

Full Jet Reconstruction in p+p and Heavy-ion Collisions with PHENIX

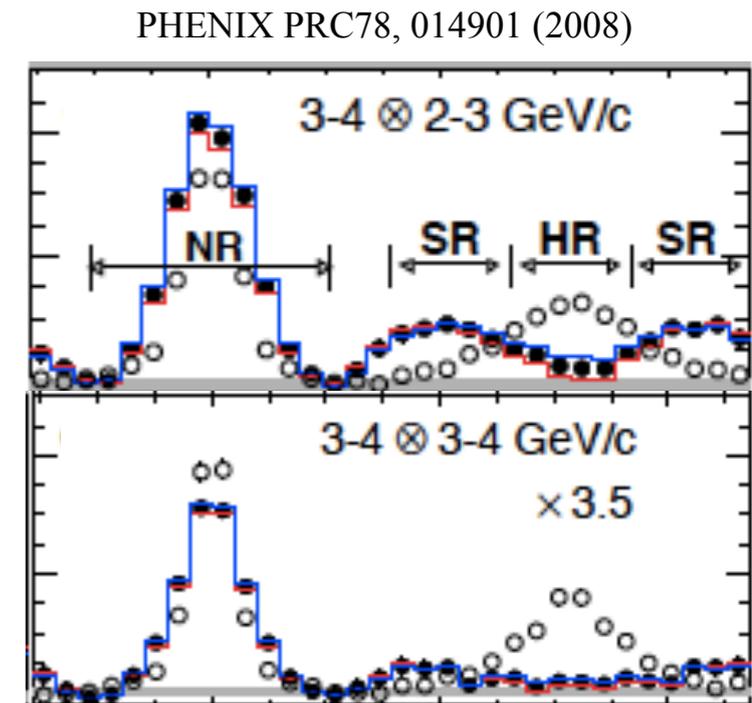
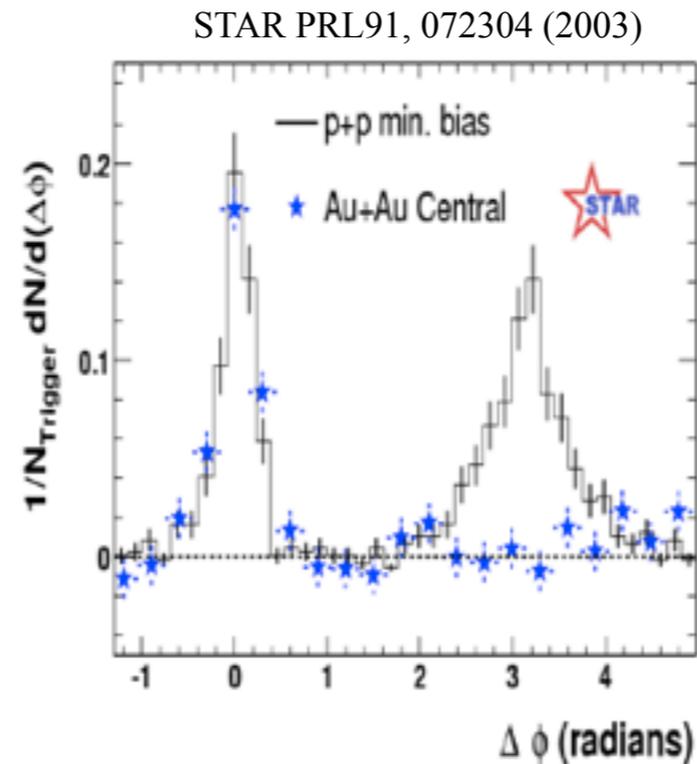
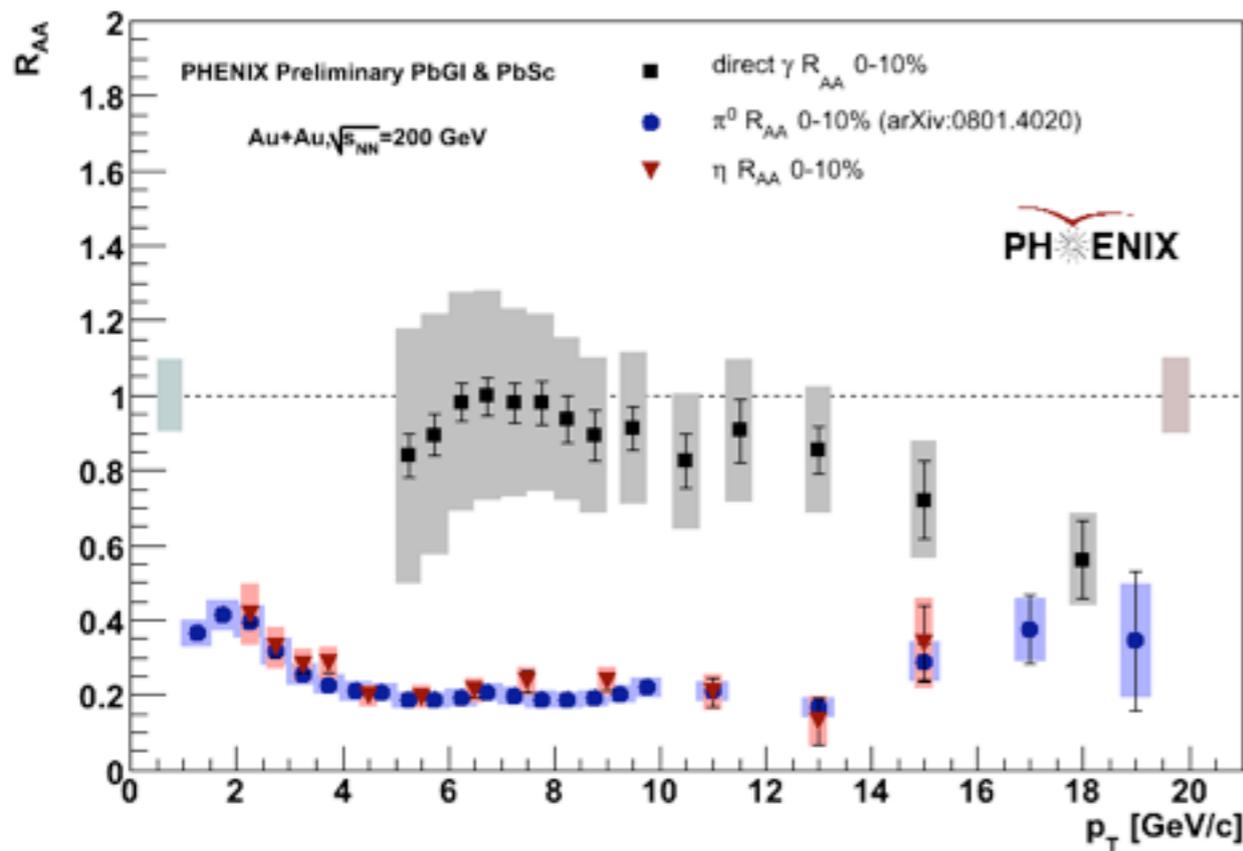
XIX International Workshop on Deep-Inelastic Scattering and Related Subjects

- *Ali Hanks*

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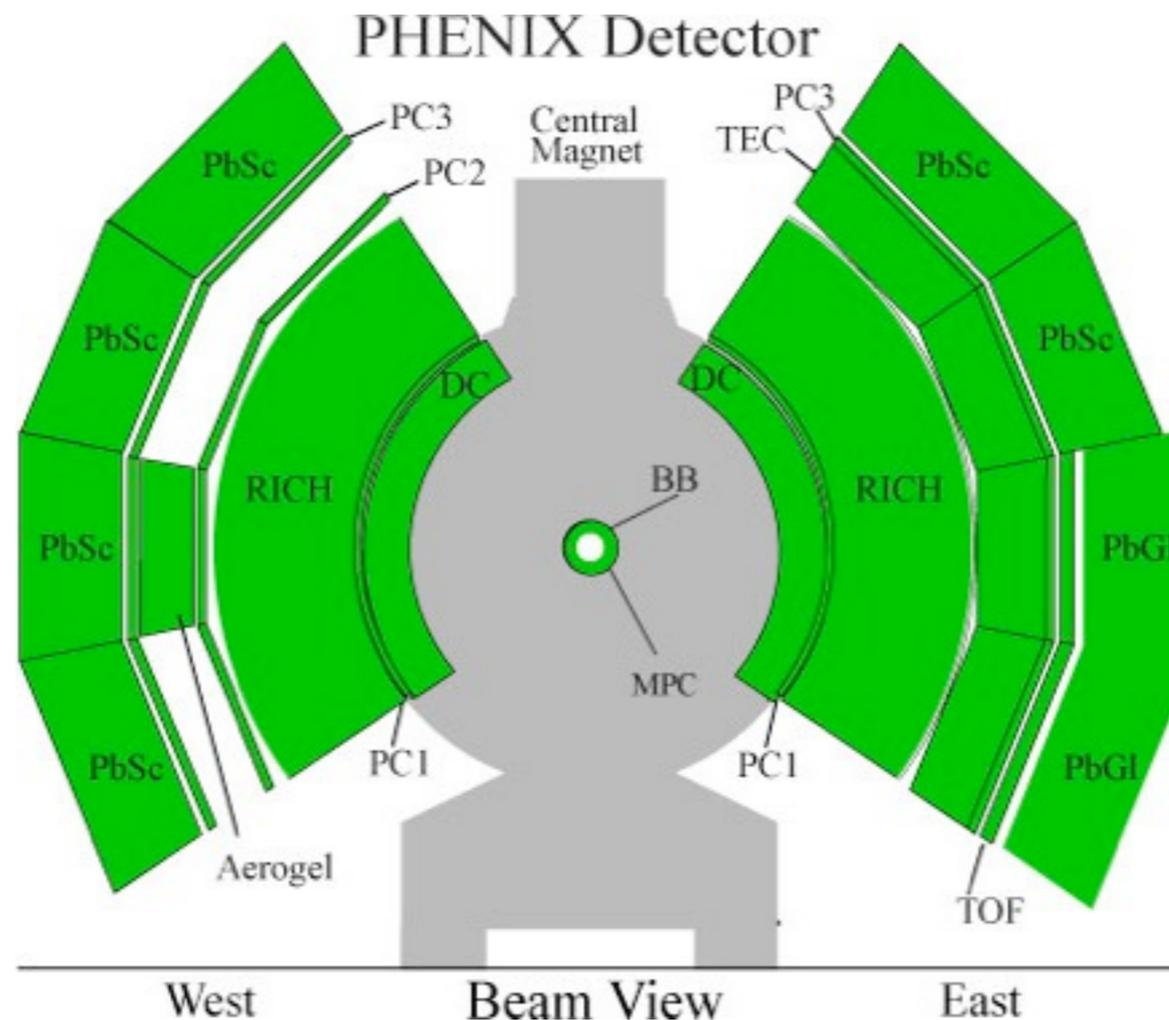


Jet quenching in the QGP



- Single hadrons: strong suppression for wide range of p_T
 - indirect measure of energy loss of initial parton
- Two particle correlations: disappearing away-side
 - modified away-side indication of modified fragmentation or is it all flow?
- Both difficult to model theoretically and indirect measure of parton
 - provide weak constraints: indirect link to initial parton energy and fragmentation
 - full jet reconstruction provides clarification for both questions!

Jets in PHENIX



- Jets measured in central arms – limited ϕ and η ($|\eta| < 0.35$) coverage
 - Neutral particles using electromagnetic calorimeters (EMCal):
 - Lead-Scintillator (PbSc) and Lead-Glass (PbGl)
 - Charge particles using tracking detectors:
 - Drift Chamber, Pad Chambers, and RICH
 - No hadronic calorimetry
 - Good tracking, EMCal resolution, electron id \rightarrow no energy double counting

Gaussian filter algorithm

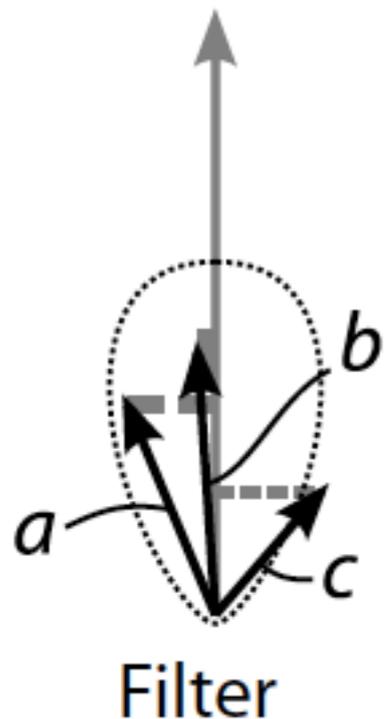
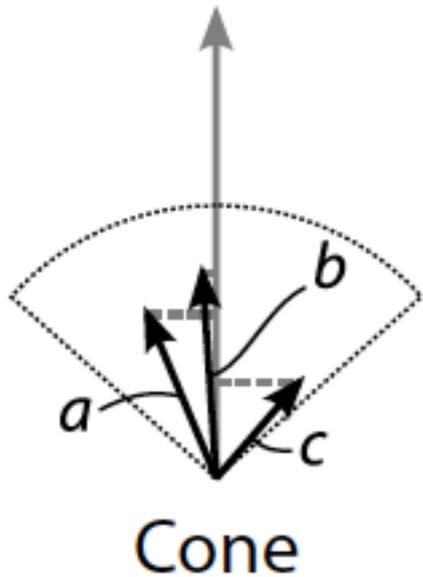
- Construct the p_T density for the event

$$p_T(\eta, \phi) = \sum_{i \in \text{particles}} p_{T,i} \delta(\eta - \eta_i) \delta(\phi - \phi_i)$$

- Determine weighted density at each point convolving the p_T density with a Gaussian filter function

$$p_T^{\text{filt}}(\eta, \phi) = \iint d\eta' d\phi' p_T(\eta', \phi') \exp\left(-\frac{(\eta - \eta')^2 + (\phi - \phi')^2}{2\sigma_{\text{filter}}}\right)$$

- Local maxima correspond to reconstructed jets
- Similar to seedless cone algorithm BUT
- No hard angular cut-off
 - naturally infrared and collinear safe
- Gaussian shape:
 - focuses on core of jet: optimizes signal to background and stabilizes jet axis in large background environment
 - reduces impact of limited acceptance
- Details found in arxiv:0806.1499 (Y.S. Lai, B.A. Cole)

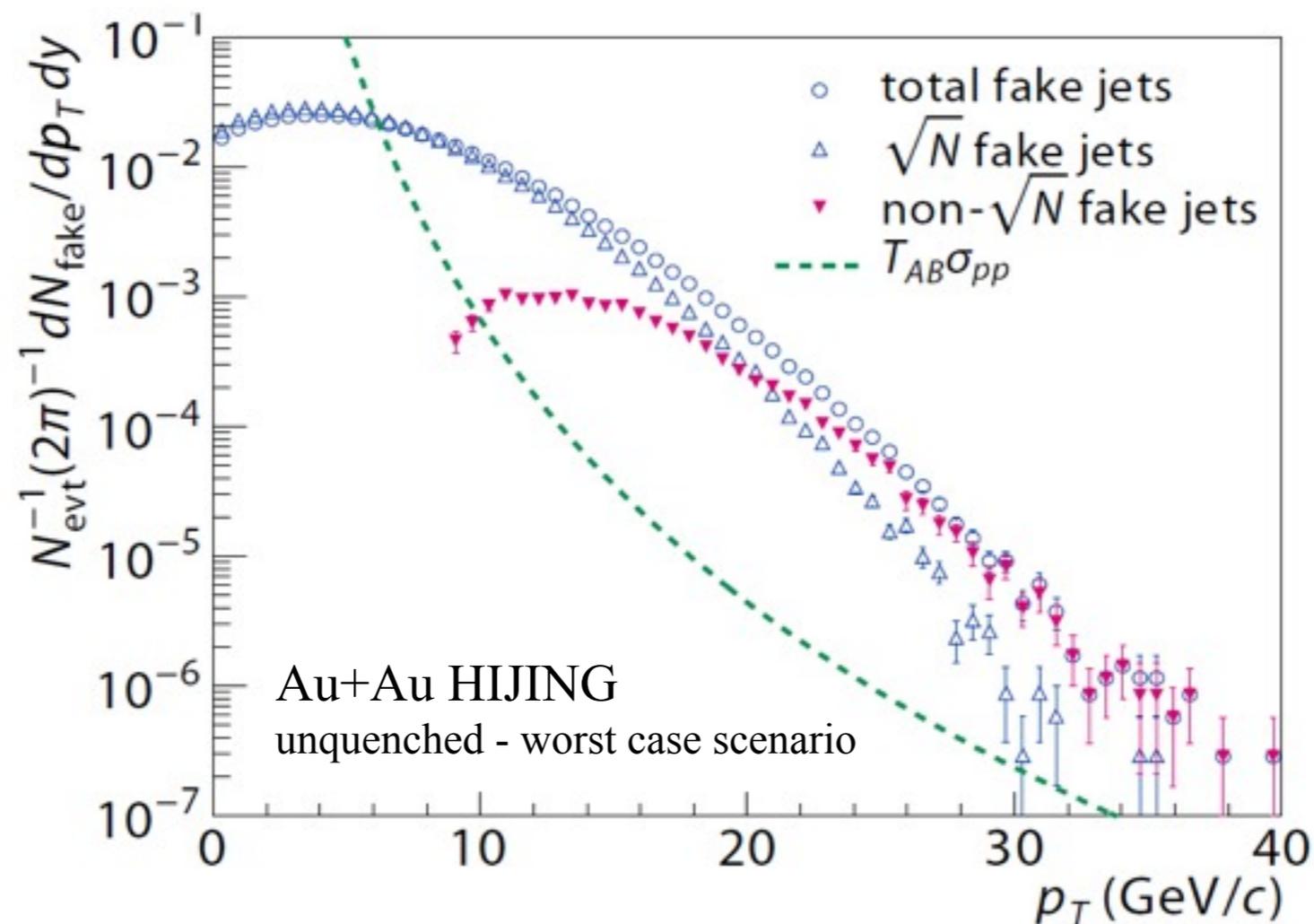


Jet filter in HI environment

- Central heavy-ion events dominated by soft background
- Modified p_T density function: mean p_T of background estimated and subtracted

$$p_T(\eta, \phi) = \sum_{i \in \text{particles}} p_{T,i} \delta(\eta - \eta_i) \delta(\phi - \phi_i) - p_{T,BG}(\eta, \phi)$$

- Fluctuations give rise to substantial fake jet contamination
 - non-trivial correction: not simply \sqrt{N} fluctuations



Fake jet rejection

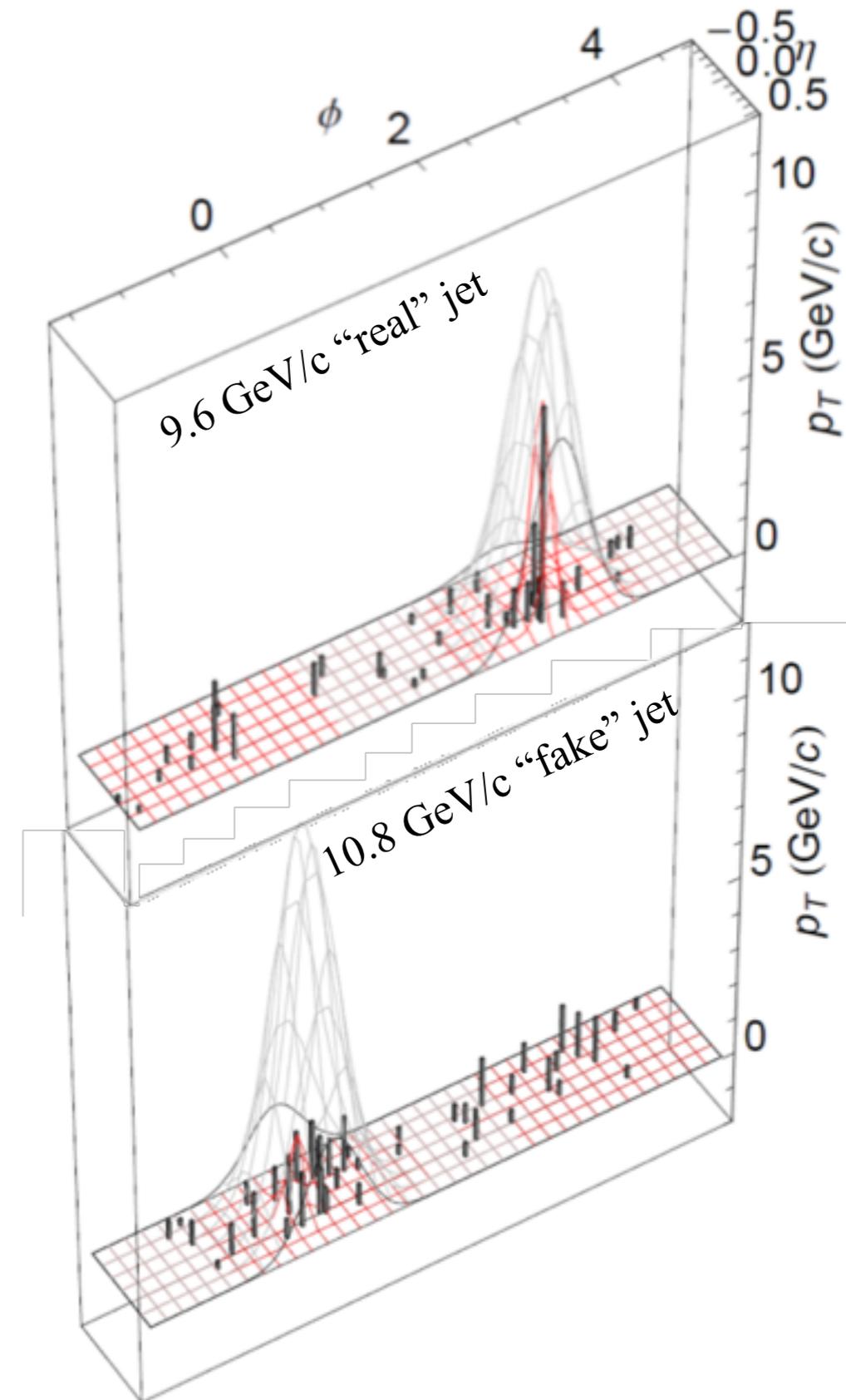
- Several approaches available:
 - Reconstruct only very high p_T jets
 - fake jets become negligible in Cu+Cu above $\sim 15-18$ GeV
 - Apply large p_T cut on fragments
 - Statistically subtract background
 - randomize particles in event and reconstruct fake jets
 - Direct rejection of fake jets
 - fake jets should not behave like real jets so in principle can be identified algorithmically
- PHENIX applies direct rejection motivated by principle of the Gaussian filter
 - low and controllable biases
 - systematic uncertainties easier to estimate and/or correct for

Fake jet rejection

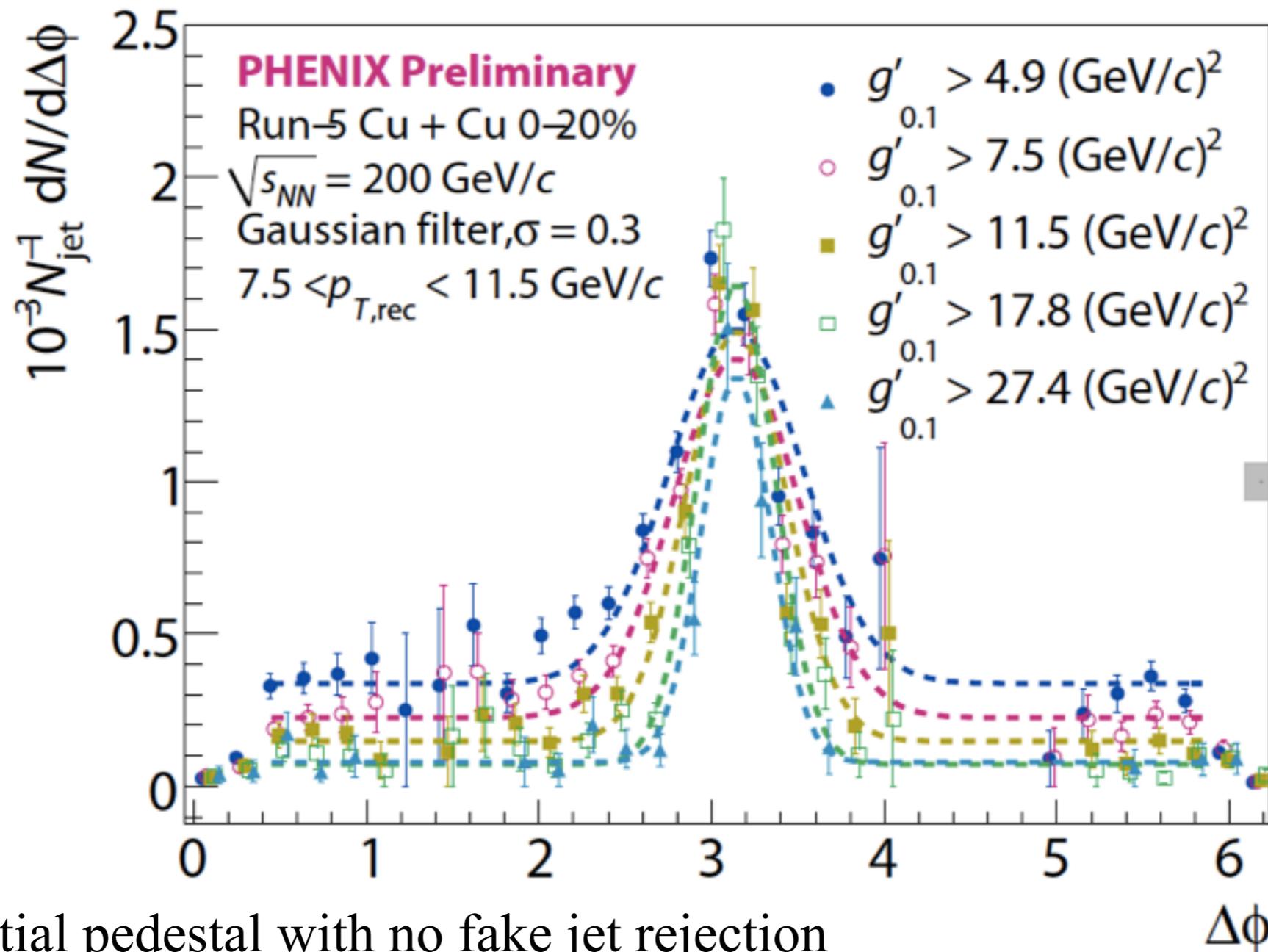
- Fake jets result from broad clusters of low p_T background particles that fluctuate above mean
 - dramatically different shape
- Cut on shape of the reconstructed jet
 - use Gaussian weighted p_T^2 sum:

$$g_{\sigma_{\text{dis}}}(\eta, \varphi) = \sum_{i \in \text{fragment}} p_{T,i}^2 \exp \left[-\frac{(\eta_i - \eta)^2 + (\varphi_i - \varphi)^2}{2\sigma_{\text{dis}}^2} \right]$$

- narrow width of $\sigma_{\text{dis}} \approx 0.1$
- cut on $g_{0.1} =$ weighted p_T^2 -sum
- Use di-jet $\Delta\phi$ distribution as metric for success of fake jet rejection
 - vary $g_{0.1}$ until di-jet pedestal stops changing

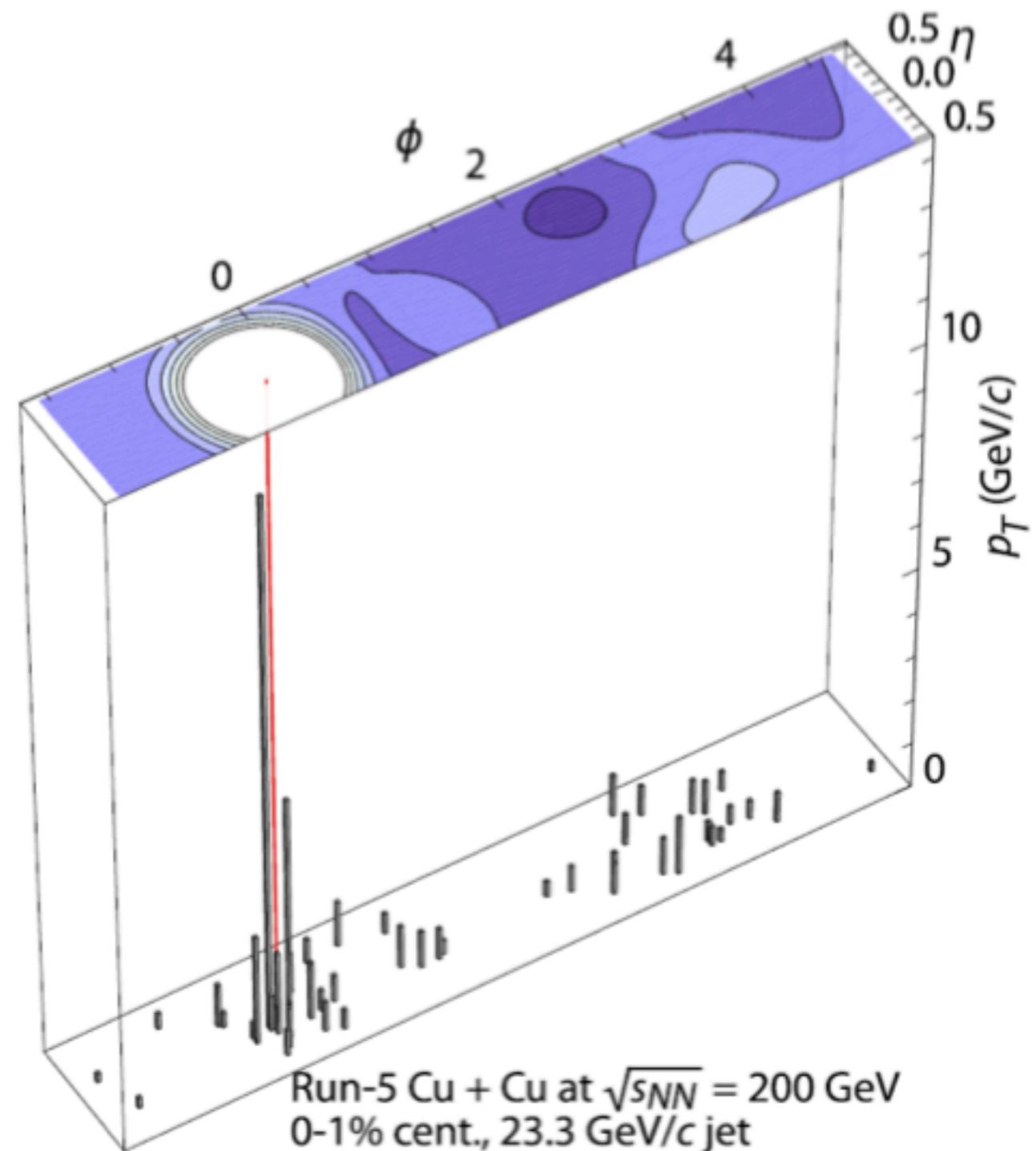
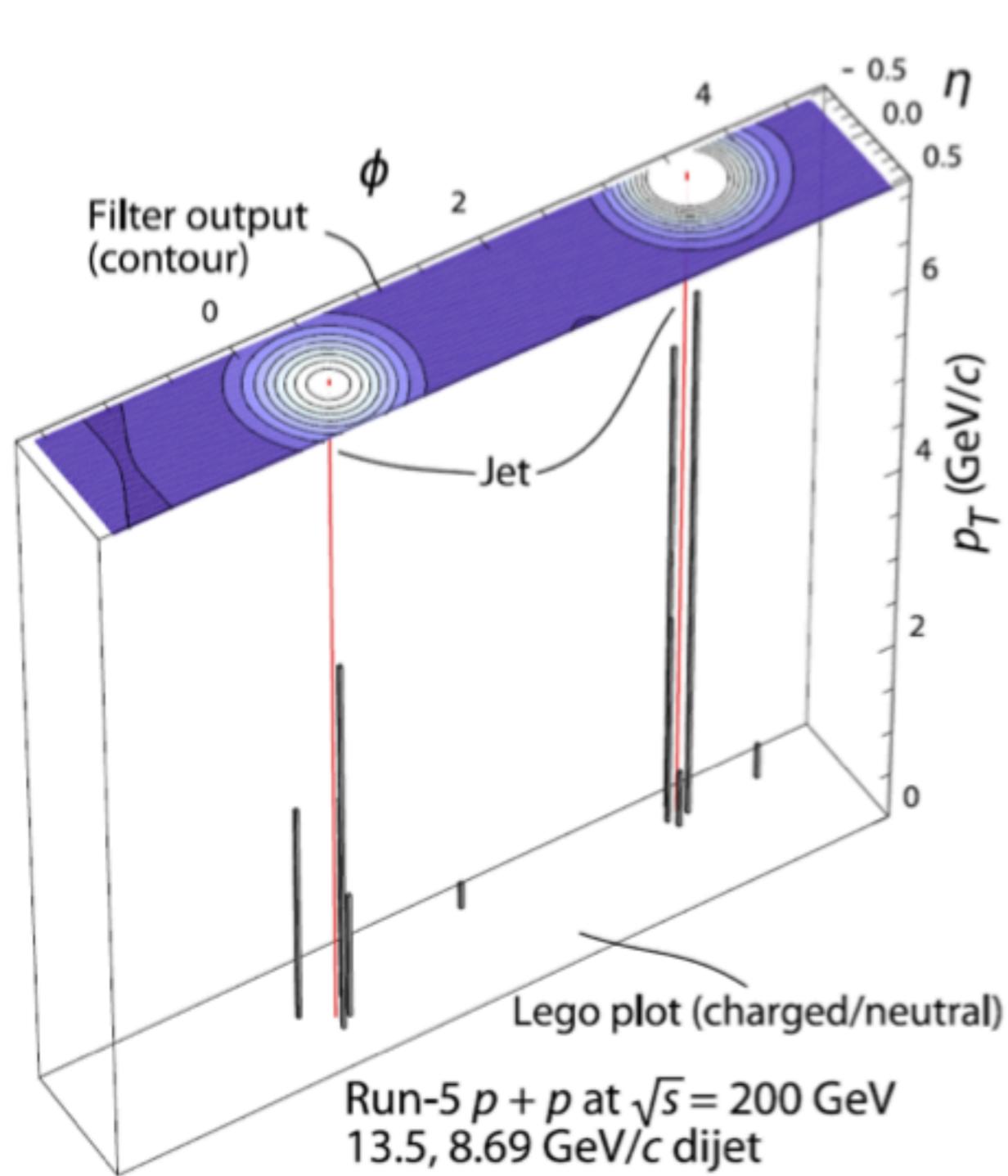


Fake jet rejection

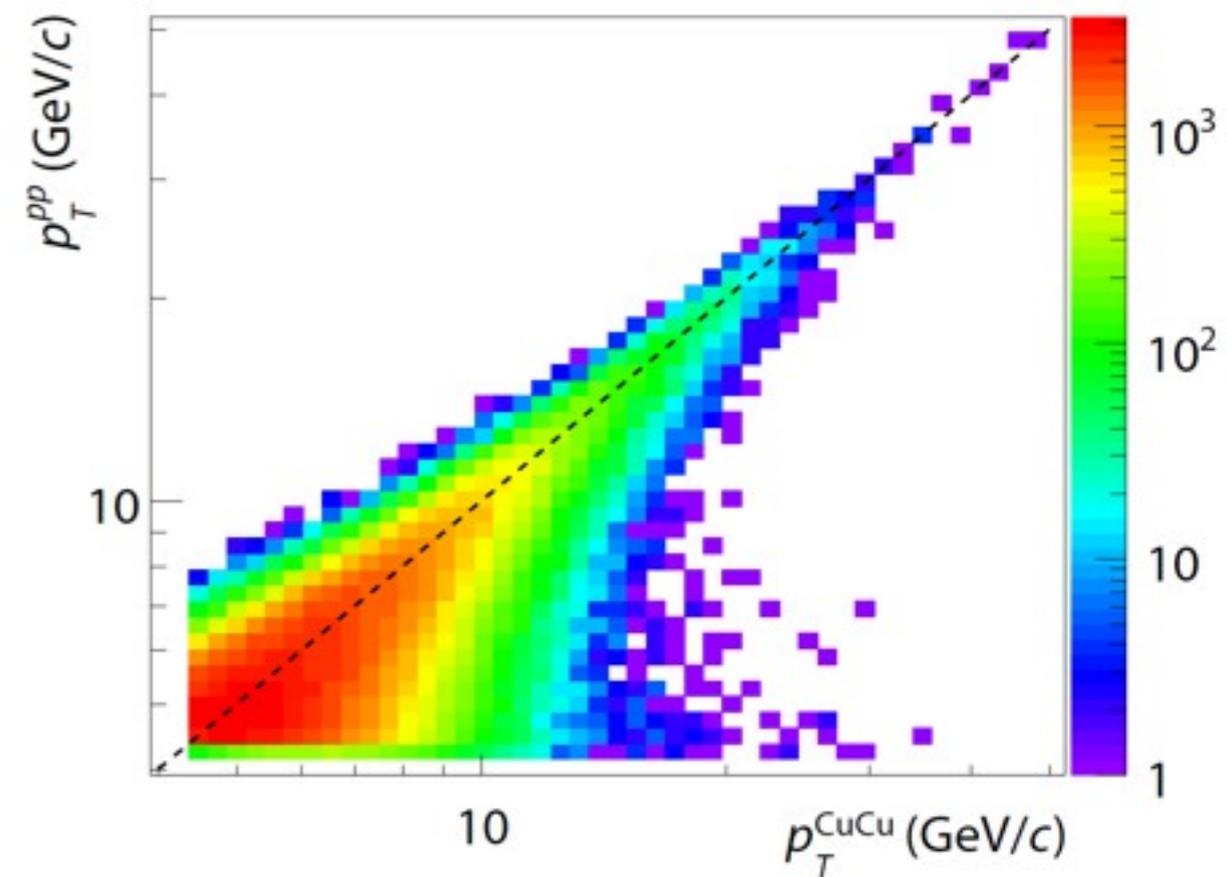
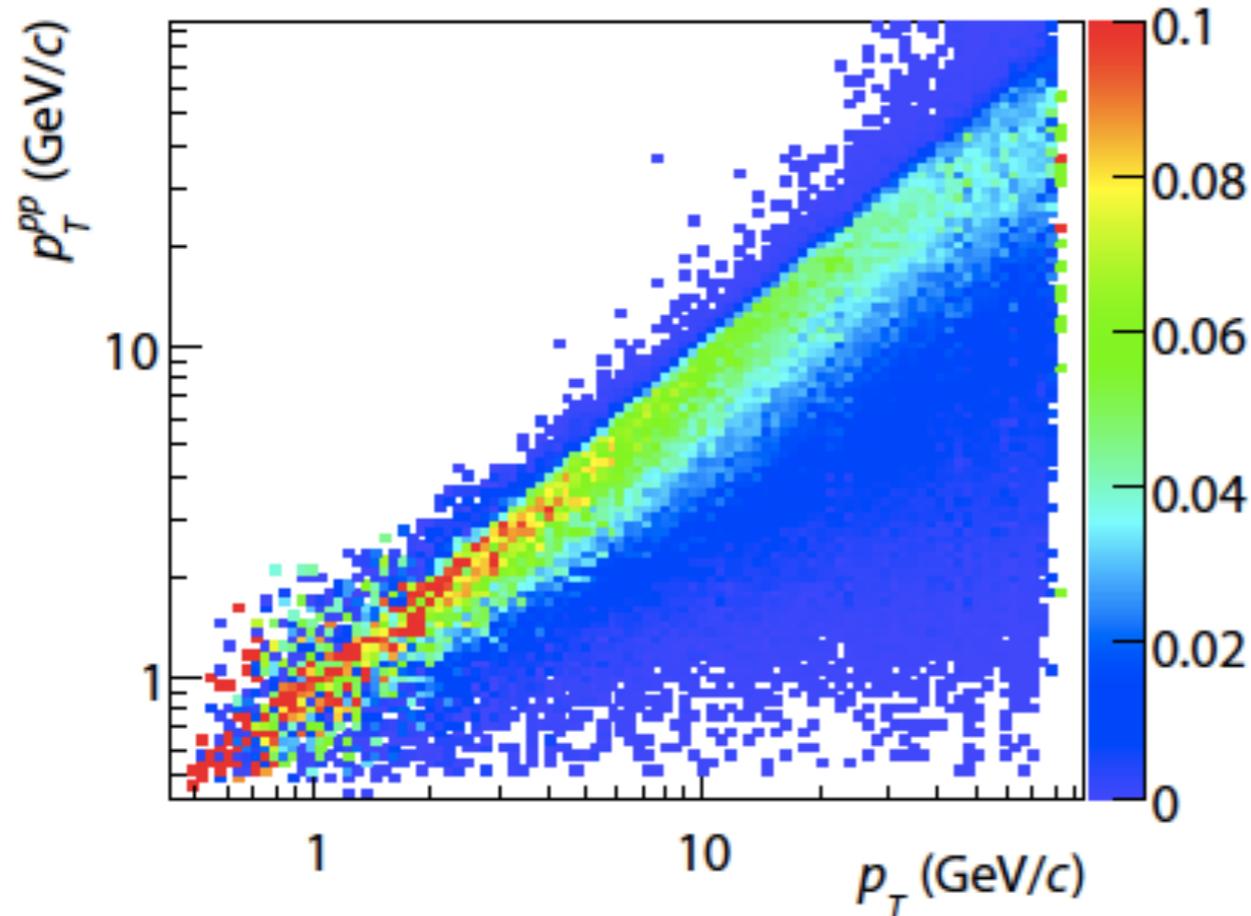


- See substantial pedestal with no fake jet rejection
- Above $g_{0.1} \sim 17.8 \text{ (GeV}/c)^2$ pedestal is stable - chosen as standard fake jet cut level
 - $< 10\%$ contamination at $7.5 \text{ GeV}/c$
- No rejection needed above $\sim 15 \text{ GeV}/c$ (cut already $< 10\%$ effect and \downarrow as $p_T \uparrow$)

p+p and Cu+Cu event displays

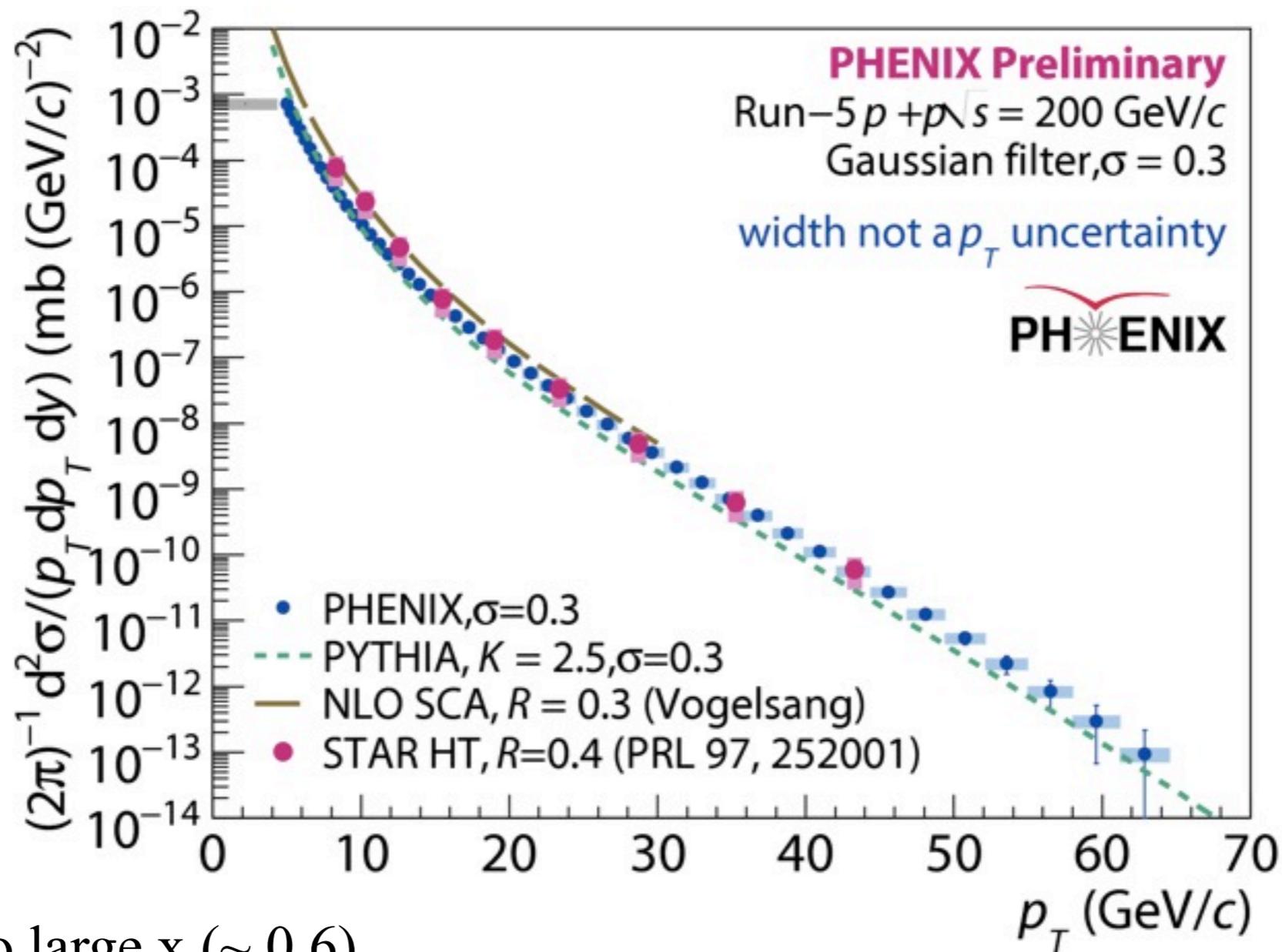


Unfolding the jet energy



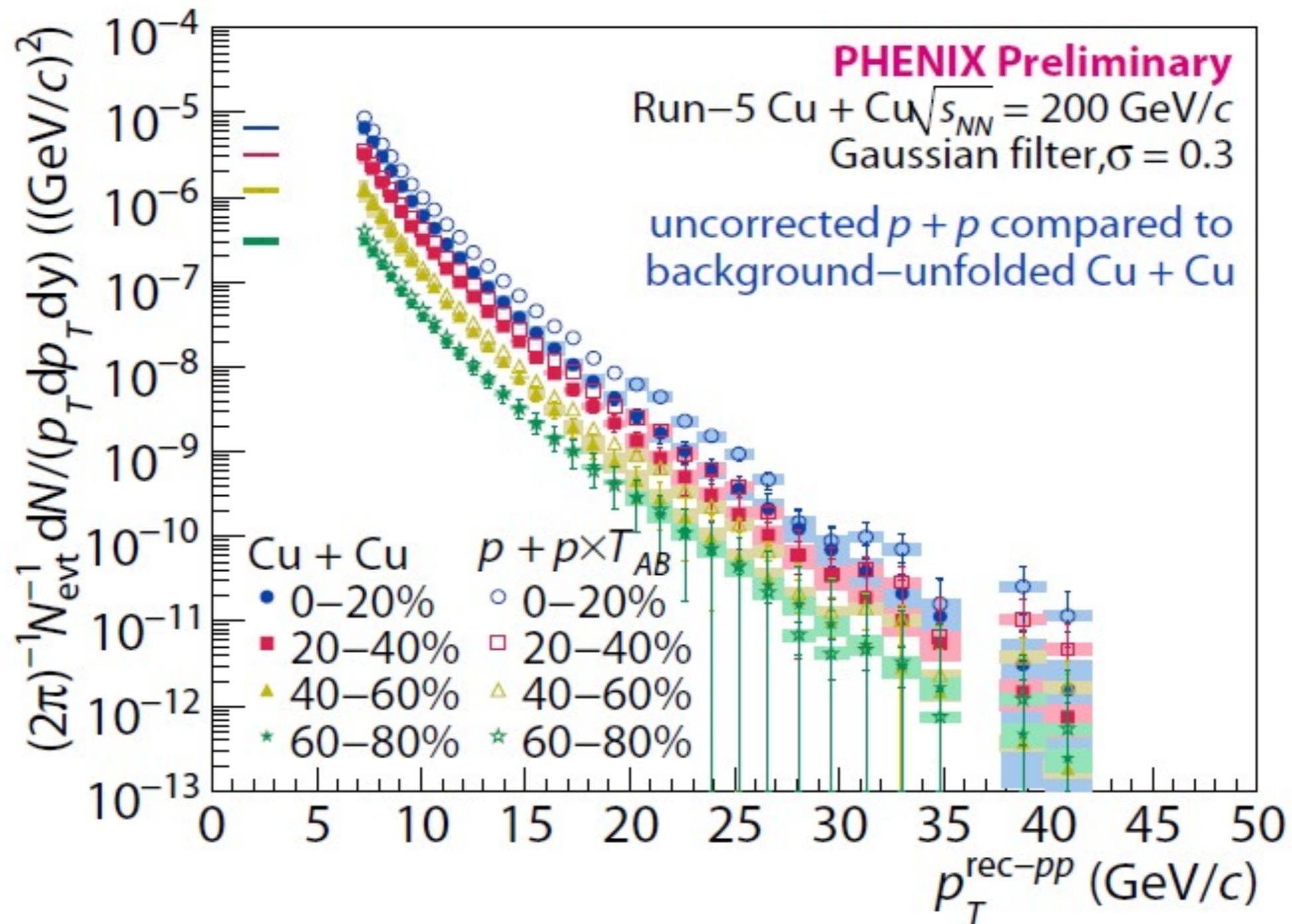
- Regularized SVD unfolding (GURU, Höcker & Karvelishvili, NIM A 372, 469)
- Unfolding to true jet energy (only in p+p so far)
 - Generate transfer matrix between true jet energy and measured using GEANT+PYTHIA
- Unfolding Cu+Cu to p+p jet energy
 - HI background smears reconstructed jets to higher p_T
 - embed p+p jets in Cu+Cu events to generate transfer matrix
 - cross check: compare uncorrected Cu+Cu jets to embedded p+p

p+p inclusive jet cross-section



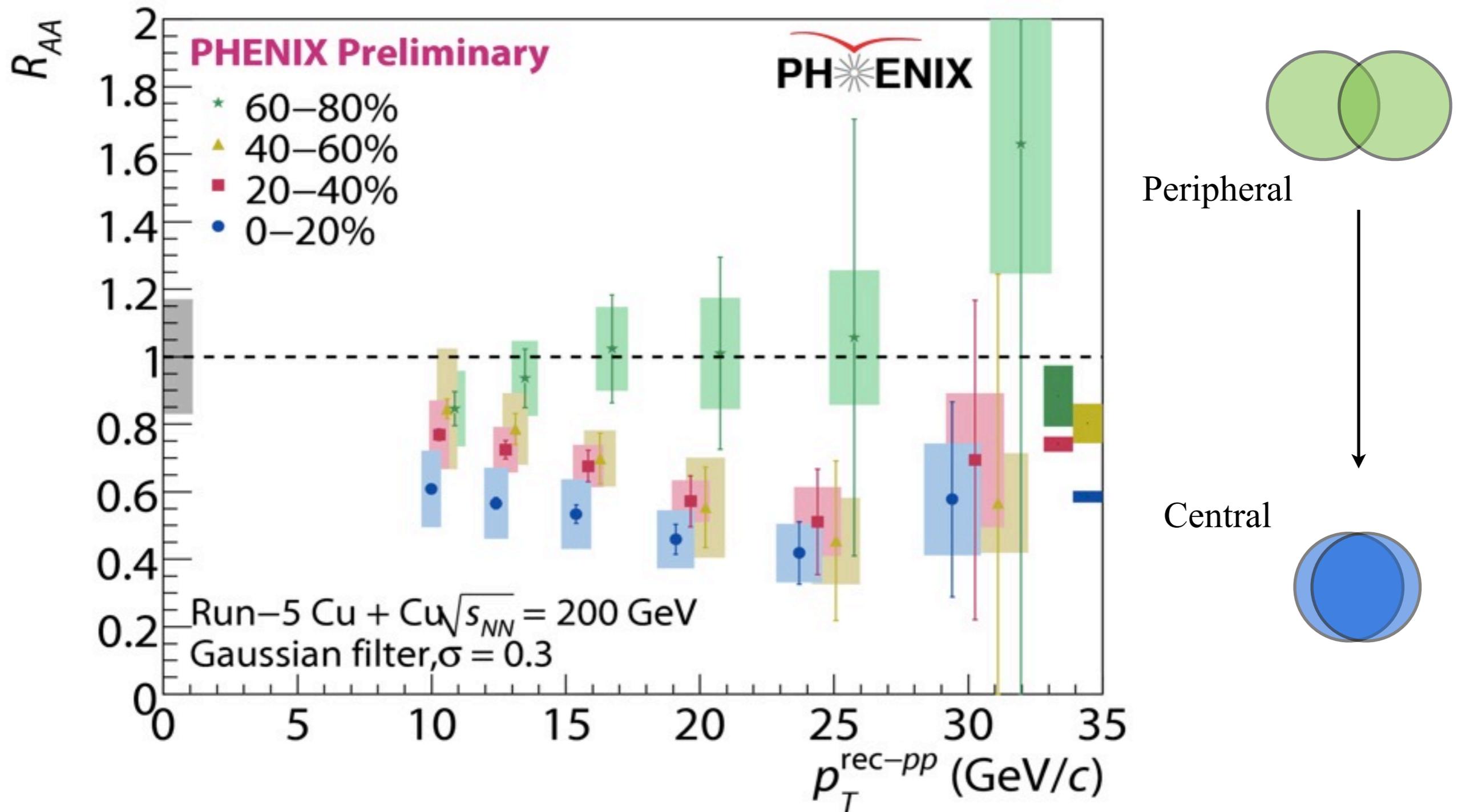
- p_T reach out to large x (~ 0.6)
- No direct comparisons BUT:
 - Consistent with STAR using mid-point cone algorithm with $R=0.4$
 - Compares reasonably well with both PYTHIA leading order K and NLO SCA
 - for direct comparison need NLO calculations to higher p_T and using filter algorithm

Cu+Cu jet spectra



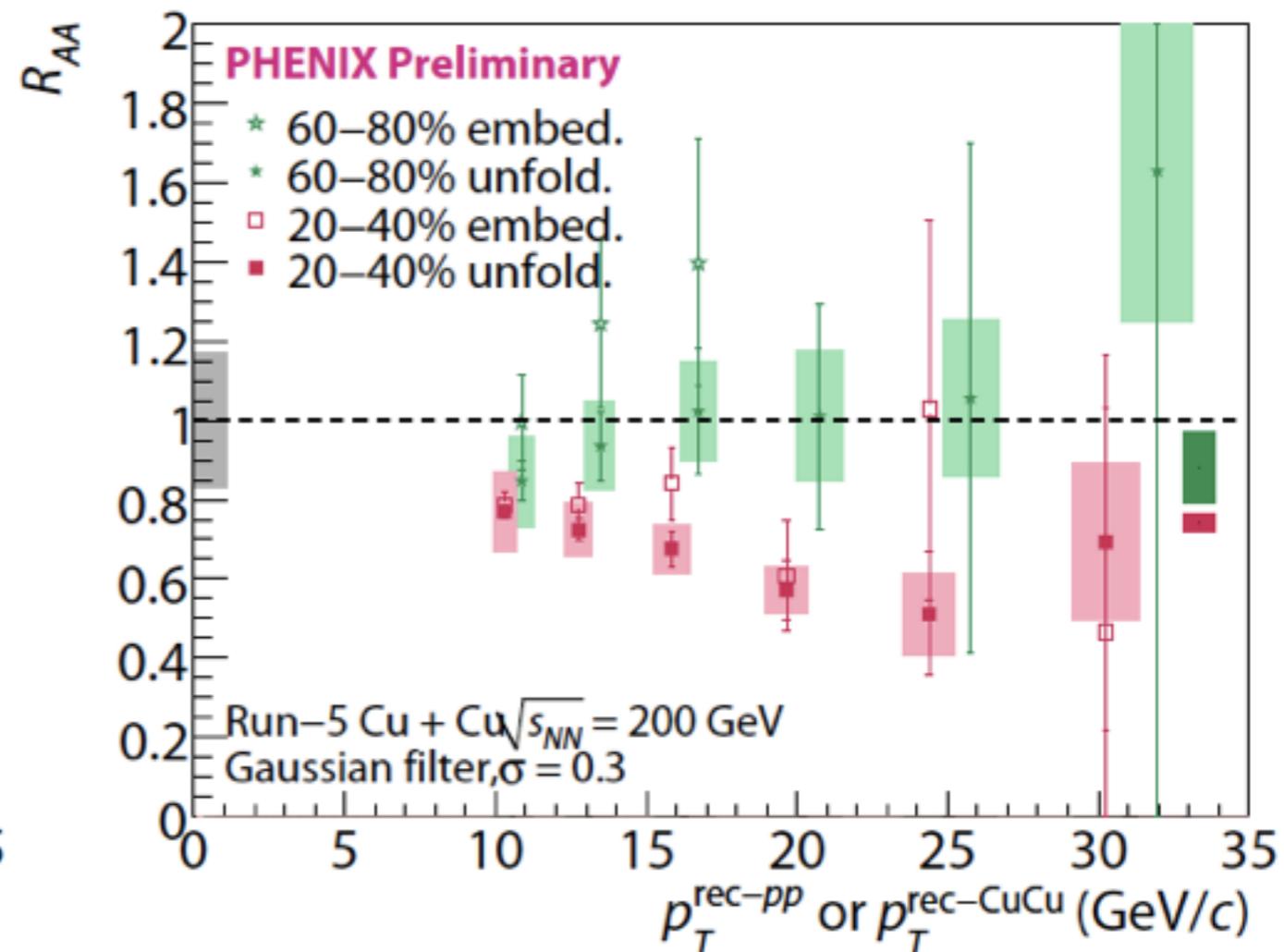
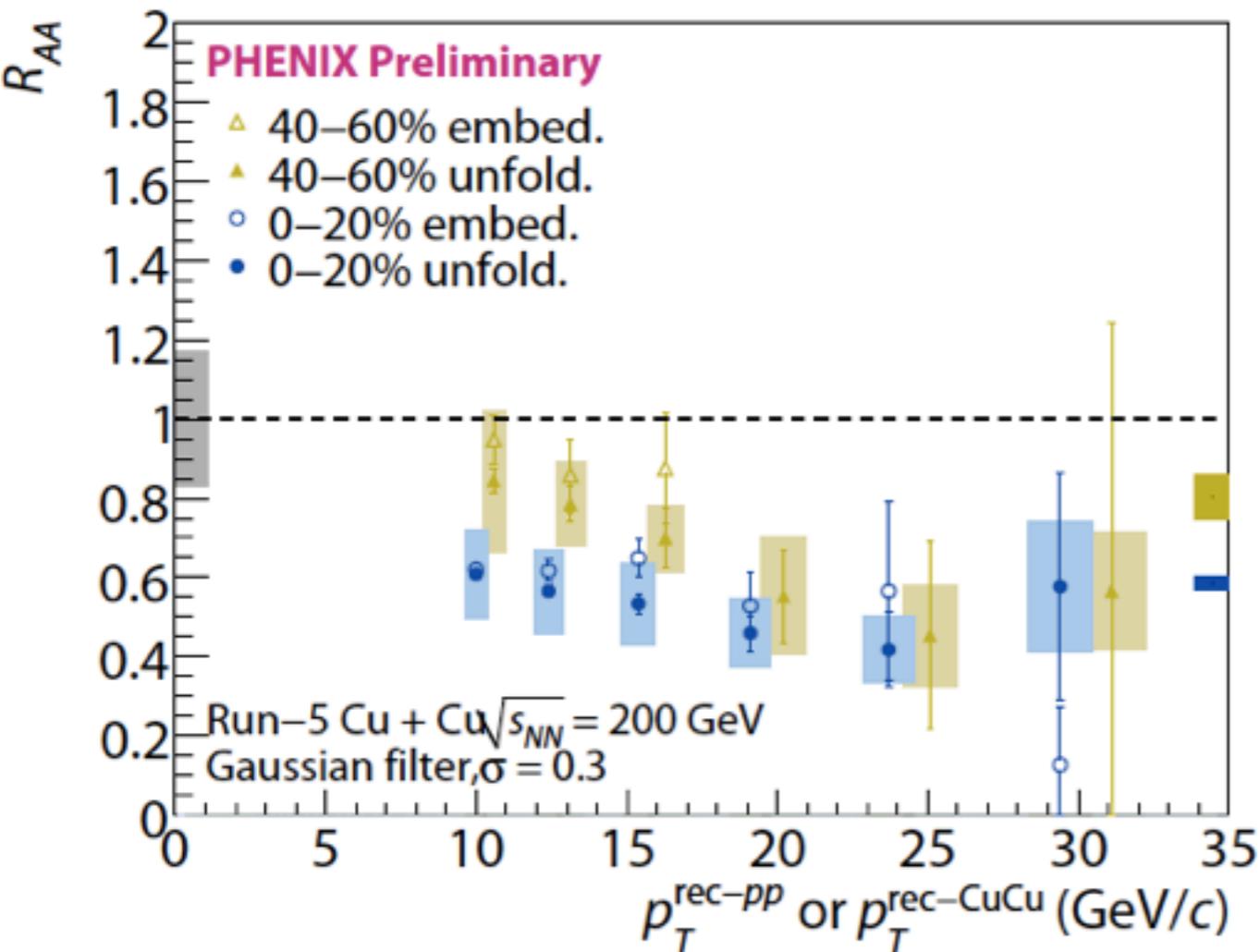
- Uncorrected $p+p$ jets scaled by T_{AB} compared to background-unfolded Cu+Cu
- Additional systematics from different acceptance between $p+p$ and Cu+Cu

Cu+Cu jet nuclear modification (R_{AA})



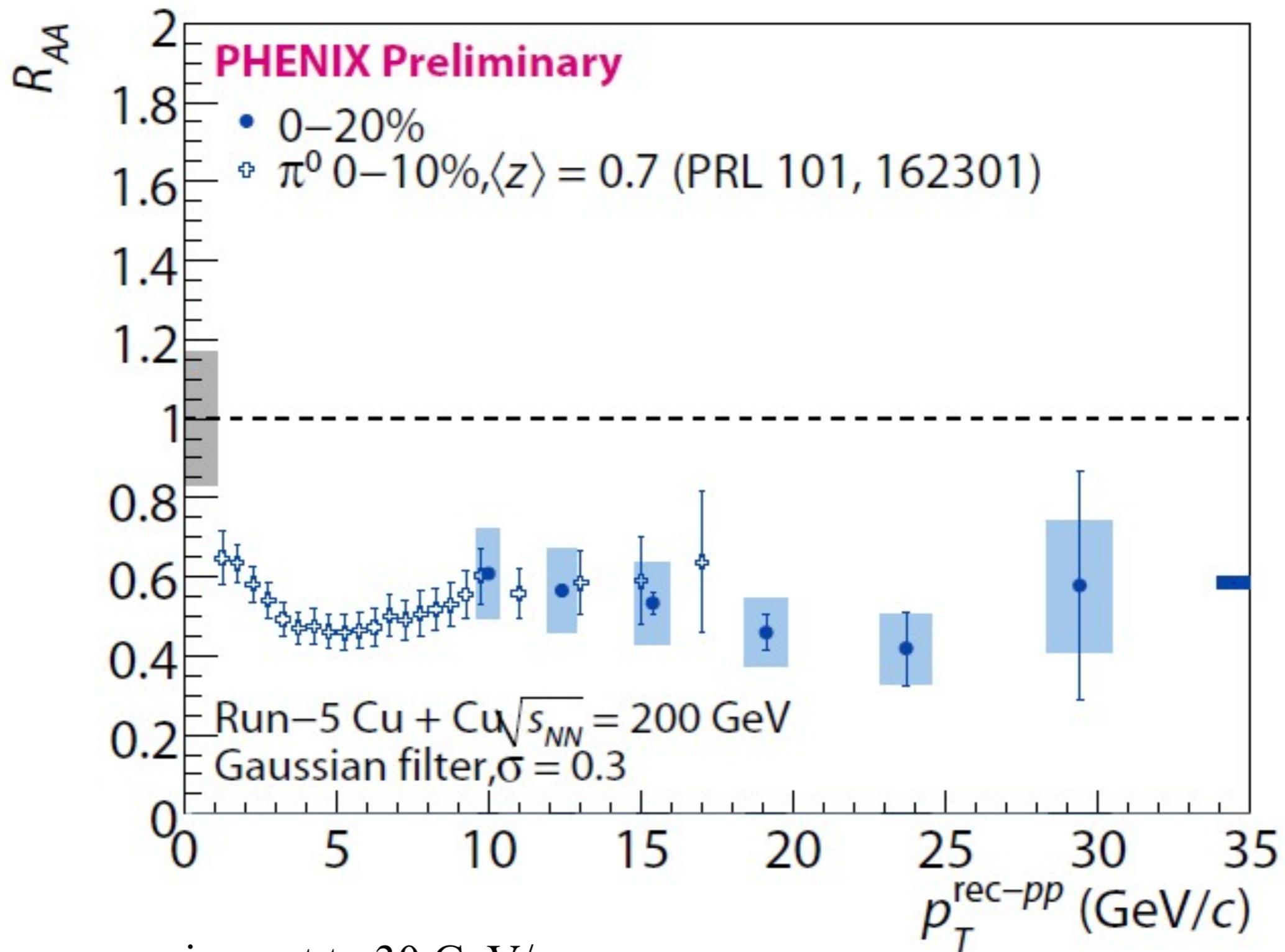
- Ratio of unfolded Cu+Cu jet spectrum to uncorrected scaled p+p jet spectrum
- Jet yield strongly suppressed in more central collisions

Cross check: embedding vs unfolding



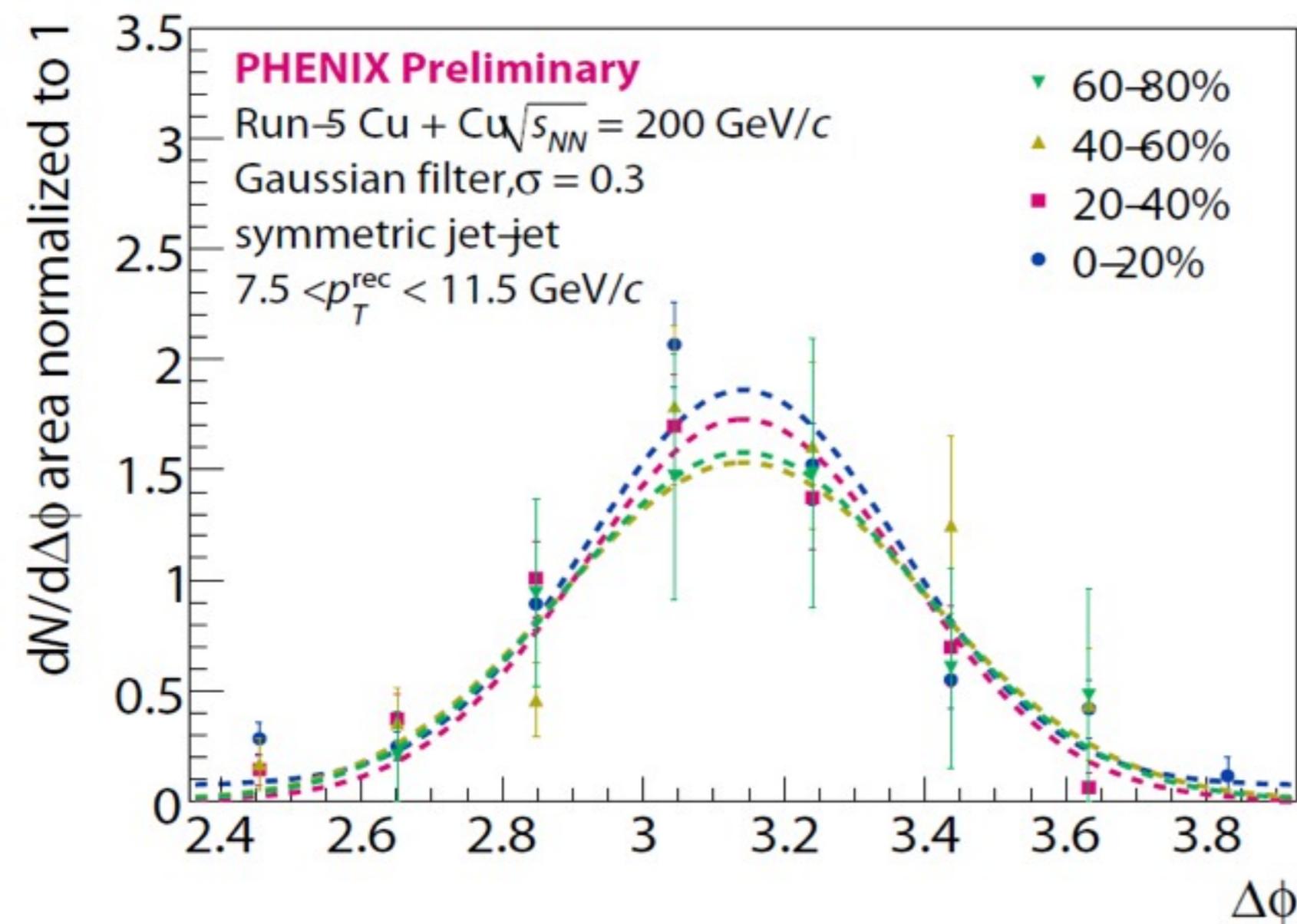
- Unfolded: uncorrected p+p compared to background-unfolded Cu+Cu
- Embedded: embedded p+p compared to uncorrected Cu+Cu
- Energies scales between the two do not match
 - roughly flat R_{AA} makes them comparable

Jet suppression vs single particles



- Similar suppression out to 30 GeV/c

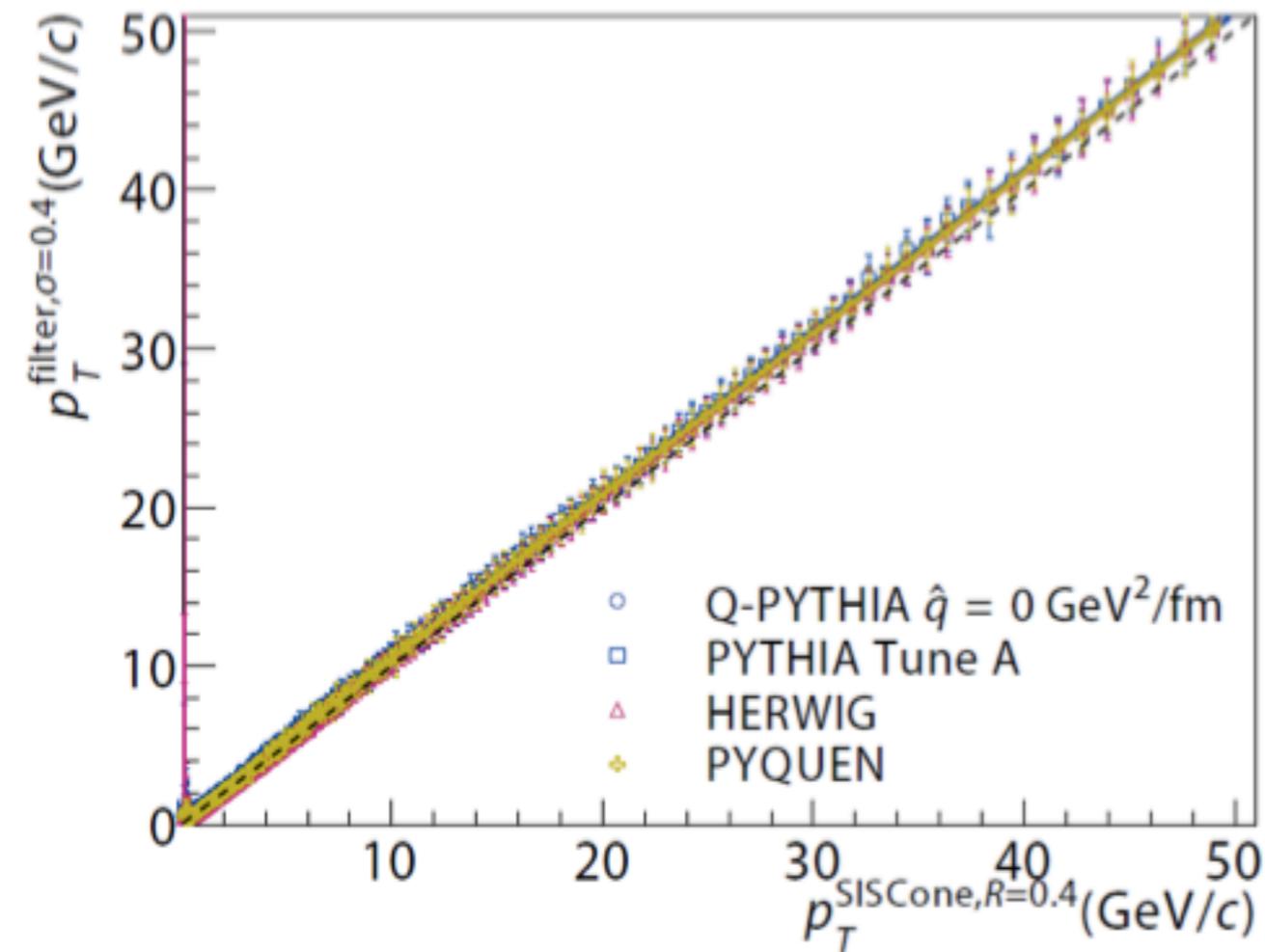
Jet-jet azimuthal correlations



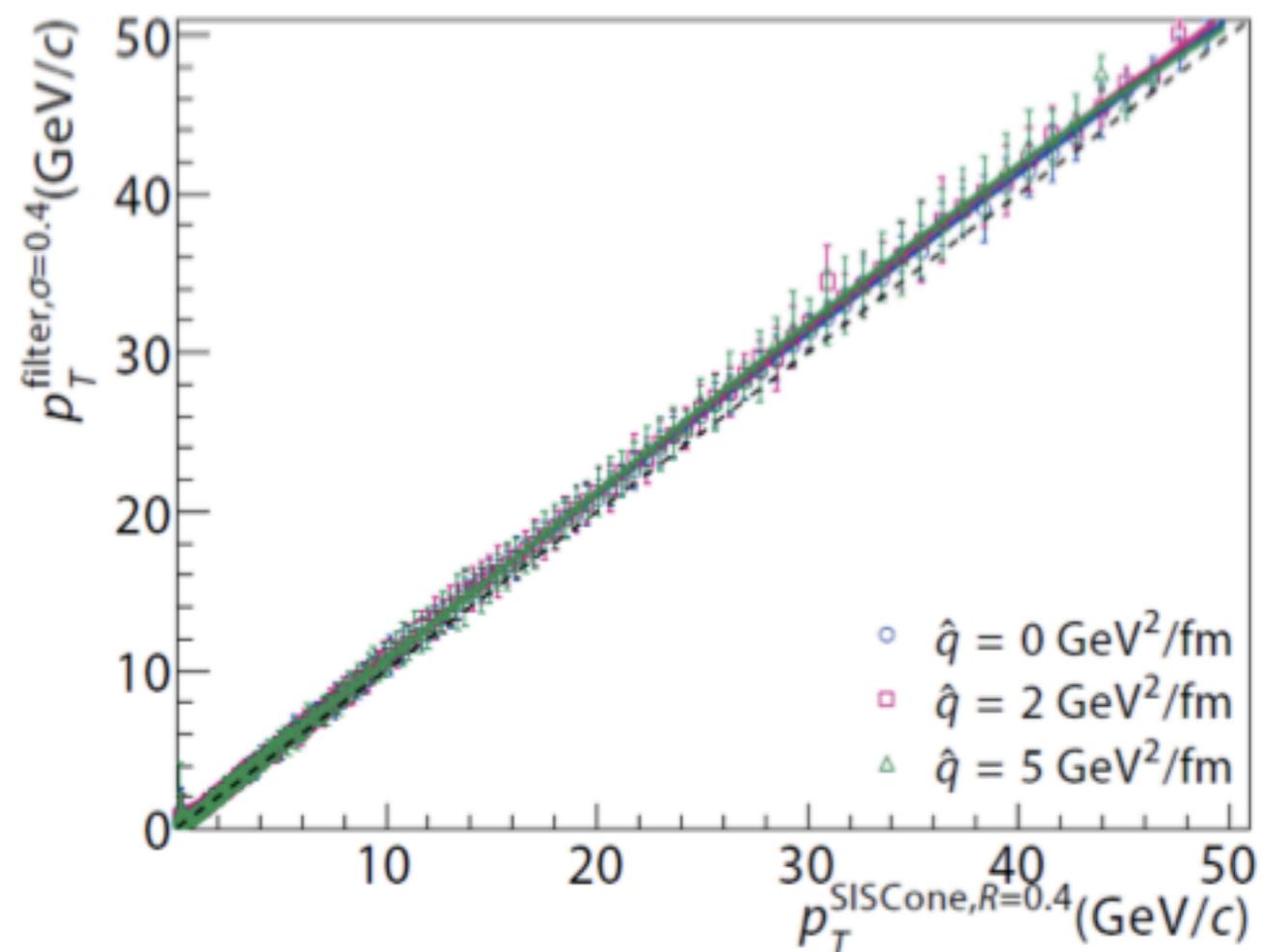
Centrality	$\Delta\phi \approx \pi$ width σ
0-20%	0.223 ± 0.017
20-40%	0.231 ± 0.016
40-60%	0.260 ± 0.059
60-80%	0.253 ± 0.055

- No significant broadening or shape modification observed within current sensitivity
 - limited acceptance \rightarrow large statistical uncertainty

Is there a bias in the algorithm?



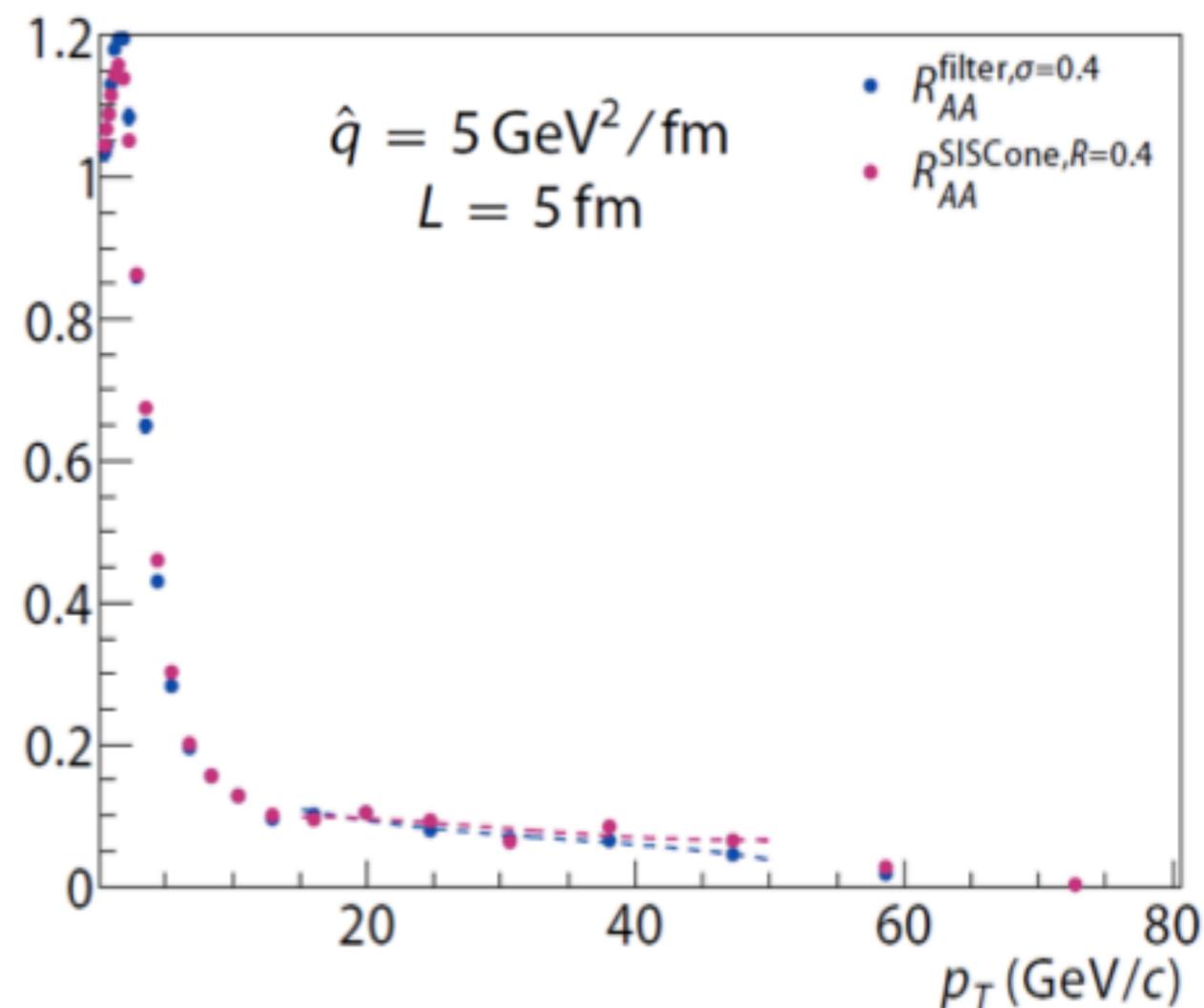
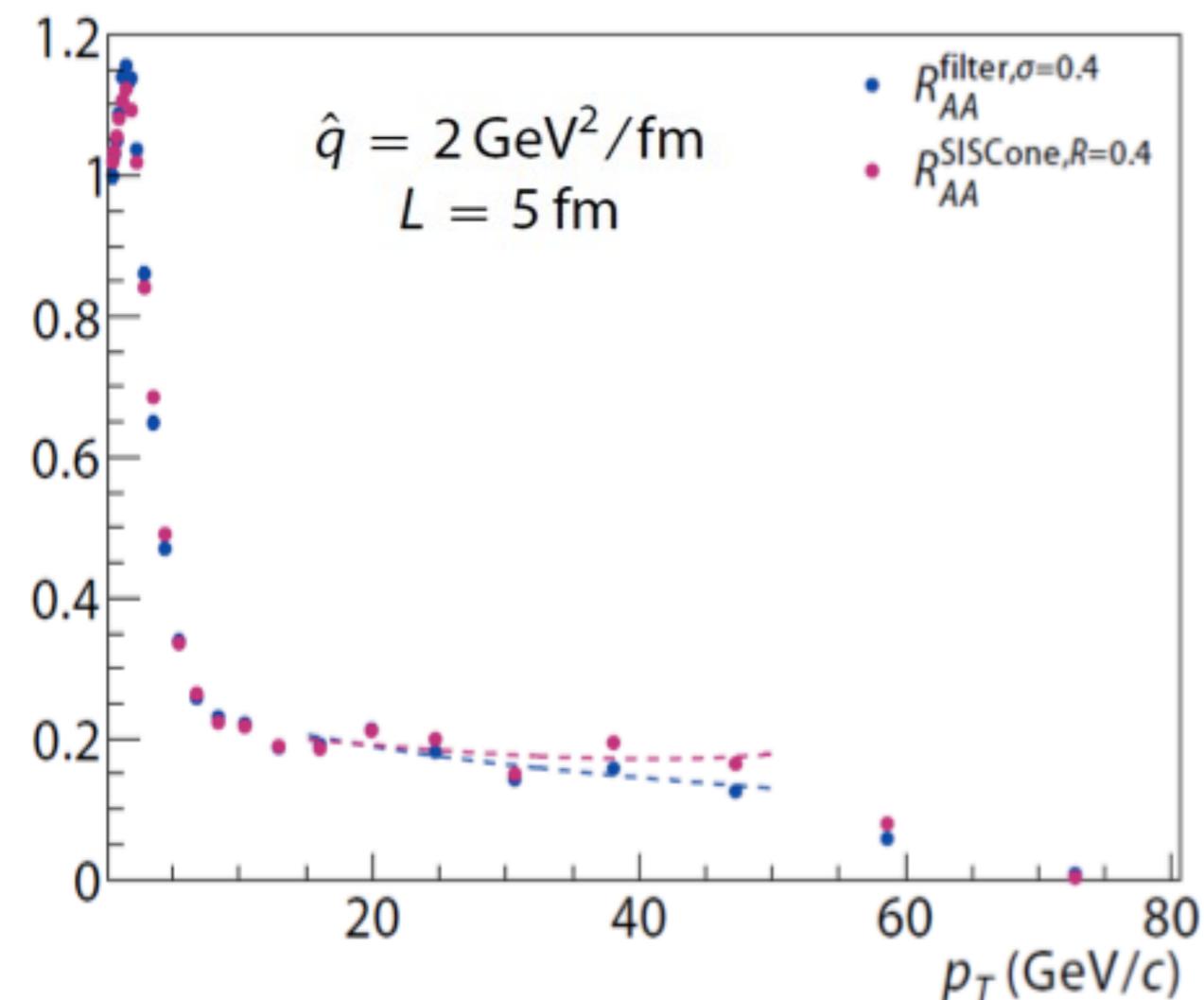
Default settings



Q-PYTHIA $L = 5$ fm

- Compare $\sigma = 0.4$ Gaussian filter to $R=0.4$ SIS Cone
- Very similar response to different quenching scenarios
- Any bias towards vacuum or quenched jets is well below current systematic uncertainties

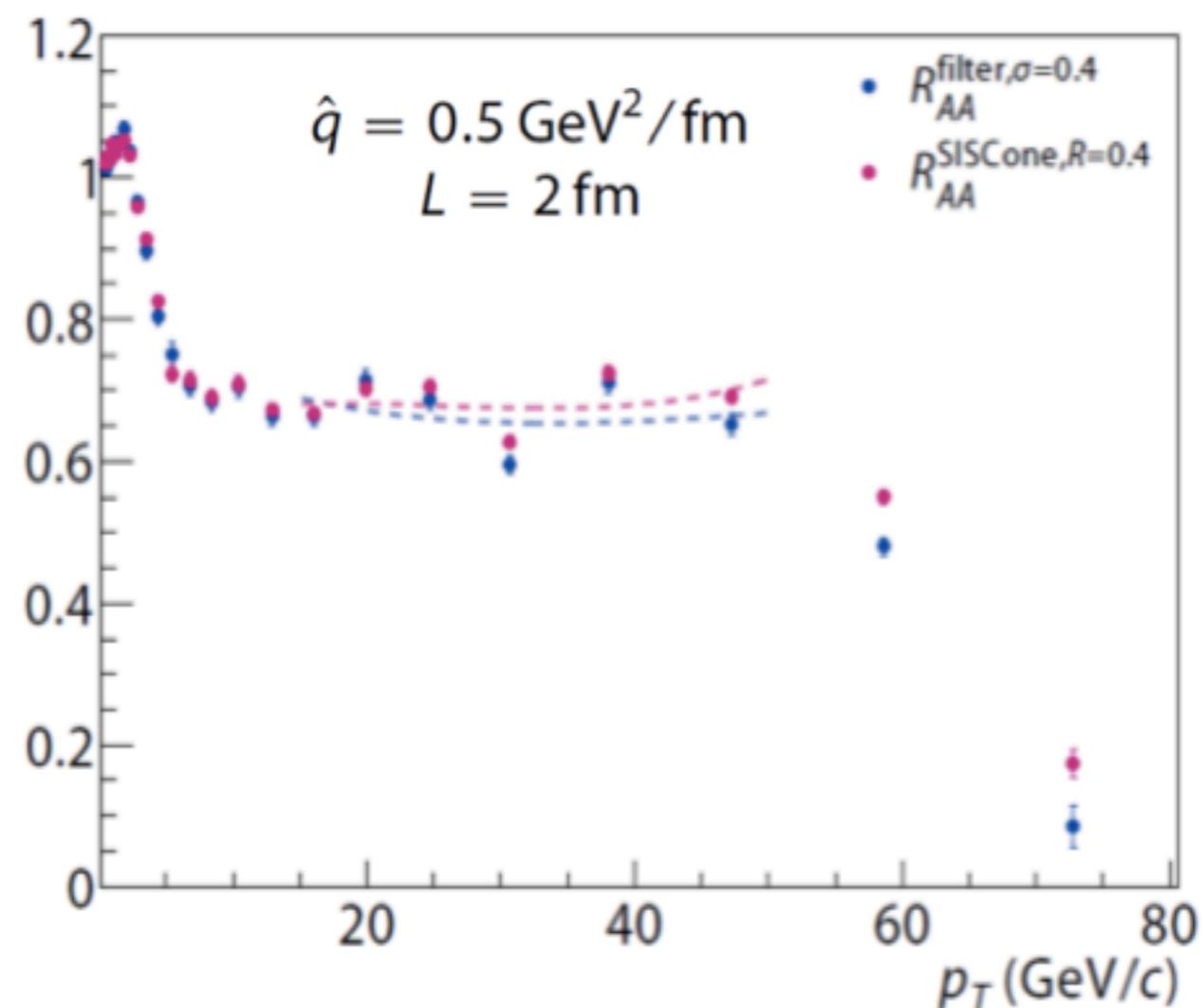
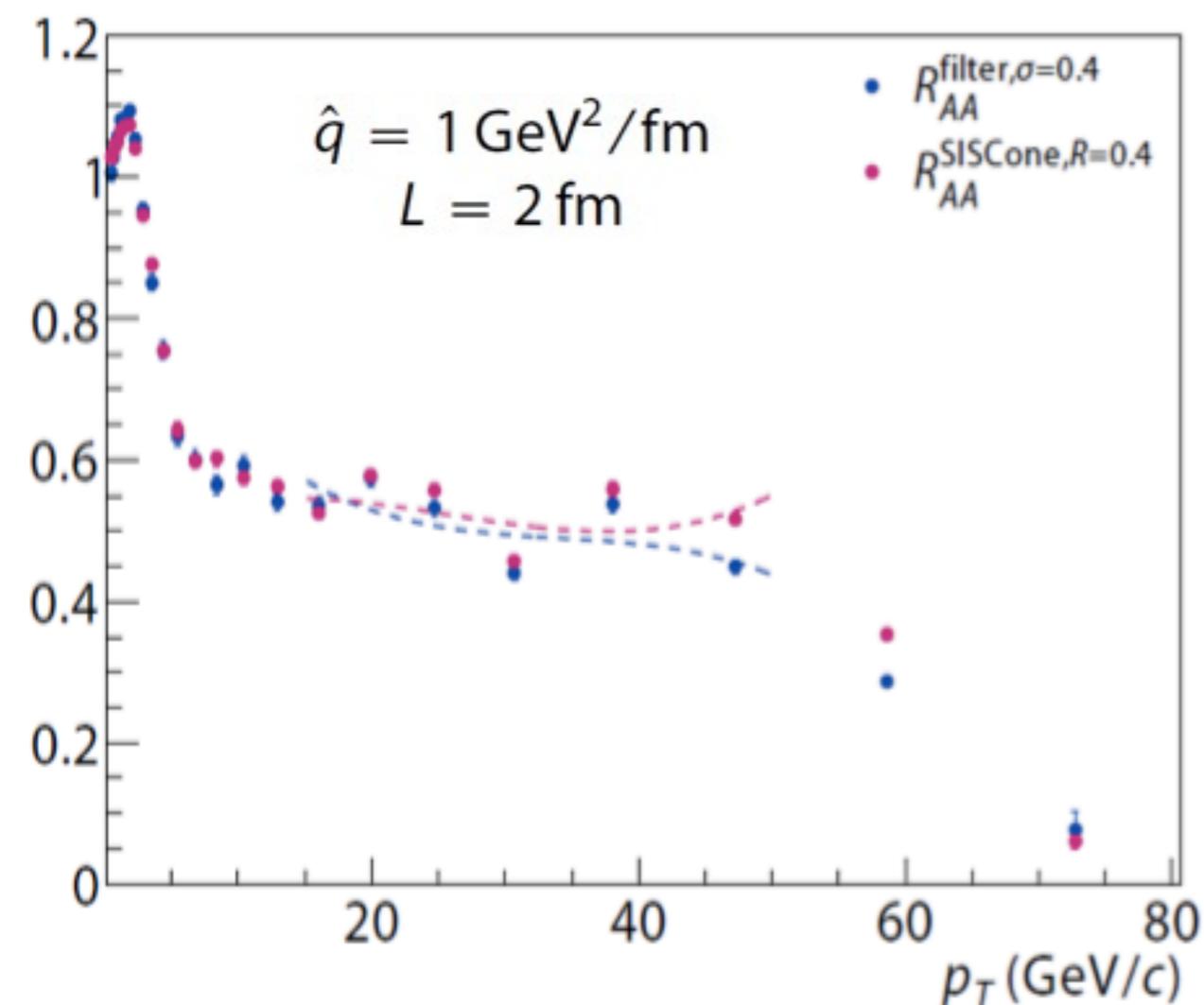
Is there a bias in R_{AA}



Strong quenching comparison

- Algorithm dependence of R_{AA} prediction from Q-PYTHIA is small
 - $\Delta R_{AA} \approx 0.05$
 - Only becomes significant beyond current p_T reach (30 GeV/c)
- Inaccessible with current detector limitations

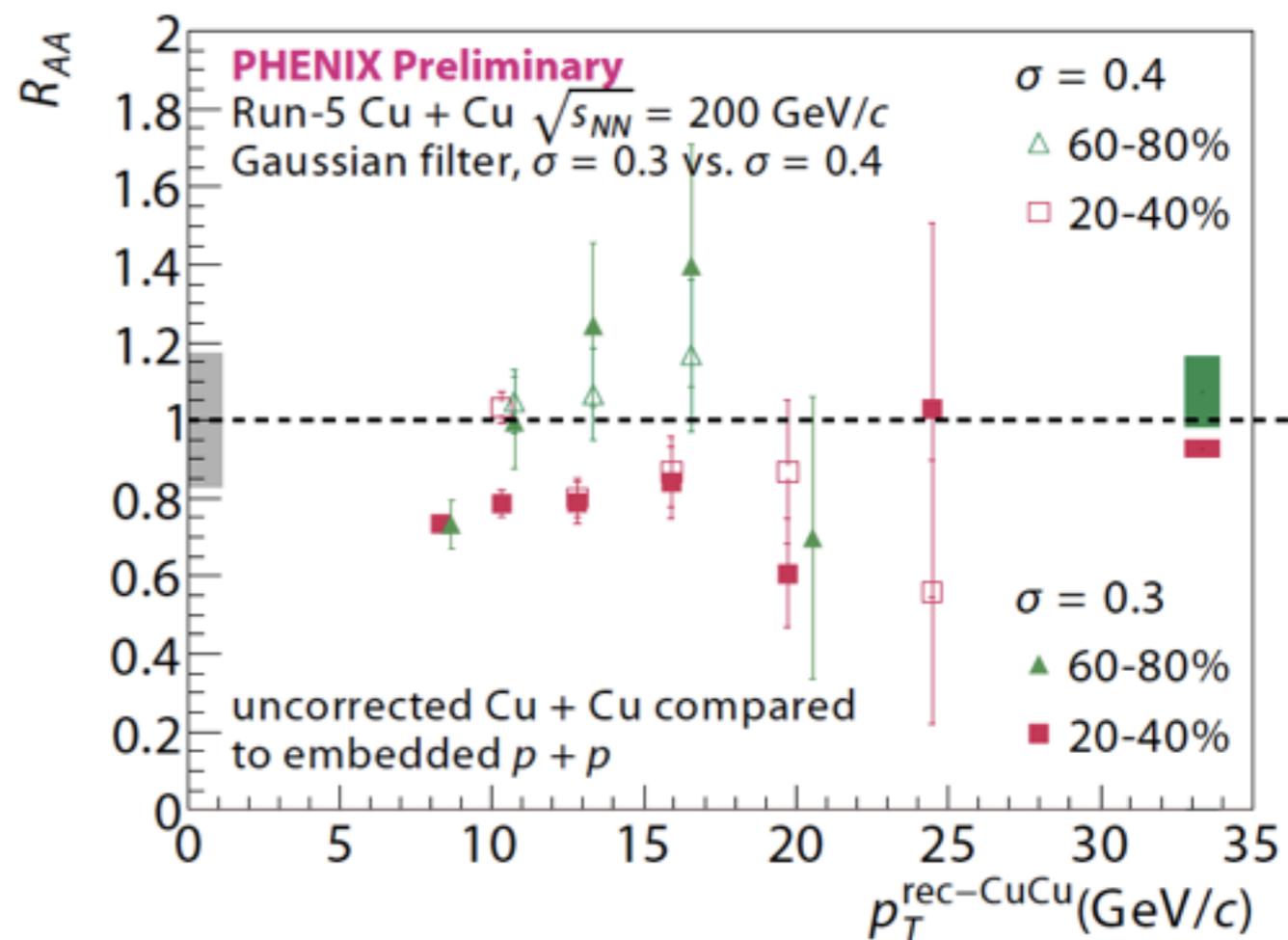
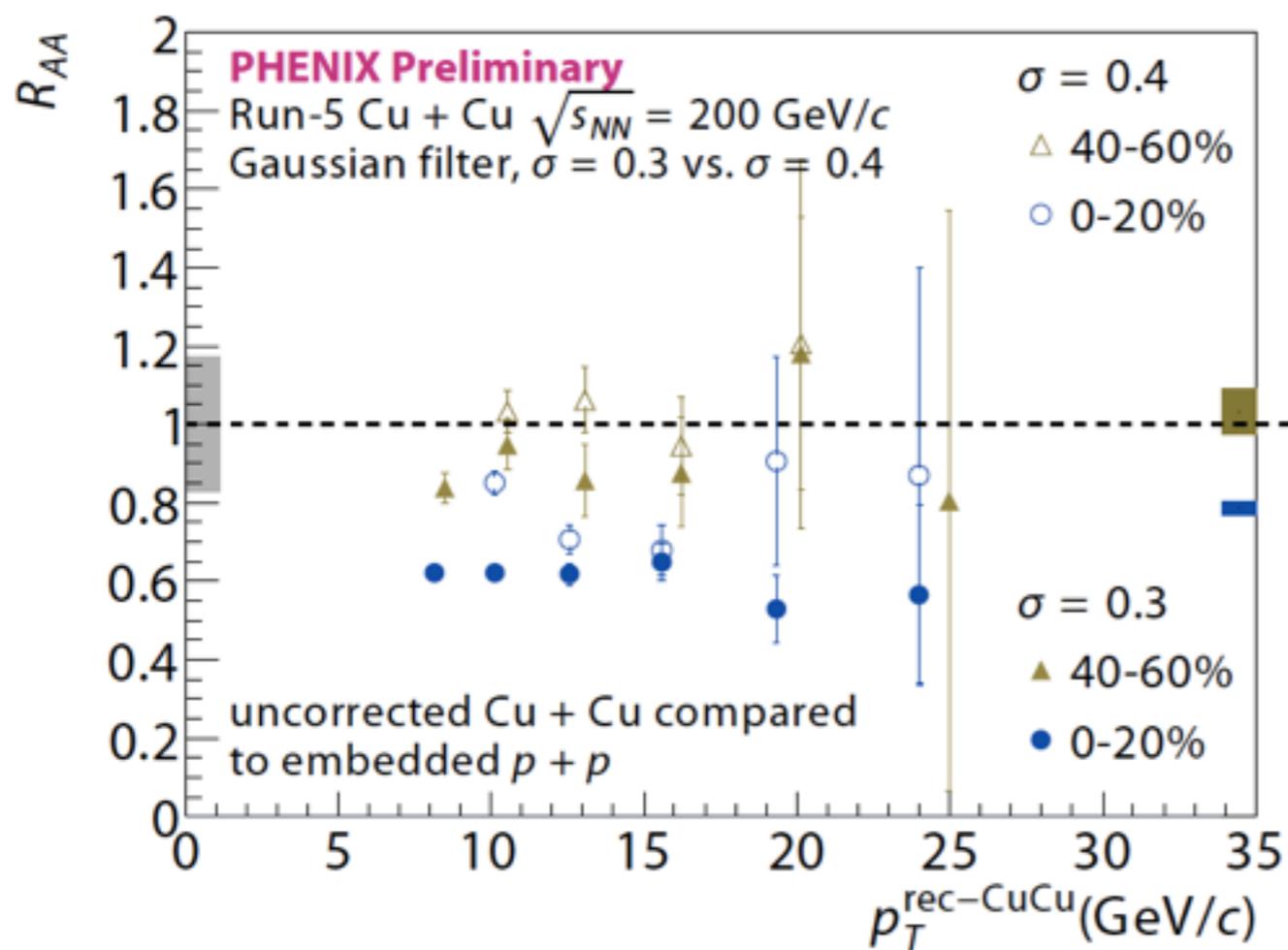
Is there a bias in R_{AA}



Weak quenching comparison

- Algorithm dependence of R_{AA} prediction from Q-PYTHIA is small
 - $\Delta R_{AA} \approx 0.05$
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- Inaccessible with current detector limitations

Modified jet shape?

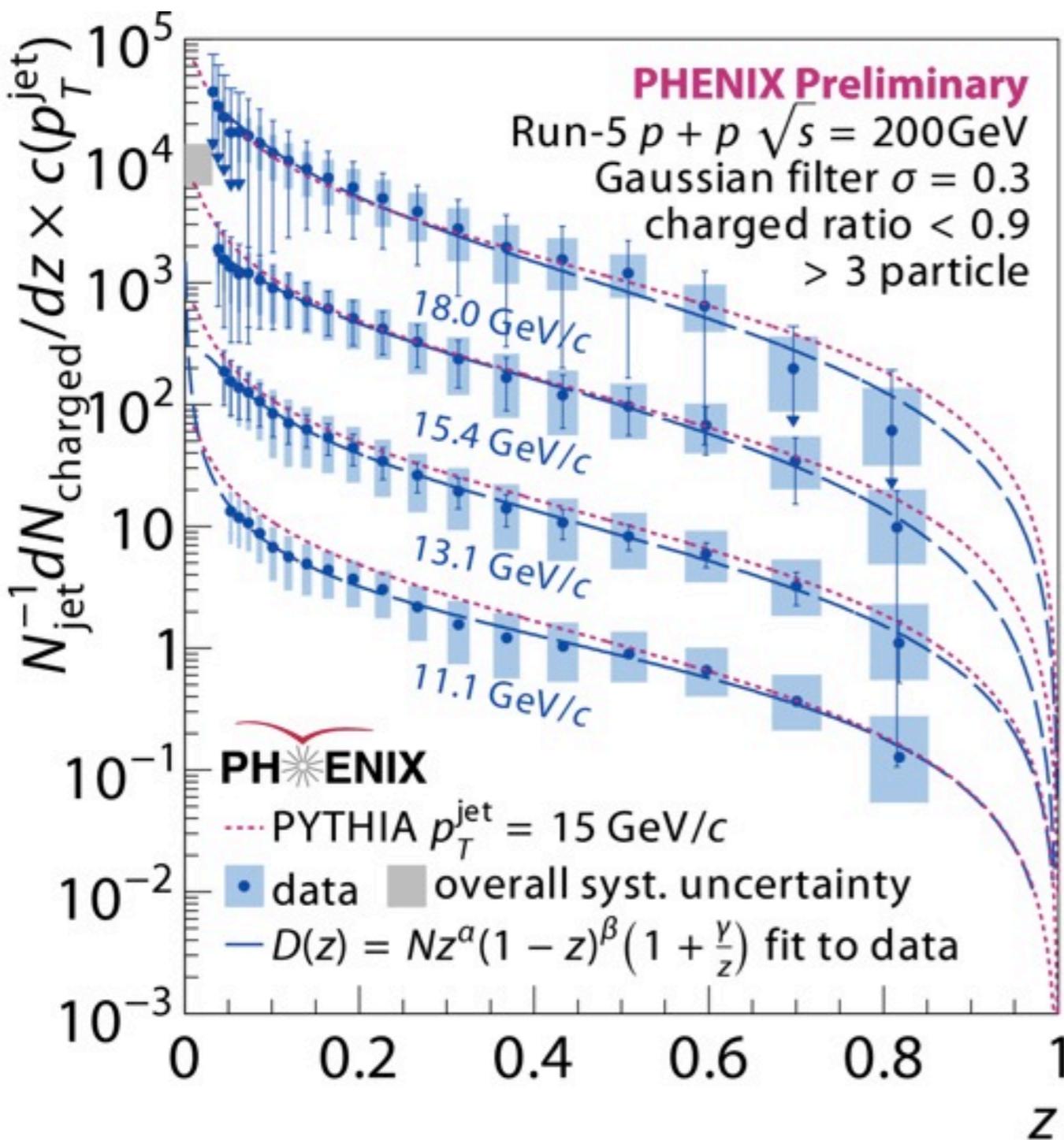


- Compare $\sigma = 0.3$ and $\sigma = 0.4$
 - If larger σ recovers jets with modified shape should see increase in R_{AA}
- Slight variation but with somewhat large uncertainties
 - low p_T variation in region with large fake jet rejection rate

Beyond inclusive jet spectra

- Jet fragmentation function: do jets fragment within the medium?
- establish p+p baseline first: non-trivial
 - $z = p^{\text{particle}}/p^{\text{jet}}$
 - p^{jet} must be true jet energy to make unbiased comparisons (no z-shift)
- 2D unfolding needed
 - need true energy scale for both p^{particle} and p^{jet}
 - not been done before: required modification to current available unfolding framework
- Unfold p+p to true jet energy from PYTHIA
 - direct comparison out to 15GeV/c
- Particle species:
 - non-identified charged tracks
 - neutral EM clusters
- Single particle resolution not unfolded (small effect)

p+p fragmentation function

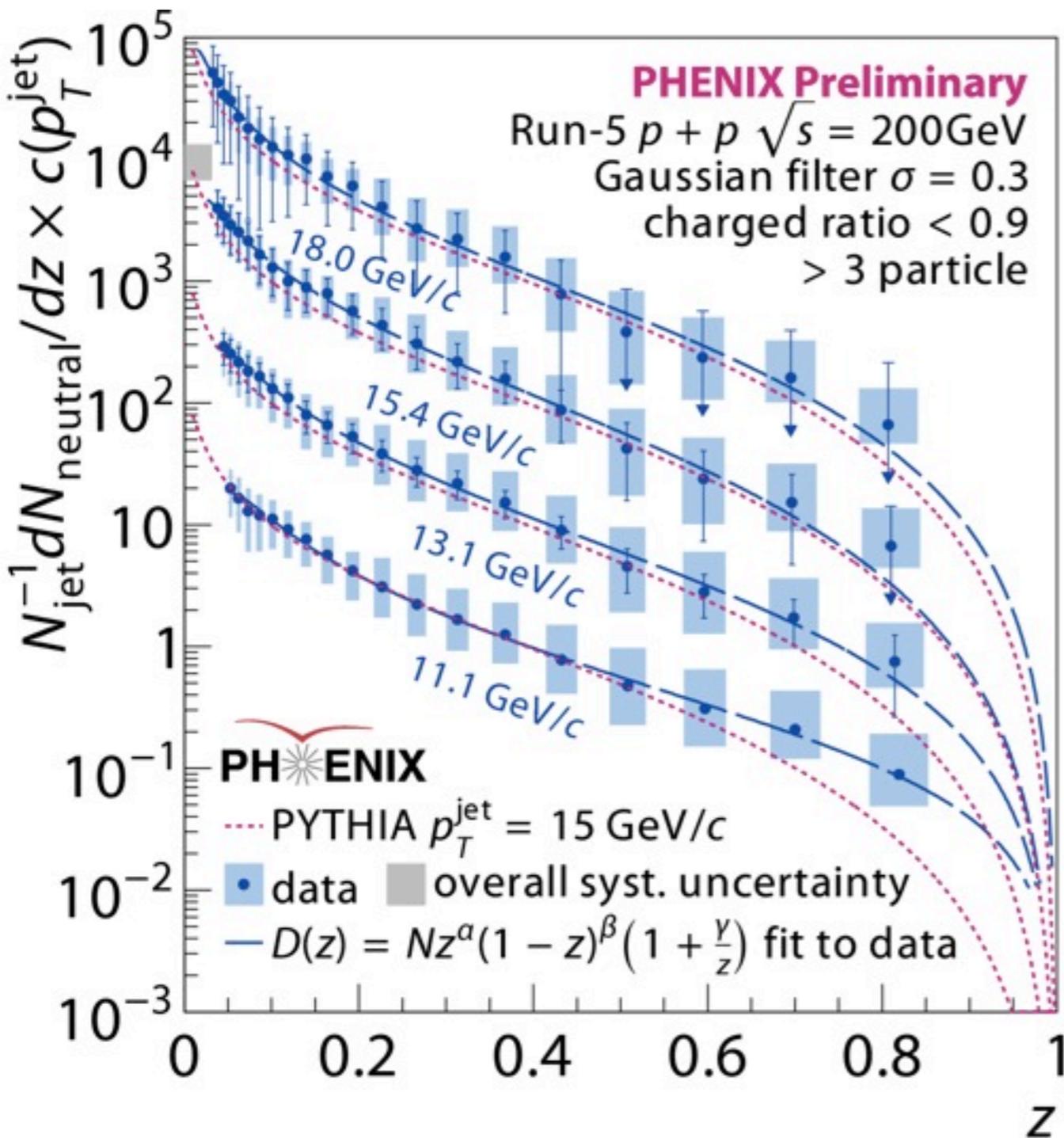


- Charged particles

$$z = p_{\parallel}^{\text{particle}} / p^{\text{jet}}$$

- Cuts on jets to remove contamination from conversions, calorimeter noise, or high p_T particle decays
 - # of particles > 3
 - charge fraction < 0.9
 - $z < 0.81$
- Jet selection bias fully contained in systematics quoted
- Consistent with PYTHIA FF scaling

p+p fragmentation function



- Neutral particles

$$z = p_{\parallel}^{\text{particle}} / p^{\text{jet}}$$

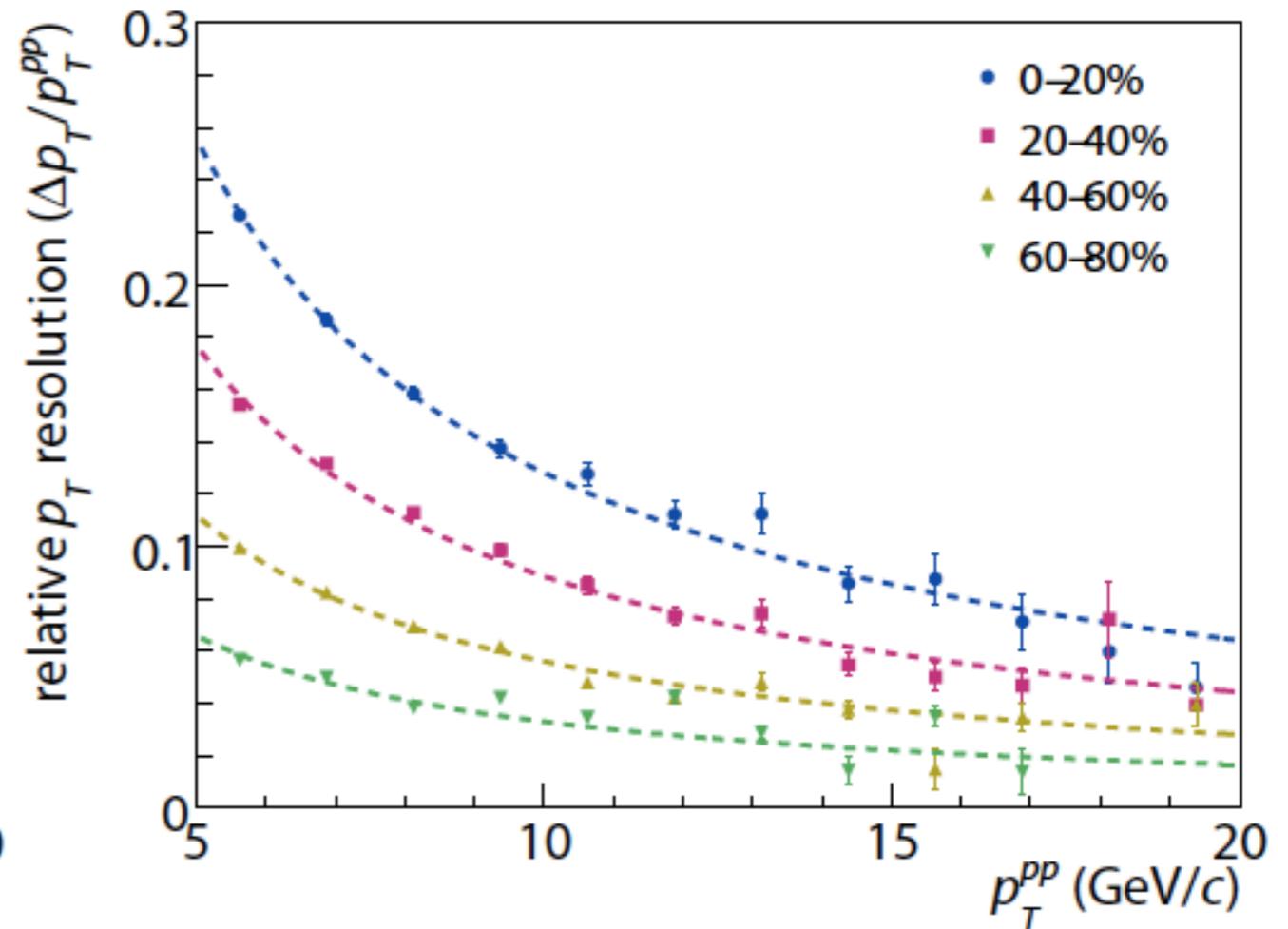
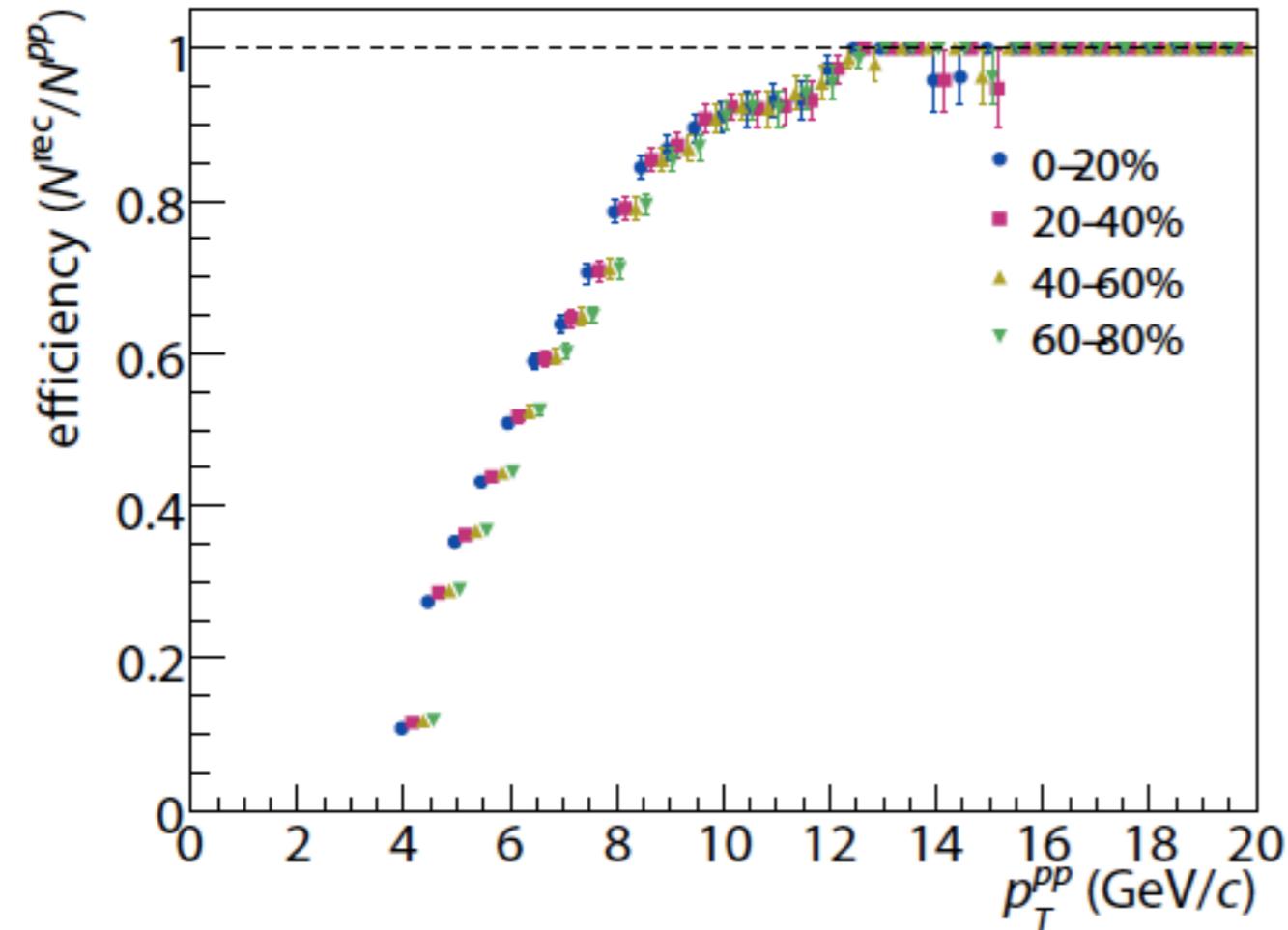
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- Jet selection bias fully contained in systematics quoted
- Consistent with PYTHIA FF scaling

Summary and outlook

- Gaussian filter with Gaussian fake rejection shown to be a highly effective algorithm for jet reconstruction at RHIC energies in the high multiplicity environment of heavy-ion collisions
 - large p_T range, high efficiency, minimal fake jet contamination
- Observe a strong jet suppression relatively constant out to ~ 30 GeV/c
- See no significant broadening seen in jet-jet azimuthal correlations
- Have first measurement of p+p jet inclusive fragmentation function up to $z \approx 0.8$
 - well established framework for extracting comparable fragmentation function in heavy-ion collisions
- To come: fragmentation function in Cu+Cu
 - comparison with p+p will help to further constrain models of medium modification to partons
- Future upgrades aim to establish PHENIX as a dedicated jet detector

Backup Slides

Reconstruction efficiency in HI



- Estimate using embedding
 - p+p jets in Cu+Cu events
- Goes to 1 at low jet p_T
- Negligible centrality dependence
- Includes fake rejection effects