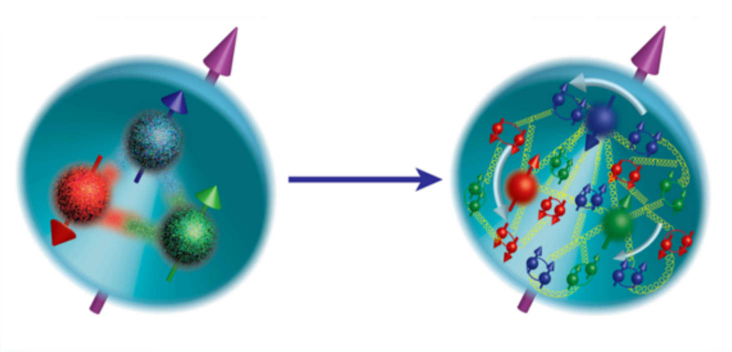
Jets for 3D imaging

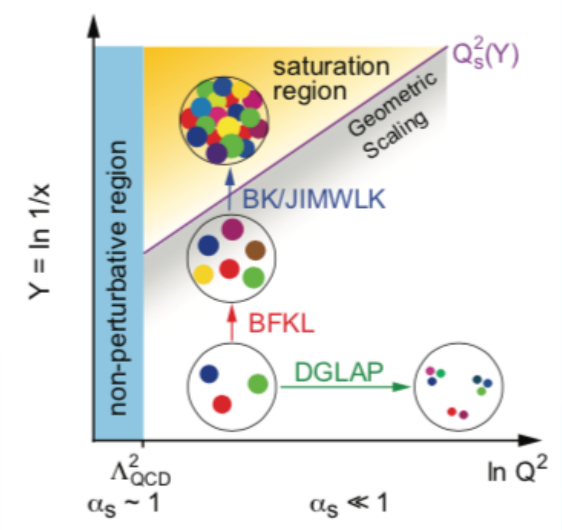
Zhongbo Kang
UCLA

HENPIC online seminar
August 12, 2020

The proton in QCD

- Proton is made of
  - 2 up quarks + 1 down quarks ➡ **valence quarks**
  - + any number of quark-antiquark pairs ➡ **sea quarks**
  - + any number of gluons





✓ **Infinite many body dynamic system of quarks and gluons**

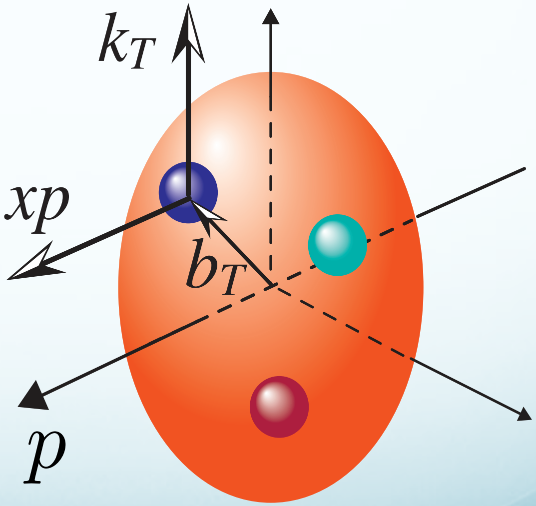
✓ **By changing *x* and *Q*, we probe different aspects of the proton wave function**

Quark and gluon structure of the nucleon

- Goal: quantum tomography in terms of quarks and gluons
  - **Momentum**: how do the quarks, antiquarks, gluons move inside?
  - **Position**: where are they located?
  - **Orbit**: do they orbit, carry orbital angular momentum?
  - **Correlation**: quantum correlations between motion and overall nucleon properties, e.g., spin? How do they respond to the external probes?

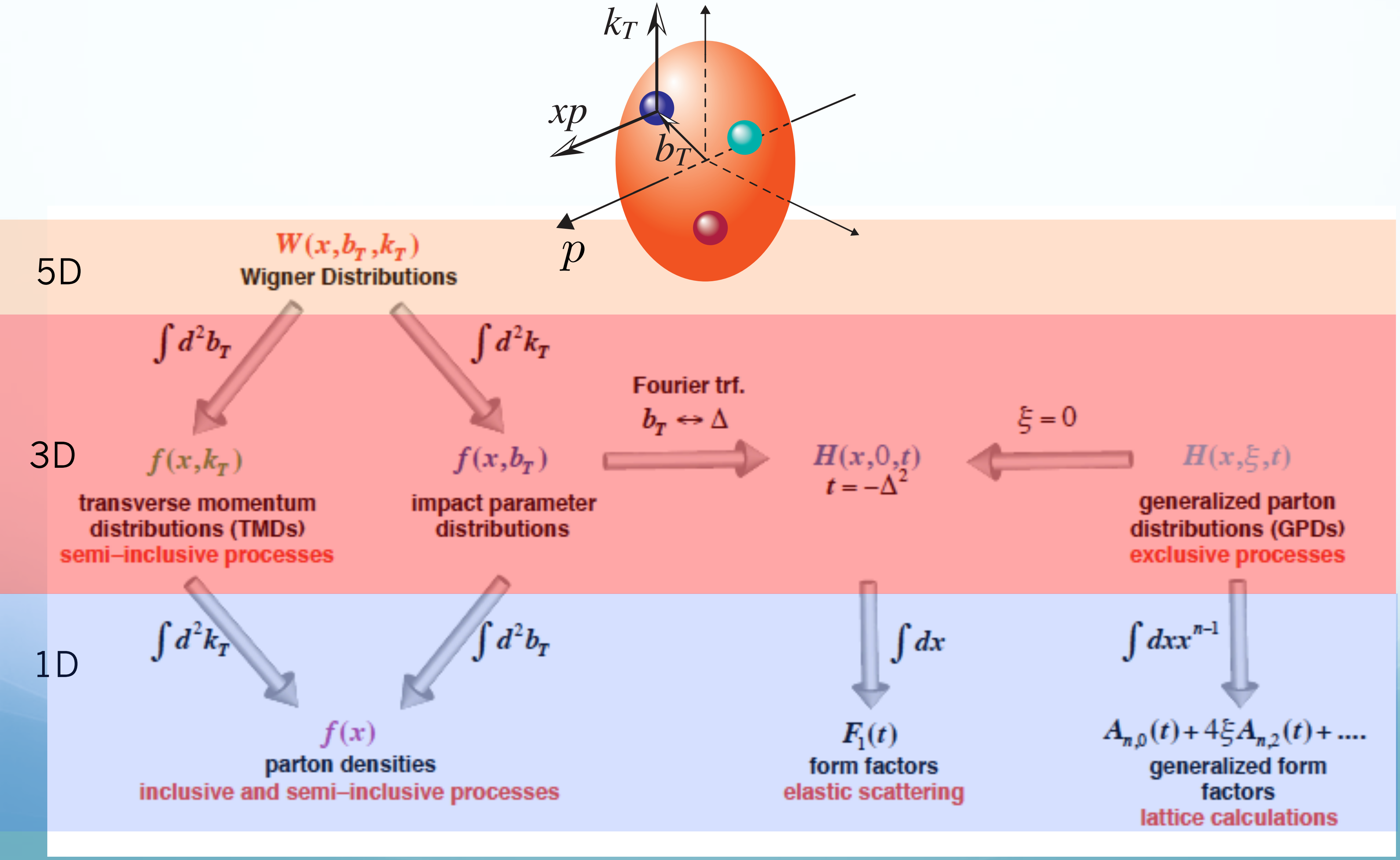
Internal landscape of the nucleon

Such information are defined as a set of **parton distribution functions**



Unified view: internal landscape

- Wigner distributions: a quantum version of phase-space distribution



5D

$W(x, b_T, k_T)$
Wigner Distributions

$\int d^2 b_T$ $\int d^2 k_T$

3D

$f(x, k_T)$
transverse momentum distributions (TMDs)
semi–inclusive processes

$f(x, b_T)$
impact parameter distributions

Fourier trf.
$b_T \leftrightarrow \Delta$

$H(x, 0, t)$
$t = -\Delta^2$

$\xi = 0$

$H(x, \xi, t)$
generalized parton distributions (GPDs)
exclusive processes

1D

$\int d^2 k_T$ $\int d^2 b_T$ $\int dx$ $\int dx x^{n-1}$

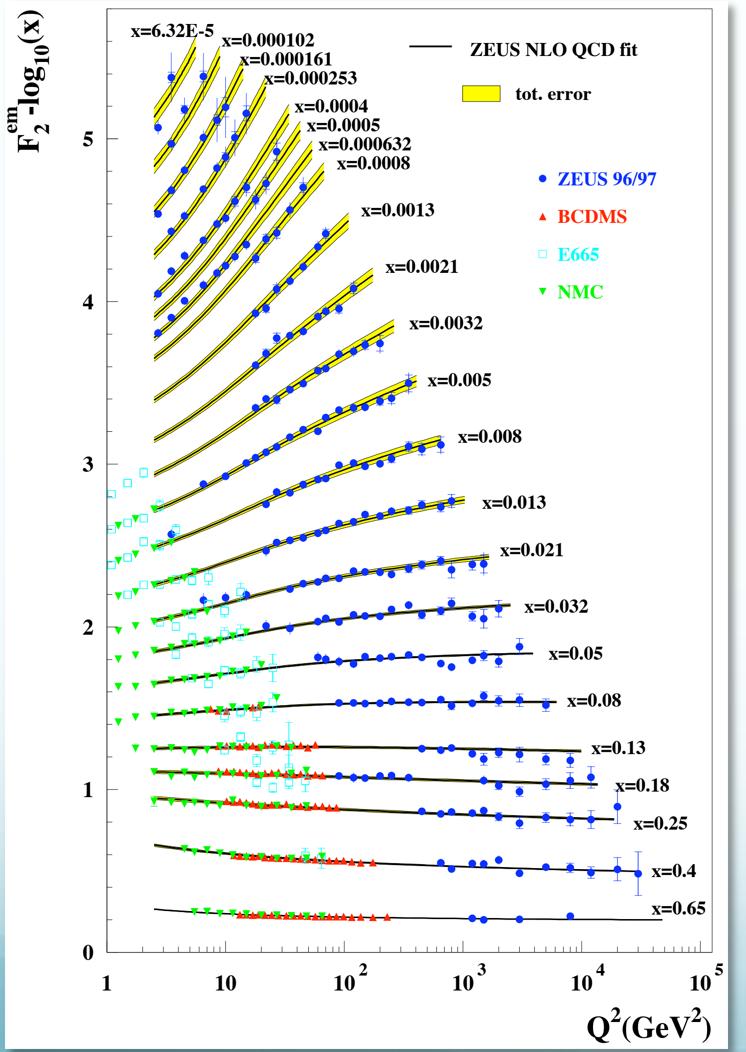
$f(x)$
parton densities
inclusive and semi–inclusive processes

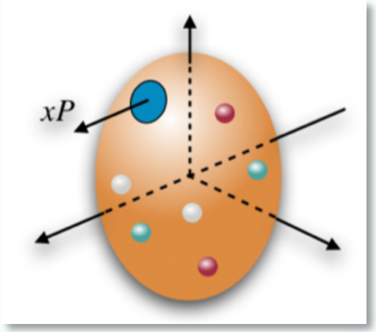
$F_1(t)$
form factors
elastic scattering

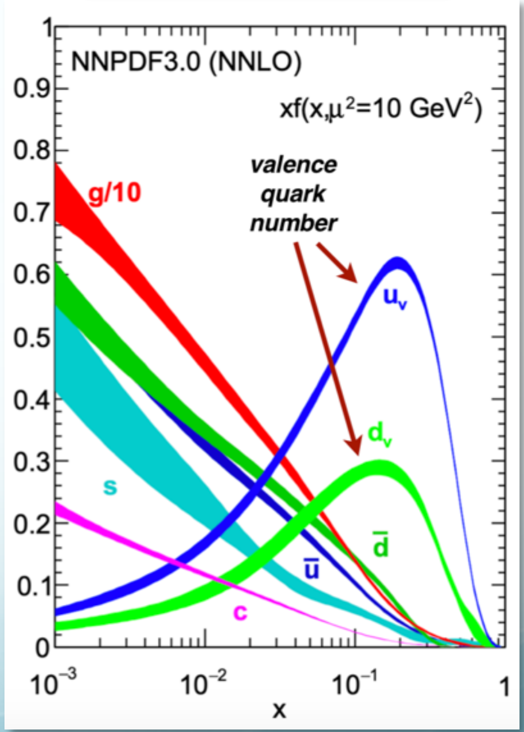
$A_{n,0}(t) + 4\xi A_{n,2}(t) + \ldots.$
generalized form factors
lattice calculations

Colinear PDFs

- One dimensional structure of the proton: longitudinal motion







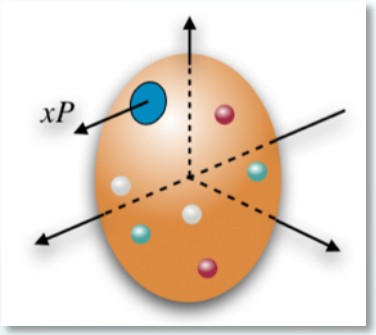
See E. R. Nocera talk

Moving forward

- 30+ years' study, good knowledge about parton's longitudinal motion: 1D

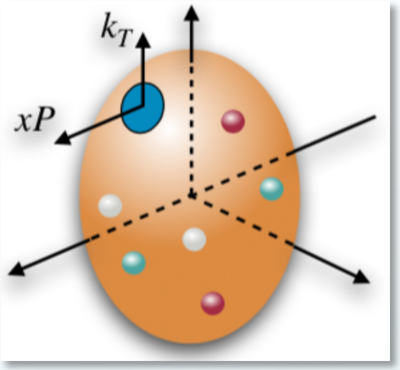
- Nucleon 3D structure: both longitudinal + transverse momentum dependent structure

Transverse Momentum Dependent parton distributions (TMDs)



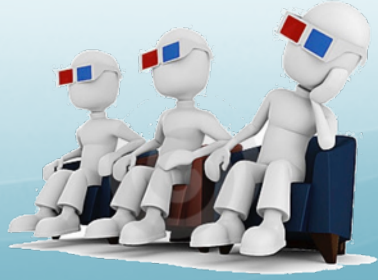
$f(x)$

Longitudinal motion only



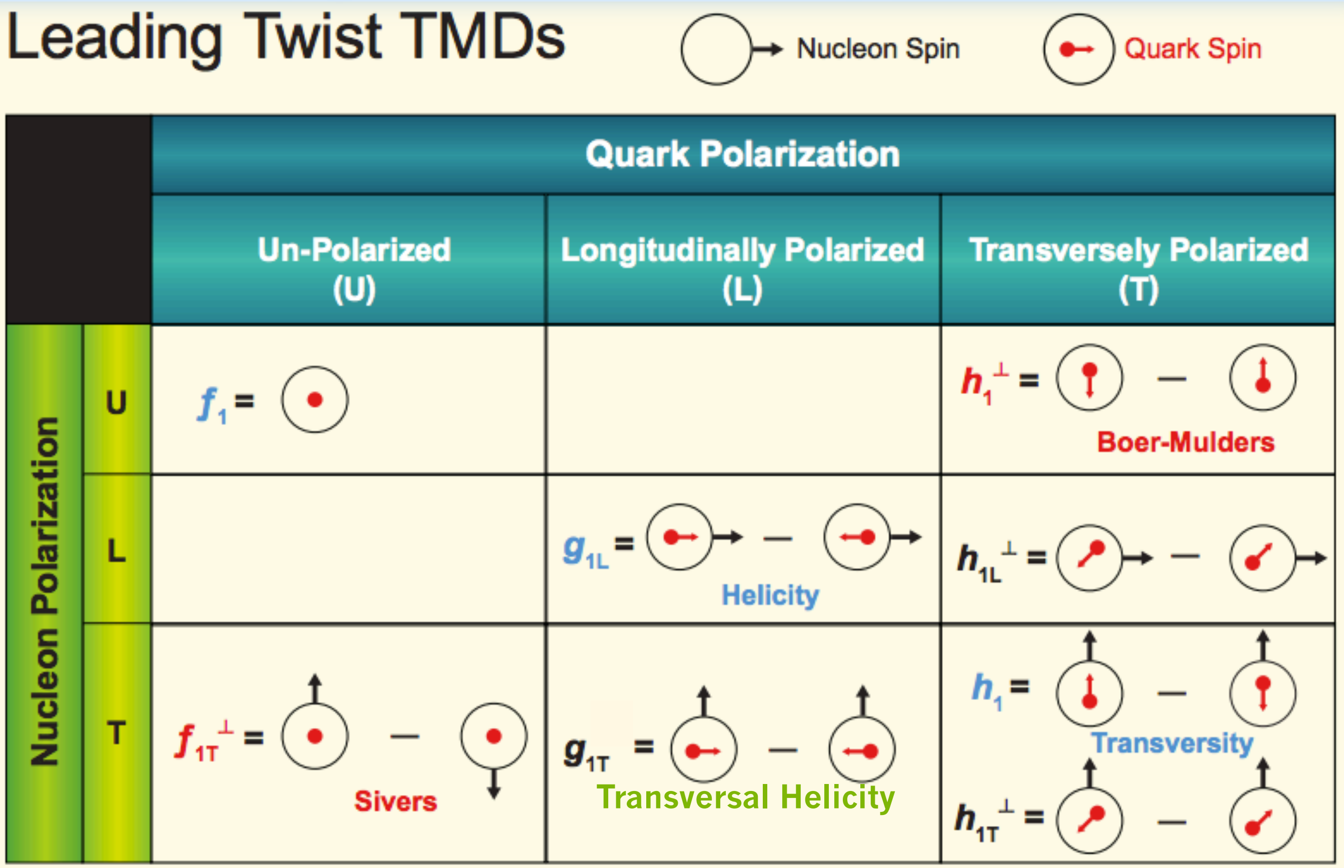
$f(x, k_T)$

Longitudinal + transverse motion



TMDs: rich quantum correlations

TMD parton distribution



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} = − Transversal Helicity	h_1 = − Transversity $h_{1T}^\perp$ = −

TMD fragmentation function

	Quark Polarization		
	U	L	T
Pion	D_1		$H_1^\perp$ **Collins**

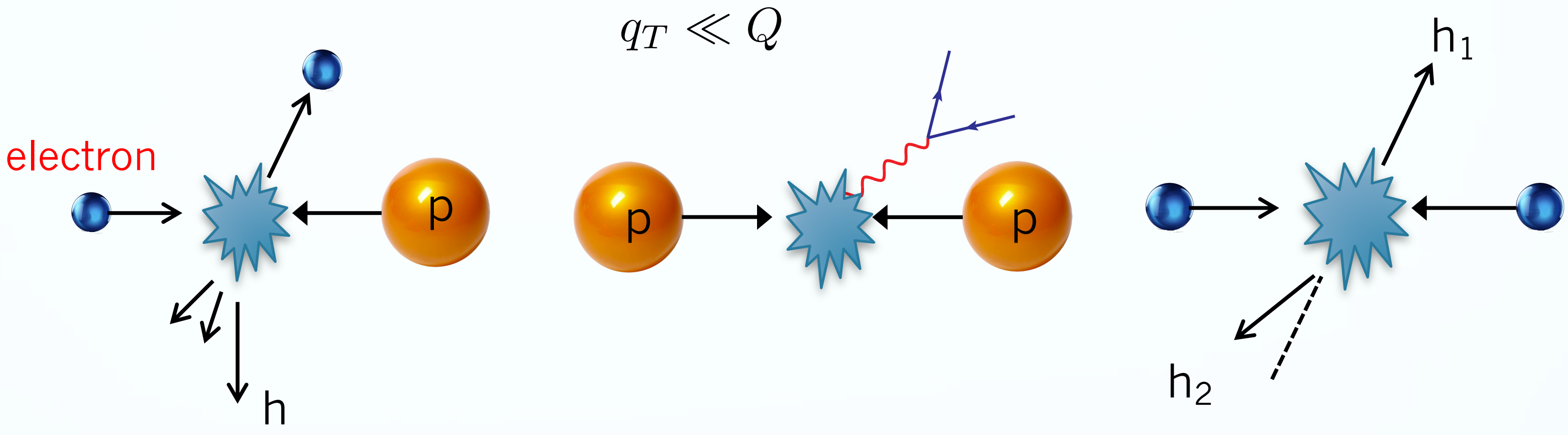
Novel insights from TMDs

- Quantum correlation: spin-spin, spin-momentum (orbit) correlations
  - Akin to those in hydrogen atoms and topological insulators
- 3D imagining
  - Both longitudinal and transverse motion
- Orbital motion
  - Most TMDs would vanish in the absence of parton orbital angular momentum
- Color gauge invariance at a very deep level
  - Akin to Aharonov-Bohm Effect

Using the nucleon as
a QCD “laboratory”

Standard processes to extract TMDs

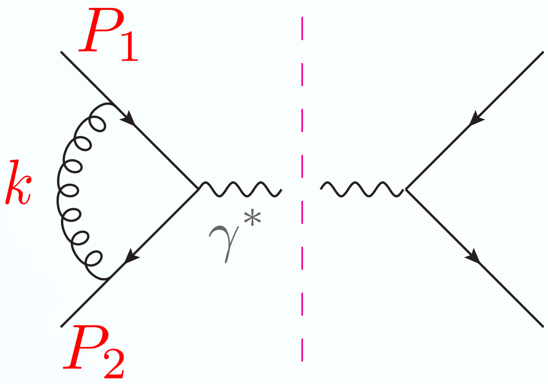
- SIDIS, Drell-Yan, dihadron in e^+e^-



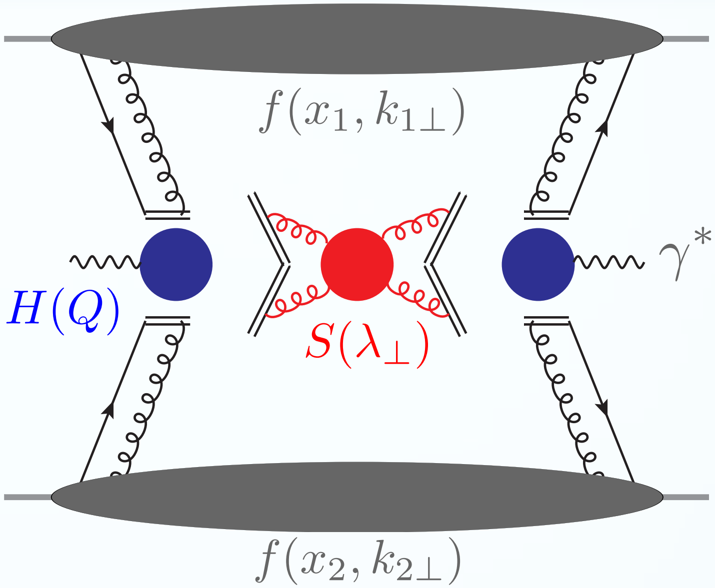
- They have a well-established TMD factorization formalism

TMD factorization in a nut-shell

- Drell-Yan: $p + p \to [\gamma^* \to \ell^+ \ell^-] + X$



Factorization of regions:
(1) k//P_1, (2) k//P_2, (3) k soft, (4) k hard



- Factorized form and mimic “parton model”

$$\frac{d\sigma}{dQ^2 dy d^2 q_\perp} \propto \int d^2 k_{1\perp}\, d^2 k_{2\perp}\, d^2 \lambda_\perp H(Q) f(x_1, k_{1\perp}) f(x_2, k_{2\perp}) S(\lambda_\perp) \delta^2(k_{1\perp} + k_{2\perp} + \lambda_\perp - q_\perp)$$

$$= \int \frac{d^2 b}{(2\pi)^2} e^{i q_\perp \cdot b} H(Q) f(x_1, b) f(x_2, b) S(b)$$

$$\downarrow$$

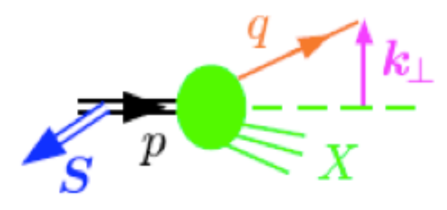
$$\boxed{F(x, b) = f(x, b)\sqrt{S(b)}}$$

$$\boxed{= \int \frac{d^2 b}{(2\pi)^2} e^{i q_\perp \cdot b} H(Q) F(x_1, b) F(x_2, b)}$$

mimic “parton model”

Sivers function: non-universal

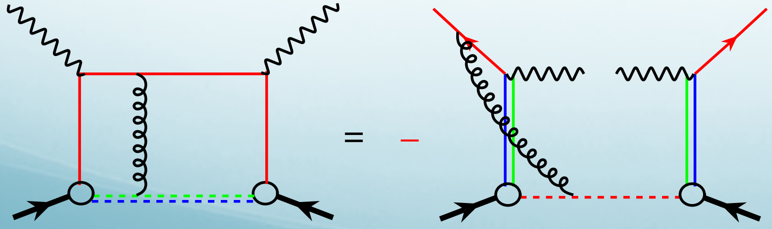
- Sivers function: unpolarized quark distribution inside a transversely polarized proton



$$f_{q/h^\uparrow}(x,\mathbf{k}_\perp,\vec{S}) \equiv f_{q/h}(x,k_\perp) - \frac{1}{M} f_{1T}^{\perp q}(x,k_\perp)\,\vec{S}\cdot(\hat{p}\times\mathbf{k}_\perp)$$

Spin-independent Spin-dependent

- ✓ 1990: introduced by D. Sivers, to describe the large single spin asymmetry measured in inclusive hadron production in p+p collisions at Fermilab
- ✓ 1993: J. Collins shows Sivers function has to vanish due to time-reversal invariance
- ✓ 2002: Brodsky, Hwang, Schmidt performed an explicit model calculation, showed the existence of the Sivers function
- ✓ 2002: Original proof missed the gauge link (needed to properly define gauge invariant distribution), once added, found Sivers function in SIDIS is opposite to that in Drell-Yan



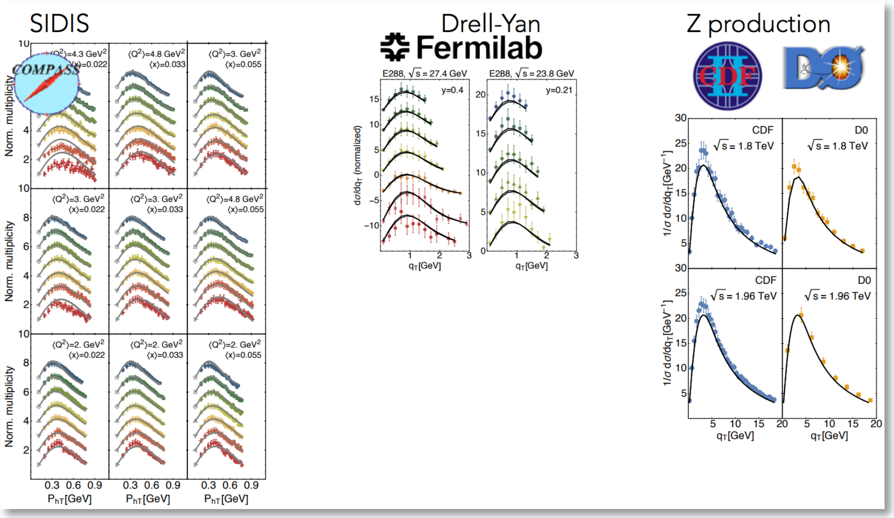
SIDIS = – DY

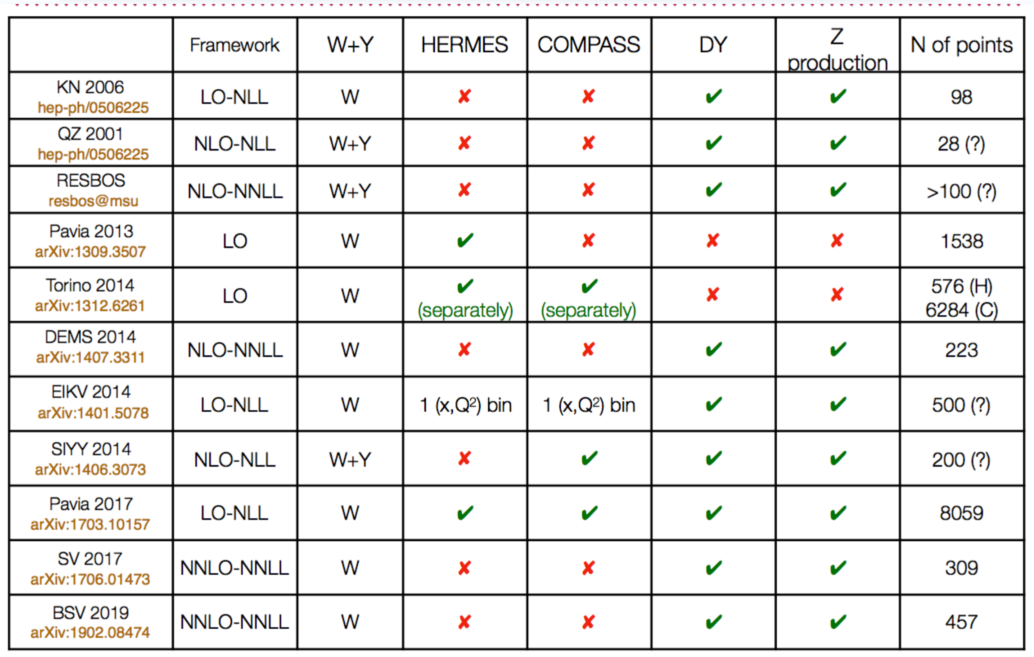
$$f_{1T}^{\perp\text{DIS}}(x,k_\perp) = -f_{1T}^{\perp\text{DY}}(x,k_\perp)$$

Collins 02, Boer-Mulders-Pijlman 03, Kang-Qiu, 09 ...

Extremely active phenomenology

- Examples: Pavia, Torino, EIKV, KSPY, DEMS, SV, EKT, …



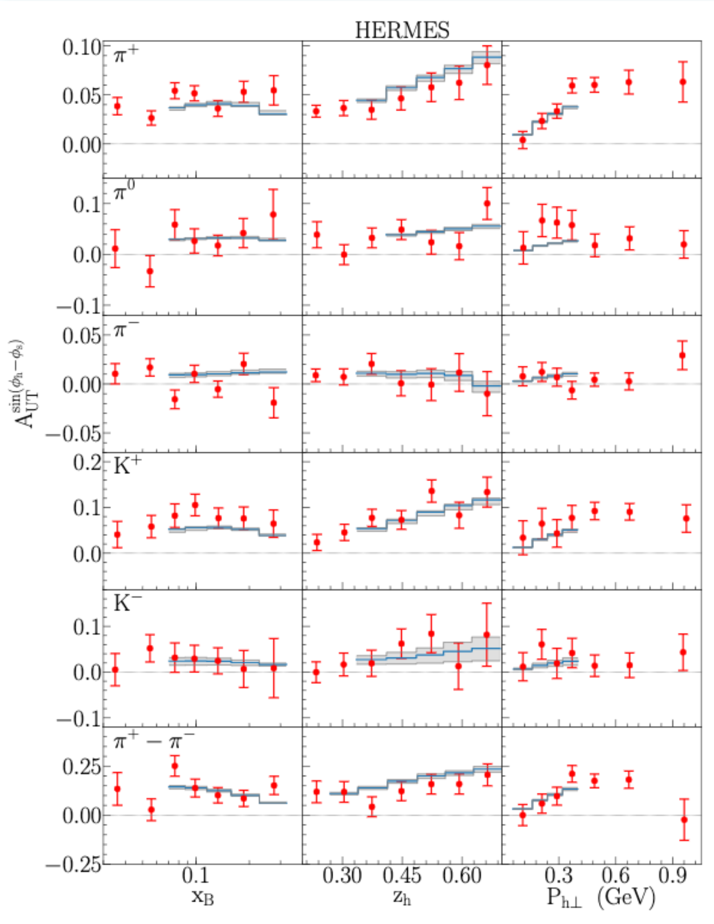


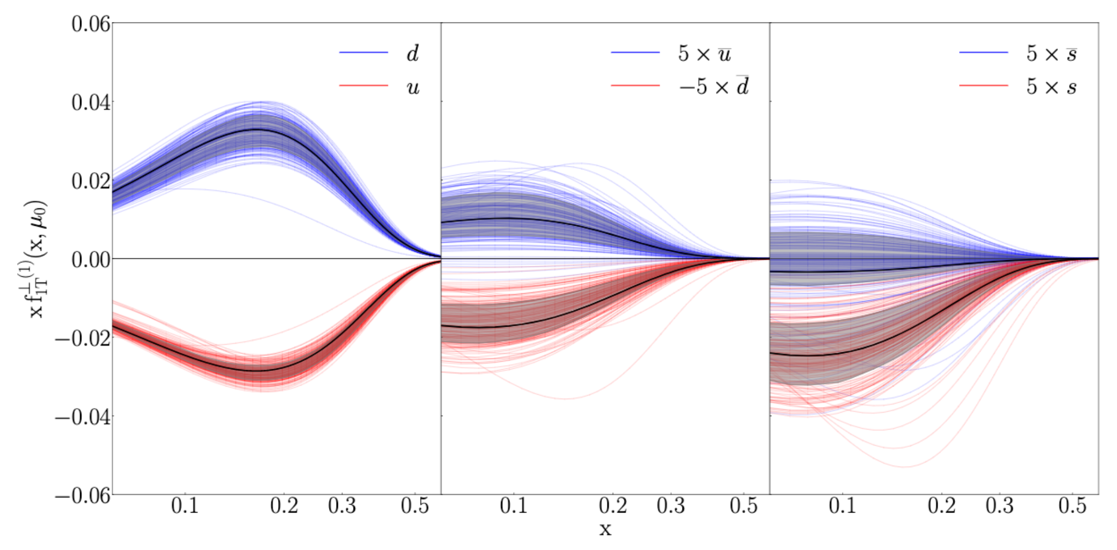
	Framework	W+Y	HERMES	COMPASS	DY	Z production	N of points
KN 2006 hep-ph/0506225	LO-NLL	W	✘	✘	✔	✔	98
QZ 2001 hep-ph/0506225	NLO-NLL	W+Y	✘	✘	✔	✔	28 (?)
RESBOS resbos@msu	NLO-NNLL	W+Y	✘	✘	✔	✔	>100 (?)
Pavia 2013 arXiv:1309.3507	LO	W	✔	✘	✘	✘	1538
Torino 2014 arXiv:1312.6261	LO	W	✔ (separately)	✔ (separately)	✘	✘	576 (H) 6284 (C)
DEMS 2014 arXiv:1407.3311	NLO-NNLL	W	✘	✘	✔	✔	223
EIKV 2014 arXiv:1401.5078	LO-NLL	W	1 (x,Q²) bin	1 (x,Q²) bin	✔	✔	500 (?)
SIYY 2014 arXiv:1406.3073	NLO-NLL	W+Y	✘	✔	✔	✔	200 (?)
Pavia 2017 arXiv:1703.10157	LO-NLL	W	✔	✔	✔	✔	8059
SV 2017 arXiv:1706.01473	NNLO-NNLL	W	✘	✘	✔	✔	309
BSV 2019 arXiv:1902.08474	NNLO-NNLL	W	✘	✘	✔	✔	457

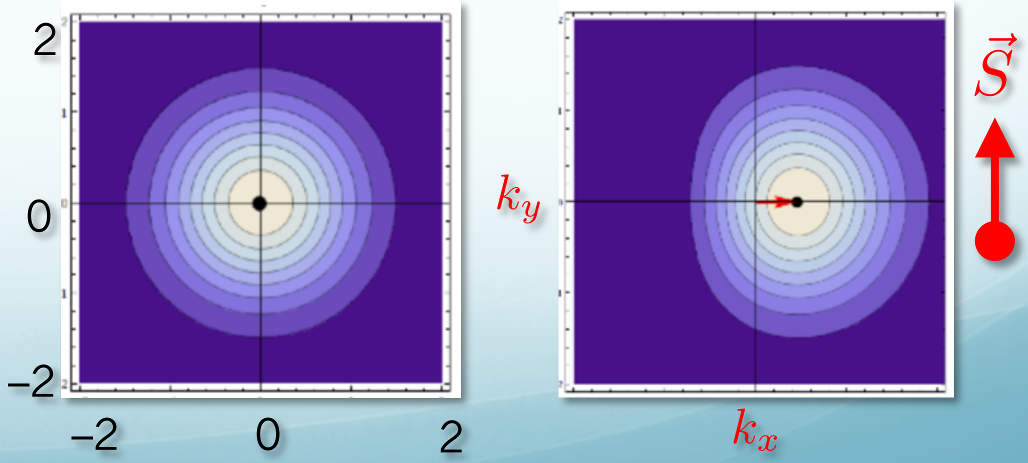
Current status of Sivers extraction

- u/d dominant, sea small

Echevarria, Kang, Terry, to appear

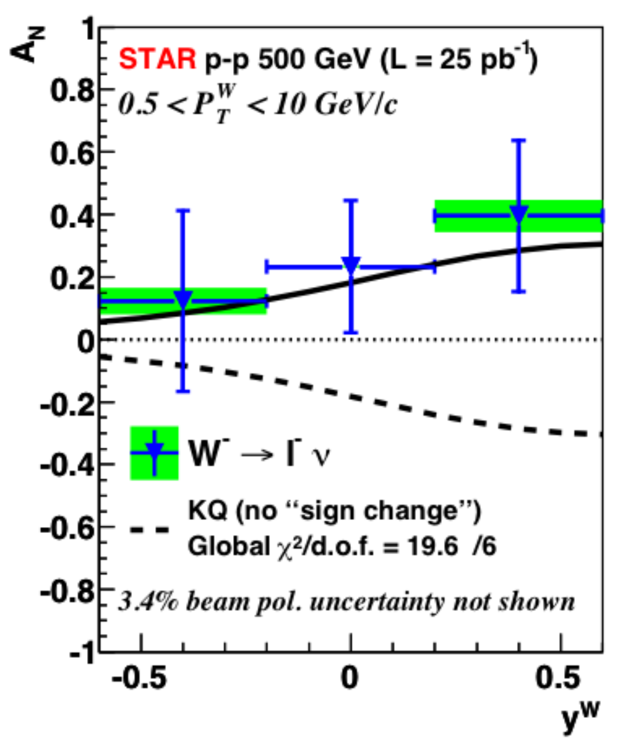




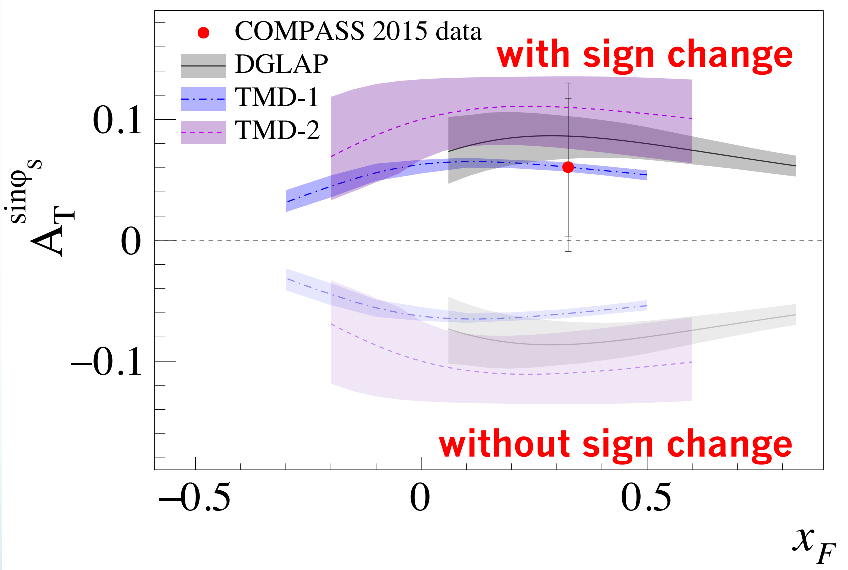


Experimental evidence of sign change

- STAR and COMPASS: the data seem to favor sign change
- Both theory and experiment has large uncertainty: will be improved in the future runs



DY lepton pair



with sign change

without sign change

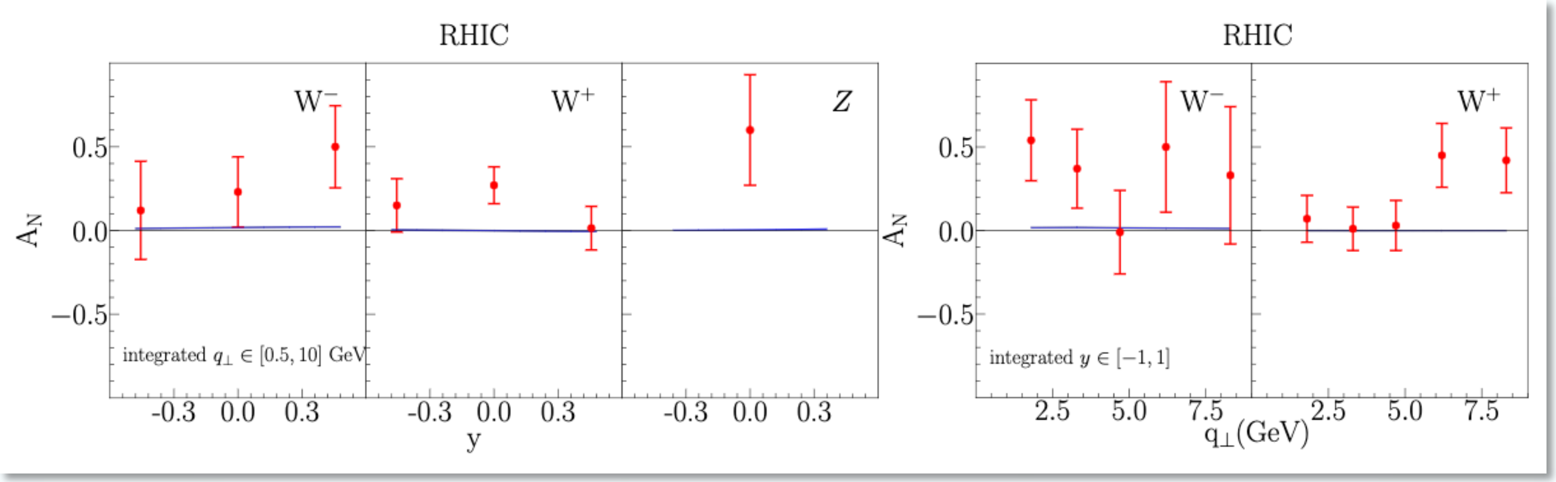
KQ = Kang, Qiu

STAR, arXiv:1511.06003, PRL

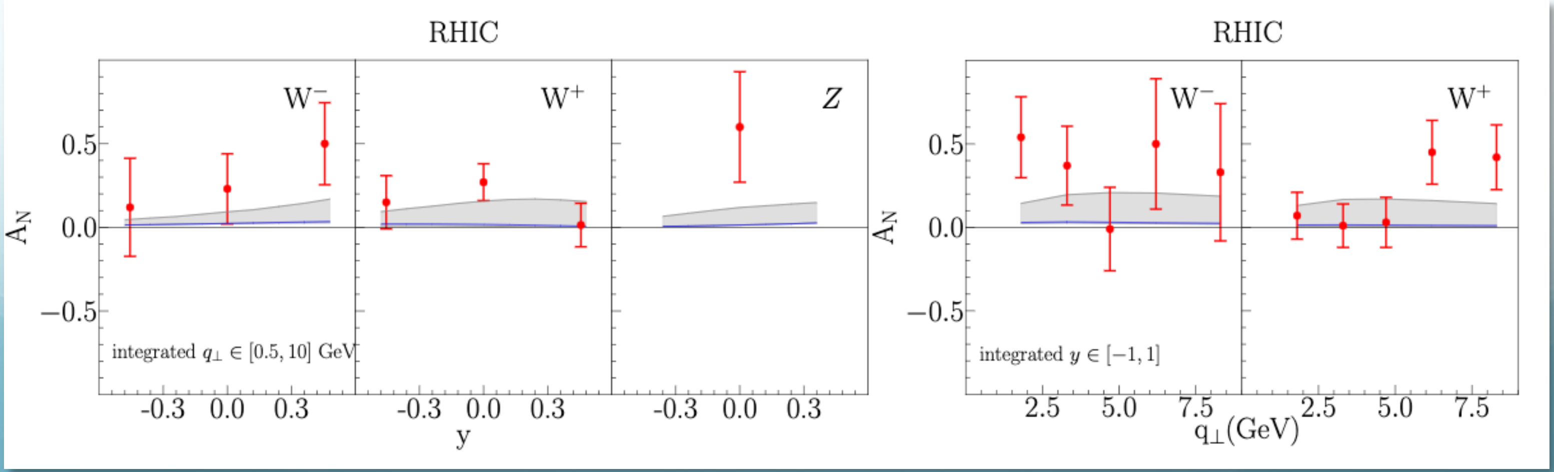
COMPASS, 1704.00488

Within the standard process

- Open questions: TMD evolution – how strong is it?
  - Add the TMD evolution, see what happens   Echevarria, Kang, Terry, to appear



  - Try really really hard



How to move forward

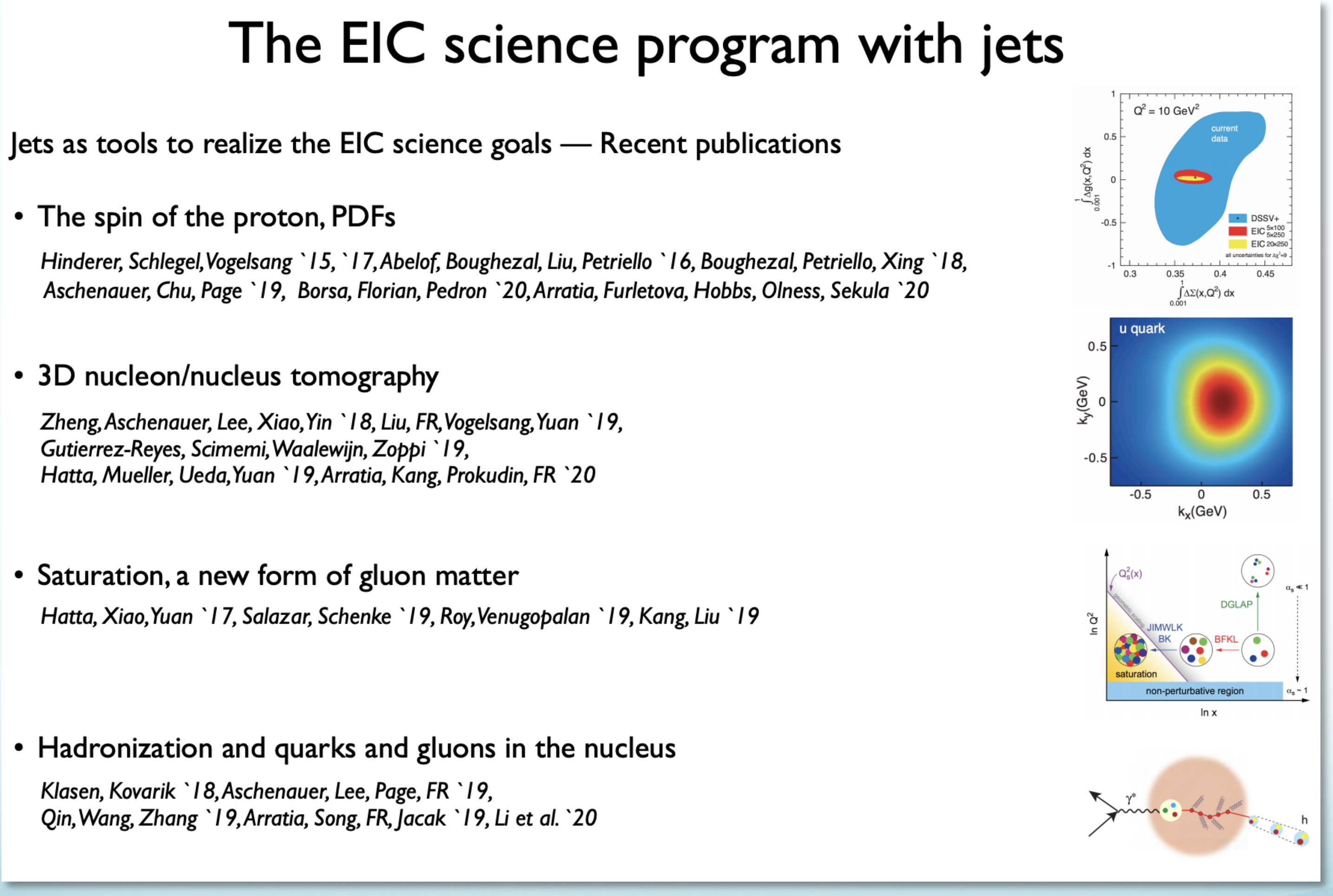
- Constraining ourselves ONLY to these three processes would limit the productivity of ourselves
- It is opportune time to explore other opportunities
- What are they?

Open the door is good for us

- Once you open this door (processes beyond standard ones), a new world is open for you

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

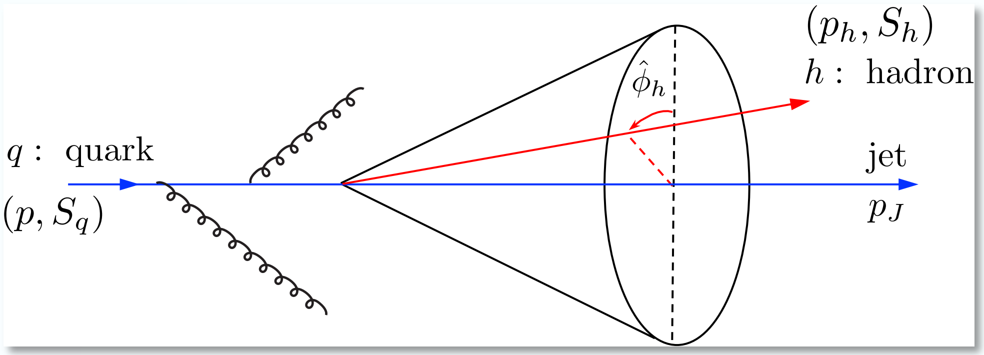
Jets
for
at the EIC
3D imaging

Riverside, CA. 17-18 Nov 2020

Organizing Committee
Miguel Arratia (University of California, Riverside)
Renee Fatemi (University of Kentucky)
Zhongbo Kang (University of California, Los Angeles)
Alexei Prokudin (Penn State Berks & JLab)
Felix Ringer (University of California, Berkeley)

How to get TMDs via jets

- TMD FFs via jet substructure: jet fragmentation functions

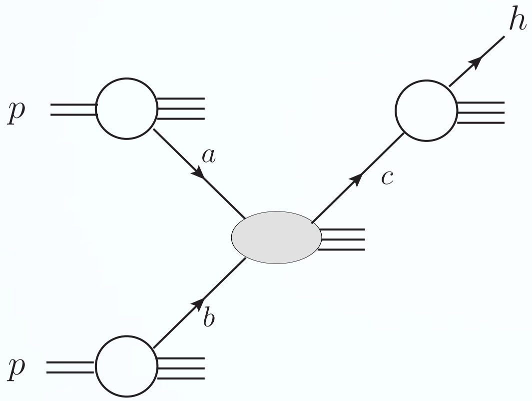


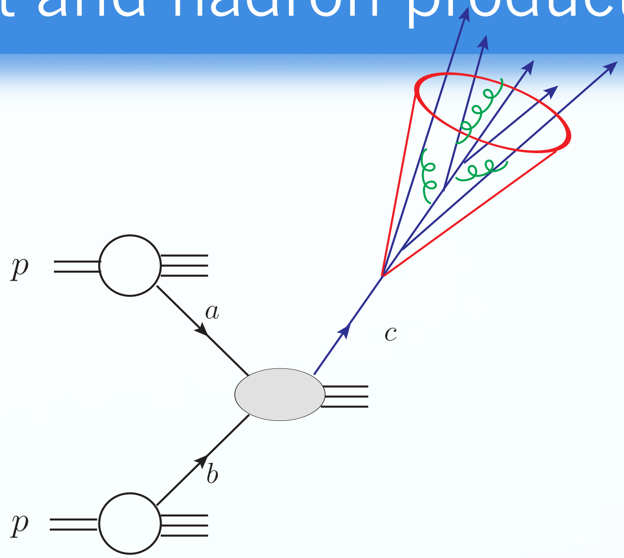
$$z_h = \frac{p_{hT}}{p_{JT}}$$

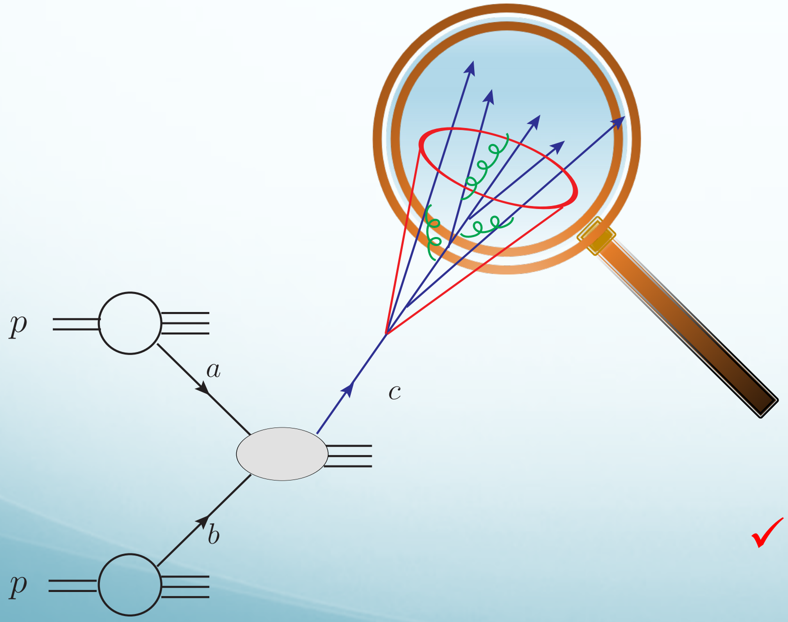
$$j_T$$

- 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

A unified framework for jet and hadron production







$$\frac{d\sigma^{pp\to hX}}{dp_T d\eta} \sim f_a \otimes f_b \otimes H_{ab\to c} \otimes D_c^h(z,\mu)$$

$$\frac{d\sigma^{pp\to \mathrm{jet}X}}{dp_T d\eta} \sim f_a \otimes f_b \otimes H_{ab\to c} \otimes J_c(z,p_T R,\mu)$$

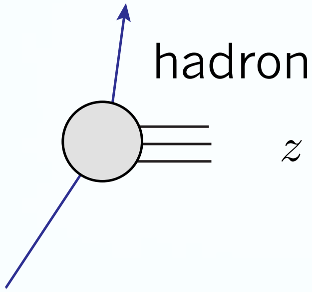
$$\frac{d\sigma^{pp\to \mathrm{jet}(\tau)X}}{dp_T d\eta} \sim f_a \otimes f_b \otimes H_{ab\to c} \otimes \mathcal{G}_c(z,p_T R,\tau,\mu)$$

✓ Same hard functions, telling us the quark and gluon jet ratios order by order in pQCD

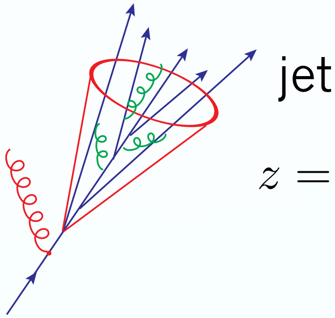
Kang, Ringer, Vitev, 1606.06732, 1606.07063, Dai, Kim, Leibovich, 1606.07411, see also, Kaufmann, Mukherjee, Vogelsang, 1506.01415

What are these jet functions?

- They are usually referred to as “semi-inclusive jet function”



$$z = \frac{p_{\rm h}^{+}}{p_{\rm parton}^{+}}$$



$$z = \frac{p_{\rm jet}^{+}}{p_{\rm parton}^{+}}$$

- They follow DGLAP evolution equation
  - All jet substructures are contained in these functions

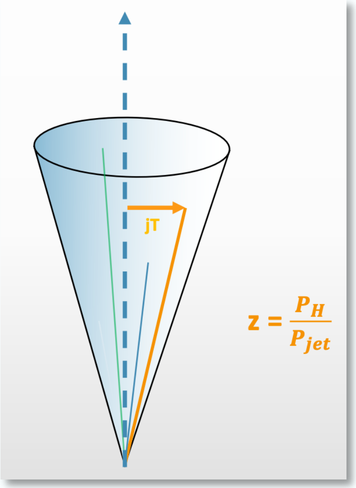
$$\mu\frac{d}{d\mu}D_i^h(z,\mu) = \sum_j P_{ji}\otimes D_j^h(z,\mu)$$

$$\mu\frac{d}{d\mu}J_i(z,p_TR,\mu) = \sum_j P_{ji}\otimes J_j(z,p_TR,\mu)$$

$$\mu\frac{d}{d\mu}\mathcal{G}_i(z,p_TR,\tau,\mu) = \sum_j P_{ji}\otimes \mathcal{G}_j(z,p_TR,\tau,\mu)$$

TMD hadron distribution inside the jet?

- Definition



- Factorization formalism

Kang, Liu, Ringer, Xing, 1705.08443

$$\frac{d\sigma}{dp_T d\eta dz_h d^2 j_\perp} \propto \sum_{a,b,c} f_a \otimes f_b \otimes H_{ab\to c} \otimes \mathcal{G}_c^h(z, z_h, \omega_J R, j_\perp, \mu)$$

- Related to transverse momentum dependent (TMD) fragmenting function

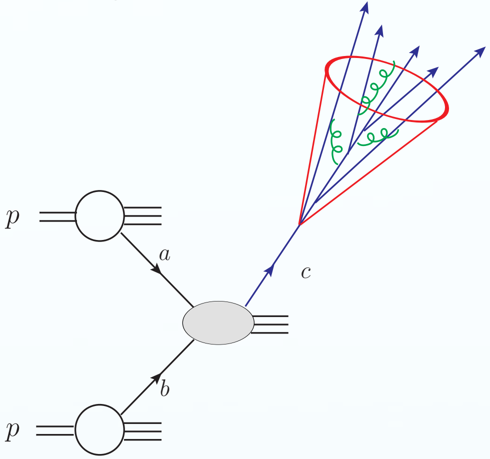
$$\mathcal{G}_c^h(z, z_h, \omega_J R, \boldsymbol{j}_\perp, \mu) = \mathcal{H}_{c\to i}(z, \omega_J R, \mu) \int d^2\boldsymbol{k}_\perp d^2\boldsymbol{\lambda}_\perp \delta^2\left(z_h \boldsymbol{\lambda}_\perp + \boldsymbol{k}_\perp - \boldsymbol{j}_\perp\right)$$
$$\times D_{h/i}(z_h, \boldsymbol{k}_\perp, \mu, \nu) S_i(\boldsymbol{\lambda}_\perp, \mu, \nu R)$$

Characteristics: hadron in the jet

- Soft radiation has to happen inside the jet
  - Only the soft radiation inside the jet can change the hadron transverse momentum with respect to the jet axis
- Restricts soft radiation to be within the jet
  - Cuts half of the rapidity divergence

$$\int_0^\infty \frac{dy}{y} \Rightarrow \int_0^{\tan^2\frac{R}{2}} \frac{dy}{y}$$

$$y \sim \frac{\ell^+}{\ell^-}$$

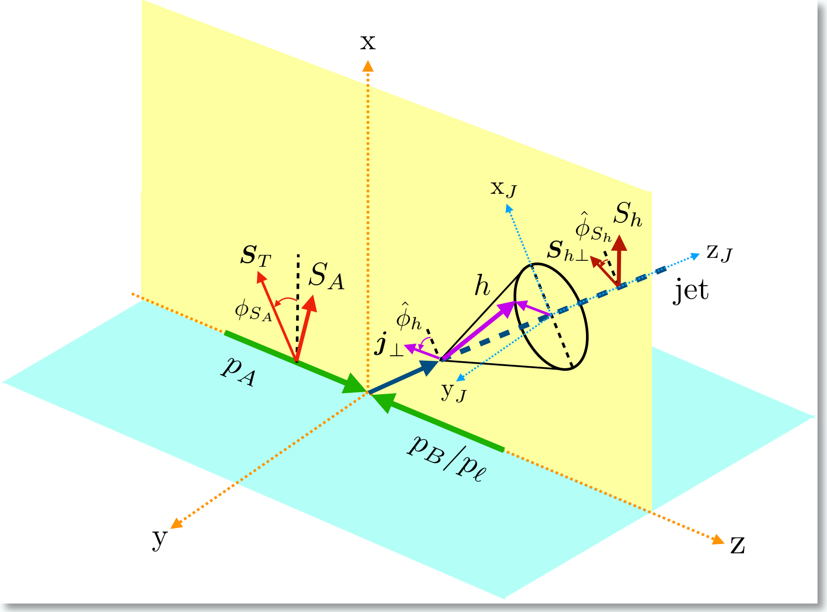


- Rapidity divergence cancel between restricted "soft factor" and TMD FFs
  - At least up to this order, the combined evolution is the same as the usual TMD evolution in SIDIS, e+e-; justify the use of same TMD evolution here

$$\sqrt{S(b)}\,D_c^h(z_h,b)_{\mathrm{e^+e^-}} \Rightarrow S(b,R)\,D_c^h(z_h,b)_{\mathrm{pp}}$$

Azimuthal angular dependence

- All the azimuthal angular dependence for single inclusive jet



Kang, Kyle, Zhao, arXiv:2005.02398

Collins effect

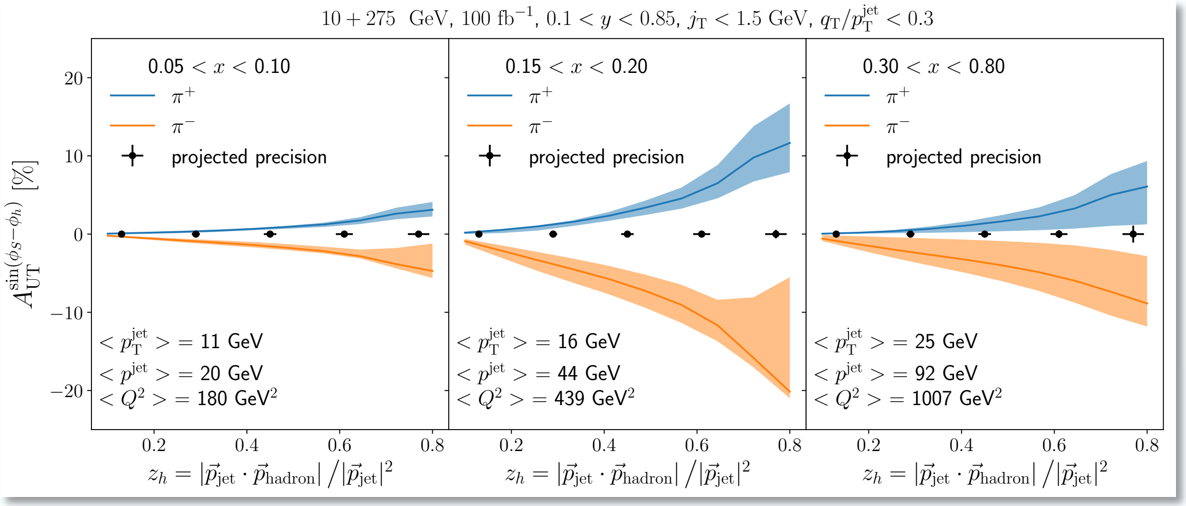
$$\frac{d\sigma^{p(S_A)+p/e\to(\mathrm{jet}\,h(S_h))X}}{dp_{JT}d\eta_J dz_h d^2\boldsymbol{j}_\perp} = F_{UU,U} + |\boldsymbol{S}_T|\sin(\phi_{S_A}-\hat{\phi}_h)F_{TU,U}^{\sin(\phi_{S_A}-\hat{\phi}_h)} + \Lambda_h\left[\lambda F_{LU,L} + |\boldsymbol{S}_T|\cos(\phi_{S_A}-\hat{\phi}_h)F_{TU,L}^{\cos(\phi_{S_A}-\hat{\phi}_h)}\right]$$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

Lambda polarization

Examples

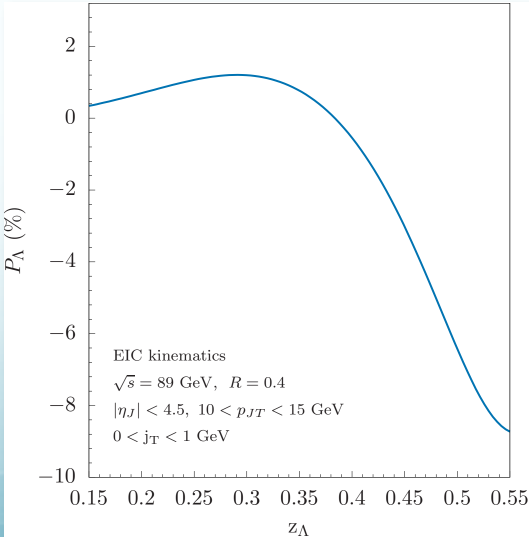
- Collins effect at the EIC

Arratia, Kang, Prokudin, Ringer, arXiv:2007.07281



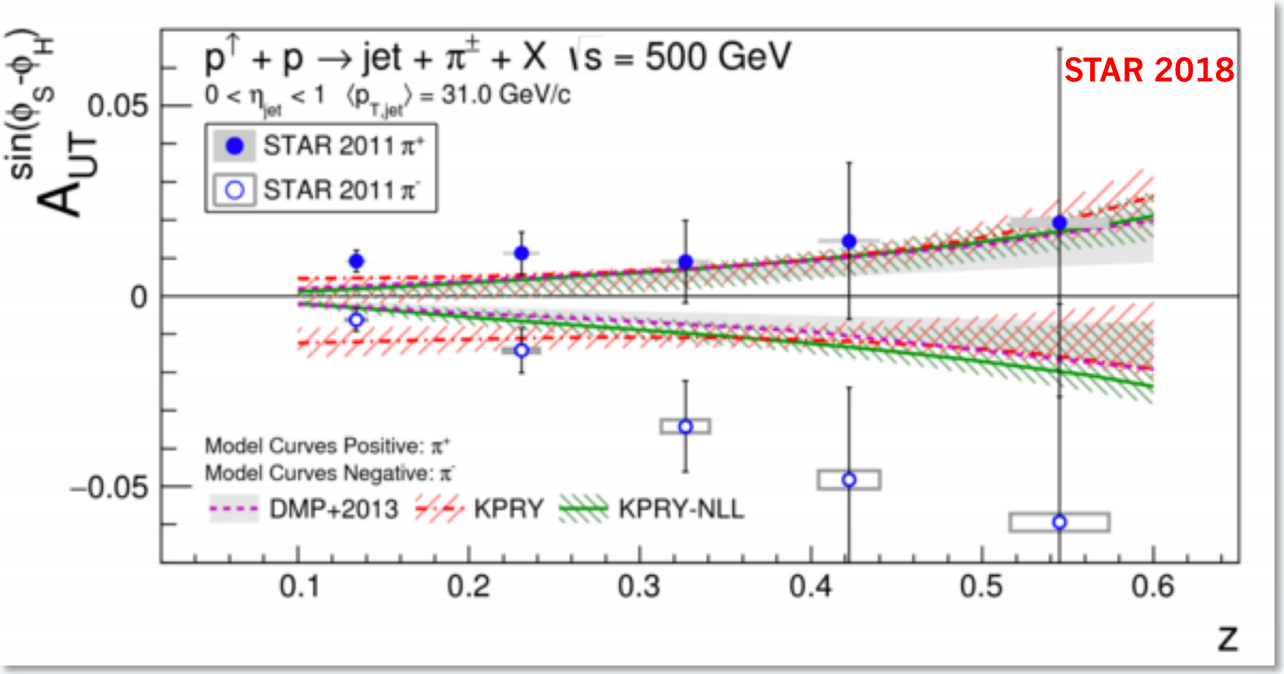
- Lambda polarization at the EIC

Kang, Kyle, Zhao, arXiv:2005.02398



Collins asymmetry in p+p

$$p^{\uparrow}\left[\vec{S}_{\perp}(\phi_S)\right] + p \to [\text{jet}\, h(\phi_H)] + X$$

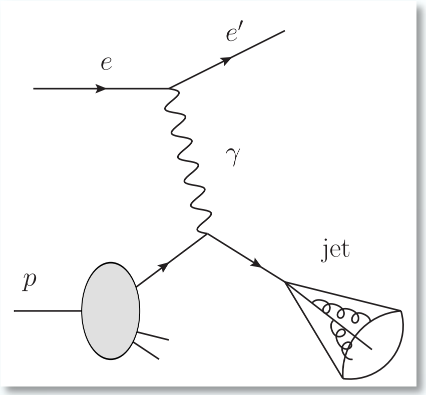


- Universality of Collins function between e+p, e+e, and p+p
- Test TMD evolution

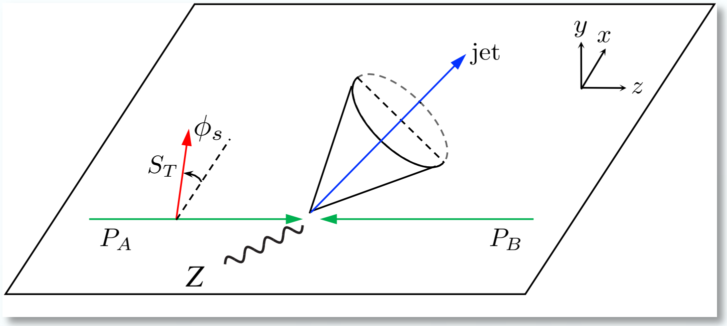
Kang, Prokudin, Ringer, Yuan, 1707.00913

TMD PDFs: back-to-back jet production

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



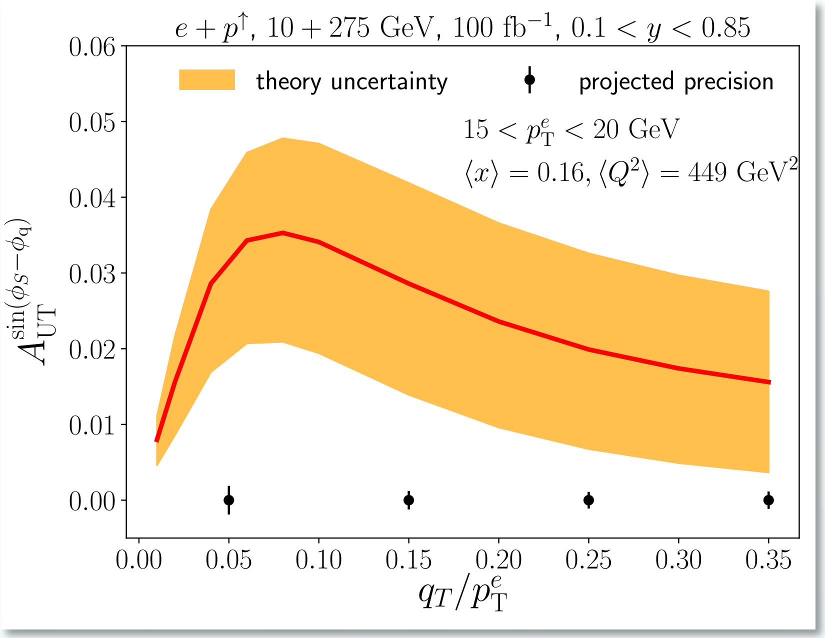
Kang, Lee, Terry, Xing, arXiv:1906.07187
Chien, Shao, Wu, arXiv:1905.01335, ...



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

Examples

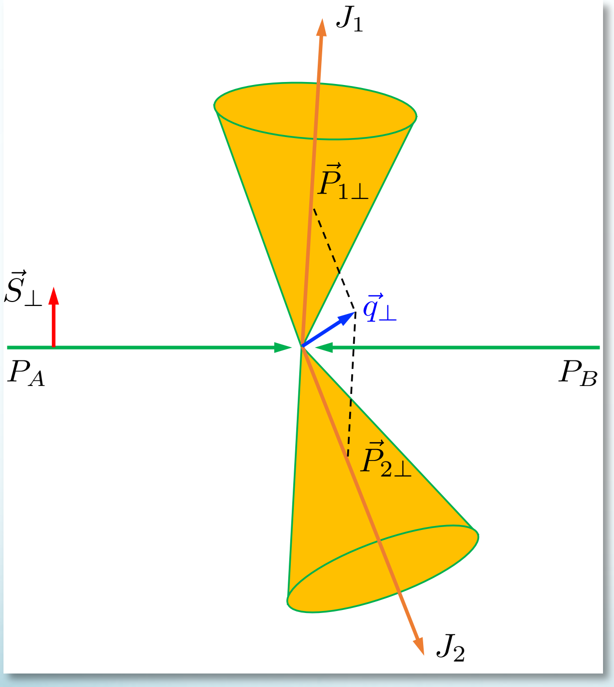
- Sivers asymmetry at the EIC
  - electron-jet back-to-back production

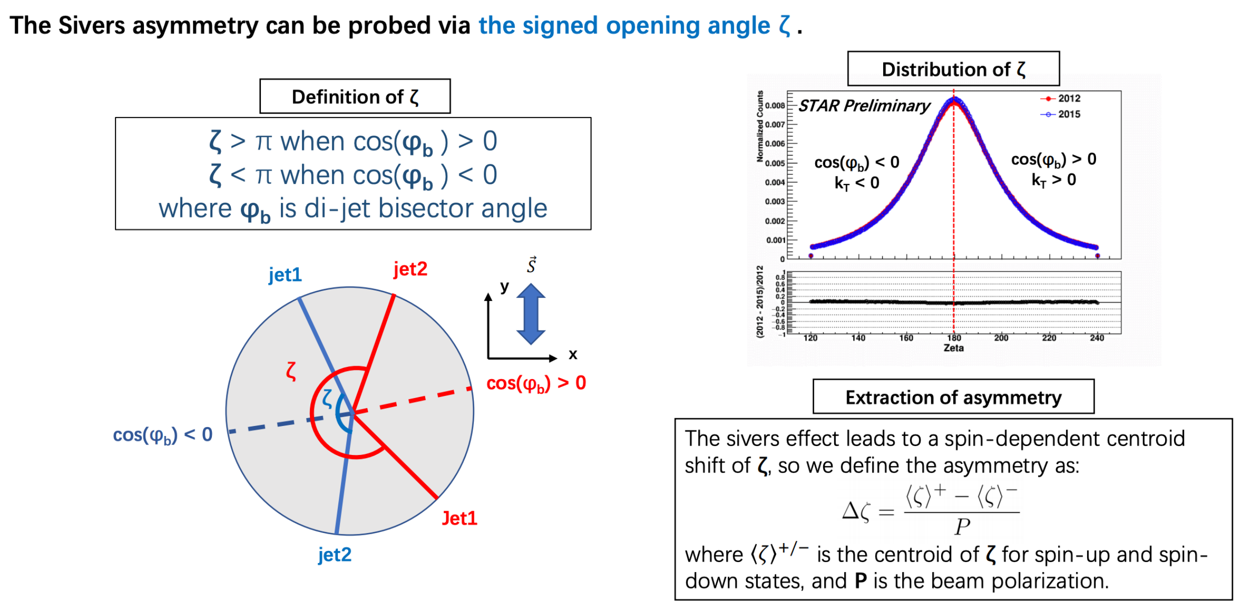


Arratia, Kang, Prokudin, Ringer, arXiv:2007.07281

Dijet Sivers asymmetry in p+p

- Dijet spin asymmetry
    - Spin vector and transverse momentum imbalance vector can correlate and generate asymmetry $\sin(\phi_q - \phi_S)$





The Sivers asymmetry can be probed via the signed opening angle ζ .

Definition of ζ

ζ > π when cos(φ_b) > 0
ζ < π when cos(φ_b) < 0
where φ_b is di-jet bisector angle

Distribution of ζ

Extraction of asymmetry

The sivers effect leads to a spin-dependent centroid shift of **ζ**, so we define the asymmetry as:

$$\Delta\zeta = \frac{\langle\zeta\rangle^+ - \langle\zeta\rangle^-}{P}$$

where $\langle\zeta\rangle^{+/-}$ is the centroid of **ζ** for spin-up and spin-down states, and **P** is the beam polarization.

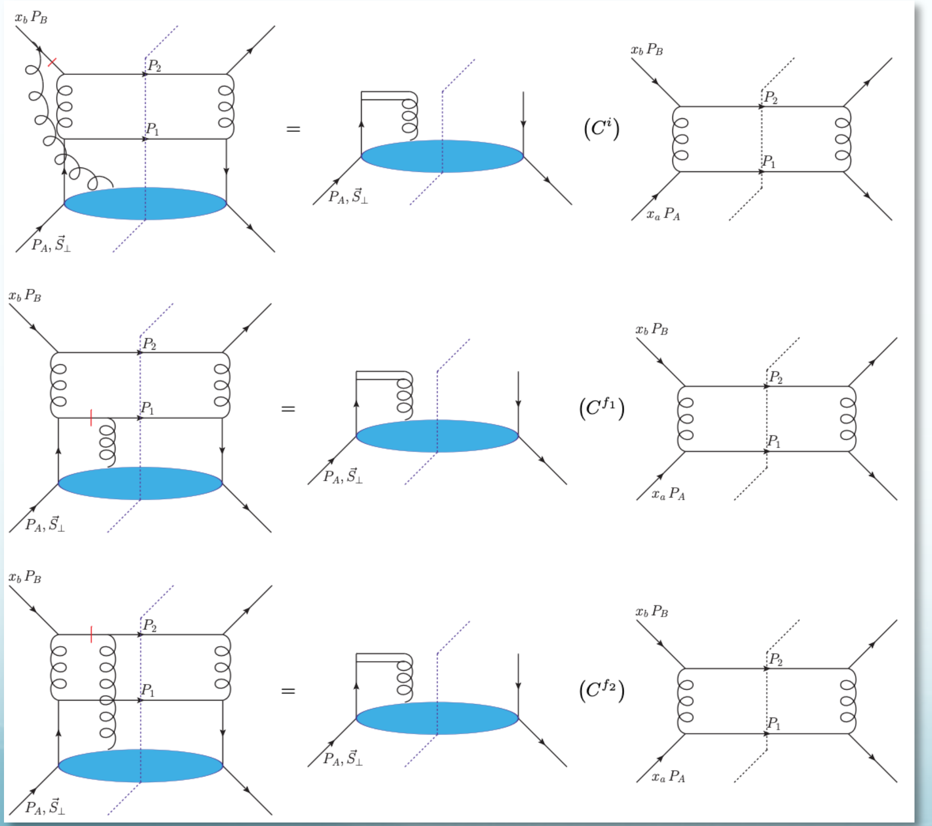
Renee Fatemi, Huanzhao Liu, BNL talk in July 2020

Boer, Vogelsang, 2003

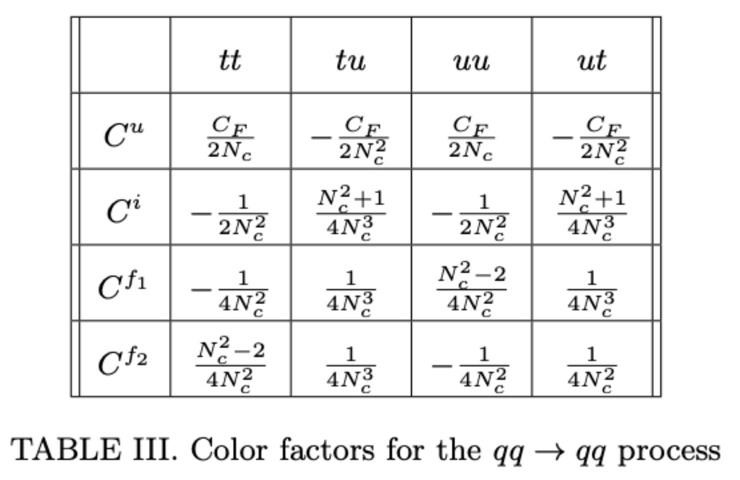
Theory

- A lot of motivations
  - Sivers function and its non-universality
  - TMD factorization breaking
  - …

Collins, Qiu, 07, Mulers, Rogers, 10
Liu, Ringer, Vogelsang, Yuan, arXiv:2008.03666



Kang, Lee, Shao, Terry, arXiv:2008.05470
Qiu, Vogelsange, Yuan, arXiv:0706.1196, …

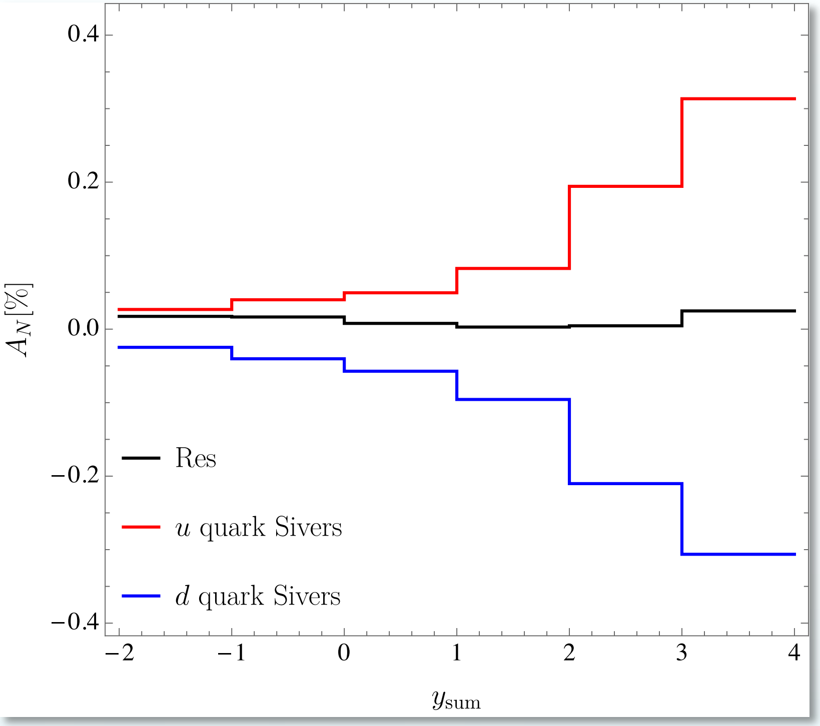


	tt	tu	uu	ut
C^u	$\frac{C_F}{2N_c}$	$-\frac{C_F}{2N_c^2}$	$\frac{C_F}{2N_c}$	$-\frac{C_F}{2N_c^2}$
C^i	$-\frac{1}{2N_c^2}$	$\frac{N_c^2+1}{4N_c^3}$	$-\frac{1}{2N_c^2}$	$\frac{N_c^2+1}{4N_c^3}$
C^{f_1}	$-\frac{1}{4N_c^2}$	$\frac{1}{4N_c^3}$	$\frac{N_c^2-2}{4N_c^2}$	$\frac{1}{4N_c^3}$
C^{f_2}	$\frac{N_c^2-2}{4N_c^2}$	$\frac{1}{4N_c^3}$	$-\frac{1}{4N_c^2}$	$\frac{1}{4N_c^2}$

TABLE III. Color factors for the $qq \to qq$ process

Only problem

- Asymmetry is too small
  - Cancelation between u and d quark Sivers functions



Kang, Lee, Shao, Terry, arXiv:2008.05470
See also, Liu, Ringer, Vogelsang, Yuan, arXiv:2008.03666

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

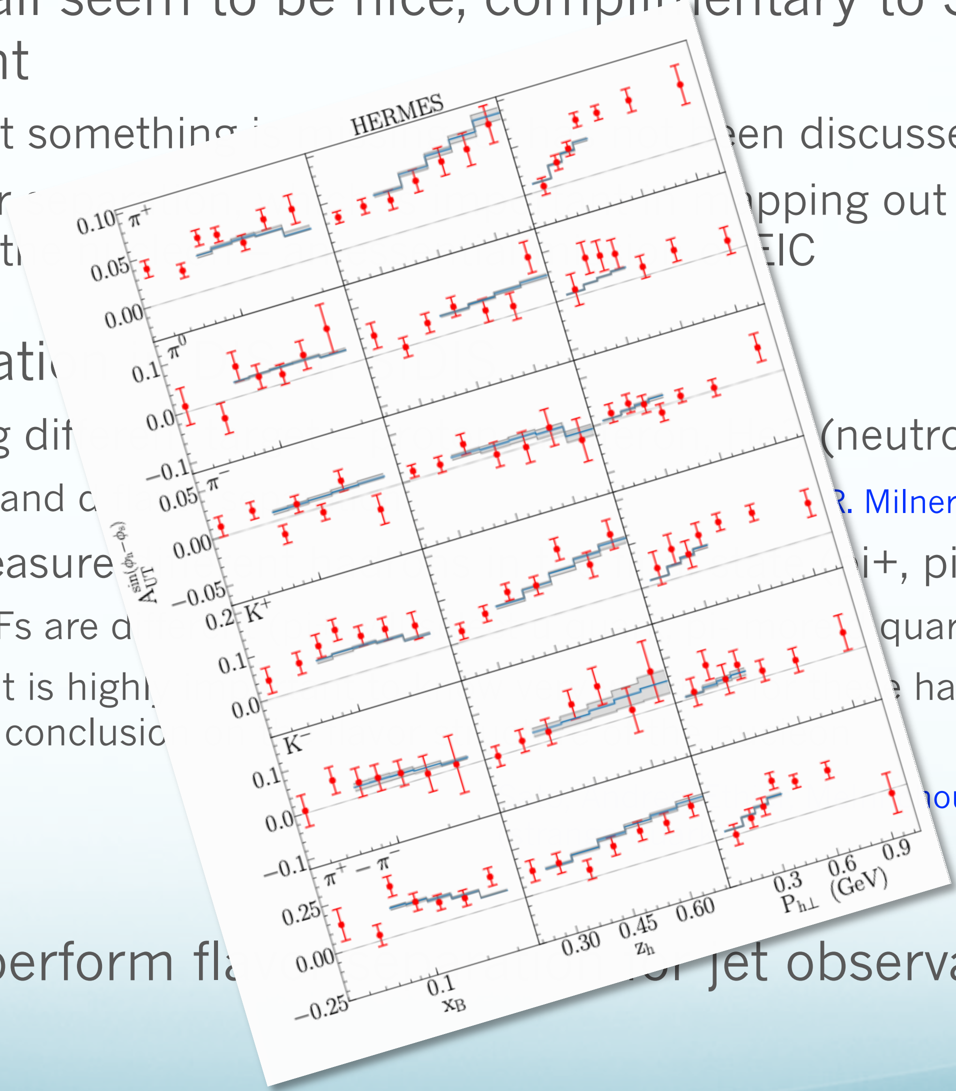
  - In SIDIS: measure different hadrons in the final state (pi+, pi-, K+, K-, etc)
    - Because FFs are different (pi+ will select u quark, pi- more d quark, Kaons for s quark)
    - Of course it is highly important to know very well FFs for these hadrons, in order to make firm conclusion on the flavor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

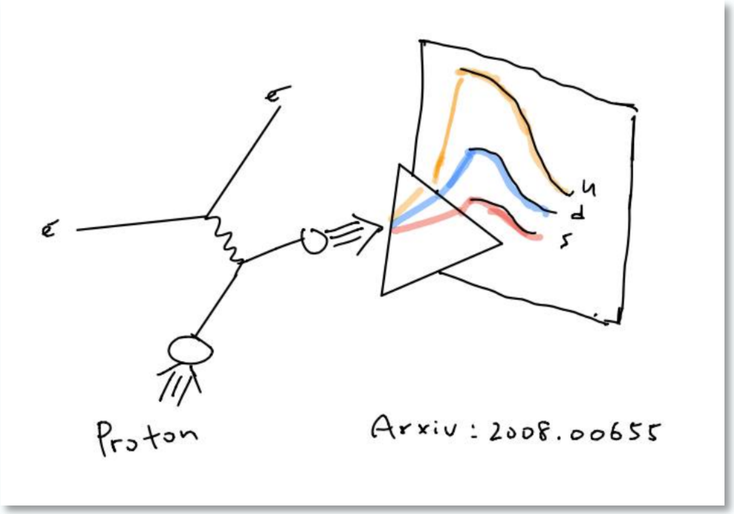
- Perception: all seem to be nice, complimentary to SIDIS measurement
  - It seems that somethin een discussed much
  - That is flavor pping out the flavor and spin structure of t EIC
- Flavor separati
  - In DIS: using dif (neutron)
    - gives us u and R. Milner, arXiv:1809.05626
  - In SIDIS: measure i+, pi-, K+, K-, etc)
    - Because FFs are d quark, Kaons for s quark)
    - Of course it is high hadrons, in order to make firm conclusio
    - ouk, arXiv:1905.03788



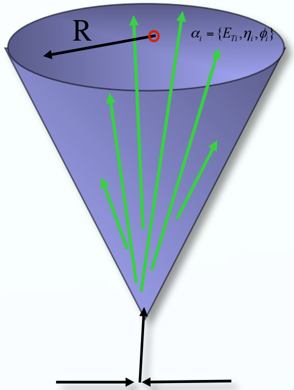
- How do we perform fl jet observables?

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

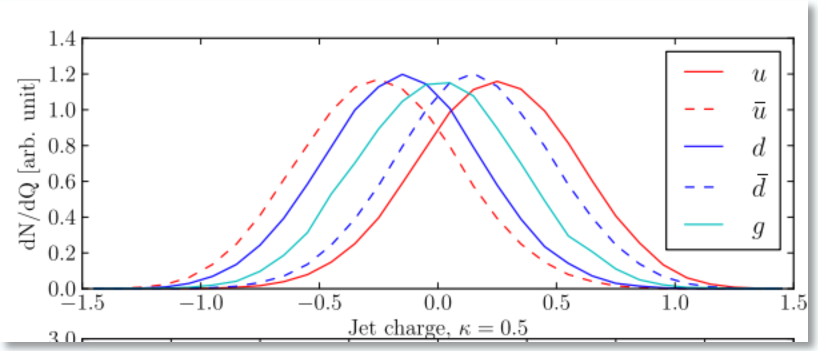
$$Q_\kappa = \sum_h Q_\kappa^h \equiv \sum_{h \in \text{jet}} z_h^\kappa Q_h$$

Charge of the hadron

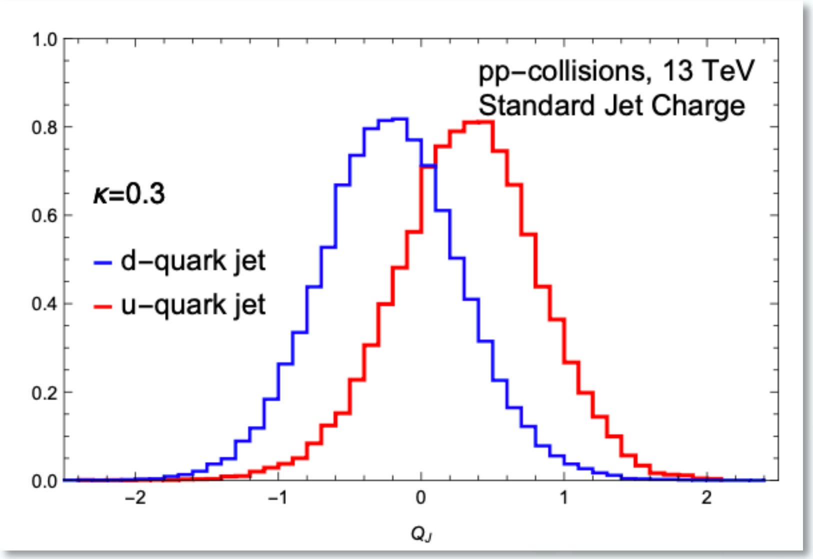
$$z_h = \frac{p_{hT}}{p_{JT}} \qquad \kappa = 0.3, 0.4, \cdots, 1.0$$

Charge distribution of u and d quark jets

- Jet charge distribution



Krohn, Schwartz, Lin, Waalewijn, arXiv:1209.2421

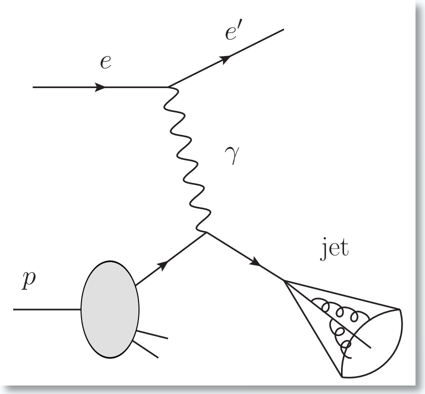


Courtesy of S. Mantry

- 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

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

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"

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

  - In comparison with the standard jet production

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

  - 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

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

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

  - 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**

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

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

The weighting factor

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

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

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

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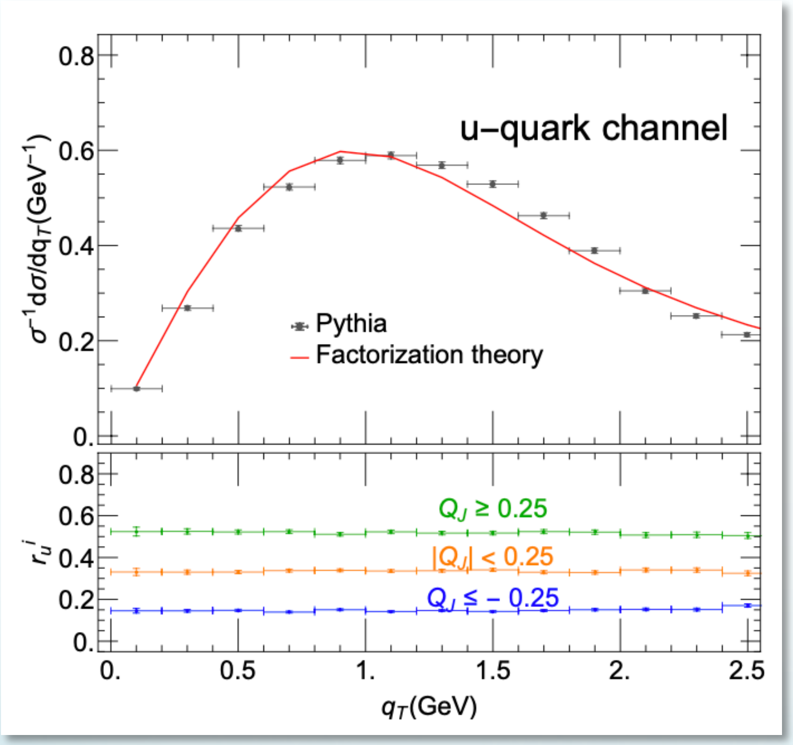
$$\frac{\mathrm{d}\sigma_{U}}{\mathrm{d}y_e\mathrm{d} \quad q_T} = \sum_{i=u,d\cdots}\langle (Q_\kappa^i)^N\rangle_{\rm bin}\frac{\mathrm{d}\sigma^i_{UU}}{\mathrm{d}y_e\mathrm{d}^2p_T^e\mathrm{d}^2q_T}$$

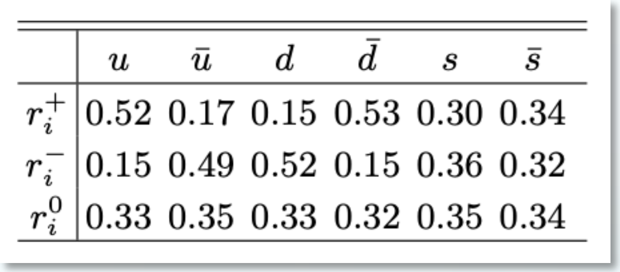
$$\frac{\mathrm{d}\sigma_{UT}(S_\perp, Q^N_{\kappa,\rm bin})}{\mathrm{d}y_e\mathrm{d}^2p_T^e\mathrm{d}^2q_T} = \sum_{i=u,d,\cdots}\langle (Q_\kappa^i)^N\rangle_{\rm bin}\frac{\mathrm{d}\sigma^i_{UT}(S_\perp)}{\mathrm{d}y_e\mathrm{d}^2p_T^e\mathrm{d}^2q_T}$$

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

Unpolarized: weighting factors

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



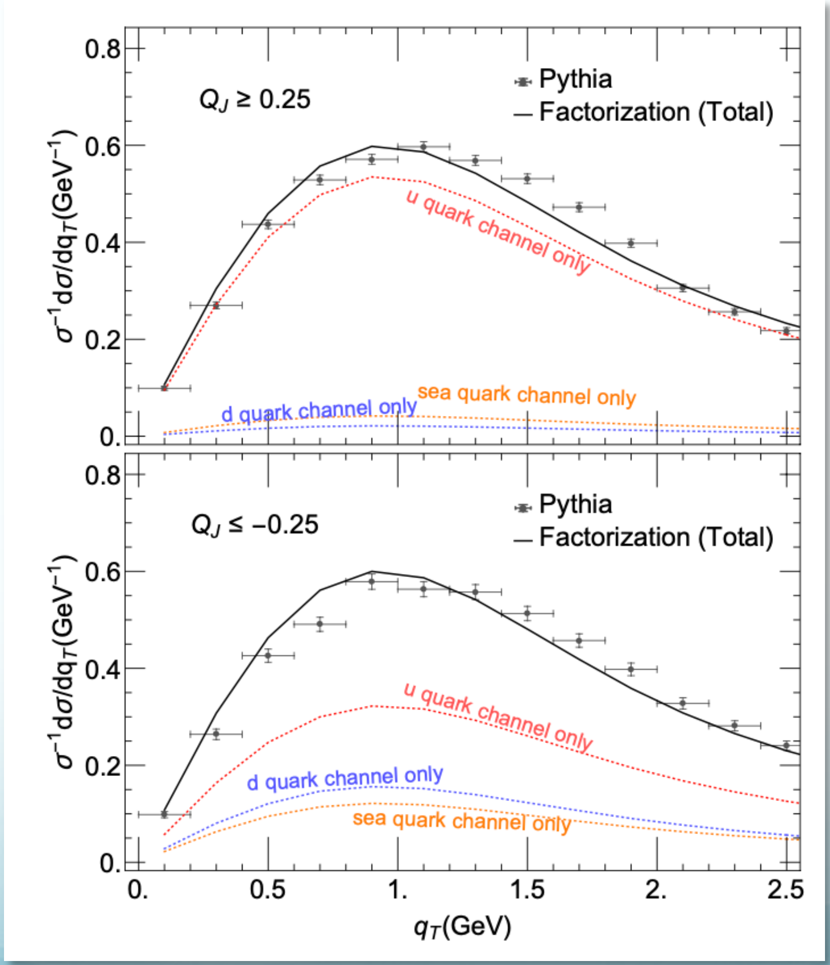


	u	$\bar{u}$	d	$\bar{d}$	s	$\bar{s}$
r_i^+	0.52	0.17	0.15	0.53	0.30	0.34
r_i^-	0.15	0.49	0.52	0.15	0.36	0.32
r_i^0	0.33	0.35	0.33	0.32	0.35	0.34

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

Unpolarized: sensitivity

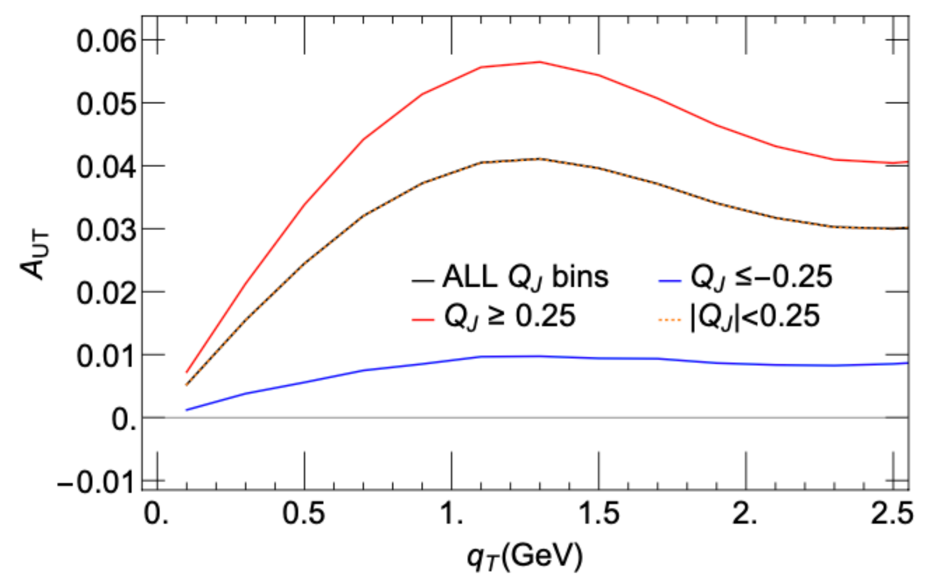
- In general, u quark is more dominant (charge enhancement e_u^2 vs e_d^2)
  - By selecting negative jet charge bin, one can enhance the d quark sensitivity a lot



Sivers asymmetry

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

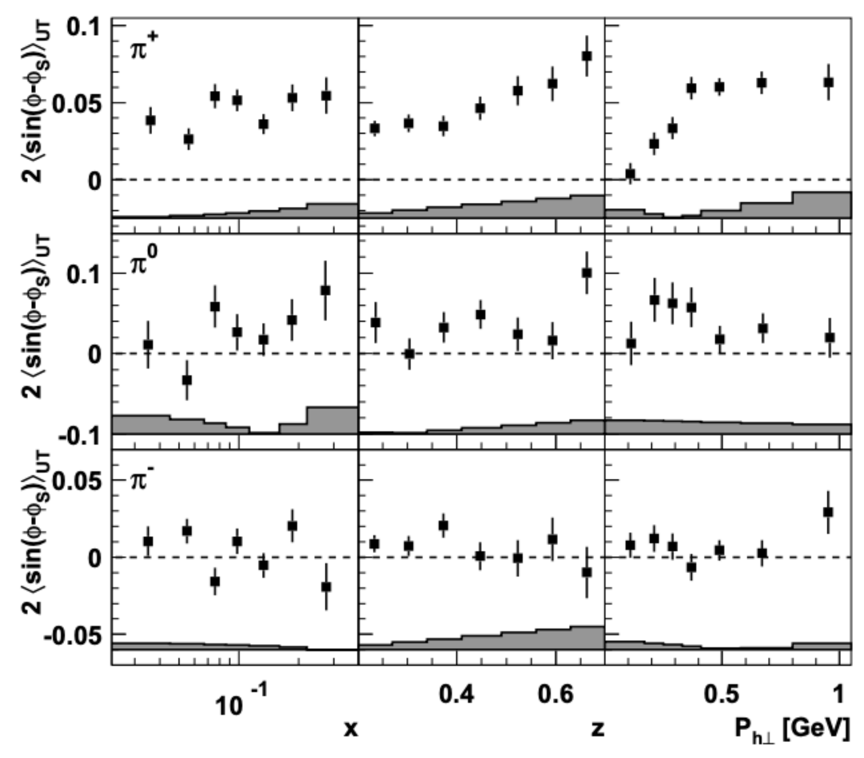
$$A_{UT}(Q^N_{\kappa,\mathrm{bin}}) = \frac{d\sigma(S^{\uparrow}) - d\sigma(S^{\downarrow})}{d\sigma(S^{\uparrow}) + d\sigma(S^{\downarrow})} = \frac{d\sigma_{UT}(Q^N_{\kappa,\mathrm{bin}})}{d\sigma_{UU}(Q^N_{\kappa,\mathrm{bin}})}$$



Looks familiar?

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

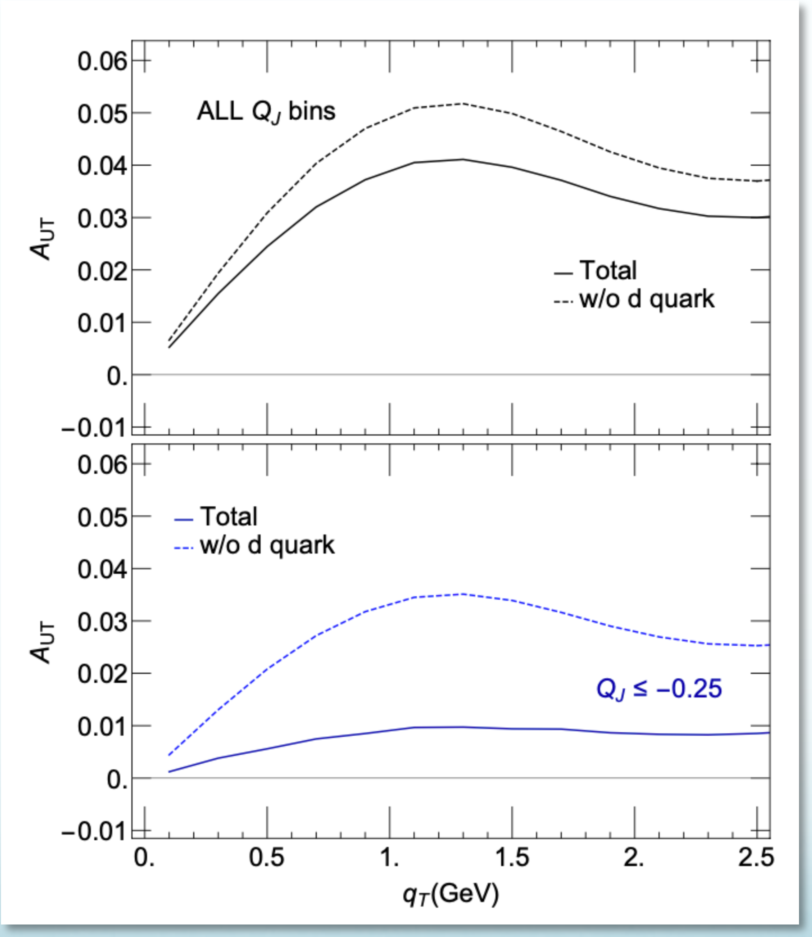
HERMES collaboration, arXiv:0906.3918



- **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

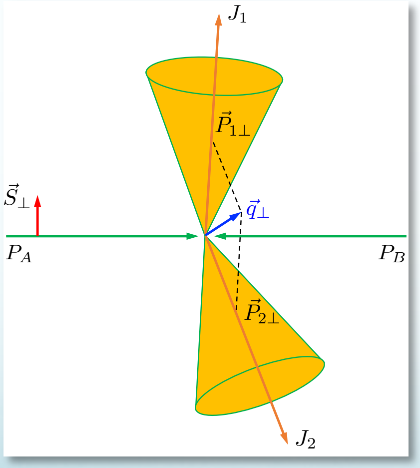
- With jet charge bin selection, the sensitivity to d-quark Sivers is significantly enhanced

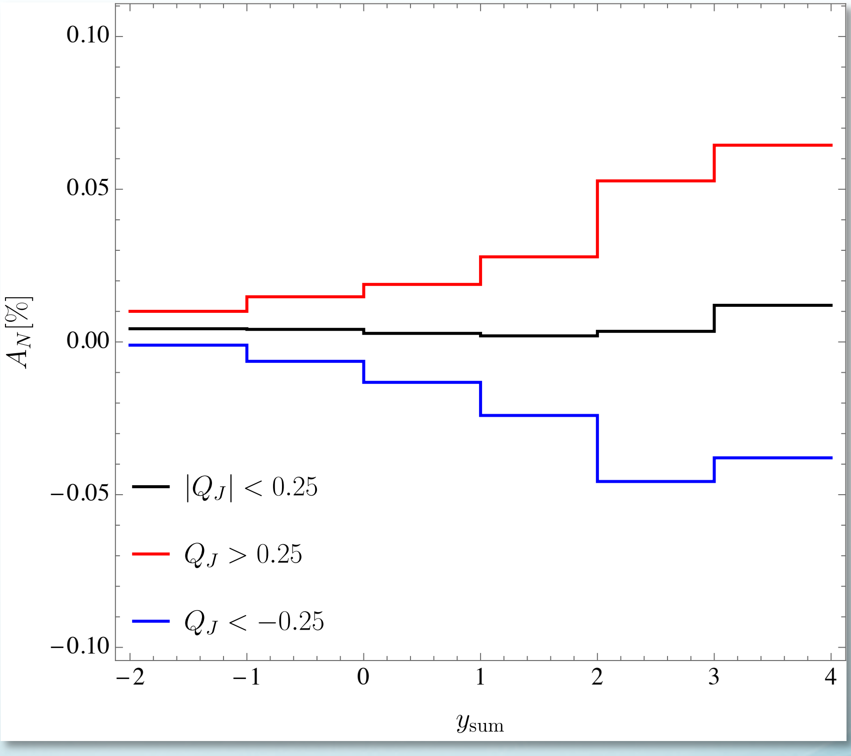


Apply jet charge to dijet in p+p

- Still quite small, but it might be measurable at the RHIC
  - Numerator: only quark Sivers contribution, gluon is small?
  - Denominator: gluon-gluon channel contributes enormously

$$A_N = \frac{\sigma(S_\perp) - \sigma(-S_\perp)}{2\sigma_{\text{spin-average}}}$$

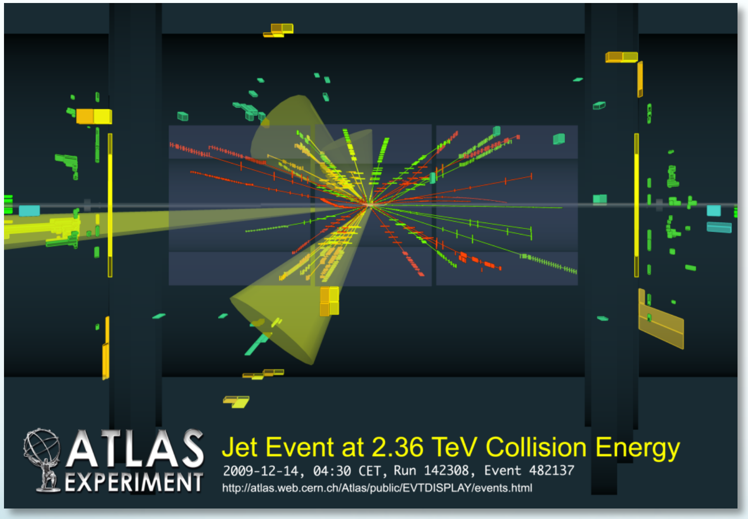


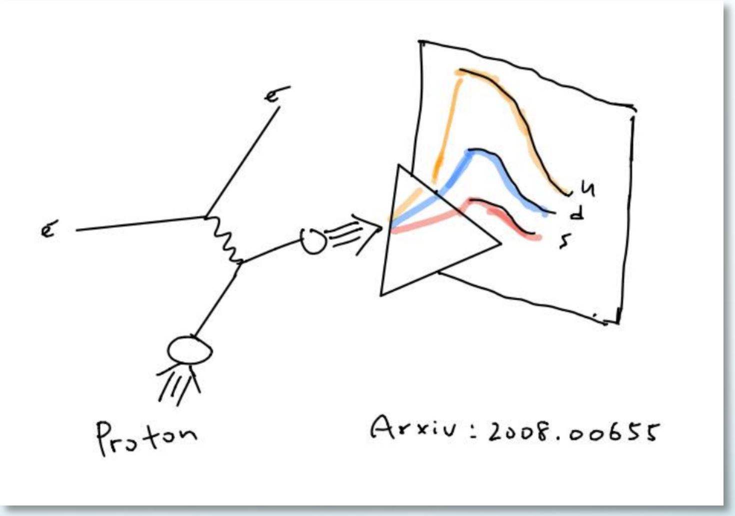


Kang, Lee, Shao, Terry, arXiv:2008.05470

Summary

- Jets are powerful tools
- For 3D imaging, jet observables have become quite promising and complementary to the standard SIDIS process
- Flavor separation can be achieved via e.g., jet charge





Thank you!