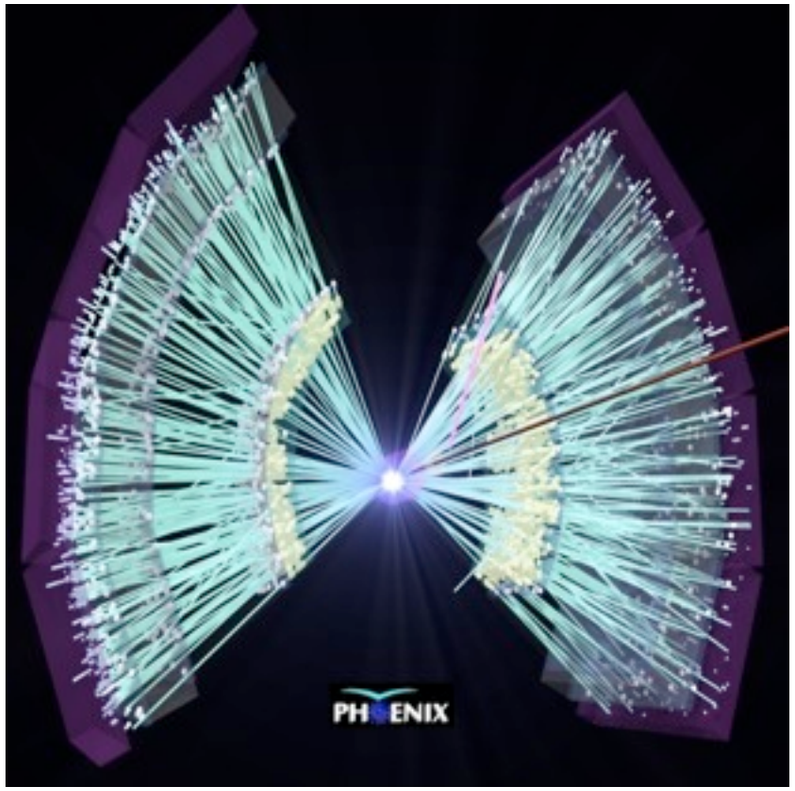
Full Jet Reconstruction in p+p and Heavy-ion Collisions with PHENIX



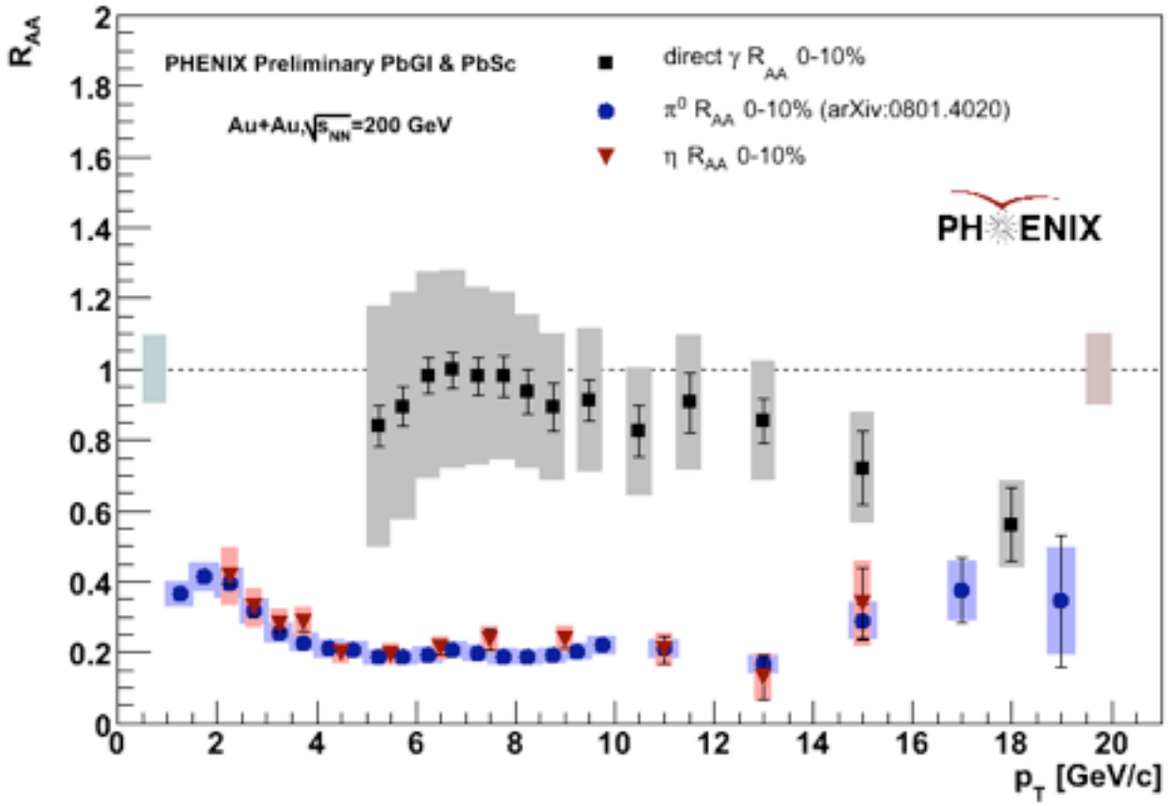
XIX International Workshop on Deep-Inelastic Scattering and Related Subjects

- Ali Hanks

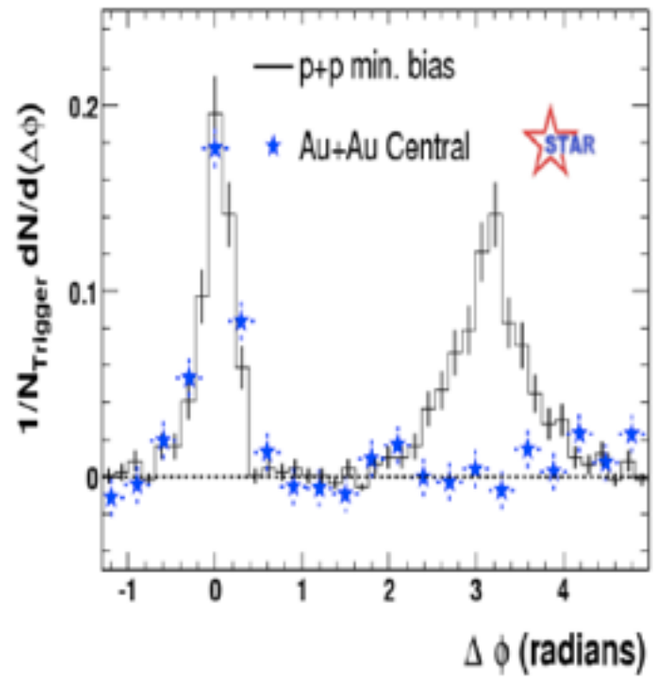
April 12th, 2011

COLUMBIA UNIVERSITY
IN THE CITY OF NEW YORK

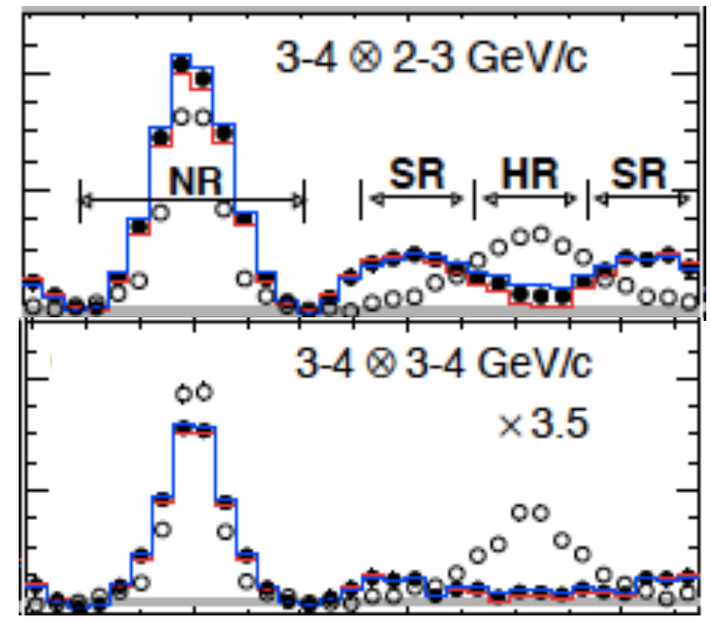
Jet quenching in the QGP



STAR PRL91, 072304 (2003)

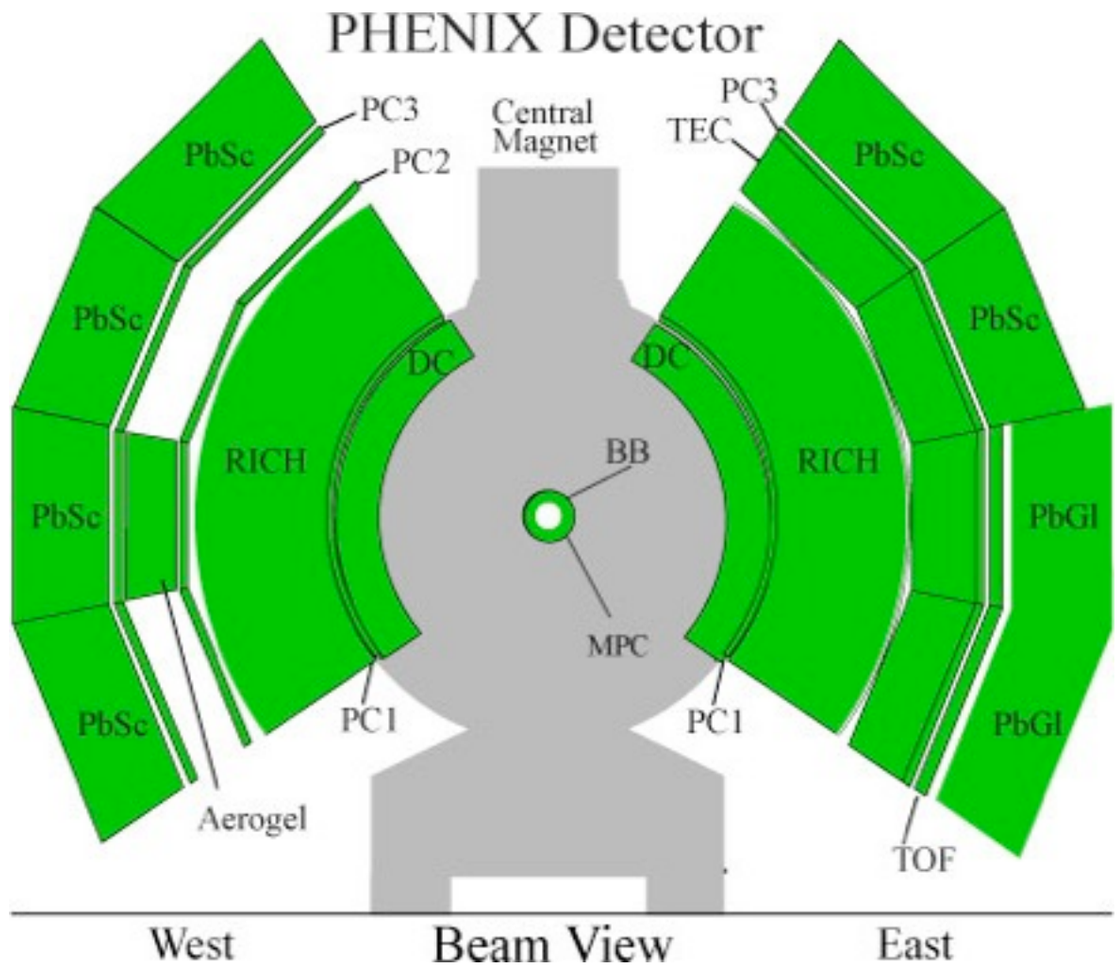


PHENIX PRC78, 014901 (2008)



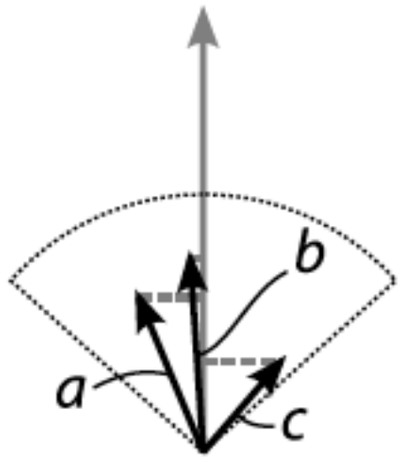
- Single hadrons: strong suppression for wide range of p_T
  - indirect measure of energy loss of initial parton
- Two particle correlations: disappearing away-side
  - modified away-side indication of modified fragmentation or is it all flow?
- Both difficult to model theoretically and indirect measure 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 → no energy double counting

Gaussian filter algorithm



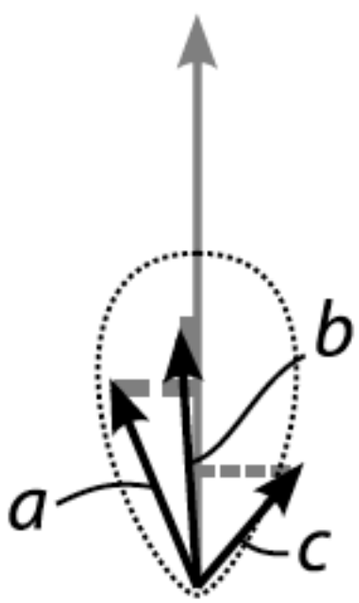
Cone

- 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

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



Filter

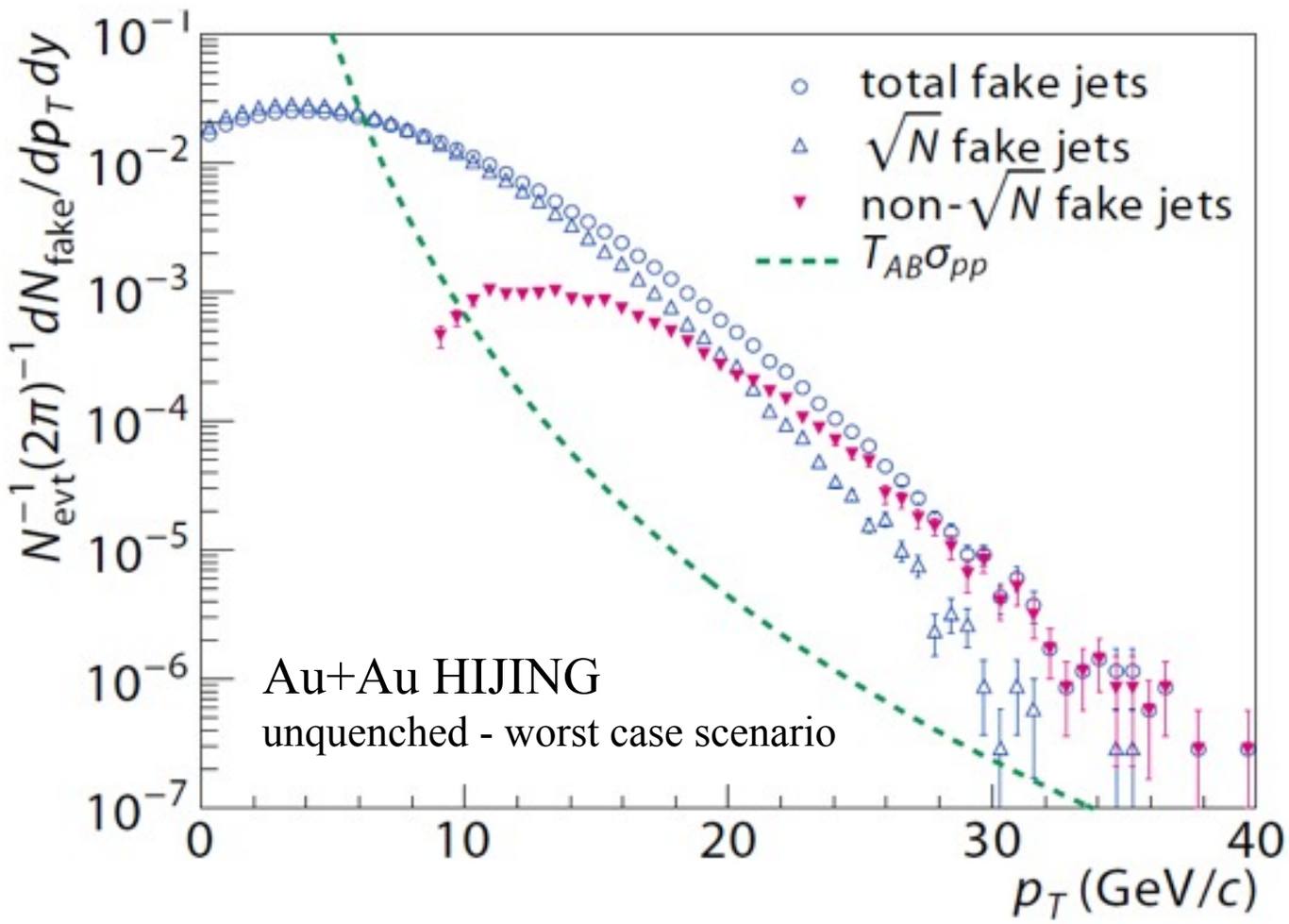
- Local maxima correspond to reconstructed jets
- Similar to seedless cone algorithm BUT
- No hard angular cut-off
  - naturally infrared and collinear safe
- Gaussian shape:
  - focuses on core of jet: optimizes signal to background and stabilizes jet axis in large background environment
  - reduces 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

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

- Fluctuations give rise to substantial fake jet contamination
  - non-trivial correction: not simply √N fluctuations



Fake jet rejection

- Several approaches available:
  - Reconstruct only very high pT jets
    - fake jets become negligible in Cu+Cu above ~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

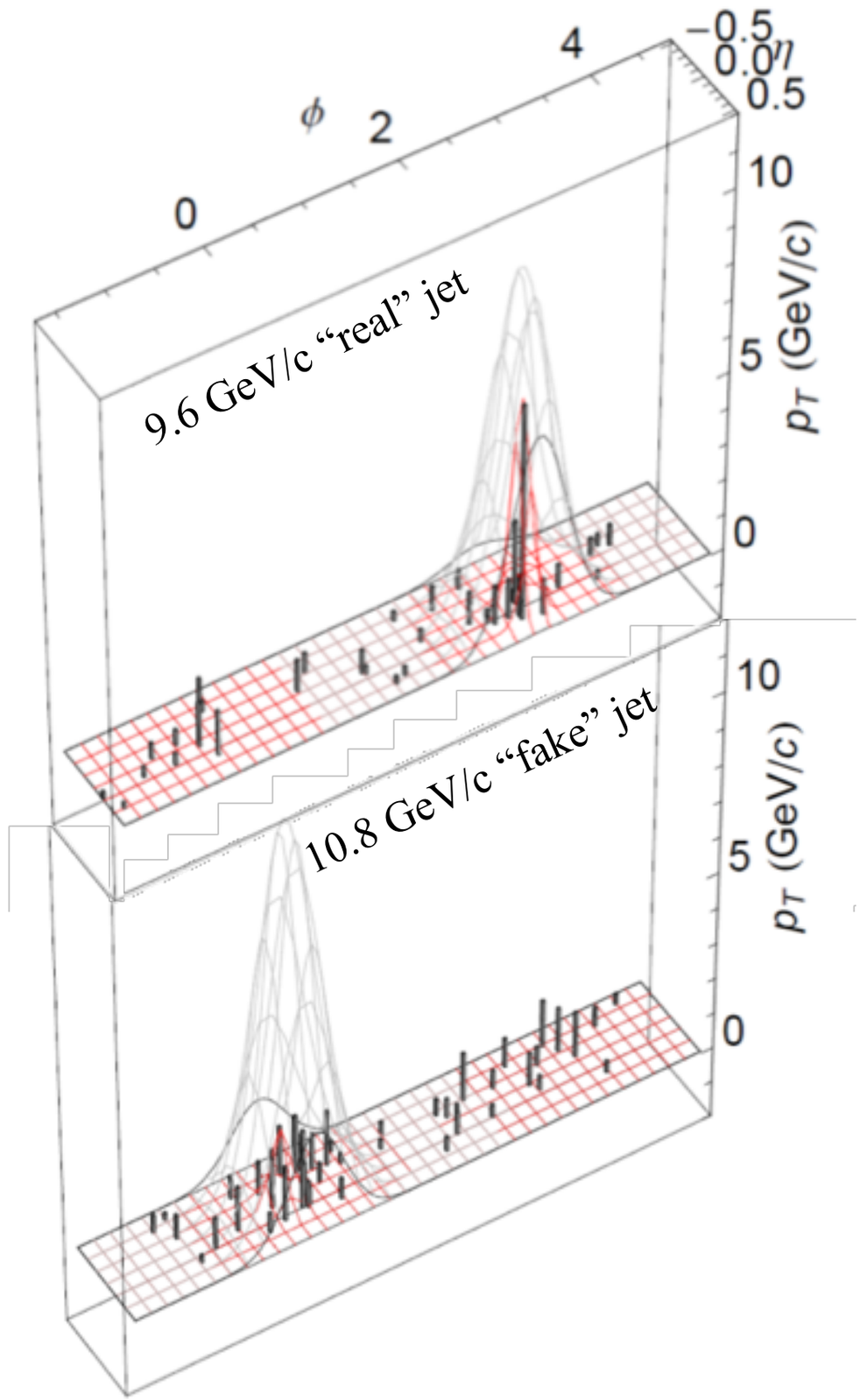
Fake jet rejection

- 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:

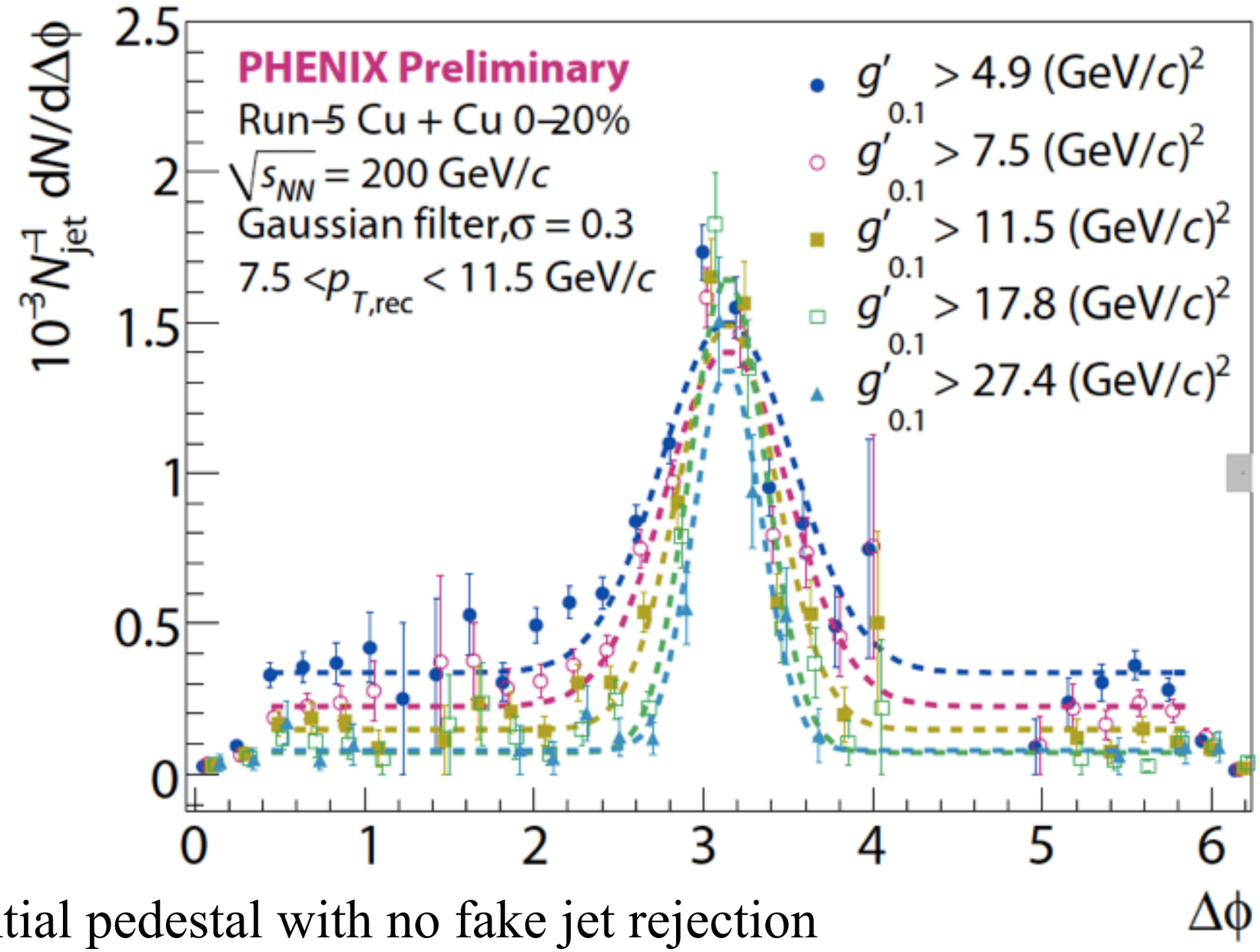
$$g_{\sigma_{\rm dis}}(\eta,\varphi) = \sum_{i\in\text{fragment}} p_{T,i}^2 \exp\left[-\frac{(\eta_i-\eta)^2+(\varphi_i-\varphi)^2}{2\sigma_{\rm dis}^2}\right]$$

  - narrow width of $\sigma_{\rm dis} \approx 0.1$
  - 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

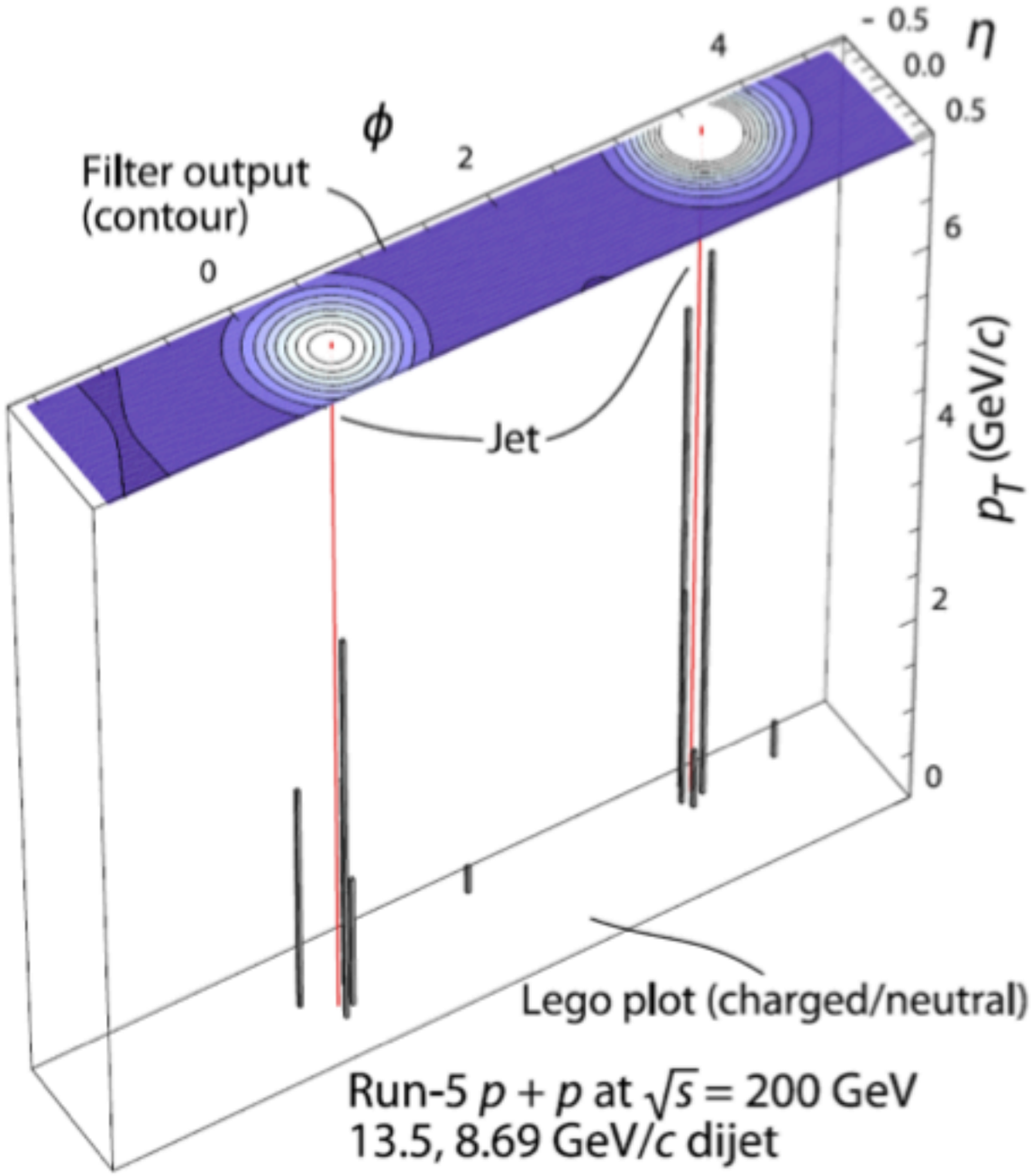


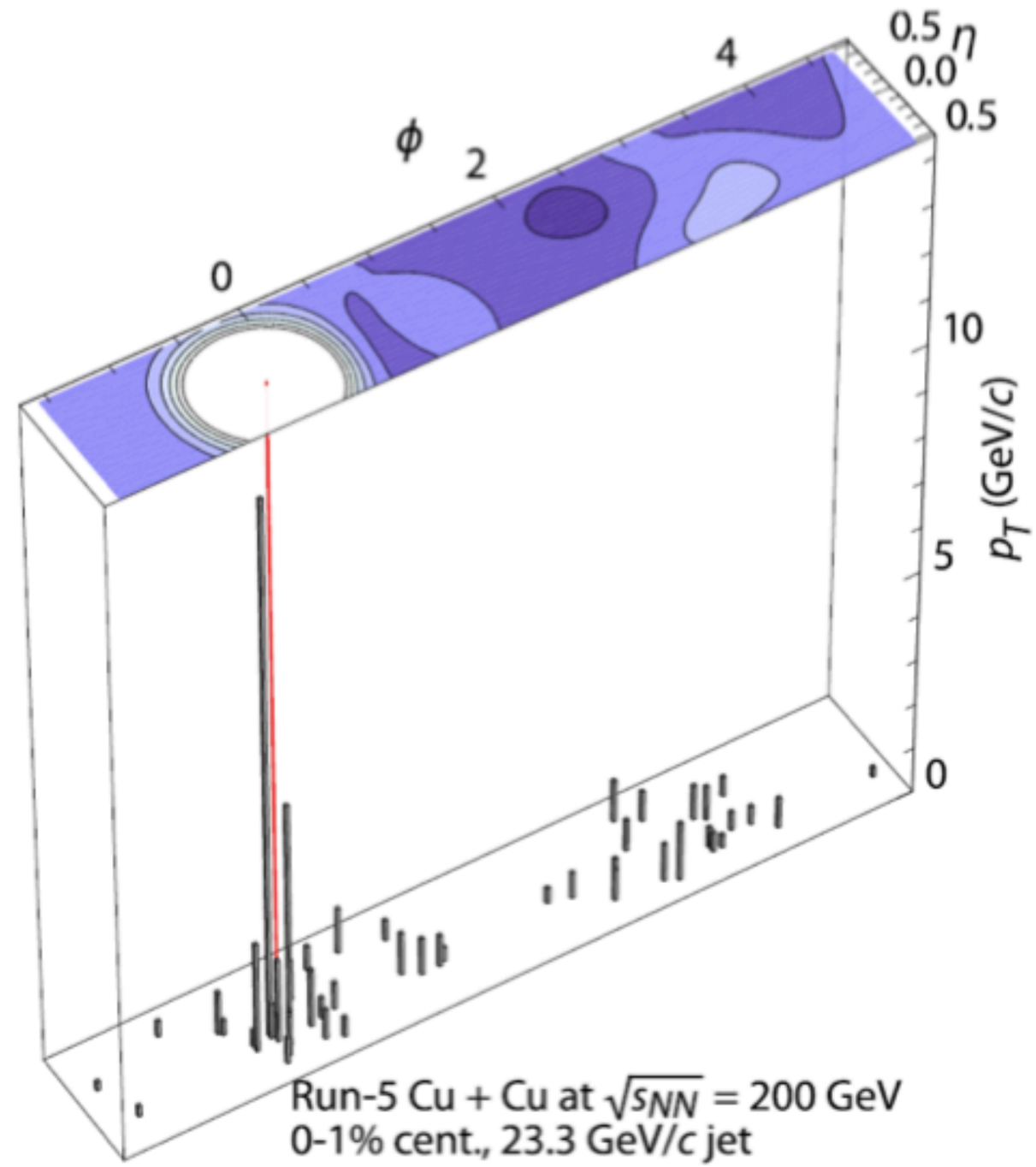
Fake jet rejection



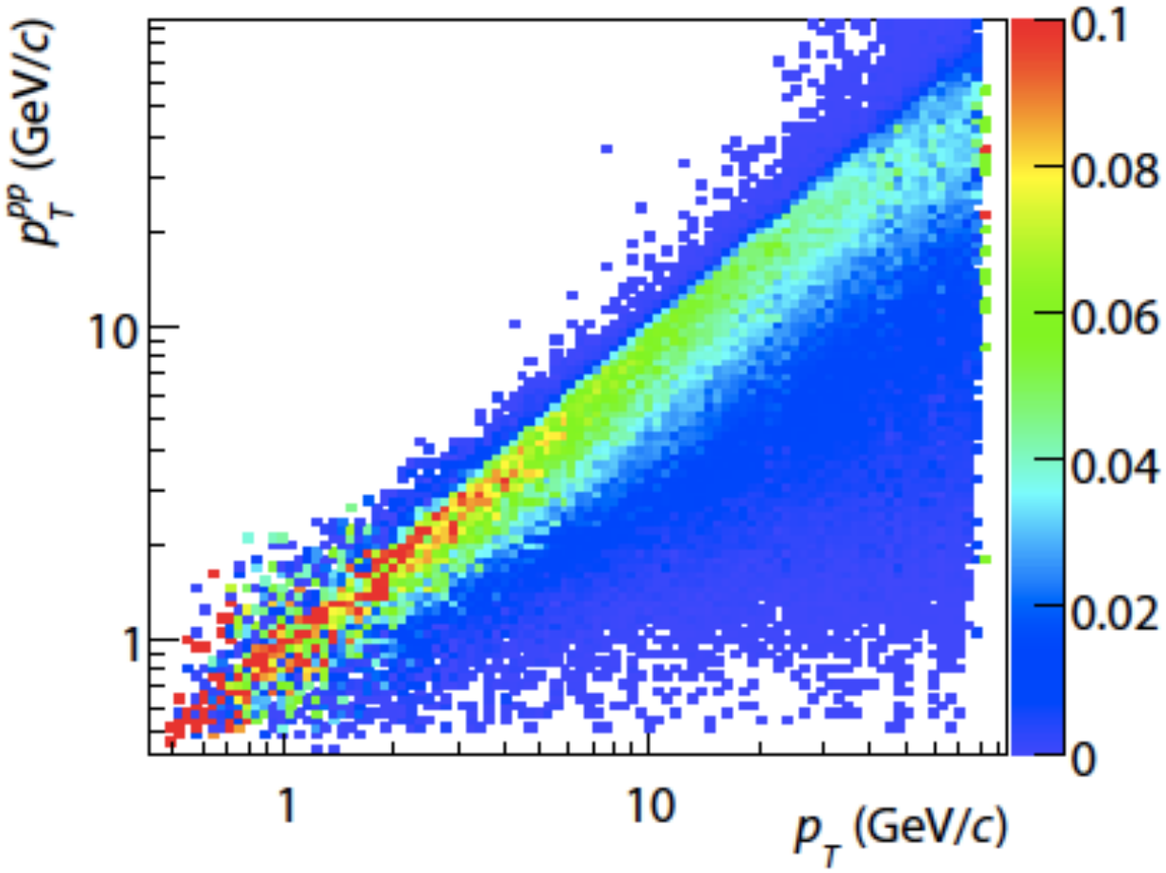
- See substantial pedestal with no fake jet rejection
- Above $g_{0.1}$ ~ 17.8 (GeV/c)^2 pedestal is stable - chosen as standard fake jet cut level
  - < 10% contamination at 7.5 GeV/c
- No rejection needed above ~15GeV/c (cut already < 10% effect and ↓ as p_T ↑)

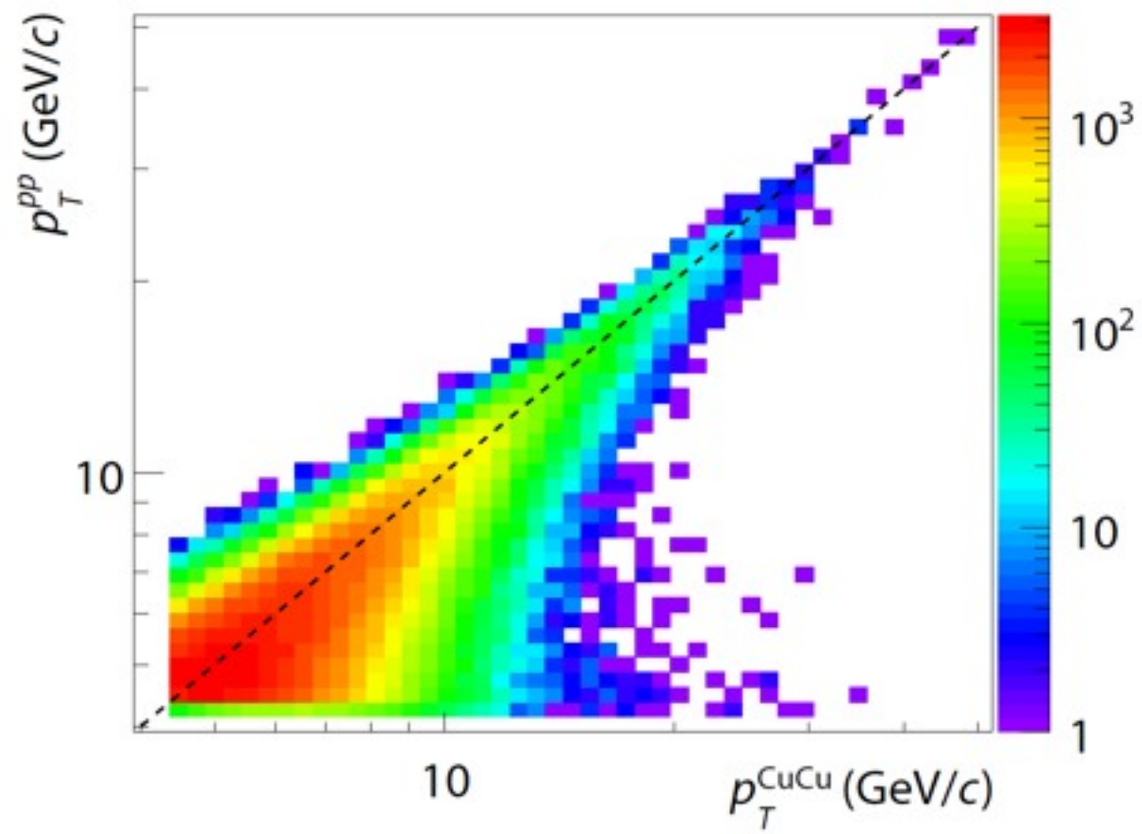
p+p and Cu+Cu event displays





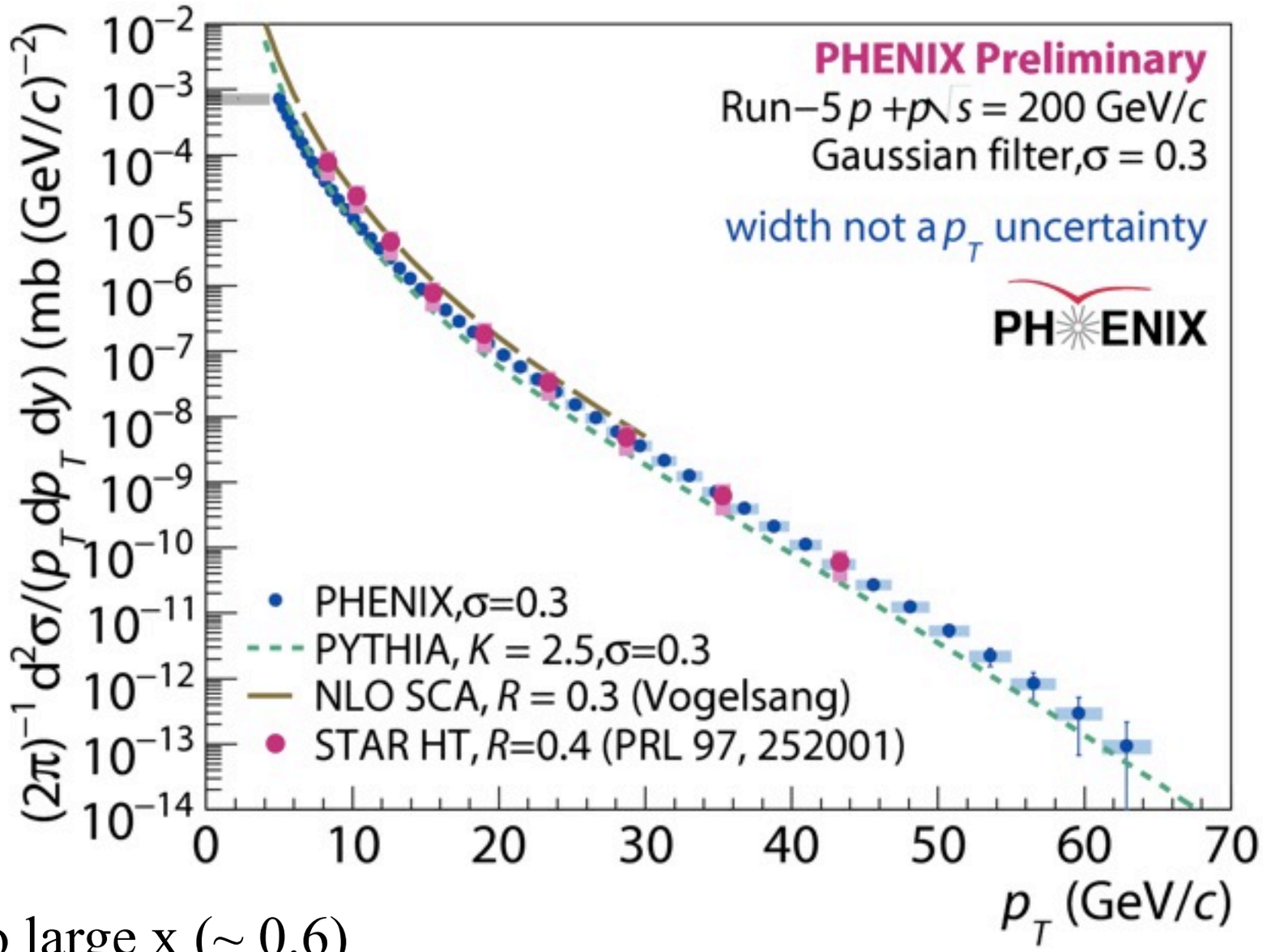
Unfolding the jet energy





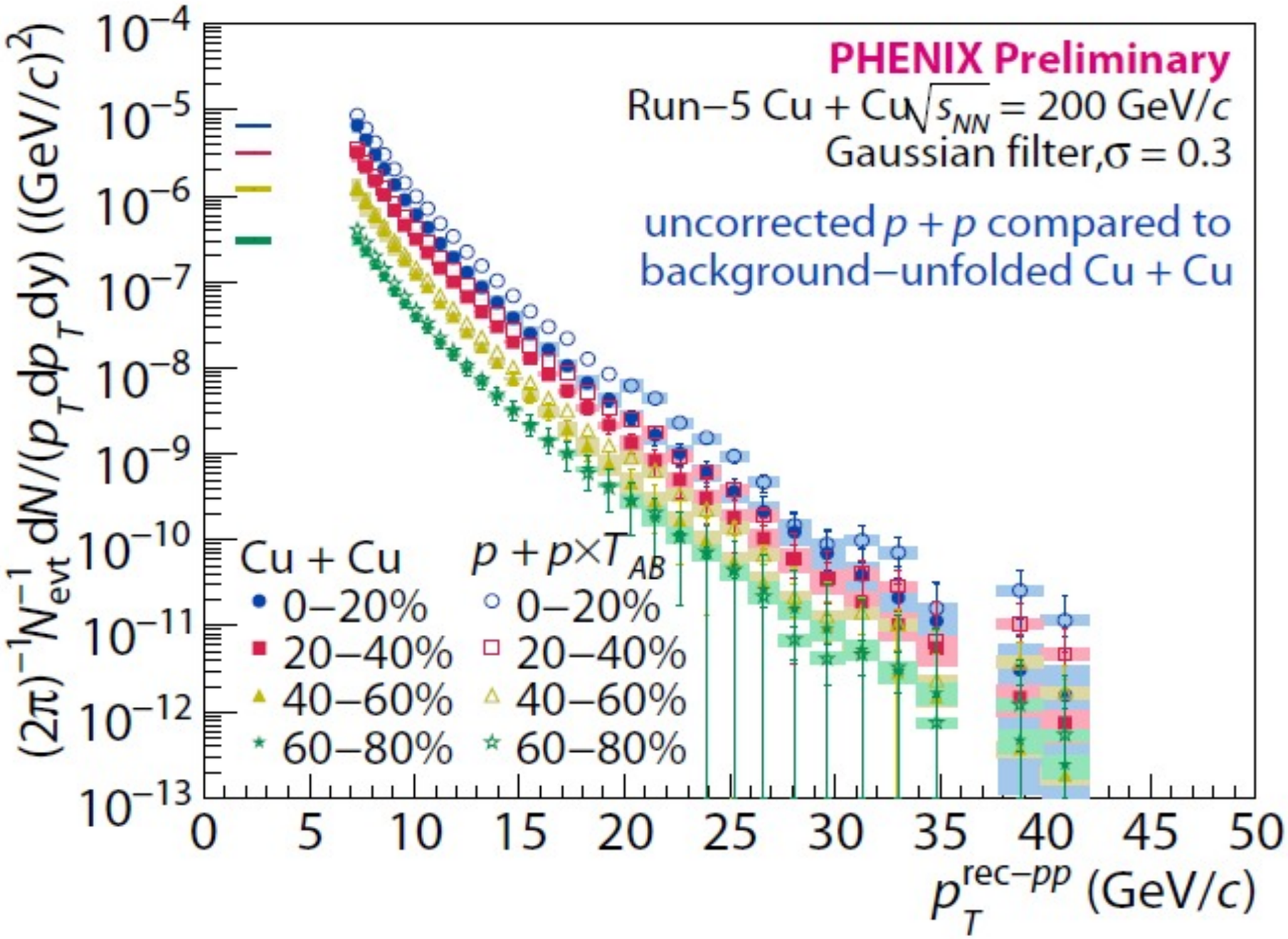
- Regularized SVD unfolding (GURU, Höcker & Karvelishvili, NIM A 372, 469)
- Unfolding to true jet energy (only in p+p so far)
  - Generate transfer matrix between true jet energy and measured using GEANT+PYTHIA
- Unfolding to Cu+Cu to p+p jet energy
  - HI background smears reconstructed jets to higher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



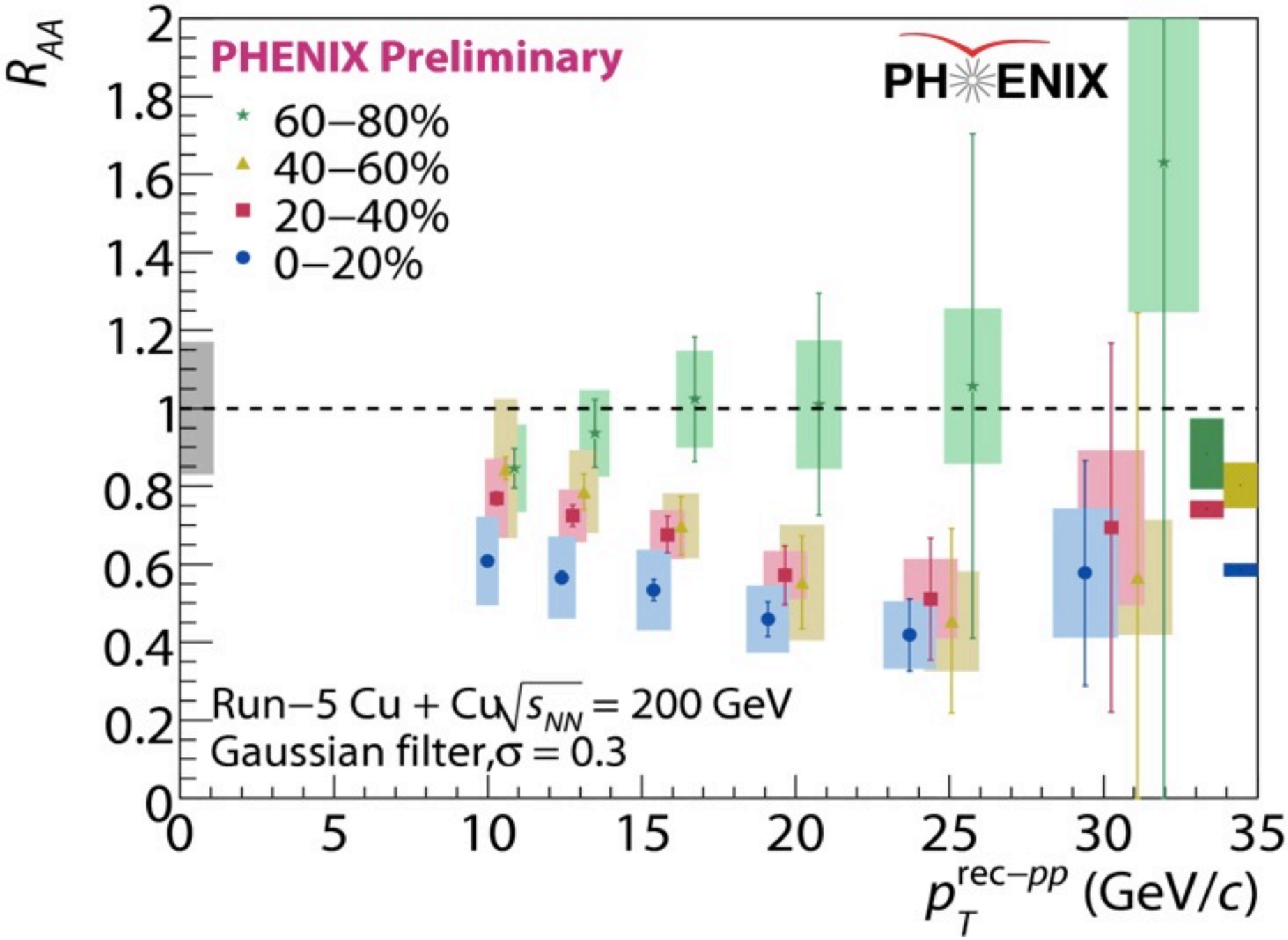
- p_T reach out to large x (~ 0.6)
- No direct comparisons BUT:
  - Consistent with STAR using mid-point cone algorithm with R=0.4
  - Compares reasonably well with both PYTHIA leading order K and NLO SCA
  - for direct comparison need NLO calculations to higher p_T and using filter algorithm

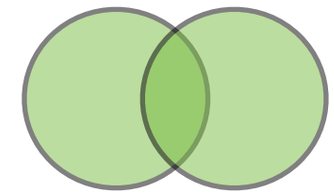
Cu+Cu jet spectra



- 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

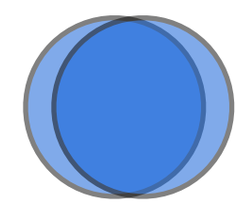
Cu+Cu jet nuclear modification (R_{AA})





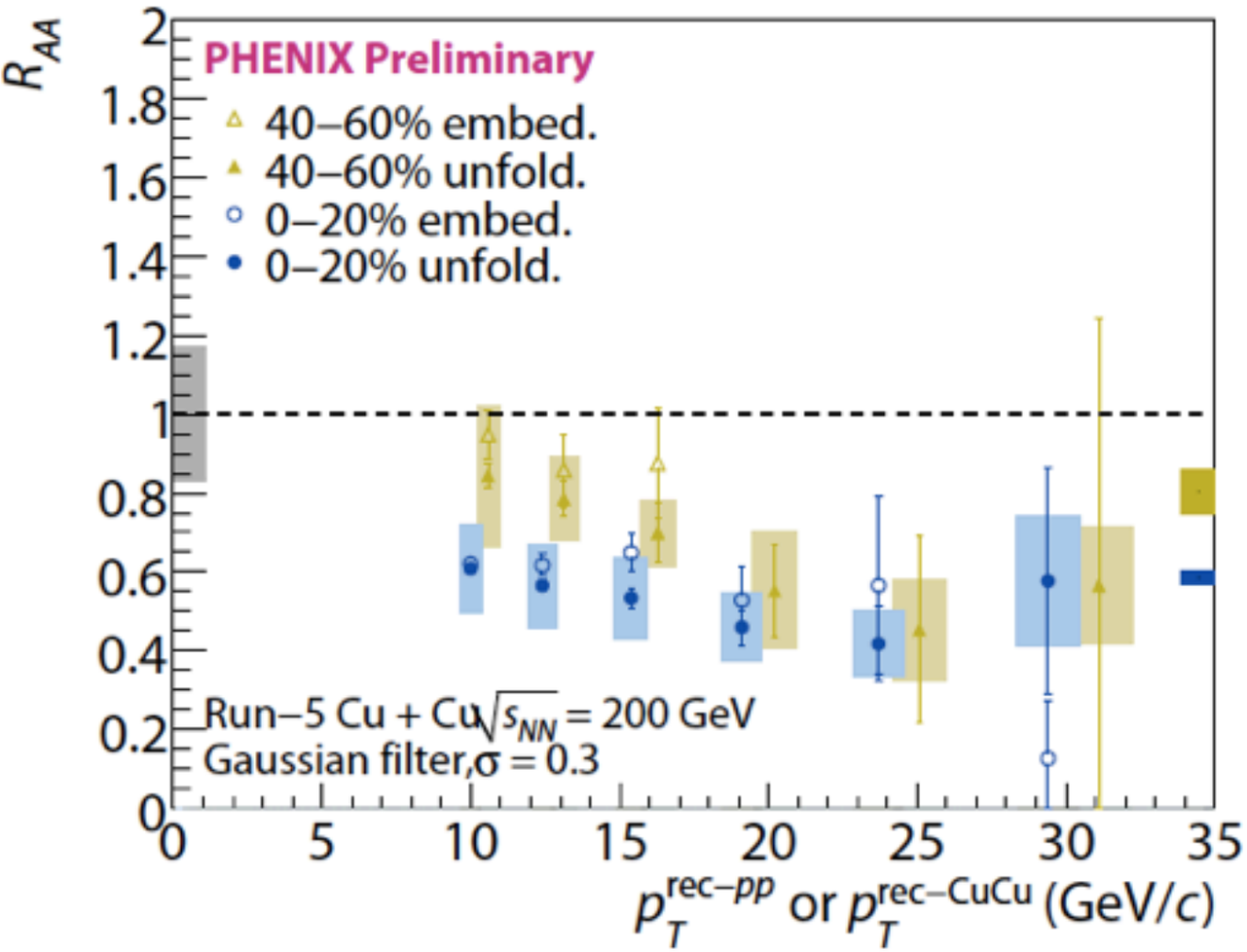
Peripheral

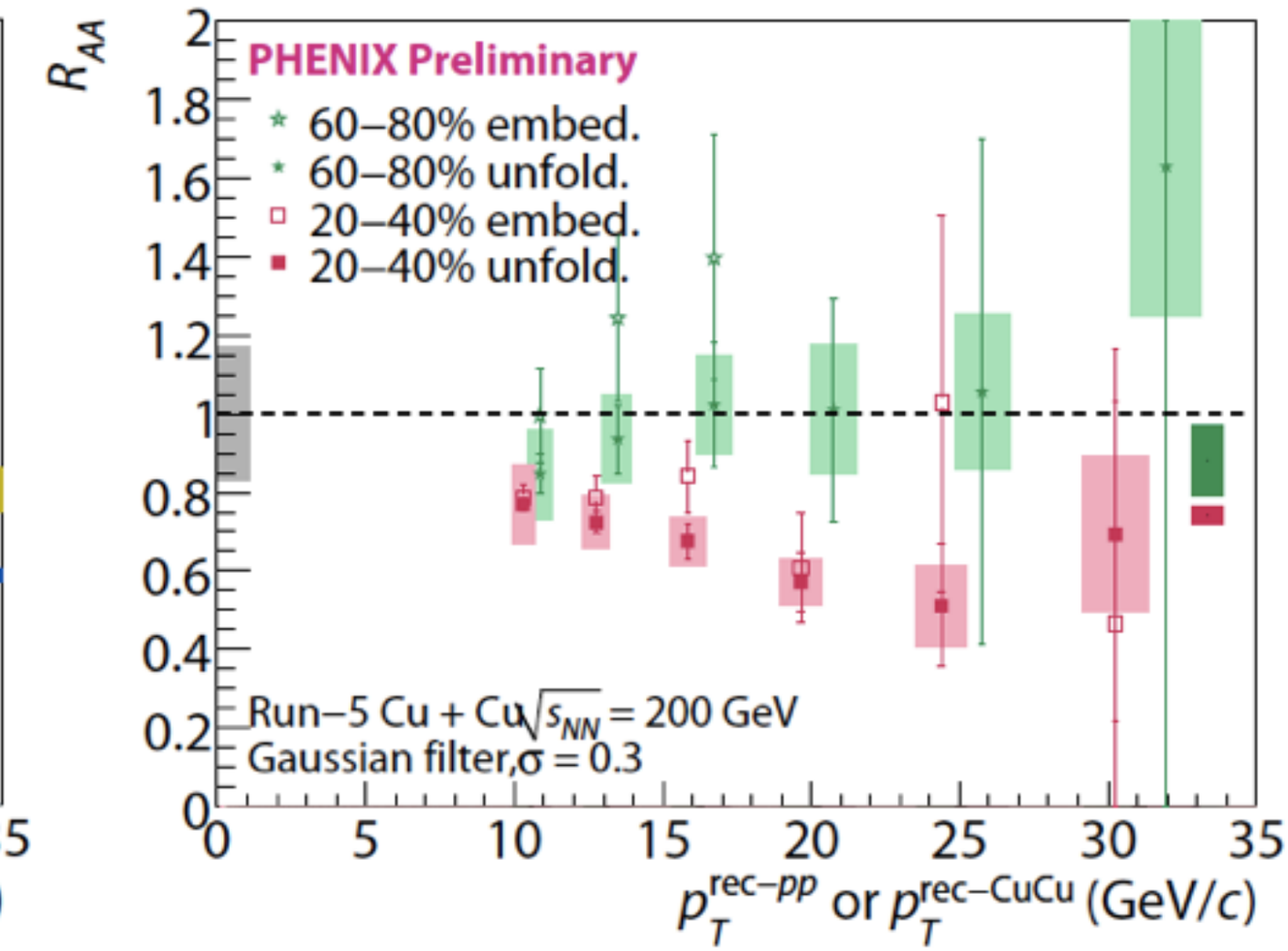
Central



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

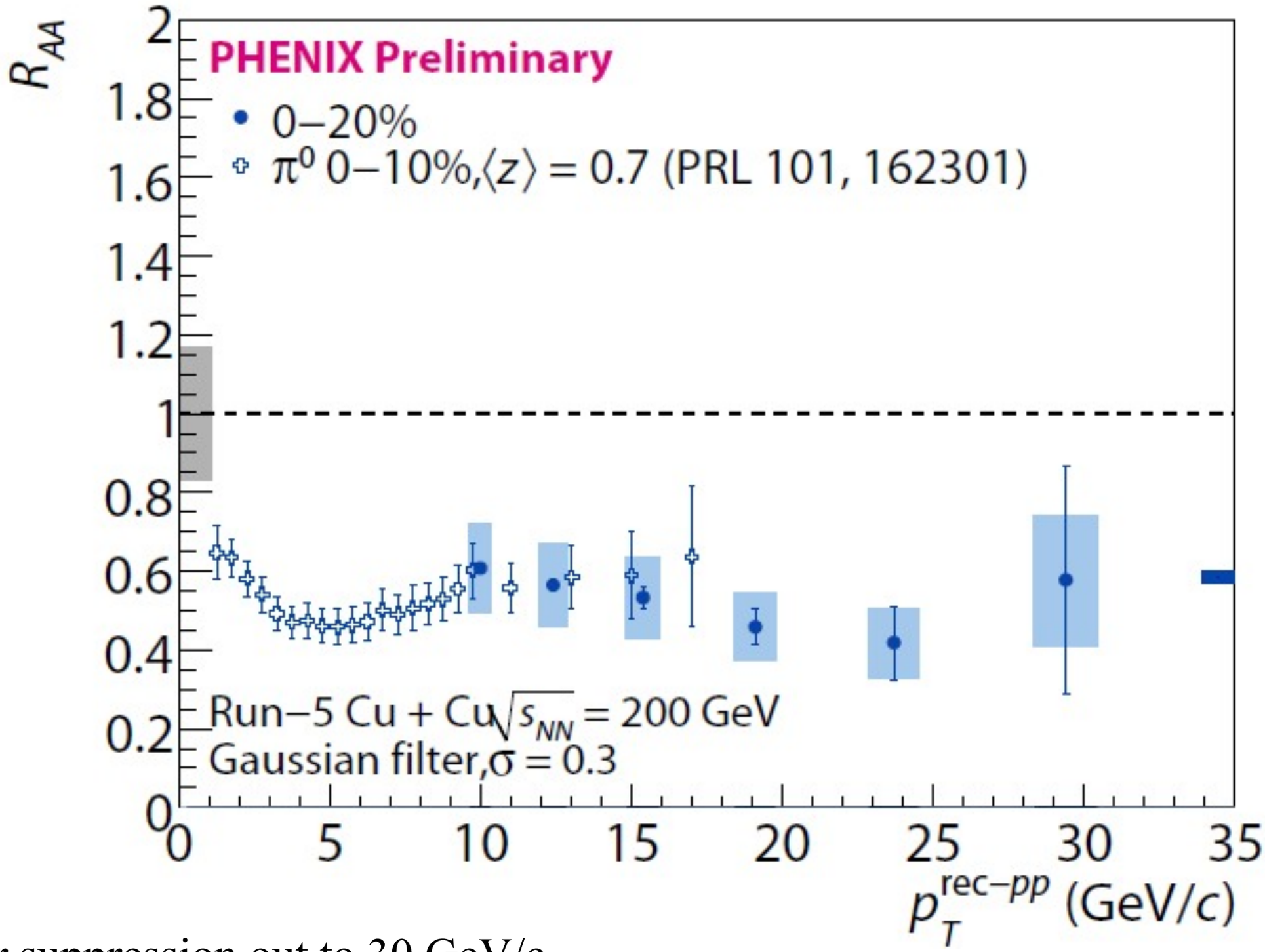
Cross check: embedding vs unfolding





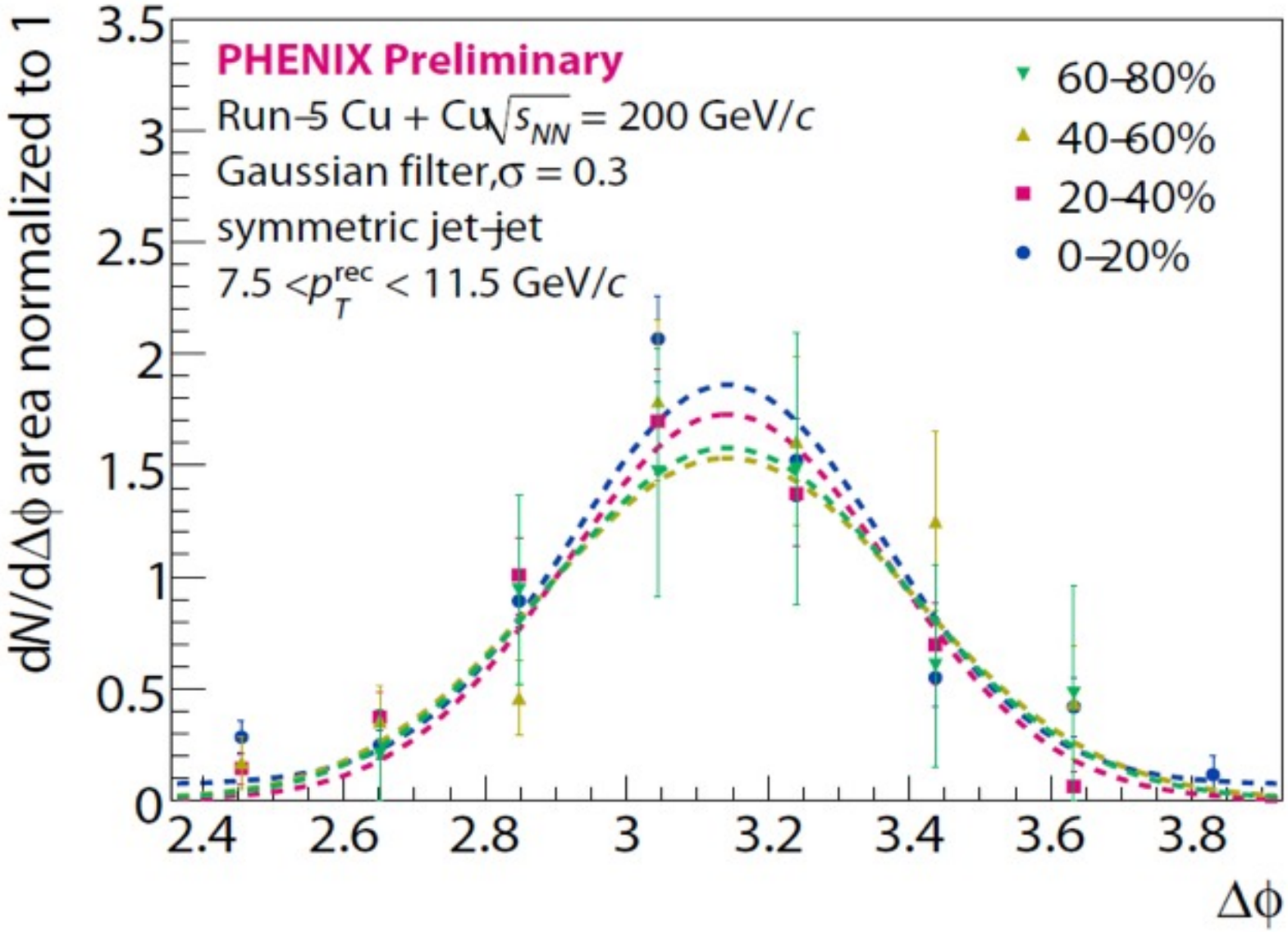
- Unfolded: uncorrected p+p compared to background-unfolded Cu+Cu
- Embedded: embedded p+p compared to uncorrected Cu+Cu
- Energies scales between the two do not match
  - roughly flat R_{AA} makes them comparable

Jet suppression vs single particles



- Similar suppression out to 30 GeV/c

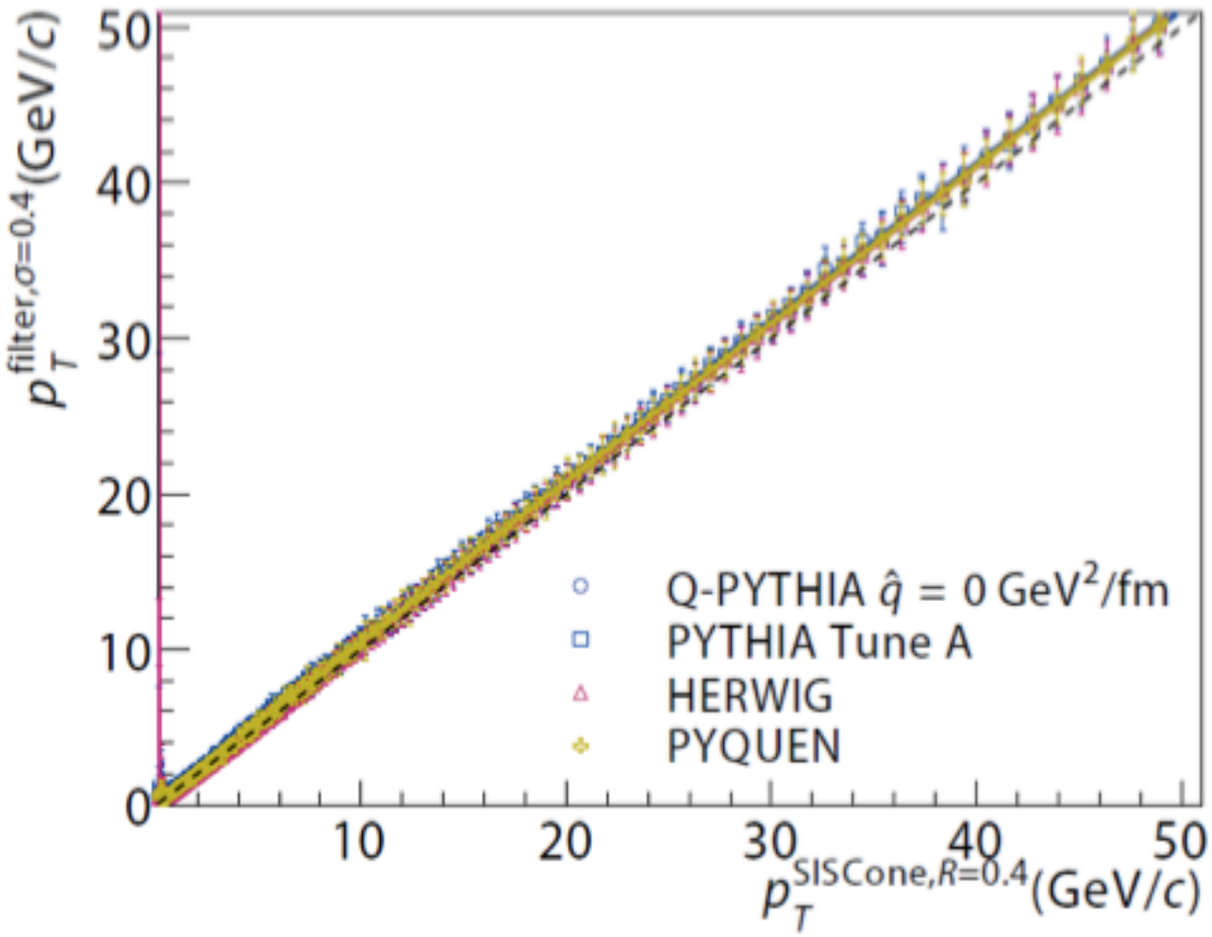
Jet-jet azimuthal correlations



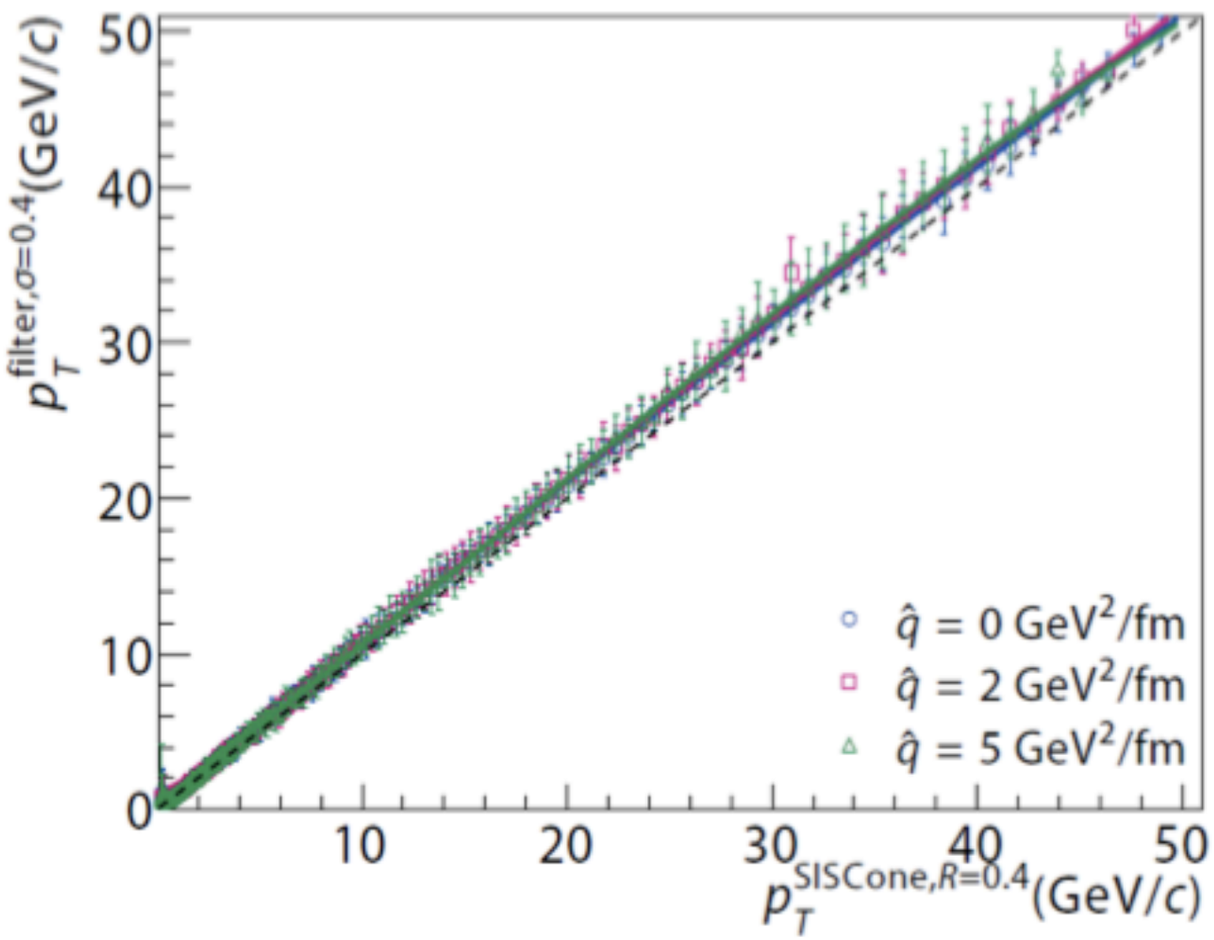
Centrality	$\Delta\varphi \approx \pi$ width σ
0–20%	0.223 ± 0.017
20–40%	0.231 ± 0.016
40–60%	0.260 ± 0.059
60–80%	0.253 ± 0.055

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

Is there a bias in the algorithm?



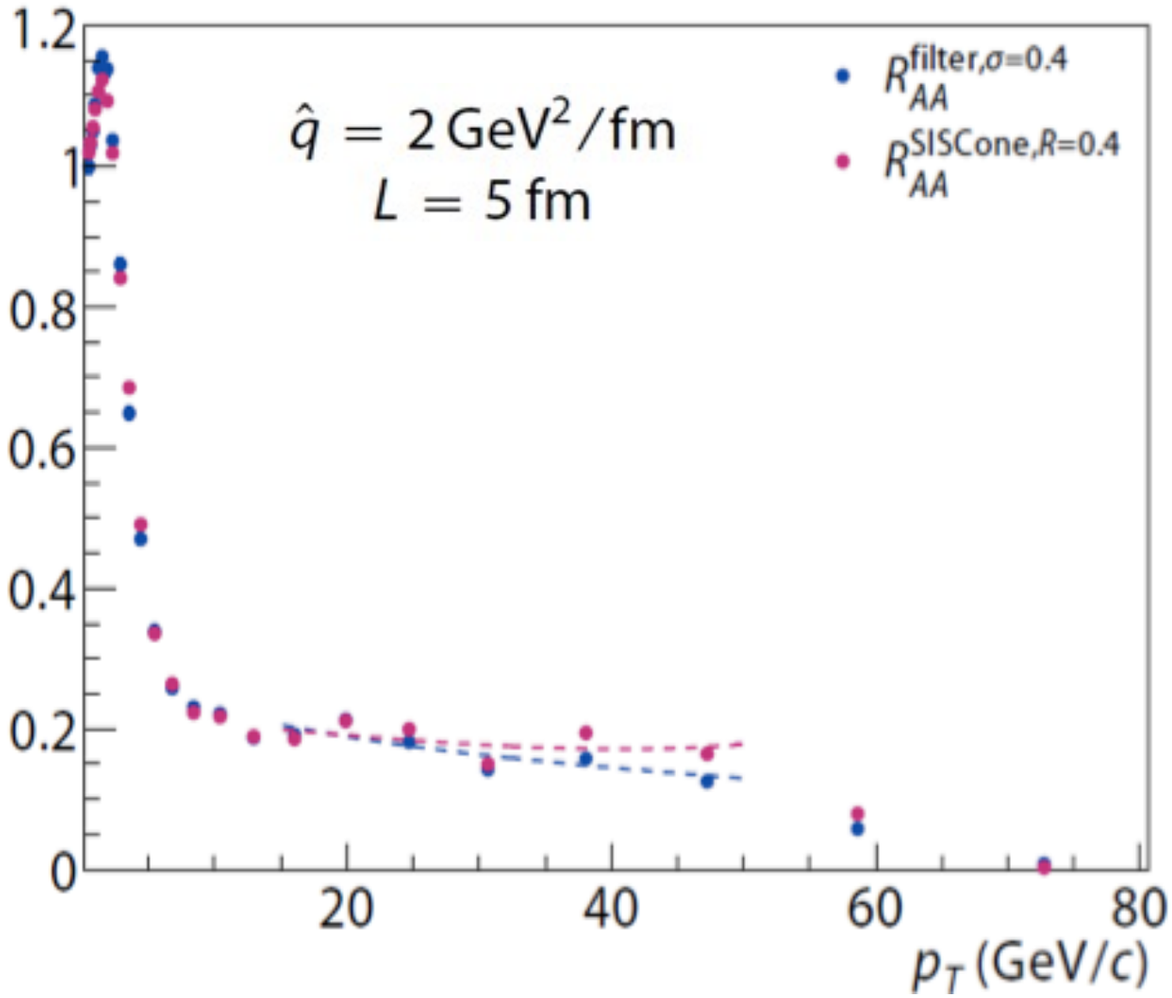
Default settings

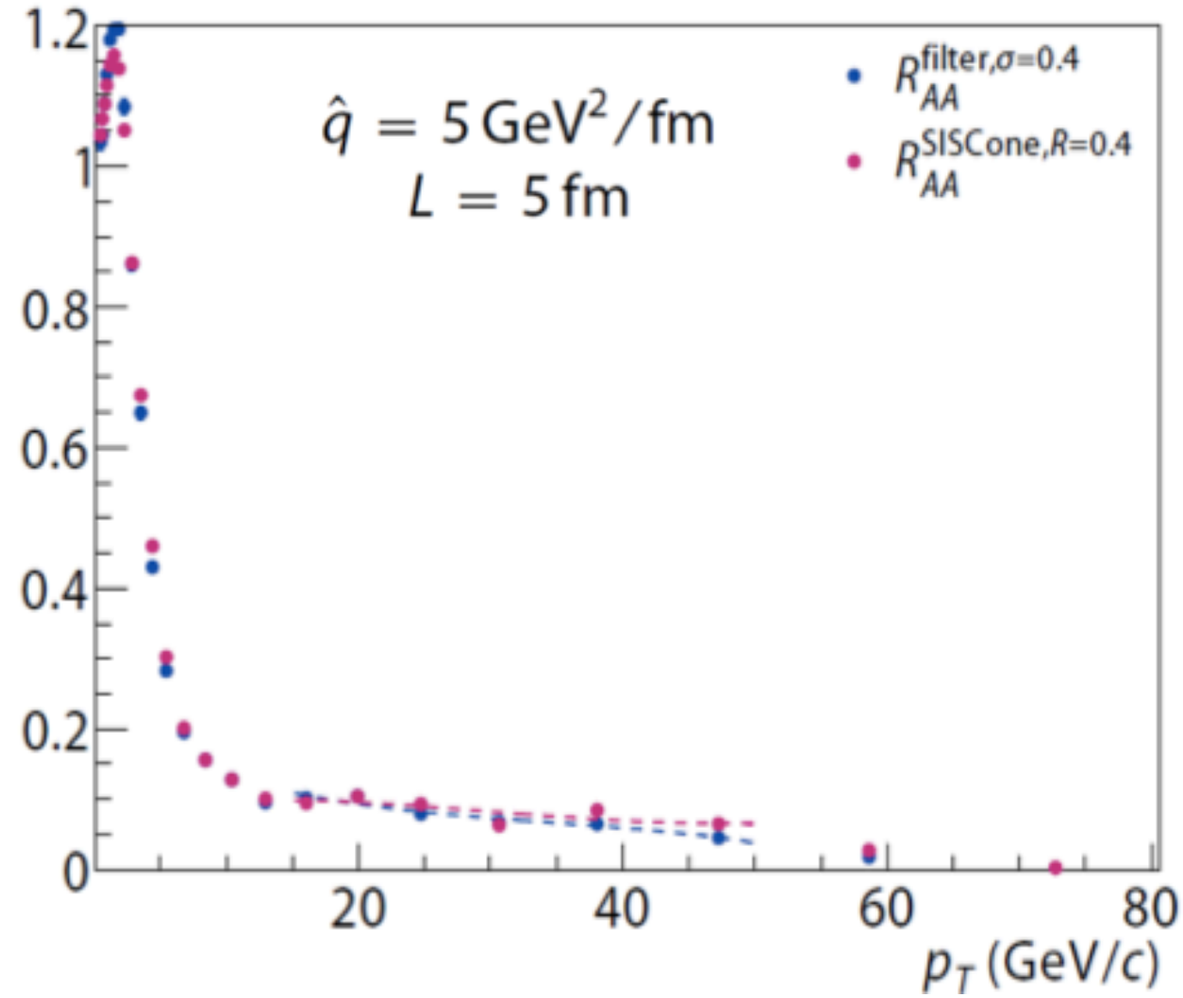


Q-PYTHIA L = 5 fm

- Compare σ = 0.4 Gaussian filter to R=0.4 SISCone
- 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}

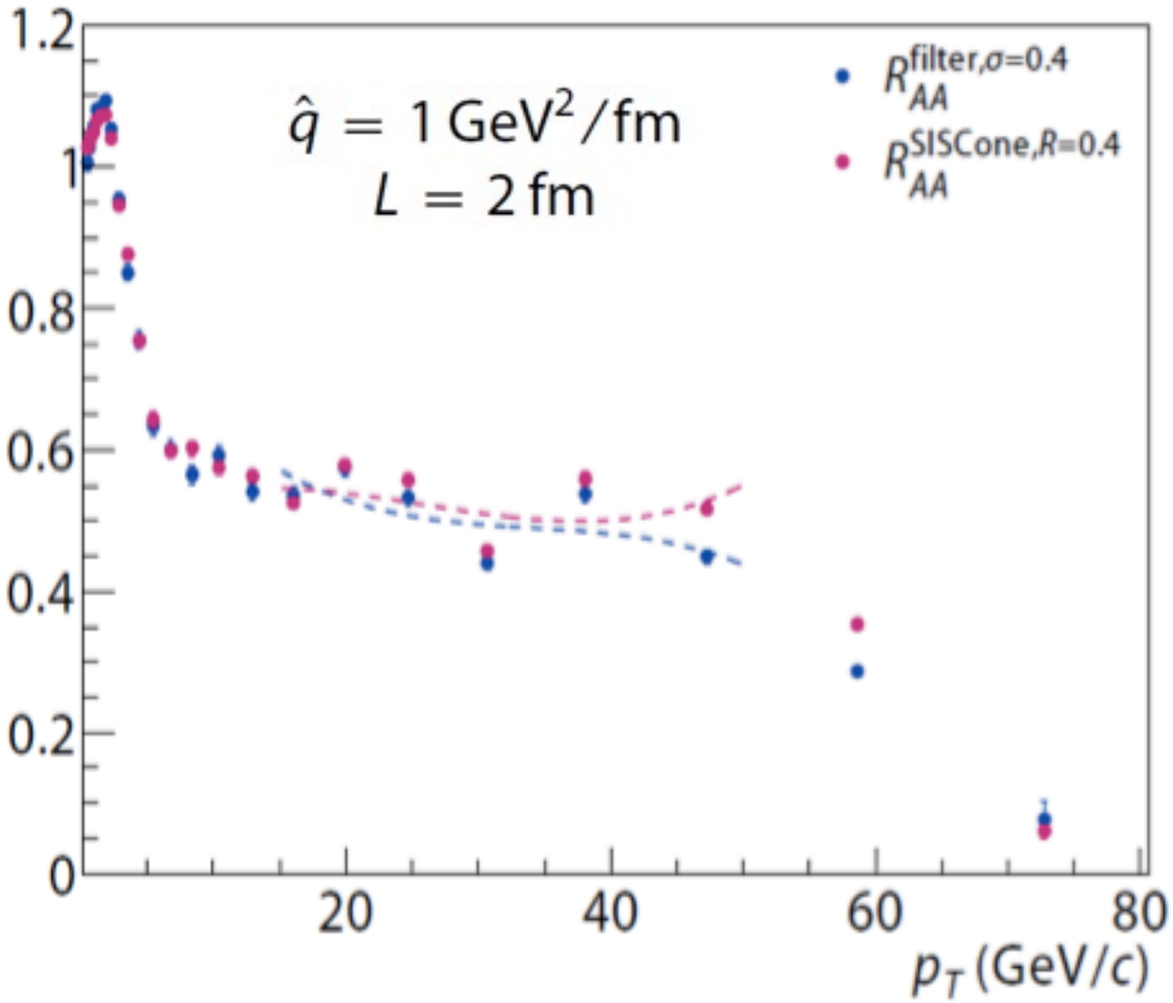


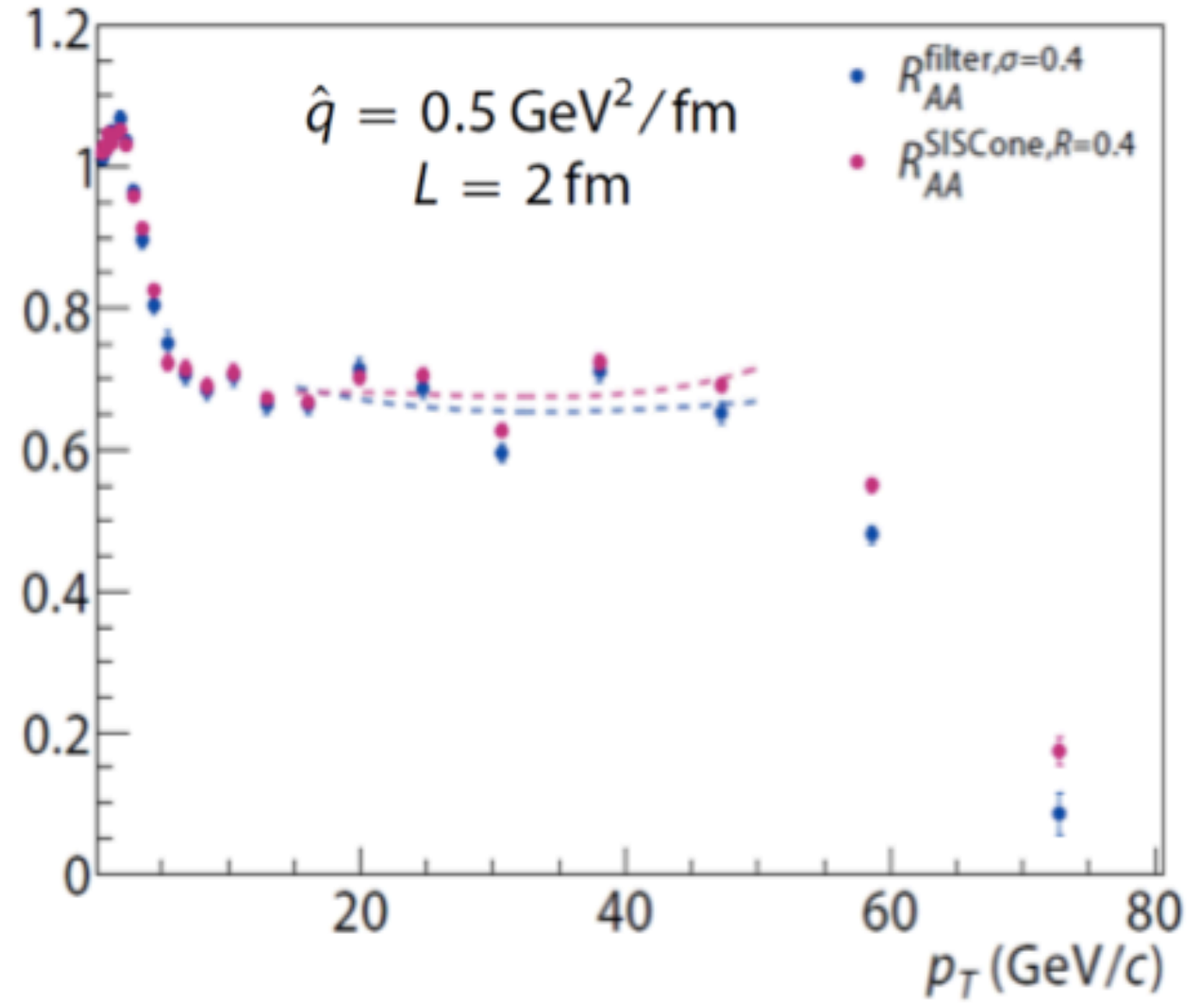


Strong quenching comparison

- 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 (30GeV/c)
- Inaccessible with current detector limitations

Is there a bias in R_{AA}

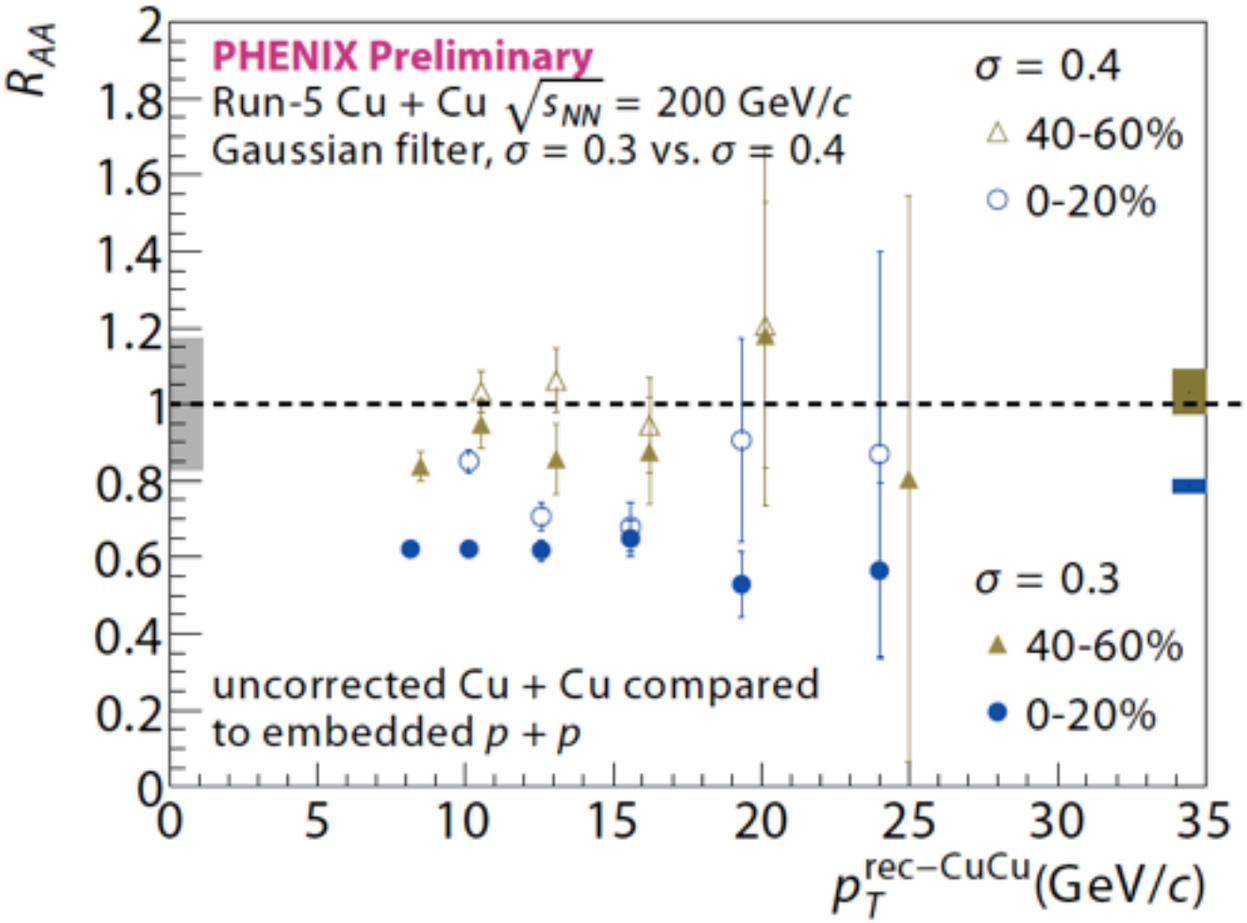


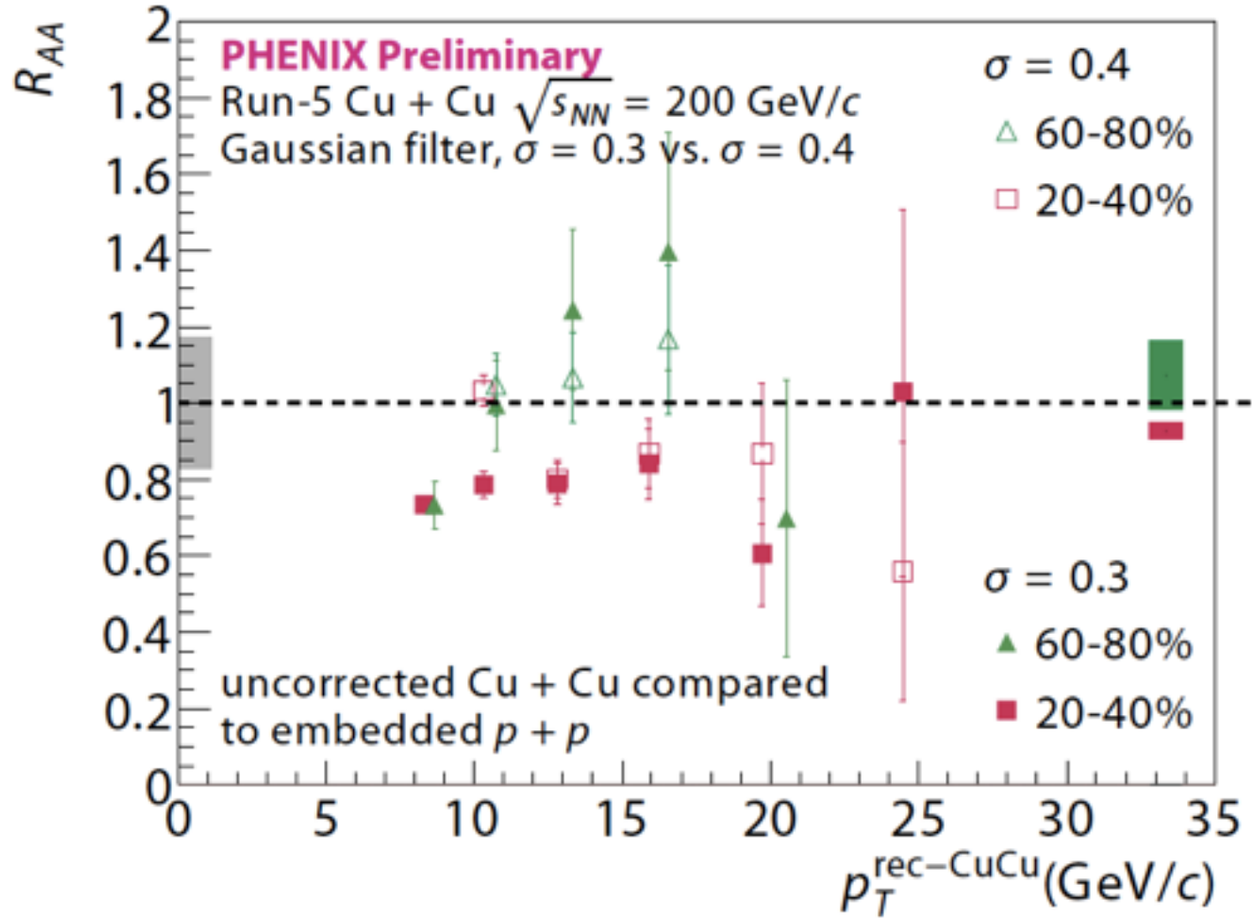


Weak quenching comparison

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

Modified jet shape?



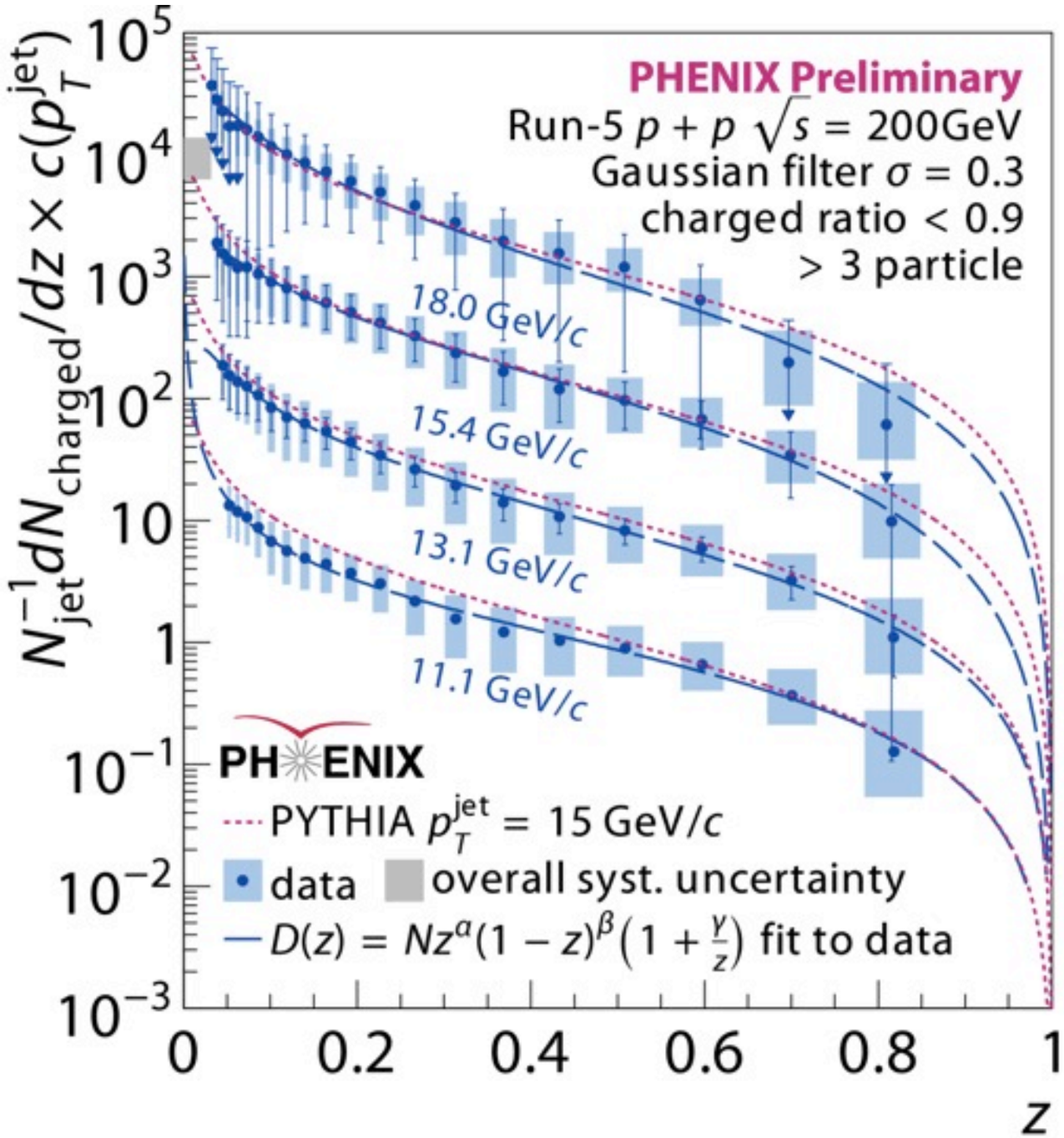


- Compare σ = 0.3 and σ = 0.4
  - If larger σ recovers jets with modified shape should see increase in R_{AA}
- Slight variation but with somewhat large uncertainties
  - low p_T variation in region with large fake jet rejection rate

Beyond inclusive cross sections

- Jet fragmentation function: do jets fragment within the medium?
- establish p+p baseline first: non-trivial
  - $z = p^{particle}/p^{jet}$
  - p^{jet} must be true jet energy to make unbiassed 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

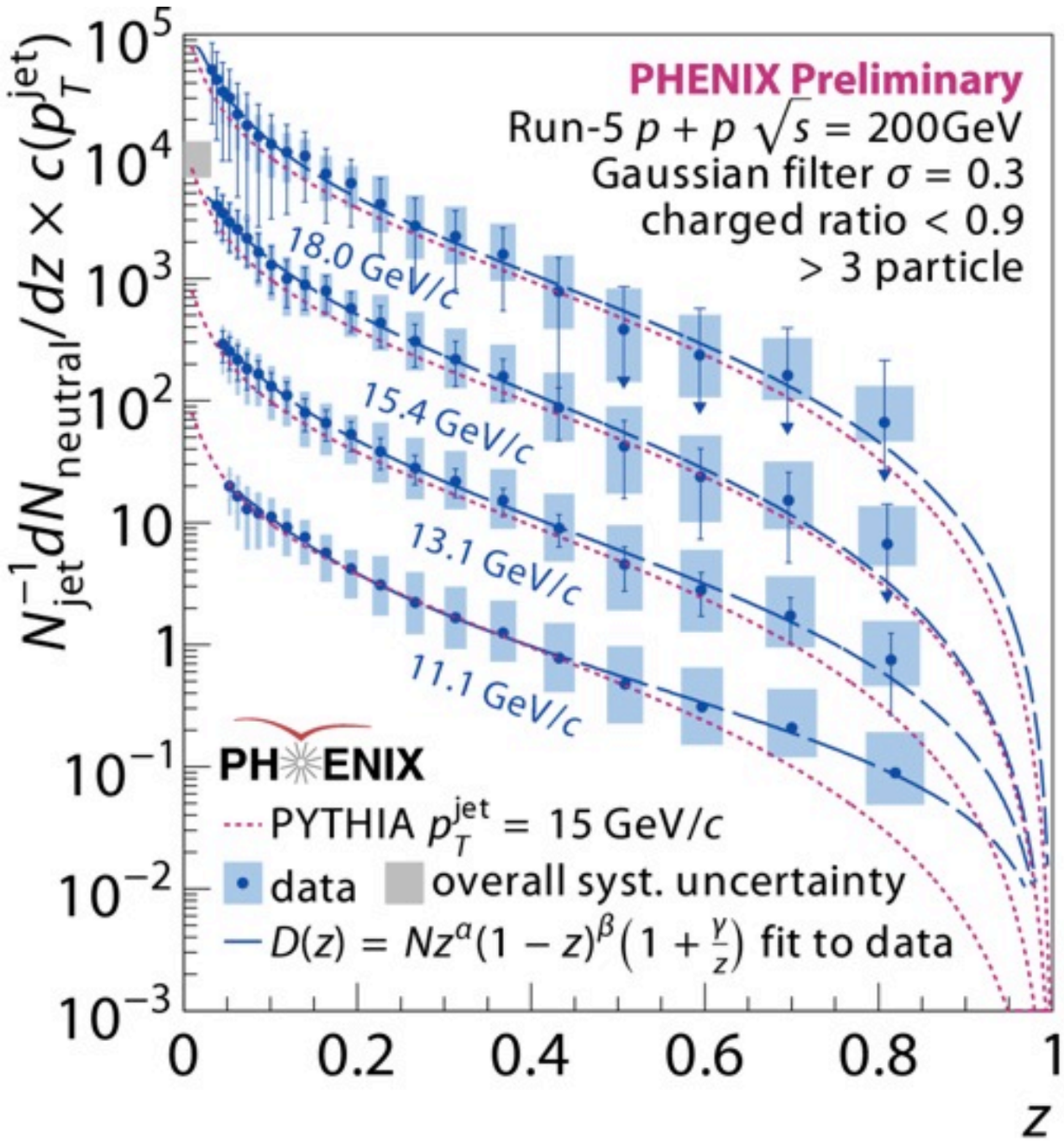


- Charged particles

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

- 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

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

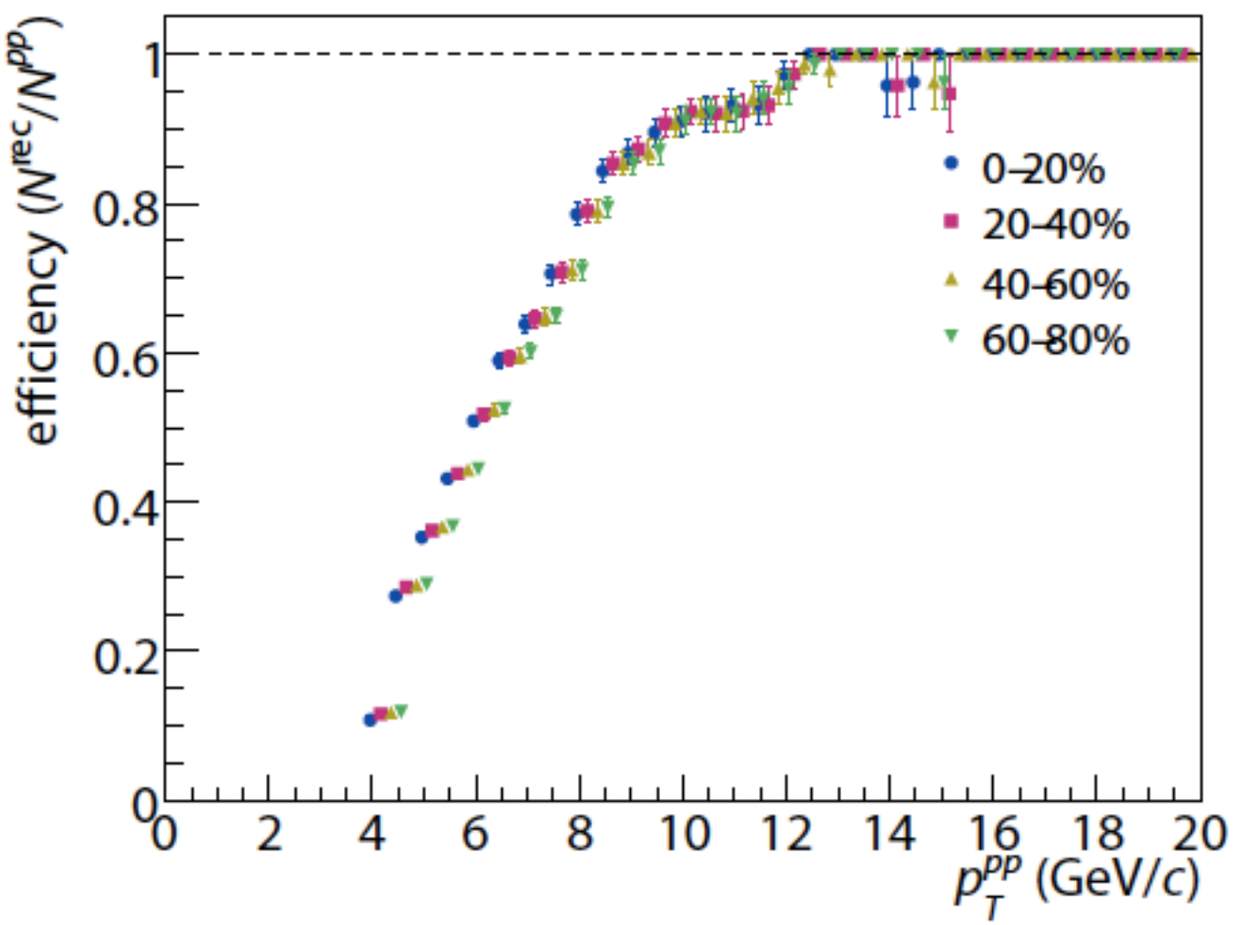
- Cuts on jets to remove contamination from conversions, calorimeter noise, or high p_T particle decays
  - # of particles > 3
  - charge fraction < 0.9
  - z < 0.81
- Jet selection bias fully contained in systematics quoted
- Consistent with PYTHIA FF scaling

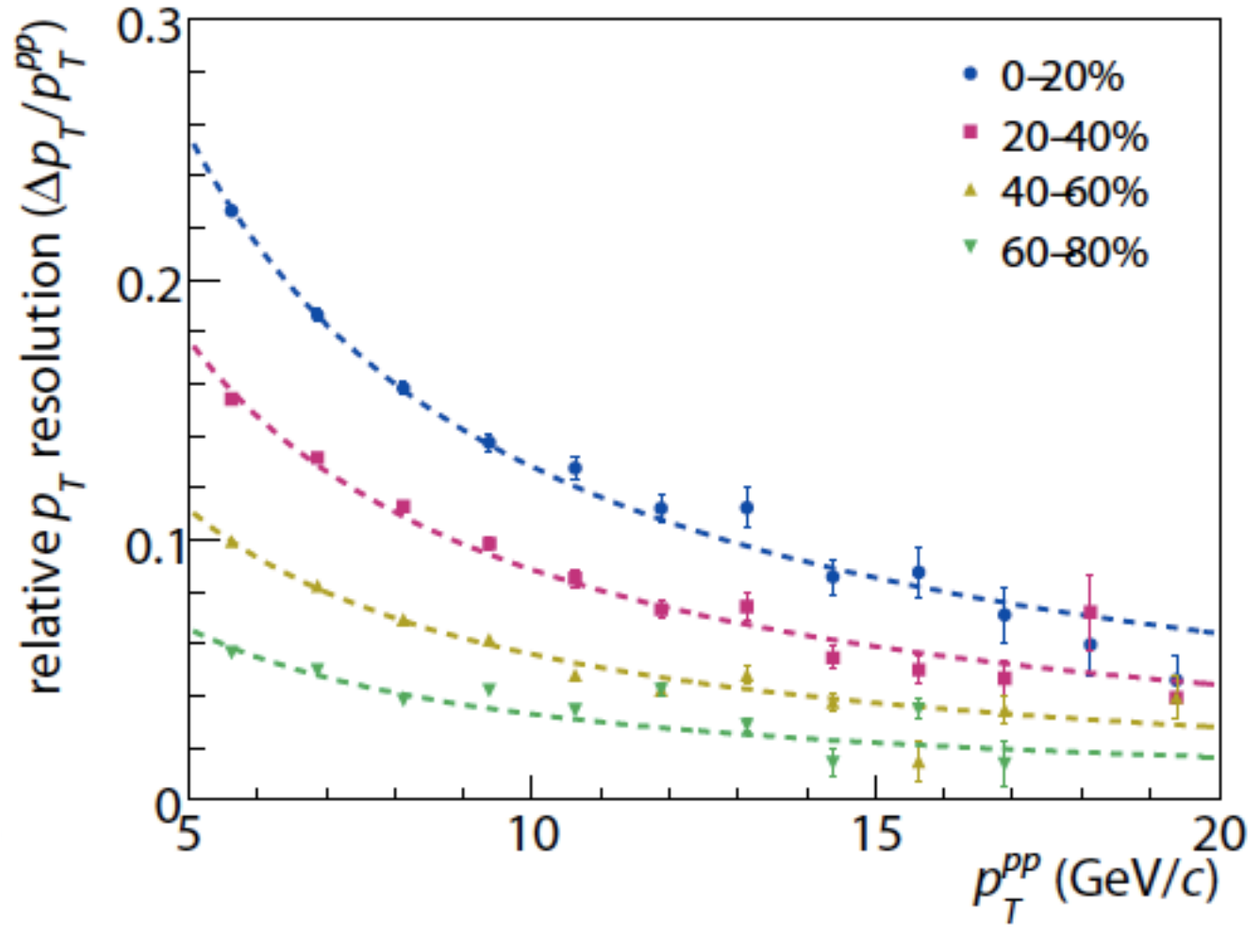
Summary and outlook

- 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 pT 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