV, π/K/p/γ, |η|<4.5
p_T^{jet1}>4.5 GeV, p_T^{jet2}>4 GeV
$\int Ldt = 10\ fb^{-1}$

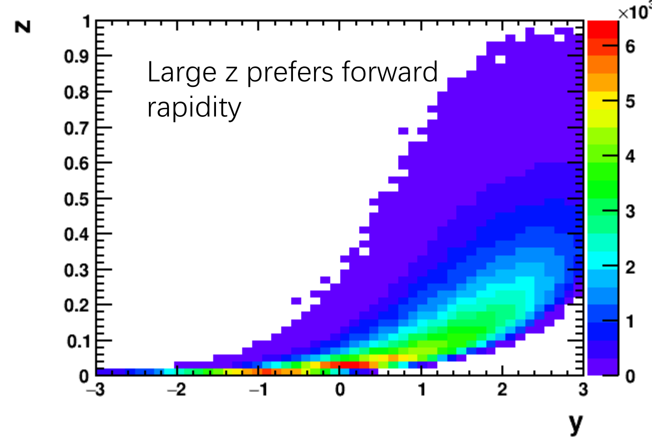
- Hadron fragmentation momentum smearing and resonance decay are important
- Other smearing effects in dijet process



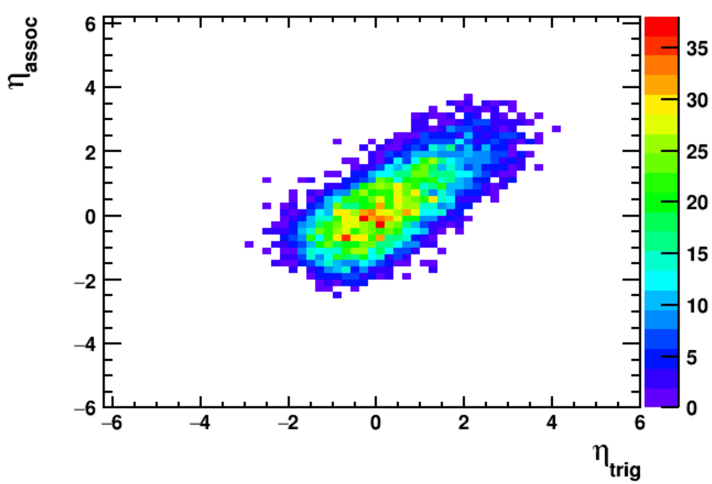


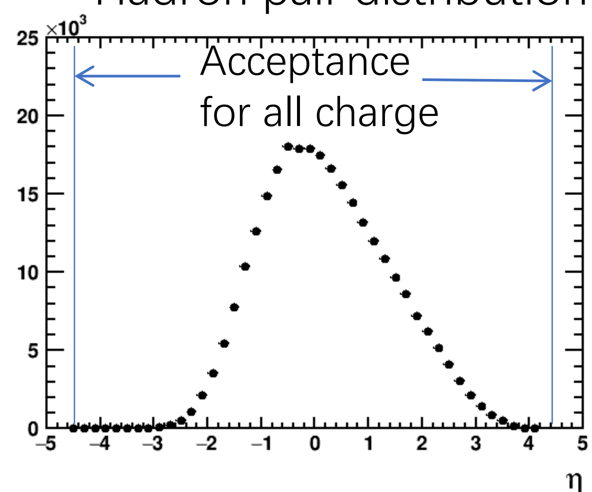
Dihadron pair selection

Kinematic cuts:
ep 20x250 GeV
$0.01<y<0.95$
$1<Q^2<20$ GeV^2
$p_T>1.7$ GeV, $z_h>0.1$, $|\eta|<4.5$
Back-to-back limit: $k_T' < 0.7P_T'$



Hadron pair distribution

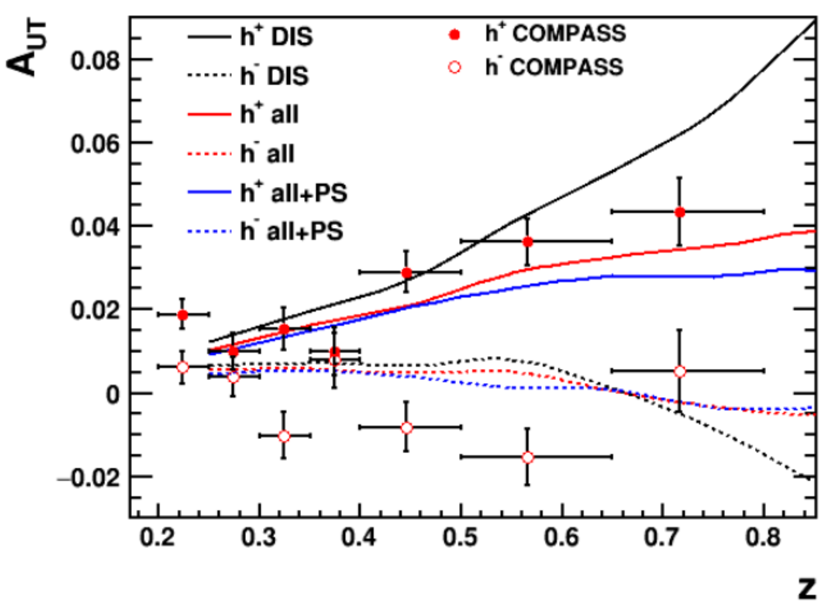


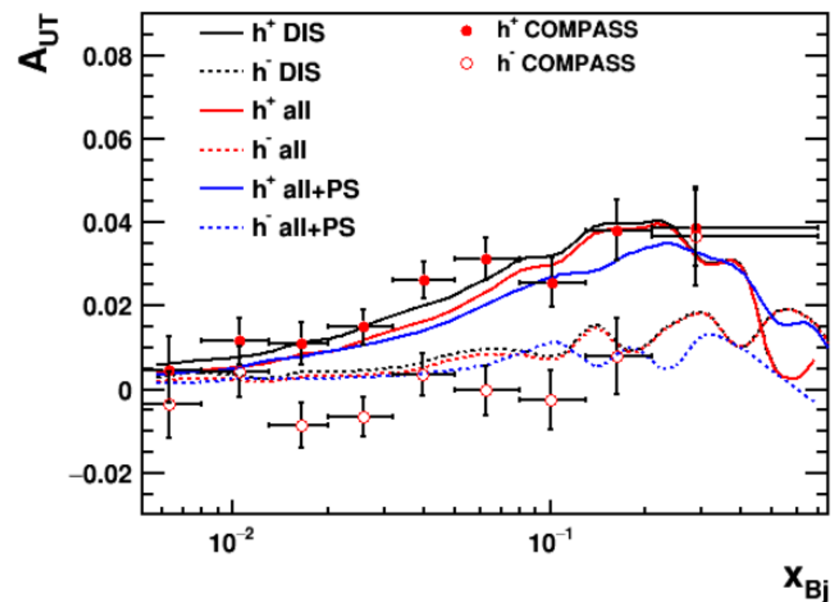


Comparing to Sivers data

- COMPASS results well reproduced
- Gluon radiations weakly smear the asymmetry size at COMPASS energy

COMPASS kinematics
160 GeV μ beam on fixed target
$0.1<y<0.9$, $Q^2>1$, $W>5$



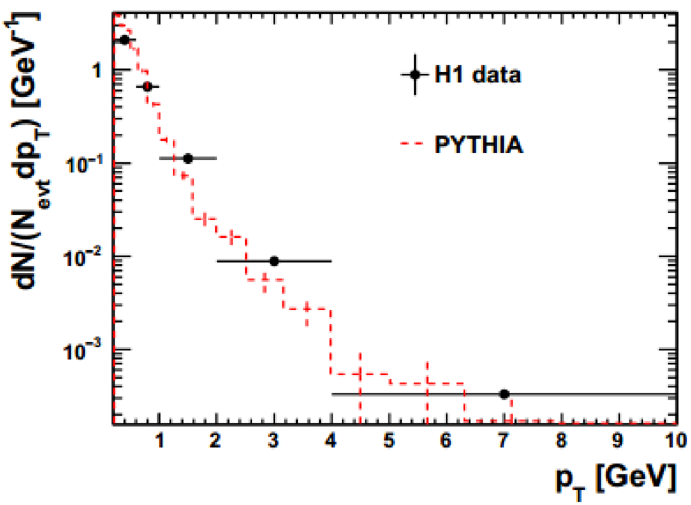


Comparing to experimental data

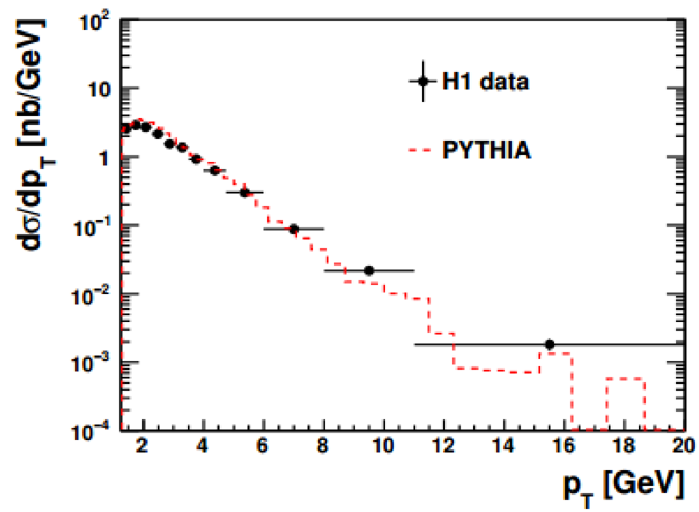
H1 charged particle and heavy flavor particle production well described

ep 27.6 GeV x 920 GeV
$5<Q^2<10$, $0.0005<x_{Bj}<0.002$
p_T*, $\eta*$ defined in gamma-hadron center of mass frame

Charged particle

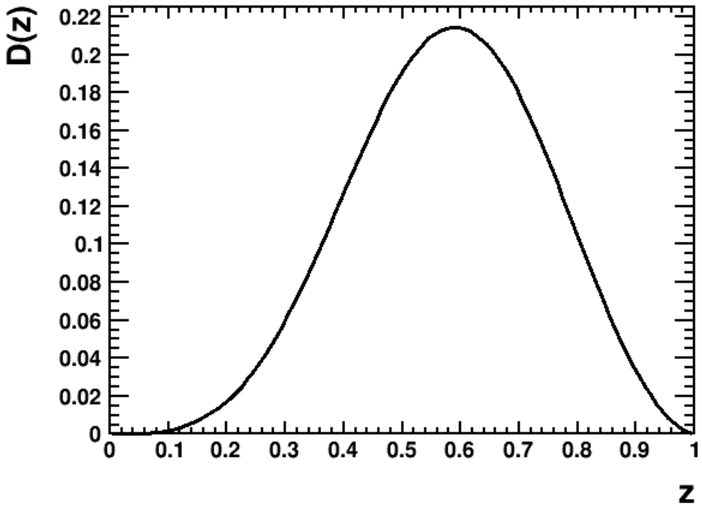


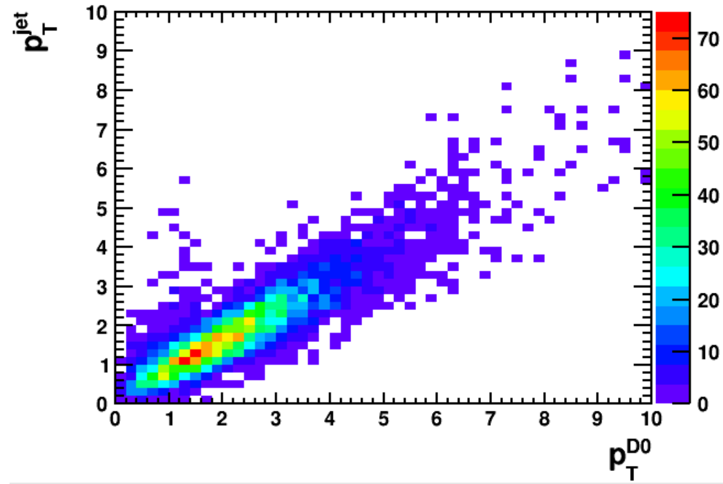
D*

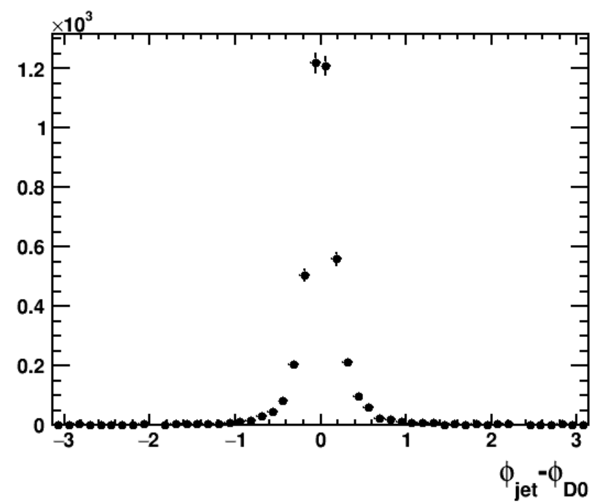


Data from EPJC 73, 2406 (2013)

D^0 as charm quark proxy



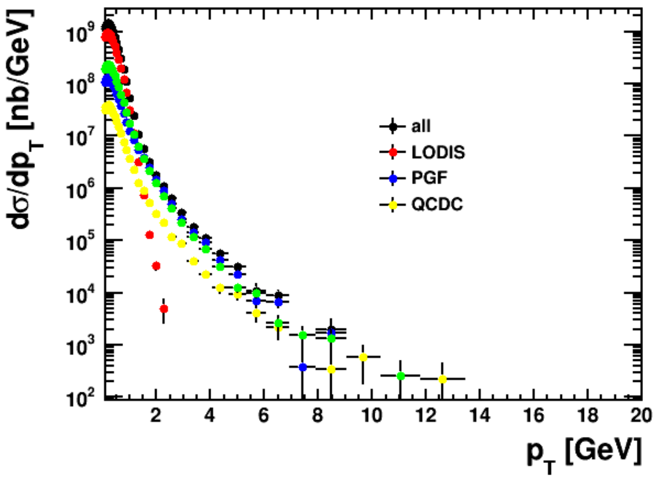


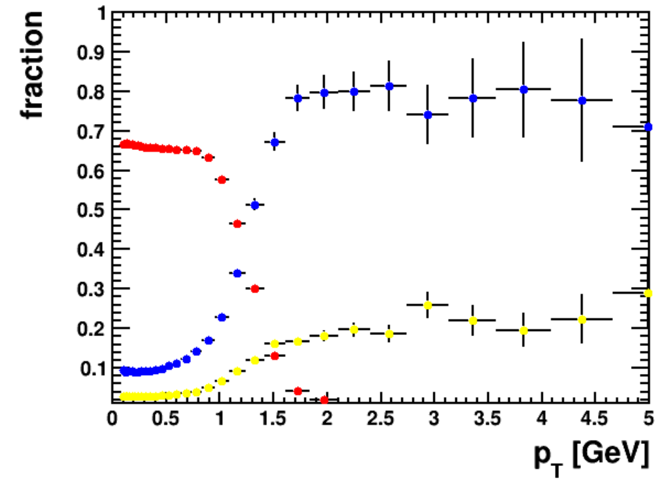


D meson takes a large fraction of the charm quark energy, serves as a proxy to the charm jet information.

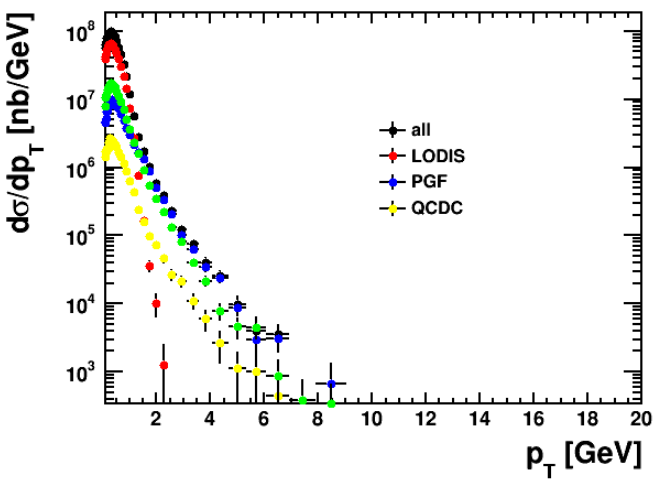
Charged hadron vs kaon spectrum

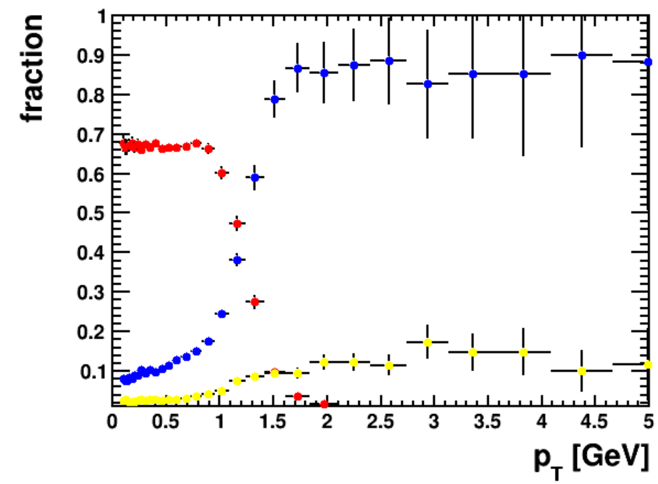
Charged hadron



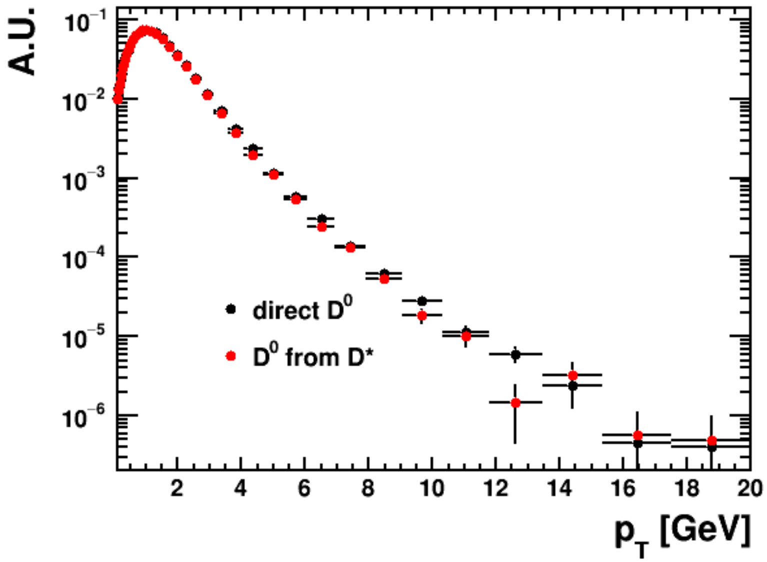


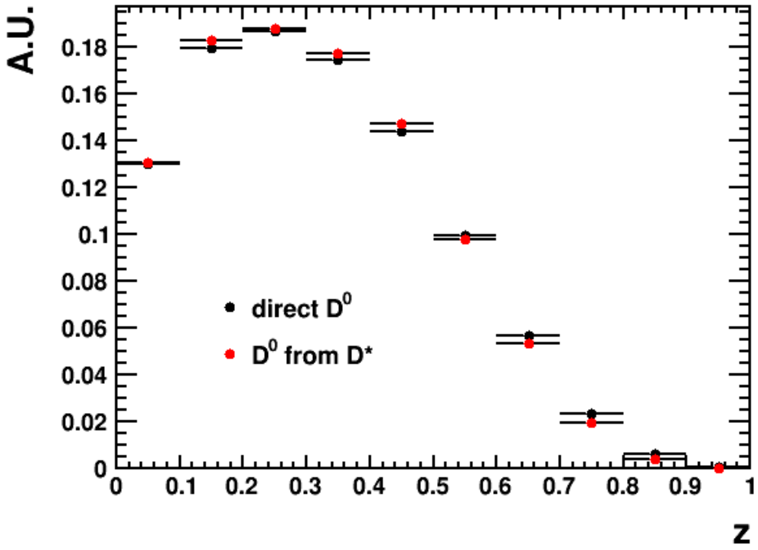
Charged Kaon





D^0 feed-down from D*





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

Current knowledge to quark Sivers function

$$\frac{d\sigma}{dx\,dy\,d\phi_S\,dz\,d\phi_h\,dP_{hT}^2} \propto F_{UU,T} + |\boldsymbol{S}_\perp|\sin(\phi_h - \phi_S)F_{UT,T}^{\sin(\phi_h-\phi_S)} + \ldots$$

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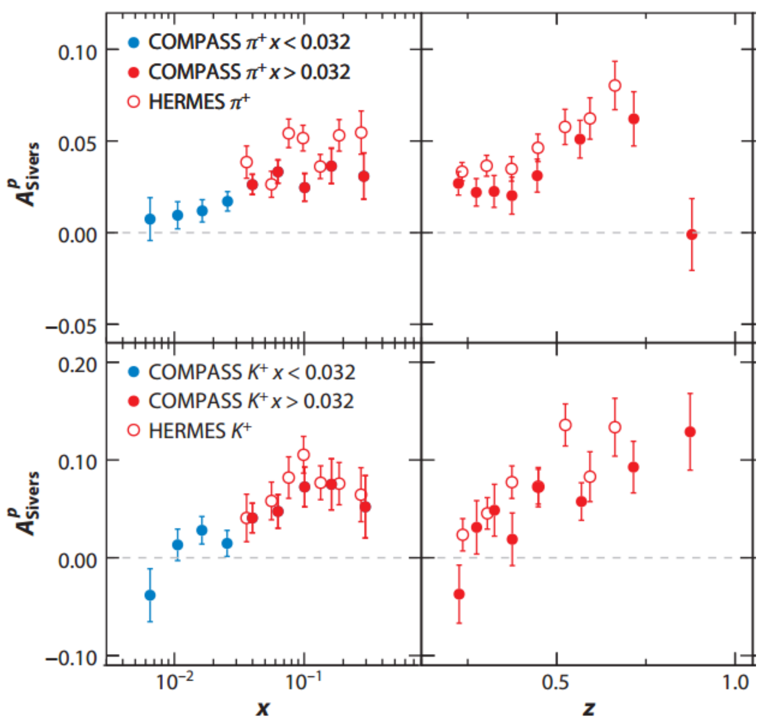
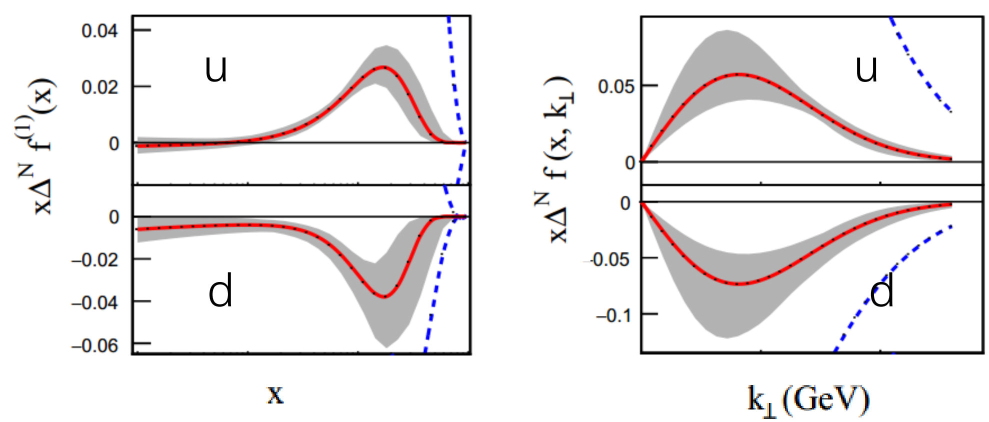


PRL 103, 152002 (2009) HERMES data
PLB 717, 383 (2012) COMPASS data

- Accessed with SIDIS measurements.
- Sizable Sivers effect.
- u, d quark Sivers with opposite sign.
- Subject to large uncertainty.



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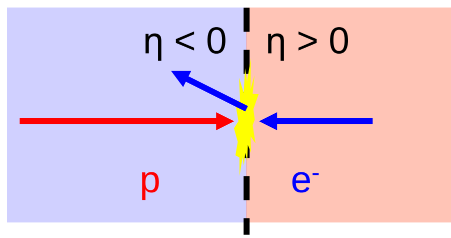
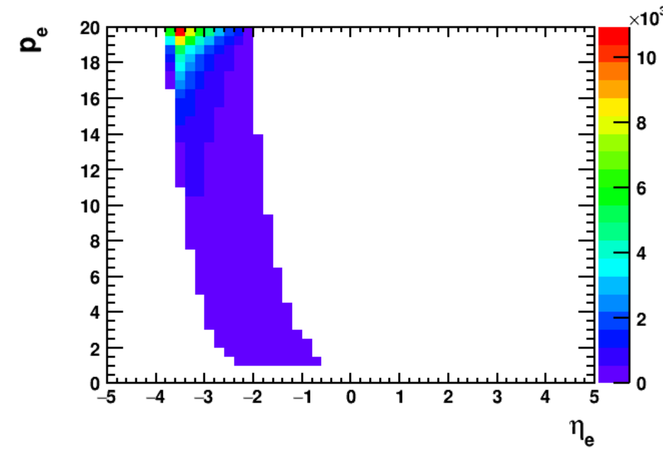
EIC setup for gluon SSA study

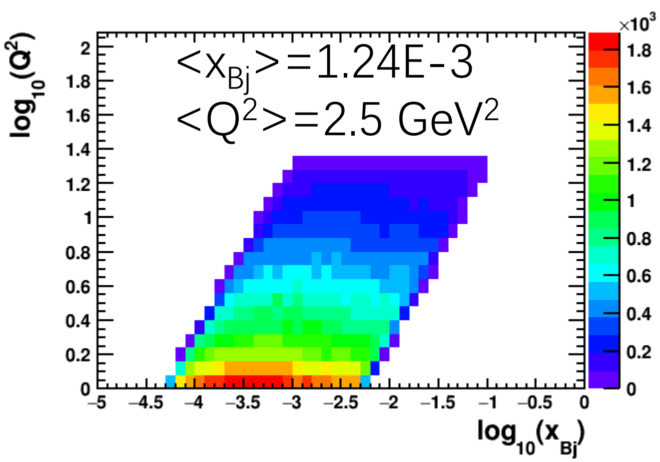
Kinematics:
$ep^{\uparrow}$ 20x250 GeV
$\sqrt{s}$=141 GeV
0.01<y<0.95
$1<Q^2<20$ GeV^2

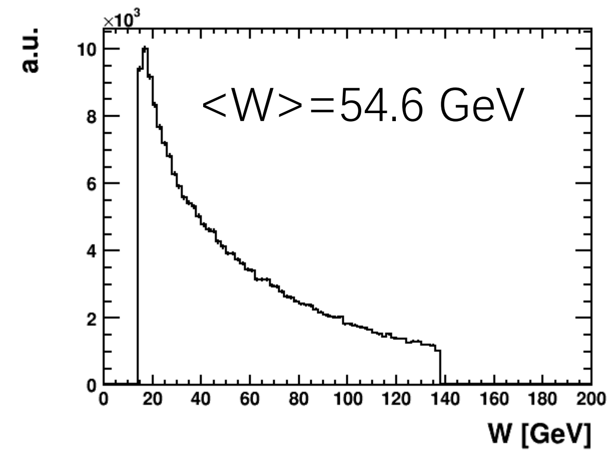


Scattered electron



Final state observables
1. Open charm
2. Charged hadron pair
3. Dijet pair





Open charm channel

D^0 cut:
$D \to K + \pi$ (3.9%)
Acceptance $|\eta|^{pi/K}<3.5$
$p_T^{pi/K}>0.2$ GeV, $p_T^D>0.7$ GeV,
$z^D>0.1$
$L_{int} = 10\ fb^{-1}$

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