Hard Probes: Past, Present and Future

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Disclaimer:

I am a member of both PHENIX and ATLAS collaborations. I will, of course, endeavor to be unbiased \( \text{wrt} \) experiments.

But I have clear prejudices on physics …
An Embarrassment of Riches (past)
But what do we really know? (present)

High $p_T$ quarks & gluons are quenched

- Is the energy loss radiative? collisional? both?
- Wrong question – of course it’s both
  - But, then, what are relative contributions?

- Unless the partons interact with something other than individual charges in the medium (e.g. chromo-B fields)?
  - or

- Unless the quarks and gluons don’t even interact perturbatively (e.g. due to strong coupling)?

- Can we even tell???
  - Unfortunately, this is a question we still have to entertain …
  - Ideally we would answer questions from bottom to top
One Reason to be Suspicious

**• Striking result from STAR**
  - High $p_T$ protons less suppressed than $\pi$.

**• But protons tend to come more from gluons.**
  - Pions more from quarks.

**• But we expect larger energy loss for gluons than quarks?**
  - Nominally 9/4.

**• No evidence for QCD color factors???**

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From talk by Bedanga

![Graph showing $R_{AA}$ Au+Au central 0-12% vs $p_T$ (GeV/c)](Graph)

Needs quantitative, careful evaluation, more knowledge re: baryon FF functions (STAR?)
Another Reason to be Suspicious

Single electron (c, b semi-leptonic decay) $R_{AA}$

- Heavy quarks show same suppression as light quarks at high $p_T$?? With substantial bottom contribution??
- Occam’s razor: maybe there is some universal suppression mechanism (i.e. not usual energy loss) ??
On the other hand …

• This result is very interesting:

\[ R_{AA}^p > R_{AA}^\pi \]

• If protons more sensitive to gluon quenching than pions
  – Naively conclude that gluons lose less energy than quarks???

• Hard to imagine in any quenching scenario!
  – Proton D(Z) modified by quenching/medium?

From talk by Bedanga

Yet another surprise from RHIC data – but I don’t think we understand it yet.

Stay tuned (esp. w/ more statistics)
On the other hand …

- Moore & Teaney, Vitev, van Hees
  - Heavy quarks may hadronize inside/interact non-perturbatively in the medium (implication for light quarks?)
- Or: AdS/CFT drag (talk by Horowitz w/test)
- Or: heavy quarks lost to baryons
  - Measure $\Lambda_c$!

Not yet clear whether heavy quark suppression kills perturbative energy loss
Evidence that we do understand quenching?

- Quark/gluon fraction vs $p_T$ changes with $\sqrt{s}$
- If quenching didn’t depend on color factors, presumably, would not obtain agreement?!
  - But, depends on assumption re: medium properties vs $\sqrt{s}$
More evidence we understand quenching?

C. Loizides arxiv:

- PQM can describe Au+Au, Cu+Cu data with same calculation
  - Systems w/ different geometry & opacity

- More important (?)
  - Describes slow growth of RAA with $p_T$

  ⇒ Characteristic feature of radiative energy loss

  ⇒ But sensitive to parton spectrum, shadowing(b), …
Understand quenching (PQM)? Not so fast…

• **Centrality dependence in Au+Au well described**
  – Provides more sensitivity to medium than central $R_{AA}(p_T)$

• **But Cu+Cu? Maybe, maybe not.**
  – **Data not precise enough!**
  – No Cronin in PQM(?). But then Au+Au??
Single Hadron $R_{AA}$ and Fragility

T. Renk,

Central Au+Au $\pi^0$

$R_{AA}$ compared to (dramatically) different energy loss scenarios

• I think we can all agree that
  – A SINGLE SET OF $R_{AA}(p_T)$ IS NOT SUFFICIENT FOR DETERMINING MEDIUM PARAMETERS, or even CONSTRAINING ENERGY LOSS MODELS

• But, models don’t describe the data equally well either
  – Need quantitative tests against the data!
II. Fragility of single/dihadron suppression factors

Simultaneous fit of single/dihadron spectra
Quantitative tests against data (2)

From parallel session talk by H-Z Zhang

- $\chi^2$-fit to both suppression factors
  - in most central $\text{Au+Au}$

For dihadron:
- $p_T^{\text{trig}} = 8 - 15 \text{GeV}$
- $\tau_T = 0.45 - 0.95$

For single:
- $p_T = 4 - 20 \text{GeV}$

$\xi_0 = 1.5 - 2.1 \text{GeV/fm}$


Iaa robust when Raa fragile at RHIC

- Exactly what we needed!? Yes, and no.
First, need to test models

From plenary talk by B. Mohanty, parallel talk by O. Catu

Away-side Di-hadron Fragmentation Function

\[ D_{h_1h_2}(z_T, p_T^{\text{trig}}) = \frac{dN_{h_1h_2}}{dp_T^{\text{trig}}} \frac{d\sigma_{AA}}{dp_T^{\text{trig}}} \]

\[ Z_T = \frac{p_{T\text{assoc}}}{p_T^{\text{trig}}} \]

\[ I_{AA} = \frac{D_{AA}(z_T, p_T^{\text{trig}})}{D_{pp}(z_T, p_T^{\text{trig}})} \]

\[ 6 \leq p_T^{\text{trig}} < 10 \text{ GeV} \]

\( \frac{1}{N_T} \cdot \frac{dN}{dz_T} \) \( \frac{dN}{dz_T} \)

\( I_{AA} \)

\( \frac{dN}{dz_T} \) \( \frac{dN}{dz_T} \)

\( I_{AA} \)

\( Z_T \)

\[ \checkmark \] Inconsistent with PQM calculations

\[ \checkmark \] Modified fragmentation model better


H. Zhong et al., PRl 97 (2006) 252001

\( Qana\ Catu,\ Parallel\ Talk,\ 8th\ February \)
Bootstrapping our way to jet tomography (present)

• Tomography (our goal):
  – studying an unknown medium with a well understood & calibrated probe.

• Unfortunately, this is not what we are doing
  – We have some assumptions/calculations of medium properties.
  – And incomplete understanding of how our probe(s) interact with that medium.

⇒ We must simultaneously test descriptions of the medium and our understanding of energy loss.
⇒ Only when we have demonstrated that we have consistent description of energy loss & medium can we really start to extract $\hat{q}$ (e.g.)
What are (some of) the issues?

• Do we understand energy loss at all?
  – We must determine whether energy loss is perturbative
  – e.g. determine whether quenching depends on color factors.
    ⇒ Otherwise we’re wasting many person-years, many $$$

• We must come to terms with collisional energy loss
  – Calculations without it should be viewed as toys.
  – If we don’t have sufficient theoretical understanding
    ⇒ Then we have to improve that understanding
    ⇒ Otherwise we’re wasting many person-years, many $$$

• Need to address open issues in (pert.) energy loss
  – Role of collective flow on energy loss.
  – Thick vs. thin medium, opacity expansion (talk by S. Wicks)
  – Massive gluons, running coupling, non-static charges, …
What are (some of) the issues? (2)

• When new ideas/solutions to open problems in parton energy loss arise we need to critically test them.
  – If they survive the tests, must be incorporated into a “canonical” energy loss model.
  – If they don’t, they must be rejected or fixed.
  – Need to do this in an organized way across community.
    ⇒ Otherwise we’re wasting many person-years, many $$$

• We need to test different, viable energy loss calculations in same, realistic geometry(ies).
  – Then quantitative tests against data make sense.
  – Toy models no longer suffice except for proof of principle.
  – Need to do this in an organized way across community.
    ⇒ Otherwise we’re wasting many person-years, many $$$
Signs of progress

Discriminative Power of $R_{AA}$

- $R_{AA}$ in (semi-)central collisions is well described by all jet energy-loss schemes
- parameters reflect tuning of medium structure hard-wired into schemes
- do differing medium assumptions have impact on analysis?
  - more sophisticated analysis/observables needed!

This is just a start – must follow through as community

<table>
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<th>HT</th>
<th>AMY</th>
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<tbody>
<tr>
<td>$K=3.6$</td>
<td>$q_0=1.5$</td>
<td>$\alpha_s=0.33$</td>
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Medium response: conical? flow

From BAC talk QM 2005

- For PHENIX reaction plane resolution & chosen bin sizes, $\Delta \phi_{\text{trig}}$ bin 4 has smallest flow effects.
- Even without subtracting flow contribution, a dip is seen for central collisions.

• Let’s get one thing straight:
  - The cones? are not an artifact of background subtraction!
  - We should not have to discuss this issue any more …
• The position of the cone does not change with angle of trigger hadron \( \text{wrt} \) reaction plane.
  - But we do see the di-jet remnant behave as expected
    \( \Rightarrow \) Decreases as \( \phi_t - \Psi_{RP} \) increases.
Conical? flow – RP dependence (STAR)

From parallel talk by A. Feng

- PHENIX & STAR results on RP dependence in excellent qualitative agreement.
Conical flow – other results shown this week

From M. McCumber parallel talk

From talk by B. Mohanty

Beware: PHENIX measurement from 2 particle, STAR 3 particle

• Cone angle does not change appreciably as a function of $p_T$ of trigger or associated hadron.
  – Or centrality, or angle $wrt$ reaction plane
  – Can you find the pattern here…
Conical Flow – what is it really?

- Other observations from data
  - 3-particle correlations from STAR & PHENIX may suggest conical flow pattern.
  - pT spectrum in the cone? consistent w/ medium not jets.
  - We are developing a large body of data that I believe is difficult to explain via “geometric” effect.

- If we are going to take “bent-jet” as serious candidate for conical flow, then:
  - We should evaluate using real jet quenching model
  - In a realistic description of medium (e.g. hydro)
  - No free parameters – it will work or not. But ???

- Similarly, if we are going to take gluon radiation as serious candidate for conical flow, then
  - We need a complete calculation w/ realistic geometry.
Mach Cone?

• We have good reason to think the medium can support, propagate shocks.
  – But can they produce the signal we see (not obviously).
  – Stay tuned (on the edge of your seat …)
The Ridge: also seen by PHENIX, PHOBOS

**p+p, peripheral Au+Au**

**central Au+Au**

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Talk by McCumber

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**p+p PYTHIA v6.325**

\[
\frac{1}{N_{\text{trig}}} \frac{d^2N_{\text{ch}}}{d\Delta\phi \ d\Delta\eta}
\]

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Talk by E. Wenger

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**Au+Au 0-30% central**

PHOBOS preliminary
The Ridge: new insights

- Study yield in ridge vs angle of trigger hadron \( \text{wrt} \) reac. plane
  - Ridge yield concentrated in the reaction plane (beware sys. err.)
  - Flat for larger \( \phi_t - \Psi_{RP} \)
  - Non-zero or zero?

⇒ Important to establish!!

Parallel talk by A. Feng

STAR Preliminary
The Ridge: new insights

- Ridge extends over loo000ong range in $\Delta \eta$.
- How close is the $\Delta \phi$ distribution to that of jets?
  - A crucial question to be answered (quantitatively)
- Momentum and flavor dist. characteristic of medium.
  - (data not shown for brevity)
- We assembling the data that we need to test models.
The Ridge: Models

Shamelessly ripped off from Wenger (sincerest form of flattery?)

Theoretical Interpretations of Ridge

Very different proposed mechanisms qualitatively describe “ridge” at $|\Delta \eta| < 2$

- Coupling of induced radiation to longitudinal flow
  Armesto et al., PRL 93, 242301

- Recombination of shower + thermal partons
  Hwa, arXiv:nucl-th/0609017v1

- Anisotropic plasma
  Romatschke, PRC 75, 014901

- Turbulent color fields

- Bremsstrahlung + transverse flow + jet-quenching
  Shuryak, arXiv:0706.3531v1

- Splashback from away-side shock
  Pantuev, arXiv:0710.1882v1

- Momentum kick imparted on medium partons
  Wong, arXiv:0707.2385v2

So far we can’t rule any of these out.

Somehow we must exclude all but 1 (or 0)

- Theorists: help us kill your model (you know it best!)
- Otherwise we’re wasting many person-years, many $$$
Conclusions

• We desperately need a coherent theory+expt. effort
  – To address issues with energy loss models
  – To test models against consistent set of realistic geometries
  – Examples for how to do this: MRST & CTEQ
    ⇒ Only then can we really bootstrap our way to tomography

• It’s time to get past/get over fragility
  – Yes, we know already!
  – But $R_{AA}(p_T, A, N_{part}, φ-Ψ)$ absolutely necessary for

• It’s too early to be trying to determine $\hat{q}$ to 10, 20, 30%
  – When there are much larger theoretical uncertainties.
  – We experimentalists should be using (and refining our) data to help resolve those theoretical uncertainties.

• Exciting data on medium response, but still inconclusive
• The $\Delta E$ bias is one of the biggest (but not the only) problems that we face in understanding quenching.
  – Simply don’t see a large fraction of the jets.

• In principle, full jet measurements fix this problem
  – e.g. 100 GeV jet @ LHC should always be visible.
  – Unless quenching is completely non-perturbative & strong.
    ⇒ The data will then at least be definitive.

• Will happen @ LHC within ~2 years.
  – But RHIC experiments also pursuing full jets, $\gamma$-h/jet.