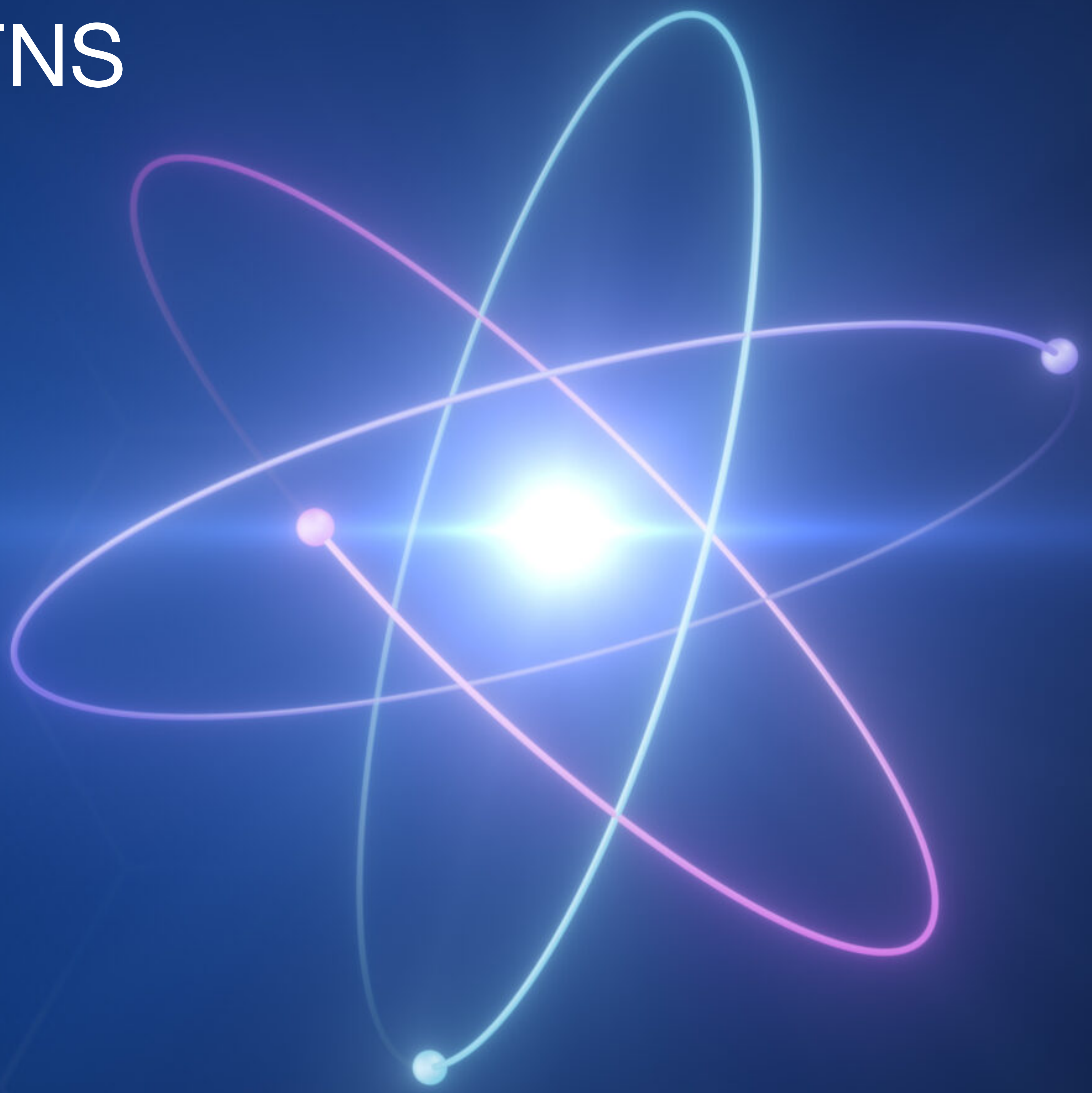
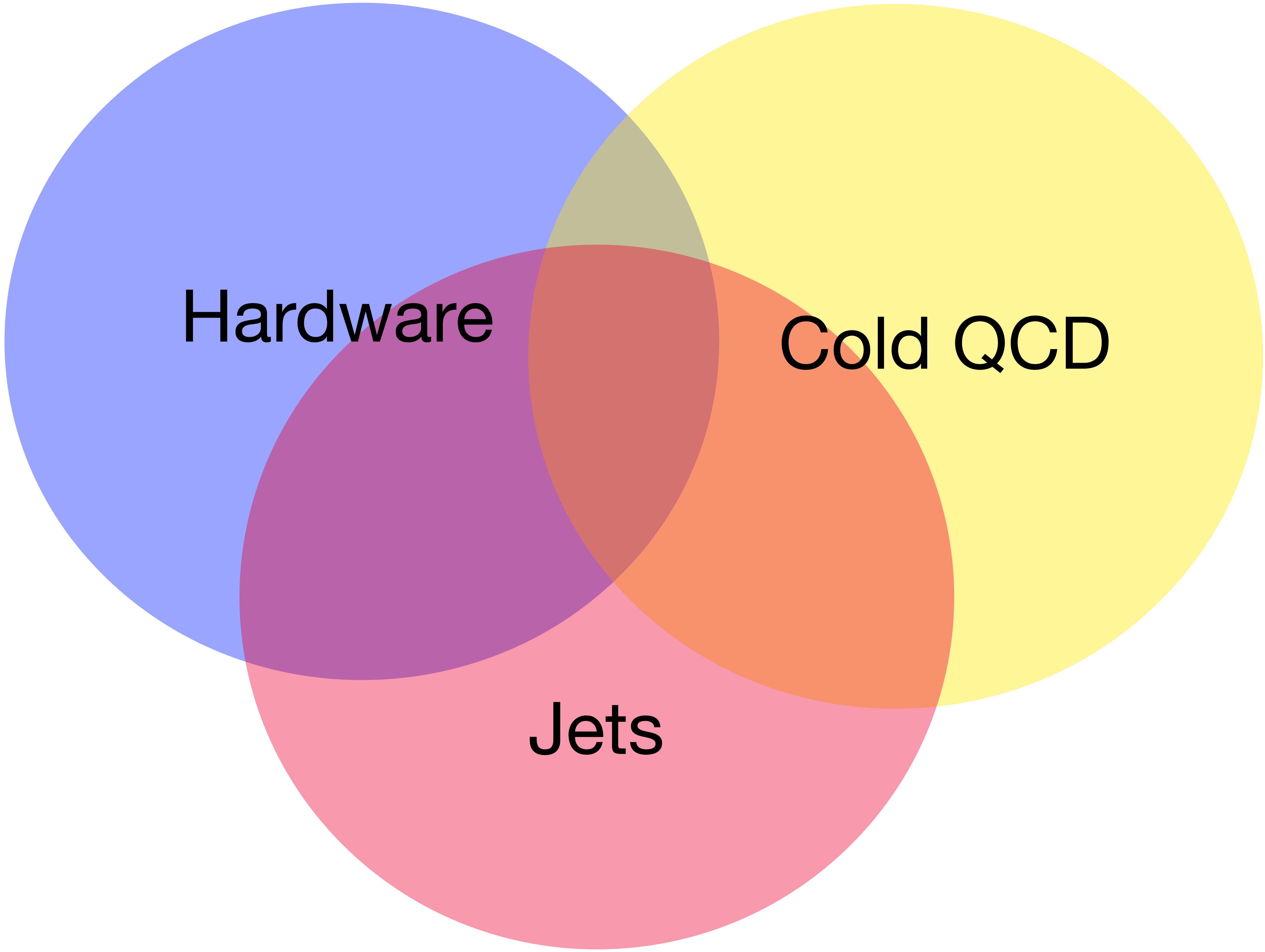
The Many Faces of the Strong Interaction

— and the Many Human Faces at CFNS



Activities



Datta, Deshpande, Kharzeev, Naim, Tu PRL.134.111902

Quantum Entanglement in Jets

Entanglement is a **key feature** of **quantum mechanics**

It represents **non-local correlations** between **subsystems**

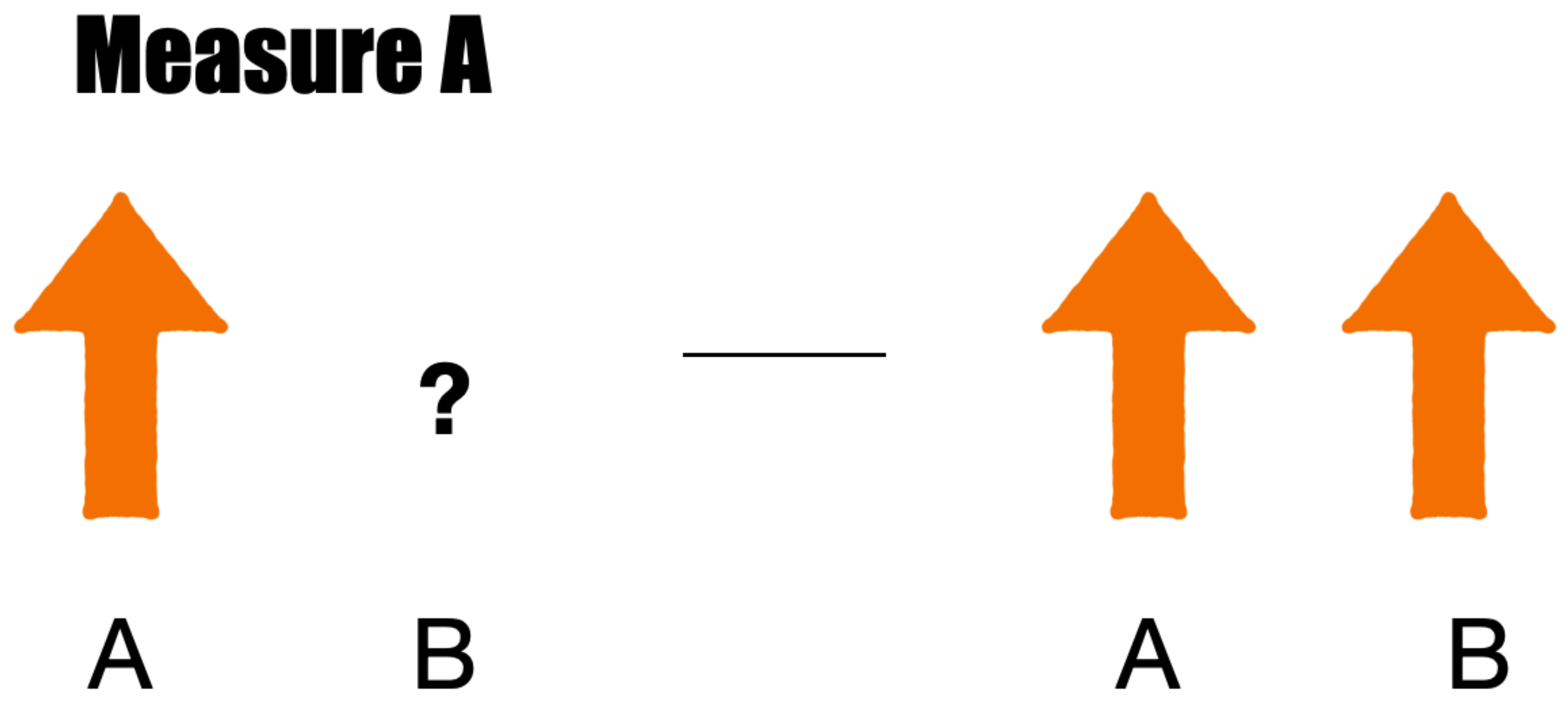
- A pure state $|\psi\rangle$ of a bipartite system **A** $\otimes$ **B** is entangled

if it cannot be written as a tensor product:

$$|\psi\rangle \neq |\phi_a\rangle \otimes |\chi_\beta\rangle$$

- **Example: Bell state**

$$|\Phi^+\rangle = (1/\sqrt{2})\,(\,|00\rangle + |11\rangle\,)$$



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Quantum Entanglement in Jets

The most entangled states maximize the entanglement entropy

- **Von Neumann entropy** for a bipartite state:

$$S_A = -\mathrm{Tr}(\rho_A \log \rho_A), \quad \rho_A = \mathrm{Tr}_B(|\psi\rangle\langle\psi|)$$

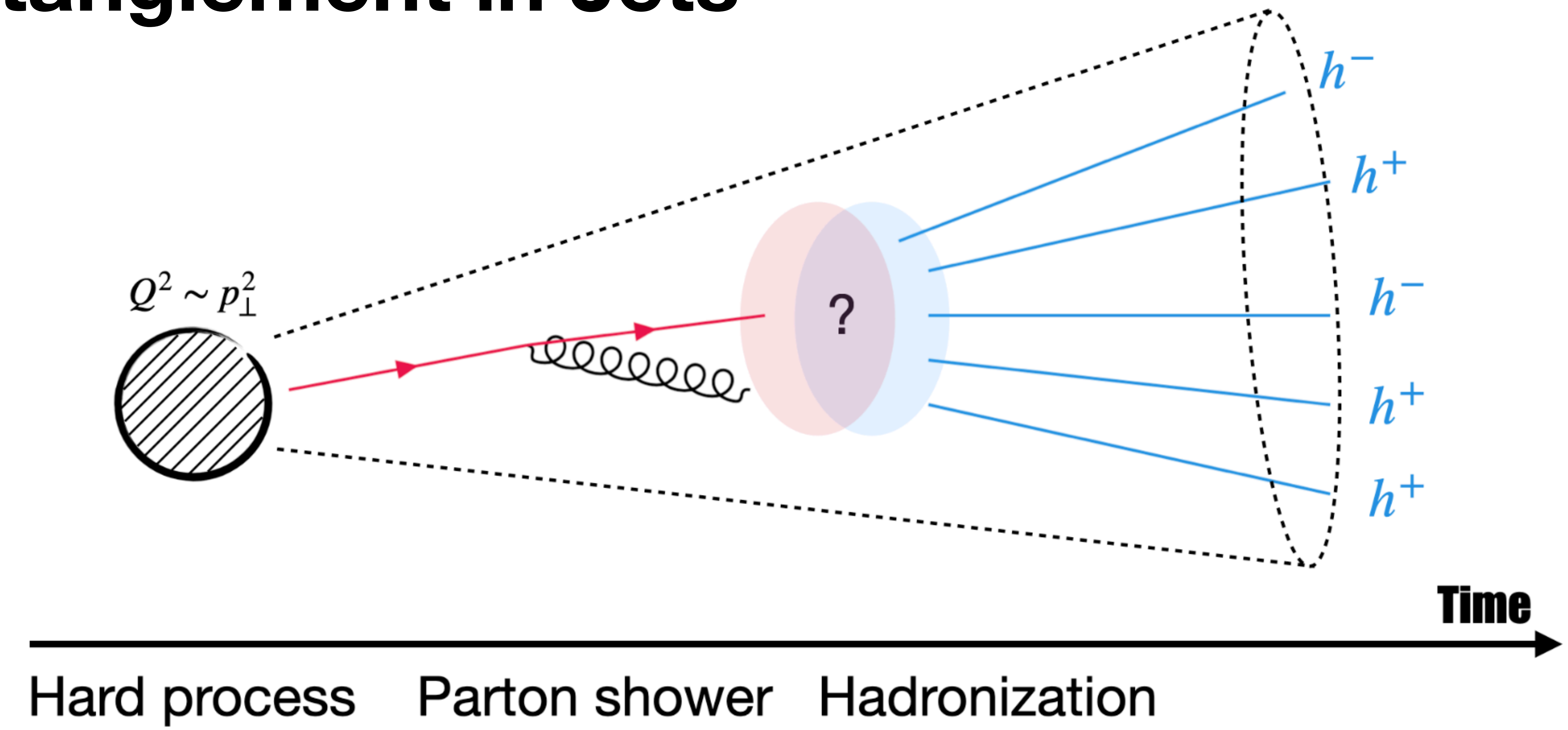
- **Bell state entropy**:

$$\rho_A = \frac{1}{2} I \Rightarrow S_A = \log 2$$

Strong condition for maximum entanglement: $S_A = S_B$

Datta, Deshpande, Kharzeev, Naim, Tu [PRL.134.111902](PRL.134.111902)

Quantum Entanglement in Jets

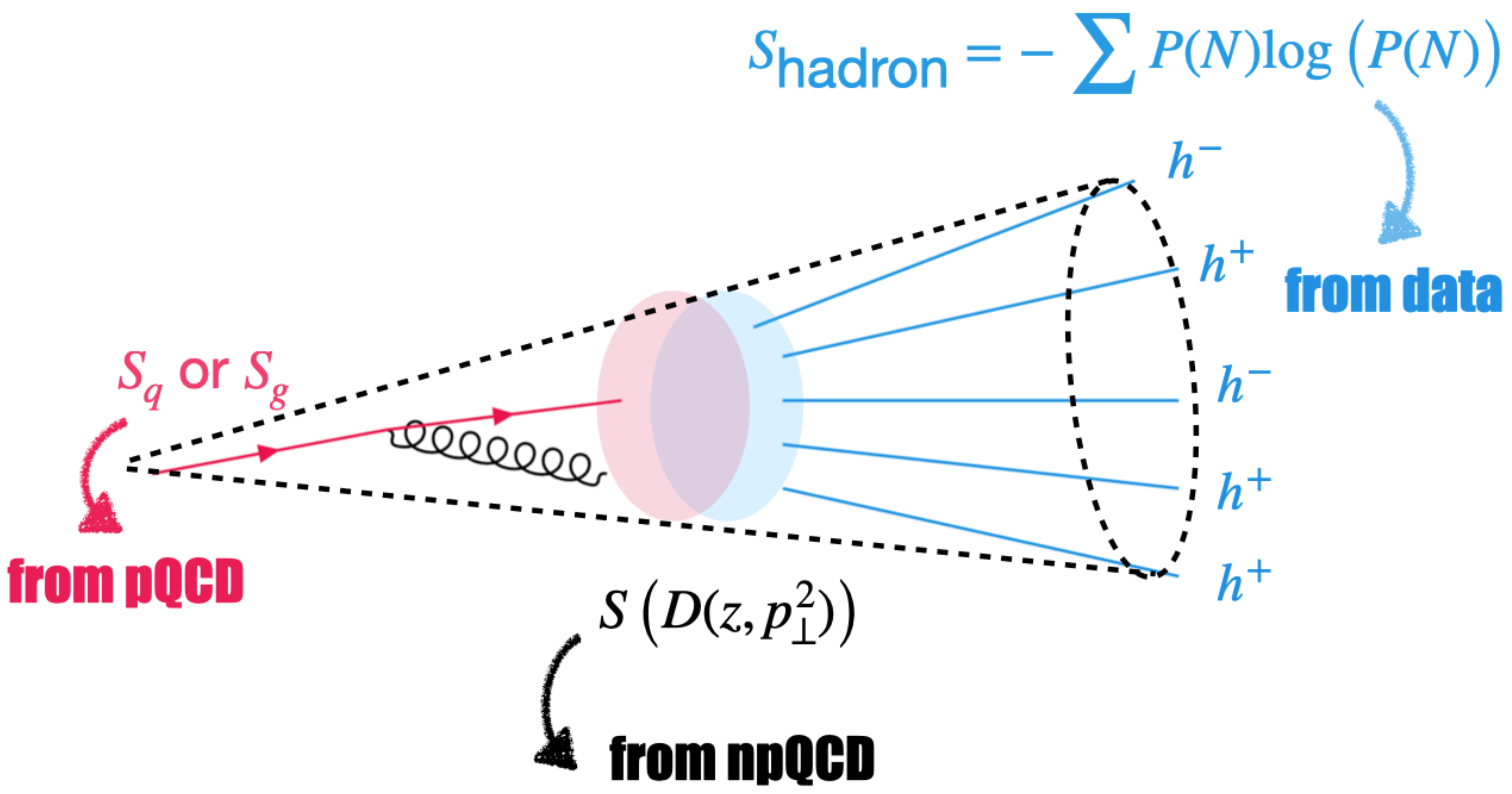


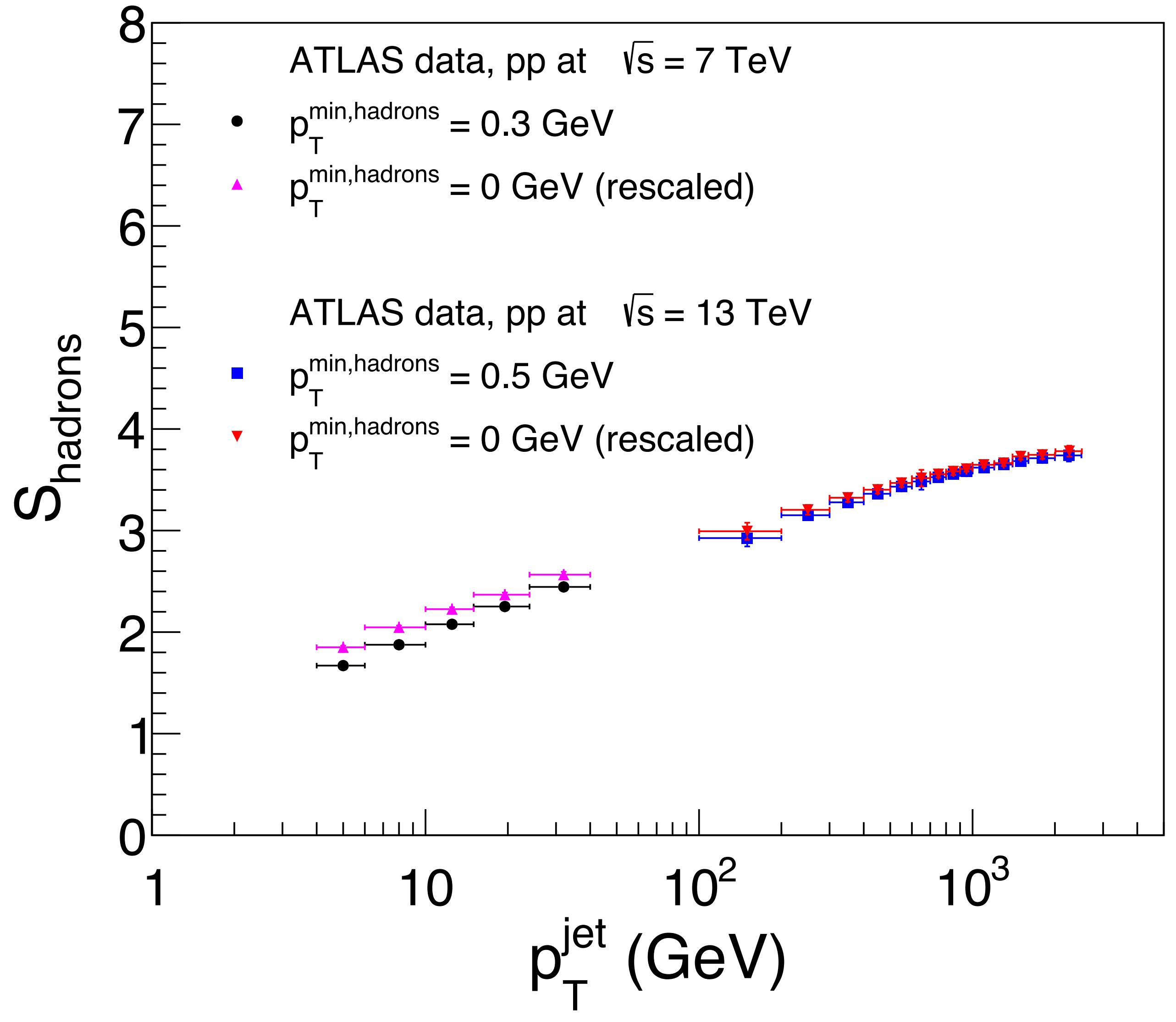
- Derived from **maximal entanglement in the proton:** $S_A \sim \log\left[xG(x, Q^2)\right]$
- By crossing symmetry, **applies to fragmentation:** $S_A \sim \log\left[D(z, p_\perp^2)\right]$

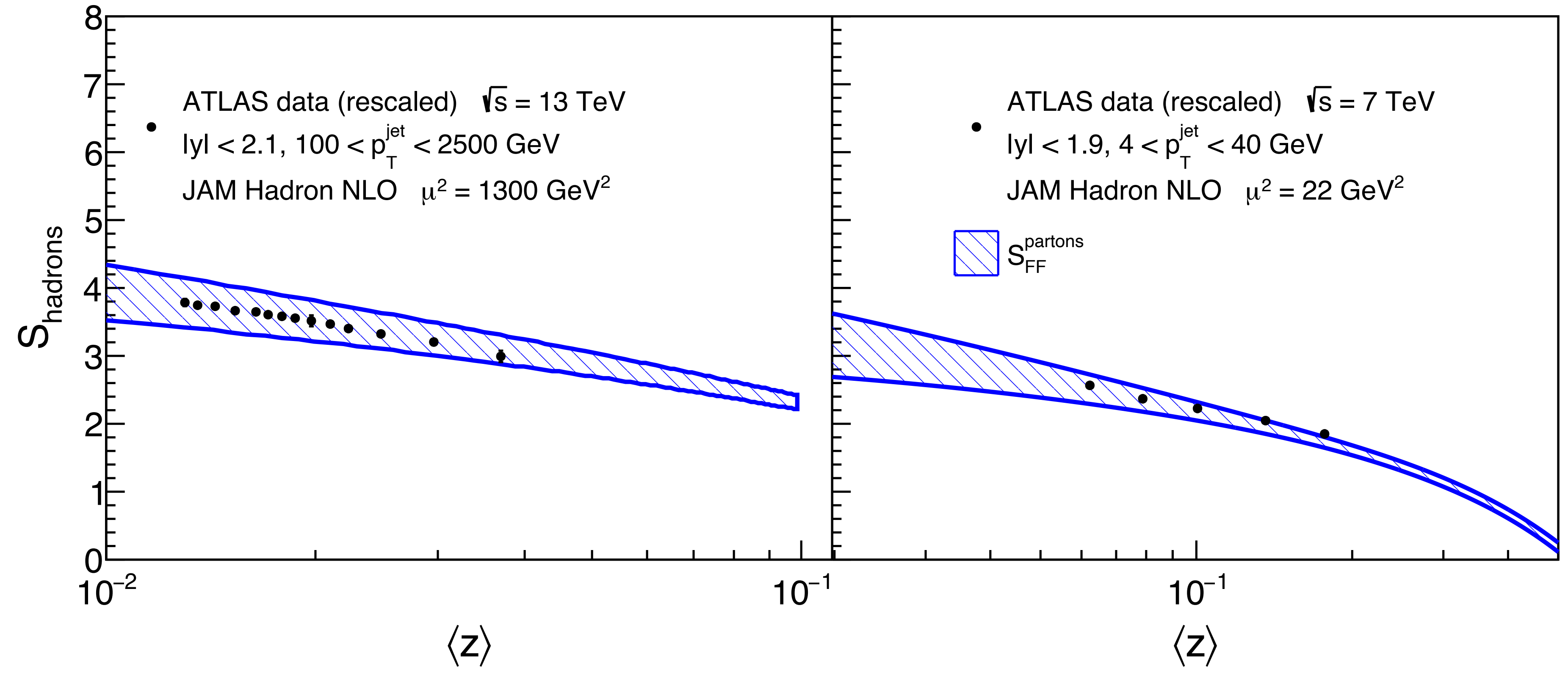
Crossing symmetry: relates PDFs and FFs, e.g., $f_{i/p}(x) \longleftrightarrow D_{j/h}(z)$

Datta, Deshpande, Kharzeev, Naim, Tu PRL.134.111902

Quantum Entanglement in Jets





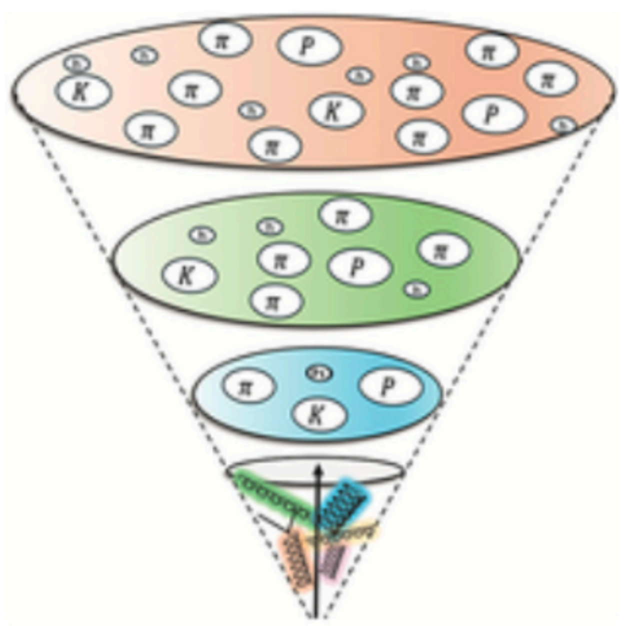


Strong indication supporting maximum entanglement entropy!

$$S_{FF} = S_{hadrons}$$

Datta, Deshpande, Kharzeev, Naim, Tu [PRL.134.111902](PRL.134.111902)

Quantum Entanglement in Jets



EDITORS' SUGGESTION

Entanglement as a Probe of Hadronization

Jaydeep Datta, Abhay Deshpande, Dmitri E. Kharzeev, Charles Joseph Naïm, and Zhoudunming Tu

Phys. Rev. Lett. **134**, 111902 (2025) - Published 19 March, 2025

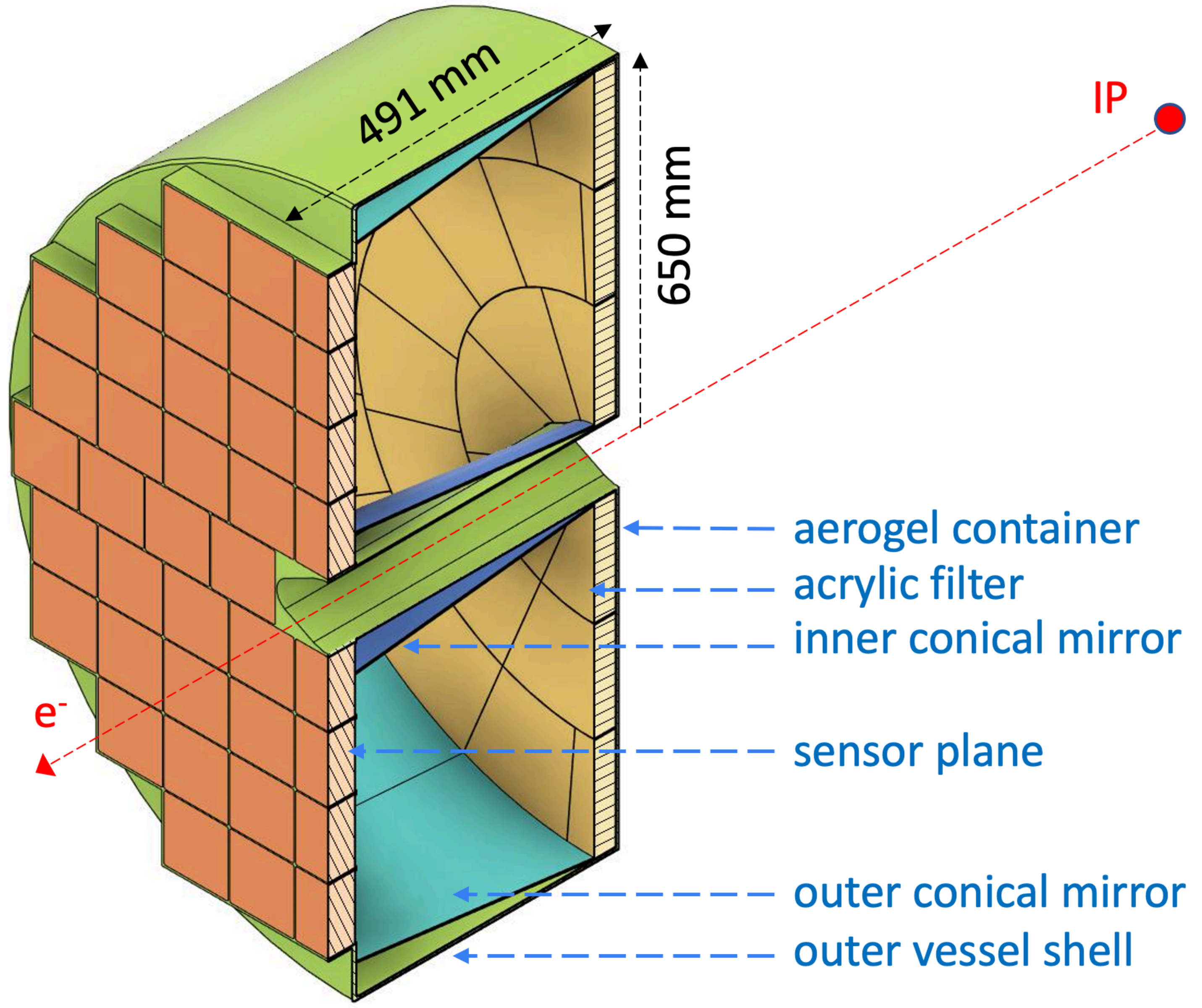
The entropy of hadrons produced within highly energetic jets can be related to the fragmentation function if the initial quarks and gluons in the jets are maximally entangled.

Center for Frontiers in Nuclear Science

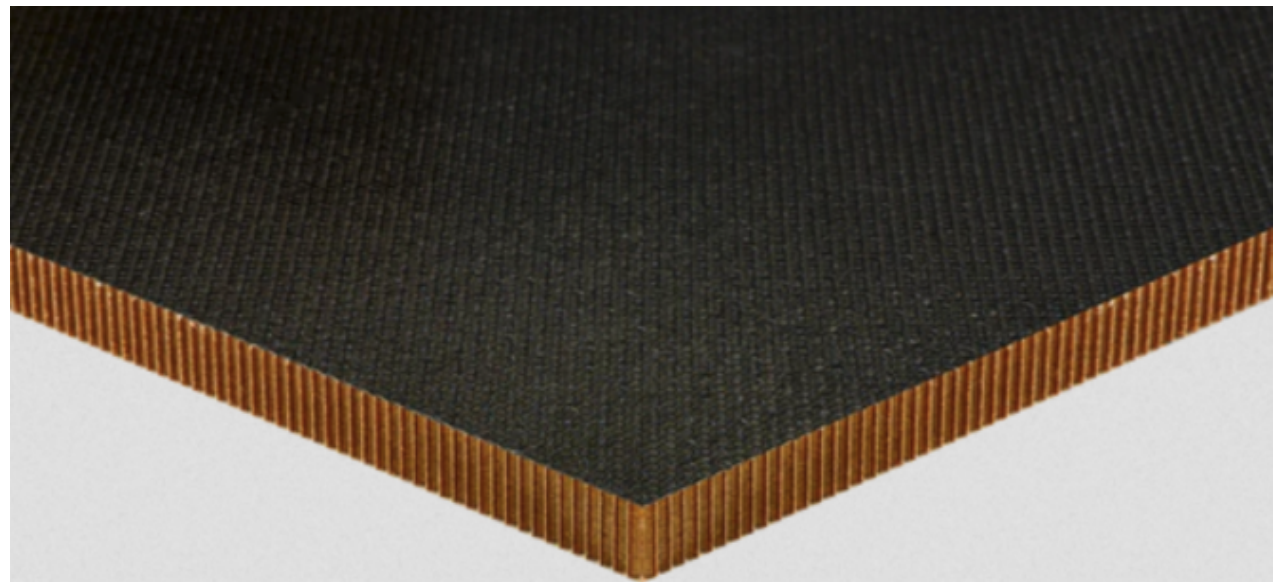
Stony Brook University

Brookhaven National Laboratory

pfRICH at ePIC (EIC)

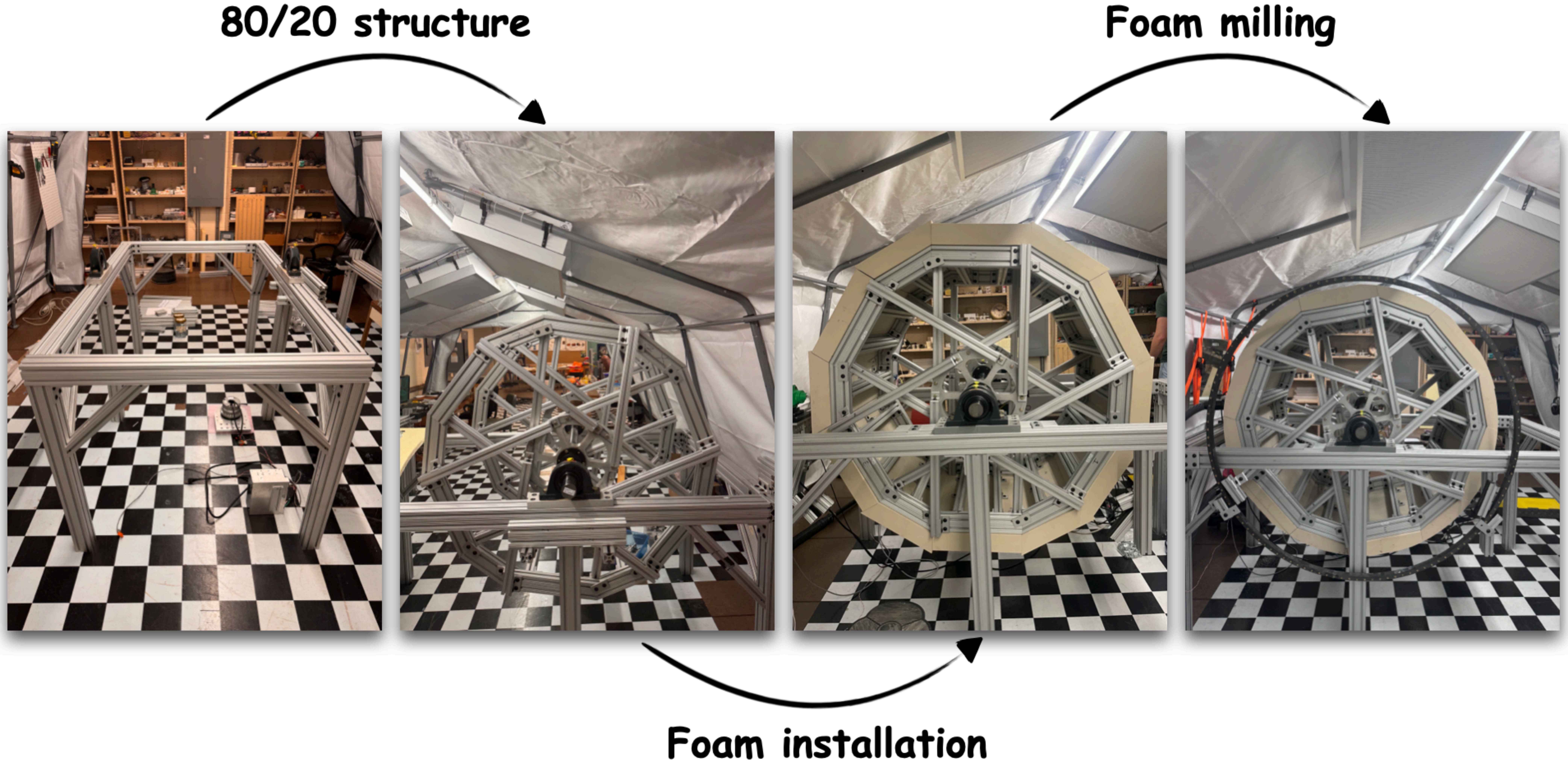


- Particle Identification in the backward region
- Cherenkov detector
- Pion, kaon, proton separation up to 7 GeV



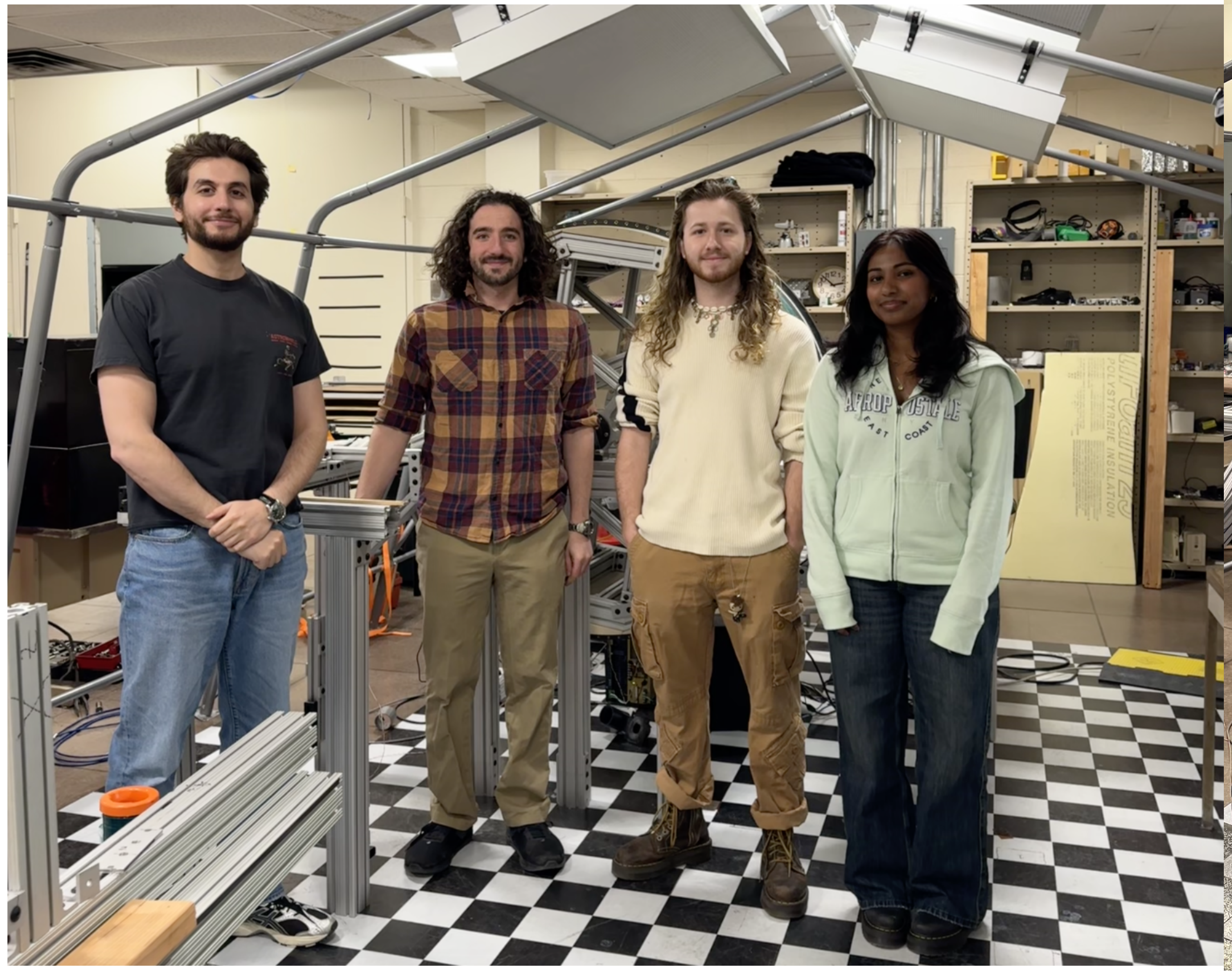
- Vessel made with carbon fiber and honeycomb
- Lightweight and robust

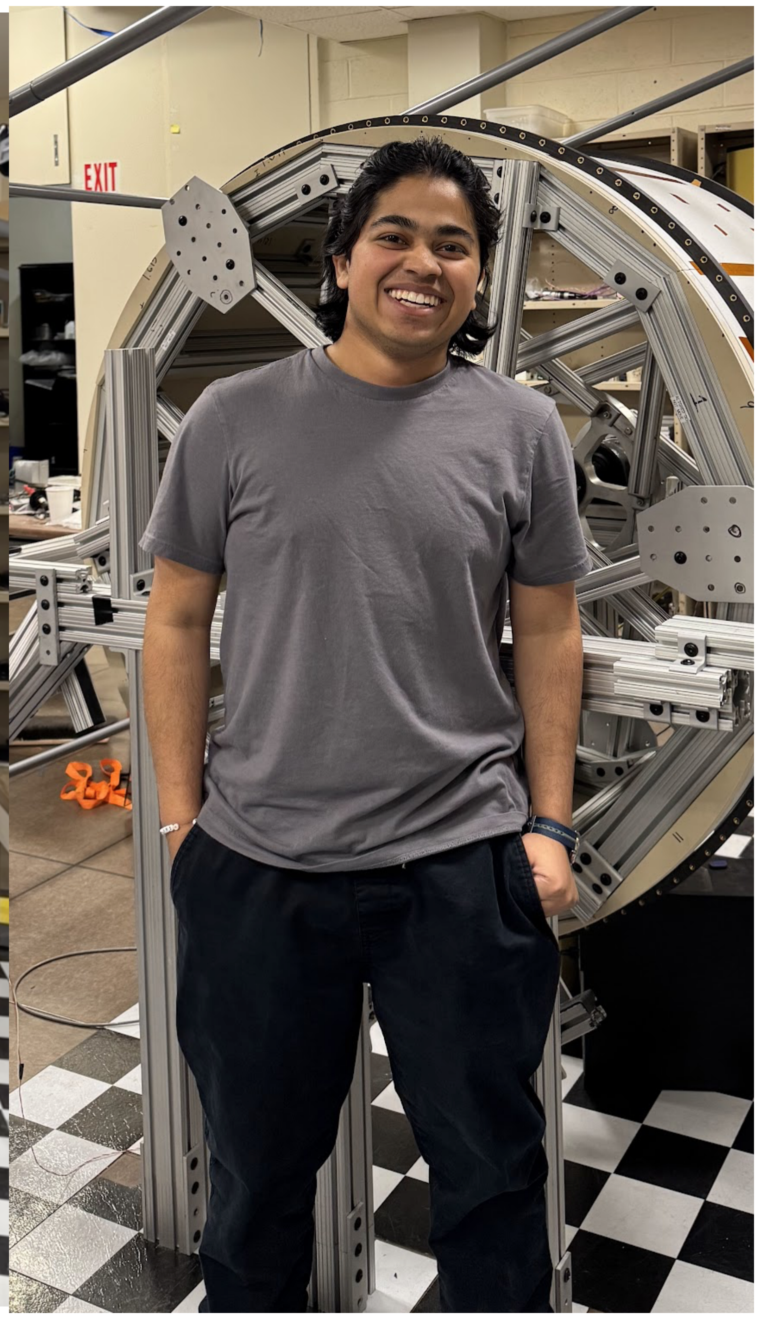
pfRICH at ePIC (EIC)

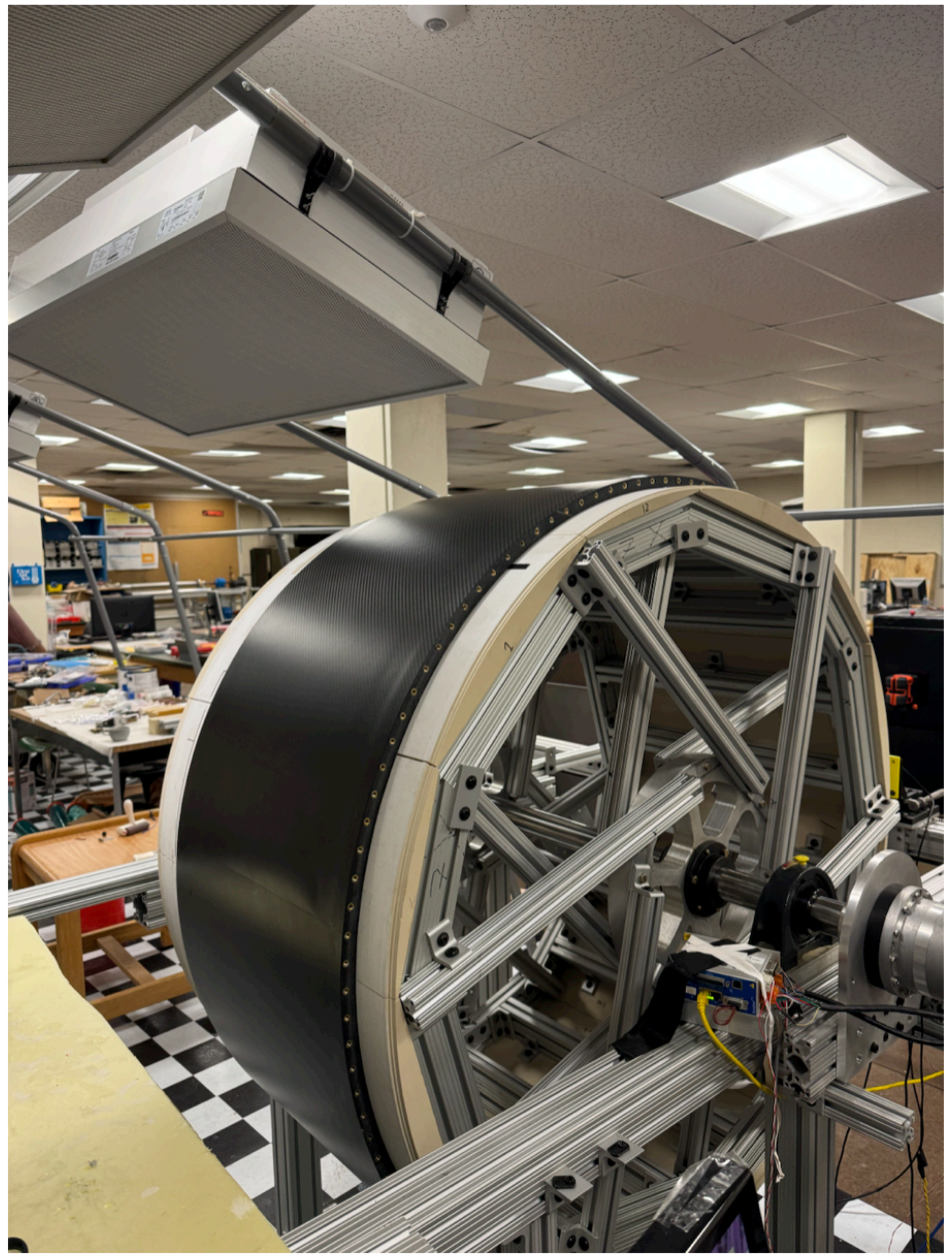


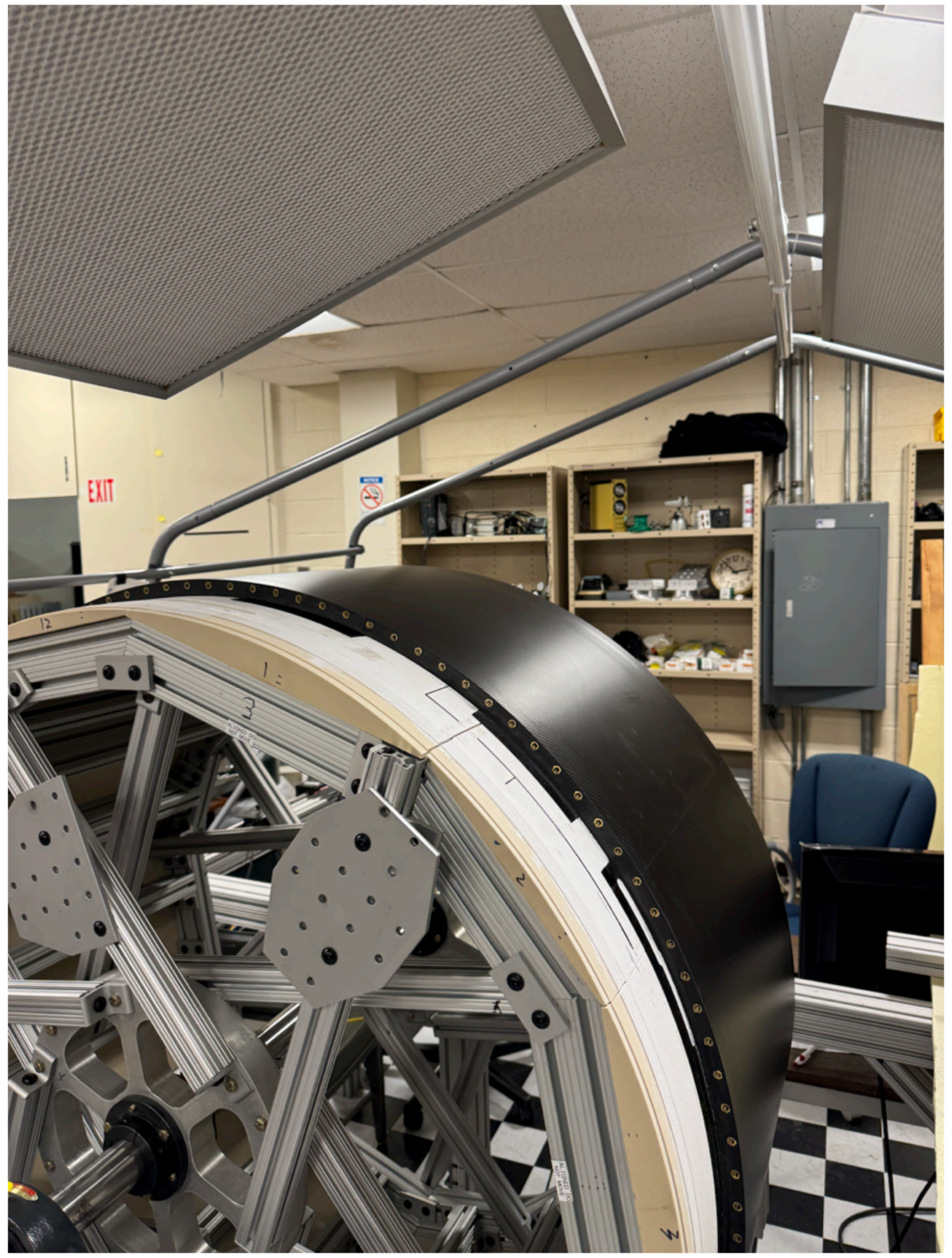
pfRICH at ePIC (EIC)

- The vessel is finished
- Disassembly procedure ongoing









- SBU selected for full construction

— exciting next steps ahead!

Nuclear Cold QCD: Review and Future Strategy, Arleo *et al* 2506.17454

Nuclear Cold QCD

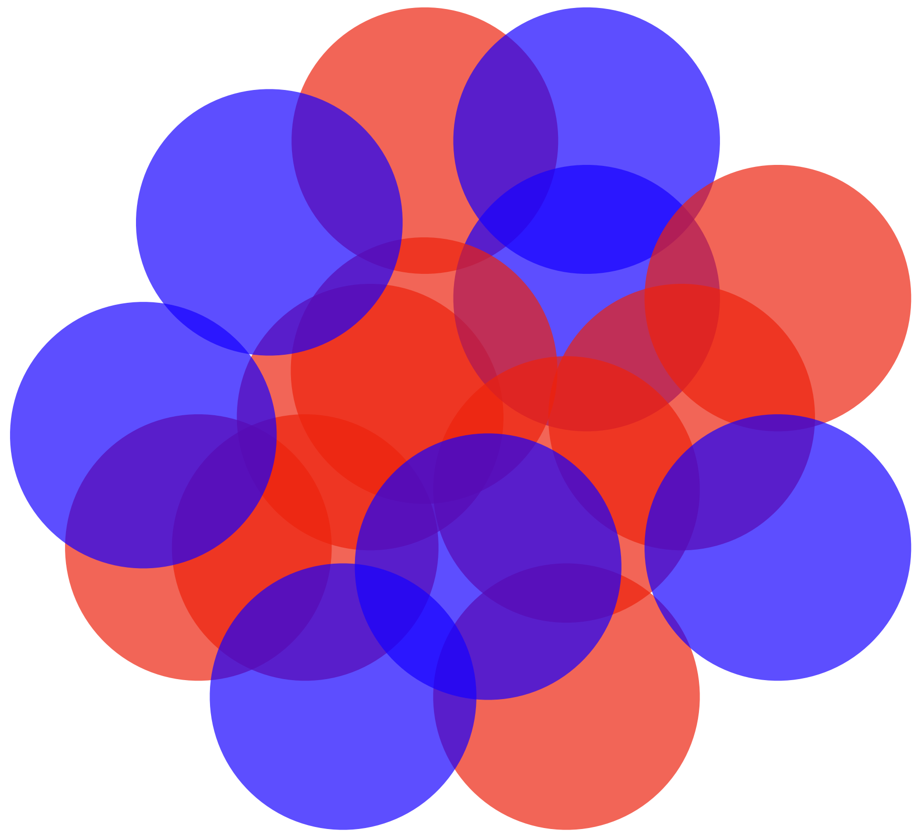
How nuclear medium affects the particle production?

$eA \rightarrow e + h + X$ (SIDIS)

- Initial-state interactions

$hA \rightarrow \gamma^* + X$ (DY)

- Final-state interactions



$hA \rightarrow q\bar{q}(\rightarrow J/\psi, D, B \ldots) + X$ (Quarkonia, Heavy Flavor Production)

- Initial- and final-state interactions

Nuclear Cold QCD: Review and Future Strategy, Arleo *et al* 2506.17454

Nuclear Cold QCD

Gluon saturation (pQCD) vs nPDF (npQCD)

- Initial-state effect

Impact of Energy loss on particles production

- Initial- and final-state effect

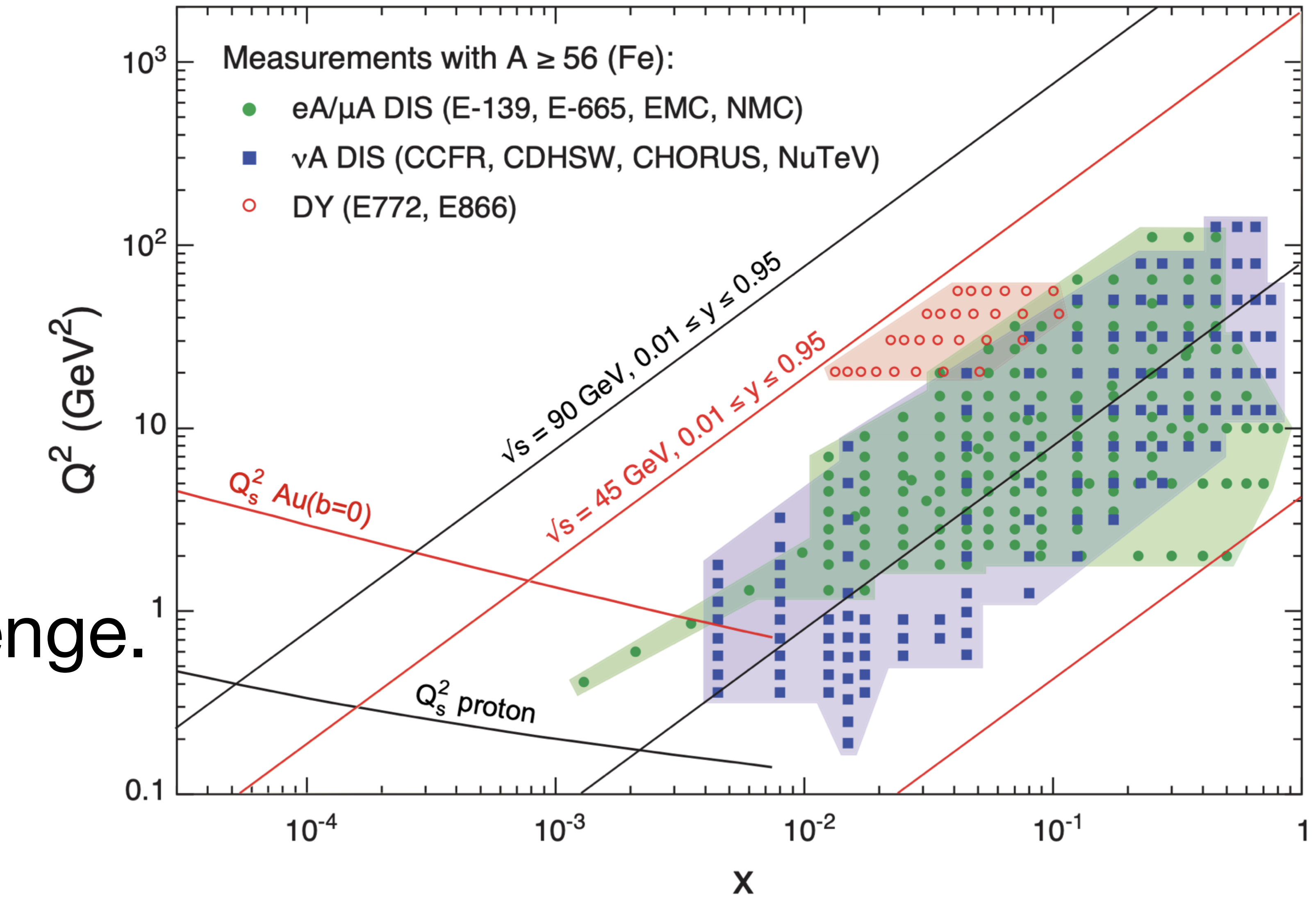
Beyond Energy loss effects

- Final-state effect

Nuclear Cold QCD: Review and Future Strategy, Arleo *et al* 2506.17454

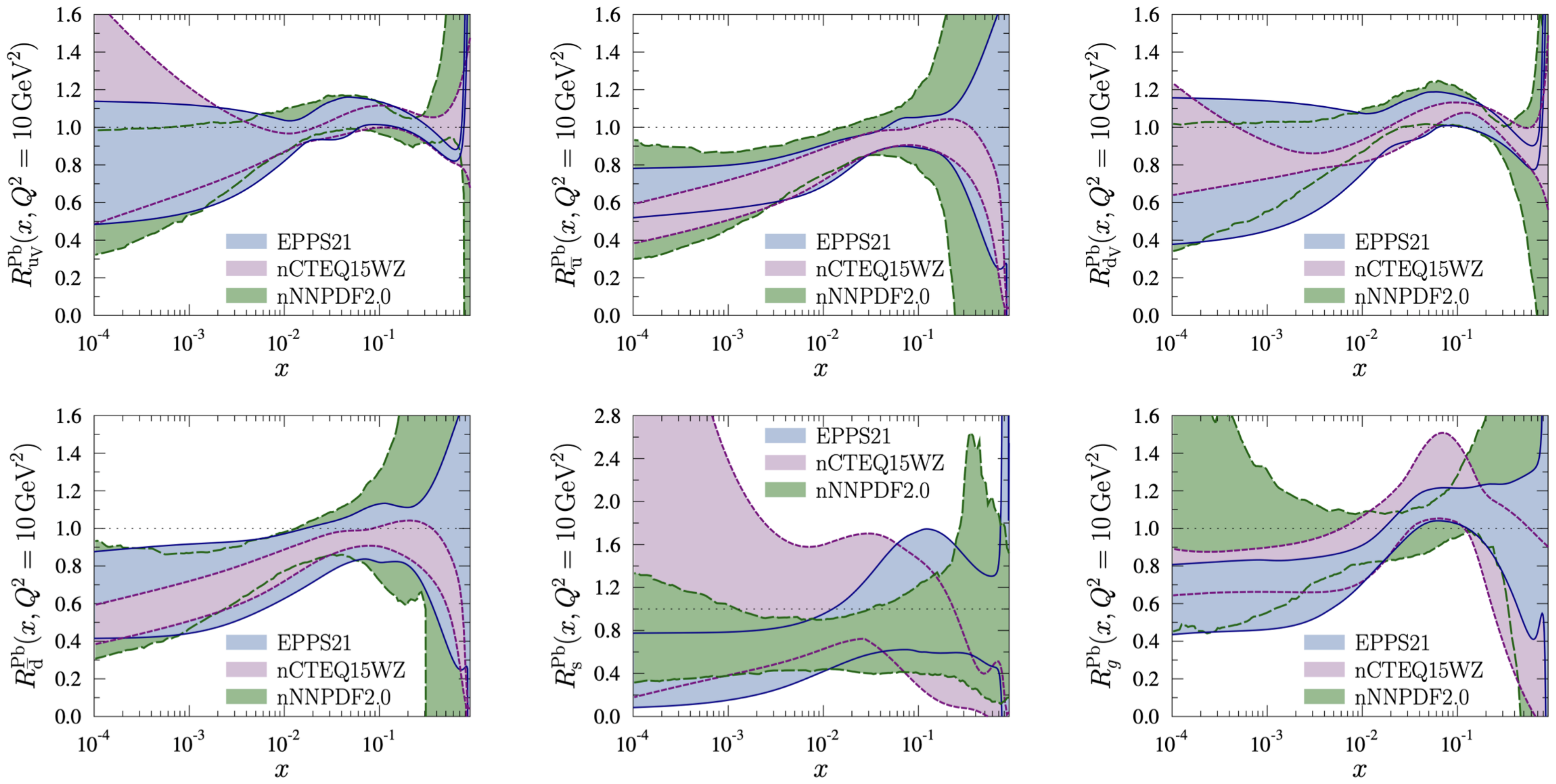
Nuclear Cold QCD

Gluon saturation (pQCD) vs nPDF (npQCD)



- Disentangling **leading-twist nPDFs from small-x saturation** is a major challenge.
- Global **nPDF fits often mix dynamic suppression** with true PDF effects.
- Inclusive, semi-inclusive, and diffractive data are key.
- Needed to separate nonperturbative effects

from saturation suppression.

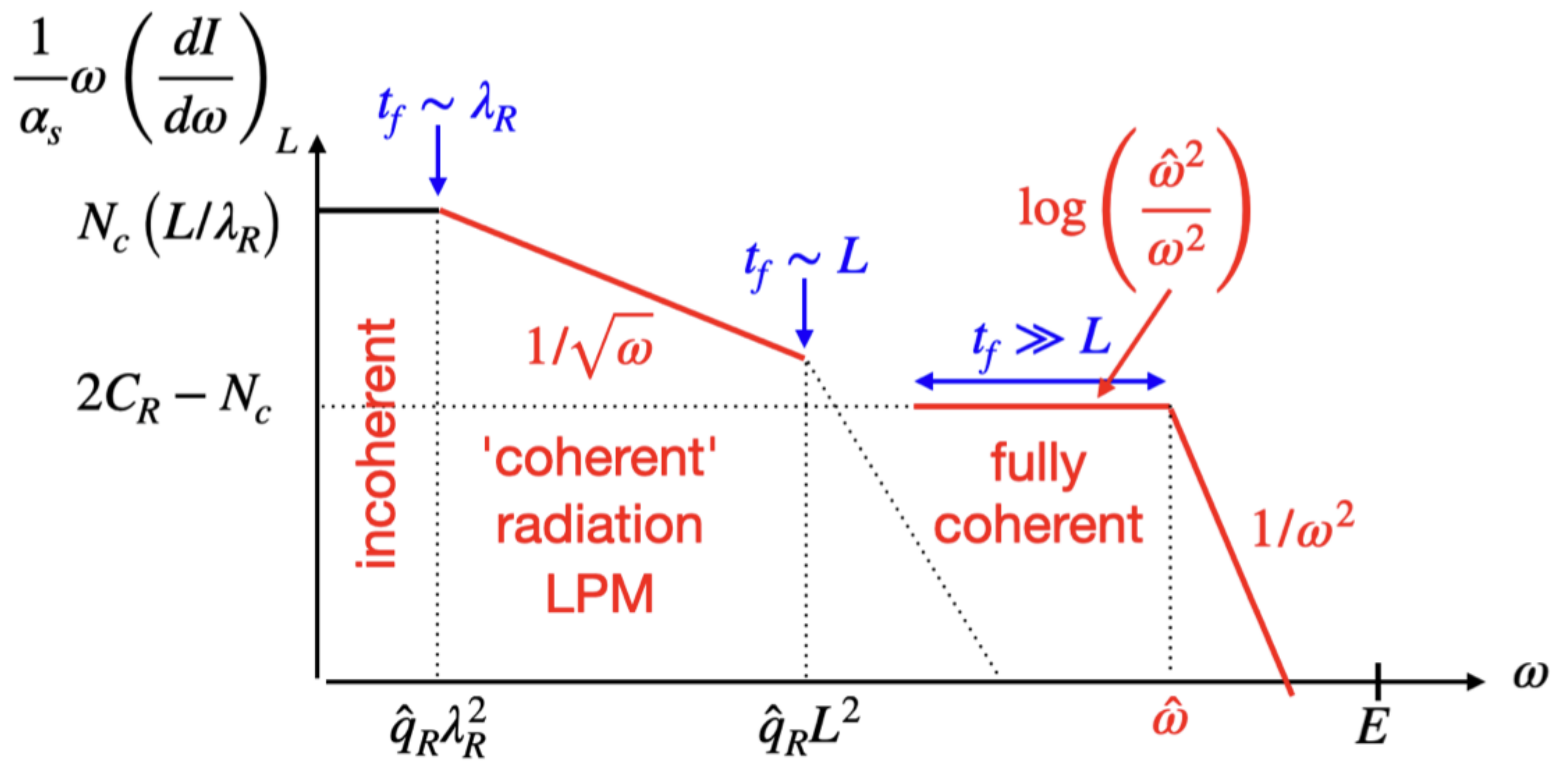


Nuclear Cold QCD: Review and Future Strategy, Arleo *et al* 2506.17454

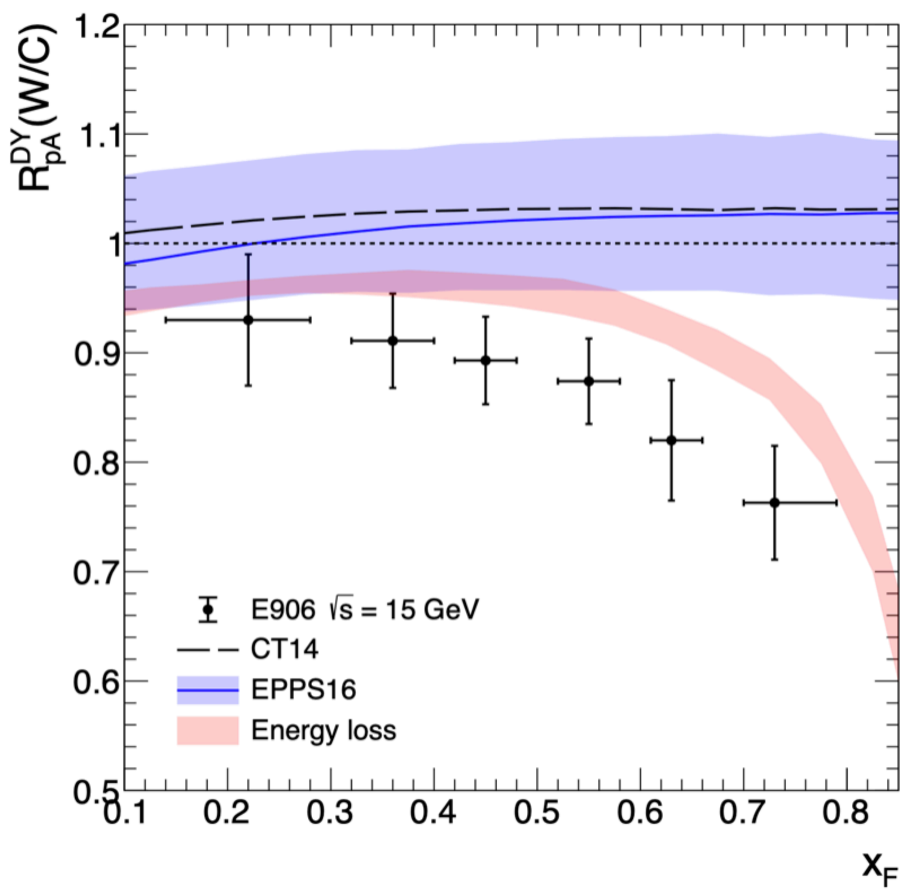
Nuclear Cold QCD

Impact of Energy loss on particles production

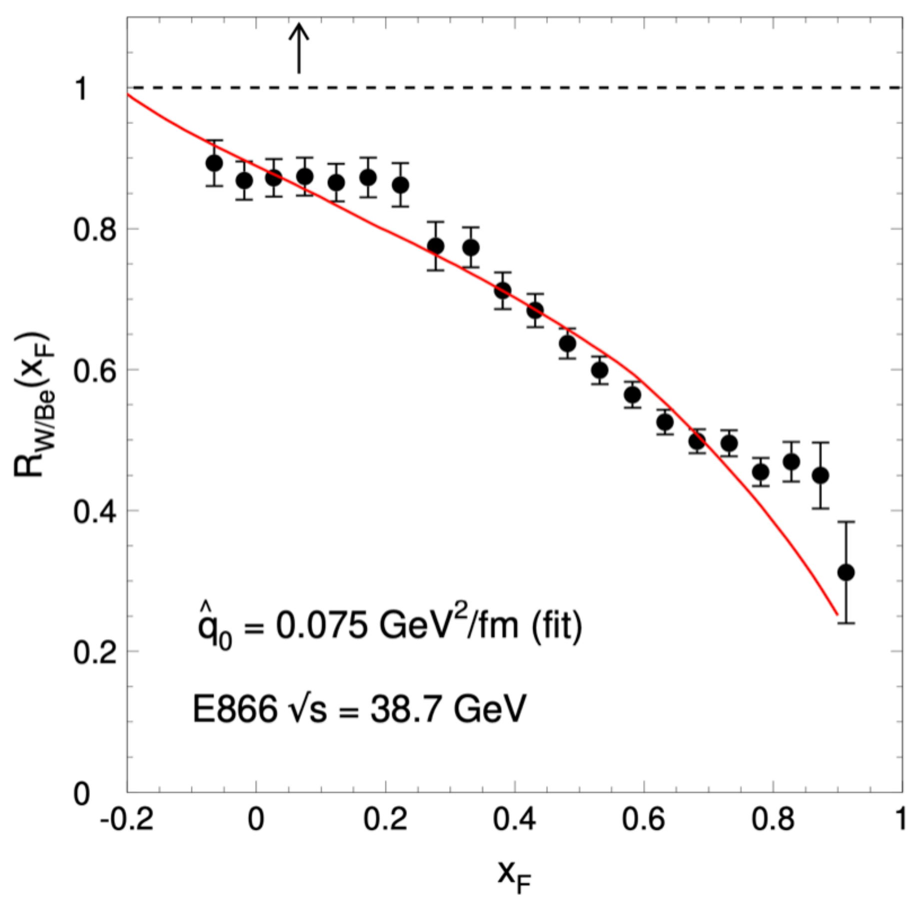
- Energy loss in cold nuclear matter varies with process and kinematics.
- No universal regime covers all observables.
- The transport coefficient $\hat{q}$ **unifies medium scattering properties.**
- Key observables and strategies help constrain $\hat{q}$.



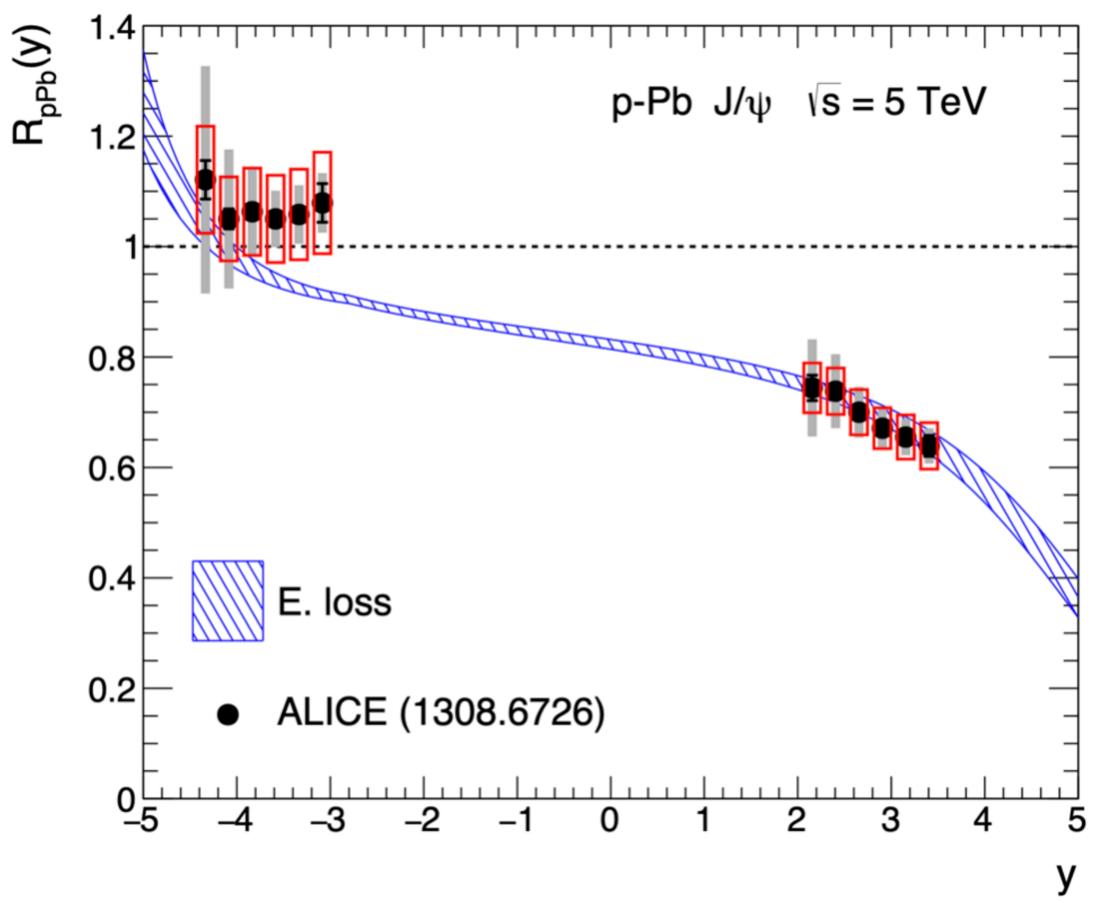
DY



J/ψ



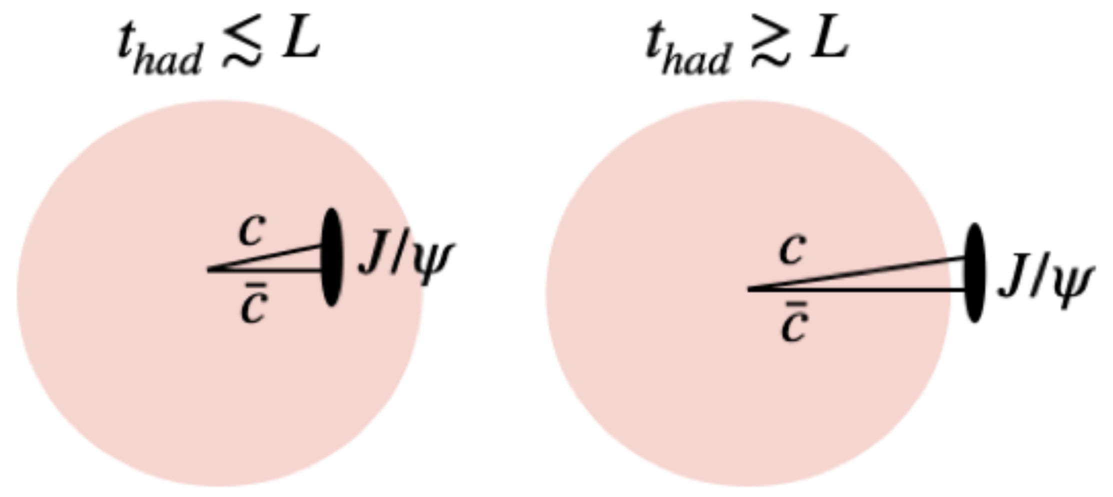
J/ψ



Nuclear Cold QCD

Nuclear Cold QCD: Review and Future Strategy, Arleo *et al* 2506.17454

Beyond Energy loss effects

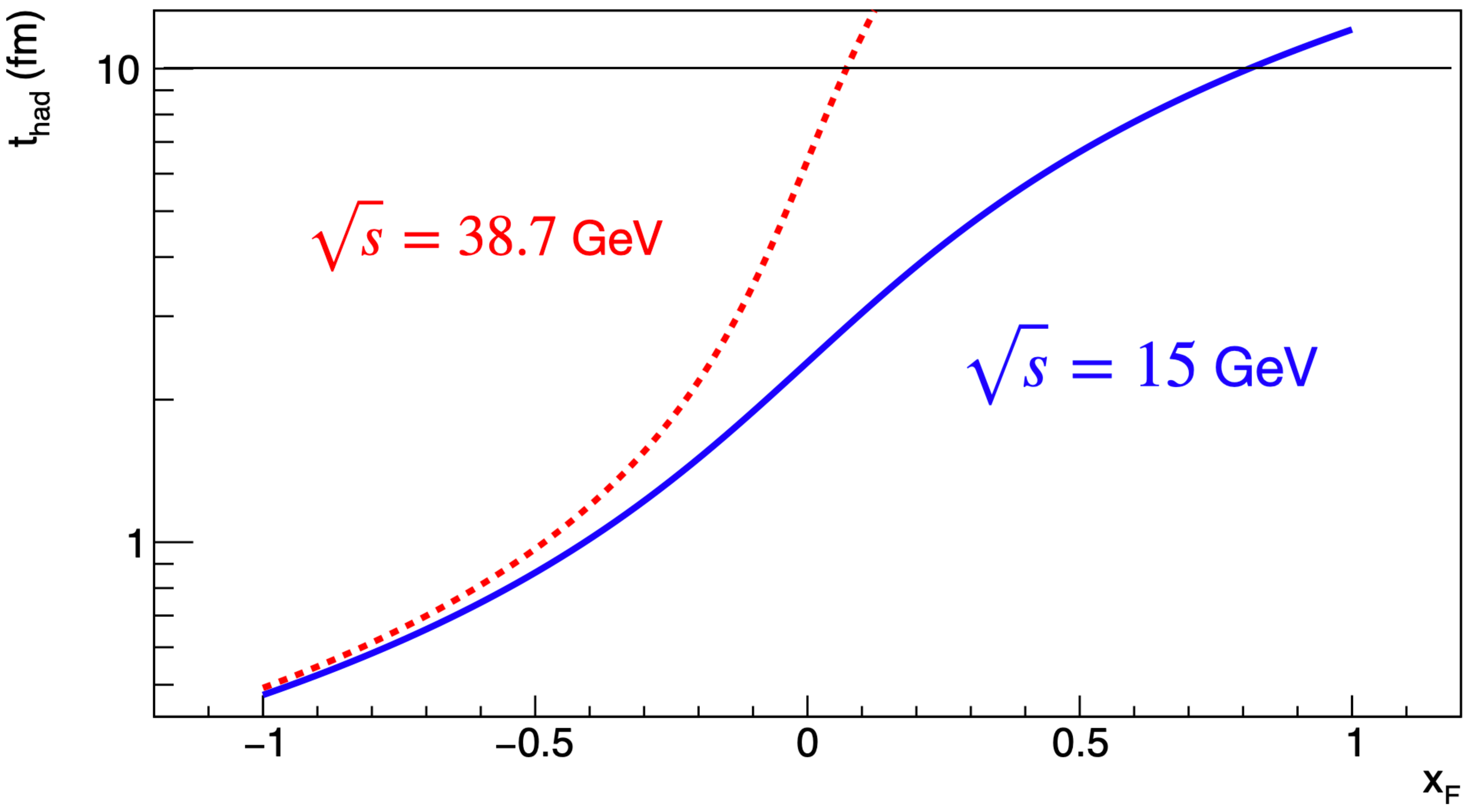


- Final-state effects (**absorption, comovers**) **suppress hadron yields**, especially at mid/backward rapidity.
- **Short formation times enhance these effects.**
- Rapidity and particle species dependence

help isolate their contribution.

- **Clear separation** from other CNM effects

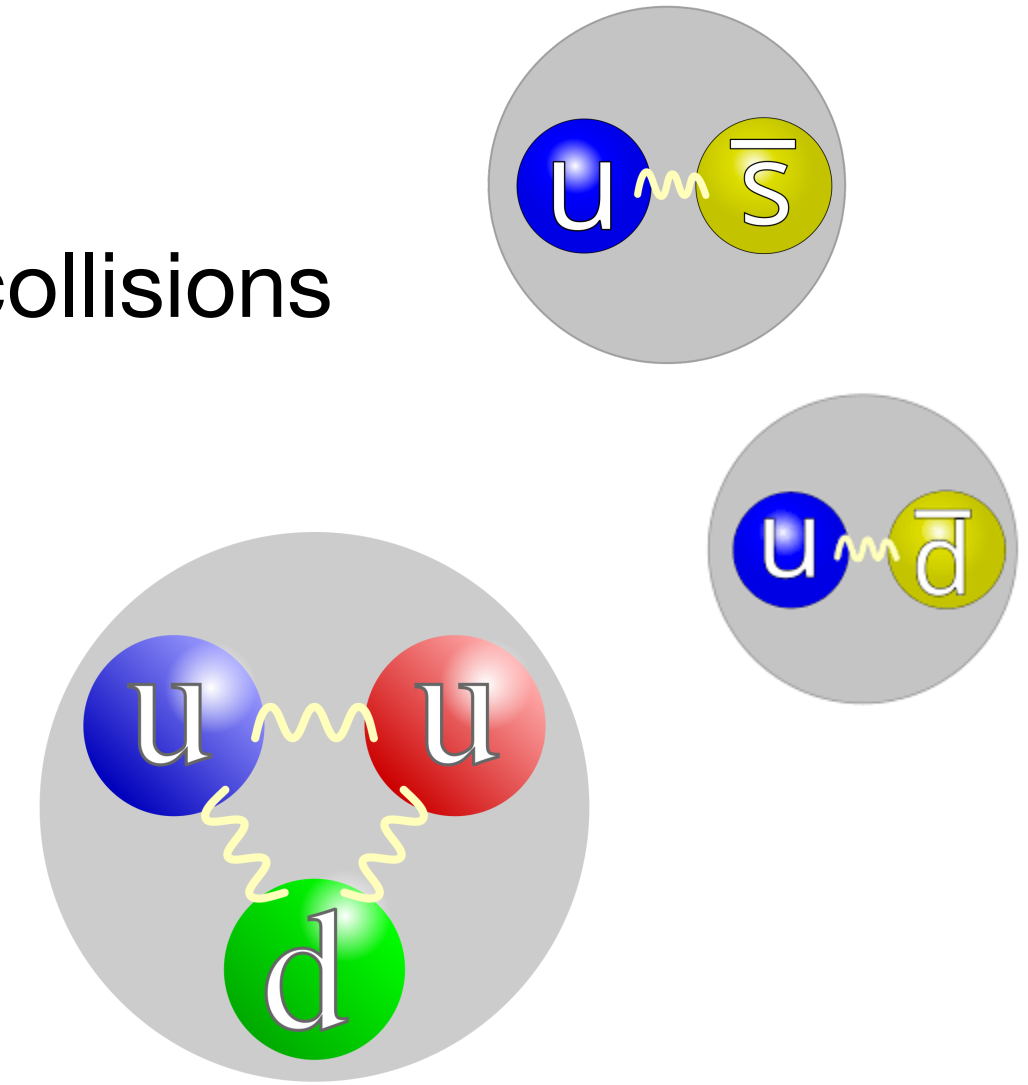
is essential to avoid misinterpretation.

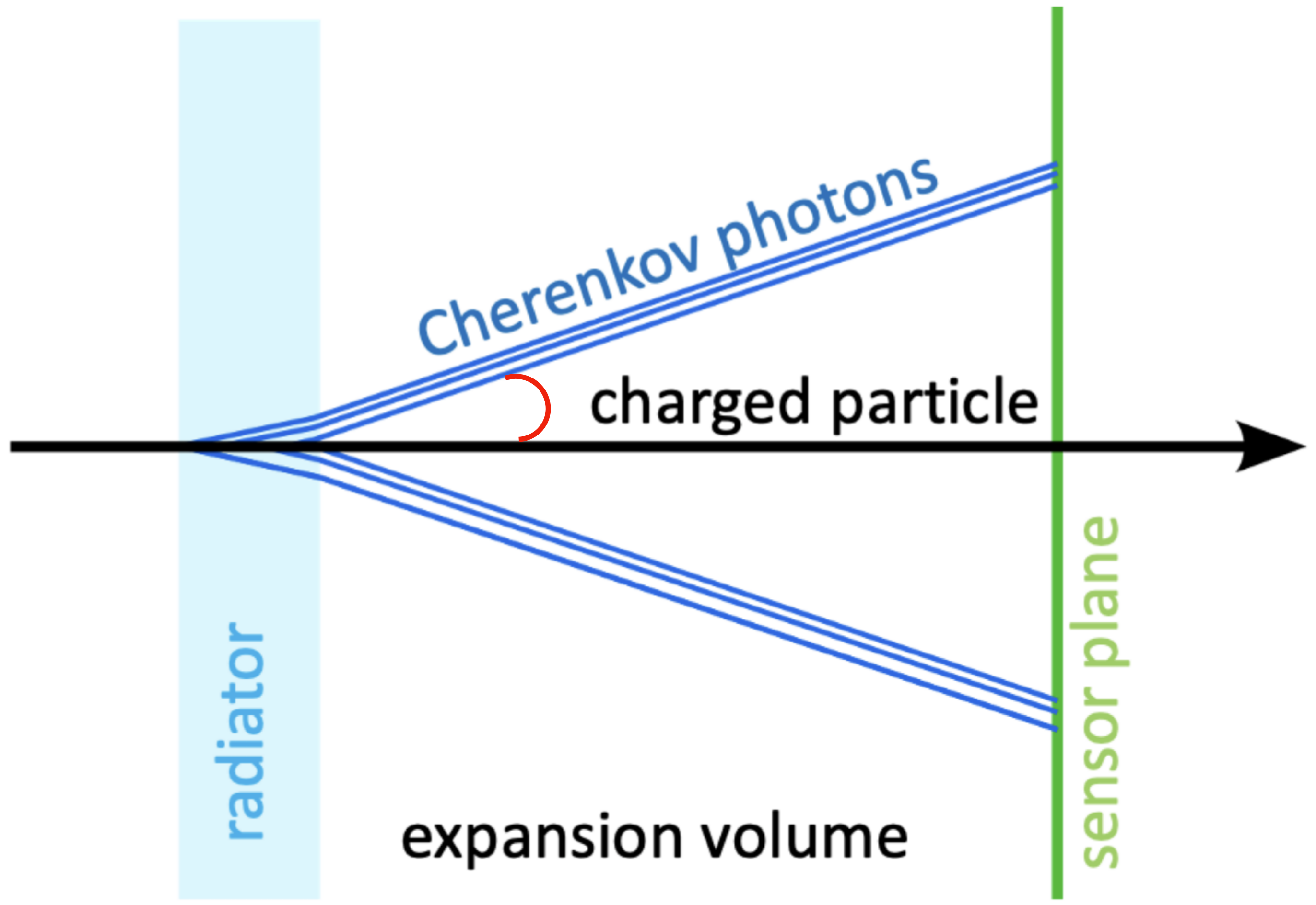


Summer student: Lucas Rhode

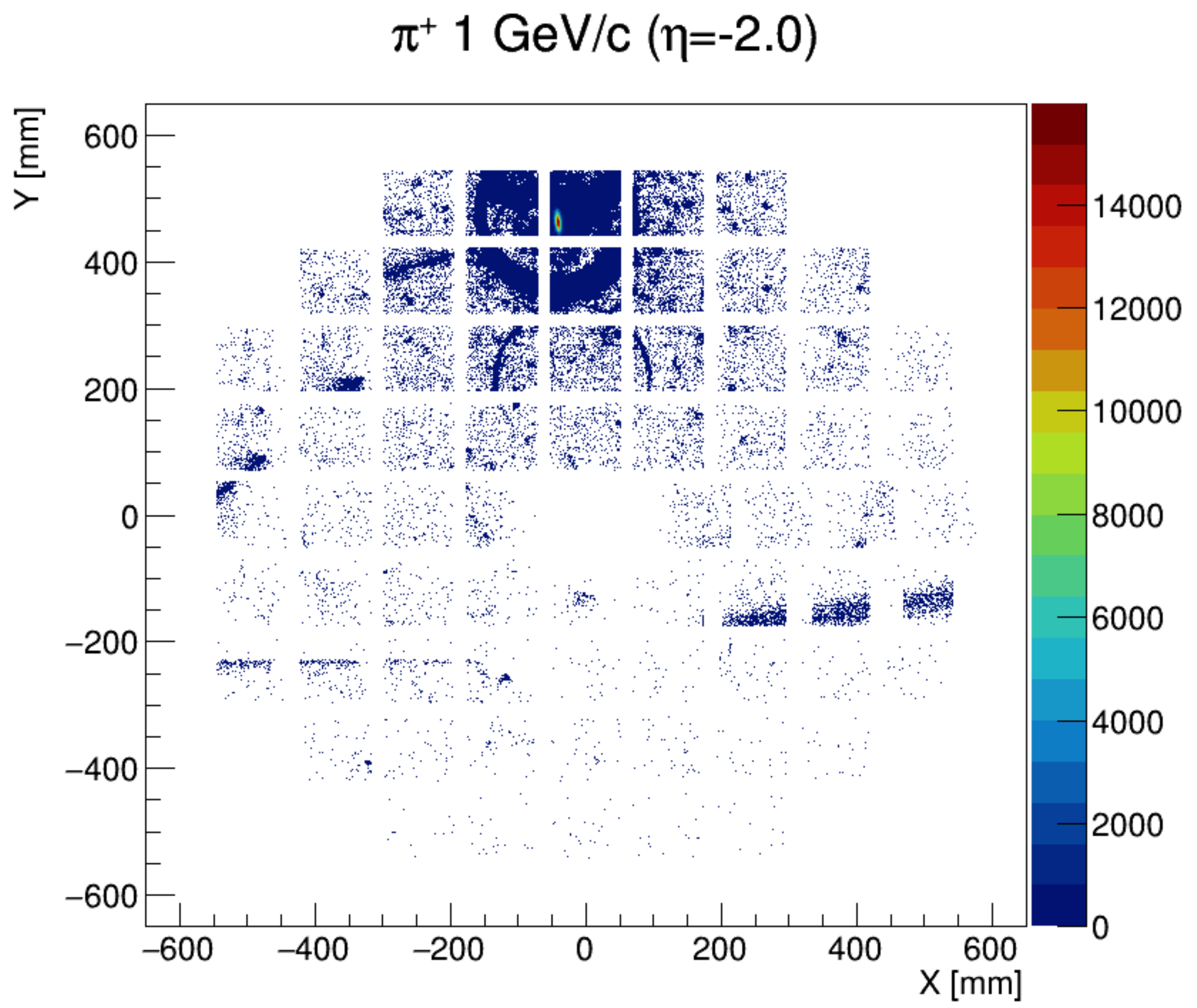
MI/ML projects at CFNS

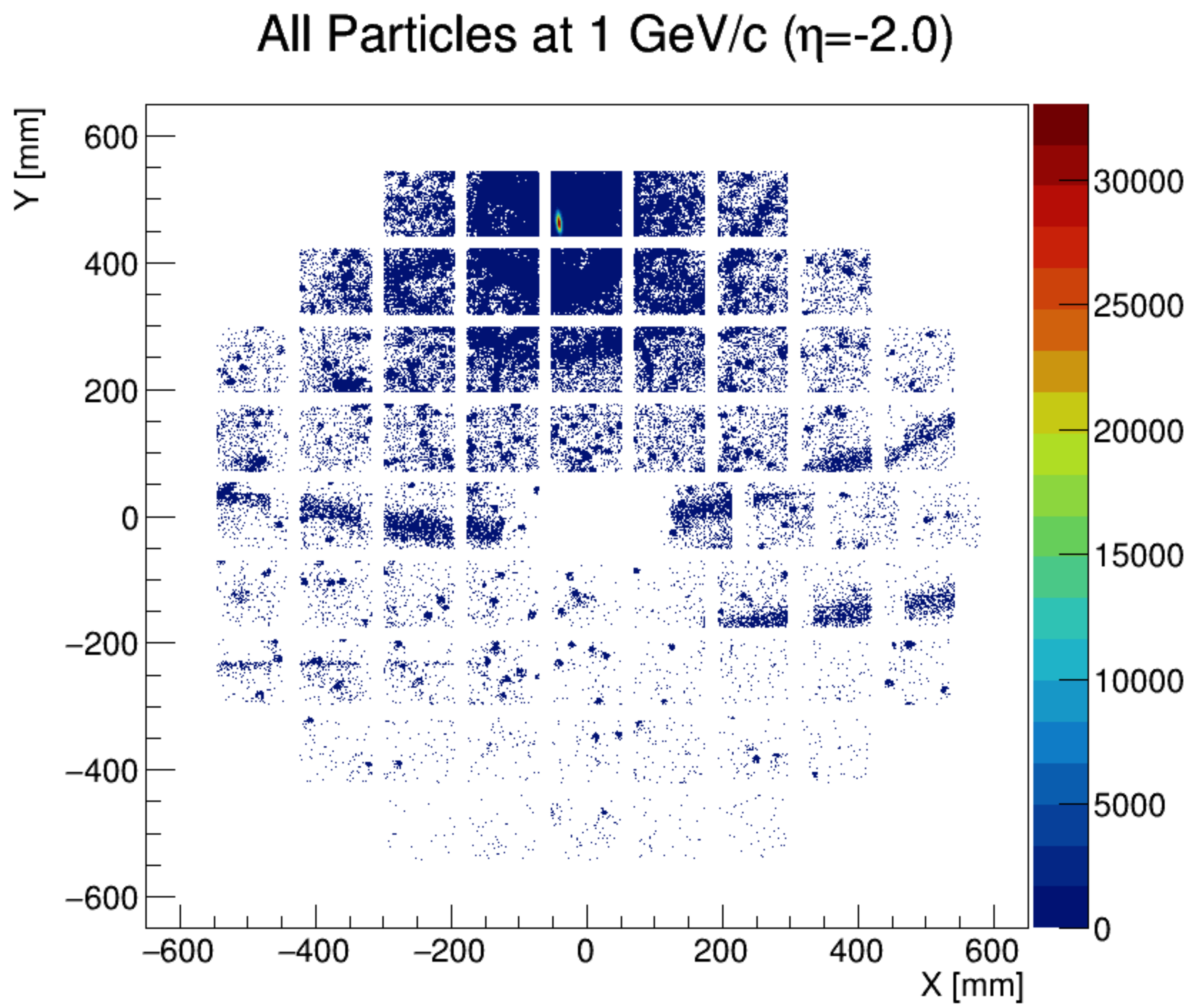
- Apply to pfRICH PID detector
- Hadrons are produced in the final state of ep(A) collisions
- The PID resolution decreases at high momentum





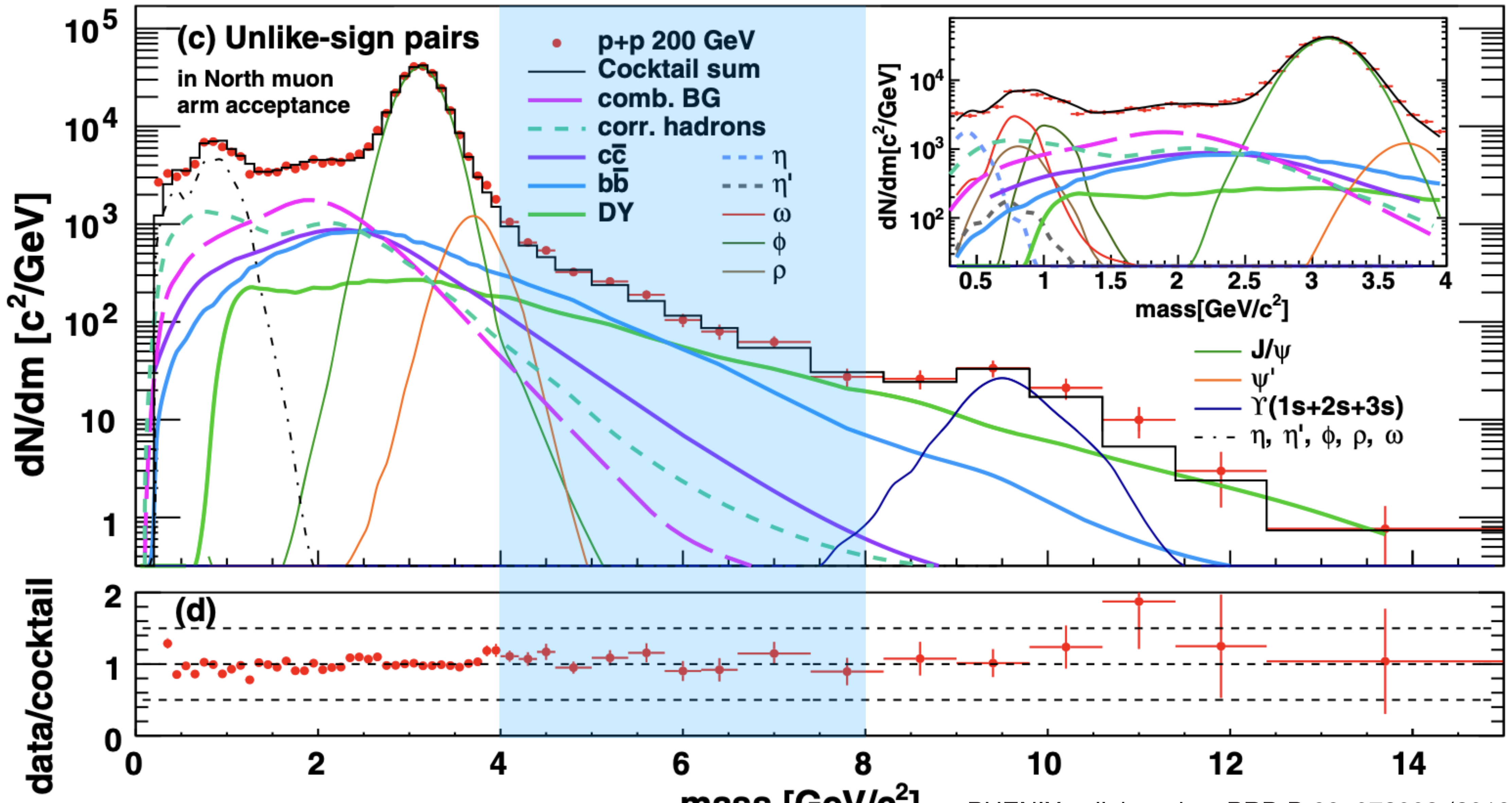
$$\theta^2 \sim \theta_{\mathrm{sat}}^2 - \frac{m^2}{p^2}$$





MI/ML projects at CFNS

- Apply to **signal extraction in dilepton production** from hadronic collisions.
- **Drell–Yan offers a clean probe** (e.g. gluon PDF at high pT): low QCD background at high invariant mass.
- Cross section decreases with mass → requires high luminosity and precision.
- **Extend the mass range to improve the statistics**.



PHENIX collaboration, PRD D 99, 072003 (2019)

Fundamental Physics to Societal Applications

Collaboration with Nuclear Non Proliferation at BNL

- AI/ML group member applying methods to nuclear nonproliferation.
- Simulating uranium enrichment with multi-detector gamma setups.
- Gamma spectroscopy with semiconductor detectors for nuclear material identification.

Next steps and directions

- Leading the pfRICH assembly protocol and preparing the final detector at SBU.
- Advancing global analyses of cold QCD in nuclear environments.
- Contributing to JLab physics in preparation for the EIC; advocating for a fixed-target program at IP8.
- Fostering interdisciplinary work between nuclear nonproliferation and fundamental physics.