# Probing Nuclear Matter with Jets and γ-Jets: Results from PHENIX

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# Overview

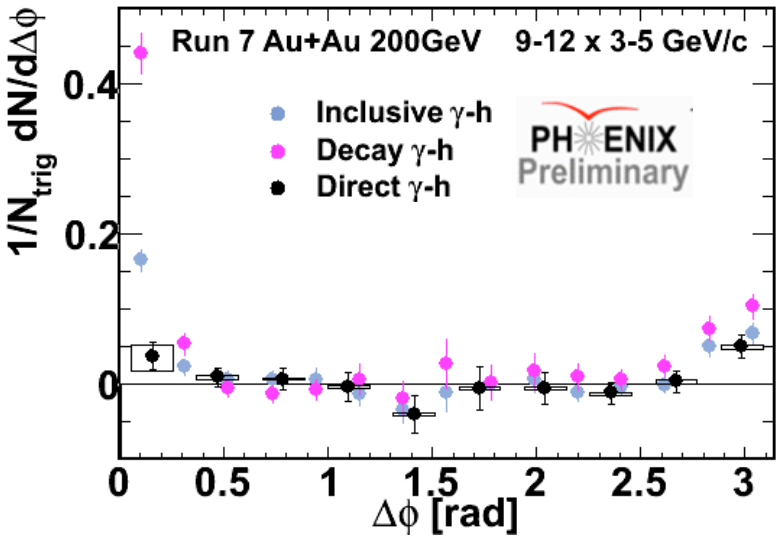
I will discuss effects on jets and γ-hadron correlations from

- hot, dense nuclear matter (Cu+Cu and Au+Au)
  - Fragmentation function shapes
  - Jet yields
- cold nuclear matter (d+Au)
  - Jet Yields
  - Di-jet Correlations

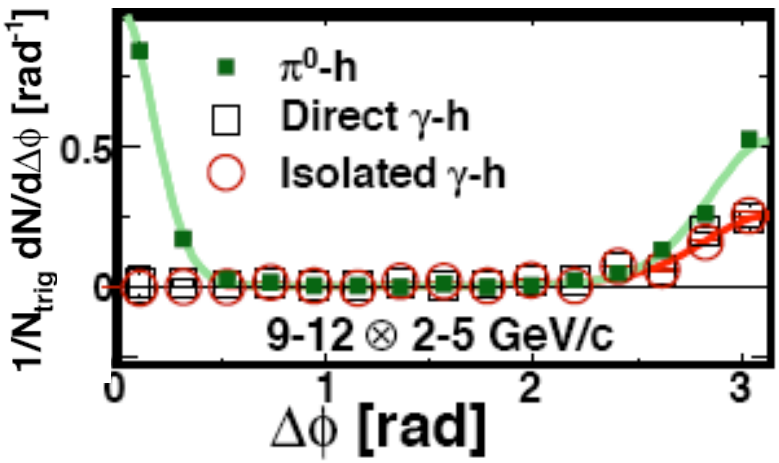
# Fragmentation Functions in Au+Au

# Measuring γ-hadron Correlations

Statistical (Au+Au)




Isolation(p+p) **PRD 82** 072001



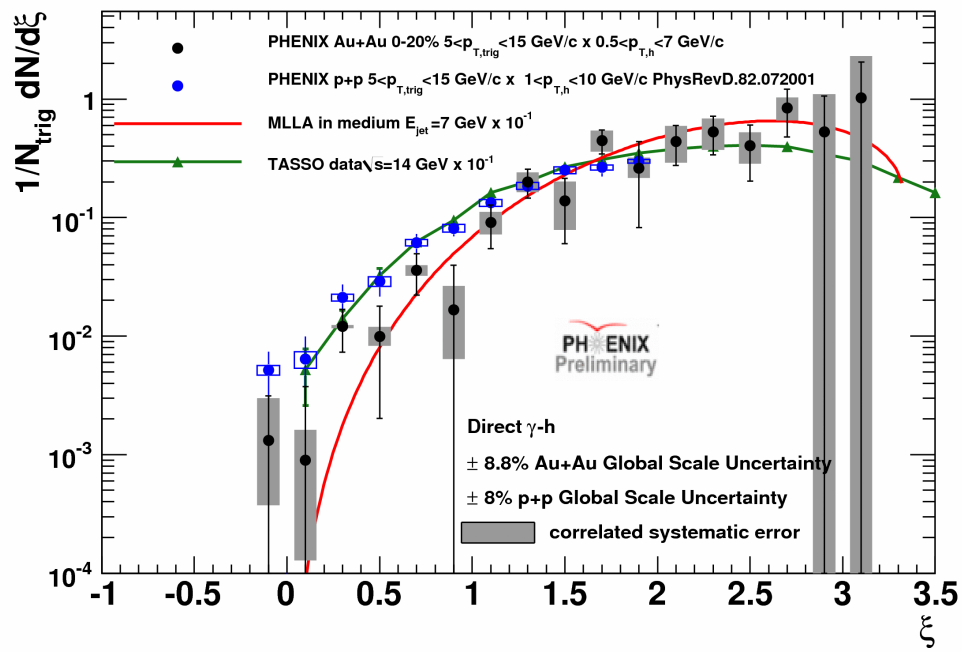

$$Y_{direct} = \frac{R_\gamma Y_{incl} - Y_{decay}}{R_\gamma - 1} \qquad R_\gamma = \frac{N_{incl}}{N_{decay}}$$

$$E_{cone} = \sum_{tracks} p_T + \sum_{clusters} E$$

$$R_{cone} = 0.3 \qquad E_{cone} < 10\% E_\gamma$$

# Measuring Fragmentation Functions

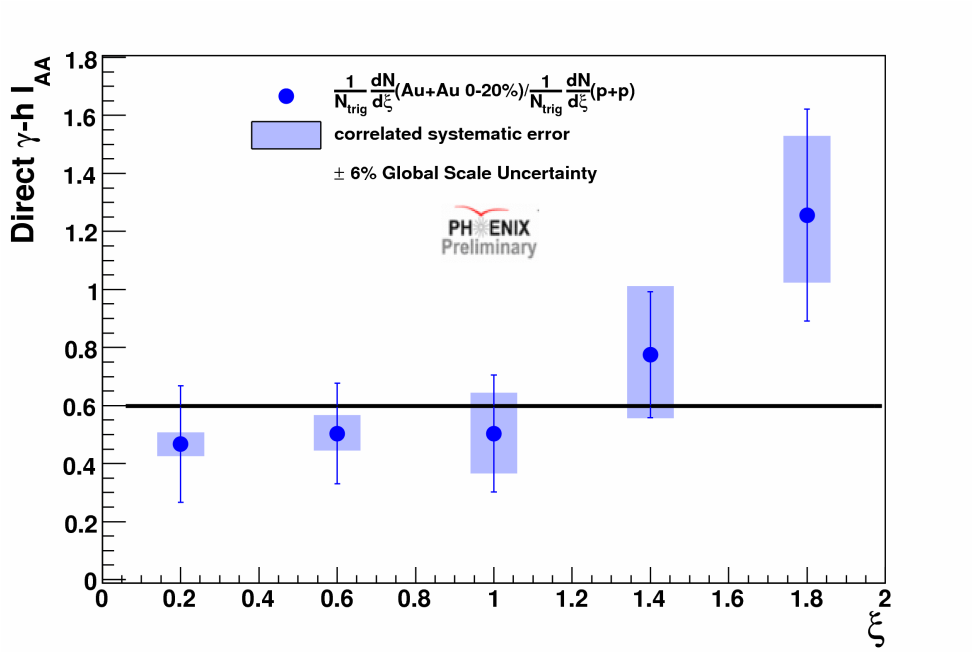
- Plot away-side ($\Delta\phi > \pi/2$) yield vs. MLLA $\xi$
- p+p shape (blue) compares well with TASSO's shape (green)
- Au+Au shape (black) compared with MLLA with energy loss (red)
- Au+Au plotted to lower down to $\xi \sim 3$!




$$\xi = -\ln\left(\frac{p_T^h}{p_T^\gamma}\right)$$

MLLA: Borghini and Wiedemann hep-ph/0506218

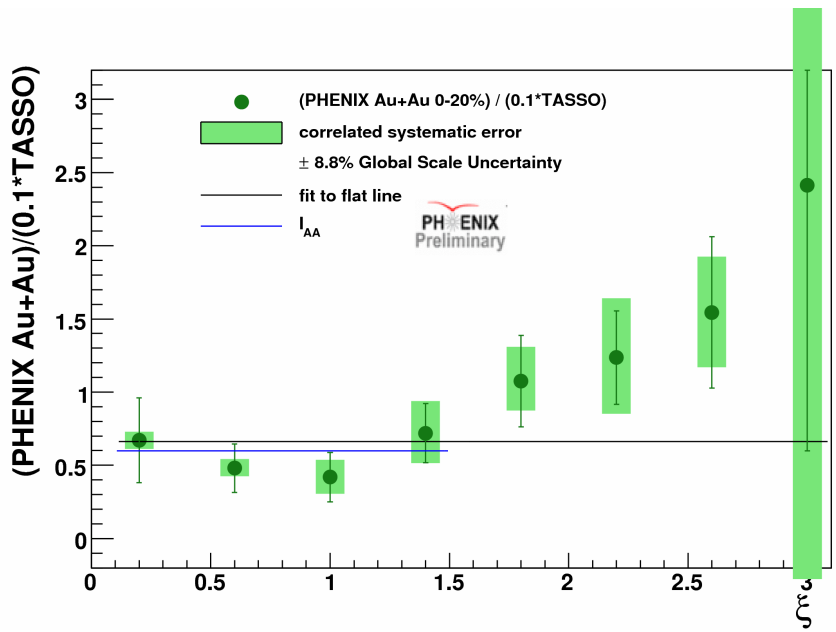
# Fragmentation Function Shape: Au+Au to p+p




$$\langle I_{AA} \rangle = 0.598 \pm 0.095$$

- The ratio of fragmentation functions in p+p and Au+Au
- Consistent with a flat ratio
  - $\chi^2/ndf = 4.85/4$

# Fragmentation Function Shape: Au+Au to TASSO




$$\langle I_{AA} \rangle = 0.662 \pm 0.087$$

$$\chi^2 / NDF = 12.16 / 7$$

- Au+Au goes down to ξ~3, below p+p baseline
- When comparing Au+Au to TASSO there is a shape difference
- Caveat: cannot ignore $k_T$ differences between p+p and $e^+e^-$

# Reconstructed Jets in Cu+Cu

# Filter Jet Reconstruction in p+p

- Filter Jet: seedless, infrared and collinearly safe algorithm with angular weighting (Lai and Cole arXiv:0806:1499)
- Calculate

$$\tilde{p}_T(\eta,\phi) = \iint d\eta' \, d\phi' \, p_T(\eta,\phi) h(\eta,\phi,\eta',\phi')$$

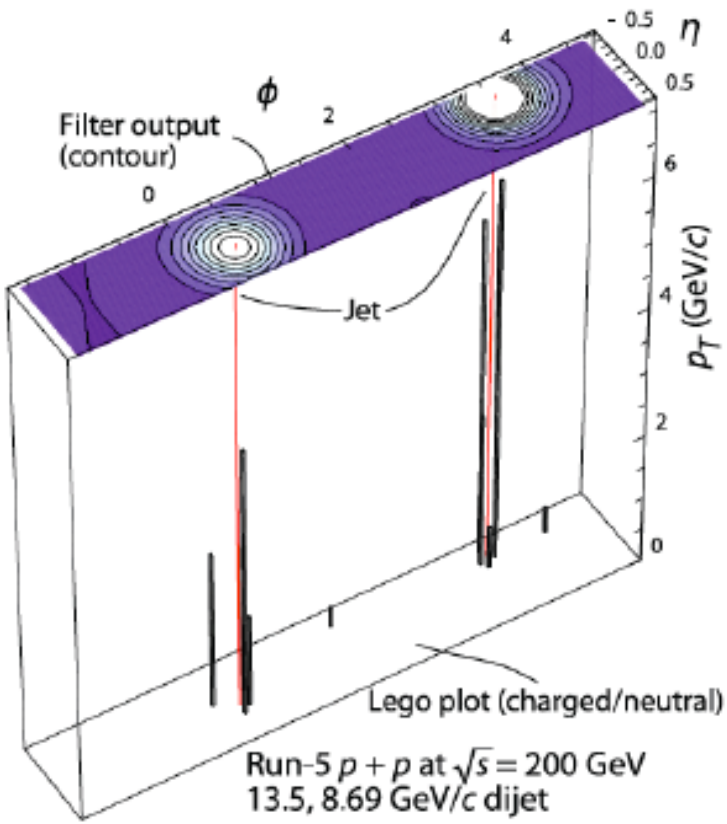
where

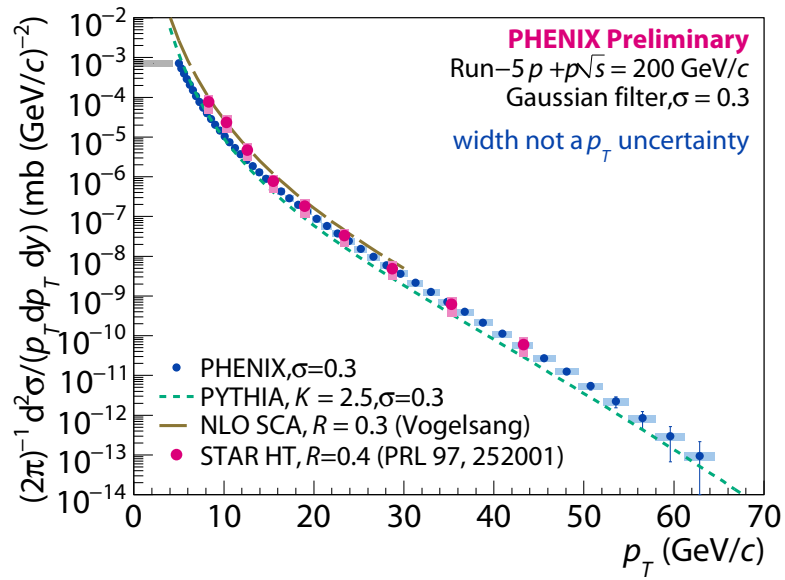
$$p_T(\eta,\phi) = \sum_{i \in \text{particles}} p_{T,i}(\eta,\phi)$$

and

$$h(\eta,\phi,\eta',\phi') = \frac{1}{\sqrt{2\pi}\sigma} \exp\left[ -\frac{(\eta-\eta')^2 + (\phi-\phi')^2}{2\sigma^2} \right]$$

# Filter Jet Reconstruction in p+p



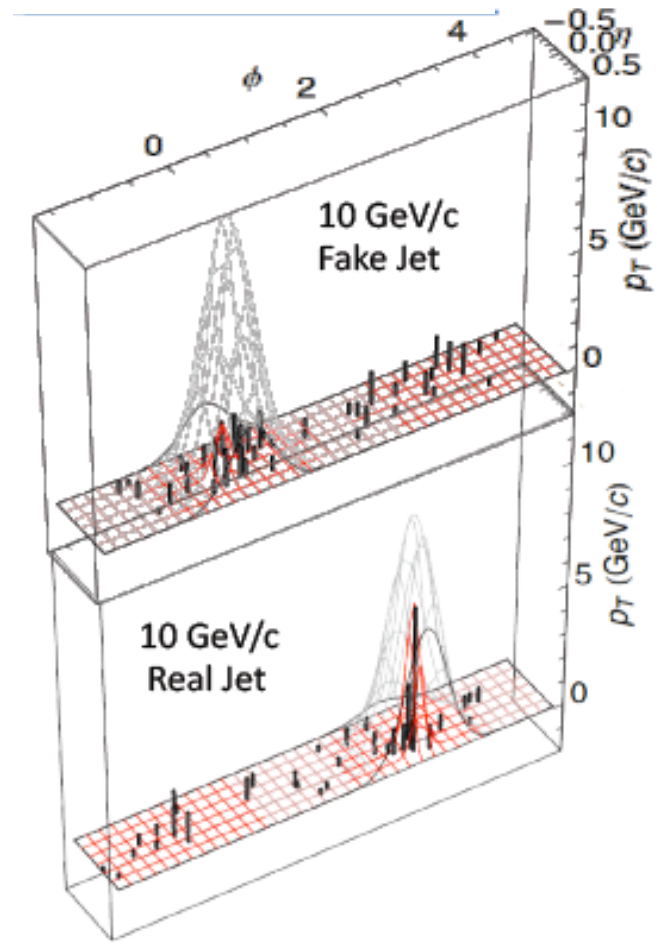

- Invariant cross-section in p+p compared with STAR data, PYTHIA, and NLO seedless cone algorithm.

# Filter Jet Reconstruction in Cu+Cu: Background and Fake Jets

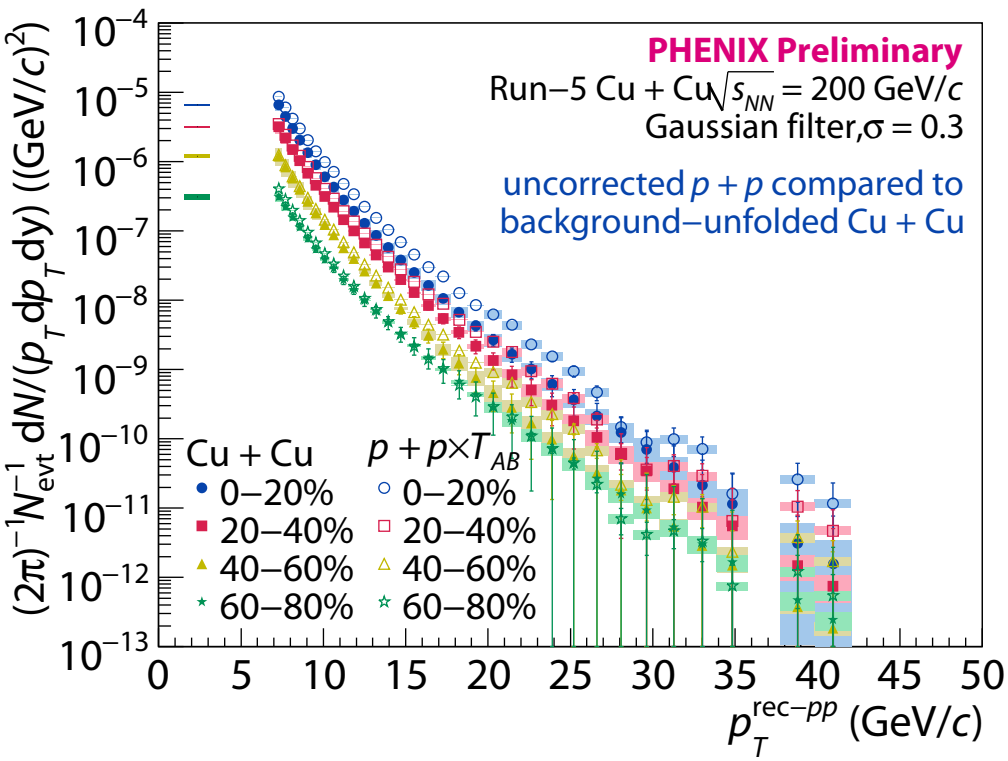
- Subtract off underlying event $p_T$ density

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

- Angular weighting reduces effect of background being found randomly in the region of the jet.
- Fake jets from underlying event still exist
- Remove by shape analysis.



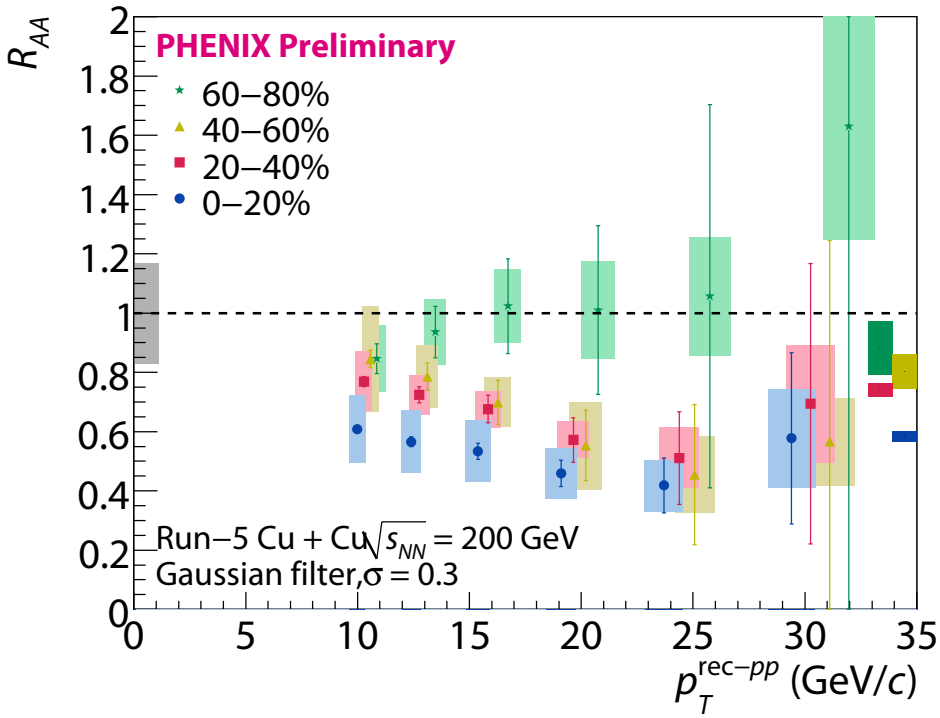
# Hot Nuclear Matter Effects: Jet Yields




- Invariant yields of ($T_{AB}$-scaled) p+p and Cu+Cu filter jets with σ=0.3
- Background subtracted, resolution accounted for with unfolding.

At the raw p+p jet scale

# Hot Nuclear Matter Effects: Jet $R_{AA}$



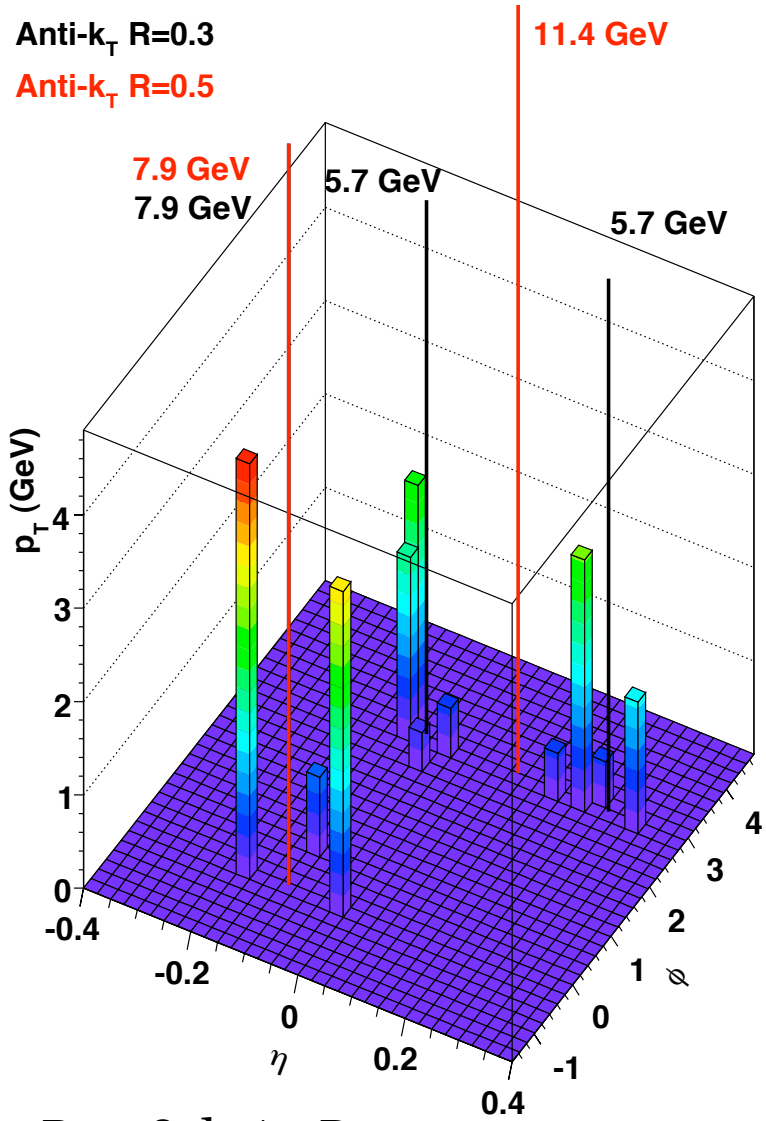

At the raw p+p jet scale

- Centrality-dependent suppression of jet yields observed.
- Due to
  - out-of-cone radiation from medium interaction
  - modified jets being removed by fake jet rejection cut.

# Reconstructed Jets in d+Au

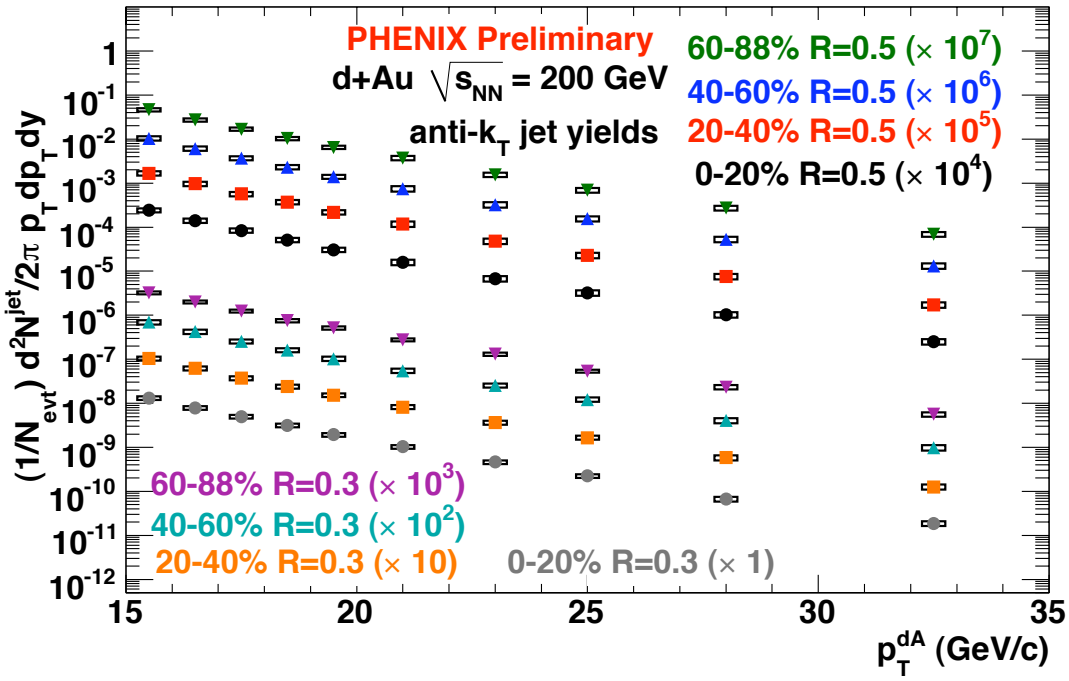
# Anti-$k_T$ Jets in d+Au

- Start with the highest $p_T$ particle and cluster things nearby it
- Less sensitive to PHENIX edges than cone and $k_T$ algorithms.
- Unknown heavy ion background sensitivity
  - Reconstruct jets with different R(=0.3,0.5) parameters to test systematics of background.




Run-8 d+Au Data

# Anti-kT Jets in d+Au: Jet Yields

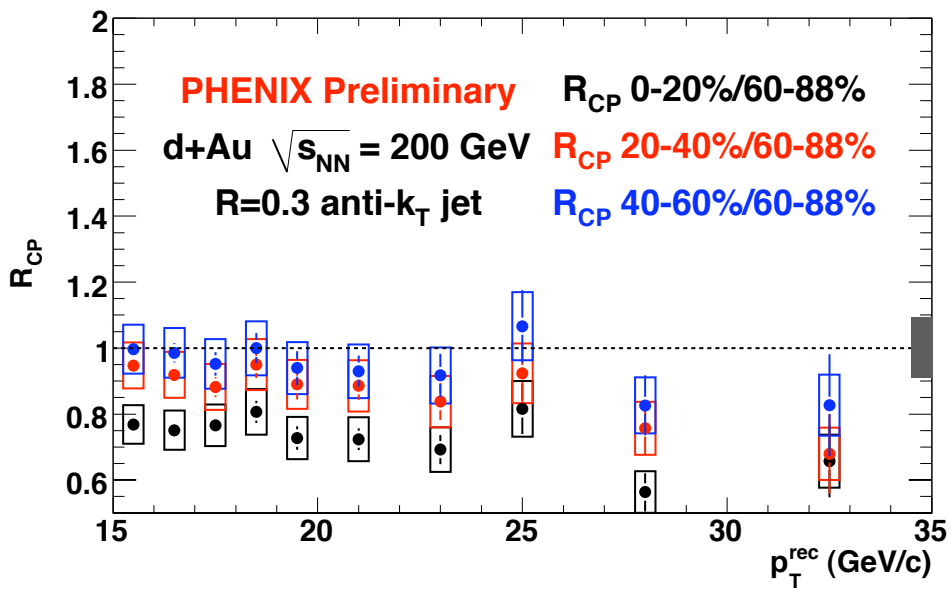



- d+Au jet yields into the PHENIX acceptance.
- $p_T^{dA} > 15$ GeV where fake rate is negligible

At the raw d+Au jet scale

# Cold Nuclear Matter Effects: $R_{CP}$

- Unfolded the smearing from the small underlying event in d+Au
- Centrality-dependent suppression of high-$p_T$ jets is observed.
- Likely due to
  - modifications of the nPDFs
  - cold nuclear matter energy loss




At the raw p+p jet scale

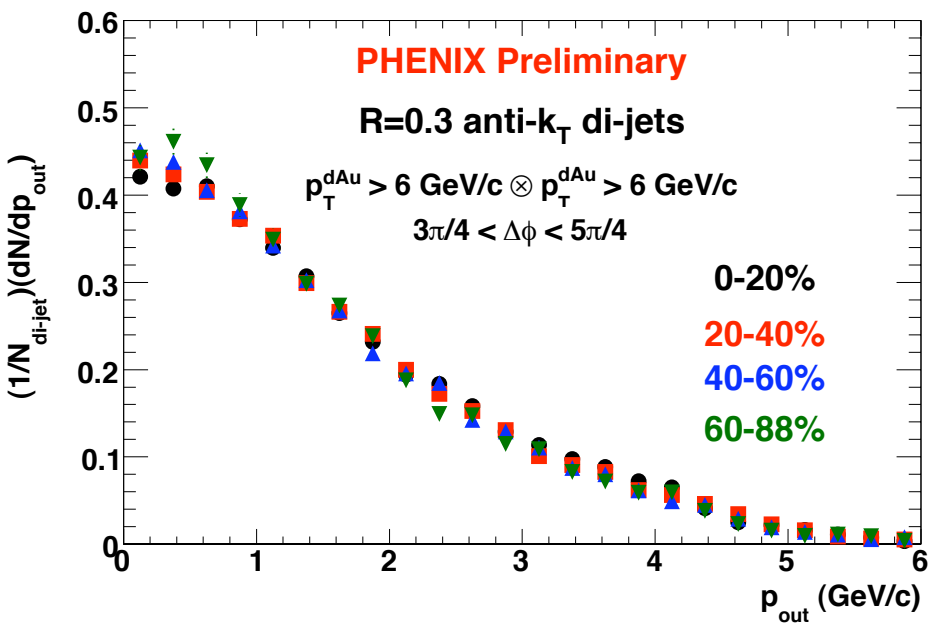
# Cold Nuclear Matter Effects: Di-jet $p_{out}$

- Search for broadening of jets

$$p_{out} = p_{T,2} \sin \Delta\phi$$

where $p_{T,2}$ is the lower-$p_T$ jet

- No indication of combinatorial background from fake jets.
- Tail of pout strongly constrains the centrality-dependent broadening.




At the raw d+Au jet scale

# Summary & Conclusions

- PHENIX has measured effects on hard probes from both hot, dense and cold nuclear matter.
- γ-hadron correlations indicate a modified shape compared to $e^+e^-$ data.
  - Expected from perturbative parton energy loss
- Direct jet reconstruction in Cu+Cu shows a centrality-dependent suppression of the jet yield.
  - Indicating out-of-cone radiation and/or rate of modified jets
- Direct jet reconstruction in d+Au shows a centrality-dependent suppression of the jet yield.
  - Indicating either cold nuclear matter energy loss or modified nPDFs
  - If the latter, this data is an important constrain on nPDFs at both RHIC and the LHC.

# Backup Slides

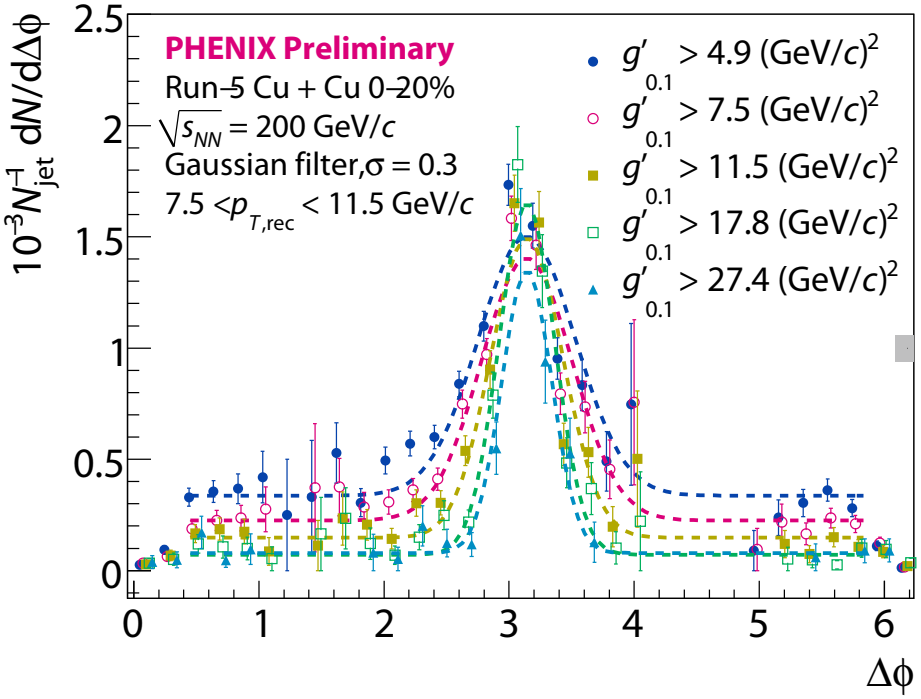
# Gaussian fake rejection

- Cut on the overall shape of the jet
- Inspired by the principle of Gaussian filter
- Strategy:
  1. Sum $p_T^2$ inside a Gaussian kernel to obtain a discriminant:

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

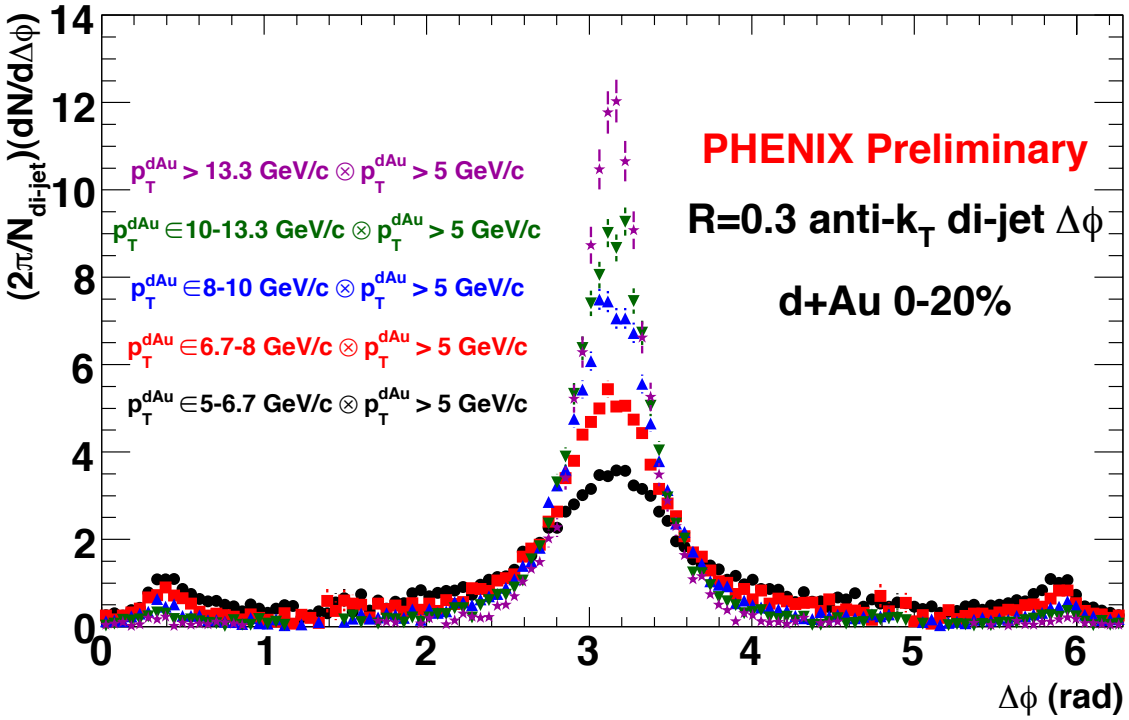
  2. Gaussian kernel $\sigma_{\text{dis}} \approx 0.1$
  3. (Technical detail: allow adaption for jets with very close maxima, obtain an updated $g'_{\sigma_{\text{dis}}}$)
- Cut on $g'_{0.1}$ = weighted $p_T^2$-sum
- In central Au + Au HIJING simulation proves to be more effective than $\sigma/\sqrt{\langle A \rangle}$ (Cacciari & Salam, Phys. Lett. B **659**, 119, 2008) and $\Sigma j_T$ (Grau *et al.*, arXiv:0810.1219, 2008)

# Fake rejection in Cu + Cu



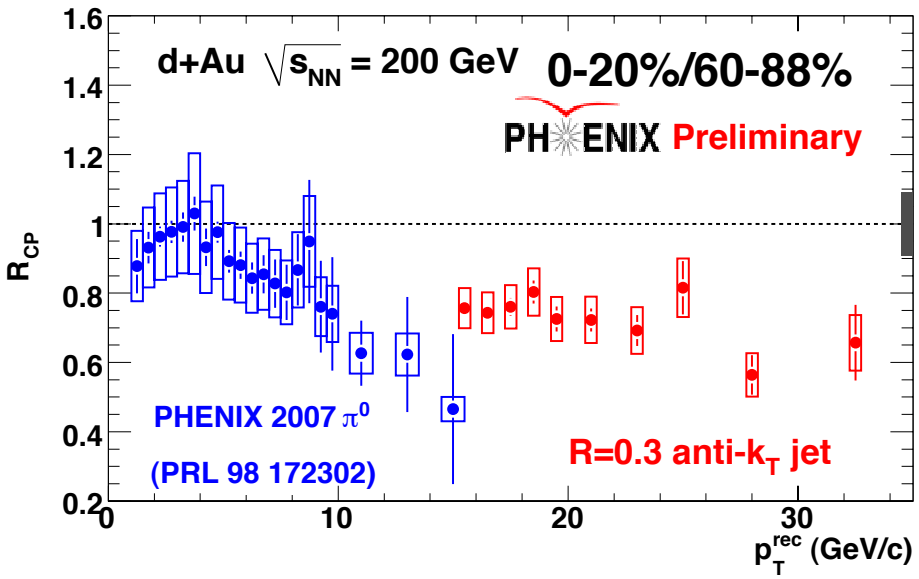

- Pedestal $\approx 0.3 \times 10^{-3}$ translates into $\frac{1}{2\pi}\frac{1}{N_{evt}}\frac{dN}{p_T dp_T dy} \approx 10^{-5}(\mathrm{GeV}/c)^{-2}$, substantial contamination for 7.5 GeV/$c$
- 17.8 $(\mathrm{GeV}/c)^2$ used as standard fake rejection cut level:
  - $\Rightarrow$ $<$ 10% contamination at 7.5 GeV/$c$

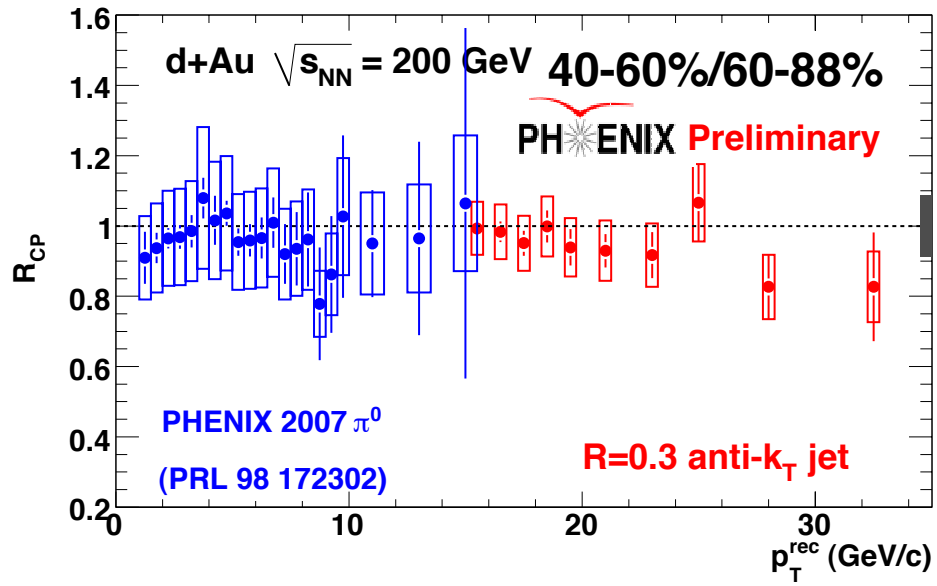
# Di-jet Δϕ Distributions




- Clear peak from di-jets indicates strength of signal
- Combinatorial background seen at lower $p_T$

# d+Au $R_{CP}$ Comparison to Single




- Comparison to published data from $\pi^0$
- Singles data used in EPS09 nPDF fits
- $R_{dA}$ is not as low for $\pi^0$