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

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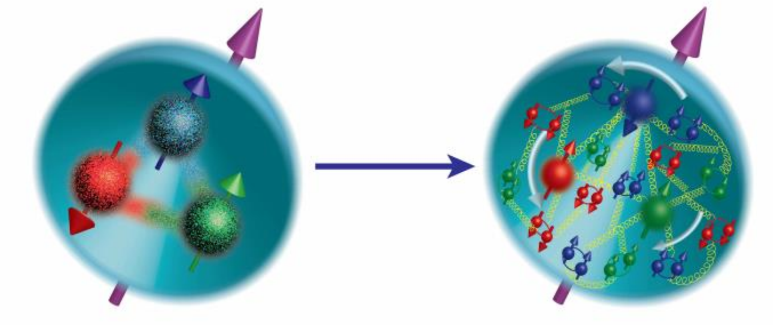
Exploring nucleon structure

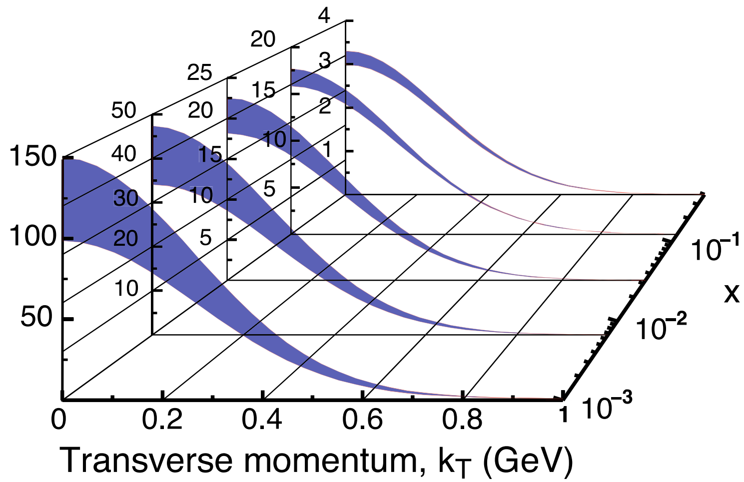
- Nucleon is a dynamical system of quarks and gluons
  - How are the partons distributed in space and momentum inside the nucleon?
  - How are these quark and gluon distributions correlated with the overall nucleon properties, such as spin direction?
  - Spin as fundamental intrinsic property and also as a mechanism to do tomography of many body system of quarks and gluons
- EIC: polarized collider to have full access to the nucleon dynamics.



2+1 D partonic image of the nucleon

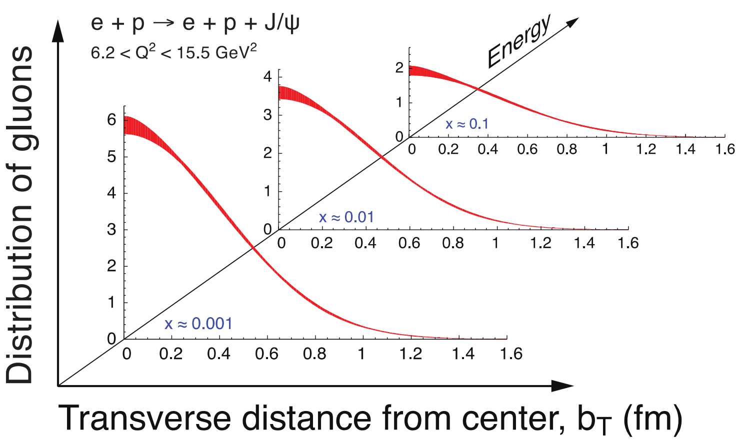
Transverse Momentum Dependent parton distributions (TMDs)

- Spin dependent 3D momentum space image
- Semi-inclusive DIS
- $f(x,k_T)$



Generalized Parton Distributions (GPDs)

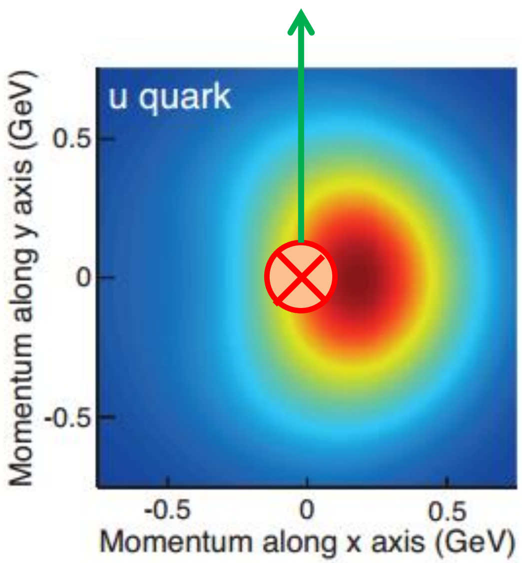
- Spin dependent 2D coordinate space (transverse) + 1D momentum space (longitudinal) image
- exclusive DIS
- $f(x,b_T)$



TMDs and Sivers function

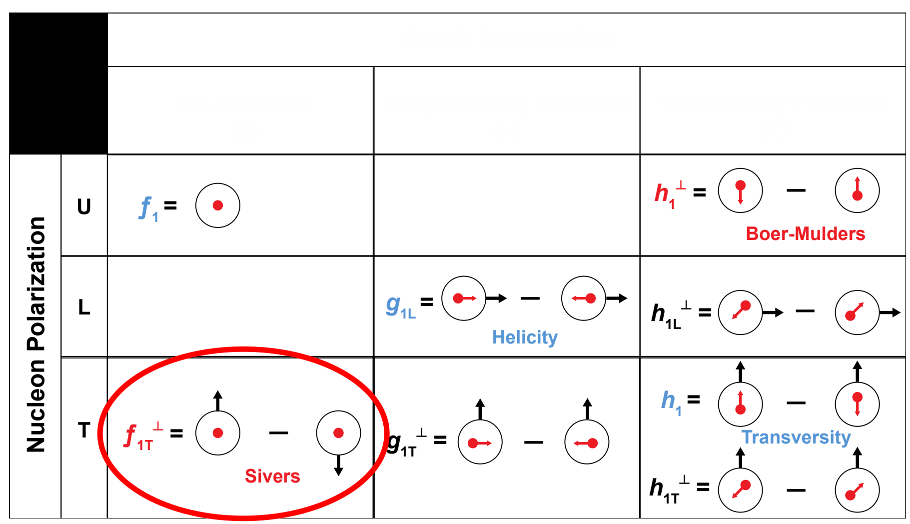
- Transverse Momentum Dependent (TMD) parton distributions provide useful tools to image the nucleon 3D structure in momentum space.
- Sivers function describes the correlation of k_T and S_T.
- Non-trivial QCD color gauge invariance.

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



Leading Twist TMDs

Nucleon Spin   Quark Spin

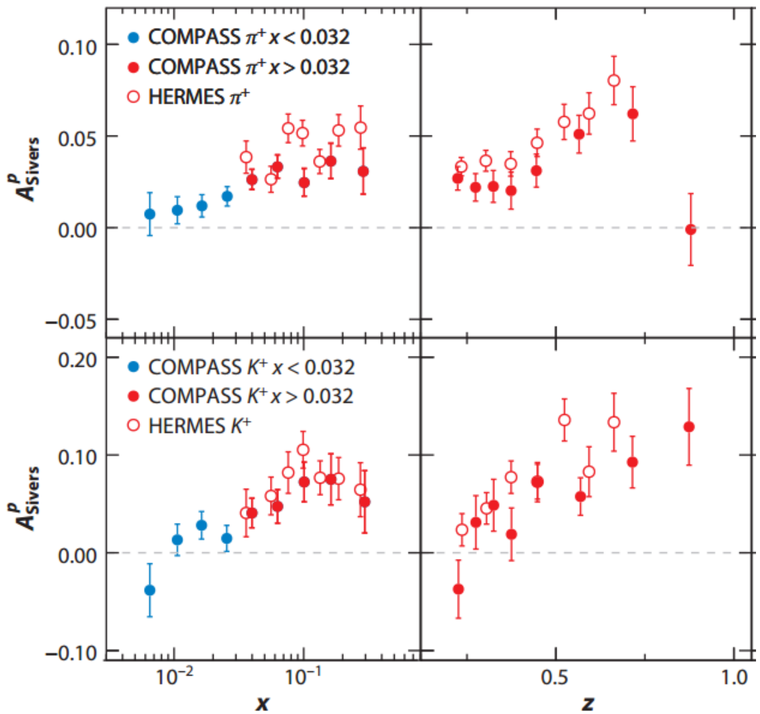


Similar for gluons

Current knowledge to quark Sivers

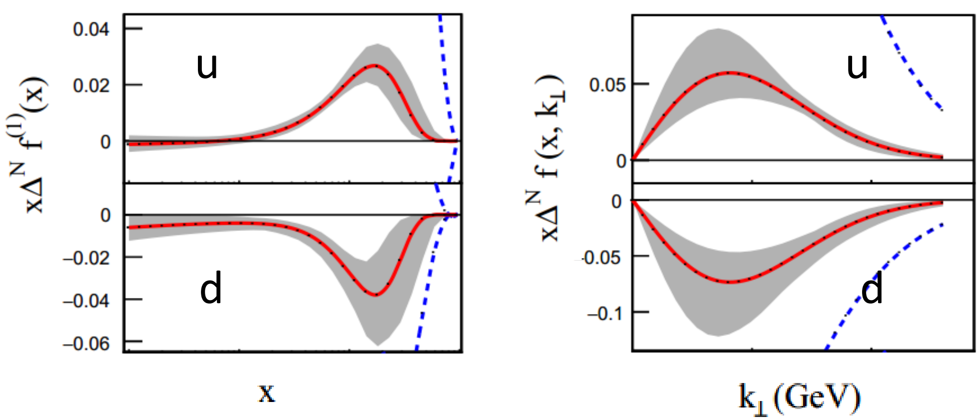
$$\frac{d\sigma}{dx\,dy\,d\phi_S\,dz\,d\phi_h\,dP_{hT}^2} \propto F_{UU,T} + |\boldsymbol{S}_\perp| \sin(\phi_h - \phi_S) F_{UT,T}^{\sin(\phi_h-\phi_S)} + \ldots$$

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



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

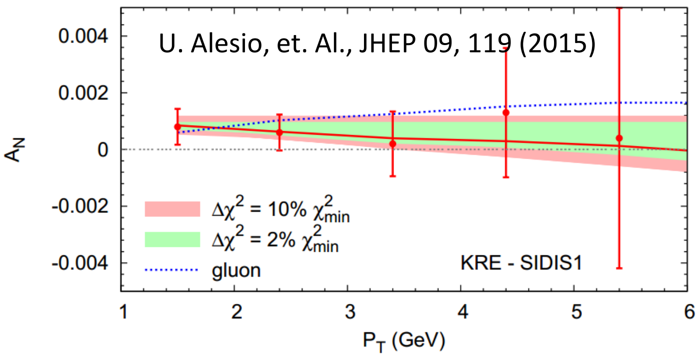
- Accessed with SIDIS measurements.
- Sizable Sivers effect.
- u, d quark Sivers with opposite sign.
- Subject to large uncertainty.

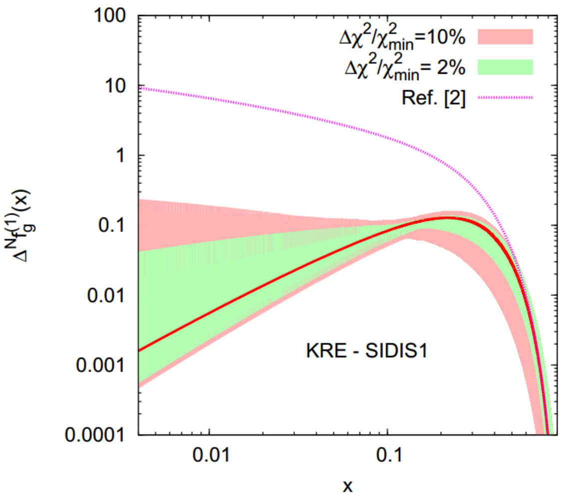


JHEP 04(2017) Anselmino et. al.

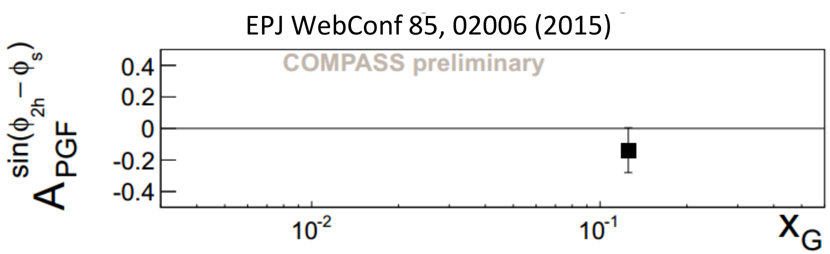
Current constraints on gluon Sivers

Extraction based on A_N data at RHIC





Extraction on COMPASS data

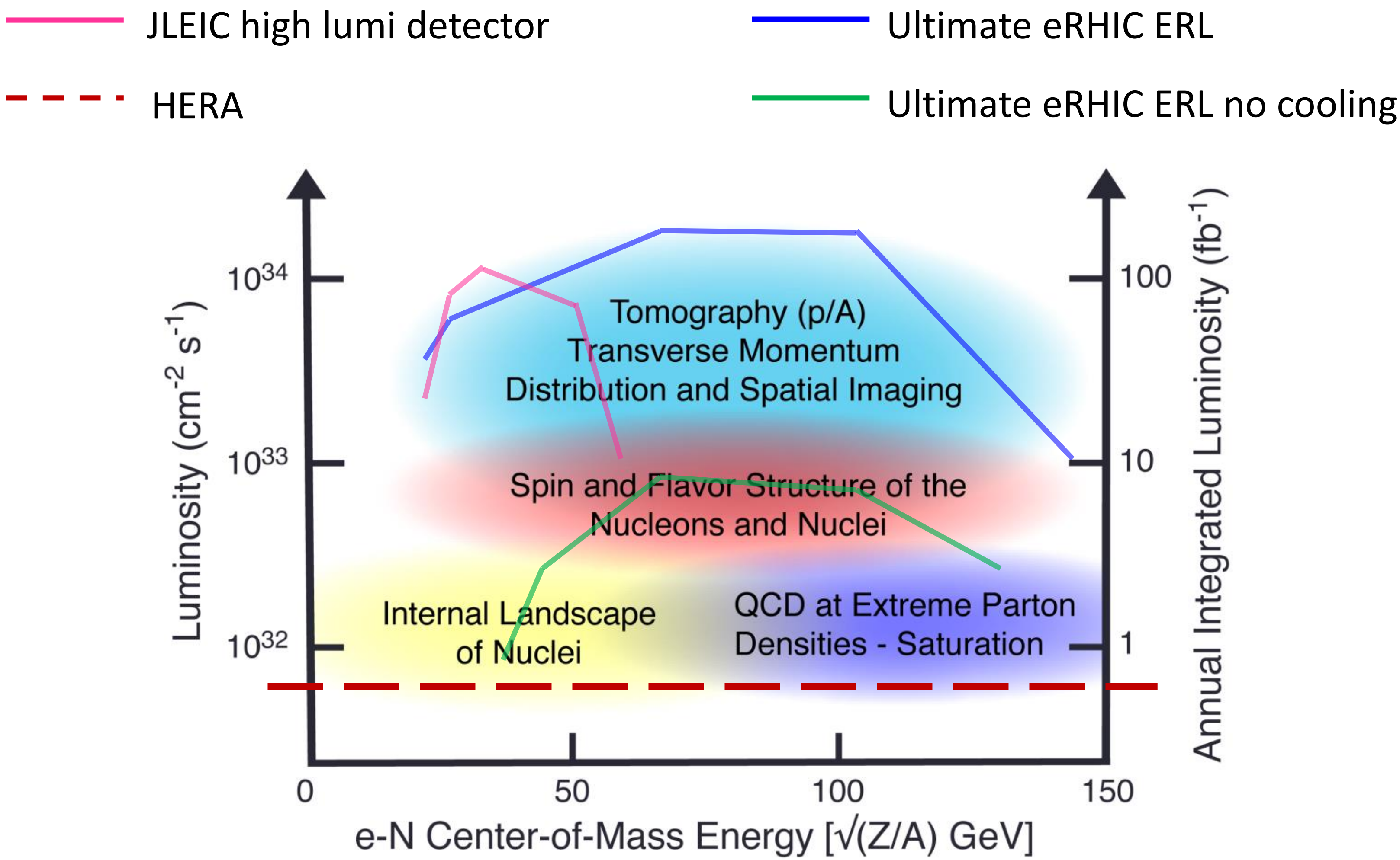


$$A_{PGF}^{\sin(\phi_{2h}-\phi_S)} = -0.14 \pm 0.15(\text{stat.})$$

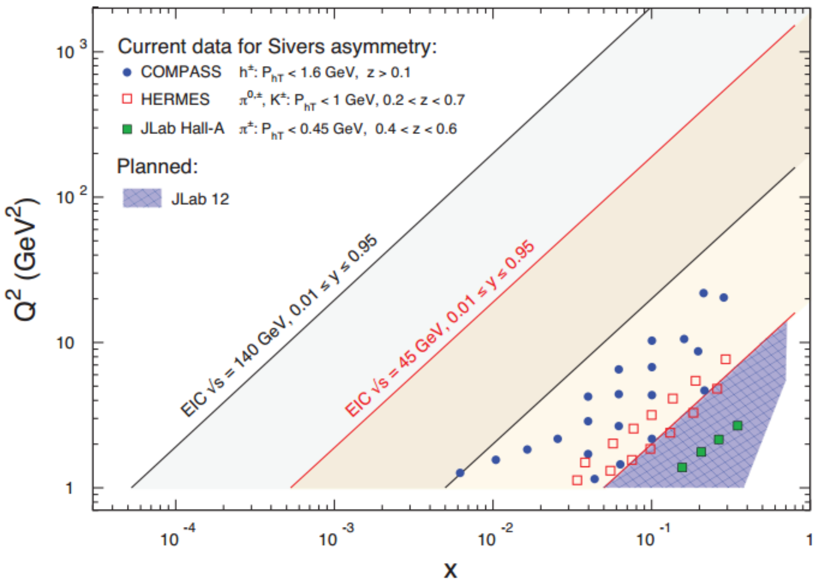
$$\langle x_G \rangle = 0.126$$

- 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.

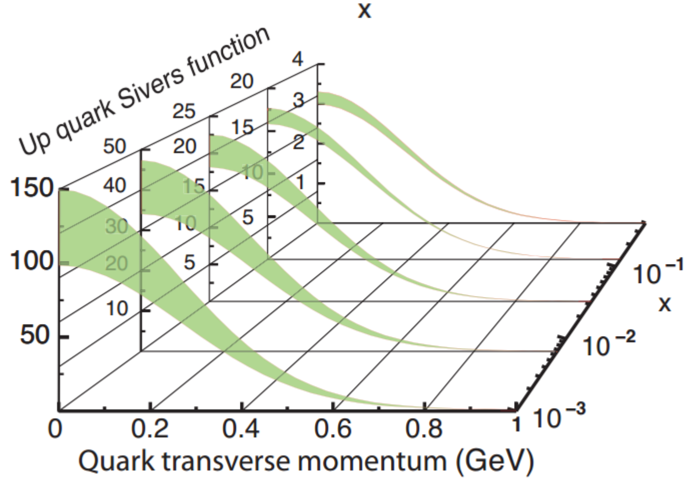
EIC Physics vs Luminosity and Energy



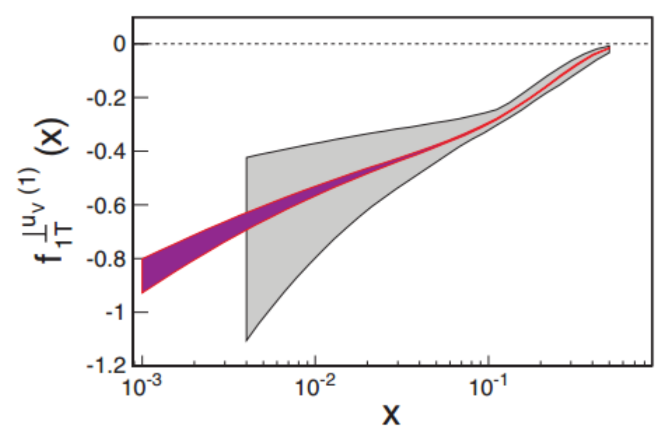
Studying Sivers in the EIC era



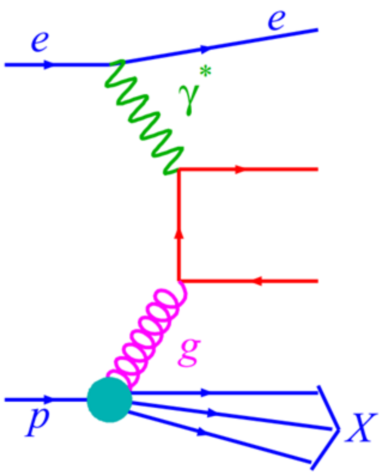
- Disentangle Sivers and Collins asymmetries.
- Extend the current Sivers data to smaller x.
- Large Q^2, x, coverage to pin down TMD evolution.

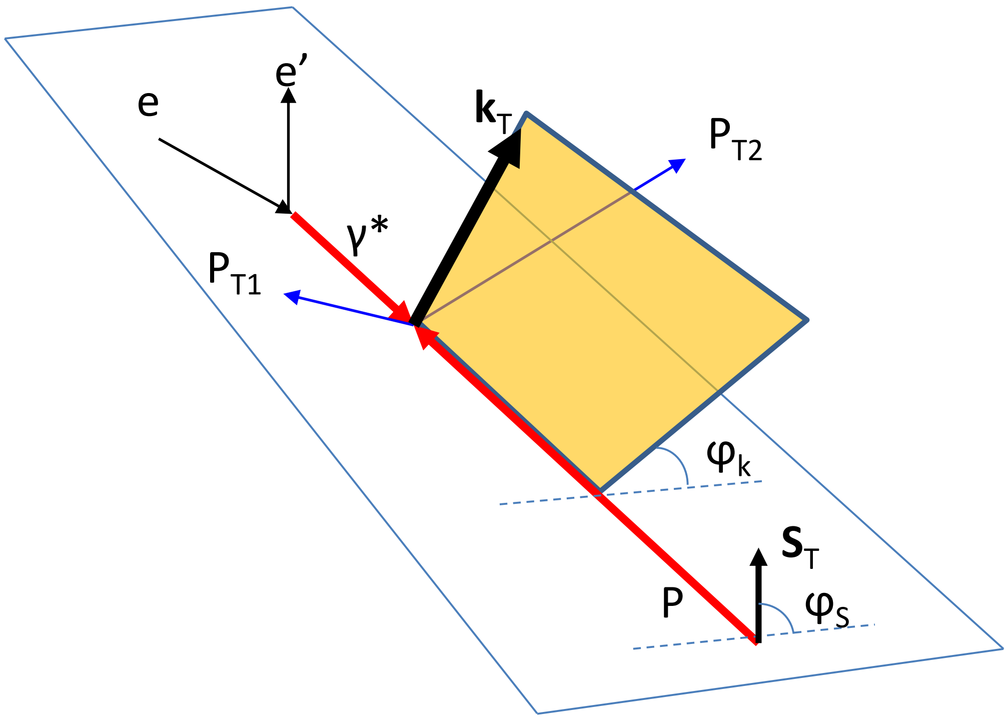


Quark Sivers before and after EIC



Accessing gluon Sivers at EIC





s: center-of-mass energy squared

***Q*²**: resolution power

***x*_B**: the fraction of the nucleon's momentum carried by the struck quark (0<x<1)

y: inelasticity

Treatable single spin asymmetry (SSA) sensitive to gluon Sivers

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

Inputs to the model calculation

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

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

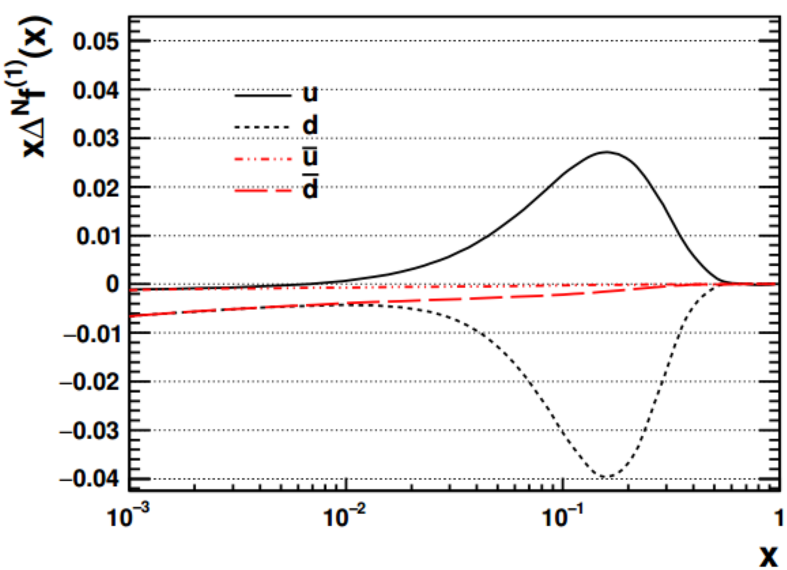
$$A_{UT} = R_g \frac{\Sigma_i^{N_g} w_i}{N_g} + R_q \frac{\Sigma_i^{N_q} w_i}{N_q}$$

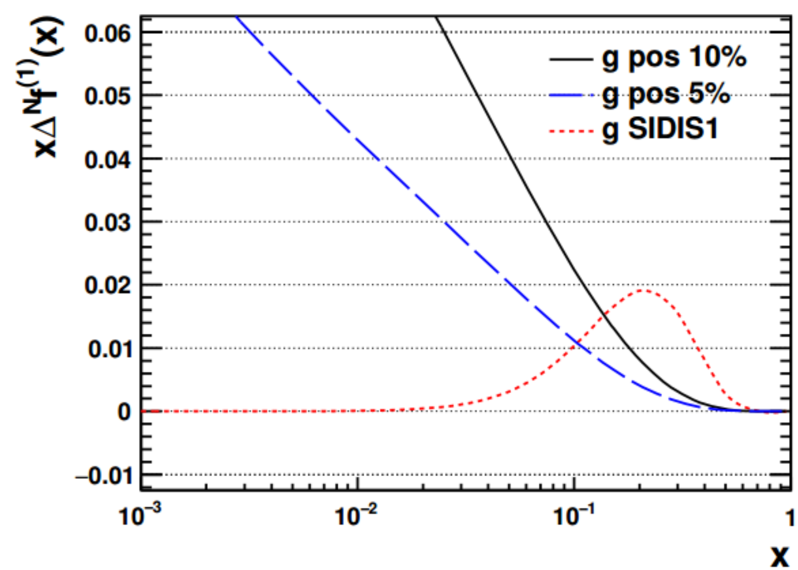
Quark Sivers: JHEP 04(2017) Anselmino et. al.
u and d quarks

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

Positivity bound ansatz:

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



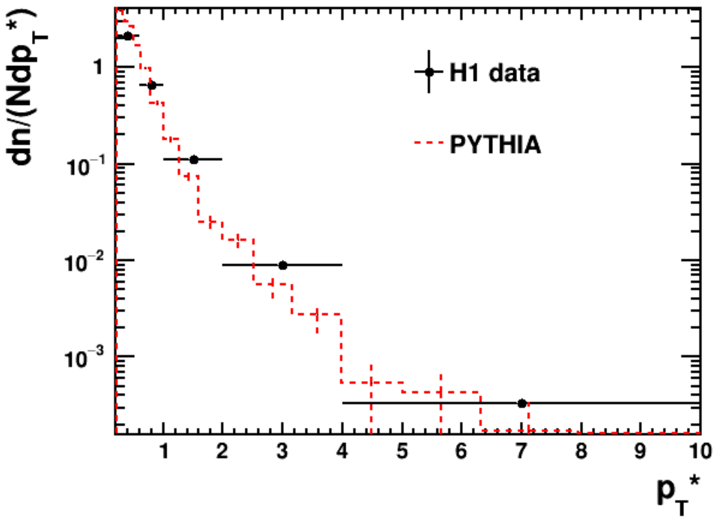


Confronting simulation with Data

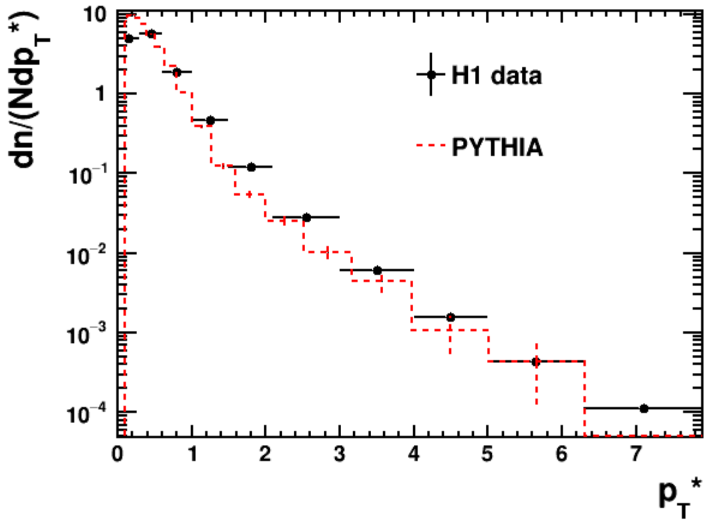
Comparing with charged hadron density measurements from HERA

Kinematics:
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

$0<\eta^*<1.5$



$1.5<\eta^*<5$

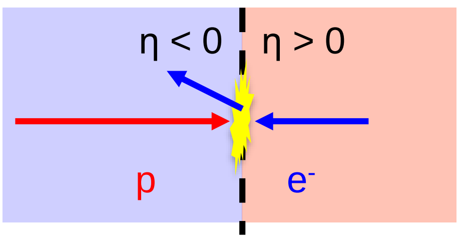


Data from EPJC 73, 2406 (2013)

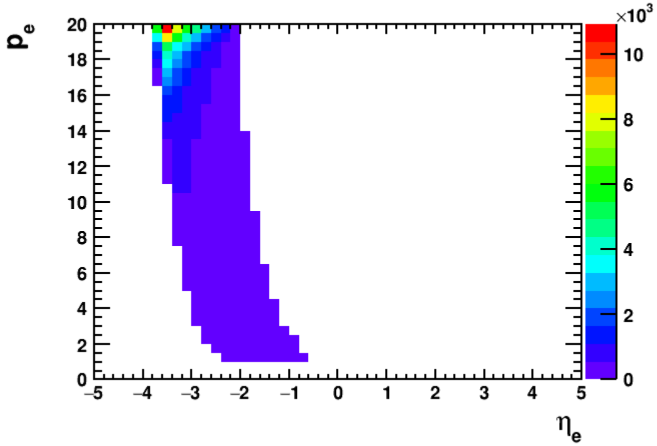
H1 charged particle density data reasonably described by simulations.

EIC setup for gluon SSA study

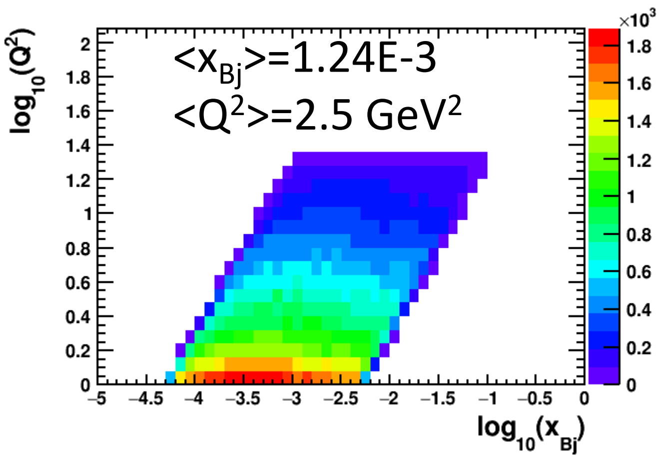
Kinematics:
$ep^{\uparrow}$ 20x250 GeV
$\sqrt{s}$=141 GeV
0.01<y<0.95
$1<Q^2<20$ GeV^2

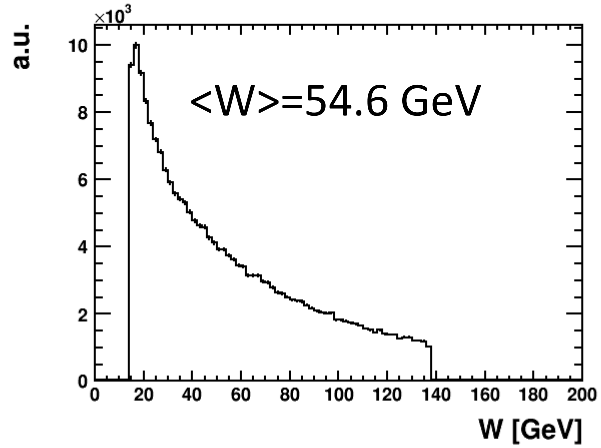


Scattered electron



Final state observables
1. D^0 pair
2. Charged hadron pair
3. Dijet pair





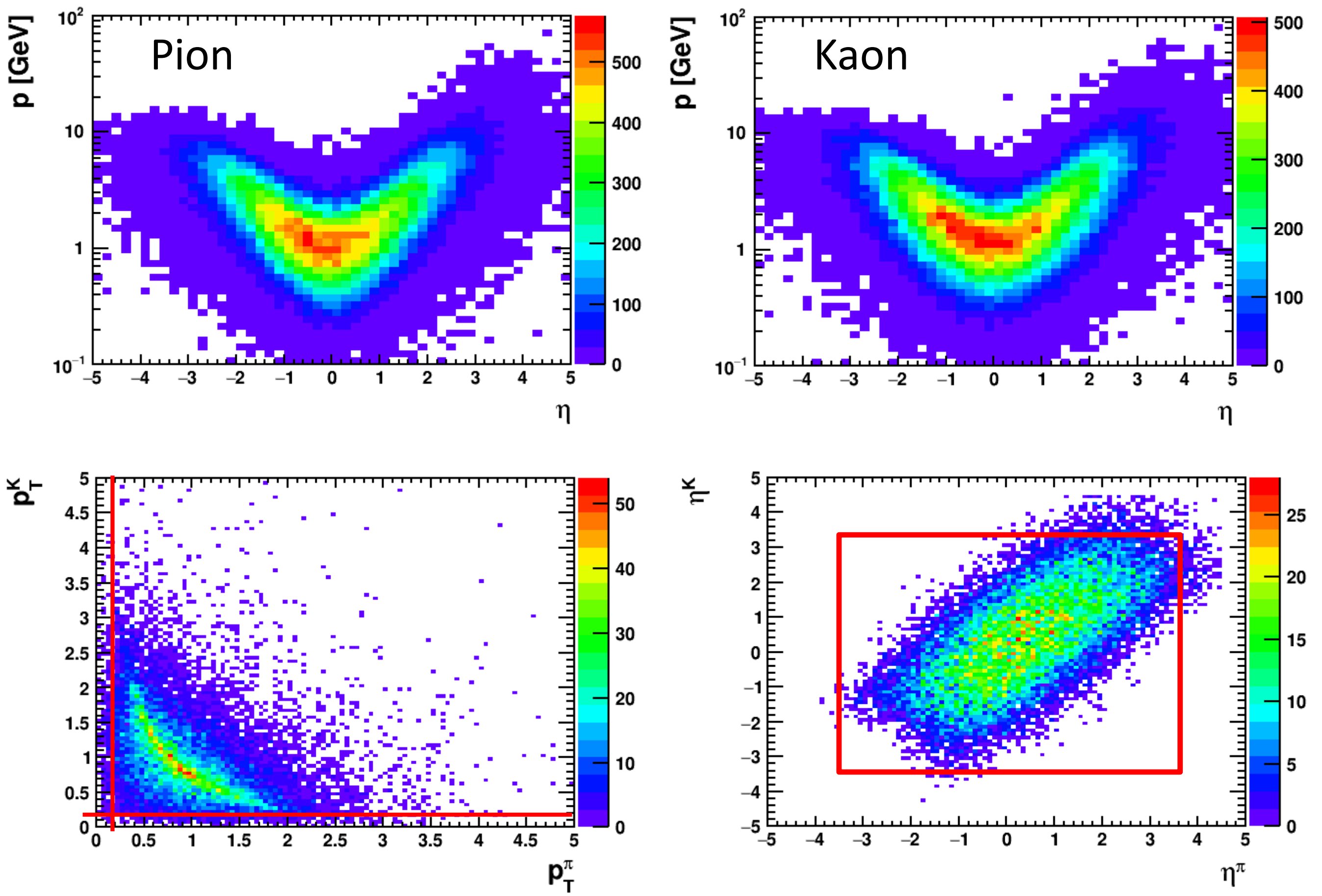
D meson pair selection

Branching ratio: 3.9%

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

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

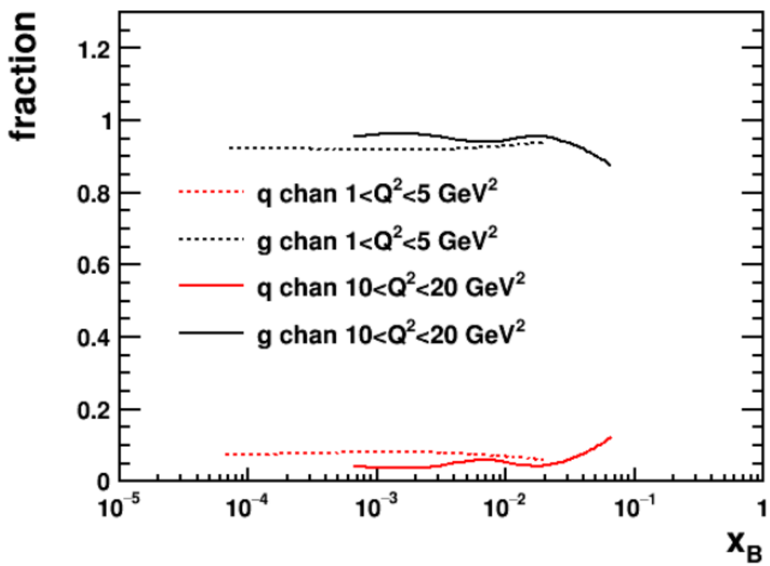
- Acceptance for PID is assumed to be |η|<3.5
- Decay products from D mesons are mostly less than 10 GeV in mid-rapidity.
- Decay products p_T>0.2 GeV.

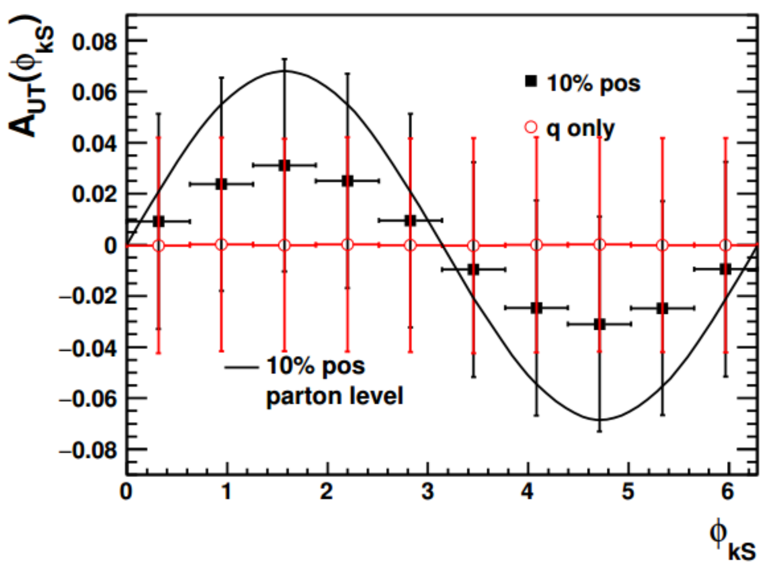


Projections for the SSA with open charm probe

$ep^{\uparrow}$ 20x250 GeV
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, $z^D>0.1$
$\int Ldt = 10\ fb^{-1}$

- Gluon initiated events account for 90% of D meson production
- D can be regarded as a good parton kinematics proxy
- Statistics not enough to resolve the gluon Sivers level even on 10% positivity bound

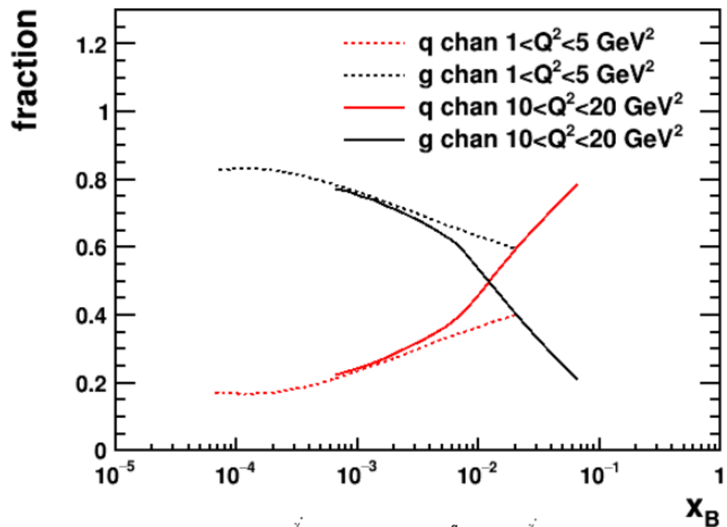


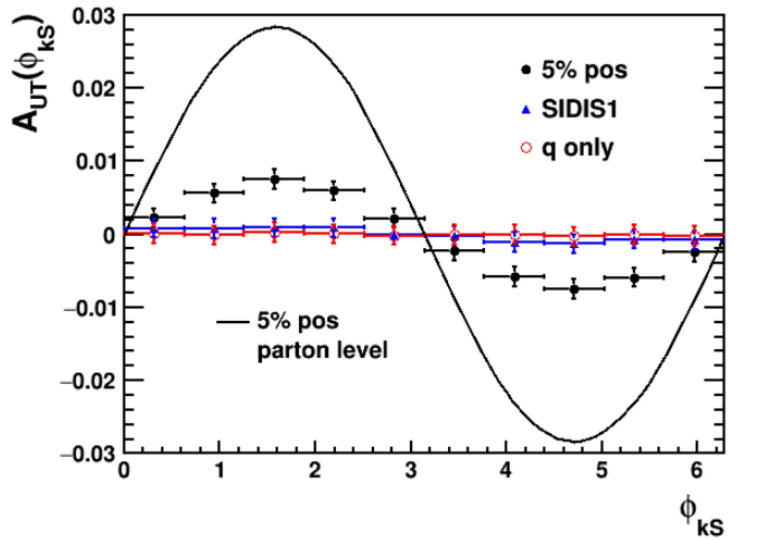


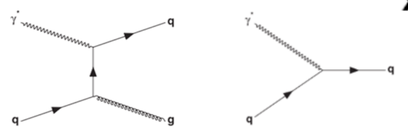
Projections on the SSA with charged dihadron probe

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: $k_T' < 0.7P_T'$
$\int Ldt = 10\ fb^{-1}$

- Gluon initiated process account for a large fraction of events at small x_B
- Smear to parton level asymmetry becomes stronger
- Statistically more favored than open charm, resolve 5% positivity bound gluon Sivers size





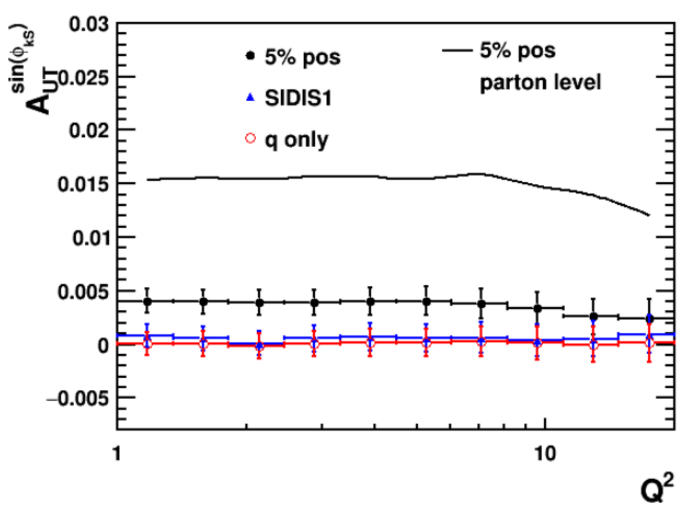


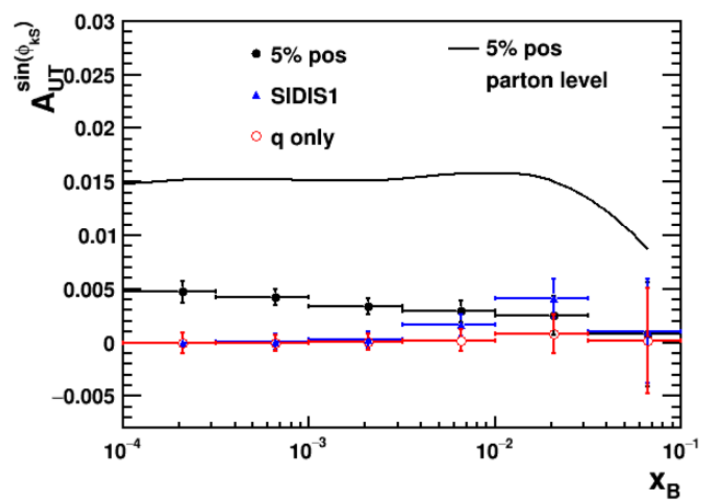
Projections on the SSA with charged dihadron probe

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 xB, Q2 can be identified with 5% positivity bound
- Clearer sense of direction to distinguish model discrepancy in x_B behavior
- No significant Q^2 trend as missing TMD evolution.

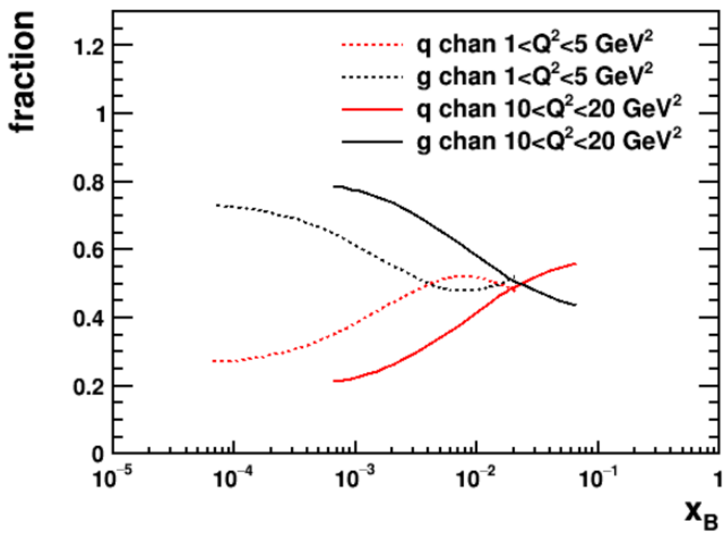


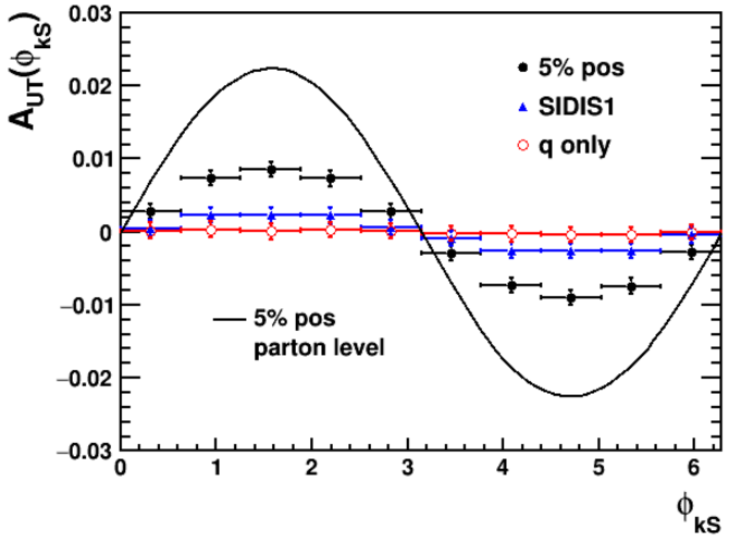


Projections on the SSA with dijet probe

Kinematic cuts:
ep 20x250 GeV
$0.01<y<0.95$
$1<Q^2<20$ GeV^2
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}

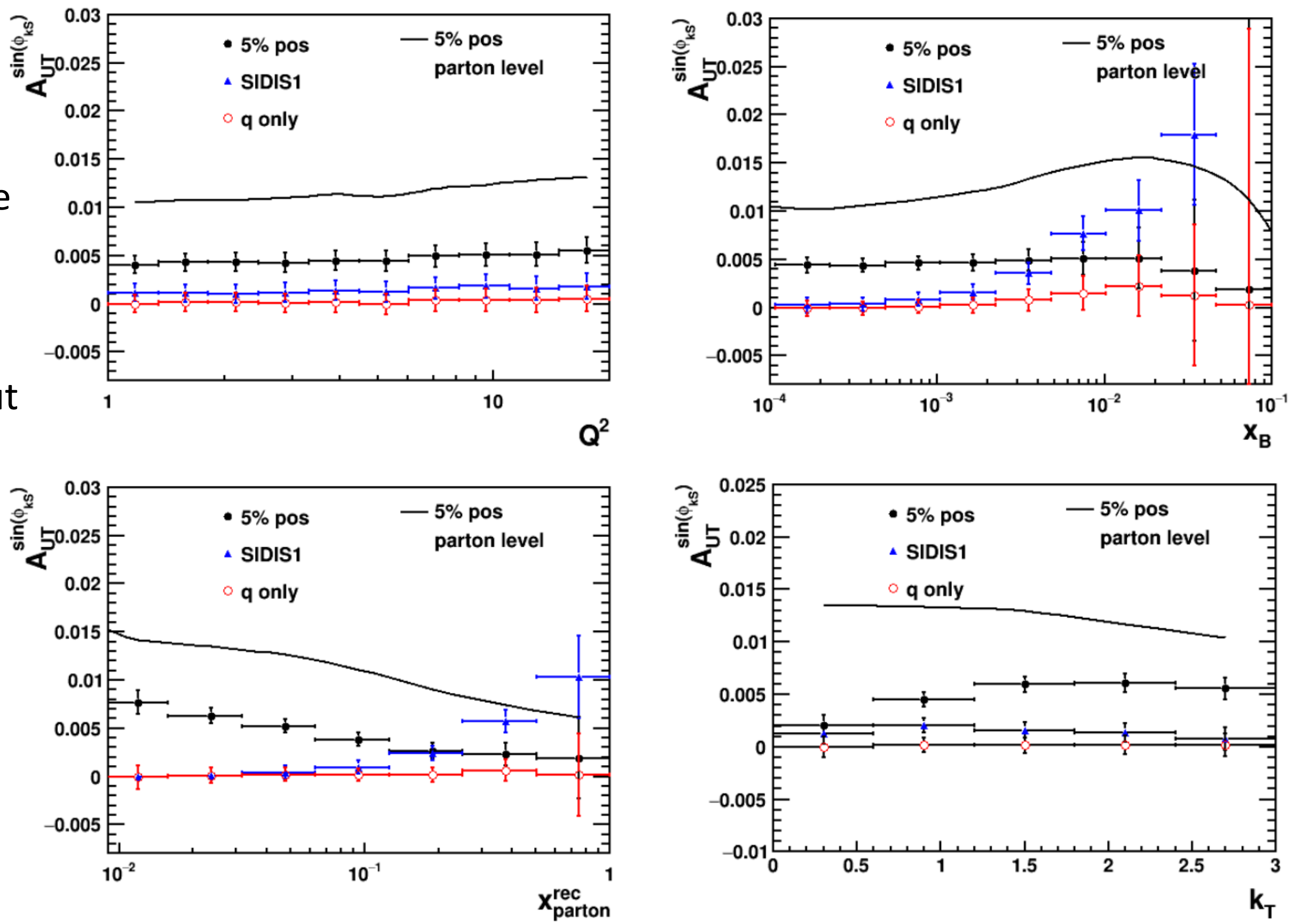
- Gluon initiated process still dominant at small x_B
- Stronger final state observable to parton kinematics correlation
- Resolution down to 5% positivity bound gluon Sivers size





Projections on the SSA with dijet probe

- SSA amplitude can be analyzed in multiple dimensions.
- Direct handle on parton kinematics put stronger constraint such as x_{parton}

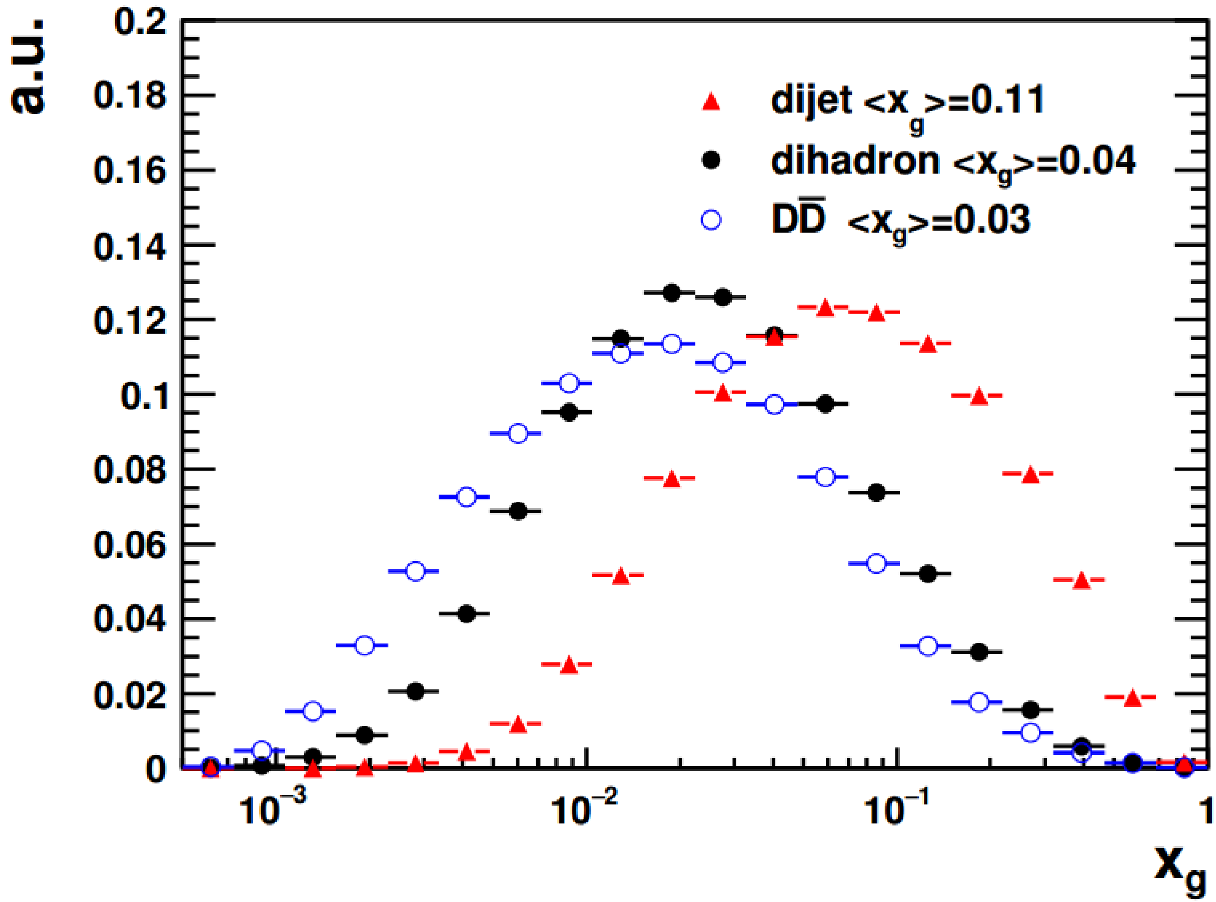


Summary

- 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.
- Charged dihadron and dijet methods are more statistically favored compared to the open charm production.
- Different probes can be complementary to each other at EIC.

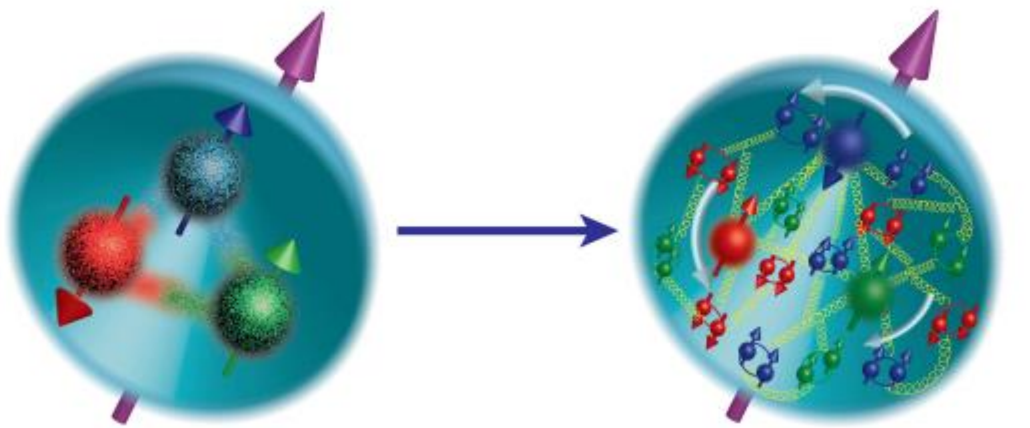

BACKUP

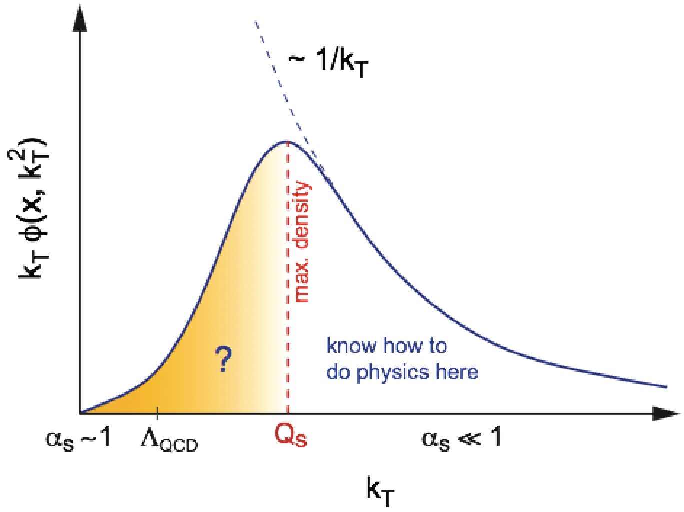
Explored x_g in different probes



Nucleon structure and Sivers function

- Collisions on the hadronic objects as incoherent superposition off partonic constituents.
- TMD framework provides a useful tool to image the nucleon structure in 2+1D momentum space.





Accessing Sivers in SIDIS

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

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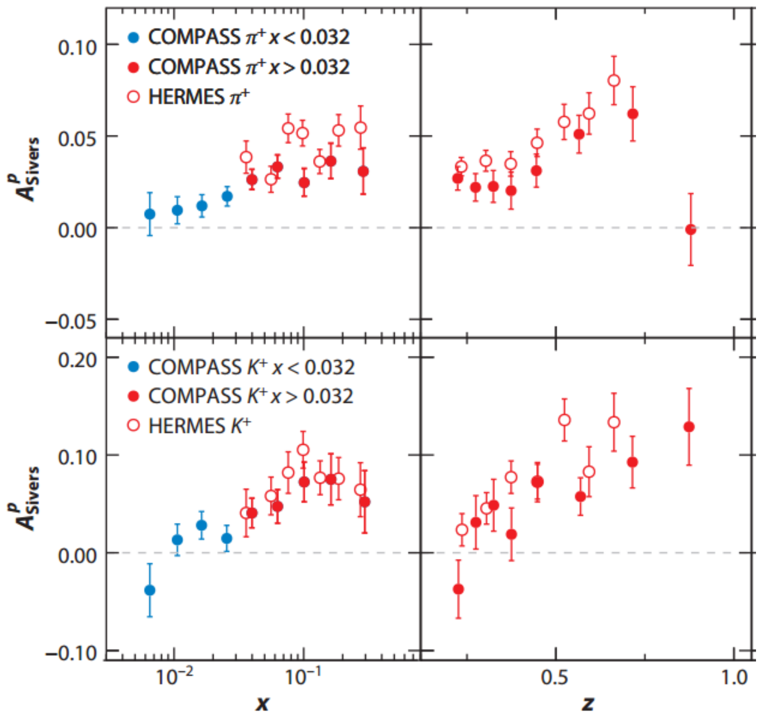
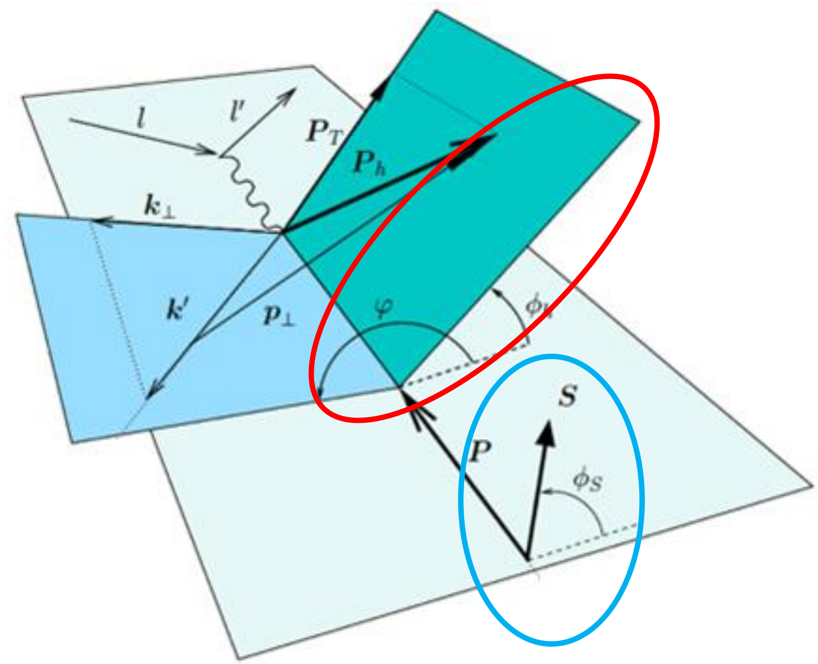




PRL 103, 152002 (2009) HERMES data
PLB 717, 383 (2012) COMPASS data

Accessing gluon Sivers at EIC

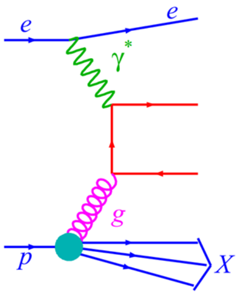
$$\hat{f}_{a/p^\uparrow}(x,k_\perp) = f_{a/p}(x,k_\perp) - f_{1T}^{\perp a}(x,k_\perp)\frac{\vec{S}\cdot(\hat{\vec{P}}\times\vec{k}_\perp)}{M_p}$$

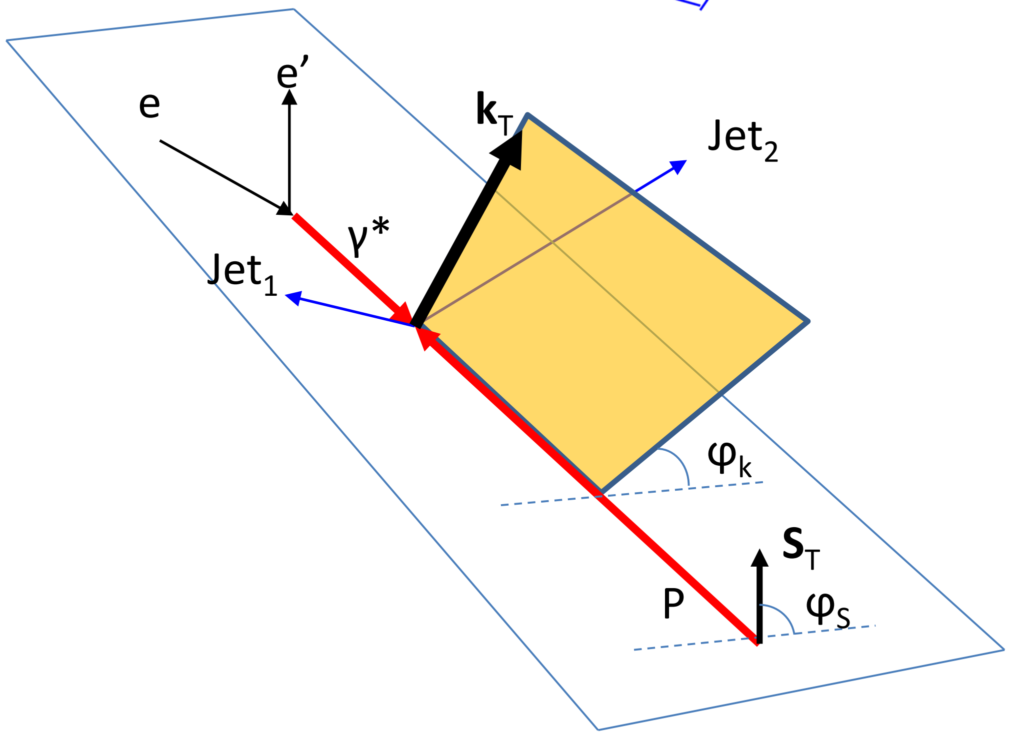
$$\Delta^N f_{a/p^\uparrow}(x,k_\perp) = -\frac{2k_\perp}{M_p} f_{1T}^{\perp a}(x,k_\perp)$$

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

$$\mathcal{N}_a(x) = N_a x^{\alpha_a}(1-x)^{\beta_a}\frac{(\alpha_a+\beta_a)^{(\alpha_a+\beta_a)}}{\alpha_a^{\alpha_a}\beta_a^{\beta_a}}$$

$$h(k_\perp) = \sqrt{2e}\,\frac{k_\perp}{M}\,e^{-k_\perp^2/M^2}$$





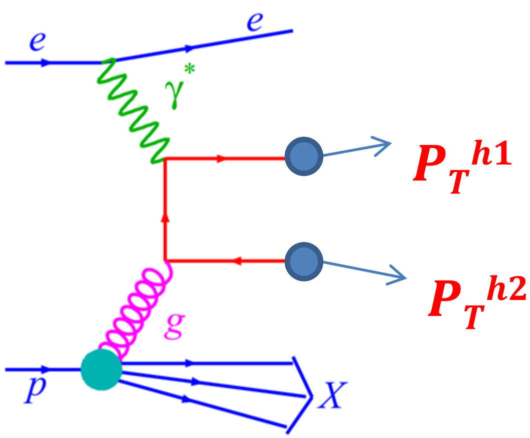
Treatable single spin asymmetry (SSA) sensitive to gluon Sivers

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

Accessing gluon Sivers at an EIC

$$\frac{d\sigma_{\rm tot}^{\gamma^*+p^\uparrow\to h_1+h_2+X}}{dz_{h1}dz_{h2}d^2p_{h1\perp}d^2p_{h2\perp}} = C\int_{z_{h1}}^{1-z_{h2}}\sum_q dz_q \frac{z_q(1-z_q)}{z_{h2}^2 z_{h1}^2} d^2p_{1\perp}d^2p_{2\perp}\hat{f}_{g/p^\uparrow}(x_g,k_\perp)$$

$$\times\,\mathcal{H}_{\rm tot}^{\gamma^* g\to q\bar{q}}(z_q,k_{1\perp},k_{2\perp})e_q^2 D_{h1/q}(\tfrac{z_{h1}}{z_q},p_{1\perp})D_{h2/\bar{q}}(\tfrac{z_{h2}}{1-z_q},p_{2\perp})$$



Treatable single spin asymmetry (SSA) sensitive to gluon Sivers

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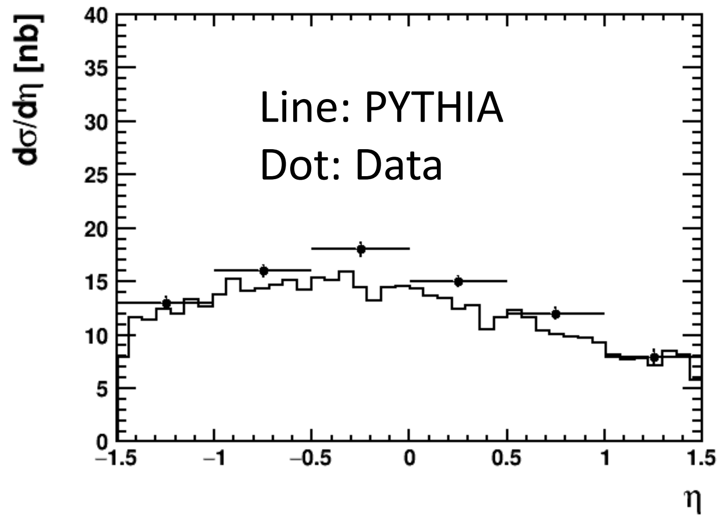
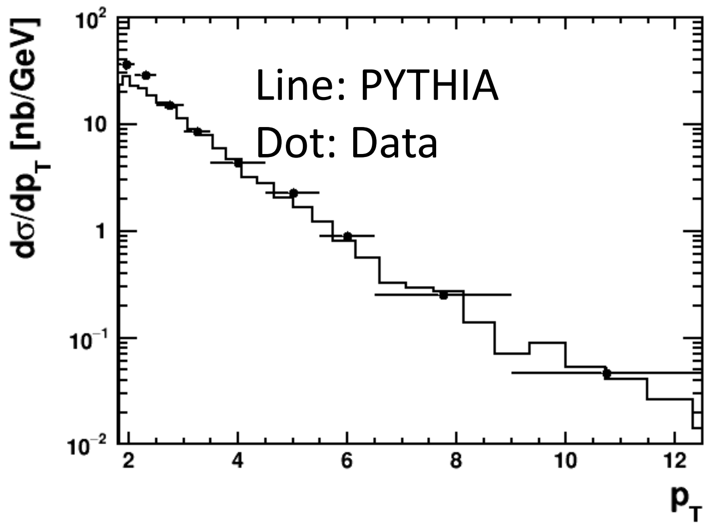
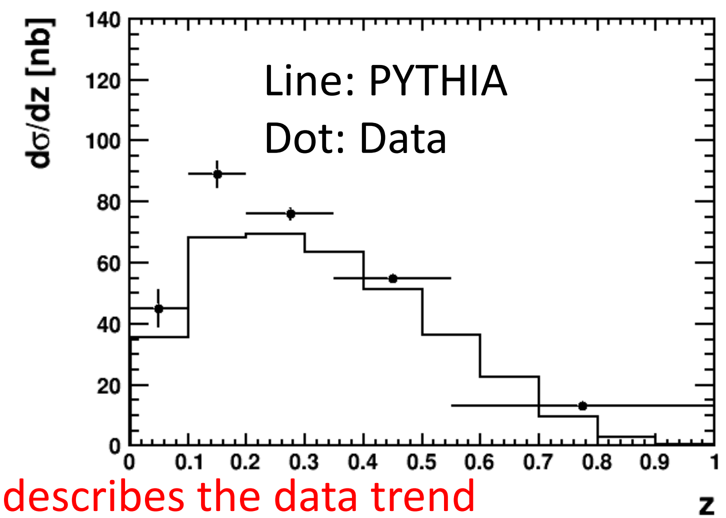
PYTHIA confronted with HERA data

Data taken from: EPJC 72, 1995 (2012)

Comparing with D* measurements from HERA
ep 27.6 GeV x 920 GeV
Q^2<2 GeV^2, 100<W<285 GeV, |η|<1.5
p_T, η defined in gamma-hadron center of mass frame



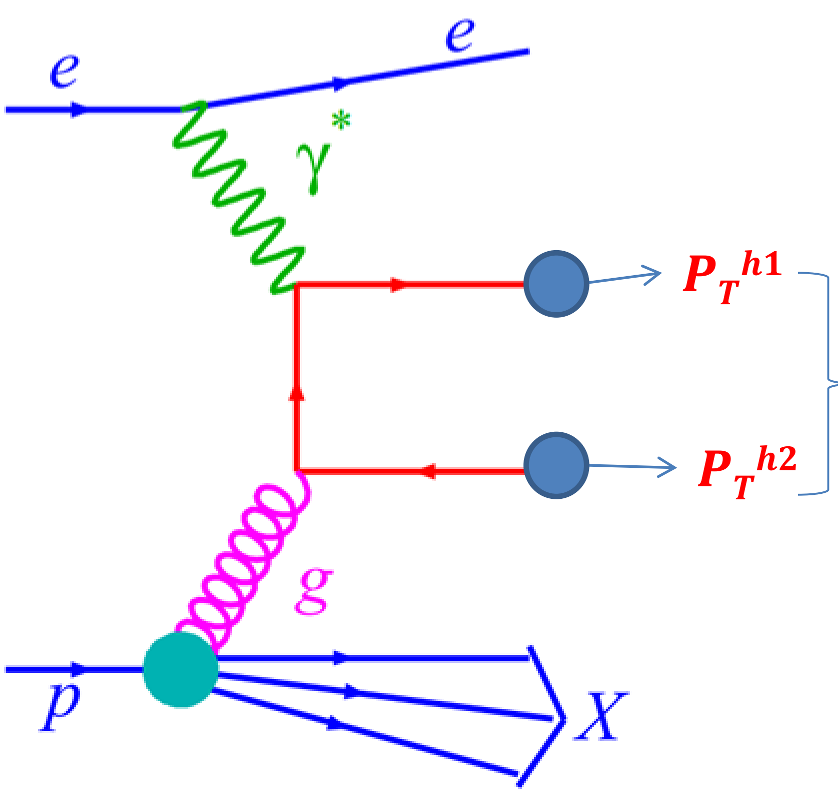




Simulation describes the data trend reasonably.

Accessing gluon dynamics DIS collisions

Photon-Gluon Fusion (PGF)



1. Tag photon-gluon fusion events.
2. Find back-to-back hadron pairs from the quark-antiquark jet.
3. Reconstruct the gluon dynamics with the hadron pair information.

Gluon information can be extracted with the hadron pairs from the quark-antiquark jet.

Back-to-back limit:

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

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

$k_T' << P_T'$

Theoretical framework for the model calculation

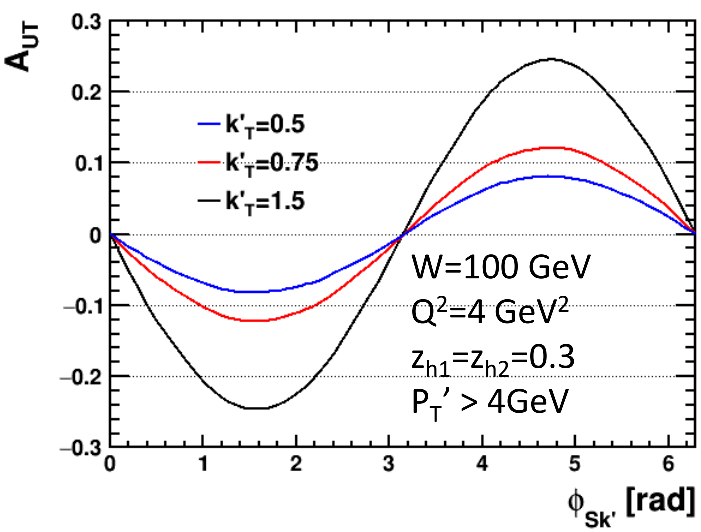
$$\frac{d\sigma_{\rm tot}^{\gamma^*+p^\uparrow\to h_1+h_2+X}}{dz_{h1}dz_{h2}d^2p_{h1\perp}d^2p_{h2\perp}} = C\int_{z_{h1}}^{1-z_{h2}}\sum_q dz_q \frac{z_q(1-z_q)}{z_{h2}^2 z_{h1}^2} d^2p_{1\perp}d^2p_{2\perp}\hat{f}_{g/p^\uparrow}(x_g,k_\perp)$$

$$\times\mathcal{H}_{\rm tot}^{\gamma^* g\to q\bar{q}}(z_q,k_{1\perp},k_{2\perp})e_q^2 D_{h1/q}(\tfrac{z_{h1}}{z_q},p_{1\perp})D_{h2/\bar{q}}(\tfrac{z_{h2}}{1-z_q},p_{2\perp})$$

$$\hat{f}_{a/p^\uparrow}(x,k_\perp) = f_{a/p}(x,k_\perp) - f_{1T}^{\perp a}(x,k_\perp)\frac{\vec{S}\cdot(\hat{\vec{P}}\times\vec{k}_\perp)}{M_p}$$

$$f_{1T}^{\perp a}(x,k_\perp) = \frac{2\sigma M_p}{k_\perp^2+\sigma^2}f_1^g(x,k_\perp)$$

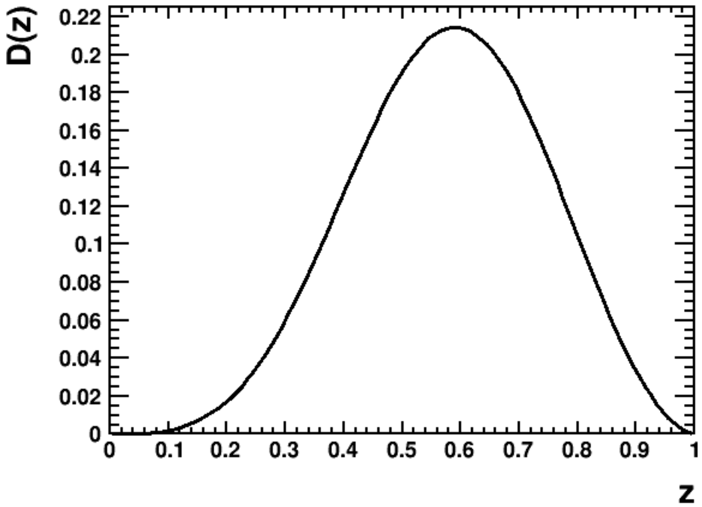
$$A_{UT} = \frac{d\sigma^\uparrow - d\sigma^\downarrow}{d\sigma^\uparrow + d\sigma^\downarrow} \propto \frac{\Delta^N f_{g/p^\uparrow}(x,k_\perp)}{f_1^g(x_g,k_\perp)}$$

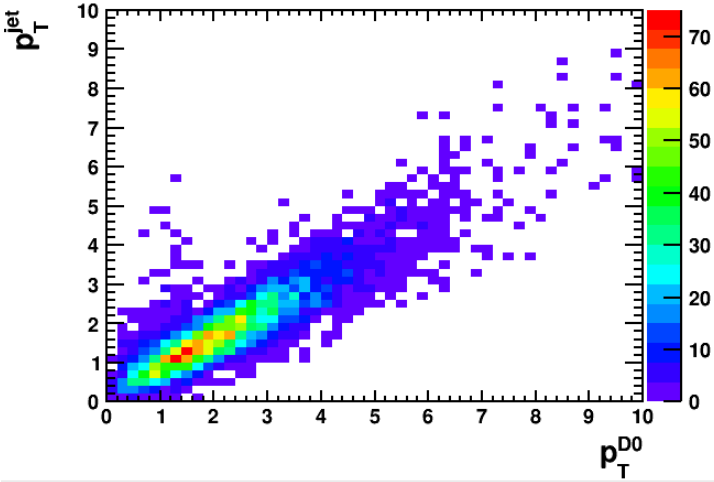


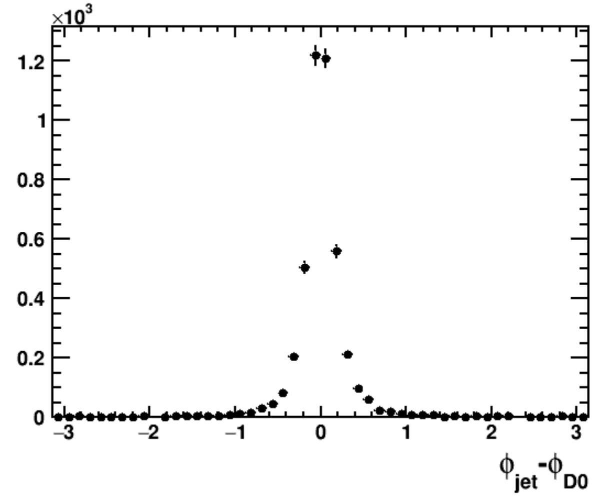
- A negative gluon Sivers saturating the positivity bound is assumed.
- Stronger asymmetry size observed for larger k_T'.

$$\phi_{Sk'} = \phi_S - \phi_{k'_T}$$

D^0 as charm quark proxy



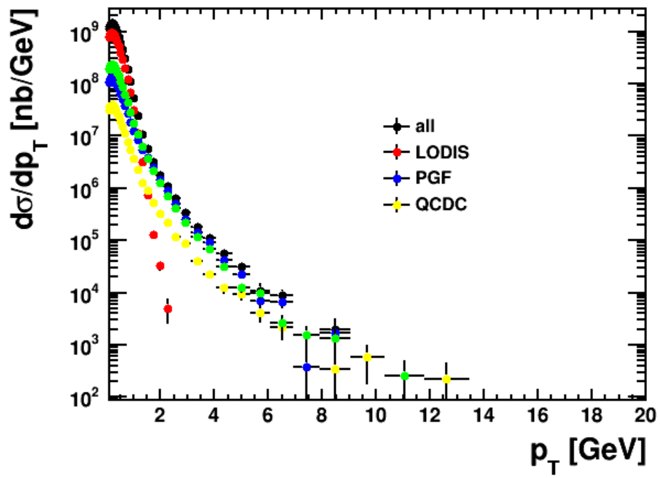


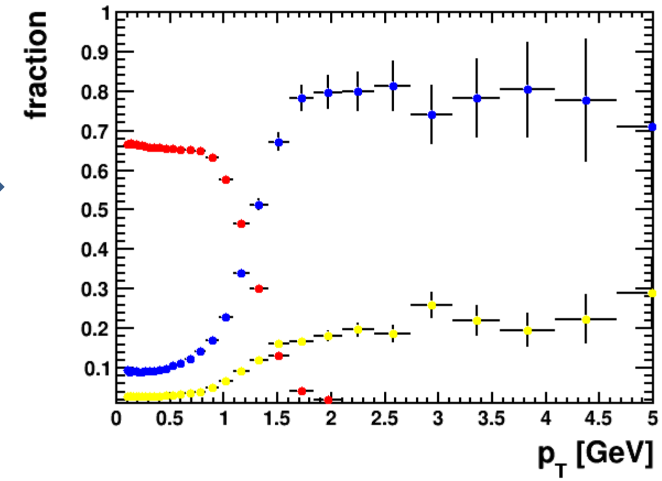


D meson takes a large fraction of the charm quark energy, serves as a proxy to the charm jet information.

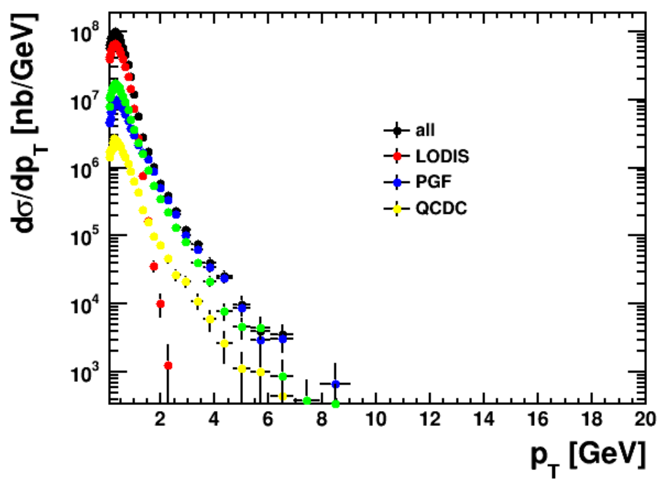
Charged hadron vs kaon spectrum

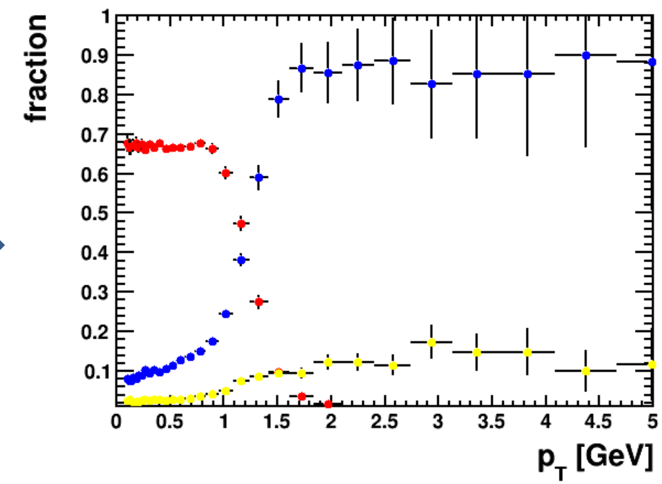
Charged hadron



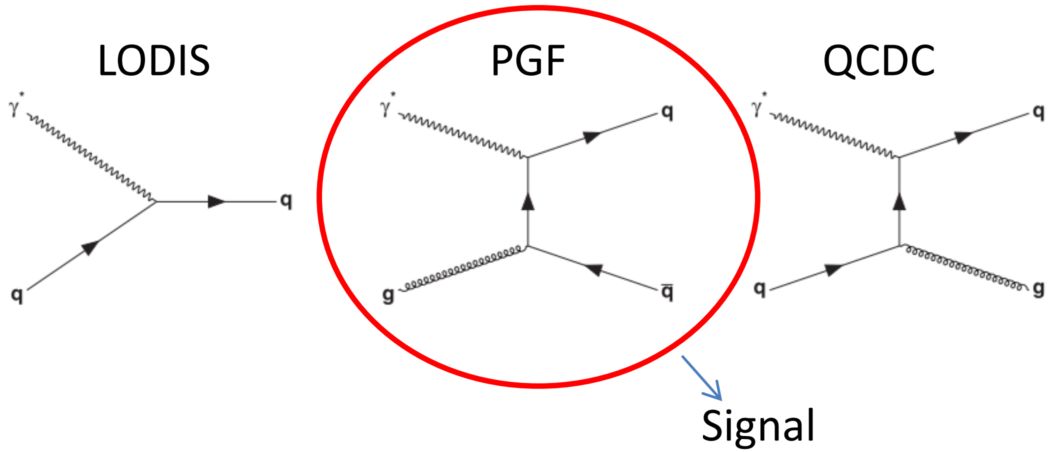


Charged Kaon

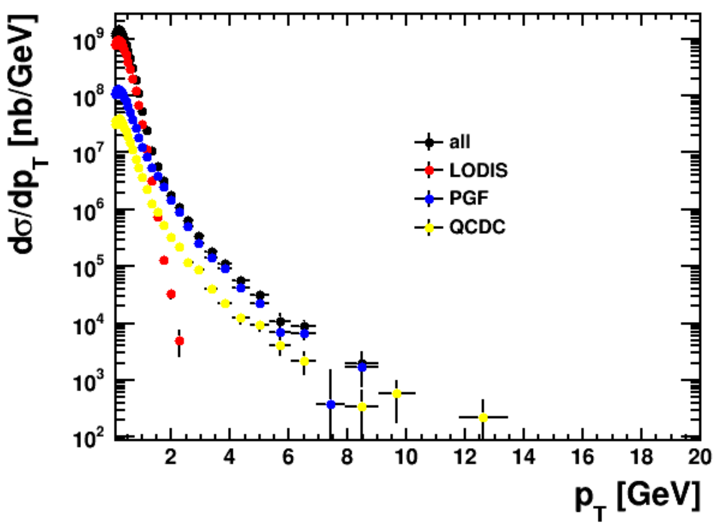


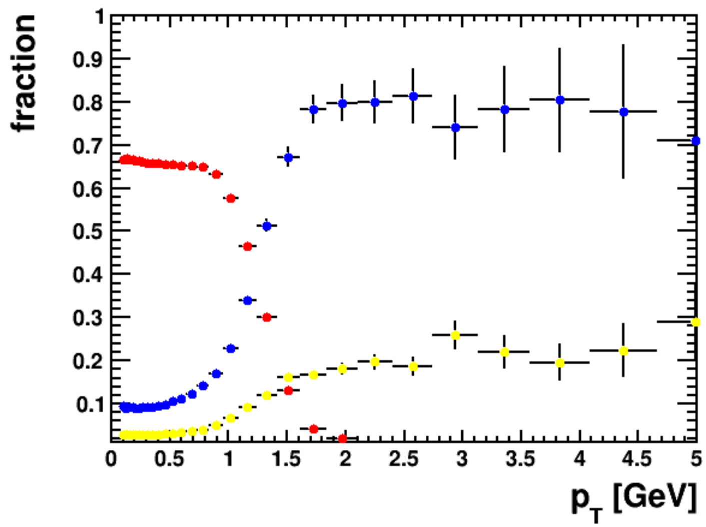


Dihadron pair selection

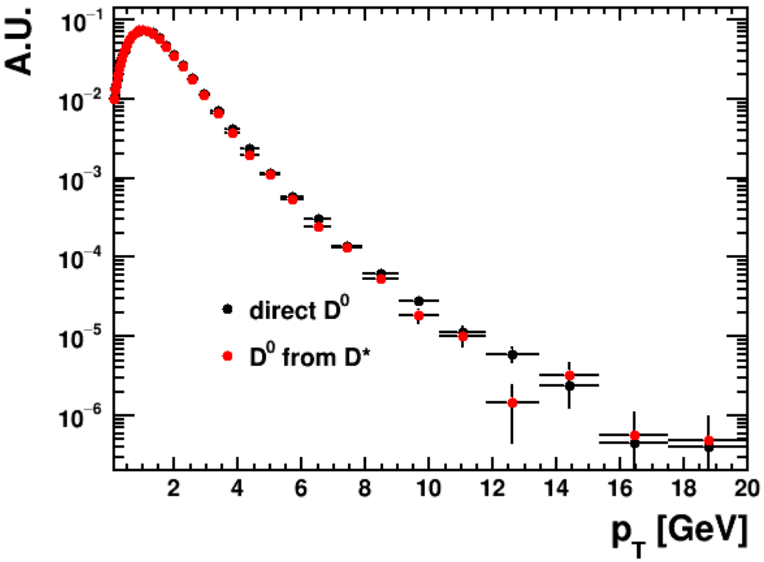


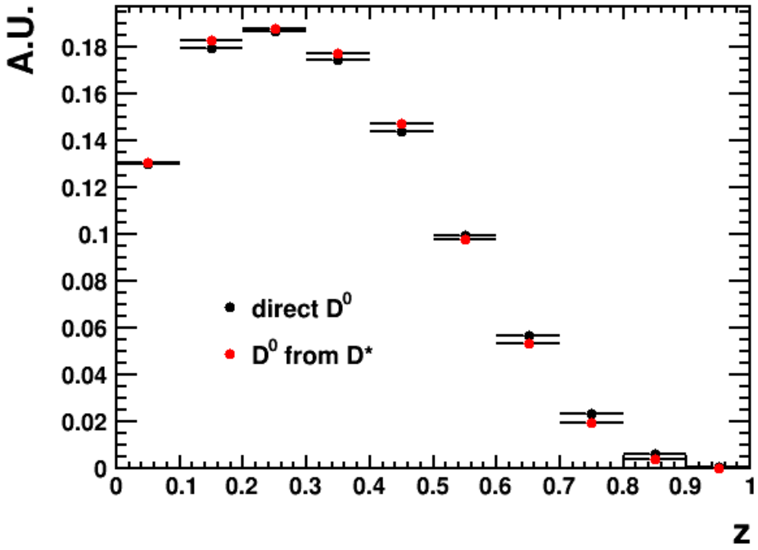
p_T>1.7 GeV effectively enhances the gluon initiated process.





D^0 feed-down from D*

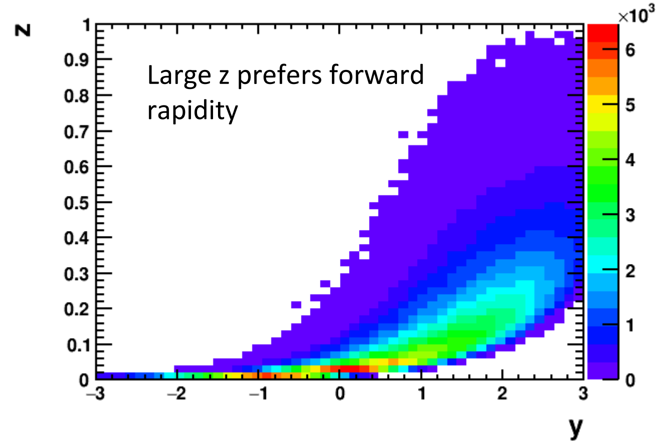


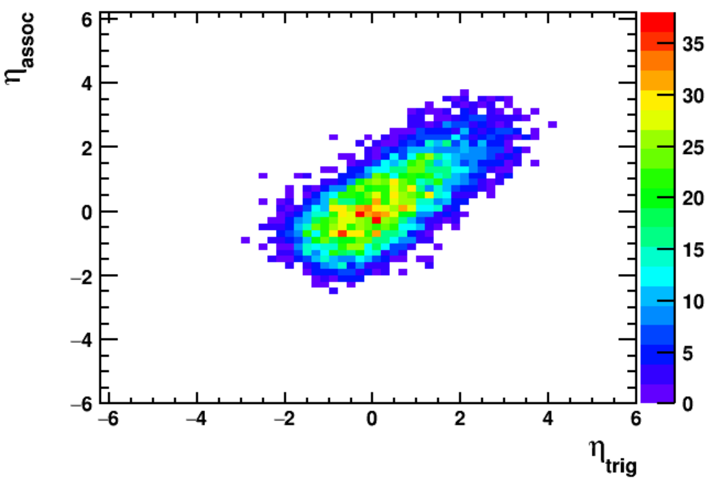


D^0 from D* decay similar to the directly generated D^0s, therefore all D^0s are analyzed.

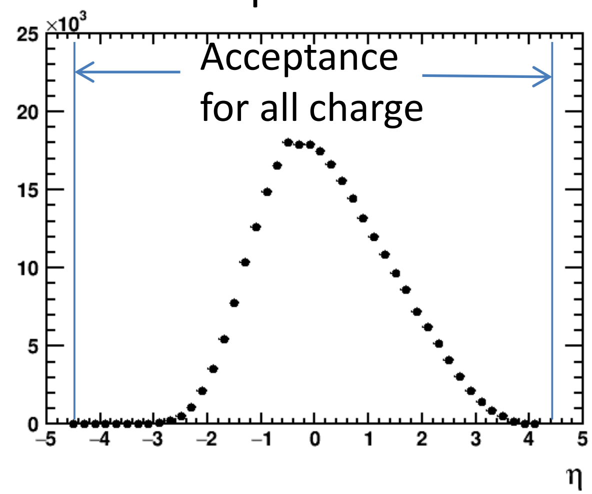
Dihadron pair selection

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



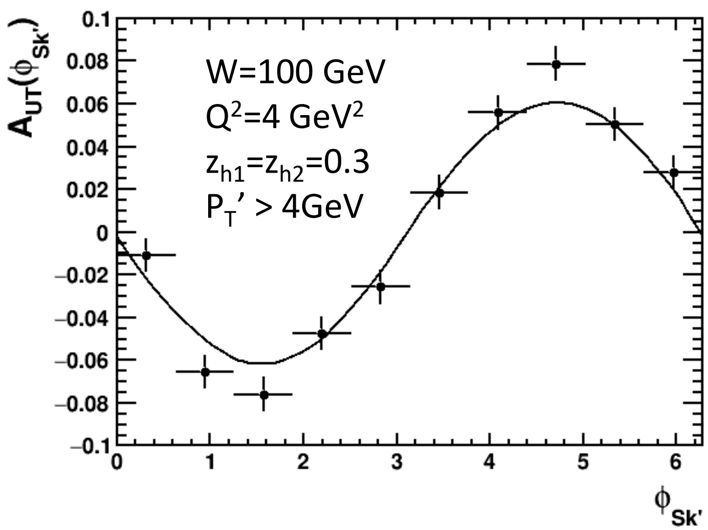
Weighting strategy vs numerical estimation

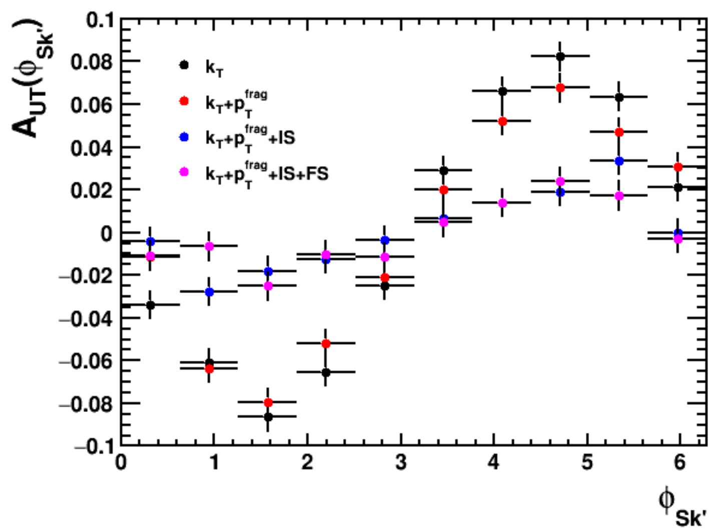
A_{UT} can be evaluated with the weighting based on input Sivers function

$$A_i = \frac{1}{N_i} \sum_{k=1}^{N_i} w_k$$

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

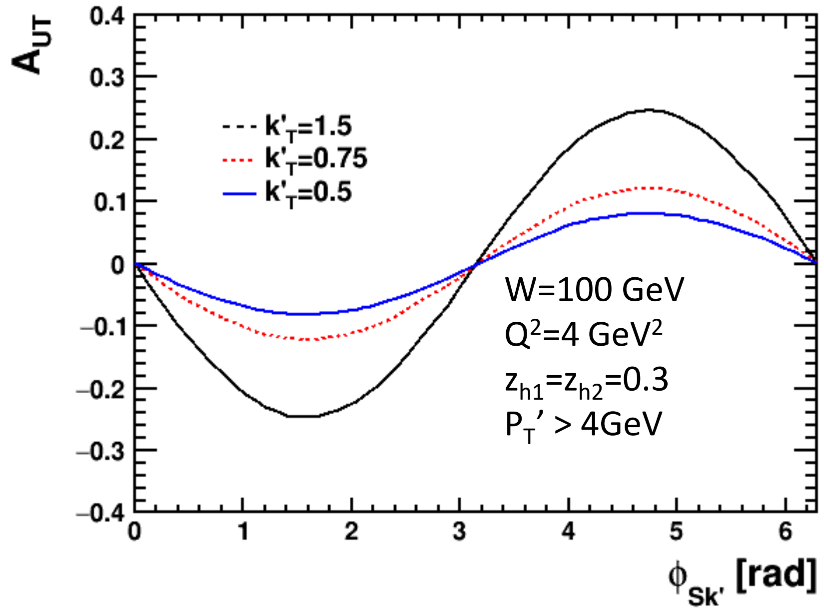
- Weighted results agree with the numerical estimations.
- Initial state parton shower suppresses the azimuthal asymmetry significantly.



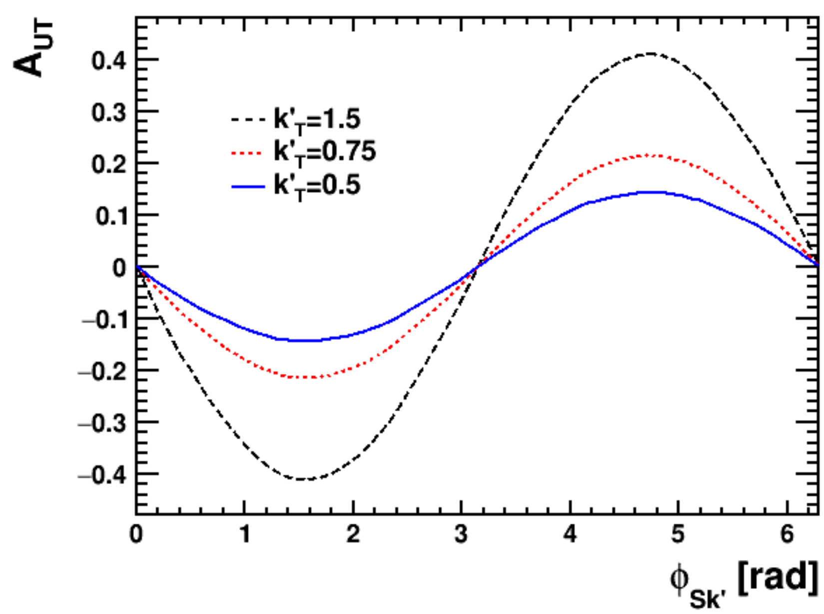


Numerical estimation of gluon SSA with positivity bound

D^0 $\langle p_T^2 \rangle_{frag}$=0.64



Charged dihadron $\langle p_T^2 \rangle_{frag}$=0.2



Collection of different probes

Event sample summary:
ep 20x250 GeV
sqrt(s)=141 GeV
$0.01<y<0.95$
$1<Q^2<20$ GeV^2

σ_{tot}=562.5 nb (all events)
$\sigma_{dihadron}$=5.0E-1 nb, Gluon initiated: 80%
σ_{K+K-}=1.6E-2 nb, Gluon initiated: 94%
$\sigma_{DDbar\ pair}$ = 2.4E-4 nb, Gluon initiated: 100%
$\sigma_{dihadron} \sim 31\sigma_{K+K-} \sim 67\ \sigma_{DDbar\ pair}$

dihadron cuts:
Acceptance $|\eta|<4.5$
$z>0.1$, $p_T>1.7$ GeV, Correlation limit: $k_T' < 0.7P_T'$

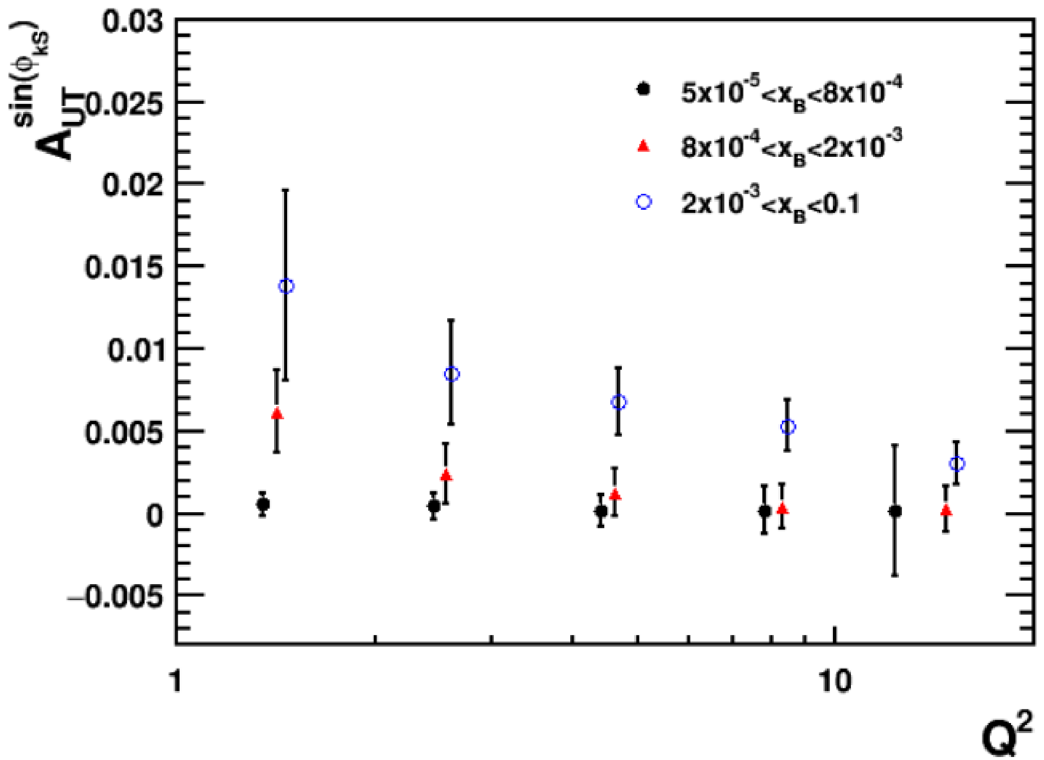
K+K- cuts:
Acceptance $|\eta|<1$
$z>0.1$, $p_T>1.7$ GeV, Correlation limit: $k_T' < 0.7P_T'$

D^0 cut: D->K + pi (3.9%)
Acceptance $|\eta|^{pi/K}<1$
$p_T^{pi/K}>0.2$ GeV, $z>0.1$, Correlation limit: $k_T' < 0.7P_T'$

With 100 fb^{-1} statistics and P=70% polarization $\delta A_N = \frac{1}{P\sqrt{\sigma L}} = \frac{1}{P\sqrt{N}}$
$\delta A_{UT}{}^{dihadron} \approx$ 6.4E-4, $\delta A_{UT}{}^{K^+K^-} \approx$ 3.8E-3, $\delta A_{UT}{}^{DDbar} \approx$ 2.8E-2 (Uncertainty divided into 10 bins in ϕ_{Sk})

Projections on the SSA with dijet probe

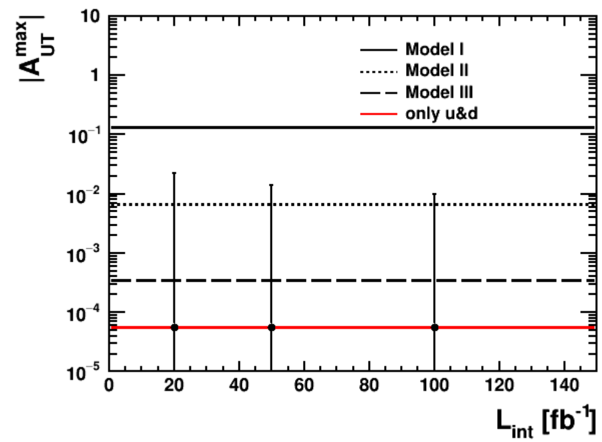
- Possible to do 2D binning in x_B and Q2
- Structures difficult to extract in 1D analysis observed
- Helpful to pin down the evolution feature of gluon Sivers



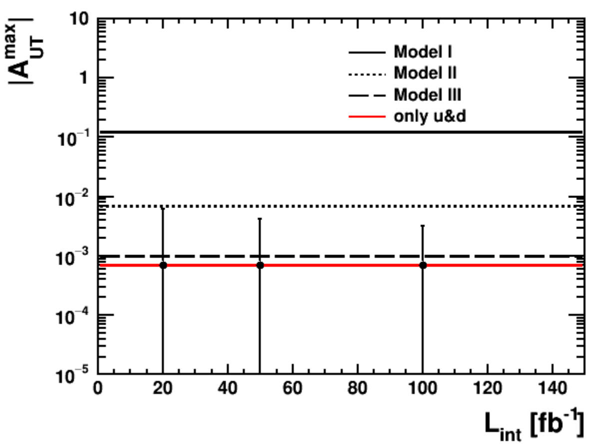
Comparison of all the probes

- Gluon Sivers effect is a luminosity hungry measurement.
- Vertical line represents the statistical uncertainty.
- Charged dihadron probe is the most statistically favored.
- D meson probe is mostly dominated by gluon dynamics.

D meson



K^+K^-



Charged dihadron