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RHIC Correlations and High-p_T Measurements with ATLAS

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Many new results on high-p_T particle production in heavy ion collisions have resulted from measurements at RHIC. However, since the first evidence of jet quenching from single particle spectra [1], many new and surprising results have become available. In this talk we review the current state of high-p_T correlations from RHIC and ask the questions that these data provide. We then discuss the ATLAS detector at the LHC and their capabilities of jet measurements. This is done in the context of the possibility of event-by-event measurements and measuring the jet energy scale illuminating the RHIC discoveries.

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1. High-p_T Puzzles at RHIC

Since the advent of Au+Au collisions at RHIC, high-p_T physics has been a topic of interest for a large number of experimentalists and theorists. The striking evidence of single particle suppression [1] was one of the first key measurements at RHIC and the first confirmed prediction from theorists [2, 3]. Since the initial running at RHIC a wealth of high-p_T data exists for single particles and for pair correlations. More questions have arisen since that time and we outline a few of these here.

First, single particle suppression is expressed as R_{AA} defined as

$$R_{AA}(p_T) = \frac{(1/N_{evt})\, d^2N^{A+A}/dp_T d\eta}{\left(\langle N_{binary}\rangle/\sigma_{inel}^{N+N}\right) d^2\sigma^{N+N}/dp_T d\eta} \tag{1.1}$$

After the first RHIC data on R_{AA}, many theorists produced reproductions of this quantity. A current trend from theorists is that R_{AA} is fragile, that is it loses sensitivity to medium properties for large observed quenching. An example of extreme insensitivity to medium properties was shown by Renk [4]. Several scenarios of quenching weights, the probability to lose a fraction ΔE at a given energy E, were studied and R_{AA} was produced from each. Fig. 1 shows the results that for drastically different energy loss scenarios nearly the same R_{AA} results. It is unlikely that the correlated systematic errors are consistent with the rising trend seen in most of the model calculations. However, the fact that the strikingly different scenarios result in the same R_{AA} is an interesting result.

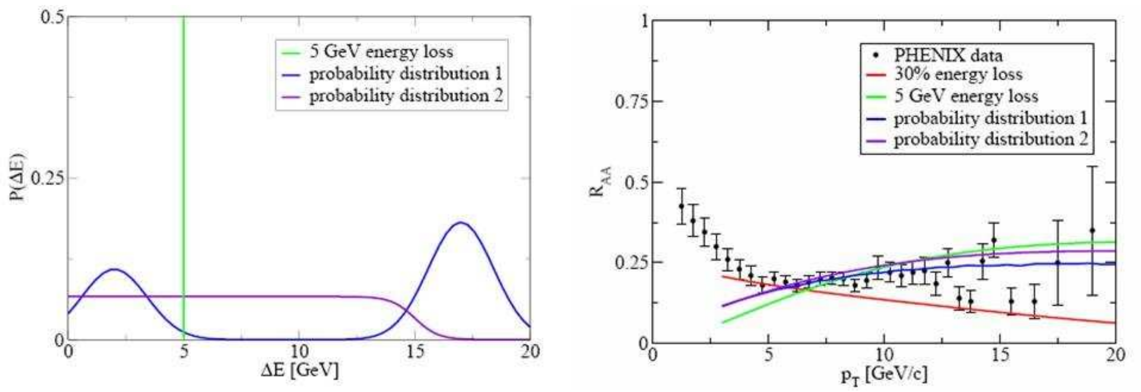

Figure 1: *Left:* Different quenching weights used in the study of R_{AA} in Ref. [4]. *Right:* Results for R_{AA} from the different energy loss scenarios.

Secondly, and more relevant to this talk, are more direct measurements of jets in heavy ion collisions via two particle correlations. Pairs of high-p_T particles are predominantly produced from $2 \to 2$ QCD processes where two partons are emitted roughly back-to-back. Two particles from the same jet are located at $\Delta\phi \sim \Delta\eta \sim 0$, the near side, whereas two particles from opposing jets are emitted at a $\Delta\phi \sim \pi$, the away side. By triggering on a high-p_T particle, there is a bias for measuring jets produced near the surface of the almond region. As such, a study of the particles produced on the away side could yield information of the recoil jet that traverses the medium. These measurements have been performed at RHIC and the p_T reach is adequate to see a clear correlated away-side structure [5][6]. These data are sufficient to show that the away-side yields are suppressed in Au+Au compared to d+Au. Fig. 2 shows both the per-trigger yield in the away-side as well as the RMS of the away-side $\Delta\phi$ distribution. What is striking is the yield is suppressed while the RMS is unchanged. This is puzzling because a random walk, bremsstrahlung process should produce a suppression and a broadening of the correlation [7]. Two possible scenarios which would explain the data are punch through jets or tangential jets. Punch through jets [8] are those jets which lose little to no energy and are sensitive only to $P(\Delta E = 0)$. Tangential jets [9] are those originating from and emitted tangential to the surface such that neither jet feels much medium. In either scenario much of the information to be gained from two-particle correlations are lost.

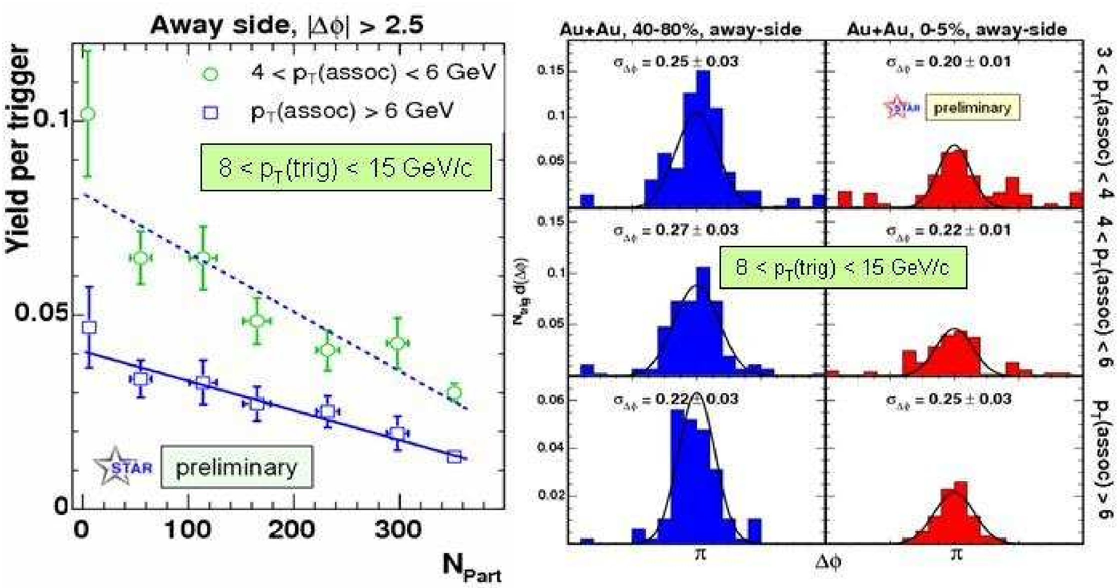

Figure 2: *Left:* Per-trigger yield on the away-side ($\Delta\phi \sim \pi$) for trigger-associated pairs of hadrons in the given p_T ranges. A clear suppression is seen as a function of centrality. *Right:* $\Delta\phi$ distribution of the same trigger-associated hadron pairs for peripheral and central Au+Au collisions. The fitted Gaussian RMS is given, no appreciable increase from peripheral to central collisions is observed [6].

Another feature of the data is the experimental fact that the away-side I_{AA}, the two particle equivalent of R_{AA} defined as

$$I_{AA} = \frac{(1/N_{trig})\, dN^{A+A}/dp_{T,assoc}}{(1/N_{trig})\, dN^{p+p}/dp_{T,assoc}} \tag{1.2}$$

and R_{AA} are approximately numerically equivalent. This has been measured in Au+Au collisions and in Cu+Cu collisions (see Fig. 3). To be more precise the Au+Au data indicate that $I_{AA} \sim R_{AA}^{assoc}$ [10] while the Cu+Cu data shows that $I_{AA} \sim R_{AA}^{trig}$ [11].

To understand the implications of this we consider the following derivation using Eqn. 1.1 and Eqn. 1.2.

$$I_{AA} = \frac{N_{pair}^{A+A}/N_{trig}^{A+A}}{N_{pair}^{p+p}/N_{trig}^{p+p}}$$

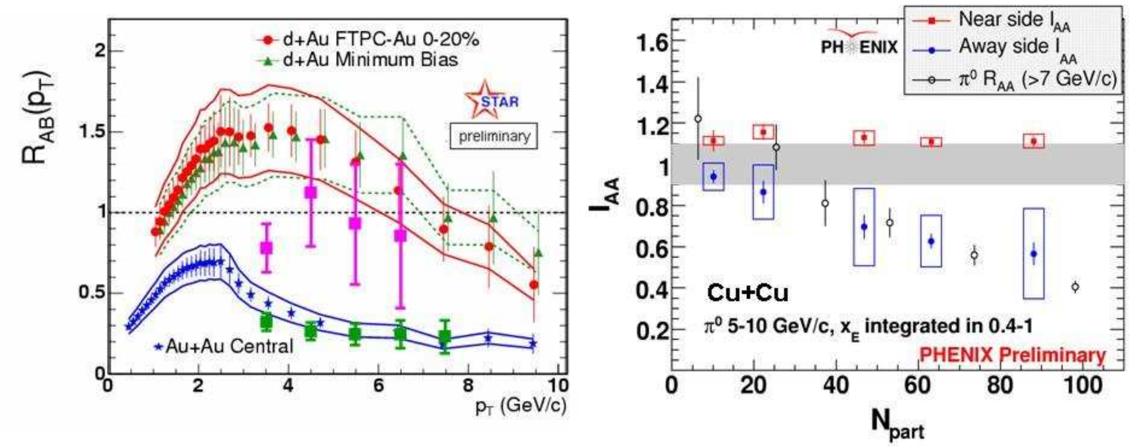

Figure 3: *Left:* Comparison of hadron-hadron I_{AA} (boxes) and single hadron R_{AA} from d+Au(circles and triangles) and Au+Au(stars) [10]. *Right:* Comparison of away-side I_{AA}(filled circles) from π^0-hadron correlations compared to π^0 R_{AA}(open circles) from Cu+Cu collisions [11]. The data seem to indicated away-side $I_{AA} \sim R_{AA}$.

$$= \frac{1}{R_{AA}^{trig}} \frac{N_{pair}^{A+A}}{N_{coll} N_{pair}^{p+p}}$$
$$= \frac{D_{AA}}{R_{AA}^{trig}} \tag{1.3}$$

where we define $D_{AA} \equiv \frac{N_{pair}^{A+A}}{N_{coll} N_{pair}^{p+p}}$ as the pair modification factor. Therefore, if $I_{AA} \sim R_{AA}^{assoc} (= R_{AA}^{trig}$ at high p_T) then $D_{AA} \sim R_{AA}^{trig} R_{AA}^{assoc}$. This appears at face value to be a factorization of the energy loss, the pair suppression being equal to the product of the single particle suppressions. The pair modification factor has been measured recently [12]. These are plotted in Fig. 4 along with the result $R_{AA}^{trig} R_{AA}^{assoc}$ for the highest associated bin. Within errors these results are equivalent.

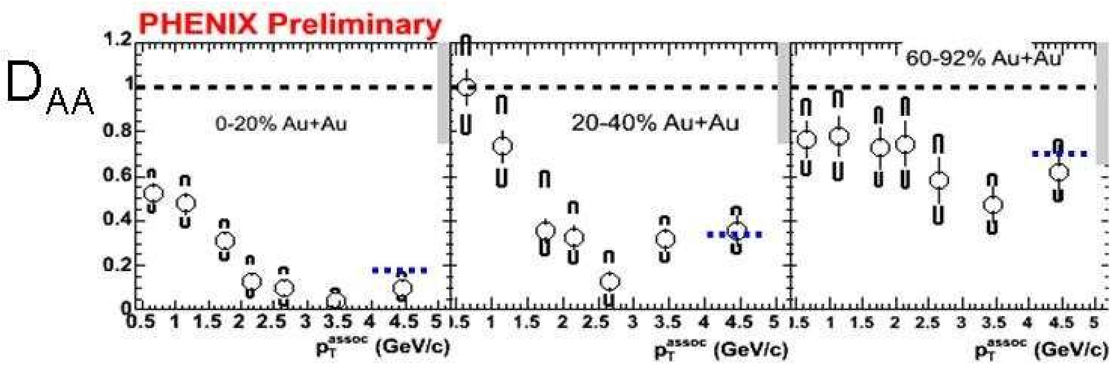

Figure 4: Measured pair modification factor D_{AA} [12] for hadron-hadron correlations for triggers from 2-3 GeV/c as a function of associated p_T and centrality. Dashed lines indicate the level of $R_{AA}^{trigg} R_{AA}^{assoc}$.

Such a factorization of the energy loss is not expected. The motivation for measuring two particle correlations is to exploit the bias of the trigger particle which results in the associated particle seeing more medium. If such a scenario were true, the factorization would not hold.

Finally a new result may point to more direct evidence of energy loss in A+A collisions at RHIC. From π^0-hadron correlations in Cu+Cu collisions, the j_T distribution, the p_T with respect to the jet axis, has been measured [13]. Fig. 5 shows the j_T distribution of hadrons measured in Cu+Cu and in p+p. The Cu+Cu data indicates a large increase in the hard tail of the distribution. This is qualitatively consistent with hard radiation from parton energy loss. This hard radiation is perturbatively calculable [14]. What is puzzling is how such a large increase is seen on the *near* side correlation which are supposed to be biased towards seeing less of the medium.

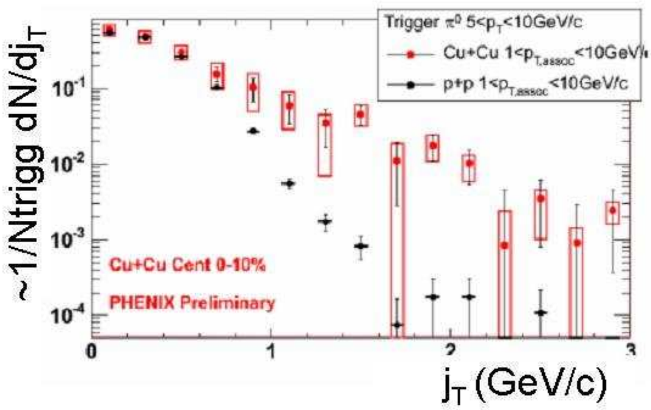

Figure 5: Measured distribution of j_T, p_T with respect to the jet axis, of the π^0-hadron correlations [13]. The (red) circles are Cu+Cu data and the (black) circles are p+p data.

Taken together, these data indicate a clear difference in A+A collisions compared to p+p collisions. However, there is no consistent picture of energy loss that can describe the breadth of data that has been presented here. There are other pieces which have not been touched on such as the reaction plane dependence of the correlations or v_2 at high-p_T. All of these data must consort to form a consistent picture of energy loss at RHIC.

One hinderance of the data is that we have only measured integral quantities via correlation functions summed over many events. Structures such as mach shocks have not been directly measured. One advantage of jet measurements at the LHC is large acceptance detectors and the ability to detect the many large E_T jets distinguishable from the underlying heavy ion event. Further, a direct measurement of the jet energy scale will remove the ambiguity of working with purely hadronic variables. The jet energy scale and event-by-event information such as mach cones or single hard radiation should provide invaluable information on energy loss in the nuclear medium created in A+A collisions.

2. High-p_T Jet Measurements with ATLAS at the LHC

Currently the ATLAS collaboration is actively preparing for heavy ion collisions at the LHC [15][16]. Within the heavy ion program of ATLAS, jet studies are an important part. The ATLAS detector is a large multipurpose detector designed for study of highp_T processes in p+p collisions [17]. However, nearly all of the detector has central HIJING event occupancies useful for heavy ion studies. The inner tracking system is composed of three pixel layers, four double-sided strip detectors, and a transition radiation tracker all within a 2 T solenoidal field and covering full azimuth and $|\eta| < 2.5$. The ATLAS calorimeter is composed of several independent longitudinal sampling layers of electromagnetic and hadronic calorimetery with full azimuthal and $|\eta| < 5$ units coverage. Finally the muon spectrometer is located outside of the hadronic calorimeters and within a toroidal field.

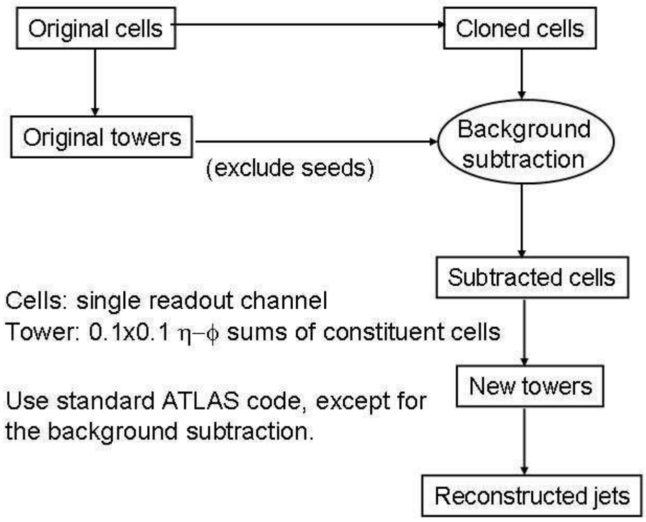

Figure 6: Flow diagram of the jet reconstruction scheme for heavy ion events. Cells, smallest readout elements of the calorimeter, are subtracted to remove the underlying event and then combined into towers which form jets.

Jet reconstruction has been studied with jets from PYTHIA embedded into HIJING events. Because of the underlying event, background subtraction schemes have been developed to subtract the underlying event from the calorimeter towers prior to jet reconstruction. Fig. 6 outlines the flow diagram for the jet reconstruction algorithm via the cone algorithm for heavy ion events in ATLAS. Subtraction is performed on the cell level, the single readout channels, prior to tower building and jet reconstruction. Currently H1-style calibrations [18] are applied after jet reconstruction and no additional calibrations based the subtraction have been applied.

The background subtraction scheme presented here is based on subtracting an η-dependent average energy measured in each longitudinal segment of the calorimeter. The average background is determined from calorimeter cells that are not in regions of expected jets (seeds). Seeds are determined from calorimeter towers with $E_T > 10$ GeV. Cells within a radius ($=\sqrt{\Delta\phi^2 + \Delta\eta^2}$) of 0.8 units are excluded from the average determination. Fig. 7 shows the position and energy resolution from this background subtraction scheme on jets embedded in b=2 fm HIJING events. Jets were reconstructed using an R=0.4 cone algorithm with seed towers (after subtraction) of 5 GeV. For this brute force approach the position and energy resolutions are very good. These results also show an energy resolution that is essentially uniform across the calorimeter.

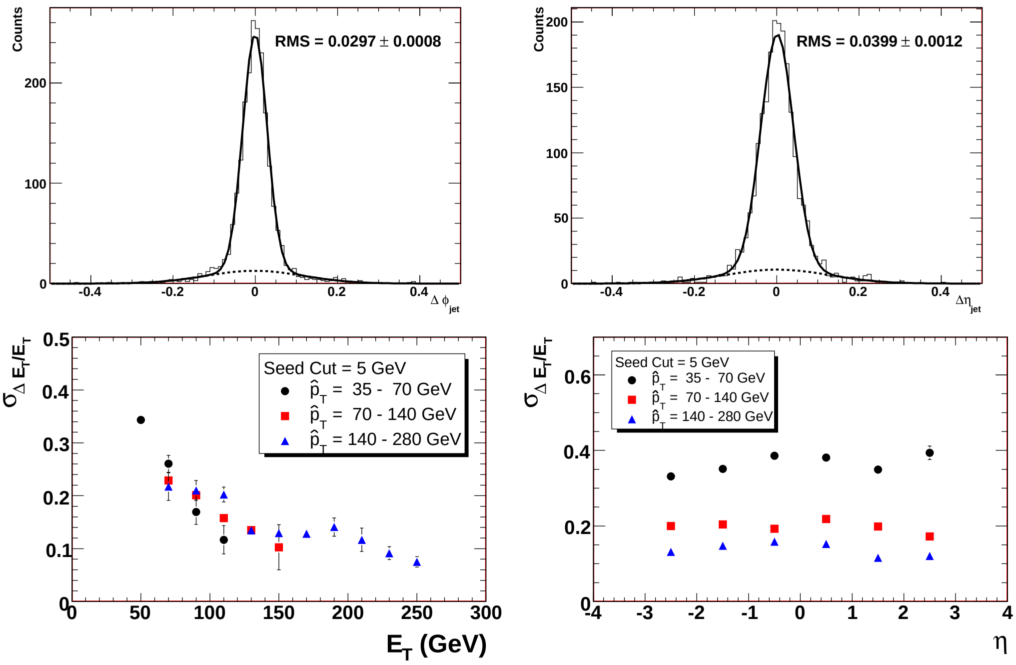

Figure 7: *Upper left:* ϕ position resolution between reconstructed jets embedded in HIJING events compared with the PYTHIA input. *Upper right:* Same but for the η resolution. *Lower left:* Energy resolution as a function of input PYTHIA jet E_T. *Lower right:* Energy resolution as a function of η. These figures are ATLAS preliminary based on a modified release of Athena 11.0.41.

ATLAS has studied the k_T algorithm for jet reconstruction as well. For full details see Ref. [19]. The prospects are exciting for the k_T algorithm since 1) it can more easily handle hard radiation which produce irregular-shaped jets, 2) it is not seeded, 3) using the Fast-k_T algorithm [20], running on heavy ion events is possible *before* background subtraction. Fig. 8 shows a HIJING event with a di-jet embedded and the Fast-k_T algorithm applied. Because of the large multiplicity, every tower is associated with some jet. However, most jets correspond to the sum of soft underlying event and should be rejected. One possible discriminating variable between te “fake” background jets and the true jets is the ratio of the maximum to average cell energy within the jet. This is shown in the right of Fig. 8 where the embedded pythia jets are well separated from the “fake” jets. The next step is to subtract the underlying event energy from the true jets based on those “fake” jets.

These single jet measurements are important on an event-by-event basis. Combined with tracking these jets will produce fragmentation functions and j_T distributions(see Fig. 5). Both of these are predicted to be modified due to energy loss of the parton in the medium [14][21]. An important difference from RHIC correlations will be the reduced surface bias given that all of the energy of the jet should be reconstructed. Probing effects from deeper into the medium should be possible. One critical measurement from single jets is showing that the jet cross-section scales with the number of binary collisions, much like the direct photon cross-section scales at RHIC [22]. Once convinced that the energy of the jet is reproduced, modifications of measurements dependent on the jet energy scale become sensitive to the medium.

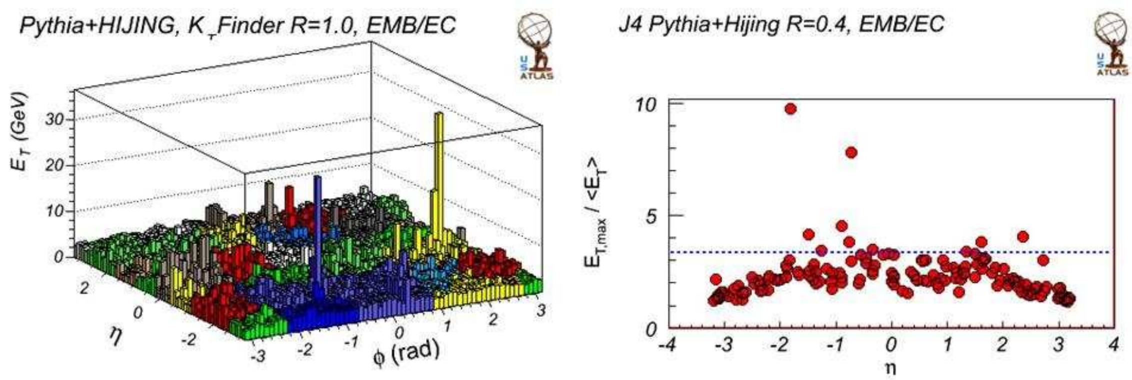

Figure 8: *Left:* Calorimeter towers from a PYTHIA di-jet embedded in b=2 fm HIJING. Each of the (colored) regions represent a different jet from the Fast-k_T algorithm [20]. *Right:* Event distribution for the ratio of the maximum cell energy to the average cell energy in the jet. This figure is ATLAS preliminary based on a modified release of Athena 11.0.41.

One important way to measure the jet energy scale is to study γ-jet events, since the recoil jet approximately balances the γ. These events also exploit a unique feature of the ATLAS calorimeter which is seen in the left panel of Fig. 9. This shows the $\eta - \phi$ segmentation of the different longitudinal segments of the barrel electromagnetic calorimeter ($|\eta| <$1.5). The first layer is finely segmented in η (typically $\Delta\phi$ =0.003). Such fine segmentation was built into the calorimeter to vector $H \rightarrow \gamma\gamma$ events and for $\pi^0 \rightarrow \gamma\gamma$ rejection. For π^0 with E_T below $\sim$40 GeV, the two photons are resolvable in the calorimeter as separate peaks in the strip layer. A single photon typically deposits the majority of it's energy in a single strip. This is shown in the right panel of Fig. 9 which is a γ-jet event embedded in a b=2 fm HIJING event. It is important to note that, not only is the γ contained in a single strip but that the γ is clearly visible above the high multiplicity HIJING background. Studies from $p+p$ collisions indicate that using only the strip information a factor of 4 rejection of π^0 is obtained [23]. While this isn't sufficient to study prompt photons event-by-event, it provides a way to measure the background directly. Further, since a jet deposits a large amount of energy over a much broader range in the calorimeter, isolation will provide a large additional rejection making γ-jet detection feasible.

The jet capabilities outlined above are certainly not an exhaustive list of the studies that are possible. Not only will single jets provide, for example, fragmentation functions and j_T distributions, but information from displaced vertices or muon-tagged jets will provide information on heavy quark energy loss. Further use of the muon spectrometer allows for Z reconstruction and a study of Z+jet or $Z \rightarrow b\bar{b}$. After single jet studies, multijet studies will be possible and will yield information on acoplanarity of di-jets and hard radiation from jets, both of which are expected to become modified by the medium.

3. Summary and Conclusions

With the additional measurements that the LHC will provide, puzzles presented by RHIC data may help become resolved. RHIC's wealth of single particle and correlation data are impressive,

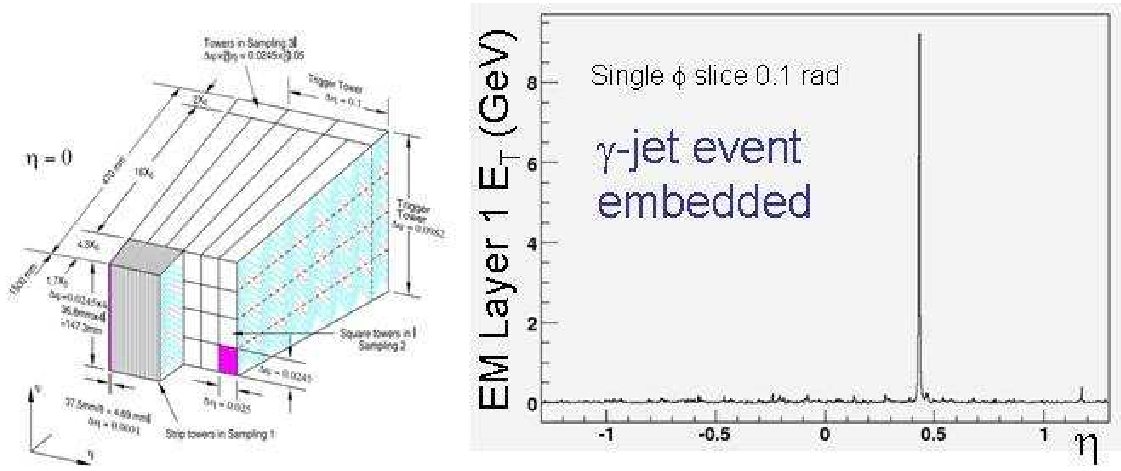

Figure 9: *Left:* View of the barrel electromagnetic calorimeter longitudinal segments. The first layer has a segmentation of 0.1 in ϕ and 0.003 in η. *Right:* Example of the energy deposited in the strip layer from a 75 GeV photon in one ϕ strip and embedded in a b=2 fm HIJING event.

but lack necessary event-by-event and/or jet energy scale information to disentangle or distinguish competing models of energy loss and medium excitation from the energy loss. ATLAS is in a position, using its highly segmented calorimeter, to make a large impact on jet measurements at the LHC via single jet and γ+jet measurements and beyond.

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