

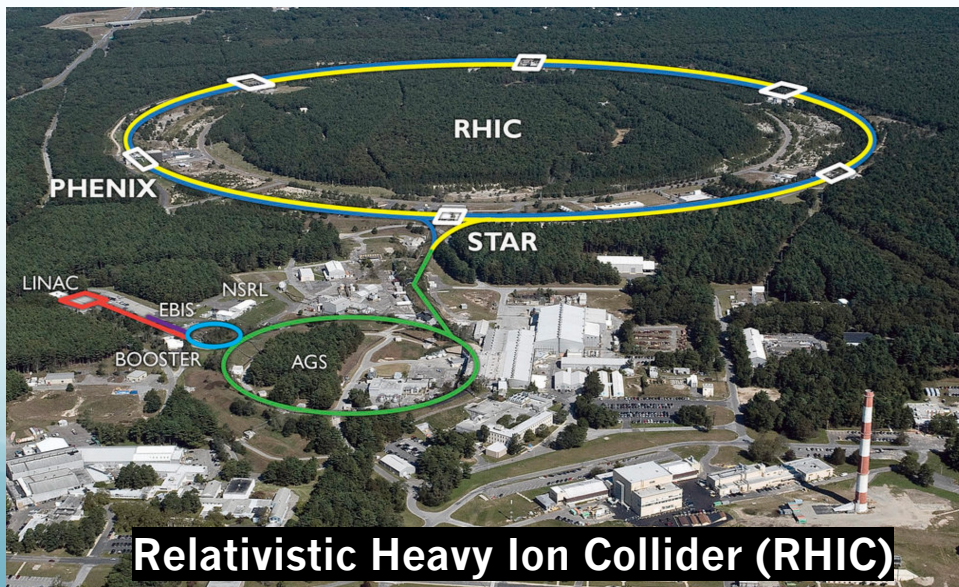
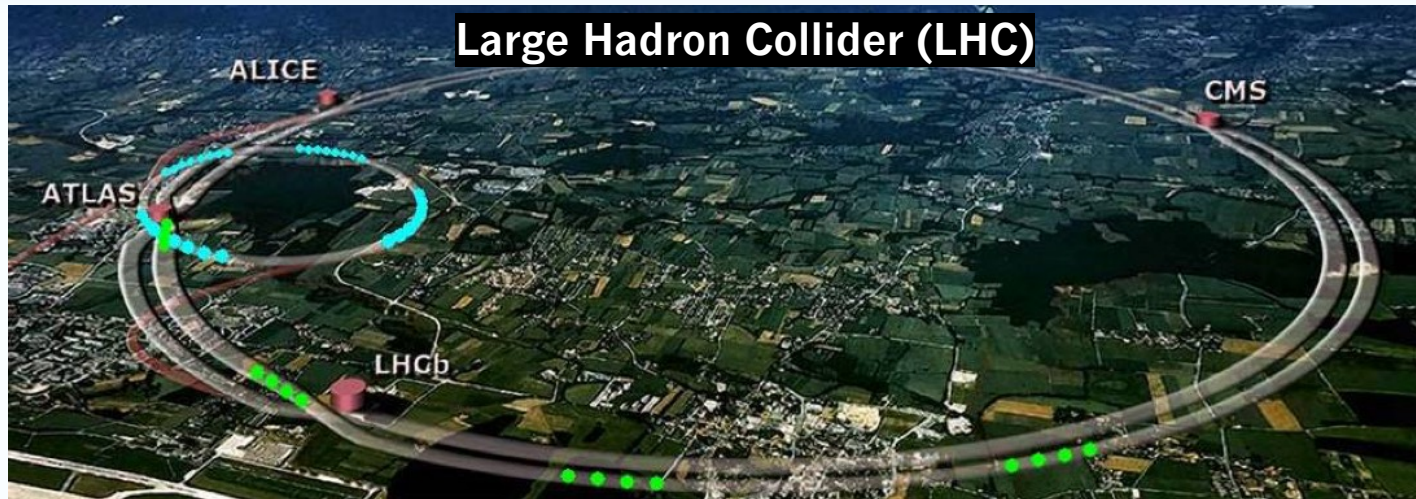
Jet Physics at the EIC

Zhongbo Kang
UCLA

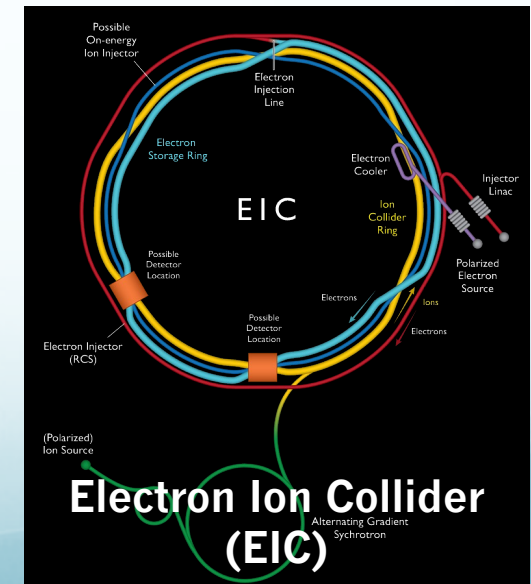
 @ZhongboK

Workshop: Theory for EIC in the next decade
September 20 - 22, 2022

Key facilities: LHC, RHIC, and EIC



~ 2031



A recent CFNS jet workshop

Workshop: Jet Physics: From RHIC/LHC to EIC

29 June 2022 to 1 July 2022

Physics Building

US/Eastern timezone

Overview

[Call for Abstracts](#)

[Timetable](#)

[My Conference](#)

[My Contributions](#)

[Registration](#)

[Participant List](#)

[Parking, Hotel and
Restaurant](#)

Contact

✉ cfns_contact@stonybro...

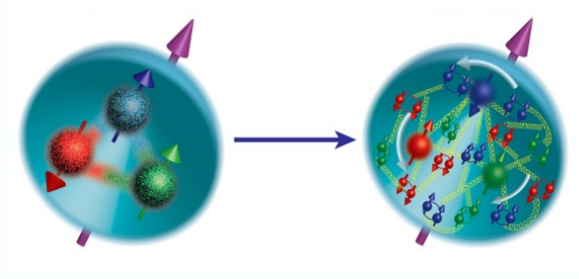
This event is part of the CFNS workshop/ad-hoc meeting series. See the [CFNS conferences](#) page for other events.

Location: Room C-120 (called “Peter Paul Seminar Room”) on the C-floor of the Physics Building. Once registered, the online participants will receive a zoom link via email.

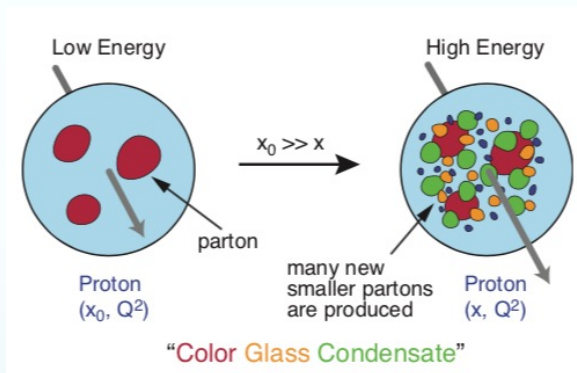
Jet studies have played a key role in the exploration of QCD since its conception. With the advances in experimental techniques and theory developments over time, jets have become powerful tools for QCD physics, such as exploring the fundamental properties and regimes of QCD and probing the cold and hot nuclear medium in eA, pA, and AA collisions. In recent years, measurements of jets and jet substructure at RHIC and LHC have progressed significantly. In the meantime, theoretical developments in computing jet cross-sections and their substructures within perturbative QCD and effective field theory as well as introducing various grooming techniques have further triggered renewed interest and novel measurements in the field. Concurrently, Monte Carlo simulations in understanding jets inside both cold and dense medium such as large nuclei and quark-gluon plasma have seen significant progress in the last few years, e.g. within the JETSCAPE framework. On top of that, the sPHENIX experiment at RHIC and the STAR forward upgrade will start data taking in early 2023 and 2022, respectively, and will undoubtedly provide exciting results on jet observables. With all these advancements, this is the opportune time to have a focused discussion on jet physics, to take advantage of the knowledge accumulated for jet studies at RHIC and LHC, and used for jet studies at the EIC. The usefulness of jets for EIC physics is highlighted in the EIC yellow report.

EIC Scientific Pillars

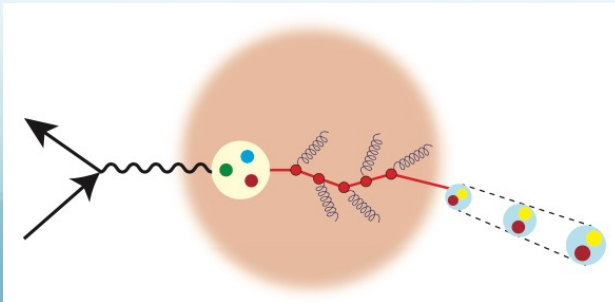
❖ Quantum Imaging of protons and nuclei



❖ A new form of matter - color glass condensate

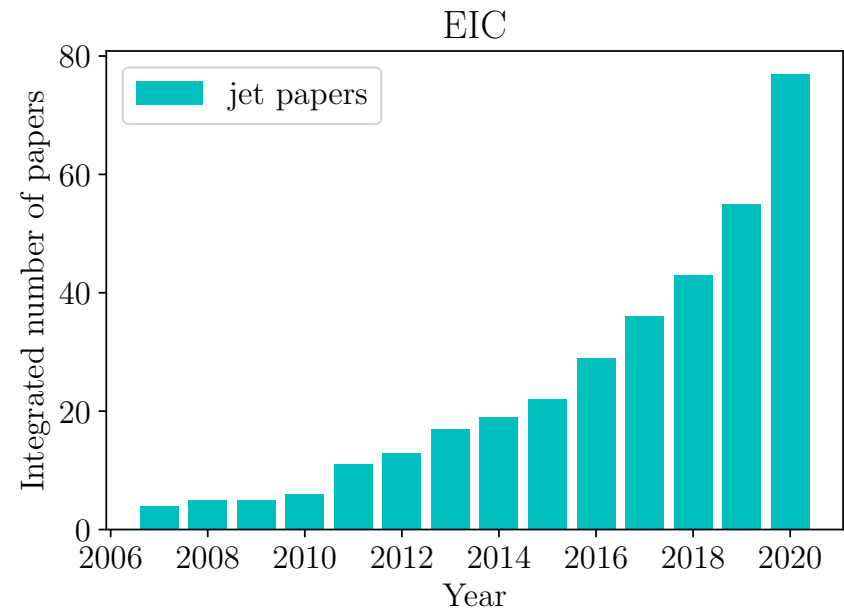
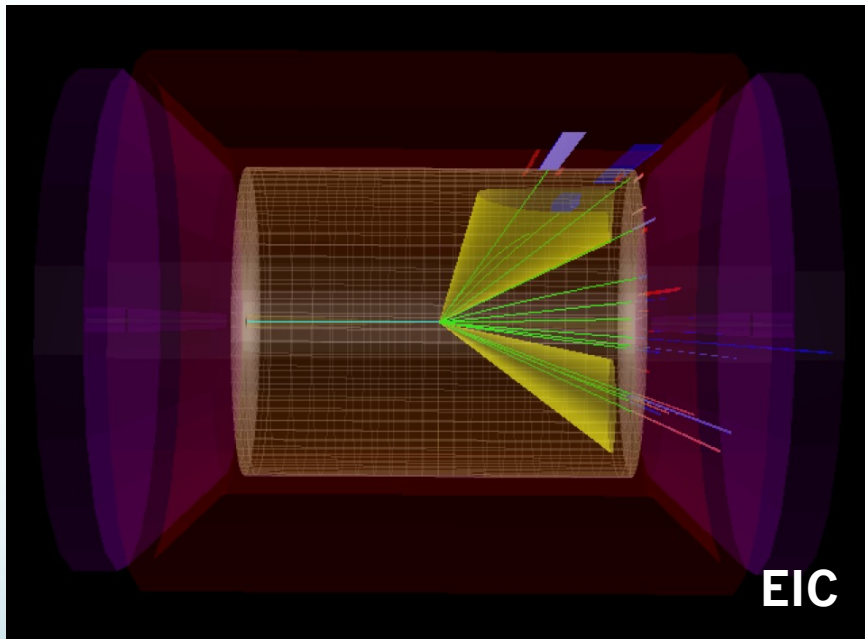


❖ Jet propagation in cold nuclear matter



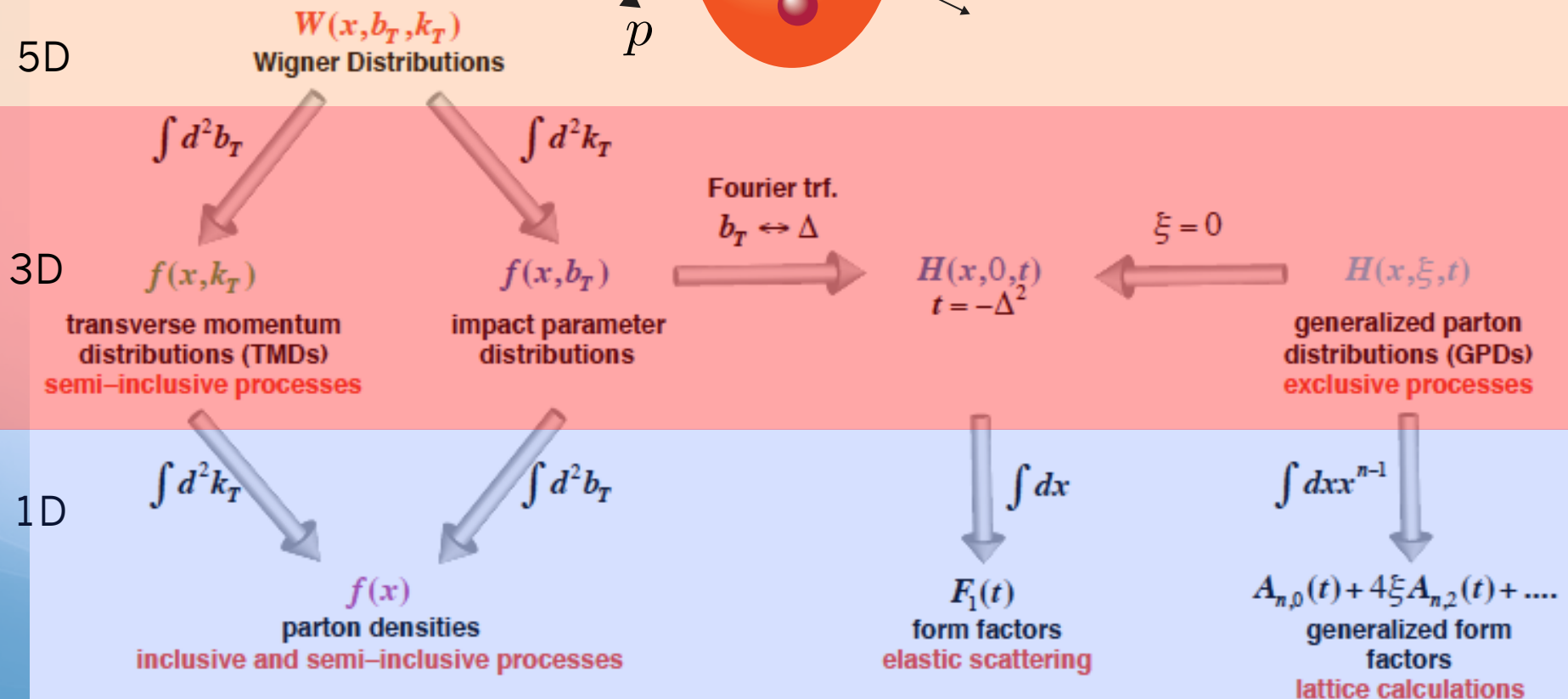
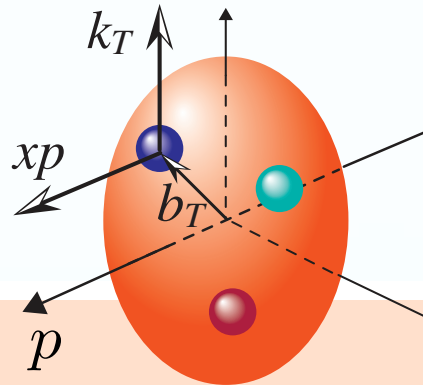
Jets are useful tools in all three directions

- Active study at the EIC
 - EIC jet papers grow exponentially



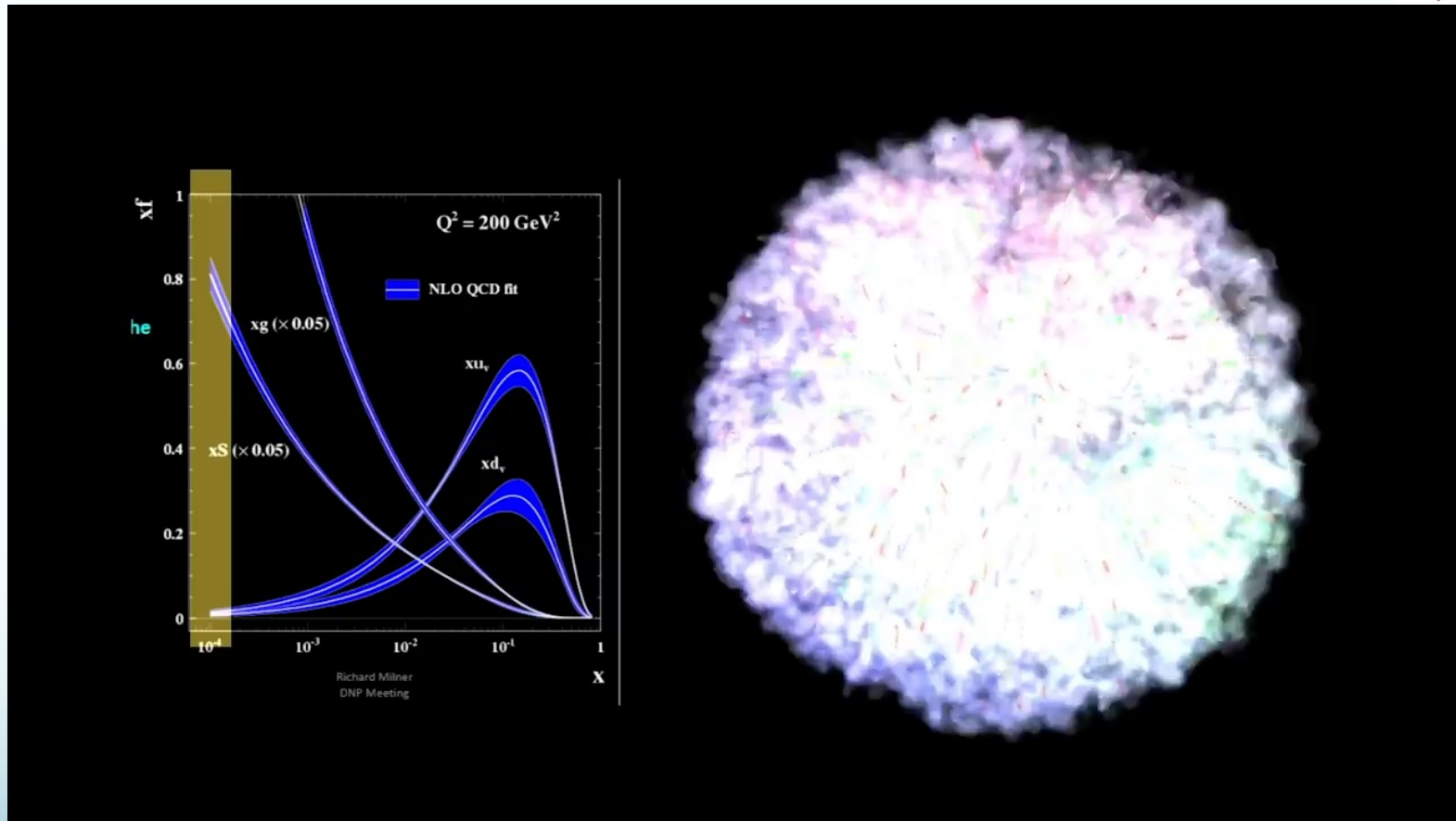
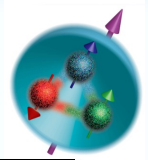
Jets for quantum imaging

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



1D: unpolarized PDFs

- Longitudinal motion



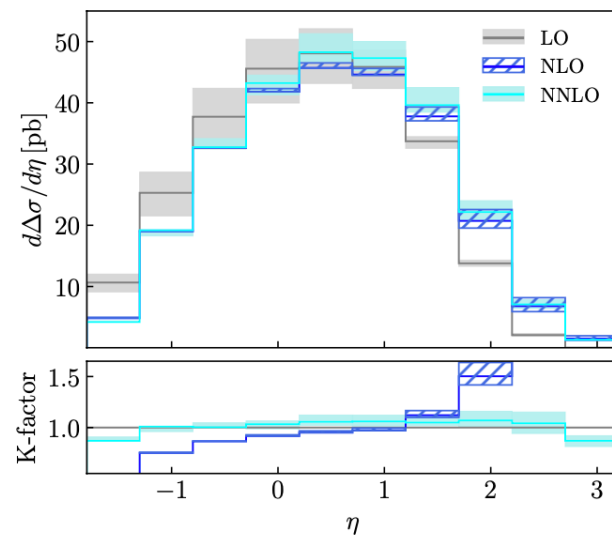
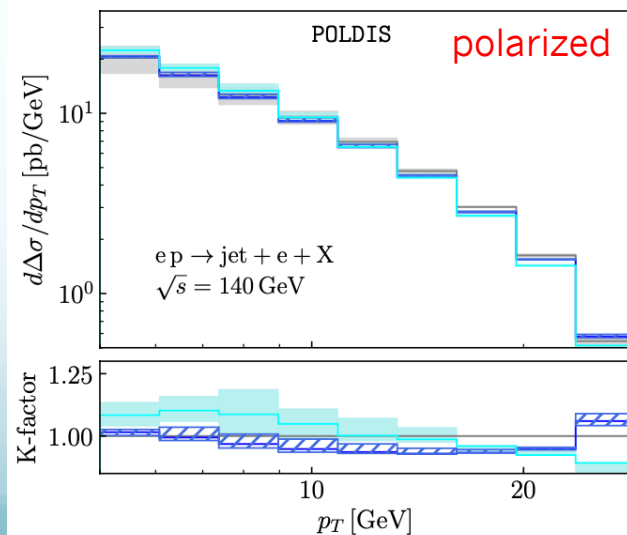
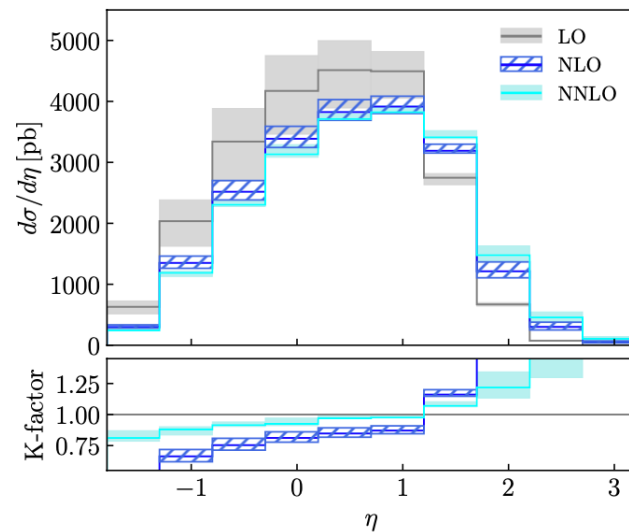
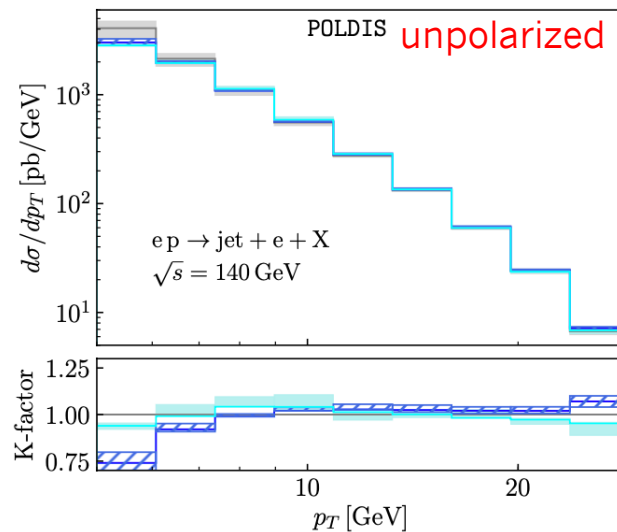
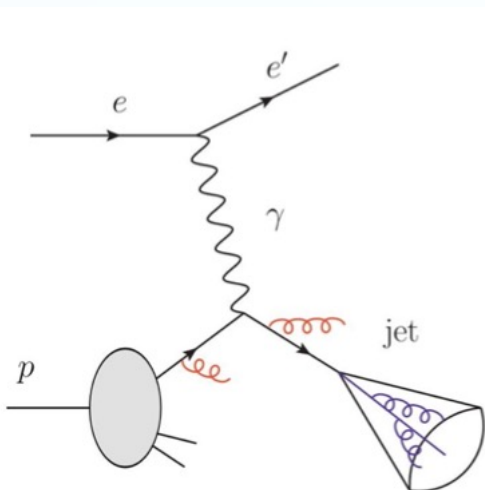
Physicist: Milner (MIT), Ent-Yoshida (Jlab), 04/2022

Documentary Filmmaker: Boebel-McMaster (MIT), LaPlante (Sputnik Animation)

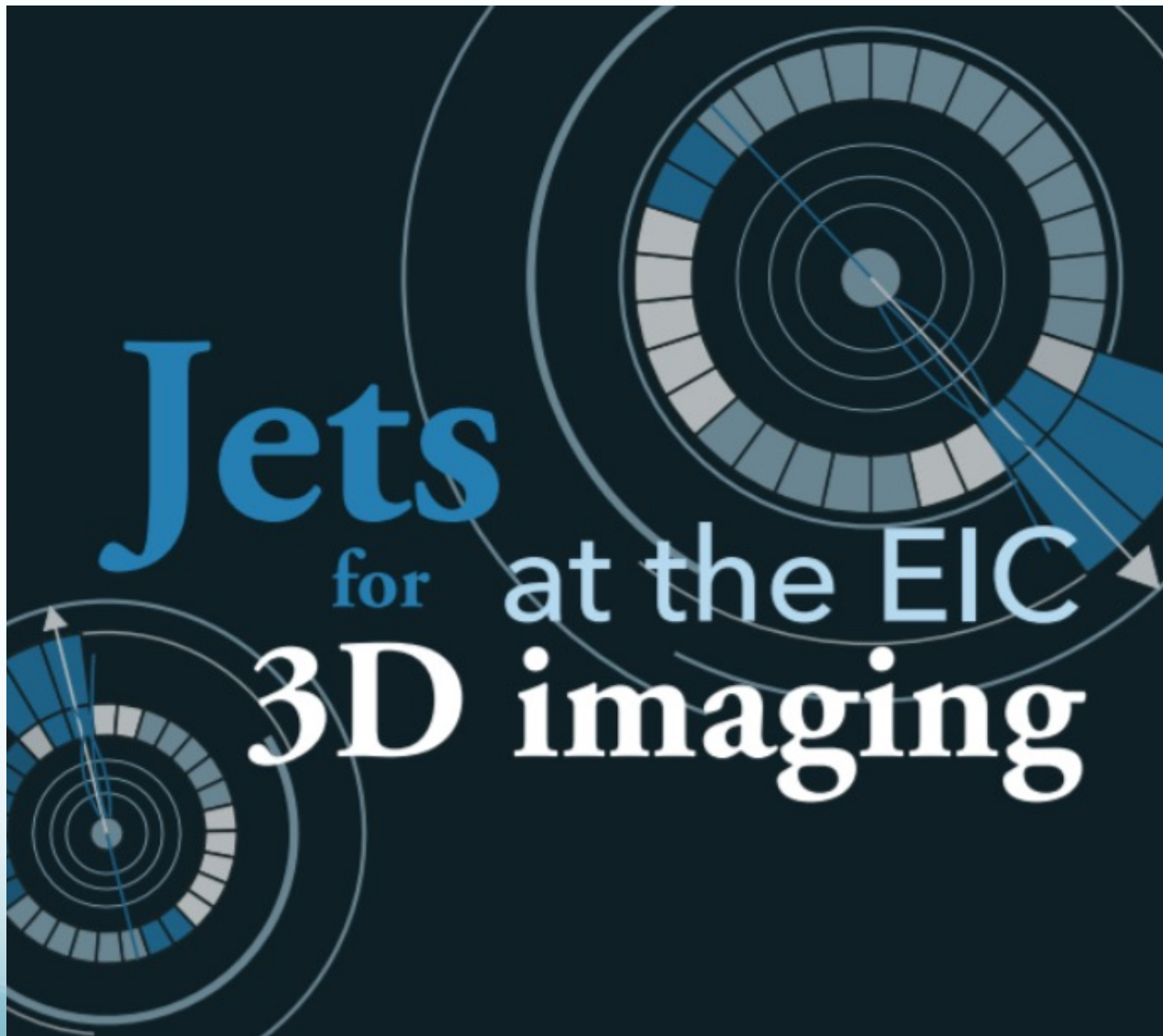
Jet production in e+p collisions

LO, NLO, NNLO frontiers

Borsa, de Florian, Pedron, PRL 20, PRD 21



Jets for 3D imaging



Jets for 3D imaging: TMDs

Leading Twist TMDs



Nucleon Spin



Quark Spin

TMD parton
distribution

		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 $h_{1T}^\perp =$ -

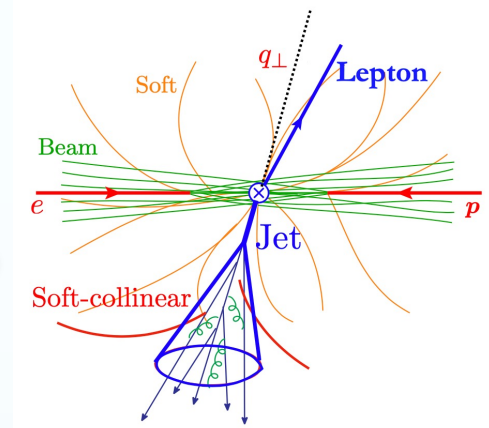
TMD
fragmentation
function

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

Jet production in e+p collisions

- Back-to-back lepton+jet production at ep collisions
 - One probes the small imbalance region
- Factorization formalism $e + p \rightarrow e + \text{jet} + X$
 - Because of small imbalance, we are sensitive to small transverse momentum
 - We now have TMD PDFs + soft function

$$\frac{d\sigma}{dp_T dq_T} \propto \hat{\sigma}_0 H(Q) \sum_q e_q^2 J_q(p_T R, \mu) \int f_1^q(x, k_T) S_{\text{global}}(\lambda_T, \mu) S_{cs}(\ell_T, R, \mu) \times \delta^2(\vec{q}_T - \vec{k}_T - \vec{\lambda}_T - \vec{\ell}_T)$$



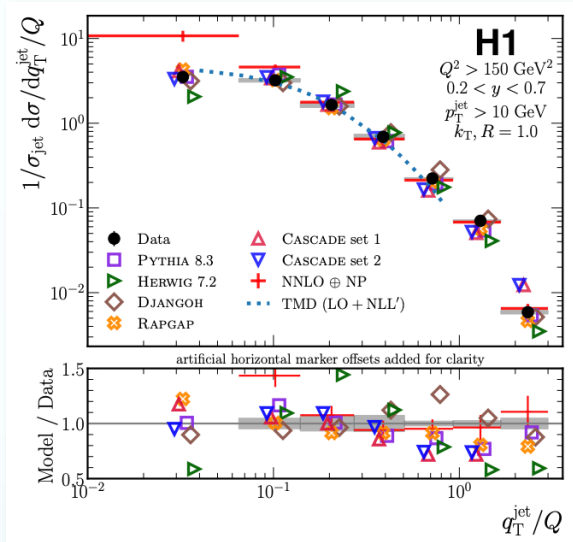
- Two soft functions
 - Global: can radiate everywhere
 - Collinear-soft: soft radiation inside jet does not affect imbalance

Arratia, Kang, Prokudin, Ringer, 2007.07281
 Kang, Lee, Shao, Zhao, 2106.15624
 Liu, Ringer, Vogelsang, Yuan, 18, 20, ...

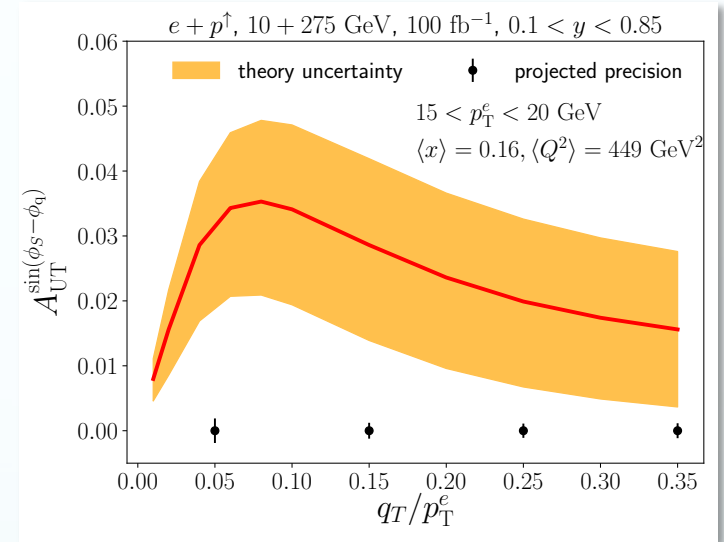
Jets for 3D imaging

- Constrain TMDs (without fragmentation function)
 - Unpolarized scattering: recent HERA measurement

HERA, arXiv:2108.12376, PRL 22



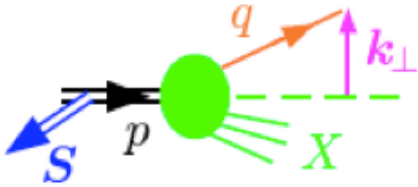
Arratia, Kang, Prokudin, Ringer, 2007.07281, PRD



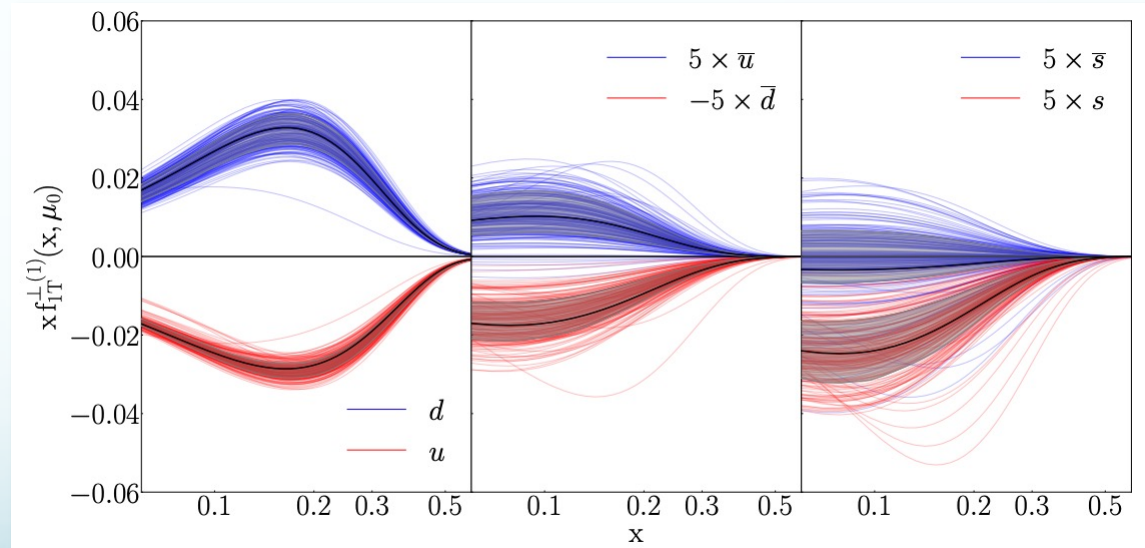
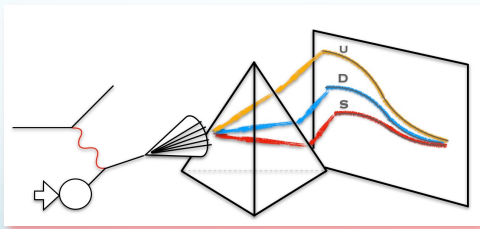
- Transversely polarized proton scattering: Sivers function (right plot)

Flavor separation for jet production

- Spin-dependent functions of different flavors tend to cancel
 - Because spin-dependent functions tend to be flavor dependent, e.g. Sivers function



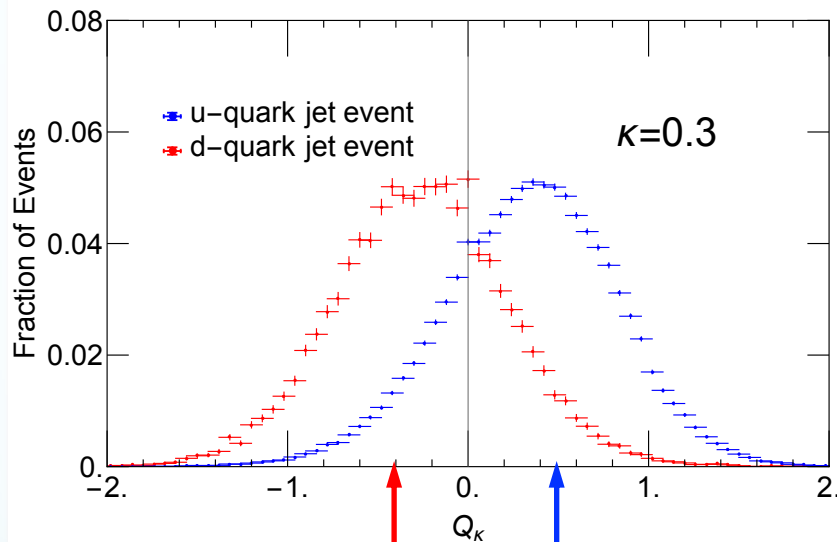
$$f_{q/h^\uparrow}(x, \mathbf{k}_\perp, \vec{S}) \equiv f_{q/h}(x, k_\perp) - \frac{1}{M} f_{1T}^{\perp q}(x, k_\perp) \vec{S} \cdot (\hat{p} \times \mathbf{k}_\perp)$$



Echevarria, Kang, Terry, 2009.10710, JHEP (2021)

Jet charge for flavor separation

- Spin asymmetry in e+p collisions
 - No jet charge selection:** taking out d quark, small change, thus no sensitivity
 - With negative jet charge bin selection:** dramatic change, much greater sensitivity



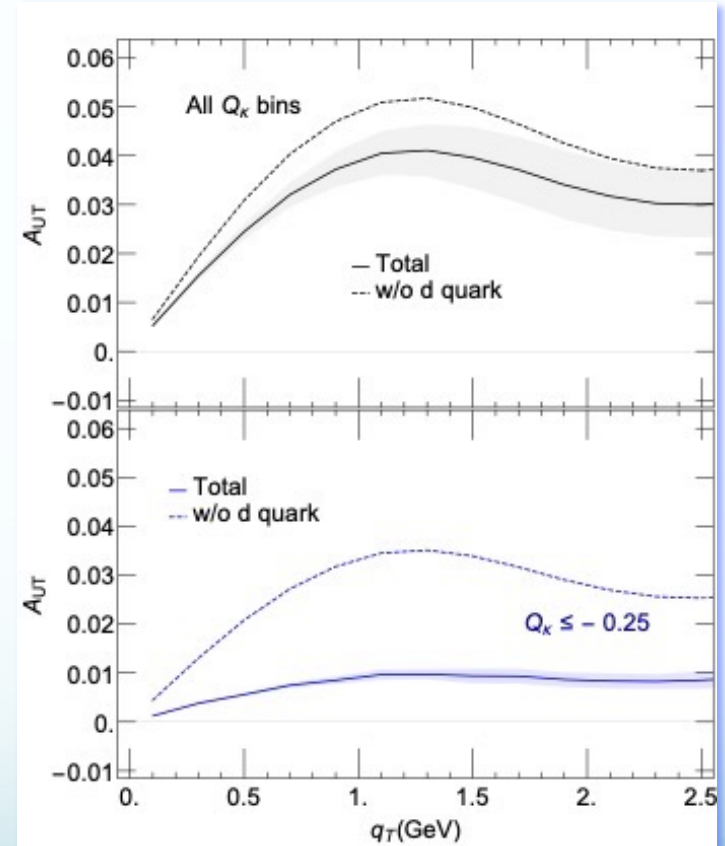
Jet charge definition

- A weighted sum of charges for hadrons inside the jet

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

Charge of the hadron

$$z_h = \frac{p_{hT}}{p_{JT}} \quad \kappa = 0.3, 0.4, \dots, 1.0$$

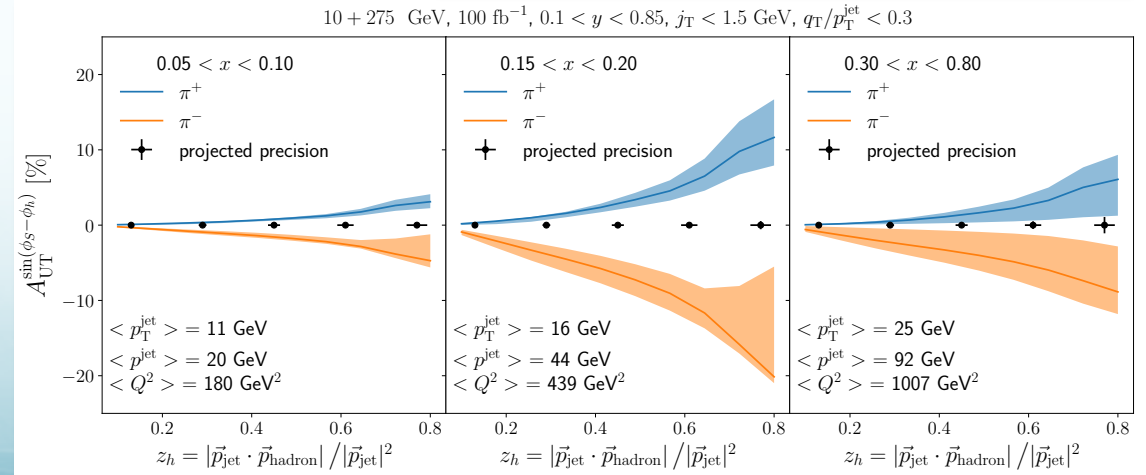
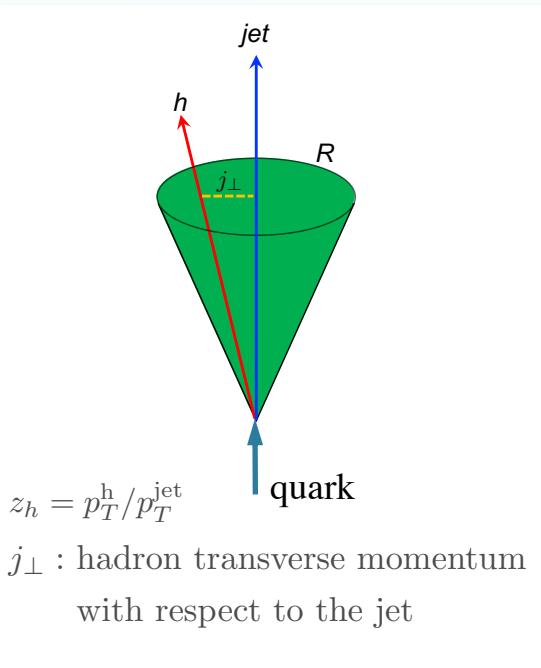
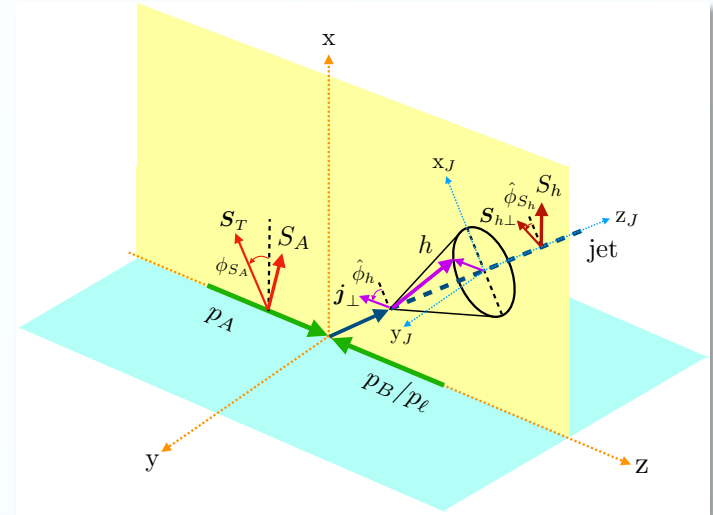


Kang, Liu, Mantry, Shao, PRL, 20

Jet substructure: polarized jet fragmentation function

- One can further measure distribution of hadrons inside the jet
 - Two axes: imbalance controls TMD PDFs, while the hadron transverse momentum w.r.t jet axis controls TMD FFs
 - Advantage over hadron production SIDIS

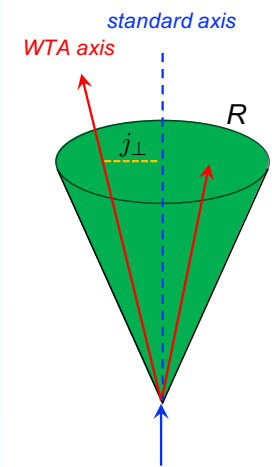
Kang, Lee, Zhao, PLB 20
 Arratia, Kang, Ringer, Prokudin, 20
 Kang, Lee, Shao, Zhao, JHEP 21
 Kang, Terry, Vossen, Xu, Zhang, PRD 22



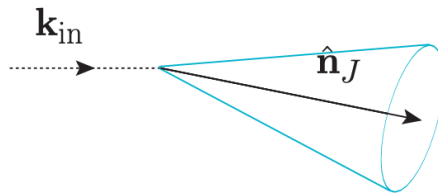
Utilizing different jet axis

- Winner-take-all (WTA) jet axis

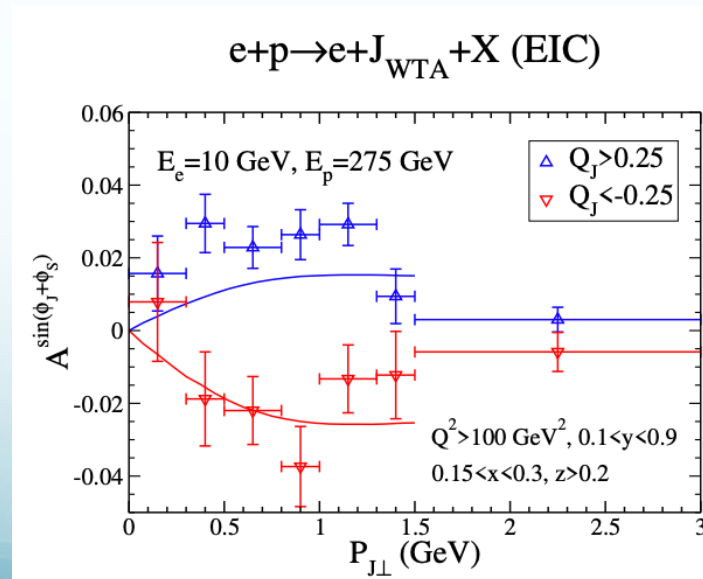
Gutierrez-Reyes, Scimemi, Waalewijn, Zoppi, JHEP 19
Lai, Liu, Wang, Xing, 2205.04570



$$\hat{n}_r = \begin{cases} \hat{n}_1, & \text{if } E_1 > E_2 \\ \hat{n}_2, & \text{if } E_2 > E_1 \end{cases}$$



$$\mathcal{J}(z, k_T) = \mathcal{J}_1(z, k_T^2) \frac{\not{k}_T}{2} + i \mathcal{J}_T(z, k_T^2) \frac{k_T \not{\vec{e}}_T}{2}$$



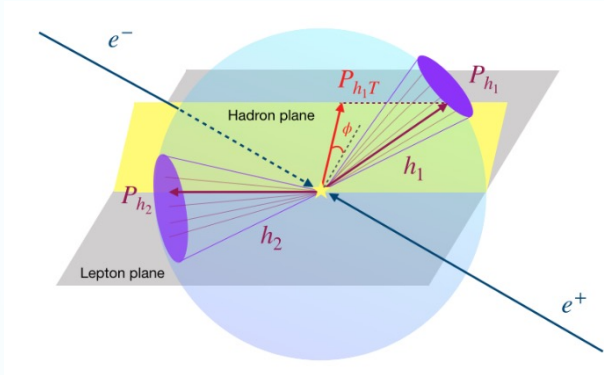
Jet-like: energy-energy correlator (EEC)

- EEC in the back-to-back region would be sensitive to the TMD physics

Moult, Zhu, 2019

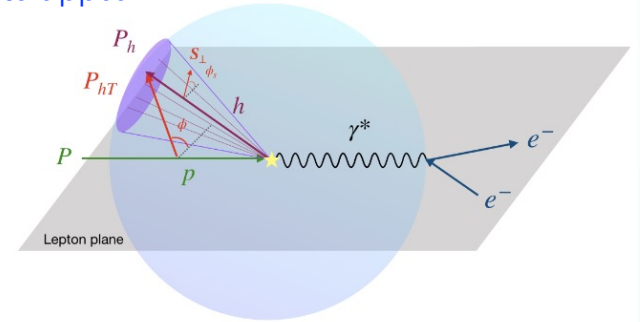
Li, Makris, Vitev, 2021

- Generalize to include azimuthal angle



Kang, Lee, Shao, Yuan, Zhao, to appear

$$\tau = \frac{1 + \cos \theta_{ij}}{2}$$



- Sensitive to polarized TMDs: Collins jet function (sum rule to Collins function), Sivers function, etc

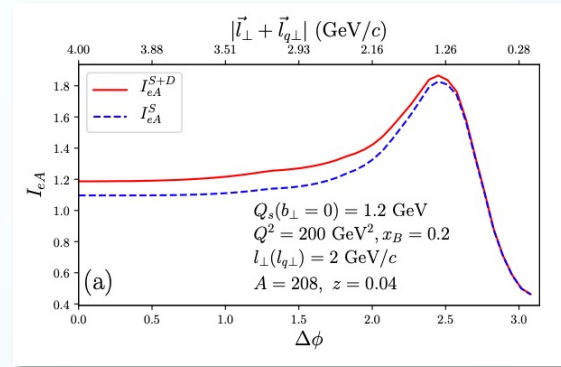
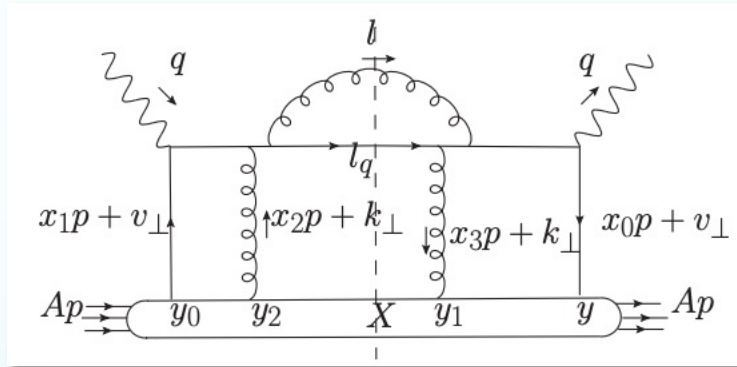
$$\begin{aligned} \text{EEC}_{e^+e^-}(\tau, \phi) &= \frac{1}{\sigma} \frac{d\Sigma_{e^+e^-}}{d\tau d\phi} = \frac{1}{2} \sum_{i,j} \int d^2 \mathbf{q}_T dz_i dz_j z_i z_j \frac{1}{\sigma} \frac{d\sigma}{d^2 \mathbf{q}_T dz_i dz_j} \delta\left(\tau - \frac{\mathbf{q}_T^2}{Q^2}\right) \delta(\phi - \phi_{q_T}) \\ \frac{d\Sigma_{e^+e^-}}{d\tau d\phi} &= \frac{2\pi N_c \alpha_{\text{em}}^2}{3Q^2} \sum_q e_q^2 \int d\mathbf{q}_T^2 \delta\left(\tau - \frac{\mathbf{q}_T^2}{Q^2}\right) \int \frac{b db}{2\pi} \left[J_0(bq_T) J_q(\mathbf{b}, \mu, \zeta/\nu^2) J_{\bar{q}}(\mathbf{b}, \mu, \zeta/\nu^2) S(\mathbf{b}^2, \mu, \nu) \right. \\ &\quad \left. + \frac{b^2}{8} \cos 2\phi J_2(bq_T) J_q^\perp(\mathbf{b}, \mu, \zeta/\nu^2) J_{\bar{q}}^\perp(\mathbf{b}, \mu, \zeta/\nu^2) S(\mathbf{b}^2, \mu, \nu) \right], \end{aligned} \quad (1.5)$$

$$\text{EEC}_{\text{DIS}}(\tau, \phi) \equiv \frac{1}{\sigma} \frac{d\Sigma_{\text{DIS}}}{d\tau d\phi} = \frac{1}{2} \sum_a \int d\theta_a dz_a z_a \frac{1}{\sigma} \frac{d\sigma}{d\theta_a d\phi_a dz_a} \delta\left(\tau - \left(\frac{1 + \cos \theta_{ap}}{2}\right)\right) \delta(\phi - \phi_{ap})$$

Jets for Color Glass Condensate

- Jet production in nucleus: multiple scattering in heavy nucleus
 - High-twist
 - CGC approach: resum all order rescattering to Wilson lines
- A recent high-twist calculation
 - Dijet production in e+A at LO

Zhang, Wang, PRD 2022



$$\frac{d\sigma_{eA}^D}{dx_B dQ^2 dz d^2l_\perp d^2l_{q\perp}} = \frac{2\pi\alpha_{\text{em}}^2}{Q^4} \sum_q e_q^2 \left[1 + \left(1 - \frac{Q^2}{x_B s} \right)^2 \right] \frac{\alpha_s}{2\pi} \frac{1+z^2}{1-z} \frac{2\pi\alpha_s}{N_c} \int \frac{d^2k_\perp}{(2\pi)^2} \int d^2b_\perp dy_0^- dy_1^-$$

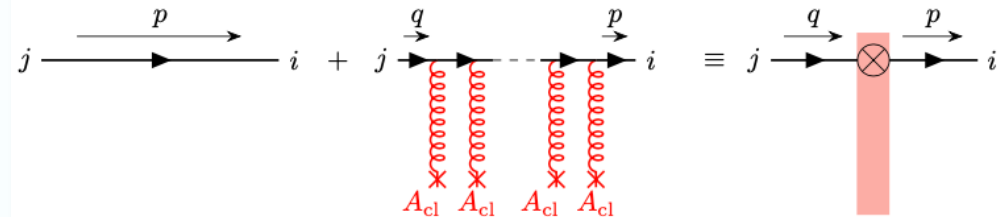
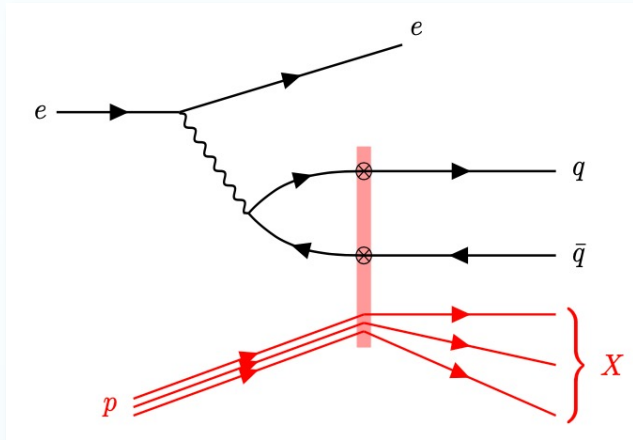
$$\times \rho_A(y_0^-, b_\perp) \rho_A(y_1^-, b_\perp) q_N(x_B, \vec{v}_\perp, b_\perp) \frac{\phi_N(x_G, \vec{k}_\perp)}{k_\perp^2} \left[\mathcal{N}_g^{\text{qLPM}} + \mathcal{N}_g^{\text{gLPM}} + \mathcal{N}_g^{\text{nonLPM}} \right].$$

Jet production in CGC

- NLO computations just started in very recently

Dominguez, Marquet, Xiao, Yuan, 2011

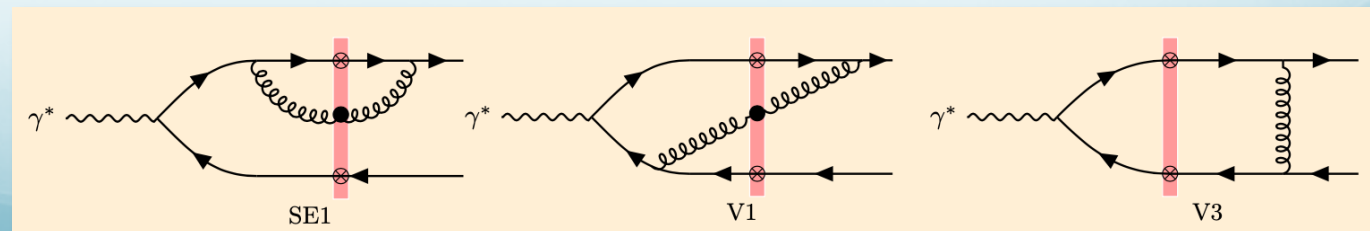
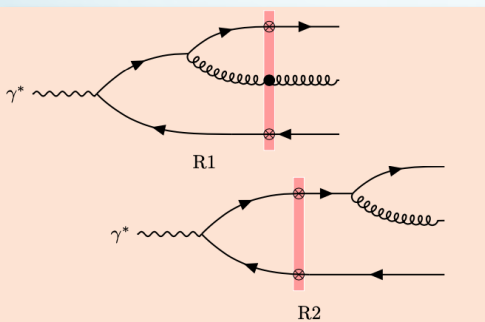
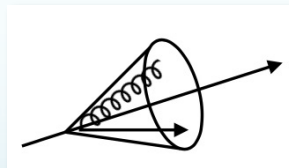
- LO available in 2011
- LO had no jet structure



$$V_{ij}(\mathbf{x}) = P \exp \left\{ ig \int dx^- A_{cl}^{+,a}(\mathbf{x}, x^-) t^a \right\}$$

- NLO available in 2021
 - Jet algorithm is simplified

Caucal, Salazar, Schenke, Venugopalan, 2021, 2022



Jet production in p+A

■ Jet algorithm

Liu, Xie, Kang, Liu, 2204.03026, JHEP, 22

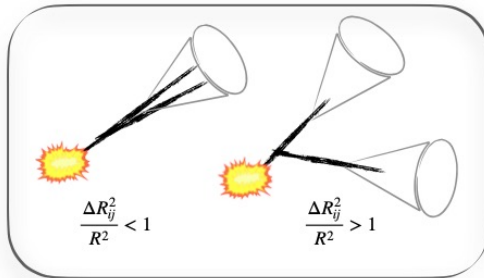
- Properly handle jet algorithm on top of complicated CGC computations
- Study its small- R approximation: factorized into a semi-inclusive jet function
- Can be readily used for jet production in e+A: also [jet substructure](#)

anti- k_T Cacciari, Salam, Soyez, 2008

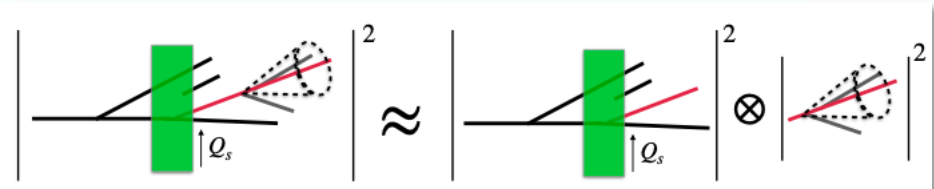
- If ρ_{ij} is the smallest, combine i and j
- If ρ_i is the smallest, promote i as a jet candidate and remove from the list
- Do recursively

$$\rho_i = k_{i\perp}^{-2\alpha} \quad \rho_{ij} = \min[k_{i\perp}^{-2\alpha}, k_{j\perp}^{-2\alpha}] \frac{\Delta R_{ij}^2}{R^2}$$

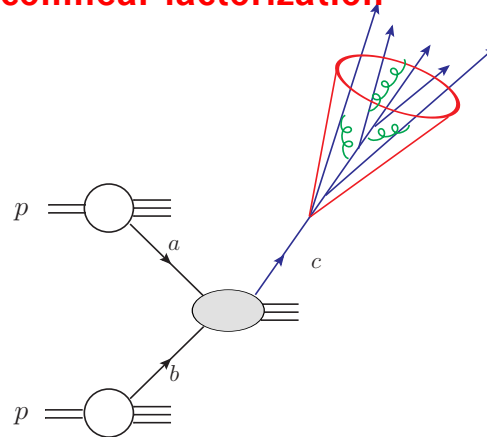
$$\Delta R_{ij}^2 = \Delta\phi_{ij}^2 + \Delta\eta_{ij}^2$$



CGC factorization in small R



collinear factorization



Kang, Ringer, Vitev, JHEP, 2016

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

Jets in cold nuclear matter

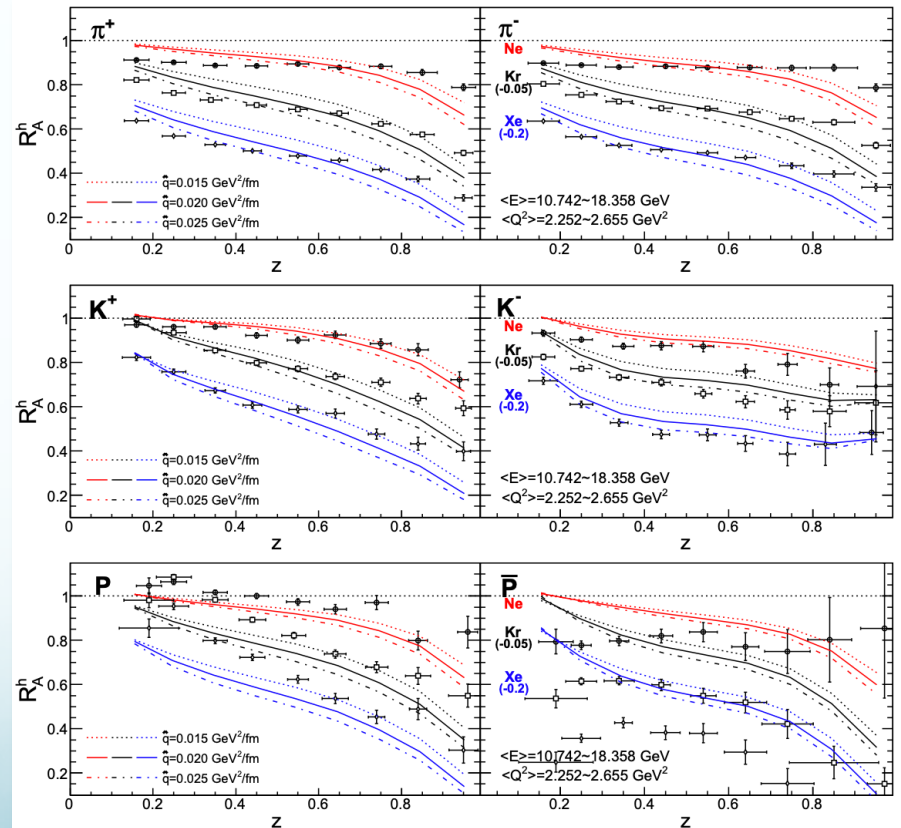
- The early HERMES data: hadron multiplicity modification

- Modified fragmentation function in medium

Chang, Deng, Wang, 2014, PRC
See also Li, Liu, Vitev, 2020, PLB

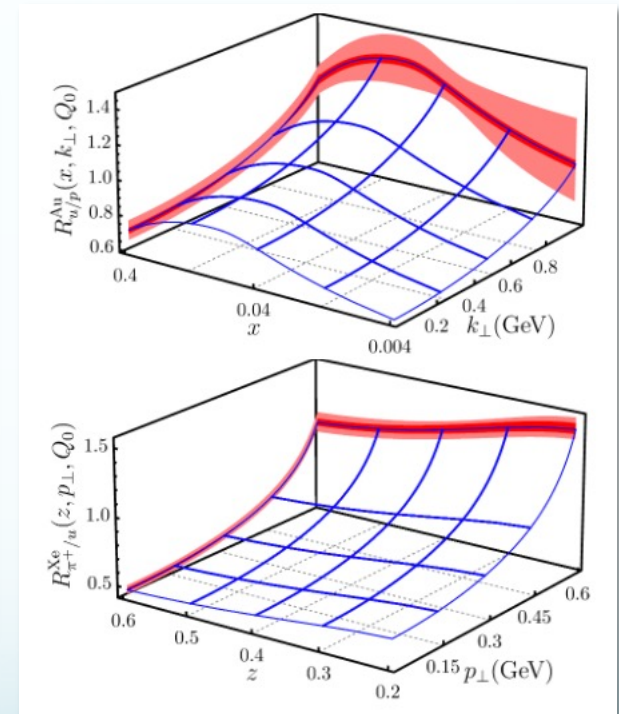
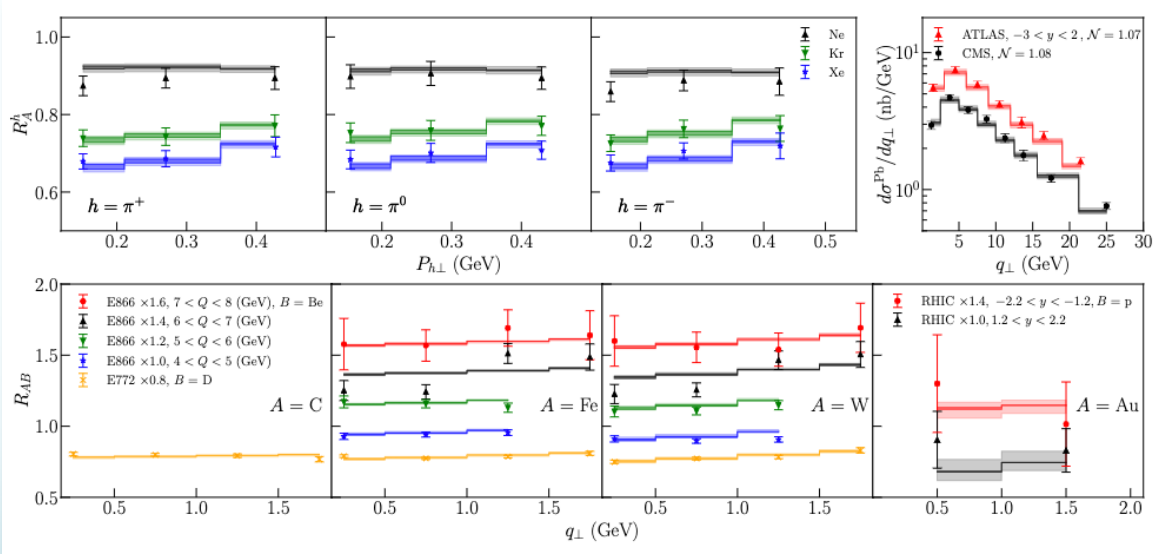
$$R_A^h(z, \nu) = \left(\frac{N^h(z, \nu)}{N^e(\nu)} \right)_A / \left(\frac{N^h(z, \nu)}{N^e(\nu)} \right)_D$$

$$= \left(\frac{\Sigma e_q^2 q(x) \tilde{D}_q^h(z)}{\Sigma e_q^2 q(x)} \right)_A / \left(\frac{\Sigma e_q^2 q(x) D_q^h(z)}{\Sigma e_q^2 q(x)} \right)_D$$



A different interpretation: data-driven approach

- Extract TMD PDFs and TMD FFs in a heavy nucleus via global analysis
 - Similar to nuclear collinear PDFs idea (EKS98, EPPS16, etc)
 - Use the same TMD factorization for hadron production in e+A, except replacing with nuclear TMDs [via broadening parameters]



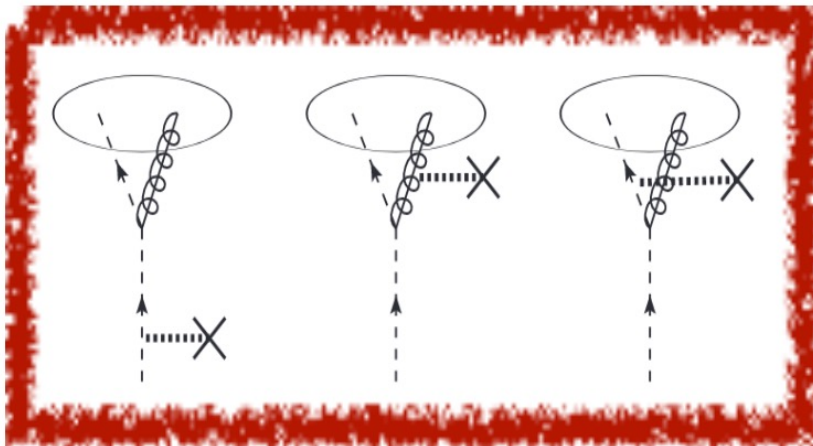
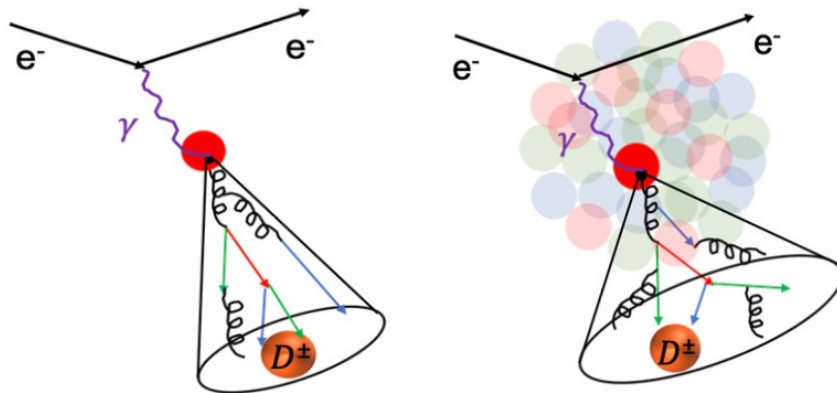
$$\frac{d\sigma}{dx_B dQ^2 dz_h d^2 P_{hT}} \propto \int d^2 k_T d^2 q_T f_q(x_B, k_T) D(z_h, q_T) \delta^2(z_h k_T + q_T - P_{hT})$$

Alrashed, Anderle, Kang, Terry, Xing, 2021

Jet modification in e+A

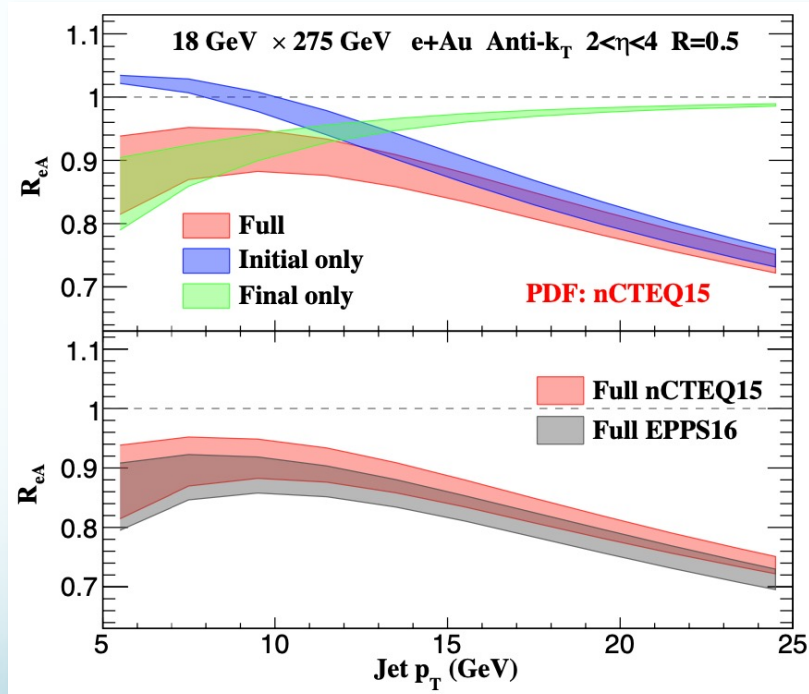
- Similar formalism in A+A applied to e+A collisions

$$e^- + p \rightarrow e^- + jet(D^\pm) + X \quad e^- + Au \rightarrow e^- + jet(D^\pm) + X$$



Kang, Ringer, Vitev, PLB 2017

Li, Vitev, 2020



Jet anisotropy in e+p collisions

- Such azimuthal anisotropy arises from soft radiation
 - Soft radiation outside the jet cone

$$e(l) + p(P) \rightarrow e(l') + J_q(p_J) + X$$

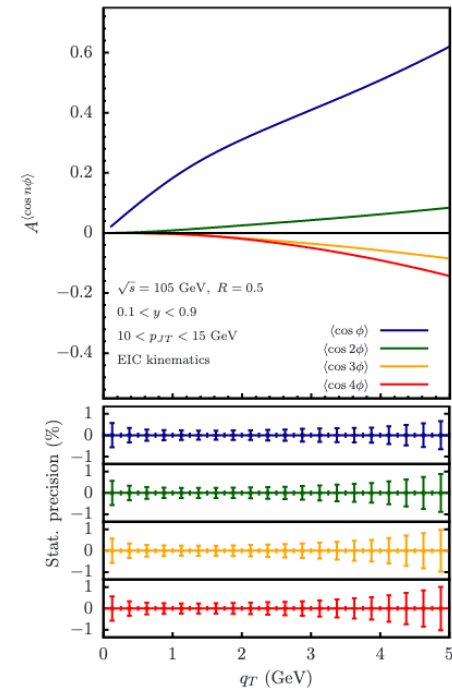
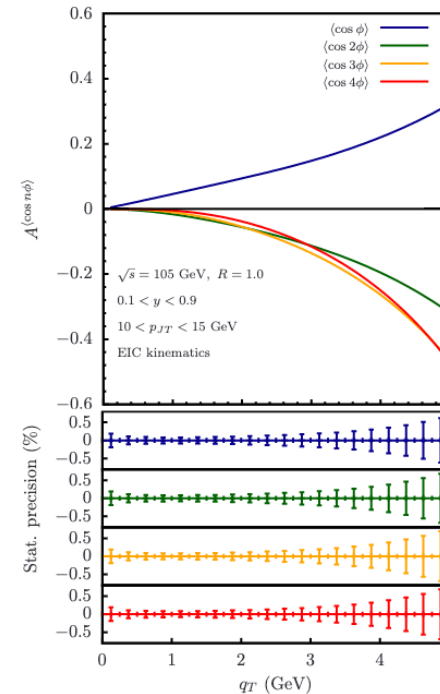
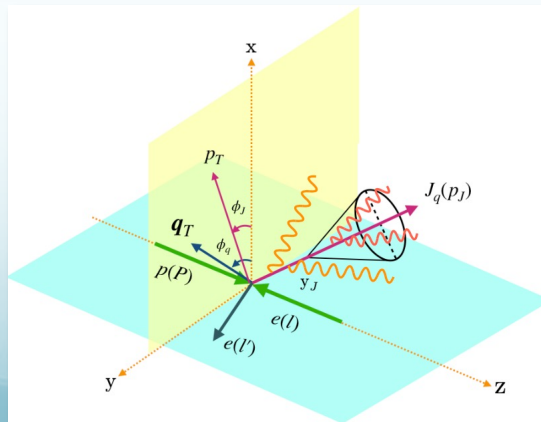
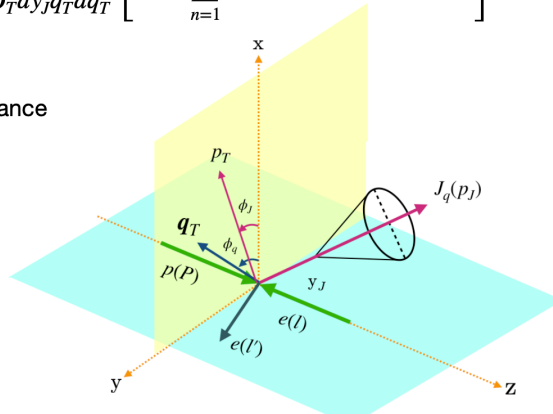
$$\frac{d\sigma}{d^2p_T dy_J d\phi_J d^2q_T} = \frac{d\sigma}{2\pi d^2p_T dy_J q_T dq_T} \left[1 + 2 \sum_{n=1}^{\infty} v_n(p_T, y_T) \cos(n(\phi_q - \phi_J)) \right]$$

q_T : transverse momentum imbalance

$$q_T = l'_T + p_{JT}$$

p_T : jet transverse momentum

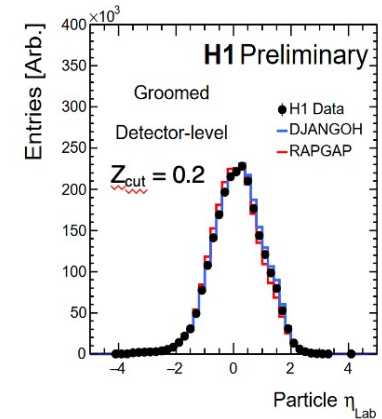
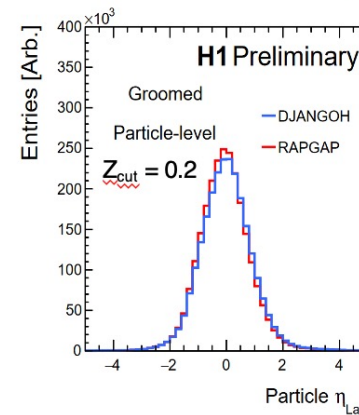
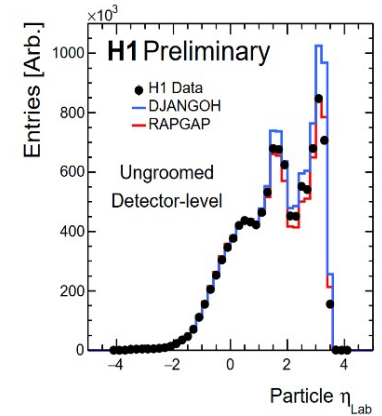
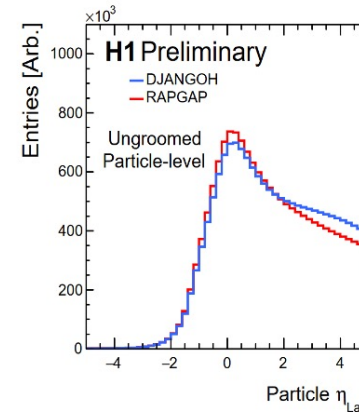
y_J : jet rapidity



Esha, Kang, Lee, Shao, Zhao, to appear
See also Hatta, Xiao, Yuan, Zhou, 2021

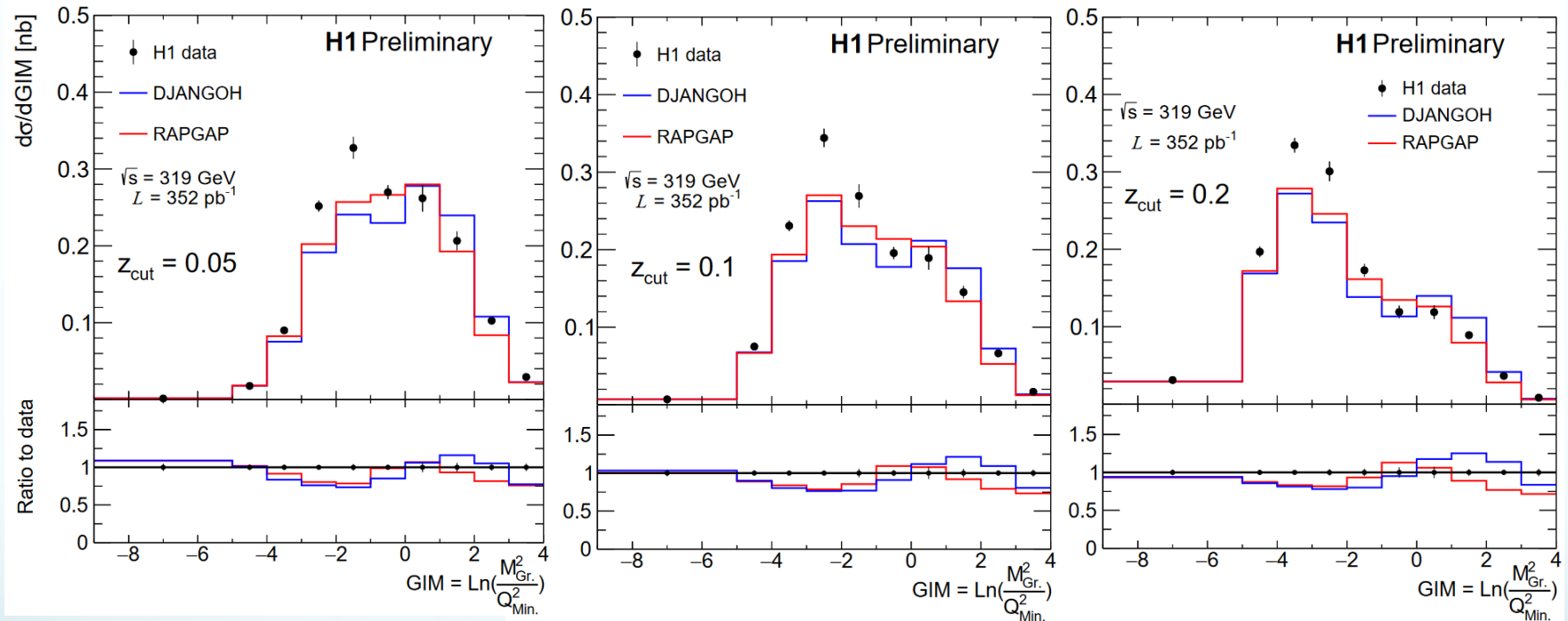
Grooming Benefits

- No underlying event, why groom?
 - Less affected by lab-frame detector acceptance
 - Mitigate QCD remnant, ISR
 - No theoretically challenging non-global logarithms
- Ungroomed detector-level shows significant difference from particle-level
 - Detector acceptance, efficiencies
- Grooming events brings particle-level and detector-level distributions into much better agreement!



Groomed jet mass from HERA

- Most recent results on groomed jet mass in $e+p$

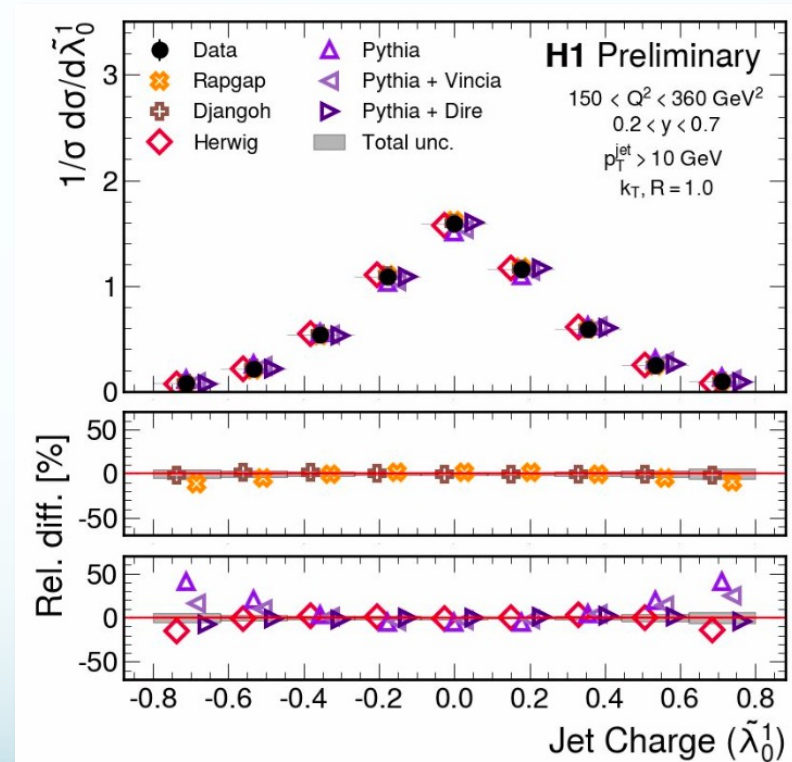
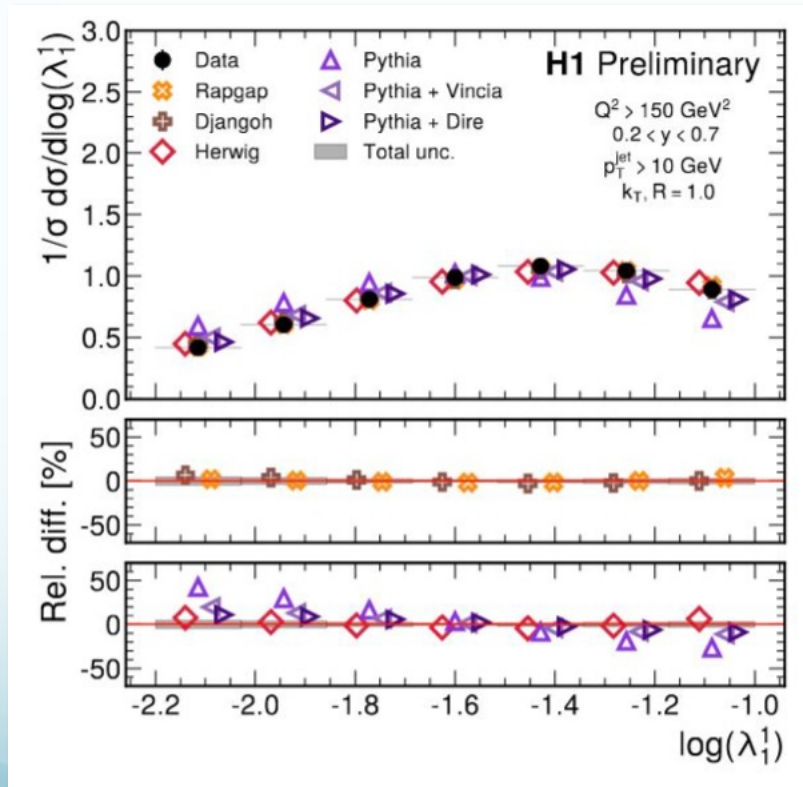


Klest, June 8

Jet angularity

- Recent measurement on jet angularity using ML

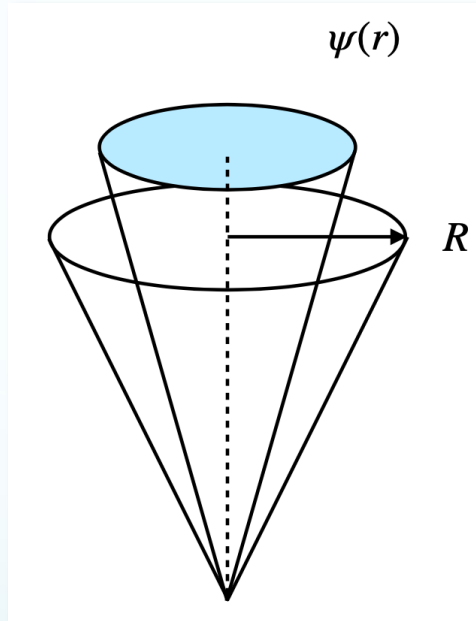
$$\lambda_{\beta}^{\kappa} = \sum_{i \in \text{jet}} z_i^{\kappa} \left(\frac{R_i}{R_0} \right)^{\beta} \quad \tilde{\lambda}_0^{\kappa} = Q_{\kappa} = \sum_{i \in \text{jet}} q_i \times z_i^{\kappa}$$



Mikuni, Nachman, June 8

Jet shape

- Jet shape at the EIC



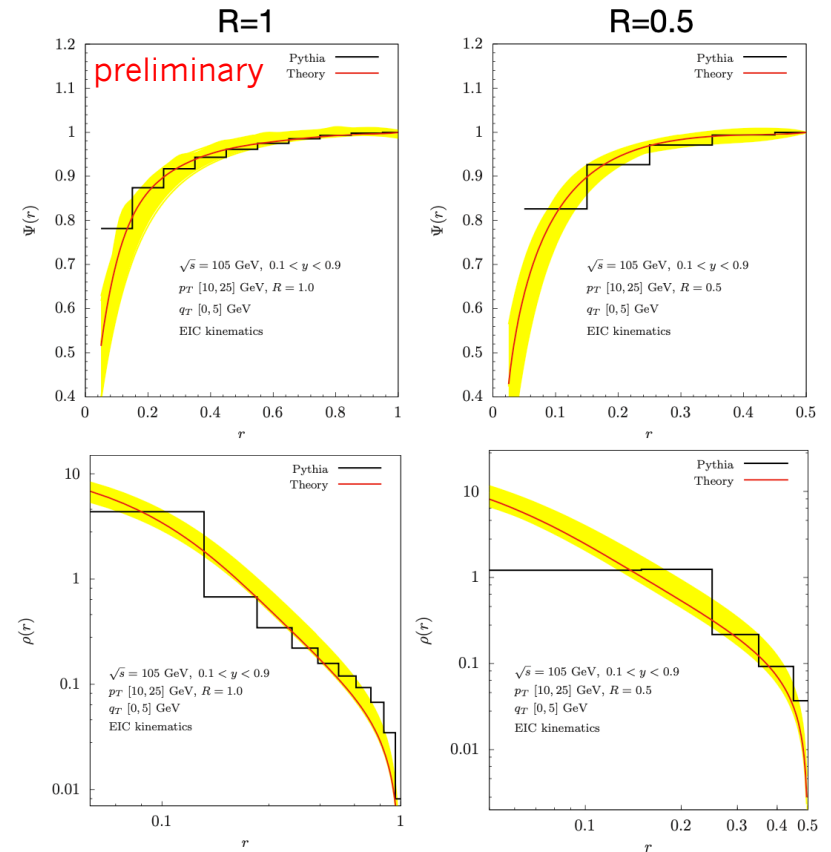
EIC kinematics

Integrated jet shape:

$$\psi(r) = \frac{\int dz_r z_r \frac{d\sigma}{d^2p_T dy_j d^2q_T dz_r}}{\frac{d\sigma}{d^2p_T dy_j d^2q_T}}$$

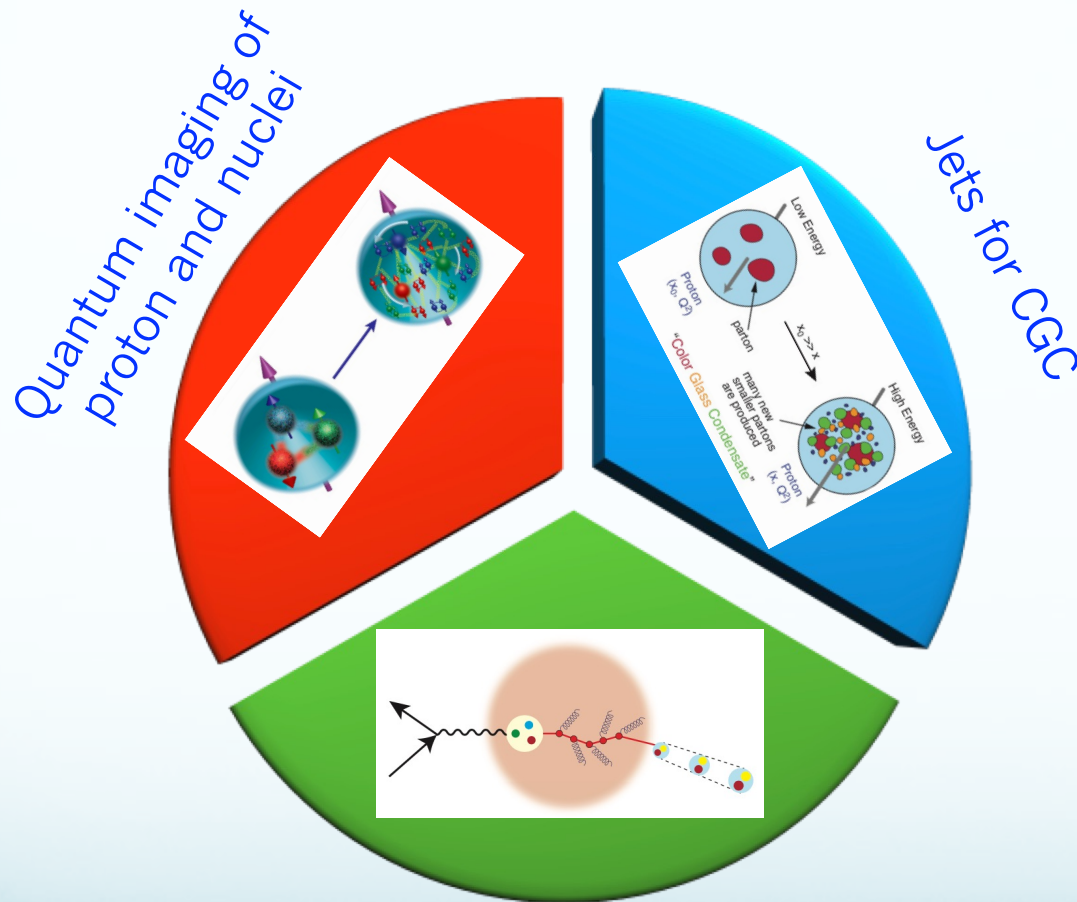
Differential jet shape:

$$\rho(r) = \frac{d\psi(r)}{dr}$$



Esha, Kang, Lee, Shao, Zhao, to appear

Summary: jets are powerful tools



Jet propagation in nuclei

Thank you!