

PHENIX Results on Reconstructed Jets in $p+p$, $d+Au$, & $Cu+Au$ Collisions

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for the **PHENIX** Collaboration

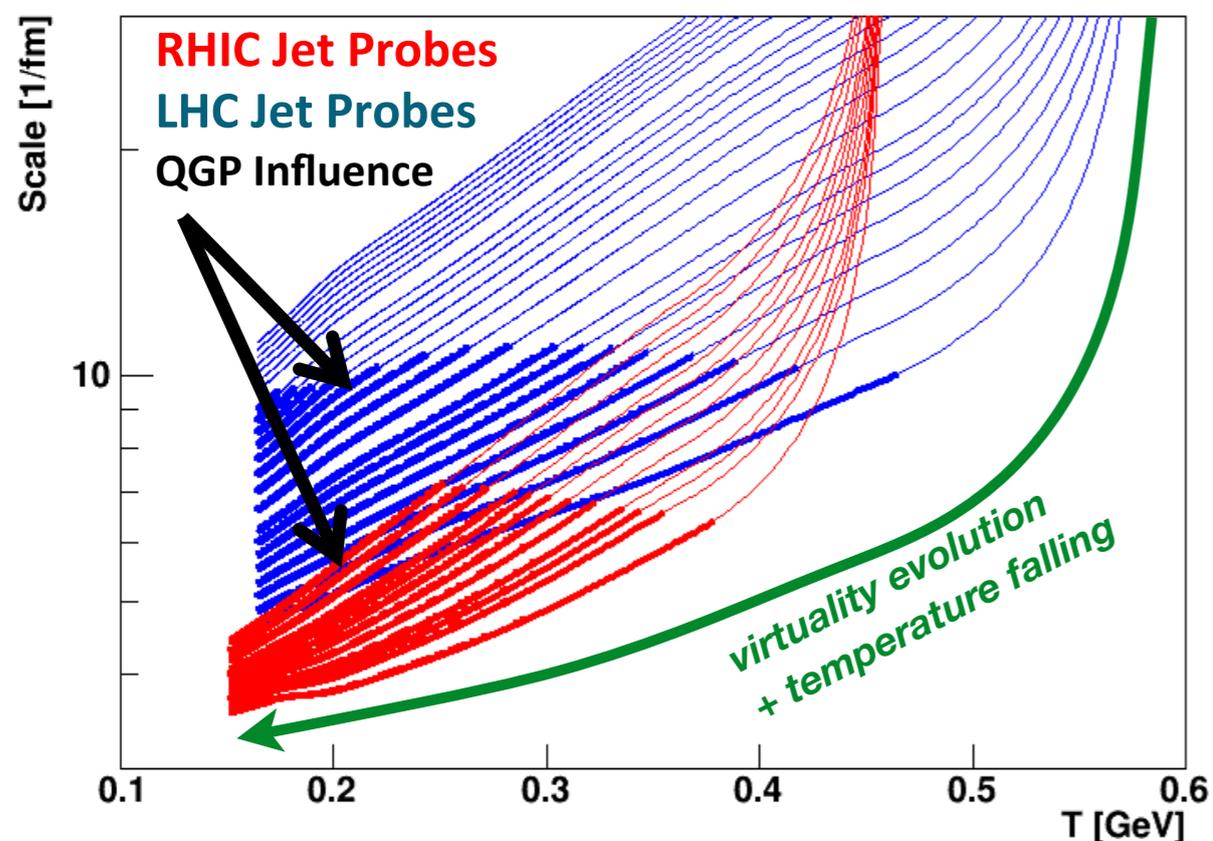
Winter Workshop on Nuclear Dynamics 2016

Guadeloupe
March 4th 2016

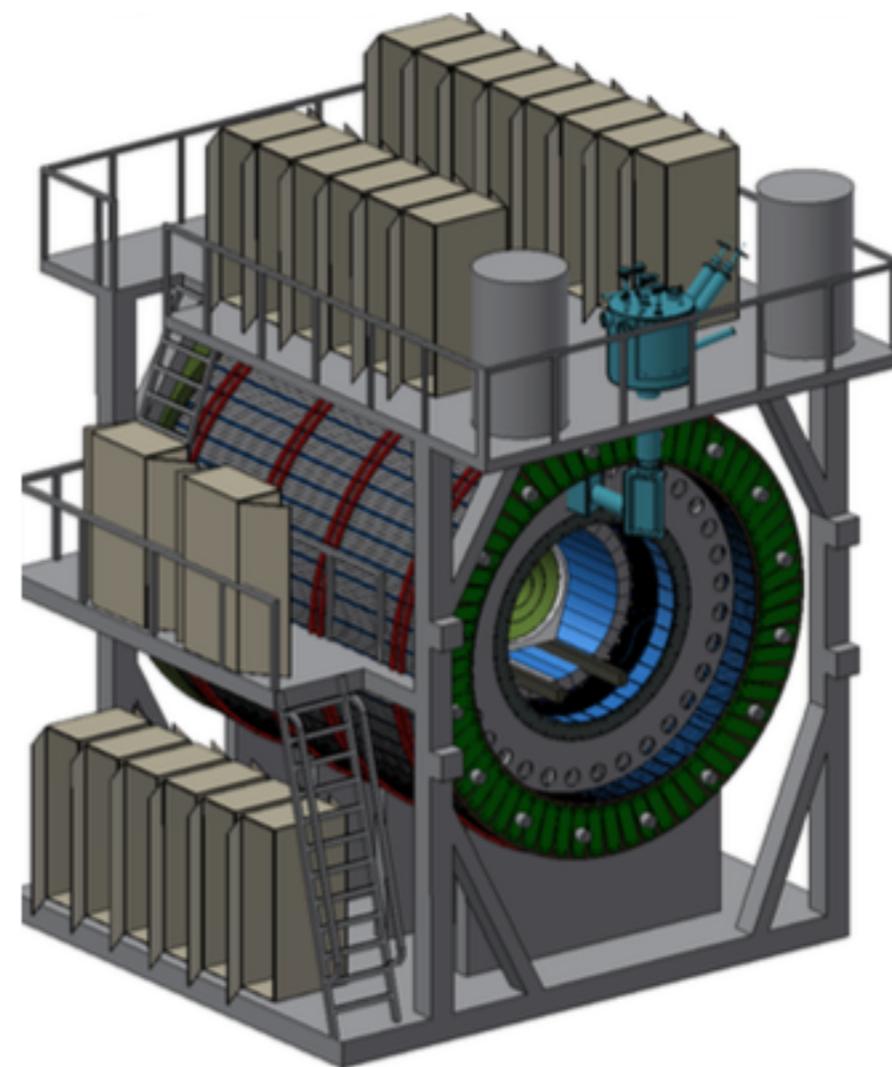
Reconstructing Jets at RHIC

Rich program of jet observables at the LHC is leading an entirely new program for studying the plasma

Jets at RHIC interact with the QGP:
 for a **larger time fraction**
 at **larger length scales** in medium
 at **temperatures closer to T_c**

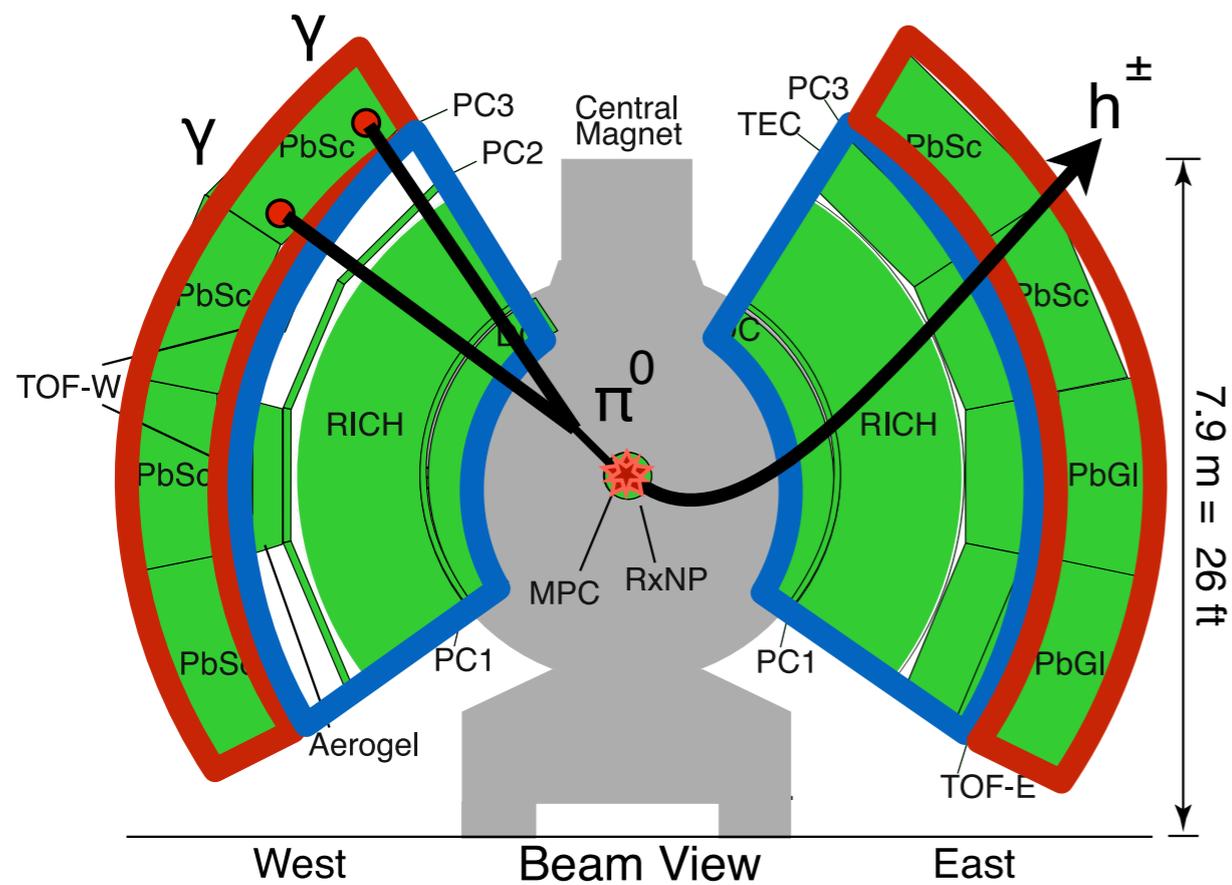


Things to come...  **PHENIX**



New sPHENIX detector will follow through fully on this program
 (stay for Megan's talk later this morning)

PHENIX Detector



Meanwhile at... **PHENIX**

Electromagnetic Calorimeters for photon and electron clusters

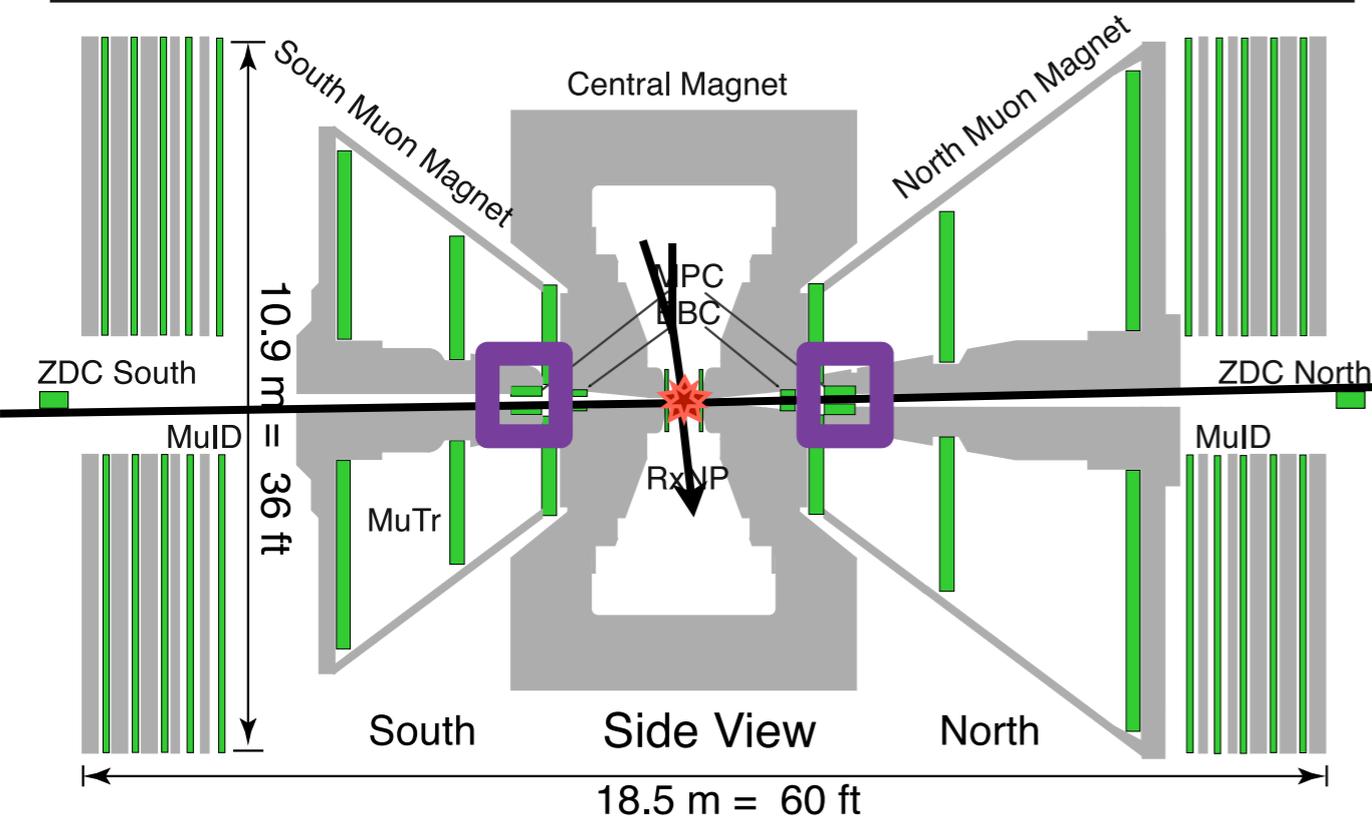
p+p: trigger condition

Drift and Pad Chambers + Ring Imaging Cherenkov Detector for charged particle tracks

modest coverage at mid-rapidity,
 $|\eta| < 0.35$ and $\Delta\phi = 180^\circ$

Beam-beam counters provide vertex, centrality, reaction plane
($2.1 < |\eta| < 3.8$)

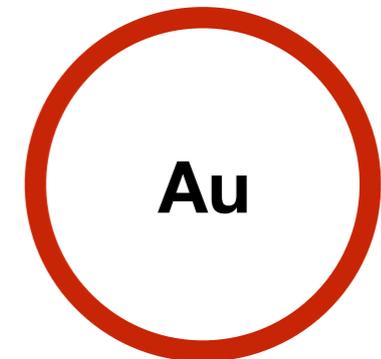
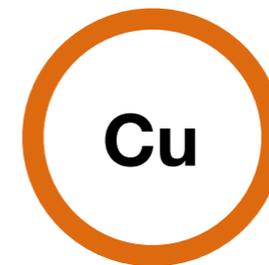
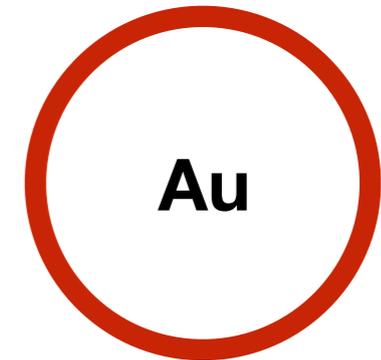
d+Au centrality: only Au-going direction



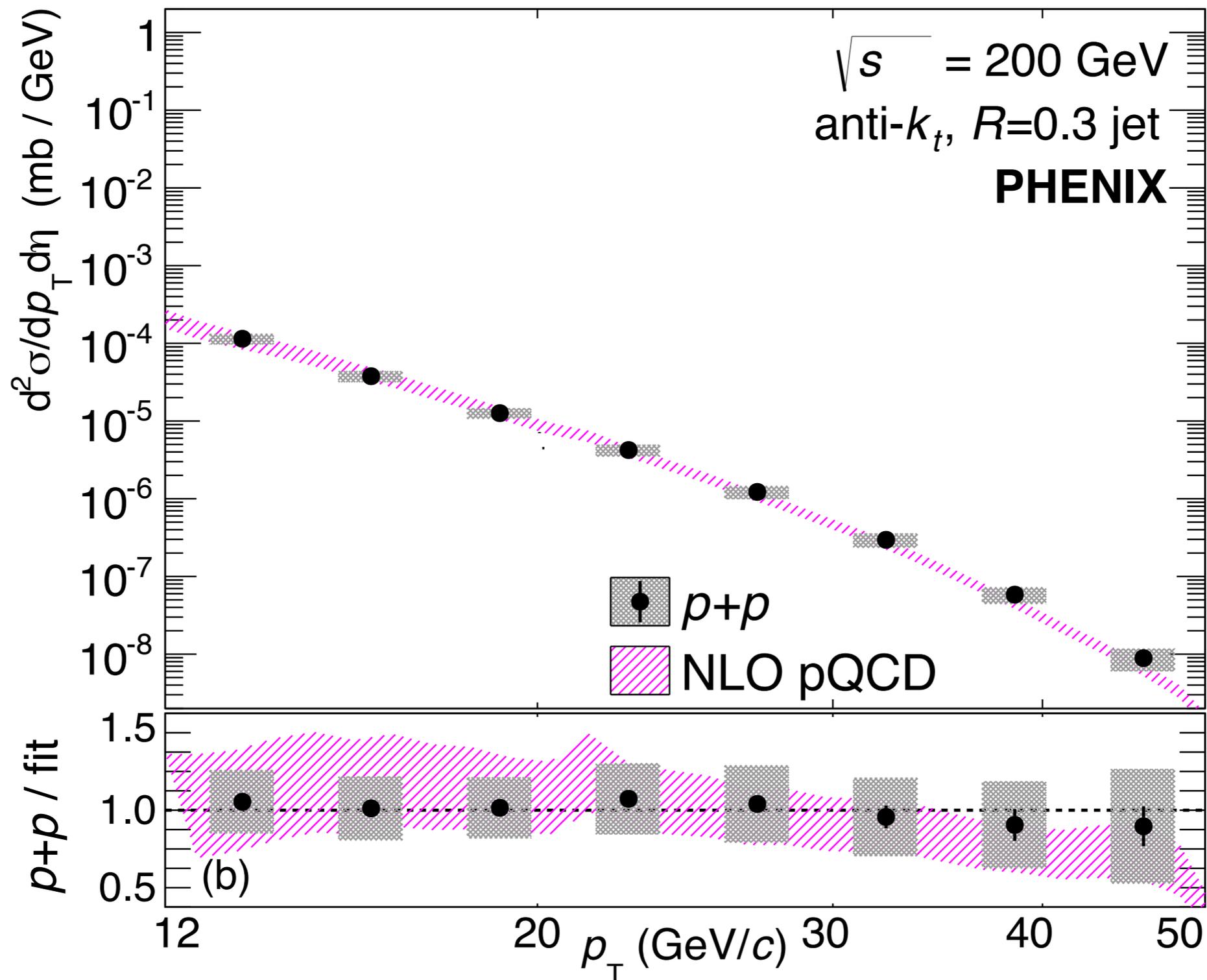
Jet Results from PHENIX

Two new results shown first at Quark Matter 2015

- **d+Au** and **p+p** jet spectra (2008 data)
 - lead analyzer: Dennis Perepelitsa (BNL)
 - nucl-ex/1509.04657, accepted to PRL
 - $R=0.3$ anti-kt algorithm, establish nuclear effects
 - Nature teaches us: impact of kinematic constraints on our geometric controls
- **Cu+Au** and **p+p** jet spectra (2012 data)
 - lead analyzer: Arbin Timilsina (ISU)
 - Preliminary measurement, manuscript being written
 - $R=0.2$ anti-kt to heavily suppress backgrounds in HI environment
 - develop techniques to utilize PHENIX as a jet detector
 - initial look by PHENIX at suppression of jet spectra by the QGP



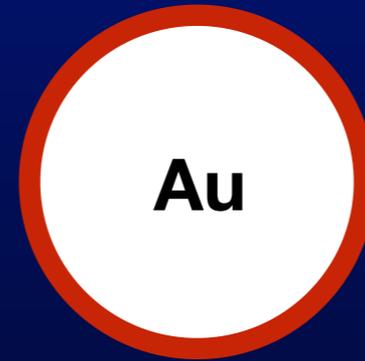
Jet Spectra in p+p Collisions



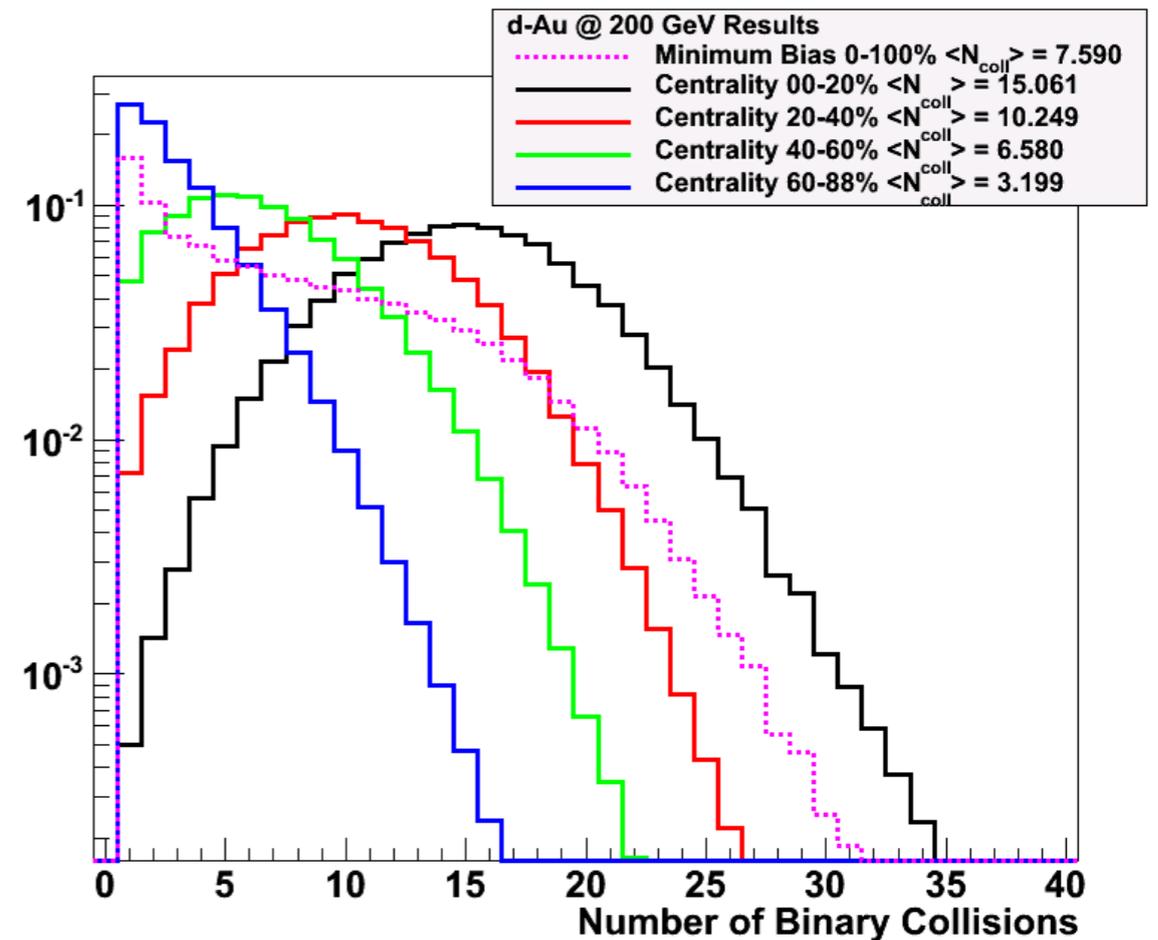
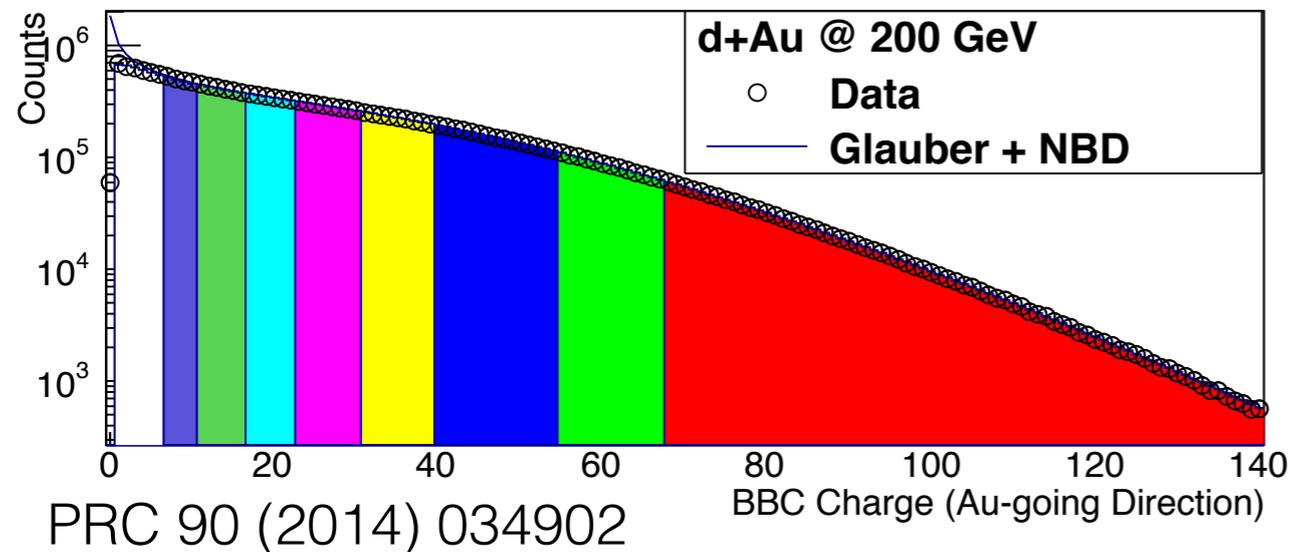
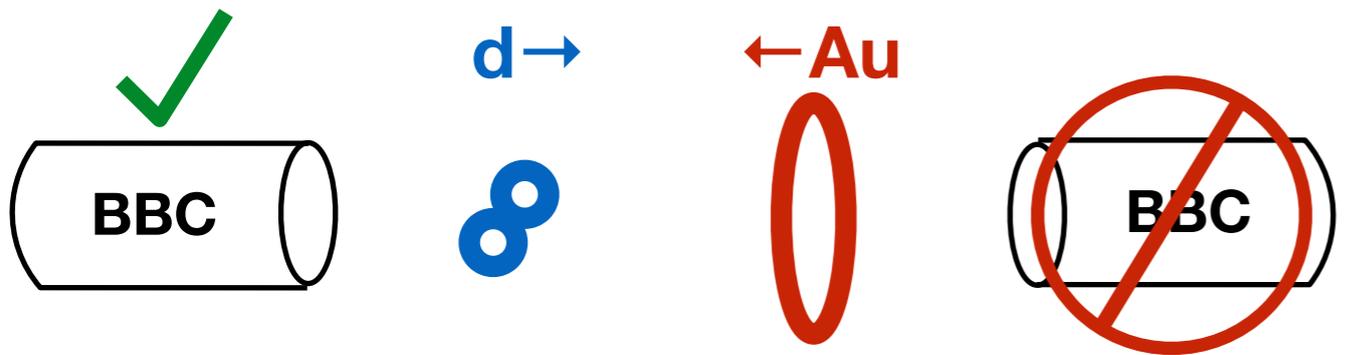
p+p jets: compare well with **NLO pQCD calculation**

important step in validating PHENIX for jet reconstruction

d+Au Collisions: Testing Ground for Nuclear Effects



Centrality in d+Au Collisions

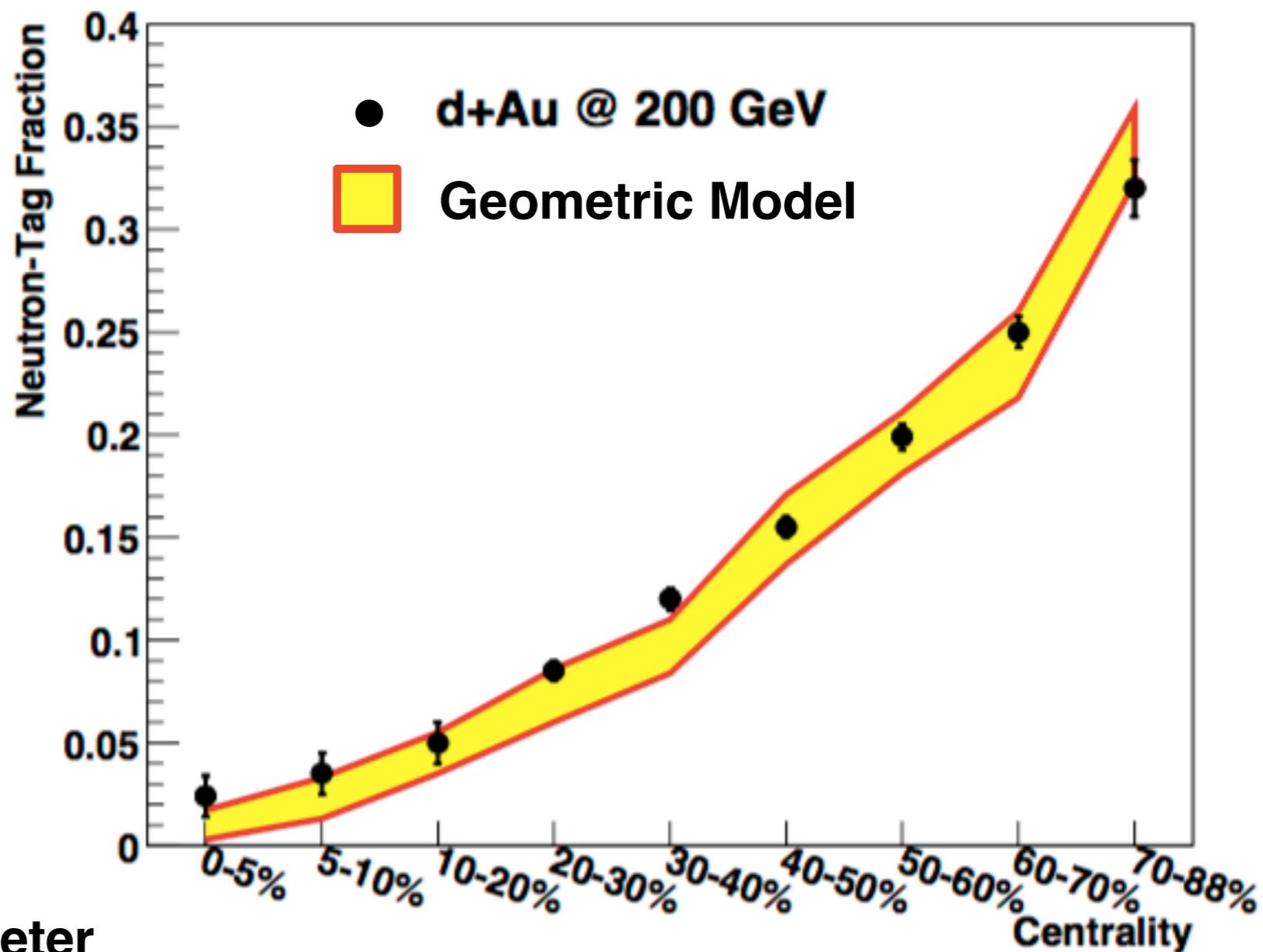
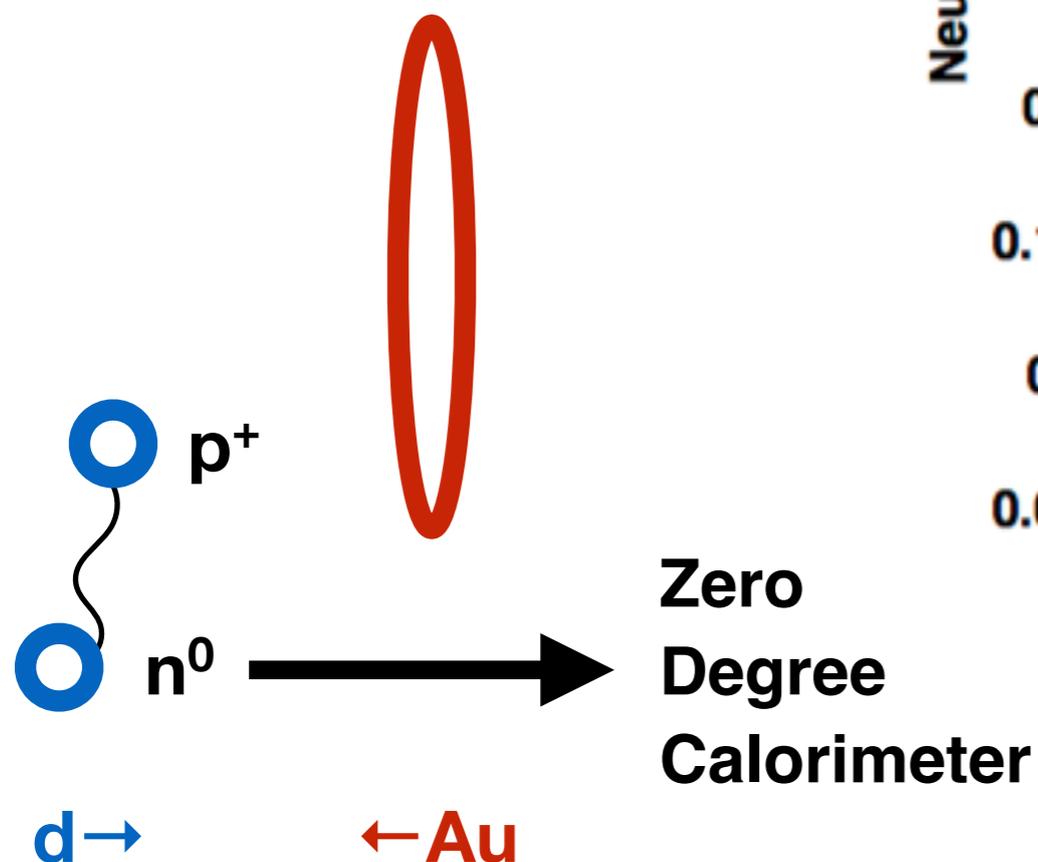


- Total charge Q in Au-going beam-beam counter ($-3.8 < \eta < -2.1$) used to characterize centrality
- Glauber Monte Carlo simulation of $d+Au$ collisions + model dN/dQ distribution as scaling with N_{coll}
 - ➔ estimate nuclear overlap factor T_{dAu} for classes of $d+Au$ collisions
 - ➔ previously successful with hard and soft observables

Validation: Spectator Neutron Rate

Deuterons are **not** compact

Events where only the proton interacts are common



The fraction of neutron spectator events within the centrality class can be used to **confirm the geometrical configuration** (impact parameter)

Previous Results with Single Hadrons

Large p_T neutral pions:

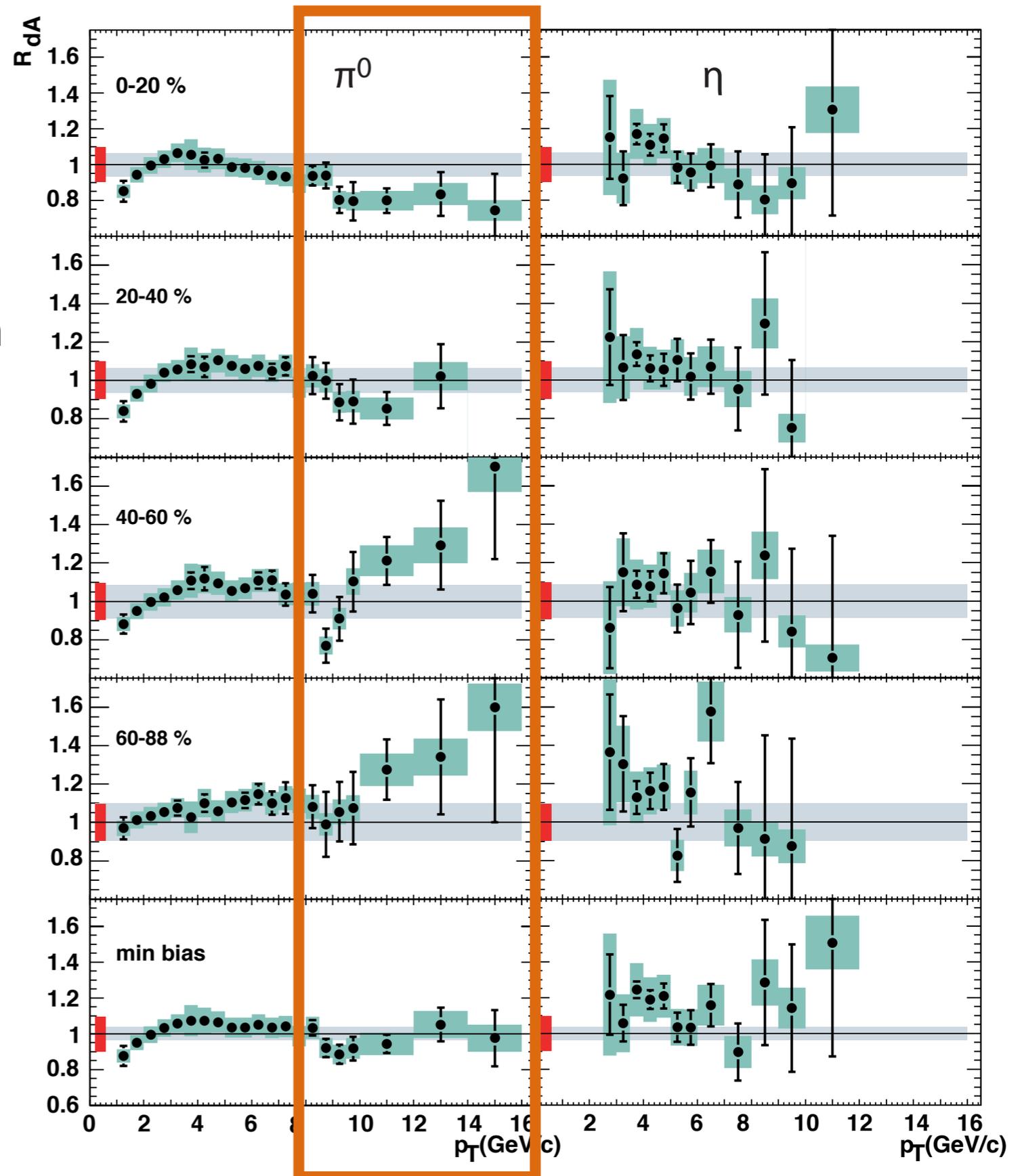
Minimum Bias consistent with unity

Central Events suggest a suppression

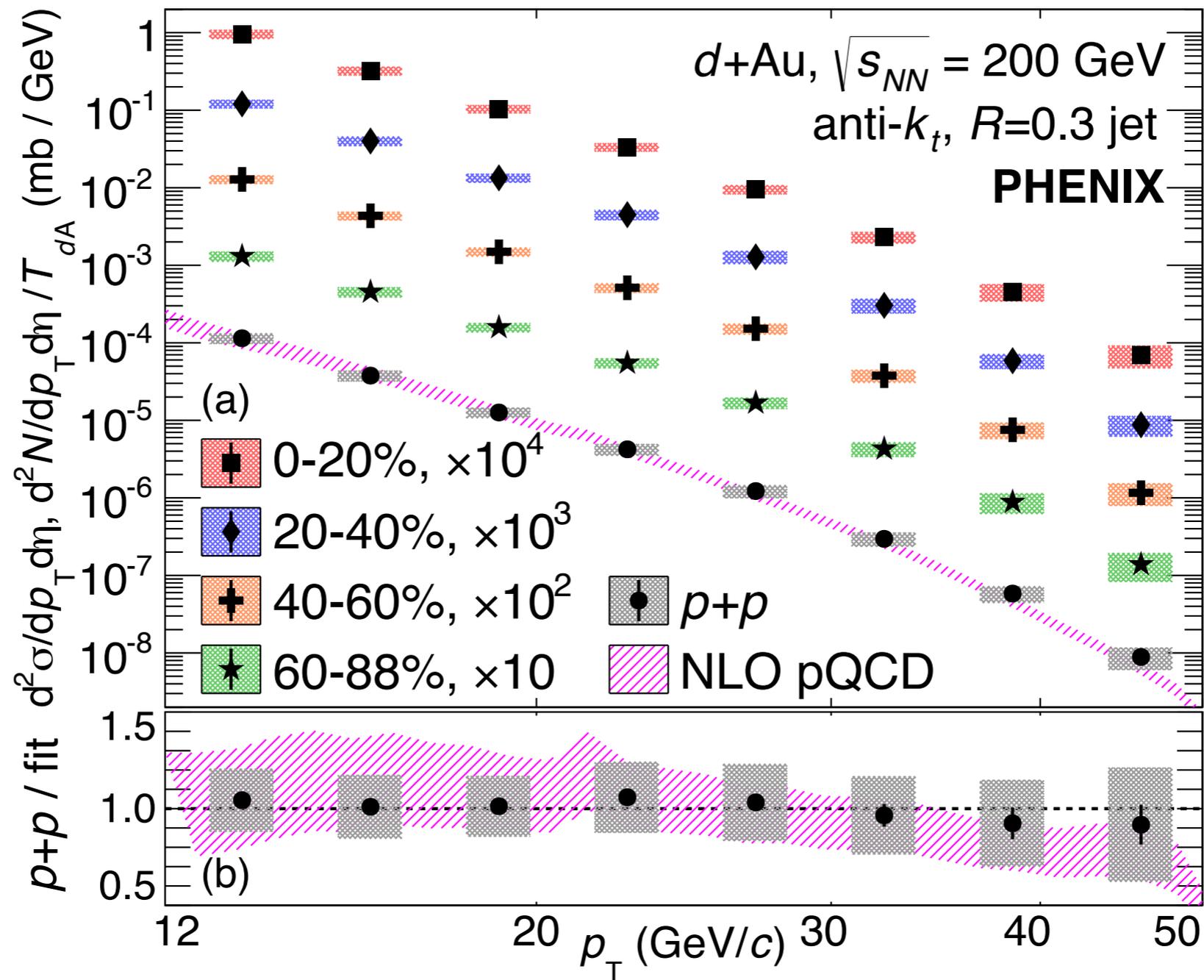
Peripheral Events suggest a rise

This was noticed at the time, but the uncertainties do not support a conclusion other than consistency

Jet kinematics allow a much greater extension of this data and stress test these models



Jet yields in d+Au



d+Au per-event yields: first publication of jet production in asymmetric systems at RHIC

Minimum Bias Jet Rate

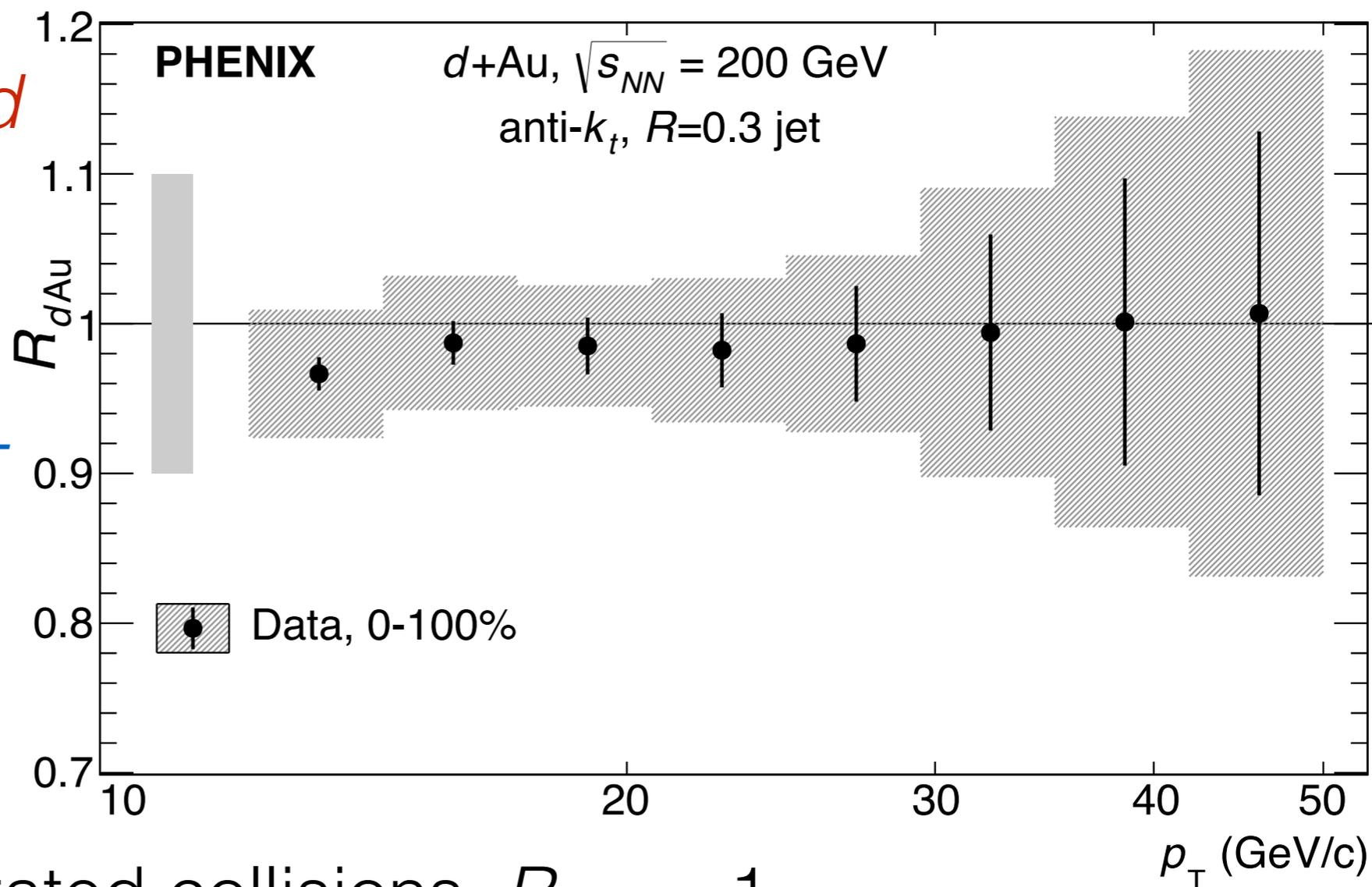
d+Au yield

$$R_{dAu} = \frac{dN^{d+Au}/dp_T}{T_{dA} \times d\sigma^{p+p}/dp_T}$$

nuclear overlap

p+p cross-section

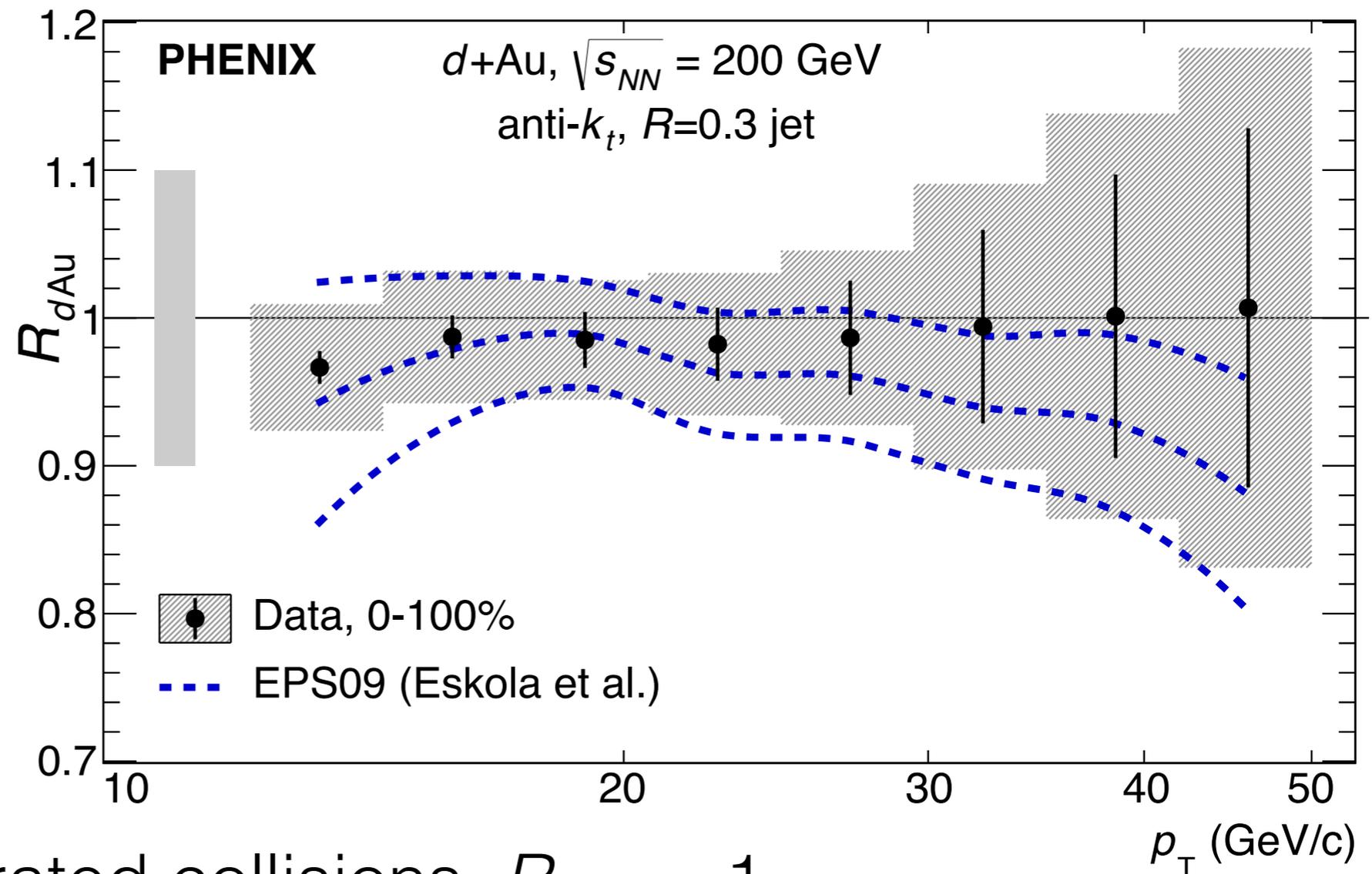
$$(\approx A \times \sigma^{d+Au} / \sigma^{p+p})$$



- In centrality-integrated collisions, $R_{dAu} = 1$

Minimum Bias Jet Rate

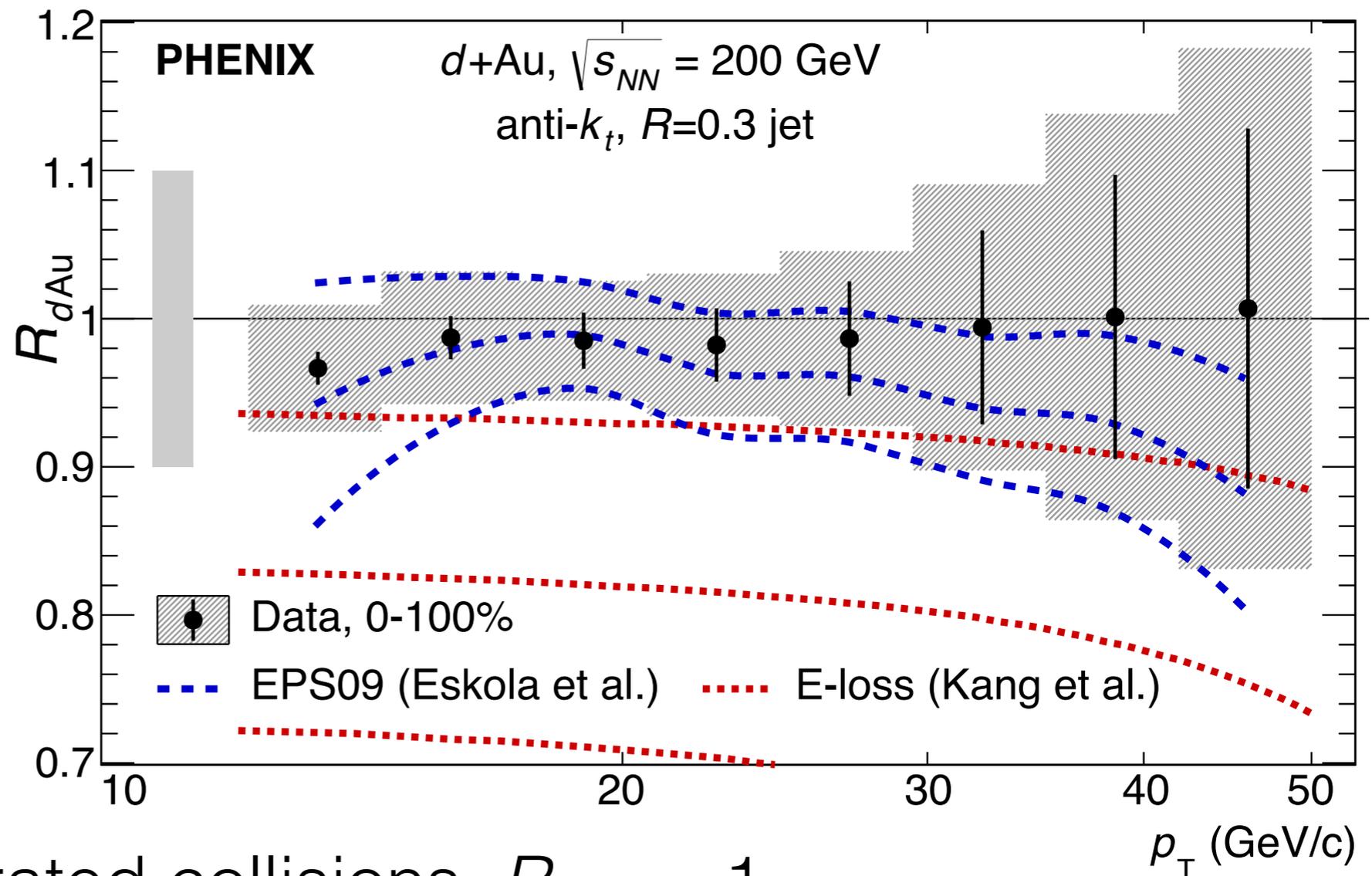
$$R_{dAu} = \frac{dN^{d+Au}/dp_T}{T_{dA} \times d\sigma^{p+p}/dp_T}$$



- In centrality-integrated collisions, $R_{dAu} = 1$
 - ➔ compares favorably to global nuclear PDF analyses (**EPS09**) within uncertainties

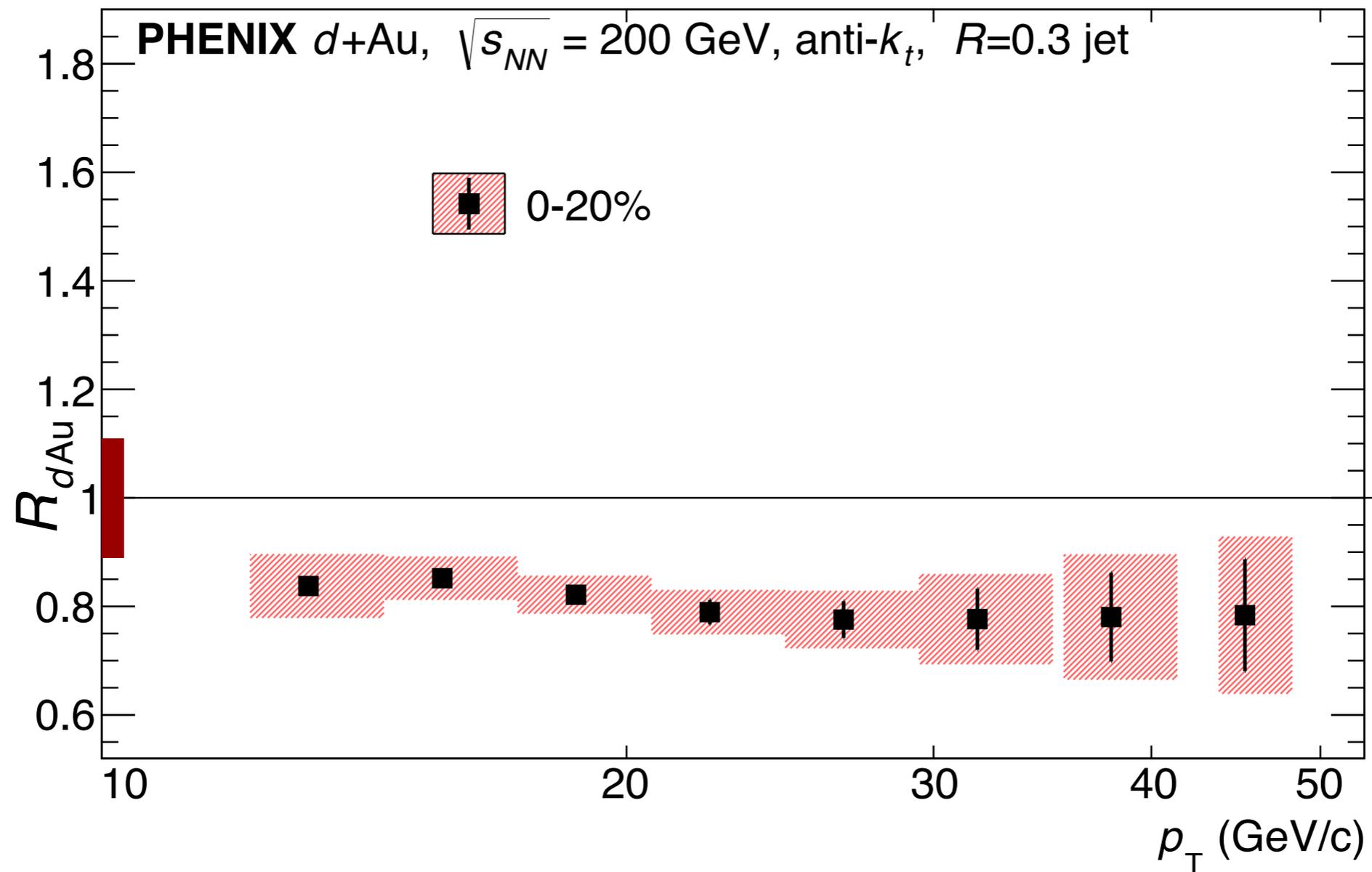
Minimum Bias Jet Rate

$$R_{dAu} = \frac{dN^{d+Au}/dp_T}{T_{dA} \times d\sigma^{p+p}/dp_T}$$



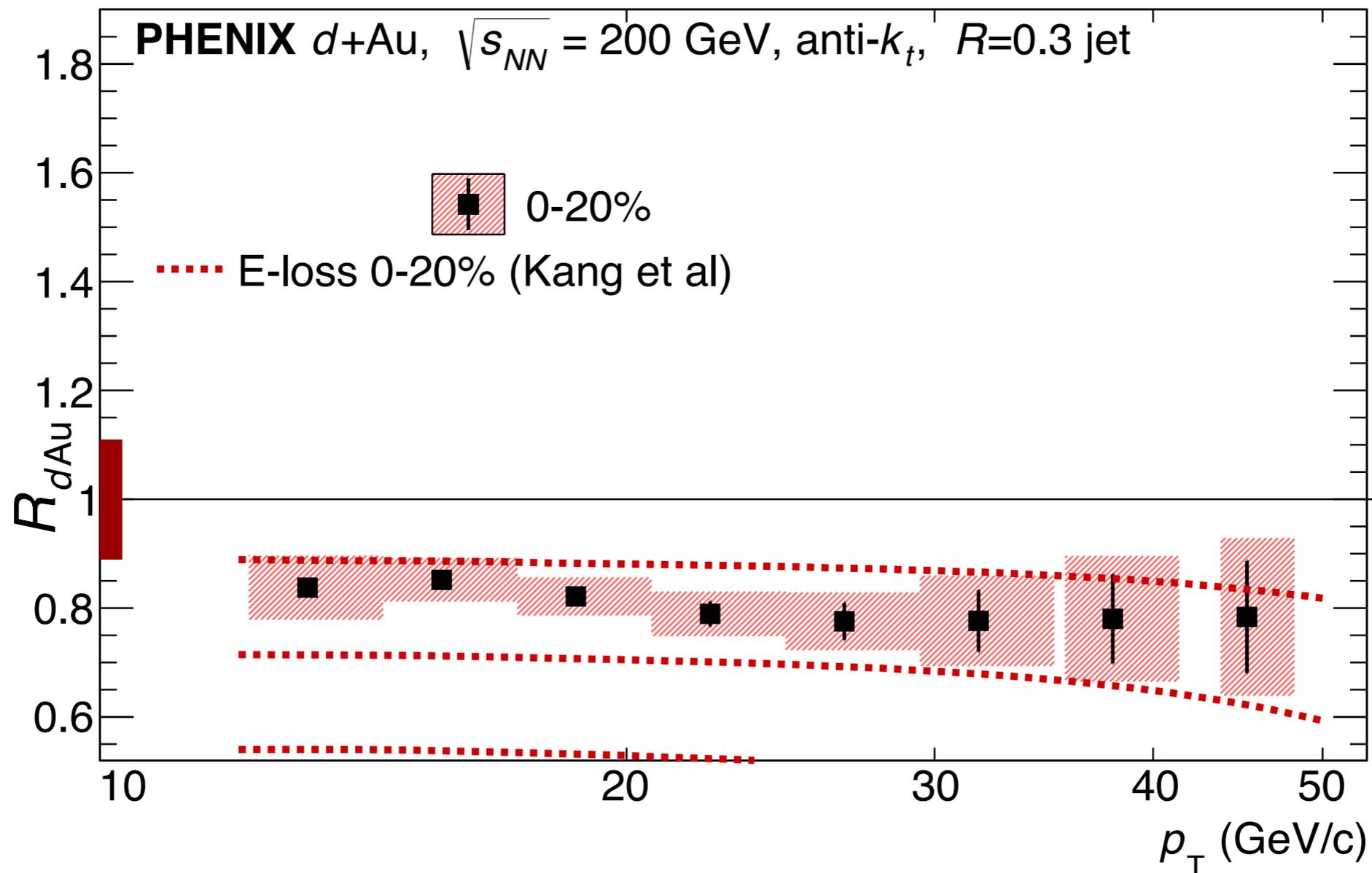
- In centrality-integrated collisions, $R_{dAu} = 1$
 - ➔ compares favorably to global nuclear PDF analyses (**EPS09**) within uncertainties
 - ➔ within an **initial state E-loss calculations**, favors only small *parton* ↔ *nuclear material* momentum transfer

Jet Rate with Centrality Selection



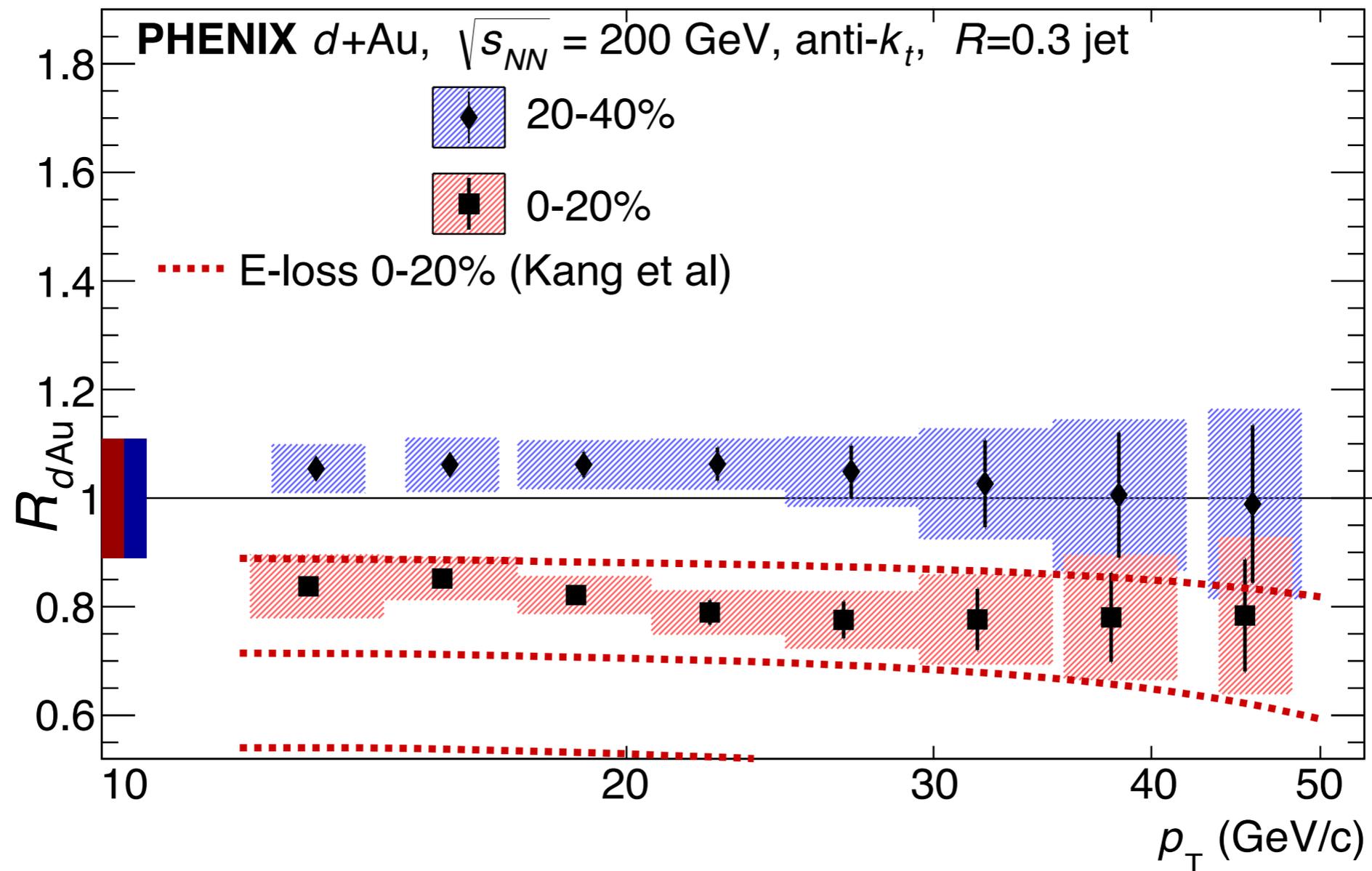
- Suppression of jet rate in **central 0-20%** (large N_{coll}) events

Jet Rate with Centrality Selection



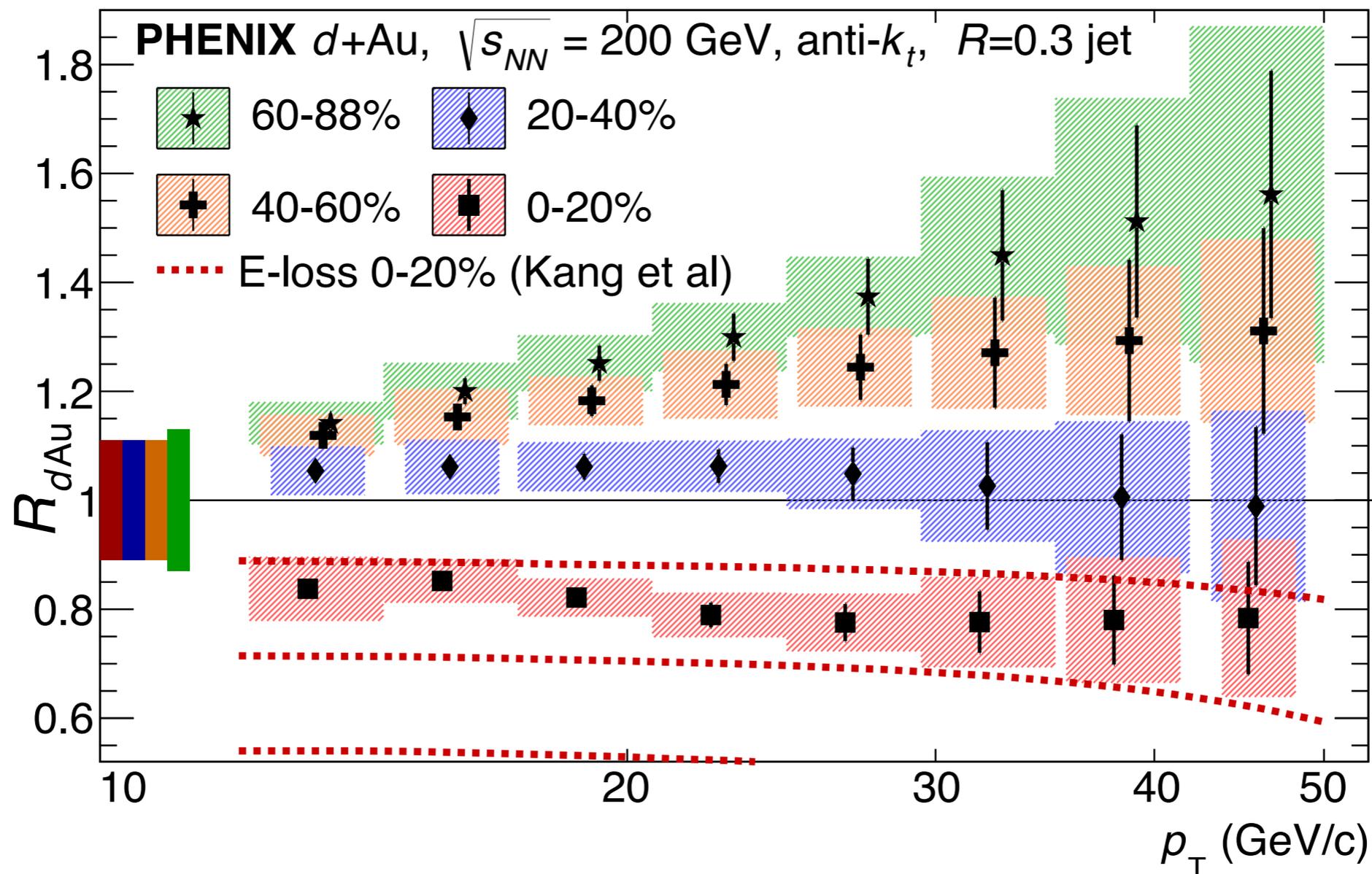
- Suppression of jet rate in **central 0-20%** (large N_{coll}) events
 → comparable with initial state E-loss calculation?

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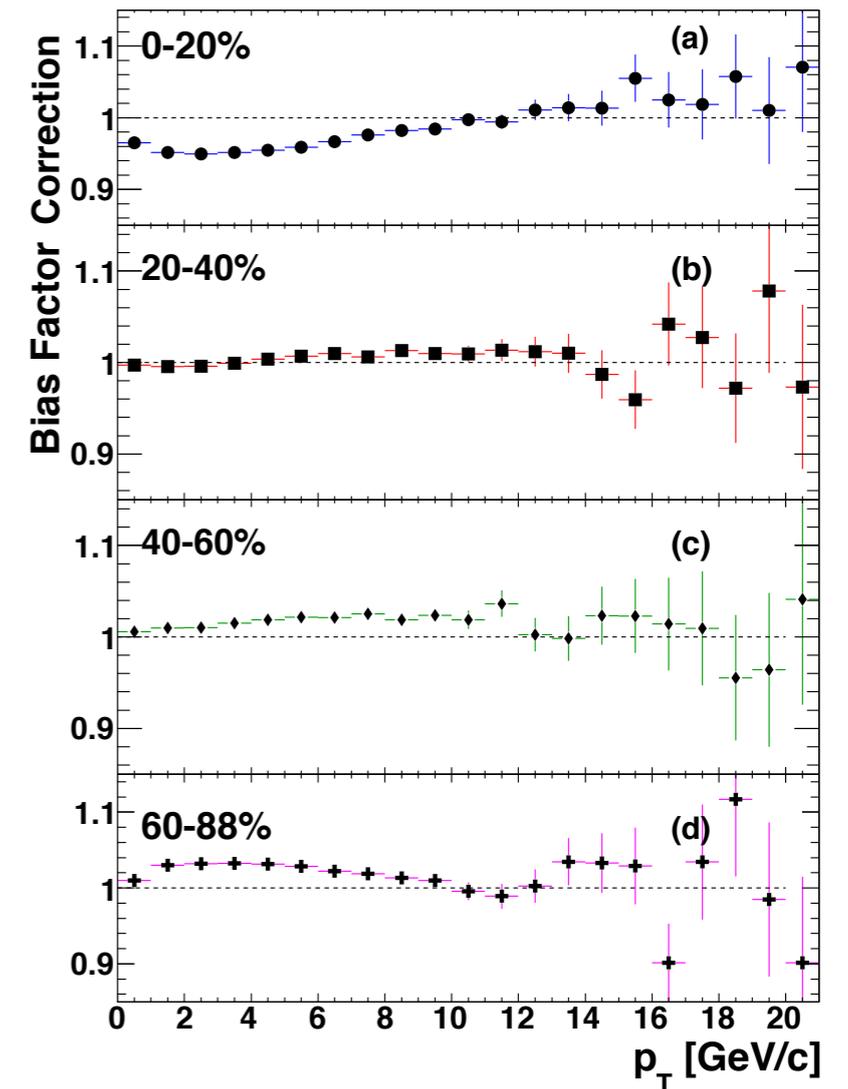
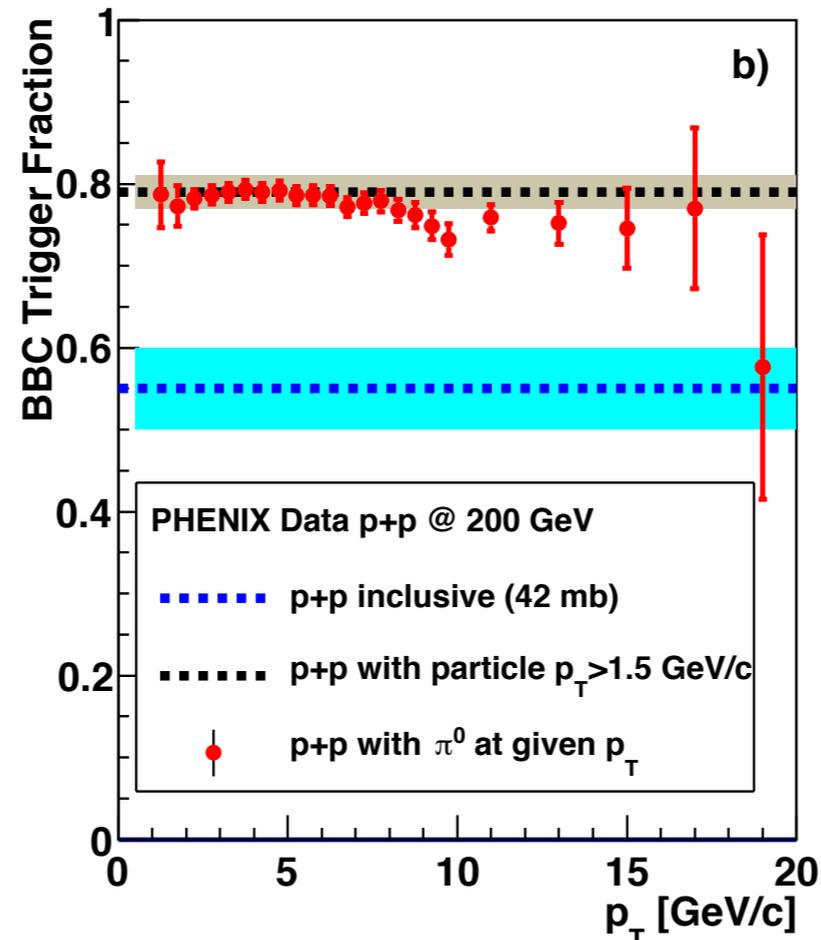
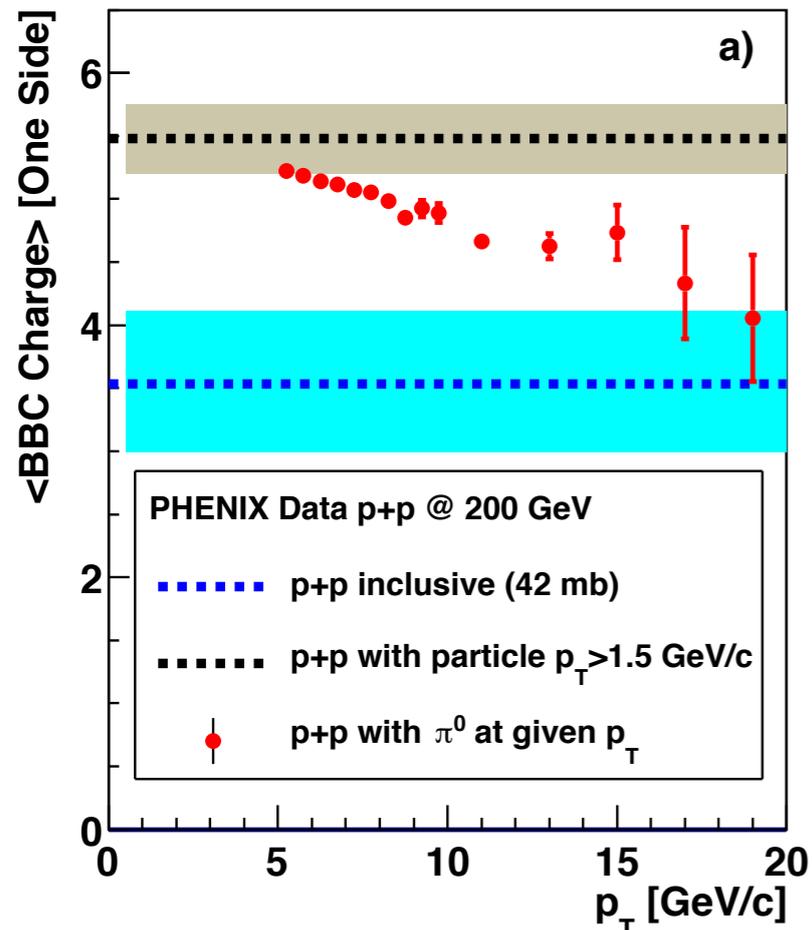
Jet Rate with Centrality Selection



- Suppression of jet rate in **central 0-20%** (large N_{coll}) events
 - ➔ comparable with initial state E-loss calculation?
- Enhancement in **40-60%** and **60-88%** (small N_{coll}) events
 - ➔ very challenging to explain within existing frameworks...

Centrality with Hard Scattering

PRC 90 (2014) 034902

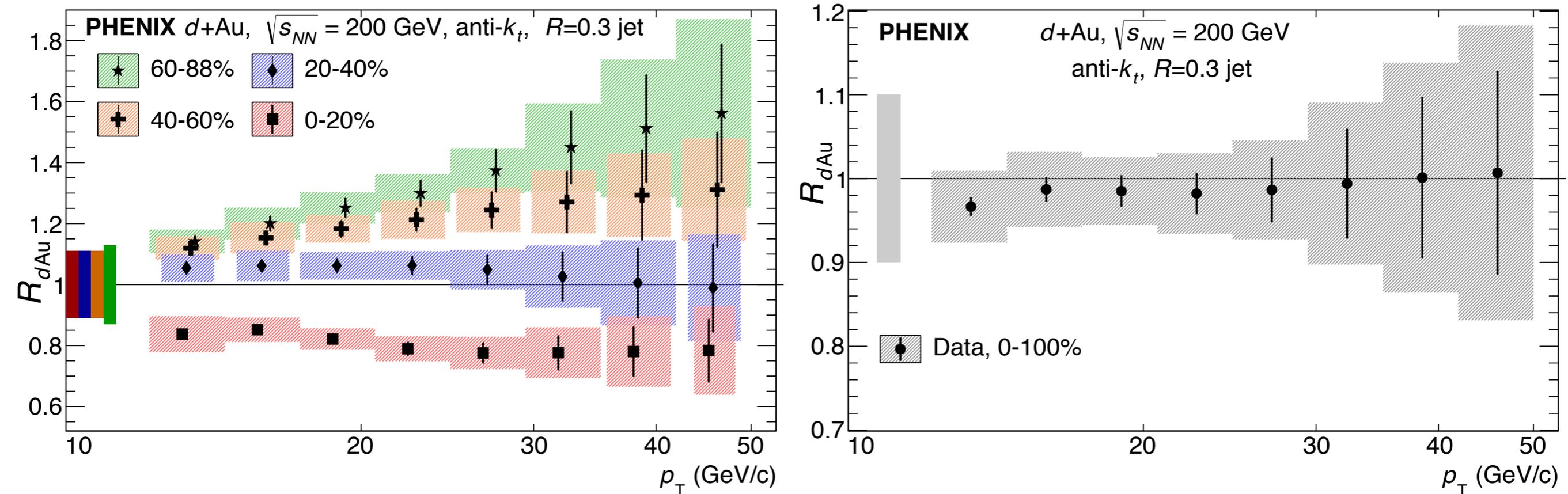


Previously known effect present in p+p collisions shows correlations between BBC charge and large momentum pions

Common feature of all PHENIX d+Au publications has been to correct for the bias as a set of *individual nucleon-nucleon collisions*

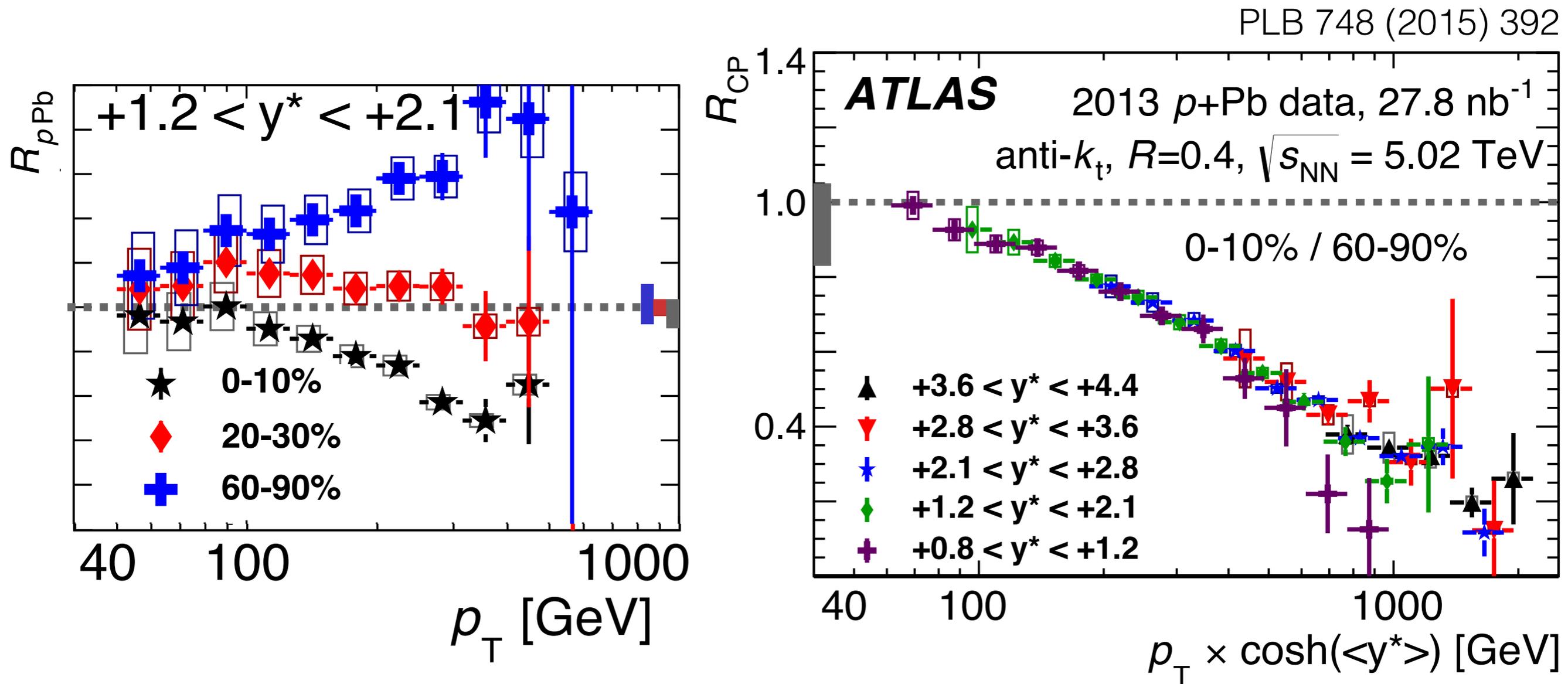
Correction is small w.r.t. other systematics and also pulls the wrong direction to explain the new d+Au puzzle

Reconciling the Puzzle

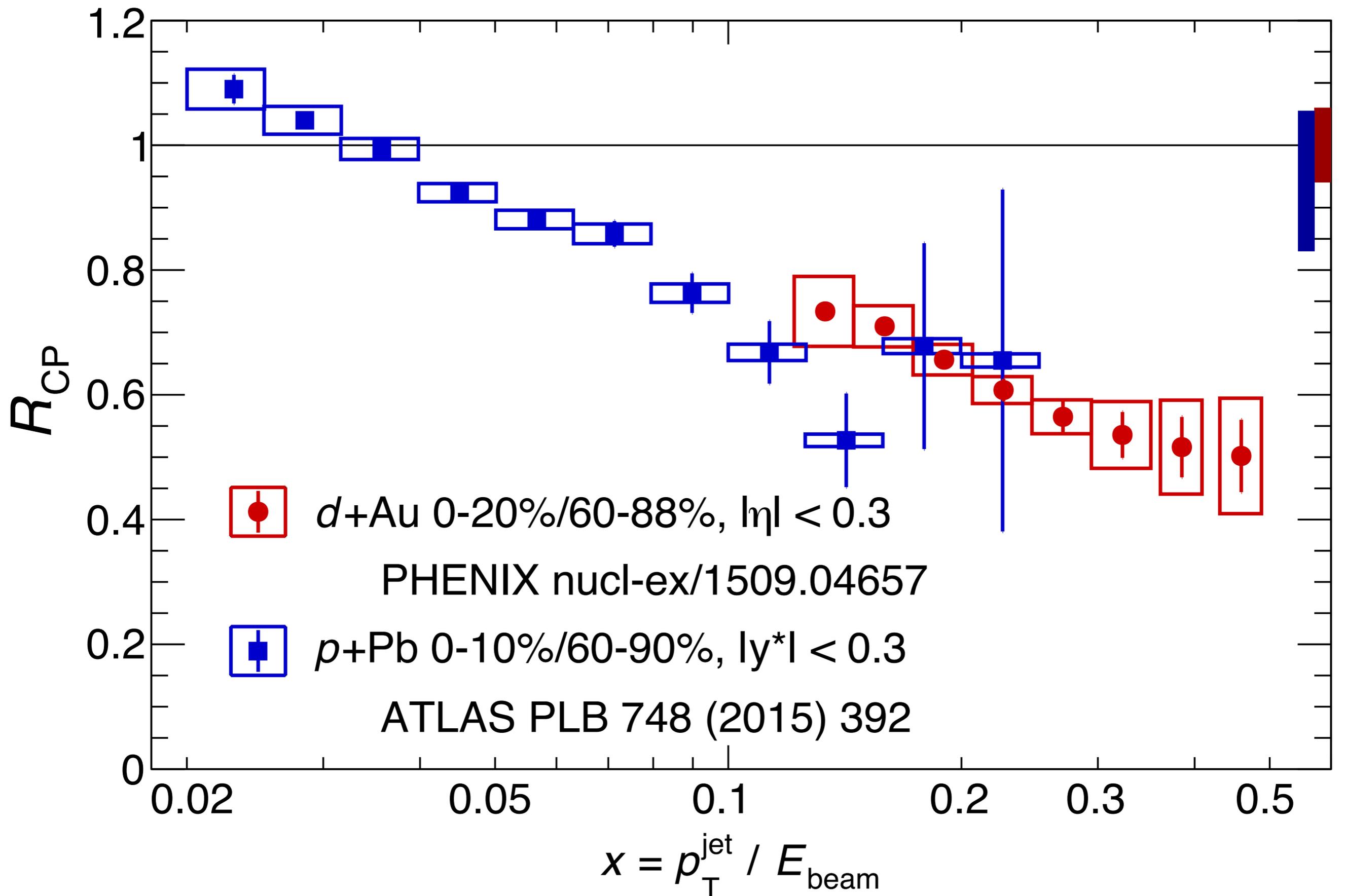


- Physics bias affects the centrality signals for high- p_T jet events
 - ➔ not a *trivial* bias which arises “just” from a feature of $p+p$ collisions
 - ➔ somehow the presence of the nucleus is important...

An Additional Clue from ATLAS



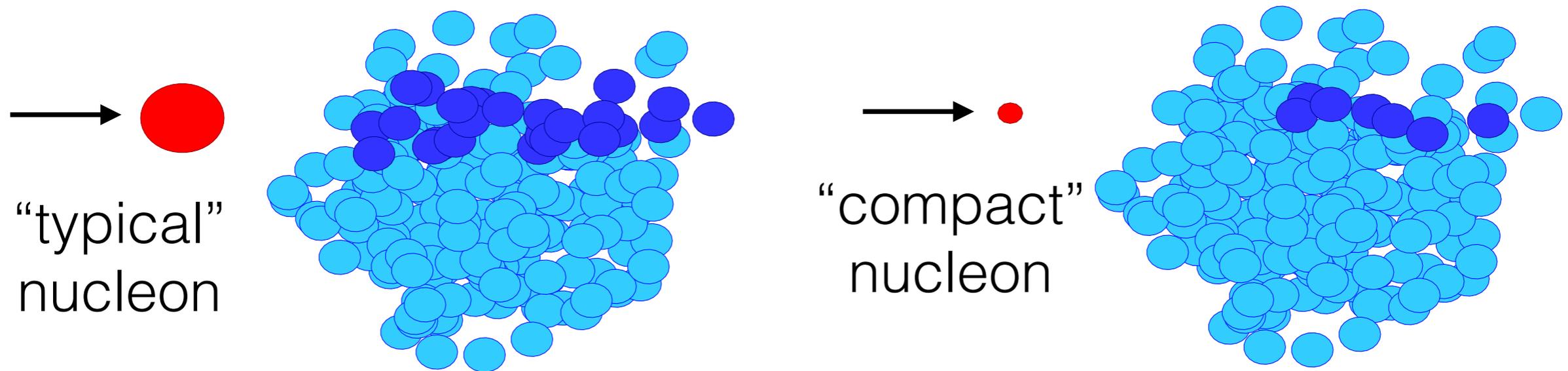
- Same modification pattern, in the same Bjorken- x range
- Modifications to the R_{pPb} / R_{CP} shown to scale only with proton- x and not depend on nuclear- x



→ Same (universal) hadron physics at RHIC and the LHC?

“Shrinking” Proton Model

M. Strikman, DVP, et al. hep-ex/1409.7381

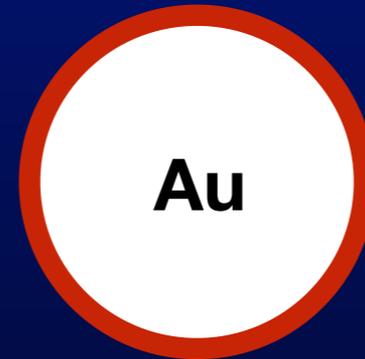


- Geometric interpretation: as these compact configurations traverse the large nucleus, they strike fewer nucleons
 - ➔ so peripheral $R_{dAu} > 1$, central $R_{dAu} < 1$
- Large nucleus acts as a filter on the transverse nucleon size
 - ➔ larger deuteron- x (nuclear- x irrelevant) ➔ more compact configurations ➔ larger deviations from $R_{dAu} = 1$

See also Bzdak et al. hep-ph/1408.3156, Armesto et al. PLB 747 (2015) 441

MPM: I speculate that less exotic (beam remnant)-(nucleon) descriptions are needed to follow the hard scattering and reduce the backward going production

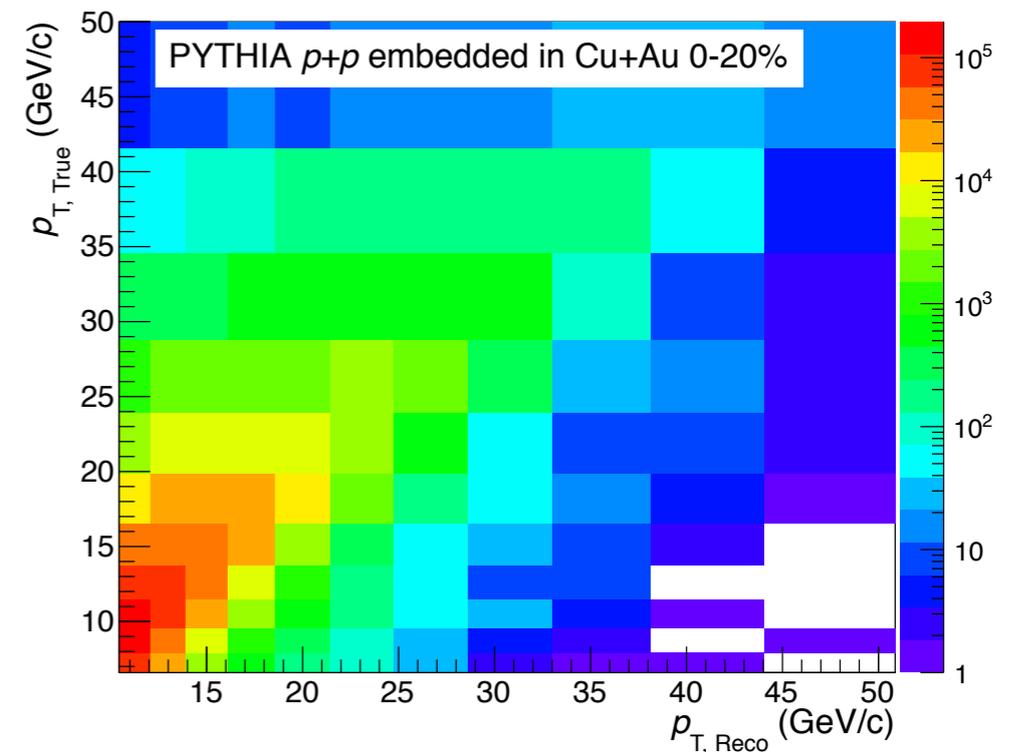
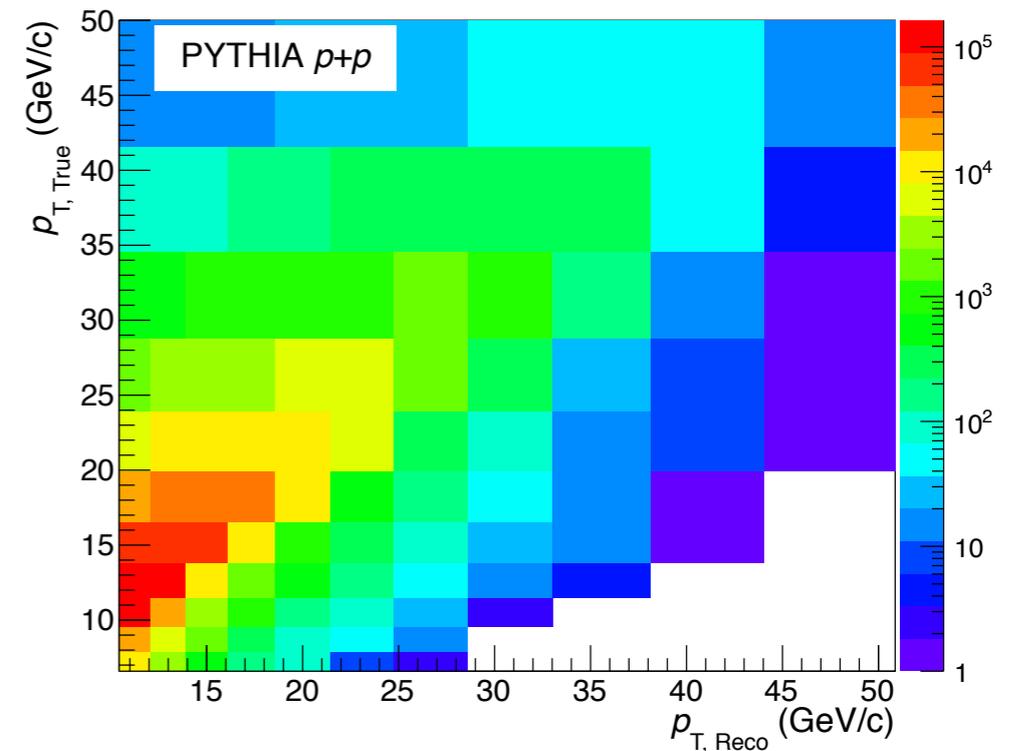
Cu+Au Collisions: Interactions with the Quark-Gluon Plasma



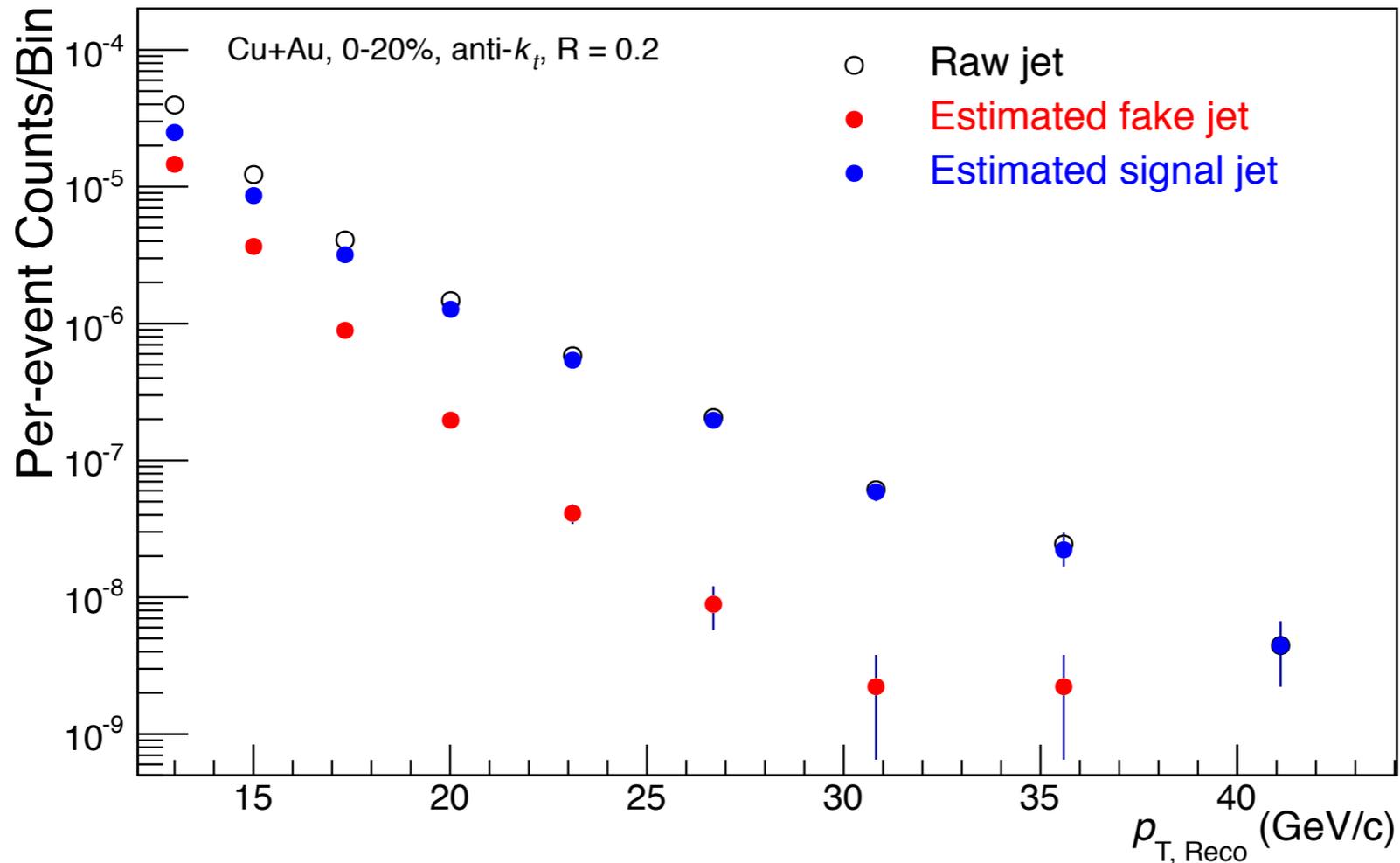
Jets in Cu+Au Collisions

- 2012 $\sqrt{s_{NN}} = 200$ GeV $p+p$ and Cu+Au
- Jets reconstructed using the anti- k_t algorithm with $R = 0.2$
 - track $p_T > 500$ MeV/c
 - clusters energy > 500 MeV
- Jet level cuts
 - number of constituents ≥ 3
 - $0.2 < \text{charged fraction} < 0.7$
- Centrality-dependent response matrices generated by embedding PYTHIA $p+p$ jets into real Cu+Au events

Sample Response Matrices



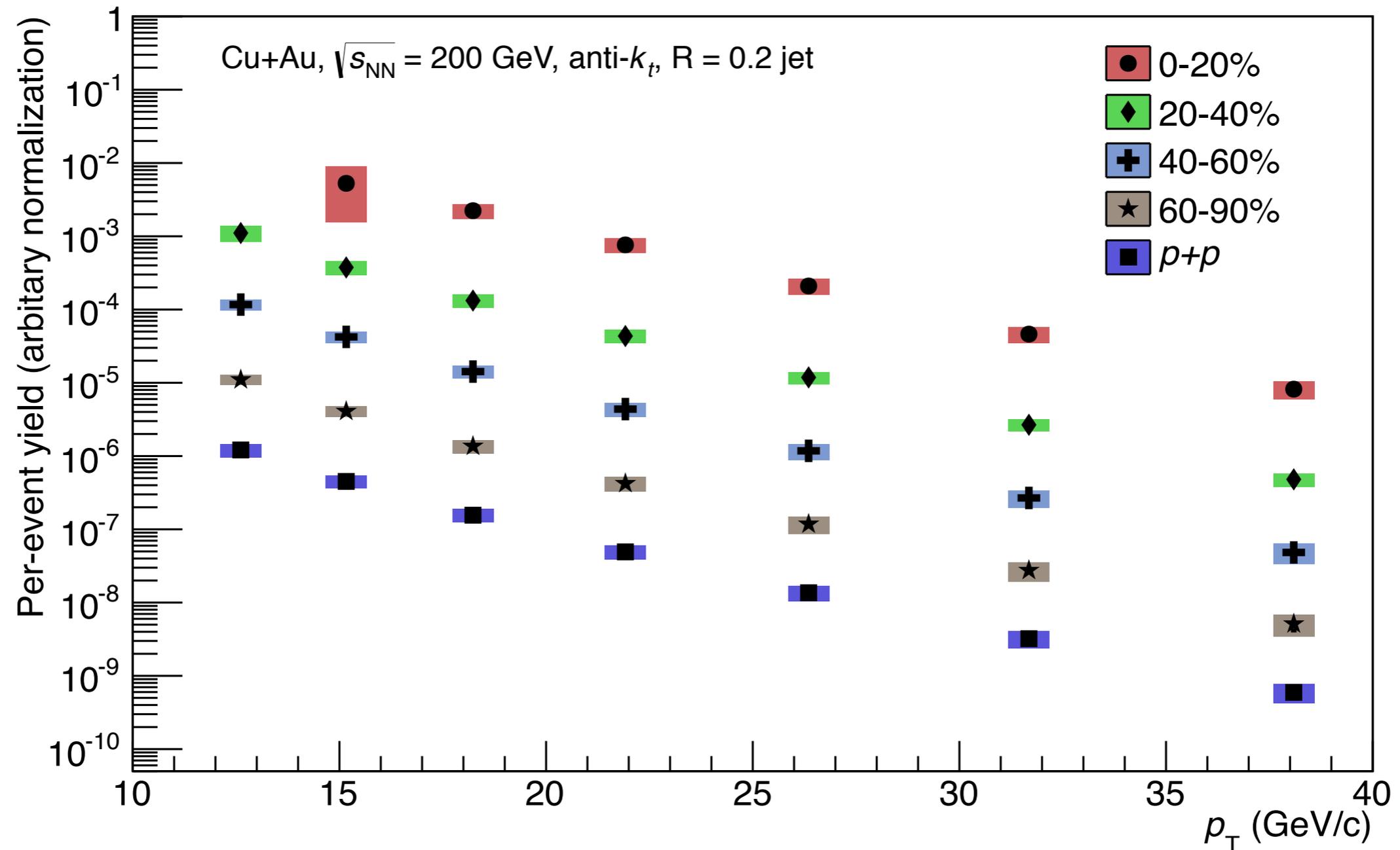
Fake Jet Rate Estimations



Data driven method of estimating and statistically subtracting fake jet contribution

- For events in which jet is not reconstructed, position (η , ϕ) of tracks and clusters are randomly swapped independently
- Jet reconstruction performed in these swapped tracks and clusters
-> returns **estimated fake jet**
- Estimated fake jet yield is statistically subtracted from the raw jet yield
-> returns **estimated signal jet**

Cu+Au Spectral Coverage



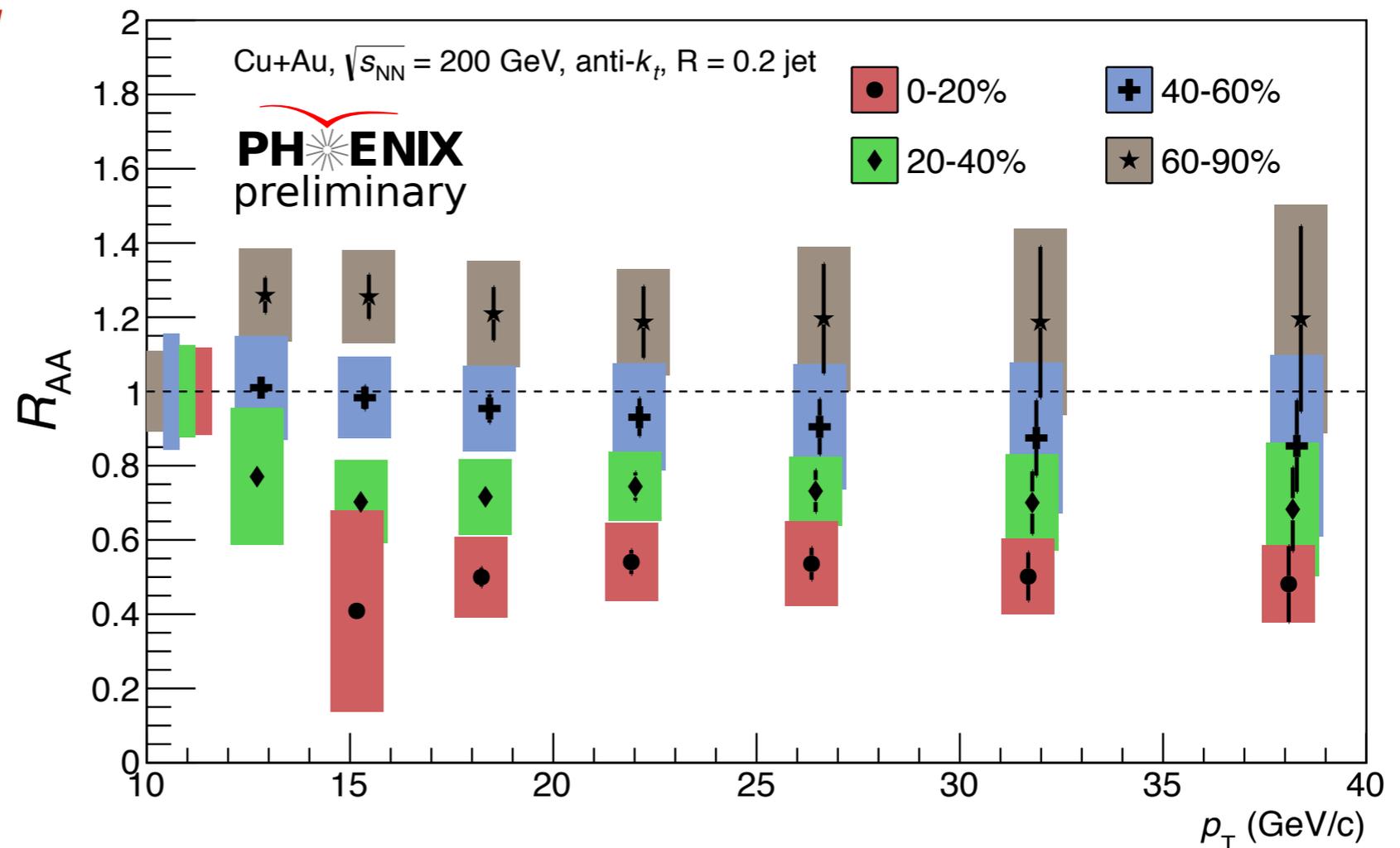
- Expanded systematics for **low- p_T jets in most central events**

Suppression in Cu+Au

Cu+Au yield

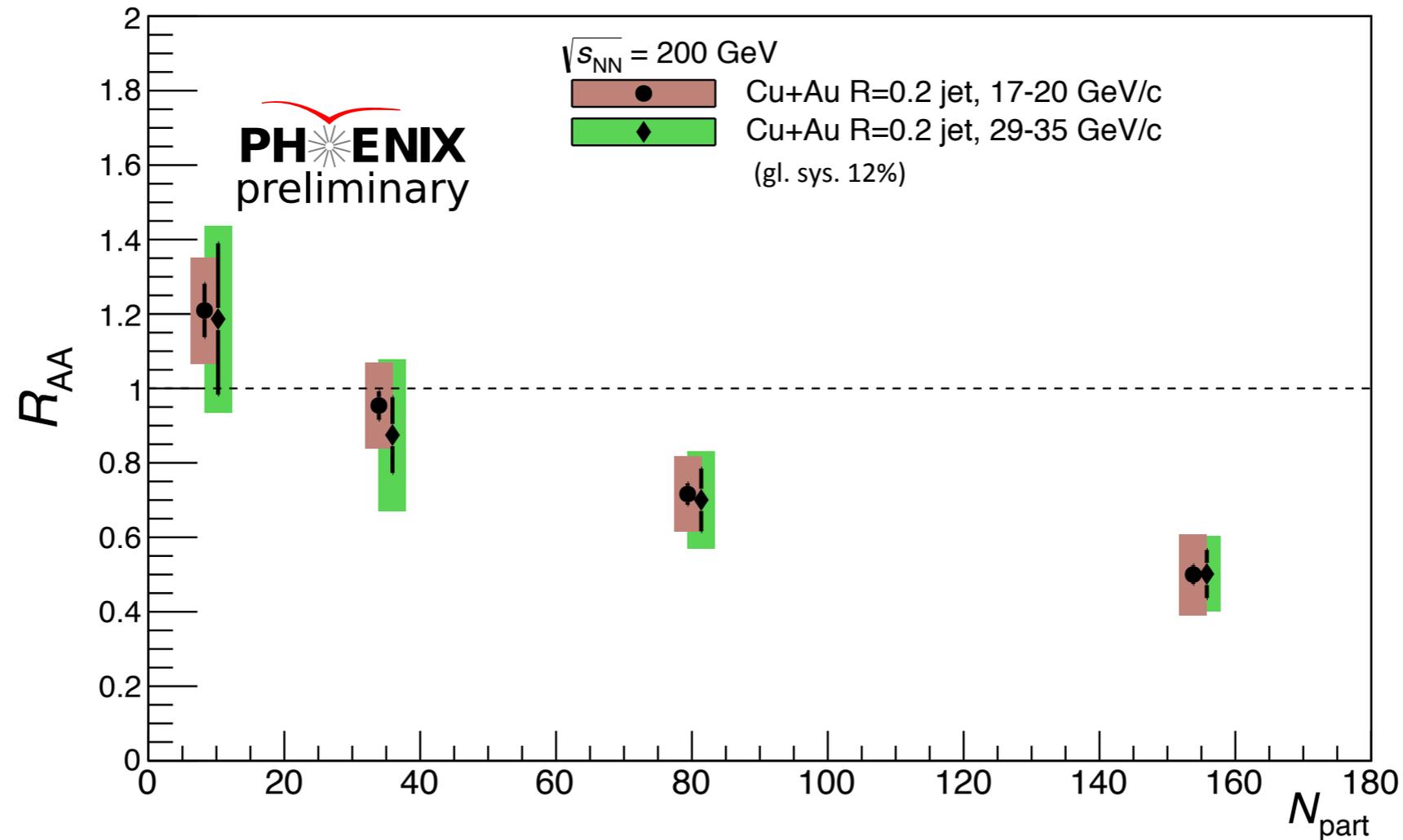
$$R_{AA} = \frac{\text{d}N/\text{d}p_{\text{T}}}{T_{AA} \times \text{d}\sigma/\text{d}p_{\text{T}}}$$

nuclear overlap $p+p$
yield $x\text{-sect.}$



- Differential, centrality-dependent suppression of N_{coll} -scaled yield
 - ➔ **peripheral events** just consistent with $R_{AA} = 1$
 - ➔ factor of 2 suppression in **central events**
- Interestingly, flat with p_{T}

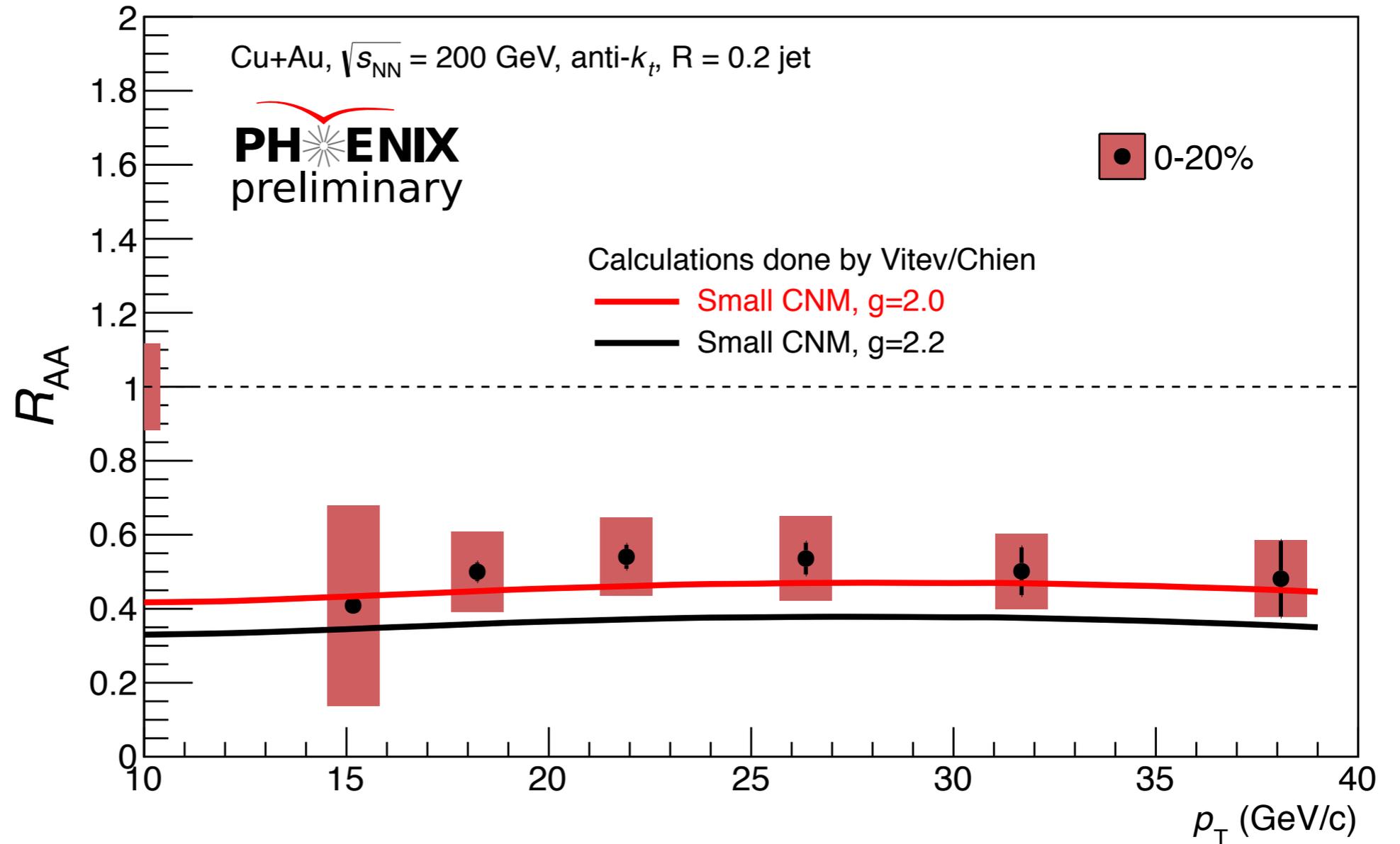
Suppression in Cu+Au vs N_{part}



- Another look at the N_{part} -dependence of suppression
- No p_{T} dependence within sensitivity over this kinematic range

Theory Prediction

Using SCET_G
calculation in
hep-ph/
1509.07257



- Cu+Au system is relatively novel, more calculations welcome
 - ➔ quantitatively in line with state-of-the-art jet quenching calculations

Summary

- Progress on jet measurements in small and large systems with PHENIX detector
 - ➔ good guidance for future heavy ion jet program at RHIC
- Jet rate in $p+p$ and minimum bias $d+Au$ collisions establish pQCD / nPDF baseline
 - ➔ limits on initial state energy loss in new regime
- Surprising, unexpected centrality dependence
 - ➔ one possibility: are we sensitive to the fact that high- x nucleons are “smaller” than average?
- Preliminary measurement of a centrality-dependent suppression of narrow-cone jets in Cu+Au collisions

A tropical beach scene with a rainbow over the ocean and palm trees in the foreground. The sky is overcast with grey clouds, and a vibrant rainbow arches across the horizon. The ocean is a deep blue-green, with white waves crashing onto a golden sand beach. In the foreground, there is lush green vegetation, including several palm trees and dense bushes. The overall atmosphere is serene and picturesque.

BACKUP SLIDES

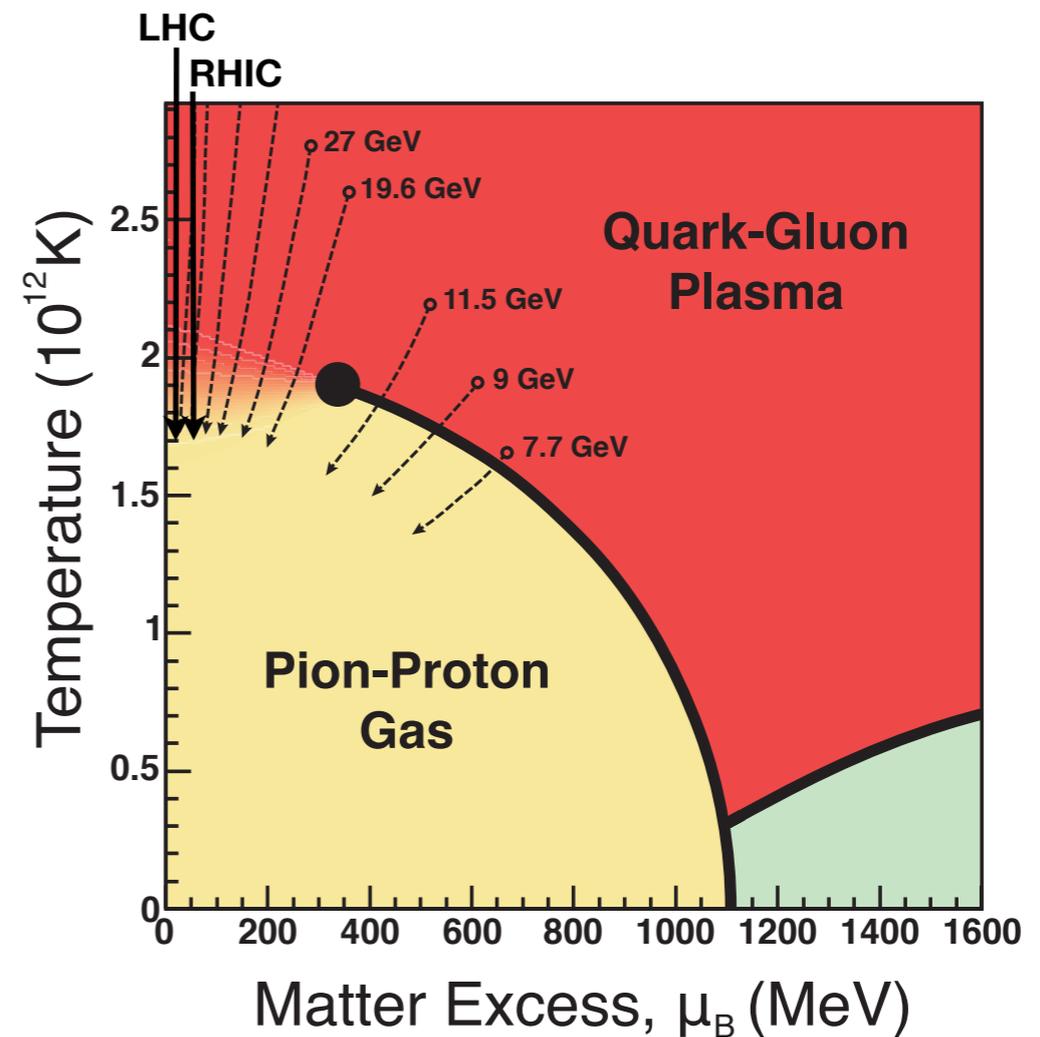
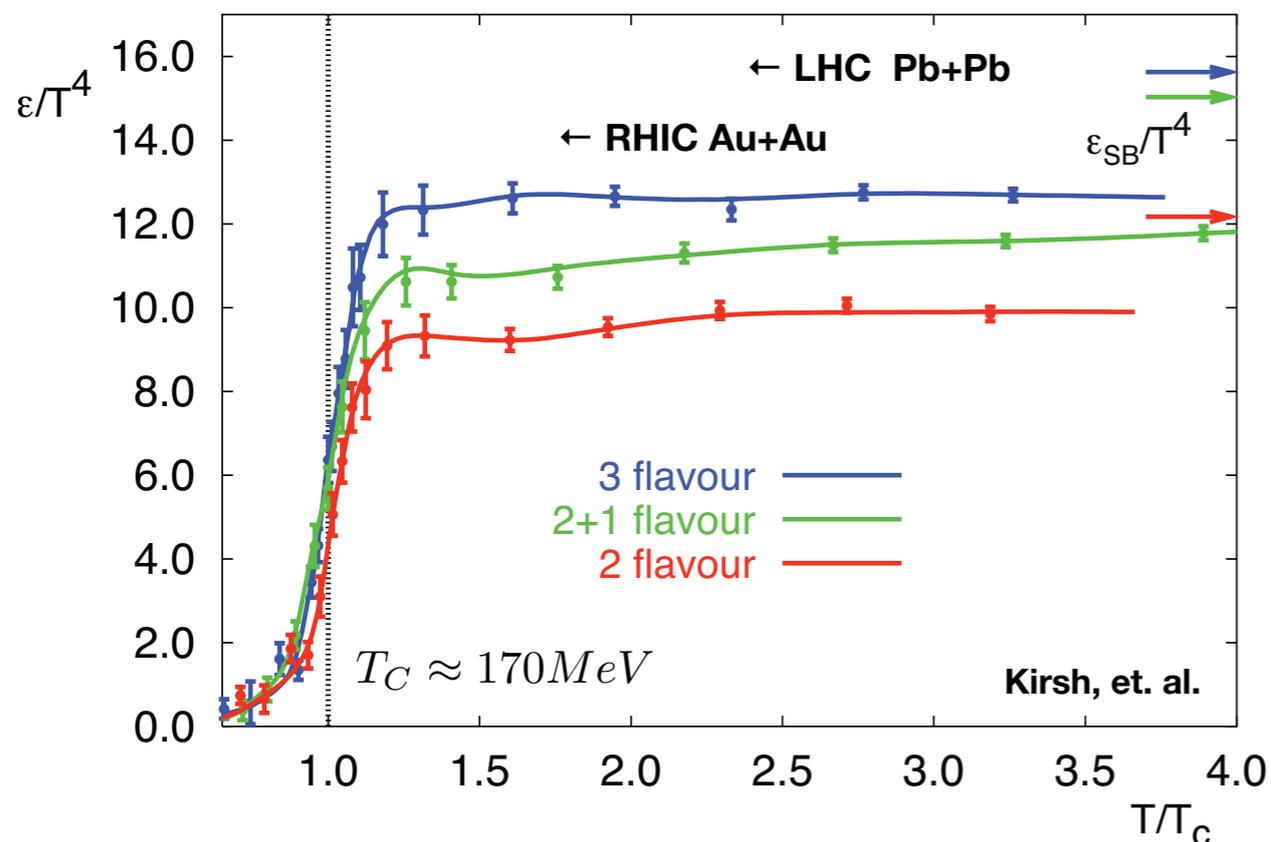
Heavy Ion Collisions

QCD Phase Diagram

Quark-gluon plasma above a few 10^{12} K

Reachable by collider facilities

Critical point being sought



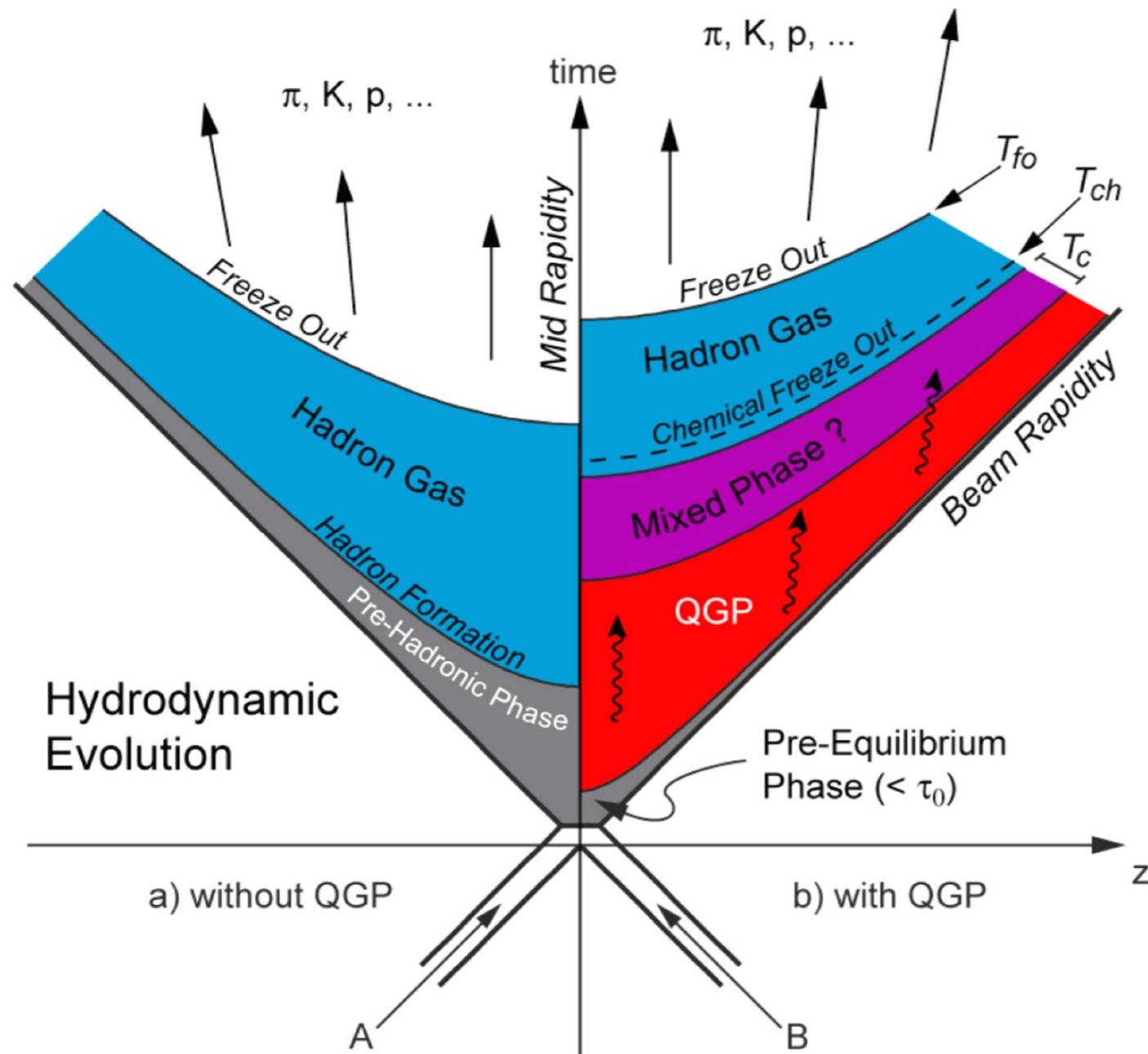
Lattice QCD Calculations

Energy density indicates partonic degrees of freedom open at $T_c \approx 170$ MeV

Ideal gas of quarks and gluons at arbitrarily large T

(Data) Strongly-coupled fluid near T_c

Space-Time Evolution



Kinetic Freeze Out ($\sim 10-15$ fm/c)

Chemical Freeze Out (~ 7 fm/c)

Hadron Gas

Phase Transition (~ 4 fm/c)

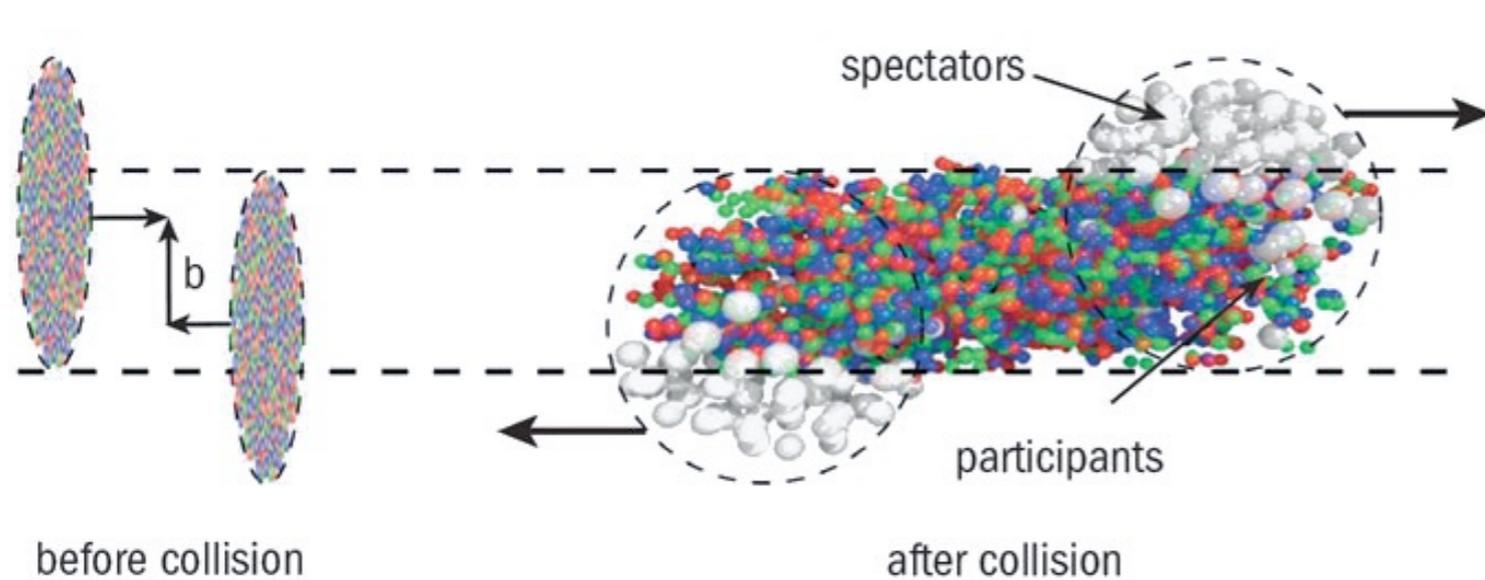
QGP

Thermalization (~ 0.6 fm/c)

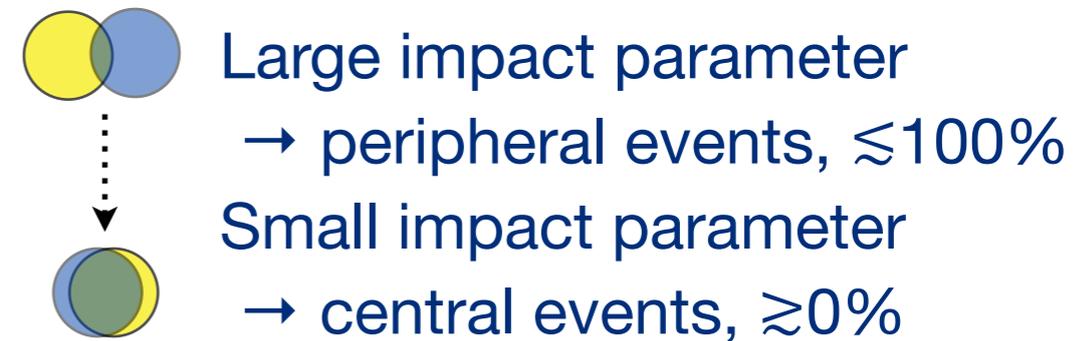
Nuclear Crossing (~ 0.1 fm/c)

**values for RHIC at 200 GeV*

Event Geometry Controls



Impact parameter studied via **centrality** selection



Measured at large pseudorapidity

Tool: Glauber Monte Carlo simulation

Simple geometric description of A+A

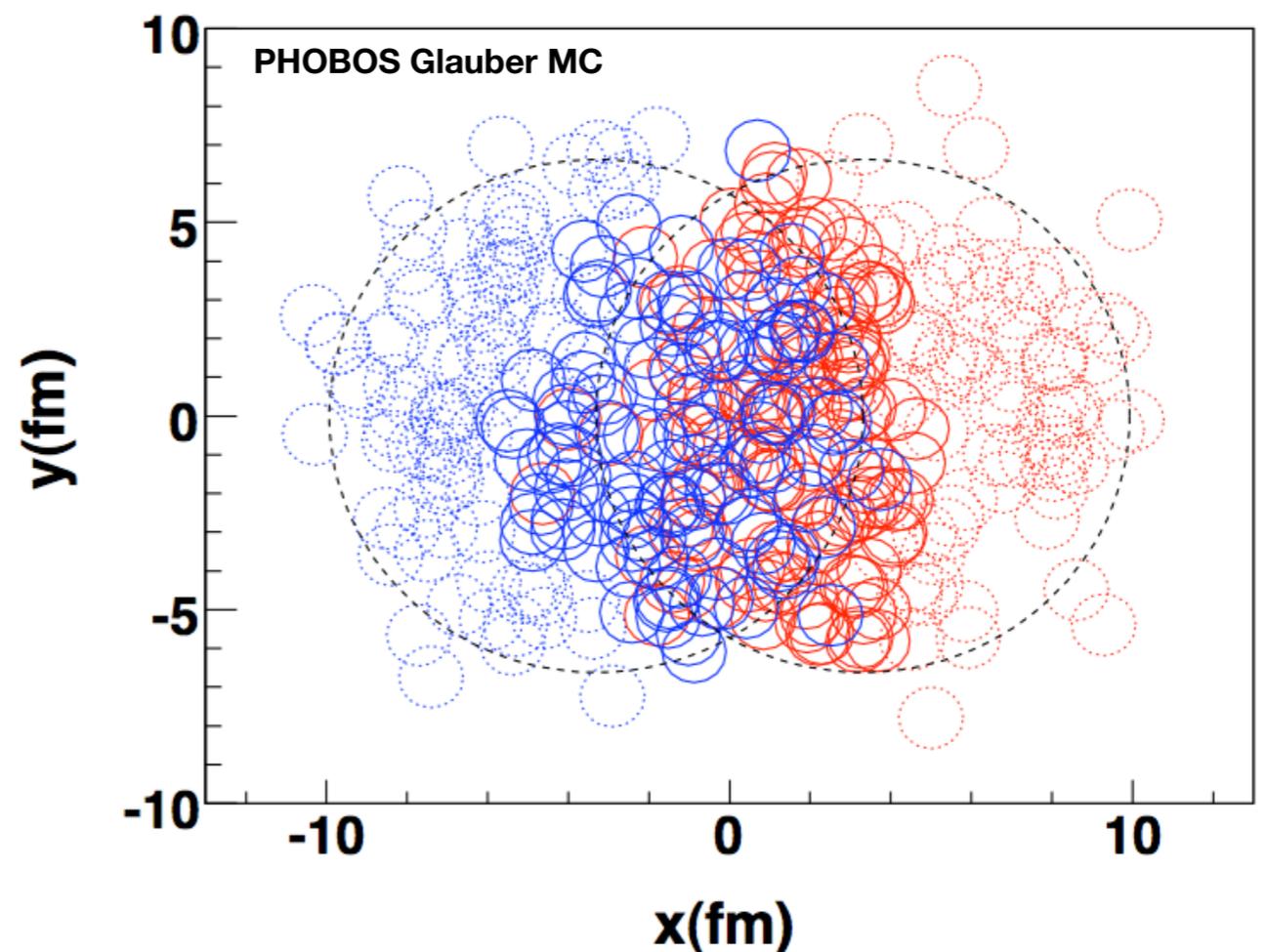
Includes statistical fluctuations

Number of Participating Nucleons, N_{part}

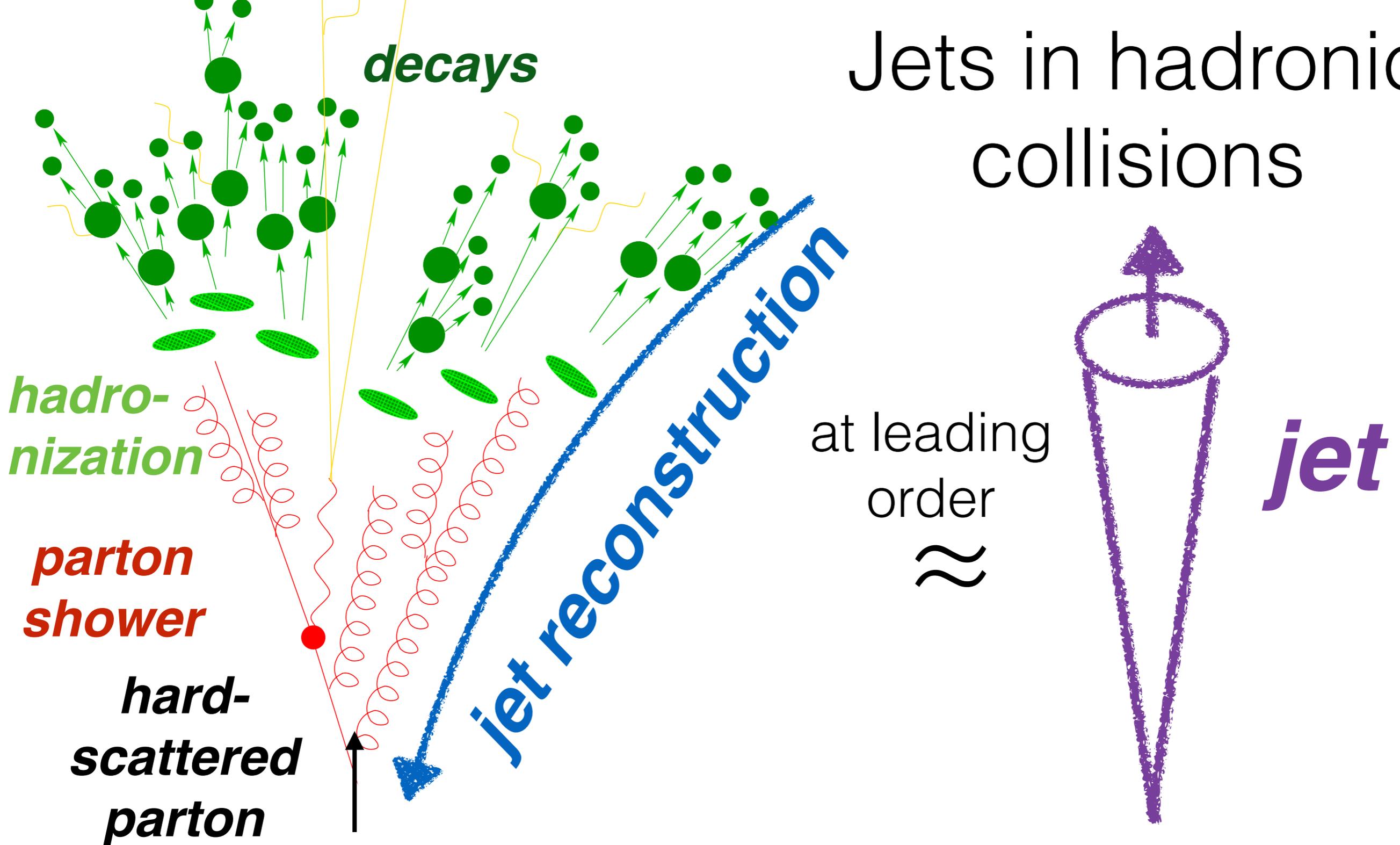
~ system size

Number of Binary Scatterings, N_{coll}

~ hard process cross-section



Jets in hadronic collisions



- Most abundant, fundamental final-state QCD observable
- Approximate relationship to hard parton-parton kinematics
- Increased kinematic reach over single hadron measurements



New York

Switzerland



RHIC

PHENIX

STAR

1.2 km

beam	energy (GeV)
$\vec{p}+\vec{p}$	62 - 510
$(p,d,He^3)+Au$	22-200
Cu+Cu	22 - 200
Cu+Au	200
Au+Au	7 - 200
U+U	193



CMS

LHC

LHCb

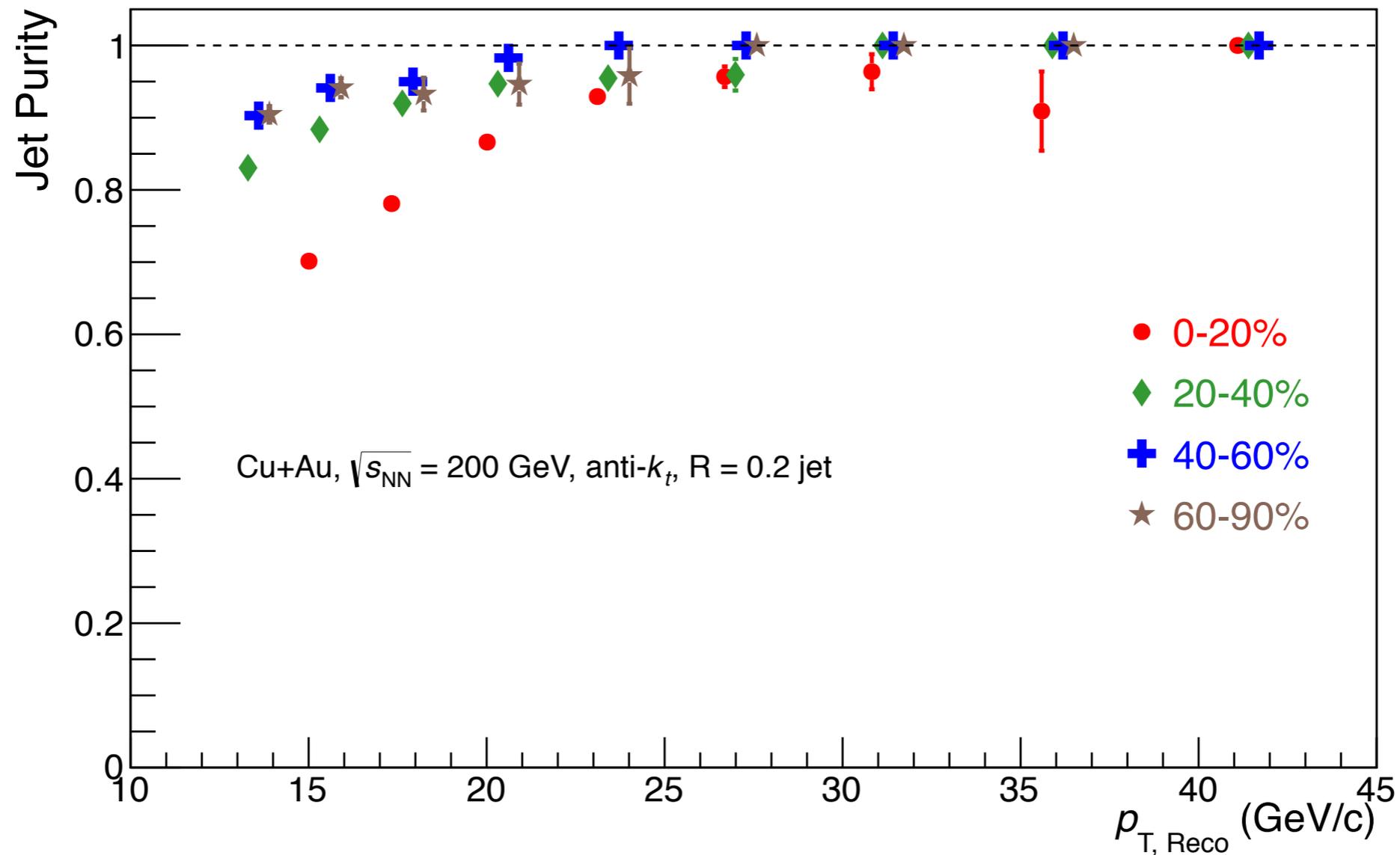
ATLAS

ALICE

8.6 km

beam	energy (GeV)
p+p	7000-8000
p+Pb	5020
Pb+Pb	2760

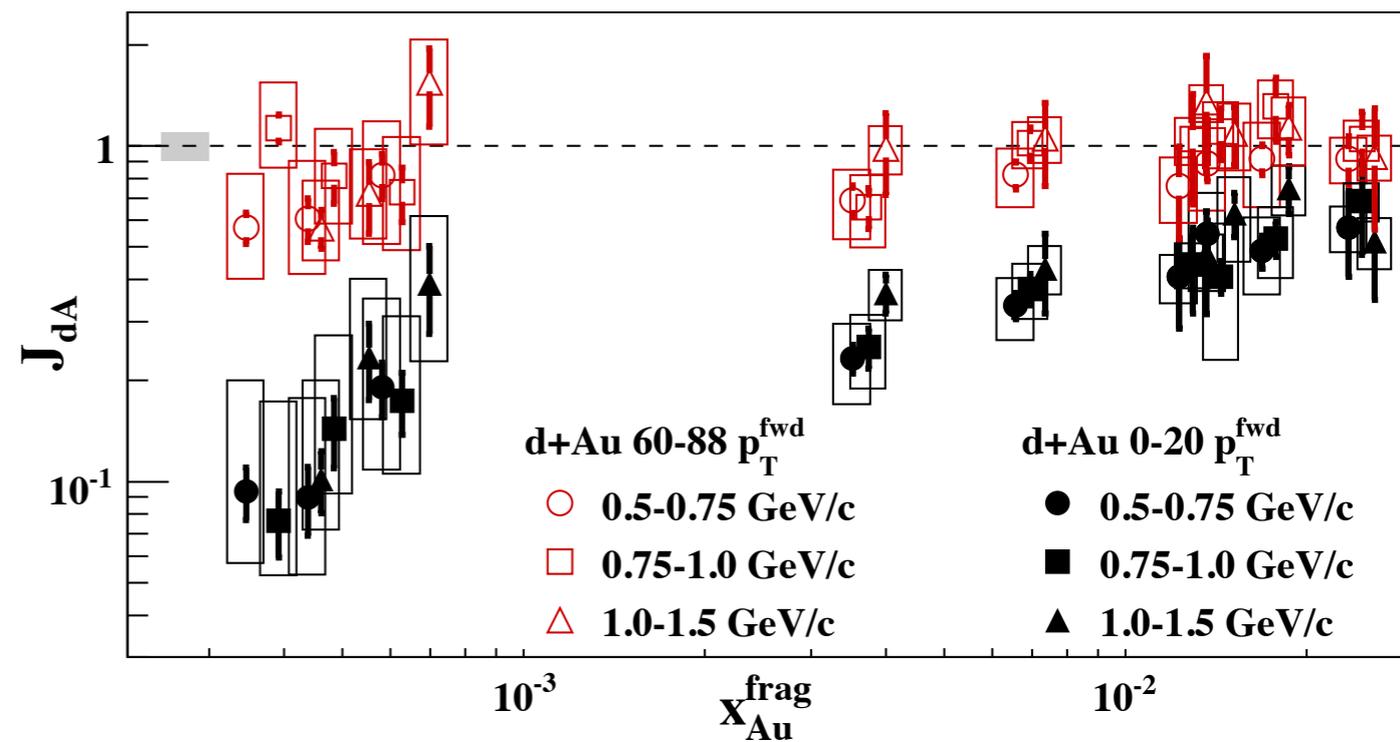
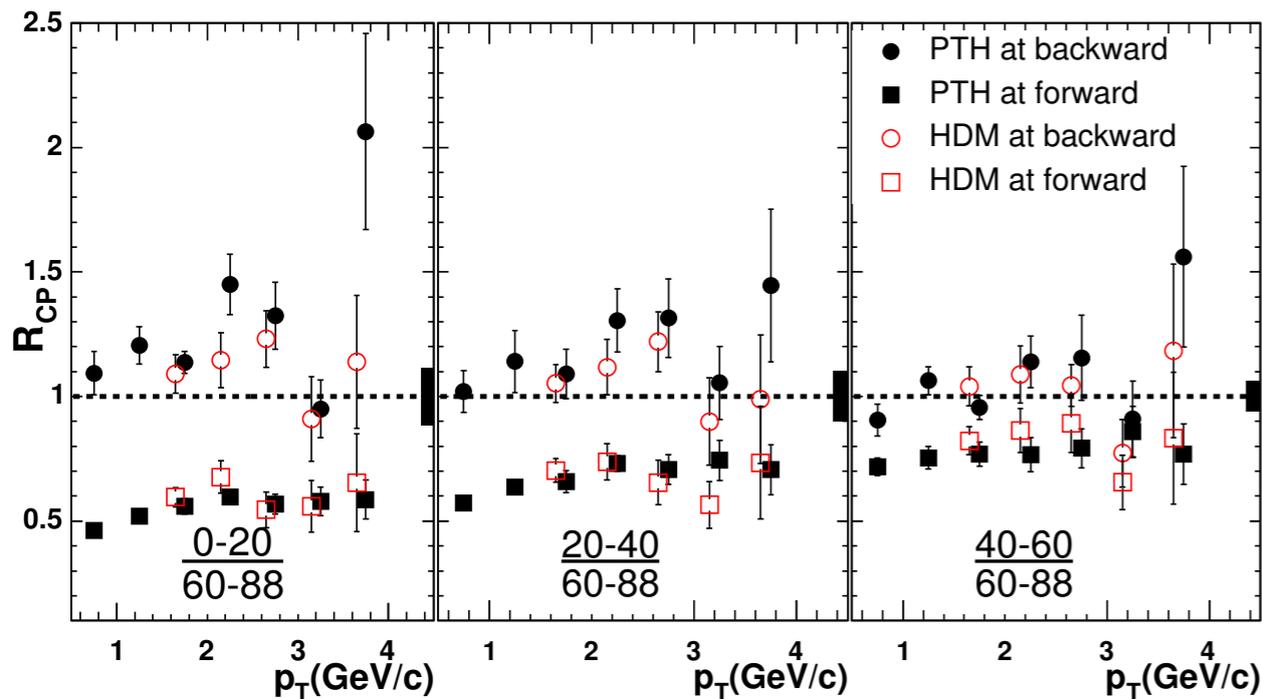
Jet Purity



- Fake jet contribution is both p_T and centrality dependent; the contribution being largest for central collisions and at low p_T
 - for 0-20%, purity is 70% (93%) at 15 GeV/c (23 GeV/c)

**Concept: Restrict analysis to large purity regions
limits uncertainty on systematics from removal**

New angle on previous data?



- Strong centrality dependence in forward hadron and di-hadron production in $d+Au$
 - ➔ even though $\langle b \rangle$ does not change so much
 - ➔ attributed by many to low nuclear- x effects (CGC?), but kinematic region also associated with large deuteron- x
- My two cents: there's an overall suppression, but most of the centrality "dependence" is from large x_d , **not** small x_{Au}