Jet Probes at RHIC

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I present a brief review of RHIC results focusing on hard scattering. The $A+A$ (nucleus+nucleus) data indicate the presence of a final state medium with a rich set of characteristics which modifies jet fragmentation significantly. RHIC also has a strong $p+p$ program at energies ranging from $\sqrt{s}$ of 62.4-500 GeV, which has been used as a control to the $A+A$ measurements as well as to study the spin structure of the nucleon. We are interested in measuring event shape observables in $p+p$, which should be possible and beneficial to the "Power Correction community" since we are focused on lower scattering energies as well as attempting to observe their expected modification in $A+A$ [1]. As a start, I propose to look at the Energy-Energy Correlation (EEC) and especially, to avoid bias with the limited acceptance detectors like PHENIX, in events tagged with a direct photon–a proposal which is also tantalizing for $A+A$, since the RHIC $A+A$ data show a novel, substantial increase in direct photon signal relative to jet background.

1. RHIC: Basic Results

RHIC is the Relativistic Heavy Ion Collider located at Brookhaven National Lab capable of colliding a variety of hadronic and nuclear systems including $A+A$, $d+A$, and $p+p$, at a variety of energies which for $p+p$ extends to $\sqrt{s}$ 500 GeV. The $p+p$ program is mainly focused on Spin Physics using RHIC's additional beam spin polarization capabilities (proton beam polarizations for both beams of up to ∼60% have been achieved so far), but is also available for non-spin analysis, and has been used in this manner to make control measurements to those made in $A+A$. So far the majority of data taken at RHIC's nuclear maximum energy of $\sqrt{s_{NN}}$ of 200 GeV, however 400 GeV commissioning has been acheived for $p+p$ and 500 GeV running is expected to start in upcoming near future runs. RHIC detectors [9] are optimized to study both soft and hard physics.

The scope of this talk is too short to survey all the interesting results that have come from RHIC so far, but in addition to putting the some of the world's best constraints so far on the gluon spin in it's $p+p$ program, many new phenomena have been observed in $A+A$ collisions which are indicative of the creation of new state of matter. [20] Some of these include:

- evidence for extremely large energy, particle number, and QCD charge densities
- evidence for thermalization/statistical equilibrium
- evidence for hydro-dynamic flow of the medium, which cannot be explained by interactions of normal hadrons, and which favor non-hadron degrees of freedom
- large baryon excesses in low momentum particle production which recombination of quarks might explain
- significant modifications to hard scattering/jet fragmentation which have never been previously observed

Whether indeed the matter behind these manifestations is, in fact, the coveted Quark Gluon Plasma (QGP) state for which it was RHIC's goal to create and discover, is still being debated, but this debate may largely be a question of semantics. As experimentalists we wish to study and characterize the new state of matter whatever its name.

2. Hard Scattering, pQCD, Jet Physics and at RHIC

Perturbative QCD describes the RHIC $p+p$ and d+Au (within expected small nuclear effects) at high transverse momentum (p_T) particle production at mid-rapidity quite well. [13] [18] In $A+A$ events, comparisons to perturbative QCD is clouded by an extremely large soft "underlying event", typically contributing up to factors of hundreds times

the multiplicity and total transverse energy of a typical single $p+p$ inelastic event at the same energy. However, because this extra multiplicity comes virtually all at very low momentum, by looking at production of particles above $p_T \sim$ 3-5 GeV/c, one finds that things look enough like enough like the pQCD description that we can be confident that this is indeed the underlying production mechanism. For example, the high p_T $A+A$ data scales with x_T with almost exactly the same spectral shape as observed in $p+p$, QCD event generators, and NLO pQCD. Hard direct photon production appears to match all of the above with hardly any modifications whatsoever. [12] Jet formation is clearly observed with many of the same properties of all of the above. On the other hand, it is also clear that certain aspects of the jet production are clearly modified.

First, while the spectral shape is very similar, the total yield of high p_T hadrons is suppressed in Au+Au collisions, particularly in central (impact parameter $\rightarrow 0$) events, compared to what would be expected from $p+p$, scaled for the nuclear thickness. [20] That such scaling is correct is confirmed in a number of ways, notably the fact that it works in d+Au collisions (much smaller but expected nuclear effects are not excluded) and most dramatically by the before-mentioned direct photon production which in the same events is not suppressed according to the scaling. The high p_T suppression is quantified by the ratio $R_{AA} = d\sigma_{p+p}(p_T)/(T_{AA} d\sigma_{A+A})$ where T_{AA} is the nuclear thickness factor, as shown in figure 1. I also note that the high p_T suppression of hadrons in $A+A$ was predicted before RHIC turned on, and these energy loss models which are based on increased medium-induced gluon Bremstrahlung of fragmenting color charges (*ie* jets) describe the data well. [19]

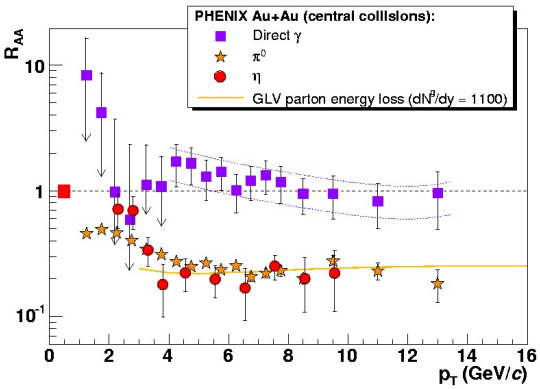

Figure 1: R_{AA}'s for various particles at RHIC. ([3])

The second type of modification to jet fragmentation observed so far at RHIC is the modification of the angular distribution (shape and multiplicity) of jet events in certain kinematic regions. In order to explain these observations it is necessary to first explain the method of two-particle correlations used to study these angular distributions at RHIC.

Because of the before mentioned large soft multiplicity background, traditional jet finding (cone, k_T, etc..) algorithms have not been attempted in the $A+A$ environment, though it should be noted that such algorithms have been successfully applied to $p+p$ data at RHIC. Instead for $A+A$, simple two particle correlations are constructed where the distribution of particle pairs as a function of the opening angle of the pair is measured [11], [17]. At mid-rapidity, only the projection of the opening angle in the transverse plane, $\Delta\phi$, is usually considered, and p_T ranges allowed for the two particles are varied, defining two categories of particles: "triggers" with p_T^t and "associated" p_T^a (other naming conventions abound). With sufficienctly high transverse momentum cuts ($p_T > 1$ GeV/c), for example as shown in figure 2, production is strongly, and with increasing p_T cuts (as in the figure), nearly completely, correlated around opening angle of 0 and pi due to the expected perturbative QCD dominance of di-jets. The width of the "nearside" peak around 0 is related to the intrinsic j_T of jet fragmentation while the "awayside" peak width includes this as well as a spreading out due the intrinsic parton k_T. 3-jet and higher jet multiplicity contributions appear to be either undetectable (so far) or hidden in the underlying $p+p$ "pedestal". Such correlations made for the same kinematic cuts in PYTHIA events at the same energy look nearly identical as do such correlations constructed in

d+Au and the least central (called peripheral) $A + A$ events. [7] Therefore such correlation distributions define a control with which to compare the shapes of similar but more central $A + A$ events. Indeed, when this is done a similar picture emerges as in the case of the single particle production spectral shapes, where the correlations look enough like the $p+p$ control that we can be confident that we are dealing in fact with jet correlations, but in perhaps an even more emphatic fashion than in the case of the singles, quite interesting modifications are observed.

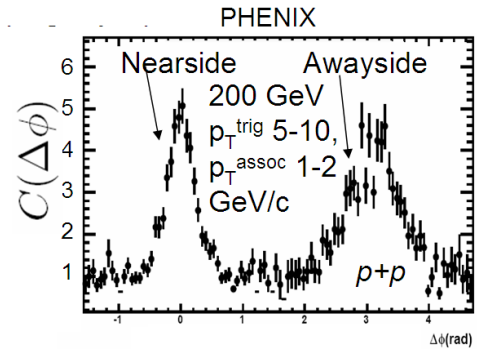

Figure 2: An example correlation function for $p + p$ data made with PHENIX. [10]

First, a little about combinatoric background in the more central events. For p_Tś below $\sim$ 4 GeV, there is still a rather large soft underlying multiplicity and to a smaller degree multiple independent di-jets which cause combinatoric background pairs. The contribution of this background must be separated from the true di-jet correlations themselves. This background however is not expected to be completely uncorrelated however as both the soft and hard particles in semi-central events, where the collision overlap region of the two spherical nuclei is almond-shape, are observed to also be azimuthally asymmetric, exhibiting a "v2" cosine 2x modulation with respect to the transverse projection of the nucleus-nucleus impact parameter (which itself is measurable **??**). For the soft multiplicity this modulation is interpreted as hydrodynamic flow of the matter created in the collisions and which hydrodynamic models describe well. For harder particles the modulation is interpreted as jet energy loss differences for different paths across the collision overlap. Whatever the process, these modulations should be reflected in turn in a harmonic modulation of the combinatoric pairs in the correlation function. Thus the total correlation is assumed to be comprised of "two sources", harmonic and jet, and an independently determined harmonic shape is subtracted from the correlation function to obtain the jet shape. [11] This is demonstrated in figure 3, along with examples of the general types of modifications to the awayside shape of the corrrelations observed at RHIC, which include a "disappearance", an enhancement, a large broadening of the awayside, and even an apparently "radical' modification causing a new local maximum to appear displaced from $\Delta\phi = \pi$. Some speculate that the latter may be due to oversubtraction due to faulty assumptions or details of the two-source model subtractions, and thus simply again represent large broadening. Each of these modifications occur at different combinations of very low ($<$ 500 MeV/c), low ($\sim$1-3 GeV/c), intermediate (3-5 GeV/c) and high p_T ($>$ 5 GeV/c). Meanwhile for most cases, the shape and per-trigger yield of the nearside correlation appears to be hardly different at all across all centralities and hardly different from what is seen in $p + p$ and d+Au collisions. **??**

3. QCD Event Shapes at RHIC?

Since jets are already being used as probes of the RHIC $A + A$ medium, it is natural to try to extend the measurements of simple 2-particle correlations into more complicated aspects of modification of the perturbative QCD event characteristics. A (perhaps lofty) goal would be to make the same or similar types of "QCD Event Shape" measurements have been made previously perhaps even some of the ones that this workshop has been focused on. As there appear to be many such quantities studied in both e+/e- and e-h, as well as in h-h including new proposals

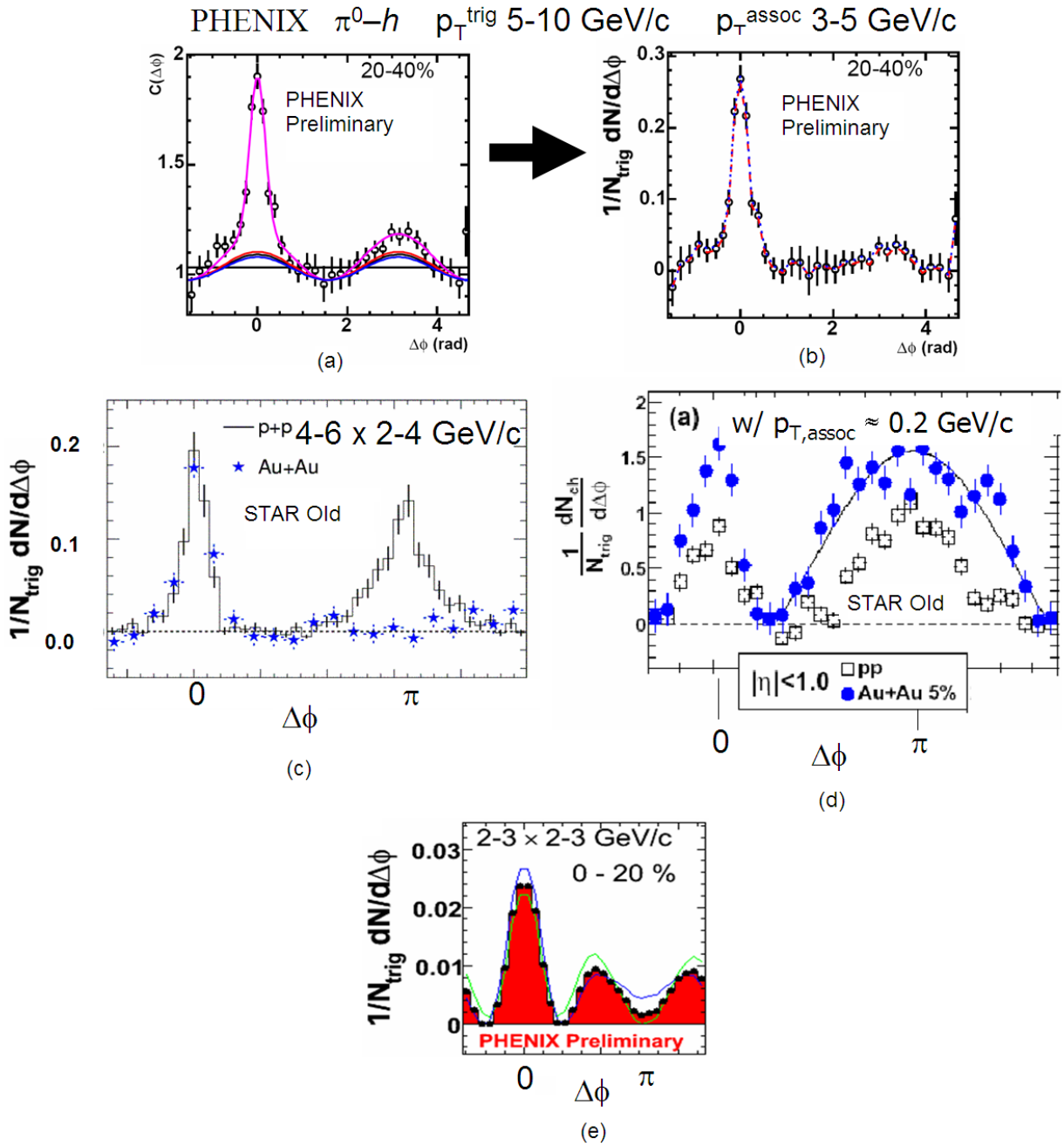

Figure 3: Bunches of Correlation Plots: a) and b) visually demonstrate the flow subtraction discussed in the text for an example of 20-40% central PHENIX data. [16] c) older STAR data [14] showing the "disappearance" of the awayside correlation. d) older STAR data showing the enhancement and broadening of the awayside correlation at the lowest p_T^a's. [15] e) PHENIX data showing the appearance of a displaced peak away from the awayside 180 degrees. [16]

directly related to Power Correction studies, there very well may exist some subset that can be measured and yield interesting information RHIC. In fact, since we have lots of $p+p$ data, it could be directly advantageous to the Power Correction community for us to make the measurements only in plain $p+p$ collisions. The advantage that RHIC $p+p$ data might present to this community is that since at RHIC we have been traditionally focused on scattering with much lower Q values, we likely can make more accurate measurements in that kinematic regime–

exactly where the power corrections themselves are expected to be largest. [4]. The disadvantage of course is we are not used to making such measurements and our detectors may not be optimal for doing so. For example, the PHENIX detector has limited (1/2) azimuthal acceptance at mid-rapidity. Making such measurements in the $A + A$ environment may also not prove impossible and if it were, it might be interesting to observe how things deviate from the power correction/pQCD predictions. For example suppose the data could still be fit reasonably well with the power correction model in $A + A$, what might that imply. From the comments of Al Muller at the workshop [1], we should expect these effects to be dramatically different in the presence of a QGP–it might be interesting to see if that is indeed the case.

As a first step in this direction I propose to start by measuring the Energy Energy Correlation (EEC). It is already known that in e+e- collisions the EEC in the awayside is sensitive to Non-Perturbative effects, possibly describe-able (at least in part) by power corrections. [4]. The closely related projection of this correlation into the transverse plane has been suggested by other authors to be sensitive to higher order perturbative effects (e.g. hard gluon emission) in hadron-hadron collisions [2] and several authors have even proposed that it be measured in heavy ion collisions since it could be sensitive to multiple scattering [5], [21]. It is a natural starting point considering the close relation to the two particle $\Delta\phi$correlations which have already been performed at RHIC: essentially the EEC is simply the sum of the two particle correlations made over all p_T ranges with an additional weighting by the energy.

Note that the inclusion of the scattering energy Q (which depends on the x's of the incident particles in the hadron/nuclear case) or its proxy E_T, is mainly for normalizing different scattering energies over a certain range. Restricting the range of Q's is desirable since we wish to study Q dependent effects. Obviously without such a restriction, due to the relatively steep fall off of the scattering energy, integrating over a large range in Q, for example by making a minimum $E_T$cut ($E_T > E_T^{min}$), would result in an EEC which is dominated by low Q scatters, how low being determined by the value of E_T^{min}. Thus it may not even be necessary to perform such a normalization in order to be sensitive to certain effects.

In the PHENIX detector at RHIC, there is a limited phi acceptance, π instead of 2π ϕ coverage [9]. Therefore on an event by event basis, the measured E_T can be much less than the true scattering energy. This is shown for example in 200 GeV $p + p$ PYTHIA events in figure 4 along with an estimate of the relative distortions of the measured EEC in a mocked up version of the PHENIX acceptance. Presumably a statistical correction can be made to the full event averaged EEC value, but this will presumably suffer from systematics from fragmentation uncertainties.

In order to alleviate this problem, as well as for other reasons I also propose measuring the transverse EEC in direct photon events. Due to the fine segmentation of the PHENIX Electromagnetic Calorimeter [9] two photons from a π^0 decay can be separated up to at least p_T ~25 GeV/c and thus direct photons can be tagged on this basis, without isolation cuts, with an increasing purity of greater than ~50% at $p_T = \sim 15$ GeV/c going up to $> 90\%$ by $p_T = 20$ GeV. Even for 50% purity, a statistical subtraction of the di-jet contribution to the correlation should be possible in order to reveal the average signal in true direct photon events. The prospect for achieving a pure direct photon sample in Au+Au [1] is actually also good, due to the before-mentioned hadron suppression effect, a new phenomena at RHIC which reduces the π^0 background photons by up to a factor of ~5 and thus increases the intrinsic signal to background by the same factor. [8], [12]. Obviously since the direct photon carries a majority of the scattering energy, as demonstrated in figure 5 (a), using $2E_T^{\gamma}$ as a proxy for Q could result in much less bias than the PHENIX measured E_T. Studying photon-jet event shape characteristics in Au+Au and comparing them to those in di-jet events is important at RHIC since the two cases should average very different paths through the medium, since the suppressed di-jets are biased towards the surface of the medium.

Direct photon events in $h + h$ collsions are similar to t-channel $e + q \rightarrow e + q$ scattering already studied in the power correction studies in Deep Inelastic Scattering, to quote Thomas Kluge [6] "resembles half an $e^+ + e^- \rightarrow$2 jet event." In figure 5 (b) I present the EEC created from $p + p$ direct photon events from PYTHIA at $\sqrt{s}$ 200 GeV. One can imagine two scenarios: including the direct photon itself in the EEC and not including it. Not including it

[1] again without isolation cuts, which are not very effective anyway due to the large underlying background

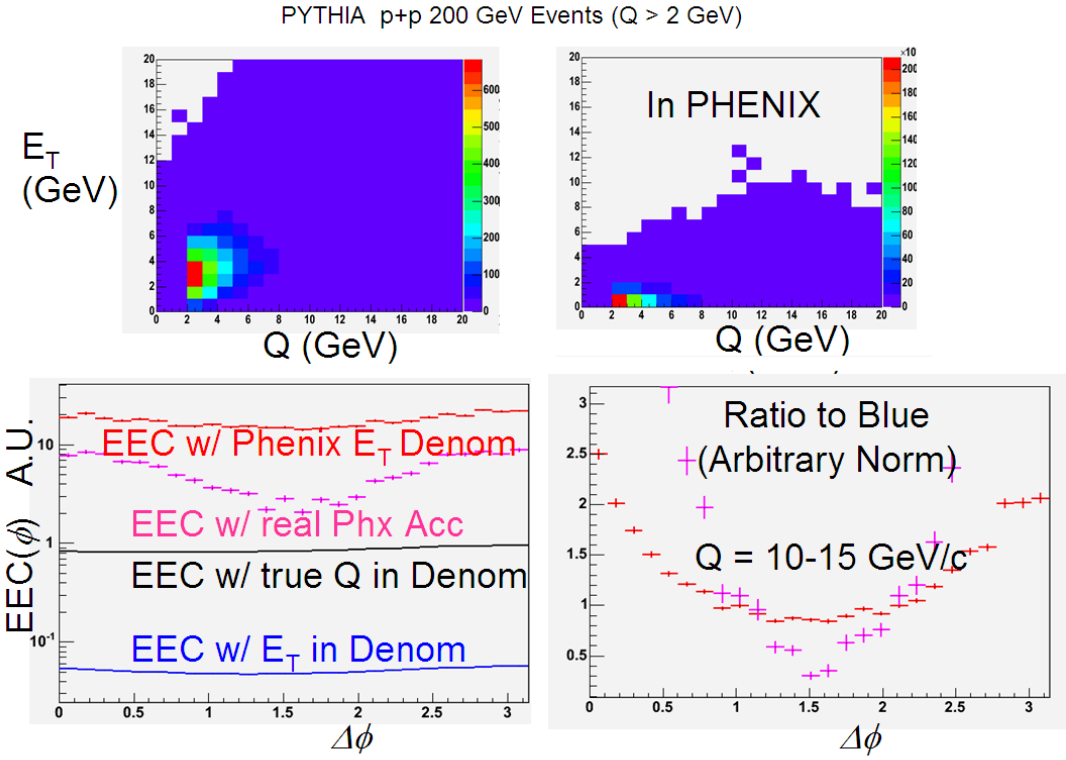

Figure 4: top: correlation between total final state E_T and scattering energy Q in PYTHIA events with wide $|\eta| < 3$ and full azimuthal acceptance and with the PHENIX acceptance. ($|\eta| < 0.35$, $\phi = \pi$) bottom: the effect of the PHENIX acceptance on the EEC.

results in the expected extreme reduction of the awayside correlation. Since this is essentially similar to removing the leading order contribution, could this make it's shape even more sensitive to higher order and non-perturbative effects? Can the transverse EEC be calculated for direct photon events in $p + p$?

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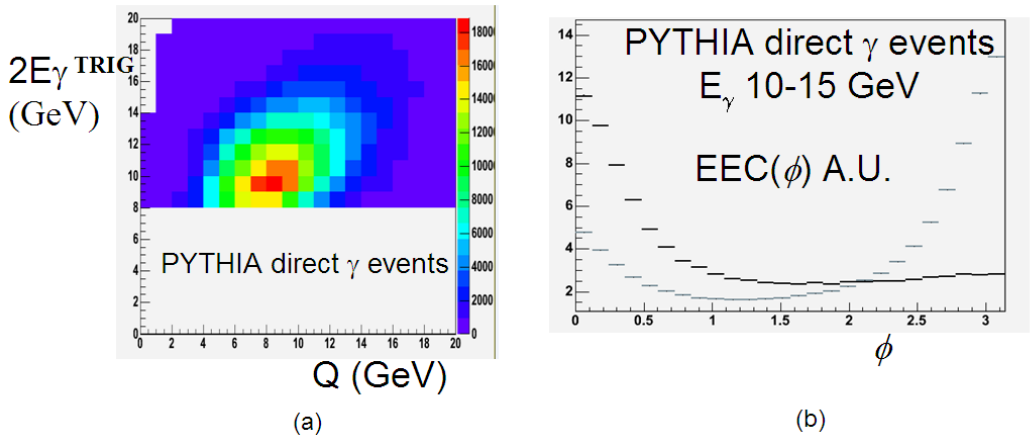

Figure 5: (a) Correlation between $2E^{\gamma}$ and scattering energy Q in PYTHIA events with direct photons 10-15 GeV. (b) The tranverse EEC in the same PYTHIA events. In grey, the EEC includes direct photon energy, in black it does not.

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