Accessing the gluon Sivers function at a future Electron-Ion Collider

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Phys. Rev. D 98, 034011 (2018)

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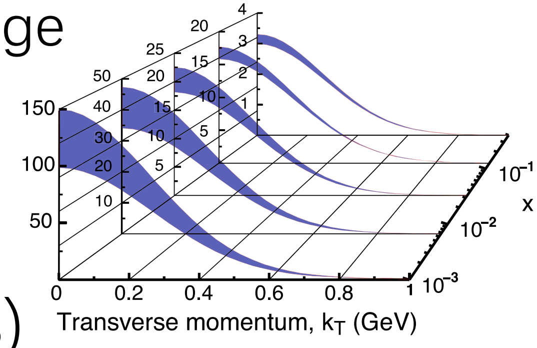
23rd International Spin Symposium
10-14 September, 2018
Ferrara, Italy

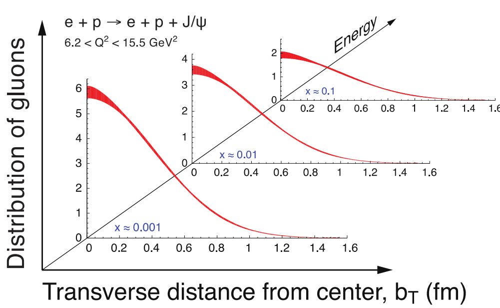
SPIN 2018

Exploring nucleon structure

- Nucleon is a dynamical system of quarks and gluons
- EIC: polarized collider to have full access to the nucleon dynamics.
- Transverse Momentum Dependent parton distributions (TMDs)
  - Spin dependent 3D momentum space image
  - Semi-inclusive DIS
  - $f(x,k_T)$



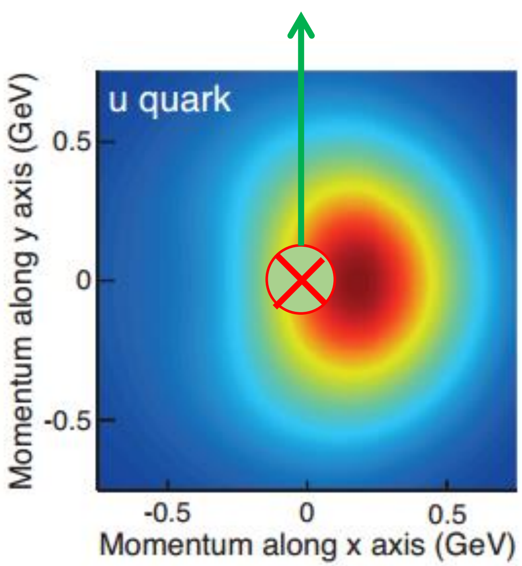
- Generalized Parton Distributions (GPDs)
  - Spin dependent 2D coordinate space (transverse) + 1D longitudinal momentum space
  - exclusive DIS
  - $f(x,b_T)$



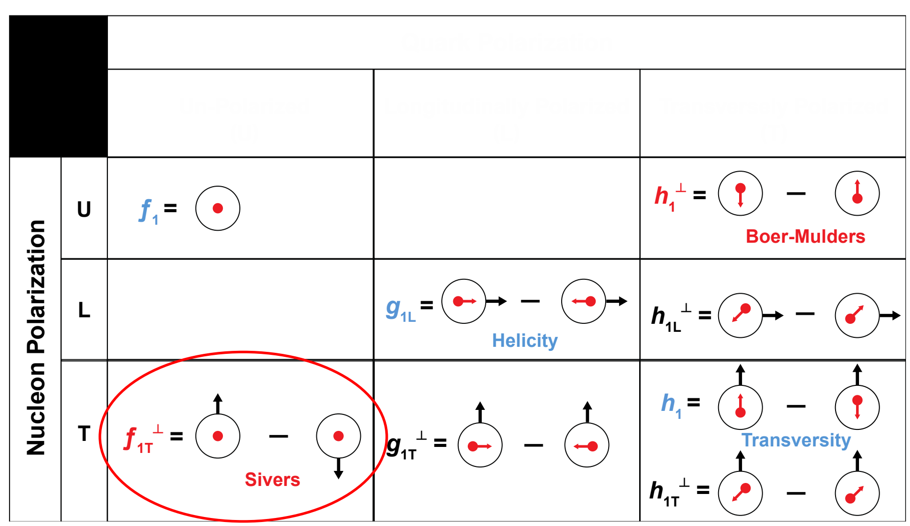
TMDs and Sivers function

- 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.
- Non-trivial QCD color gauge invariance.

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



Leading Twist TMDs



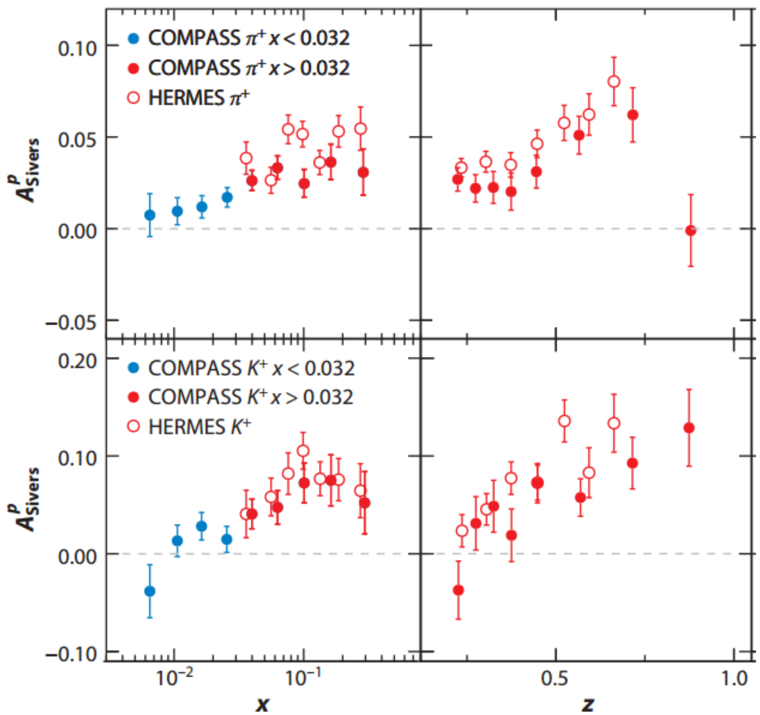
Similar for gluons

Current knowledge to quark Sivers function

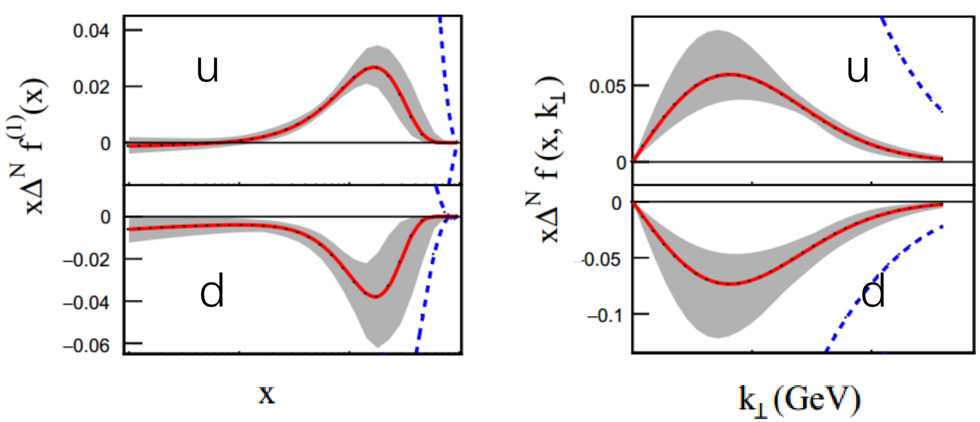
$$\frac{d\sigma}{dx\,dy\,d\phi_S\,dz\,d\phi_h\,dP_{hT}^2} \propto F_{UU,T} + |\boldsymbol{S}_\perp| \sin(\phi_h - \phi_S) F_{UT,T}^{\sin(\phi_h-\phi_S)} + \ldots$$

Annu. Rev. Nucl. Part. Sci. 65 429 (2015)

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



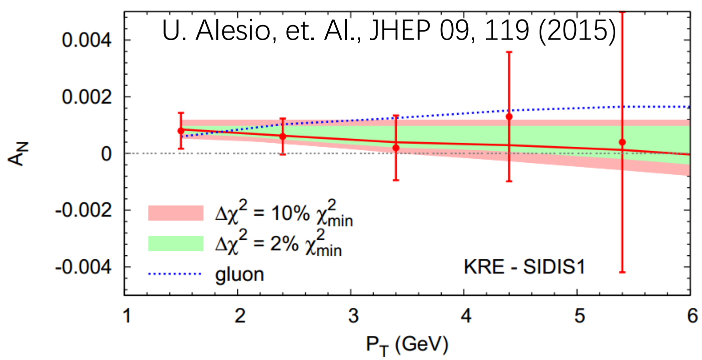
PRL 103, 152002 (2009) HERMES data
PLB 717, 383 (2012) COMPASS data

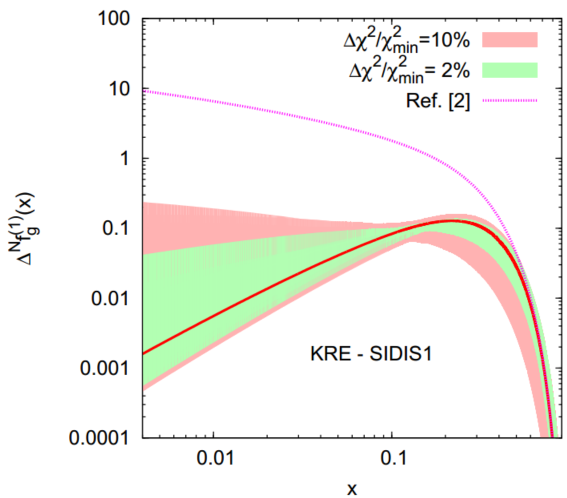


JHEP 04(2017) Anselmino et. al.

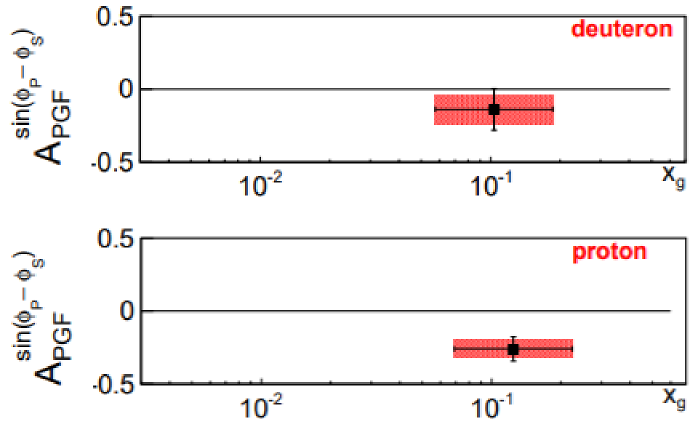
Current constraints on gluon Sivers function

Extraction based on PHENIX π^0 A_N data at RHIC





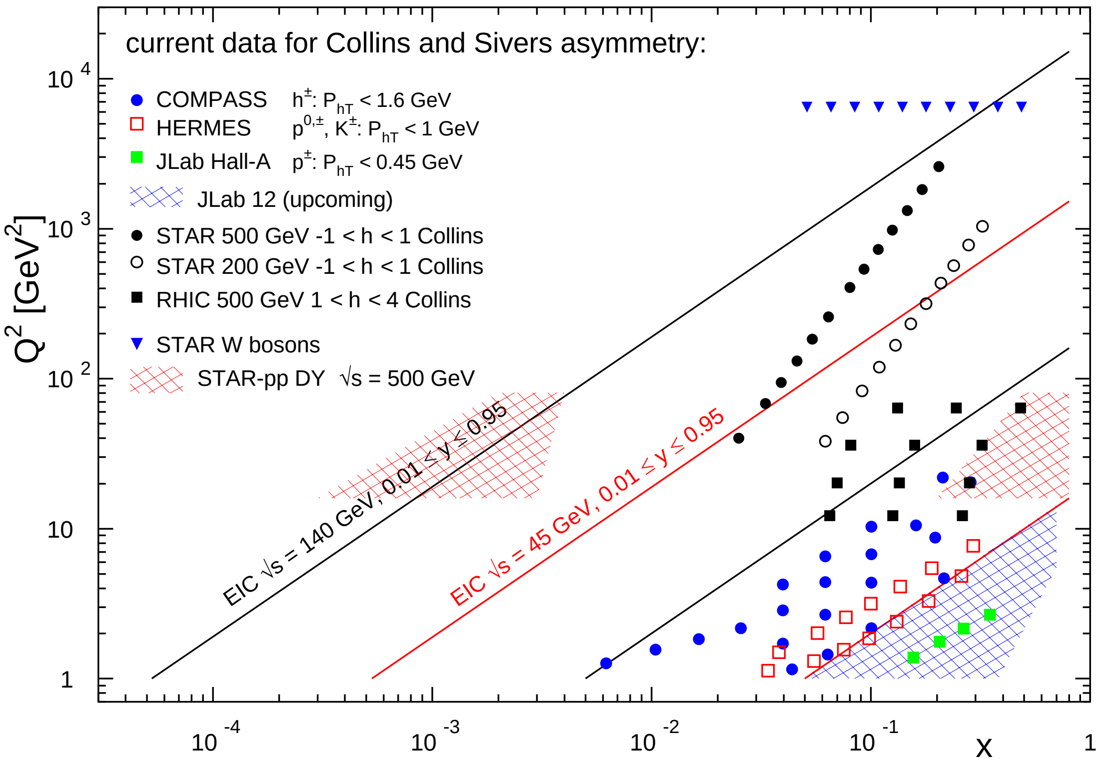
COMPASS dihadron measurements



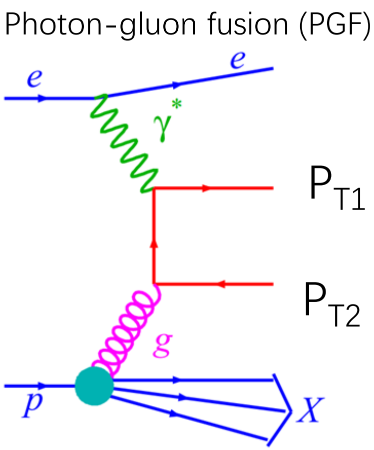
- Effective gluon Sivers from A_N may differ from the actual gluon Sivers in TMD.
- Limited x and Q^2 range explored in SIDIS. Still allow for gluon Sivers contributions of $1/N_c$.
- No hard constraints at this moment.

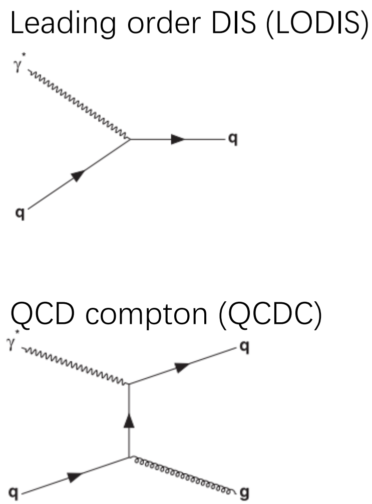
Studying Sivers function in the EIC era

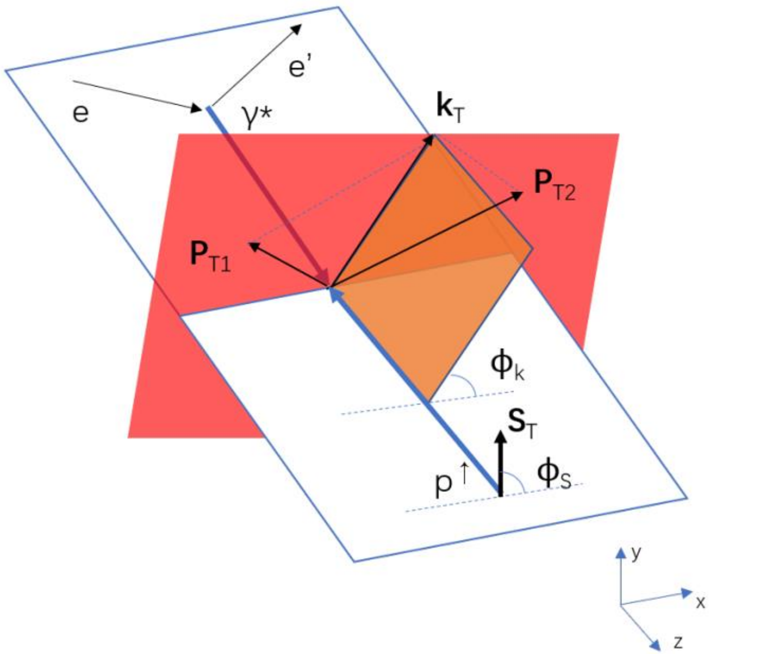
- ep data mainly from fixed target experiment: high x, low Q2
- EIC will largely extend the kinematic coverage



Accessing gluon Sivers at EIC







- PGF is the signal process.
- Vector sum of p_{T1} and p_{T2} reconstruct the gluon k_T in $\gamma{*}p$ c.m.s frame.
- Process dependence of gluon Sivers function (WW)

Single Spin Asymmetry (SSA)

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

Event weighting method

PYTHIA
event generator

Beam energy

Partonic flavor, kinematic info

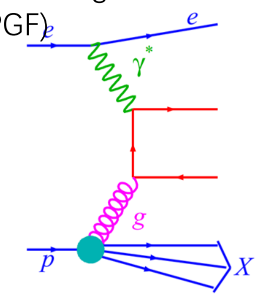
hadronization

SSA in final state observable

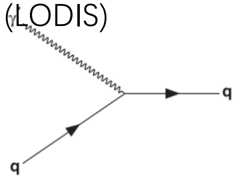
Weighting events in a final state observable

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

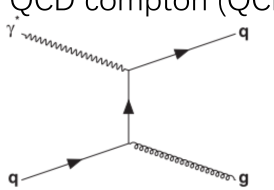
Photon-gluon fusion (PGF)



Leading order DIS (LODIS)



QCD compton (QCDC)



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

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

Inputs to the model calculation

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

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

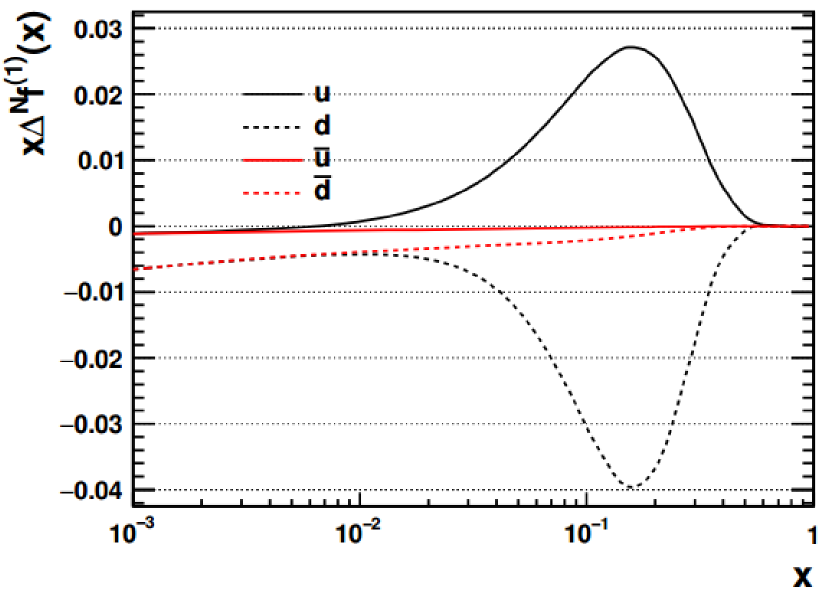
$$A_{UT} = R_g \frac{\Sigma_i^{N_g} w_i}{N_g} + R_q \frac{\Sigma_i^{N_q} w_i}{N_q}$$

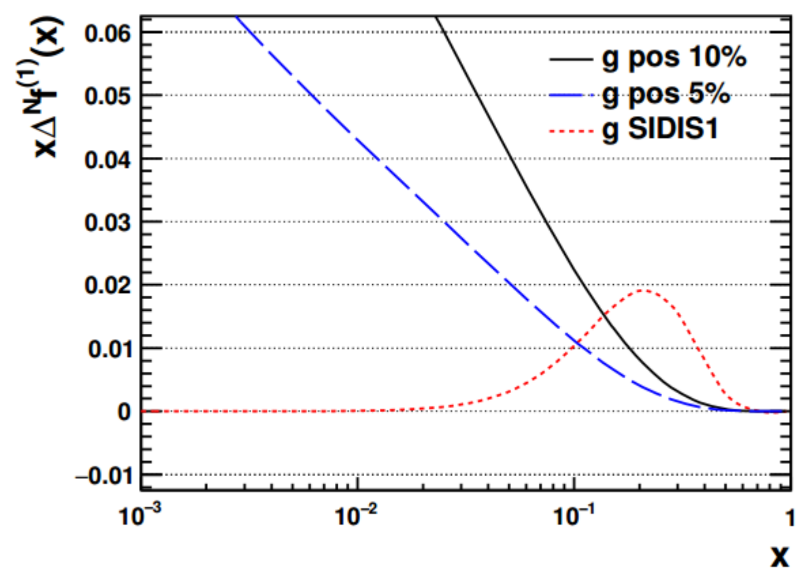
Quark Sivers: JHEP 04(2017) Anselmino et. al.
u and d quarks

Gluon Sivers: JHEP 09 (2015) 119 D' Alesio et. al.
u, d + Kretzer FF (SIDIS1)

Positivity bound ansatz:

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



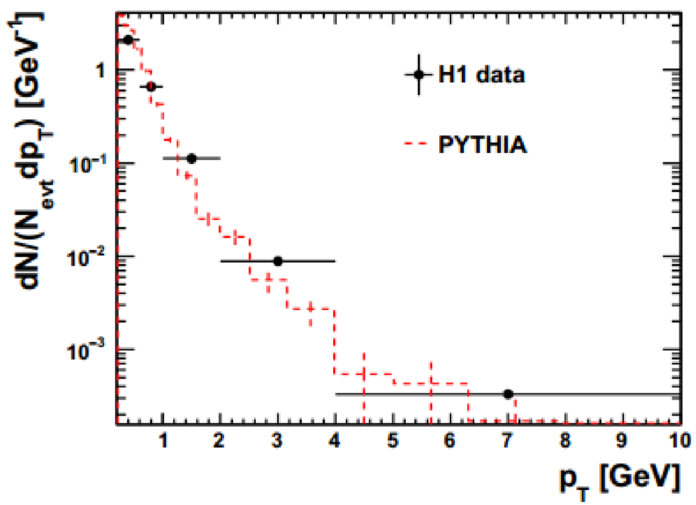


Comparing to unpolarized data

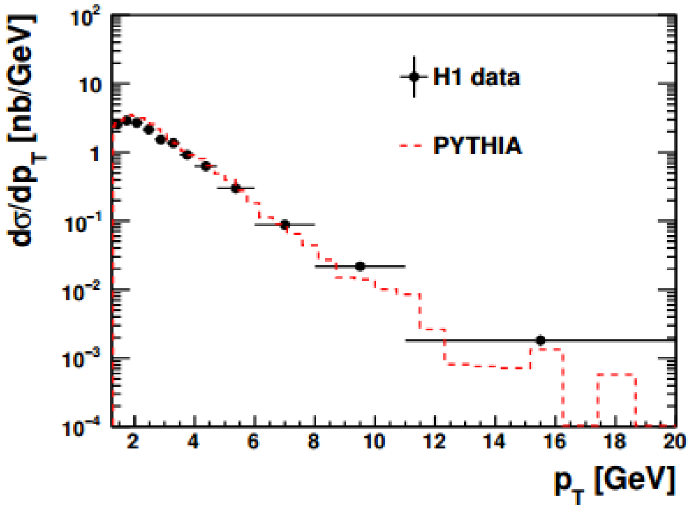
H1 charged particle and heavy flavor particle production well described

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

Charged particle



D*

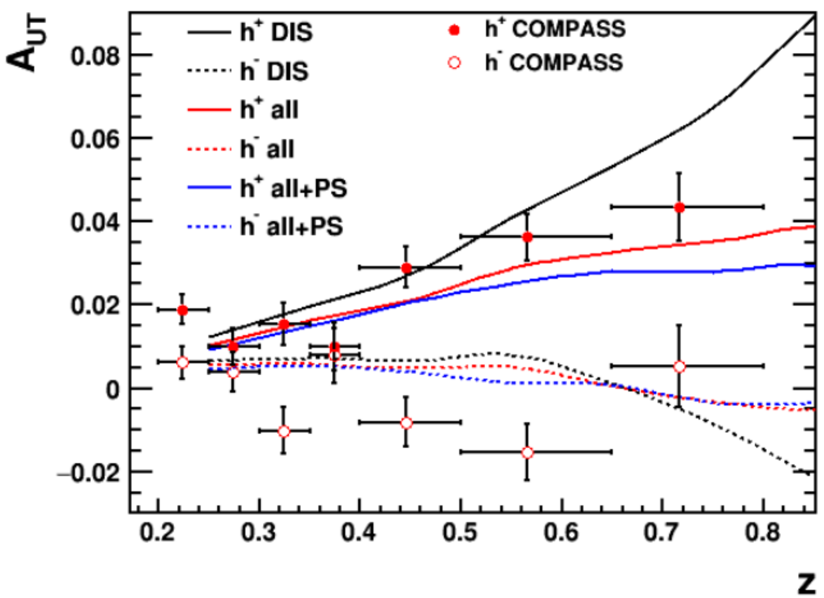


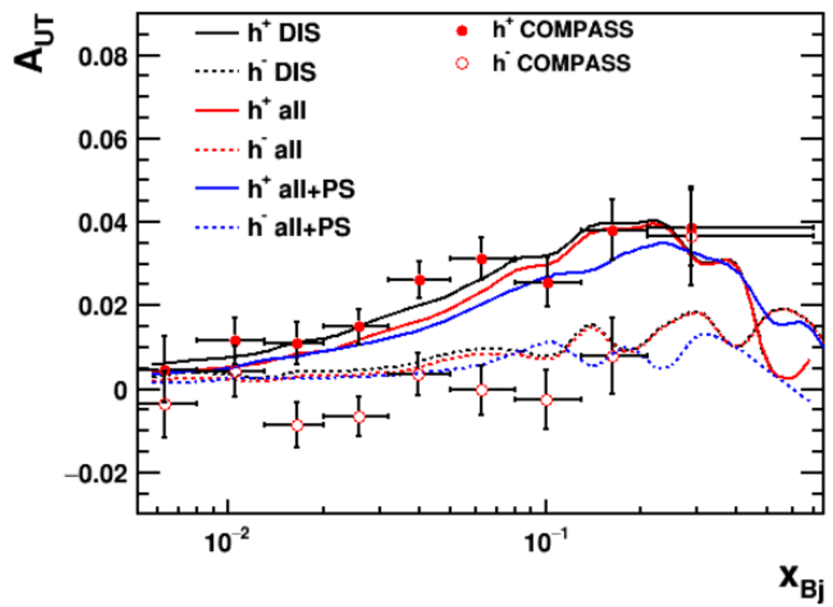
Data from EPJC 73, 2406 (2013)

Comparing to Sivers data

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

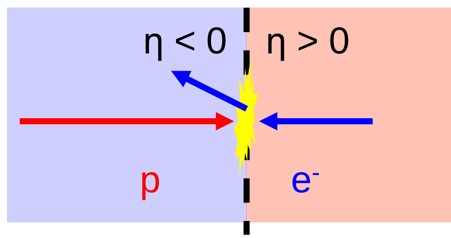
COMPASS kinematics
160 GeV μ beam on fixed target
$0.1<y<0.9$, $Q^2>1$, $W>5$



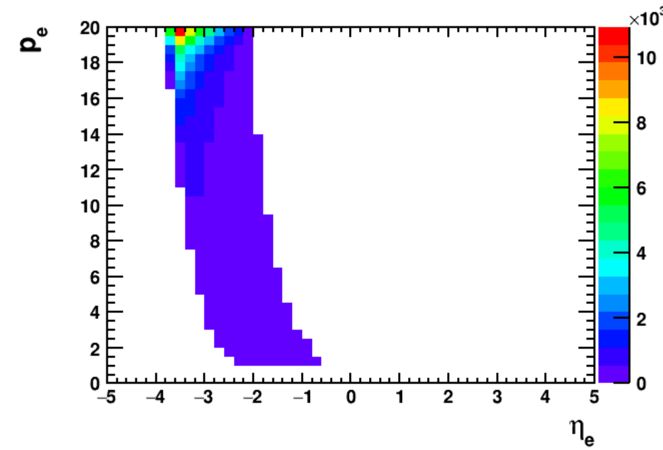


EIC setup for gluon SSA study

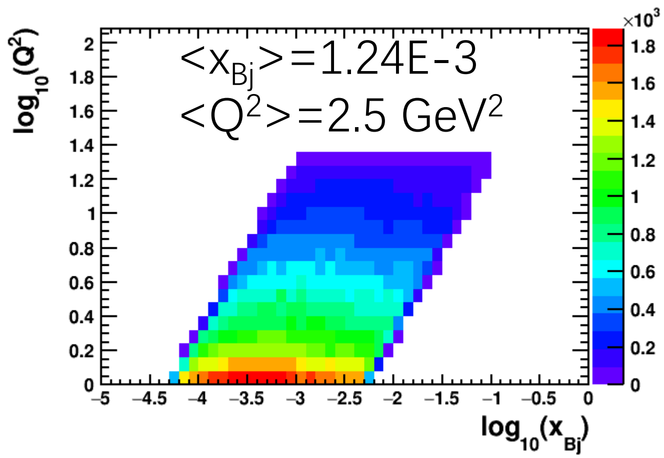
Kinematics:
$ep^{\uparrow}$ 20x250 GeV
$\sqrt{s}$=141 GeV
$0.01<y<0.95$
$1<Q^2<20$ GeV^2

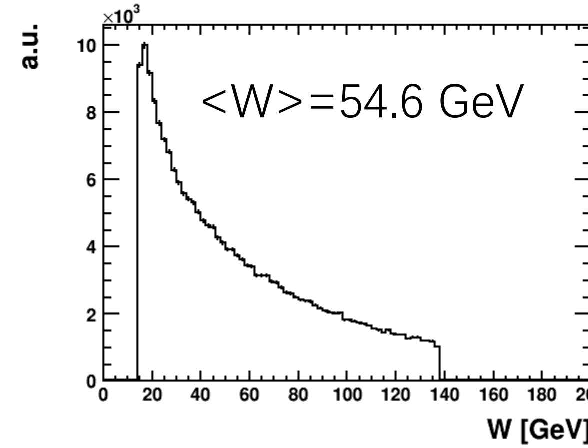


Scattered electron



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



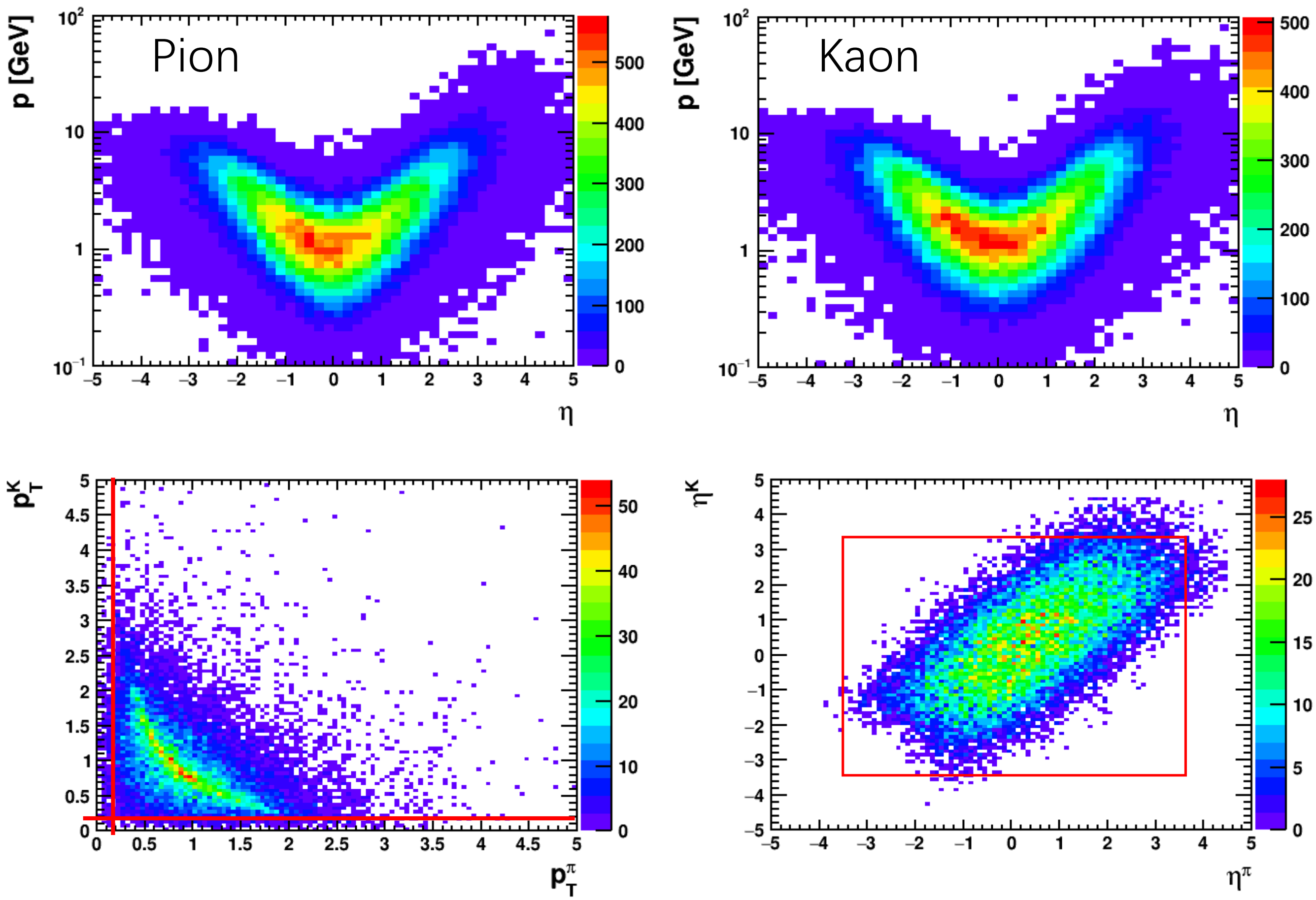


D meson reconstruction

Branching ratio: 3.9%

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

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

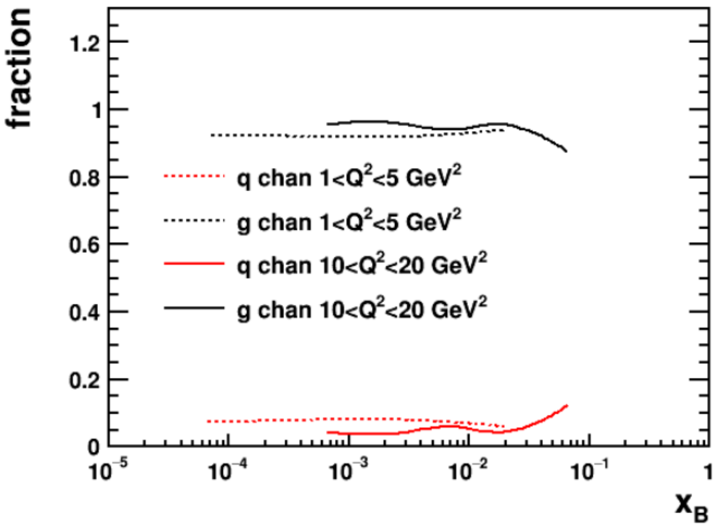


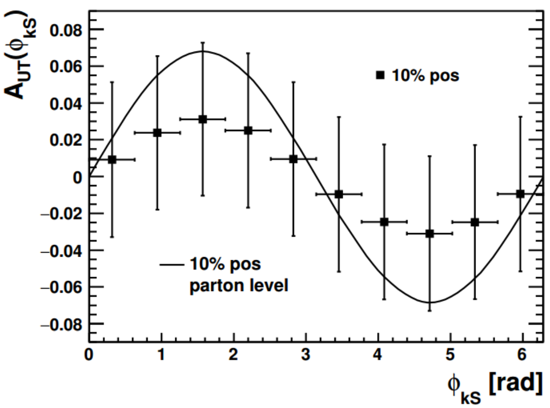
- Acceptance for PID is assumed to be |η|<3.5
- Decay products from D mesons are mostly less than 10 GeV in mid-rapidity.
- Decay products p_T>0.2 GeV.

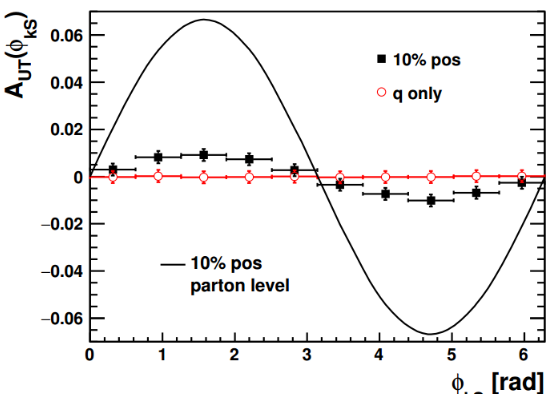
Constraint from open charm

D^0 cut:
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



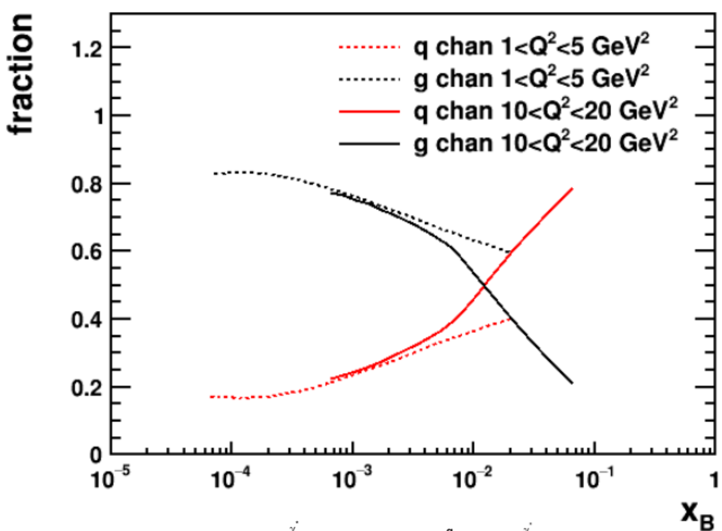


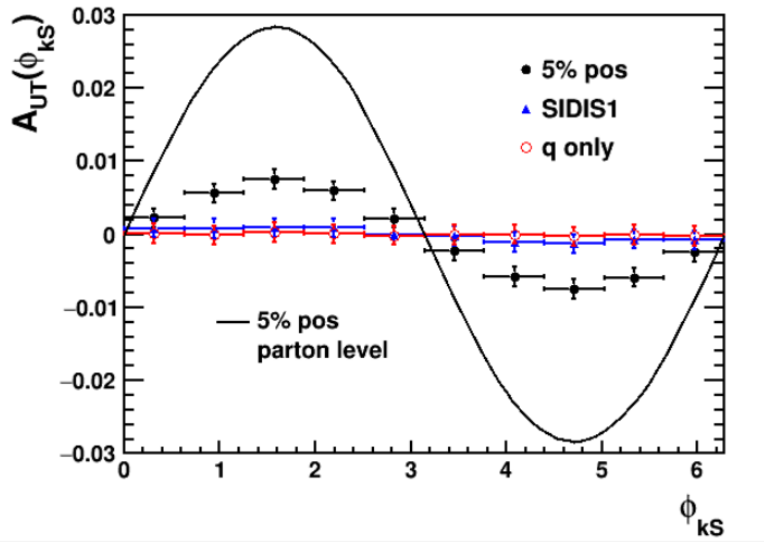


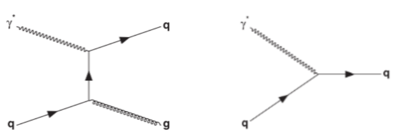
Constraint from dihadron

Kinematic cuts:
π/K/p
p_T>1.4 GeV, z_h>0.1, |η|<4.5
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





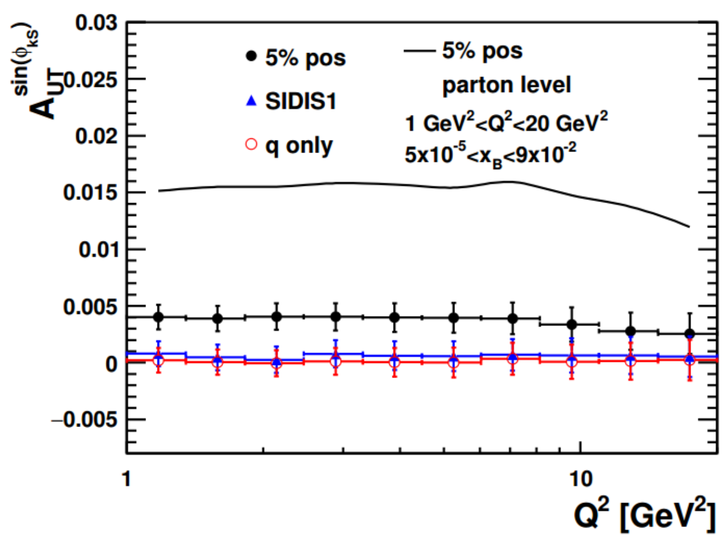


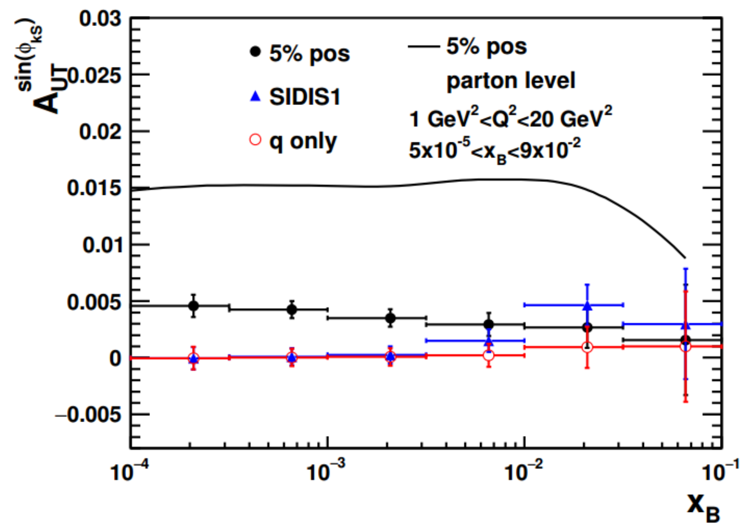
Constraint from dihadron

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

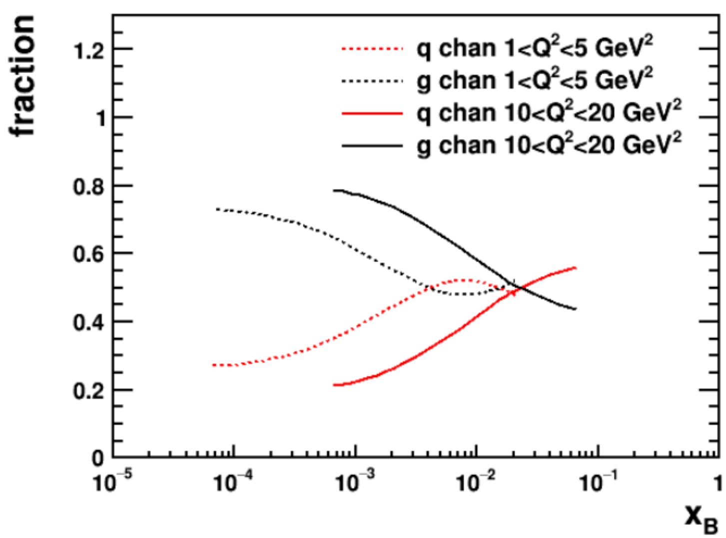


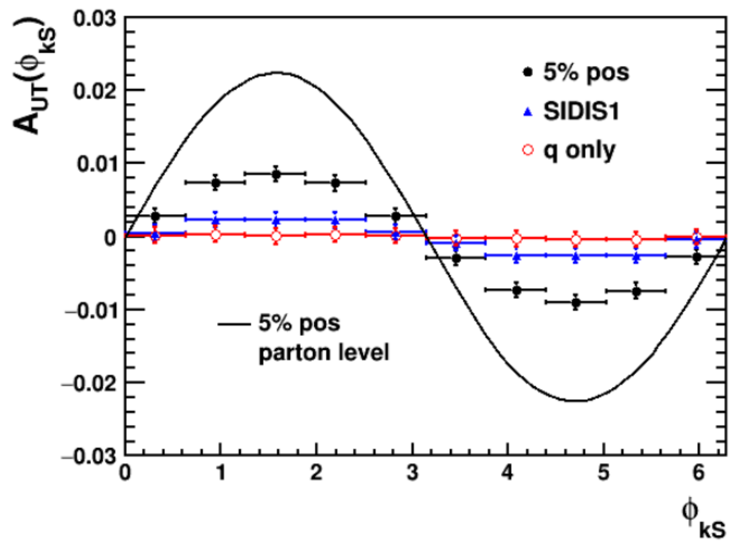


Constraint from dijet

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
$\int Ldt = 10\ fb^{-1}$

- 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

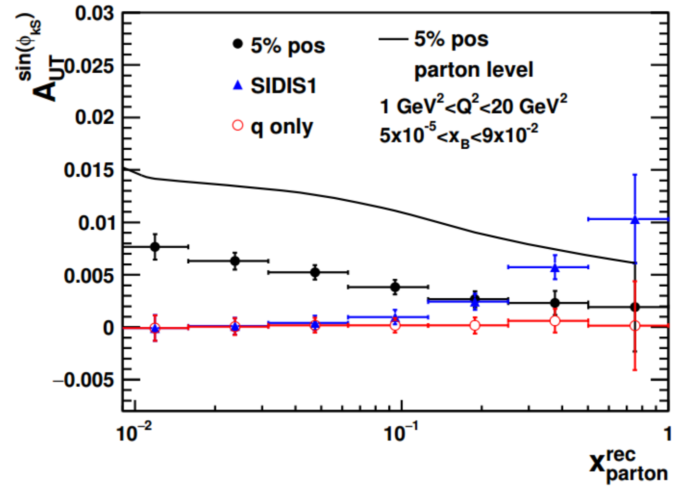


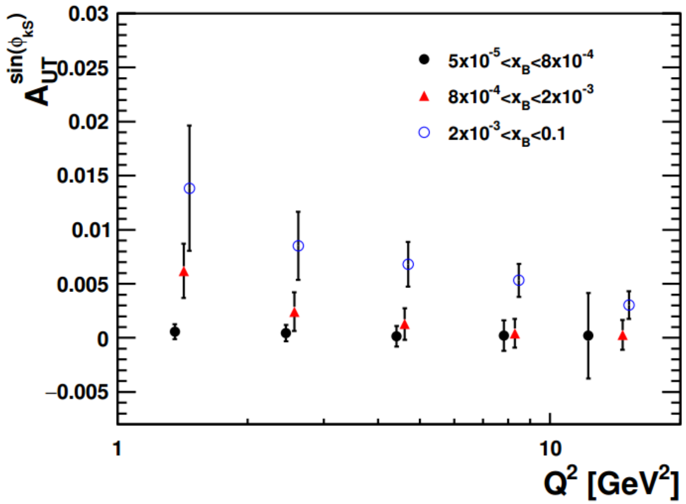


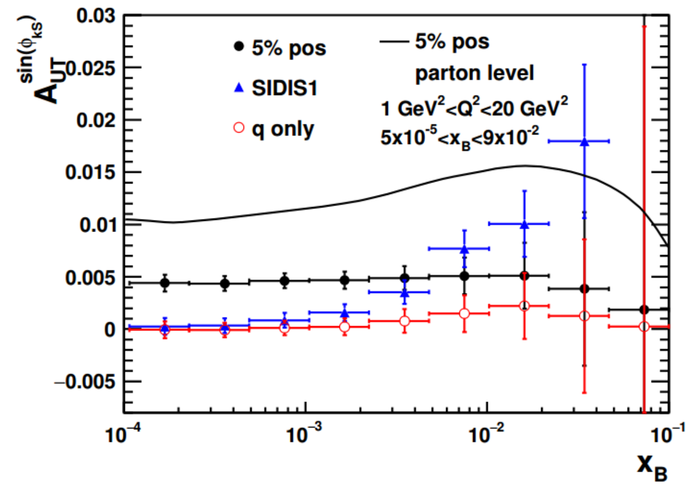
Constraint from dijet

- 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.

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







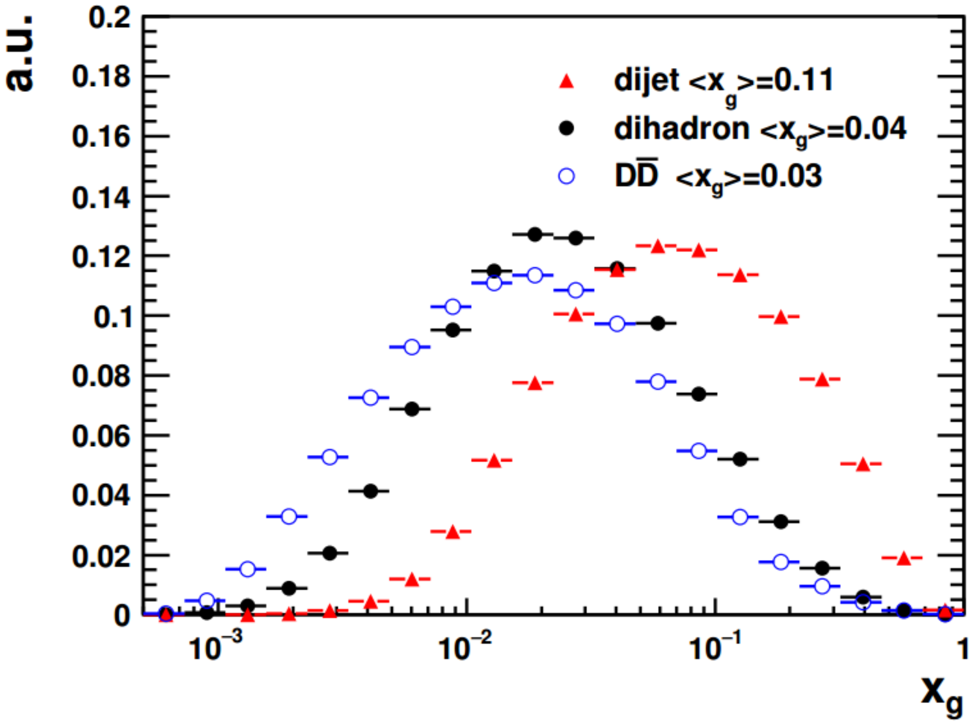
Summary

- Gluon Sivers function 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.
- Gluon Sivers extracted at EIC will be complementary to measurements in other processes.


BACKUP

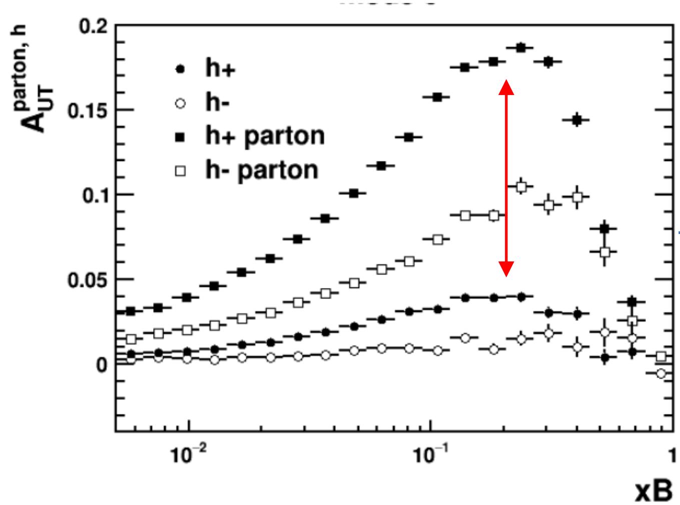
Explored x_g in different probes

Different probes at EIC can be complementary in x_g coverage.



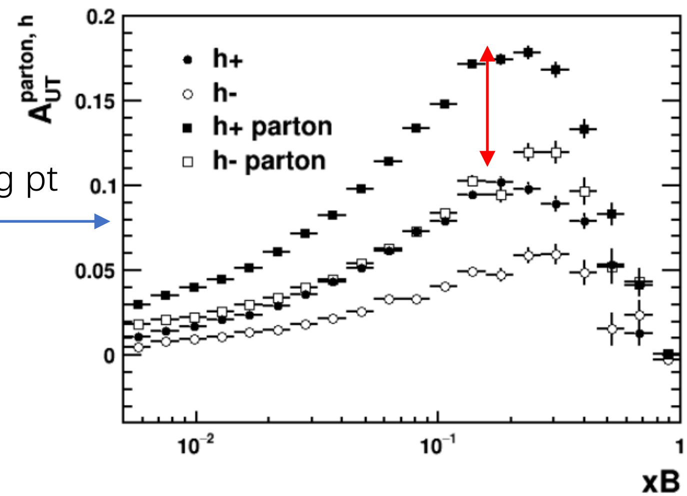
Dilution of parton level asymmetry

all on



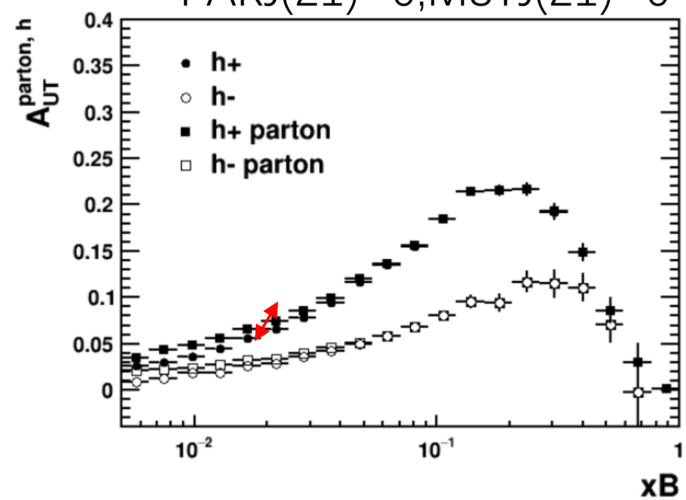
Turn off frag pt

PARJ(21)=0



Turn off decay

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

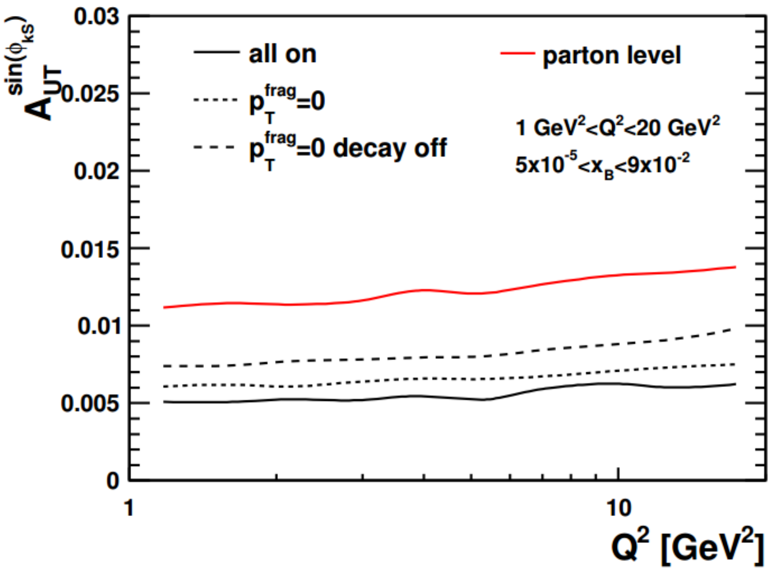


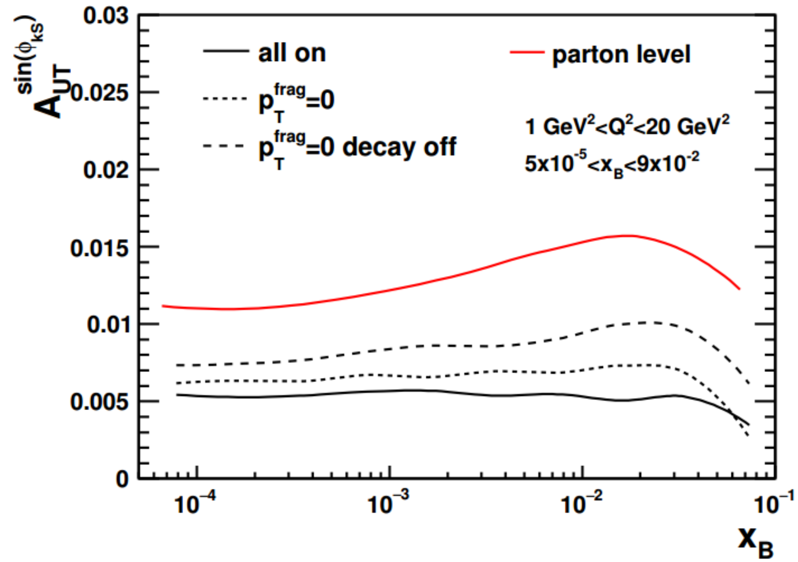
Fragmentation momenta smearing and resonance decay contribution accounts for the parton to hadron level asymmetry dilution at COMPASS energy.

Dilution of parton level asymmetry

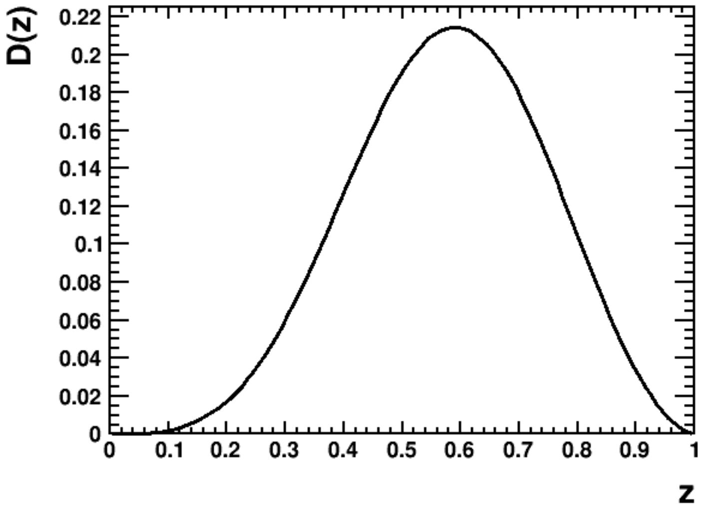
Anti-k_T, R=1
jet constituent:
p_T>250 MeV, $\pi/K/p/\gamma$, $|\eta|<4.5$
p_T^{jet1}>4.5 GeV, p_T^{jet2}>4 GeV
$\int Ldt = 10\ fb^{-1}$

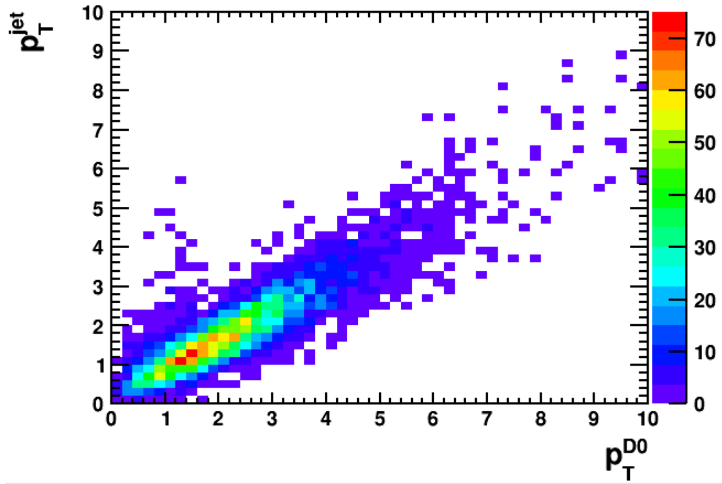
- Hadron fragmentation momentum smearing and resonance decay are important
- Other smearing effects in dijet process

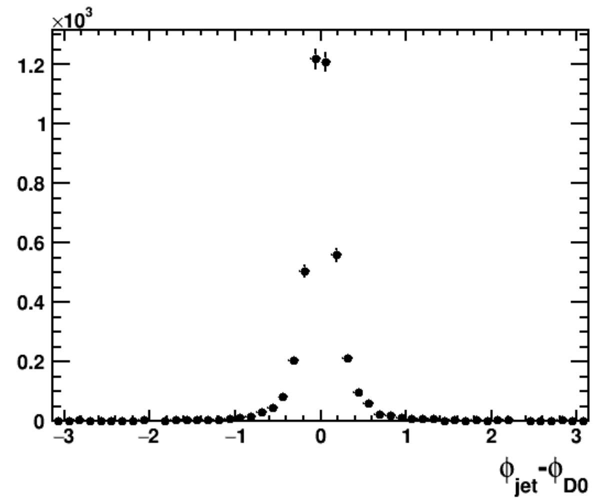




D^0 as charm quark proxy



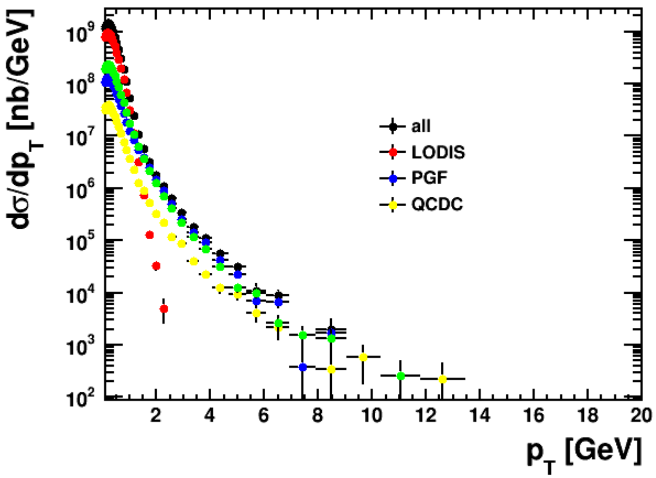


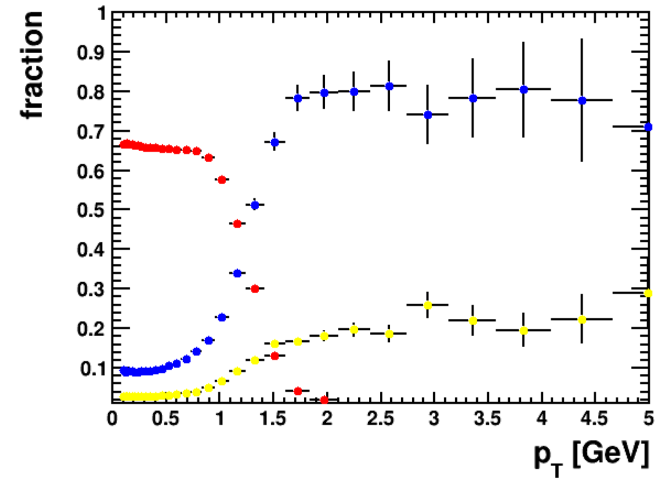


D meson takes a large fraction of the charm quark energy, serves as a proxy to the charm jet information.

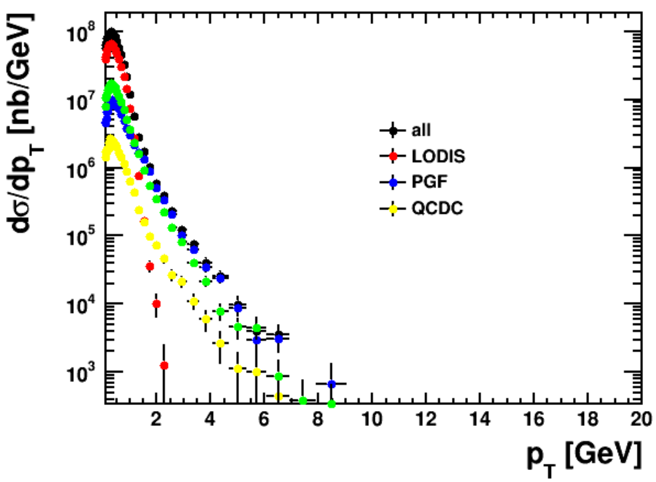
Charged hadron vs kaon spectrum

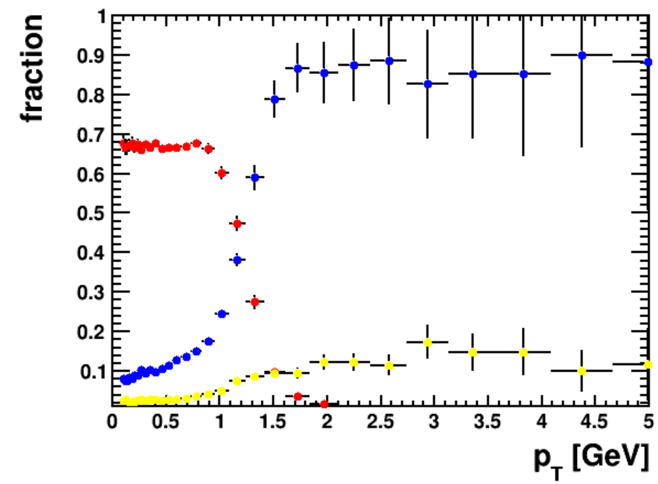
Charged hadron



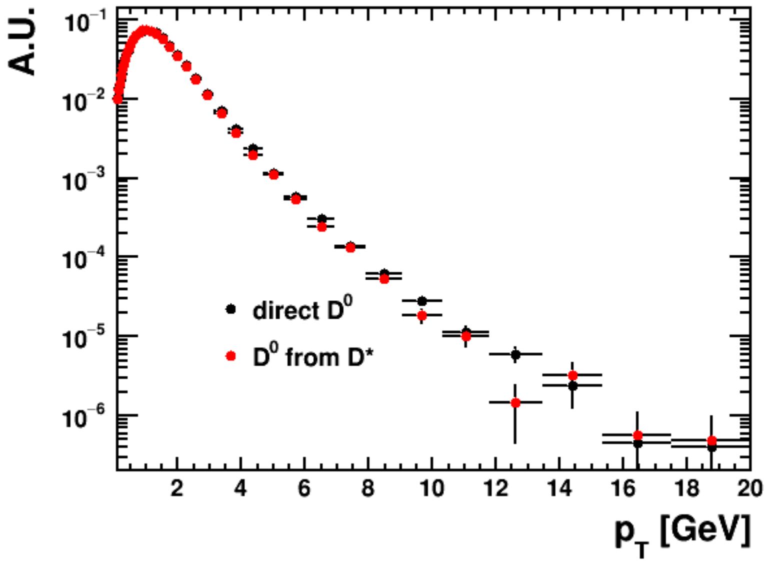


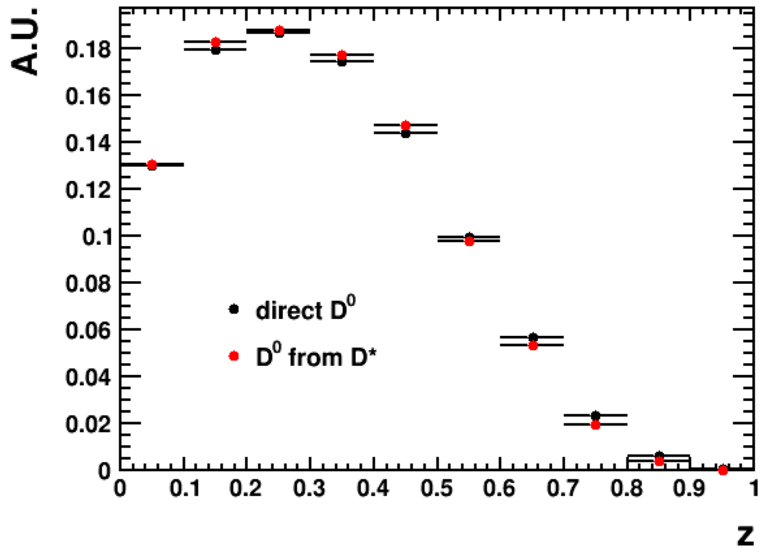
Charged Kaon





D^0 feed-down from D*

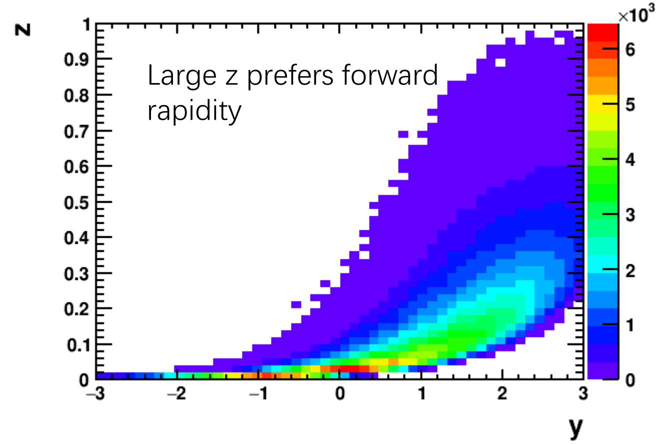


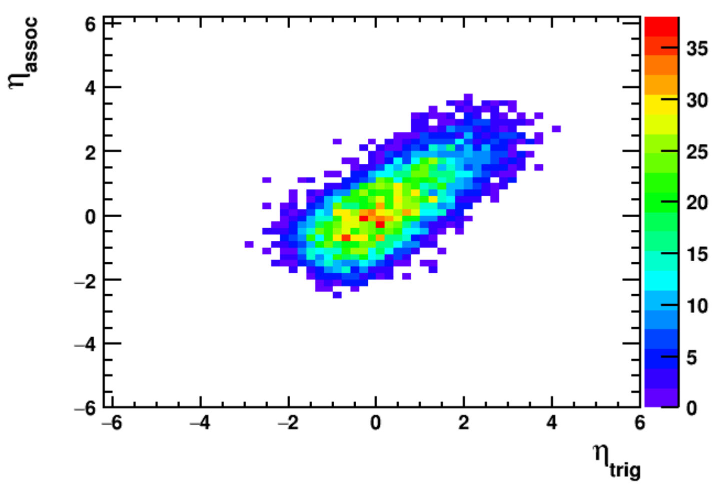


D^0 from D* decay similar to the directly generated D^0s, therefore all D^0s are analyzed.

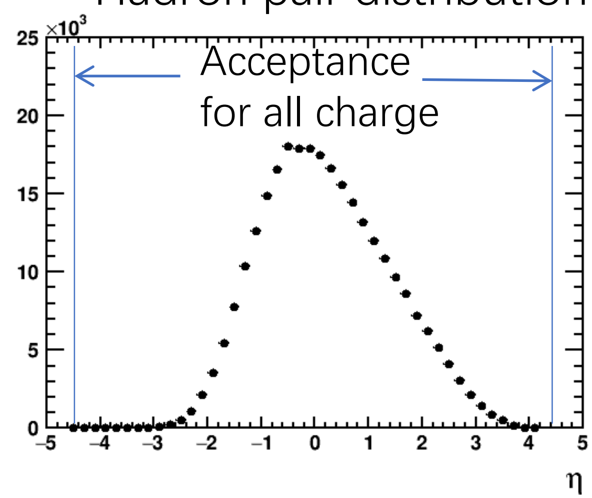
Dihadron pair selection

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



EIC Physics vs Luminosity and Energy

JLEIC high lumi detector

HERA

Ultimate eRHIC ERL

Ultimate eRHIC ERL no cooling