Probing Nuclear Matter with Jets and $\gamma$-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 $\gamma$-hadron Correlations

Statistical (Au+Au)

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

$$R_\gamma = \frac{N_{\text{incl}}}{N_{\text{decay}}}$$

Isolation (p+p) PRD 82 072001

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

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

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

$\langle I_{AA} \rangle = 0.598 \pm 0.095$
Fragmentation Function Shape: Au+Au to TASSO

- **Au+Au** goes down to $\xi \sim 3$, 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$^-$

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

$$\chi^2 / NDF = 12.16 / 7$$
Reconstructed Jets in Cu+Cu
Filter Jet Reconstruction in p+p

- Calculate

\[ \tilde{p}_T(\eta,\phi) = \int \int d\eta' d\phi' p_T(\eta,\phi) h(\eta,\phi,\eta',\phi') \]

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

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

- 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 $(T_{AB}-\text{scaled})$ p+p and Cu+Cu filter jets with $\sigma=0.3$
- Background subtracted, resolution accounted for with unfolding.

At the raw p+p jet scale
Hot Nuclear Matter Effects: Jet $R_{AA}$

- 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.

At the raw p+p jet scale
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-\(k_T\) 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 $p_{\text{out}}$

- Search for broadening of jets
  \[ p_{\text{out}} = p_{T,2} \sin \Delta \phi \]
  where $p_{T,2}$ is the lower-$p_T$ jet
- No indication of combinatorial background from fake jets.
- Tail of $p_{\text{out}}$ 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 $g'_{0.1} = \text{weighted } p_T^2$-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
  \[ \frac{1}{2\pi N_{\text{evt}}} \frac{1}{p_T dp_T dy} \approx 10^{-5} (\text{GeV}/c)^{-2}, \]
  substantial contamination for 7.5 GeV/c

- 17.8 (GeV/c)$^2$ used as standard fake rejection cut level:
  \[ \Rightarrow < 10\% \text{ contamination at 7.5 GeV/c} \]
Di-jet $\Delta\phi$ 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 $\pi^0$