



Experimental Aspects of Jet Physics at a Future EIC

Xiaoxuan Chu, BNL

Santa Fe Jets and Heavy Flavor Workshop, UCLA, 2019

- ❑ L. Zheng, E.C. Aschenauer, J.H. Lee, Bo-Wen Xiao, and Zhong-Bao Yin, Phys. Rev. D 98 (2018), 034011
- ❑ B. Page, X. Chu and E.C. Aschenauer, Experimental aspects of jets at EIC, arxiv soon
- ❑ X. Chu, E.C. Aschenauer and J.H. Lee, Phys. Rev. D96 (2017), 074035



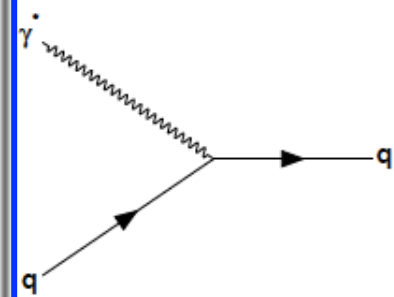
Jets in ep collisions

Jets at EIC: How jets are reconstructed, how do jets look like...

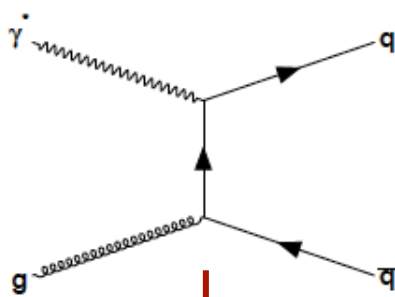
High p_T dijets are produced
Underlying events via dijet method

Direct process

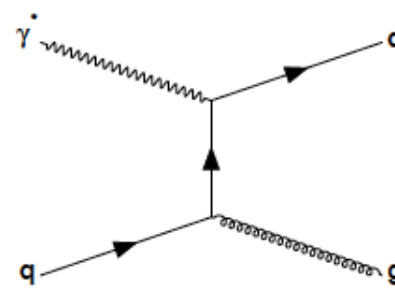
LO DIS



Photon Gluon Fusion (PGF)

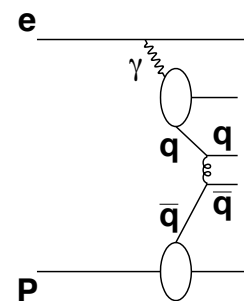


QCD Compton (QCDC)



Probe the parton dynamics inside the proton:
i.e. ΔG , Gluon Sivers function, ...

Resolved process



Low Q^2 events, quasireal
photon production,
probe the **photon**
structure

Jet Algorithm

➤ Cone- Type algorithm

➤ **SISCone**: All circles defined by pairs of edge points are all stable cones

➤ Clustering algorithm

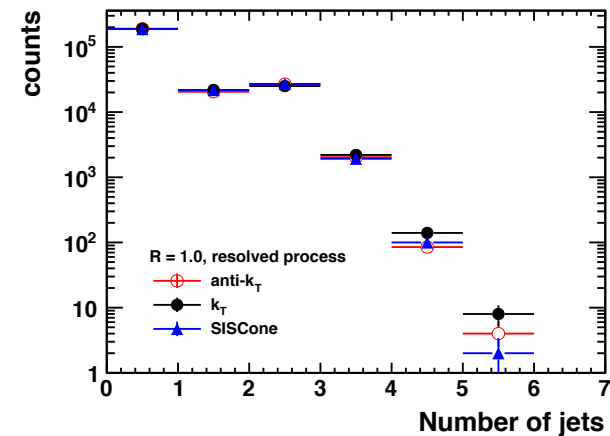
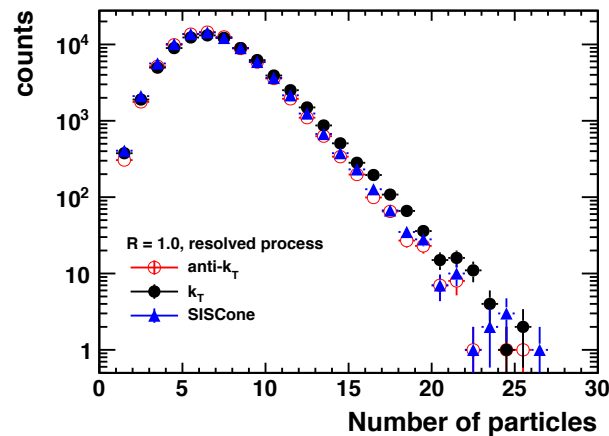
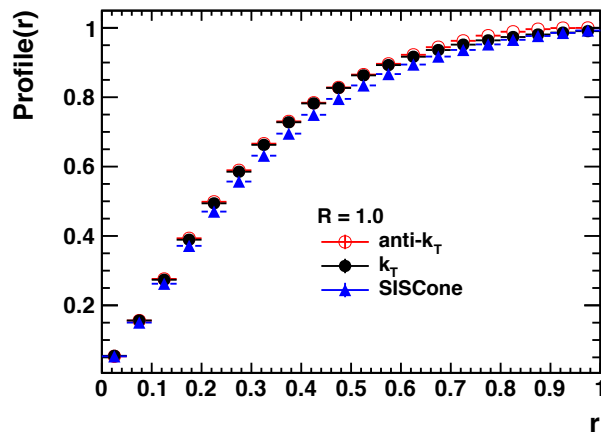
➤ k_T algorithm

➤ **Anti- k_T algorithm**

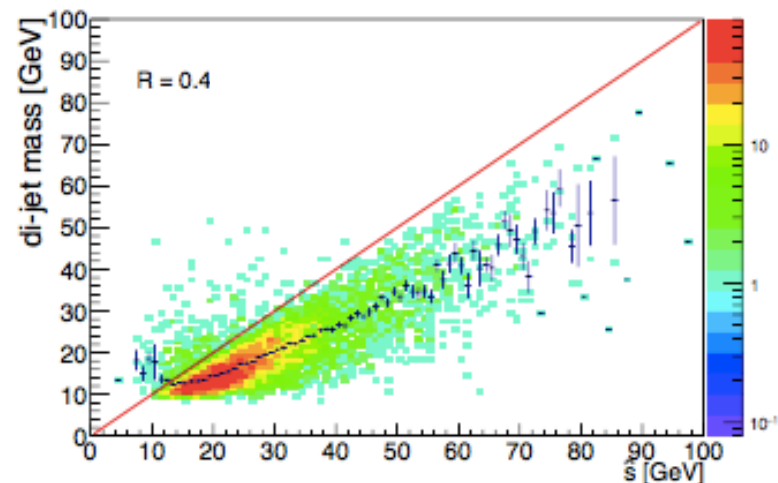
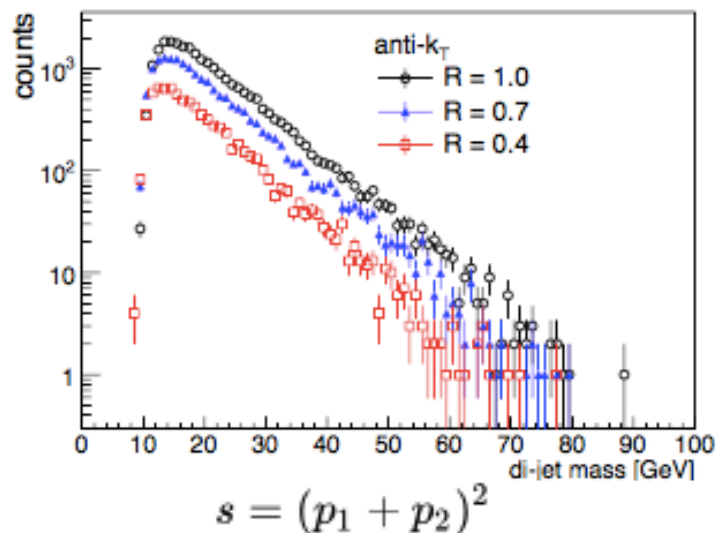
ep: 20×250 GeV

Particles selection:

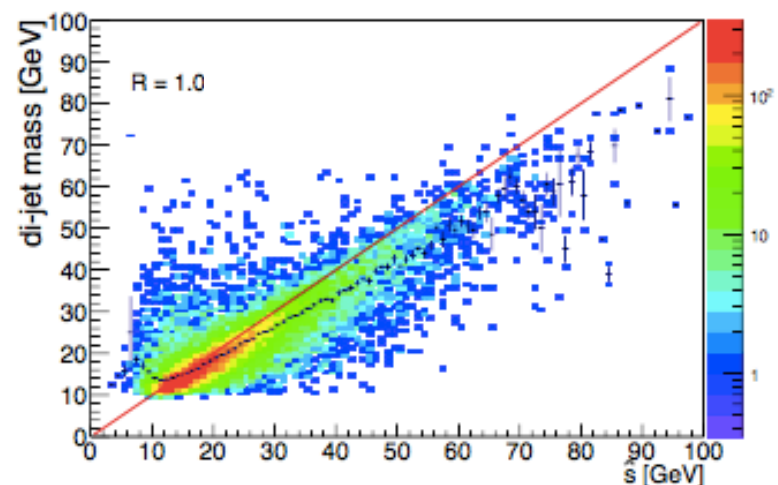
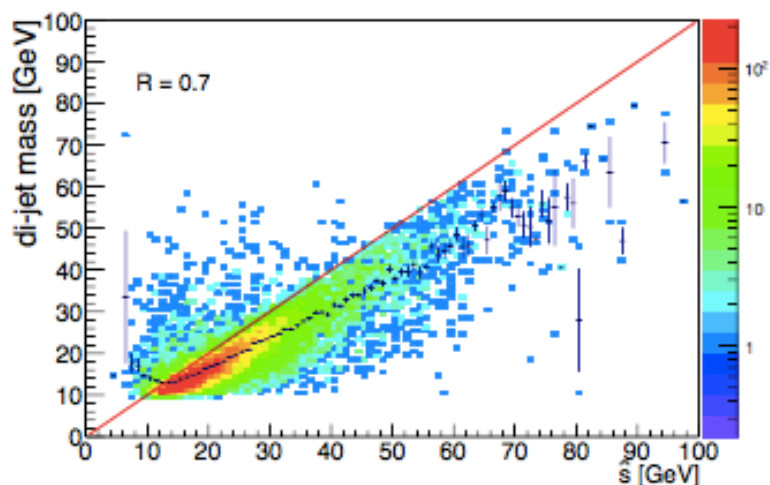
stable particles, $p_T > 250$ MeV/c, $-4.5 < \eta < 4.5$



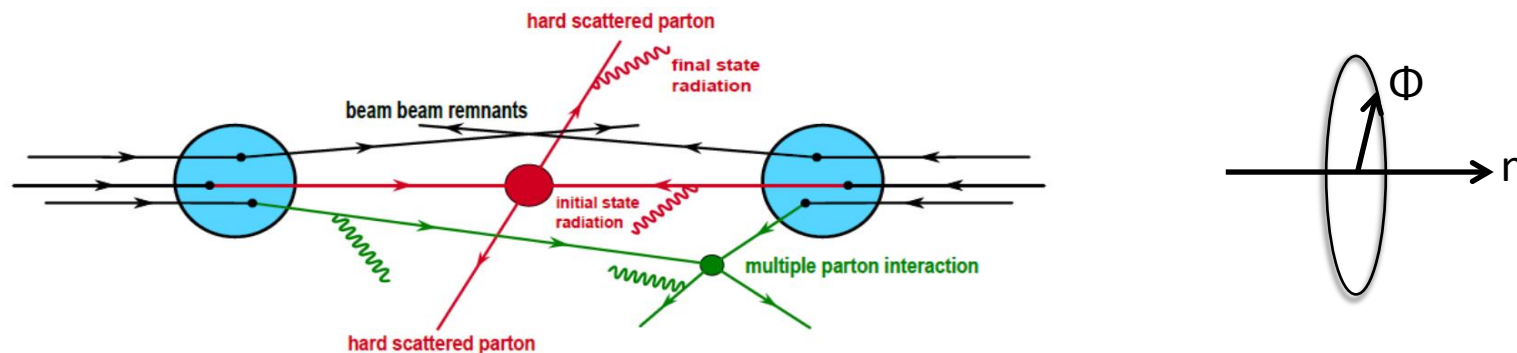
Jet Radius



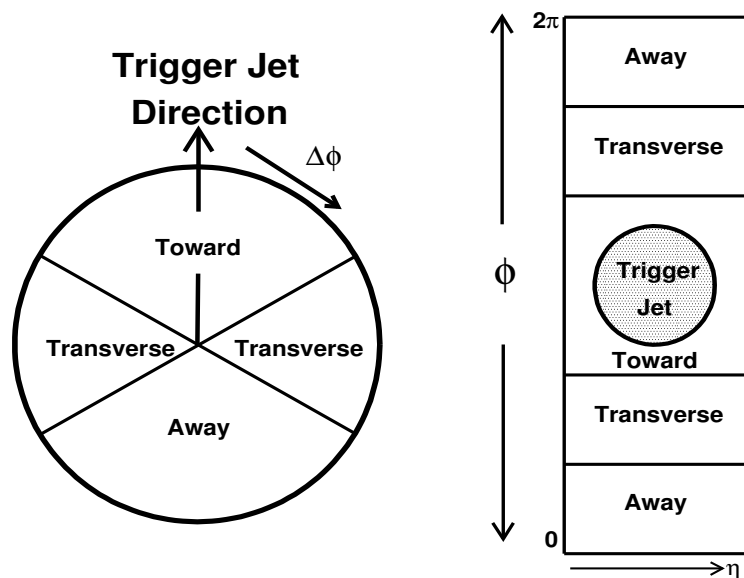
$$M \approx \sqrt{2p_{T1}p_{T2} (\cosh(\Delta\eta) - \cos(\Delta\phi))}$$



Underlying events

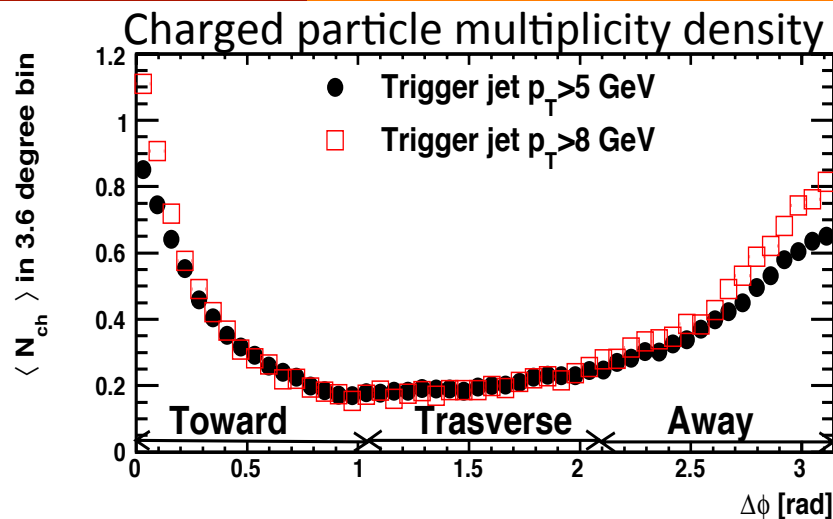


Underlying events: everything except the particles fragmented from the hard scattered partons

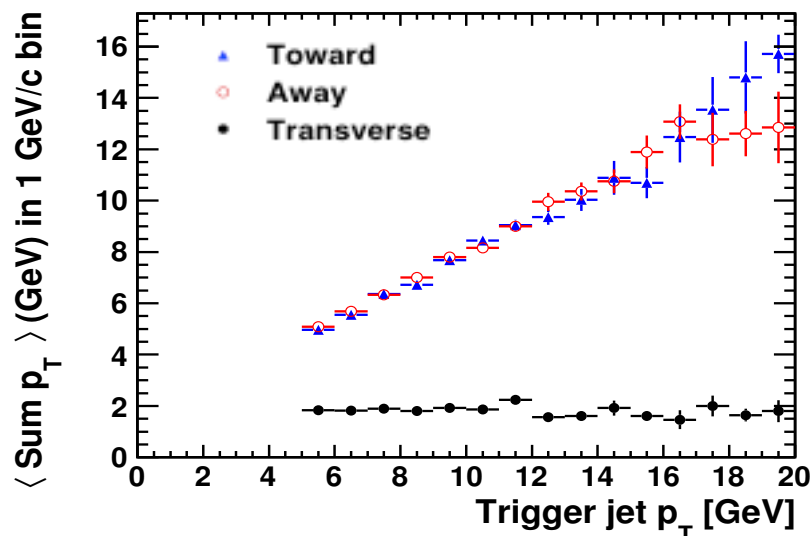
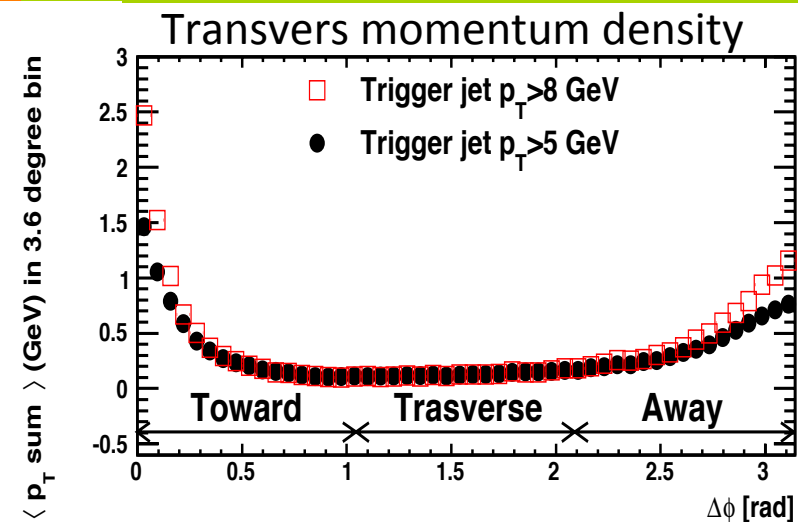


- **Toward:** $|\Delta\Phi| < 60$ degree,
 - **Transverse:** $60 < |\Delta\Phi| < 120$,
 - **Away:** $|\Delta\Phi| > 120$
 - Trigger Jet is Jet with highest p_T ,
 $\Delta\Phi = \Phi_{\text{part}} - \Phi_{\text{Jet1}}$
- Measurements**
- charged multiplicity density,
sum p_T density
 - Density difference in 3 regions

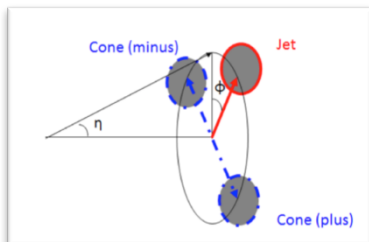
Underlying events



Transverse region:
No dependence on trigger jet p_T

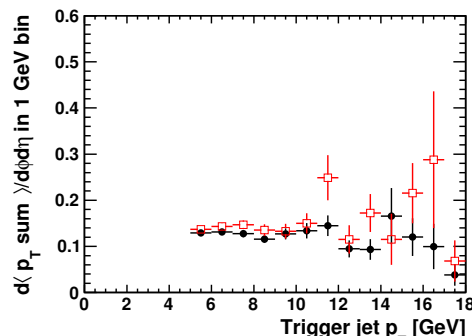
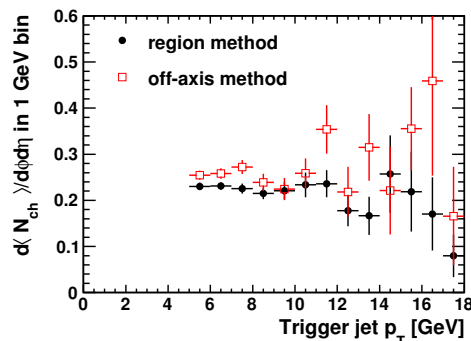


Off-axis method

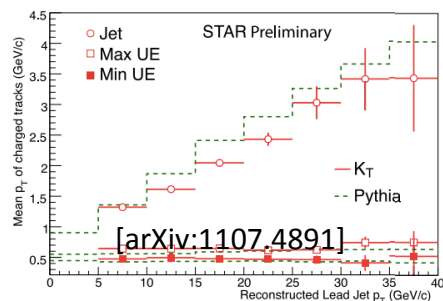


[Phys. Rev. D 91, 112012 (2015)]

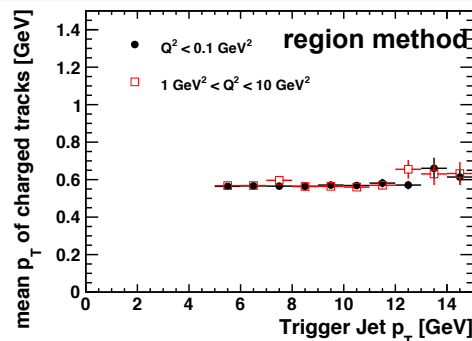
- ✓ In each event, we analyze jets with high momentum, jet by jet.
- ✓ For each jet, we define two cones ($r = 0.4$).
- ✓ Each cone is centered at the same as the jet but $\pm\pi/2$ away in Φ from the jet Φ .
- ✓ Take the particles from the two cones as underlying event.



Results from the two different methods are consistent.

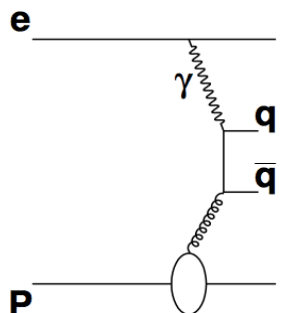


[arXiv:1107.4891]



Compared with data from STAR.

Dijet method to probe the resolved photon



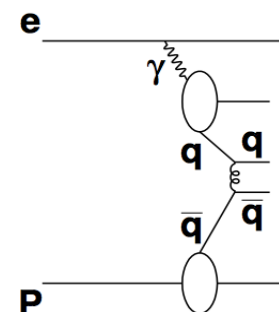
PGF: Di-jet produced

“Direct process”

- Point-like photon (no substructure)
- x_γ is equal to 1

“Resolved process”

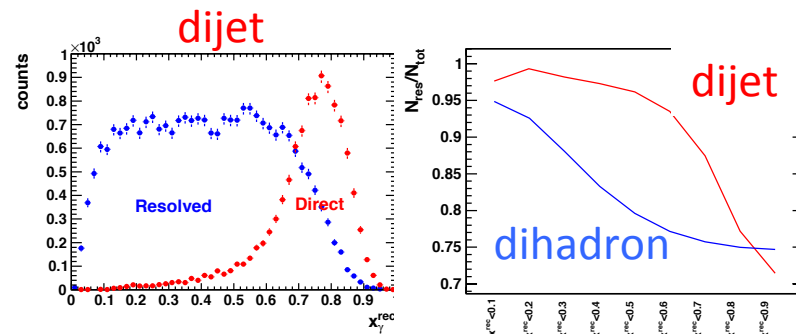
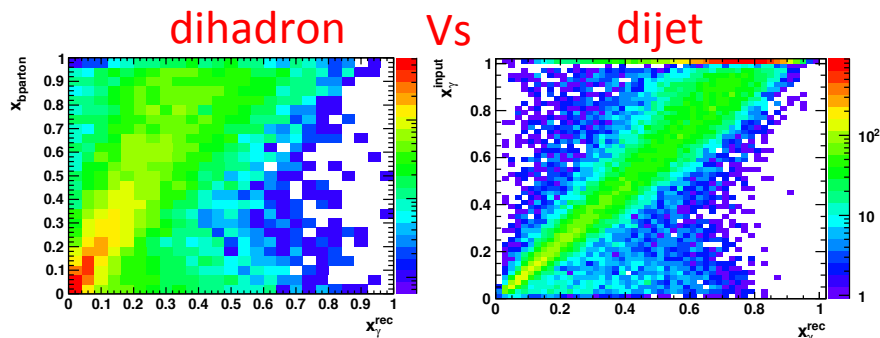
- Hadronic photon (with structure)
- x_γ is smaller than 1



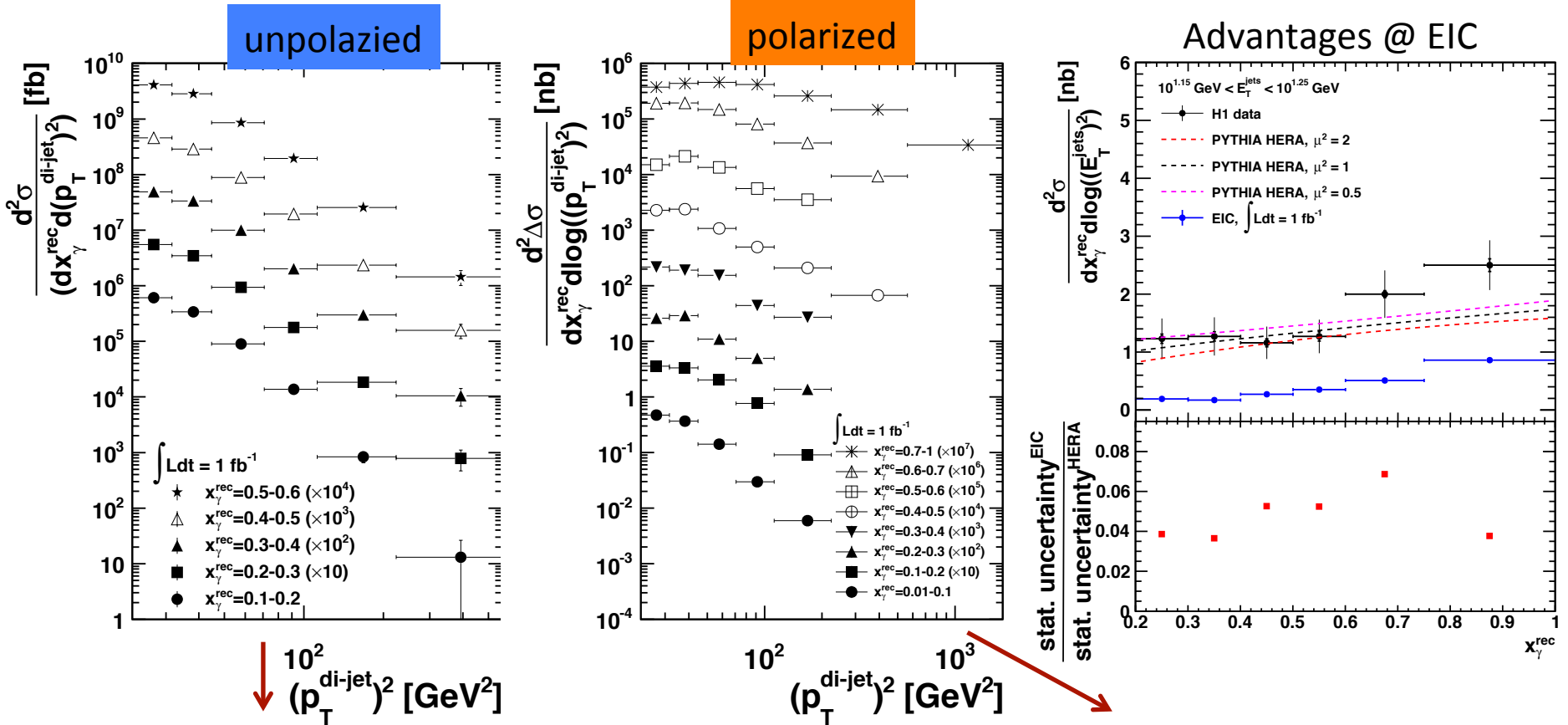
Similar with pp collision

- **Separate resolved and direct processes**, to enhance resolved process
- Reconstruct x_γ by using dijet/dihadron as observables:
Two hadrons/jets with highest p_T

$$x_\gamma^{rec} = \frac{1}{2E_e y} (p_{T1} e^{-\eta_1} + p_{T2} e^{-\eta_2})$$



(un)pol. Photon PDF at EIC



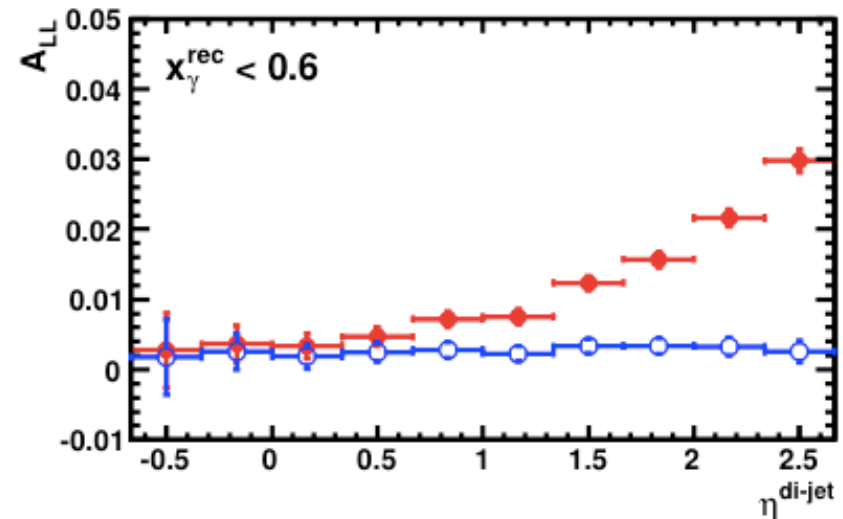
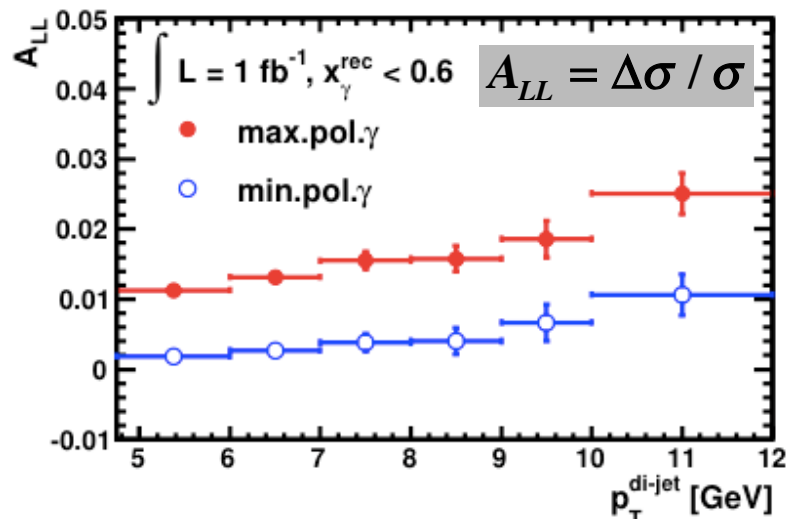
$$\frac{d^2\sigma}{dx_\gamma dp_T} = \gamma_{flux} \otimes PDF_\gamma(x_\gamma, Q^2, \mu) \otimes PDF_p(x_p, \mu) \otimes d\sigma_{ij}(\theta^*, Q^2, \mu)$$

XChu

$$\Delta\sigma = \frac{1}{2}(\sigma^{++} - \sigma^{+-})$$

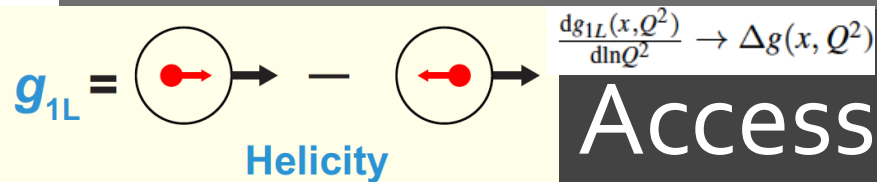
Asymmetry

Input: polarized proton-PDF: DSSV-14; photon-PDF: [Phys. Lett. B 337 373-375 (1994)]

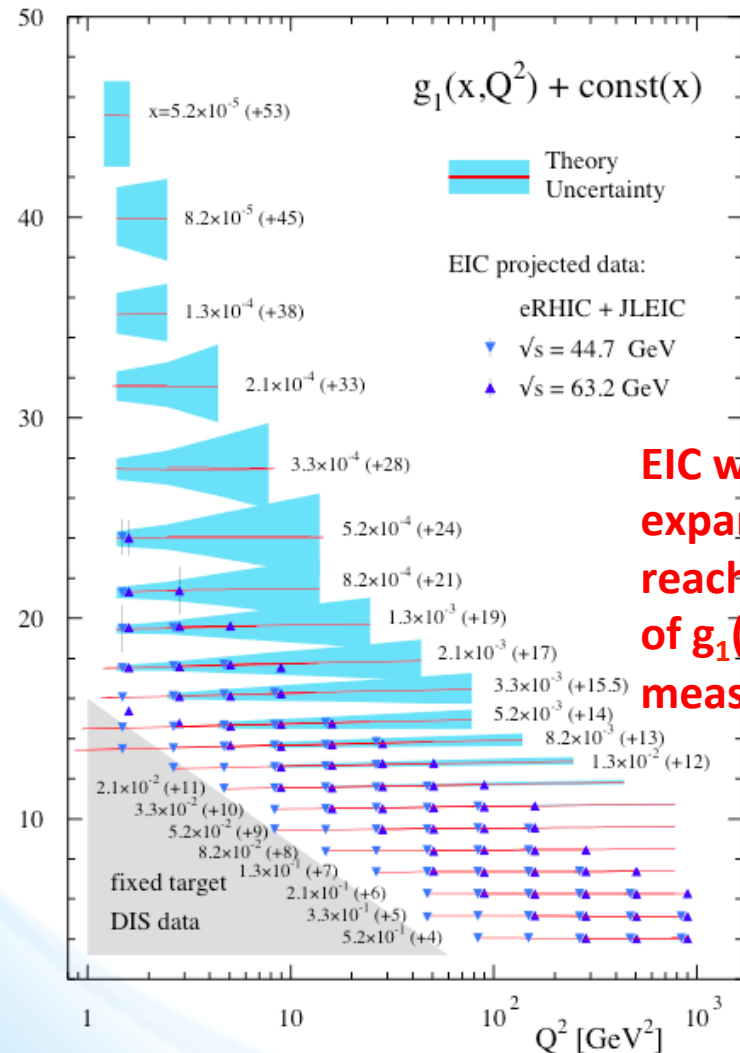
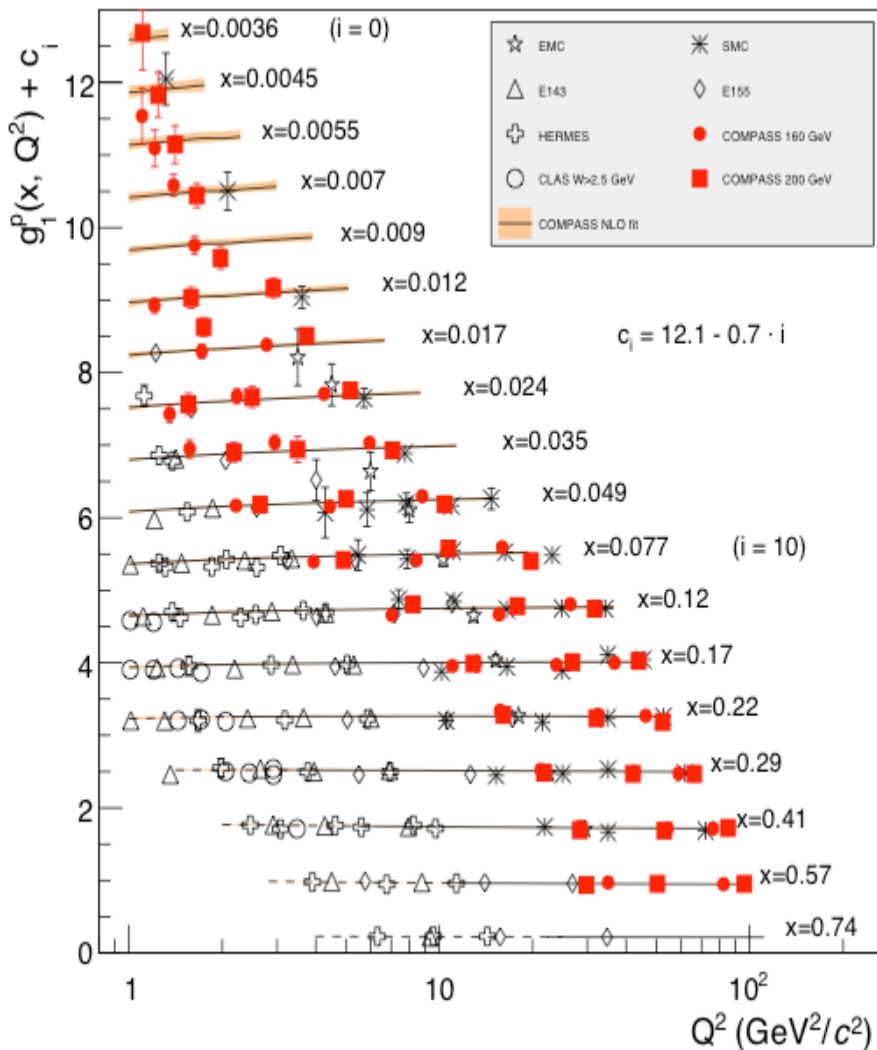


- ☐ Max.pol and min.pol can be separated from experimental measurement at EIC
- ☐ Polarized photon PDF will be firstly measured at EIC





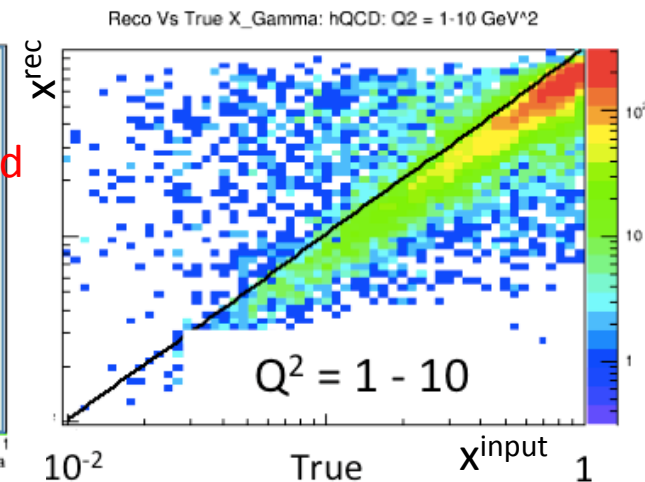
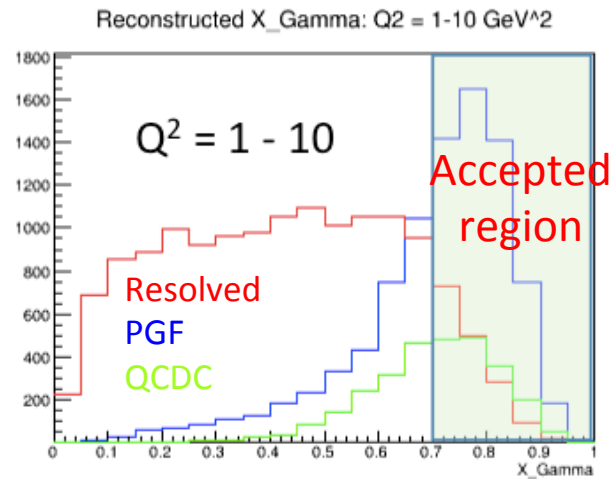
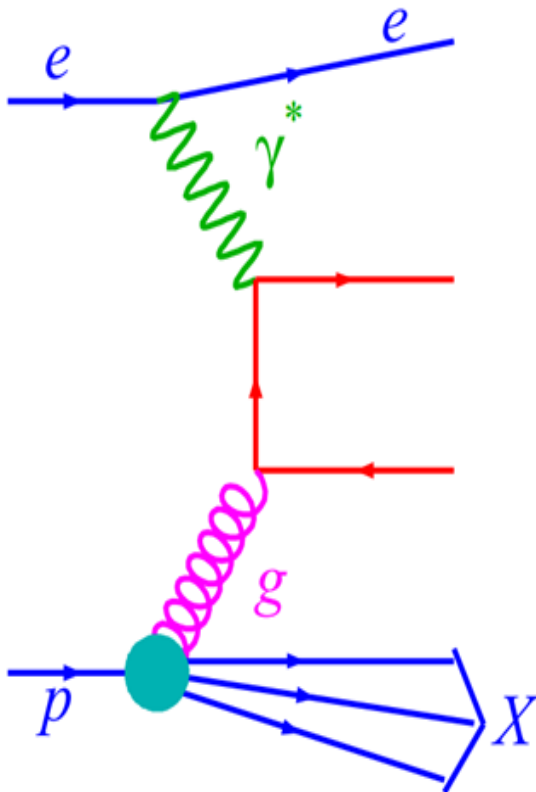
Accessing ΔG Via g_1 at an EIC



EIC would greatly expand kinematic reach and precision of $g_1(x, Q^2)$ measurements!

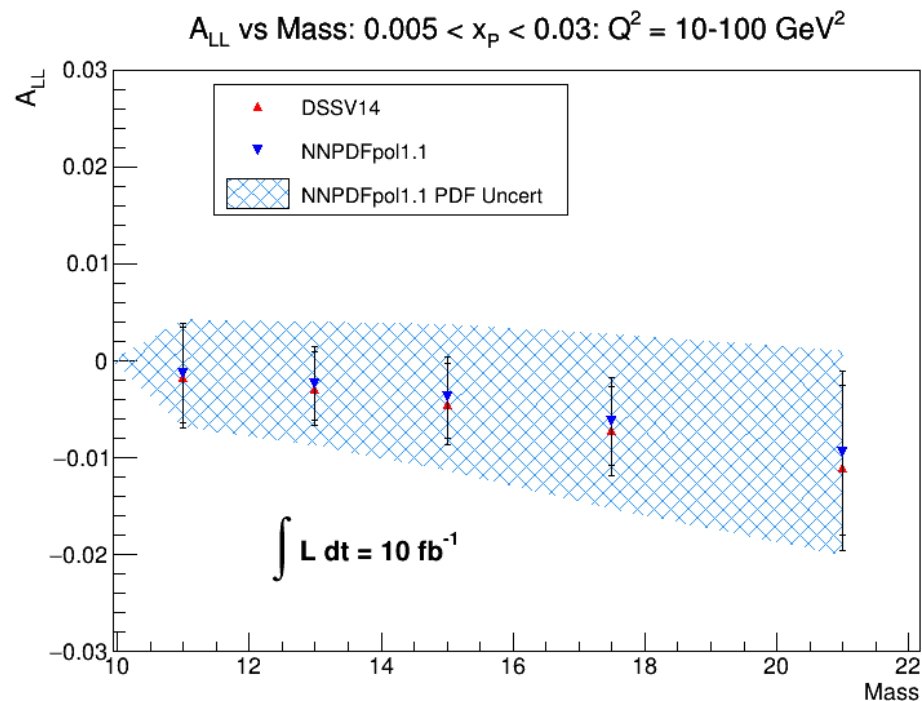
Gluon Polarization with Di-jets

Photon Gluon Fusion



- ❑ Gluons can be probed in DIS via the higher-order photon gluon fusion process.
 - A_{LL} for jets is sensitive to **gluon polarization**.
- ❑ Virtual photon momentum fraction is used to discriminate between resolved and direct processes.
- ❑ Di-jets are found in Breit frame and require one jet with $p_T \geq 5 \text{ GeV}$ and the other with $p_T \geq 4 \text{ GeV}$.

A_{LL} as a function of dijet mass

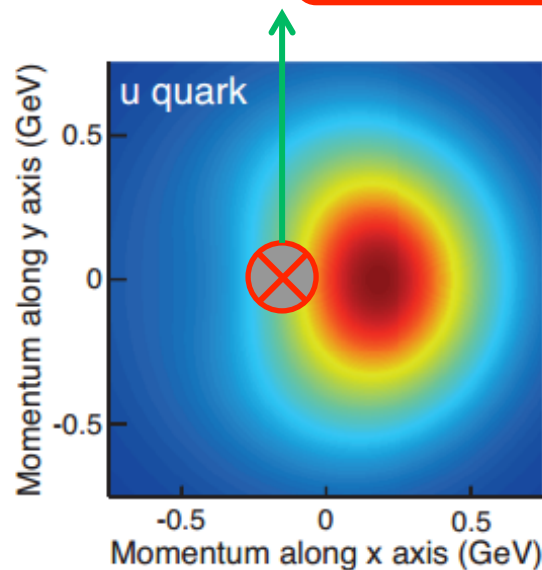


- ❑ The PDF uncertainties represent the current knowledge on the helicity structure of the proton.
- ❑ A significant amount of integrated luminosity will be needed for the dijet A_{LL} measurement to place meaningful constraints on the polarized PDFs.

Gluon Sivers Functions

- **Transverse Momentum Dependent parton distributions** (TMDs) provide useful tools to image the nucleon 2+1 D (k_T) structure in momentum space.
- Sivers function describes the correlation of k_T and S_T .

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



Leading Twist TMDs



Nucleon Spin



Quark Spin

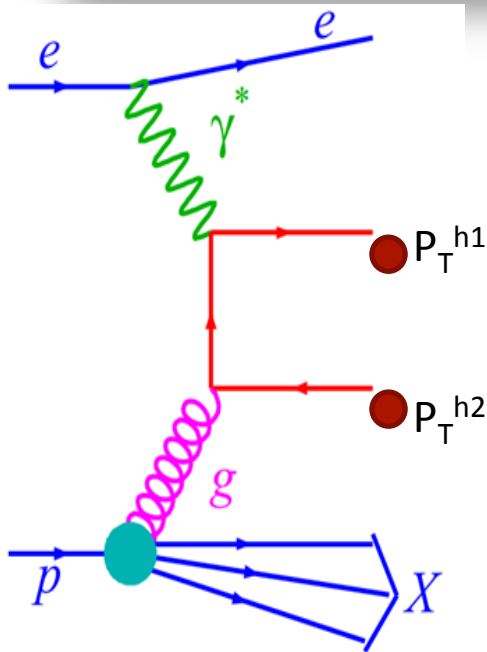
		Quark Polarization		
		Un-Polarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
Nucleon Polarization	U	$f_1 =$		$h_1^\perp =$ — Boer-Mulders
	L		$g_{1L} =$ — Helicity	$h_{1L}^\perp =$ —
	T	$f_{1T}^\perp =$ — Sivers	$g_{1T}^\perp =$ —	$h_1 =$ — Transversity $h_{1T}^\perp =$ —

Similar for gluons

- Due to different gauge link, the gluon Sivers function extracted at EIC will be independent from that measured in pp collisions.

Accessing Gluon Sivers at an EIC

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



Back-to-back limit:

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

Single Spin Asymmetry (SSA)
dependent on gluon Sivers

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

1. Dijet method
2. Charged dihadron
3. D^0 pair (Single D^0)

Inputs for Sivers function parameterization

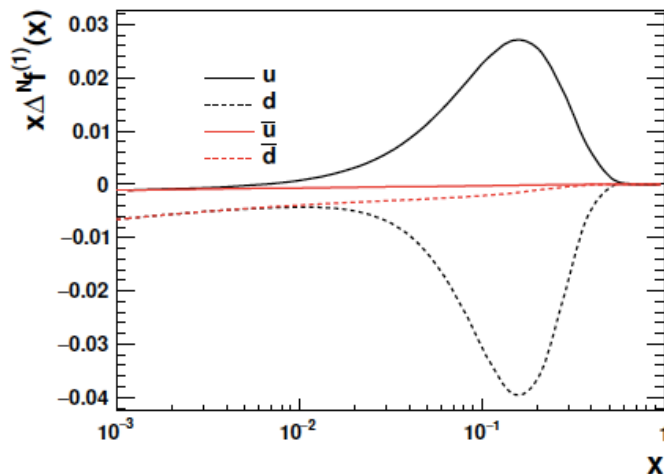
Quark Sivers JHEP 04 (2017) 046 Anselmino et al.

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

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

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

$$\begin{array}{lll} N_u = 0.40 & \alpha_u = 0.35 & \beta_u = 2.6 \\ N_d = -0.97 & \alpha_d = 0.44 & \beta_d = 0.90 \\ & M_1^2 = 0.19 \text{ GeV}^2 & \end{array}$$



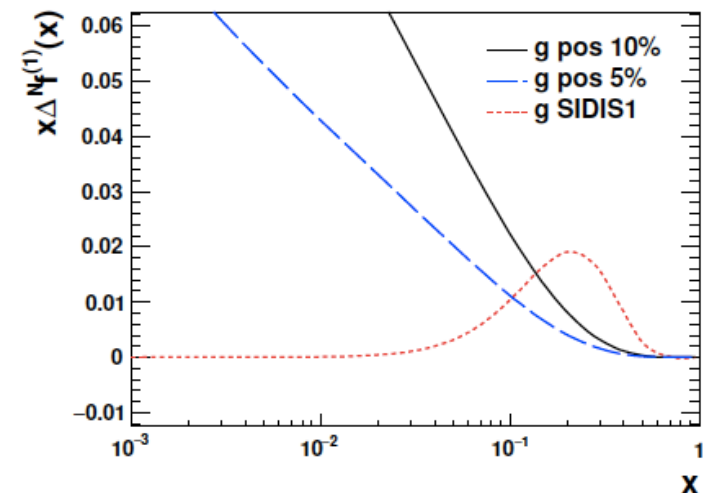
Gluon Sivers JHEP 09 (2015) 119 D' Alesio et. al.

“SIDIS1”

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

Positivity bound

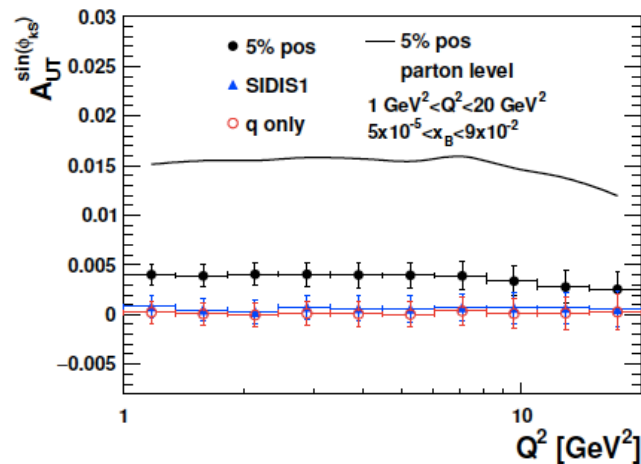
$$f_{1T}^{\perp g} = -\frac{2\sigma M_p}{k_\perp^2 + \sigma^2} f_g(x, k_\perp), \quad \sigma = 0.8$$



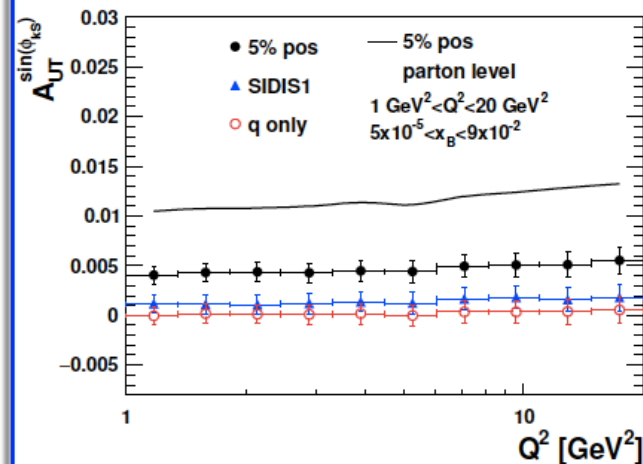
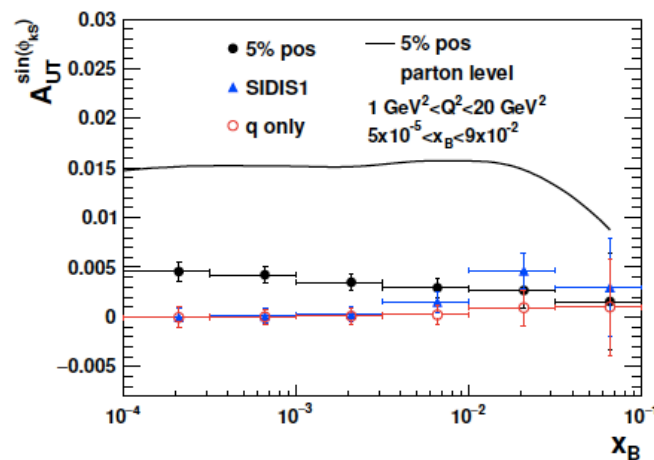
Projections for the SSA with dihadron/ dijet

$$A_{UT}^{\sin(\phi_{KS})} = \frac{\int d\phi_{KS} (d\sigma^{\uparrow} - d\sigma^{\downarrow}) \sin(\phi_{KS})}{\int d\phi_{KS} (d\sigma^{\uparrow} + d\sigma^{\downarrow})}$$

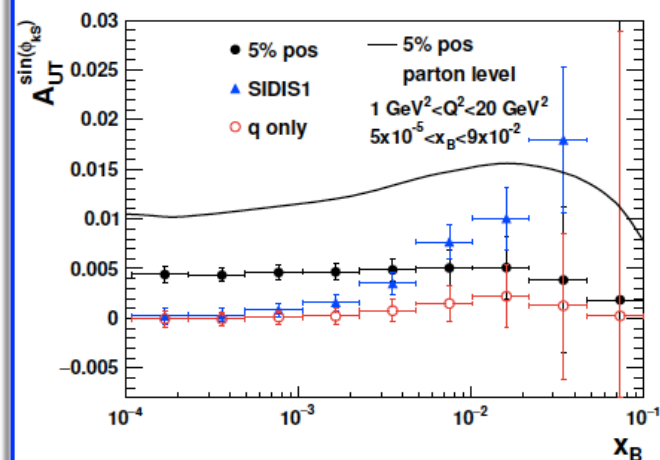
ep 20x250 GeV
 $1 < Q^2 < 20 \text{ GeV}^2$, $0.01 < y < 0.95$
 Charged $\pi/K/p$, $|\eta| < 4.5$
 Correlation limit: $k'_T < 0.7P_T'$
 $z > 0.1$, $p_T > 1.4$
 $\int L dt = 20 \text{ fb}^{-1}$



Dihadron



Dijet



Dijet reconstruction:
 $p_T^h > 250 \text{ MeV}$, $\pi/K/p/\gamma$,
 $|\eta| < 4.5$
 Jet cone $R=1.0$, anti- k_T
 $p_T^{\text{jet1}} > 4.5 \text{ GeV}$, $p_T^{\text{jet2}} > 4 \text{ GeV}$

Projections for the SSA with 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.

$$x_{\text{parton}}^{\text{rec}} = \frac{1}{W} (p_{T1} e^{-\eta_1} + p_{T2} e^{-\eta_2})$$

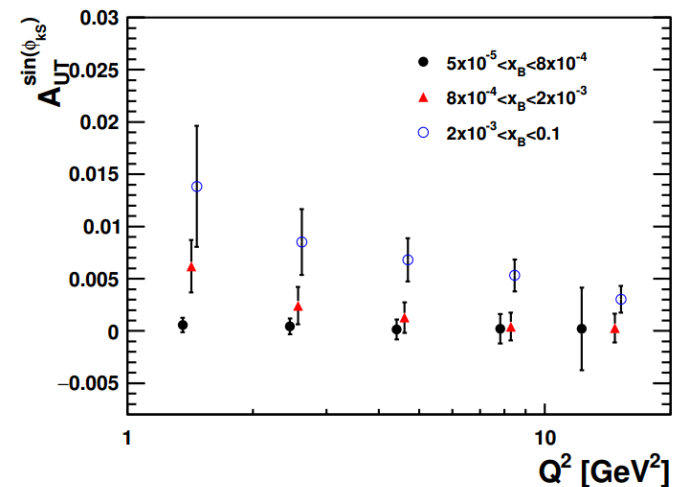
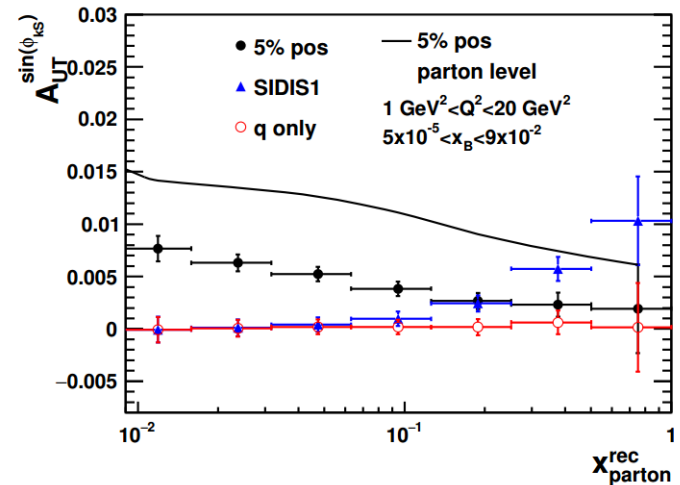
Dijet reconstruction:

$p_T^h > 250$ MeV, $\pi/K/p/\gamma$,

$|\eta| < 4.5$

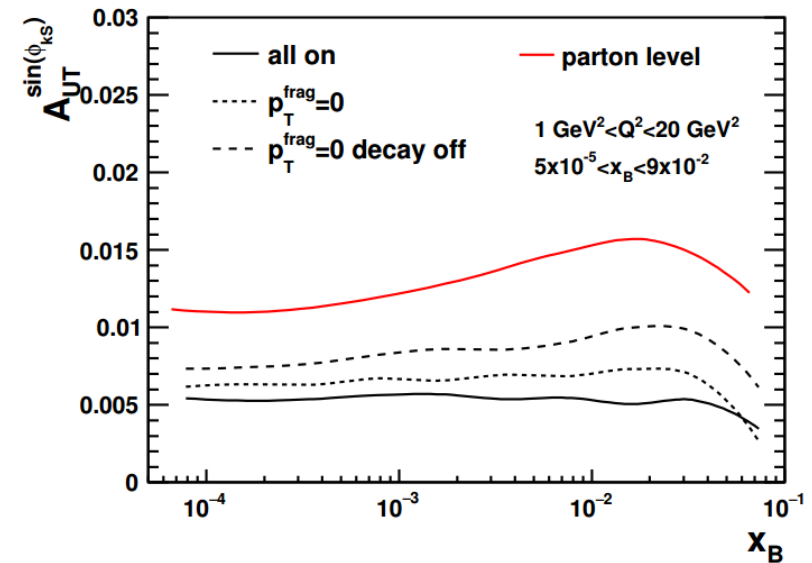
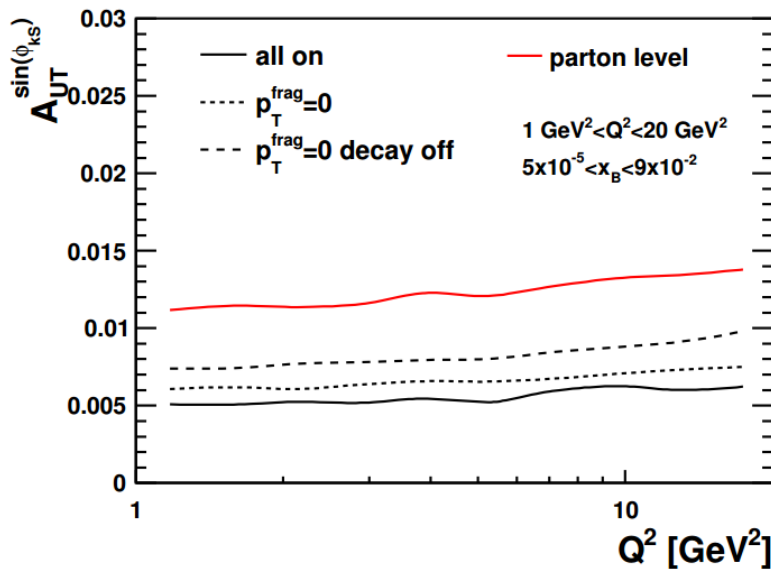
Jet cone $R=1.0$, anti- k_T

$p_T^{\text{jet1}} > 4.5$ GeV, $p_T^{\text{jet2}} > 4$ GeV



Dilution of parton level asymmetry with dijet

- Hadron fragmentation momentum smearing and resonance decay are important
- Other smearing effects in dijet processes → parton radiation



Summary

- Jet observables have proven to be powerful tools for the exploration EIC physics including:
 - Estimate the underlying effects: comparable with STAR result.
 - Photon structure: wide kinematics range, polarized photon PDFs, flavor tagging.
 - Gluon polarization: improvement of constraining ΔG to probe proton spin.
 - Gluon Sivers: the most precise analyzer for the gluon Sivers effects at an EIC is the di-jet channel, due to its statistical advantage it provides the best sensitivity.



BACK UP

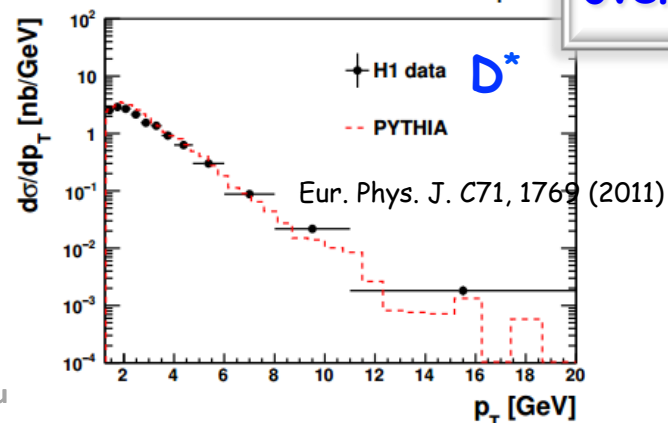
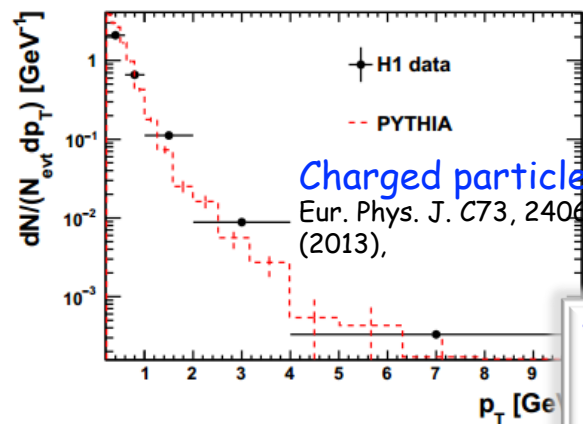
Gluon Sivers

- ❑ Gluon TMDs is ingredient of complete 3D imaging of nucleon, and can be uniquely measured at EIC by measuring gluon Sivers function.
- ❑ Gluon Sivers functions can be measured via photon gluon fusion through tagging D^0 meson, dihadron and dijet at EIC.
 - The heavy favor D meson pair production is the cleanest channel to tag gluon initiated processes, however the most statistically challenging process and therefore the sensitivity to small gluon Sivers effects is limited.
 - The most precise analyzer for the gluon Sivers effects at an EIC is the di-jet channel, due to its statistical advantage it provides the best sensitivity even for the small Sivers effects and can span the largest Q^2 -range to study TMD evolution effects.

MC: Comparing to existing Data

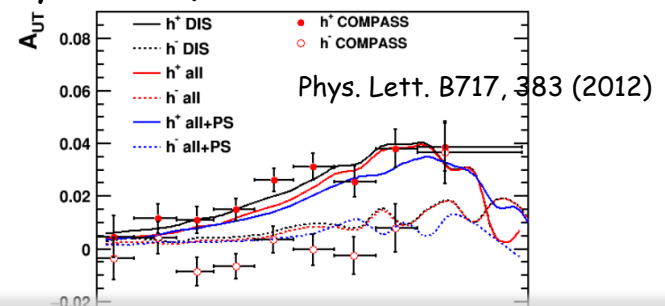
Unpolarized Data from H1:

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

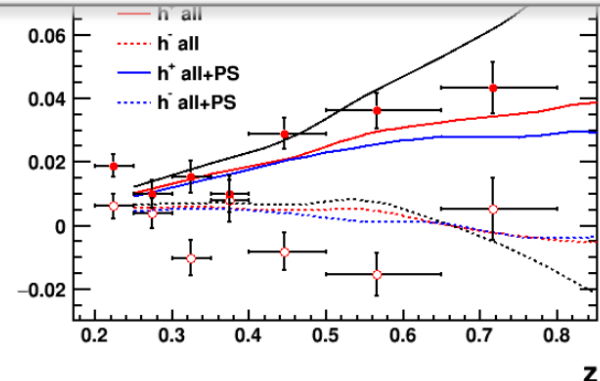


Polarized Data (Sivers) from COMPASS

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

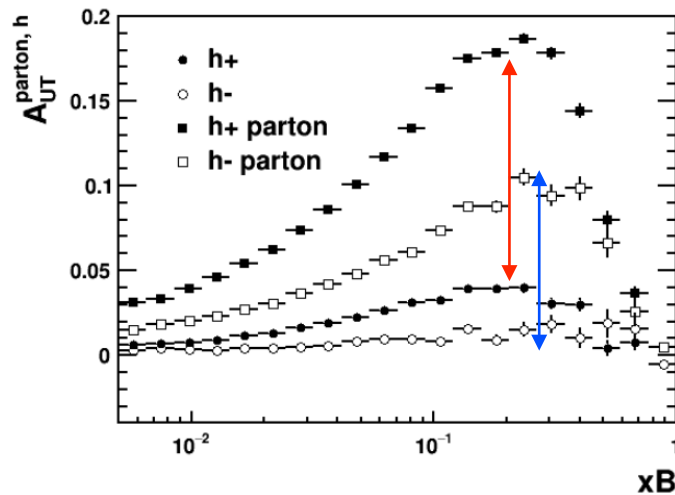


The MC reproduces a wide range of data over a wide range of kinematics extremely well



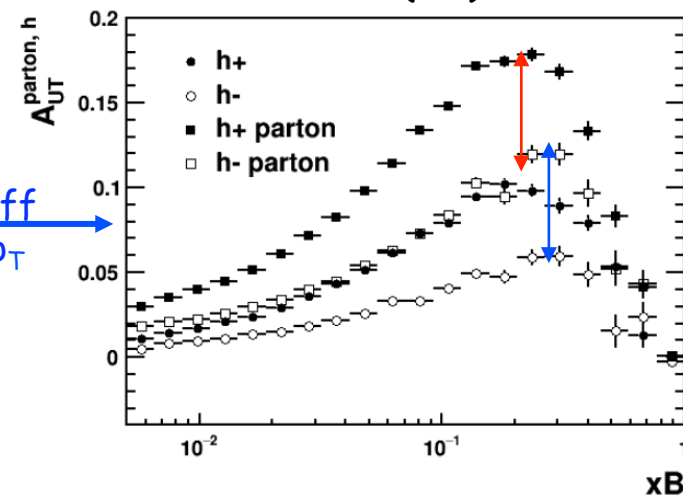
Dilution of parton level asymmetry

Full simulation

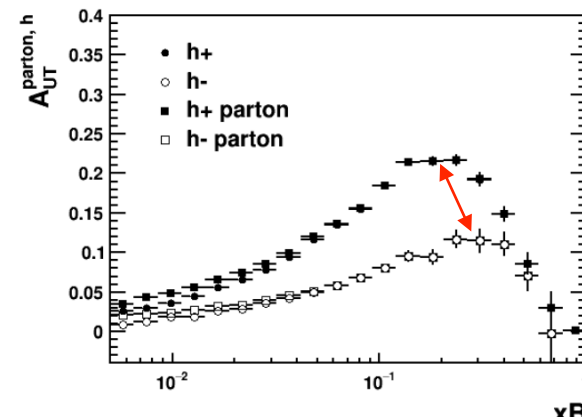


Turn off
frag p_T

PARJ(21)=0



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



Turn off decay
of resonances

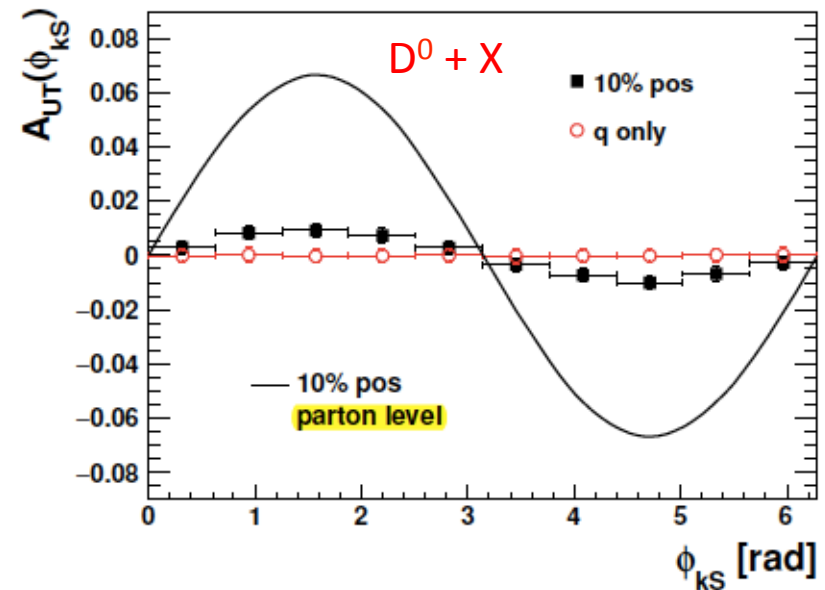
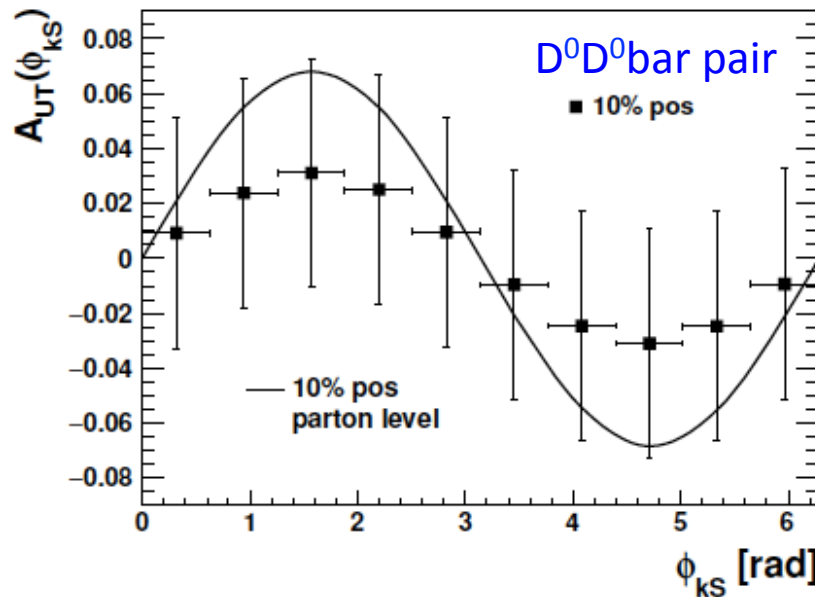
Fragmentation momenta smearing and resonance decay contribution accounts for the parton to hadron level asymmetry dilution at COMPASS energy.

Projections for the SSA with D^0

ep 20x250 GeV, $1 < Q^2 < 20 \text{ GeV}^2$, $0.01 < y < 0.95$, $z > 0.1$, $p_T > 0.7$, $\int L dt = 20 \text{ fb}^{-1}$

D^0 cut: Acceptance $|\eta|^{\text{pi/K}} < 3.5$, $p_T^{\text{pi/K}} > 0.2 \text{ GeV}$, $z^{\text{pi/K}} > 0.1$

$$\delta A = \sqrt{\frac{1}{P^2 N} - \frac{A^2}{N}}$$



- The small branching ratio ($D \rightarrow K + \pi$ (3.9%)) makes it challenging to precisely determine the gluon Sivers function.
- Asymmetry for single D mesons is reduced since the transverse momentum of one D meson is not a good proxy for the initial gluon transverse momentum.

Jet algorithm

■ Clustering Algorithms

- k_T : $d_i = p_{T,i}^2$, $d_{ij} = \min(p_{T,i}^2, p_{T,j}^2) \times \frac{\Delta R_{ij}^2}{R^2} = \min(p_{T,i}^2, p_{T,j}^2) \times \frac{(y_i - y_j)^2 + (\phi_i - \phi_j)^2}{R^2}$, if $d_{min} = \min(d_i, d_{ij})$ is d_{ij} ; else, remove j from the list as a jet.
- anti- k_T : $d_i = \frac{1}{p_{T,i}^2}$, $d_{ij} = \min(\frac{1}{p_{T,i}^2}, \frac{1}{p_{T,j}^2}) \times \frac{\Delta R_{ij}^2}{R^2}$.

Given $p_{T,j}$ is very small, also $\frac{\Delta R_{ij}^2}{R^2} > 1$:

$$\text{anti-}k_T: d_{ij} = \frac{1}{p_{T,i}^2} \times \frac{\Delta R_{ij}^2}{R^2} > \frac{1}{p_{T,i}^2}.$$

It's more likely that j will be a candidate particle for jets by applying k_T algorithm than that of anti- k_T . The back reaction sensitivity is highly suppressed by using anti- k_T algorithm in comparison with k_T algorithm.

■ Cone-Type Algorithms

- SISCone: All circles defined by pairs of edge points are all stable cones.

MC: Comparing to existing Data

