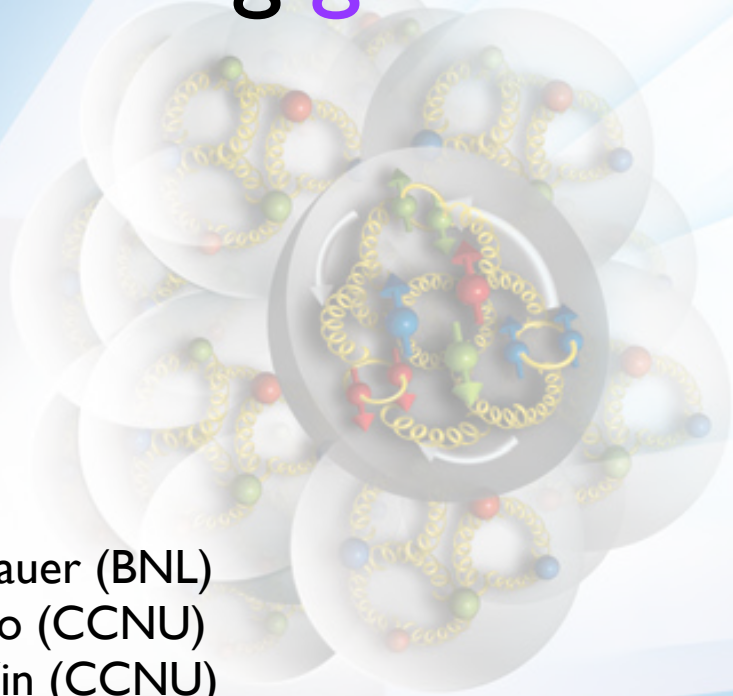
Accessing gluon Sivers at EIC



J.H. Lee

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Liang Zheng (CCNU)

Nucleon Landscape

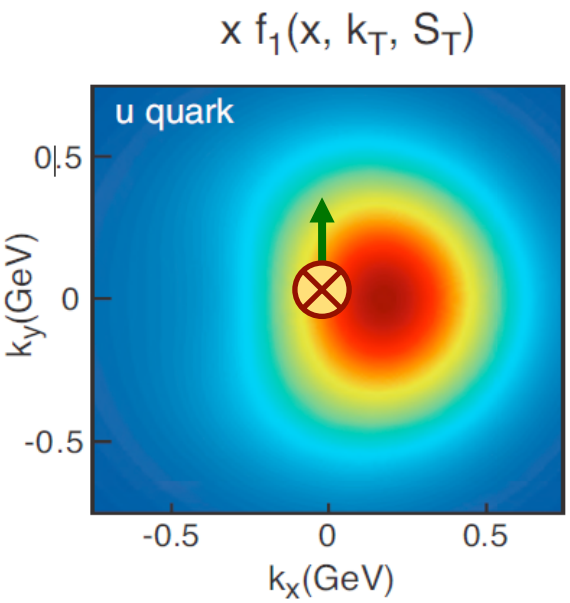
- Nucleon is a dynamical system of quarks and gluons
  - How partons are distributed in space and momentum inside the nucleon?
  - How are these **quark and gluon distributions correlated** with the over all nucleon properties, such as **spin** direction?
  - Spin as fundamental intrinsic property and 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

3D imaging of partonic structure of nucleon

Transverse Momentum Dependent parton distributions (TMDs)

confined motion in a nucleon (semi-inclusive DIS)

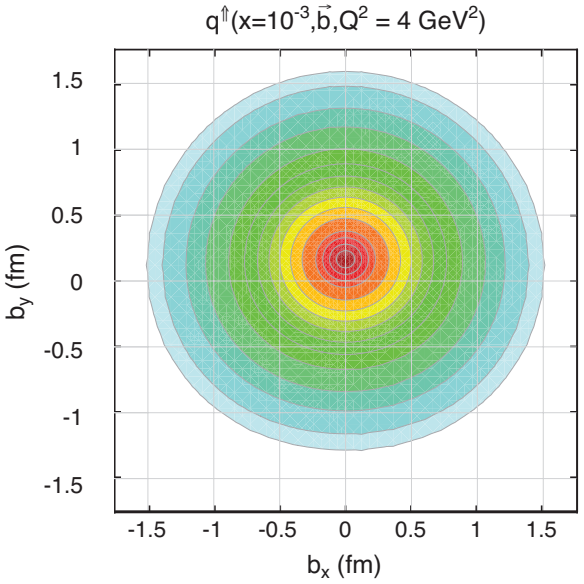
2+1D picture in momentum space (k_T)



Generalized Parton Distributions (GPDs)

Spatial imaging of quarks and gluons (exclusive DIS)

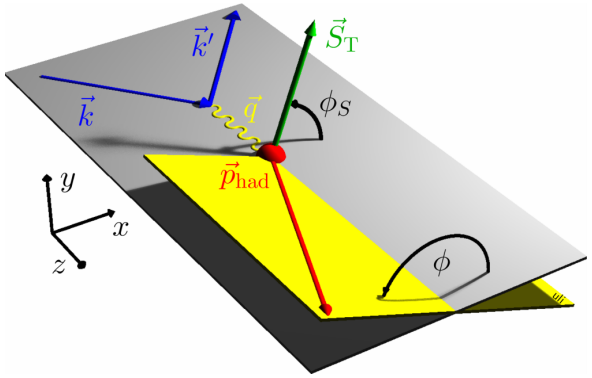
2+1D picture in impact parameter space (b)



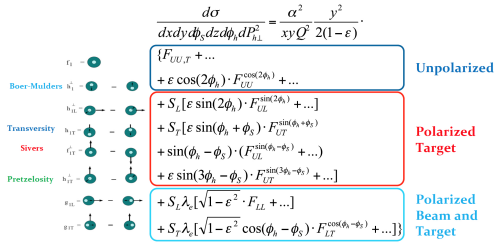
Transverse Momentum Dependent PDFs

observable: azimuthal modulations of 6-fold differential SIDIS cross section

$$\frac{d\sigma}{dx dQ^2 dz d\phi_s d\phi_h dp_T^h}$$



- multi-scale process: Q^2, p_T
- TMD framework/factorization applicable for $Q^2 >> p_T$
- so far only valence quark TMDs extracted from fixed target data
- very different evolution then collinear PDFs: pertubative & non-pertubative contributions
- different TMDs can be defined and probed in SIDIS



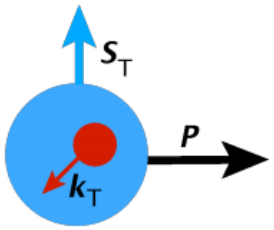
Leading Twist TMDs

Nucleon Spin Quark Spin

Similar for gluons

Nucleon Polarization	Quark Polarization: Un-Polarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
U	f_1 =		$h_1^\perp$ = − Boer-Mulders
L		g_{1L} = − Helicity	$h_{1L}^\perp$ = −
T	$f_{1T}^\perp$ = − Sivers	$g_{1T}^\perp$ = −	h_1 = − Transversity; $h_{1T}^\perp$ = −

Sivers Function



Correlation of nucleon's transverse spin with k_T of an unpolarized quark: Can be viewed as partonic motion inside nucleon

$$f_{q/P^\uparrow}(x, \mathbf{k}_\perp, S) = f_1(x, \mathbf{k}_\perp^2) - \frac{\mathbf{S} \cdot (\hat{\mathbf{P}} \times \mathbf{k}_\perp)}{M} f_{1T}^\perp(x, \mathbf{k}_\perp^2)$$: $\sin(\Phi_h - \Phi_S)$ modulation

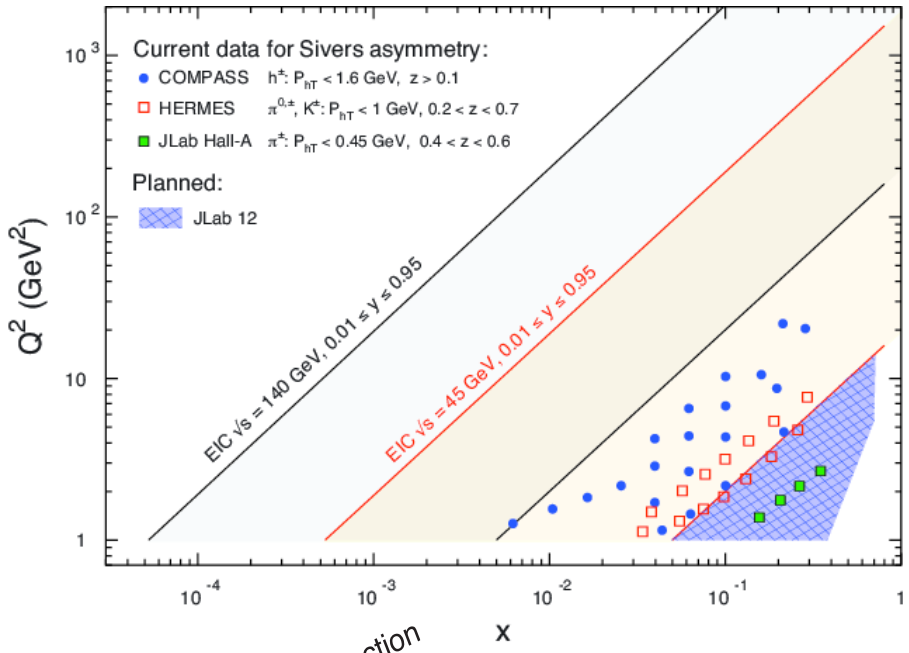
unpolarized TMD

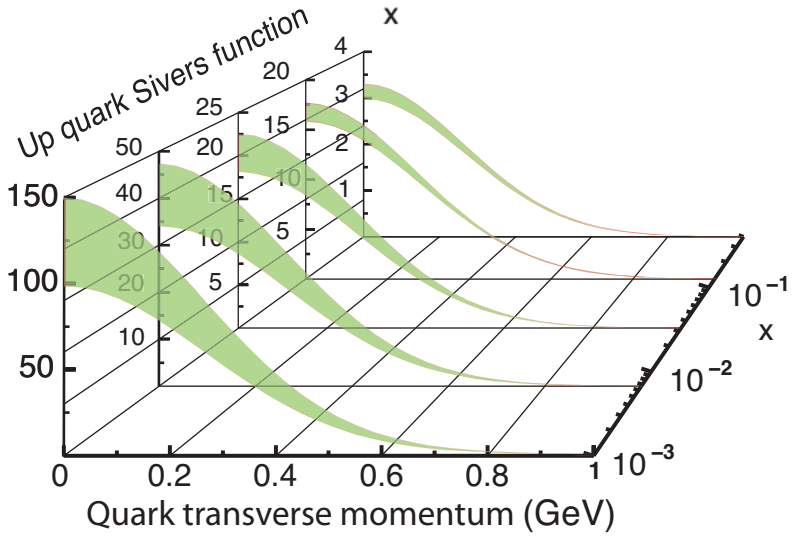
Sivers function

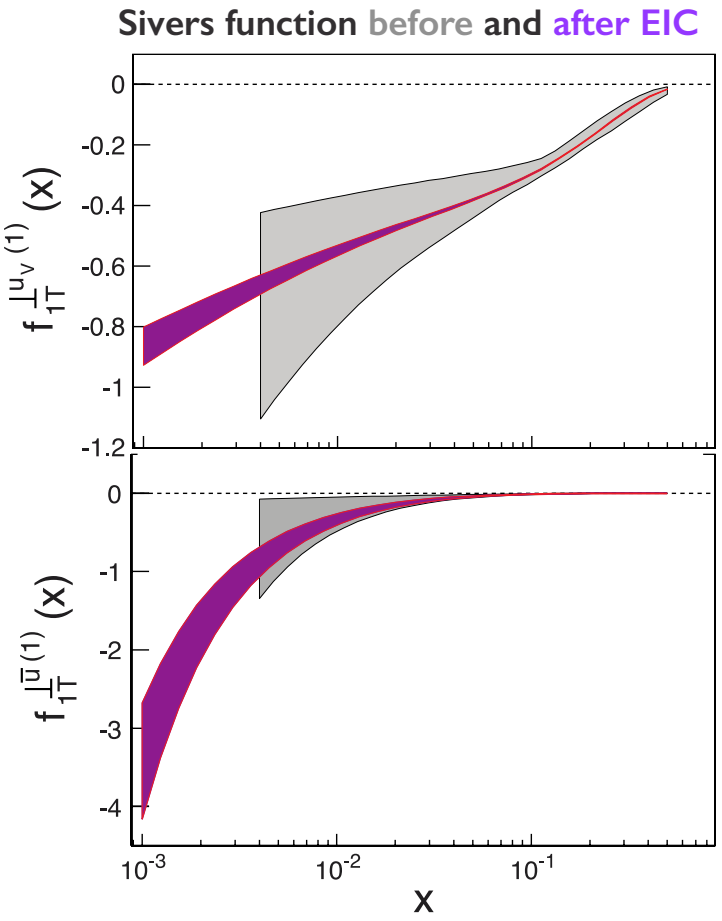
important link to physics of gluon saturation at small x

- "dipole" deformation
- measures spin-orbit correlations
- link to parton orbital motion (through models)
- reveals non-trivial aspects of QCD color gauge invariance

quark Sivers at EIC







EIC: Luminosity vs energy

Science case areas indicate the range of peak luminosities with which a statistically significant result can be achieved in about one year (10^7 sec) of running.

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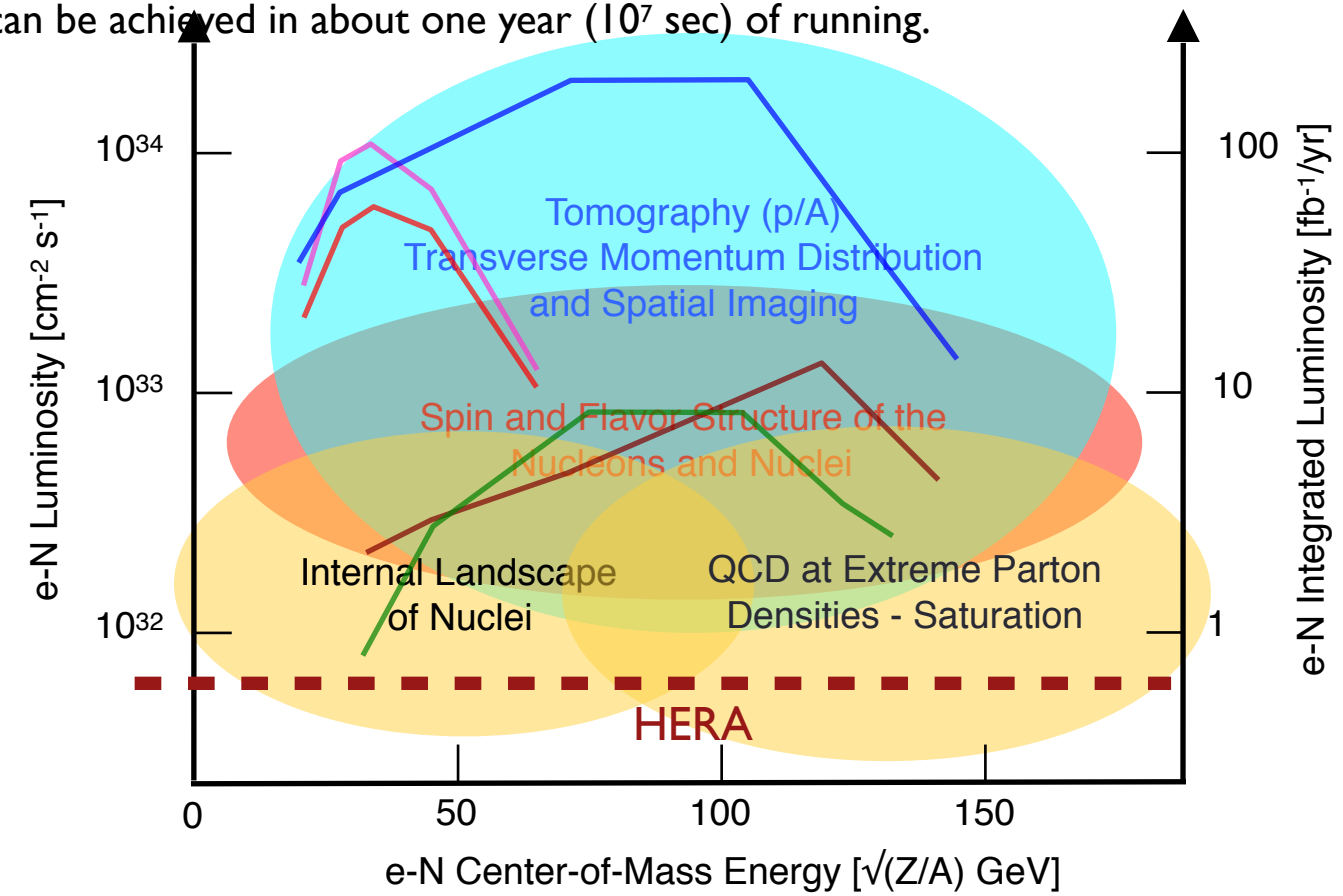


Ultimate eRHIC ERL-Ring design

JLEIC full acceptance detector

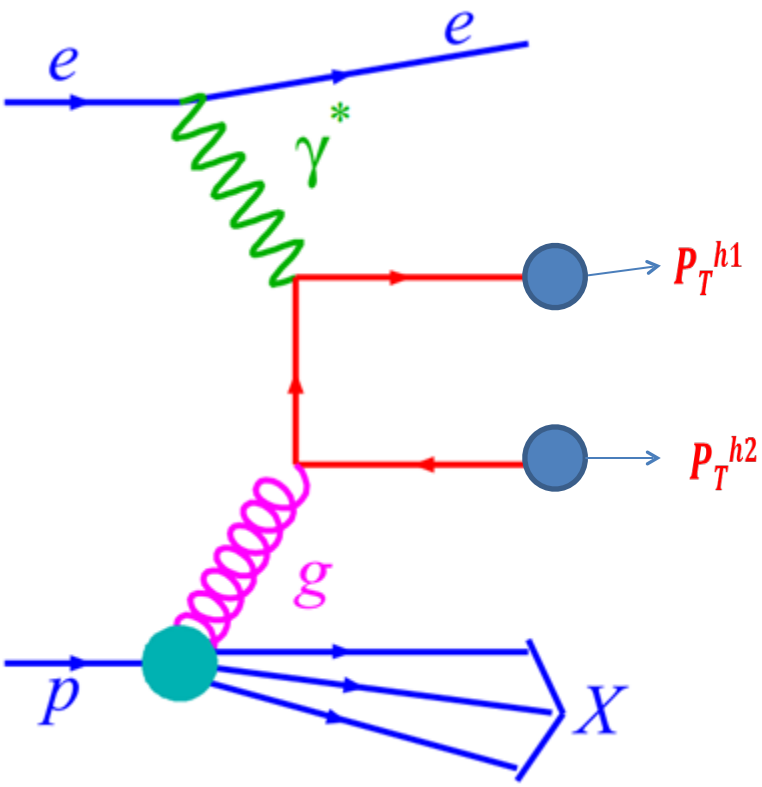
JLEIC high luminosity detector

eRHIC ERL-Ring design, no cooling of protons, P_{synch} ~ 2.5 MW

eRHIC Ring-Ring design, some cooling, 330 bunches, P_{synch} ~ 10 MW

Accessing gluon dynamics in DIS

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/jet pair information

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

Back-to-back limit:

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

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

$k_T' << P_T'$

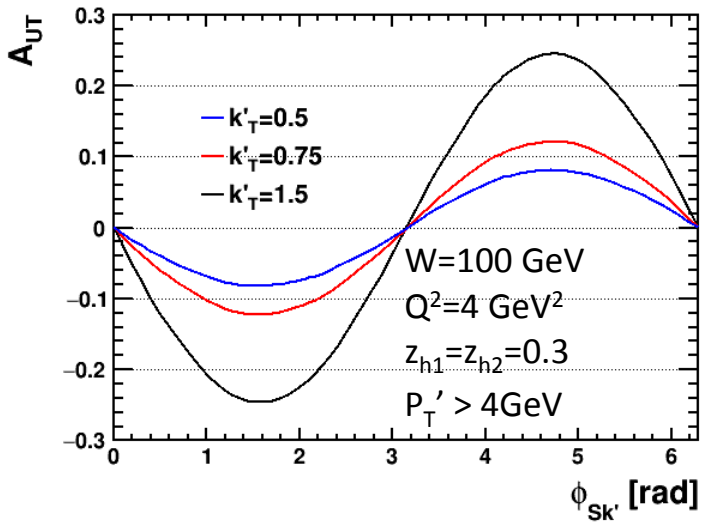
Theoretical framework for the model calculation

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

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

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

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



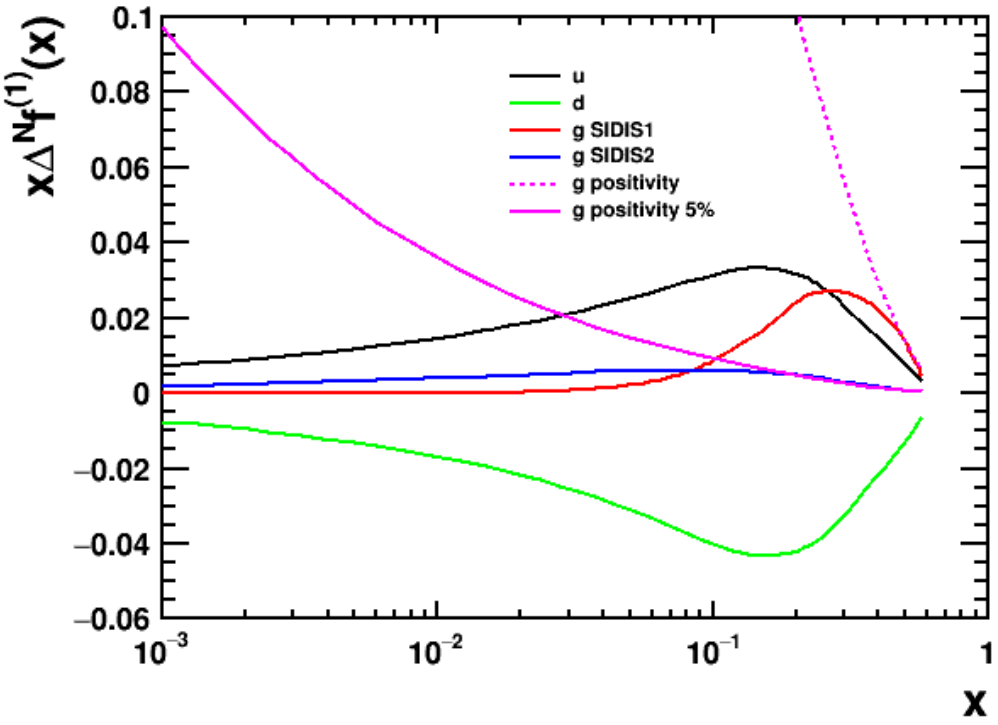
- Negative gluon Sivers saturating the positivity bound is assumed.
- Stronger asymmetry size observed for larger k_T'.

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

Inputs to the model calculation

Quark Sivers: arXiv:1107.4446 Anselmino et al.

Gluon Sivers: JHEP 09 (2015) 119 D'Alesio et al.
u,d + Kretzer FF (SIDIS1)
u,d+sea + DSS FF (SIDIS2)



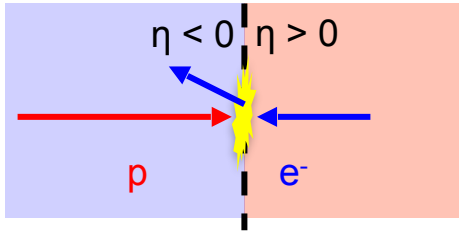
Positivity bound ansatz:

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

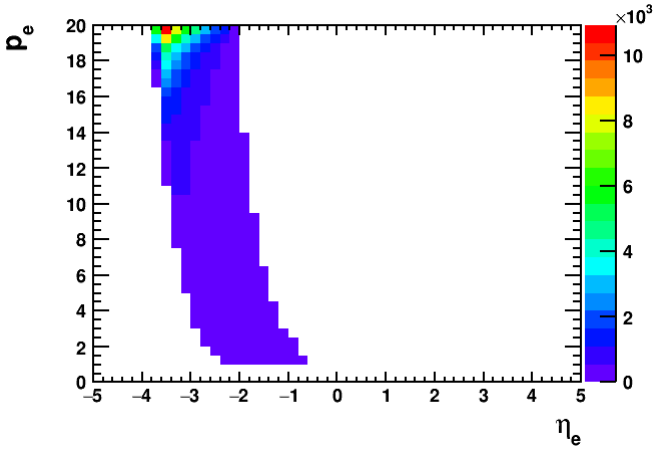
- Quark Sivers with only u and d contribution extracted from HERMES and COMPASS data.
- Gluon Sivers from a fit to RHIC A_N data.
- Fitted gluon Sivers is much smaller than quark Sivers in a wide range of x.

EIC setup for gluon SSA study

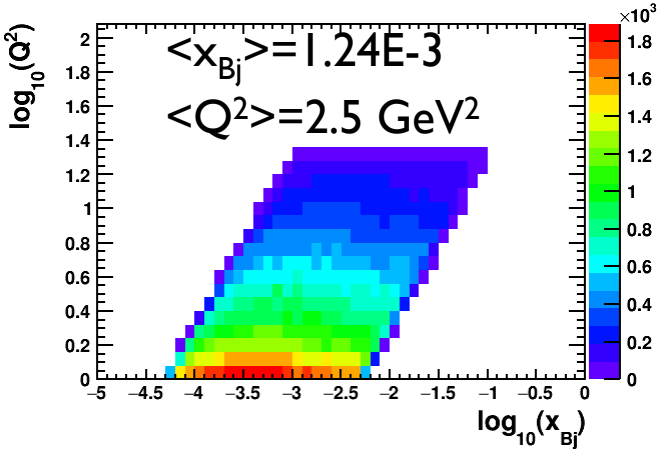
Kinematics:
ep↑ 20x250 GeV
$\sqrt{s}$=141 GeV
0.01<y<0.95
1<Q^2<20 GeV^2

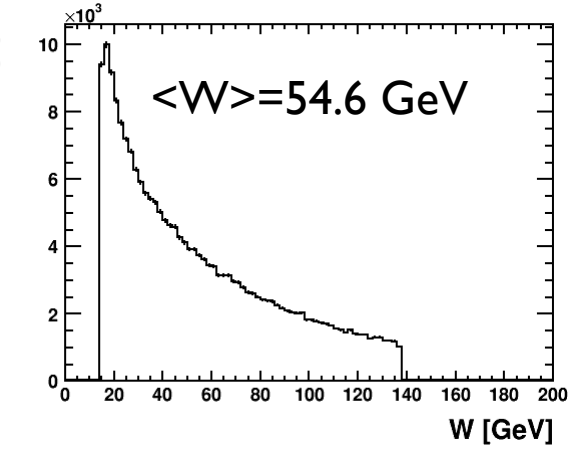


Scattered electron



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

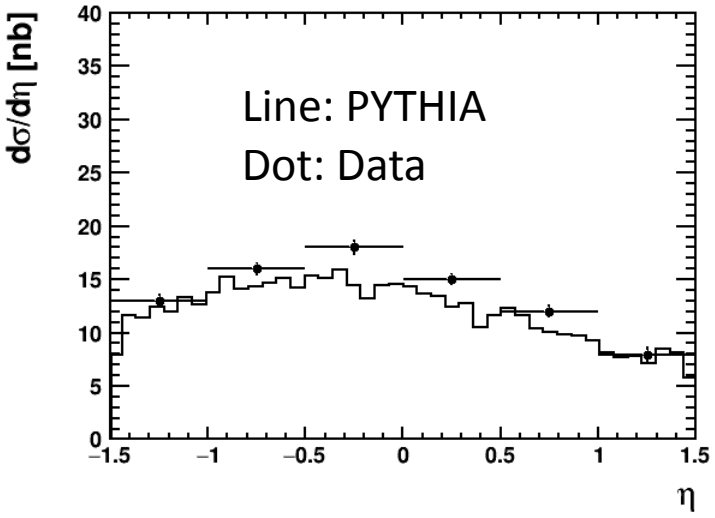


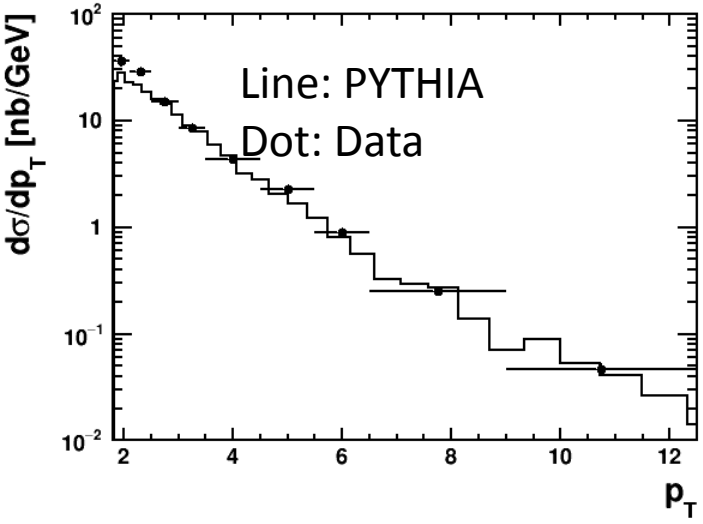


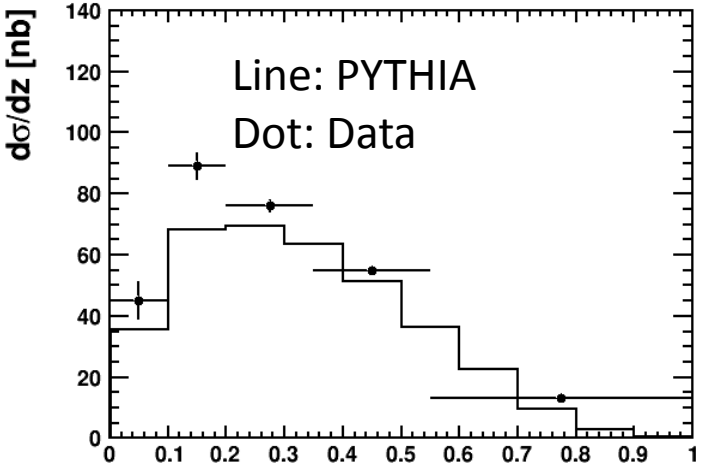
PYTHIA confronted with HERA data

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, $|\eta|<1.5$
p_T, η defined in gamma-hadron center of mass frame







Simulation describes the data trend.

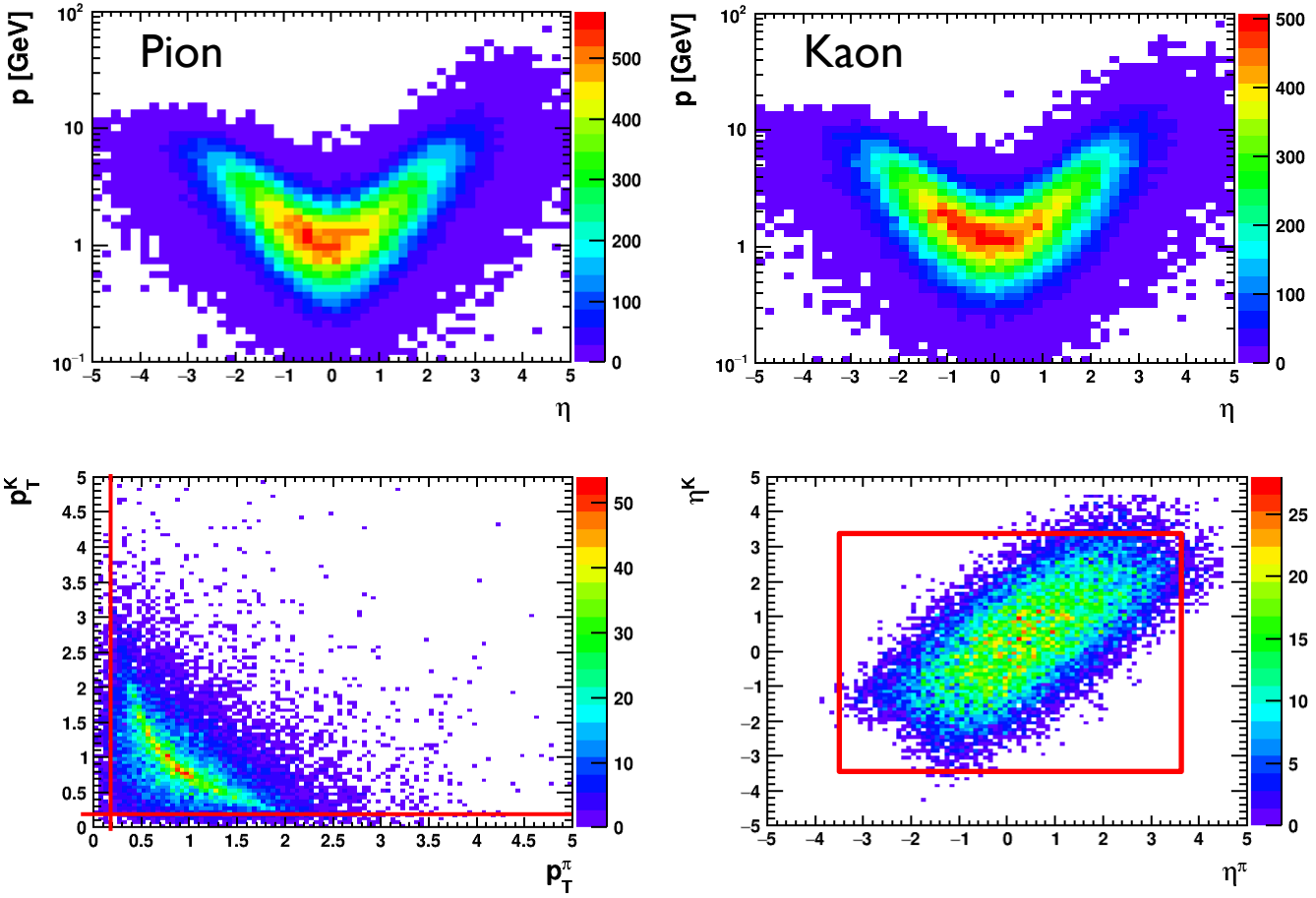
D^0 pair selection

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

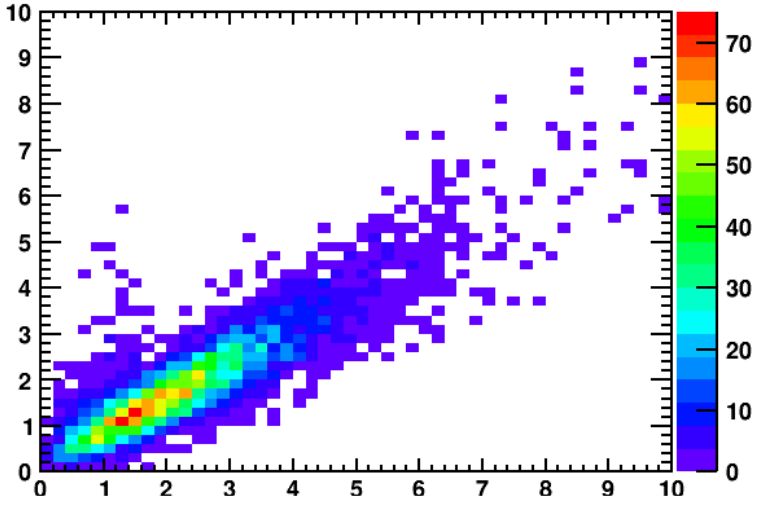
$\bar{D}^0(\bar{c}u) \rightarrow \pi^-(\bar{u}d)K^+(u\bar{s})$

Branching ratio: 3.9%

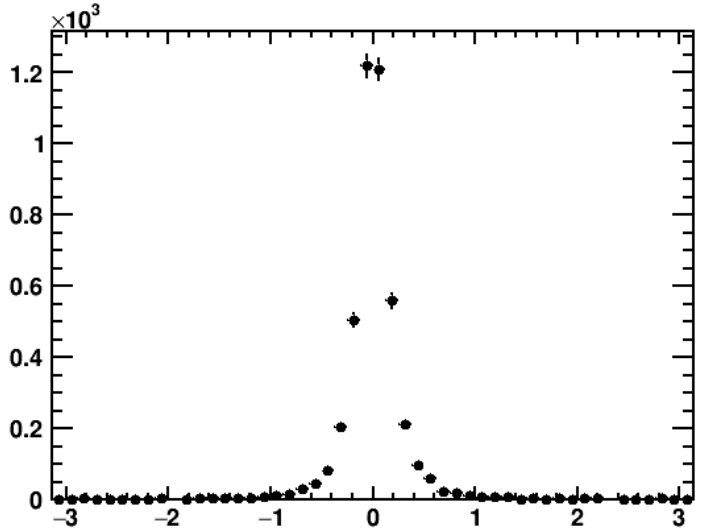
- Acceptance for PID is assumed to be |η| <3.5
- Decay products from D mesons are mostly less than 10 GeV within |η|<1
- Decay products p_T>0.2 GeV (94% survival)



D^0 as charm quark proxy



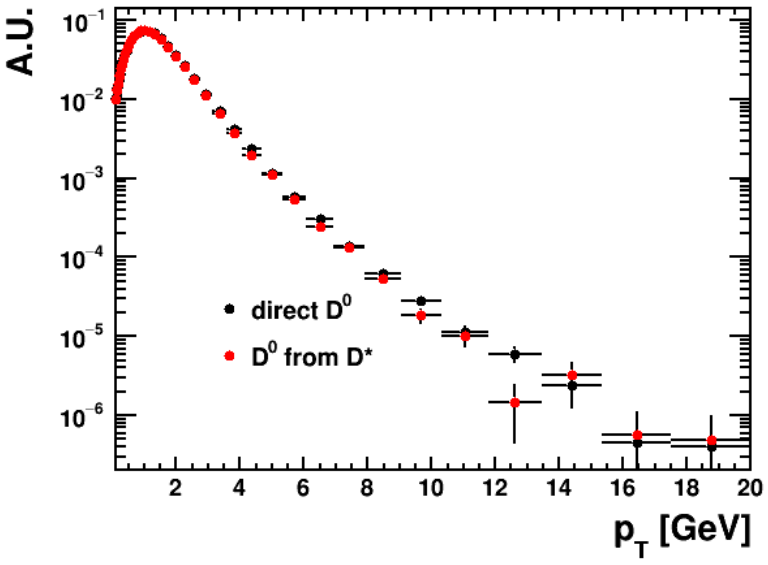
p_T D^0 vs p_T c-quark (GeV)

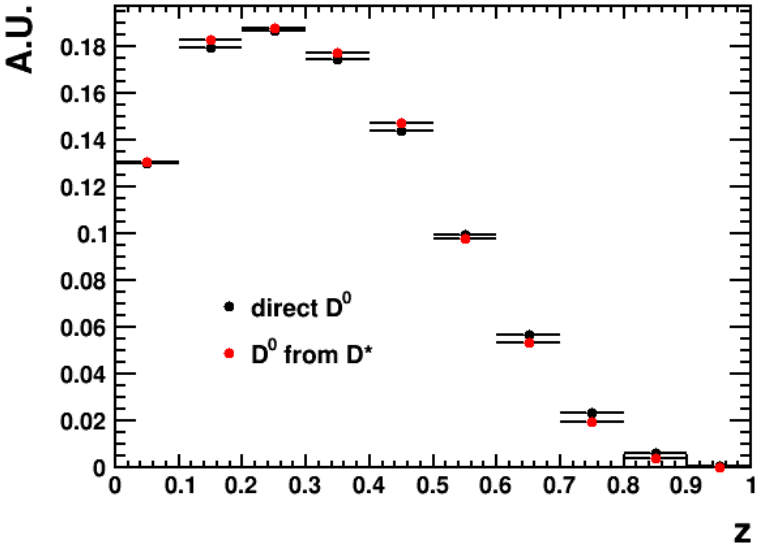


$\Phi_{c\text{-}quark} - \Phi_{D^0}$

D^0 meson takes a large fraction of the charm quark energy, serves as a proxy to the c-quark information.

D^0 feed-down from D*



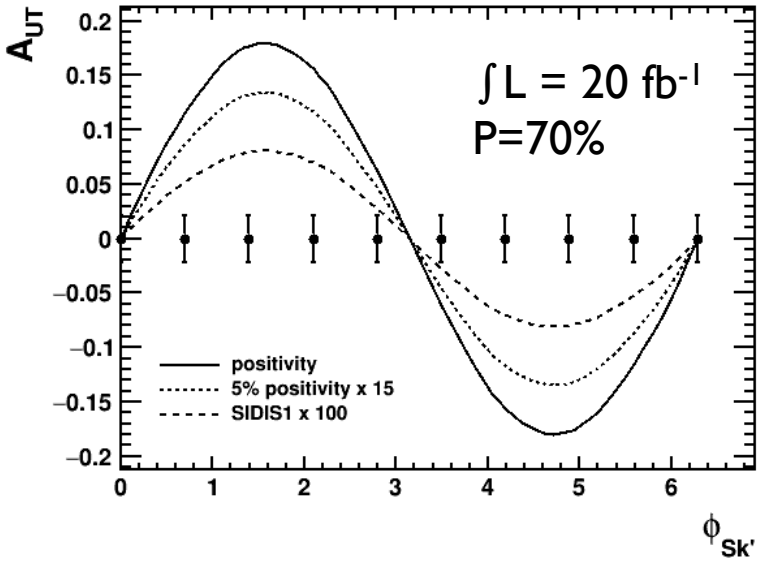


D^0 from D* decay similar to the directly generated D^0s, therefore all D^0s are analyzed.

Projections for the SSA with D^0 pairs

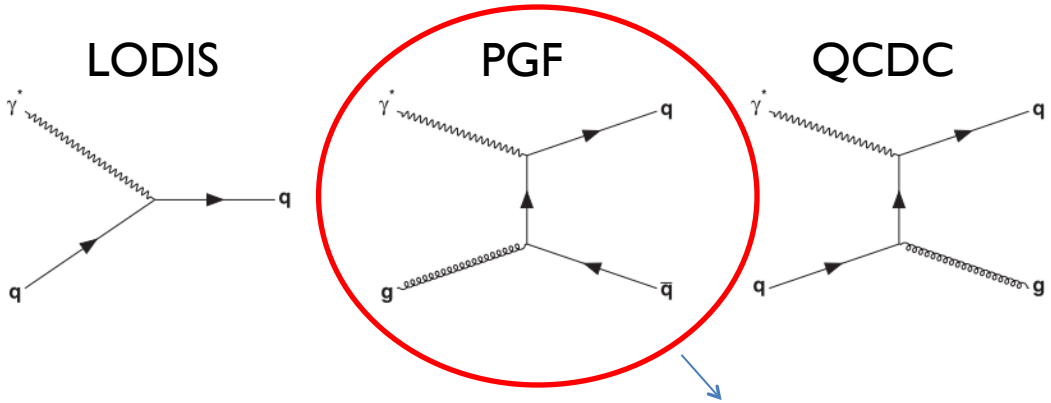
$$ep^{\uparrow} \rightarrow e' c\bar{c} X$$

- ep 20x250 GeV
- $D^0 \rightarrow K\pi$ in acceptance
- $p_T > 0.2$ GeV, $z > 0.1$
- correlation limit: $k_T < 0.5 * P_T$
- $\langle x_g \rangle = 0.03$
- $\sigma_{DDbar} = 2.7 \times 10^{-3}$ nb
- Integrated luminosity 20 fb^{-1}: $\delta A_{UT} \sim 0.02$



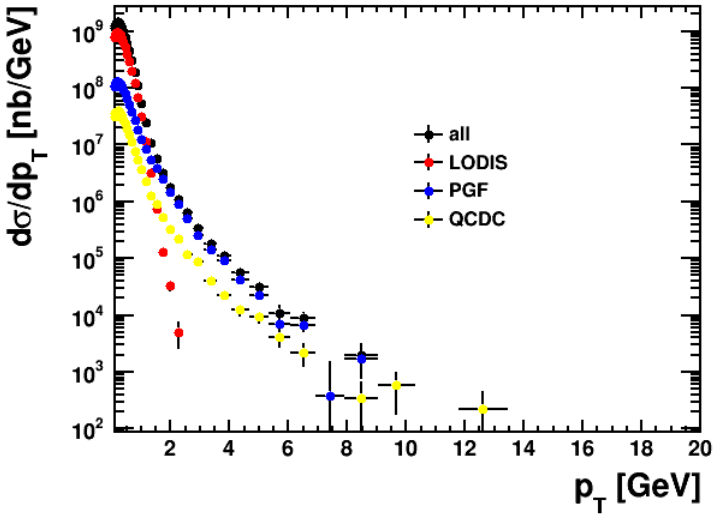
The statistical uncertainty obtained with P=70% polarization $(\delta A_{UT})^2 = \frac{1}{P^2 \sigma L}$

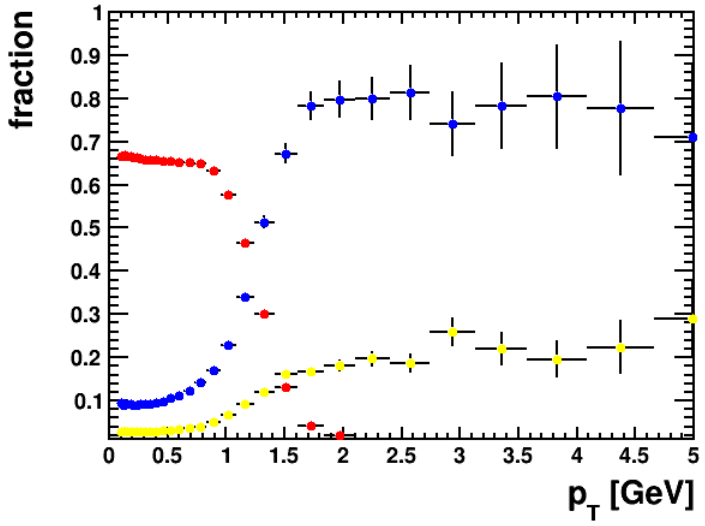
Dihadron pair in PGF



Signal

p_T>1.7 GeV effectively enhances the gluon initiated process.





Dihadron pair selection

Kinematic cuts:

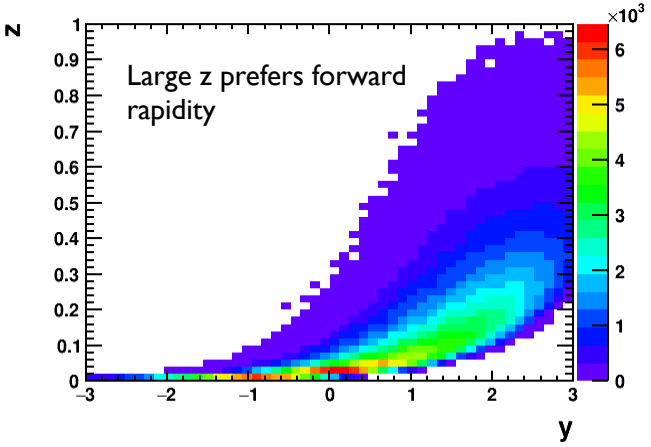
ep 20x250 GeV

$0.01<y<0.95$

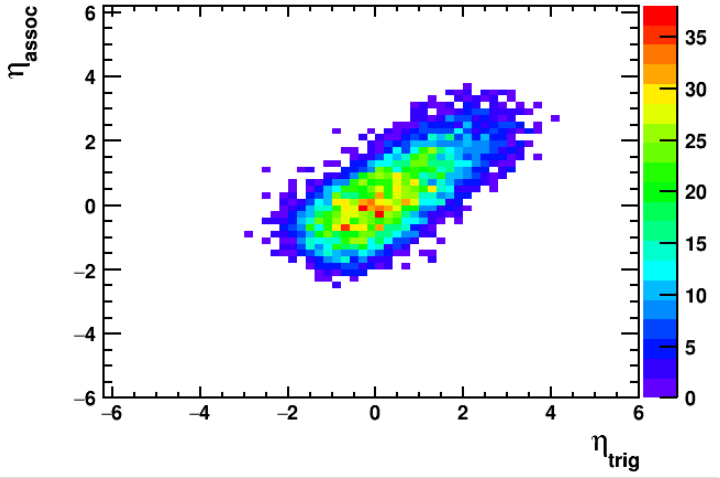
$1<Q^2<20\ GeV^2$

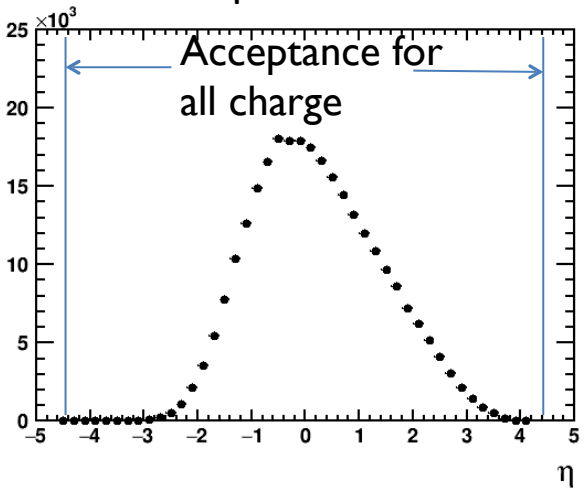
$p_T>1.7$ GeV, $z_h>0.1$, $|\eta|<4.5$

Back-to-back limit: $k_T' < 0.7P_T'$



Hadron pair distribution





Projections on the SSA with charged dihadron pairs

Kinematic cuts:

ep 20x250 GeV

$0.01<y<0.95$

$1<Q^2<20\ \mathrm{GeV}^2$

$p_T>1.7$ GeV, $z_h>0.1$, $|\eta|<4.5$

Back-to-back limit: $k_T' < 0.7P_T'$

$\sigma_{dihadron}=0.5$ nb

$\langle x_g \rangle=0.063$

- Resolution power down to the SIDIS1 set constrained by RHIC A_N data.
- PGF events accounting for 80%.
- Integrated Luminosity: 20 fb^{-1} delivers δA_{UT} ≈ 1.4x10^{-3}

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

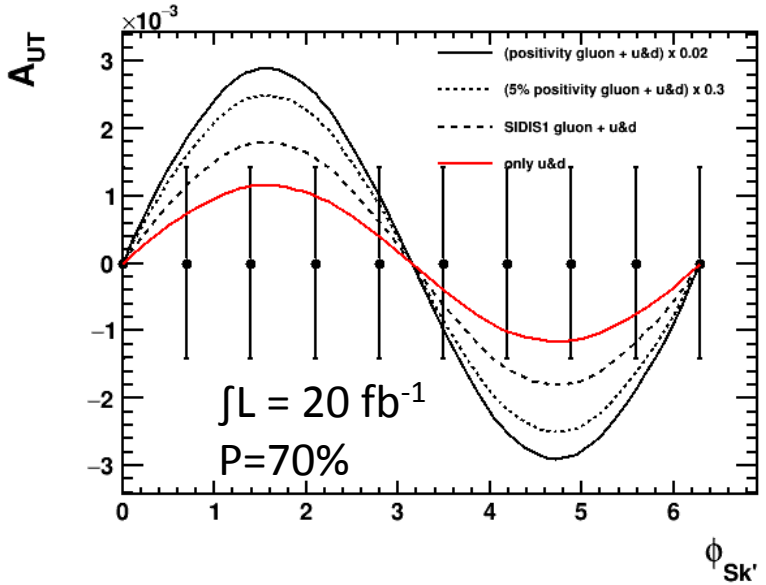
SIDIS1 Set

$$N_g = 0.65, \alpha_g = 2.8, \beta_g = 2.8, M_g^2 = 0.43\mathrm{GeV}^2$$

Quark Sivers parameters (Anselmino et al.)

$$N_u = 0.4, \alpha_u = 0.35, \beta_u = 2.6,$$
$$N_d = -0.94, \alpha_d = 0.44, \beta_d = 0.9,$$
$$M_u^2 = M_d^2 = 0.19\mathrm{GeV}^2$$

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



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, |η|<3.5

Back-to-back limit: k_T' < 0.7P_T'

$\sigma_{K^+K^-}$=1.6x10^{-2} nb

<x_g>=0.05

- Resolution power down to 5% positivity bound.
- PGF events accounting for 92.7%.
- Integrated Luminosity: 20 fb^{-1} delivers δA_{UT} ≈ 5.5x10^{-3}

Difference between black and red shows the effect of gluon Sivers

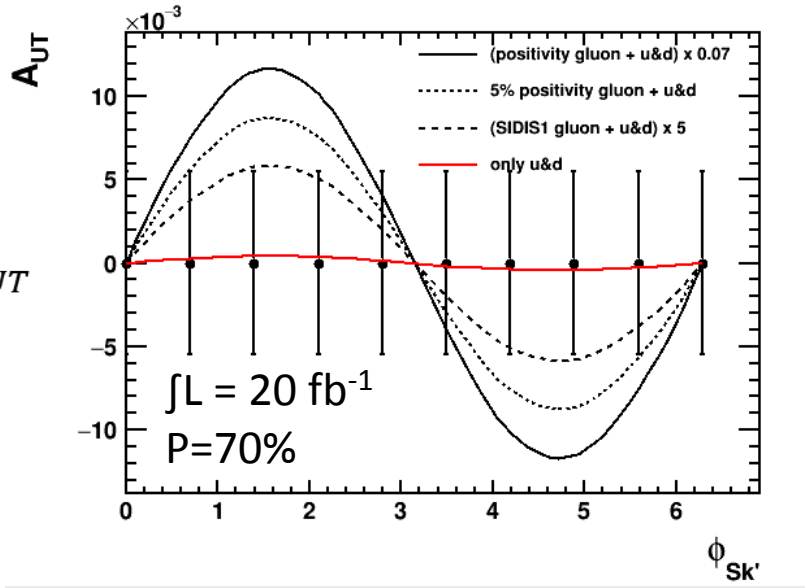
SIDIS1 Set

$$N_g = 0.65, \alpha_g = 2.8, \beta_g = 2.8, M_g^2 = 0.43\text{GeV}^2$$

Quark Sivers parameters (Anselmino et al.)

$$N_u = 0.4, \alpha_u = 0.35, \beta_u = 2.6,$$
$$N_d = -0.94, \alpha_d = 0.44, \beta_d = 0.9,$$
$$M_u^2 = M_d^2 = 0.19\text{GeV}^2$$

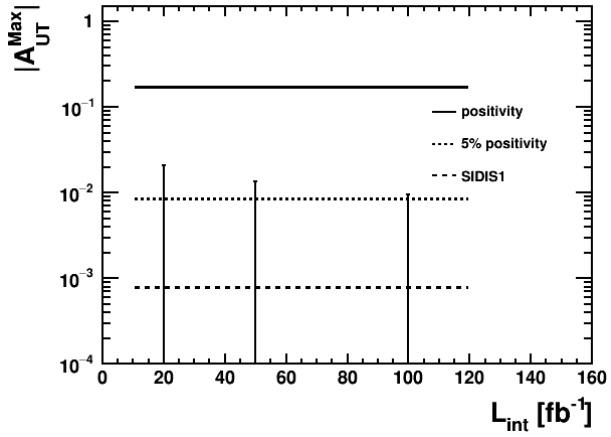
$$A(\phi_{Sk}) = R^{SIG} A^{SIG}(\phi_{Sk}) + R^{BG} A^{BG}(\phi_{Sk})$$



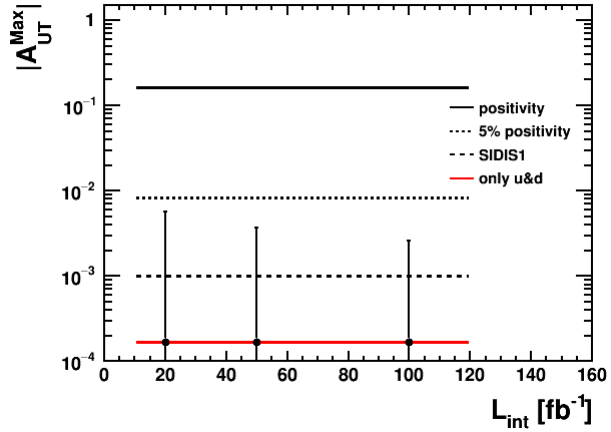
Resolution power of all the probes

Gluon Sivers effect is a luminosity hungry measurement. Vertical bar shows the statistical uncertainty at that integrated luminosity.

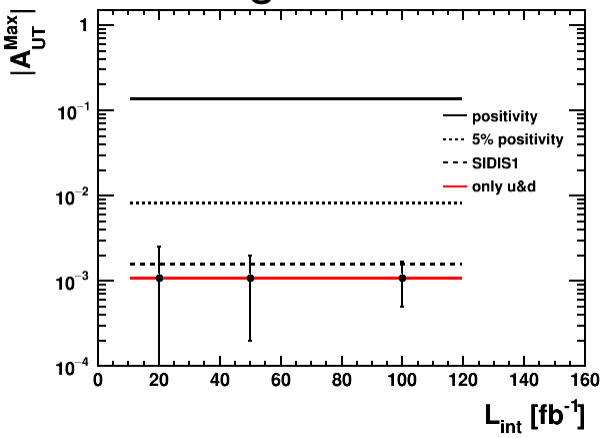
D meson



K^+K^-



Charged dihadron



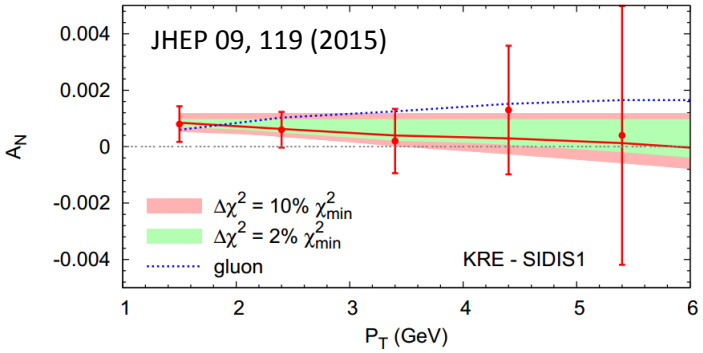
Summary

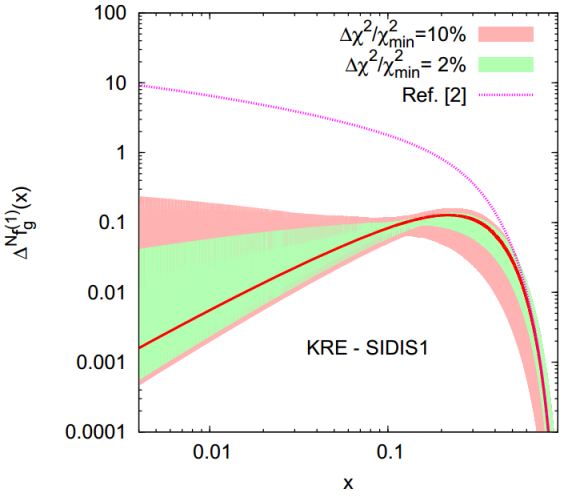
- Gluon TMDs is ingredient of complete 3D imaging of nucleon, and can be uniquely measured at EIC by measuring gluon Sivers function
- Gluon Sivers can be accessible and constrained in a wide kinematic range via photon-gluon coupling - D^0 pair, K^+K^-, h^+h^- within EIC's machine and detector reach

BACKUP

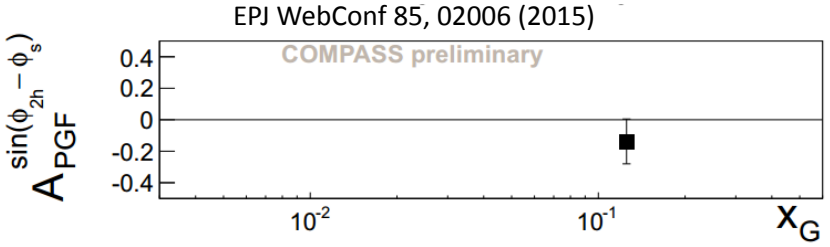
Current constraints on gluon Sivers

Extraction based on A_N data at RHIC (pi0)





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.

Extraction of quark Sivers

- Ansatz for transverse momentum and x dependence
- Sizable Sivers effect
- u, d quark Sivers with opposite sign

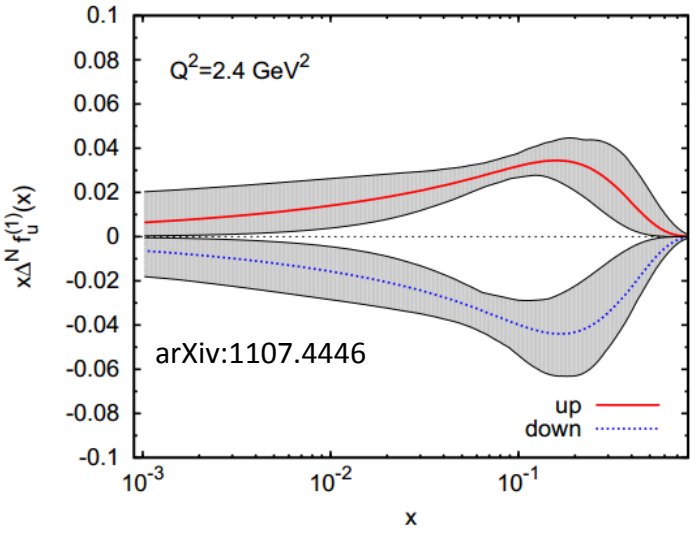
$$\hat{f}_{a/p^\uparrow}(x,k_\perp) = f_{a/p}(x,k_\perp) - f_{1T}^{\perp a}(x,k_\perp)\frac{\vec{S}\cdot(\hat{\vec{P}}\times\vec{k}_\perp)}{M_p}$$

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

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

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

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



Barely known for the gluon Sivers!

Inputs to the model calculation

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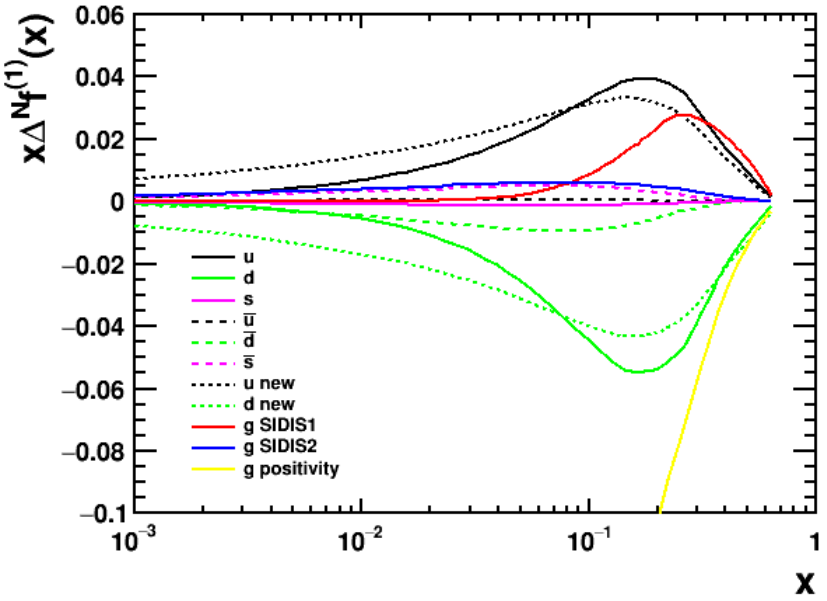
$N_u = 0.35^{+0.08}_{-0.08}$ $N_d = -0.90^{+0.43}_{-0.10}$ $N_s = -0.24^{+0.62}_{-0.50}$

$N_{\bar{u}} = 0.04^{+0.22}_{-0.24}$ $N_{\bar{d}} = -0.40^{+0.33}_{-0.44}$ $N_{\bar{s}} = 1^{+0}_{-0.0001}$

$\alpha_u = 0.73^{+0.72}_{-0.58}$ $\alpha_d = 1.08^{+0.82}_{-0.65}$ $\alpha_{sea} = 0.79^{+0.56}_{-0.47}$

$\beta = 3.46^{+4.87}_{-2.90}$ $M_1^2 = 0.34^{+0.30}_{-0.16}\,(\mathrm{GeV}/c)^2$



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$N_g = 0.05$ $\alpha = 0.8$ $\beta = 1.4$ $\rho = 0.576$ (SIDIS2)

$N_g = 0.65$ $\alpha = 2.8$ $\beta = 2.8$ $\rho = 0.687$ (SIDIS1)

arXiv:1107.4446

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

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

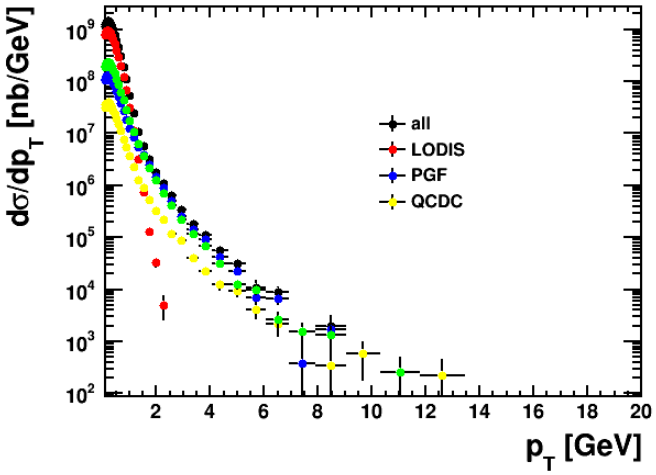
$M_1^2 = 0.19\ \mathrm{GeV}^2$

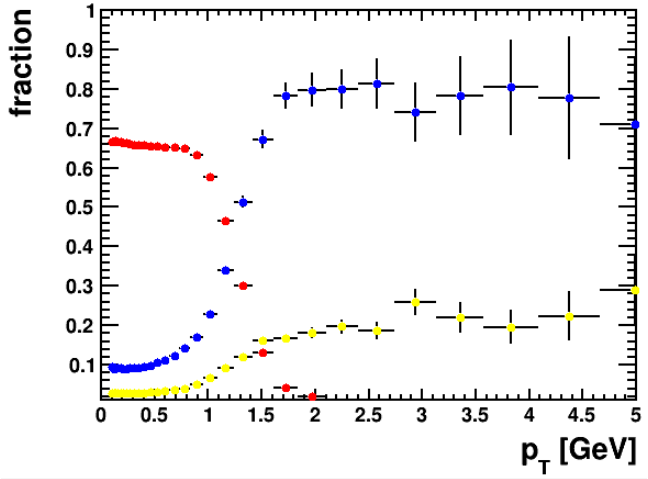
Positivity bound for gluon Sivers

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

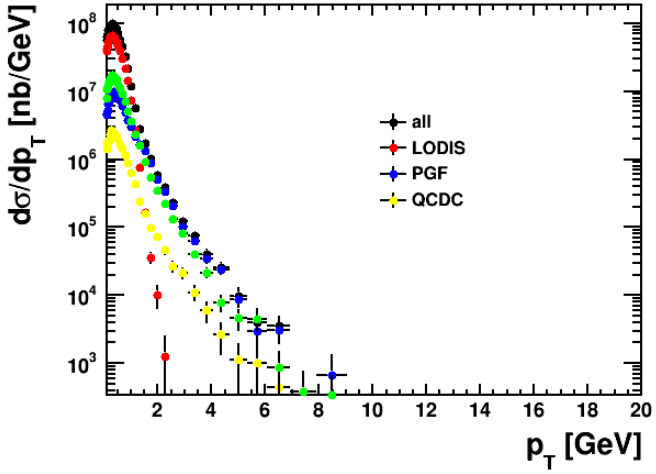
Charged hadron vs kaon spectrum

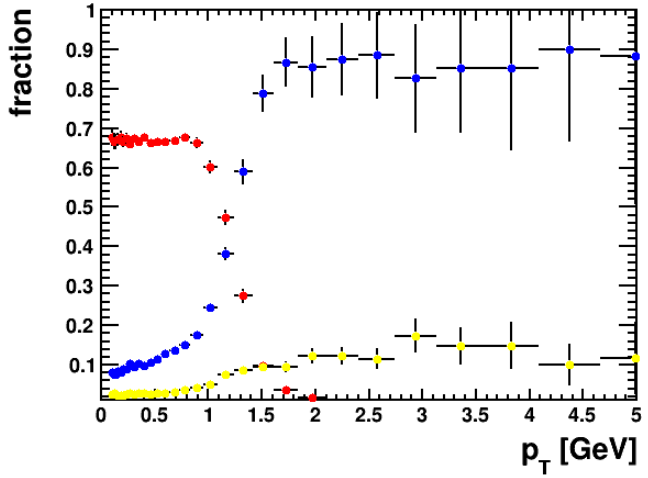
Charged hadron





Charged Kaon





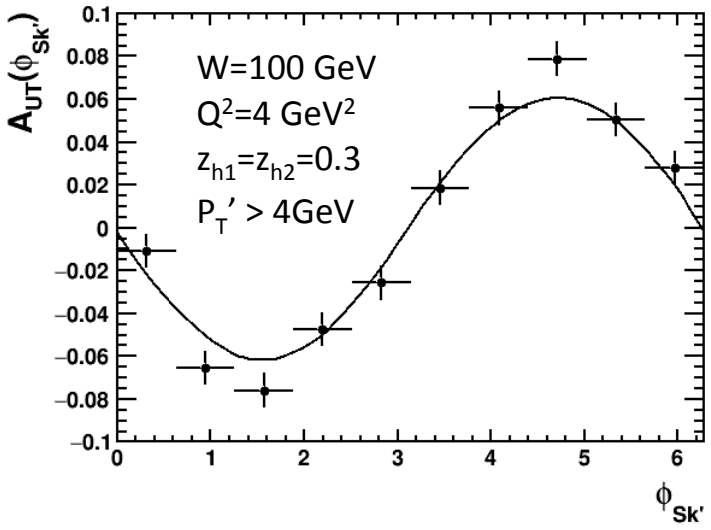
Weighting strategy vs numerical estimation

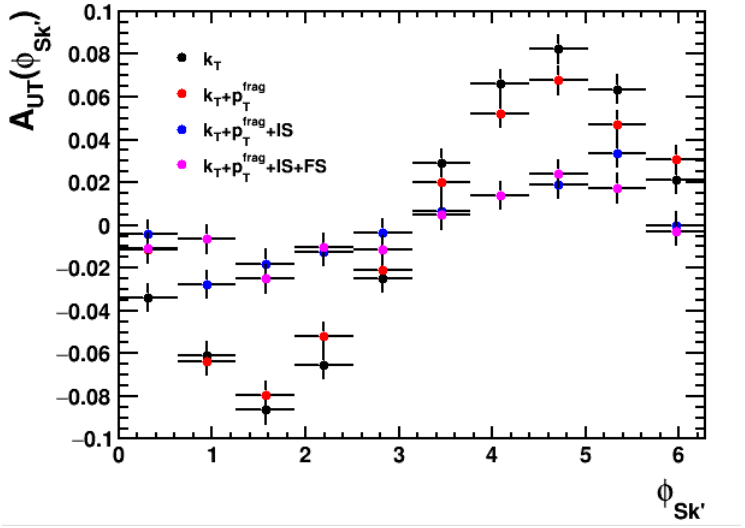
A_{UT} can be evaluated with the weighting based on input Sivers function

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

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

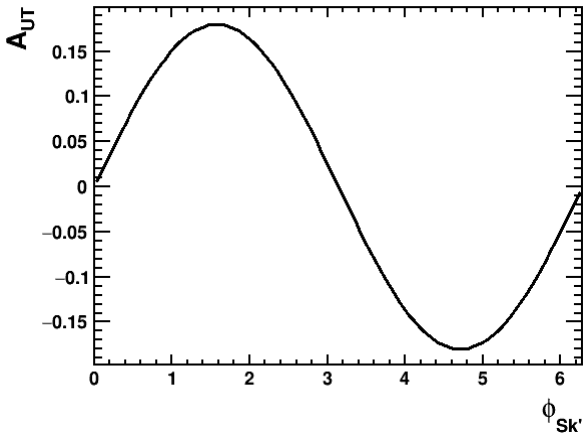
- Weighted results agree with the numerical estimations.
- Initial state parton shower suppresses the azimuthal asymmetry significantly.



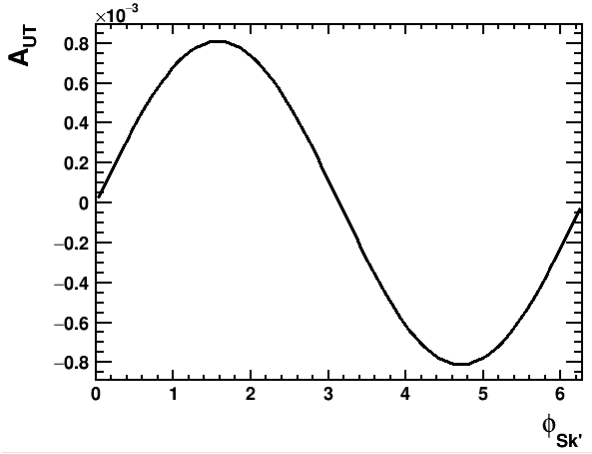


Estimates for the SSA in different processes

PGF postivity

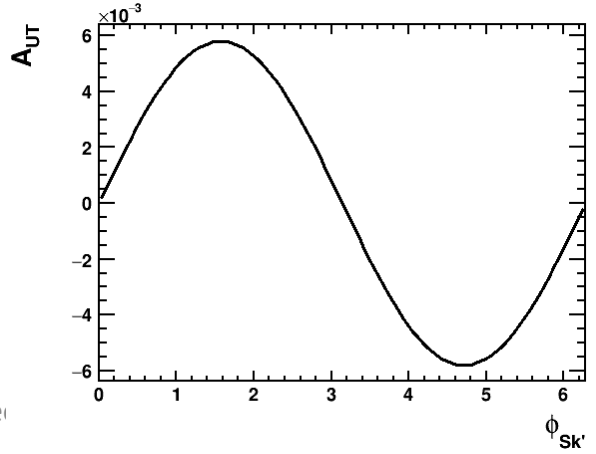


PGF SIDIS1



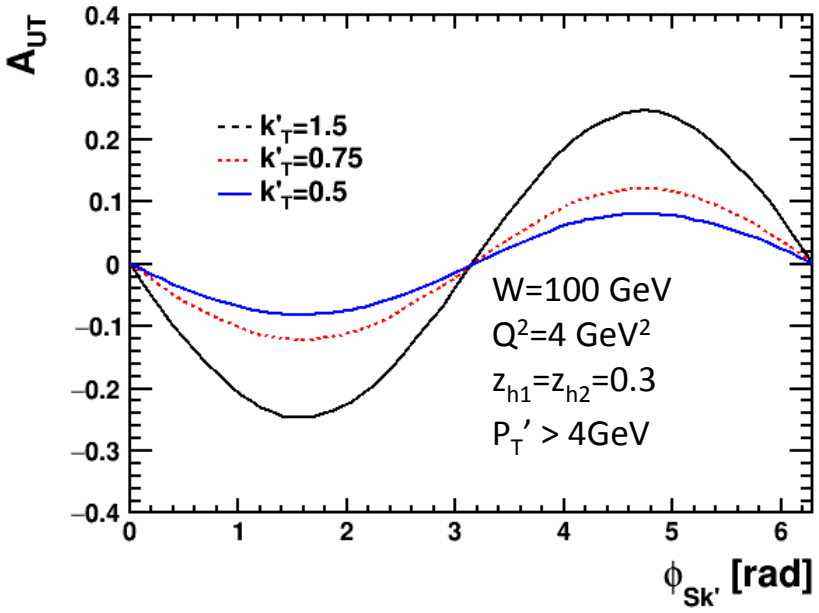
Event sample summary:
ep 20x250 GeV
$0.01<y<0.95$
$1<Q^2<20\ GeV^2$

QCDC SIDIS1

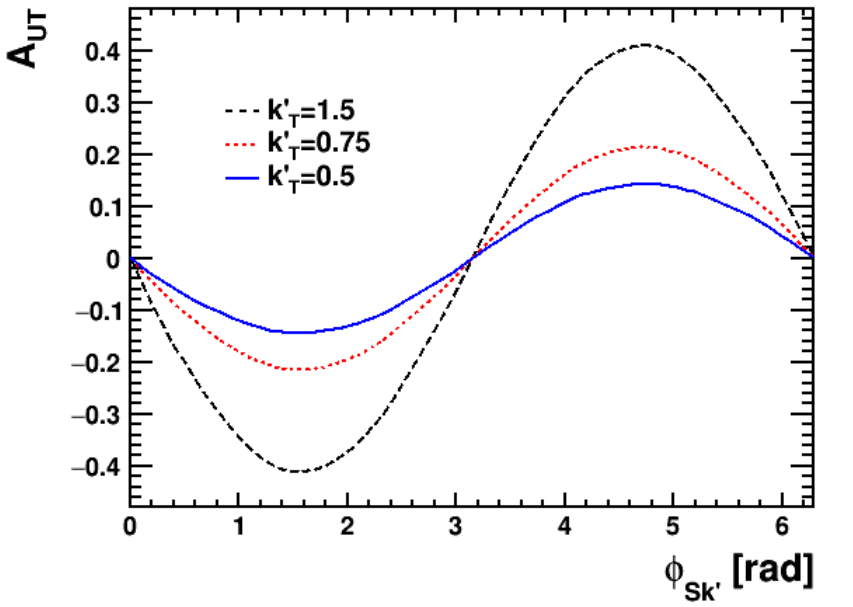


Numerical estimation of gluon SSA with positivity bound

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

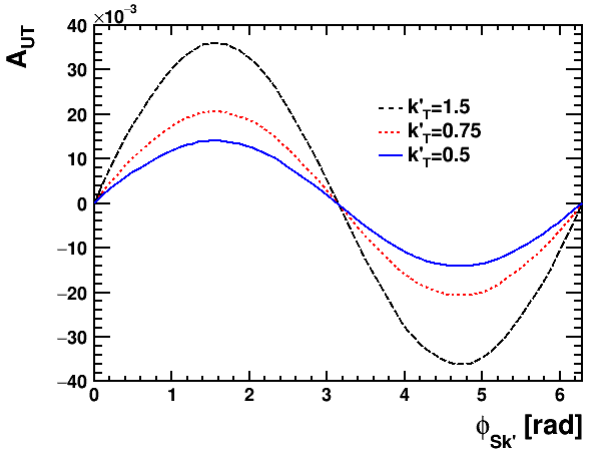


Charged dihadron $\langle p_T^2 \rangle_{frag}=0.2$

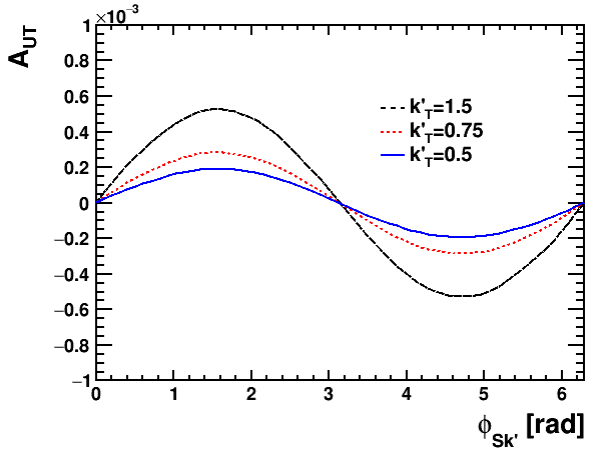


Numerical estimation of gluon SSA with data constrained parameters

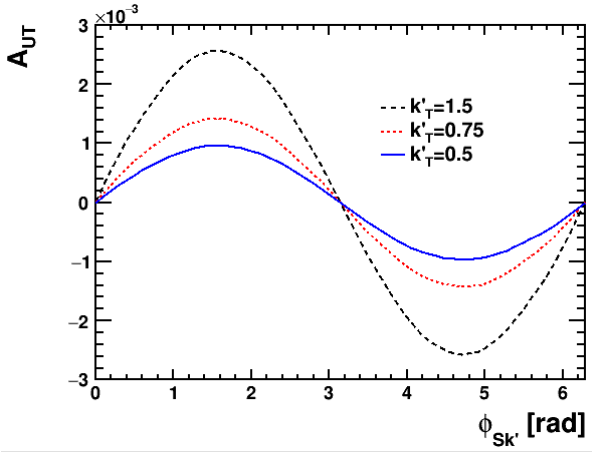
h SIDIS1 u



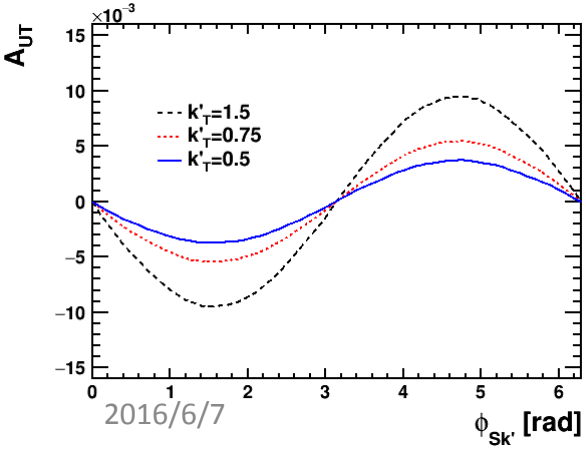
h SIDIS1 PGF



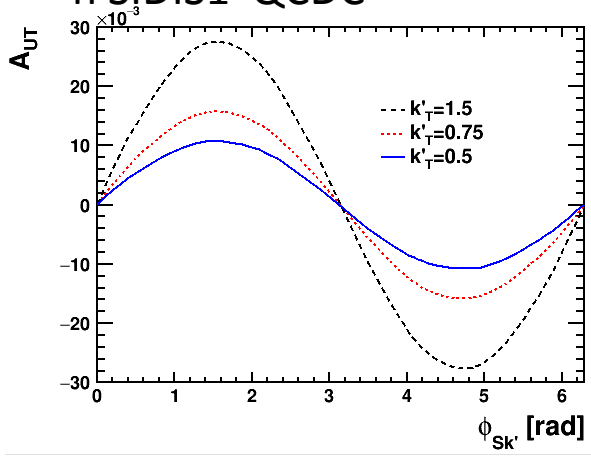
h SIDIS2 PGF



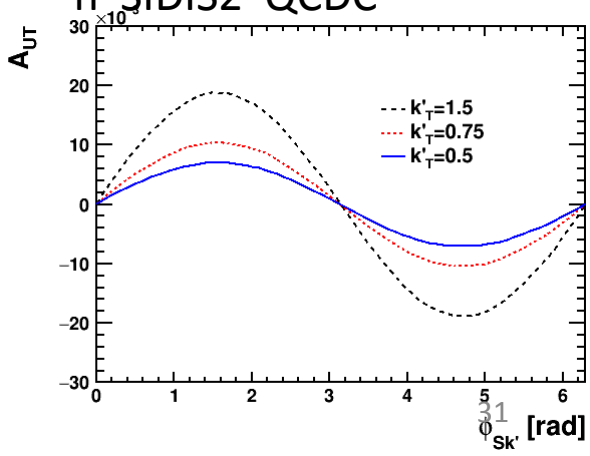
h SIDIS1 d



h SIDIS1 QCDC



h SIDIS2 QCDC

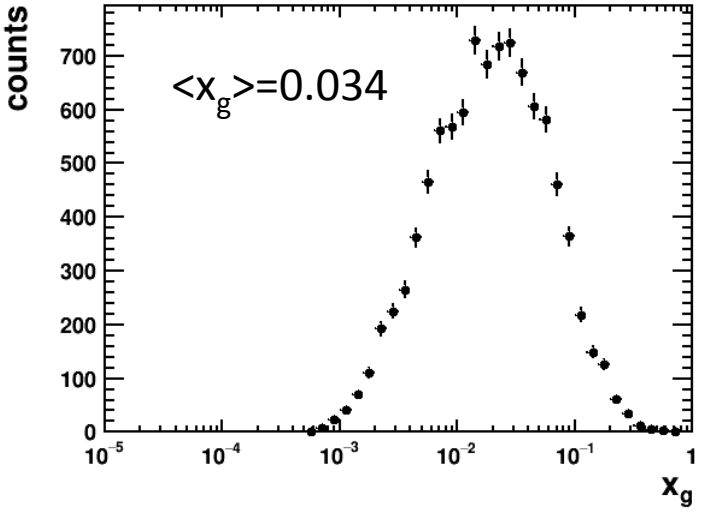


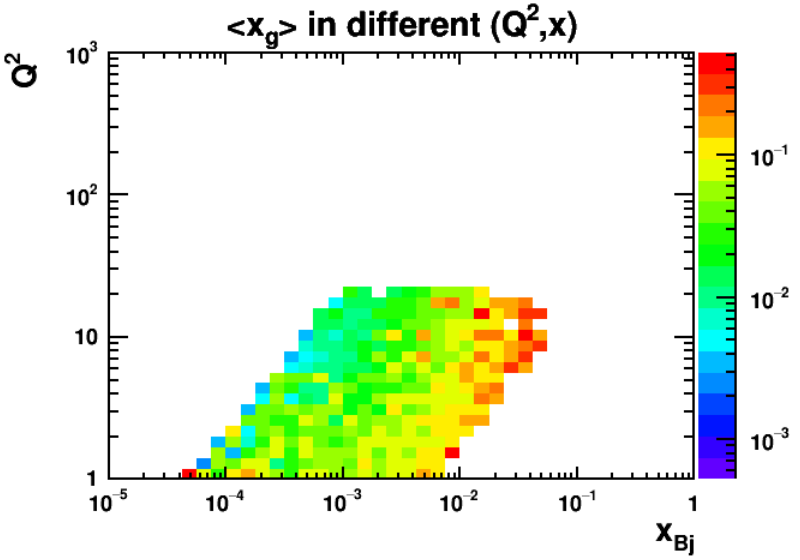
Explored gluon dynamics by the selected pairs

x_g distribution probed by the D meson pairs, overall average x_g around 10^{-2}.

<x_g> shown for every Q^2-x_{Bj} bin.

Large W ~ small x_g down to 10^{-3}.



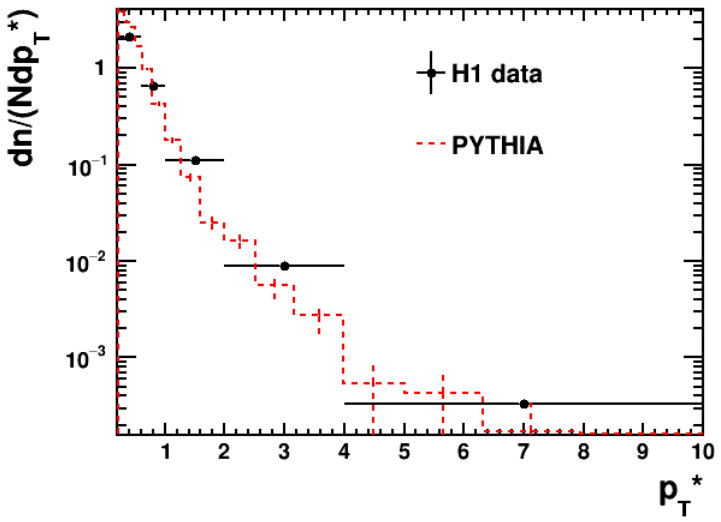


Confronting simulation with Data

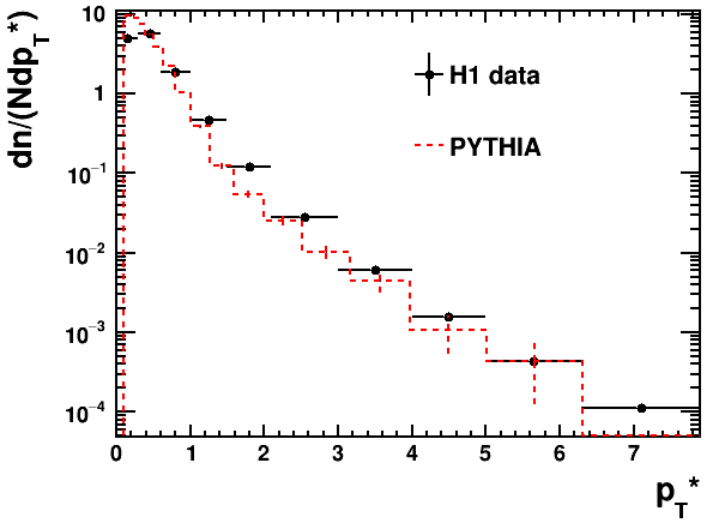
Comparing with charged hadron density measurements from HERA

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.