Jet charge: a flavor prism for spin asymmetries at the EIC

Zhongbo Kang
UCLA

EIC Yellow Report : Jet and Heavy Flavor Physics WG meeting
August 10, 2020

Based on Kang, Liu, Mantry, Shao, arXiv:2008.00655

Jet Physics at the EIC

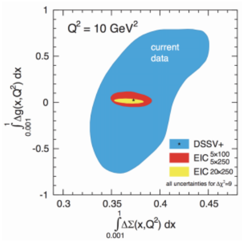
- Jet physics at the EIC: a fast emerging field of research

The EIC science program with jets

Jets as tools to realize the EIC science goals — Recent publications

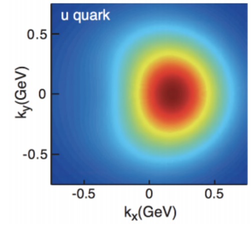
- The spin of the proton, PDFs

  Hinderer, Schlegel, Vogelsang `15, `17, Abelof, Boughezal, Liu, Petriello `16, Boughezal, Petriello, Xing `18, Aschenauer, Chu, Page `19, Borsa, Florian, Pedron `20, Arratia, Furletova, Hobbs, Olness, Sekula `20



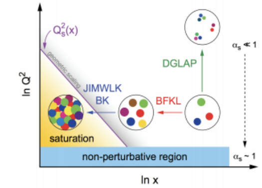
- 3D nucleon/nucleus tomography

  Zheng, Aschenauer, Lee, Xiao, Yin `18, Liu, FR, Vogelsang, Yuan `19, Gutierrez-Reyes, Scimemi, Waalewijn, Zoppi `19, Hatta, Mueller, Ueda, Yuan `19, Arratia, Kang, Prokudin, FR `20



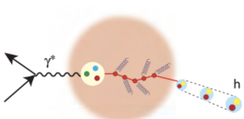
- Saturation, a new form of gluon matter

  Hatta, Xiao, Yuan `17, Salazar, Schenke `19, Roy, Venugopalan `19, Kang, Liu `19



- Hadronization and quarks and gluons in the nucleus

  Klasen, Kovarik `18, Aschenauer, Lee, Page, FR `19, Qin, Wang, Zhang `19, Arratia, Song, FR, Jacak `19, Li et al. `20



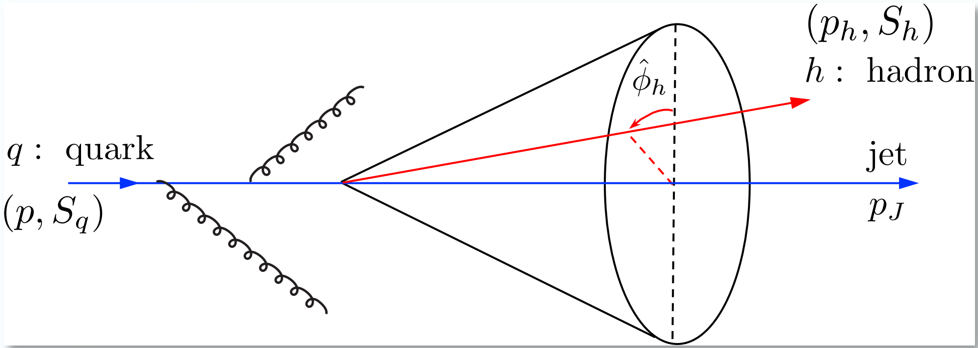
Courtesy of F. Ringer at BNL jet workshop in July

Jets for 3D imaging

- Using jets for 3D imaging of the nucleon
  - seems to become quite feasible
  - seems to attract a lot of interest

Some recent examples

- Jet fragmentation functions



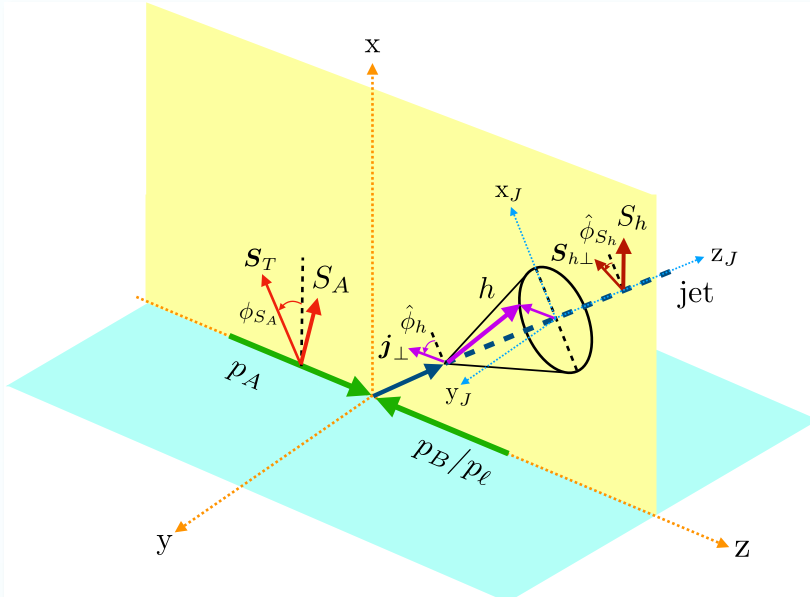
$$z_h = \frac{p_{hT}}{p_{JT}}$$

$$j_T$$

- If one measures only the z_h distribution (integrated over jT), one probes collinear FFs
  - unpolarized, longitudinally, transversely polarized
- If one measures both zh and jT distribution (3D), one probes TMD FFs
  - With all possible polarizations

Azimuthal angular dependence

- All the azimuthal angular dependence for single inclusive jet



Kang, Kyle, Zhao, arXiv:2005.02398

Collins effect

$$\frac{d\sigma^{p(S_A)+p/e\to(\text{jet}\,h(S_h))X}}{dp_{JT}\,d\eta_J\,dz_h\,d^2\boldsymbol{j}_\perp} = F_{UU,U} + |\boldsymbol{S}_T|\sin(\phi_{S_A}-\hat{\phi}_h)F_{TU,U}^{\sin(\phi_{S_A}-\hat{\phi}_h)} + \Lambda_h\left[\lambda F_{LU,L} + |\boldsymbol{S}_T|\cos(\phi_{S_A}-\hat{\phi}_h)F_{TU,L}^{\cos(\phi_{S_A}-\hat{\phi}_h)}\right]$$

$$+\,|\boldsymbol{S}_{h\perp}|\Big\{\sin(\hat{\phi}_h-\hat{\phi}_{S_h})F_{UU,T}^{\sin(\hat{\phi}_h-\hat{\phi}_{S_h})} + \lambda\cos(\hat{\phi}_h-\hat{\phi}_{S_h})F_{LU,T}^{\cos(\hat{\phi}_h-\hat{\phi}_{S_h})}$$

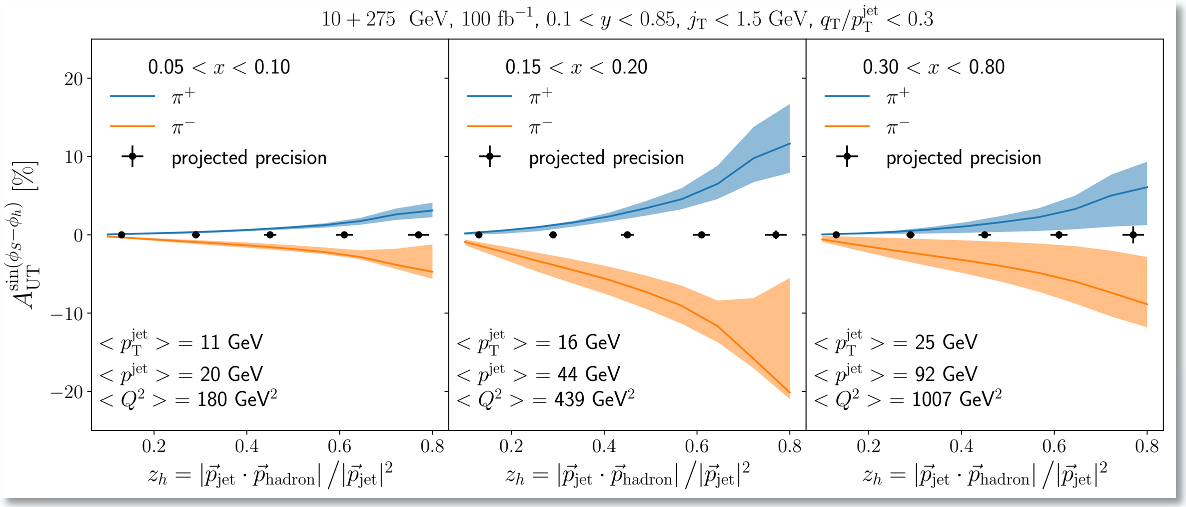
$$+\,|\boldsymbol{S}_T|\Big(\cos(\phi_{S_A}-\hat{\phi}_{S_h})F_{TU,T}^{\cos(\phi_{S_A}-\hat{\phi}_{S_h})} + \cos(2\hat{\phi}_h-\hat{\phi}_{S_h}-\phi_{S_A})F_{TU,T}^{\cos(2\hat{\phi}_h-\hat{\phi}_{S_h}-\phi_{S_A})}\Big)\Big\}$$

Lambda polarization

Examples

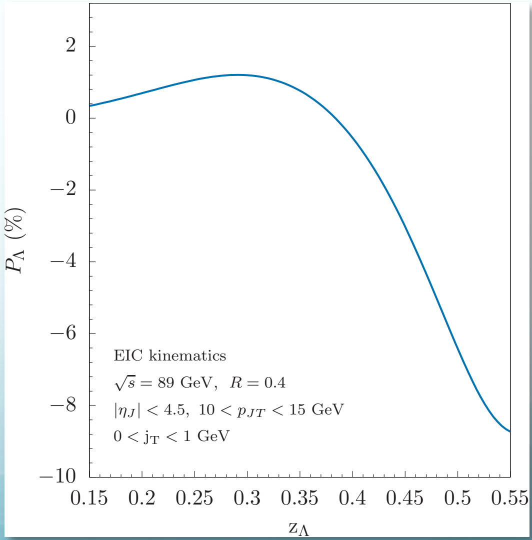
- Collins effect at the EIC

Arratia, Kang, Prokudin, Ringer, arXiv:2007.07281



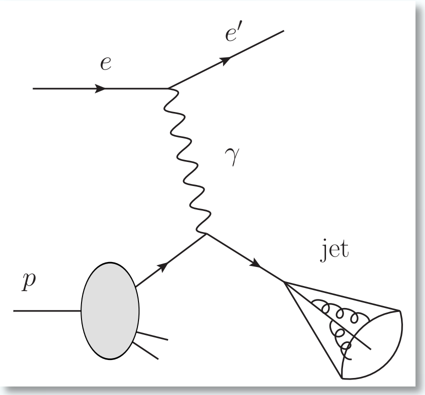
- Lambda polarization at the EIC

Kang, Kyle, Zhao, arXiv:2005.02398

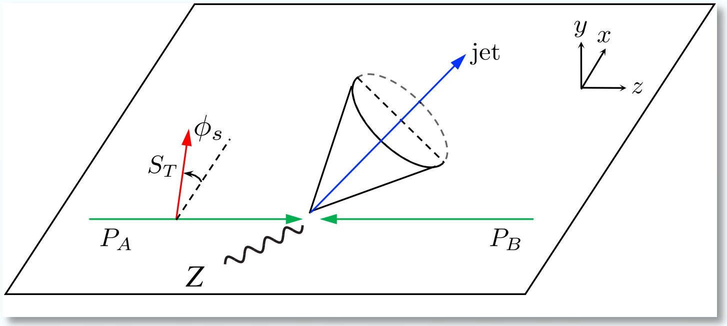


Back-to-back region for TMD PDFs

- One can also study TMD PDFs via back-to-back jet production
  - e+p→e+jet+X
  - p+p→(Z, γ, …)+jet+X



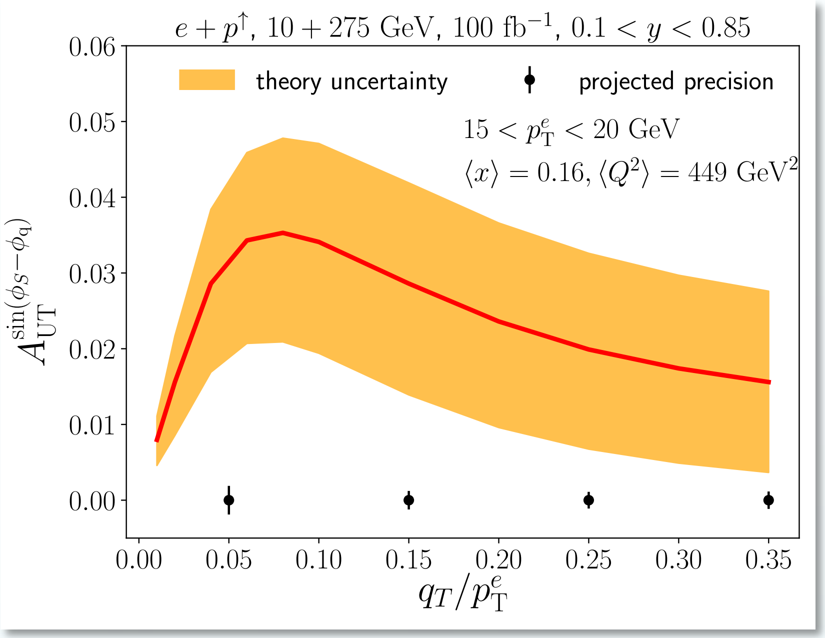
Kang, Lee, Terry, Xing, arXiv:1906.07187
Chien, Shao, Wu, arXiv:1905.01335, …



Arratia, Kang, Prokudin, Ringer, arXiv:2007.07281
Liu, Ringer, Vogelsang, Yuan, 18, 20, …

Examples

- Sivers asymmetry at the EIC
  - electron-jet back-to-back production



Arratia, Kang, Prokudin, Ringer, arXiv:2007.07281

All seem to be nice

- Perception: all seem to be nice, complimentary to SIDIS measurement
  - It seems that something is missing, or has not been discussed much
  - That is flavor separation, which is important in mapping out the flavor and spin structure of the nucleon – an essential mission of EIC

- Flavor separation in DIS or SIDIS
  - In DIS: using different target – proton, deuteron, He3 (neutron)
    - gives us u and d flavor separation

R. Milner, arXiv:1809.05626

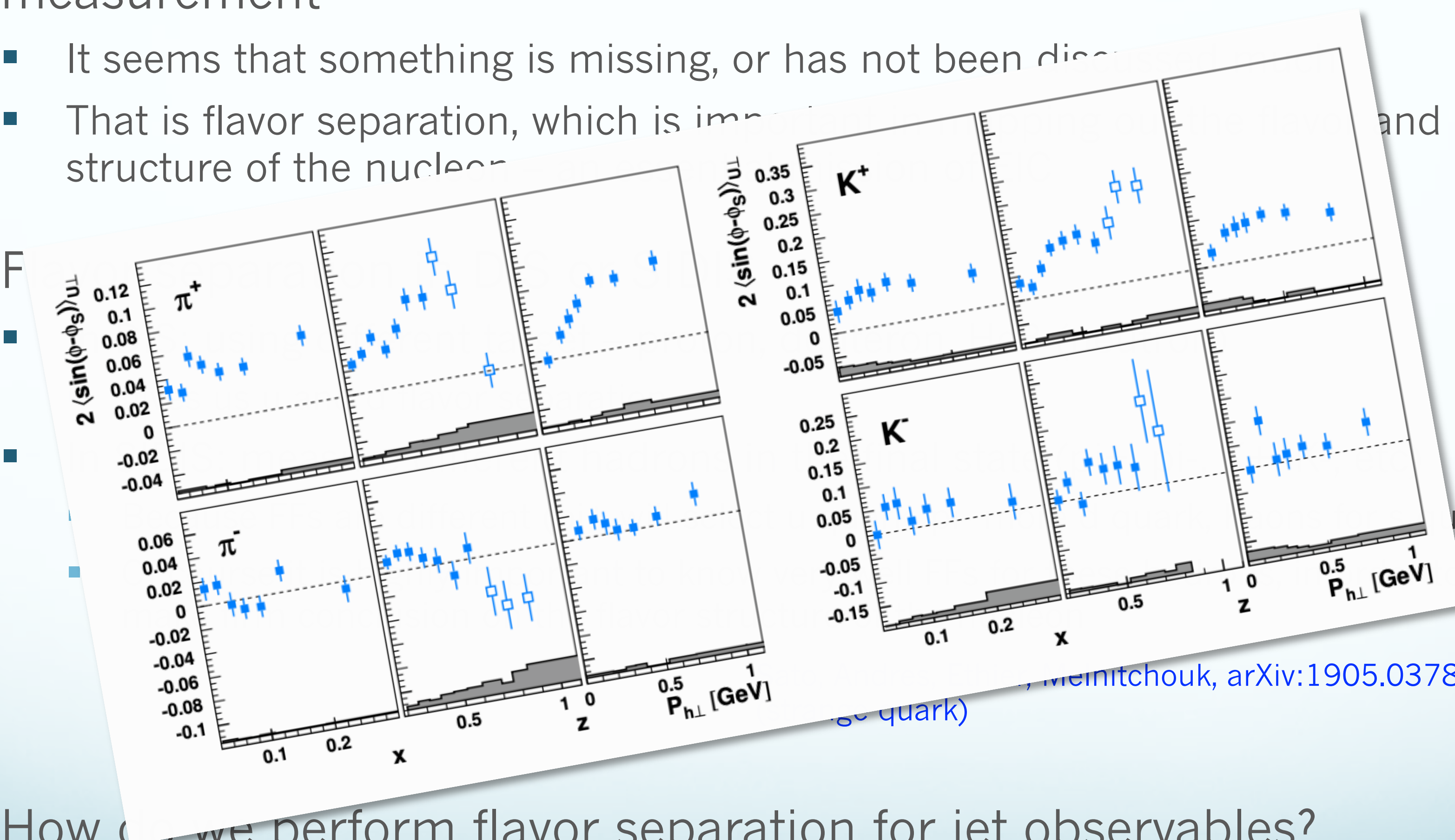
  - In SIDIS: measure different hadrons in the final state (pi+, pi-, K+, K-, etc)
    - Because FFs are different (pi+ will select u quark, pi- more d quark, Kaons for s quark)
    - Of course it is highly important to know very well FFs for these hadrons, in order to make firm conclusion on the flavor structure of the nucleon

Sato, Andres, Ethier, Melnitchouk, arXiv:1905.03788 (strange quark)

- How do we perform flavor separation for jet observables?

All seem to be nice

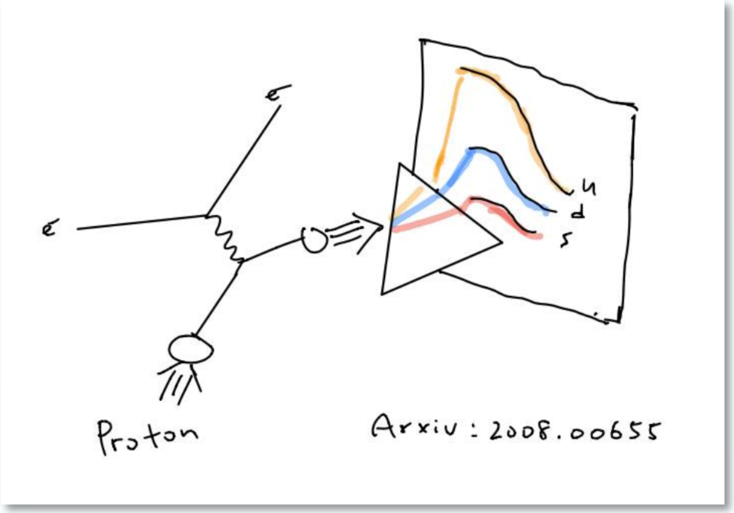
- Perception: all seem to be nice, complimentary to SIDIS measurement
  - It seems that something is missing, or has not been dis…
  - That is flavor separation, which is im… and spin structure of the nucle…
- F…
  - …
  - …ark)
    - …Melnitchouk, arXiv:1905.03788
    - …ge quark)



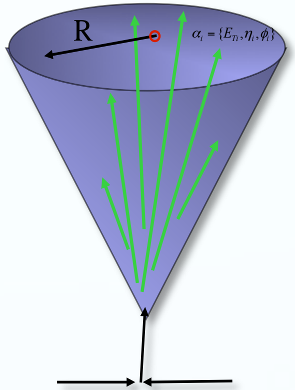
- How do we perform flavor separation for jet observables?

Jet charge

- Jet charge: a flavor prism



Courtesy of Xiaohui Liu



- Jet charge definition
  - One might use subset of hadrons (pions, Kaons) in jet to construct jet charge

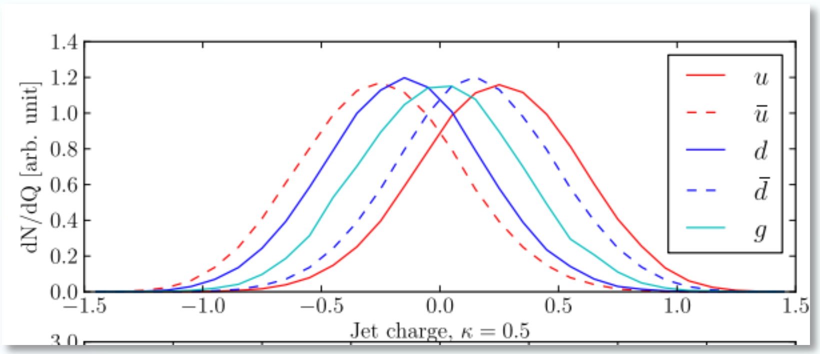
$$Q_\kappa = \sum_h Q_\kappa^h \equiv \sum_{h \in \mathrm{jet}} z_h^\kappa Q_h$$

Charge of the hadron

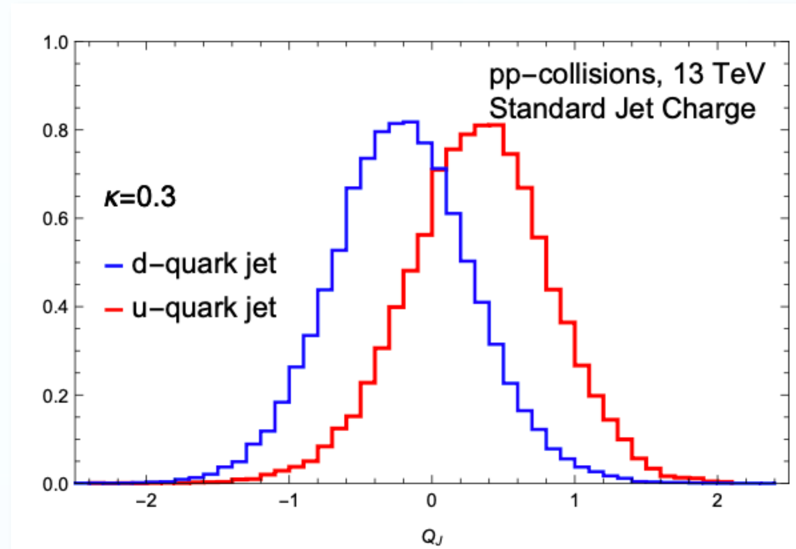
$$z_h = \frac{p_{hT}}{p_{JT}} \qquad \kappa = 0.3, 0.4, \cdots, 1.0$$

Charge distribution of u and d quark jets

- Jet charge distribution



Krohn, Schwartz, Lin, Waalewijn, arXiv:1209.2421



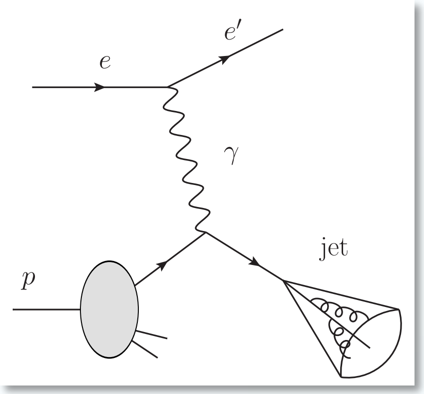
Courtesy of S. Mantry

- If one sums over all particles, u and d jet charges sum over, we have a distribution around $Q_J \sim 0$
  - If one can select the positive jet charge bin, then our result is more sensitive to u quark jet
  - Negative jet charge bin: sensitive to d quark jet

Pick an example

- Pick an example, demonstrate if it works, how it works
  - Sivers asymmetry in electron-jet back-to-back production

- In the back-to-back region
  - Nice thing: e+q → e+q dominates at leading power
  - So *jet flavor is the same as the incoming quark flavor*



- Factorization formalism
  - Unpolarized production: for a particular quark scattering (qT: imbalance)
  - Jet function: describe transition from a parton ***i*** into a jet with pT and R

$$\frac{d\sigma^i_{UU}}{dy_e d^2p^e_T d^2q_T} \propto e_i^2 \int \frac{d^2b_T}{(2\pi)^2} e^{iq_T\cdot b_T} \tilde{f}_i(x, b_T, \mu) S_J(b_T, R, \mu) H(Q, \mu) \mathcal{J}_i(p_T R, \mu)$$

Jet charge function

- Now besides characteristics (pT, R) of the jet, we also want to measure the jet charge Q_κ
  - Need a new jet function - called it "jet charge function"

$$\frac{\mathrm{d}\sigma^i_{UU}(Q_\kappa)}{\mathrm{d}y_e \mathrm{d}^2 p^e_T \mathrm{d}^2 q_T} \propto e_i^2 \int \frac{\mathrm{d}^2 b_T}{(2\pi)^2} e^{iq_T\cdot b_T} \tilde{f}_i(x, b_T, \mu) S_J(b_T, R, \mu) H(Q, \mu) \mathcal{G}_i(Q_\kappa, p_T R, \mu)$$

  - In comparison with the standard jet production

$$\frac{\mathrm{d}\sigma^i_{UU}}{\mathrm{d}y_e \mathrm{d}^2 p^e_T \mathrm{d}^2 q_T} \propto e_i^2 \int \frac{\mathrm{d}^2 b_T}{(2\pi)^2} e^{iq_T\cdot b_T} \tilde{f}_i(x, b_T, \mu) S_J(b_T, R, \mu) H(Q, \mu) \mathcal{J}_i(p_T R, \mu)$$

  - Obviously if one integrates over the jet charge Q_κ , one would get back to the usual jet function

$$\int dQ_\kappa \, \mathcal{G}_i(Q_\kappa, p_T R, \mu) = \mathcal{J}_i(p_T R, \mu)$$

  - Another NICE thing: due to RG consistency, these two jet functions have the ***same QCD evolution***

See also Waalewijn, arXiv:1209.3019

The weighting factor

- The N-th moment of the jet charge in a particular jet charge bin

$$\langle (Q_\kappa^i)^N \rangle_{\rm bin} = \int_{Q_\kappa\text{-bin}} \mathrm{d}Q_J\, Q_J^N\, \frac{\mathcal{G}_i(Q_J, p_T R, \mu)}{\mathcal{J}_i(p_T R, \mu)}$$

$$\sum_{\rm bins} \langle (Q_\kappa^i)^0 \rangle_{\rm bin} = 1, \qquad \sum_{\rm bins} \langle Q_\kappa^i \rangle_{\rm bin} = \langle Q_\kappa^i \rangle$$

  - This ratio is RG-invariant, has a small pT*R dependence from NLO as an argument in the coupling constant
  - This weighting factor is *non-perturbative but universal*, thus one can determine from other jet production process in p+p, e+e- collisions (recall STAR dijet), it is just a number (like NRQCD matrix elements)

- Then build the cross section in a specific jet charge bin, easily generalize to polarized case (Sivers effect): **same weighting factor**

$$\frac{\mathrm{d}\sigma_{UU}(Q_{\kappa,\rm bin}^N)}{\mathrm{d}y_e \mathrm{d}^2 p_T^e \mathrm{d}^2 q_T} = \sum_{i=u,d\cdots} \langle (Q_\kappa^i)^N \rangle_{\rm bin} \frac{\mathrm{d}\sigma_{UU}^i}{\mathrm{d}y_e \mathrm{d}^2 p_T^e \mathrm{d}^2 q_T}$$

$$\frac{\mathrm{d}\sigma_{UT}(S_\perp, Q_{\kappa,\rm bin}^N)}{\mathrm{d}y_e \mathrm{d}^2 p_T^e \mathrm{d}^2 q_T} = \sum_{i=u,d,\cdots} \langle (Q_\kappa^i)^N \rangle_{\rm bin} \frac{\mathrm{d}\sigma_{UT}^i(S_\perp)}{\mathrm{d}y_e \mathrm{d}^2 p_T^e \mathrm{d}^2 q_T}$$

The weighting factor

- The N-th moment of the jet charge in a particular jet charge bin

$$\langle (Q_\kappa^i)^N \rangle_{\rm bin} = \int_{Q_\kappa\text{-bin}} dQ_J\, Q_J^N \, \frac{\mathcal{G}_i(Q_J, p_T R, \mu)}{\mathcal{J}_i(p_T R, \mu)}$$

$$\sum_{\rm bins} \langle (Q_\kappa^i)^0 \rangle_{\rm bin} = 1, \qquad \ldots \langle Q_\kappa^i \rangle_{\rm bin} = \langle Q_\kappa^i \rangle$$

  - This ratio is RG-invariant, has a small pT*R deper… NLO as an argument in the coupling constant
  - This weighting factor is *non-perturbative* … thus one can determine from other jet production process in … collisions (recall STAR dijet), it is just a number (like NRQCD mat… s)

Jet charge has been measured extensively at the LHC (charge tracks), **doable at the EIC?!**

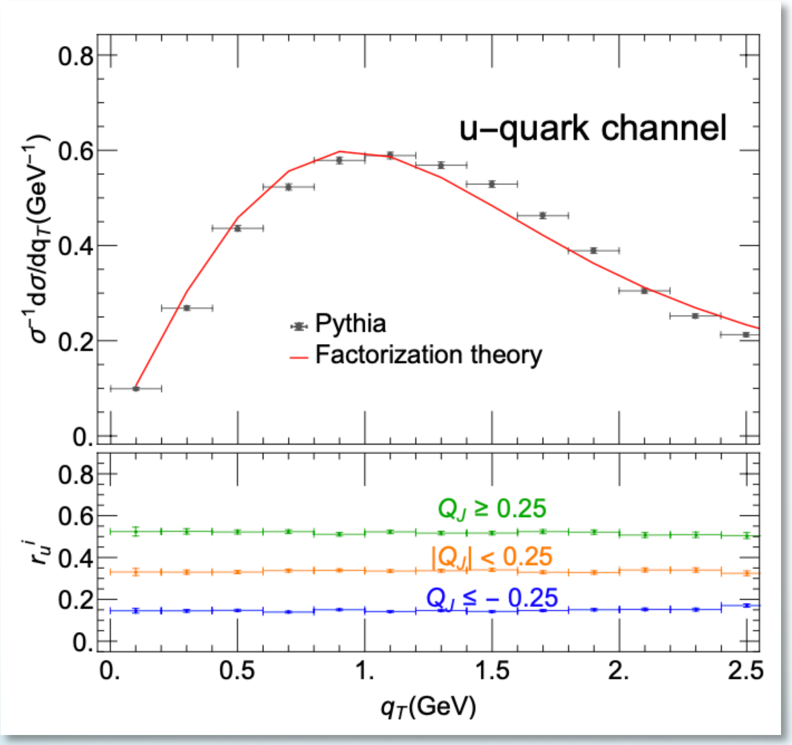
- Then build the cross s… a specific jet charge bin, easily generalize to polar… (Sivers effect): **same weighting factor**

$$\frac{d\sigma_{U\ldots}}{dy_e d\ldots q_T} = \sum_{i=u,d\cdots} \langle (Q_\kappa^i)^N \rangle_{\rm bin} \frac{d\sigma_{UU}^i}{dy_e d^2 p_T^e d^2 q_T}$$

$$\frac{d\sigma_{UT}(S_\perp, Q_{\kappa,\rm bin}^N)}{dy_e d^2 p_T^e d^2 q_T} = \sum_{i=u,d,\cdots} \langle (Q_\kappa^i)^N \rangle_{\rm bin} \frac{d\sigma_{UT}^i(S_\perp)}{dy_e d^2 p_T^e d^2 q_T}$$

Unpolarized: weighting factors

- Using Pythia for now to determine these non-perturbative weighting factors
  - Pythia works well for this observable: u-quark jet

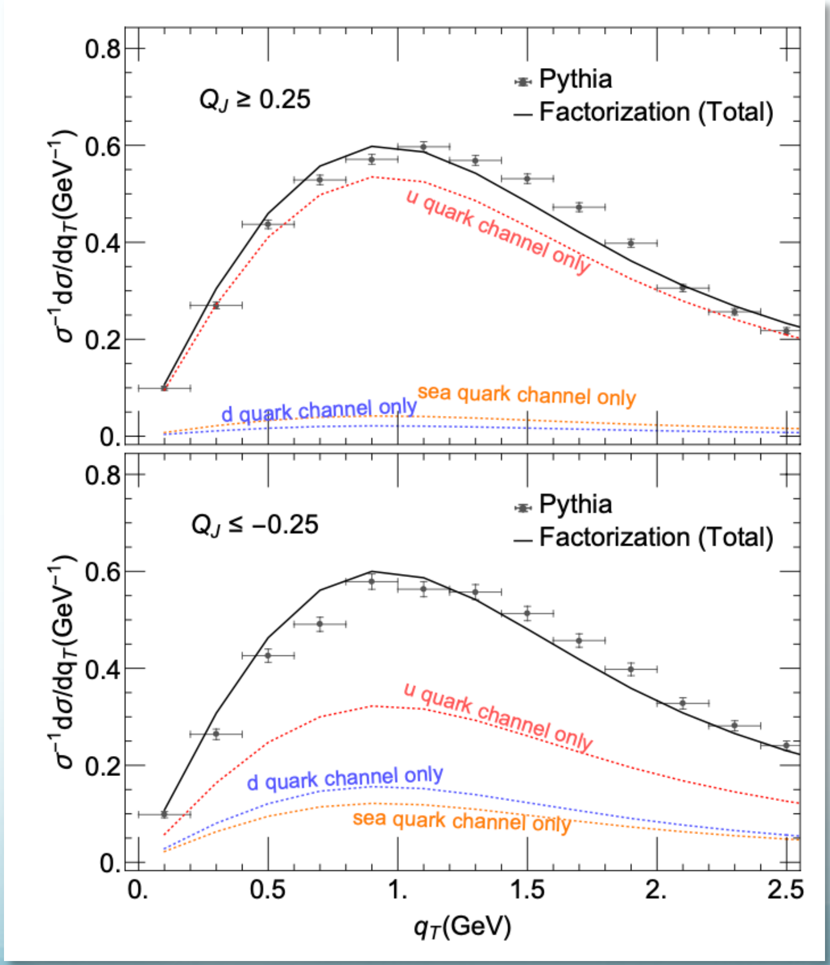


	u	$\bar{u}$	d	$\bar{d}$	s	$\bar{s}$
r_i^+	0.52	0.17	0.15	0.53	0.30	0.34
r_i^-	0.15	0.49	0.52	0.15	0.36	0.32
r_i^0	0.33	0.35	0.33	0.32	0.35	0.34

  - Kappa ~ 0.3 – 0.5, the energy dependence of these ratios are extremely small (~5%)

Unpolarized: sensitivity

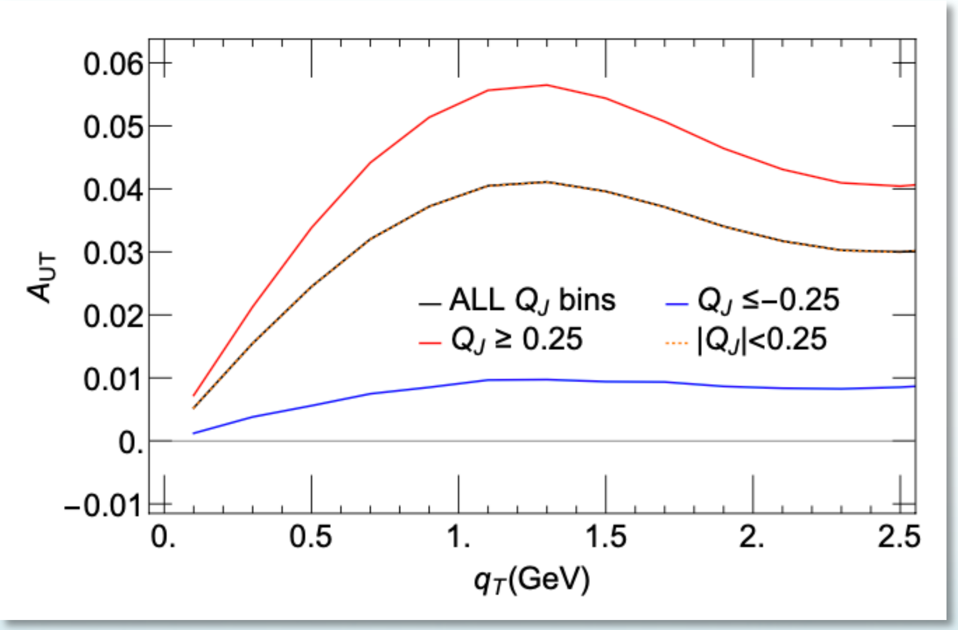
- In general, u quark is more dominant (charge enhancement e_u^2 vs e_d^2)
  - By selecting negative jet charge bin, one can enhance the d quark sensitivity a lot



Sivers asymmetry

- What will experimentalists measure?
  - Sivers asymmetry in different jet charge bins

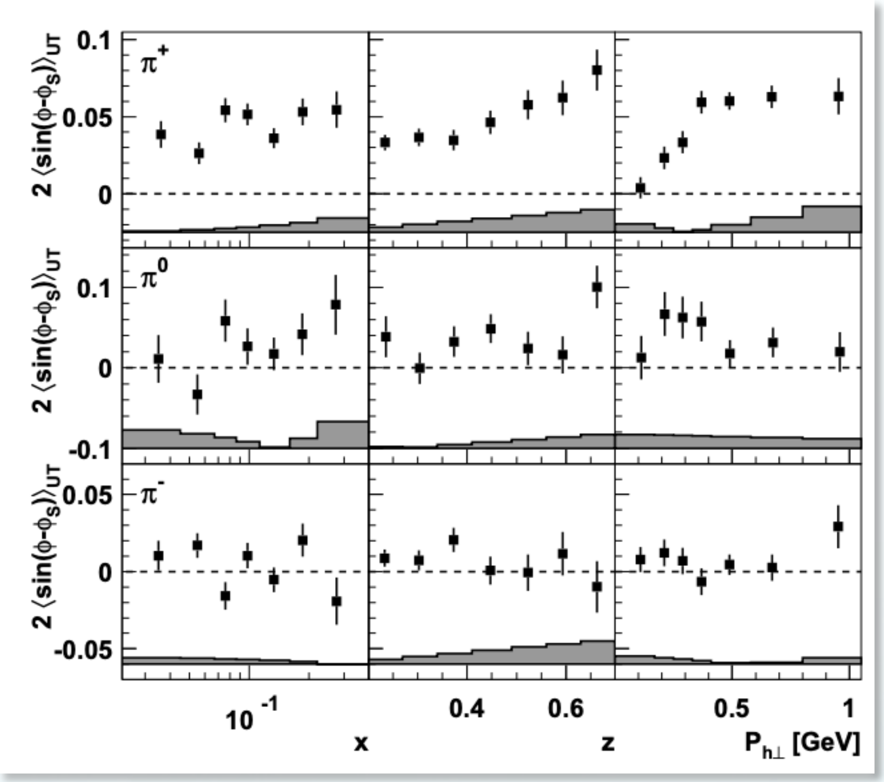
$$A_{UT}(Q^N_{\kappa,\text{bin}}) = \frac{d\sigma(S^\uparrow) - d\sigma(S^\downarrow)}{d\sigma(S^\uparrow) + d\sigma(S^\downarrow)} = \frac{d\sigma_{UT}(Q^N_{\kappa,\text{bin}})}{d\sigma_{UU}(Q^N_{\kappa,\text{bin}})}$$



Looks familiar?

- SIDIS Sivers asymmetry of pi+, pi0, pi-

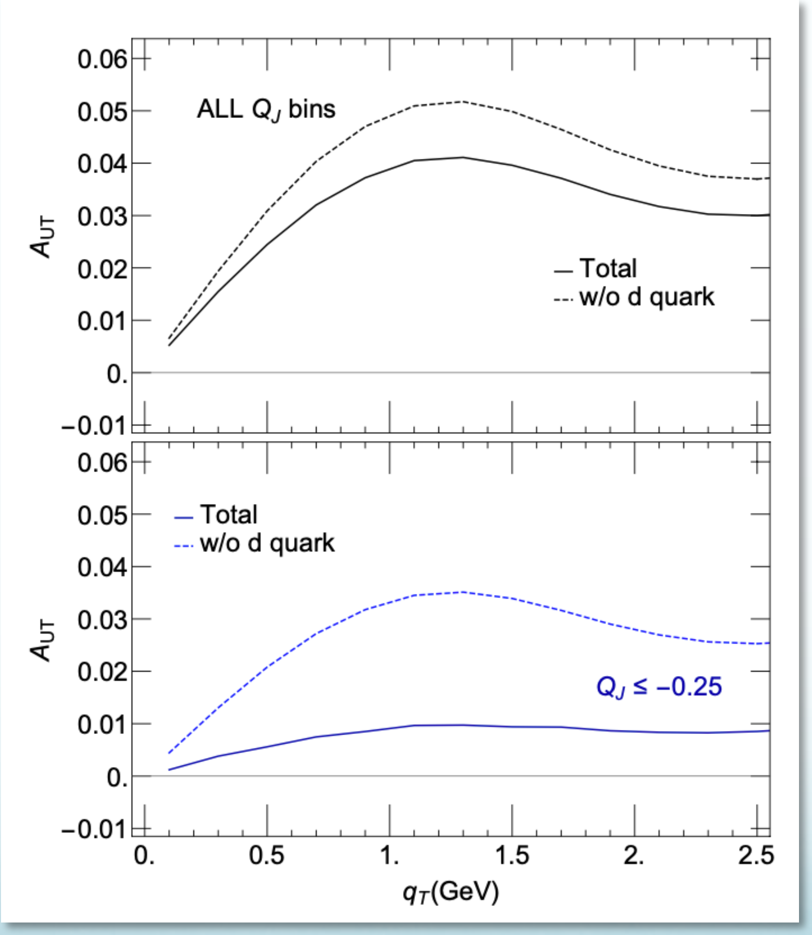
HERMES collaboration, arXiv:0906.3918



- **Fragmentation functions** in SIDIS are replaced by **jet charge weighting factors** in jet production
  - Functions → numbers
  - Both universal: can be determined via global analysis

Polarized: sensitivity

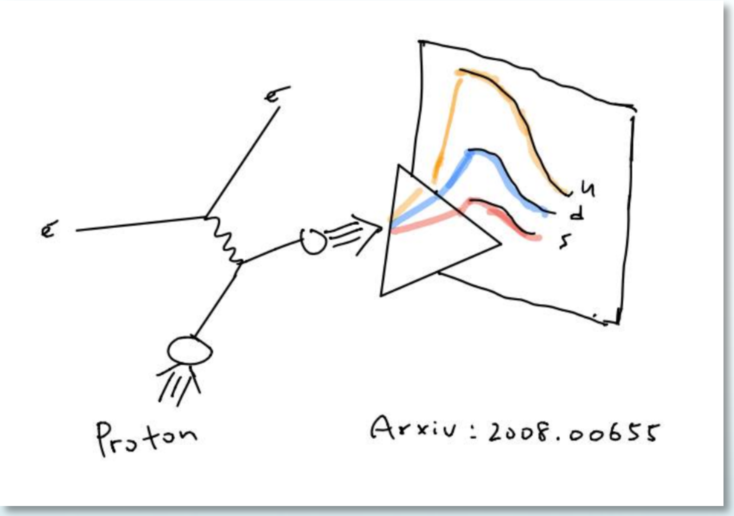
- With jet charge bin selection, the sensitivity to d-quark Sivers is significantly enhanced



Summary

- For 3D imaging, jet observables have become quite promising and complementary to the standard SIDIS process

- We demonstrate jet charge can be used for flavor separation in spin asymmetries
  - We demonstrate the effectiveness using Sivers asymmetry, but apparently it should work also for collinear functions, e.g., helicity distributions



Thank you!