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

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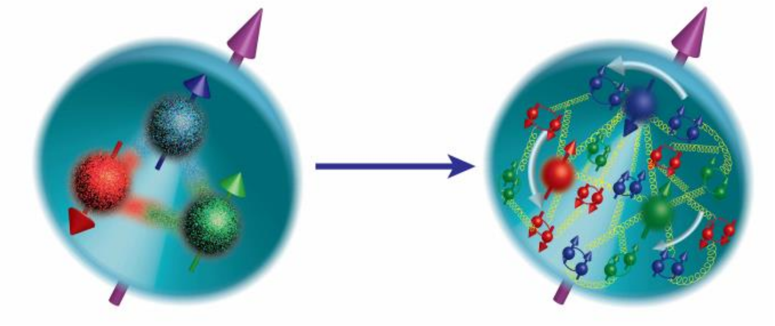
Outline

- Nucleon structure and gluon Sivers effect
- Model calculations
- Experimental considerations
- Summary

Exploring nucleon structure

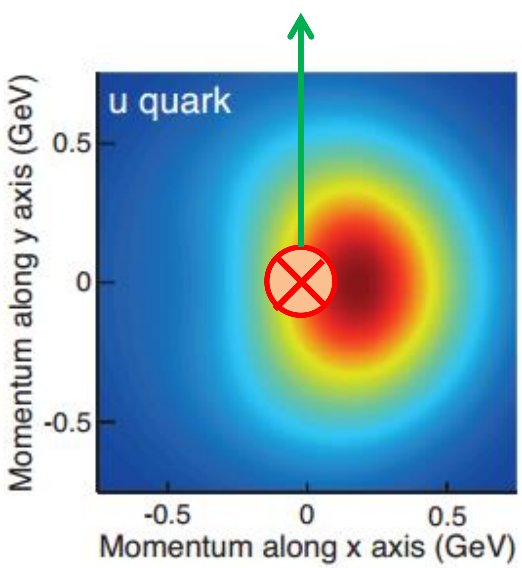
- Nucleon is a dynamical system of quarks and gluons
  - How are the partons distributed in space and momentum inside the nucleon?
  - How are these quark and gluon distributions correlated with the overall nucleon properties, such as spin direction?
  - What is the role of the orbital motion of sea quarks and gluons in building the nucleon spin.
- EIC: the ultimate machine to understand the nature of the nucleon partonic structure.



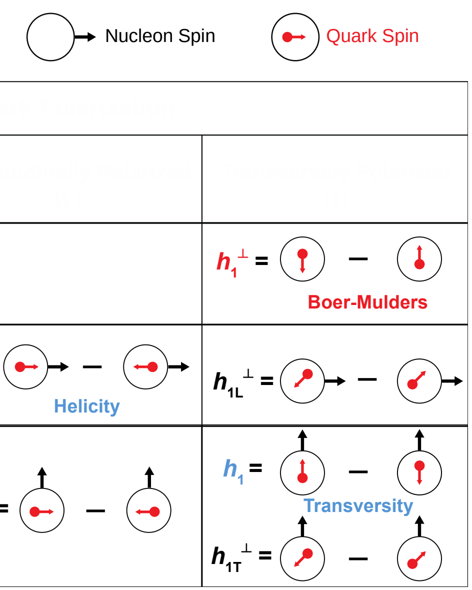
TMDs and Sivers function

- 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.

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



Leading Twist TMDs

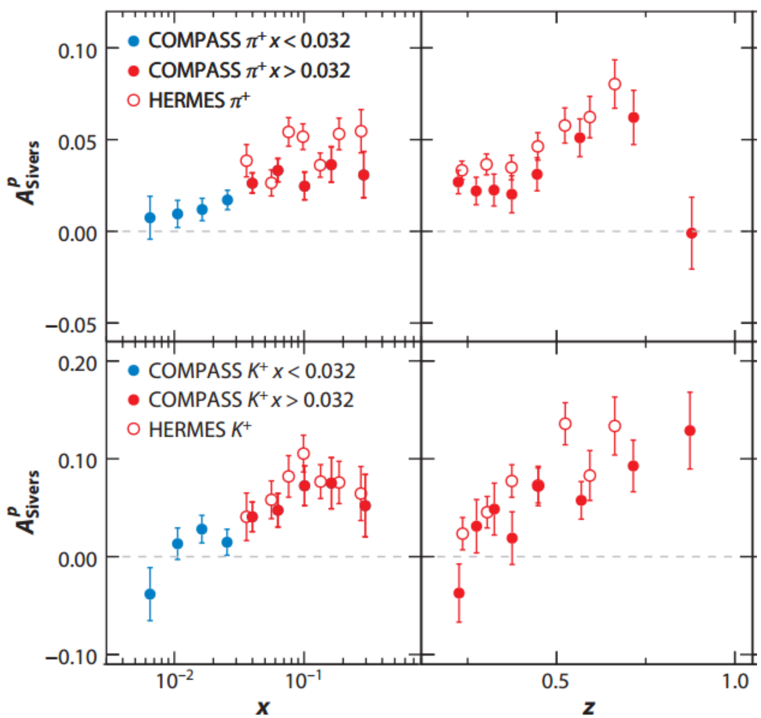


Similar for gluons

Current knowledge to quark Sivers

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

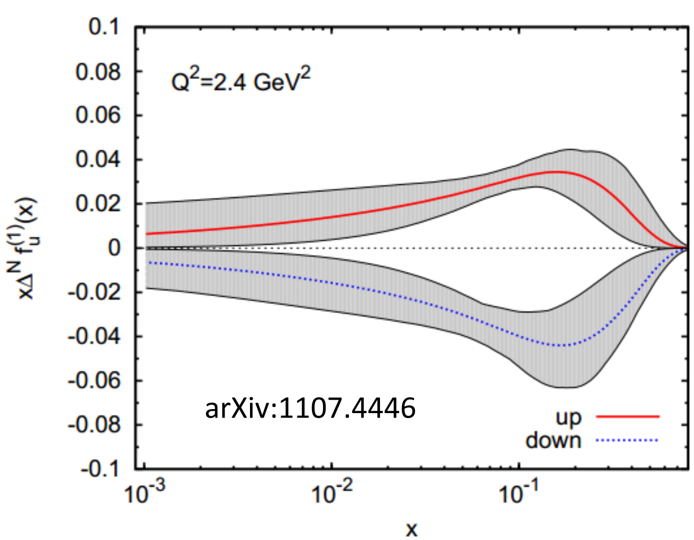
Annu. Rev. Nucl. Part. Sci. 65 429 (2015)



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

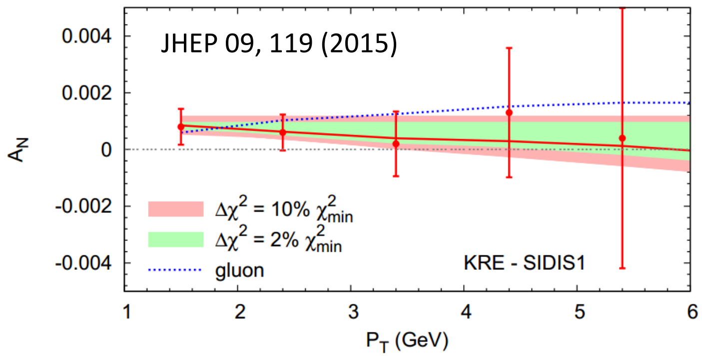
$$\Delta^N f_{a/p^\uparrow}(x, k_\perp) = -\frac{2k_\perp}{M_p} f_{1T}^{\perp a}(x, k_\perp)$$

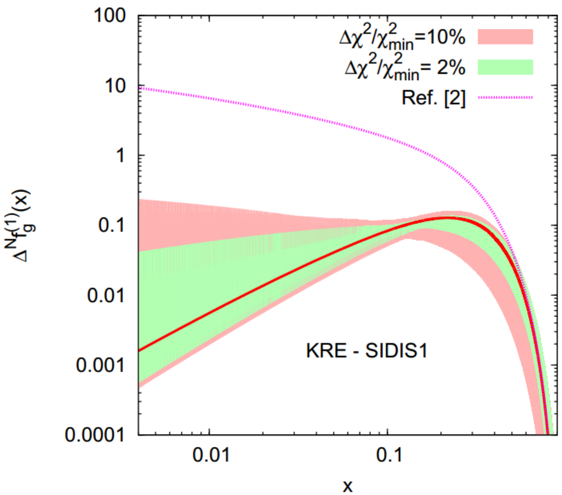
- Accessed with SIDIS measurements.
- Sizable Sivers effect.
- u, d quark Sivers with opposite sign.
- Subject to large uncertainty.



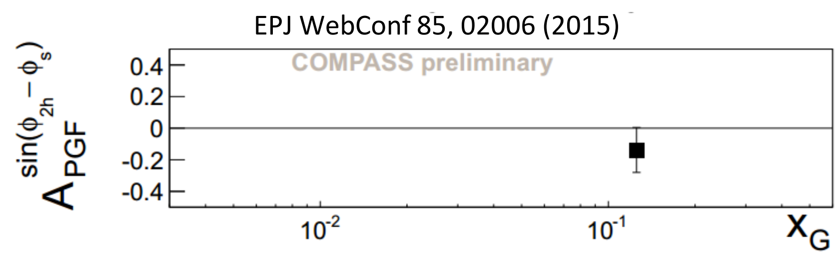
Current constraints on gluon Sivers

Extraction based on A_N data at RHIC





Extraction on COMPASS data

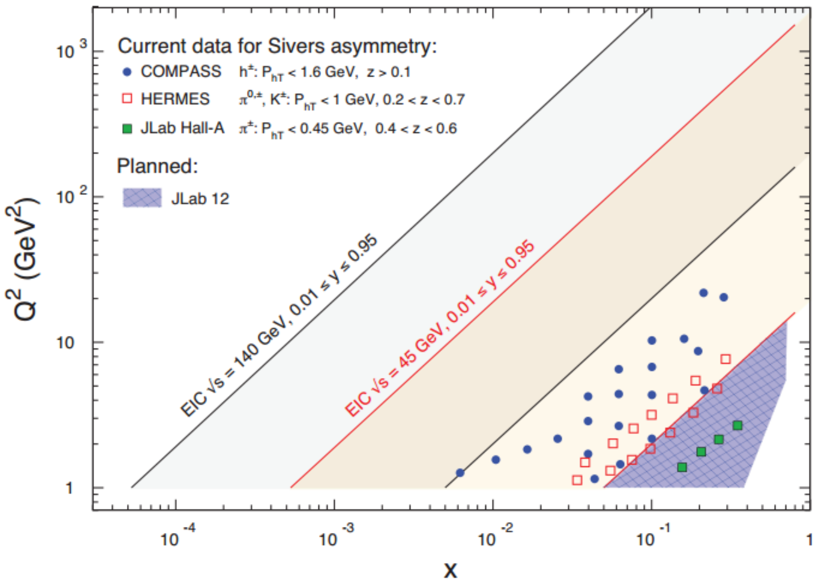


$$A_{PGF}^{\sin(\phi_{2h}-\phi_S)} = -0.14 \pm 0.15(\text{stat.})$$

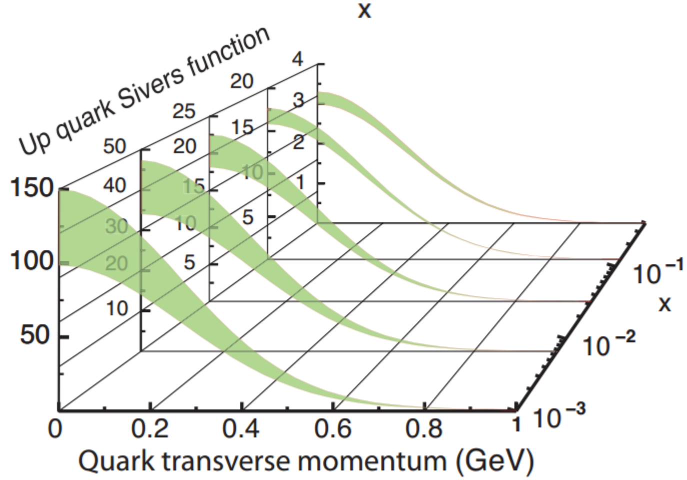
$$\langle x_G \rangle = 0.126$$

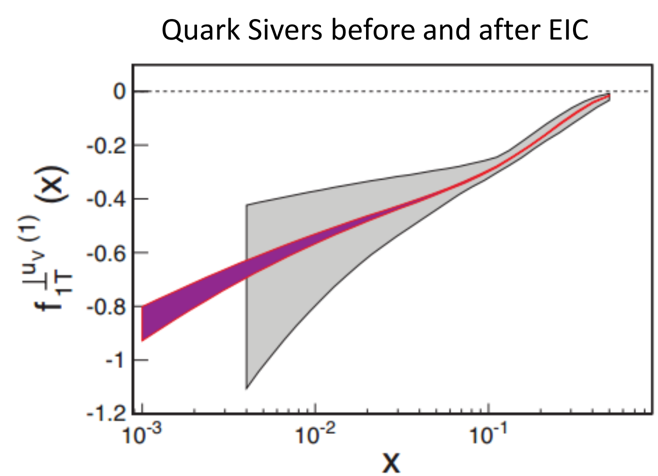
- Effective gluon Sivers from A_N may differ from the actual gluon Sivers in TMD.
- Limited x and Q^2 range explored in SIDIS. Still allow for gluon Sivers contributions of $1/N_c$.
- No hard constraints at this moment.

Studying Sivers in the EIC era



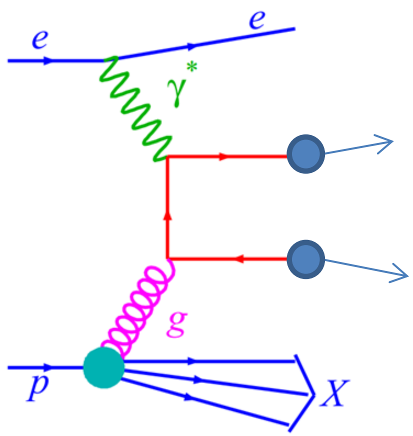
- Disentangle Sivers and Collins asymmetries.
- Extend the current Sivers data to smaller x.
- Large Q^2, x, coverage to pin down TMD evolution.





Accessing gluon Sivers at an EIC

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



Back-to-back limit:
$P_T' = |\mathbf{P}_T^{h1}-\mathbf{P}_T^{h2}|/2$
$k_T' = |\mathbf{P}_T^{h1}+\mathbf{P}_T^{h2}|$
$k_T' << P_T'$

Treatable single spin asymmetry (SSA) dependent on gluon Sivers

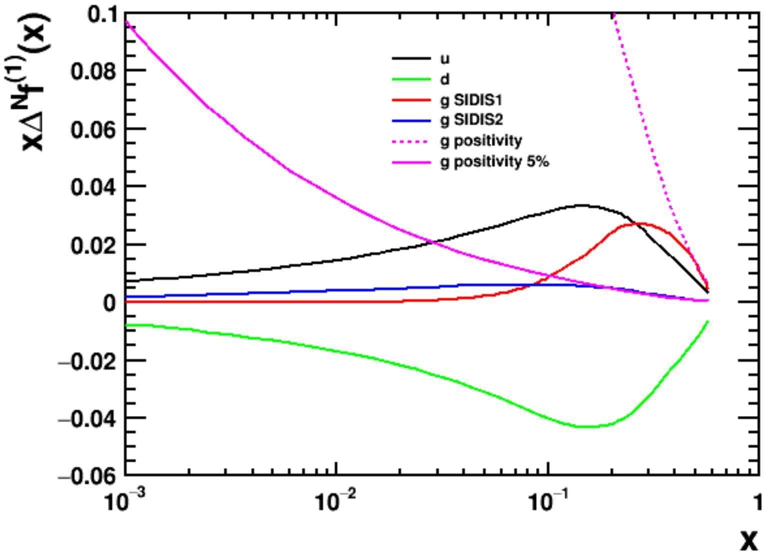
$$A_{UT} = \frac{d\sigma^\uparrow - d\sigma^\downarrow}{d\sigma^\uparrow + d\sigma^\downarrow} \propto \frac{\Delta^N f_{g/p^\uparrow}(x,k_\perp)}{f_1^g(x_g,k_\perp)}$$

Inputs to the model calculation

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

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

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



Quark Sivers: arXiv:1107.4446 Anselmino et. al.

u and d quarks only

$N_u = 0.40 \quad \alpha_u = 0.35 \quad \beta_u = 2.6$

$N_d = -0.97 \quad \alpha_d = 0.44 \quad \beta_d = 0.90$

$M_1^2 = 0.19\ \text{GeV}^2$

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

u, d + Kretzer FF (SIDIS1)

u, d + sea + DSS FF (SIDIS2)

$N_g = 0.05, \alpha_g = 0.8, \beta_g = 1.4, M_g^2 = 0.34\text{GeV}^2 \quad \text{(SIDIS1)}$

Positivity bound ansatz:

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

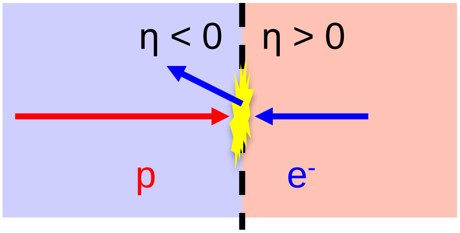
Model-I: Positivity bound

Model-II: Positivity bound x 5%

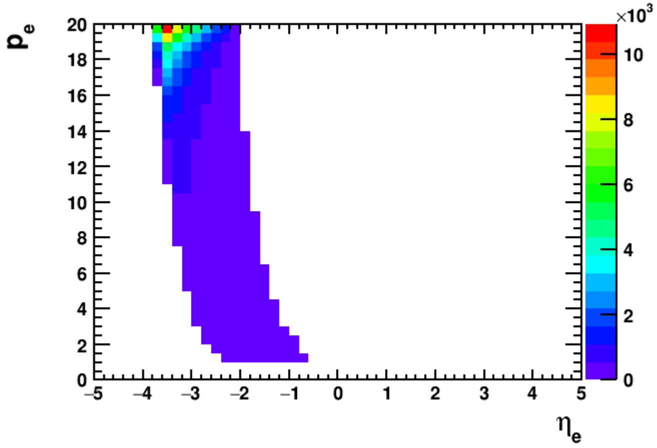
Model-III: SIDIS1 gluon Sivers fit

EIC setup for gluon SSA study

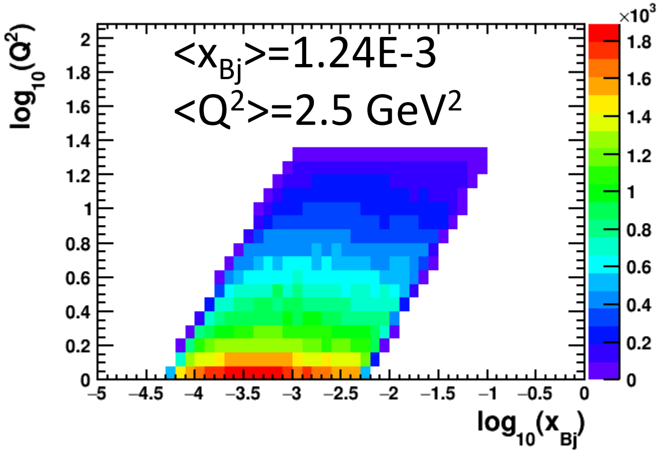
Kinematics:
$ep^{\uparrow}$ 20x250 GeV
$\sqrt{s}$=141 GeV
0.01<y<0.95
$1<Q^2<20$ GeV^2

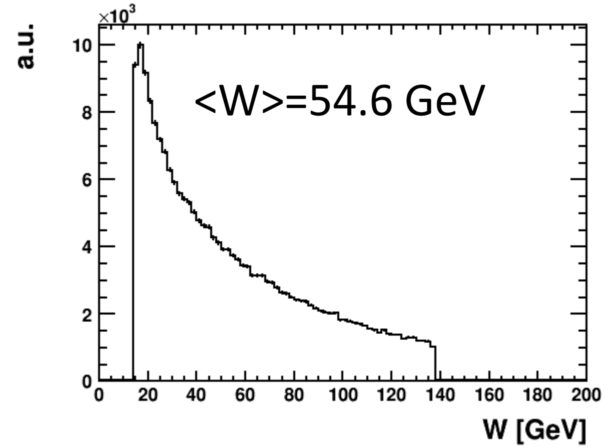


Scattered electron



Final state observables
1. D^0 pair
2. K^+K^- pair
3. Charged hadron pair





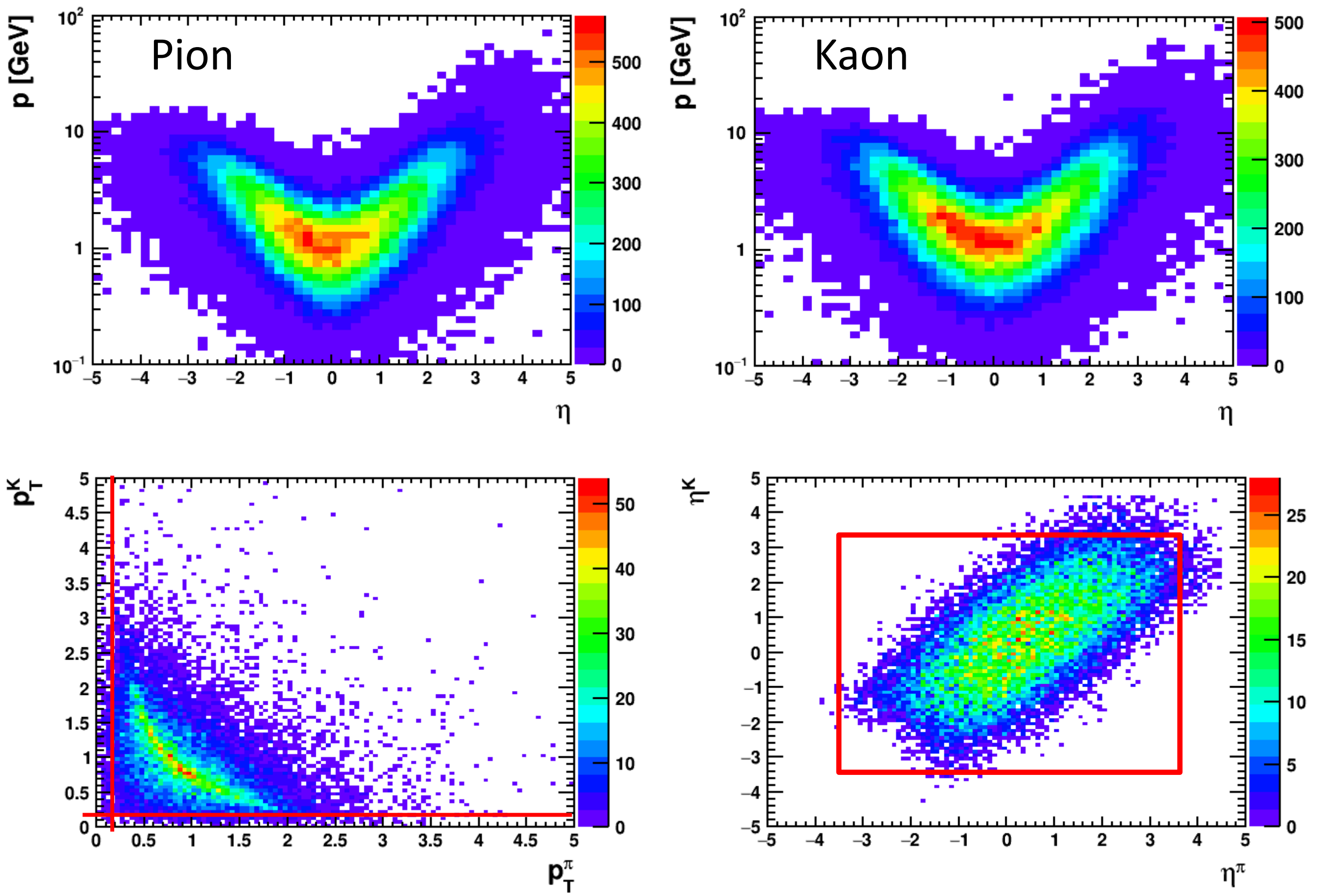
D meson pair selection

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 $|\eta|<3.5$
- 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 D meson pairs

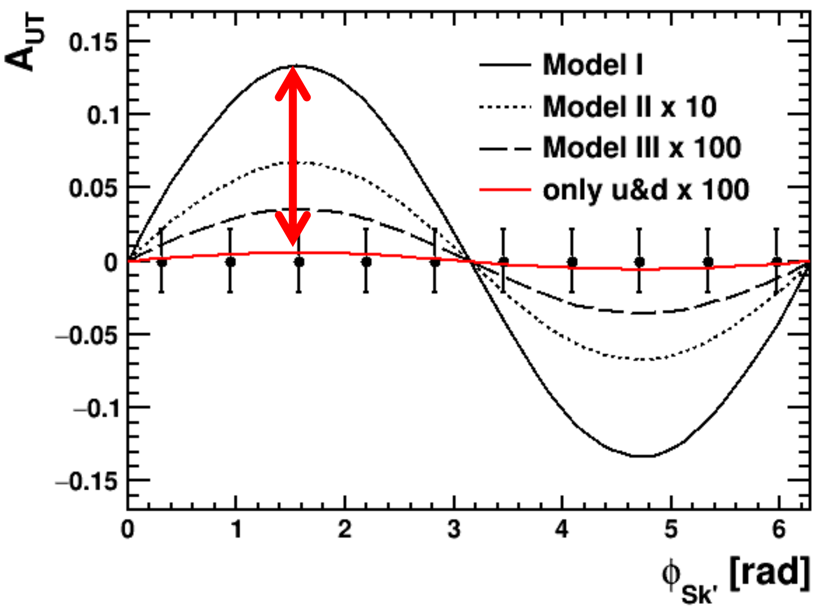
ep↑ 20x250 GeV
D^0 cut:
D->K + pi (3.9%)
Acceptance $|\eta|^{pi/K}<3.5$
$p_T^{pi/K}>0.2$ GeV, $z^{pi/K}>0.1$,
Correlation limit: $k_T' < 0.7P_T'$
$<x_g>=0.033$
$\sigma_{DDbar\ pair} = 2.2\times10^{-3}$ nb
PGF fraction:99.4%

- Gluon Sivers best identified with positivity bound: Model I.
- Dominated by Gluon Sivers effect
- Integrated Luminosity: 20 fb^{-1} delivers $\delta A_{UT} \approx 2.1\times10^{-2}$

Difference between black and red shows the effect of gluon Sivers

The statistical uncertainty obtained with P=70% polarization $(\delta A_{UT})^2 = \frac{1}{P^2\sigma L}$

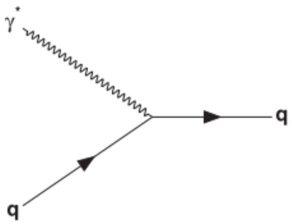
$$A(\phi_{Sk}) = R^{SIG}A^{SIG}(\phi_{Sk}) + R^{BG}A^{BG}(\phi_{Sk})$$



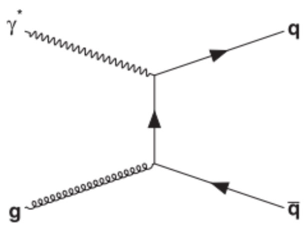
$$\phi_{Sk'} = \phi_S - \phi_{k'_T}$$

Dihadron pair selection

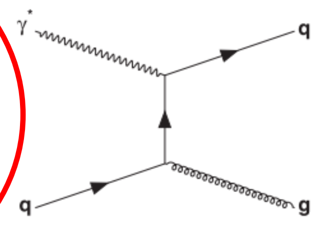
LODIS



PGF

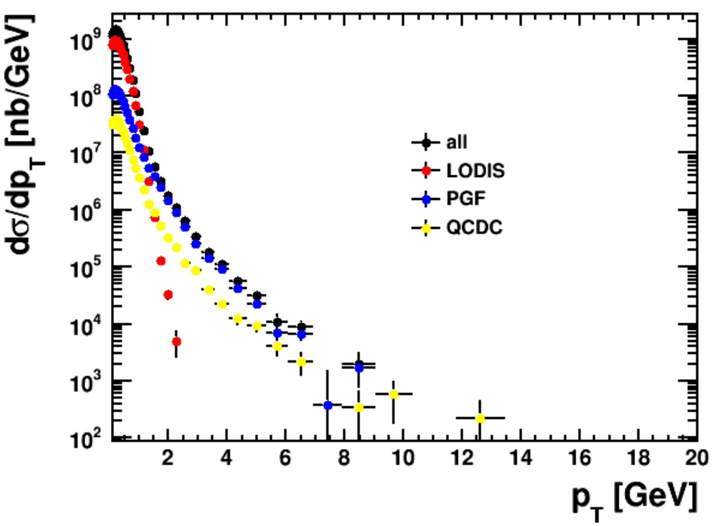


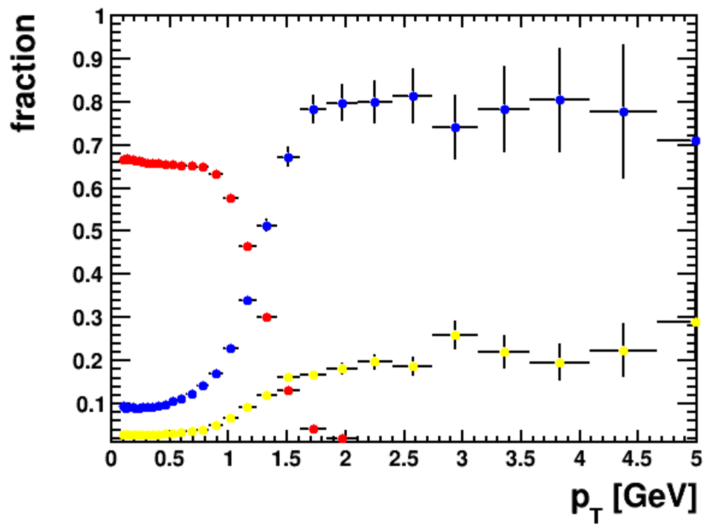
QCDC



p_T>1.7 GeV effectively enhances the gluon initiated process.

Signal





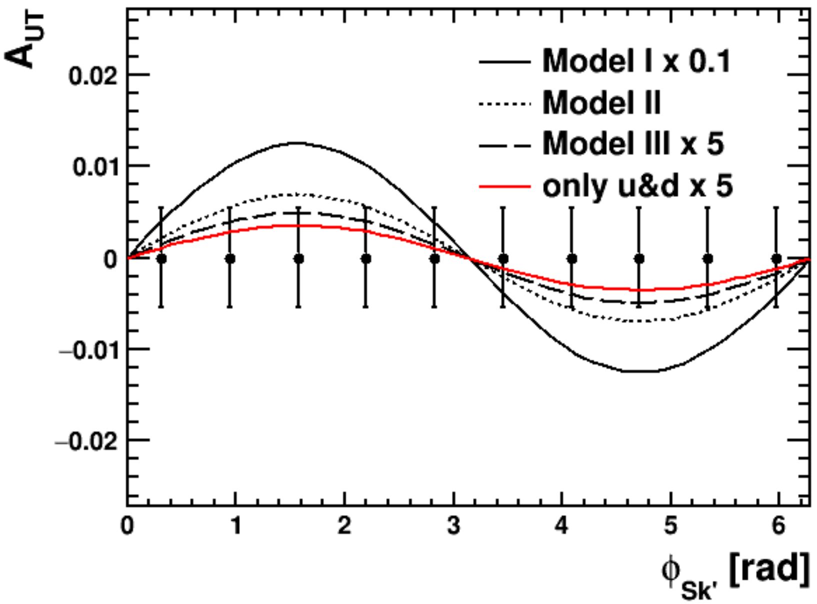
Projections on the SSA with K^+K^- pairs

Kinematic cuts:
ep 20x250 GeV
0.01<y<0.95
$1<Q^2<20$ GeV^2
$p_T>1.7$ GeV, $z_h>0.1$, $|\eta|<3.5$
Back-to-back limit: $k_T' < 0.7P_T'$
$\sigma_{K+K-}=3.4\times10^{-2}$ nb
$<x_g>=0.05$

The statistical uncertainty obtained with P=70% polarization $(\delta A_{UT})^2 = \frac{1}{P^2 \sigma L}$

$$A(\phi_{Sk}) = R^{SIG} A^{SIG}(\phi_{Sk}) + R^{BG} A^{BG}(\phi_{Sk})$$

- Hard to resolve 5% level of positivity bound: Model-II.
- PGF events accounting for 93%.
- Integrated Luminosity: 20 fb^{-1} delivers $\delta A_{UT} \approx 5.5\times10^{-3}$



Difference between black and red shows the effect of gluon Sivers

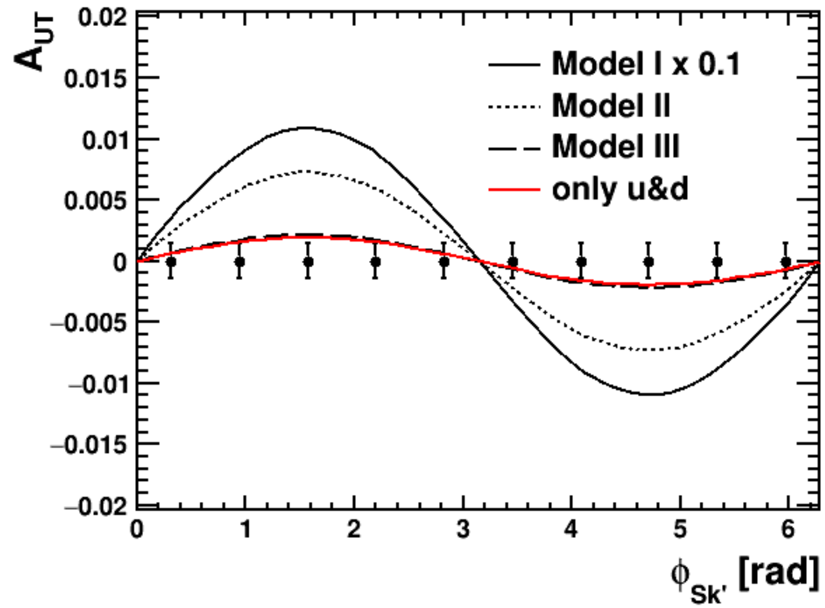
Projections on the SSA with charged dihadron pairs

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: $k_T' < 0.7P_T'$
$\sigma_{dihadron}=0.5$ nb
$<x_g>=0.063$

The statistical uncertainty obtained with P=70% polarization $(\delta A_{UT})^2 = \frac{1}{P^2 \sigma L}$

$$A(\phi_{Sk}) = R^{SIG} A^{SIG}(\phi_{Sk}) + R^{BG} A^{BG}(\phi_{Sk})$$

- Model II well identified but hard to resolve Model III.
- PGF events accounting for 80%.
- Integrated Luminosity: 20 fb^{-1} delivers $\delta A_{UT} \approx 1.4\times10^{-3}$

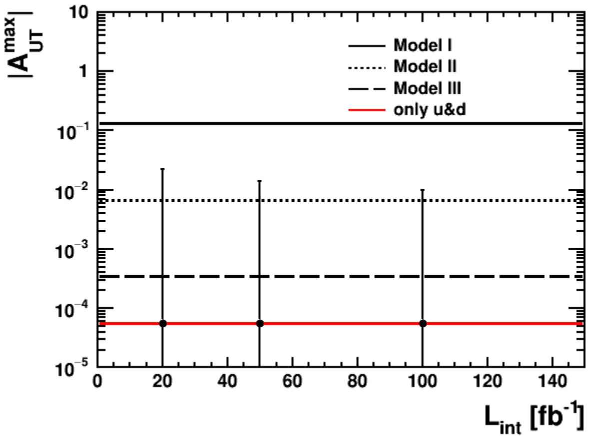


Together with well understood quark Sivers function, gluon Sivers sign and behavior can be constrained with an EIC.

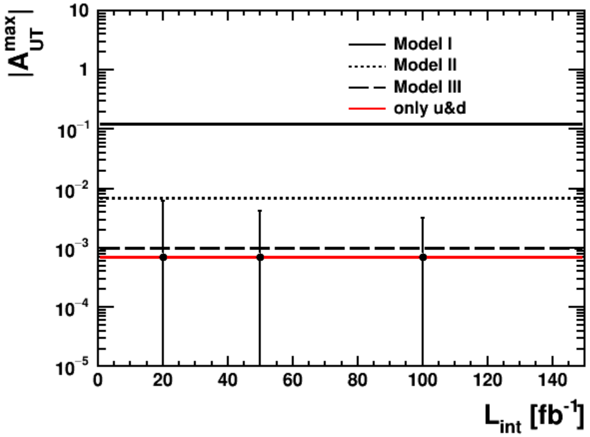
Comparison of all the probes

- 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.

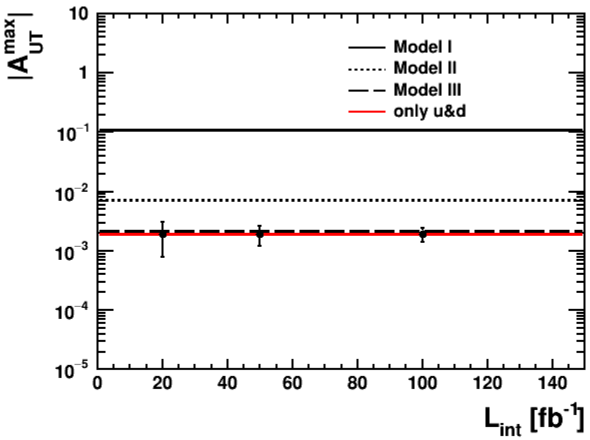
D meson



K^+K^-



Charged dihadron



Summary

- Gluon Sivers function is an important ingredient of the complete 3D imaging of the nucleon.
- The single spin asymmetry arising from gluon Sivers is treatable in an effective TMD framework.
- D meson and K^+K^- are better to tag gluon dynamics than charged dihadron, but will be more luminosity challenged.
- Gluon Sivers can be constrained via PGF coupling within EIC machine and detector reach.