RHIC & AGS
Annual Users' Meeting
Hosted By Brookhaven National Laboratory

2002
2004
2005

Jet Measurements with PHENIX

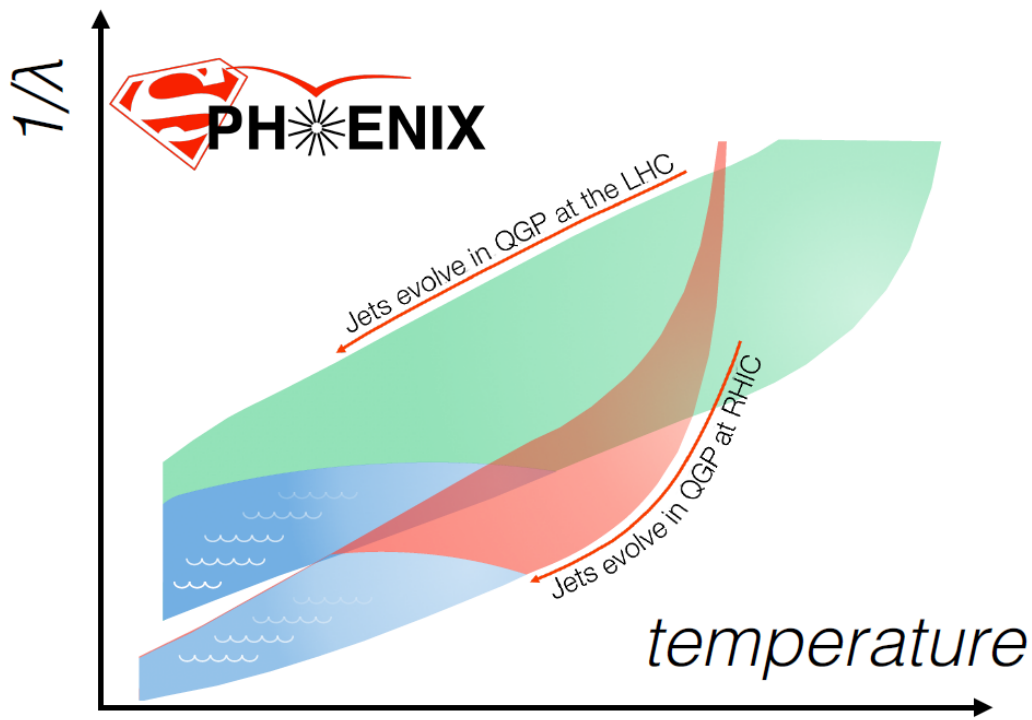
Arbin Timilsina (Iowa State University)
for the PHENIX Collaboration

June 8, 2016

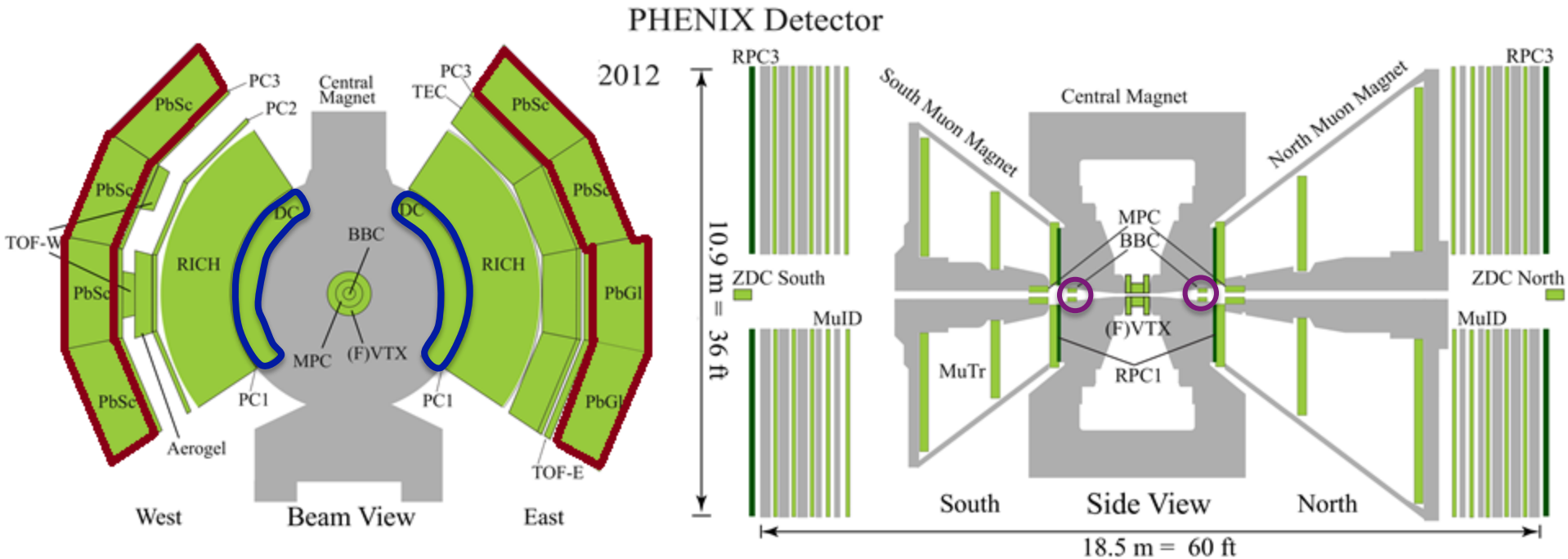
Jets at RHIC

- Versatility of RHIC provides ability to study jet modification in different collision geometries, system sizes, and energy densities

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

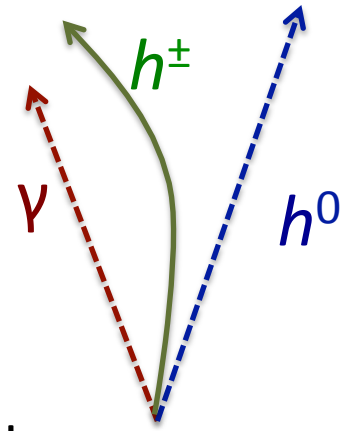


PHENIX Detector



- **Central arm: $|\eta| < 0.35$ and $\Delta\phi = \pi$**
- Charged particle tracks are reconstructed using the **Drift Chamber (DC)**, the Pad Chamber (PC), and the collision point
- Neutral clusters are measured in the **Electromagnetic Calorimeter (EMCal)**
- **Beam Beam Counters (BBCs)** provide vertex and centrality classification

Jets in PHENIX



- Jets reconstructed using the anti-k_t algorithm
  - **EMCal cluster energy** + **charged particle tracks**

- Jet-level requirements
  - number of constituents ≥ 3
  - restriction on contribution of charged constituents
  - jet axis required to be away from detector edge

- Centrality-dependent response matrices generated by embedding PYTHIA *p*+*p* jets into real heavy ion events
  - Due to missing **neutral hadronic energy** and tracking inefficiency, on average, PHENIX gets ≈ 70% of the true jet energy
  - Spectra corrected for detector effects and underlying event fluctuations with unfolding procedure

Jet results from PHENIX

Two new results shown first at Quark Matter 2015

d+Au and p+p jet spectra (2008 data)

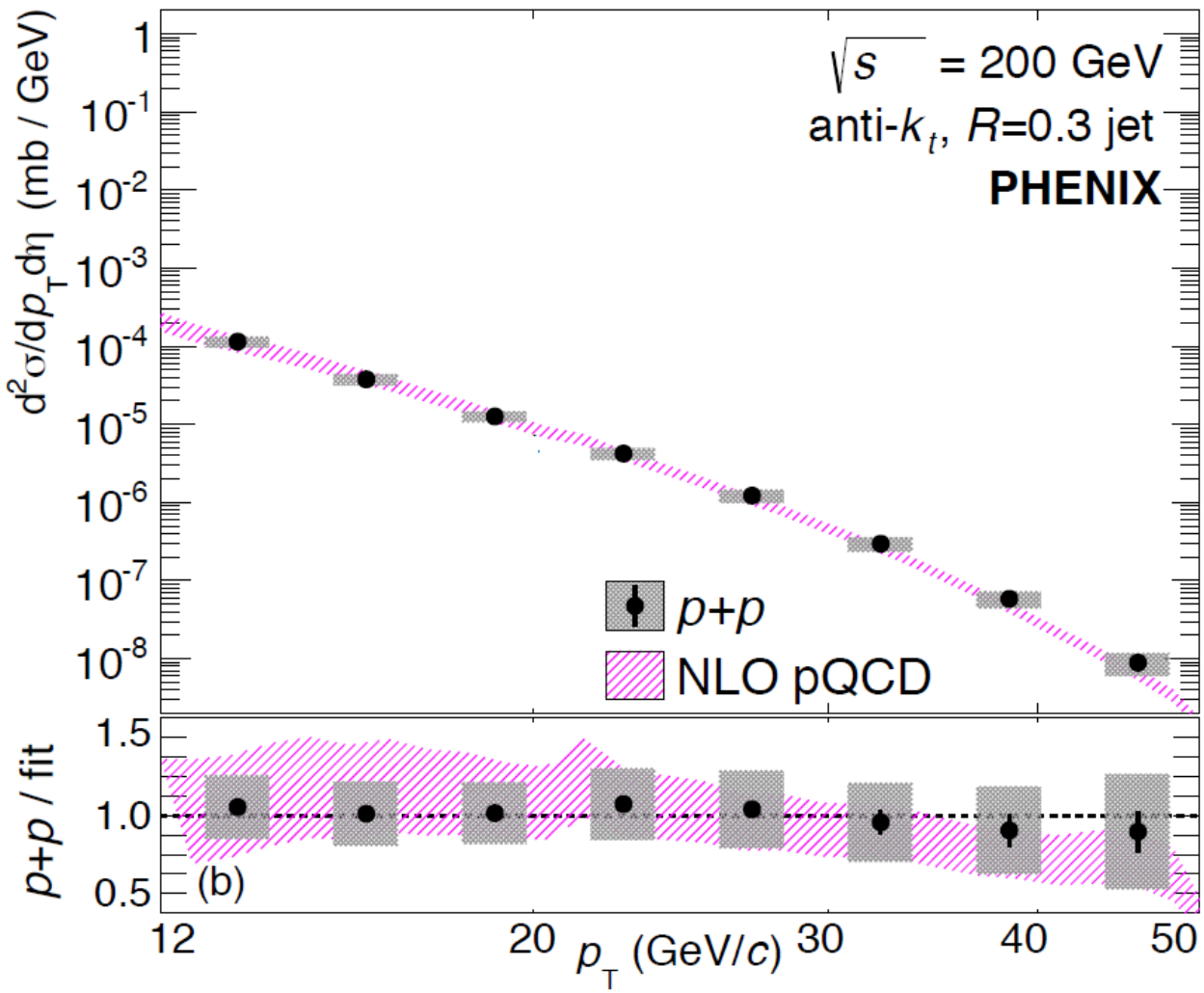
- **R=0.3** anti-k_t algorithm
- Phys.Rev.Lett. 116 (2016) no.12, 122301
- **Establish pQCD baseline**

Cu+Au and p+p jet spectra (2012 data)

- Preliminary measurement, manuscript being written
- **R=0.2** anti-k_t algorithm; choice of smaller cone size due to demands of HI environment
- **First look at inclusive suppression of jet spectra by the QGP from PHENIX!**

p+*p* collisions

Jet spectra in *p+p* collisions

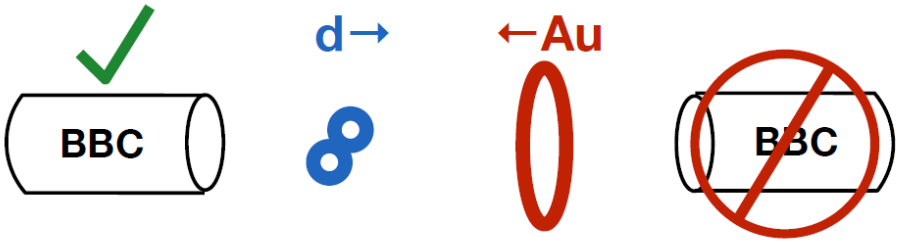


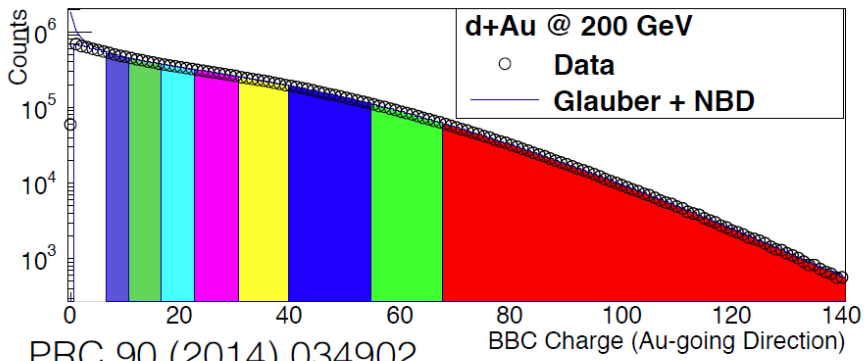
***p+p* spectra**: compare well with **NLO pQCD calculation**

- validates jet reconstruction and correction procedure in PHENIX

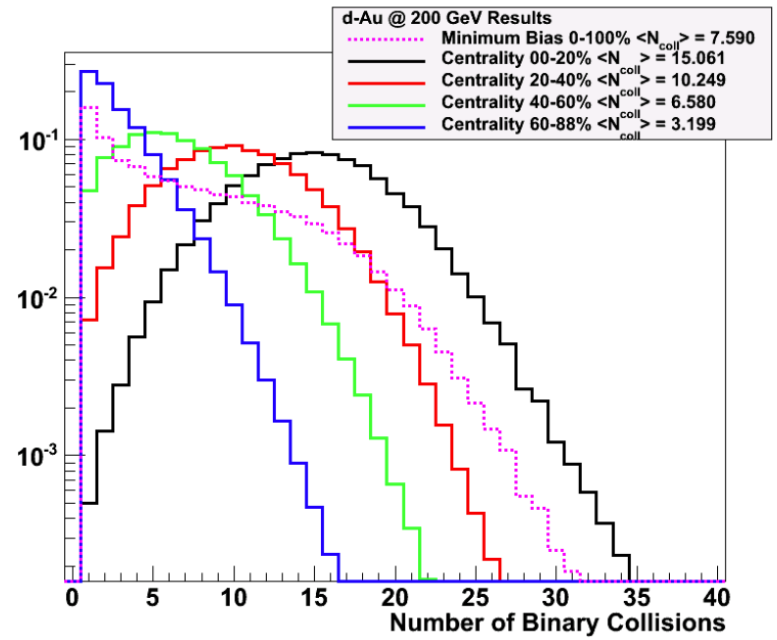
d+Au collisions

Centrality in *d*+Au collisions



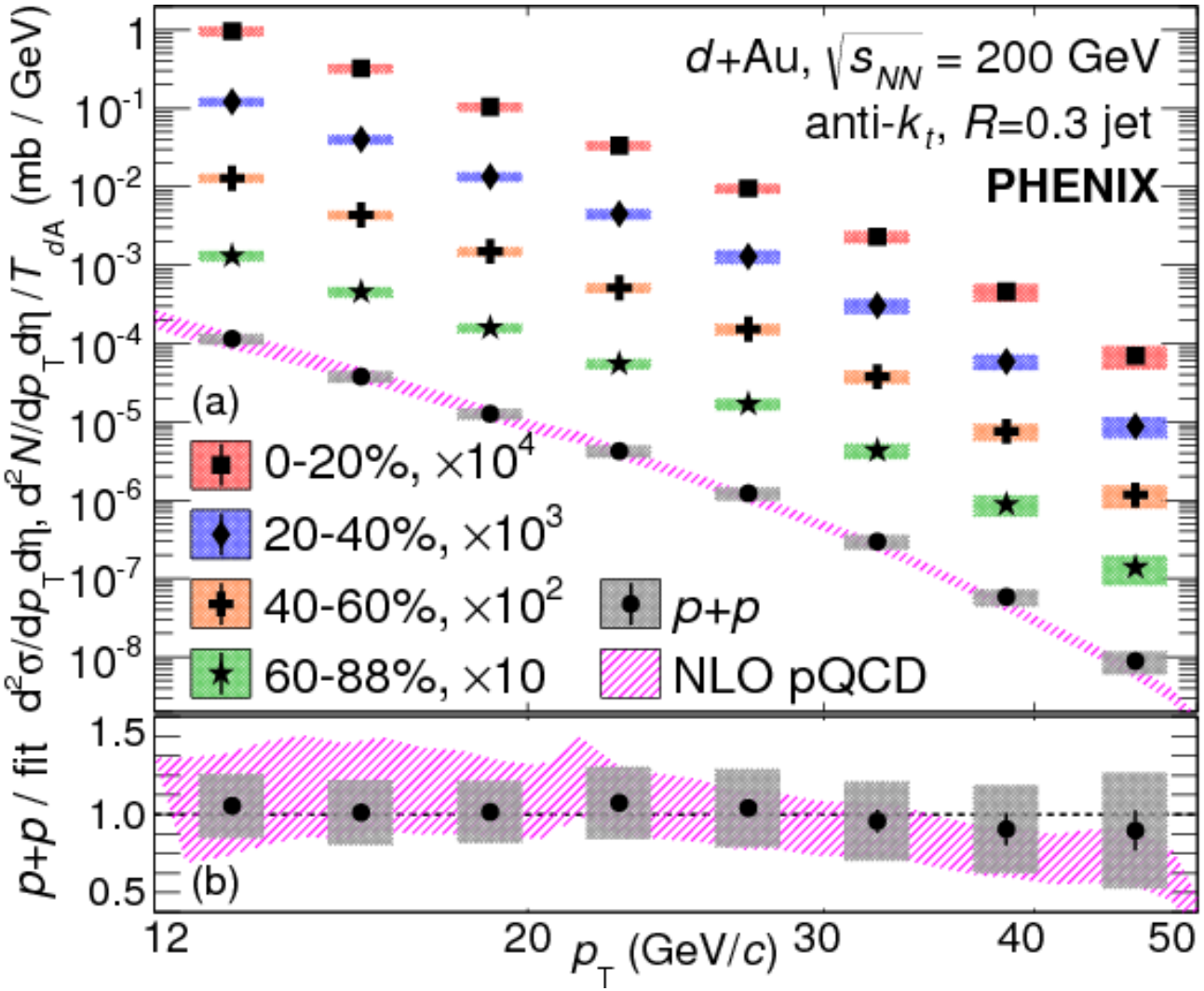


PRC 90 (2014) 034902



- Selection of centrality categories in *d*+Au collisions based on total charge in **Au-going** beam-beam counter ($-3.9 < \eta < -3.0$)
- Glauber Monte Carlo simulation to map from the measured charge to geometric quantities
  - estimate nuclear overlap factor T_{dAu} for classes of *d*+Au collisions
  - previously successful with hard and soft observables

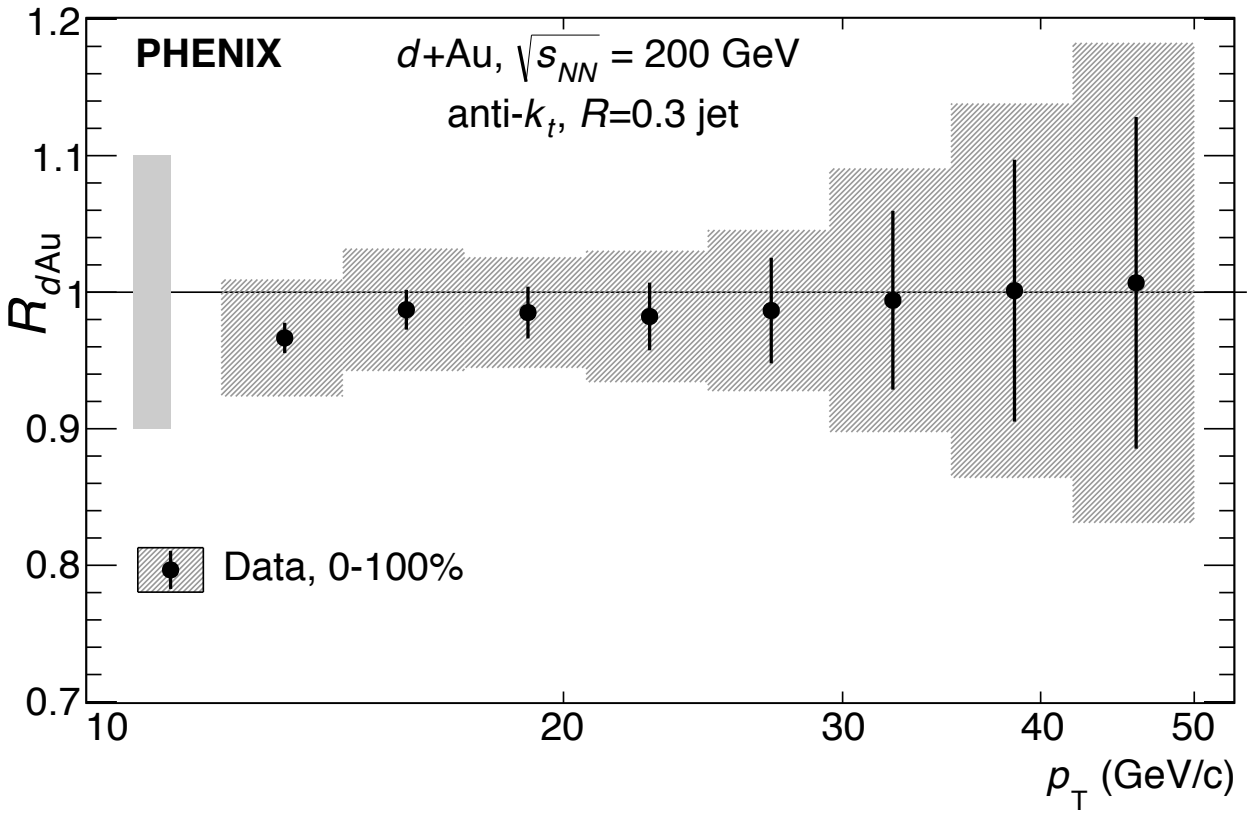
Jet yields in *d*+Au Collisions



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

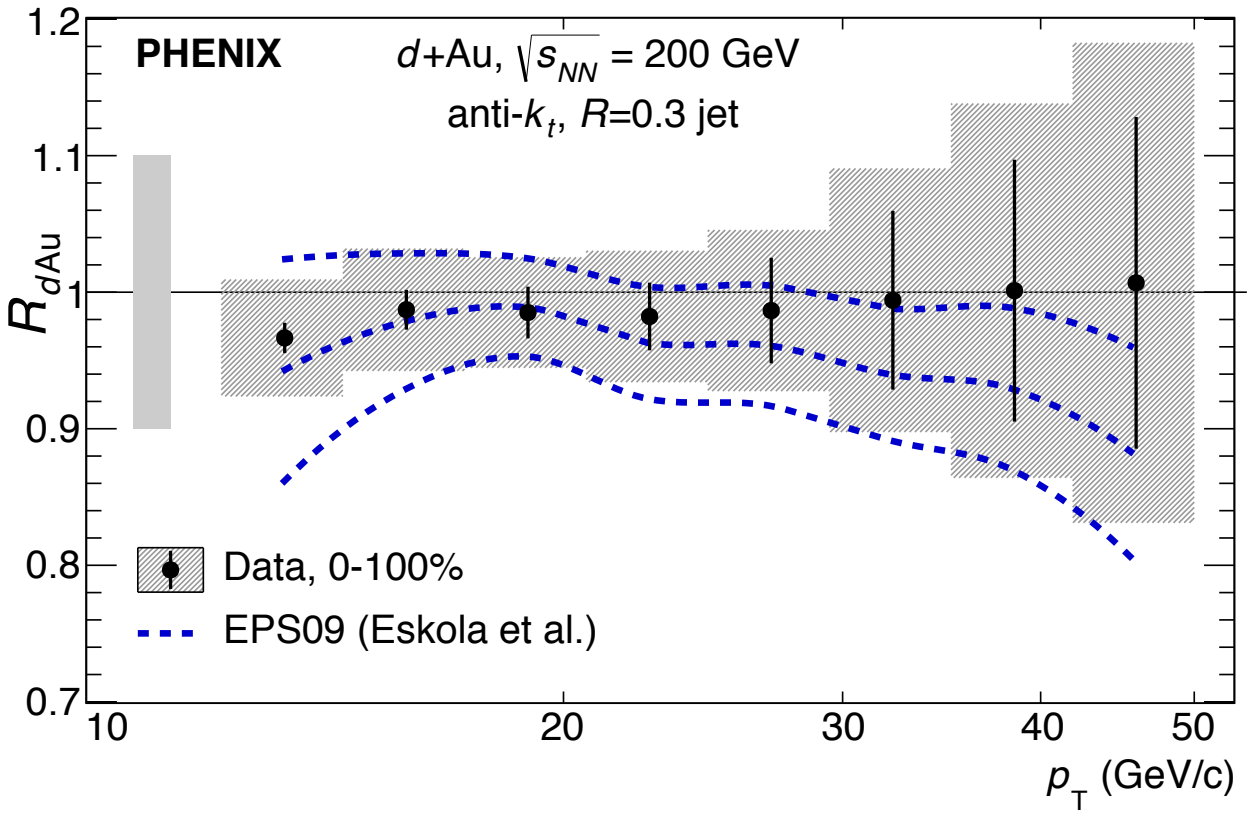
Minimum bias jet rate

$$R_{d\mathrm{Au}} = \frac{\mathrm{d}N^{d+\mathrm{Au}}/\mathrm{d}p_{\mathrm{T}}}{T_{\mathrm{dA}} \times \mathrm{d}\sigma^{p+p}/\mathrm{d}p_{\mathrm{T}}}$$



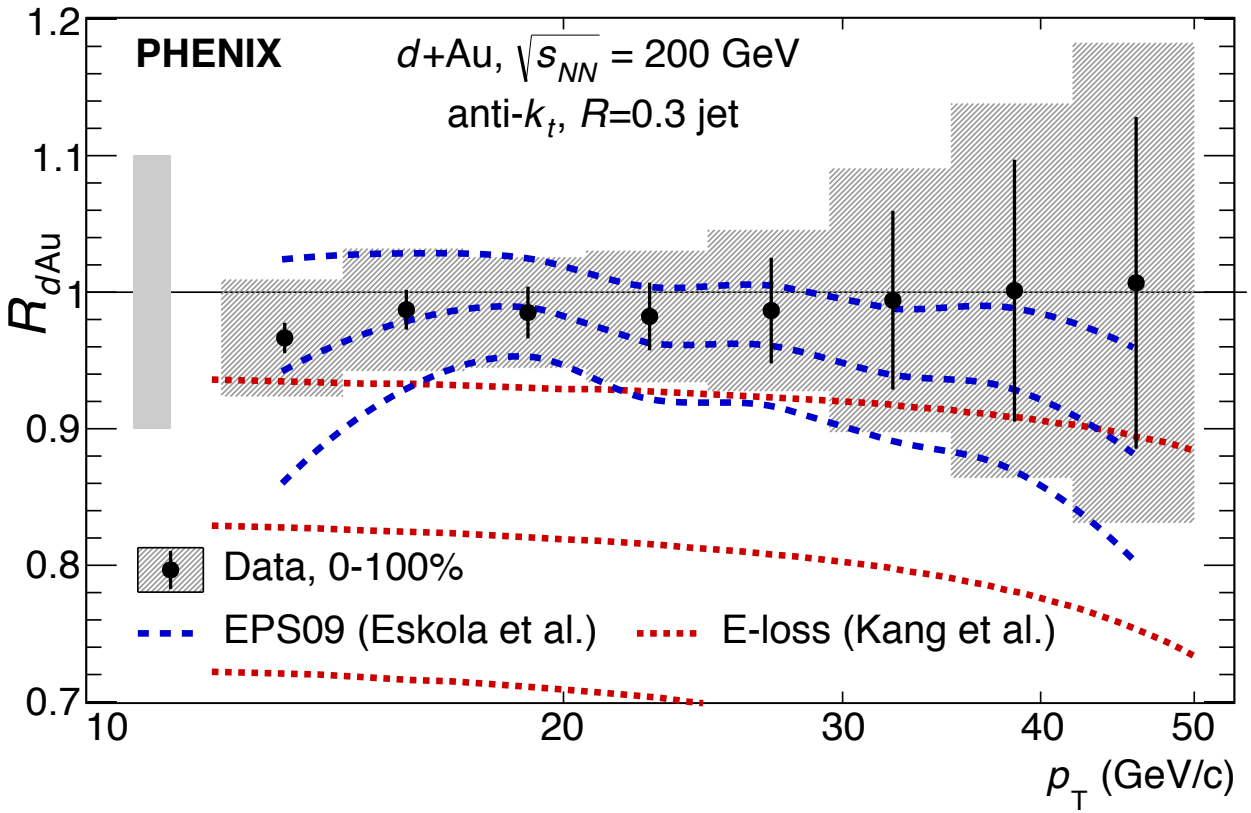
- In centrality-integrated collisions, $R_{d\mathrm{Au}} = 1$

Minimum bias jet rate



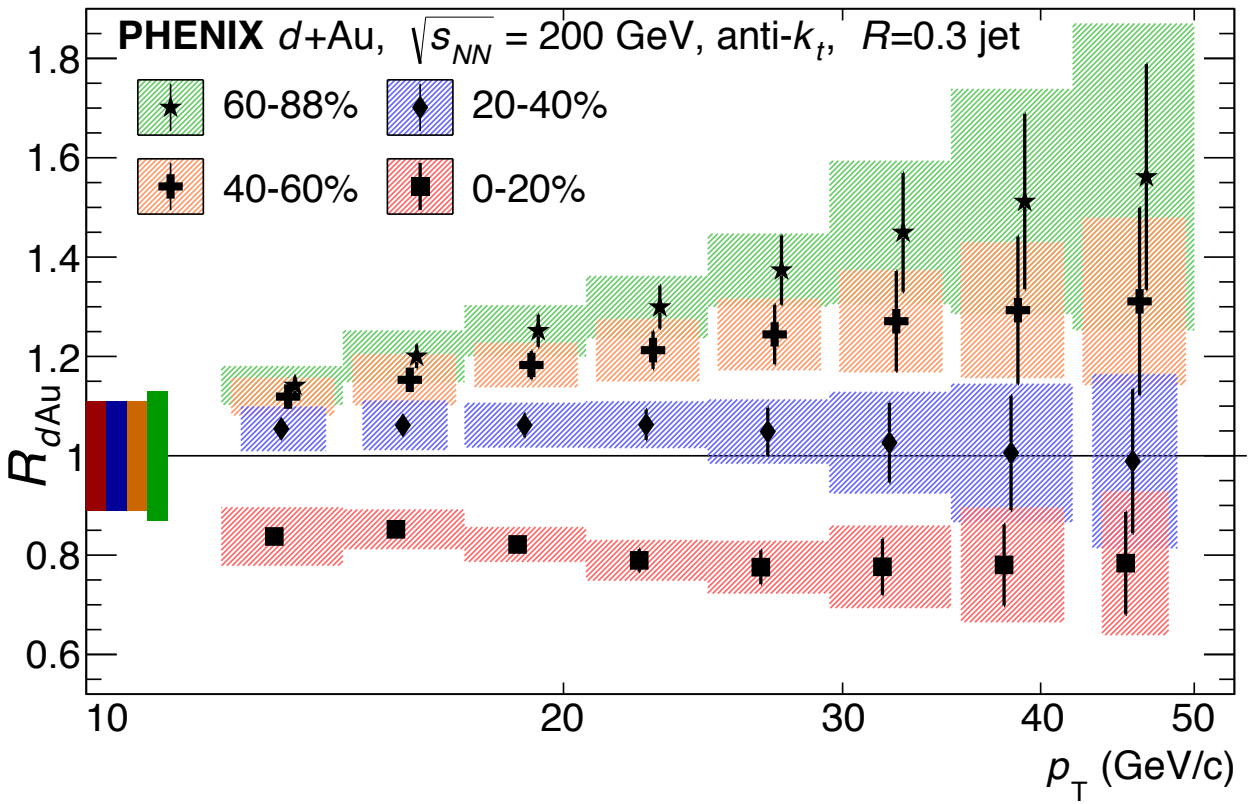
- In centrality-integrated collisions, $R_{dAu} = 1$
  - compares favorably to global nuclear PDF analyses (**EPS09**) within uncertainties

Minimum bias jet rate



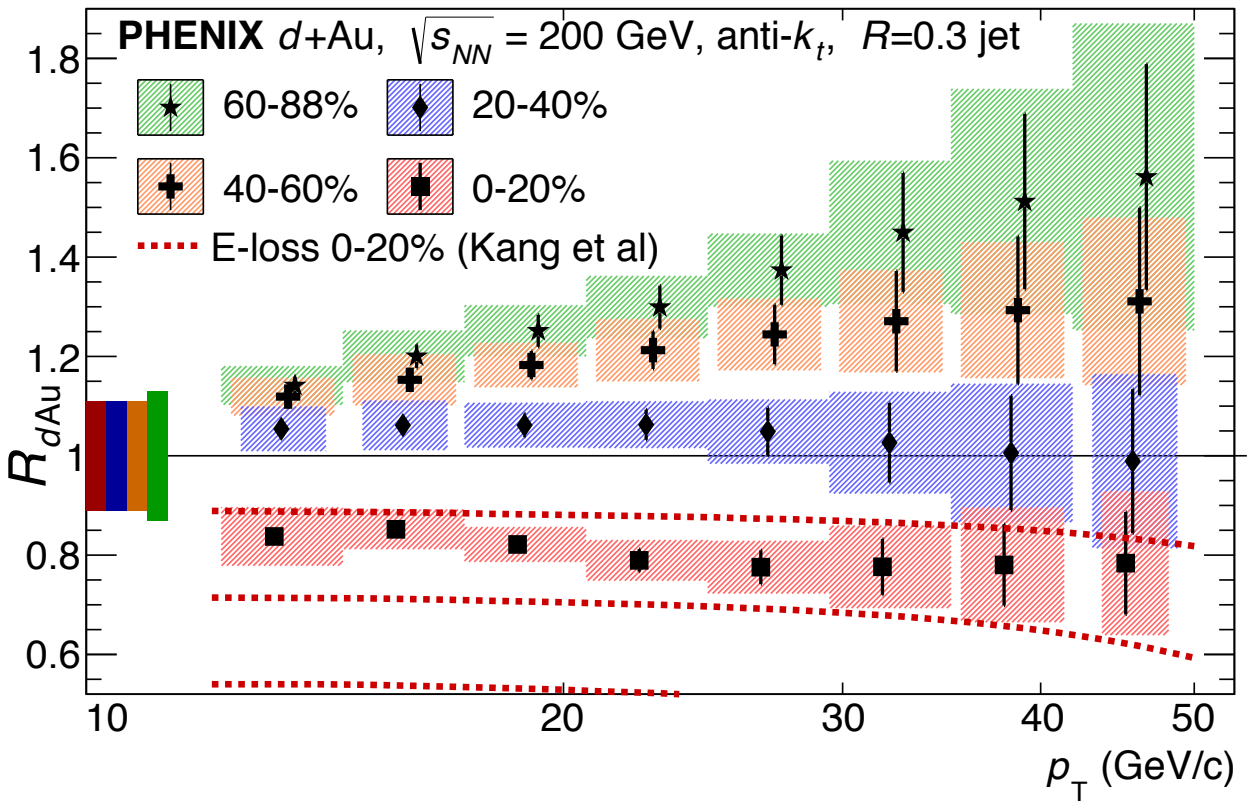
- In centrality-integrated collisions, $R_{d\mathrm{Au}} = 1$
  - compares favorably to global nuclear PDF analyzes (**EPS09**) within uncertainties
  - within **initial state E-loss** calculations, favors only small momentum transfers between parton and nuclear material

Centrality-selected jet rate



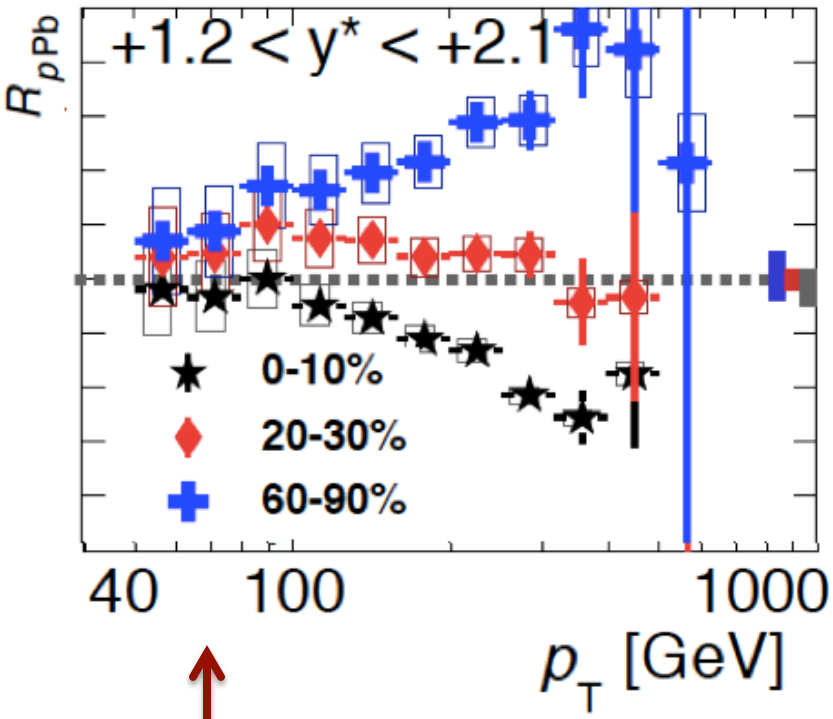
- Suppression of jet rate in central 0-20% (large N_{coll}) events
- Enhancement in 40-60% and 60-88% (small N_{coll}) events

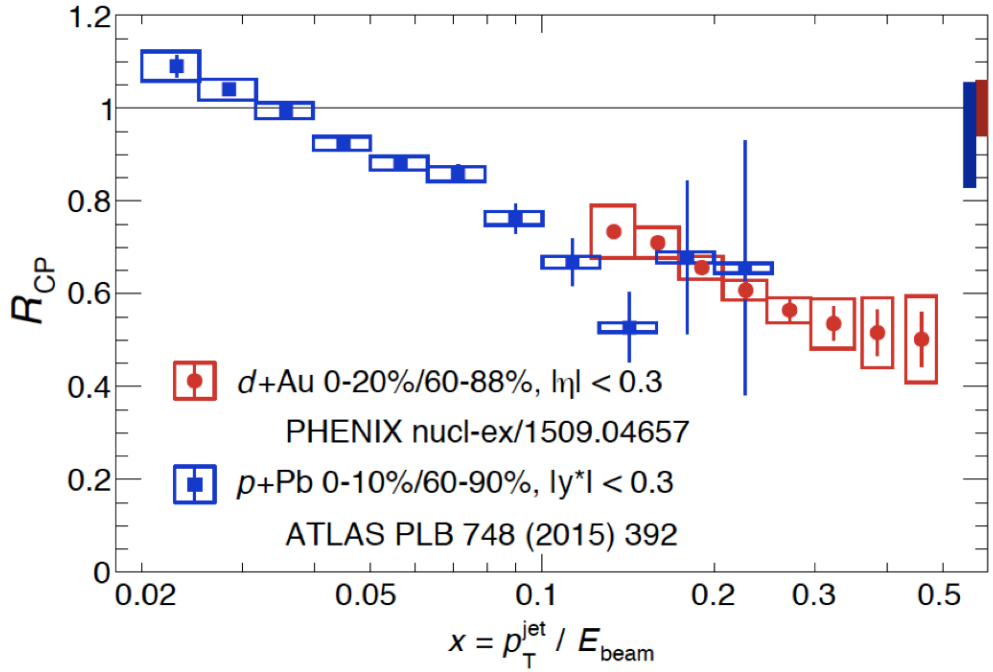
Centrality-selected jet rate



- 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**

Analogous LHC results





Same modification pattern

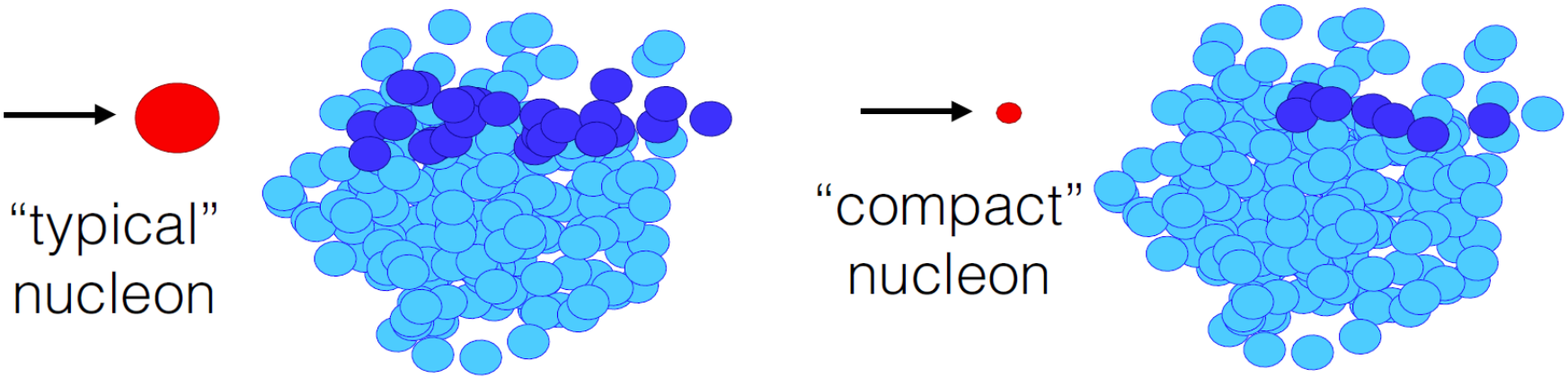
Similar hadron physics at RHIC and LHC?

Reconciling the puzzle

hep-ex/1409.7381
nucl-th/1603.06607

One possibility: "Shrinking proton" picture

- nucleon configuration with a high-x parton (>0.1) are different that "typical" configurations
- interact more weakly than average



Geometric interpretation: as these compact configurations traverse the large nucleus, they strike fewer nucleons

- relative decrease in the N_{coll} distribution
- so peripheral $R_{d\mathrm{Au}} > 1$, central $R_{d\mathrm{Au}} < 1$

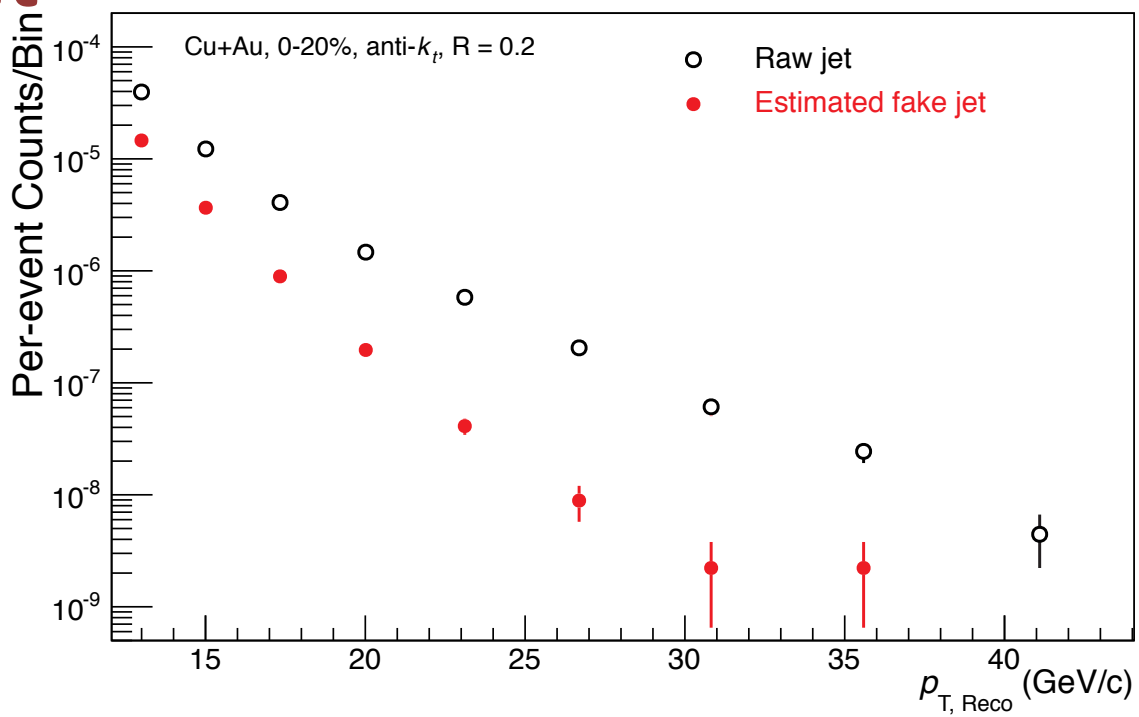
Cu+Au collisions

Cu+Au collisions

Cu+Au comes with challenges

- Stronger underlying event contribution
  -> choice of smaller cone size
- Fake jet contribution
  -> fake jet subtraction

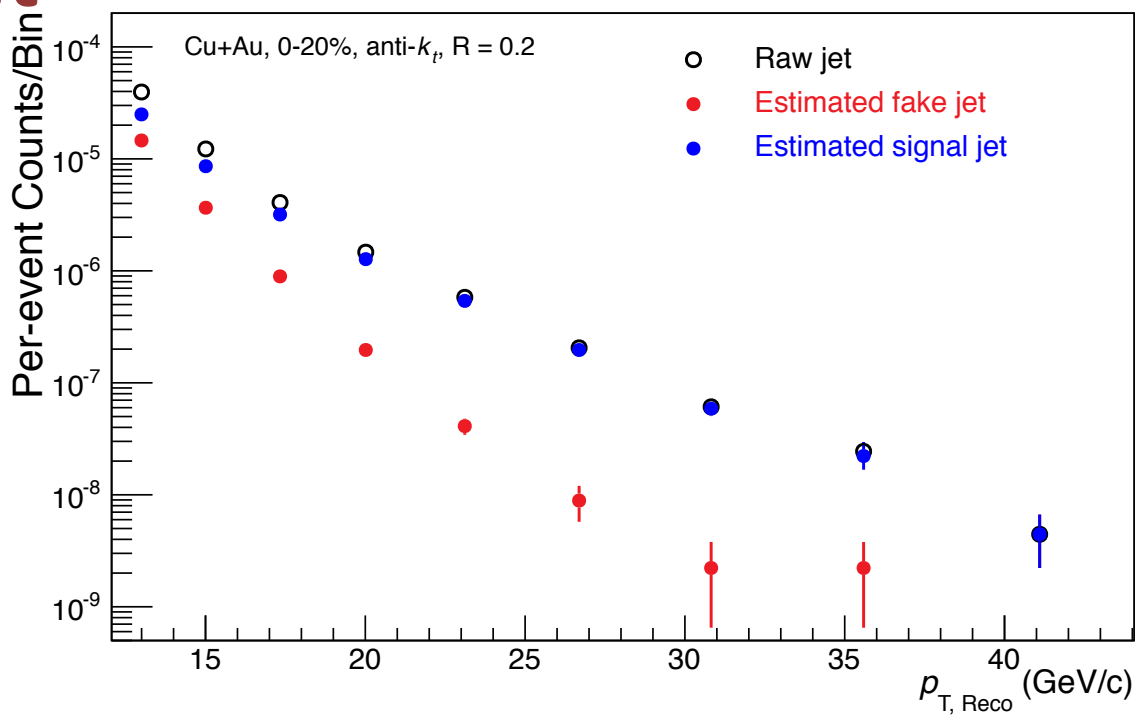
Fake jet



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 position (η, ϕ) of clusters are randomly shuffled
- Jet reconstruction performed in these shuffled tracks and clusters
  -> returns **estimated fake jet**

Fake jet

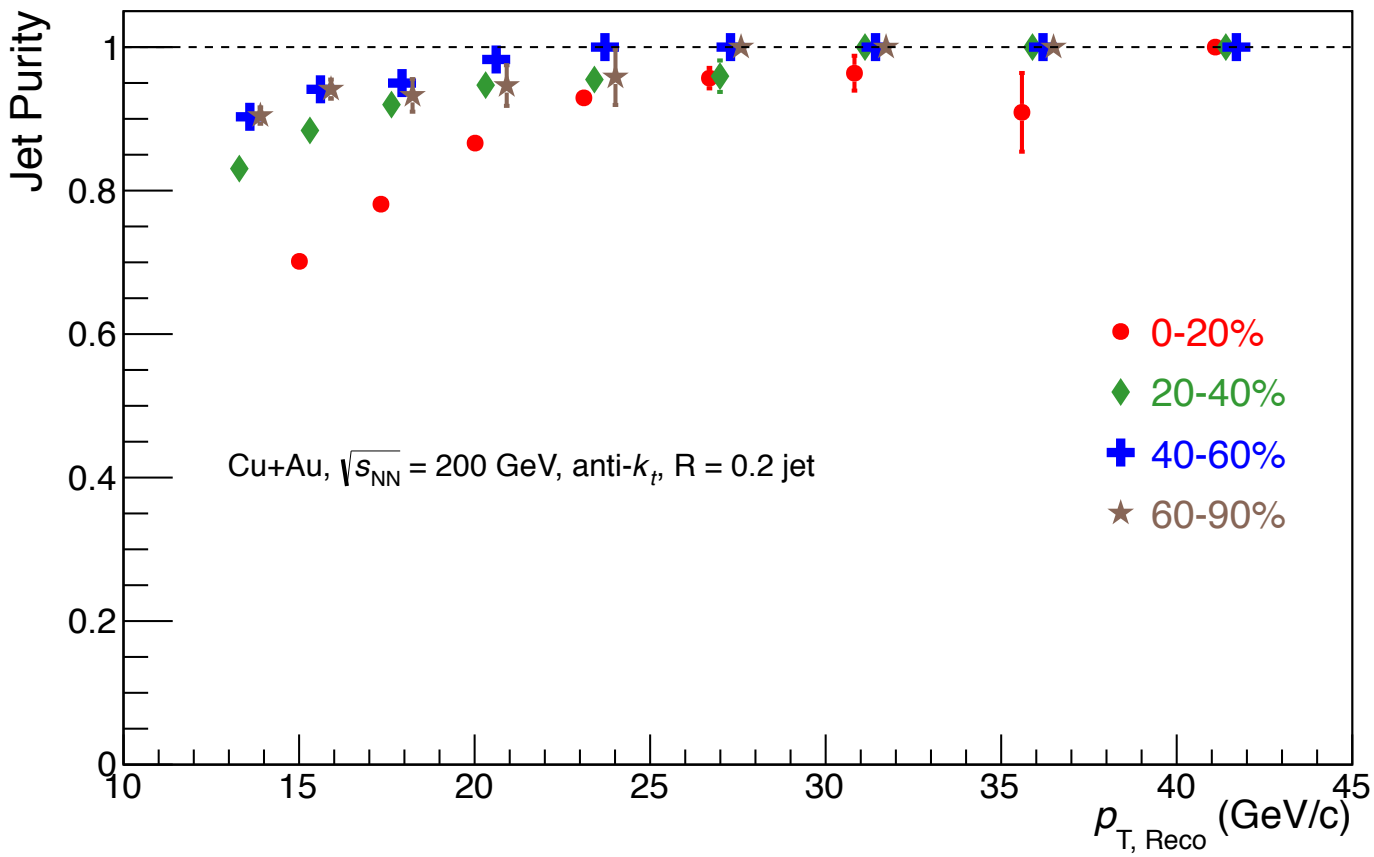


Data driven method of estimating and statistically subtracting fake jet contribution

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

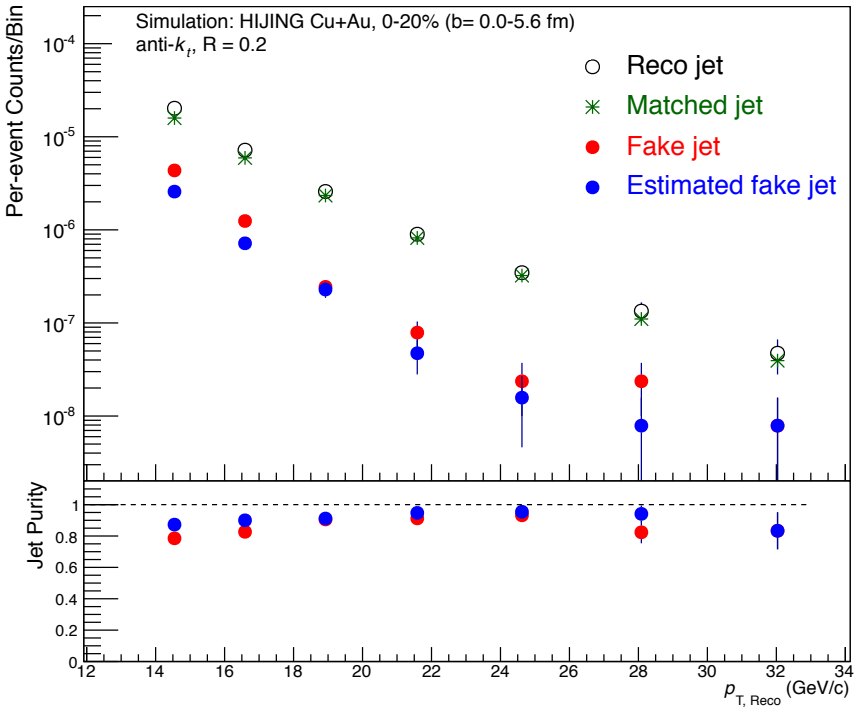
Fake jet

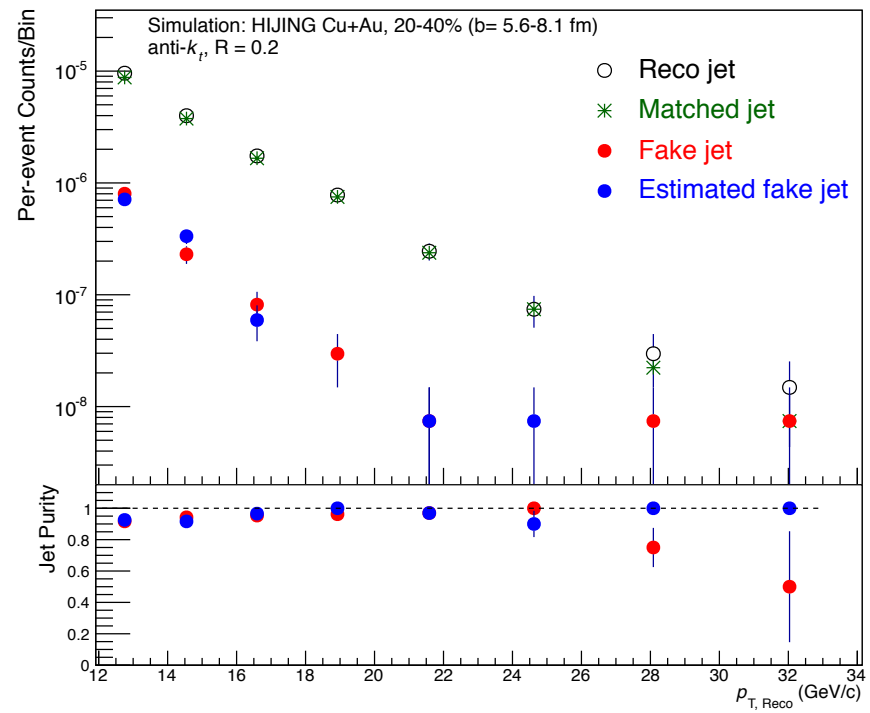
$$\text{Purity} = \frac{\text{Signal jets}}{\text{Raw jets}}$$



- 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)

Fake jet HIJING simulation study



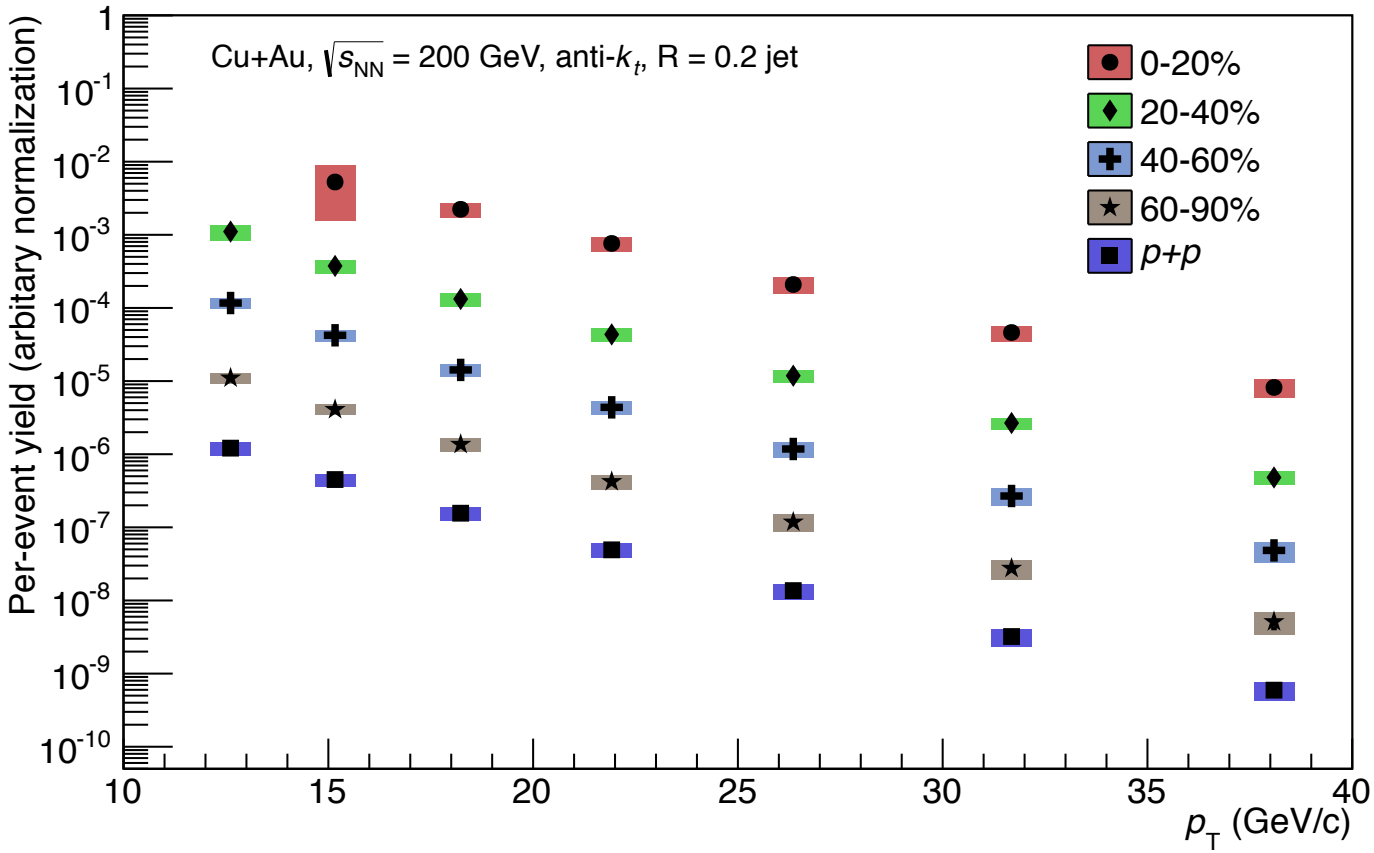


- Matched jet: Reco jet which is within $\Delta R < 0.2$ of true jet
- Fake jet: Reco jet which is not matched

Fake jet estimation procedure gives comparable result!

Fake jet contribution analyzed alternately by re-running the analysis with cluster and track selections of > 2 GeV

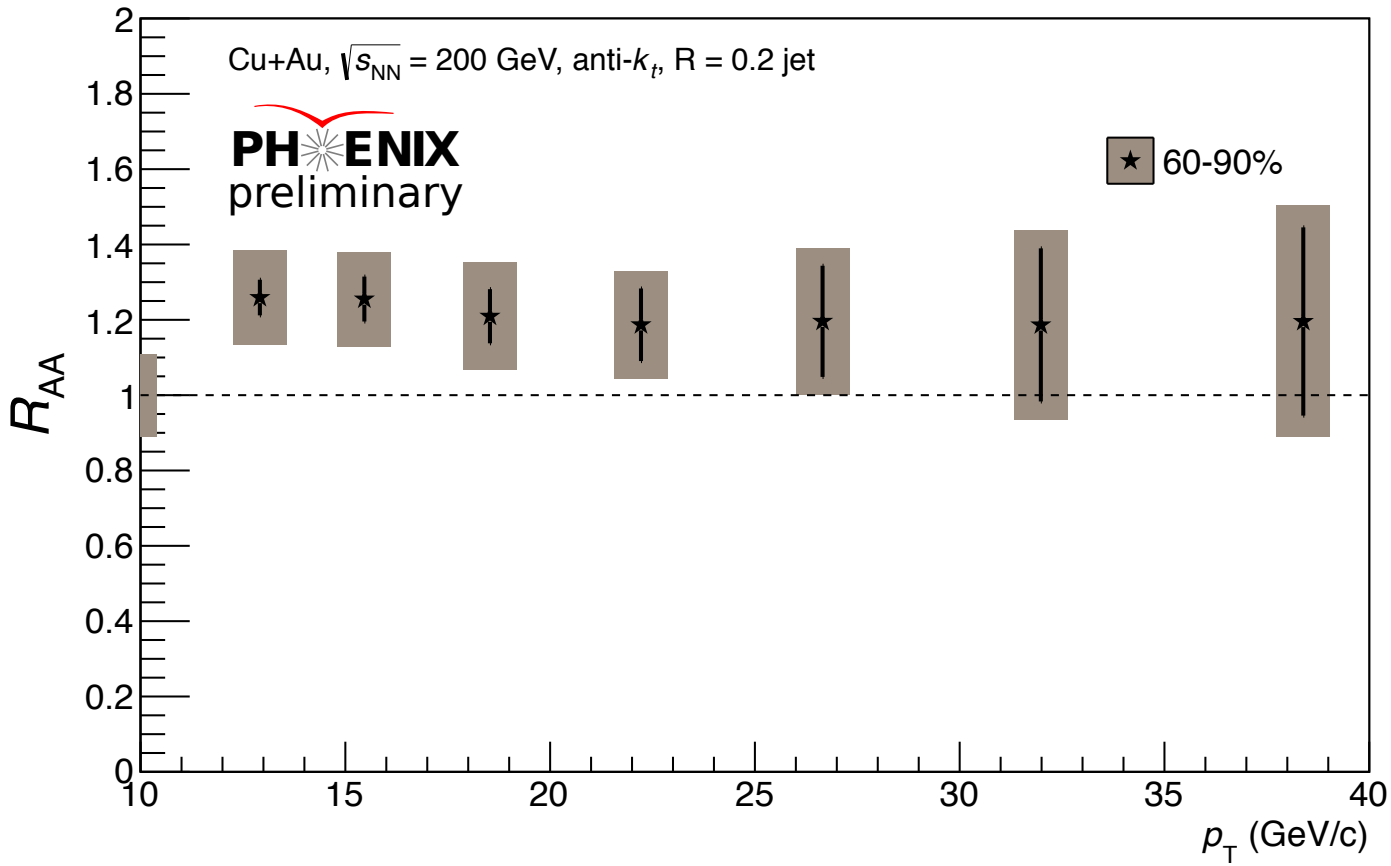
Jet spectra in *p*+*p* and Cu+Au



- Spectra unfolded using SVD method (cross-checked using iterative Bayesian method)
  - detector effects
  - centrality dependent underlying event fluctuations

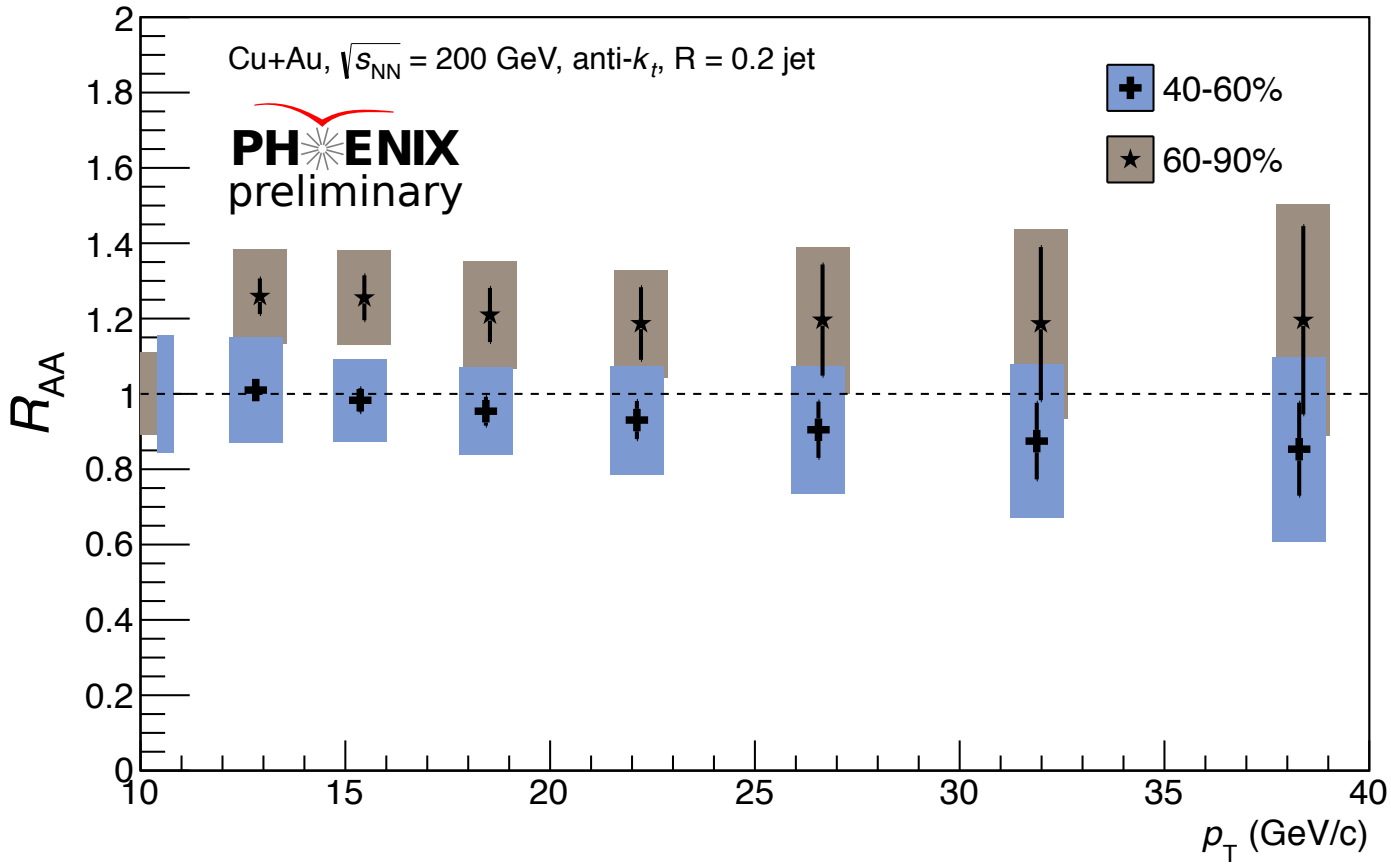
Jet suppression: R_{AA} vs. p_T

$$R_{AA}^{cent} = \frac{\left(\frac{1}{N_{evts}^{cent}}\frac{dN}{dp_T}^{cent}\right)_{CuAu}}{T_{AB}^{cent} \times \frac{d\sigma}{dp_T}}$$



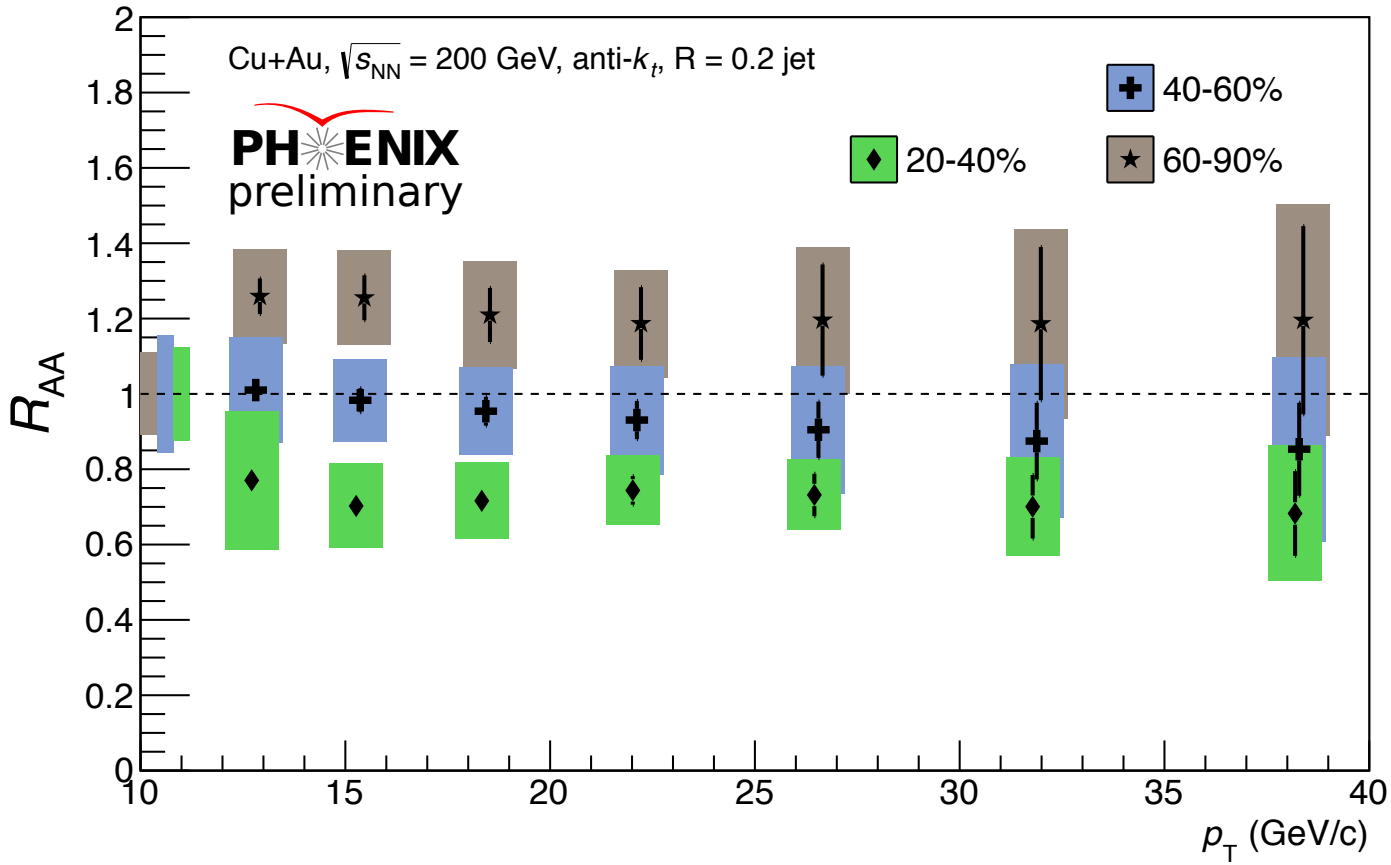
- At high p_T, consistent with 1 within the uncertainties

Jet suppression: R_{AA} vs. p_T



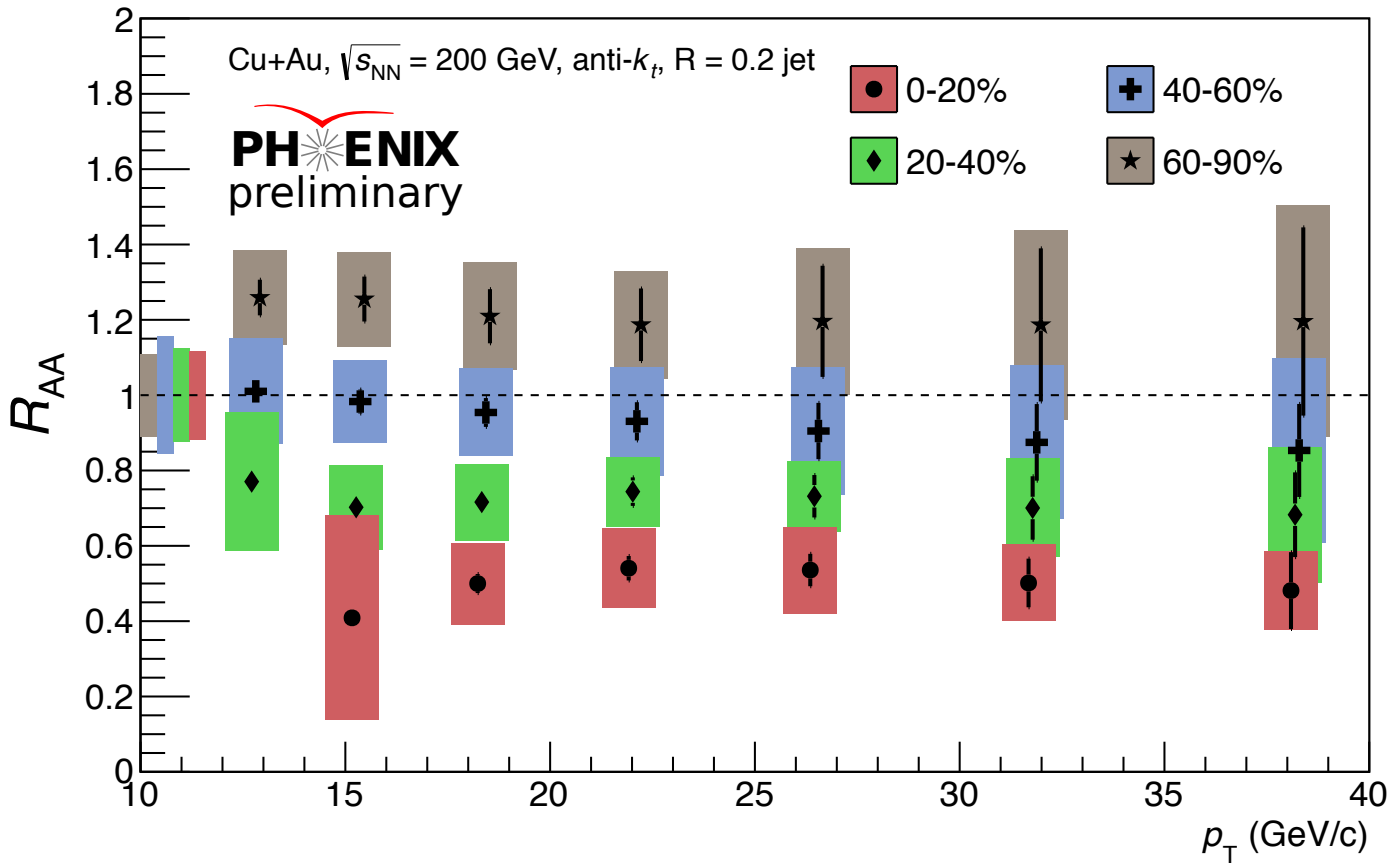
- Suppression shows centrality dependence

Jet suppression: R_{AA} vs. p_T



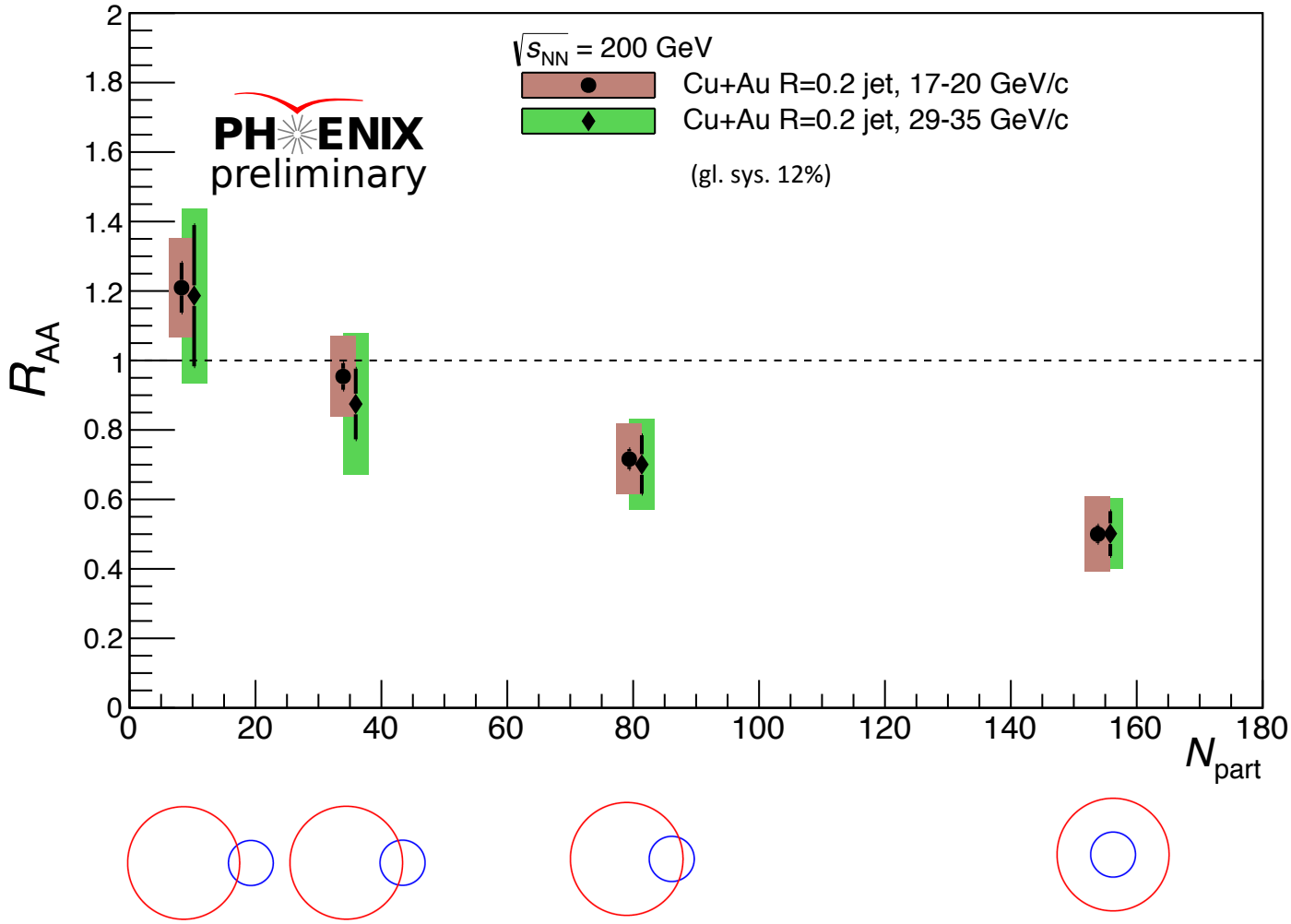
- Suppression shows centrality dependence
- No p_T dependence

Jet suppression: R_{AA} vs. p_T



- For central collisions, jets are suppressed by approximately a factor of two

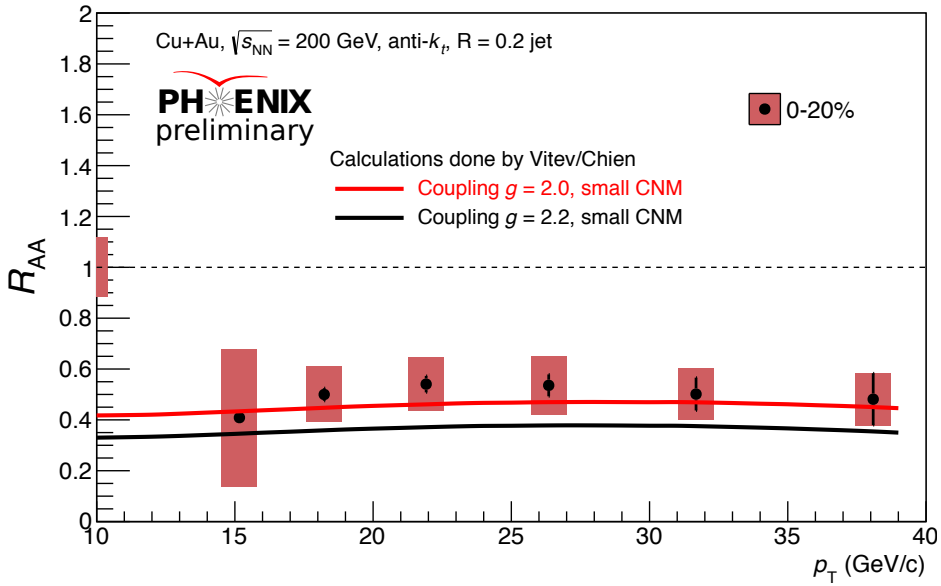
Jet suppression: R_{AA} vs. N_{part}

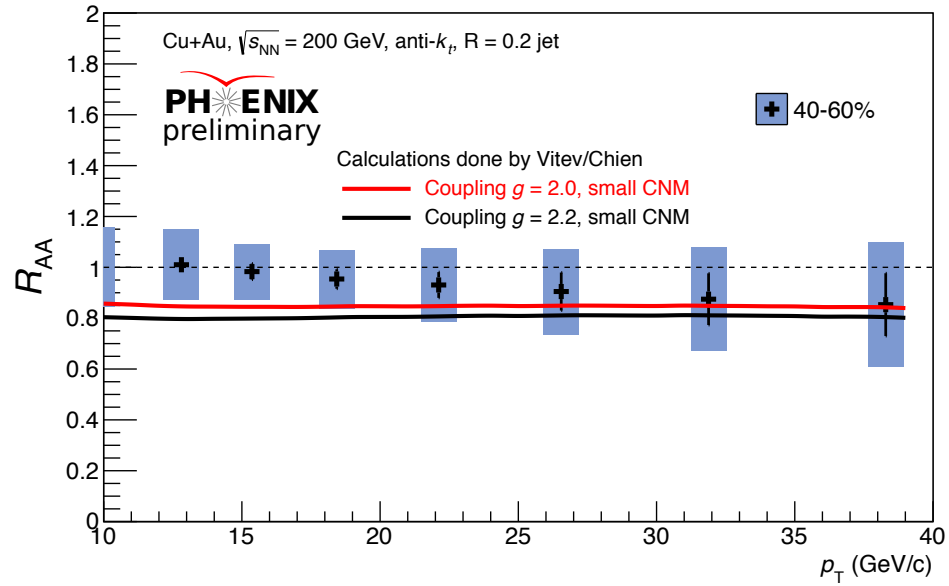


- Another look at the N_{part} dependence of suppression
- No p_T dependence within sensitivity over this kinematic range

Comparisons to theory

hep-ph/1509.07257
hep-ph/1509.02936





- **Left: 0-20%; right: 40-60%**
- $SCET_G$ calculations done for 2 different couplings between the jet and the medium (g=2.0 and g=2.2)
- 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

- Surprising, unexpected centrality dependence in *d*+Au jet rate
  - one possibility: are we sensitive to the fact that high-*x* nucleons are "smaller" than average?

- Preliminary measurement of a centrality-dependent suppression of jet in Cu+Au collisions
  - jets found to be suppressed by approximately a factor of two in central collisions
  - suppression shows no p_T dependence

Backup

Evaluation of systematic uncertainty

⇒ Variation is made in unfolding procedure. The default data is unfolded with modification in unfolding procedure.

- Shape of input spectrum: The input spectrum is obtained by modifying the power of the truth spectrum by ± 0.5.
- Unfolding is performed with Bayes method (default is SVD method).

⇒ Variation is made in simulation. The default data is unfolded with modified response matrix.

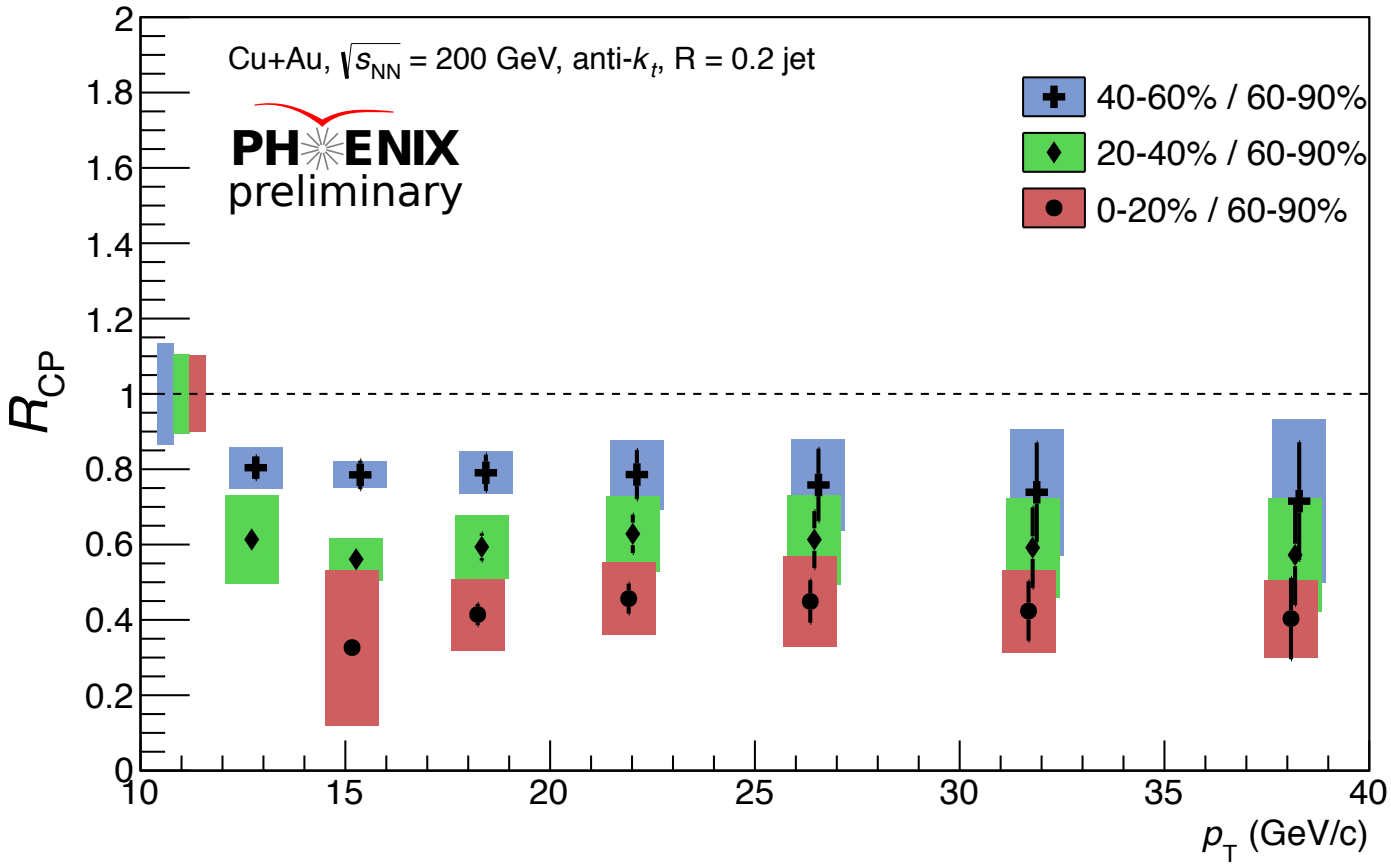
- Energy scale
  - EMCal energy scale: The energy of EMCal clusters is varied by $\pm 3\%$
  - DC p_T scale: The p_T of tracks is varied by p_T dependent way: 2% for $p_T < 10$ GeV/c and increased linearly such that it is 4% at 30 GeV/c.

⇒ Same variation is made in both data and simulation. The modified data is unfolded with modified response matrix.

- Jet-level cuts:
  - Default: $nc >= 3$ && $cf > 0.2$ && $cf < 0.7$. Variation: $nc >= 5$ && $cf > 0.2$ && $cf < 0.6$
- Acceptance
  - Fiducial cut: The reconstructed jets are required to lie within tighter phase space.
  - East/West arm: East arm yield is unfolded with response matrix for east arm and west arm yield is unfolded with response matrix for west arm.
- Fake jet
  - Default: Cluster energy > 0.5 GeV, track $p_T > 0.5$ GeV/c. Variation: Cluster energy > 2.0 GeV, track $p_T > 2.0$ GeV/c.

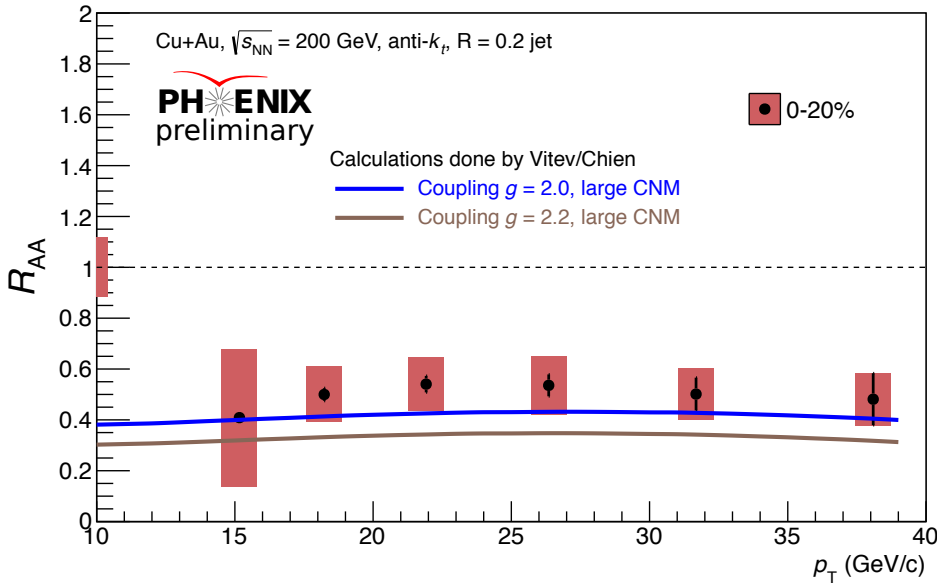
Jet suppression: R_{CP} vs. p_T

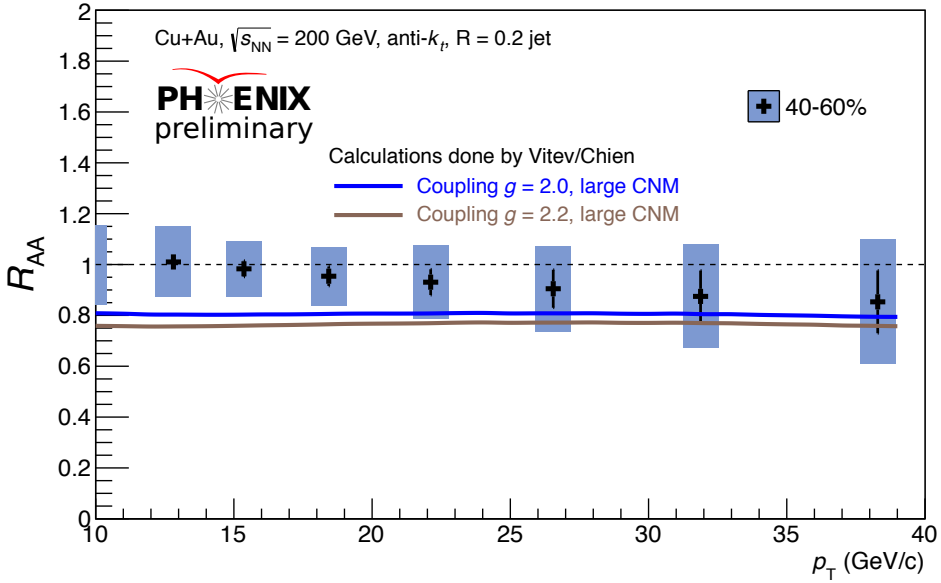
$$R_{CP}^{cent} = \frac{\left(\frac{1}{N_{coll}^{cent}}\right)\left(\frac{1}{N_{evts}^{cent}}\frac{dN}{dp_T}^{cent}\right)_{CuAu}}{\left(\frac{1}{N_{coll}^{60\%-90\%}}\right)\left(\frac{1}{N_{evts}^{60\%-90\%}}\frac{dN}{dp_T}^{60\%-90\%}\right)_{CuAu}}$$



- R_{CP} probes relative central vs. peripheral (60-90%) jet production
- Relatively reduced systematics

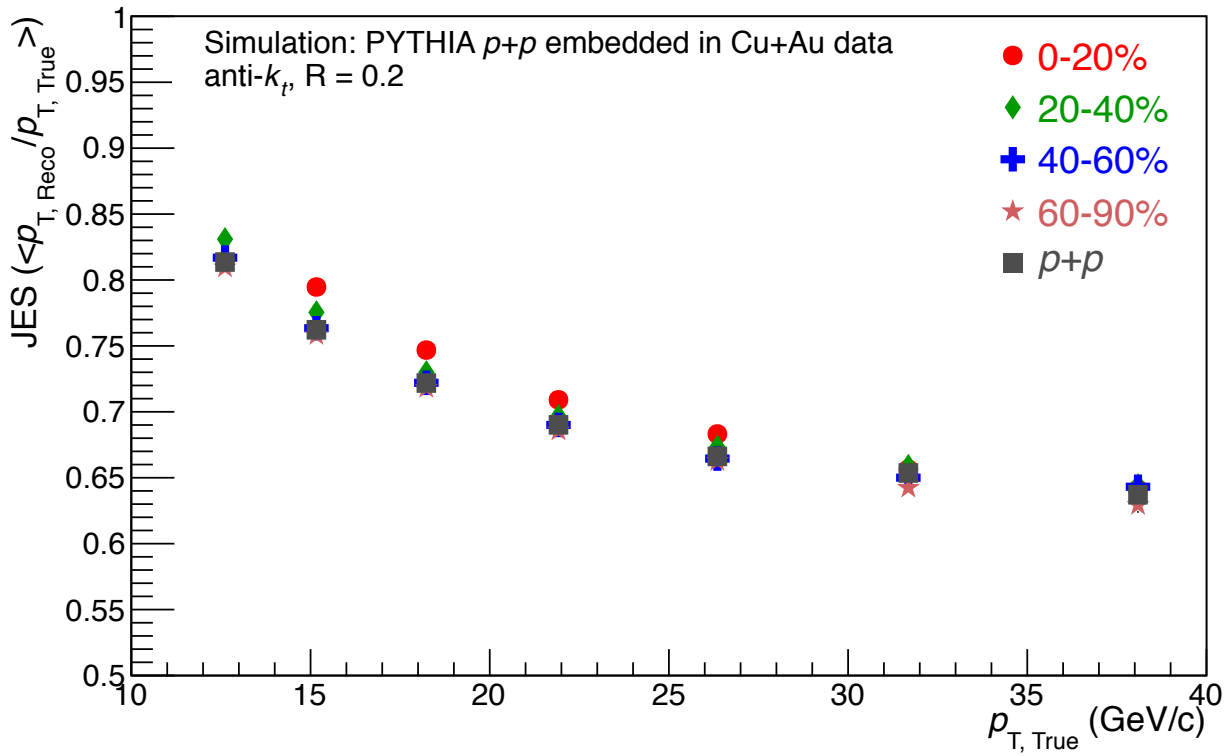
Comparisons to theory





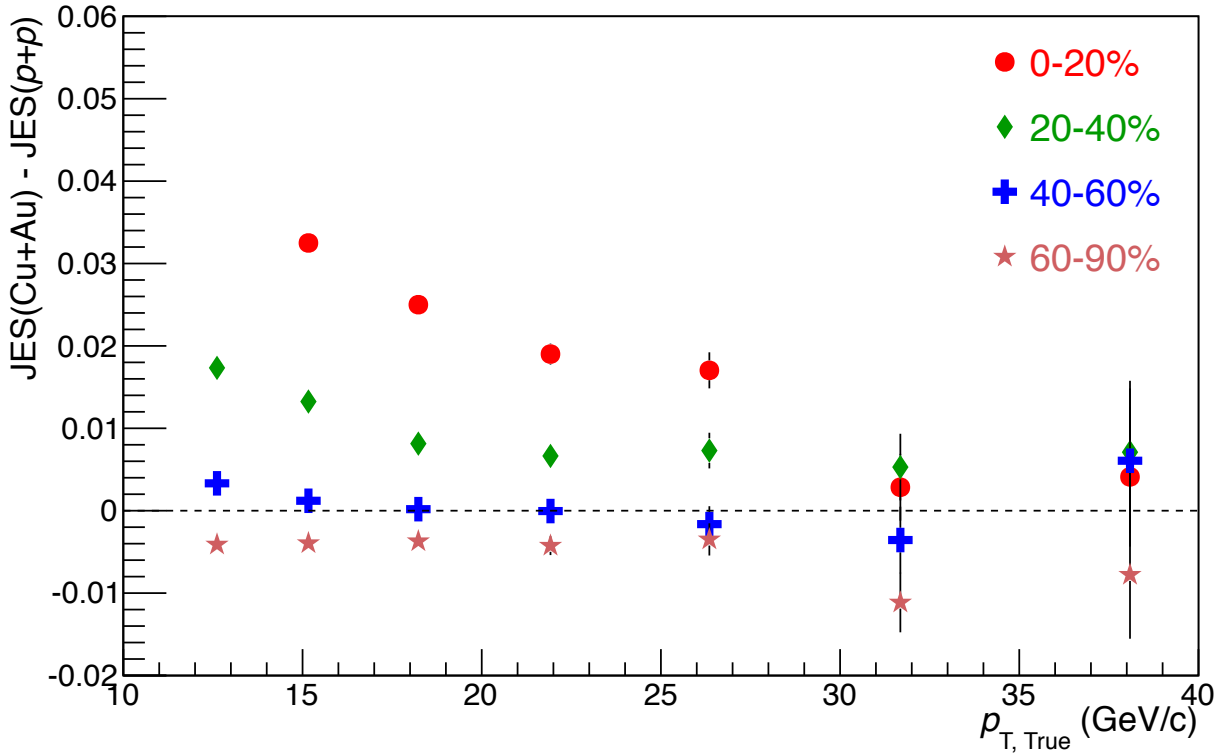
- **Left: 0-20%; right: 40-60%**
- Calculations done for 2 different couplings between the jet and the medium (g=2.0 and g=2.2).

Jets in PHENIX: Jet Energy Scale



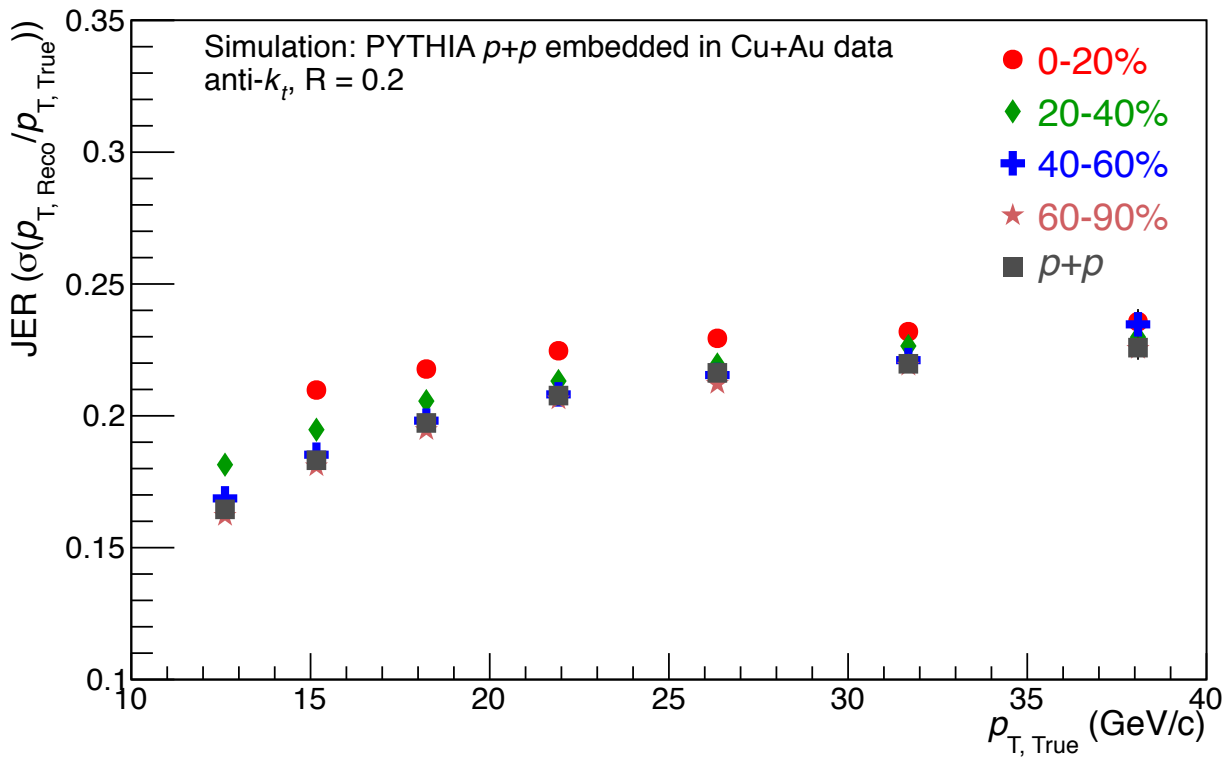
- For each $p_{T, True}$ bin, $p_{T, Reco}/p_{T, True}$ distribution is examined
- Due to missing neutral hadronic energy and tracking inefficiency, on average, PHENIX gets ≈70% of the true jet energy

Jets in PHENIX: Jet Energy Scale



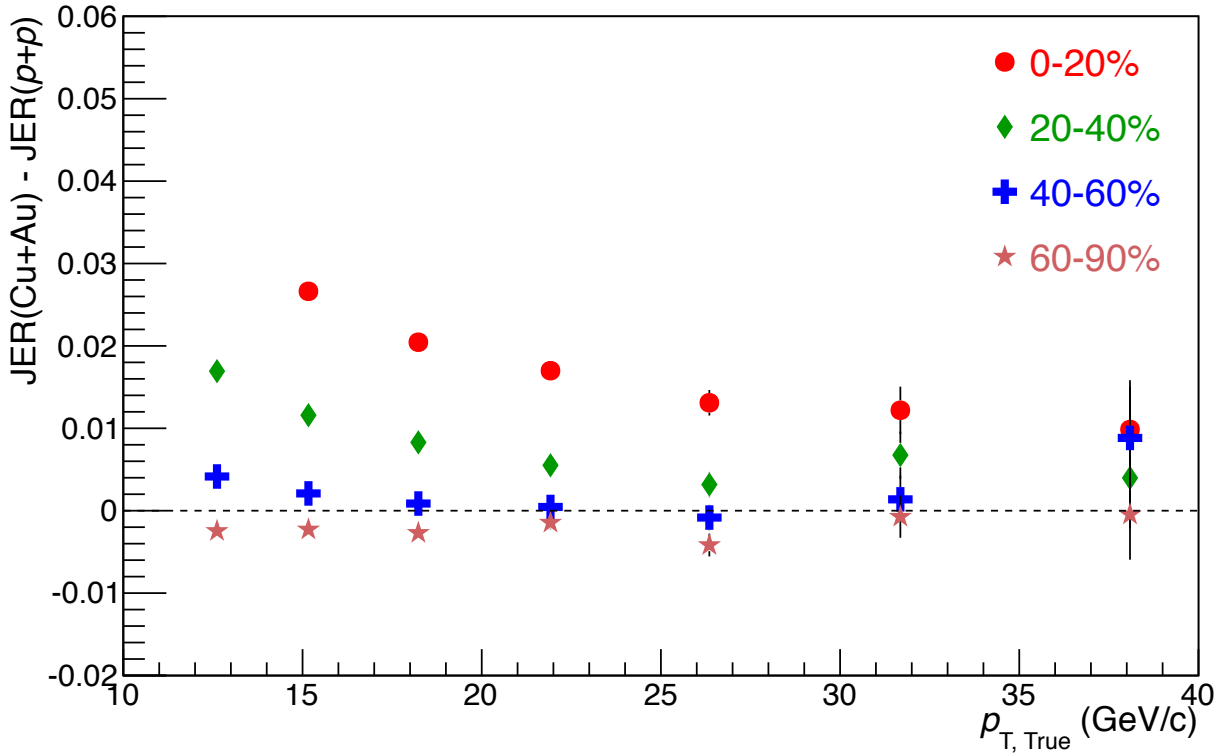
- For each $p_{T, True}$ bin, $p_{T, Reco}/p_{T, True}$ distribution is examined
- Due to missing neutral hadronic energy and tracking inefficiency, on average, PHENIX gets ≈70% of the true jet energy
- For 0-20%, the UE increases the $p_{T, Reco}$ up to 3.2% (1.7%) at 15 GeV/c (26 GeV/c) relative to that in *p*+*p* events

Jets in PHENIX: Jet Energy Resolution



- The width of $p_{T,\,Reco}/p_{T,\,True}$ distribution is ≈16-24%
- In PHENIX, the resolution is not driven by EMCal & DC resolution but by jet-by-jet fluctuations

Jets in PHENIX: Jet Energy Resolution



- The width of $p_{T,\,Reco}/p_{T,\,True}$ distribution is ≈16-24%
- In PHENIX, the resolution is not driven by EMCal & DC resolution but by jet-by-jet fluctuations
- For 0-20%, the UE increases the $p_{T,\,Reco}$ resolution up to 2.7% (1.3%) at 15 GeV/c (26 GeV/c) relative to that in *p*+*p* events