Ridge, Bulk, and Medium Response: How to Kill Models and Learn Something in the Process

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Abstract

In these proceedings, we highlight experimental data (published and preliminary) related to jet quenching and the response of the medium to this deposited energy. Signatures in two- and three-particle hadron correlations indicate interesting structures near the trigger particle in azimuth and over a broad range in pseudo-rapidity, often termed 'the ridge', and conical-like structures separated in azimuth opposite to the trigger particle. We review numerous theoretical interpretations of the ridge in particular with a critical eye for the key properties that allow one to discriminate between, or rule out, certain physical pictures and models (and hopefully learn something in the process).

1. What the Parton Deposits in the Medium

A necessary prerequisite for understanding any medium response to the traversal of a high-energy parton is to understand in detail how the parton deposits energy (i.e. how much energy on average and with what distribution in energy and in space-time). The measurement of single inclusive high $p_T$ hadron suppression ($R_{AA}$) has proven to be very useful for making an overall characterization of the energy loss. However, there are a variety of parton energy-loss formalisms that currently give approximately equal goodness-of-fit to the experimental data, but with very different implications for the quenching power of the medium [1, 2]. To be clear, the $R_{AA}$ comparison allows one to tightly constrain this quenching power within a given model, but not to discriminate between models.

It has been proposed that di-jet (as well as direct photon-jet and fully reconstructed jet) observations will provide this discriminating power. First measurements via di-hadron correlations at high $p_T$ have been made by the STAR experiment, though they are somewhat statistics limited in the $d-Au$ baseline measurement [3]. In the context of two parton energy-loss models (ZOWW [4] and PQM [5]), we show in Figure 1 the calculation results for $R_{AA}$ and $I_{AA}$ as a function of the quenching power (either $\epsilon_0$ or $\langle \hat{q} \rangle$). Also shown are the resulting modified $\chi^2 - \chi^2_{\text{minimum}}$ (including experimental statistical and systematic uncertainties, but not theoretical uncertainties) when confronted with the $R_{AA}$ and $I_{AA}$ data. It is striking that the best fit is a larger (smaller) quenching implied from $I_{AA}$ as opposed to $R_{AA}$ for ZOWW (PQM) model. There are also recent results with ASW energy-loss embedded in a hydrodynamical medium that result in a somewhat more consistent description of both $R_{AA}$ and $I_{AA}$ [6].

This provokes one to question what has been learned since this was a more discriminating observation. We can speculate that in a model with the same average energy loss, but smaller fluctuations (i.e. a larger number of lower energy radiated gluons), one might have more surface
bias and thus a lower $I_{AA}$ for the same $R_{AA}$. Currently other model differences such as medium geometry make it challenging to discriminate between the underlying energy-loss mechanisms. The TECHQM effort is working to resolve these issues, but it is undermined if the community simply claims that “all models roughly agree with the data.” The resolution to discriminating between the parton energy-loss formalisms will not come exclusively from theory; and there are additional experimental handles, including as an example the recent measure of $R_{AA}$ versus reaction plane.

2. The Ridge

The ridge is defined as a correlation in momentum space between particles that are extended over many units in pseudo-rapidity ($\Delta \eta$) and relatively narrow in azimuthal angle ($\Delta \phi$). In fact, there are multiple observations of ‘ridge-like’ phenomena (which may or may not originate from a common physics mechanism). There are preliminary results of a ‘hard ridge’ where a high $p_T$ trigger particle (3-12 GeV/$c$) is correlated with a moderate $p_T$ associated particle (2-4 GeV/$c$). There are also preliminary results of a ‘soft ridge’ where the two correlated particles are simply required to have $p_T > 0.150$ GeV/$c$. In between the two (which was referred to as the ‘just right ridge’) are published results from the PHOBOS experiment with trigger particles with $p_T > 2.5$ GeV/$c$ and associated particles with $p_T > 0.035$ GeV/$c$.

Preliminary studies from PHENIX and STAR of the transverse momentum spectra, hadron chemistry (i.e. baryon/meson ratios), and centrality scaling have been shown. These reveal that the $p_T$ spectra in the ridge is similar to that of the bulk medium (with some indications of being slightly harder). This is in striking contrast to the much harder $p_T$ spectrum of jet fragmentation. There is significant enhancement of the baryon/meson ratio in the ridge, quite similar to the bulk medium (and again in contrast to vacuum jet fragmentation). Finally the ridge yield appears to scale per trigger particle as the number of participating nucleons (similar to the bulk medium). Note that for the ‘hard’ and ‘just right’ ridge, the ridge yield is only of order a one
percent modulation of the yield of the bulk medium. This is not true for the ‘soft’ ridge where
the yield is a much larger fraction, though the experimental methodology is very different (as we
discuss later).

One additional comment regarding the ‘hard ridge’ relates to the question of whether the
ridge persists up to the highest \( p_T \) trigger particles. Results from PHENIX [13] show no evidence
for the ridge with trigger particle \( p_T > 5 \text{ GeV/c} \). However, as noted in the publication, due to the
limited pseudo-rapidity acceptance, if the jet peak is increasing with trigger \( p_T \), it may be that the
result is not sensitive to the smaller ridge contribution. This appears to be the case since STAR
preliminary results show a significant ridge yield for 0-10% central Au-Au events that appears
constant all the way up to \( p_T(\text{trigger}) > 8 \text{ GeV/c} \) with \( p_T(\text{associated}) > 2 \text{ GeV/c} \) [9].

2.1. Ridge Models

The various theoretical models can be grouped into two categories. The first are referred
to as ‘Causation Models’ (i.e. where \( A \) (for example a jet parton losing energy) causes \( B \) (the
ridge)). The second are referred to as ‘Auto-Correlation Models’ (i.e. where \( C \) causes \( A \) and \( C \)
also causes \( B \), such that \( A \) and \( B \) are auto-correlated).

Most Causation Models assume that the cause of the ‘ridge’ is a quenched jet. Examples
include calculations where the radiation from the jet is broadened in rapidity due to collective
flow [14] and where the radiation from the jet is broadened by turbulent color fields [15]. How-
ever, in both of these cases the ridge has a Gaussian shape in pseudo-rapidity with \( \sigma_{\Delta\eta} \approx 0.4 - 0.5 
units. It is difficult for models with quenching parameters that reproduce the suppression of high
\( p_T \) hadrons to achieve a broader ridge width. Note that these models would also provide no
explanation for the ‘soft ridge’. The PHOBOS experiment has shown the ‘just right’ ridge to
have a width that extends over four units of pseudo-rapidity [11]. One might have concerns that
this four units in pseudo-rapidity might be quite different in rapidity. Since PHOBOS includes
associated particles down to \( p_T = 0.035 \text{ GeV/c} \), for \( \Delta\eta = 4 \), that would only be \( \Delta y \approx 1 \) for protons
and \( \Delta y \approx 2.5 \) for pions. However, the phase space contributions at this lowest \( p_T \) are not very
large. In addition, the STAR preliminary results indicate a width of \( \sigma_{\Delta\eta} > 1.4 \) [16], and since
the \( p_T \) associated particles are much higher, pseudo-rapidity and rapidity are much closer. Thus,
these causation models are essentially ruled out as the dominant mechanism for producing the
ridge.

Another Causation Model is the ‘Momentum Kick Model’ [17]. The model includes an effect
that is similar to an initial state \( k_T \) scatter, but from the jet parton. The soft partons are given a
momentum kick (given by the parameter \( \vec{q} \)), which is tuned to match the data (where the kick is
assumed to be exactly along the direction of the jet parton). One concern in this model is that
one needs to know the \( y \) and \( p_T \) distribution of the soft partons, and an arbitrary distribution
set could essentially match any possible ridge data. Thus, it is critical to demonstrate that these
distributions are not arbitrary (e.g by having additional (non-ridge) tests and constraints on them).

With the currently published parameter set, this model gives a reasonable description of the ridge
yield and full extent of \( \Delta\eta = 4 \) as shown by the PHOBOS data. One can also compare the width
of the ridge in \( \Delta\phi \), which has been a somewhat overlooked key feature of the ridge. As shown
in Figure 2 this model significantly over-predicts the width of the ridge in \( \Delta\phi \) and has a trend
for a wider ridge width at larger rapidity gap. One can understand this effect by considering
the case where PHOBOS measures a trigger particle at pseudo-rapidity +1.5 and the associated
particle at pseudo-rapidity -2.5 (to get a gap of 4 units). Since the momentum kick \( \vec{q} \) is always
along the trigger parton, some of the kick is longitudinal (and thus there is less focusing in \( \phi \)).
Finally, the Causation Model [18] postulates that the away-side jet produces a back-splash in the
medium. Thus, the large range in pseudo-rapidity is caused by the away side jet swing (assuming the initial two partons that scattered have $x_1 \gg x_2$ or vice versa). This interesting idea requires a full simulation of the time scales involved to create the correlation to further test this picture.

The second main category of explanations are 'Auto-Correlation Models'. A common feature of these models is that there is a local hot spot (in the transverse plane) in the initial collision (i.e. at the earliest time). This hot spot expands longitudinally (and thus in rapidity space) and produces both the trigger and associated particle by different mechanisms. However, because they originate from a common location in the transverse plane, they may both be correlated with the radial vector in the overlap region (and thus auto-correlated into an extended ridge in $\Delta \eta$ and narrow in $\Delta \phi$). One such calculation is the 'Jet Induced Ridge' model [19]. In this picture there is no specific description of the longitudinally extended hot spot, and thus there is no quantitative prediction of the width in $\Delta \eta$. However, the trigger particle is focused along the transverse radial direction via jet quenching (since the radial vector represents the shortest path out of the medium). The associate particle (many units in rapidity away) is focused via radial flow from the outwardly exploding medium. We have re-calculated the results from this model and find that for any jet quenching attenuation parameter ($\lambda$ which exponentially suppresses particles traversing a given path length), the narrowest possible ridge in $\Delta \phi$ is approximately 0.8 radians. As shown in Figure 3, the trigger particle does not experience sufficient focusing to describe the ridge width in $\Delta \phi$. Also, it is notable that for $\lambda = 1.0$ fm, the single hadron nuclear modification factor is already $R_{AA} < 0.1$ (significantly lower than published experimental data). Note that the ridge is too wide in $\Delta \phi$ both for the STAR and PHOBOS data (as also shown in Figure 2).

It is striking that the radial flow is much more effective at focusing the associated particle in the above model. Thus, an alternative model is that both trigger and associated particles are focused by radial flow. This was originally proposed in [20] and is incorporated into the other calculations [21, 22]. However, they also implement a specific description of the hot spot’s longitudinal correlation (namely color glass condensate or 'glasma' flux tubes). This provides a reasonable description of the 'soft ridge' from the STAR preliminary data. This model would not have a prediction for the 'hard ridge' case. At this conference, a hybrid model was proposed [23] where focusing by radial flow is only for the 'soft ridge' and at higher $p_T$ trigger there is an in-
creasing contribution from ‘jet induced ridge’ correlations. This model gives a better description; however, for very high $p_T$ triggers (e.g. $> 8$ GeV/$c$) it should predict identical results to the ‘Jet Induced ridge’ and fail to describe the experimental data.

We performed a simple calculation, shown in Figure 3, of the ‘ridge width’ in $\Delta \phi$ assuming focusing of the trigger and associated particle by radial flow only. In the case of radial flow, the higher the $p_T$ of the particles, the larger the implied radial boost received and thus the more focusing along the radial direction. This simple calculation was performed assuming a temperature $T = 140$ MeV and a linear boost profile with $\beta_{\text{max}} = 0.7$. The exact widths are sensitive to these parameters and the linear boost profile assumption. However, this type of model makes a specific prediction, that for moderate $p_T$ trigger and associated particles, if the particles are protons instead of pions, the focusing is substantially larger. This prediction needs to be checked experimentally.

A model that takes this soft boosted picture into a full hydrodynamic regime is by Takahashi et al. [24]. In this calculation they have fluctuating event-by-event initial conditions from NEXUS, then followed by SPHERIO hydrodynamic evolution, and completed with Cooper-Frye hadronization. In this picture, the longitudinally extended hot spot (from the underlying NEXUS dynamics) results in a very clear ridge-like structure. It is notable that there is an additional jet-like peak, despite the fact that the model has in principle no jets traversing the hydrodynamic medium. More precise predictions for these ridge features as a function of trigger and associated particle $p_T$ are needed as next steps.

At the conference, R. Hwa pointed out that the narrow width of the ridge in $\Delta \phi$ could be an artifact of the ZYAM normalization. Since one forces a zero point in the correlation function (which turns out to be at $\Delta \phi \approx 1$), it is difficult to find a width in $\Delta \phi$ greater than 0.3-0.4 units. Thus, for the PHOBOS and STAR ridge results, the width values shown could be underestimates. As shown in Figure 4, we have calculated how much the true normalization would have to differ from the ZYAM normalization in order to accommodate a much wider ridge (utilizing the published PHOBOS raw correlation function data [11]). We have constrained the ridge width in $\Delta \phi$ to fixed values (stepping over a wide range) and then left as free parameters the ridge

![Figure 3: (color online) (Left panel) Calculation of the trigger particle - radial vector, associated particle - radial vector, and trigger and associated particle azimuthal correlation as a function of the jet-quenching attenuation length. The calculation employs a realistic Glauber geometry for Au-Au central events, and the methodology outlined in [19]. (Right panel) Calculation results for the ridge width in $\Delta \phi$ as a function of the trigger particle $p_T$ and for various range of associated particle $p_T$. The results are shown for pions and protons.](image-url)
yield, the away side structure (broken into a punch through peak centered at $\pi$ and two shoulder peaks centered at $\pi \pm D$), and the $v_2$ modulated background normalization. We find that for any value of the ridge width in $\Delta \phi$, one can achieve an equally good description of the experimental data. As shown in the lower left panel, if there is a 1% deviation in the background normalization from ZYAM one can have a width in $\Delta \phi$ of 0.6 units, and for 3% a width of 0.8 units. In the case of the PHOBOS data however, they have also checked that the ZYAM normalization follows an expected scaling with centrality (which is akin to the absolute normalization technique [25]). Though it deserves additional scrutiny, it appears that even a 1% normalization difference from ZYAM is unlikely. The STAR 'hard ridge' results also should be checked with absolute normalization. Note also that if the normalization is different by 1%, such that the ridge $\sigma_{\Delta \phi} \approx 0.6$ units (in agreement with the 'Momentum Kick Model' for example), the ridge yield would be much larger (then in disagreement with the 'Momentum Kick Model').

A point that deserves more attention is that the 'soft ridge' has a width in $\sigma_{\Delta \phi} \approx 0.9-1.2$ units [10 [21]. However, this preliminary analysis is not done with ZYAM, but fitting all components expected in the correlation function with floating normalizations. As the data moves towards publication, a full quantification of the correlated uncertainties in these parameters is crucial, as they currently have a much larger ridge yield and much wider width than the ridge results that utilize ZYAM. As previously mentioned, the 'soft ridge' yield is very large (a substantial fraction of the entire yield), which would also be true if we forced the ridge width to be
1.0 units for the PHOBOS correlation. We note that in the above test we performed with the PHOBOS data, we can get an equally good fit to the data (i.e. within $\Delta \chi^2 < 1.0$ from the best fit) for any normalization varying from ZYAM (even greater than 15%). Thus, in that particular test, the fit alone gives essentially no constraint on the ridge width and yield.

The models with an auto-correlation of soft boosted trigger and associated particles appears quite compelling. This physics must be there at some level. However, the ridge structure appears to persist even for trigger $p_T > 8\,\text{GeV}/c$. This seems to contradict many other pieces of evidence that $8\,\text{GeV}/c\, p_T$ particles are not predominantly soft thermal particles with a very large radial boost. In the hybrid approach [23], the ridge should show a significant broadening at high $p_T$ as one transitions to the ‘jet induced’ case. This effect is not seen, though perhaps it is masked by the ZYAM normalization. It will be important to do more checks for both the PHOBOS and STAR ridge cases. Data shown at this conference on three-particle correlations should also be of great interest, though the models at this point are already challenged by the existing two-particle correlation data and trends.

3. Away Side Structure

Di-hadron azimuthal correlations have also revealed interesting physics on the opposite side of the trigger particle. For the case of moderate $p_T$ trigger particles and low to moderate $p_T$ associated particles, there appears to be a split-peak on the away side. It has been postulated that this structure is a mach-cone from a super-sonic parton [26, 27] or gluon Cerenkov radiation or other medium disturbances. The STAR experiment has published exciting results on three-particle correlations [28]. It is notable that there are now observations of similar phenomena from CERN-SPS data that challenge the various theoretical models as a response of the medium (without significant dissipation). Simplified models can reproduce the main features of the experimental data [27], but full hydrodynamic calculations of a medium response have not. Additional attempts within the context of AdS/CFT are also being made.

Shown in Figure 4 are results that indicate a broad away side correlation for modest trigger $p_T$ particles, but no statistically significant indication for higher $p_T$ particles of anything except a single Gaussian peak. Most medium response models should predict a continued response for higher $p_T$ trigger particles, though none is currently seen. We note that it is not ruled out that the “punch-through” peak (or potentially tangential emission) may be subsuming the medium response. This is a key additional experimental test of the various explanations.

An alternative picture is emerging that proposes that the away-side structure is due to autocorrelations of an initial hot-spot with the transverse geometry and flow [29, 24]. One particular idea relates to strong initial state fluctuations that produce event-by-event spatial anisotropies that can translate into surprising momentum anisotropies with various Fourier coefficients (for example $v_3$). There are also pictures in-between where parton recombination couples these soft medium particles with those from the initial di-jet partons [30] (relating both the away-side and ridge structures). These ideas are getting serious consideration and need to also be confronted with the full set of experimental observables in a quantitative manner.

4. Summary

This exciting area of heavy ion physics has the potential to teach us an enormous amount about the hot partonic medium created. To realize this potential, experimentalists will need
to continue to work hard to publish results with fully quantified systematic uncertainties and theorists will need to continue to learn from cases where data and theory agree and where they disagree.

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