Latest QCD results from PHENIX

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Probing the medium with high-$p_T$ particles

- The overall goal is to investigate the properties of the hot, dense matter produced in heavy ion collisions.
- As hard partonic scattering occurs as the medium is forming, the probes may be modified by medium.
- We wish to quantify that modification.

Both jets are subject to interaction with the medium.
Our tools

- PHENIX controlled
  - Centrality (system size)
  - Momentum
  - Particle Identification

- RHIC controlled
  - Can turn on and off the hot, dense medium
    - Collision Species
    - Collision Energy

- Today:
  - Single spectra
  - Triggered Correlations
  - $\gamma$ (and “Full”) jet reconstruction
A brief story of high-$p_T$ at RHIC:
Single particle spectra

- Earliest measurements at high-$p_T$:
  - Large “suppression” observed at high-$p_T$
  - Interpreted as energy loss in medium - jet quenching

- Difficult to be quantitative:
  - In the level of radiative versus collisional energy loss
  - Is jet quenching a perturbative or non-perturbative process
A brief story of high-$p_T$ at RHIC:
Two-particle correlations

- More direct evidence of jet quenching:
  - “disappearance” of backward jet
    - Interpreted as suppression due to parton energy loss
  - “reappearance” at low momenta
    - Shape modification on the away side
  - “no quenching” at highest $p_T$

- Still uncertainties
  - in the energy scale of the jet
  - Modifications to the fragmentation functions (expected softening and broadening of the jet)
  - Geometrical aspects
    - Position of hard scattering in the collision overlap area
    - The path length traversed in medium
    - Energy loss by the trigger or near side jet?
A brief story of high-$p_T$ at RHIC: Full-jet and $\gamma$-jet

- $\gamma$-jet: the golden channel for Heavy-ion collisions
  - No trigger/surface bias – opposite side (jet) yield averaged over all path lengths
  - Clean probe: can calibrate energy of the jet
  - Direct measure of the fragmentation function of the jet
  - Any modification of the FF interpreted as parton energy loss in the medium

- Full-jet: a relatively recent probe at RHIC
  - Direct observation of parton-medium interaction and medium response
  - $R_{AA}^{jet}$ → parton medium induced energy loss
  - Di-jet correlations → jet broadening
Testing the jet-quenching hypothesis: d+Au at RHIC

- d+Au versus Au+Au
  - Control experiment
  - “cold” versus “hot” nuclear matter
- Result:
  - Suppression in Au+Au central events not apparent in d+Au collisions
  - Suppression in Au+Au is a “final state” effect
Road map for further detailed studies

Know:
- Spectral suppression in Au+Au
- No suppression in d+Au
- Away-side jet also modified
  - Dependent on trigger-$p_T$
  - and/or associate $p_T$

Don’t know:
- How, why
  - Radiative, collisional energy loss?
- Systematic dependencies?
  - Path length
  - Color-charge
  - Collision energy
  - System-size
- Are our measurement methods biased?
  - Can we remove the bias with new methods?
PHENIX detector
Brief Overview

- Two mid-rapidity spectrometer arms: $|\eta|<0.35$ and $\Delta\phi=\pi/2$

- Main detectors used
  - Drift Chamber (DC), Pad Chamber (1&3), Cherenkov Detector(RICH)
    - Momentum measurement for charge particles, electron Id
  - EMCal (Pb-glass & Pb-scintillator)
    - Energy for photons ($\pi^0$, $\eta$)
  - TOF
    - PID at large momentum
  - VTX, FVTX
    - Upgrades for heavy flavor

Run 12 central arm configuration
Systematic Studies:
single spectra

- Path-length dependencies

- Simplest: suppression is dependent on the number of participants, $N_{\text{part}}$

- Similar dependence observed for $\pi^0$ and $h^\pm$ at high-$p_T$

*Phys. Rev. C69, 034910 (2004)*
Systematic Studies: single spectra

- Path-length dependencies

More precision:
- Currently observed
  - Average suppression
  - Integrated over the whole medium
- Separate in-plane versus out-of-plane
  - Controlled probe of energy loss due to medium
Systematic Studies
single spectra

- Path-length dependencies
- In- versus out-of-plane dependence observed in central

\[ \text{Phys. Rev. C80, 054907 (2009)} \]
Systematic Studies: single spectra

- Path-length dependencies
- In- versus out-of-plane dependence observed in central and mid-central
Systematic Studies: single spectra

- Path-length dependencies
- In- versus out-of-plane dependence observed in central and mid-central
- Suppression strongly correlated to the path length, not just system size ($N_{\text{part}}$)
  - Becomes more sharply defined with more sophisticated “path length”
Systematic Studies: direct-$\gamma$ spectra

Question:
- Is this really a suppression?

Solution:
- Measure direct-$\gamma$, which do not couple to the medium

Answer:
- Direct photons are not suppressed – scale with $N_{\text{coll}}$ (circa 2005)
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Systematic Studies: direct-γ spectra

- Question:
  - Is this really a suppression?

- Answer:
  - Direct photons are not suppressed – scale with $N_{\text{coll}}$ (circa 2005)

- Updated (circa 2011):
  - Direct photons do not scale with $N_{\text{coll}}$ at very high-$p_T$
Systematic Studies: energy scan

“High” energy scan
- Probe energy dependence of $R_{AA}$
  - $\sqrt{s_{NN}} = 200$, 62.4 and 39 GeV
    - “suppression” observed
  - $\sqrt{s_{NN}} = 39$ GeV
    - “enhancement” peripheral

(“Low” energy scan
- $\sqrt{s_{NN}} < 20$ GeV
- Focus on studying the QCD phase diagram
- outside the scope of this talk.)
Systematic Studies: energy scan

“High” energy scan
- Probe energy dependence of $R_{AA}$
  - $\sqrt{s_{NN}} = 200, 62.4$ and $39$ GeV
    - “suppression” observed

- Path length dependence observed, and similar for energies > $39$ GeV
Ultimate energy scan:

- Comparison to LHC
  - Same old same old
  - nothing changes? Why?
Systematic Studies: species scan

- We have seen d+Au
  - What about other smaller systems?

- Same old same old
  - $R_{AA}$ for $\pi^0$ scale with $N_{\text{part}}$
  - Approximate path length dependence holds

![Graph showing $R_{AA}$ for $p_T > 7.0 \text{ GeV/c}$ with $N_{\text{part}}$ on the x-axis and $R_{AA}$ on the y-axis. The graph includes data points for integrated $R_{AuAu}$ and $R_{CuCu}$ at 200 GeV.]
Triggered correlations

- **Advantage:**
  - Jet like
  - Can tune trigger and associates to probe different kinematic regions

- **Disadvantage**
  - Need large statistics
  - Need wide coverage

- **Advantage** **AND**
  - Disadvantage
    - Surface bias
Surface bias single spectra versus h-h correlations

- No trigger / no surface bias
  - Probe full medium
  - Path length is not fixed

- Triggered / have surface bias
  - Owing to preferred interactions from edge of medium
  - Associate path length “fixed”
Systematic Studies: triggered correlations

- High-\( p_T \) – high-\( p_T \) correlation
  - Away-side suppression relative to \( p+p \) collisions
Systematic Studies: triggered correlations

- High-$p_T$ – low-$p_T$ correlation
  - Away-side shape modification relative to $p+p$ collisions
Systematic Studies: triggered correlations

- Form a nuclear modification factor, like $R_{AA}$ (now a conditional $R_{AA} \rightarrow I_{AA}$)
  - Associates:
    - Clear path length dependence
    - $p_T$ dependent
  - Trigger:
    - No dependence – surface bias?

- How does this compare to $R_{AA}$?
How does this compare to $R_{AA}$?
- Same (?)
- But we are sampling more medium with the conditional $I_{AA}$?
We should try something else ...
**γ-jet reconstruction**

- **γ-jet**
  - No γ-medium interaction

- **Two advantages:**
  - No trigger surface bias
  - Energy calibration of associate-jet

- **With no surface bias:**
  - Expect a *smaller* modification to away-side
    - Smaller average path length as triggers may come from any point in the medium

Hadron-triggered correlations:
- Both jet subject to interaction with the medium
- Surface bias probable (trigger jet must emerge)
- Associated path length “fixed”

Photon-triggered correlations:
- Only hadronic jet subject to interaction with the medium
- No surface bias
- Associated path length not fixed
γ-jet reconstruction

- γ-jet
  - No γ-medium interaction

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  - No trigger surface bias
  - Energy calibration of associate-jet

- With no surface bias:
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Hadron-triggered correlations:
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Hadronic jet FF in Au+Au

- Calibrated probe
  \[ p_T^\gamma \approx p_T^{\text{jet}} \]

- \( D_{AA}(z_T) \) and \( I_{AA} \) extracted from the “head” region on the away side of the \( \gamma+\text{hadron} \) correlation

- \( z_T \) scaling in Au+Au

- FF modification in AuAu

- \( Y \)-axis
  \[ D_q(z_T) = \frac{1}{N_{\text{ev}1}} \frac{dN}{dz_T} \]

- \( X \)-axis
  \[ z_T = \frac{p_T^h}{p_T^\gamma} \]

A. Adare et al (PHENIX) PRC 80, 024908 (2009)
Medium modification of hadronic jet

- Centrality dependence of $\gamma$-hadron $I_{AA}$
  - Consistent with $\pi^0$-hadron $I_{AA}$
  - Consistent with $R_{AA}(\pi^0)$

- Same level of suppression
  - Not expected
  - Is there surface bias?
  - Is there a path-length effect?
  - Is there suppression at all?
Full jet reconstruction

- Measure the total energy loss of the parton
  - No ambiguity from the FF modification or
  - Energy scale of the jet

- Jet $R_{AA}$ versus $p_T$
  - Energy scale is of the reconstructed $pp$ jet

- Modification is observed in central collisions
  - Gradually increasing with centrality
  - Appear unmodified in peripheral

$$R_{AA} = \frac{1/N_{evt}}{\langle T_{AB} \rangle} \times \frac{d^2 N_{Cu}/dp_T dy}{d^2 \sigma_{pp}/dp_T dy}$$
Jet modification

- Strong jet modification is observed for central Cu
- **Same level** as single-$\pi^0$ spectra for overlapping $p_T$ range
  - Within energy scale and point systematics
  - Note: $R_{AA}$ single-$\pi^0$ spectra at a different energy scale than reconstructed jets
    - $\pi^0$ are relatively squashed down
    - (a 10 GeV $\pi^0$ came from a >10 GeV jet)
Does the jet broaden in the medium?

- Dijet studies
  - No centrality difference
  - Surviving parton traversing medium has very small transverse $k_T$ broadening?
  - Jets are not deflected more in central than in peripheral
Summary

- PHENIX has made a wide range of high-$p_T$ measurements
  - Single Spectra
  - Triggered Correlations
  - Direct photons
  - Full jet reconstruction
- Have observed a clear path length dependence to the modification of the spectra relative to $pp$ interactions
- Path length dependencies are surprisingly similar for
  - Single and triggered distributions
  - Hadron and photon triggered correlations
  - Reconstructed jets
- Needs more systematic studies to complete the parton energy loss picture
Backup
Full jet reconstruction

- Gaussian filter
  - Cone-like algorithm
    - without sharp angular cut-off
  - Gaussian distributed weights, kernel size $\sigma$
    - Enhances the center signal to the periphery $\rightarrow$ optimizes signal-to-background

$$\int_{\mathbb{R} \times S^1} d\eta' d\phi' p_T(\eta', \phi') \exp \left[ -\frac{(\eta - \eta')^2 + (\phi - \phi')^2}{2\sigma^2} \right]$$

- Background:
  - Fake jet rejection scheme
    - No statistical subtraction
    - Trade-off between reconstruction efficiency and acceptable rejection rate

Lego: final state particle $p_T$
Top contour: filter output
Red lines: reconstructed jets

Run-5 Cu + Cu at $\sqrt{s_{NN}} = 200$ GeV
19-20% cent., 24.3, 10.3 GeV/c dijet
Jets in d+Au at 200 GeV

- Jet $R_{cp}$ versus $p_T$
  - Energy scale is of the reconstructed $pp$ jet

- Suppression is observed in central collisions
  - Gradually increasing with centrality
  - Appear unmodified in peripheral
  - Consistent with single particle $\pi^0$
  - Cold nuclear matter energy loss?
Jets in d+Au

- Jet $R_{cp}$ versus $p_T$
  - Energy scale is of the reconstructed $pp$ jet

- Suppression is observed in central collisions
  - Gradually increasing with centrality
  - Appear unmodified in peripheral
  - Consistent between cone size
Di-jets in d+Au

- Multiple scattering in cold nuclear matter
(Direct) Fake jet rejection

- Inspired by the Gaussian filter algorithm: cut on the shape of the jet

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

Discriminant:
- Weighted $p_T^2$ sum with a Gaussian distribution
  - $\eta, \phi$ is the reconstructed jet axis
- Size of Gaussian kernel $\sigma_{\text{dis}} = 0.1$
  - $\sim$ characteristic background particle separation
    \[ [dR_{\text{back}} = \sqrt{2\pi/(dN/d\eta)}] \]
- Allow jet axis to shift until $g_{\text{dis}}$ is maximized ($g'$)
- Cut on $g'_{0.1} > 17.8$ (GeV/c)$^2$
  - Fixed discriminant threshold $\rightarrow$ nearly centrality independent efficiency

"Real" jet passes cut

"Background fluctuation" fails cut
Jet energy correction

- Correction to true jet energy scale
  - Difficult via multiplicative factor
  - Unfolding of the measured spectrum by using an energy transfer matrix
    - Regularized inversion of the reconstructed to the “true” spectra using singular value decomposition (SVD), GURU*


Reconstructed/true jet transfer matrix for pp at 200 GeV.
Gaussian filter with $\sigma=0.3$
GEANT Pythia 6.4.20 simulation.
Jet reconstruction efficiency

200 GeV Cu+Cu collisions

Jet reconstruction efficiency
- *pp* jets embedded into Cu+Cu data
- Includes fake rejection
  - $g'_{0.1}>17.8$ (GeV/c)
  - Jets with $p_T>16$ GeV/c are above the discriminant threshold for fake jets
    - Little effect on $R_{AA}$, spectra above this $p_T$
- Nearly centrality independent

*Embedding of pp into Cu+Cu data. Efficiency includes the fake rejection.*
Fragmentation functions

- \( z = \frac{p_{\text{particle}}}{p_{\text{jet}}} \)
  - \( p_{\text{jet}} \) must be the true jet energy to perform “apple-to-apple” division, otherwise \( z \) is shifted

- 2D unfolding needed to simultaneously unfold \((p_{\text{particle}}, p_{\text{jet}})\)
  - Phenix developed a n-D generalization to GURU
  - First time 2D regularized SVD unfolding is applied in HEP/NP

- Result for Run-5 \( p + p \) minimum bias only
- Direct comparison to (perfect detector) PYTHIA at \( p_{\text{jet}} = 15 \text{ GeV/c} \)
- Particle species:
  - Non-ID charged tracks (rejecting e\(^-\), mostly from \( \gamma \) beam-pipe conversions)
  - Neutral clusters (electromagnetic)
- Single particle resolution not yet unfolded (very small effect)
  - \( \delta p/p = 0.7\% \oplus 1.0\% p/(\text{GeV/c}) \)
- Uncertainty in the absolute energy scale of the calorimeter clusters
  - \( \pm 3\% \text{(syst)} \)
Systematic Studies: species, energy scan

“High” energy scan

- Probe energy dependence of $R_{AA}$
  - $\sqrt{s_{NN}}$ = 200 and 62.4 GeV
    - “suppression” observed
  - $\sqrt{s_{NN}}$ = 22.4 GeV
    - “enhancement”

![Graph showing $R_{AA}$ vs. $p_T$](image_url)
"High" energy scan

- Probe energy dependence of $R_{AA}$
  - $\sqrt{s_{NN}}=200$ and 62.4 GeV
    - "suppression" observed
  - $\sqrt{s_{NN}}=22.4$ GeV
    - "enhancement"

- Path length dependence observed, and similar, at higher energies
Systematic Studies: identified single spectra

- Further examination
  - Color-charge dependence
  - Via Particle-ID

- Strong species dependence of $R_{AA}$
  - Proton modification distinct from meson
FF modified in Au+Au?

- $z_T$ scaling in Au+Au
- Universal fit for all jet energies to compare with $pp$
- Slopes difference
  - $p+p$, $b=6.9\pm0.8$
  - Quark fragmentation $b=8$, gluon fragmentation $b=11$
  - Au+Au, $b=9.5\pm1.4$
- Au+Au slope is $1.3\sigma$ larger than $pp$

Fit function: \[
\frac{dN}{dz_T} = N e^{-b z_T}
\]