High-pt probes of the quark-gluon plasma: STAR/PHENIX results at RHIC

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1. What happens to a high-pt parton as it travels through a quark-gluon plasma (QGP)?
2. What does this tell us about the QGP?
3. Not much time on how QGP responds to the hard parton.

QCD Phase Diagram

Within sQGP, momentum transfers ~ T ~ few 100 MeV/c => coupling large
Non-perturbatively interacting plasma of quarks and gluons far from an ideal gas
One way to probe the sQGP

**hard-scattered parton:**
calc. with perturbative QCD

jet of hadrons

**hard-scattered parton during Au+Au**

Hadron distribution changed
- singles spectra
- 2-particle correlations
- jet-structure

Information on the plasma?

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Hard-scattering as a calibrated probe

- Large scale that makes perturbative QCD applicable:
  - high momentum transfer $Q^2$
  - Assume factorization between
    - perturbative hard part $\sigma$
    - universal, non-perturbative
      - parton distribution functions ($f_A$, $f_B$)
      - fragmentation ($D_{fV}$) functions
  - from $e^+e^-$, $p+p$....
$\sqrt{s}=200$ GeV, p+p $\rightarrow$ x
NLO QCD agrees well with data

Partons lose energy as they travel through QGP

- p+p cross-section scaled by $\pi$ or nucleon collisions in Au+Au
- Fewer high-pt $\pi^0$ in Au+Au
- Energy-lost by parton => info on opacity, density of QGP
Au+Au $\pi^0$ $R_{AA}$

$$R_{AA} = \frac{dN / dp_{\perp} (Au + Au)}{N_{coll} dN / dp_{\perp} (p + p)}$$

Elliptic asymmetry at high-$pt$

Overlap zone is elliptical:

More energy-lost if parton travels through long-direction of ellipse

Fewer high-$pt$ hadrons out-of-plane

Asymmetry, $v_2$,

$$\frac{dN}{d\phi} = A(1 + 2v_2 \cos(2\phi))$$
Particles correlated with high-pt trigger

\[ \Delta \phi = \phi_1 - \phi_2 \]

\( p+p, \text{PHENIX} \)

PRD, 74 072202 (06).

Correlation survives high-multiplicity environment of A+A

Suppression of far-side hadrons

Far-side yield per trigger sensitive to relative energy lost by both partons

\[ 8 < p_{\text{trig}} < 15 \text{ GeV/c} \]

\[ 0 < |\Delta \phi - \pi| < 0.63 \]

Far-side yield per trigger

=> Alphabet of observables, D(z_T), I_AA, J_AA, …
Use measurements to learn about QGP

\[ \hat{q} = \frac{\mu^2}{\lambda} \]  

- Wiedermann: models of gluon radiation, transport parameter \( \hat{q} \)
- Note
  - Hard-scattering takes place throughout collision volume
    - Data and models average over wide range pathlengths…
  - Medium expands rapidly \( <\hat{q}> \)
    - Parton travels through a medium whose density decreases

Comparison data + models (e.g. PQM)

Vary transport parameter \( <\hat{q}> \)

\[ \chi^2(e_b, \epsilon_c, p) = \sum_{i=1}^{n} \left( \frac{y_i - \epsilon_b \sigma_{b,i} e^{- \epsilon_c \sigma_{c,i} p}}{\sigma^2_i} \right)^2 + \epsilon_b^2 + \epsilon_c^2 \]

\[ <\hat{q}> = 132 \pm 2.1 \text{ GeV}^2/\text{fm} \]

But no model uncertainty yet
**Strong energy-loss**

Large $<q>$

$\Rightarrow$ high momentum transfer

$\Rightarrow$ strong QGP coupling

**Experimentalist’s reaction:**

1) Reduce averaging over path-length

2) Other observables to check understanding of energy-loss

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**Change average over path-length:**

$R_{AA}$ versus reaction plane

Overlap zone is elliptical:

More energy-lost as parton travels through long-direction of ellipse

$R_{AA}$ smaller out-of-plane

Model T. Renk, vary $E_{\text{loss}}$

PHENIX prelim centrality 20-30%

$\pi^0$ 6<pt<7 GeV/c

This and other models fail, yet reproduce $R_{AA}$ vs pt

1. Need stronger variation of $E_{\text{loss}}$ for different paths, or

2. Sharper early spatial distribution of energy density, or

3. More rapid variation of $q$ with $\epsilon$, or ……
Test for other mechanisms of energy-loss:

- Radiation due to scattering
- Elastic collision, energy re-distribution

Many calcs on relative importance

Probe via high-pt heavy-quarks
- smaller energy loss after elastic collision
- gluon radiation also reduced
- interference during radiation dead-cone effect

S. Wicks, W. Horowitz, M. Djordjevic, M. Gyulassy (WHDG) nucl-th/0512076

Heavy-Quark Energy-loss

Semi-leptonic decays of charm beauty mesons, R. Averbeck

Strong suppression of high-pt charm

PRL98, 172301 (2007)
Radiative+collisional energy-loss models struggle


Note, BDMPs charm only, may not be realistic to remove beauty

Strong resonance interaction in-medium

Heavy-quarks may form resonances in sQGP near $T_c$

H. van Hees et al, PRL 100, 192301 (2008)
Separation charm/beauty
PHENIX VTX, STAR HFT

silicon pixel+strip detectors
Tracks extrapolate back to collision
Displaced vertices
=> charm (D), beauty (B)
Requires ~ 50 μm precision

Great hardware opportunity for post-docs

Medium Response: Low-pt far-side

Trigger: 3 < p_T < 4 GeV/c
Assoc: 1 < p_T < 2 GeV/c,


Growing evidence for conical medium response
STAR: 3-particle correlations
PHENIX: angle of conical emission independent of pt
=> not bremsstrahlung
No clean separation between medium-response and fragmentation?

Shocked medium contributes to fragmentation

e.g. coalescence of protons from shower+medium partons

=> Additional high-pt protons

R. Hwa

Protons

More protons than pions at high-pt, even out to 10 GeV/c

- Fragmentation to protons enhanced by combining with shocked medium? and/or
- As parton propagates in medium it can change flavor => energy-loss comparable for gluons and quarks,

Liu, W. and R.J. Fries, PRC 2008. 77 054902
Next Steps (I/III): Excitation Function

- Does $q$ return to perturbative QCD at LHC?
- Evaluate $q$ at SPS (in progress)
- Low-E RHIC, onset of strong opacity?

Evaluate $q$ at SPS (in progress)

Low-E RHIC, onset of strong opacity?

Other values for $q_0$: Stefan Bass

define local transport coefficient along trajectory $\xi$ for all three approaches and compare initial maximum value $q_0$:

\[
\begin{array}{|c|c|c|c|}
\hline
q_0 \text{ [GeV}^2/\text{fm}] & \text{ASW} & \text{HT} & \text{AMY} \\
\hline
T & 10 & 2.3 & 5.5 \\
\varepsilon & 20 & 4.5 & X \\
S & 3.4 & X \\
\hline
\end{array}
\]

(all values quoted for a gluon jet)

different medium scaling can affect $q$ by a factor of 2
need higher precision data and theory advances to provide guidance for proper medium scaling
$\sqrt{s_{NN}}$ Dependence: $p_T$ Dependence of $\pi^0 R_{AA}$ in Cu+Cu

- 62.4, 200 GeV:
  - Suppression consistent with parton energy loss for $p_T > 3$ GeV/c
- 22.4 GeV:
  - No suppression
  - Enhancement consistent with calculation that describes Cronin enhancement in p+A
- Parton energy loss starts to prevail over Cronin enhancement between 22.4 and 62.4 GeV

Next Steps (II/III) Measure $\Delta E$ directly

- Direct $\gamma$ to tag energy
  - Compton
  - Annihilation

- RHIC-II, LHC

Conclusion
Next Steps (III/III): Fragmentation within jet

- Jets with pt-cut off

- Higher-pt => LHC, RHIC-II

Conclusion

- Energy-loss as high-pt parton travels through QGP
  - Opaqueness parameter, momentum transferred/length $<\hat{q}>$
  - $<\hat{q}>$ larger than expected pQCD, $=>$ strongly coupled QGP

- Puzzles
  - $R_{AA}$ vs $\phi$, modeled $E_{loss}$ too flat $=>$ stronger spatial variation?
  - Large heavy-flavor $E_{loss}$ $=>$ quasi-resonances near $T_c$?
  - Proton $R_{AA}$ closer to 1 $=>$ shocked medium recombining?

- Next steps
  - Excitation function of $<\hat{q}>$, LHC, SPS, low-E RHIC
  - $E_{loss}$ via $\gamma$-h and reconstructed jets
For each proton trigger, number of mesons starts to decrease

- Additional source of protons, e.g. from medium response
Ratio of \((\text{Au+Au})/(\text{scaled p+p spectra})\)

- Mesons suppressed \(\times 5 \rightarrow\) energy-lost in QGP
- \(\gamma\) scale with parton flux

RAA \(\pi^0, \eta, \phi, J/\psi, \omega\) Mesons and Direct \(\gamma\)

- Same suppression pattern for \(\pi^0\) and \(\eta\):
  - parton energy loss and fragmentation in the vacuum
- \(R_{AA}\) for \(\phi\)'s larger than \(\pi^0\) \(R_{AA}\) for \(2 < p_T < 5 \text{ GeV/c}\)
Far-side Production of Particles

Observation of particles produced ~1 radian away from back-to-back!

Fit with 2 Gaussians, each D radians away from π
D scales with system size

=> emission consistent with medium’s response to jet

Response of medium to passage of high-pt parton

- Near-side, generation of ridge => strength large Δη (STAR talk)
- Far-side: does super-sonic parton generate a mach-cone?

hep-ph/0410067;
H.Stocker...
Jorge Casalderry-Solana
Conical flow – QM08: B. Cole

- Cone angle does not change appreciably as a function of $p_T$ of trigger or associated hadron.
- Or centrality, or angle wrt reaction plane

Fragmentation within jet: J. Putschke

- Raw data, no correction of efficiency, trigger bias and energy resolution
Strongly Interacting QGP

SU(4), Lattices with Ns/Nl=3

$|e-3p|/T^4$

$N_{s=0}$

$N_{s=3}$

$T/T_c$

1

1.2

1.4

S. Gupta QM08

LHC predictions: Xin-Nian Wang

$R_{PbPb}(p_T=20,50 \text{ GeV}/c=0)$ in central Pb+Pb at $\sqrt{s_{NN}}=5.5 \text{ TeV}$

- Wang et al., $\gamma^5$, 5% ($c_\text{V}=3.95 \pm 0.05$), WW eloss+1d exp., shadowing
- Yiter, $\gamma^5$, 10%, GLV+1g+feedb., rad+coll. alphas, $dN/dy=1.7-3.2$ ($dN/dy_{\text{MC}}$
- Pantzou, charged, $N_{s=350}$, $\gamma^5=1.2$ fm, $\gamma^5_{\text{MC}}$
- Lohitashvili et al., charged, 10% ($dN/dy_{\text{MC}}=2700$), rad+coll. alphas in MC
- Kopeliovich et al., $\gamma^5$, 10%, early hadronization
- Liu et al., $\gamma^5$, $\gamma^5_{\text{MC}}=10$, 10%, 2c+2w. conv., transv. exp.
- Jeon et al., $\gamma^5$, $p_T^{\text{CSS}}=40$, 10% ($L=1$ fm), BH alphas+QW, GTA
- Wicks et al., $\gamma^5$, 10%, rad+coll. alphas, $dN/dy_{\text{MC}}=1.75-2.9$ ($dN/dy_{\text{MC}}$
- Qin et al., charged, 10% ($dN/dy_{\text{MC}}=2500$), AMY hydro, $c_\text{V}=0.25-0.33$
- Renk et al., $\gamma^5$, 10% ($dN/dy_{\text{MC}}=2500$), BDIMPS QW with hydro env.
- Dannese et al., $\gamma^5$, 10%, BDIMPS QW with Y3, $\gamma^5_{\text{MC}}=2-3$
- Cunqueiro et al., $\gamma^5$, 10% ($dN/dy_{\text{MC}}=1500$), percolation
- Capella et al., $\gamma^5$, 10% ($dN/dy_{\text{MC}}=1800$), comovers, kinematics