Recent developments in SIDIS & Jets science at EIC

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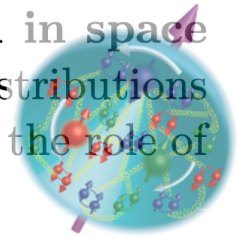
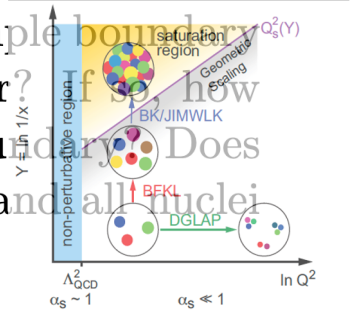
Big questions for EIC

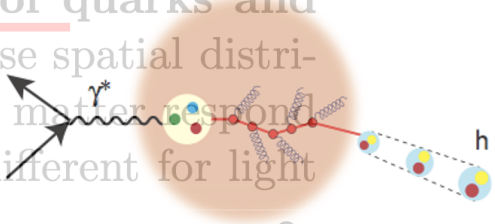
- **How are the sea quarks and gluons, and their spins, distributed in space and momentum inside the nucleon?** How are these quark and gluon distributions correlated with overall nucleon properties, such as spin direction? What is the role of the orbital motion of sea quarks and gluons in building the nucleon spin?



- **Where does the saturation of gluon densities set in?** Is there a simple boundary that separates this region from that of more dilute quark-gluon matter? If so, how do the distributions of quarks and gluons change as one crosses the boundary? Does this saturation produce matter of universal properties in the nucleon and all nuclei viewed at nearly the speed of light?

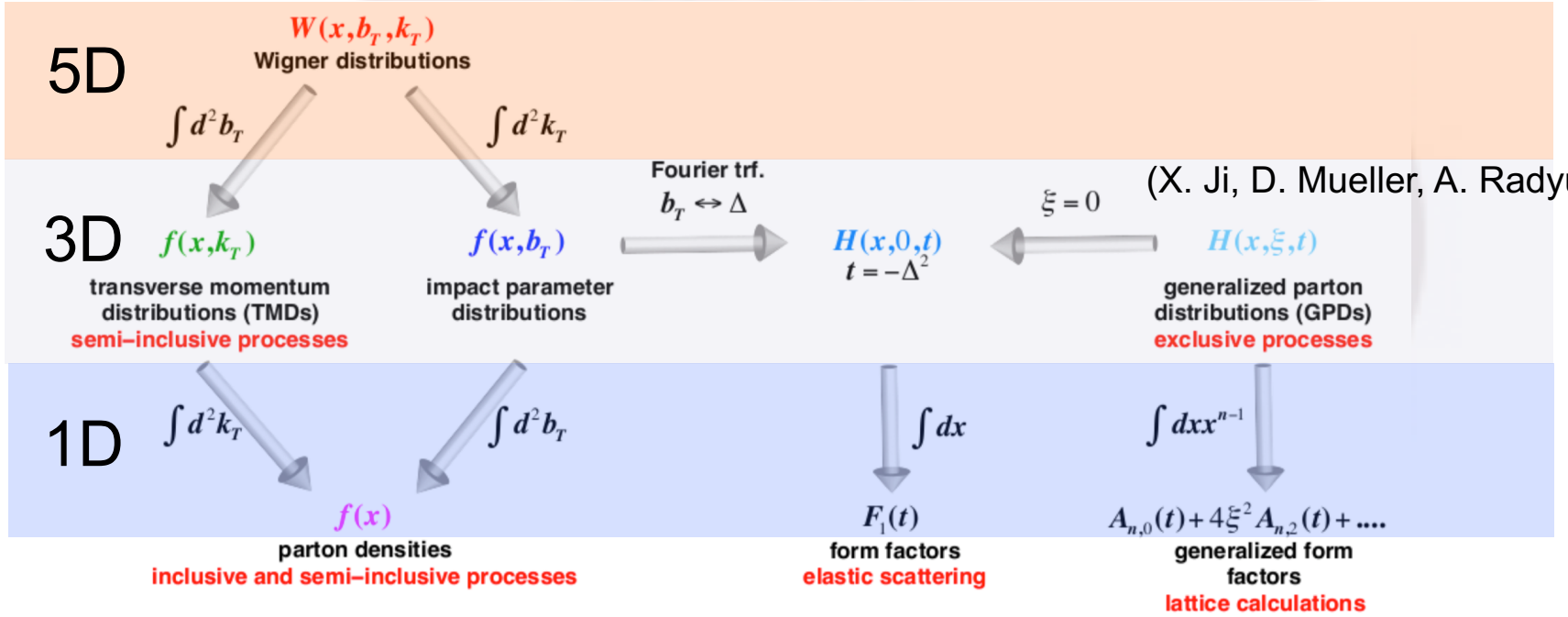


- **How does the nuclear environment affect the distribution of quarks and gluons and their interactions in nuclei?** How does the transverse spatial distribution of gluons compare to that in the nucleon? How does nuclear matter respond to a fast moving color charge passing through it? Is this response different for light and heavy quarks?

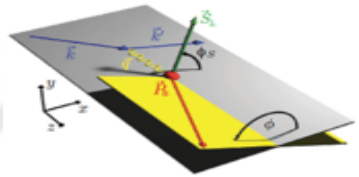


Unified view of the Nucleon

❑ Wigner distributions (Belitsky, Ji, Yuan)

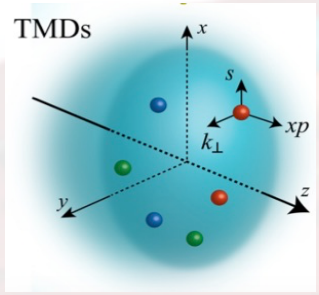


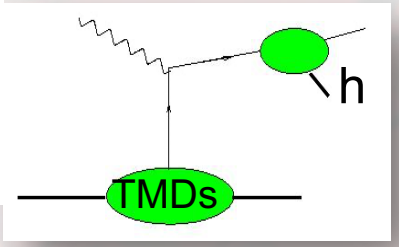
(X. Ji, D. Mueller, A. Radyushkin)



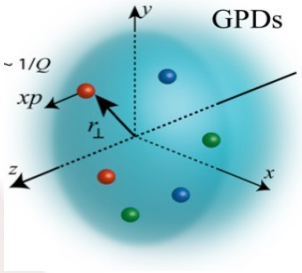
Zoo of TMDs & GPDs

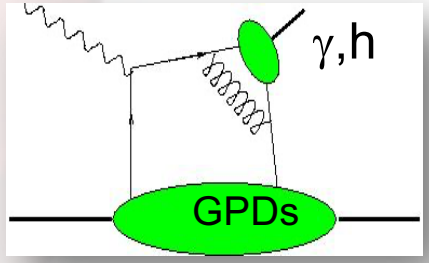
	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	$h_1, h_{1T}^\perp$





	U	L	T
U	H		$\mathcal{E}_T$
L		$\widetilde{H}$	
T	E		$H_T, \widetilde{H}_T$



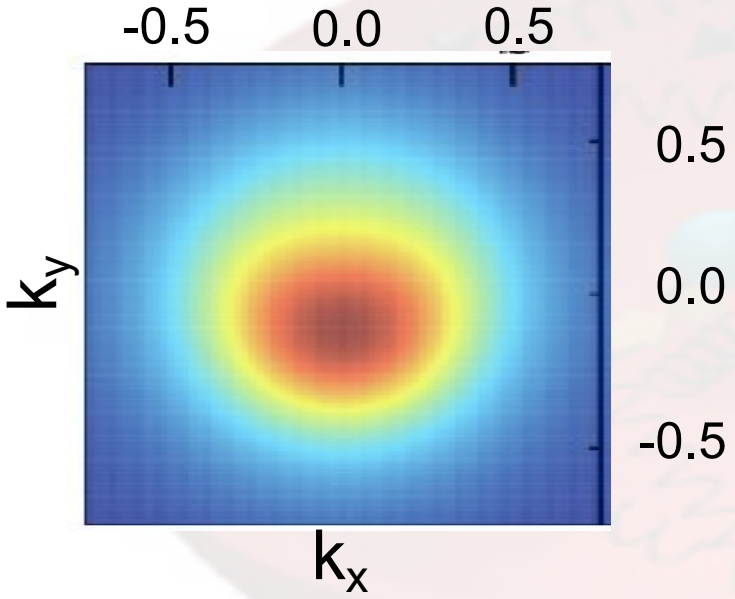


- NOT directly accessible
- Their extractions require measurements of x-sections and asymmetries in **a large kinematic domain of** x_B, t, Q^2 (GPD) and x_B, P_T, Q^2 , z (TMD)

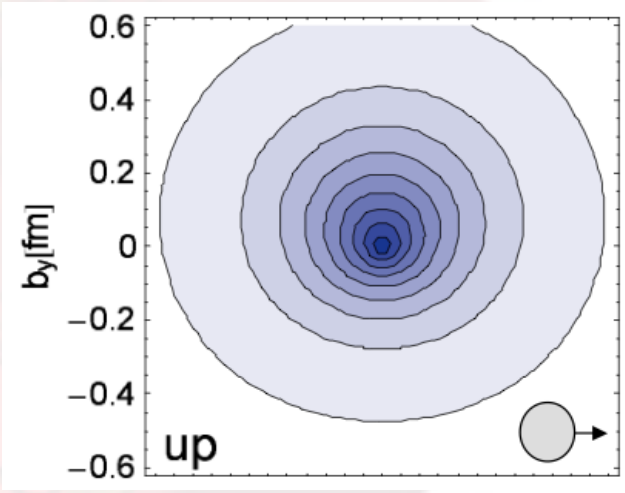
What can we learn

- 3D Imaging of partons inside the nucleon (non-trivial correlations)
  - Try to answer more detailed questions as Rutherford was doing for atomic matter more than 100 years ago
- QCD dynamics involved in these processes
  - Transverse momentum distributions: universality, factorization, evolutions,…
  - Small-x resummation: BFKL and Sudakov

Deformation when nucleon is transversely polarized



Quark Sivers function fit to the SIDIS Data, Anselmino, et al. 2009



Lattice Calculation of the transvese density Of Up quark, QCDSF/UKQCD Coll., 2006

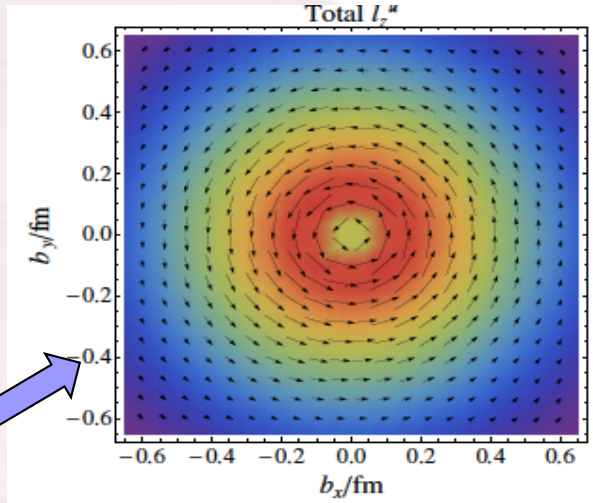
Parton's orbital motion through the Wigner Distributions

Phase space distribution:

Projection onto p (x) to get the momentum (probability) density

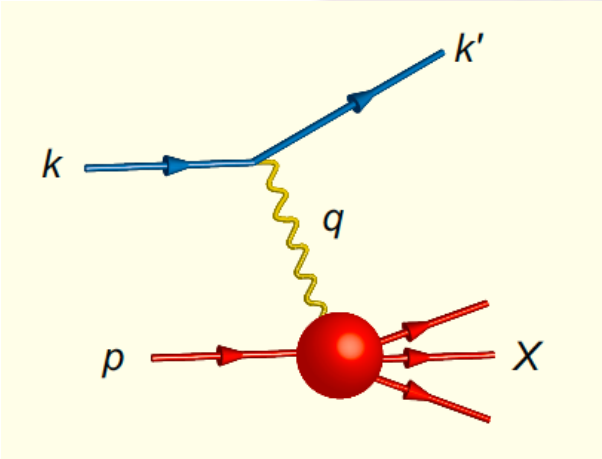
Quark orbital angular momentum

$$L(x) = \int (\vec{b}_\perp \times \vec{k}_\perp) W(x, \vec{b}_\perp, \vec{k}_\perp) d^2\vec{b}_\perp d^2\vec{k}_\perp$$



Well defined in QCD:
Ji, Xiong, Yuan, PRL, 2012; PRD, 2013
Lorce, Pasquini, Xiong, Yuan, PRD, 2012
Lorce-Pasquini 2011
Hatta 2011

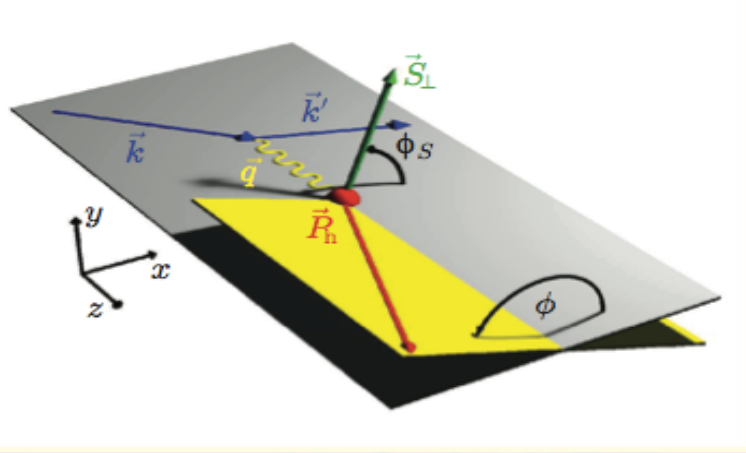
Basics



- Inclusive DIS
  - Parton distributions
- Semi-inclusive DIS, measure additional hadron in final state
  - Kt-dependence
- Exclusive Processes, measure recoiled nucleon
  - Nucleon tomography
- Parity violating process

Luminosity requirement

TMDs at EIC: Semi-inclusive DIS



quark distribution
$\otimes$
fragmentation

- Novel Single Spin Asymmetries

Collins: $$A_{UT}^{\sin(\phi+\phi_S)} \propto S_\perp \frac{\sum_{q,\bar{q}} e_q^2 \delta q(x)\, H_1^\perp(z)}{\sum_{q,\bar{q}} e_q^2 q(x)\, D_1(z)}$$

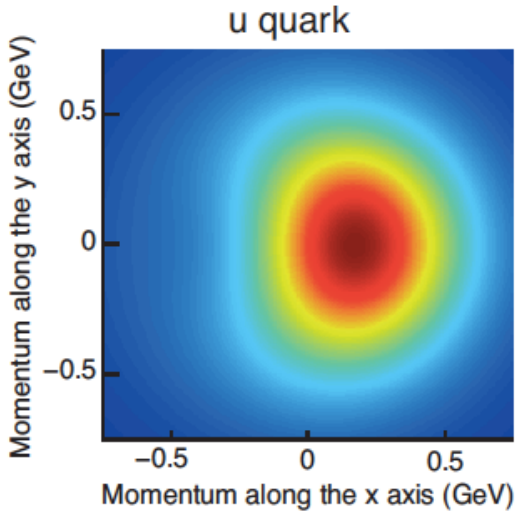
$$z \overset{lab}{=} \frac{E_h}{\nu}$$

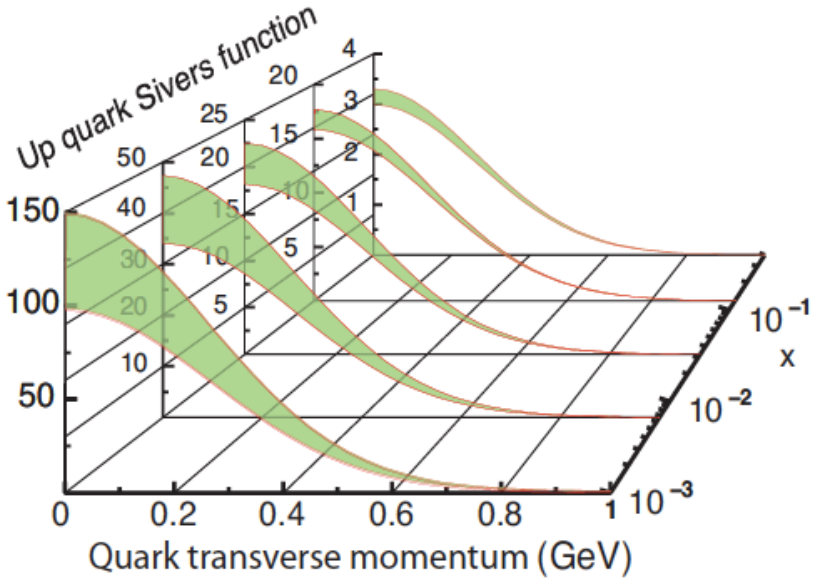
Sivers: $$A_{UT}^{\sin(\phi-\phi_S)} \propto S_\perp \frac{\sum_{q,\bar{q}} e_q^2 f_{1T}^{\perp,q}(x) \cdot D_1(z)}{\sum_{q,\bar{q}} e_q^2 q(x)\, D_1(z)}$$

U: unpolarized beam
T: transversely polarized target

What EIC can offer

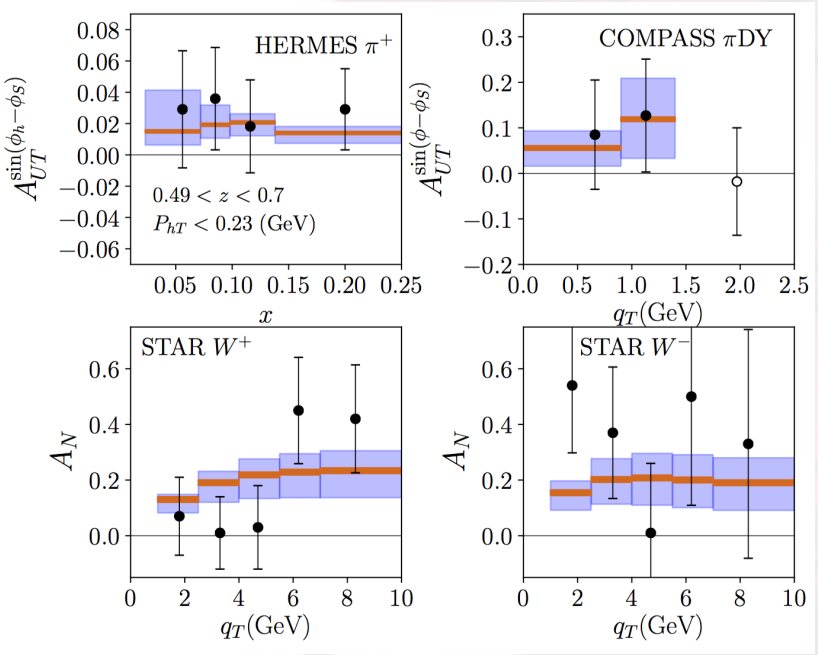
- In the EIC-White paper, a leading order analysis was carried out for the impact on the quark Sivers functions

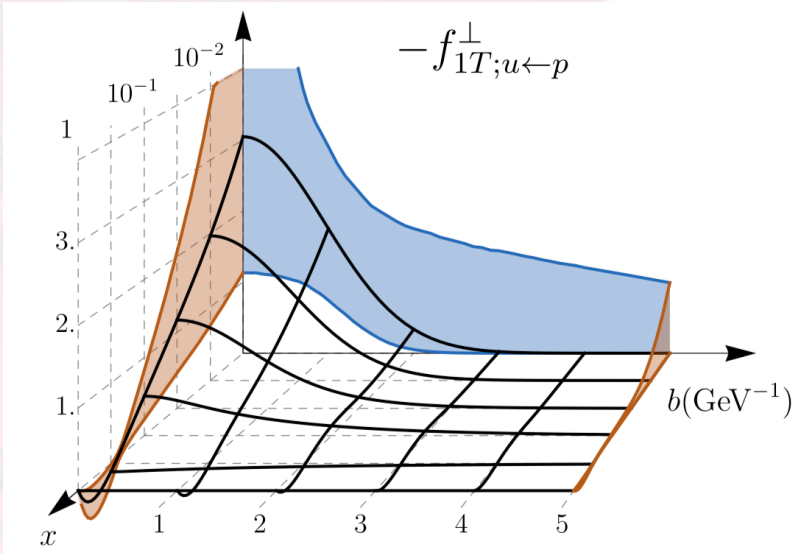




Theory advances are available

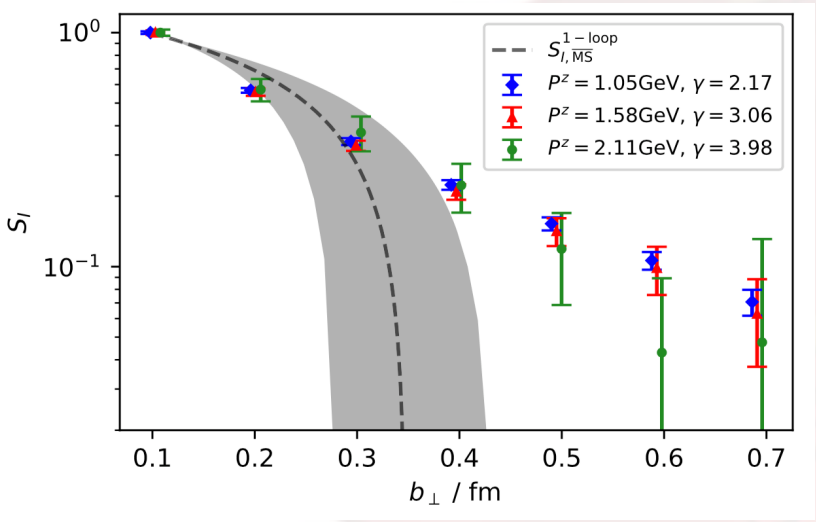
- N^{3}LO analysis of Sivers asymmetries



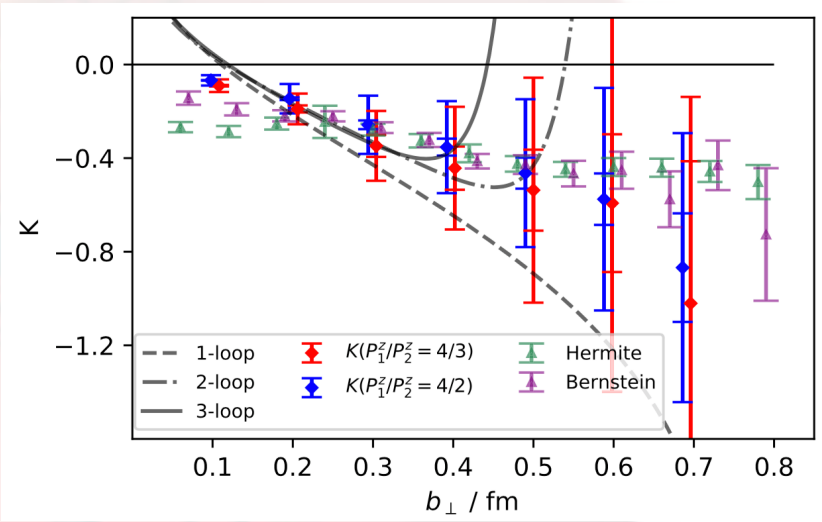


Bury, Prokudin, Vladimirov, 2012.05135
See also, JAM coll., 2002.08384; Bacchetta, Delcarro, Pisano, Radici, 2004.14278; Echevarria, Kang, Terry, 2009.10710

TMDs from Lattice (LaMET)



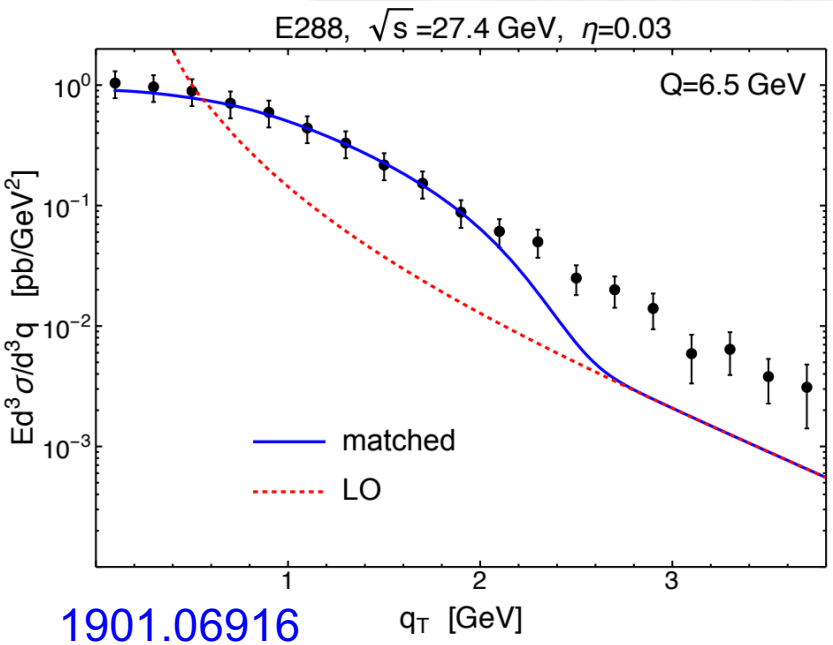
Soft factor



Collins-Soper kernel

Q.A. Zhang et al, PRL 2020, 2005.14572; for Collins-Soper kernel, see, also, Shanahan, Wagman, Zhao, 1911.00800, 2003.06063

Matching to collinear calculations provides opportunity to study QCD dynamics



1901.06916

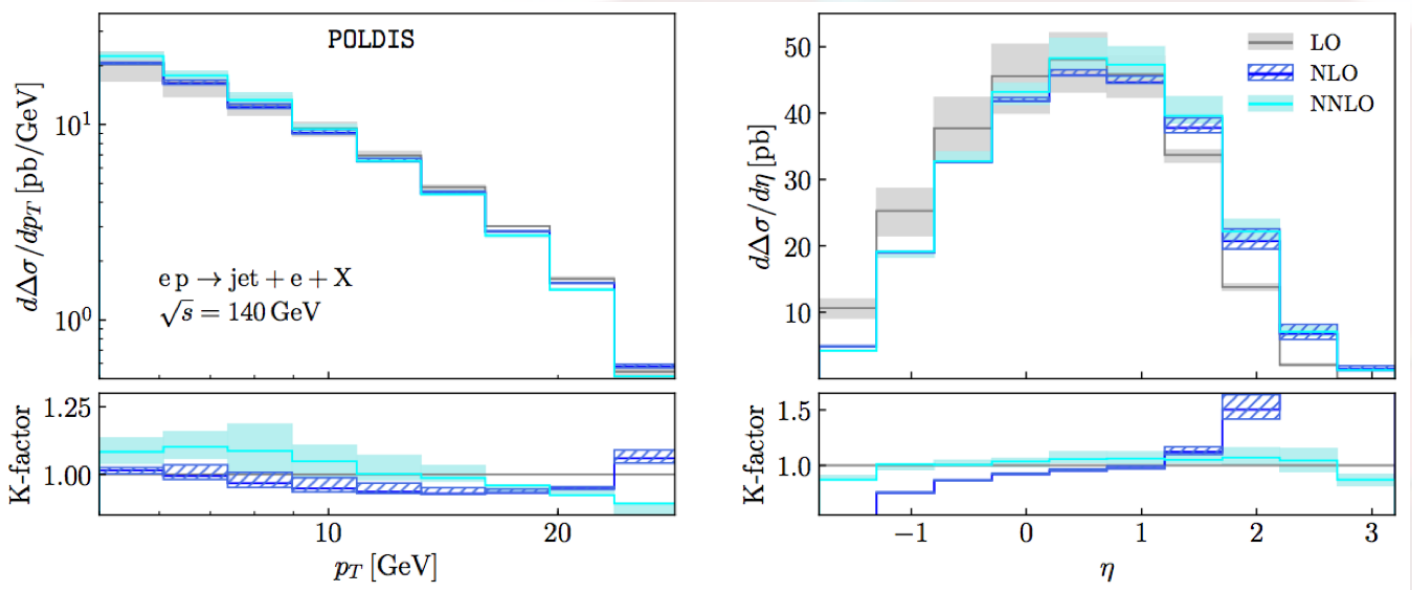
- Bacchetta, et al., 1901.06916 for Drell-Yan processes
- SIDIS, similar studies
  - Sun, Isaacson, C.P. Yuan, FY, 1406.3073
  - Boglione, Hernandez, Melis, Prokudin,1412.1383
  - Wang, Gonzalez-Hernandez, Rogers, Sato, 1903.01529
  - Liu, Qiu, 1907.06136
- **Wide kinematics of EIC is an ideal place to systematically study this!**

Jet @EIC has been very active in recent years

- Contribute to all three physics topics
  - Spin/tomography of nucleon
  - Small-x gluon saturation
  - Hard probe interaction with cold nuclei matter
- QCD dynamics in precision study
  - E.g., jet substructure to measure α_s, jet algorithms, jet angularity, hadronization, etc.
- Observables:
  - Leading jet/hadron, dijet/dihadron, …

Jet workshop (Nov. 2020), https://indico.bnl.gov/event/8066/

Inclusive jet: state of art



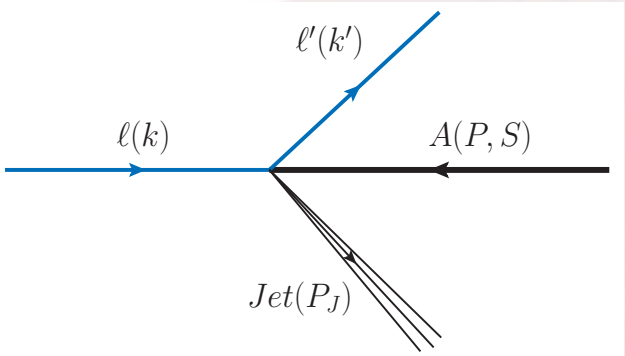
Will contribute to a global fit of parton helicity distributions in the EIC-era

Benchmark measurements:

Borsa-de Florian-Pedron, PRL 2020, 2005.10705, 2010.07354

See also: Hinderer, Schlegel, Vogelsang, 1703.10872; Boughezal, Petriello, Xing,1704.05457, 1806.07311; Page, Chu, Aschenauer, 1911.00657

Semi-inclusive processes: lepton-jet correlation



Quark distribution⊗soft factor

$$\frac{d^5\sigma(\ell p \to \ell' J)}{dy_\ell d^2k_{\ell\perp} d^2q_\perp} = \sigma_0 \int d^2k_\perp d^2\lambda_\perp x f_q(x, k_\perp, \zeta_c, \mu_F)$$
$$\times H_{\rm TMD}(Q,\mu_F) S_J(\lambda_\perp,\mu_F)\,\delta^{(2)}(q_\perp - k_\perp - \lambda_\perp)\ .$$

Liu-Ringer-Vogelsang-Yuan 1812.08077, 2007.12866

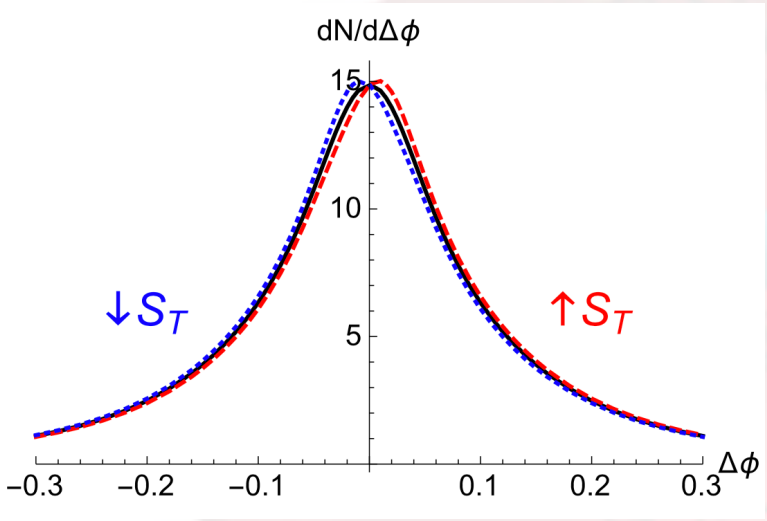
(Lab frame)
Total transverse momentum of the lepton+jet probes the TMD quark distribution

See also, Gutierrez-Reyes, Scimemi, Waalewijn, Zoppi, 1807.07573, 1904.04259

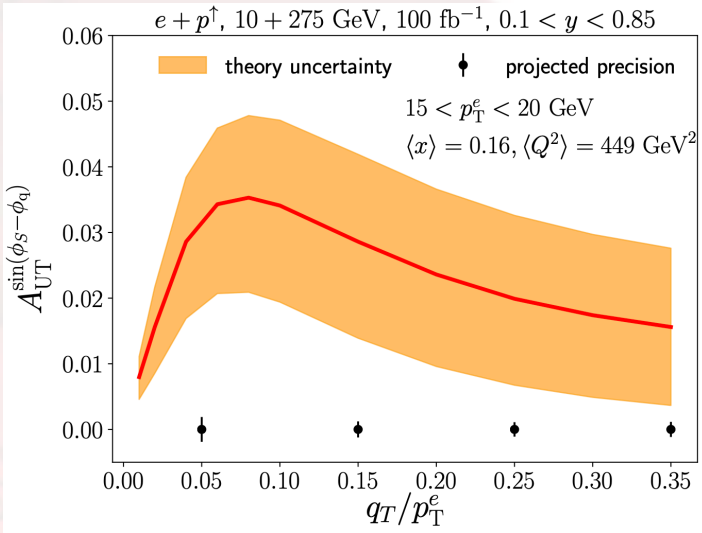
Comments on the soft factor

- New function, doesn't contain leading double logs
  - Unlike the TMD fragmentation which is leading double logs and may have difficulty in the small-z region for the SIDIS
- Soft factor can be systematically studied
  - Simulation with an event generator, hadronization effects etc.
  - Dominant contribution from the jet size dependence from experiment measurements

Complementary and unique perspective for Sivers asymmetries

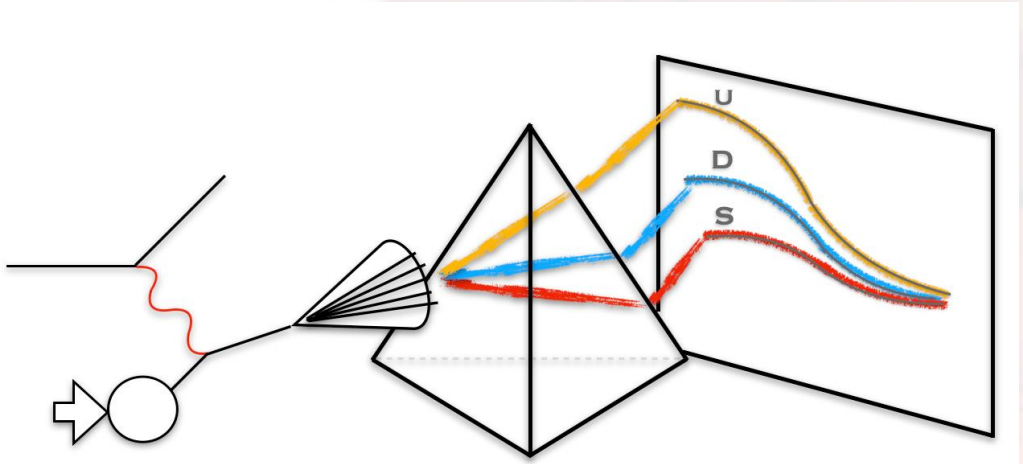


Originally proposed by Boer, Voegelsang, for pp collisions in 2003

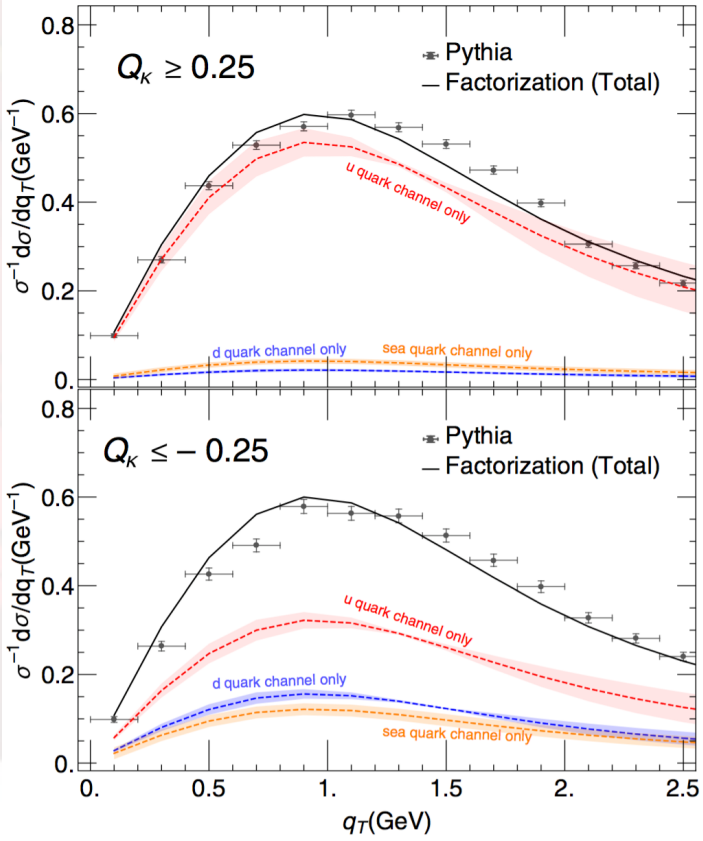


Arratia, Kang, Prokudin, Ringer, 2007.07281

Jet Charge: A Flavor Prism for Spin Asymmetries at the Electron-Ion Collider

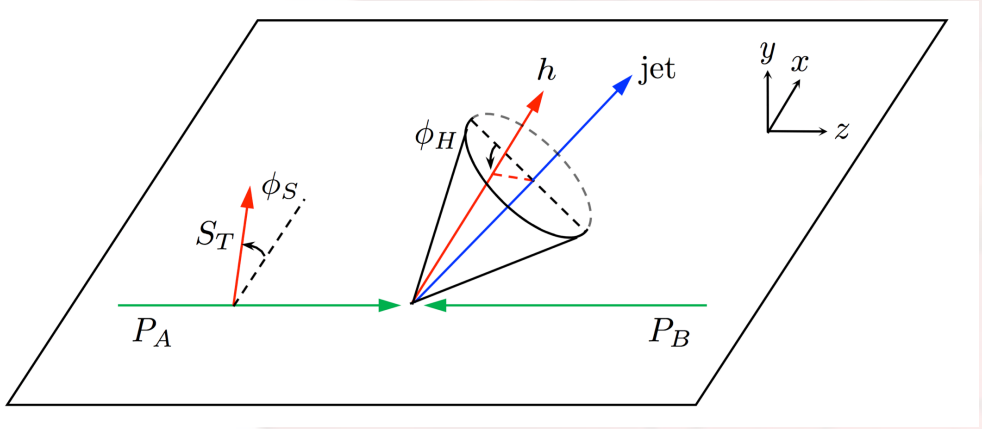


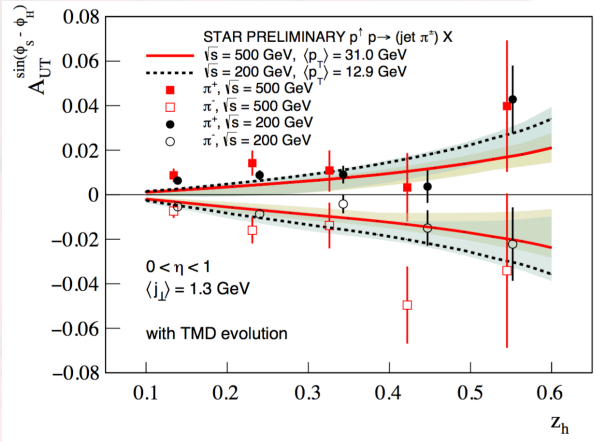
$$Q_\kappa \equiv \sum_{h \in \text{jet}} z_h^\kappa Q_h$$



Kang, Liu, Mantry, Shao, PRL 2020, 2008.00655

Jet can be utilized to measure the hadron fragmentation as well



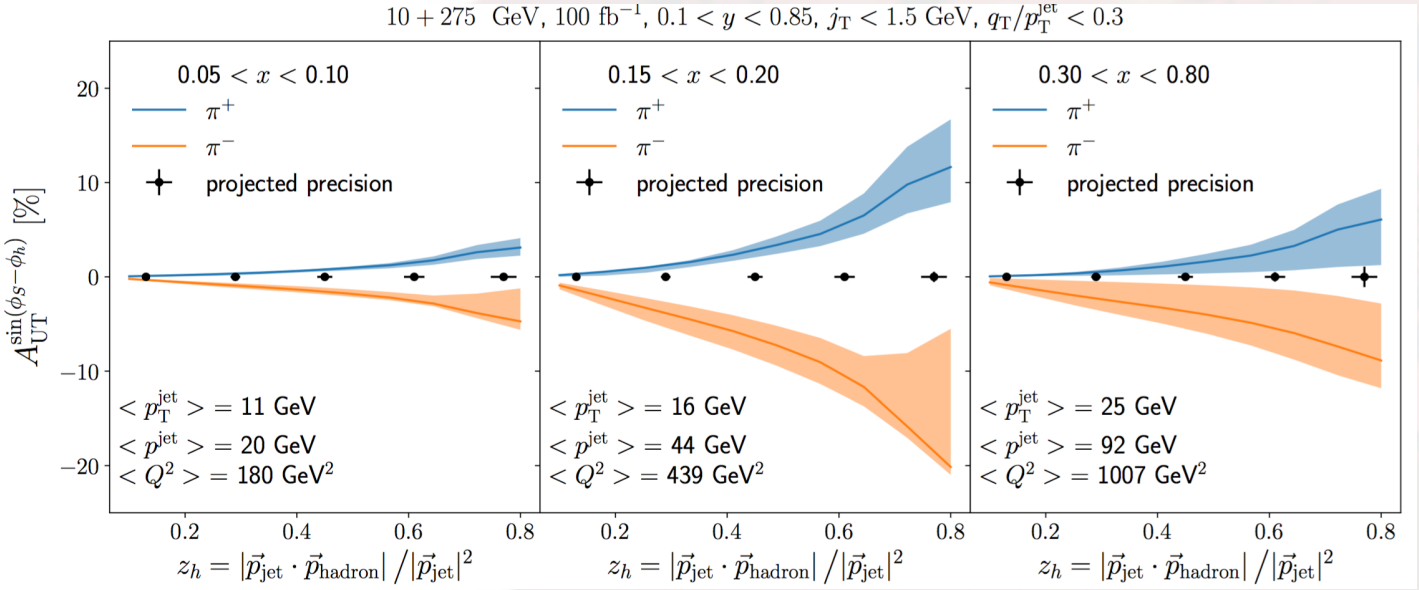


STAR coll.: 1708.07080

Kang, Prokudin, Ringer, Yuan, 1707.00913

earlier: Yuan, 0709.3272; D'Alesio, Murgia, Pisano, 1011.2692

TMD fragmentation in jet: Collins asymmetries at EIC



Factorization involves jet axis definition, applying jet thrust as an alternate approach:

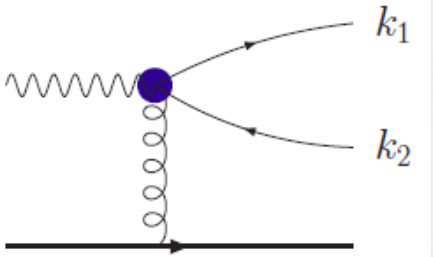
- Kang, Shao, Zhao, 2007.14425
- Boglione, Simonelli, 2011.07366
- Will be studied by Belle II experiments

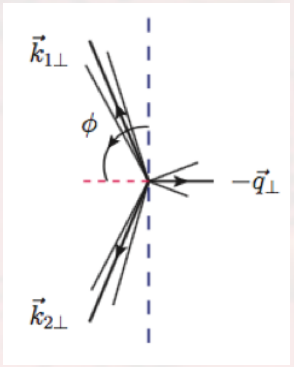
Arratia, Kang, Prokudin, Ringer, 2007.07281

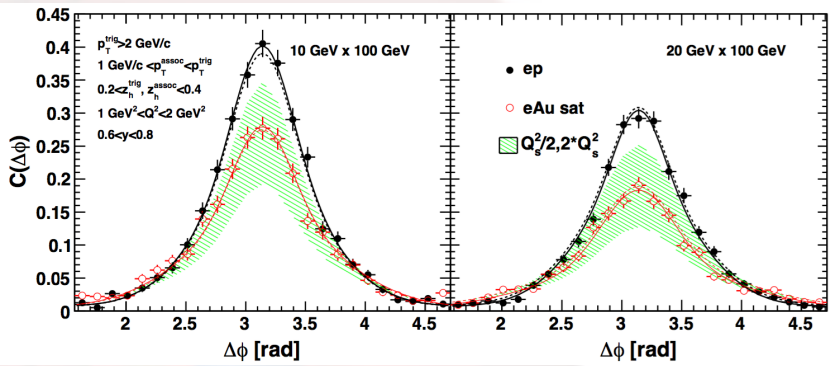
See also, polarized jet fragmentation functions: Kang, Lee, Zhao, 2005.02398

Semi-inclusive process: DIS dijet probes gluon TMDs

$$\gamma_T^* A \to q(k_1) + \bar{q}(k_2) + X$$





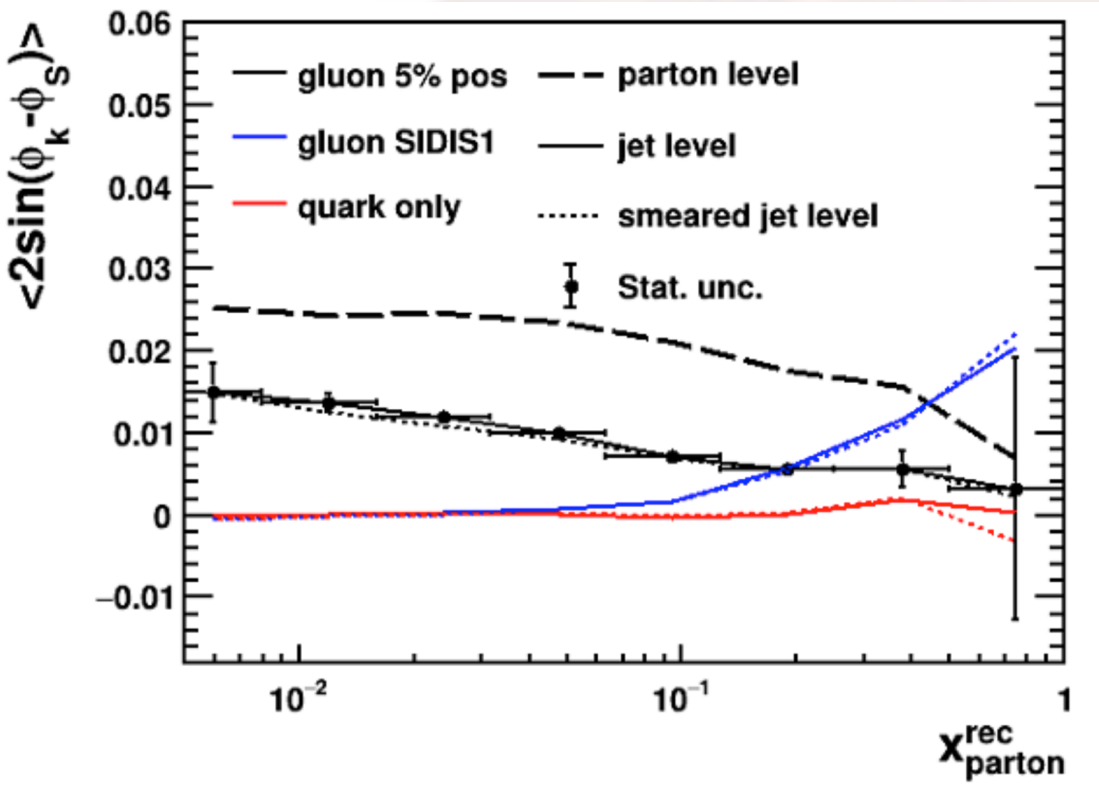


Zheng, et al., 1403.2413

- q_t-dependence measure the gluon distribution
  - Weizsacker-Williams gluon distribution in nucleus (CGC predictions)
- Various channels at the EIC: heavy flavor production, real and virtual photon

Dominguez-Marquet-Xiao-Yuan 2011

Gluon Sivers function at EIC



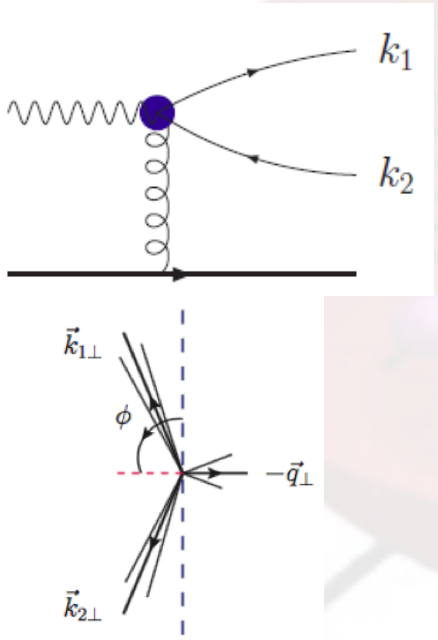
Kinematics:

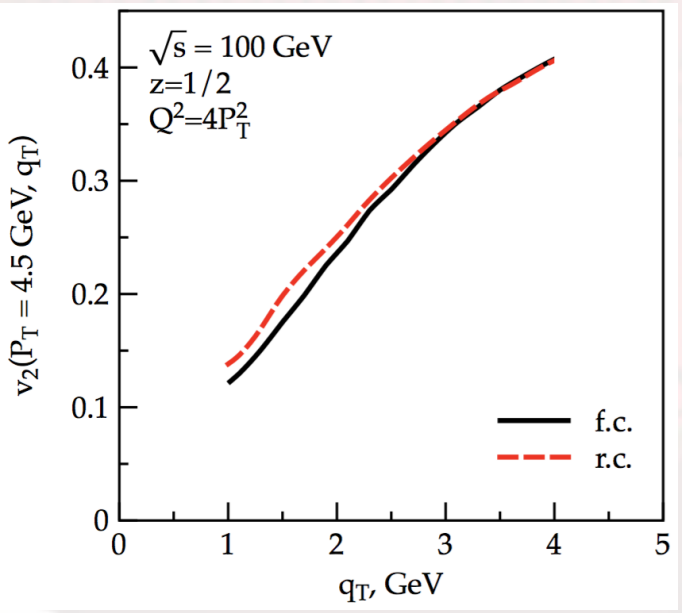
- 18X275GeV,Q>1GeV Leading jet >4.5GeV, subleading jet >4 GeV, R=0.5, |η|<2.5

L. Zheng's talk at the jet workshop, see also, 1805.05290

Cos(2ϕ) anisotropy in dijet process

- Probe the linearly polarized gluon distribution calculation





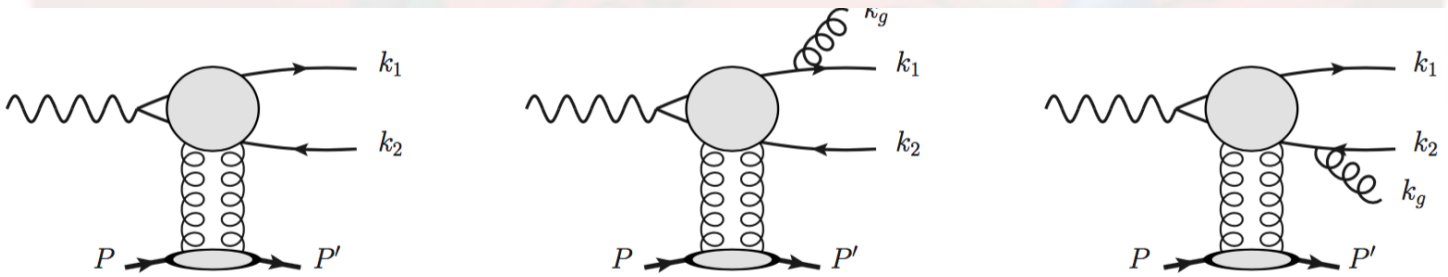
CGC calculation: Dumitru-Lappi-Skokov, 1508.04438
see also,
Boer-Brodsky-Mulders-Pisano 1011.4225
Metz-Zhou, 1105.1991
Boer et al., 1702.08195, 1605.07934
Dumitru, Skokov, Ullrich, 1809.0261
Mantysaari et al., 1902.05087, 1912.05586

QCD from gluon radiation

- Gluon radiation tends to be aligned with the jet direction

$$S_J(q_\perp) = \delta(q_\perp) + \frac{\alpha_s}{2\pi^2}\int dy_g \left(\frac{k_1\cdot k_2}{k_1\cdot k_g k_2\cdot k_g}\right)_{\vec{q}_\perp=-\vec{k}_{g\perp}}$$

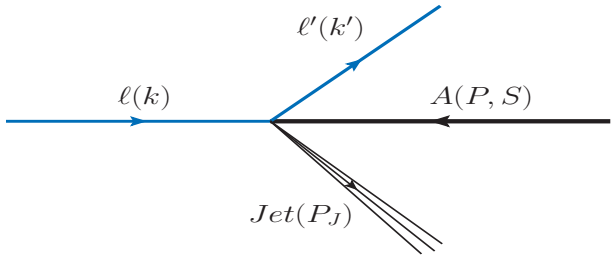
$$S_{J0}(|q_\perp|) + 2\cos(2\phi)S_{J2}(|q_\perp|) + \cdots$$

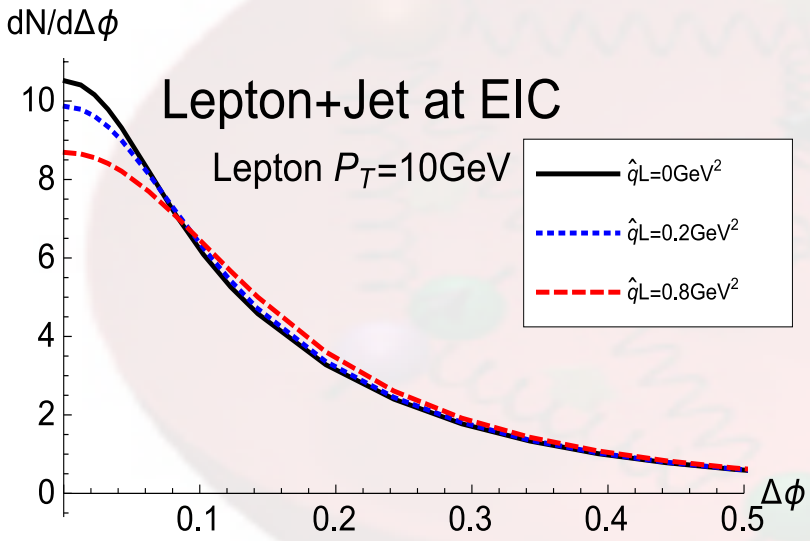


Catani-Grazzini-Sargsyan, 1703.08468; Hatta-Xiao-Yuan-Zhou, 2010.10774

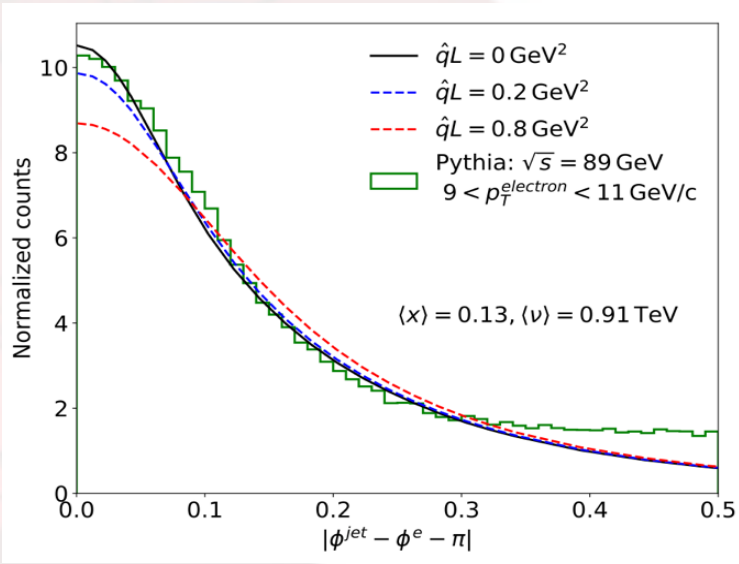
More broad context of quantum interference effects, Chen, Moult, Zhu, 2011.02492

eA collisions to probe the jet P_T-broadening in cold nuclei



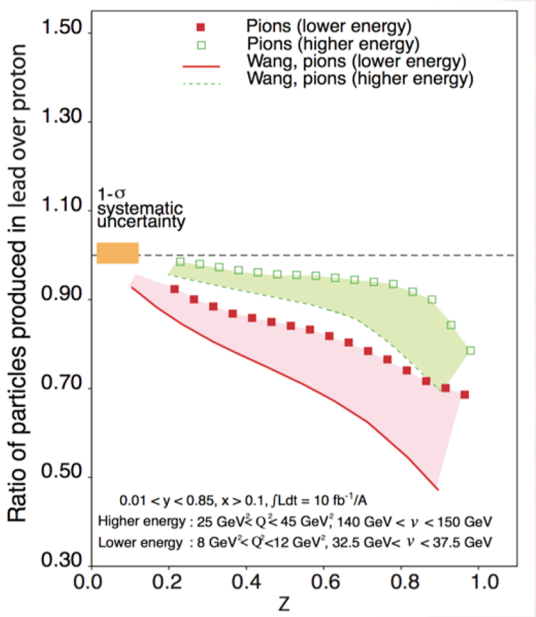


Liu-Ringer-Vogelsang-Yuan
1812.08077, 2007.12866

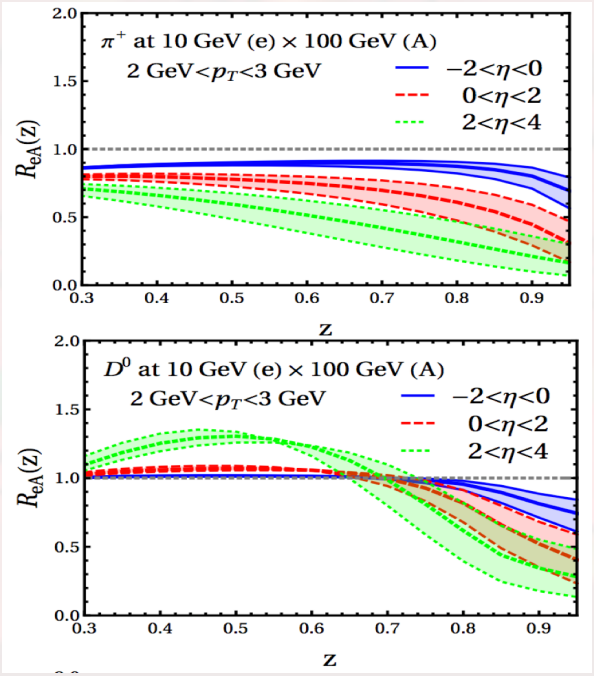


Arratia-Song-Ringer-Jacak
1912.05931

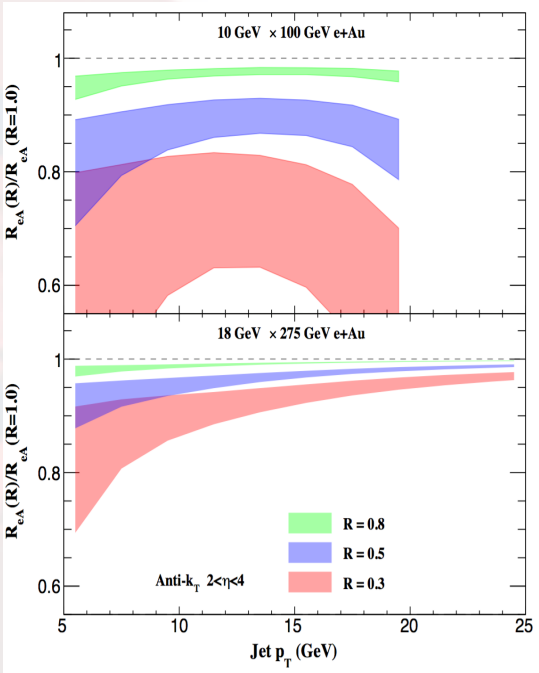
Jet quenching in cold nuclei matter becomes "hotter"



EIC-White Paper 2015;
Qin,Wang,Zhang,
1905.12699



Li, Liu Vitev, 2007.10994;
Li et al, 2002.05880



Li, Vitev, 2010.05912

Conclusion

- Great progresses been made after EIC-White Paper
  - Theory advances laid foundation for SIDIS measurements
- Jet physics at the EIC have attracted a lot of attention, one of the rapidly growing areas
  - Complementary study of TMDs, unique perspective as well
  - For jet measurements, we need tracking, kinematic reach and luminosity considerations
- EIC-Yellow report will be a good start for next chapter

Metz's talk