

Jet Physics at the EIC

Zhongbo Kang
UCLA

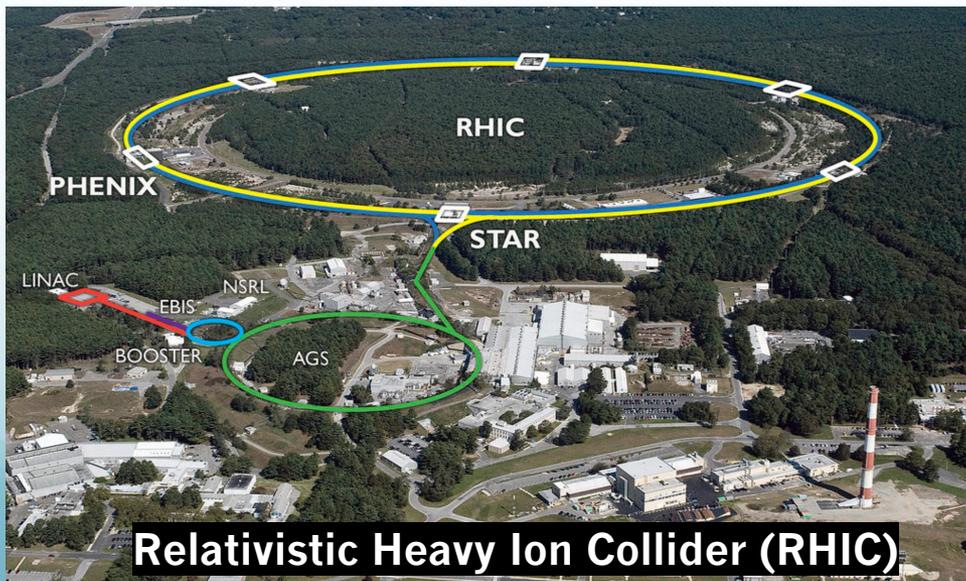
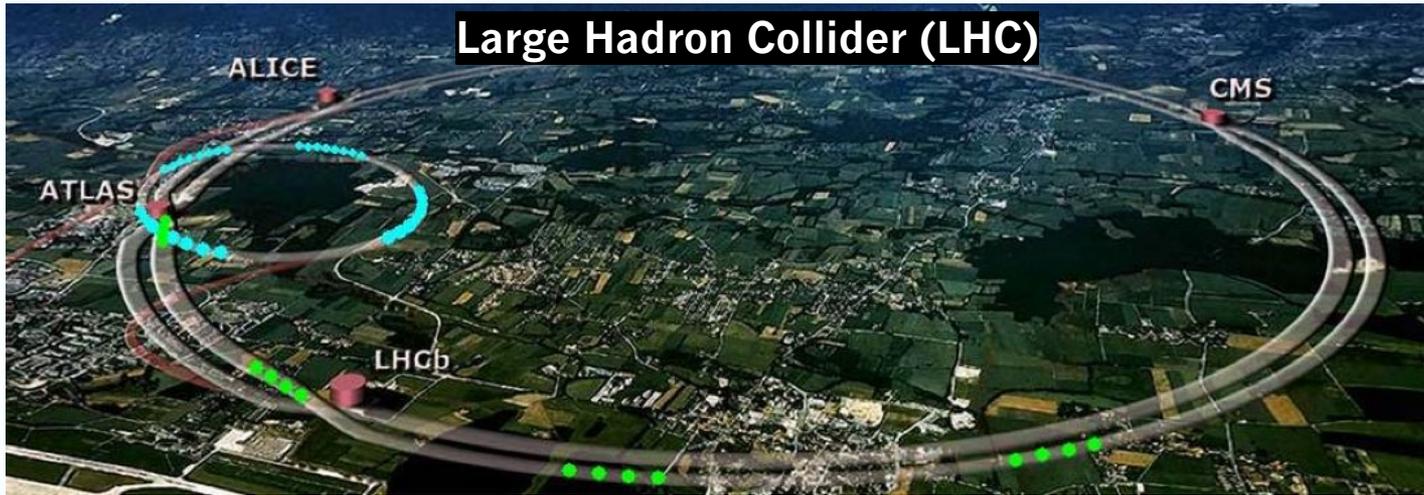
 @ZhongboK

ECT* Workshop: Jet Quenching in the Quark-Gluon Plasma
June 17, 2022

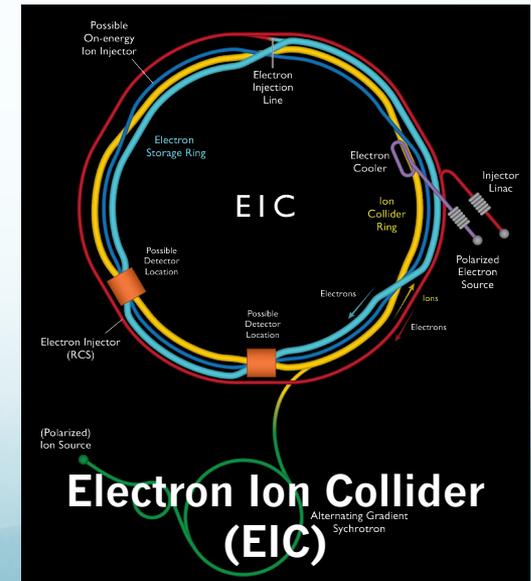
I wish I were there in-person



Key facilities: LHC, RHIC, and EIC

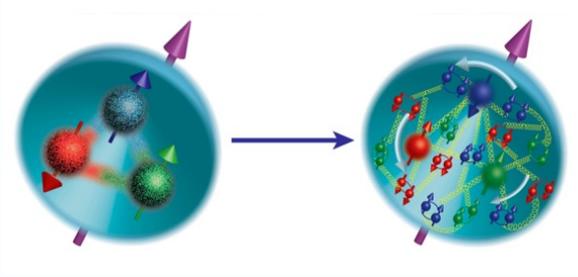


~ 2031

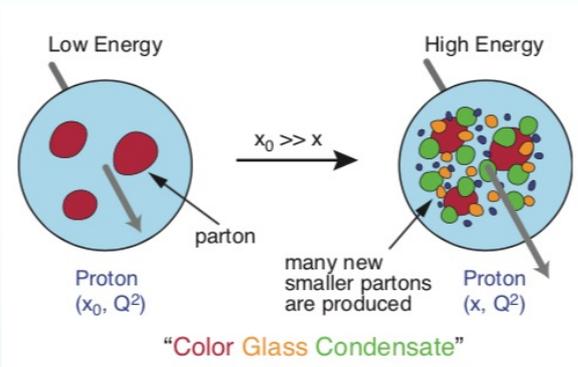


EIC Scientific Pillars

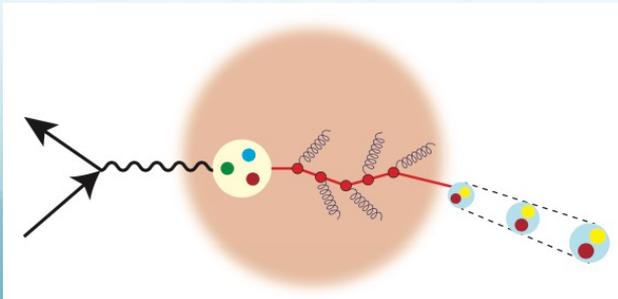
- ❖ Quantum Imaging of protons and nuclei



- ❖ A new form of matter - color glass condensate

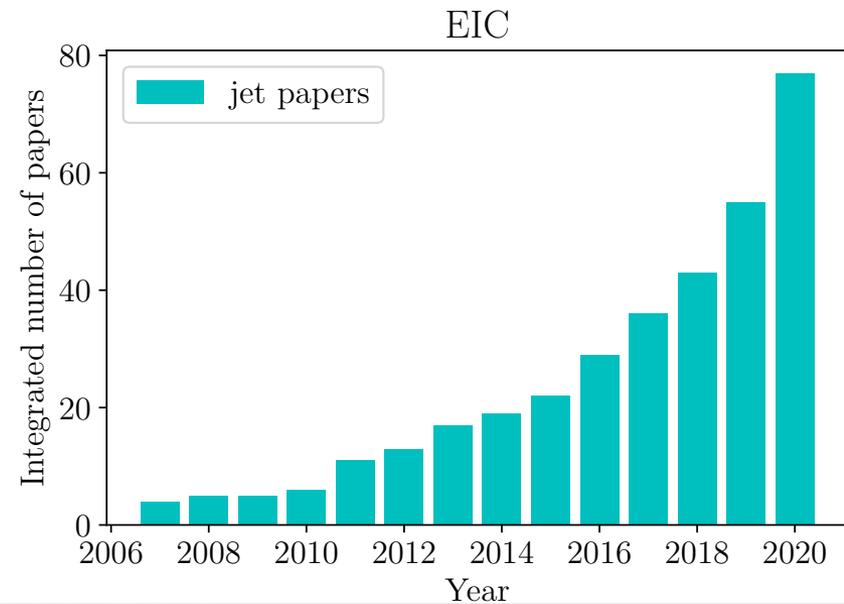
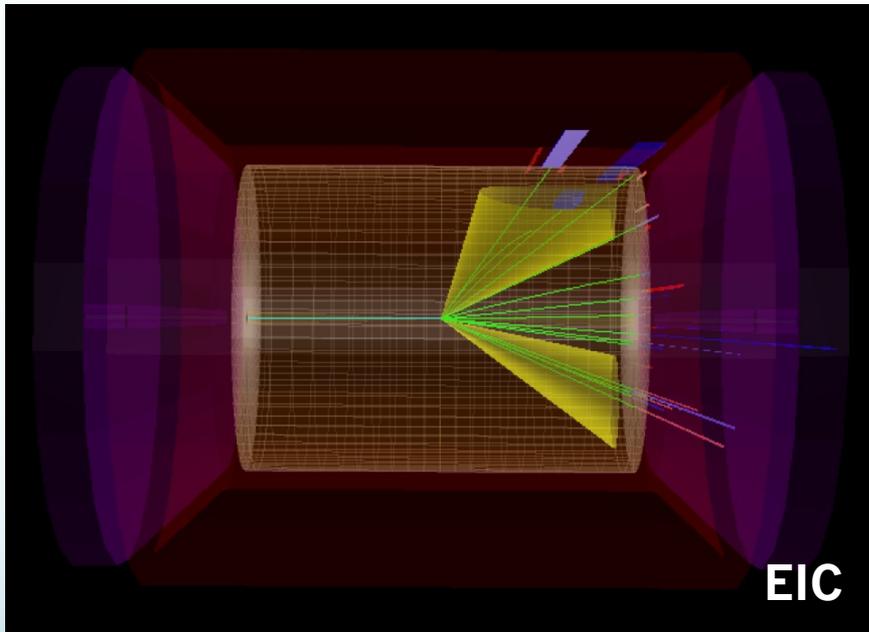


- ❖ Jet propagation in cold nuclear matter



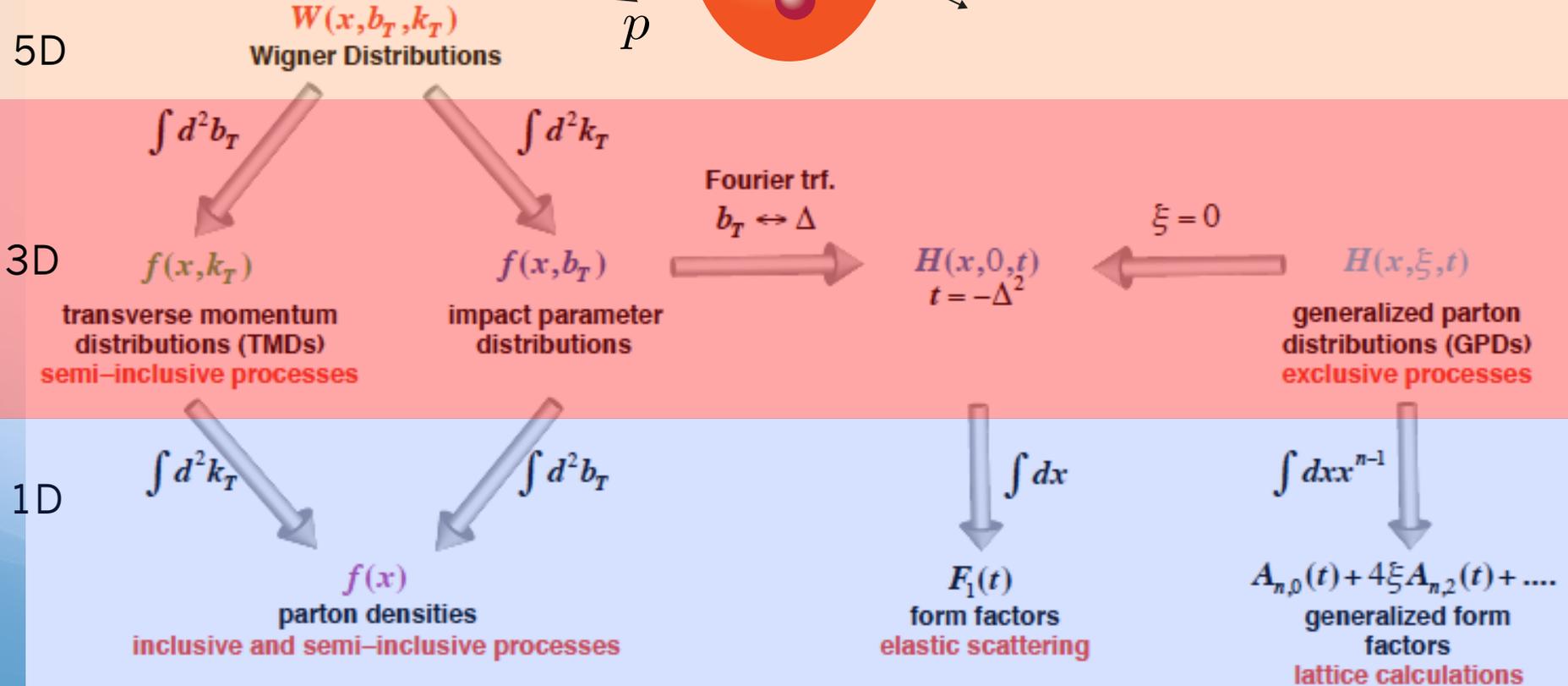
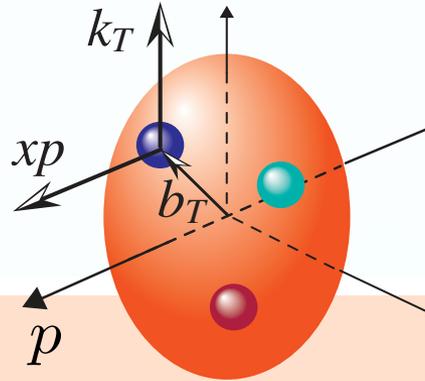
Jets are useful tools in all three directions

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



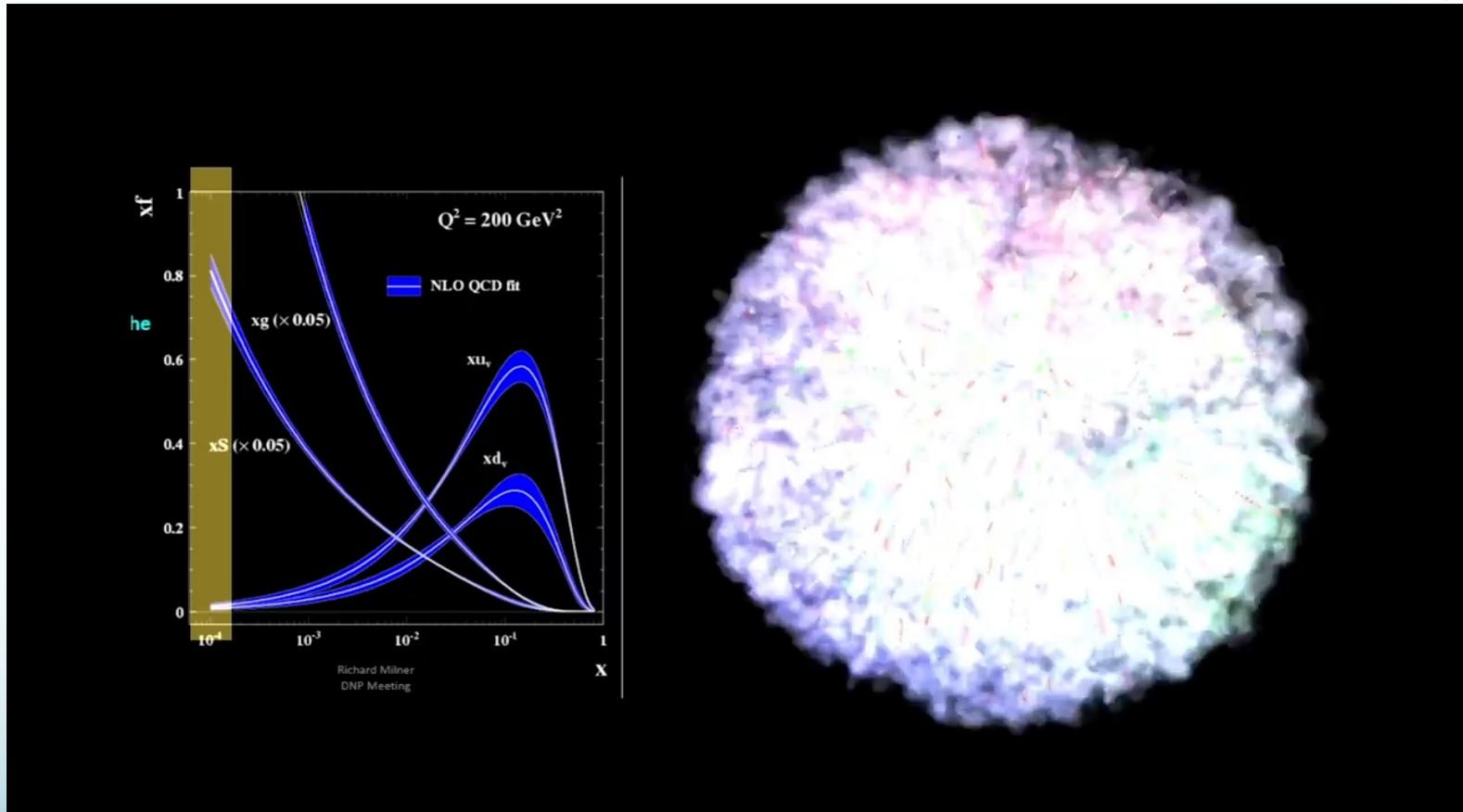
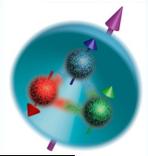
Jets for quantum imaging

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



1D: unpolarized PDFs

- Longitudinal motion

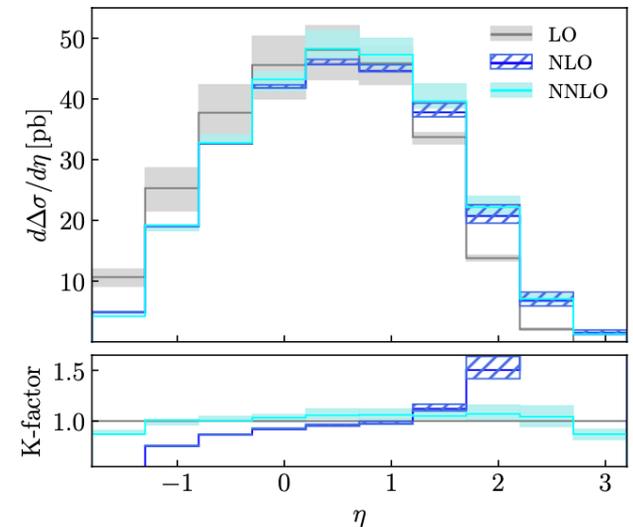
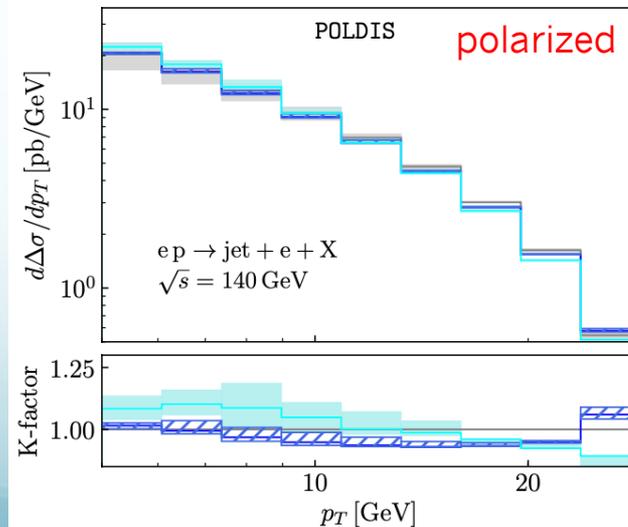
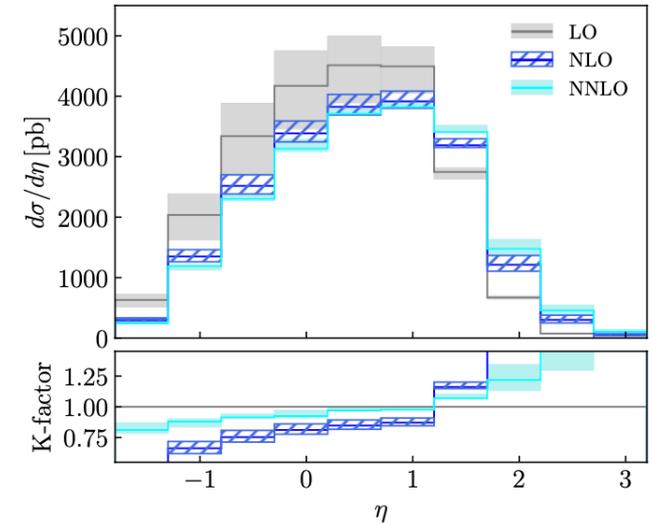
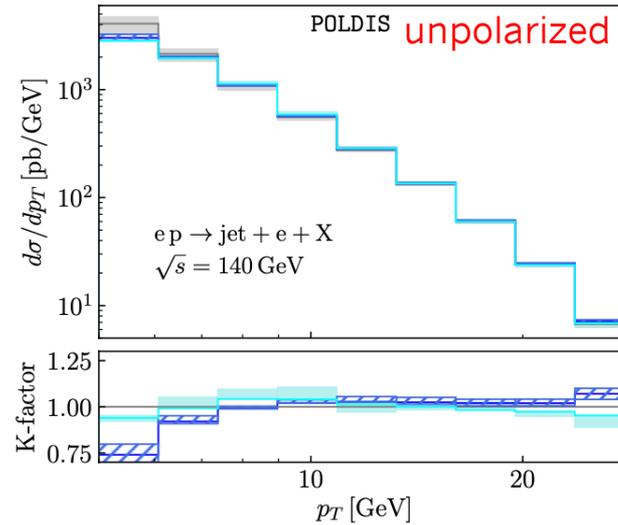
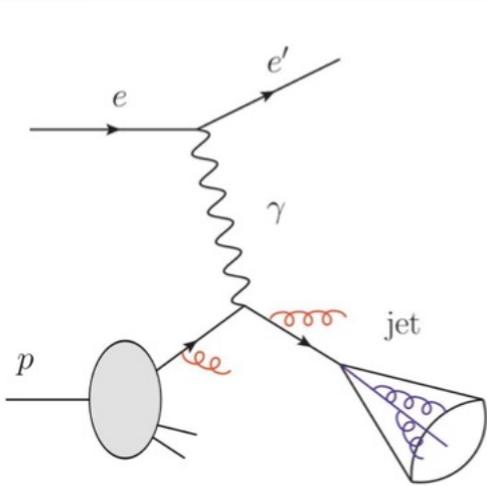


Physicist: Milner (MIT), Ent-Yoshida (Jlab), 04/2022
Documentary Filmmaker: Boebel-McMaster (MIT), LaPlante (Sputnik Animation)

Jet production in e+p collisions

- LO, NLO, NNLO frontiers

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



Jets for 3D imaging: TMDs

Leading Twist TMDs



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

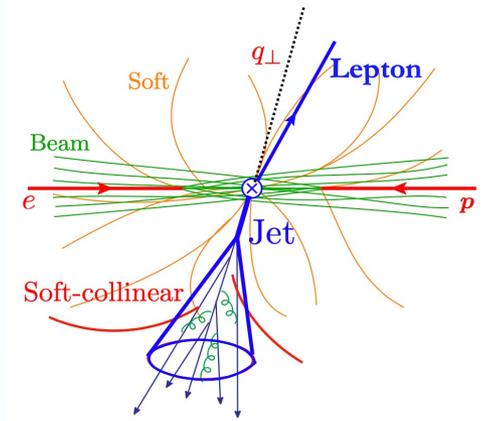
TMD fragmentation function

		Quark Polarization		
		U	L	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

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



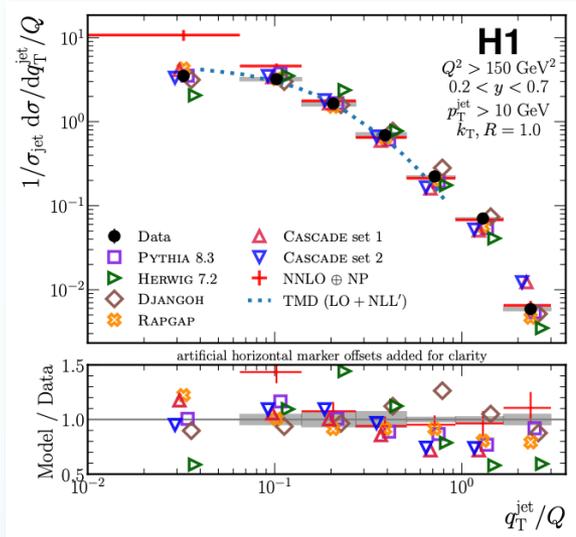
- Two soft functions
 - Global: can radiate everywhere
 - Collinear-soft: soft radiation inside jet does not affect imbalance

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

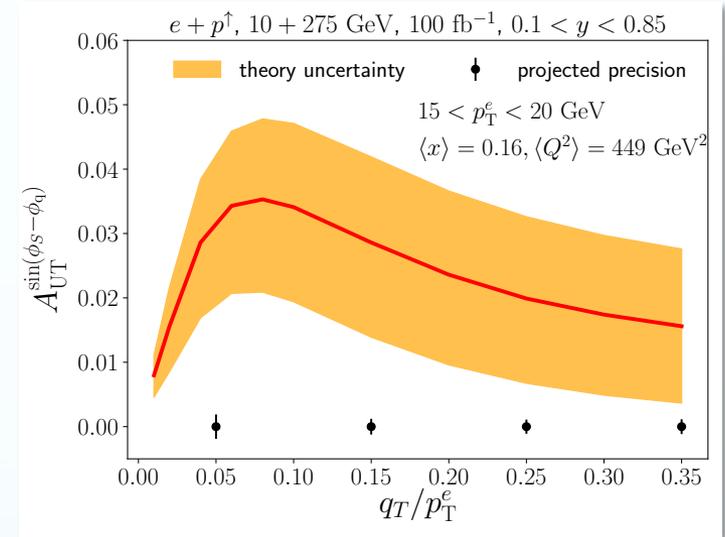
Jets for 3D imaging

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

HERA, arXiv:2108.12376, PRL 22



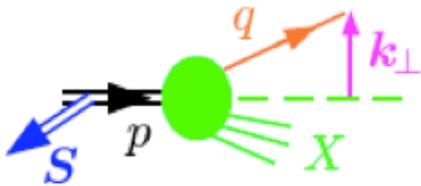
Arratia, Kang, Prokudin, Ringer, 2007.07281, PRD



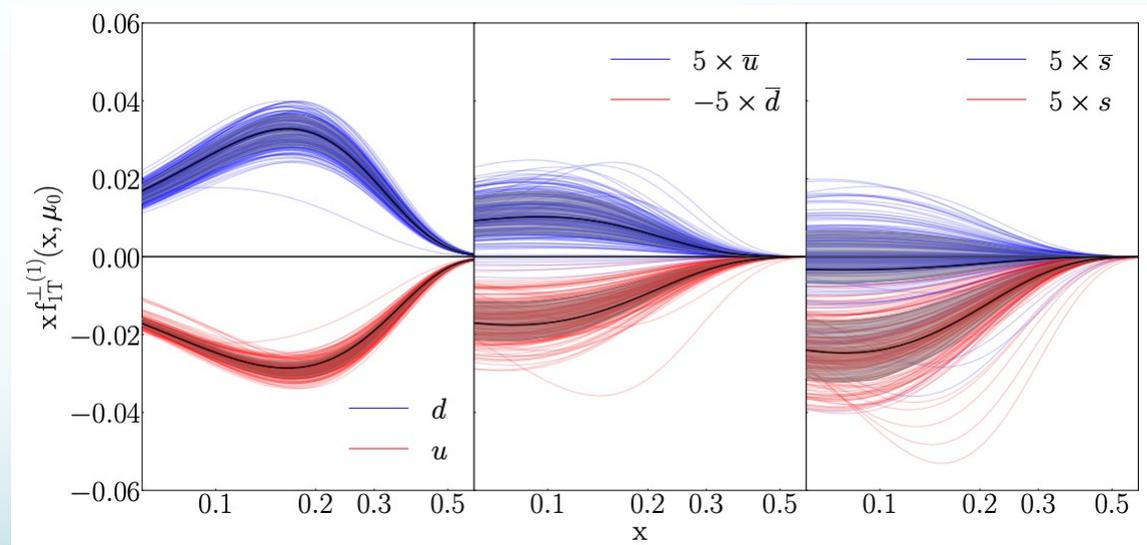
- Transversely polarized proton scattering: Sivers function (right plot)

Jet charge

- Jet charge is much more useful for polarized scattering
 - Because spin-dependent functions tend to be flavor dependent, e.g. Sivers function



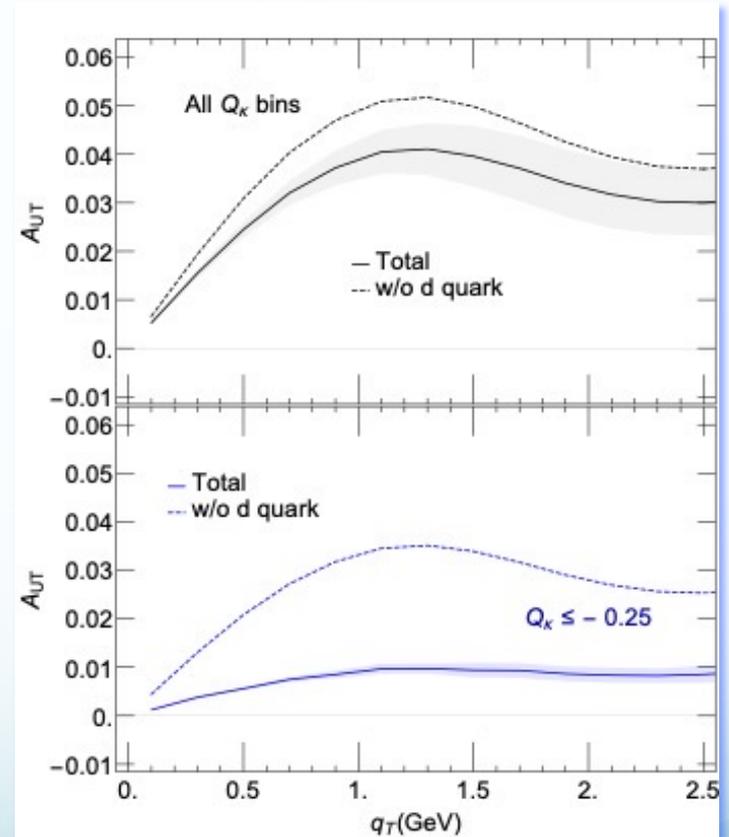
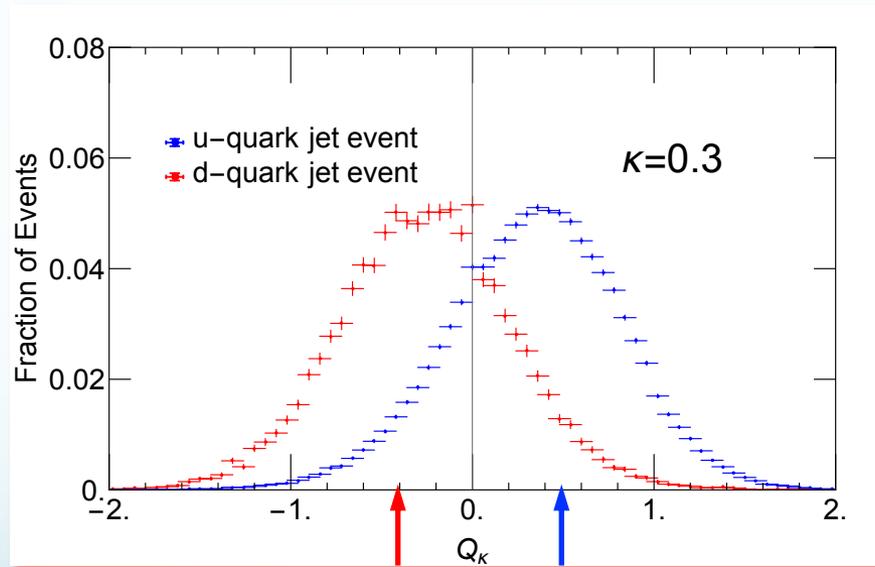
$$f_{q/h^\uparrow}(x, \mathbf{k}_\perp, \vec{S}) \equiv f_{q/h}(x, k_\perp) - \frac{1}{M} f_{1T}^{\perp q}(x, k_\perp) \vec{S} \cdot (\hat{p} \times \mathbf{k}_\perp)$$



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

Enhanced sensitivity for d quark

- 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

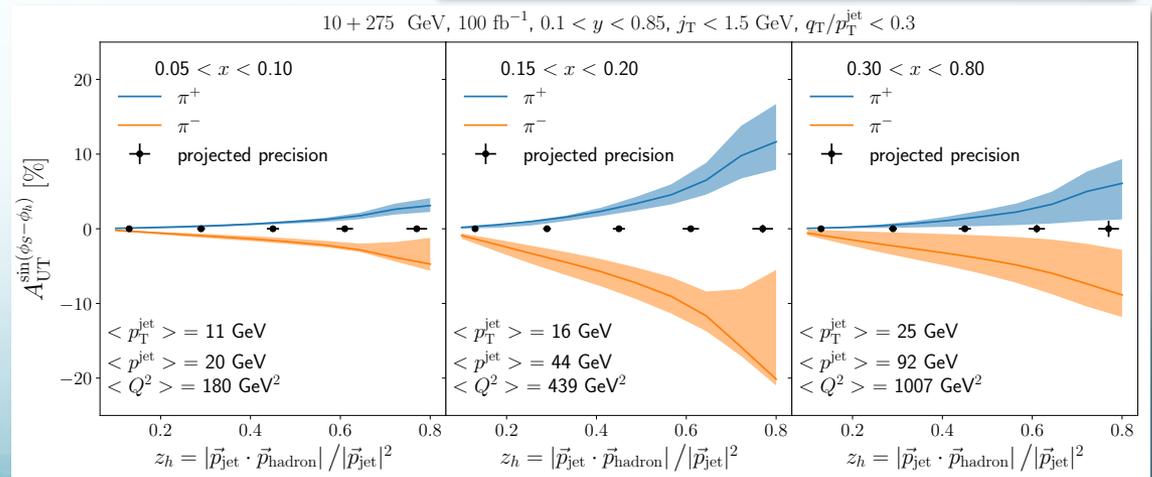
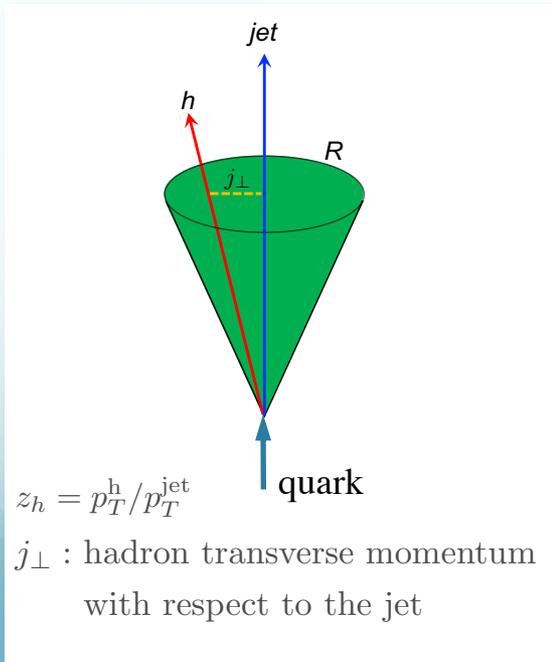
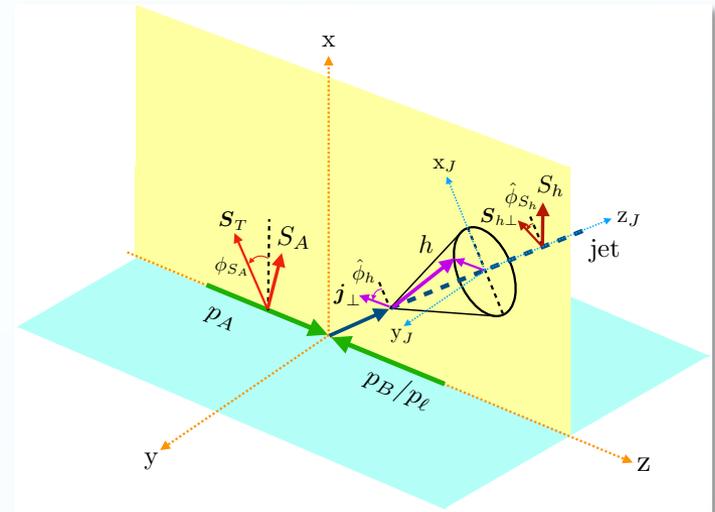


Kang, Liu, Mantry, Shao, PRL, 20

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

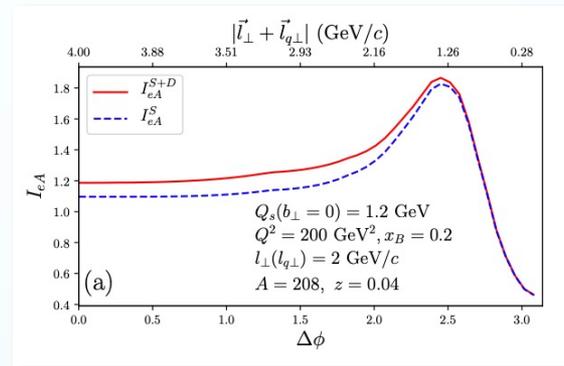
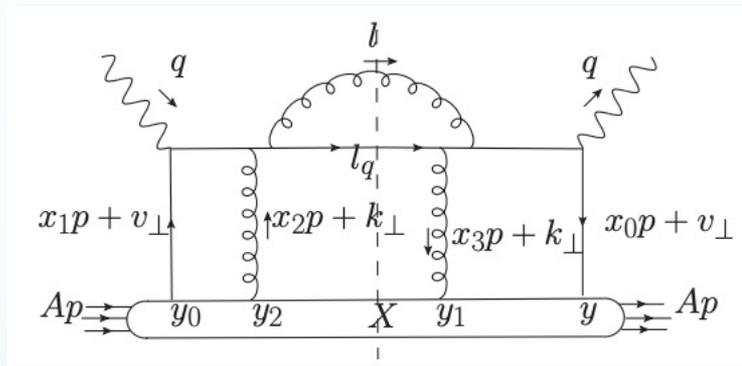
Kang, Lee, Zhao, PLB 20
Kang, Lee, Shao, Zhao, JHEP 21



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



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

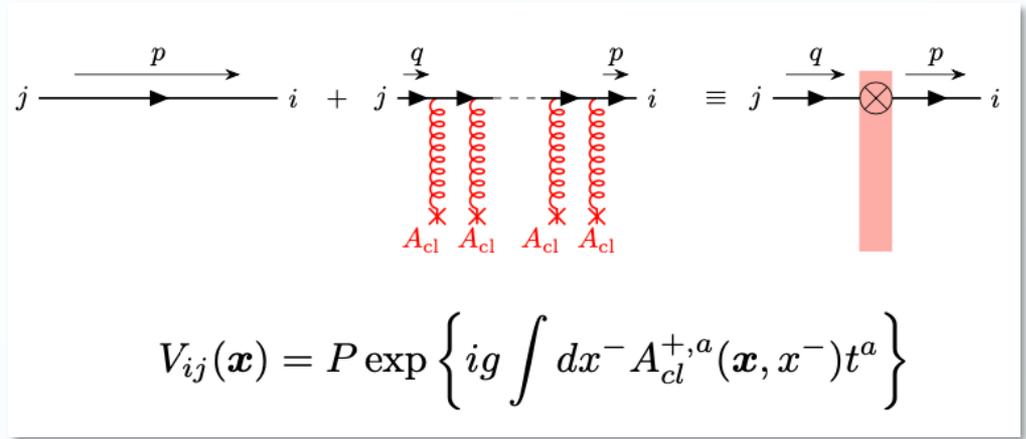
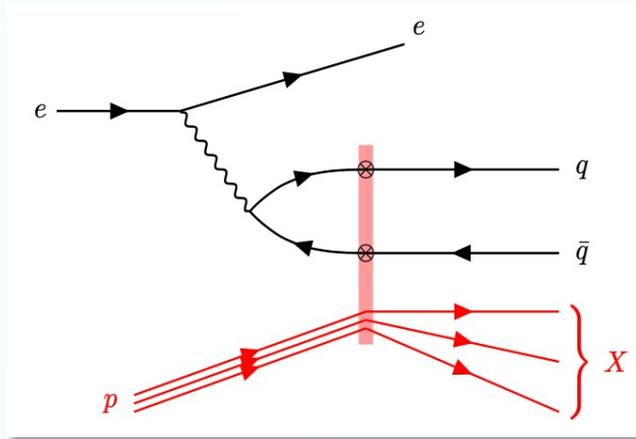
$$\times \rho_A(y_0^-, b_\perp) \rho_A(y_1^-, b_\perp) q_N(x_B, \vec{v}_\perp, b_\perp) \frac{\phi_N(x_G, \vec{k}_\perp)}{k_\perp^2} \left[\mathcal{N}_g^{\text{qLPM}} + \mathcal{N}_g^{\text{gLPM}} + \mathcal{N}_g^{\text{nonLPM}} \right].$$

Jet production in CGC

- NLO computations just started in very recently

Dominguez, Marquet, Xiao, Yuan, 2011

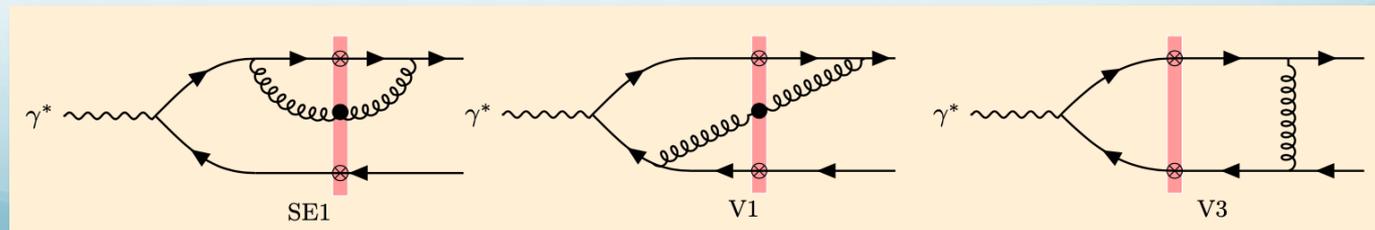
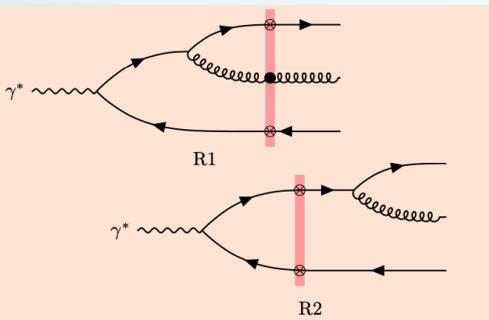
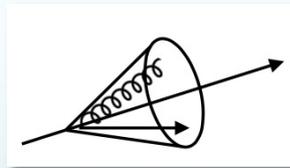
- LO available in 2011
- LO had no jet structure



- NLO available in 2021

Caucal, Salazar, Venugopalan, JHEP, 2021

- Jet algorithm is simplified



Jet production in p+A

Jet algorithm

Liu, Xie, Kang, Liu, 2204.03026, JHEP, in press, 22

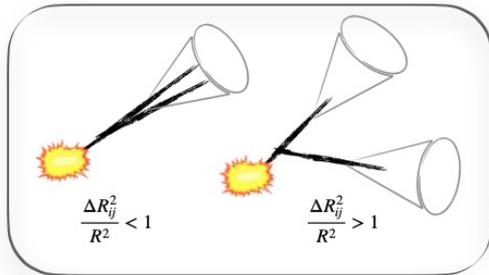
- Properly handle jet algorithm on top of complicated CGC computations
- Study its small- R approximation: factorized into a semi-inclusive jet function
- Can be readily used for jet production in e+A: also [jet substructure](#)

anti- k_T Cacciari, Salam, Soyez, 2008

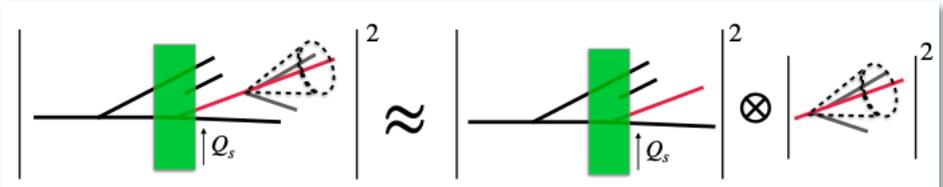
- If ρ_{ij} is the smallest, combine i and j
- If ρ_i is the smallest, promote i as a jet candidate and remove from the list
- Do recursively

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

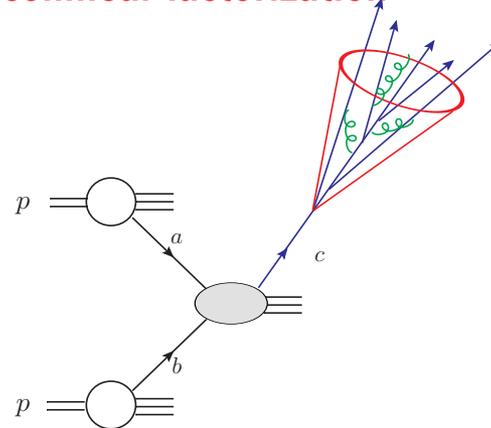
$$\Delta R_{ij}^2 = \Delta\phi_{ij}^2 + \Delta\eta_{ij}^2$$



CGC factorization in small R



collinear factorization



Kang, Ringer, Vitev, JHEP, 2016

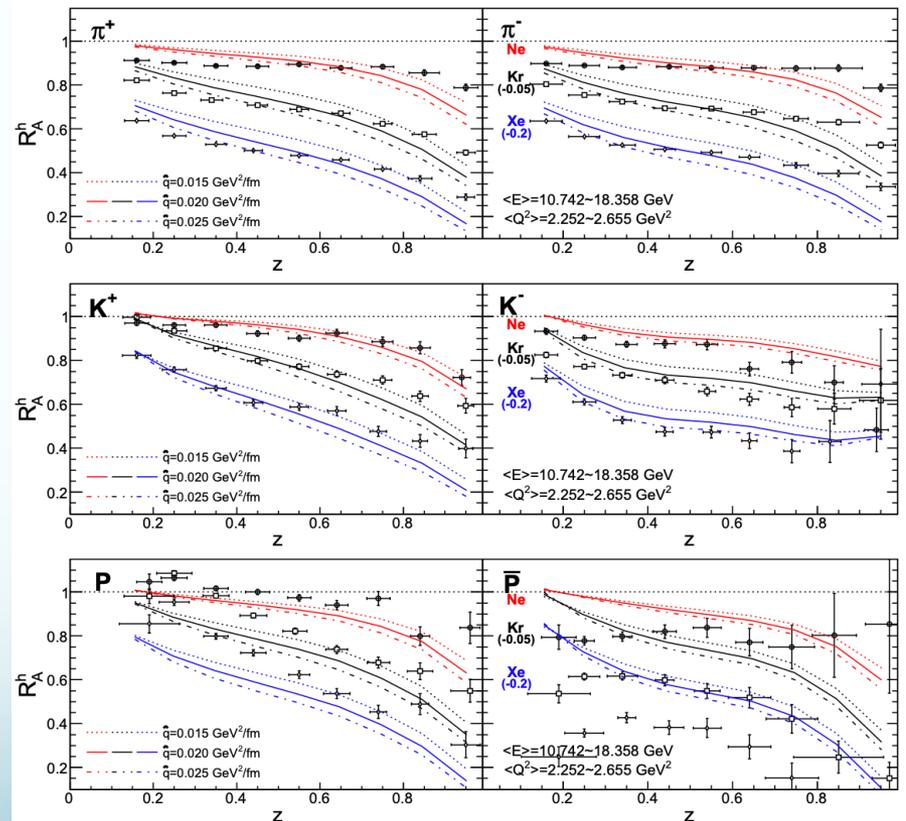
$$\frac{d\sigma^{pp \rightarrow \text{jet} X}}{dp_T d\eta} \sim f_a \otimes f_b \otimes H_{ab \rightarrow c} \otimes J_c(z, p_T R, \mu)$$

Jets in cold nuclear matter

- The early HERMES data: hadron multiplicity modification
 - Modified fragmentation function in medium Chang, Deng, Wang, 2014, PRC

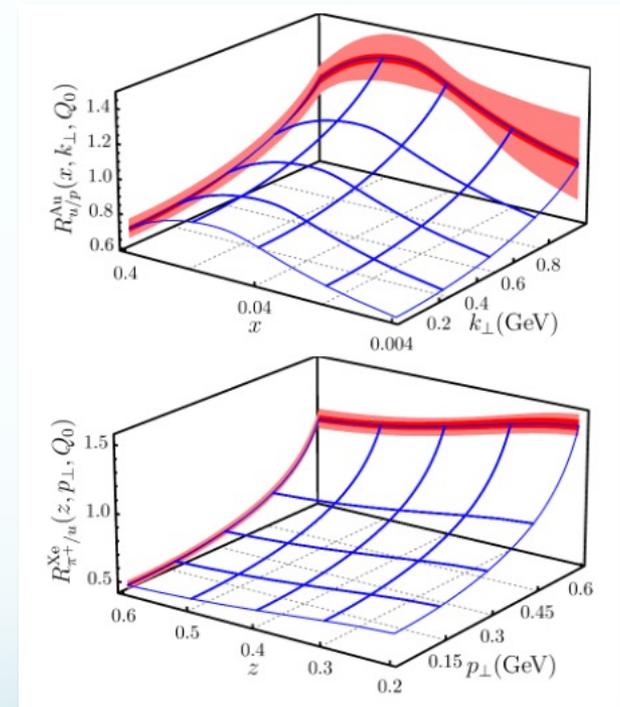
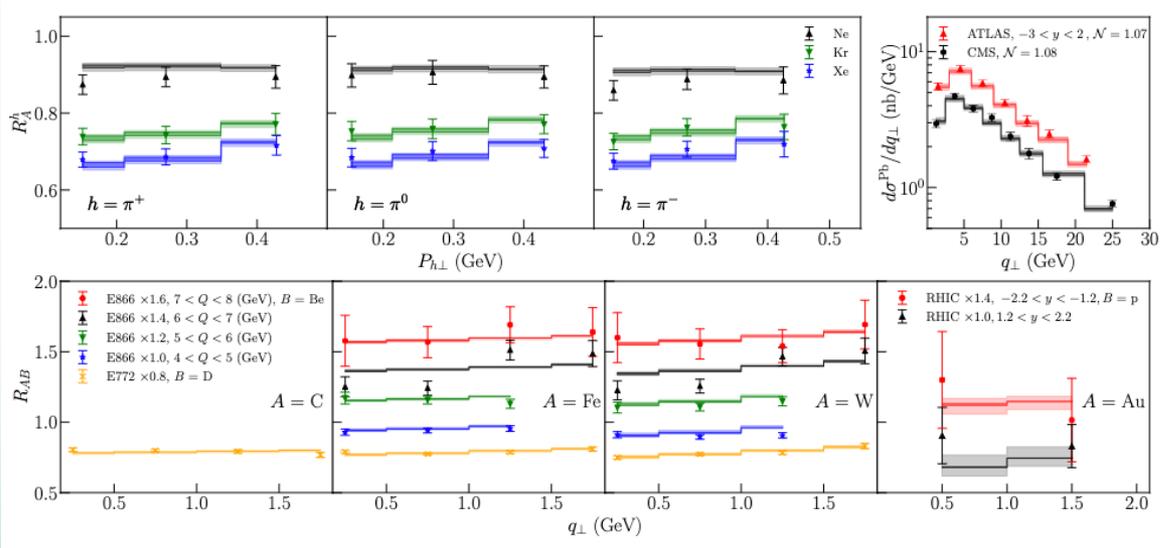
$$R_A^h(z, \nu) = \left(\frac{N^h(z, \nu)}{N^e(\nu)} \Big|_A \right) / \left(\frac{N^h(z, \nu)}{N^e(\nu)} \Big|_D \right)$$

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



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
 - Use the same TMD factorization for hadron production in e+A, except replacing with nuclear TMDs [via broadening parameters]

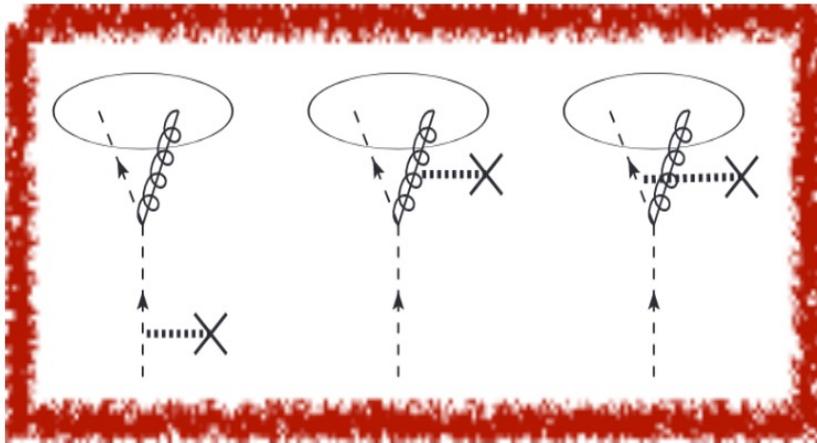
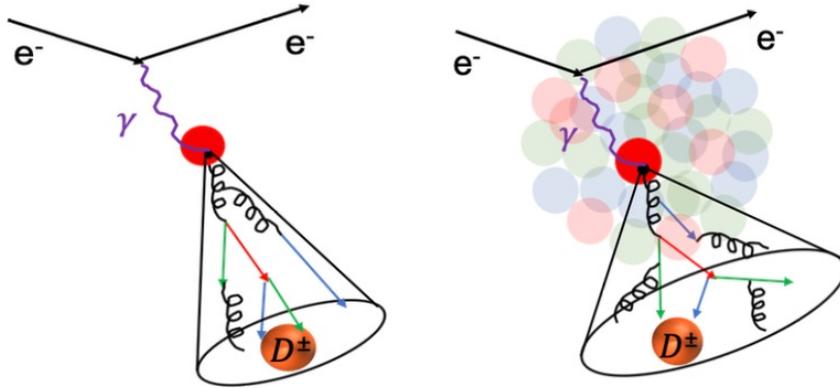


Alrashed, Anderle, Kang, Terry, Xing, 2021

Jet modification in e+A

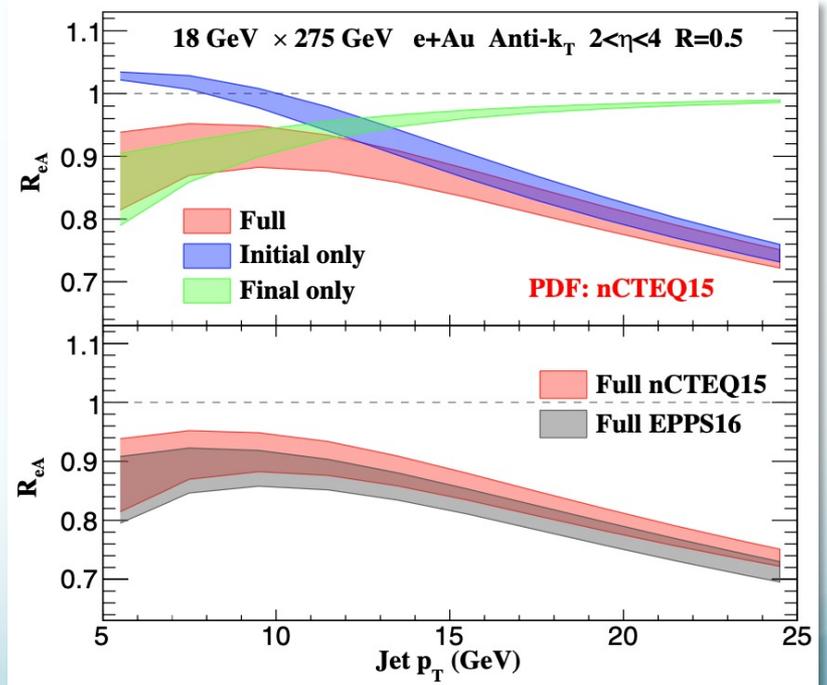
- Similar formalism in A+A applied to e+A collisions

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



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

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

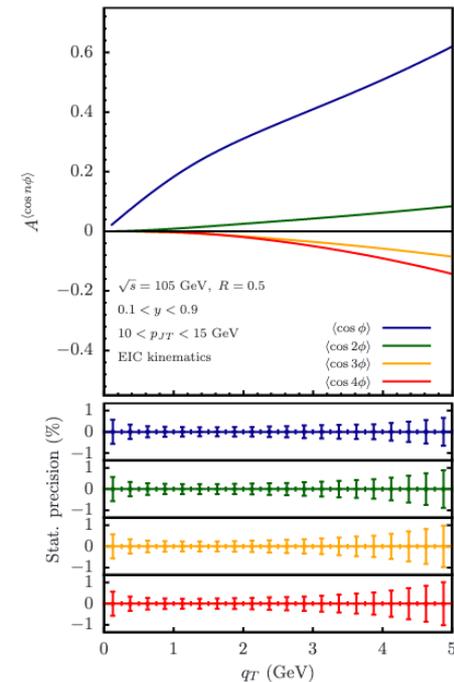
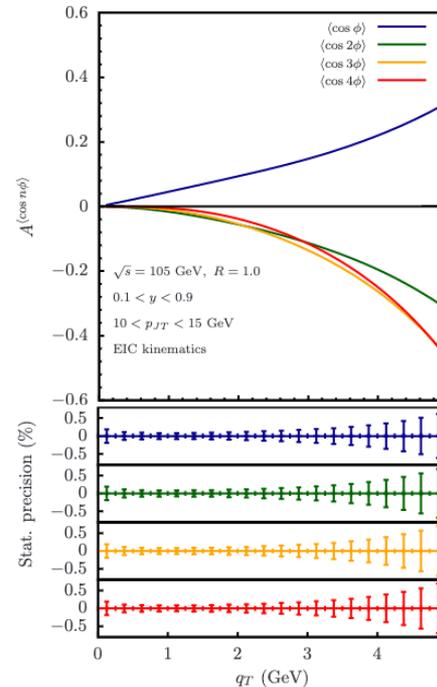
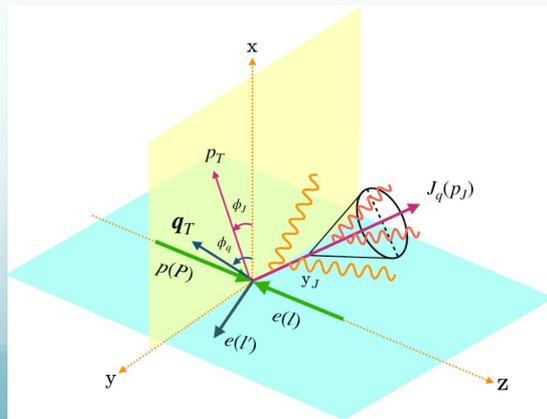
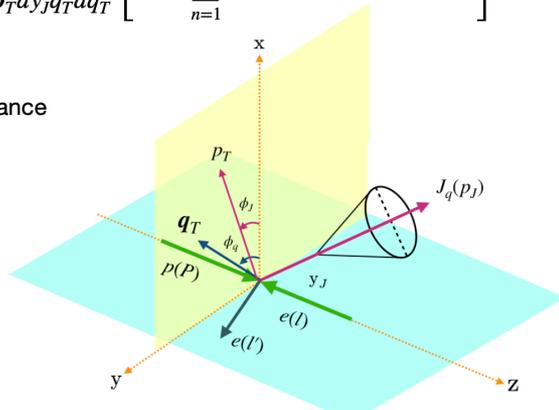
$$\frac{d\sigma}{d^2\mathbf{p}_T dy_J d\phi_J d^2\mathbf{q}_T} = \frac{d\sigma}{2\pi d^2\mathbf{p}_T dy_J q_T dq_T} \left[1 + 2 \sum_{n=1}^{\infty} v_n(p_T, y_T) \cos(n(\phi_q - \phi_J)) \right]$$

q_T : transverse momentum imbalance

$$\mathbf{q}_T = \mathbf{l}'_T + \mathbf{p}_{JT}$$

p_T : jet transverse momentum

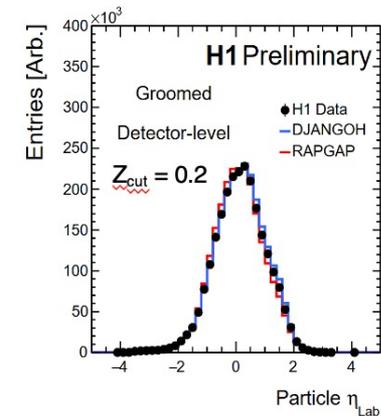
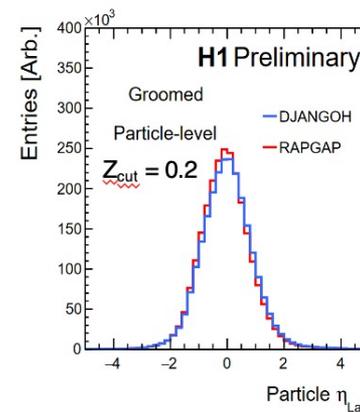
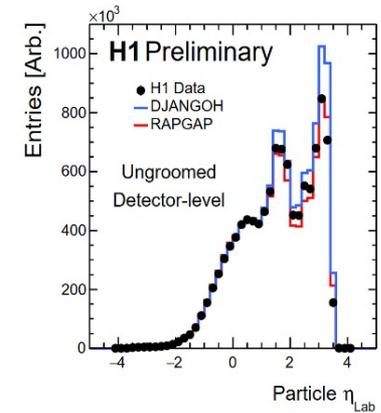
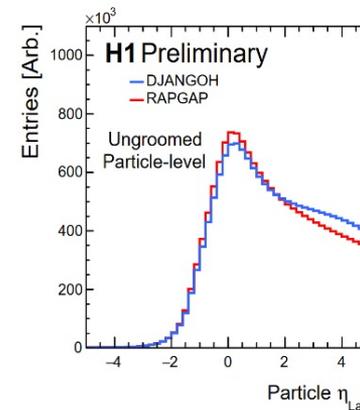
y_J : jet rapidity



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

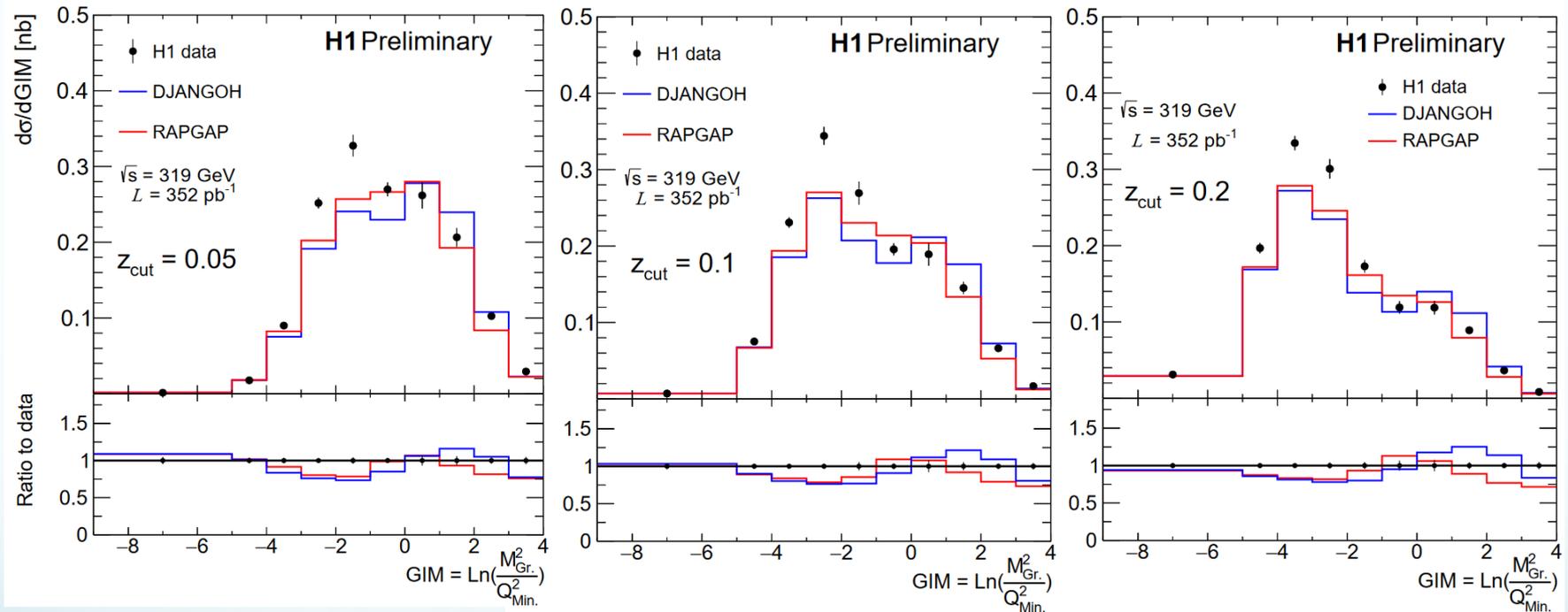
Grooming Benefits

- 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

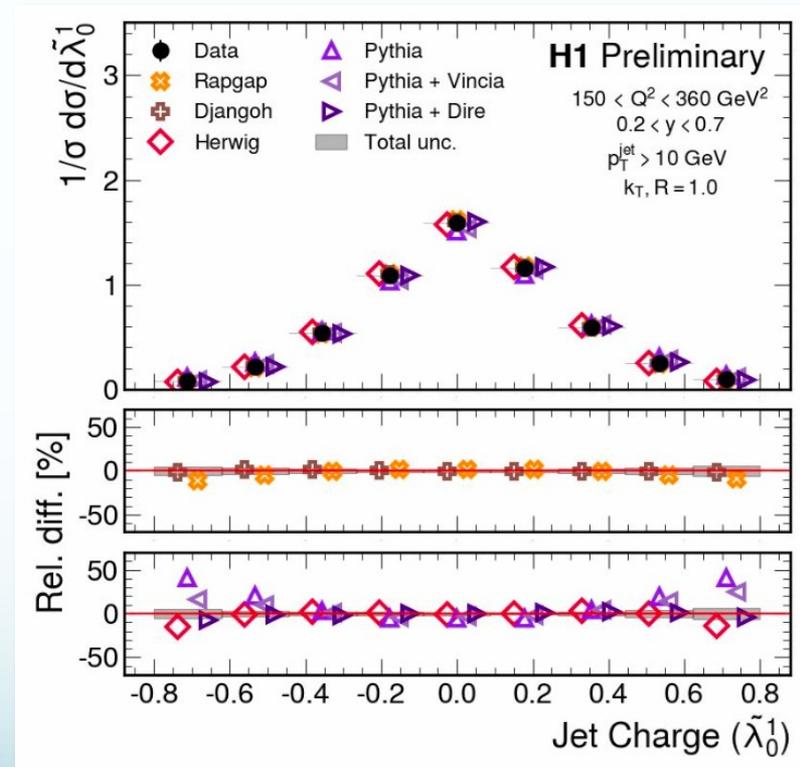
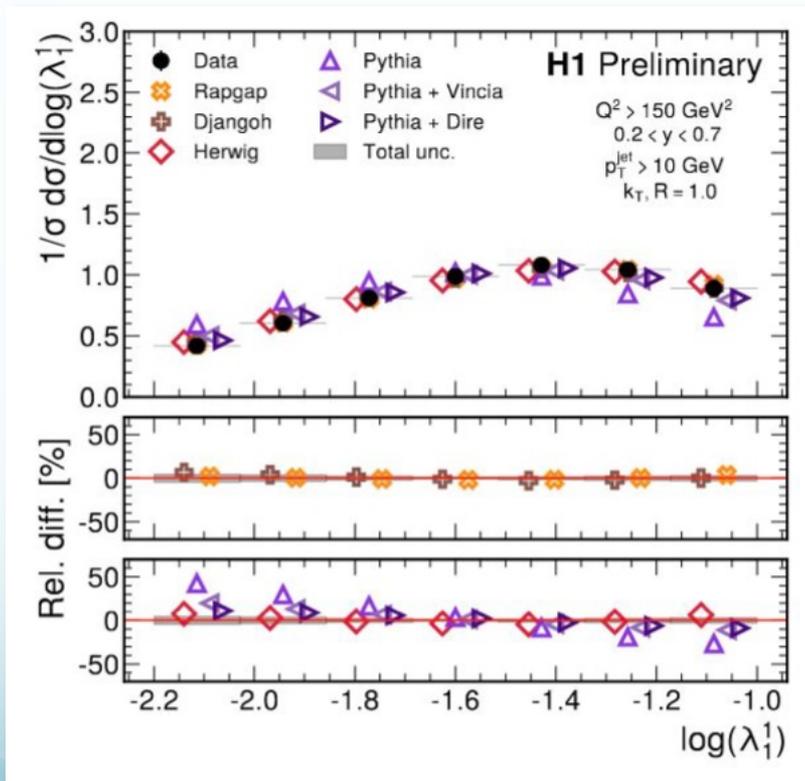


Klest, June 8

Jet angularity

- Recent measurement on jet angularity

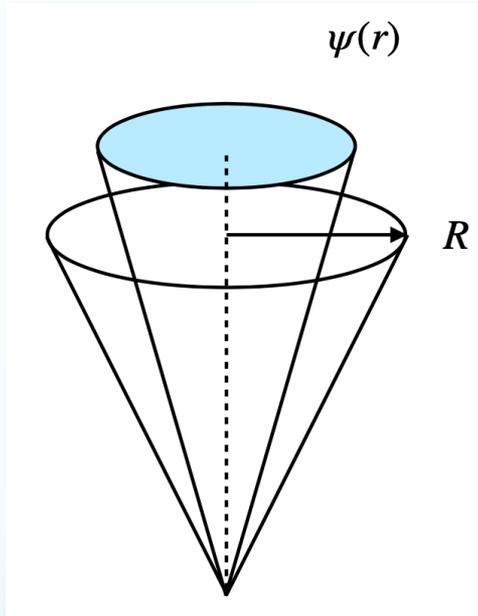
$$\lambda_{\beta}^{\kappa} = \sum_{i \in \text{jet}} z_i^{\kappa} \left(\frac{R_i}{R_0} \right)^{\beta} \quad \tilde{\lambda}_0^{\kappa} = Q_{\kappa} = \sum_{i \in \text{jet}} q_i \times z_i^{\kappa}$$



Mikuni, Nachman, June 8

Jet shape

- Jet shape at the EIC



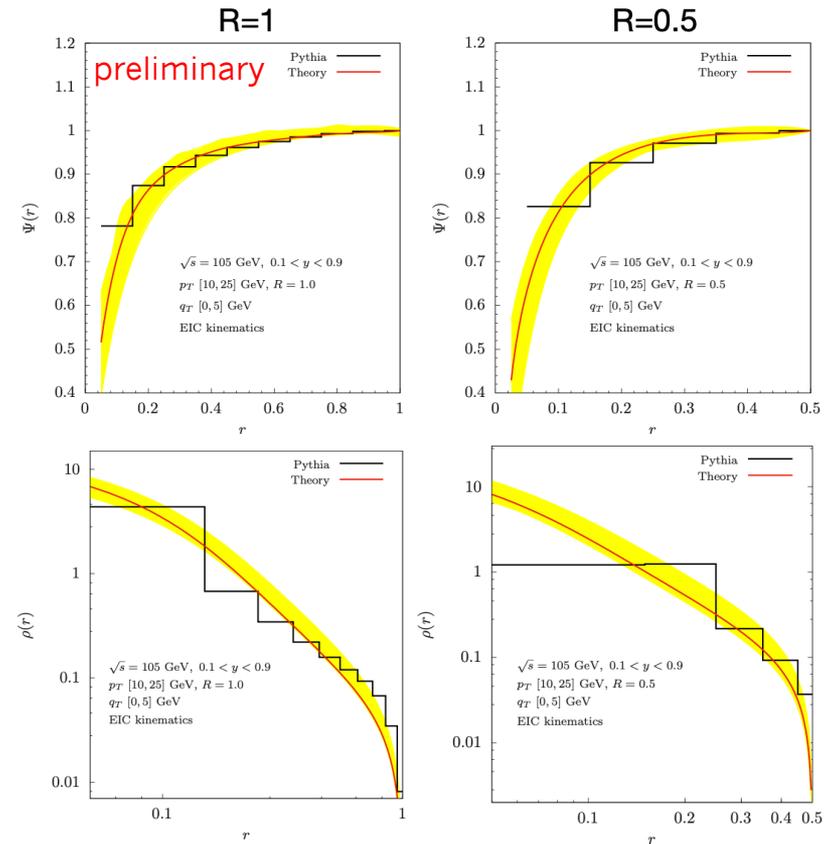
EIC kinematics

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:

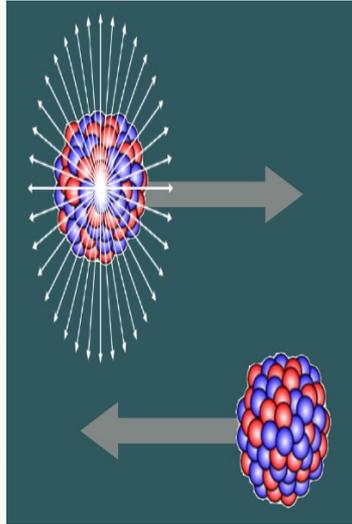
$$\rho(r) = \frac{d\psi(r)}{dr}$$



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

UPC vs EIC

- Could UPC help jet physics at EIC?



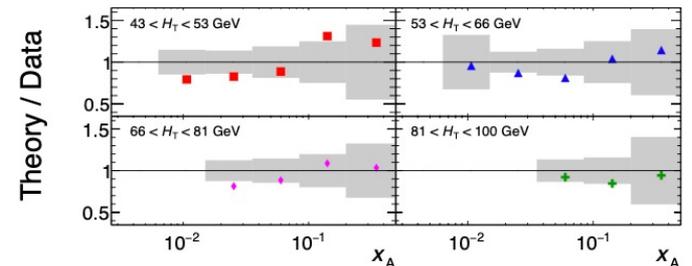
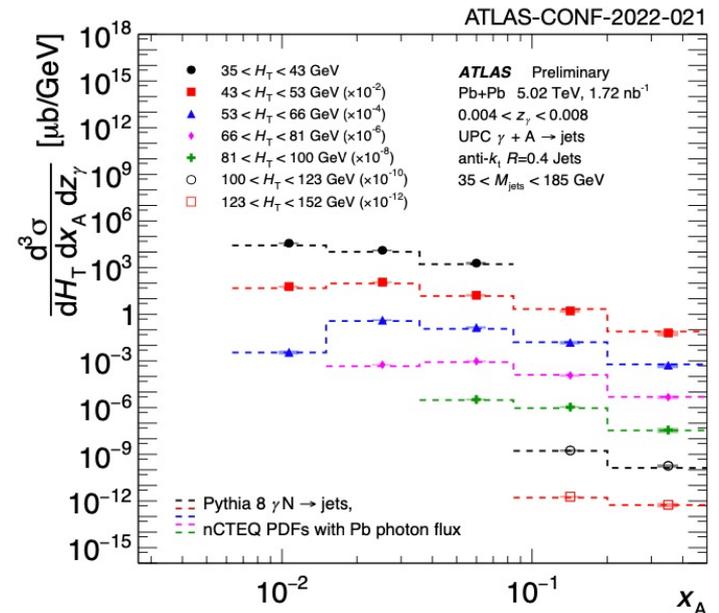
ATLAS: Triple differential UPC dijets

- Use ZDC as part of primary trigger
 - Require gaps to ensure photonuclear topology
- Use jets to define kinematic variables akin to DIS variables

$$H_T \equiv \sum_i p_T^i \quad x_A \equiv \frac{M_{jets} e^{-y_{jets}}}{\sqrt{S_{NN}}} \quad z_\gamma \equiv \frac{M_{jets} e^{+y_{jets}}}{\sqrt{S_{NN}}}$$

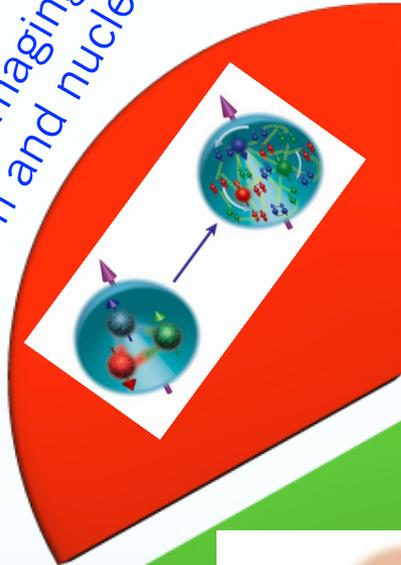
“Q²” “xy”

- Selections on z_γ to minimize acceptance affects
- Triple differential cross sections can be compared to Pythia8 using nCTEQ PDFs
 - Reweighted Pb photon flux
 - Modeled correction to account for requiring Xn0n
- Results not yet finalized, but offer prospects for first detailed direct studies of nPDFs

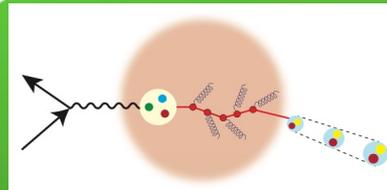
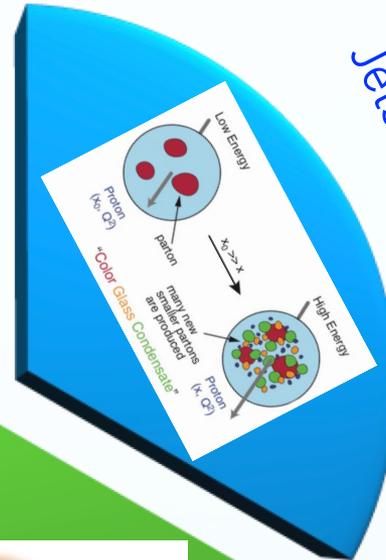


Summary: jets are powerful tools

Quantum imaging of
proton and nuclei



Jets for CGC



Jet propagation in nuclei

Thank you!