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U.S. DEPARTMENT of ENERGY

Nuclear Modification of Identified Hadrons in Small Collision Systems at RHIC

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Overview

- ★ Motivation
- ★ RHIC and STAR
- ★ Analysis method
- ★ Results: $R_h^{pA}(z, j_T)$
- ★ Conclusion and next steps

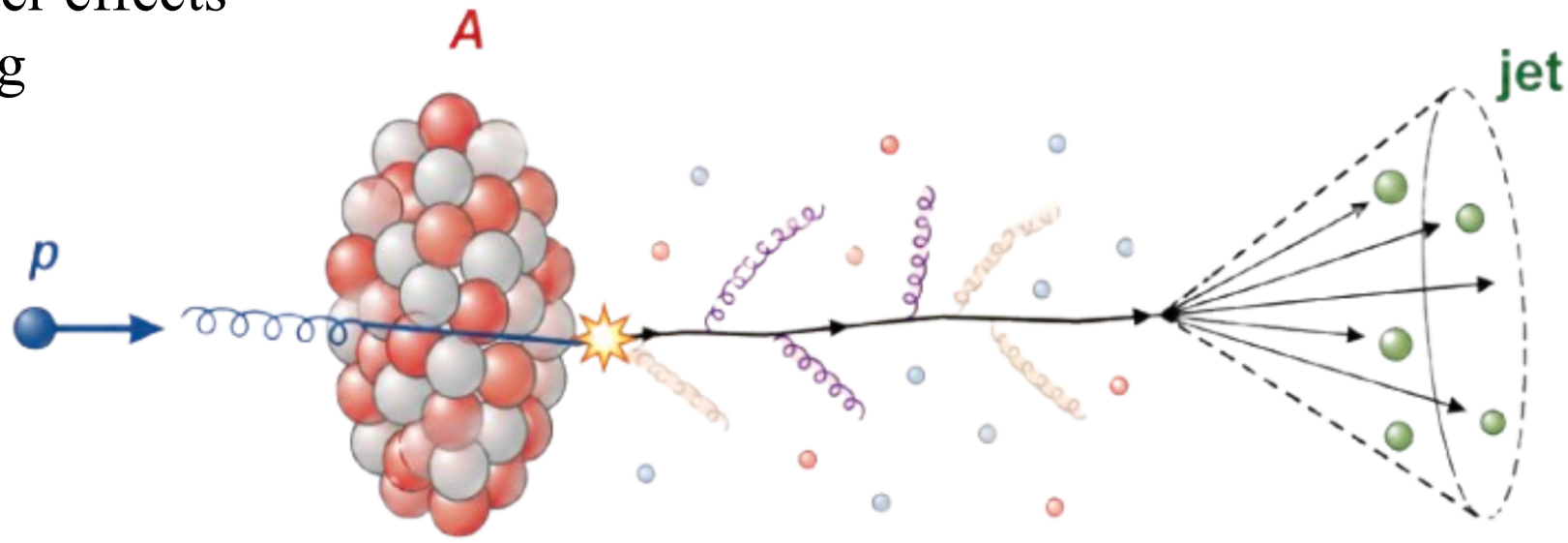
Motivation: Why Fragmentation in Nuclear Matter?

★ Understand how QCD hadronization is modified in a nuclear environment

★ Fragmentation Functions (FFs) encode parton → hadron transition

★ Sensitive to:

- Cold nuclear matter effects
- Multiple scattering
- Energy loss

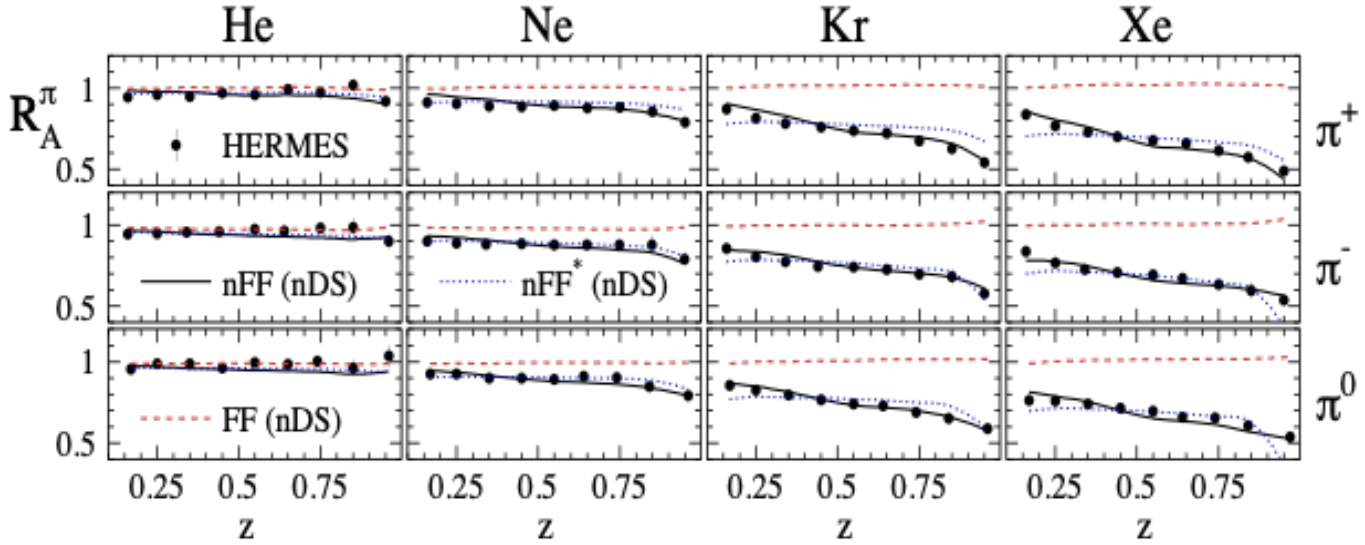


Motivation: Complementarity: e+A vs p+A

★ HERMES measured:

$R_h^A = (N_h/N_{DIS})^{eA}/(N_h/N_{DIS})^{ep}$

- e+A: clean, separate initial and final state effects



RHIC Cold QCD Plan, https://arxiv.org/abs/1602.03922

★ In p+A at RHIC: **Jet** as a proxy for struck parton → Separate final state effects

★ p+A: includes nuclear PDFs + multi-parton interaction

★ Important reference for future EIC

RHIC: Relativistic Heavy Ion Collider

★ Run year: 2015

★ Systems and CM energies:

- p+p (baseline):

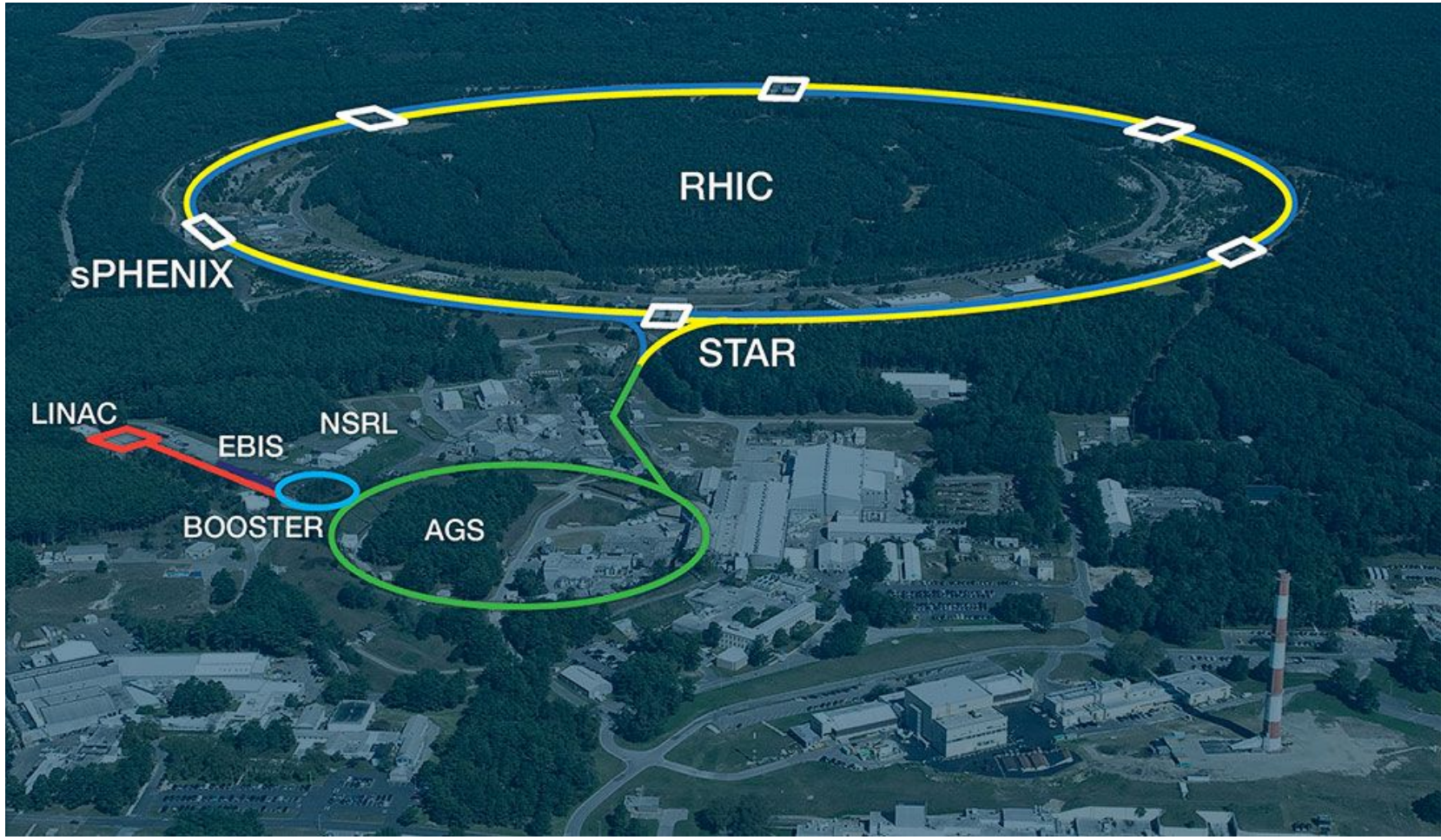
  $\sqrt{s} = 200\,\text{GeV}$

- p+Al:

  $\sqrt{s_{NN}} = 201\,\text{GeV}$

- p+Au:

  $\sqrt{s_{NN}} = 201\,\text{GeV}$



STAR: Solenoidal Tracker At RHIC

★ **TPC**: Tracking and dE/dx PID

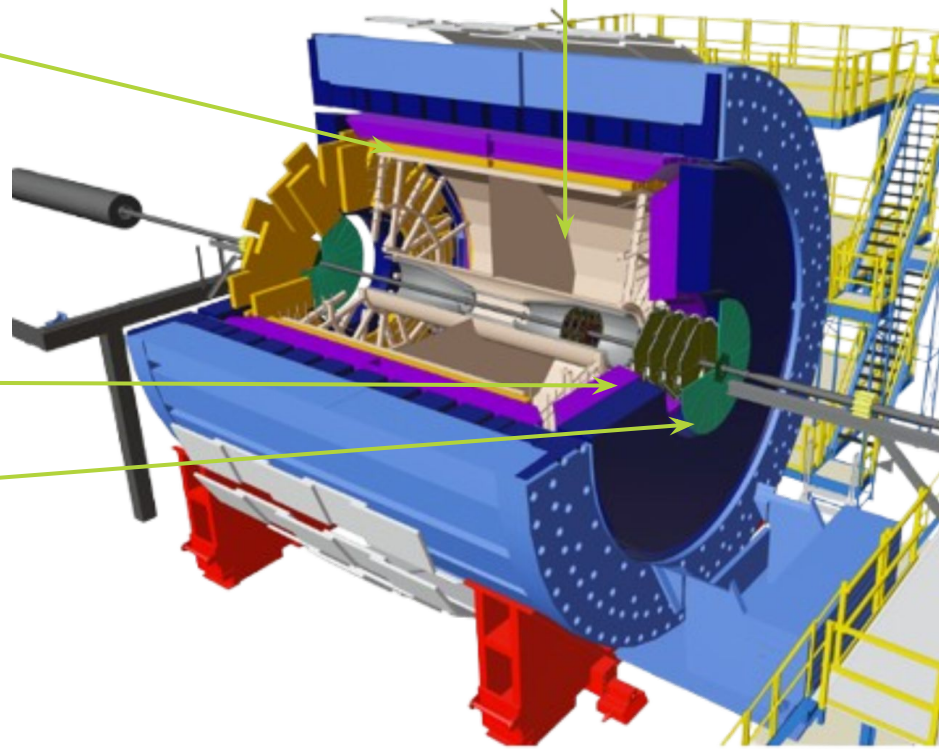
- $|\eta| < 1.3$
- Identifies π, K, p via ionization energy loss

★ **TOF**: mass^2 PID via time of flight

- $|\eta| < 1.0$
- Combined TPC+TOF:
  clean π/K/p separation

★ **BEMC** and **EEMC**: Jet reconstruction

★ **BBC** and **VPD**: Triggering



Analysis method: Event and jet selection

- ★ Minimum Bias (MB) triggers
- ★ Events selected based on vertex information
  at least one jet required
- ★ Jets are reconstructed with anti-k_T algorithm (R=0.6)
  - ○ Minimum p_T^{jet} required
  - ○ pseudo-rapidity window required for jet axis
  - ○ Minimum number of tracks and p_T^{track} requirements

Event level	
Number of vtx.	≥1
vtx. ranking	≥ 1e6
$\|z_{vtx}\|$	≤ 60 cm
Number of jets	≥1
Jet level	
p_T^{jet} (MB)	≥ 4 GeV/c
$\|\eta\|$	≤ 0.9
Single p_T^{track}	< 20 GeV/c
Sum p_T^{track}	≥ 0.5 GeV/c
N_{tracks}	> 1

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Analysis method: Track and PID selection

★ Track kinematics:

- Momentum fraction $z = \frac{|\vec{p}^{\,track}|}{|\vec{p}^{\,jet}|}$
- Transverse component $j_T = |\vec{p}^{\,track} \times \hat{p}^{jet}|$

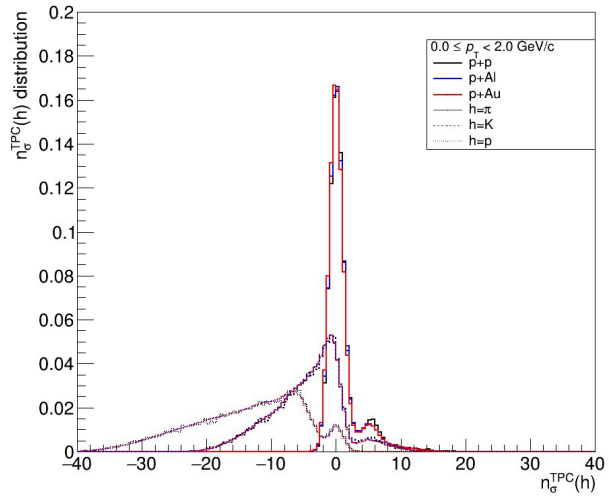
★ Minimum z requirement

★ Minimum number of hits in TPC requirement

★ **PID**: n_σ from hadron species and invariant mass window required

- For **systematics**: $|n_\sigma(h)| < 2.0$ (4.0)

Track level	
z	≥ 0.05
(nhits dEdx)/nhits	≥ 0.5
$\lvert n_\sigma^{TPC}(h)\rvert$	< 3.0
$\lvert n_\sigma^{TOF}(h)\rvert$	< 3.0
$\lvert m^2_{TOF} - m^2_h\rvert$	< 0.1



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Analysis method: Observable definition

★ Hadron in jet → Sensitive to final state

- Per-jet yield of identified hadrons (h=π,K,p)

$$D_h\left(z, j_T\right) = \frac{1}{N_{jets}} \frac{dN_h}{dz dj_T}$$

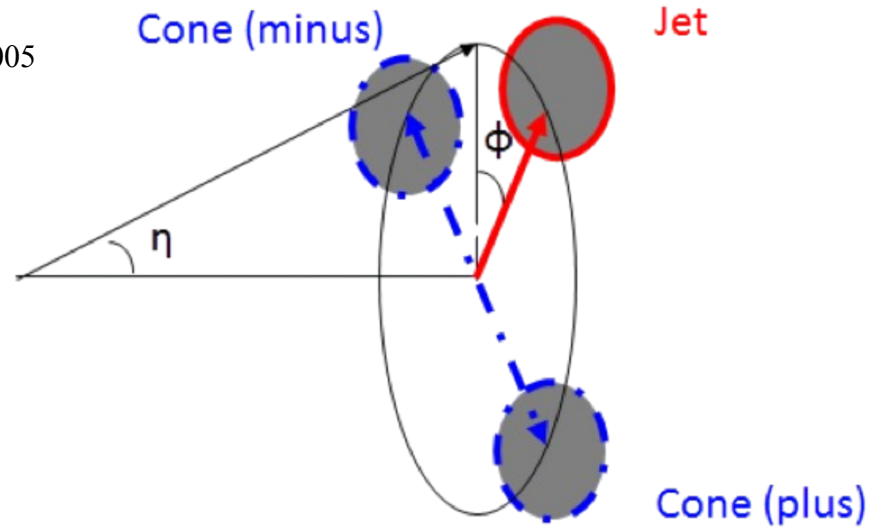
- Nuclear modification factor

$$R_h^{pA}\left(z, j_T\right) = \frac{D_h^{pA}\left(z, j_T\right)}{D_h^{pp}\left(z, j_T\right)}$$

Analysis method: Underlying Event (UE) correction

★ UE estimated using off-axis cone method (Standard at STAR) STAR Collaboration, 10.1103/PhysRevD.100.052005

- Two perpendicular cones placed at same η as jet, ±90° in ϕ
- UE cone radius R=0.6
  Effective UE area = $2A^{jet}$
  UE per-jet yield = 0.5 per-cone yield



★ Subtract UE bin-by-bin in (z, j_T) before ratio

$$D_h^{corr}(z, j_T) = D_h^{raw}(z, j_T) - D_h^{UE}(z, j_T)$$

Results: $R_{\pi}^{pA}(z, j_T)$ → Pions

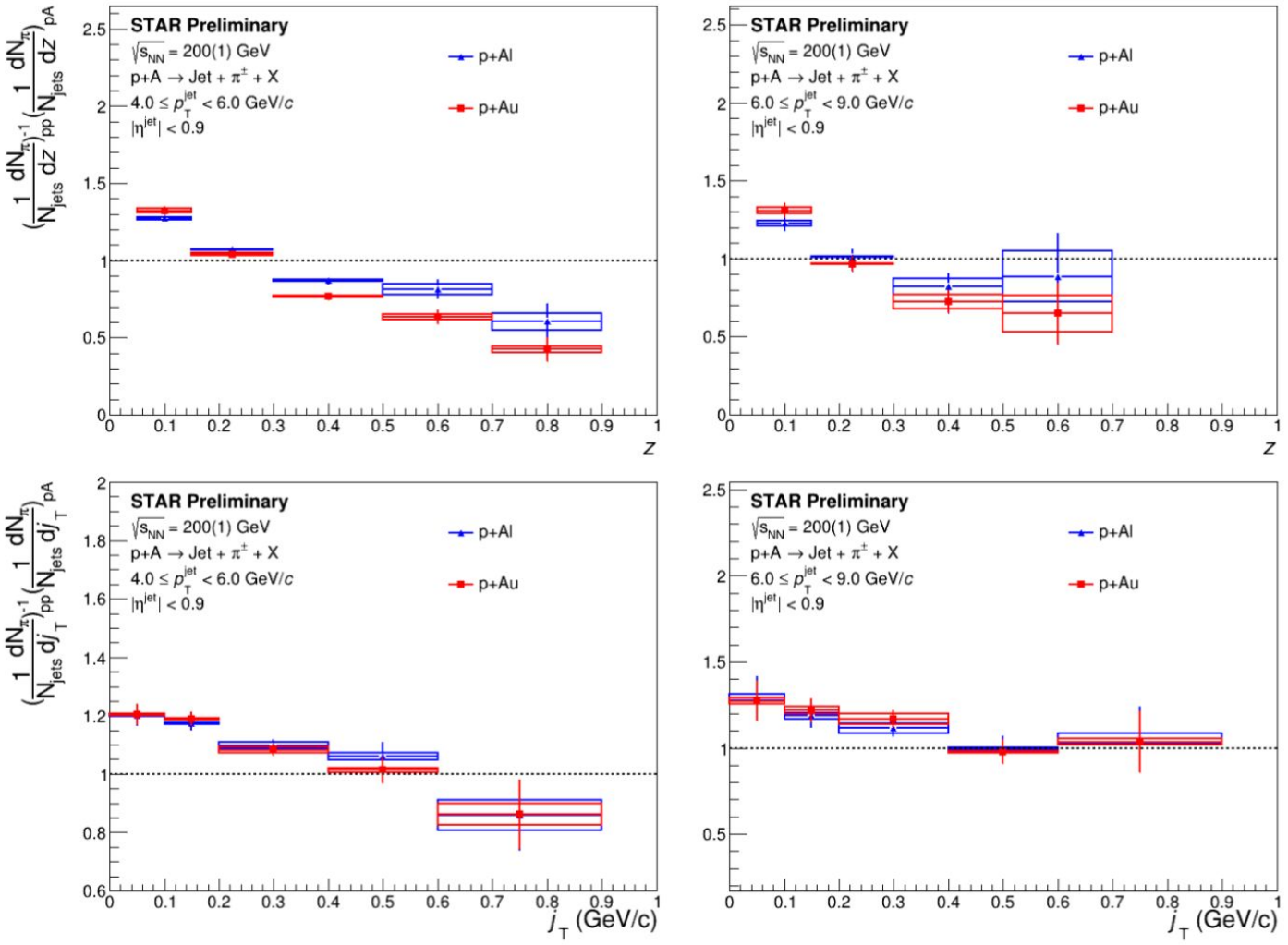
★ Enhancement at low z suppression at high z

- Effect stronger in p+Au than p+Al
- Consistent pattern across p_T^{jet}

★ Enhancement above unity in j_T

- Similar effect in p+Au and p+Al

p_T^{jet}: [4.0 , 6.0] GeV/c [6.0 , 9.0] GeV/c



Results: $R_K^{pA}(z, j_T)$ → Kaons

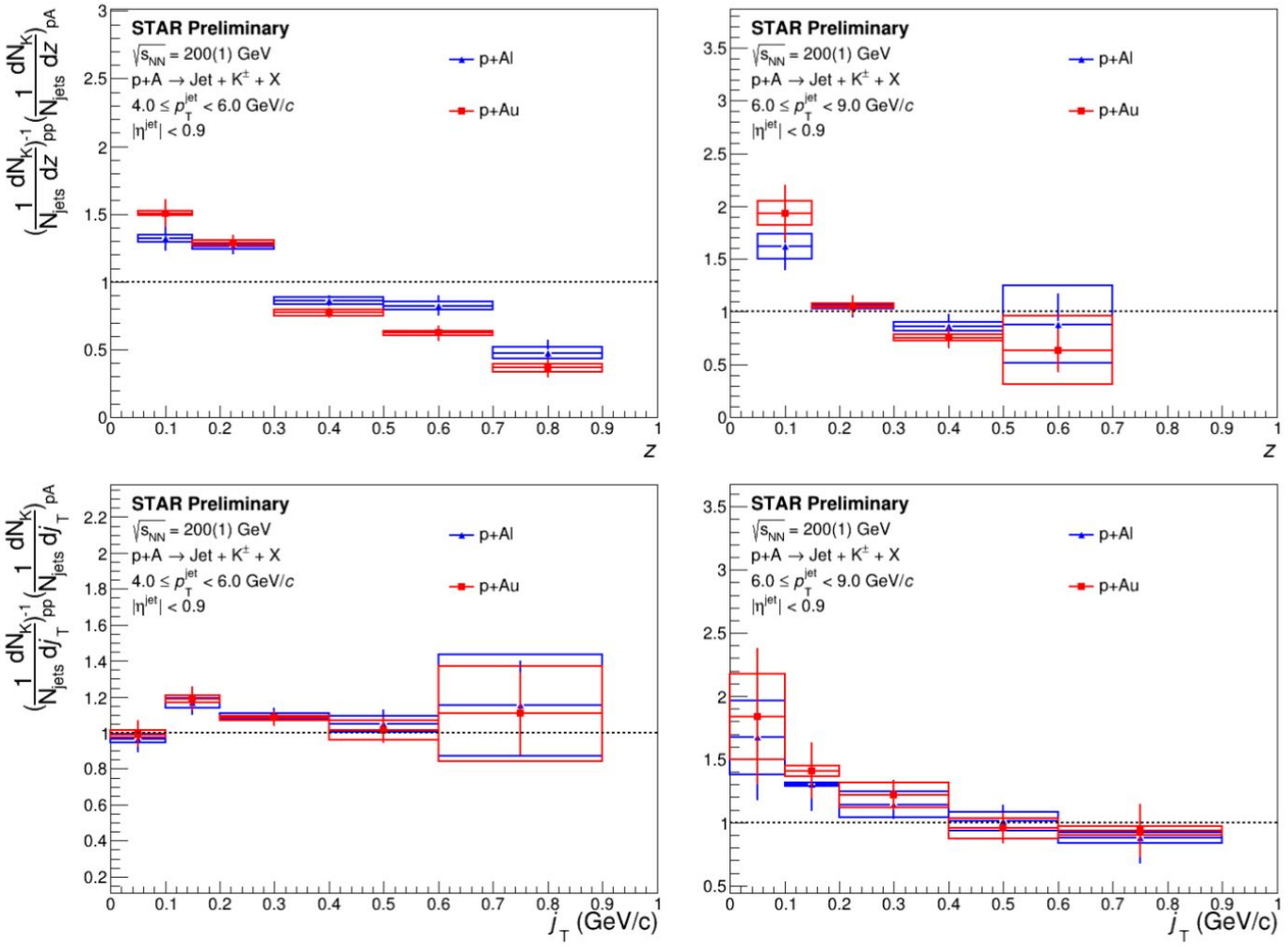
★ Enhancement at low z suppression at high z

- More pronounced effects compared to pions
- Effect stronger in p+Au than p+Al
- Consistent pattern across p_T^{jet}

★ Enhancement above unity in j_T

- Higher enhancement compared to pions

p_T^{jet}: [4.0 , 6.0] GeV/c [6.0 , 9.0] GeV/c



Results: $R_p^{pA}(z, j_T) \rightarrow$ Protons

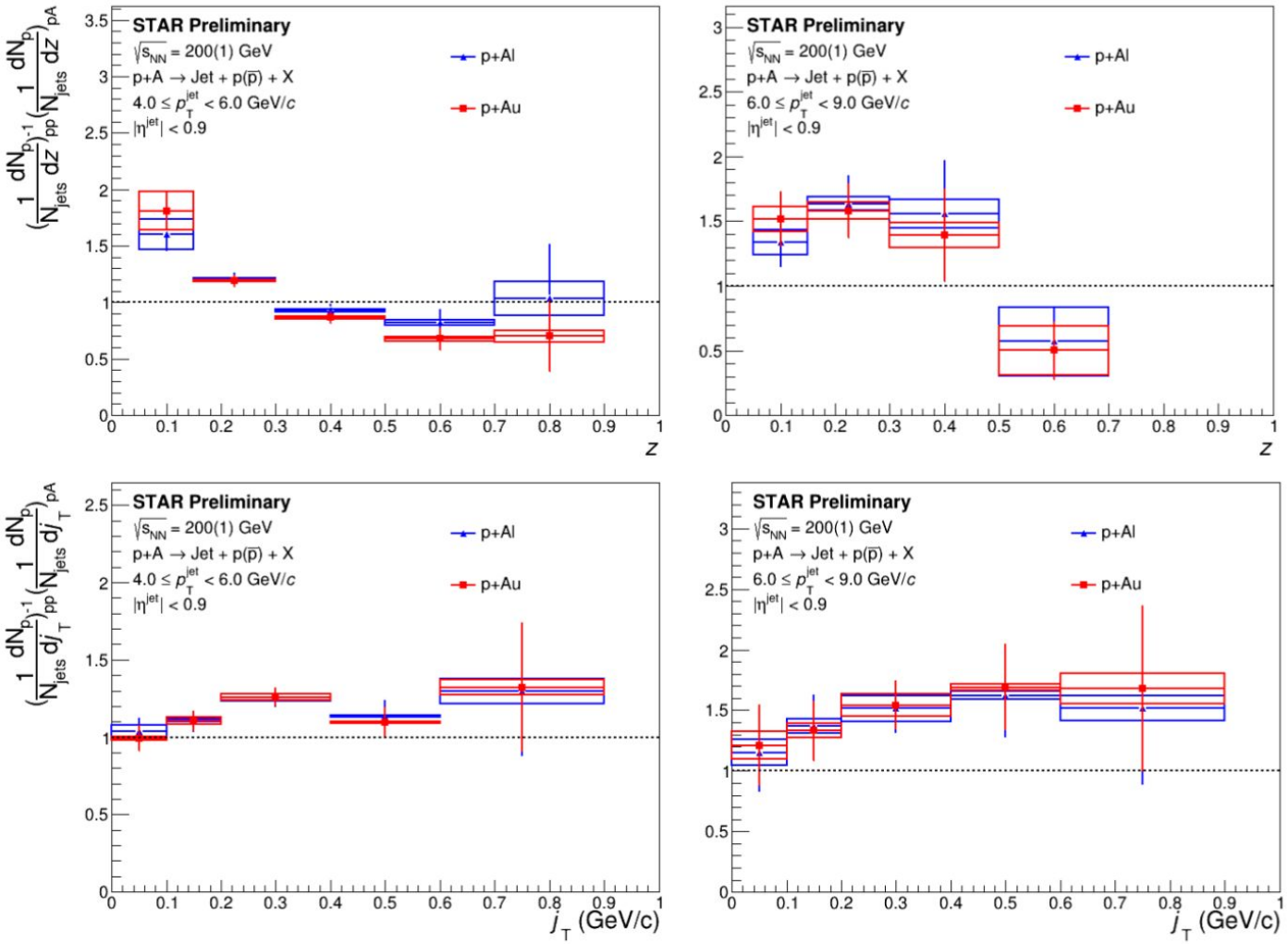
★ Enhancement at low z
suppression at high z

- Higher enhancement compared to mesons
- Suppression at high z consistent within uncertainties with mesons

★ Enhancement above unity in j_T

- Higher enhancement compared to mesons for [6.0 , 9.0] GeV/c

p_T^{jet}: [4.0 , 6.0] GeV/c [6.0 , 9.0] GeV/c



Conclusion and next steps:

★ First STAR observation of nuclear modification of identified hadrons (π, K, p) inside jets in p+Al and p+Au collisions at $\sqrt{s} = 200\,\mathrm{GeV}$

- Enhancement at low z and suppression at high z observed for all species
- Stronger effect in p+Au than p+Al, consistent with nuclear size dependence
- Ratio above unity in j_T for all hadron species, different behaviour for proton

★ Results complement HERMES e+A measurements and provide an important cold nuclear matter reference for the future EIC

Next steps:

★ Full unfolding of detector effects and jet energy scale corrections
★ Extension to higher p_T^{jet}
★ Expand systematic uncertainty studies
★ Separation of particle and antiparticle

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