Jet Physics at the EIC

Zhongbo Kang
UCLA

@ZhongboK

California EIC Consortium Collaboration Meeting
July 18, 2022

UCLA QCD Theory Group

- 1 faculty, 3 postdocs, 4 graduate students, ~ 10 undergrads

We love joint/collaborative efforts

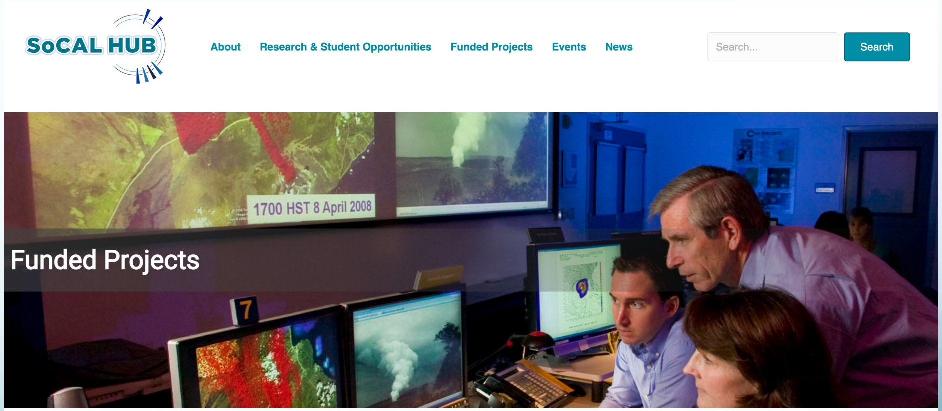
- Joint with LBNL
  - joint postdoc: Farid
  - Future joint postdoc: if funded by DOE topical collaboration
  - Integrated into their weekly seminar (HIT, nuclear theory)

- Efforts with LANL/LLNL
  - Collaboration with Vincent, Ramona
  - Project Scientist: possibility to hire a project scientist

Title of the research proposal: **SURGE -** Saturated Glue Topical Theory Collaboration

Principal investigator: Björn Schenke
Brookhaven National Laboratory

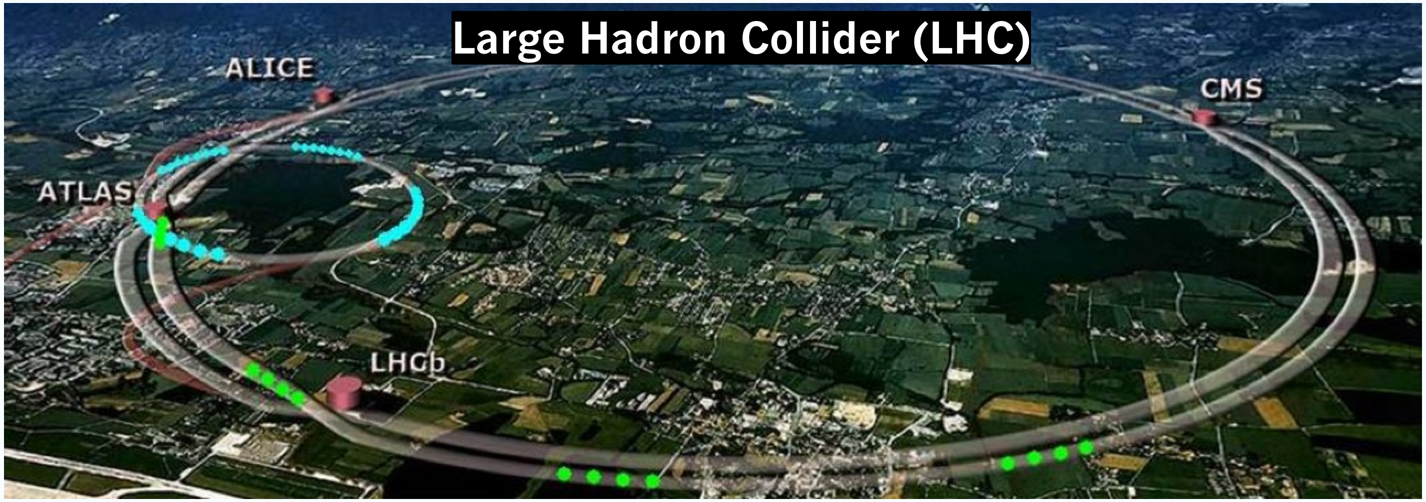
Senior personnel:
Y. Hatta, Y. Mehtar-Tani, S. Mukherjee, P. Petreczky, B. Schenke, R. Venugopalan (Brookhaven National Laboratory)
A. Stasto (Penn State University)
I. Balitsky (Thomas Jefferson Laboratory / Old Dominion University)
S. Caron-Huot (McGill University)
A. Dumitru, J. Jalilian-Marian (CUNY, Baruch College)
Z. Kang (University of California, Los Angeles)
D. Kharzeev (Stony Brook University / Brookhaven National Laboratory)
Y. Kovchegov (The Ohio State University)
A. Kovner (University of Connecticut)
D. Neill (Los Alamos National Laboratory)
J. Noronha-Hostler (University of Illinois at Urbana Champaign)
F. Olness (Southern Methodist University)
D. Pitonyak (Lebanon Valley College)
P. Shanahan (Massachusetts Institute of Technology)
M. Sievert (New Mexico State University)
V. Skokov (North Carolina State University)
X.-N. Wang (Lawrence Berkeley National Laboratory)

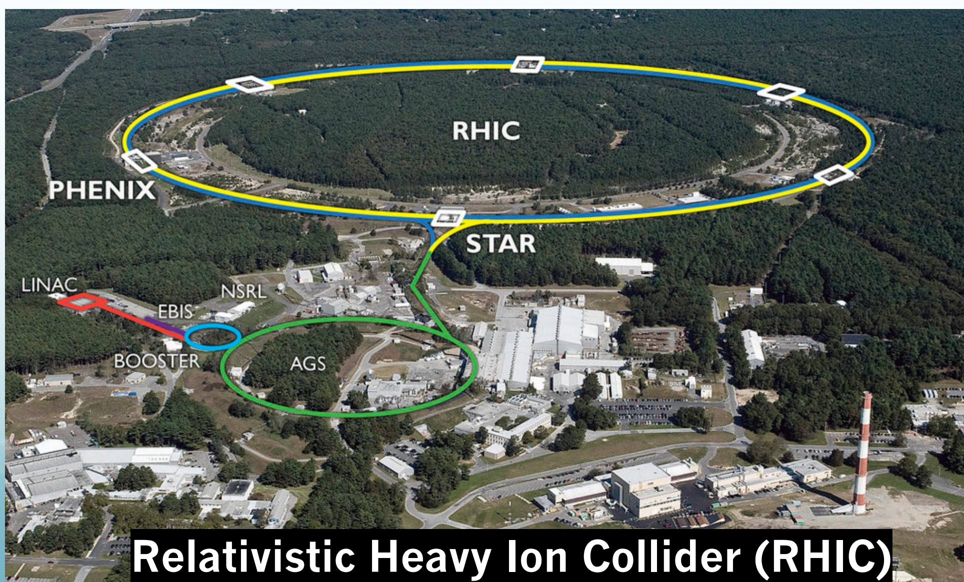


Our Cal-Bridge EIC scholars

- Grace Garmire (Cal Poly SLO)
  - Mentors: Zhongling, Ryan, Ernst, Zhongbo, Huang, Jennifer
  - Jets for 3D imaging type
- Jeisson Pulido (CSU Dominguez Hills)
  - Mentors: Farid, John, Zhongbo
  - Jets for CGC type

Key facilities: LHC, RHIC, and EIC





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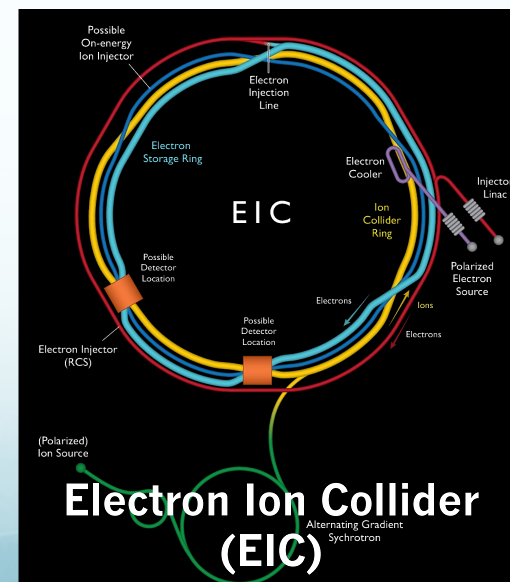


A recent CFNS jet workshop

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…

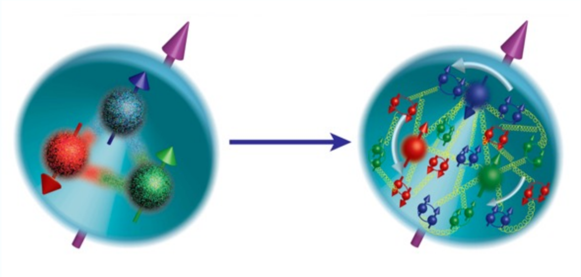
This event is part of the CFNS workshop/ad-hoc meeting series. See the CFNS conferences page for other events.

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.

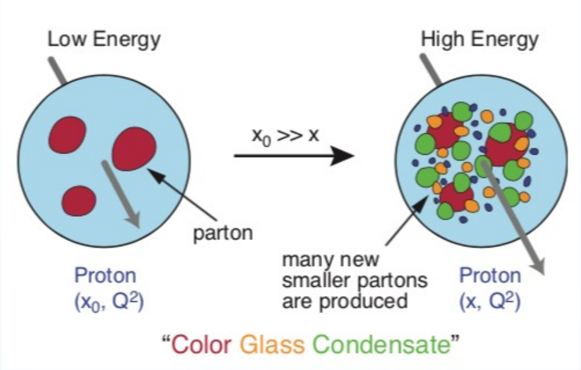
Jet studies have played a key role in the exploration of QCD since its conception. With the advances in experimental techniques and theory developments over time, jets have become powerful tools for QCD physics, such as exploring the fundamental properties and regimes of QCD and probing the cold and 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

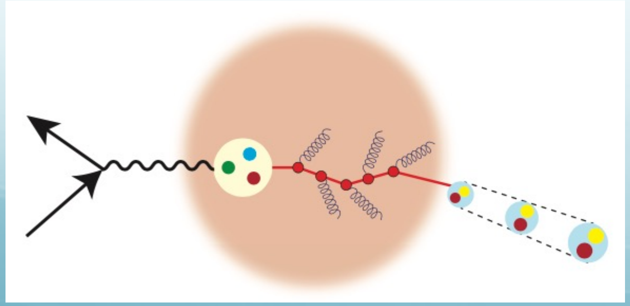
- Quantum Imaging of protons and nuclei



- A new form of matter - color glass condensate

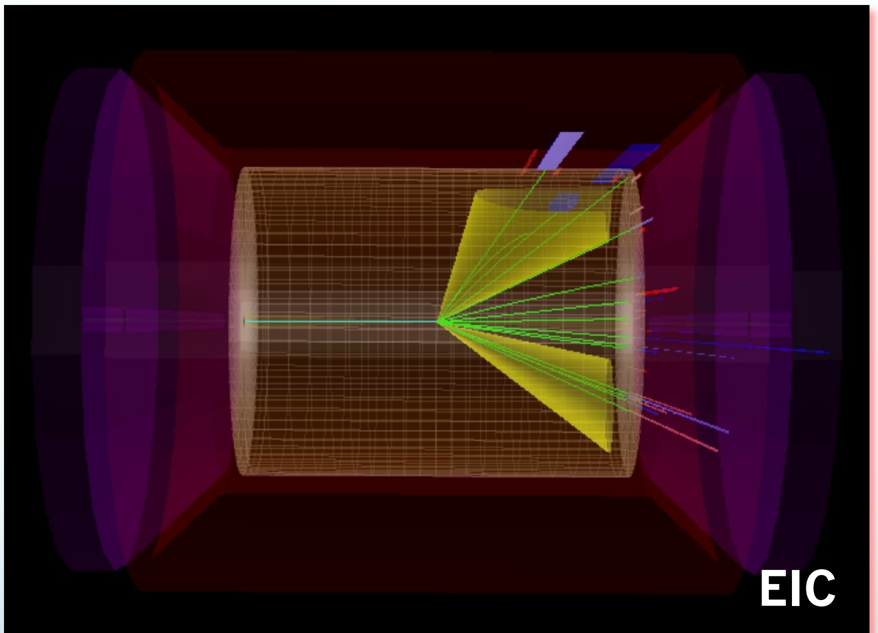


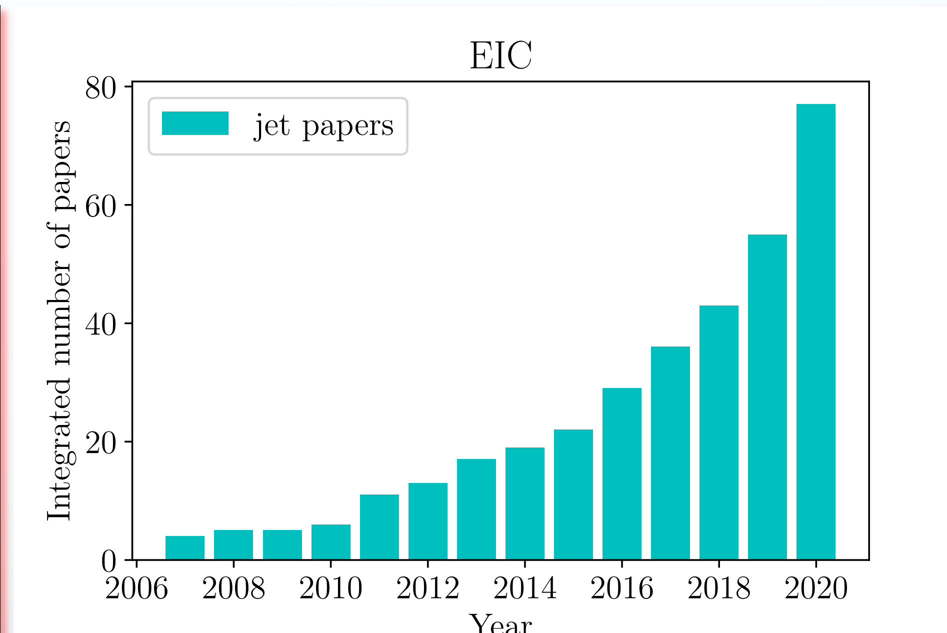
- Jet propagation in cold nuclear matter



Jets are useful tools in all three directions

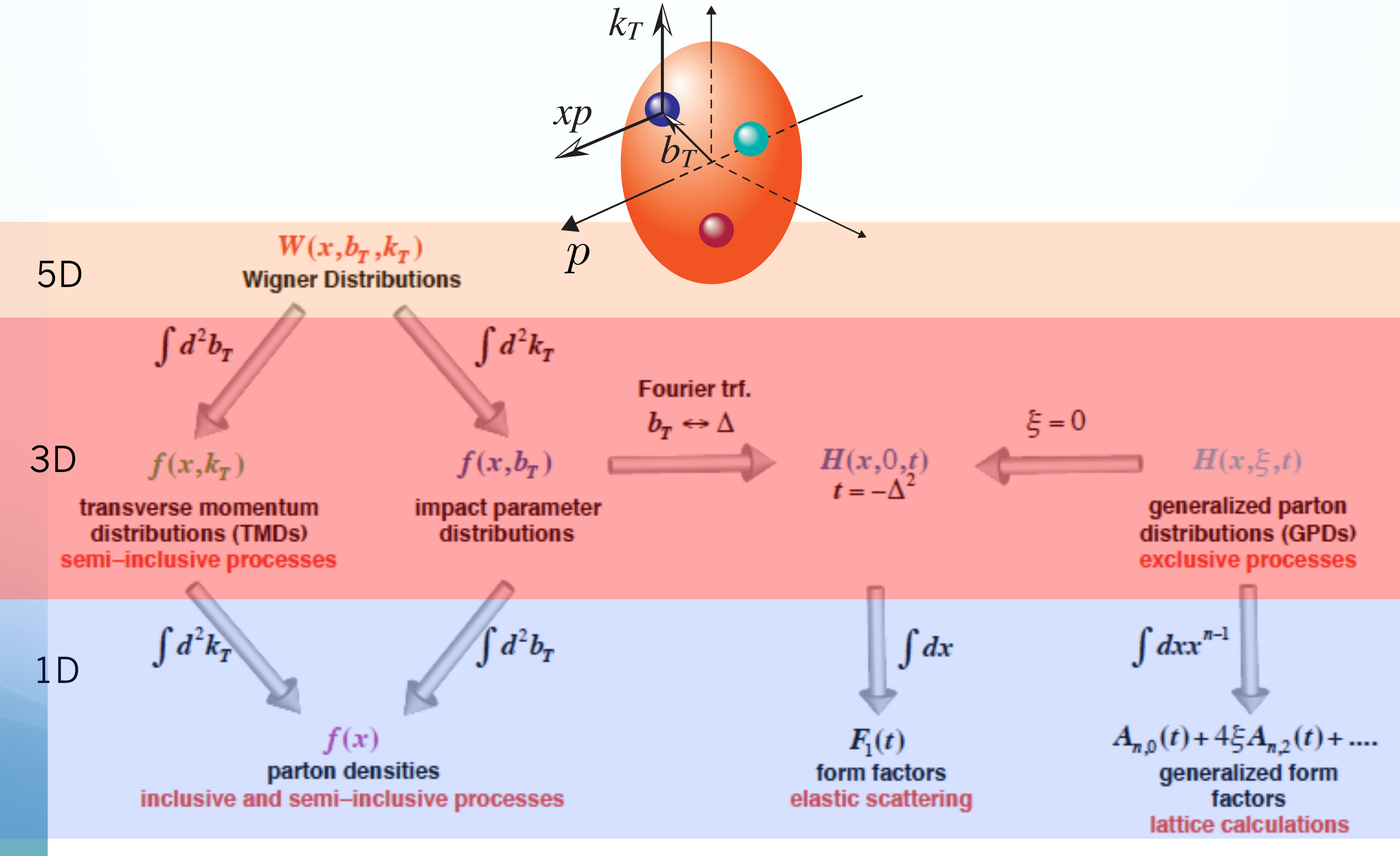
- Active study at the EIC
  - EIC jet papers grow exponentially





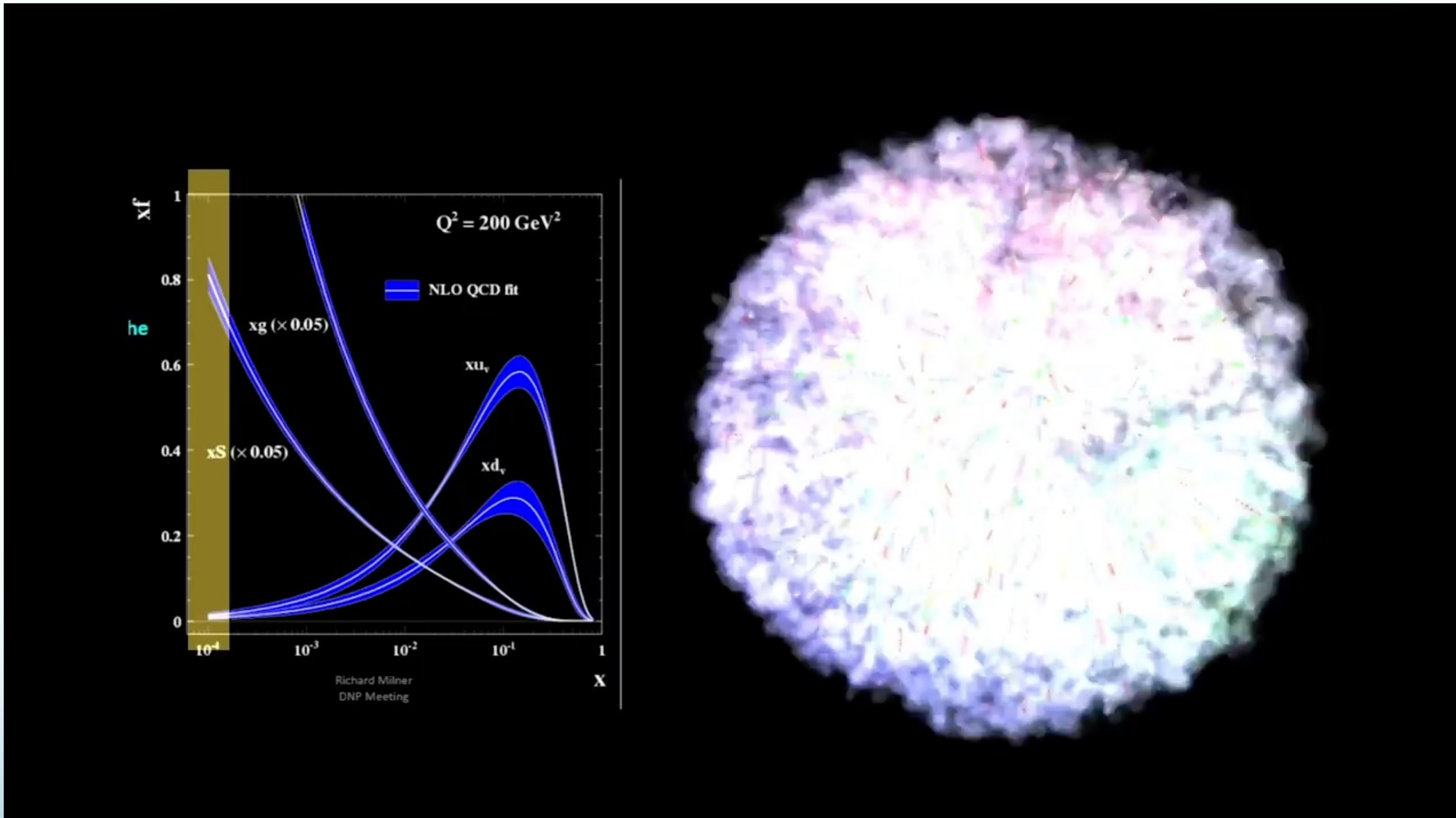
Jets for quantum imaging

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



1D: unpolarized PDFs

- Longitudinal motion

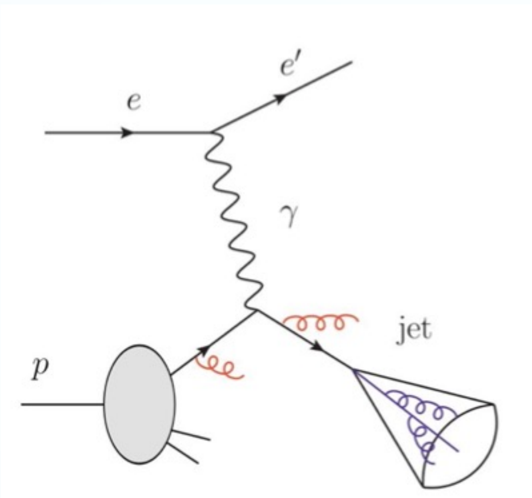


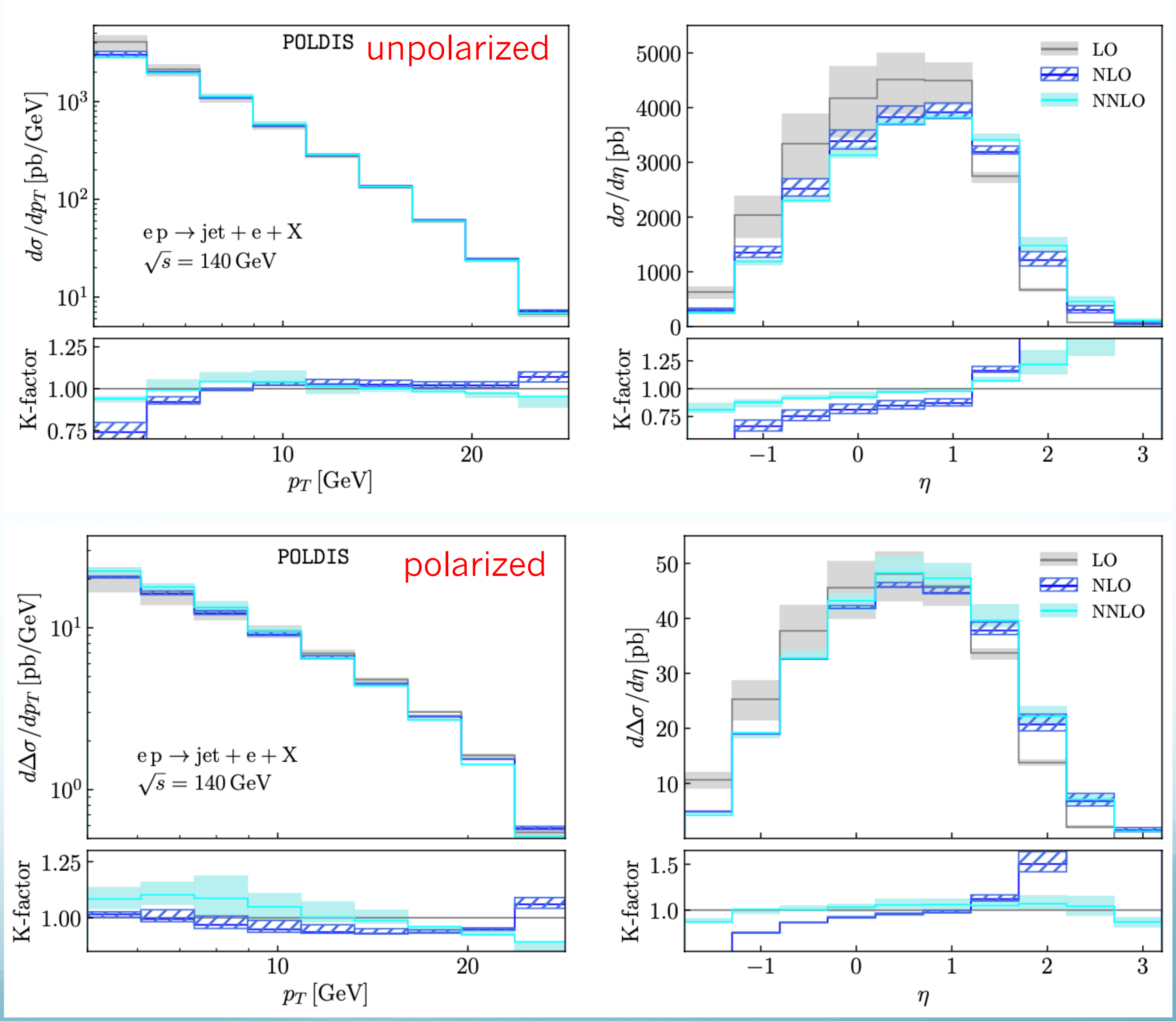
Physicist: Milner (MIT), Ent-Yoshida (Jlab), 04/2022
Documentary Filmmaker: Boebel-McMaster (MIT), LaPlante (Sputnik Animation)

Jet production in e+p collisions

- LO, NLO, NNLO frontiers

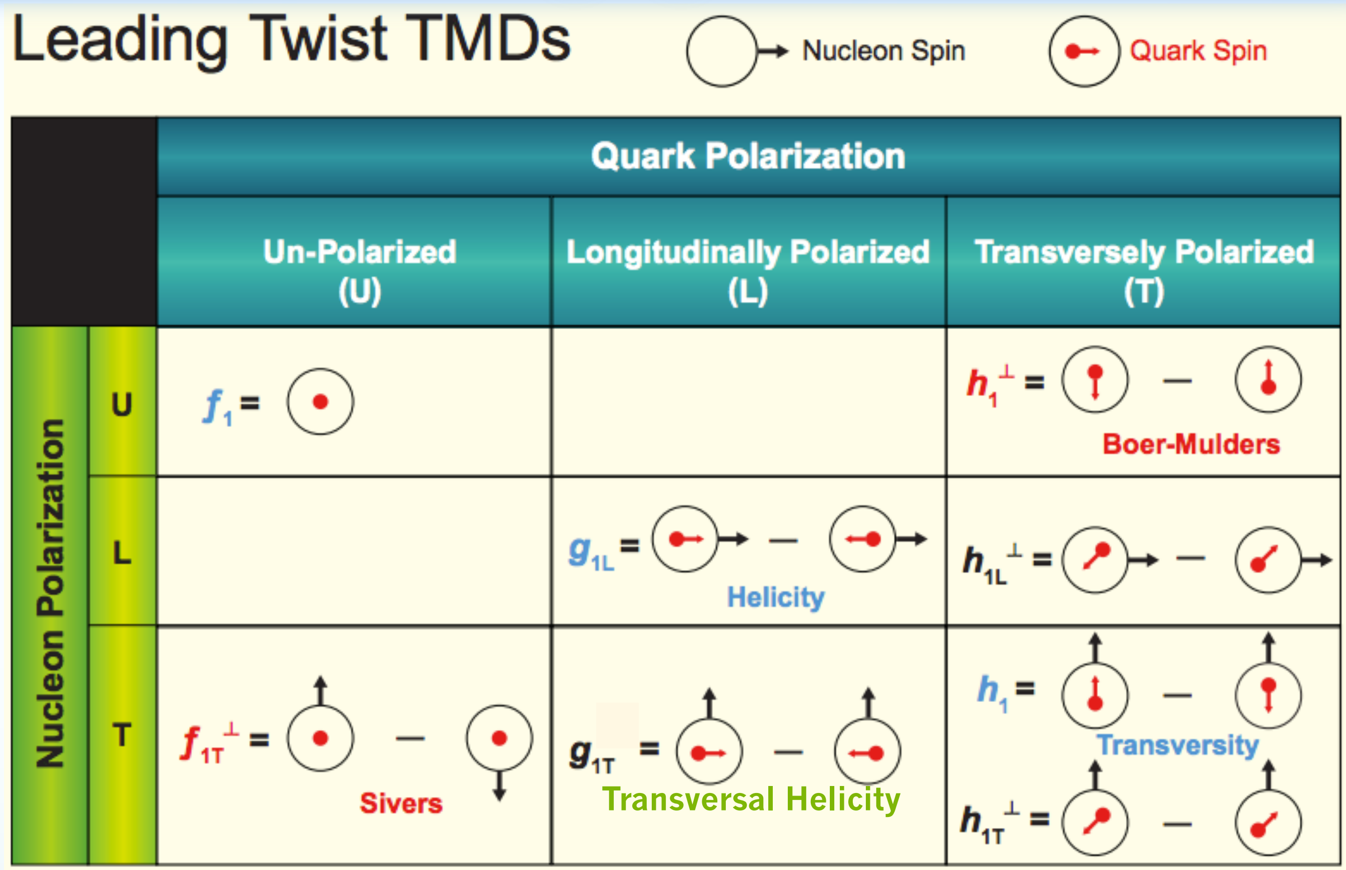
Borsa, de Florian, Pedron, PRL 20, PRD 21





Jets for 3D imaging: TMDs

TMD parton distribution

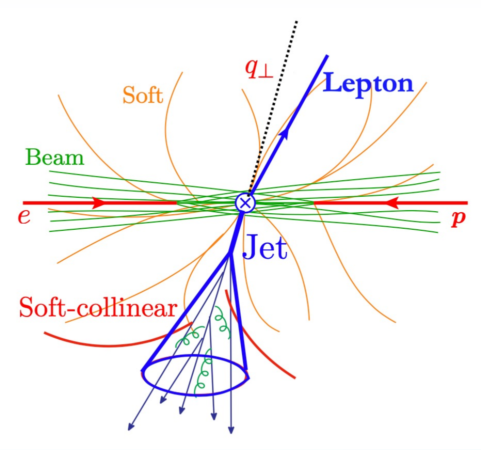


TMD fragmentation function

	Quark Polarization U	Quark Polarization L	Quark Polarization 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 $e + p \to e + \text{jet} + X$
  - Because of small imbalance, we are sensitive to small transverse momentum
  - We now have TMD PDFs + soft function



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

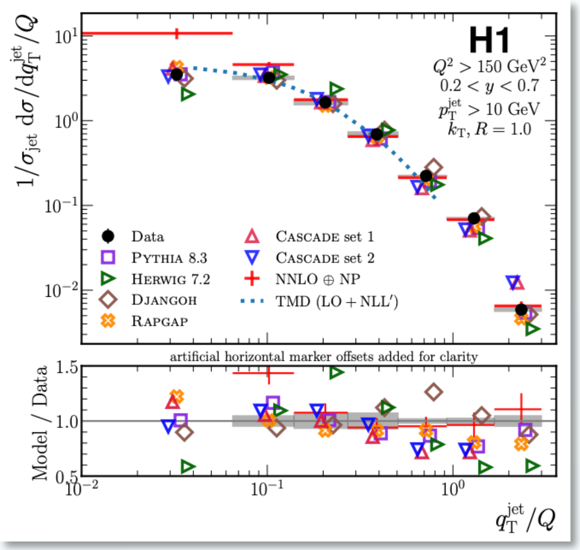
- Two soft functions
  - Global: can radiate everywhere
  - Collinear-soft: soft radiation inside jet does not affect imbalance

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

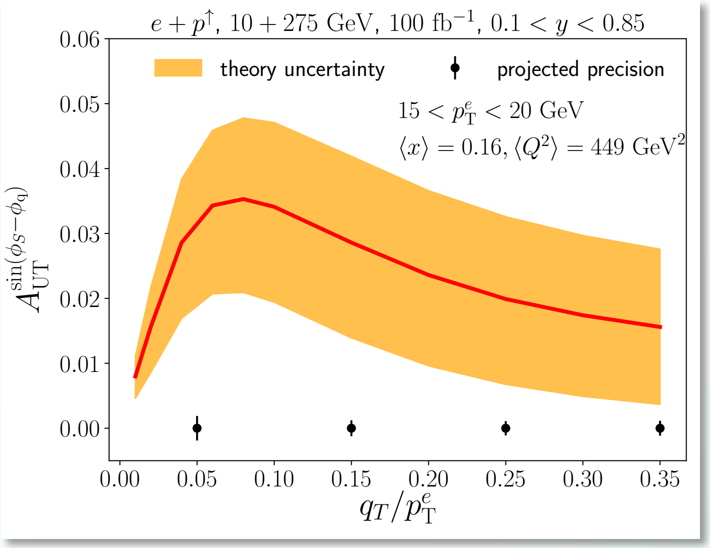
Jets for 3D imaging

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

HERA, arXiv:2108.12376, PRL 22



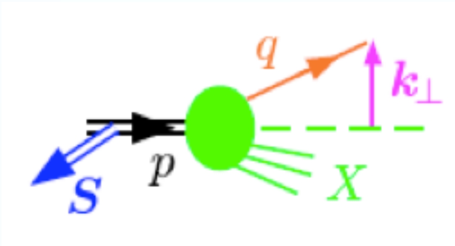
Arratia, Kang, Prokudin, Ringer, 2007.07281, PRD



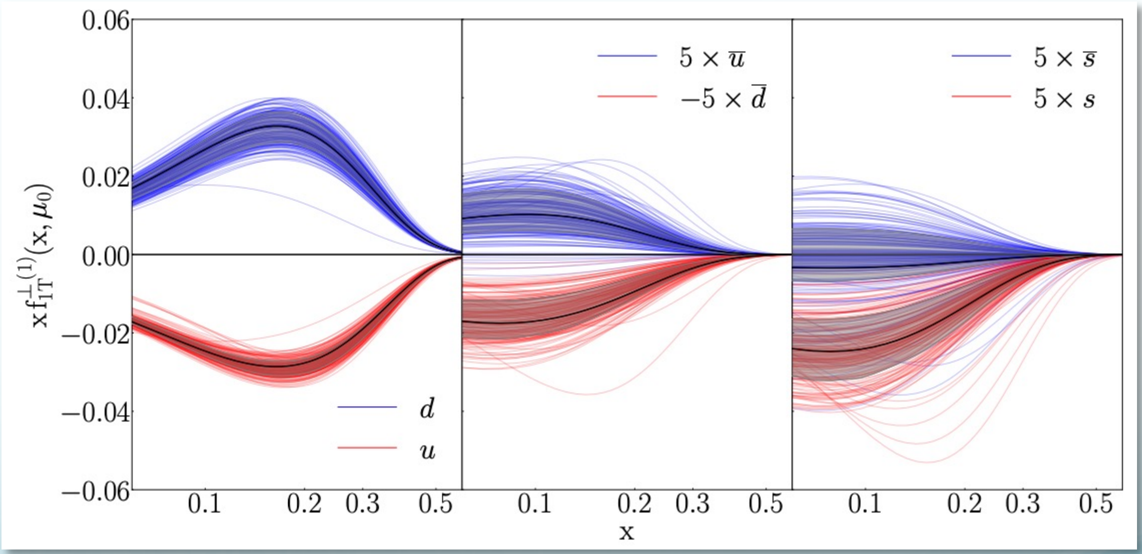
  - Transversely polarized proton scattering: Sivers function (right plot)

Jet charge

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



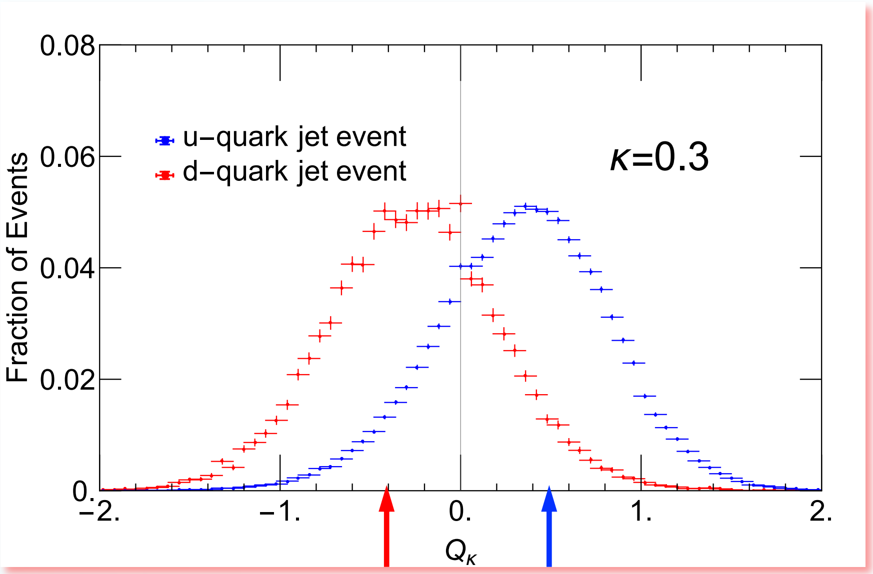
$$f_{q/h^\uparrow}(x,\mathbf{k}_\perp,\vec{S}) \equiv f_{q/h}(x,k_\perp) - \frac{1}{M} f_{1T}^{\perp q}(x,k_\perp)\,\vec{S}\cdot(\hat{p}\times\mathbf{k}_\perp)$$

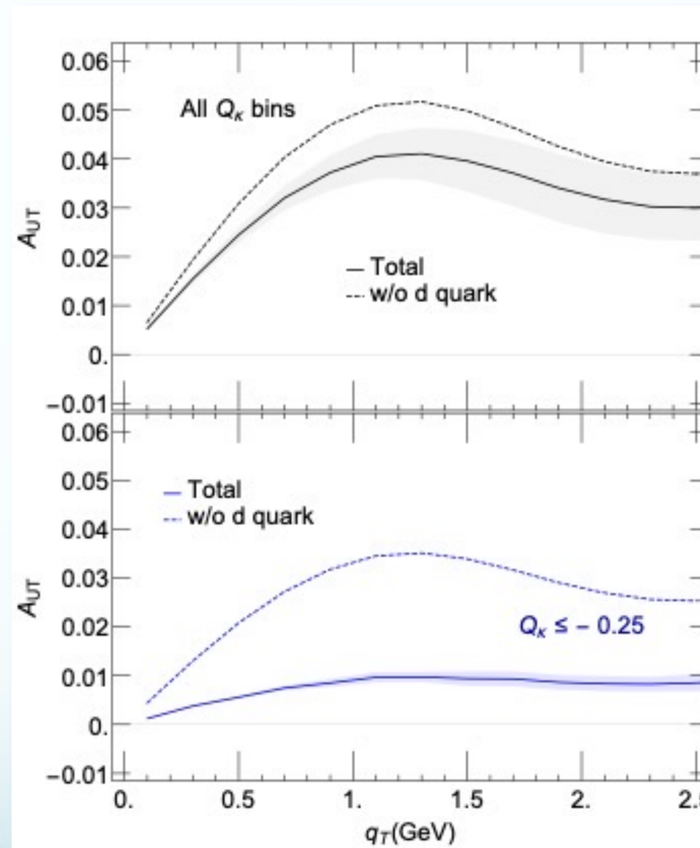


Echevarria, Kang, Terry, 2009.10710, JHEP (2021)

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





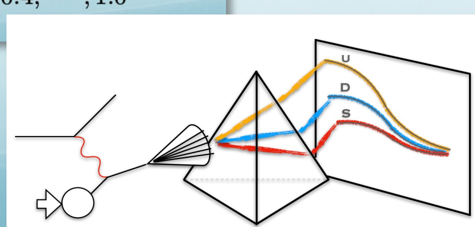
Jet charge definition

- A weighted sum of charges for hadrons inside the jet

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

Charge of the hadron

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

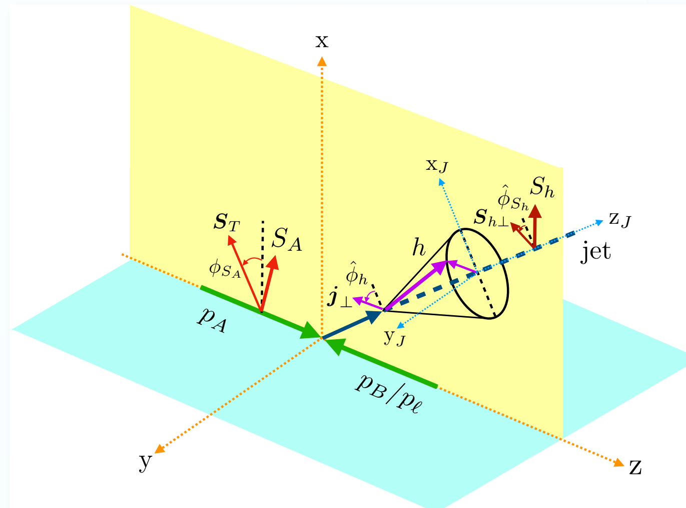


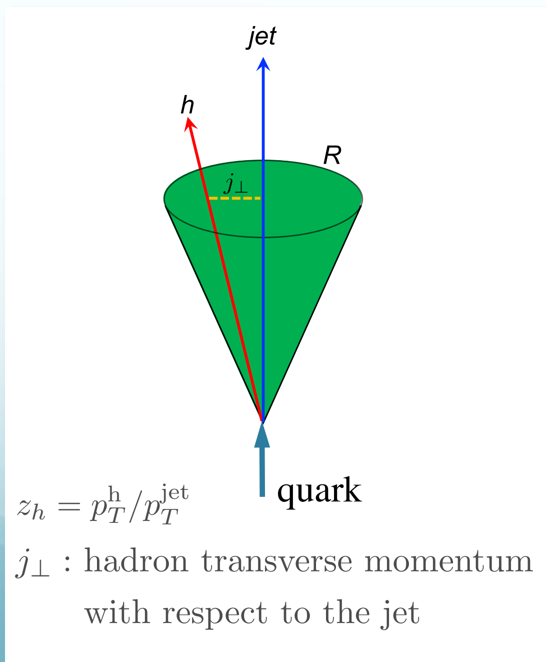
Kang, Liu, Mantry, Shao, PRL, 20

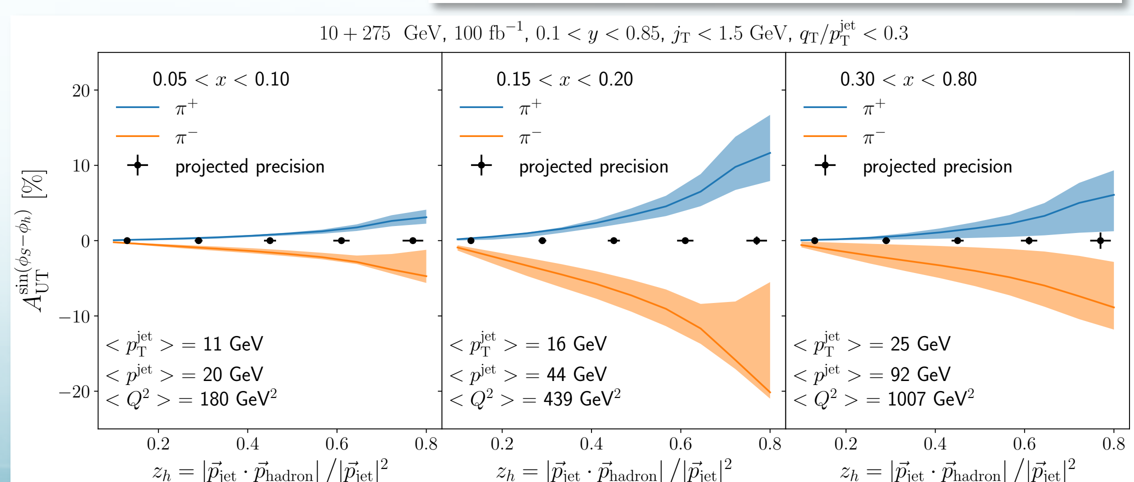
Jet substructure: polarized jet fragmentation function

- 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





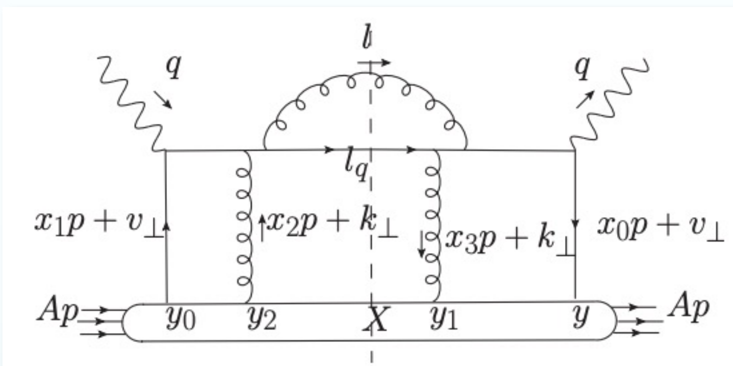


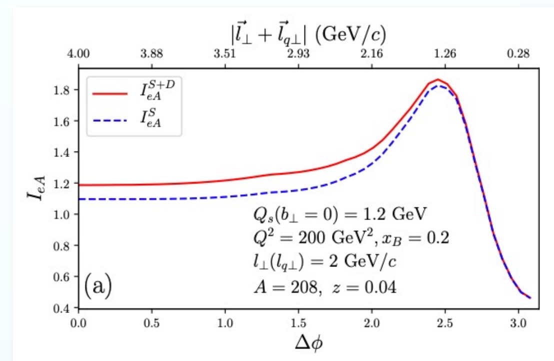
Jets for Color Glass Condensate

- 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

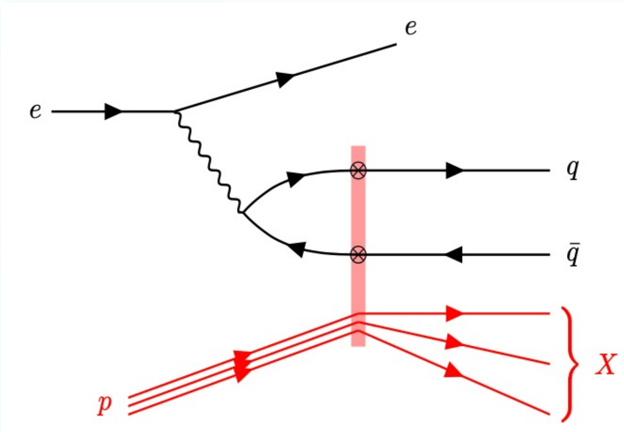


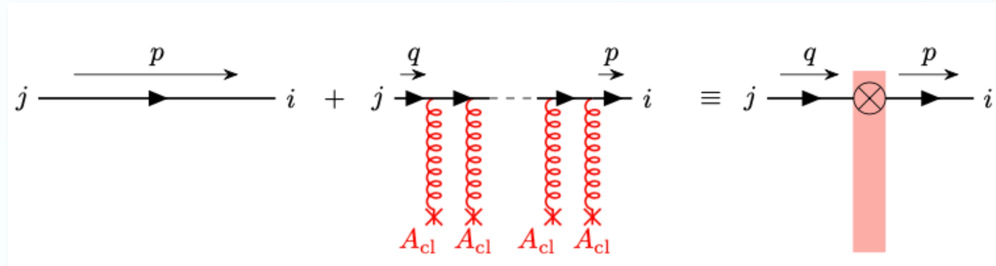


$$\frac{d\sigma_{eA}^{D}}{dx_B dQ^2 dz d^2l_\perp d^2l_{q\perp}} = \frac{2\pi\alpha_{em}^2}{Q^4}\sum_q e_q^2[1+(1-\frac{Q^2}{x_B s})^2]\frac{\alpha_s}{2\pi}\frac{1+z^2}{1-z}\frac{2\pi\alpha_s}{N_c}\int\frac{d^2k_\perp}{(2\pi)^2}\int d^2b_\perp dy_0^- dy_1^-$$
$$\times\rho_A(y_0^-, b_\perp)\rho_A(y_1^-, b_\perp)q_N(x_B, \vec{v}_\perp, b_\perp)\frac{\phi_N(x_G, \vec{k}_\perp)}{k_\perp^2}\left[\mathcal{N}_g^{\mathrm{qLPM}} + \mathcal{N}_g^{\mathrm{gLPM}} + \mathcal{N}_g^{\mathrm{nonLPM}}\right].$$

Jet production in CGC

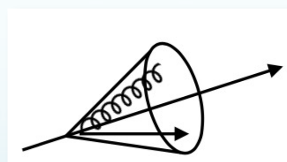
- NLO computations just started in very recently
  - LO available in 2011 — Dominguez, Marquet, Xiao, Yuan, 2011
  - LO had no jet structure

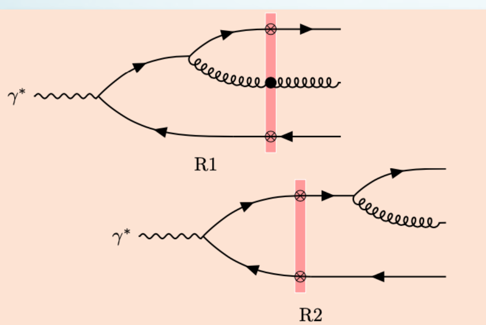


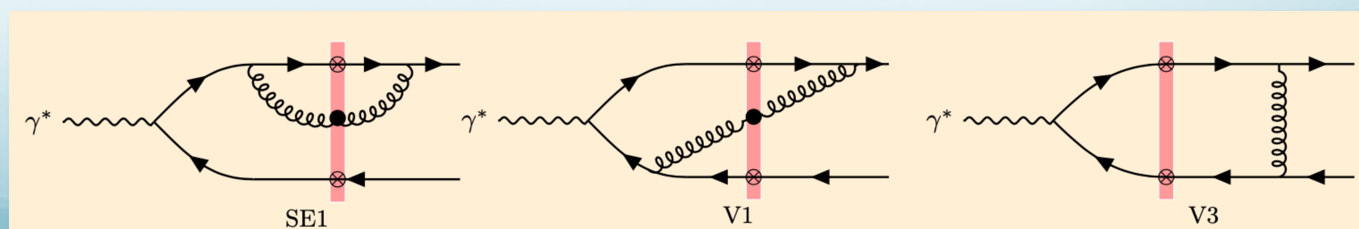


$$V_{ij}(\boldsymbol{x}) = P\exp\left\{ig\int dx^- A_{cl}^{+,a}(\boldsymbol{x},x^-)t^a\right\}$$

  - 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, 22

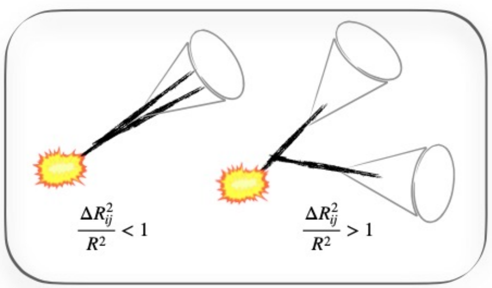
  - Properly handle jet algorithm on top of complicated CGC computations
  - Study its small-*R* approximation: factorized into a semi-inclusive jet function
  - Can be readily used for jet production in e+A: also jet substructure

anti-k_T Cacciari, Salam, Soyez, 2008

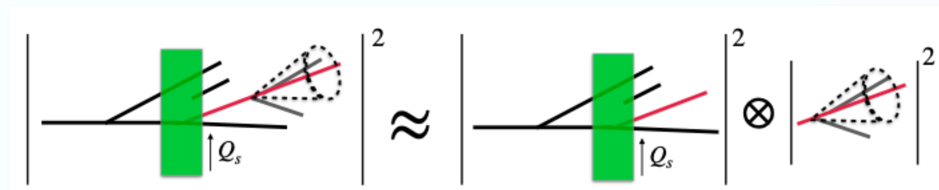
- If ρ_{ij} is the smallest, combine i and j
- If ρ_i is the smallest, promote i as a jet candidate and remove from the list
- Do recursively

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

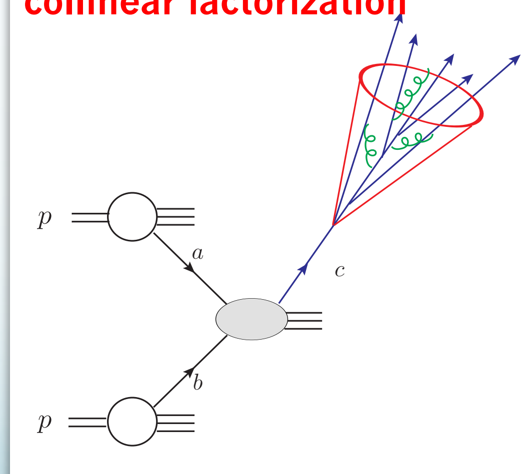
$$\Delta R_{ij}^2 = \Delta\phi_{ij}^2 + \Delta\eta_{ij}^2$$



CGC factorization in small *R*



collinear factorization



Kang, Ringer, Vitev, JHEP, 2016

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

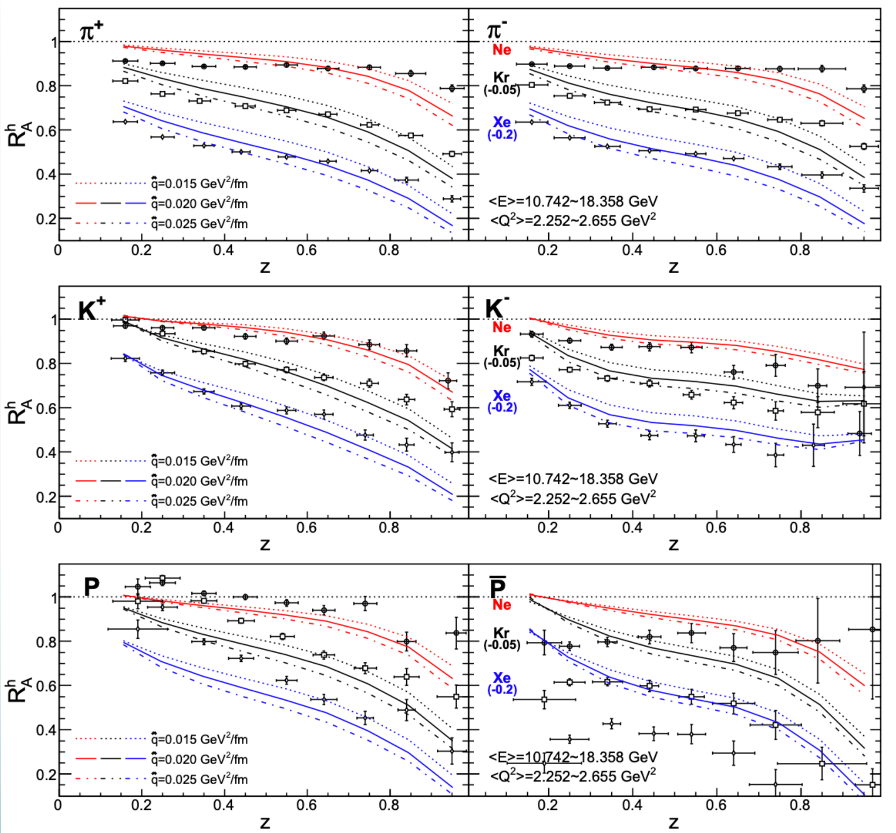
Jets in cold nuclear matter

- The early HERMES data: hadron multiplicity modification
  - Modified fragmentation function in medium

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

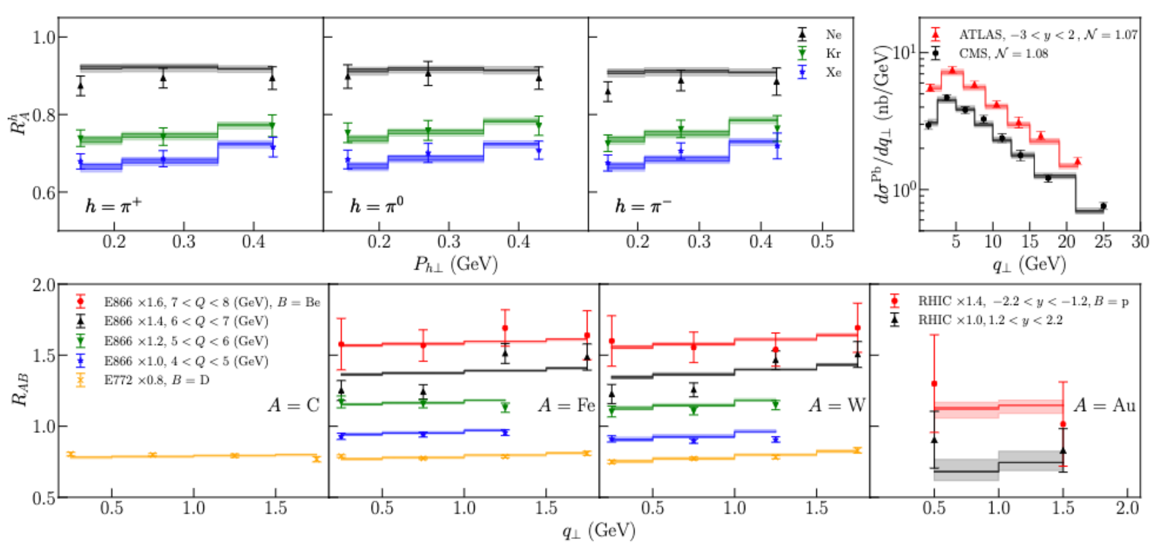
$$R_A^h(z,\nu) = \left(\frac{N^h(z,\nu)}{N^e(\nu)}|_A\right) / \left(\frac{N^h(z,\nu)}{N^e(\nu)}|_D\right)$$

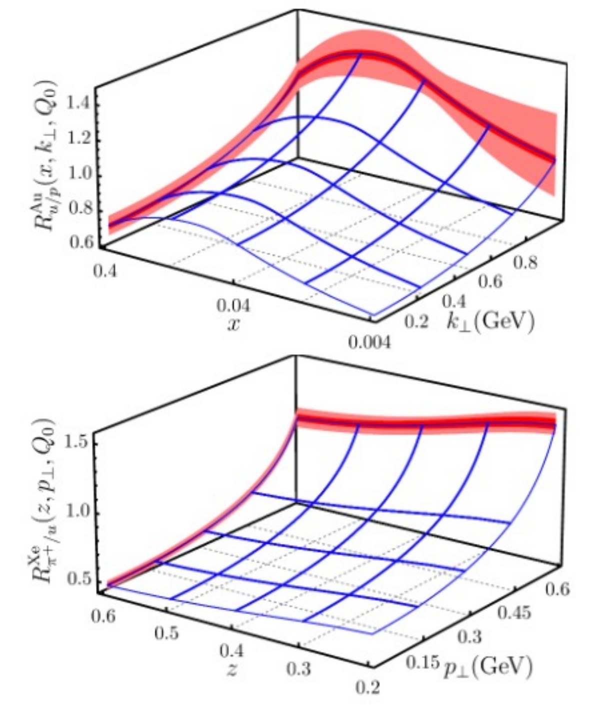
$$= \left(\frac{\Sigma e_q^2 q(x) \widetilde{D}_q^h(z)}{\Sigma e_q^2 q(x)}|_A\right) / \left(\frac{\Sigma e_q^2 q(x) D_q^h(z)}{\Sigma e_q^2 q(x)}|_D\right)$$



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]



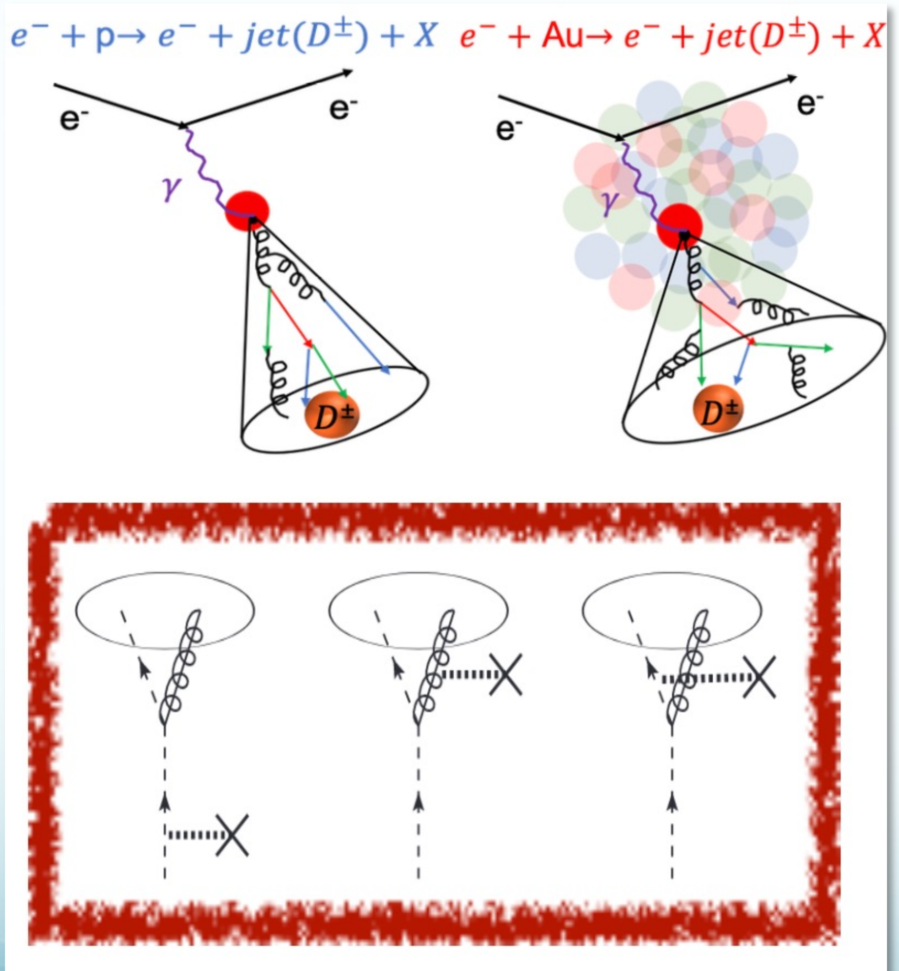


$$\frac{d\sigma}{dx_B dQ^2 dz_h d^2P_{hT}} \propto \int d^2k_T d^2q_T f_q(x_B, k_T) D(z_h, q_T) \delta^2(z_h k_T + q_T - P_{hT})$$

Alrashed, Anderle, Kang, Terry, Xing, 2021

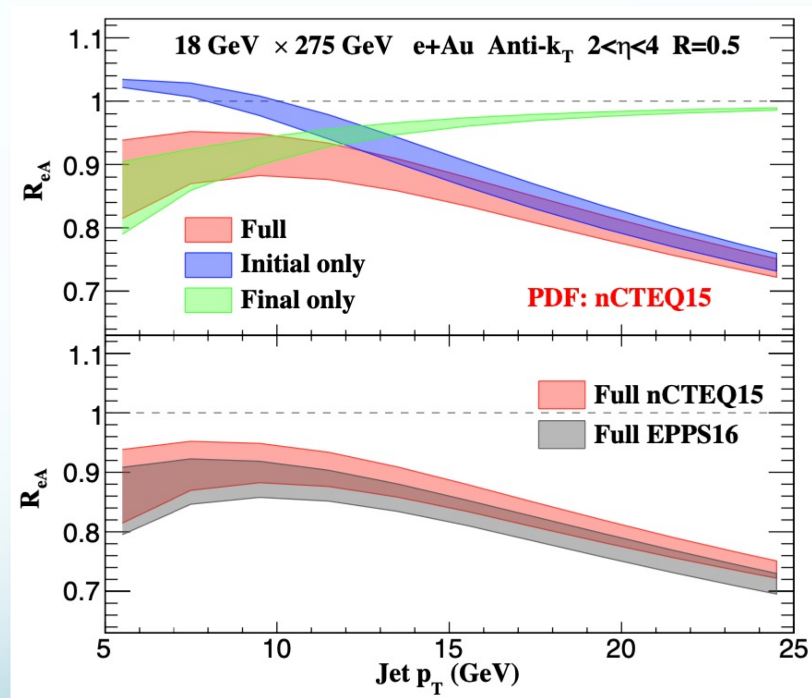
Jet modification in e+A

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



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

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

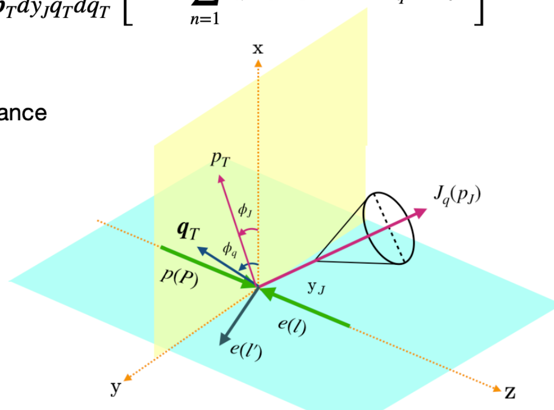
$$\frac{d\sigma}{d^2\boldsymbol{p}_T dy_J d\phi_J d^2\boldsymbol{q}_T} = \frac{d\sigma}{2\pi d^2\boldsymbol{p}_T dy_J q_T dq_T}\left[1 + 2\sum_{n=1}^{\infty} v_n(p_T, y_T)\cos(n(\phi_q - \phi_J))\right]$$

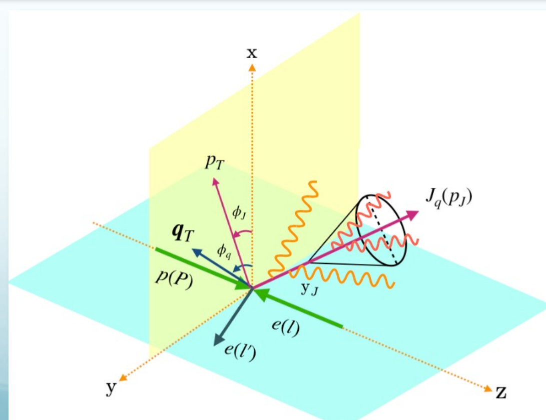
q_T : transverse momentum imbalance

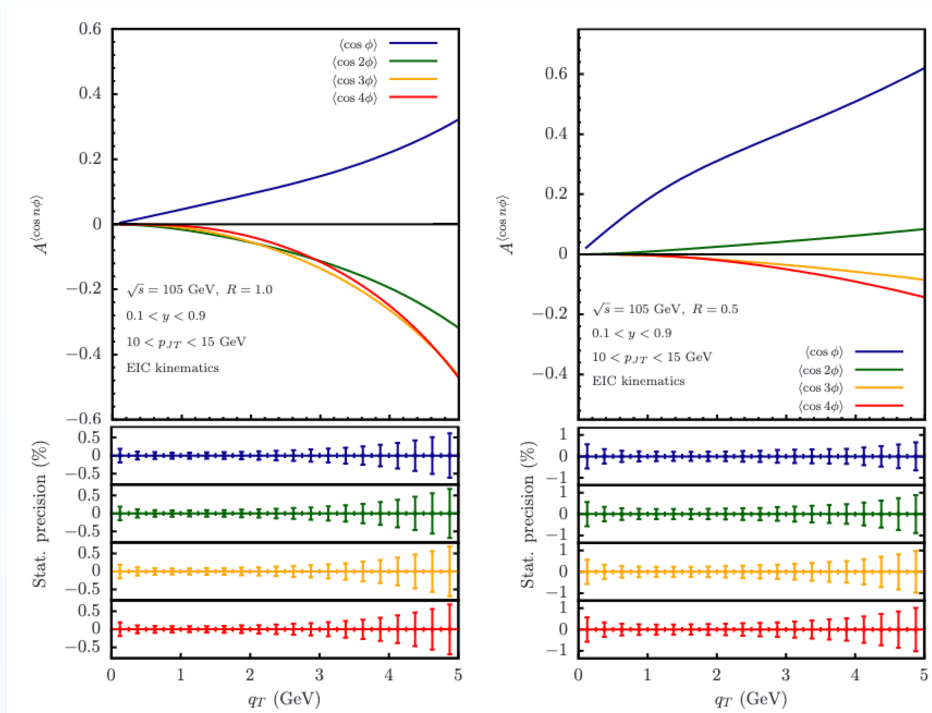
$$\boldsymbol{q}_T = \boldsymbol{l}'_T + \boldsymbol{p}_{JT}$$

p_T : jet transverse momentum

y_J : jet rapidity







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

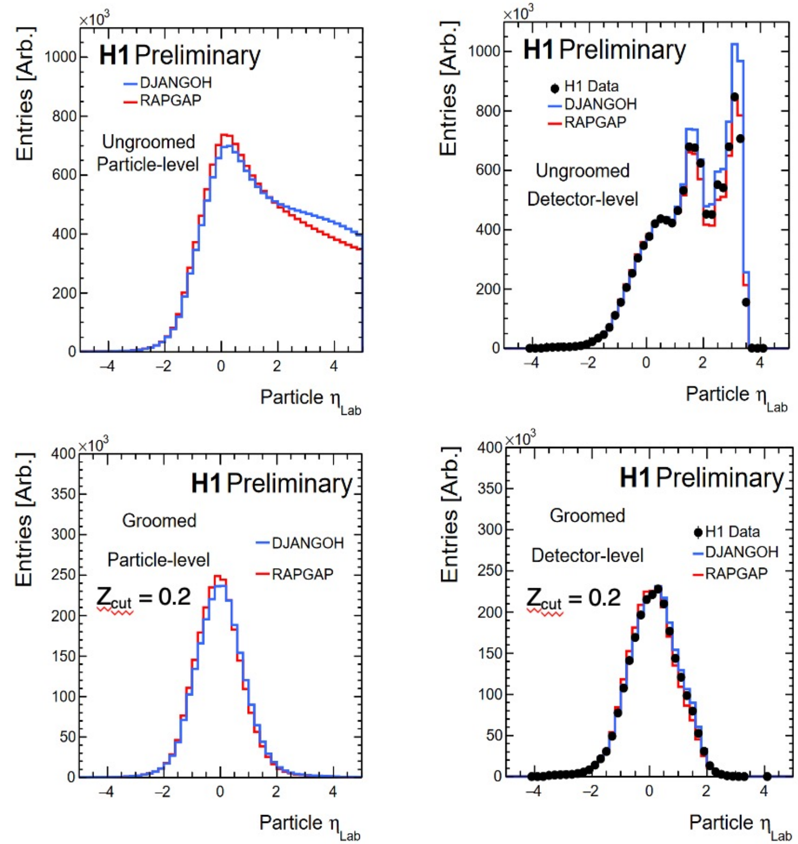
Groomed jet substructure

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!

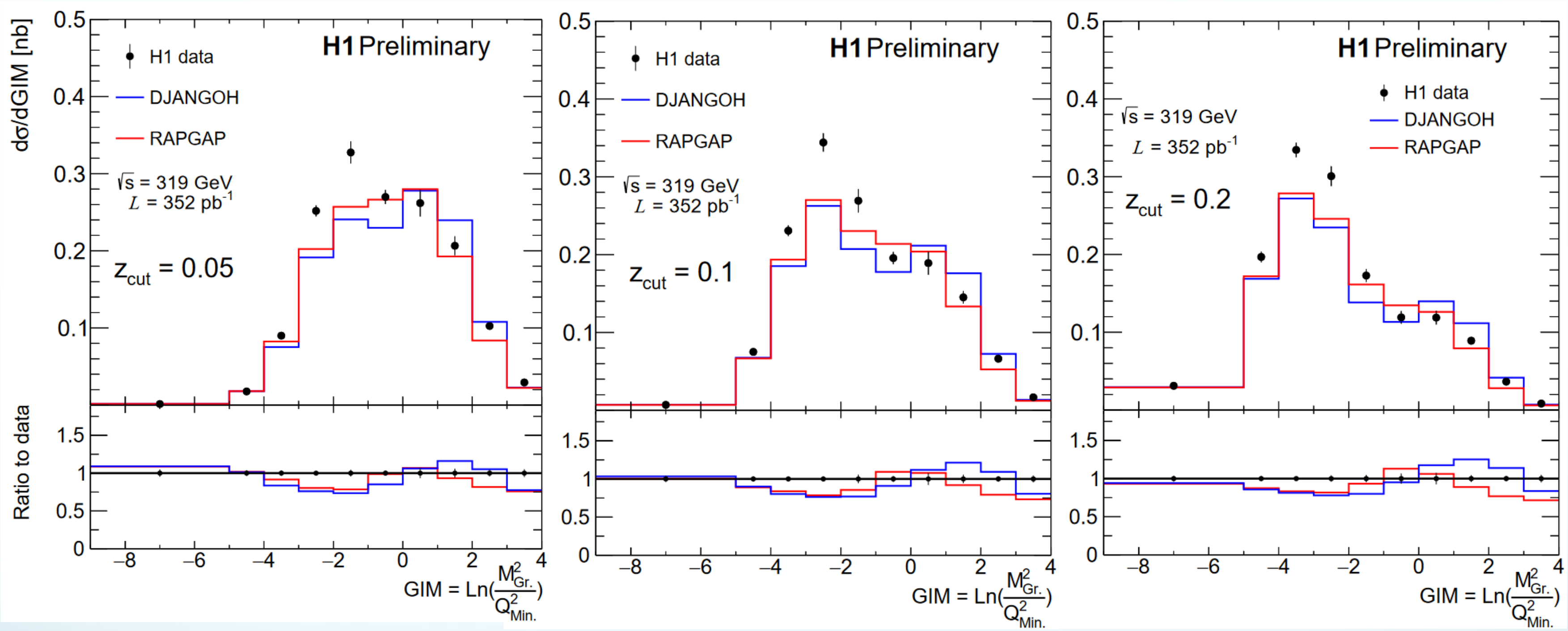


Henry Klest, HERA4EIC, June 8

9

Groomed jet mass from HERA

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

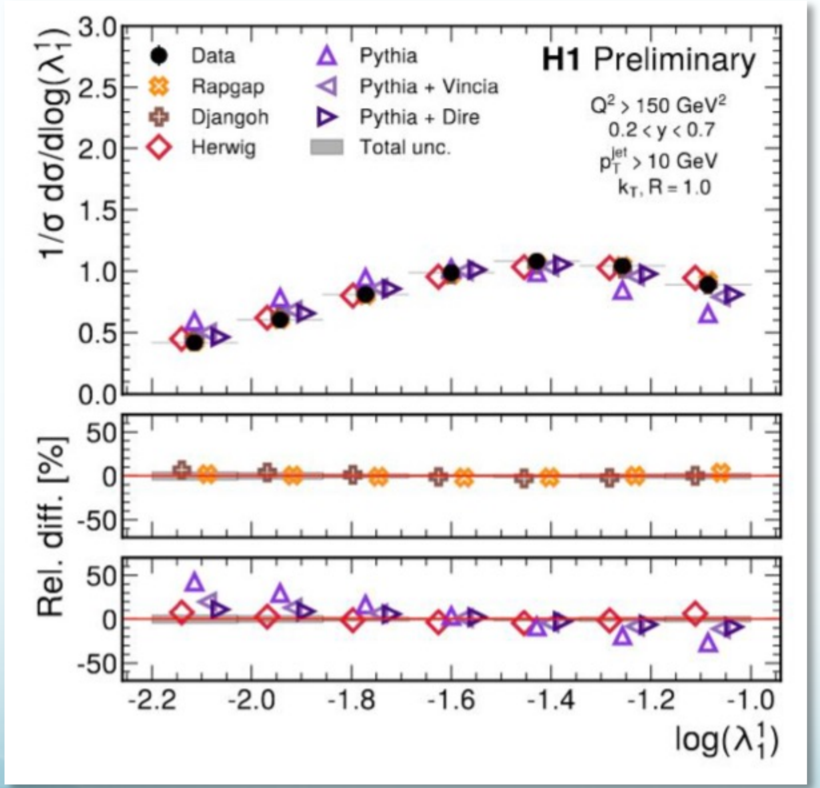


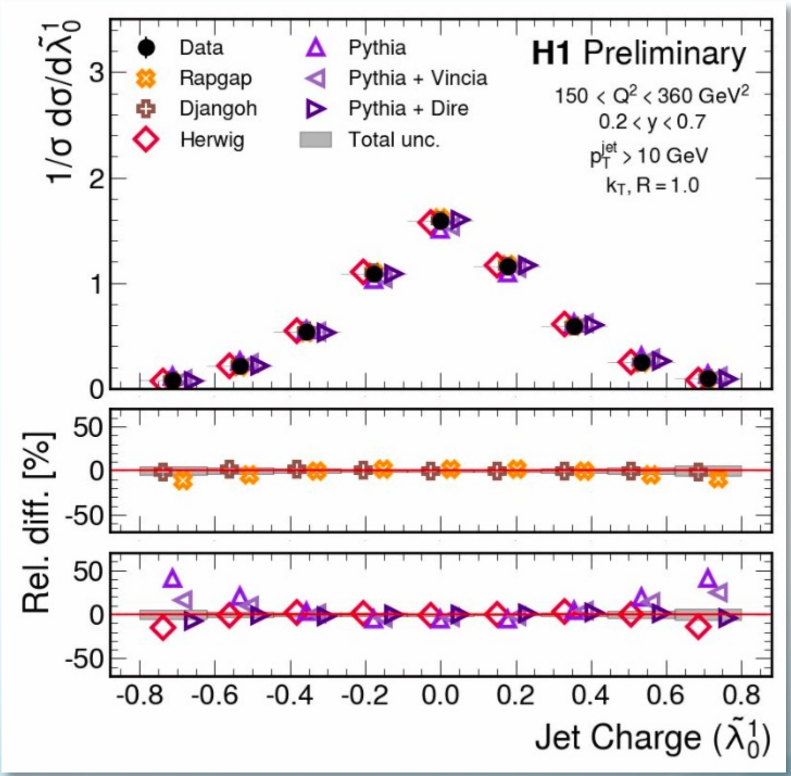
Klest, June 8

Jet angularity

- Recent measurement on jet angularity

$$\lambda^{\kappa}_{\beta} = \sum_{i \in \mathrm{jet}} z_i^{\kappa} \left(\frac{R_i}{R_0}\right)^{\beta} \qquad \tilde{\lambda}^{\kappa}_{0} = Q_{\kappa} = \sum_{i \in \mathrm{jet}} q_i \times z_i^{\kappa}$$

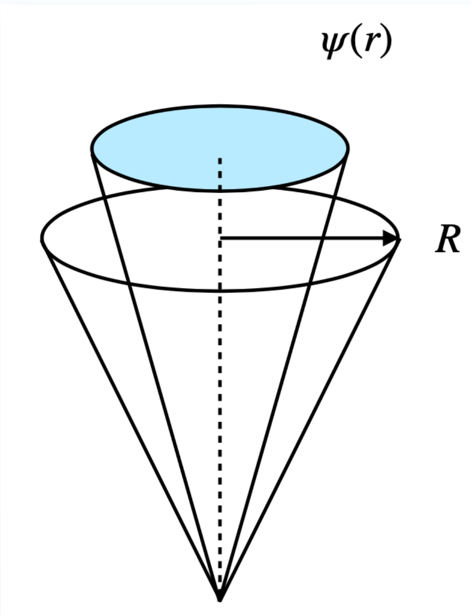




Mikuni, Nachman, June 8

Jet shape

- Jet shape at the EIC



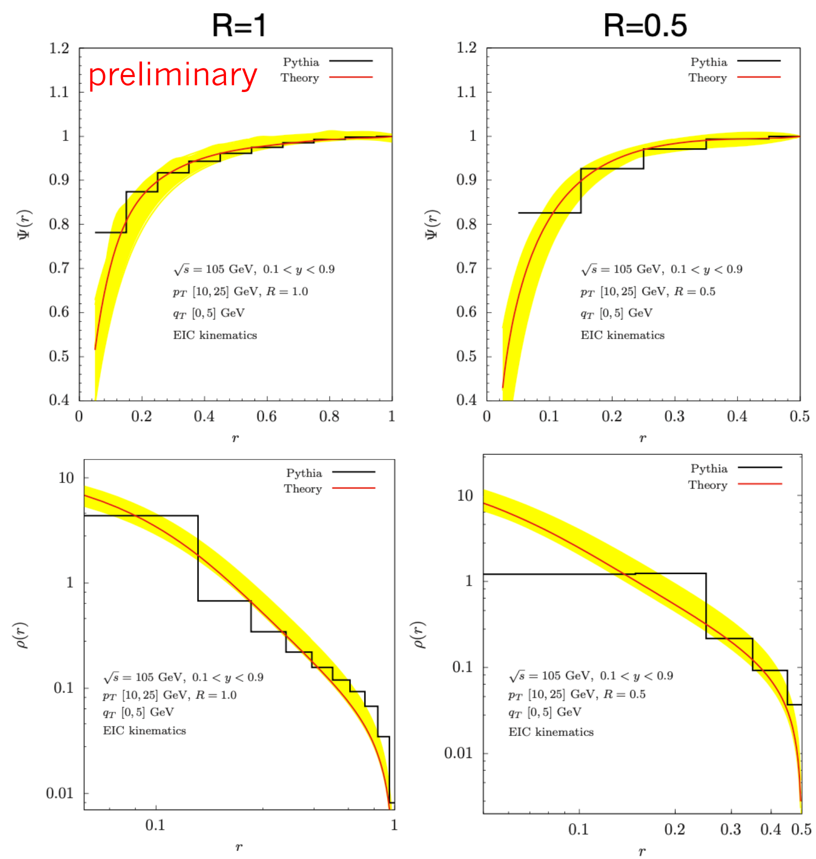
EIC kinematics

Integrated jet shape:

$$\psi(r) = \frac{\int dz_r \, z_r \frac{d\sigma}{d^2\mathbf{p}_T dy_J d^2\mathbf{q}_T dz_r}}{\frac{d\sigma}{d^2\mathbf{p}_T dy_J d^2\mathbf{q}_T}}$$

Differential jet shape:

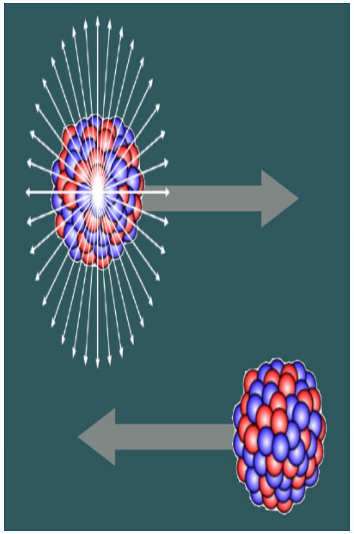
$$\rho(r) = \frac{d\psi(r)}{dr}$$



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

UPC vs EIC

- Could UPC help jet physics at EIC?



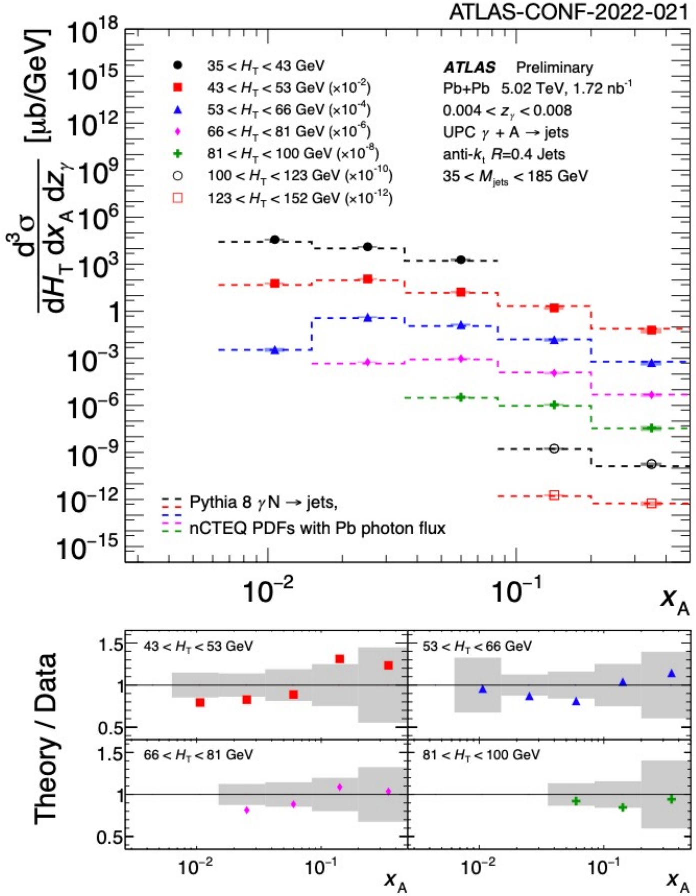
ATLAS: Triple differential UPC dijets

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

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

"Q^2" "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**

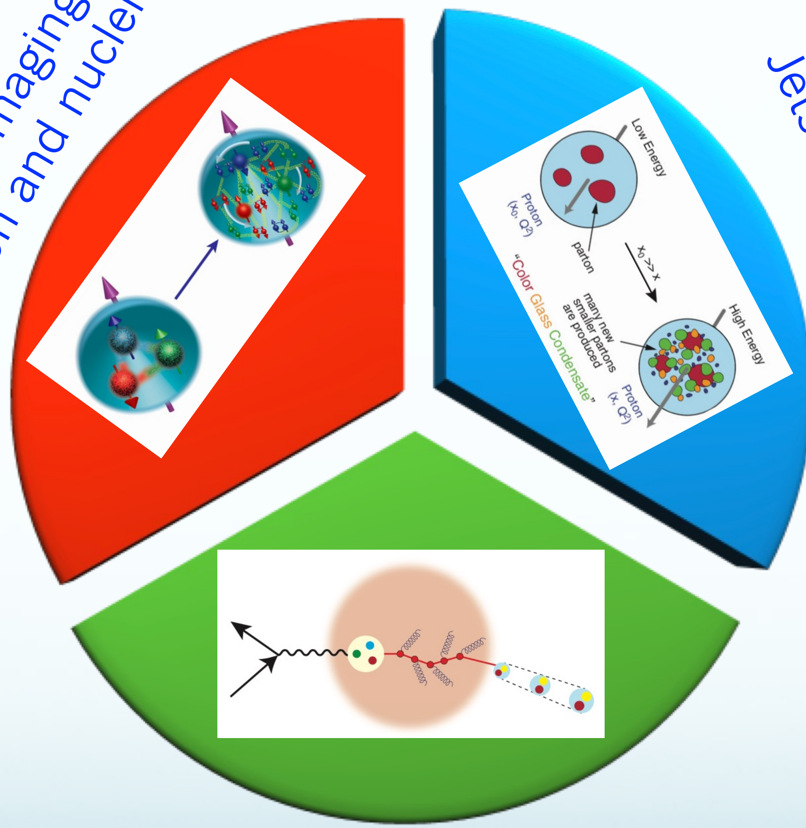


Steinberg, DIS 2022

Summary: jets are powerful tools

Quantum imaging of proton and nuclei

Jets for CGC



Jet propagation in nuclei

Thank you!