Stage 1:
The Future of Jet Physics at RHIC

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What is sPHENIX?
What is sPHENIX?
the core of a *standard model* for heavy ion collisions

but missing a comprehensive description of the hard sector:  
*parton energy loss* and *quarkonia suppression*

+ bulk medium properties and microscopic state
Can jet measurements be integrated into this standard model of heavy ion collisions in a meaningful way?
Hydro's Home Turf

spectra

\[ \frac{1}{2\pi p_T} \frac{dN}{dp_T} dy (c^2/GeV^2) \]

- **Au+Au @ 200 GeV 0-5% Central**
  - PHENIX \((\pi^+ + \pi^-)/2\)
  - PHENIX \((K^+ + K^-)/2\)
  - PHENIX \((p + \bar{p})/2\)
  - Hirano Ideal Hydro + Cascade

elliptic flow

- **Au+Au @ 200 GeV Minimum Bias**
  - PHENIX \((\pi^+ + \pi^-)/2\)
  - PHENIX \((K^+ + K^-)/2\)
  - PHENIX \((p + \bar{p})/2\)
  - Hirano Ideal Hydro + Cascade

(time)
Different descriptions of the initial state yield different best fit values for the viscosity term...

But the different descriptions are all incompatible with large values of viscosity

However, these values are near the conjectured lower bound for quantum fluids

\[ \eta/s = 1/4\pi \]
Low Viscous Fluids

- Water at 100 MPa
- Nitrogen at 3.4 MPa
- Helium at 0.1 MPa

Quantum bound

KSS PRL 94, 111601 (2005)
Perturbative QCD
Weakly-coupled description of the QGP imply a much larger viscosity and a very large scale dependence
AYM JHEP 0305:051, 2003

Quantum bound
KSS PRL 94, 111801 (2005)
sQGP Calculations

sQGP calculations all yield much lower values Internally very different...

Hydro + IQCD calculation
Kovtun, Moore, and Romatschke

Hadron gas calculation
Prakash (almost 20 years ago) 1/T^4)

Lattice QCD result
Harvey Meyer (gluodynamics)
http://arxiv.org/abs/0704.1801

QPM, finite mu_B calculation
Shrivistava and Singh

Semi-QGP calculation
Rob Pisarski with kappa = 8
If we accept: (I) the viscosity is low near $T_c$ as implied by the hydro fits... (II) at large $T$, the pQCD description is correct...

Some transition between the two must exist. Illustrative scenarios:

(I) Rapid evolution

(II) Intermediate evolution

(III) Slow evolution
Jet Quenching Implications

in the pQGP limit: \( \hat{q} = 1.25T^3/\left(\eta/s\right) \)
“[We find] the jet quenching is a few times stronger near $T_c$ relative to the QGP at $T > T_c$.”

Completely different physical source, here the creation of magnetic monopoles

Thus the evolution of $\eta/s$ likely has implications on the characteristics of jet quenching
Of course a better theoretical translation between the medium properties and energy loss characteristics is needed.

But an opportunity exists to integrate the jet observables into our wider understanding of heavy ion collisions.
It isn’t clear hydro can solve this on its own...
Hard Parton Virtuality

\[ Q_{\text{vac}}^2(t) = \frac{E}{2t} \]

\[ Q_{\text{med}}^2(t) = \int \hat{q}(t) \, dt \]

\[ Q^2(t) = Q_{\text{vac}}^2(t) + Q_{\text{med}}^2(t) \]

**LHC Scenario**

The vacuum contribution to the parton virtuality to fall below the in-medium contribution in the pQCD scenario. This effect is due to the collinear splitting in pQCD, which reduces the parton energy only gradually and thus leads to an increase in time dilation as the virtuality drops. This means that the very energetic parton hardly notices the medium for the first 3 – 4 fm of its path length. On the other hand, in the AdS/CFT scenario, parton energy and virtuality
The surprisingly transparent sQGP at LHC

W.A. Horowitz a, *, Miklos Gyulassy b


Since there are no adjustable parameters for us, the significant tension between our results and the ALICE data is a failure to simultaneously describe the normalizations of both the RHIC and LHC $R_{AA}(p_T)$. One possibility is the sQGP produced at LHC is in fact more transparent than predicted by perturbative QCD tomographic models with medium densities that scale with observed particle rapidity densities.

Beam energy variation will likely be an asset
Can we measure these jet observables at RHIC?
Huge rates allow differential measurements with geometry ($v_2$, $v_3$, $A+B$, $U+U$, ...) & precise control measurements ($d+Au$ & $p+p$).
Over 60% as dijets!

Rates based on full stochastic cooling, but no additional accelerator upgrades
γ/π⁰ very large at RHIC

good S/B >20GeV

substantial rate even >30GeV

RHIC a very good place for γ-jet correlations
(I) Irresolution: How well can we measure real jets?

metrics: jet energy scale, jet energy resolution
method: embed PYTHIA jets in HIJING events

(II) Contamination: How are the jet measurements impacted by background fluctuations masquerading as jets--fakes?

metric: relative rate of fake jets and true jets
method: 500M minimum bias HIJING events to determine relative rates of fake and real jets
A 30 GeV embedded jet picks up ~10 GeV from the background to become a 40 GeV reconstructed jet.

These tools are underdevelopment...
**Background Subtraction**

Jet - Underlying Event Separation Method for Heavy Ion Collisions at the Relativistic Heavy Ion Collider

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(Dated: March 8, 2012)

**arXiv:1203.1353**

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**Diagram:**

- Run jet reco algorithm on 0.1x0.1 calorimeter cells
- Determine set of R=0.2 seed jets
  - 1\(^{st}\) pass: towers in jet satisfy \( \frac{E_{T,max}}{<E_T>} > 3 \)
  - 2\(^{nd}\) pass: jet \( E_T > 20 \)
- Determine \( v_2 \) for event
  - exclude towers within \( \Delta \eta < 0.4 \) of seed jet
- Determine background \( E_T \) in \( \eta \) strips
  - demodulate by \( v_2 \)
  - exclude towers within \( \Delta R < 0.4 \) of seed jet
- Subtract background from jets tower-by-tower
  - first remodulate background by \( v_2 \)
- Subtract background from event tower-by-tower
  - first remodulate background by \( v_2 \)
- Run jet reco algorithm

Output: background subtracted reco jets of various R values
good performance in heavy ion background, small over-subtraction of few%

resolution only from the underlying event, no detector resolution included
Truth Jets

Implemented a modified HIJING simulation to report instances of jet production whenever those processes are called.
• $b = 1.8\text{fm}$ HIJING dijet event
• well reconstructed with anti-$k_T$ $R=0.2$
Fake Jet Example

- $b=2.4$ HIJING event, no true jets
- 30 & 10 GeV fake jets with anti-$k_T$ $R=0.4$

however, we looked at 500M events! need quantitative rate assessment

arXiv:1203.1353
Reconstructed Jets and Fakes

Au+Au @ 200 GeV, 0 - 10%

\[ \frac{1}{N_{\text{events}}} \frac{dN_{\text{jets}}}{dE_T} \left(\text{[GeV]}^{-1}\right) \]

- HIJING True Jets
- sPHENIX Recon. Jets
- sPHENIX Recon. matched
- sPHENIX Recon. not matched

R = 0.2 Anti-\( k_T \) Jets

Real jet spectrum
Fake jet spectrum

Real jets dominant above 20 GeV for R = 0.2
Conservative: no additional fake jet rejection or selective cuts.
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Impact on Dijet Measurements

NB: second jet can go much lower...

PYQUEN parameters from
Lokhtin et al.
hep-ph/0506189

\[ E_{T1} > 35 \text{ GeV}, \quad E_{T2} > 5 \text{ GeV} \]

Expected modification to \( A_J \) from quenching models clearly measurable
Impact on Dijet Measurements

NB: second jet can go much lower...

Unmodified Truth

Expected modification to $A_J$ from quenching models clearly measurable
Impact on Dijet Measurements

PB: second jet can go much lower...

PYQUEN parameters from
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$E_{T1} > 35 \text{ GeV}, E_{T2} > 5 \text{ GeV}$

Unmodified Truth

Reconstructed

Expected modification to $A_J$ from quenching models clearly measurable
Impact on Dijet Measurements

PYQUEN parameters from
Lokhtin et al.
hep-ph/0506189

\[ \text{Unmodified Truth} \]
\[ \text{Reconstructed} \]
\[ \text{Medium effects} \]

NB: second jet can go much lower...

\[ E_{T1} > 35 \text{ GeV}, \ E_{T2} > 5 \text{ GeV} \]

\[ \frac{d^2N}{dA d\mathbf{k}} \]

\[ \text{anti-}k_T \ R=0.2 \]

\[ \bullet \text{ true di-jet} \]
\[ \otimes \text{ reco di-jet} \]
\[ \triangle \text{ matched di-jet} \]

\[ \text{Au+Au @ 200 GeV, 0 - 10\%} \]

Expected modification to \( A_J \) from quenching models clearly measurable
Upgraded sPHENIX detector will measure jets out to 70 GeV, R=0.2 (0.4) above 20 (35) GeV in central collisions

Direct photons out to 50 GeV

π⁰ R_{AA} out to 40 GeV
(with additional pre-shower detector)

Jet longitudinal and transverse profiles are key in disentangling radiative and collisional

Jets substantially extend transverse energy reach!

Jets allow for full correlation and fragmentation function measurements

All put together allows one to over-constrain theory (best of all worlds)
What will sPHENIX need to look like to make these measurements?
Requirements

large acceptance

high rate

sPHENIX detector concept

Stage 1

compact 2T solenoid

tungsten-scintillator EMCal

steel-scintillator HCal and flux return

Additional

tracking layers

preshower EMCal
All heavy ion jet publications to date (i.e. ATLAS and CMS) come from hermetic calorimeter measurements!

Ability to try different methods (supplementing with tracking) is also a big advantage.

Critical to have EMCal + HCAL with hermetic coverage (no gaps, spokes, holes) with large coverage to see both jets and γ-jet and at very high rate. Then add in tracking information as key additional handle for systematic studies.

Also, when measuring fragmentation functions, hadron $p_T$ and jet energy measures are independent.
HCal Design & GEANT-4 Response

Steel-Scintillator Design
Flux Return for Magnet
Fiber Coupled to SiPM Readout
Common Electronics with EMCal

Corresponds to 75%/VE
Stage I: Compact EMCal

Innovative EMCal design

SiPMs or APDs

ρ(sintered W) ~ 0.9ρ(pure W)
formed in arbitrary shapes
& SiPMs
↓
compact EMCal
Stage 1: Compact EMCal II

Magnet + CEMC Response

Al (8.879 cm)

CEMC Design

... total 30 layers ...

1 mm 2 mm W + 0.3 mm W Epoxy

36
Stage I: Compact EMCal II

Magnet + CEMC Response

Al (8.879 cm)

Sampling Fraction ~2.75%

\[ \frac{E}{E_{\text{true}}} \text{ mean} \]

\[ \frac{E}{E_{\text{true}}} \text{ width} \]

CEMC Design

... total 30 layers ...

1 mm 2 mm W + 0.3 mm W Epoxy

9.67 cm
Stage 1: Compact EMCal II

Magnet + CEMC Response

![Al (8.879 cm)](image)

Sampling Fraction ~2.75%

Resolution = (14.2 ± 0.1)%/\sqrt{E}
Further Staged Upgrades

Charged Particle Tracking:
Add spare ladders to the VTX to fill out 2π acceptance

Add 2 or more tracking layers needed to recover tracking capability

Get intra-jet measurements (FF, jT)

Tracker

PreShower
EMCal
Solenoid
HCal

Theo Koblesky (Colorado), APS 2012
Further Staged Upgrades

Electron (π0) Identification

- Add a Preshower EMCal
- Together need ~x1000 rejection

- Get π0 spectra to 40 GeV
- Get Heavy flavor jets
- Get quarkonia decay channels

Preshower

Tracker
EMCal
Solenoid
HCal

Tracking irresolution only

Y(1S,2S,3S)

1 RHIC AuAu run
50B MB events

e^+e^-

invariant mass (GeV/c^2)
Jet measurements at RHIC can inform our understanding of the bulk behavior of the QGP.
- Discussed the viscosity quenching dualism
- Differences in behavior at RHIC vs LHC
- Eventually narrow in on a microscopic picture

Jet measurements at RHIC are feasible against the backgrounds
- Background subtraction is working
- Embedded irresolution can be handled
- Fake rates are small for a wide range of interesting kinematics

sPHENIX is being designed to meet the needs of the jet program
- Impact of detector irresolution on key physics being studied

sPHENIX => ePHENIX