Progress in reconstructed jet measurements with the PHENIX detector at RHIC

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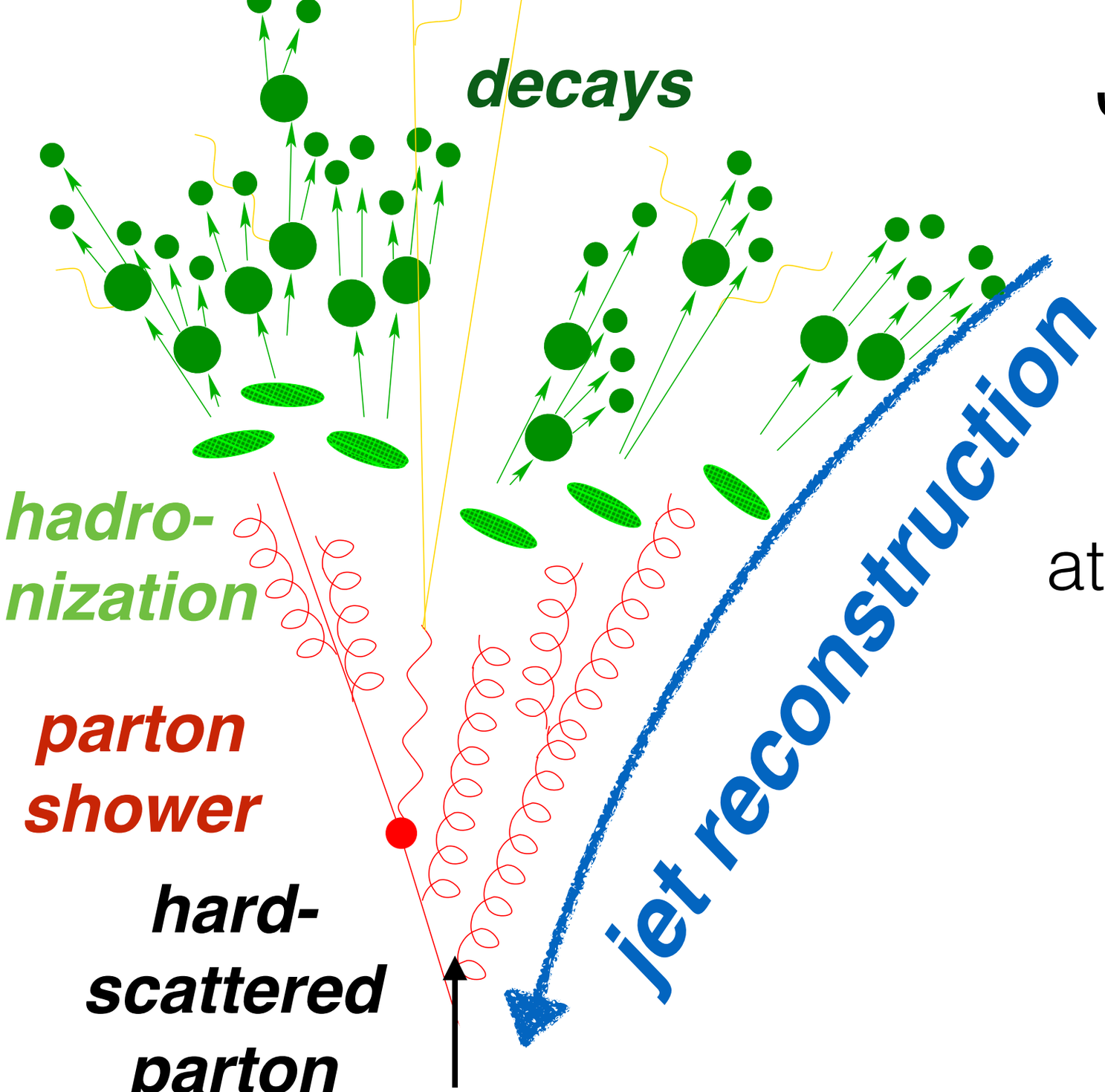
Jets in hadronic collisions

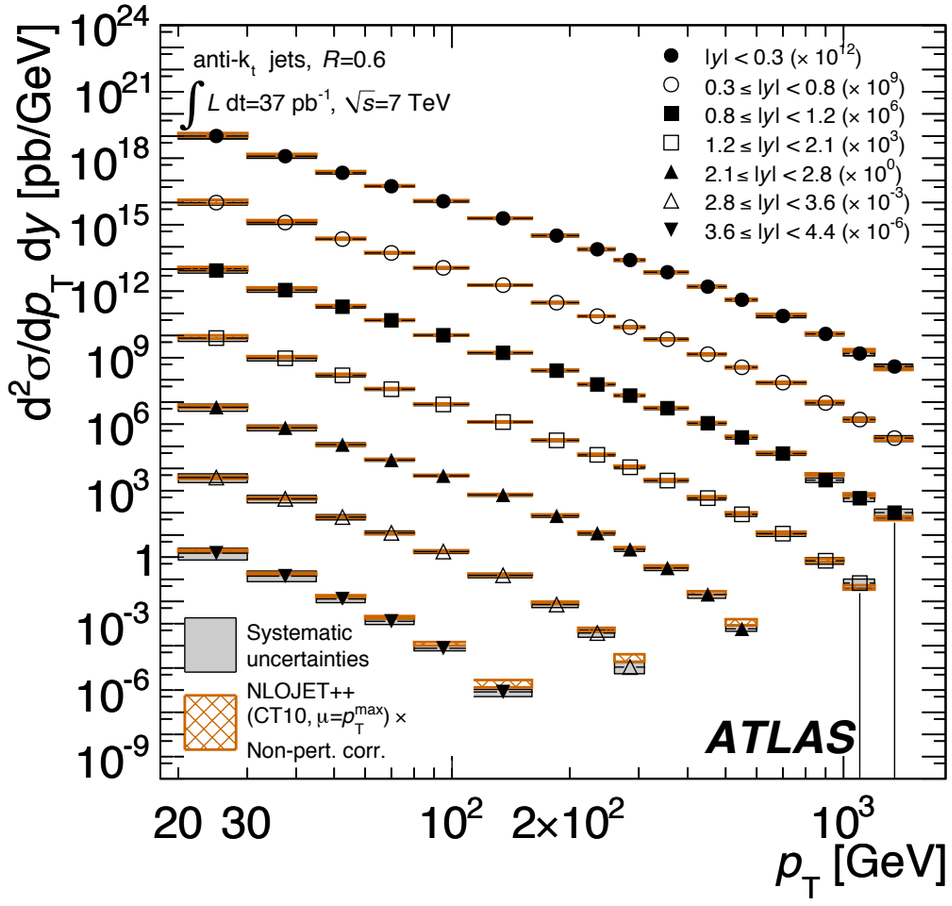


at leading order ≈

jet

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

Jets in heavy ion collisions

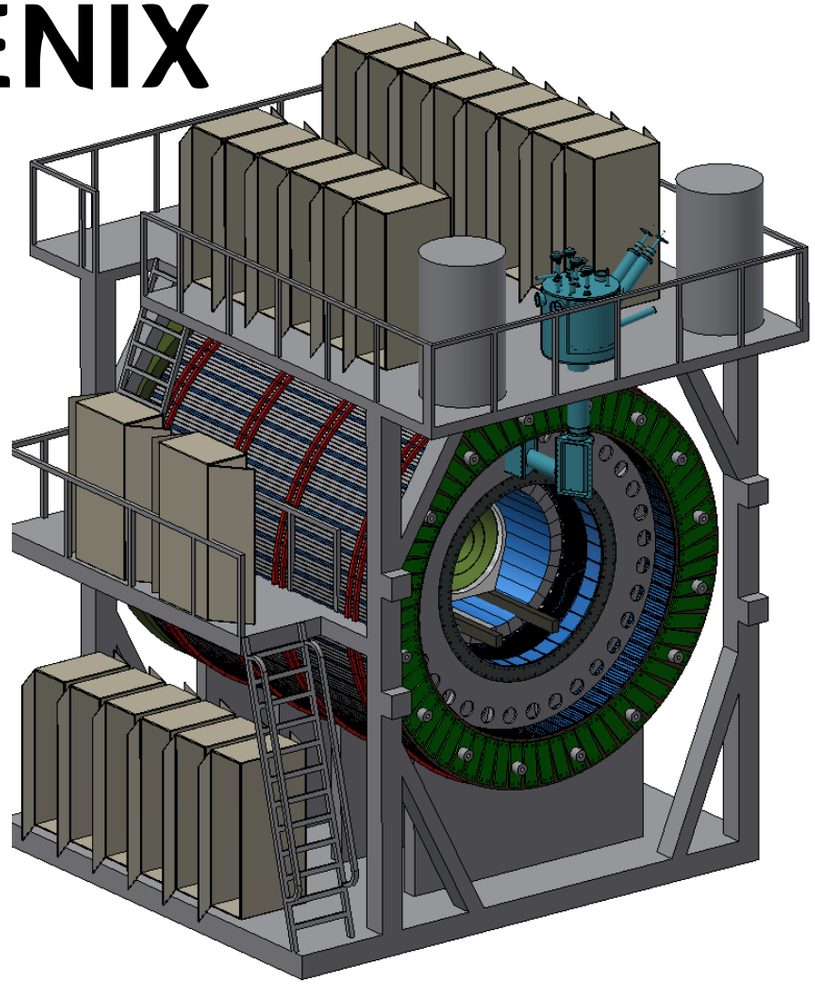


jets in HEP

Phys. Rev. D86 (2012) 014022

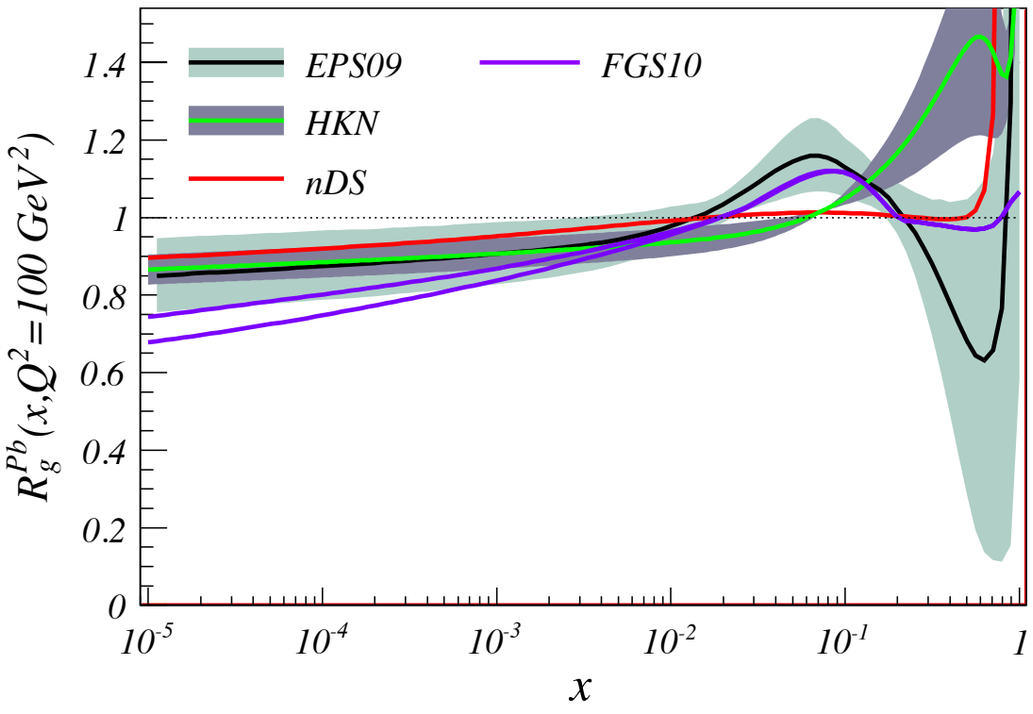
future of jets in HI at RHIC

see talk by R. Reed

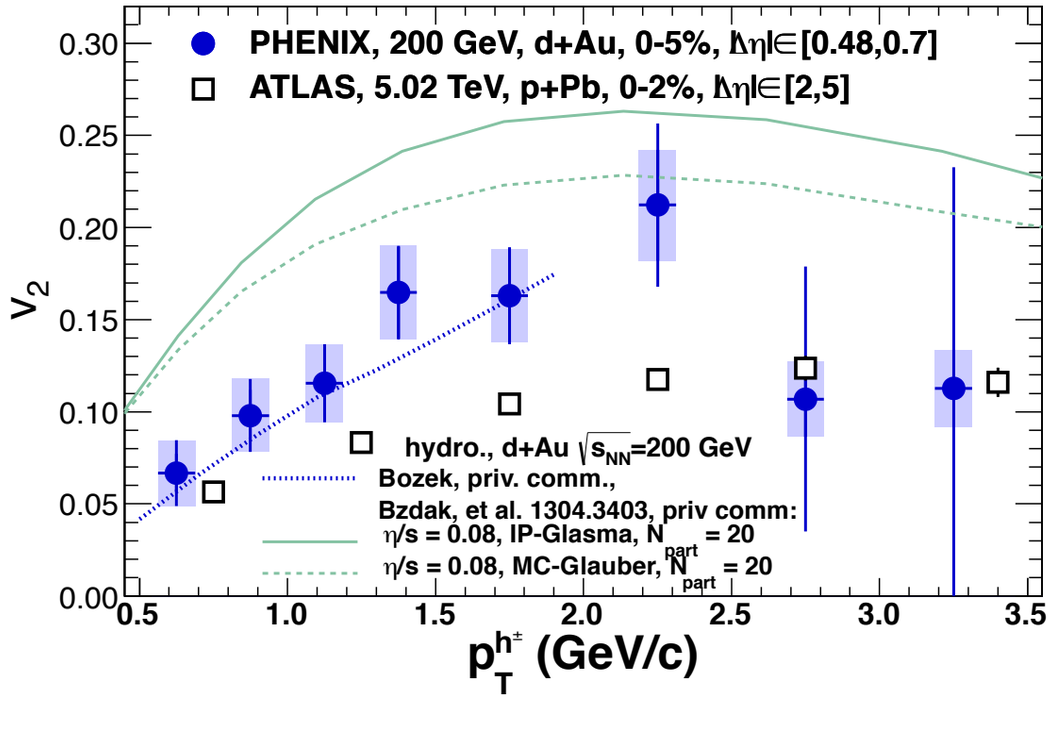


- Standard tool in HEP, but challenging in heavy ion collisions due to *large, fluctuating underlying event*
  - ➡ in nuclear collisions at the LHC, technical challenges overcome (and rewards reaped) only after substantial effort
  - ➡ in this talk, *progress in jets from PHENIX experiment at RHIC*

Small (**cold**?) collision systems



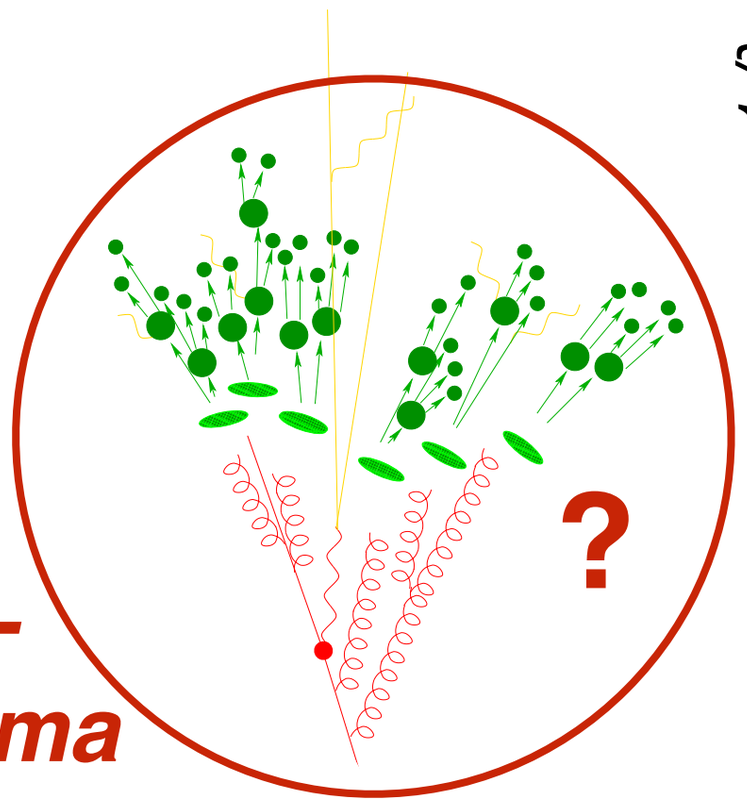
Salgado et al., hep-ph/1105.3919
example of different nuclear PDF sets



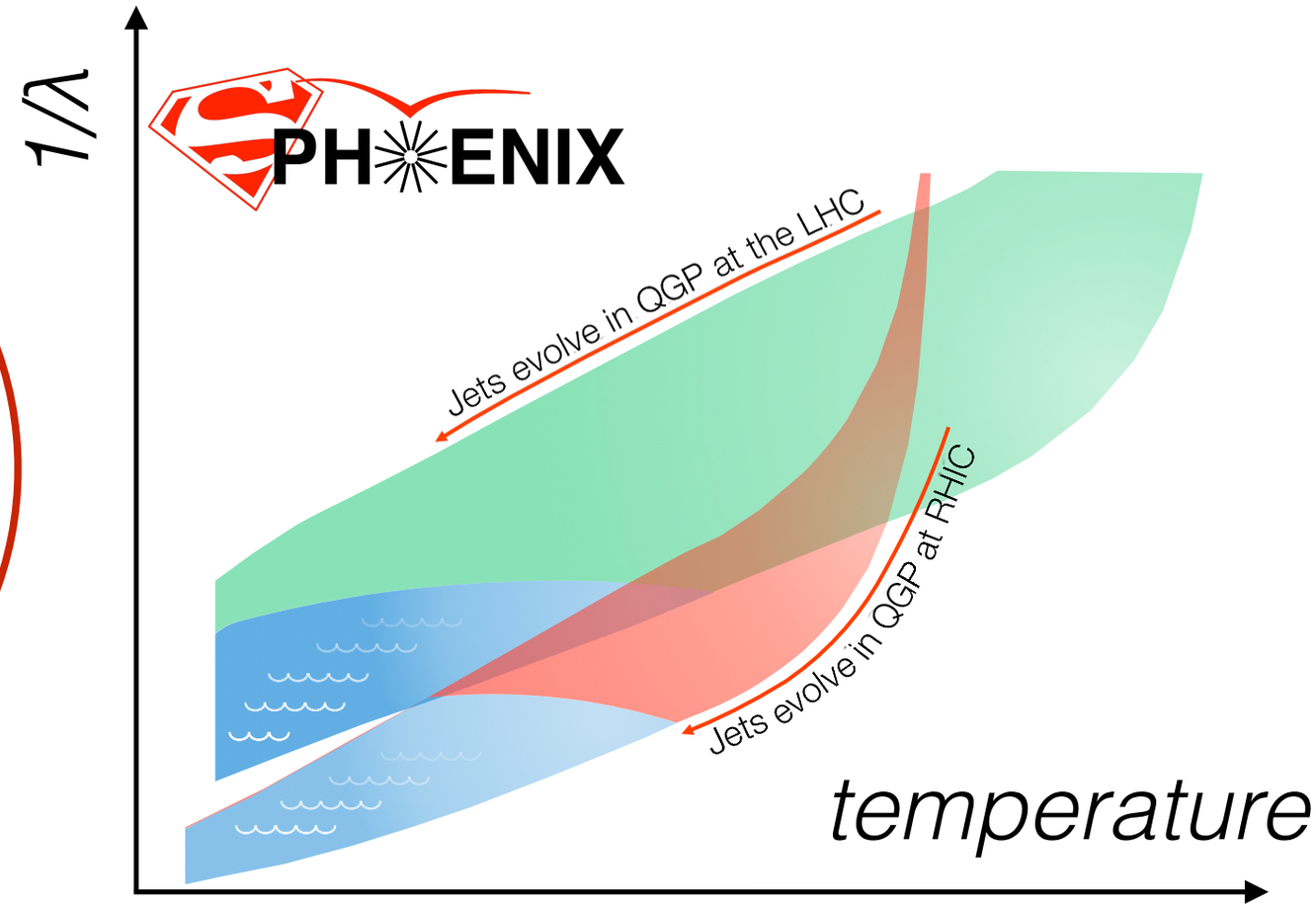
PHENIX, PRL 111 (2013) 212301
non-zero v_2 for high-p_T hadrons?

- Basic way to characterize partonic structure of any hadronic collision system
  - ➡ modification of PDFs in nuclei
  - ➡ benchmark any initial state effects for jet quenching in A+A
  - ➡ search for hot "QGP"-like energy loss in central collisions

Large (**hot**?) collision systems

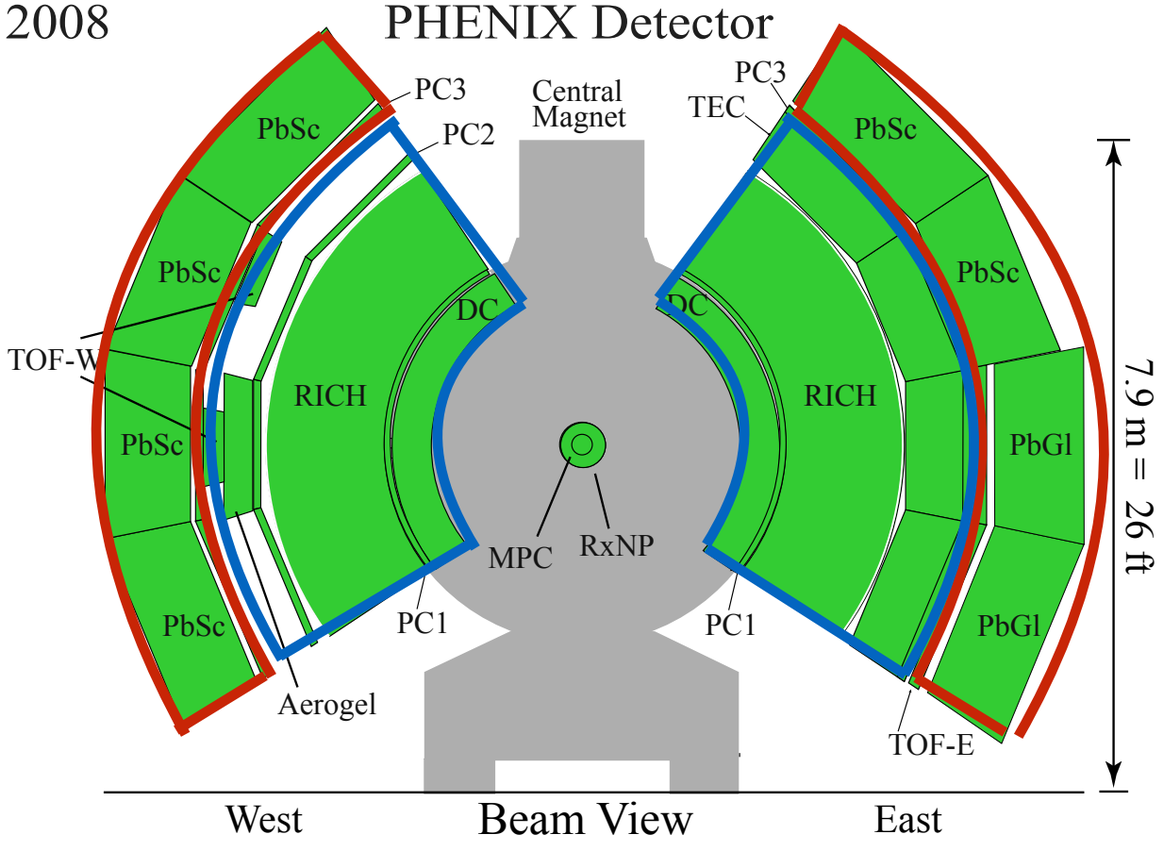


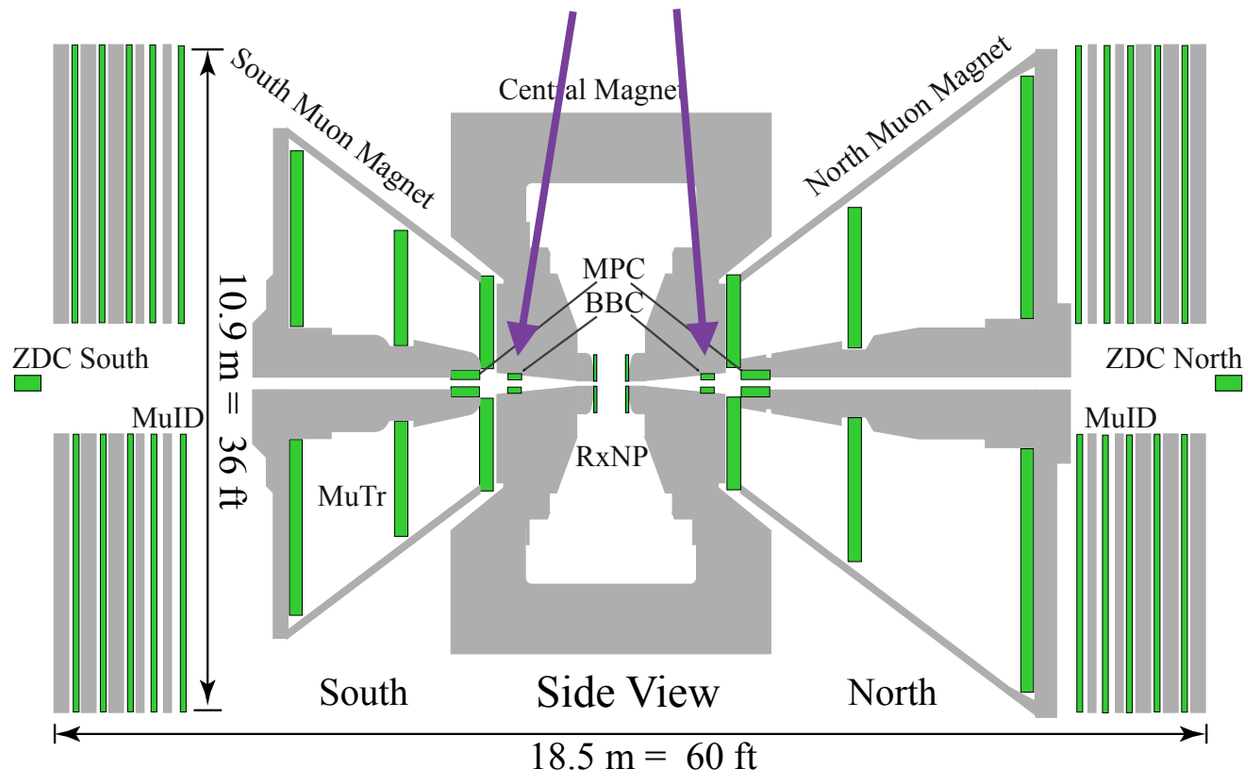
in quark-gluon plasma



- Parton shower develops *<u>in evolving QGP medium</u>*
  - ➡ *internally-generated, multi-scale probe* of QGP properties
  - ➡ jets are high-level physics objects: can examine how rates, structure, correlations, etc. are modified
  - ➡ key component of future “sPHENIX” program at RHIC

PHENIX detector





- **Electromagnetic calorimeters** with ≈18λ (PbSc) or ≈14λ (PbGl)
- **Drift & pad chambers** for measuring charged-particle tracks

  ➡ both subsystems cover $|\eta| < 0.35$, with two $\Delta\phi = \pi/2$ Arms
- **Beam-beam counters** ($2.1 < \eta < 3.8$) provide MB event definition and centrality classification
- Online hardware-based trigger on energy deposit in EMCal

Analysis overview

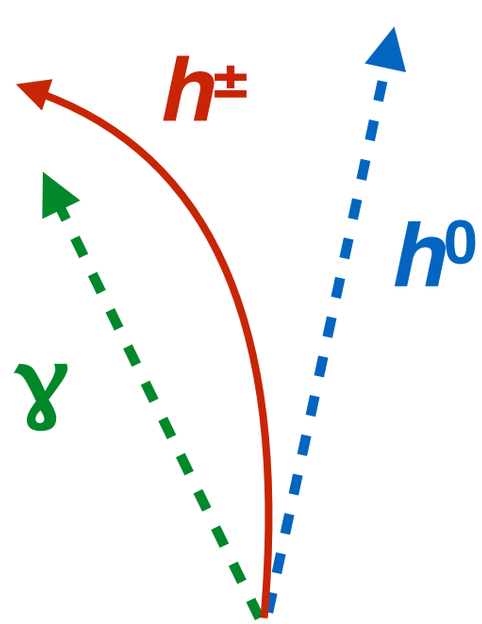
- Jets in modest-aperture detector w/o hadronic calorimeter

  ➡ non-trivial experimental challenges (*and opportunity!*)

- Cluster EMCal **energy deposits** + charged-particle **tracks**

  ➡ jet core required to be away from detector edge

  ➡ strict run-level, particle-level, jet-level QA to ensure *good measurement of jet energy*



- GEANT simulation of detector response & embedding into minimum-bias heavy ion events

- Capture *≈0.65-0.70 of jet momentum on average*

  ➡ 25%“resolution” from fluctuations in (mostly unmeasured) **neutral hadronic** component

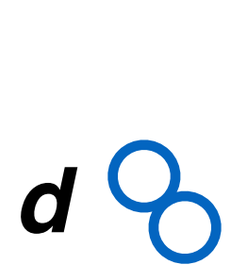
  ➡ correct spectra *for detector effects* with unfolding procedure

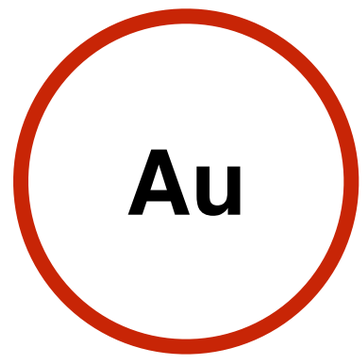
Jet results from PHENIX

- Two new results shown at Quark Matter 2015
- ***d*+Au** and ***p*+*p*** jet spectra (2008 data)

  ➡ nucl-ex/1509.04657, submitted to PRL

  ➡ *R*=0.3 anti-k_t algorithm, *establish pQCD baseline*

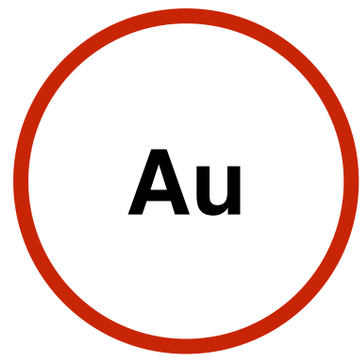




- **Cu+Au** and ***p*+*p*** jet spectra (2012 data)

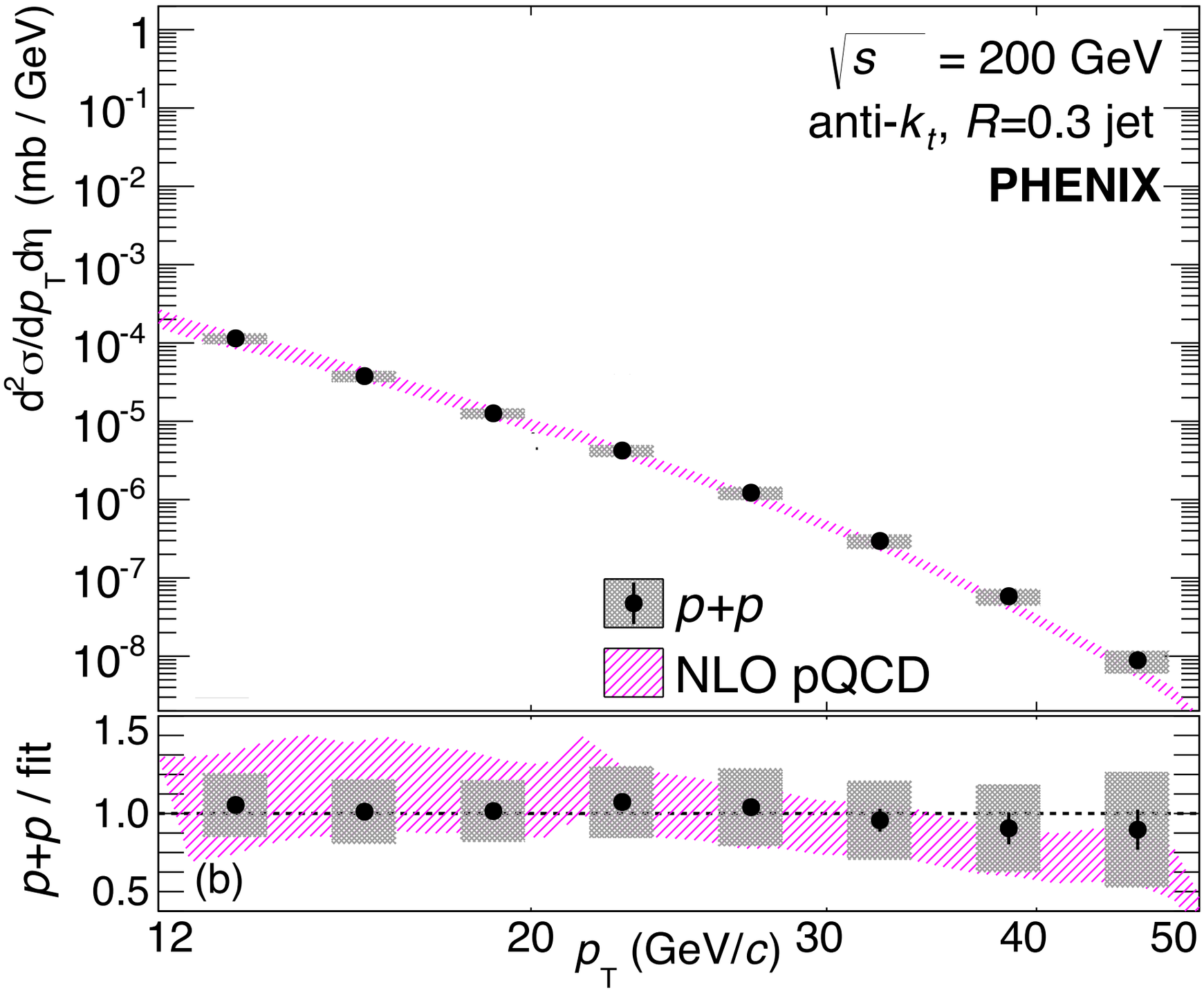
  ➡ Preliminary measurement, *R*=0.2 anti-k_t algorithm due to demands of HI environment

  ➡ *first look at inclusive suppression of full jets*



p+*p* collisions

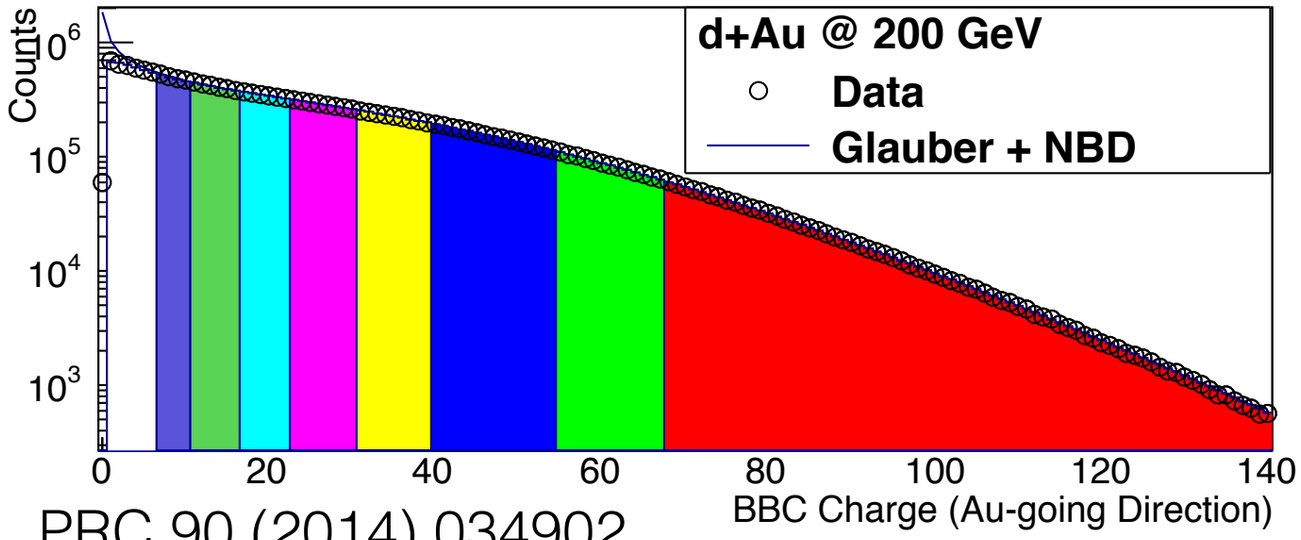
Jet spectra in *p*+*p* collisions



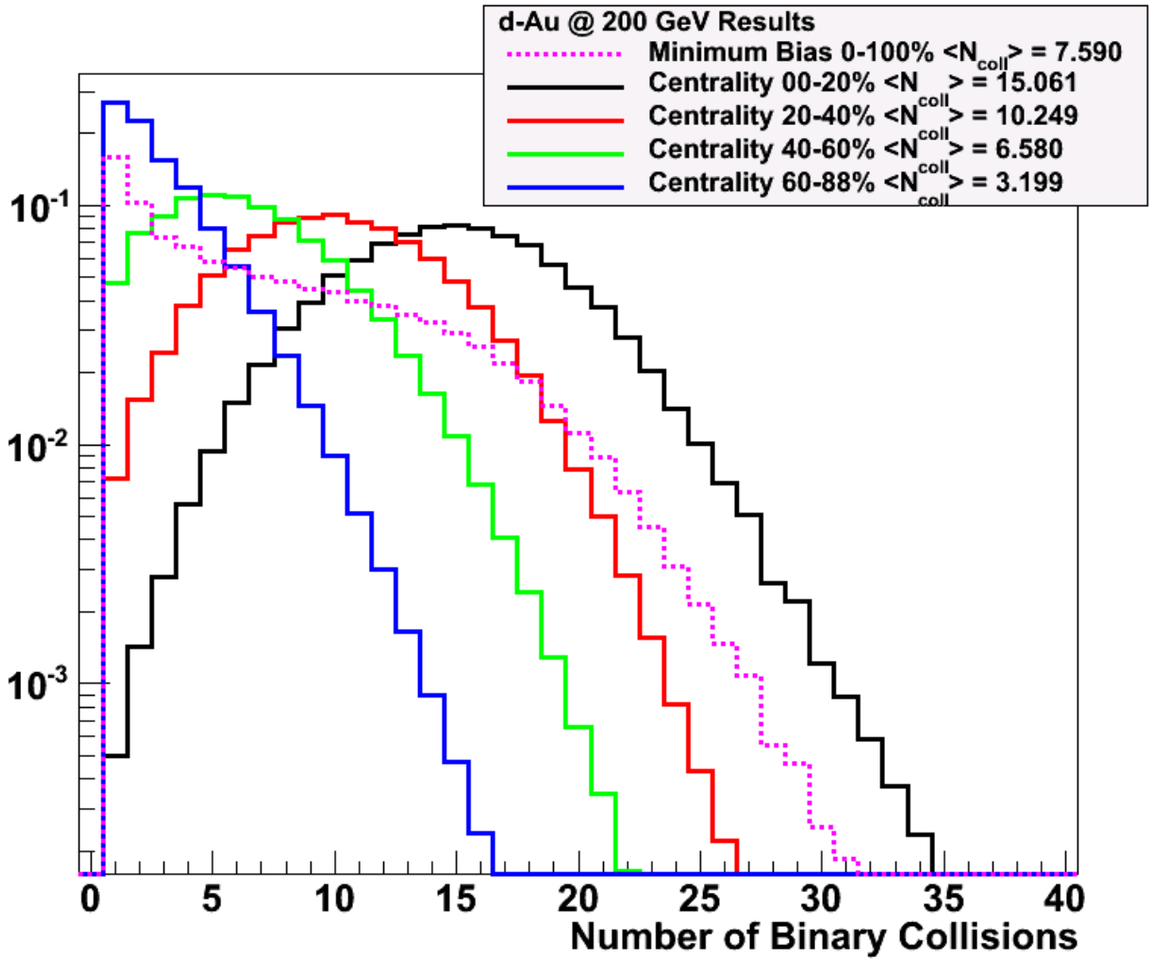
- ***p+p* spectra**: compare favorably with **NLO *p*QCD** calculation
  - ➡ validates jet reconstruction & correction procedure

d+Au collisions

Centrality in *d*+Au collisions

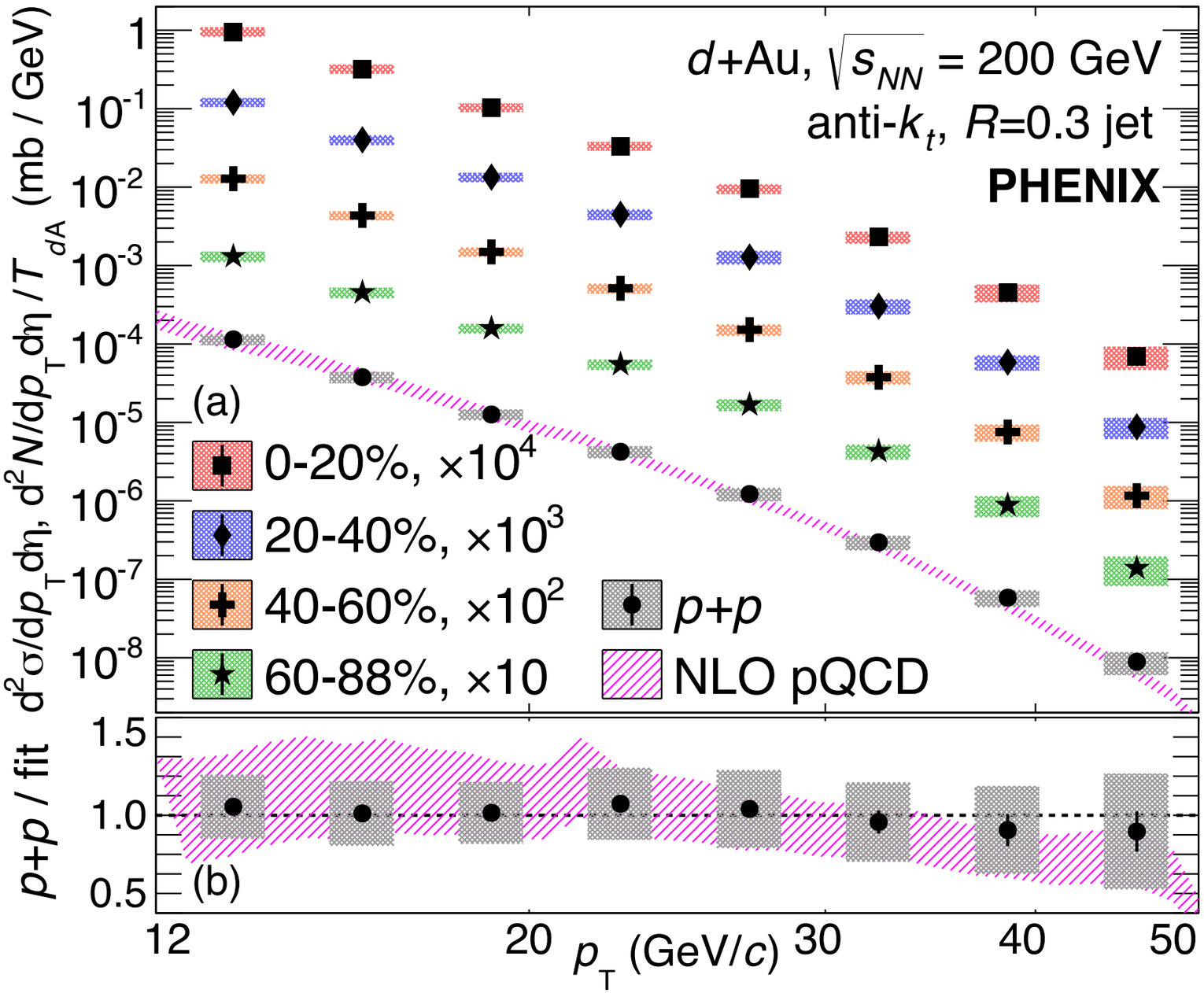


PRC 90 (2014) 034902



- 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 d*N*/d*Q* distribution as scaling with N_{coll}
  - ➡ estimate nuclear overlap factor $T_{d\text{Au}}$ for classes of d+Au collisions
  - ➡ previously successful with hard and soft observables

Jet yields in *d*+Au



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

Minimum bias jet rate

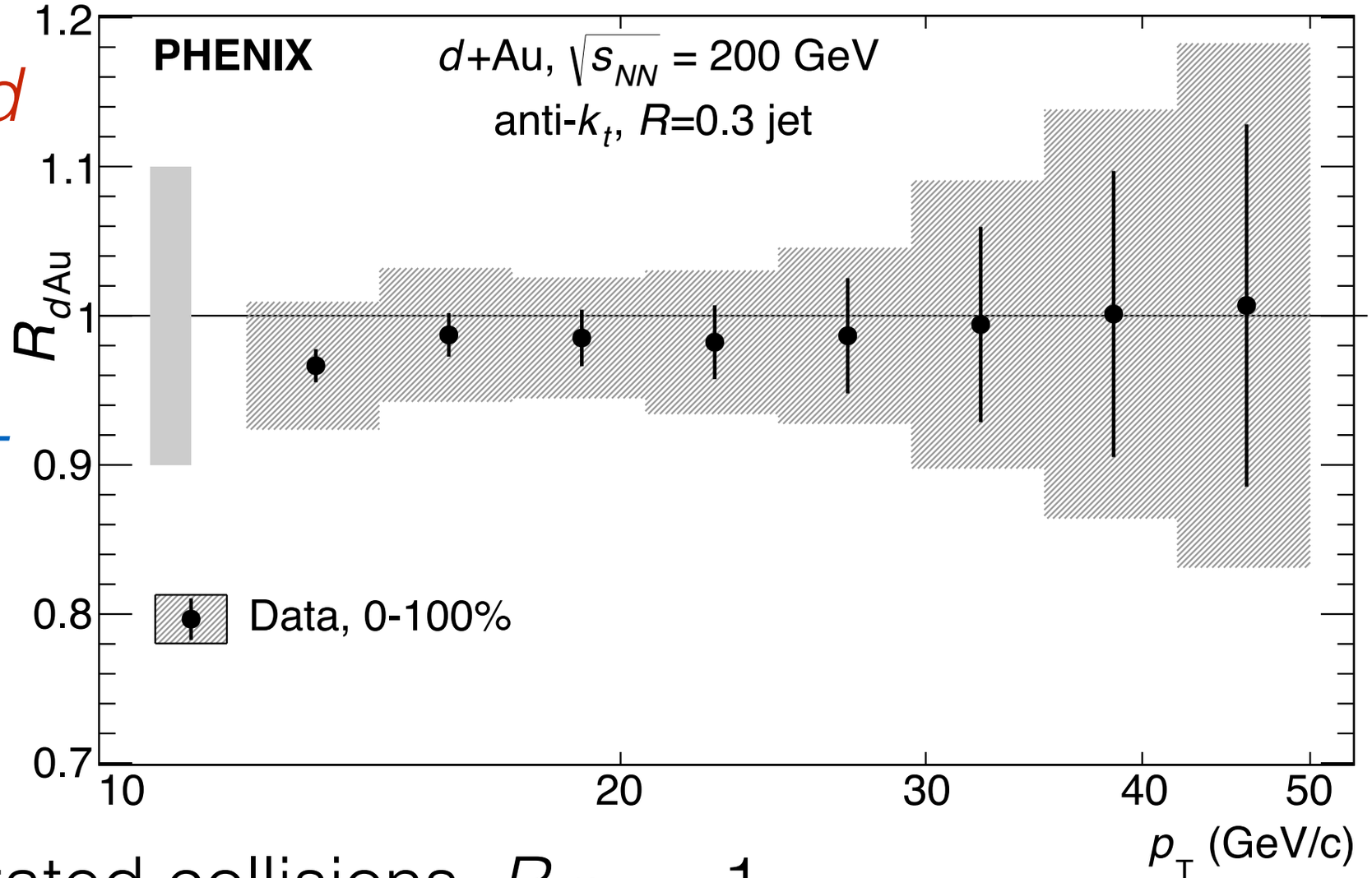
d+Au yield

$$R_{\mathrm{dAu}} = \mathbf{d}N^{d+\mathrm{Au}}/\mathbf{d}p_{\mathrm{T}} \;/\; \boldsymbol{T}_{\mathbf{dA}} \times \mathbf{d}\sigma^{p+p}/\mathbf{d}p_{\mathrm{T}}$$

nuclear overlap

p+p cross-section

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



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

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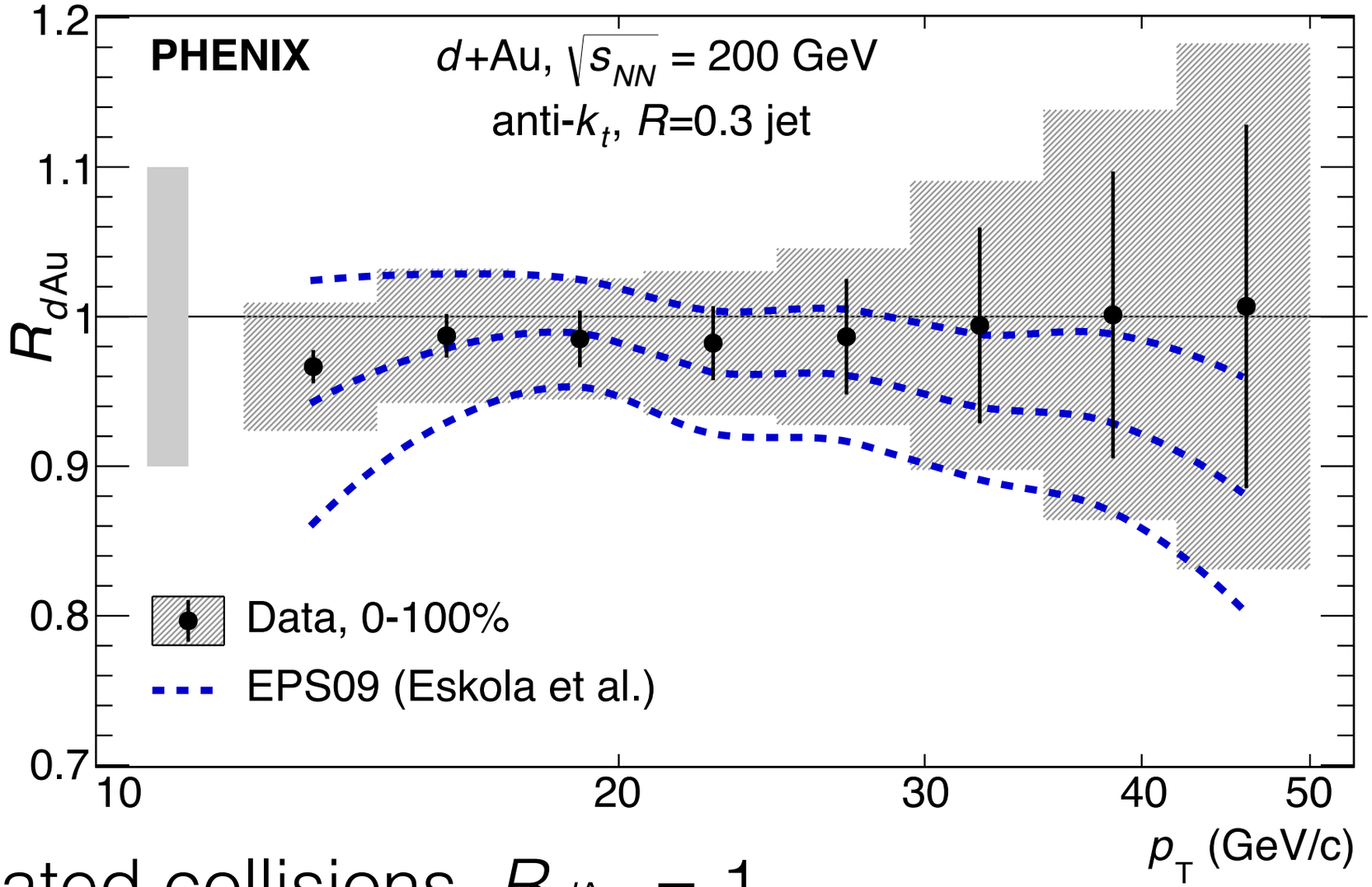

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  - ➡ compares favorably to global nuclear PDF analyses (**EPS09**) within uncertainties

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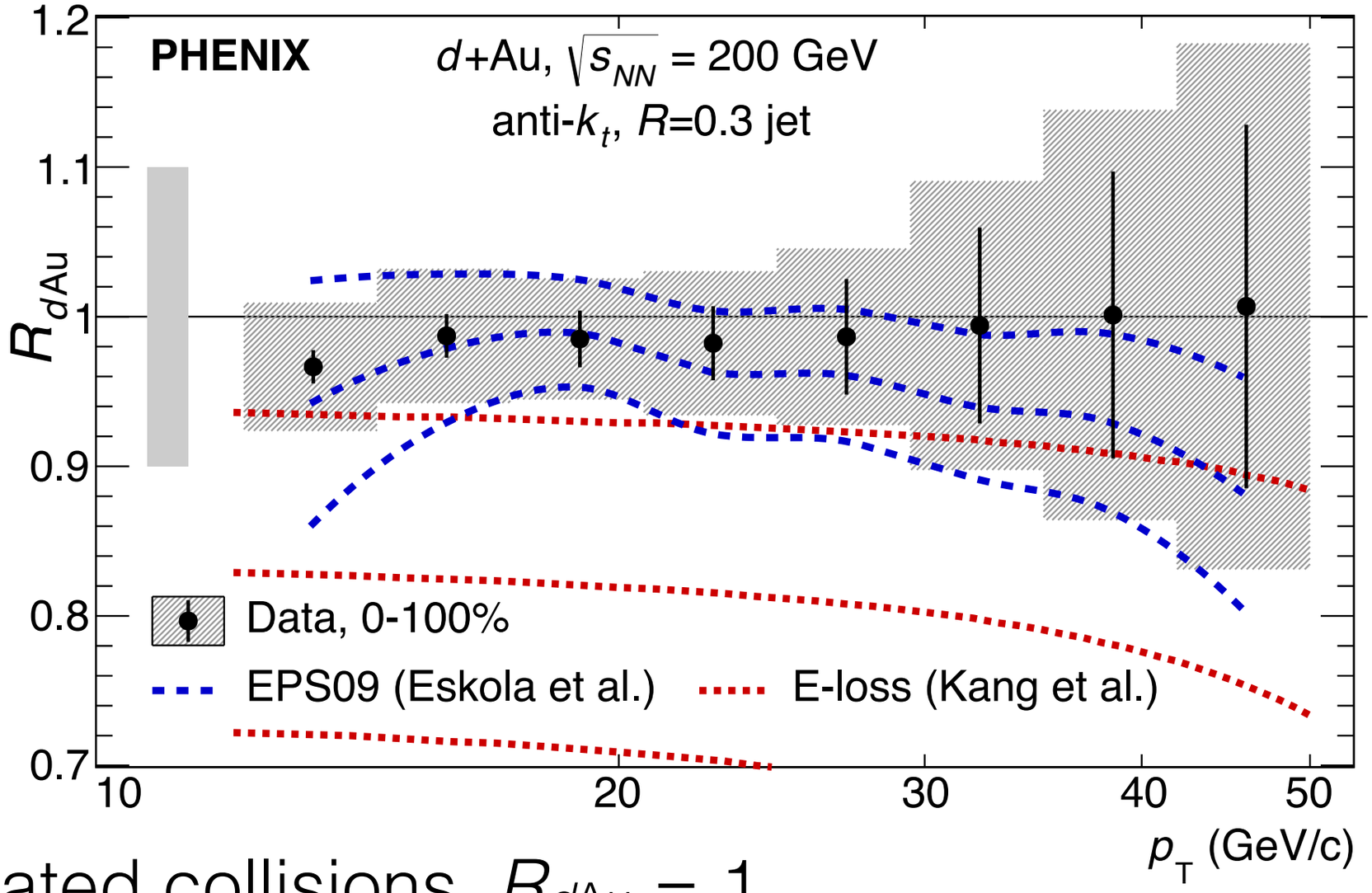
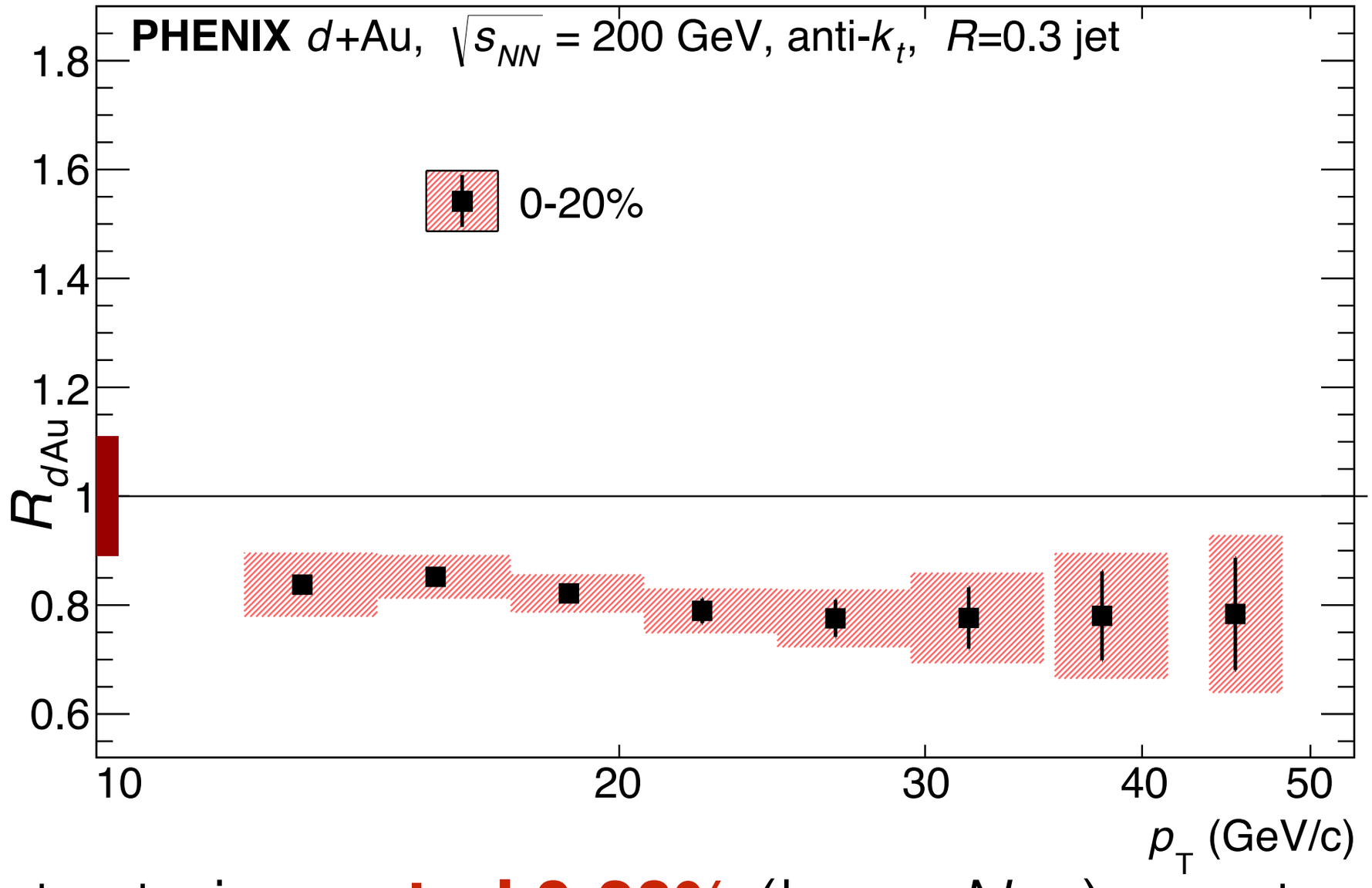


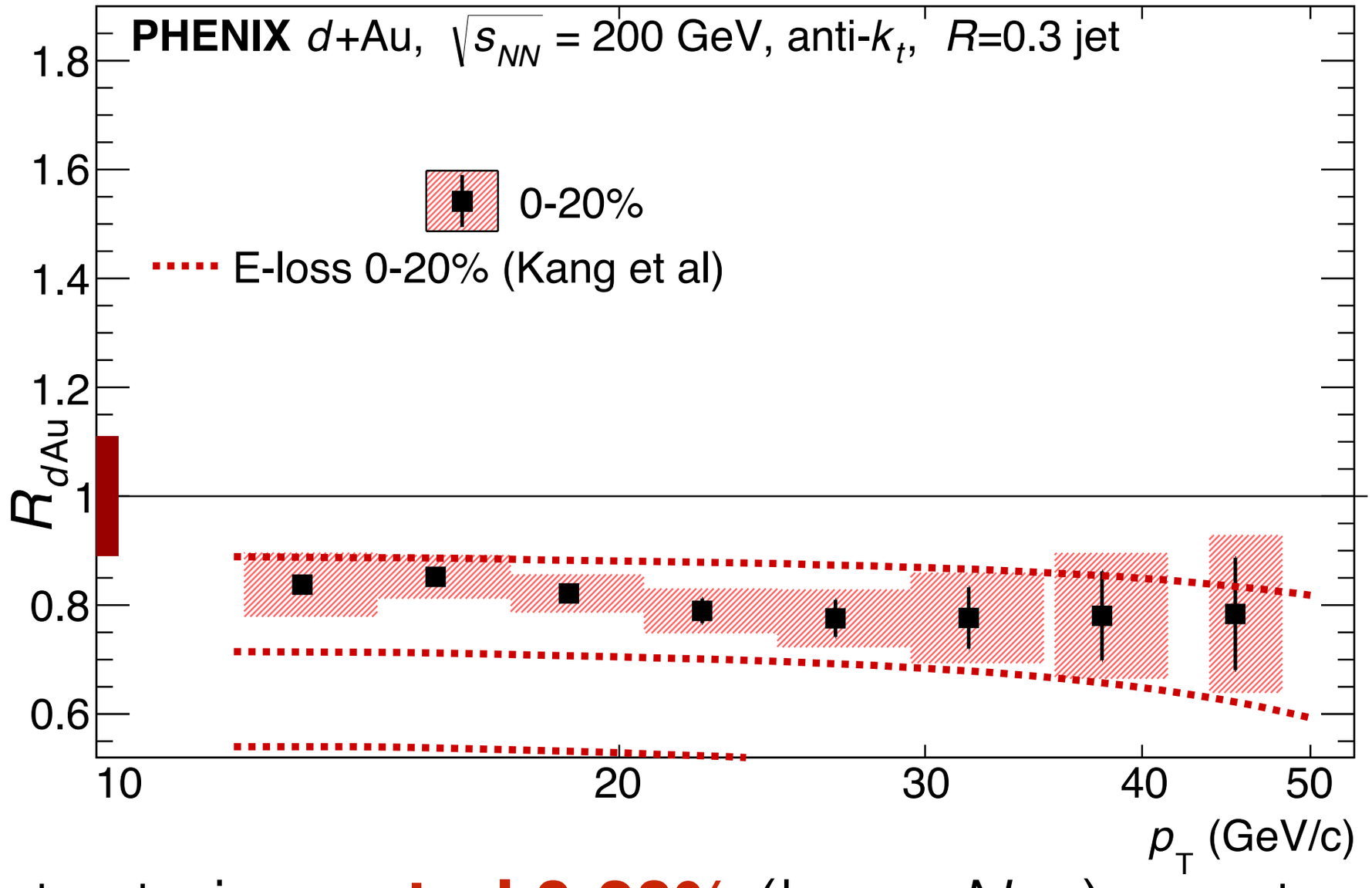
- In centrality-integrated collisions, $R_{d\mathrm{Au}} = 1$
  - ➡ compares favorably to global nuclear PDF analyses (**EPS09**) within uncertainties
  - ➡ within an **initial state E-loss calculations**, favors only small *parton* ↔ *nuclear material* momentum transfer

Centrality-selected jet rate



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

Centrality-selected jet rate



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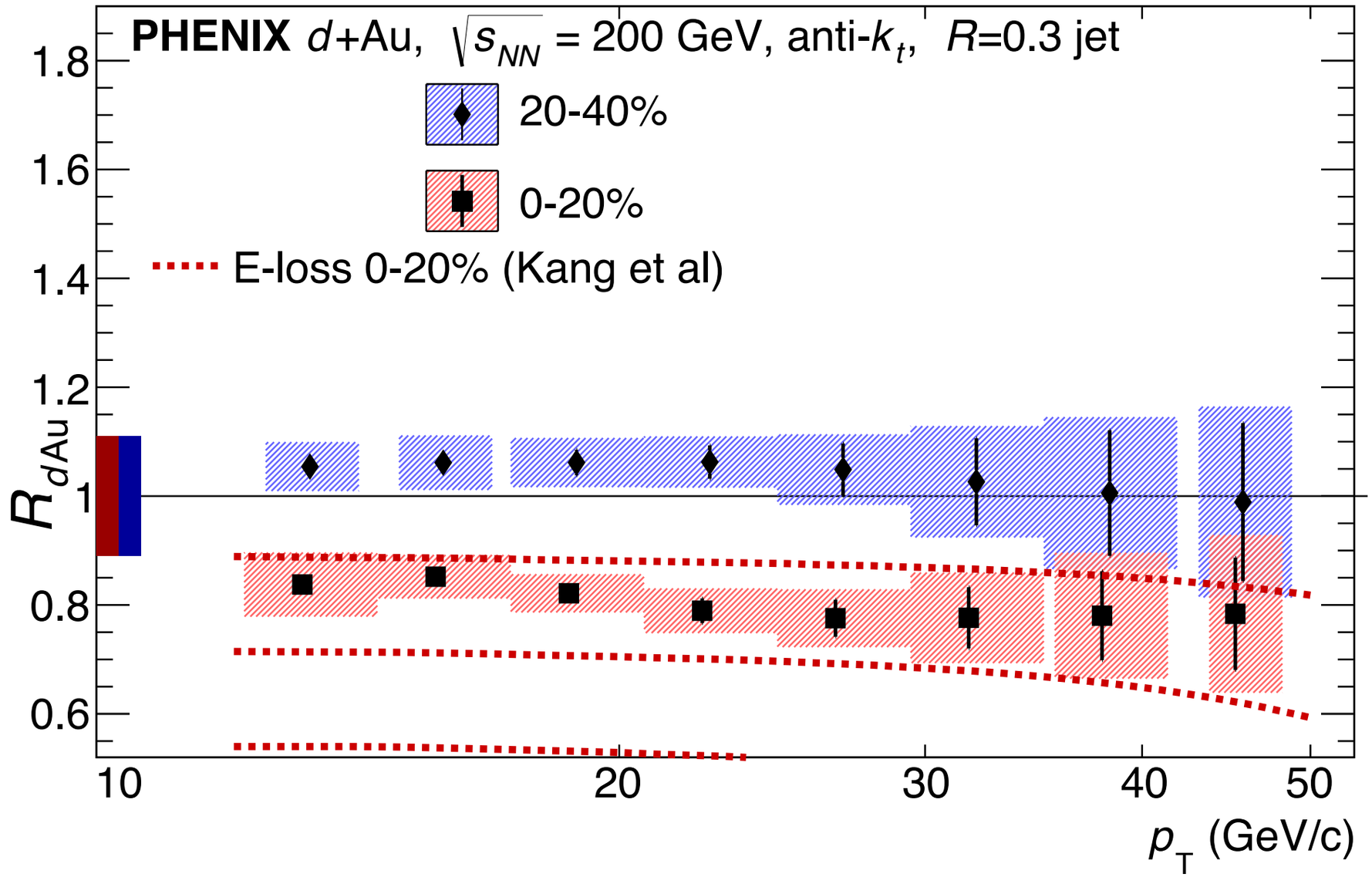

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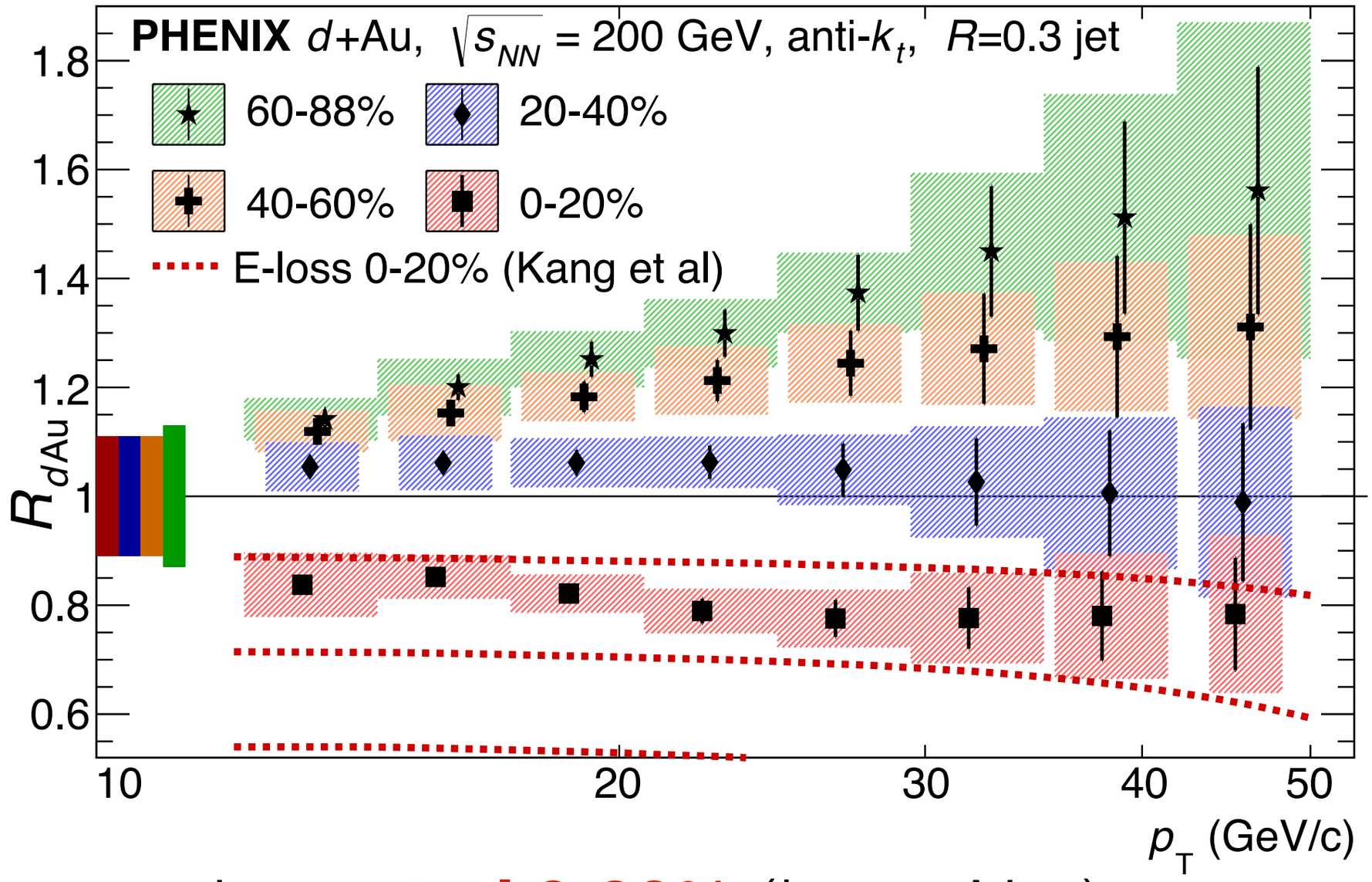
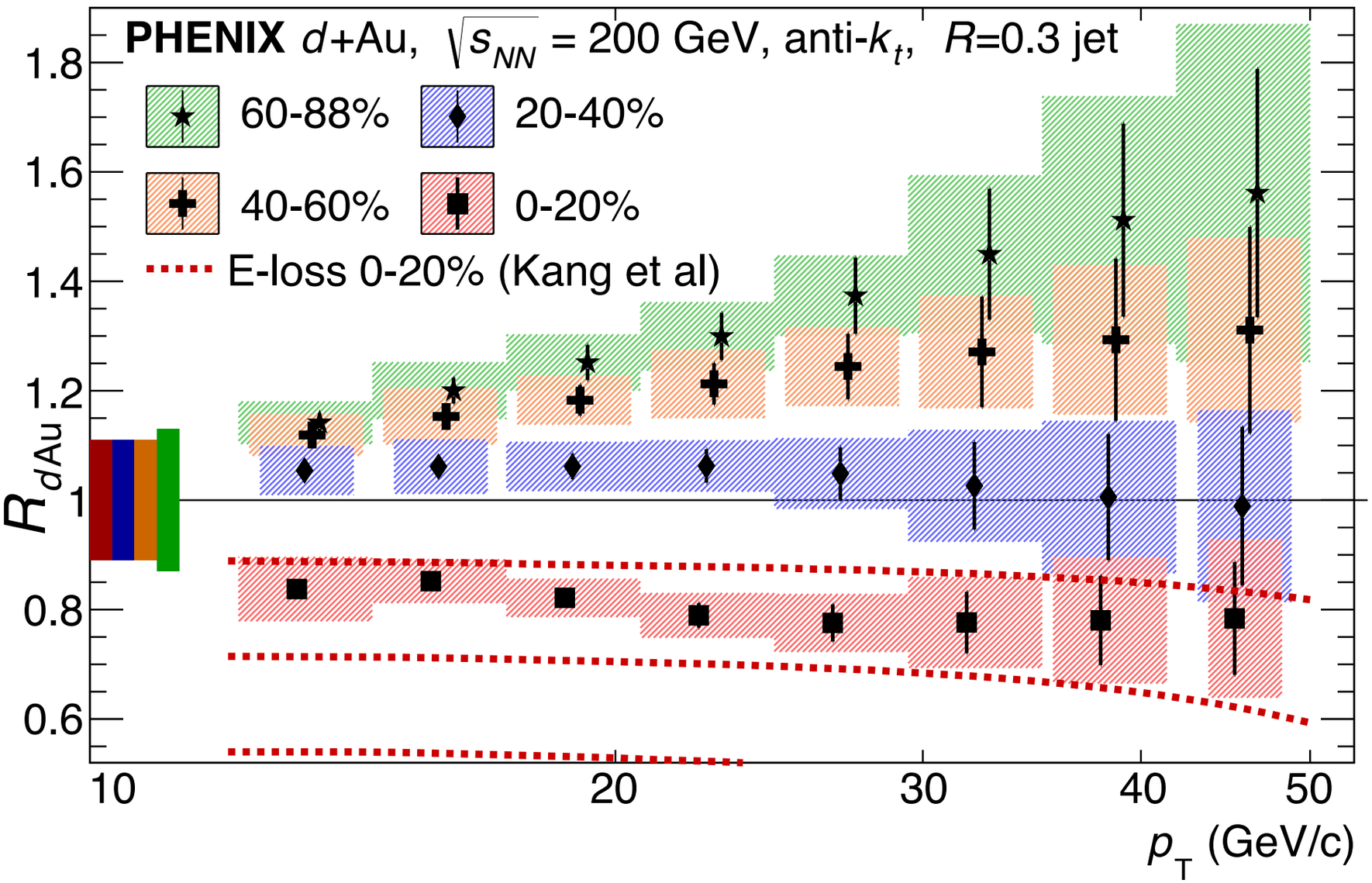


- Suppression of jet rate in **central 0-20%** (large N_{coll}) events
  - ➡ comparable with initial state E-loss calculation?
- Enhancement in **40-60%** and **60-88%** (small N_{coll}) events
  - ➡ very challenging to explain within existing frameworks…

Centrality-selected jet rate

Non-trivial deviations from $R_{dAu} = 1$!

Deviations grow with p_T…



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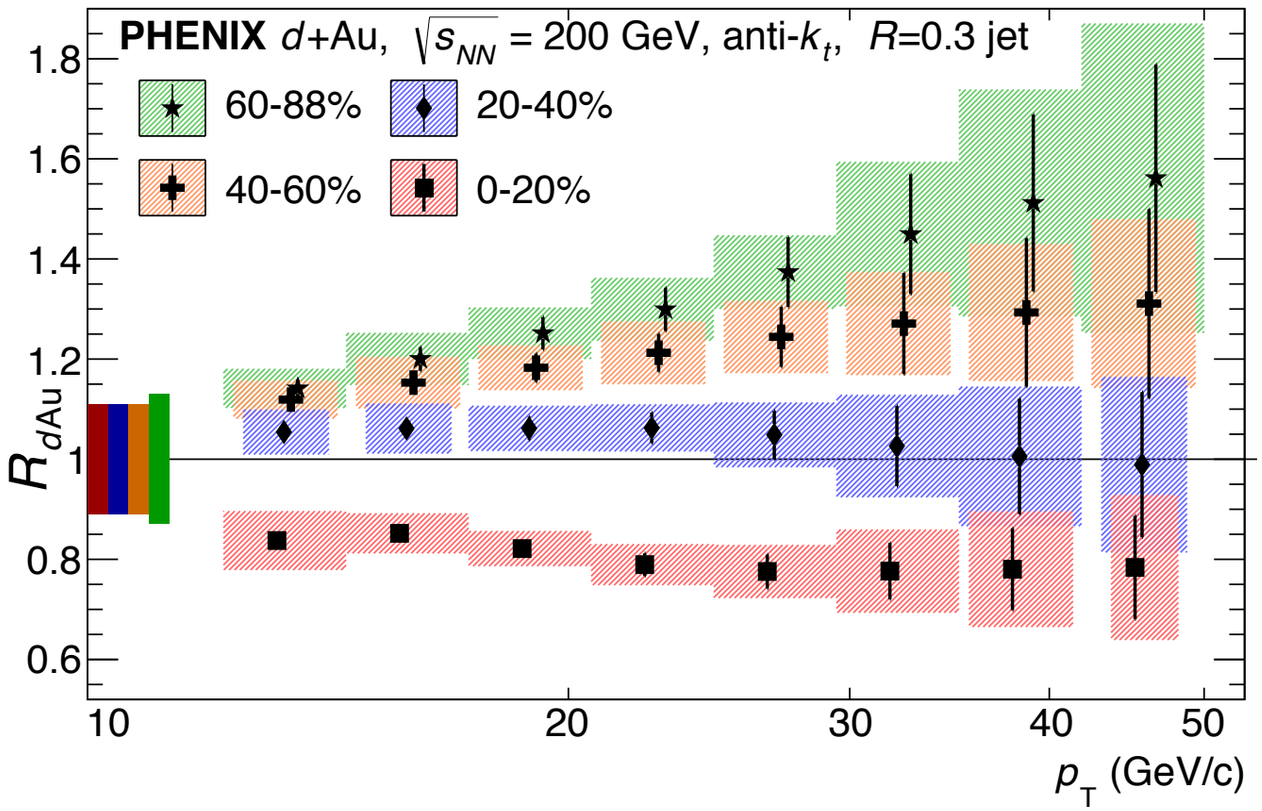
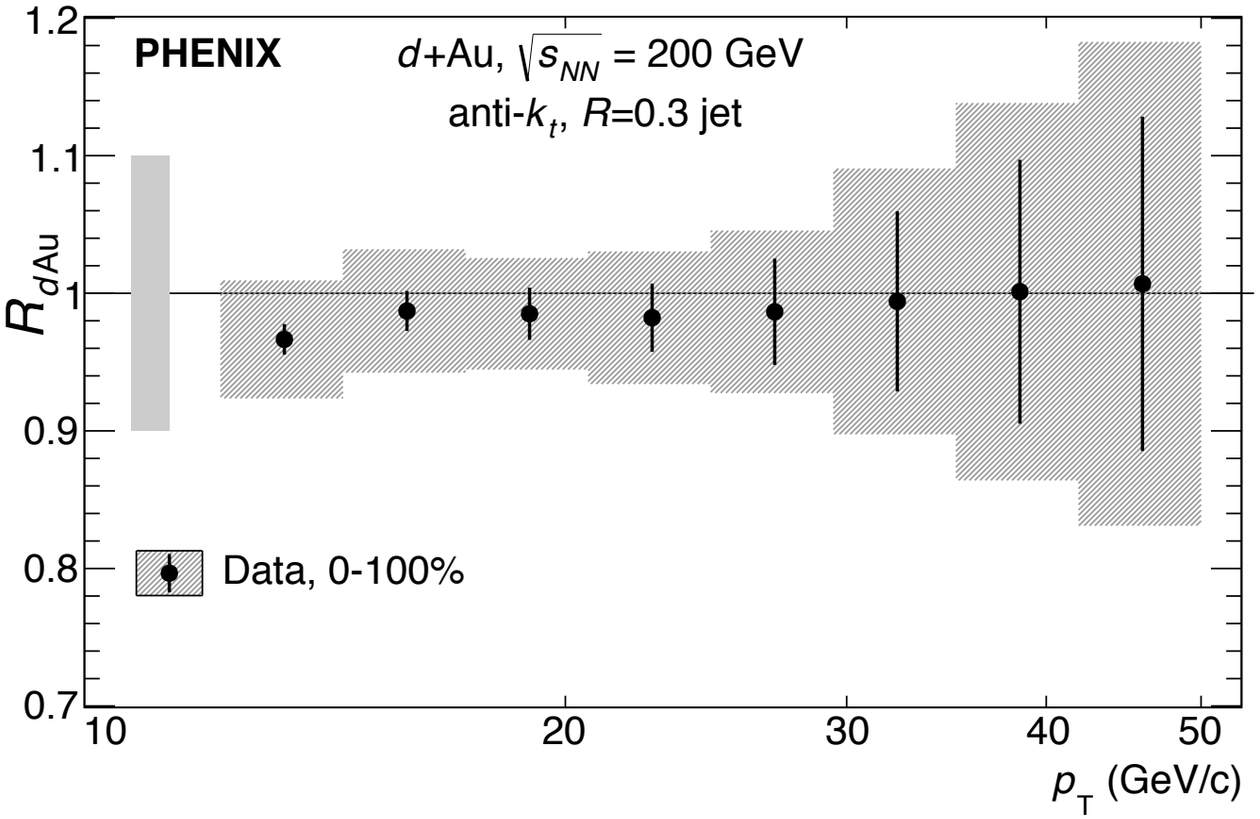
Reconciling these pictures?

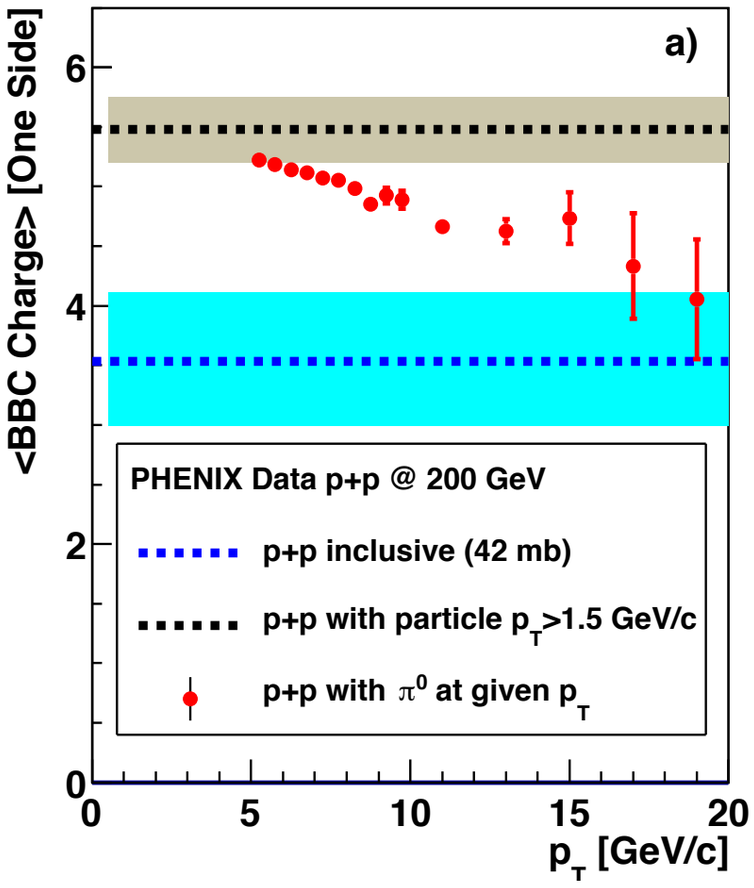


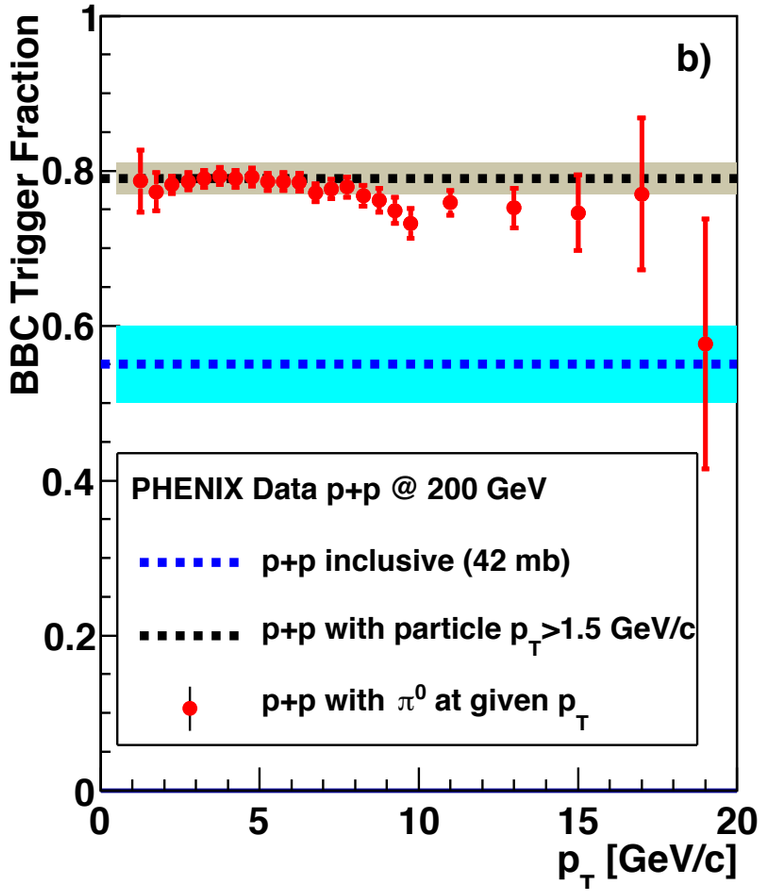


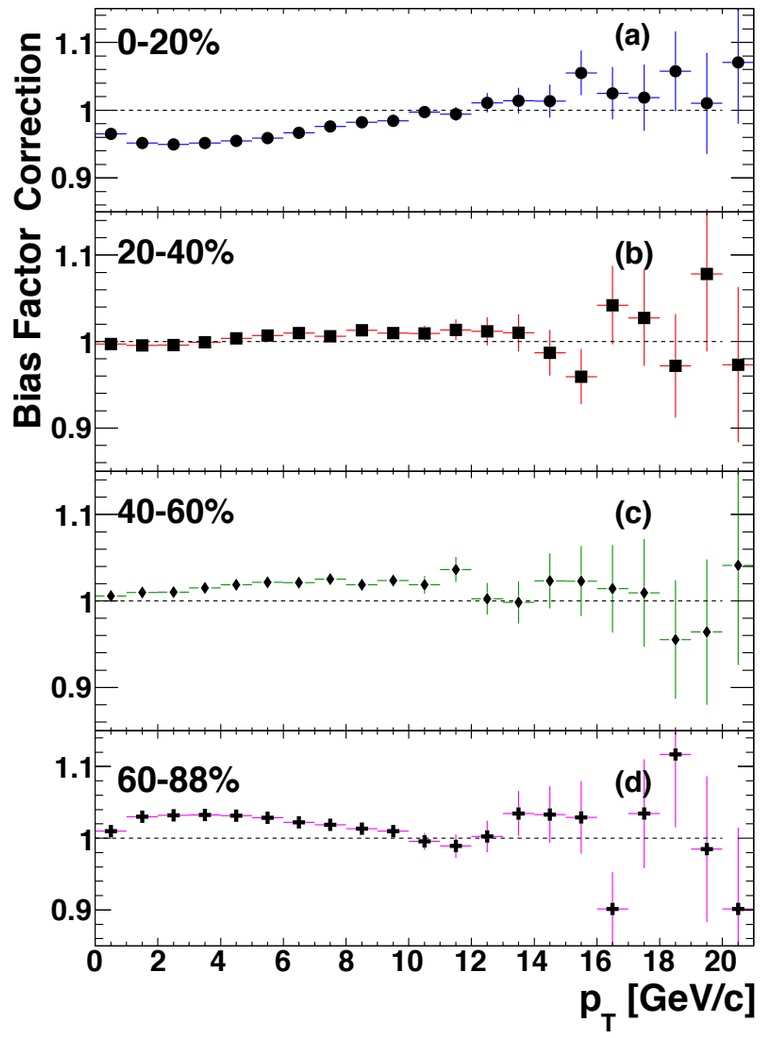
- Occam's Razor: unlikely to be a coincidence between two unrelated suppression/enhancement effects
- Idea: *jet production unmodified*, but *multiplicity in Au-going direction is modified in jet events*
  - ➡ e.g. jet events merely re-rearranged in centrality, so minimum-bias $R_{d\mathrm{Au}} = 1$ by construction

Centrality w/ hard processes

PRC 90 (2014) 034902

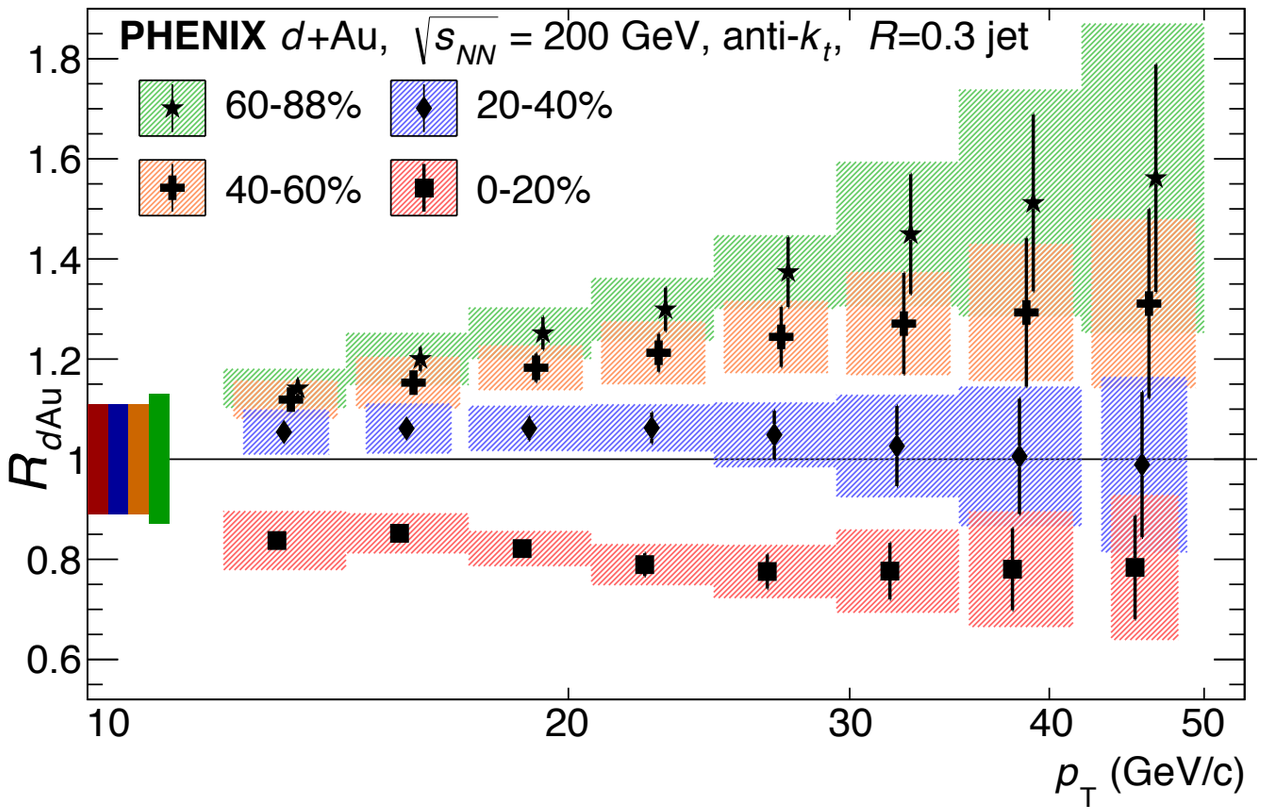


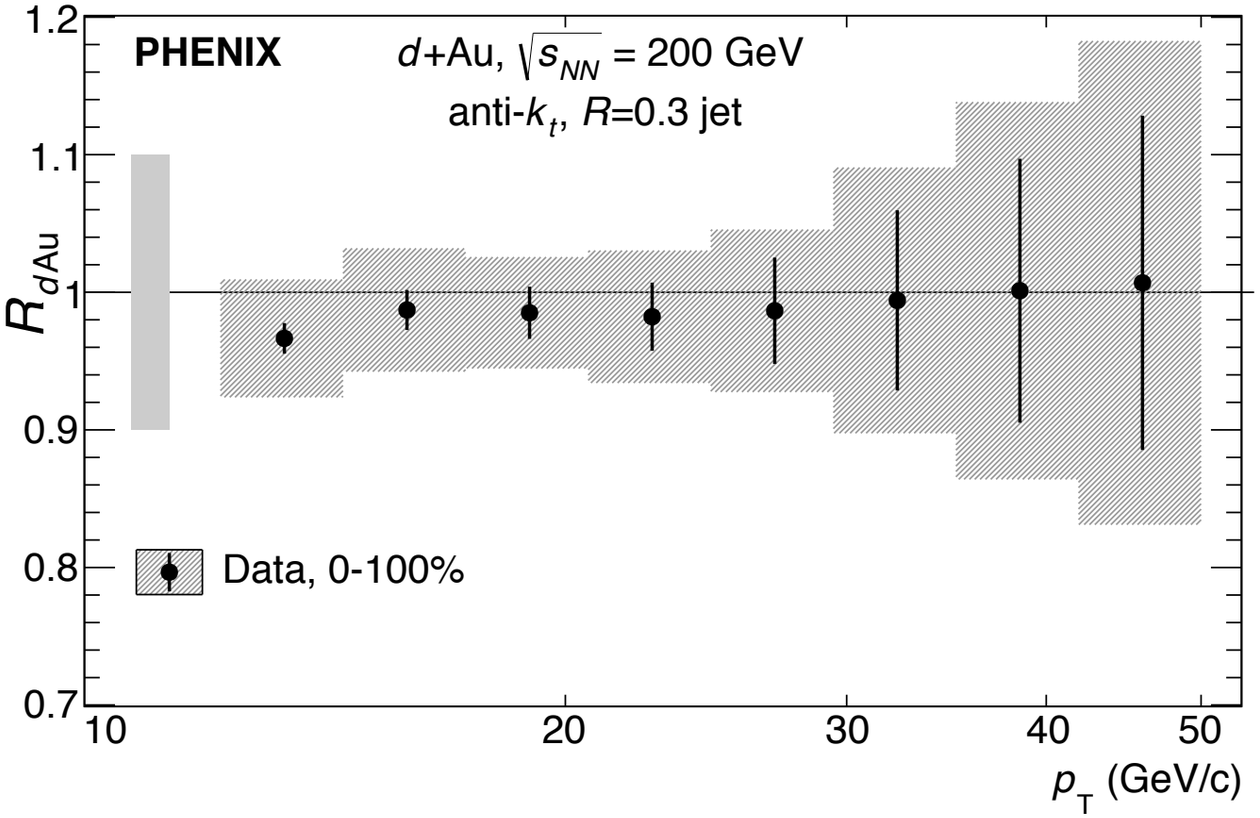




- Could this be a *bias* or *auto-correlation* between the centrality signal and the presence of a hard scattering?
  - ➡ separate PHENIX publication to address exactly this point with *p*+*p* data and *d*+Au simulation
- Conclusion: there is a small bias which, when corrected for, <u>*magnifies the results*</u>, even for very high-p_T processes

Reconciling these pictures?





- *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…

Connection to hadron physics?

- *One idea:* this is a consequence of proton color fluctuations at collider energies

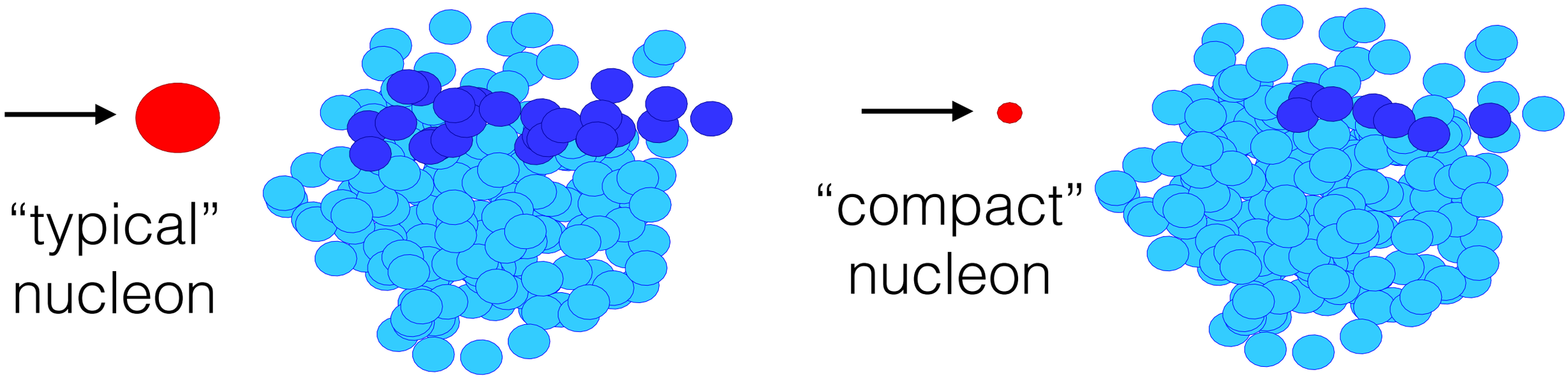
  ➡ nucleon configurations with a high-*x* parton (≳0.1) are different than “typical” configurations

  ➡ interact more weakly than average, fewer other partons, smaller transverse size, etc.

  ➡ see M. Strikman, DVP, et al. hep-ex/1409.7381, accepted by PRC RC

- Related to: hadronic cross-section fluctuations, point-like configurations, color transparency, etc.

“Shrinking proton” picture



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

  ➡ so peripheral $R_{d\mathrm{Au}} > 1$, central $R_{d\mathrm{Au}} < 1$

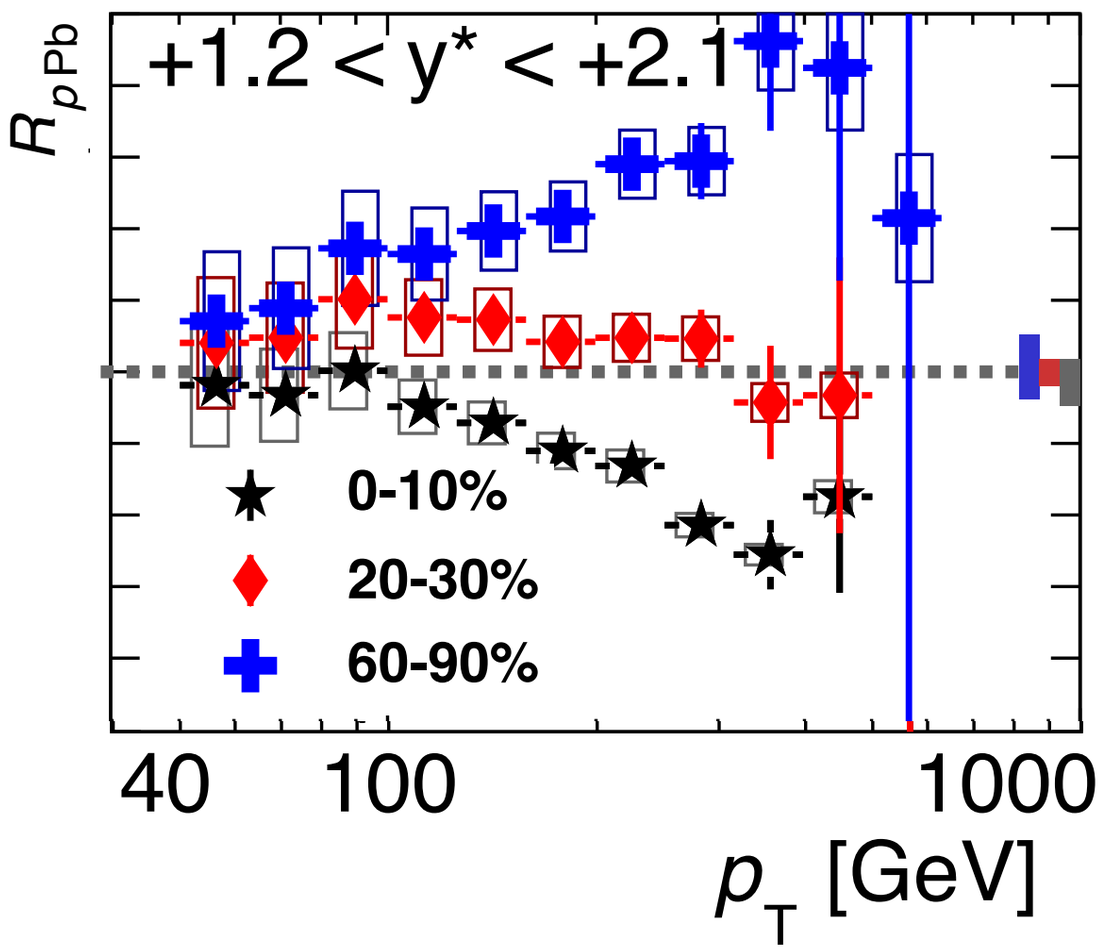
- Large nucleus acts as a filter on the transverse nucleon size

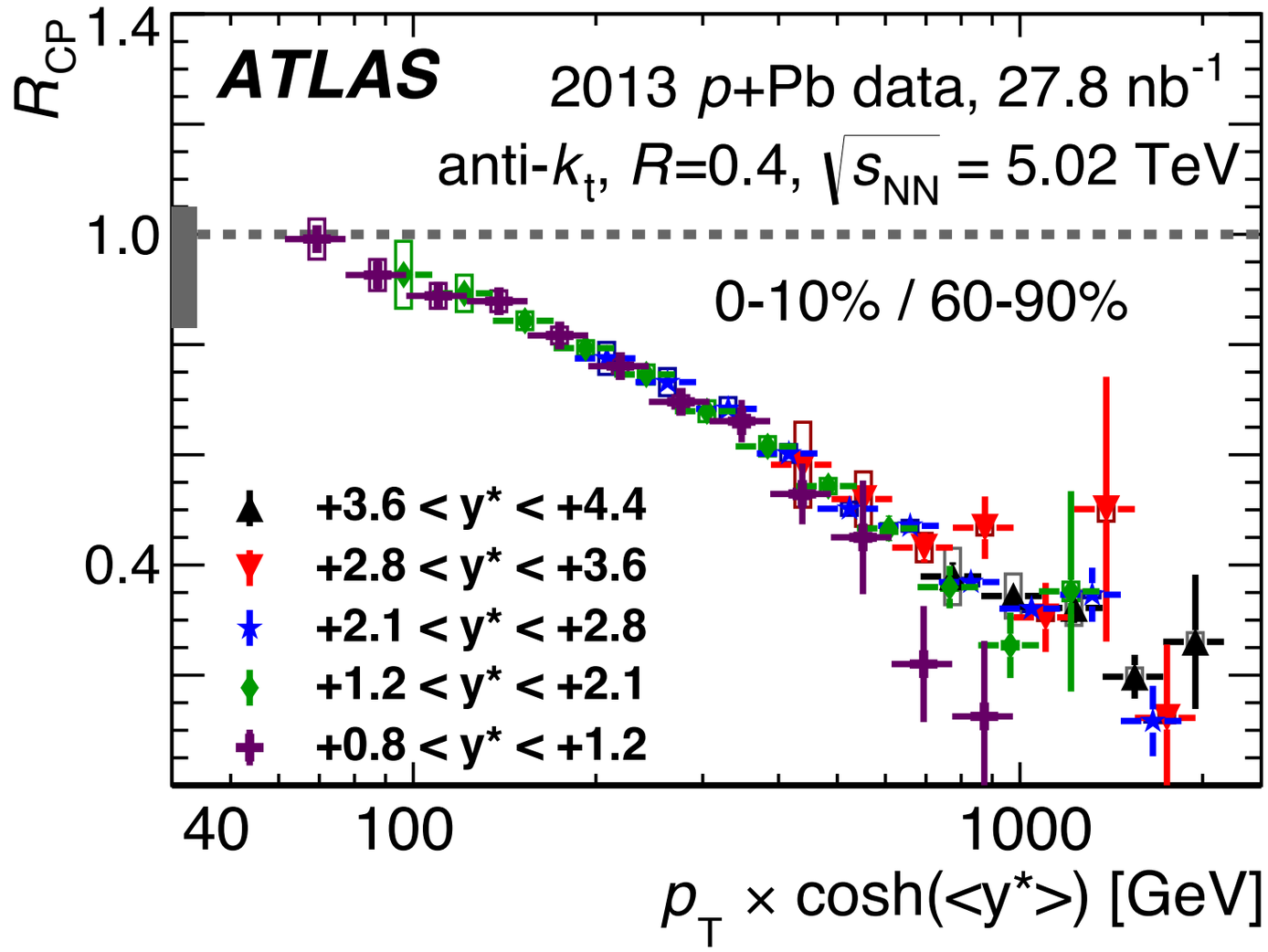
  ➡ larger deuteron-x (nuclear-x irrelevant) ➡ more compact configurations ➡ larger deviations from $R_{d\mathrm{Au}} = 1$

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

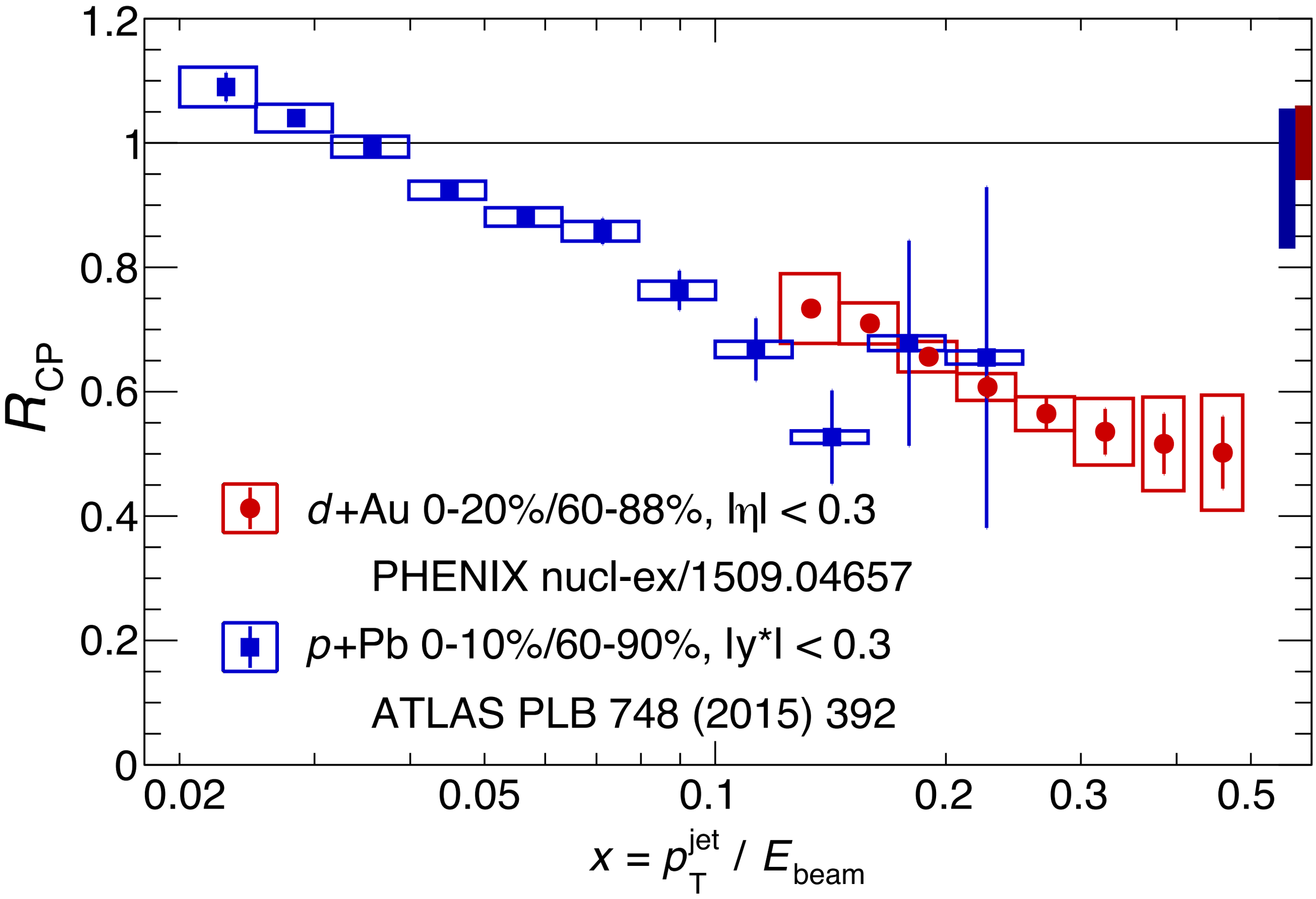
Analogous LHC results

PLB 748 (2015) 392



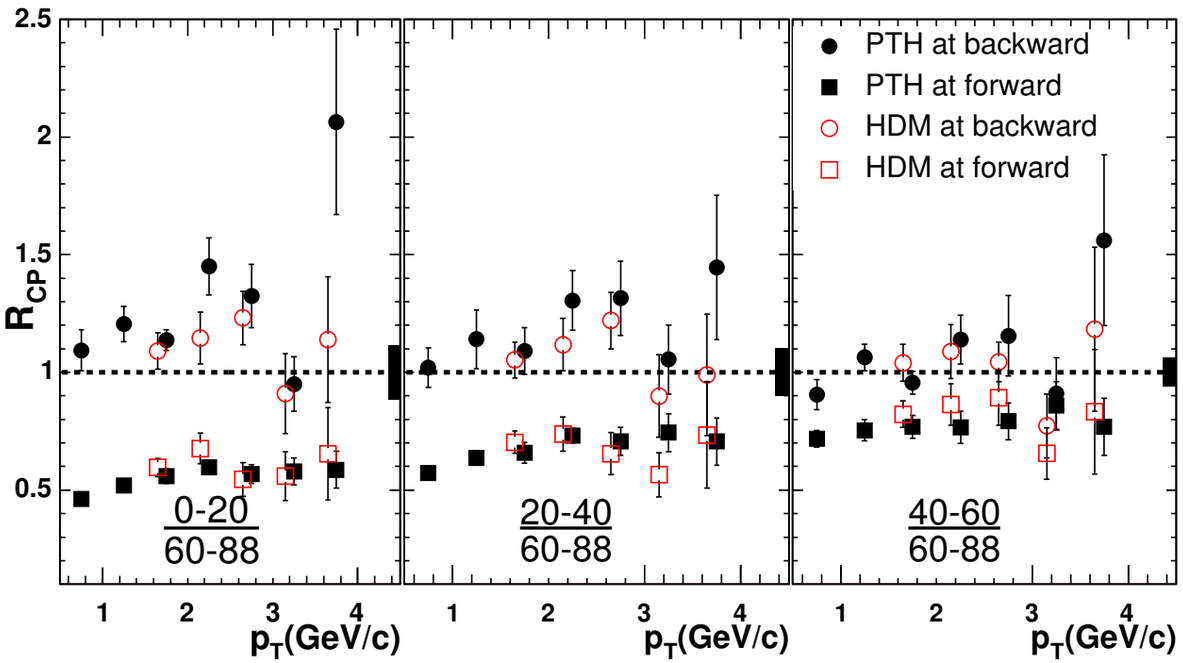


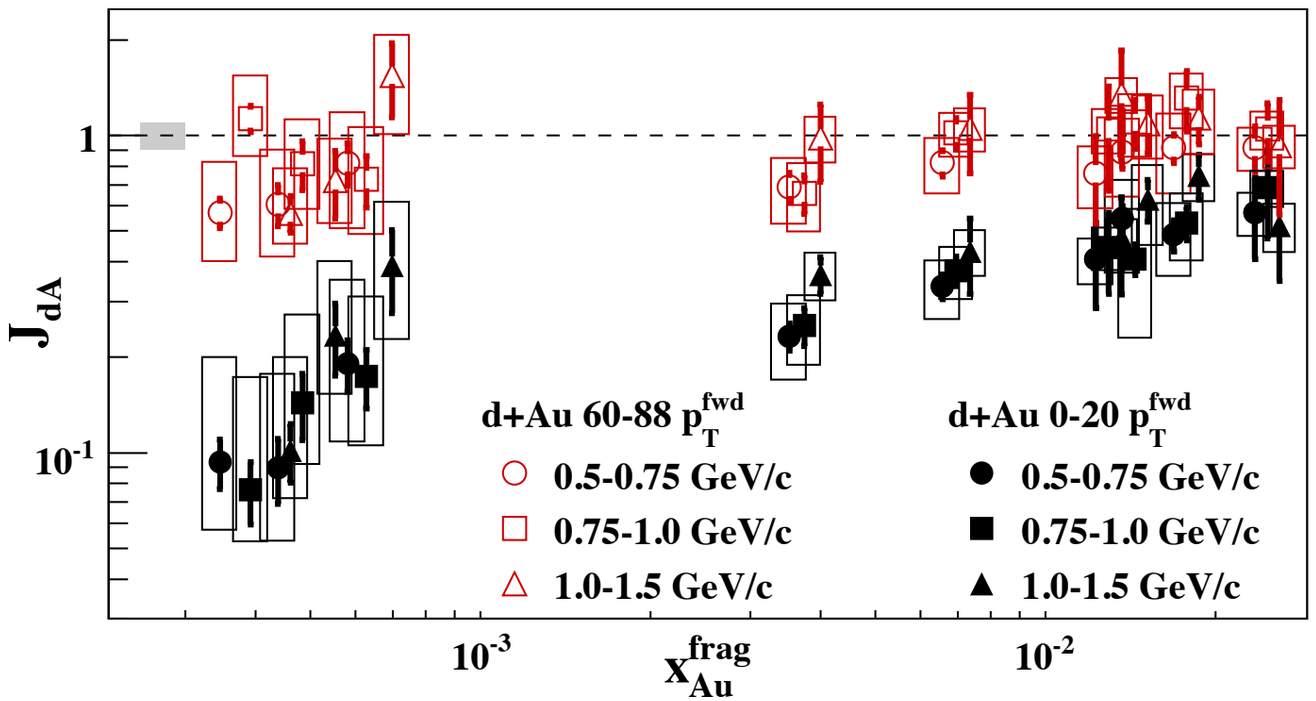
- Same modification pattern, in the same Bjorken-*x* range
- Modifications to the R_{pPb} / R_{CP} shown to scale only with *proton-x* and not depend on nuclear-*x*



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

New angle on previous data?

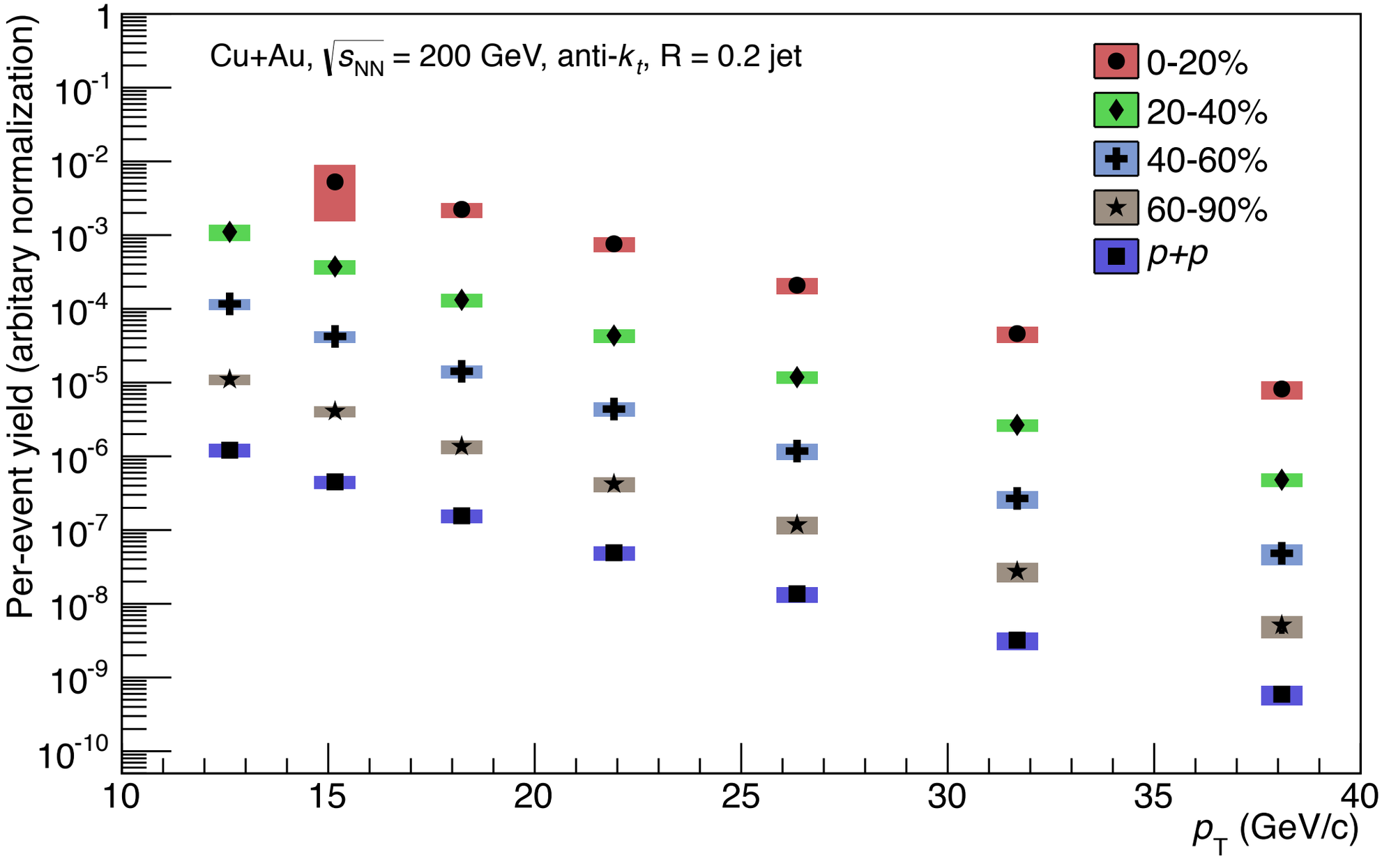




- Strong *centrality dependence* in forward hadron and di-hadron production in *d*+Au
  - ➡ even though <*b*> does not change so much
  - ➡ attributed by many to low nuclear-*x* effects (CGC?), but kinematic region also associated with large deuteron-*x*
- My two cents: there's an overall suppression,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

Cu+Au collisions

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



- For preliminary results, arbitrary normalization, but <u>*p*+*p*-to-Cu+Au normalization is fixed</u>
- Expanded systematics for **low-p_T jets in most central events**

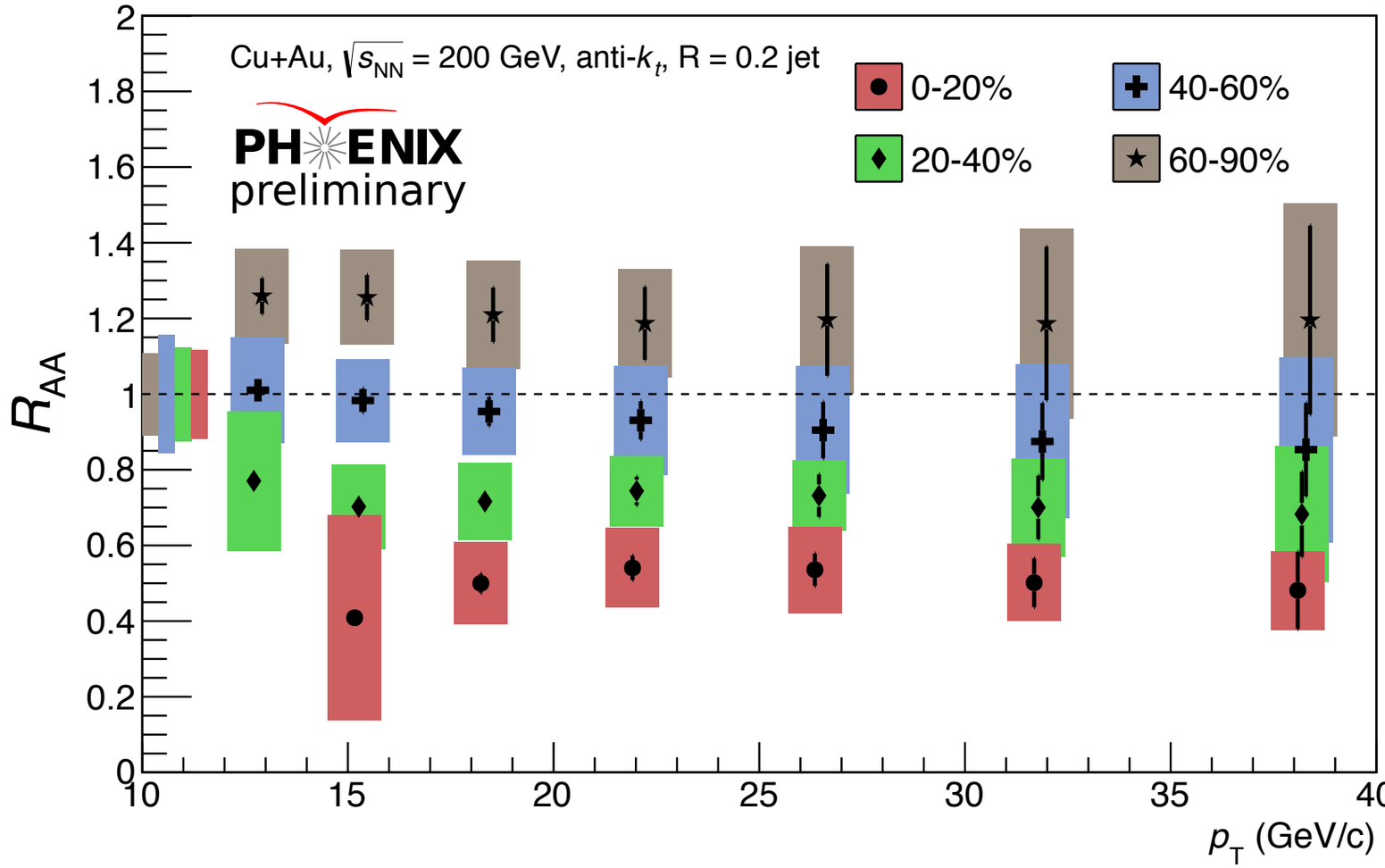
Jet suppression in Cu+Au

Cu+Au yield

$$R_{AA} = \mathbf{dN/dp_T} \;/\; \mathbf{T_{AA}} \times \mathbf{d\sigma/dp_T}$$

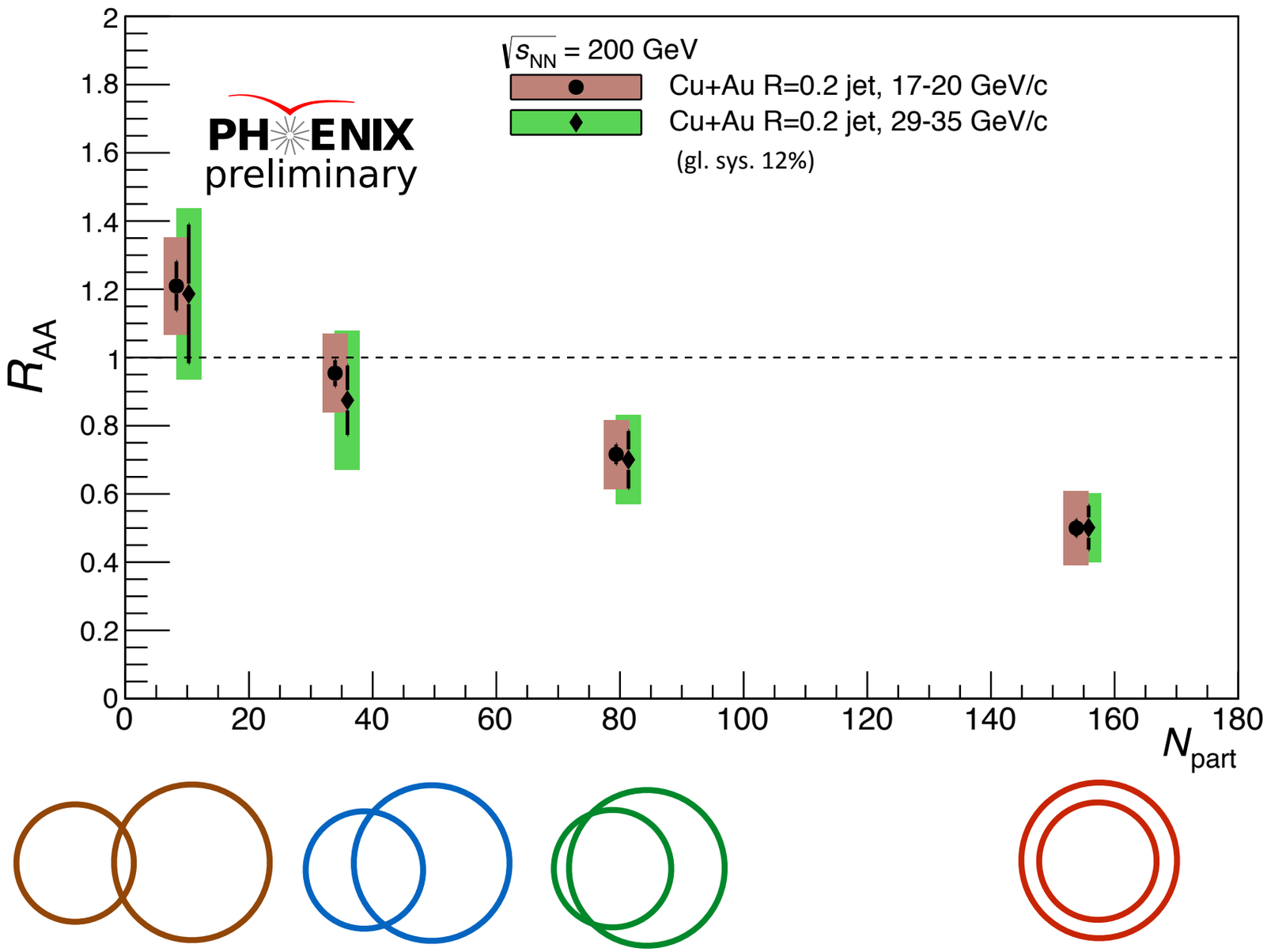
nuclear *p+p*

overlap *x-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

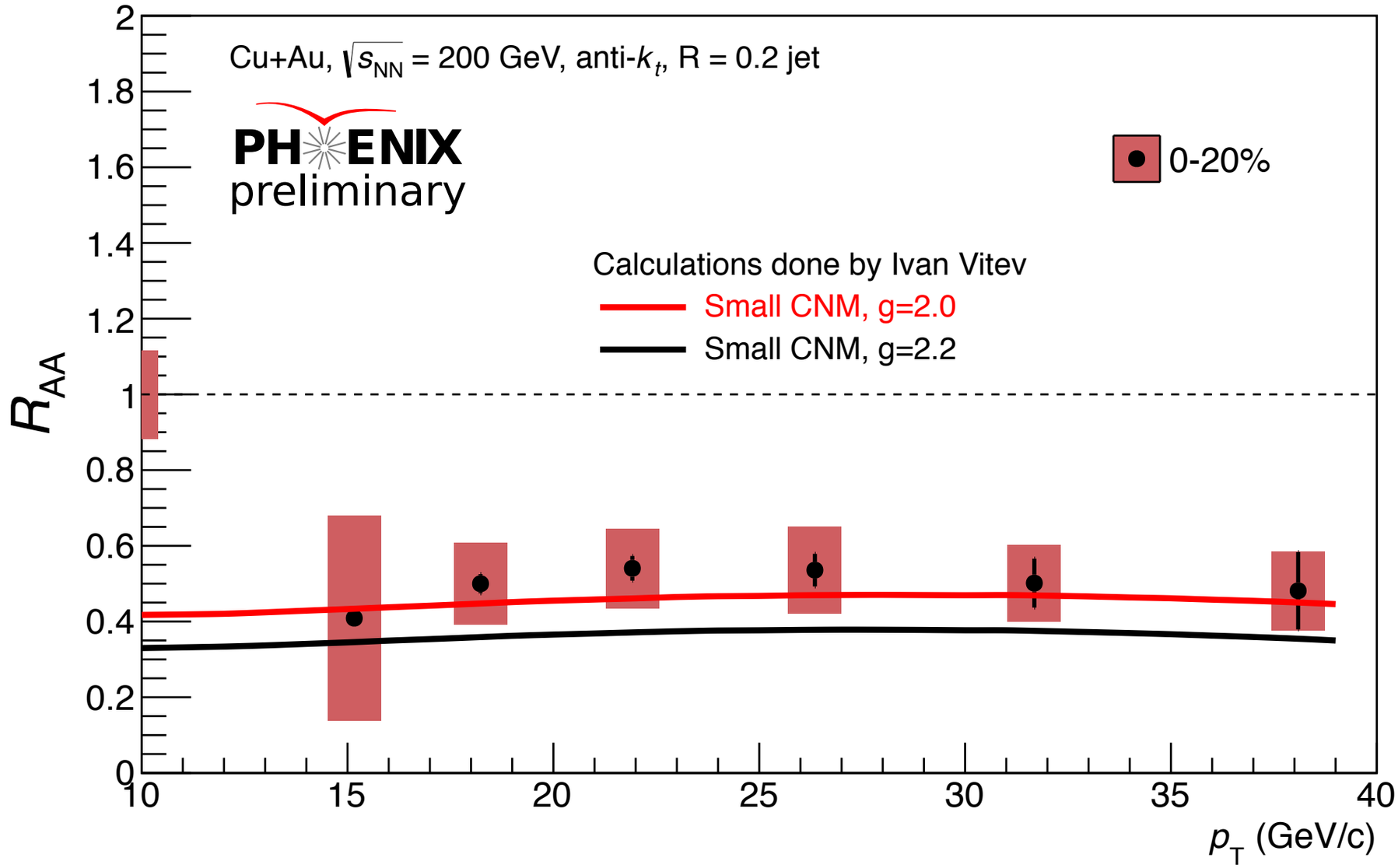
Jet suppression in Cu+Au vs. N_{part}



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

First comparisons to theory

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