Physics background of the d+Au γ and π^0 measurement

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One of the most important signatures of formation of QGP was the so-called *jet suppression* in heavy ion collisions. It is measured by the *nuclear modification factor* R_{AB}, formally defined as

$$R_{AB}(p_{\mathrm{T}}) = \frac{Y_{AB}(p_{\mathrm{T}})}{N_{\mathrm{coll}}\, Y_{pp}(p_{\mathrm{T}})}, \tag{1}$$

where A, B are two (large) nuclei, $Y_{AB}(p_{\mathrm{T}})$ is the invariant yield measured in AB collisions (for a jet, or a given particle, in our case π^0, as a function of p_{T}), $Y_{pp}(p_{\mathrm{T}})$ is the invariant yield measured in $p+p$, and N_{coll} is the "number of binary (nucleon-nucleon) collisions", or "equivalent nucleon-nucleon luminosity" if two large nuclei collide. Simply put, if the yield we observe in AB is nothing but N_{coll} times the yield observed in $p+p$, R_{AB}, the nuclear modification factor is unity. If it is smaller than one, we say the production in AB is *suppressed*, if bigger than one, we talk about *enhancement*.

1 Au+Au, N_{coll}

N_{coll} is a crucial concept, so let's dig deeper here. First, it is important to recall that while nuclear matter is pretty dense, in reality the individual nucleons are still quite far from each other [1]. Now if two heavy ions collide, there are two fundamental possibilities. One (case A) is that any time a nucleon from nucleus A hits a nucleon from nucleus B, what happens is exactly the same as would happen in a plain $p+p$ collision, irrespective of the surroundings or what happened to the nucleon before. (Don't stop here, this is only a half-crazy assumption). In other words the yield obtained in AB is simply the incoherent superposition of some number of $p+p$ collisions (N_{coll}), nothing else. How to actually "calculate" N_{coll} is a different question, see later. The second possibility (case B) is that in an AB collision something additional happens – for instance, a medium is formed, which then influences the products of the "elementary" $p+p$ collision – and what we ultimately observe is different from the N_{coll} $*p+p$ expectation.

N_{coll} of course depends on the *impact parameter* b of the collision. If $b = 0$ fm, i.e. they collide head-on, all nucleons in A have the chance to hit at least one nucleon in B (central collisions), if they just graze (in case of Au + Au $b >= 10$ fm, peripheral collisions), most nucleons don't even have a chance to hit anybody, they just fly by

[1] They are large for very low momentum exchange, like nuclear processes (MeV-scale), but small for large momentum exchange, like hard scattering, (GeV-scale, our interest)

("spectators"). – Now for any given b one can estimate the number of binary (nucleon-nucleon) collisions, and usually this is done with the Glauber-model. It takes the nuclei, distributes the nucleons within their volume randomly (remember, large empty spaces still!), then based on b looks at the region where the two volumes will overlap. In this overlap area it takes every nucleon from A, propagates it through B, and checks how many times it comes "close enough" to a nucleon in B, i.e. closer than 2*radius of the nucleon, and if this happens, increases N_{coll} by one. **Important!** Even after such a "collision" it propagates the nucleon in a straight line, as if nothing happened (low momentum-exchange, eikonal approximation), and it is still ready for another "collision" with another nucleon. – To give an idea, in the most central (b=0) Au + Au collisions N_{coll} can get as high as 1100-1200 while Au has only 197 nucleons. *The overwhelming part of these will be very low momentum exchange, maybe producing 1-2 low p_{T} particles each time.*

Why isn't this crazy at all? Because we are interested in hard scattering, high p_{T} particle production (large, many GeV momentum exchange in the nucleon-nucleon encounter), and these are very rare processes, moreover, with increasing p_{T} their probability drops like a stone. To put in context: the probability to get a hard enough scattering to produce a 5GeV π^0 in a $p + p$ collision is something like 10^{-6}, i.e. 1 in a million collisions. Now if the "equivalent $p + p$ luminosity" (N_{coll}) is 1000 in a very central Au + Au, all it means that you have to collect "only" thousand events for this process to happen once... In our region of interest (high p_{T}) N_{coll} is just a multiplier that makes an extremely small probability somewhat less extremely small...

Not so for very low momentum particles, which is the bulk, producing the overall high multiplicity in the event. Some are indeed produced each time two nucleon meet. Still the Glauber-assumption – that they usually go on almost unperturbed and ready for another "collision" – isn't unsane. The incoming nucleon had 100GeV/c momentum. It produced in a collision 2 pions (138MeV each) at, say, 400 MeV/c momentum (that's already a lot). Does it care? It sill has 99 GeV/c rushing forward, ready to meet the next nucleon almost full force. So the total multiplicity increases monotonically with the Glauber-calculated N_{coll}. (The real story is more complicated, but this simple, transparent argument is still essentially correct.)

But wait. The Glauber-calculated N_{coll} is based on the impact parameter b, which is **not** an experimental observable. b defines the (theoretical) "centrality" of the collision, which now has to be mapped to some experimental observable. Such experimental observable is in our case the multiplicity produced in the Beam-Beam Counters (BBC), forward rapidity. These are very low p_{T} particles (their production barely affects the nucleon). Now in a moderately complex process (no need to explain here, involves convolutions of negative binomials) one matches the multiplicity distribution observed in **all events** to the multiplicity distribution calculated based on Glauber N_{coll} for **all impact parameters**. Of course there are event-by-event fluctuations, but if we select from the experimentally observed multiplicities the highest 10% events, *most of them* will indeed come from very small b (the true one, which remember, is not directly observable) collisions.

This sounds hand-waving, but – jumping a bit ahead – it can be proven, at least for Au + Au. Fig. 1 shows the "PHENIX T-shirt plot", which has the nuclear modification

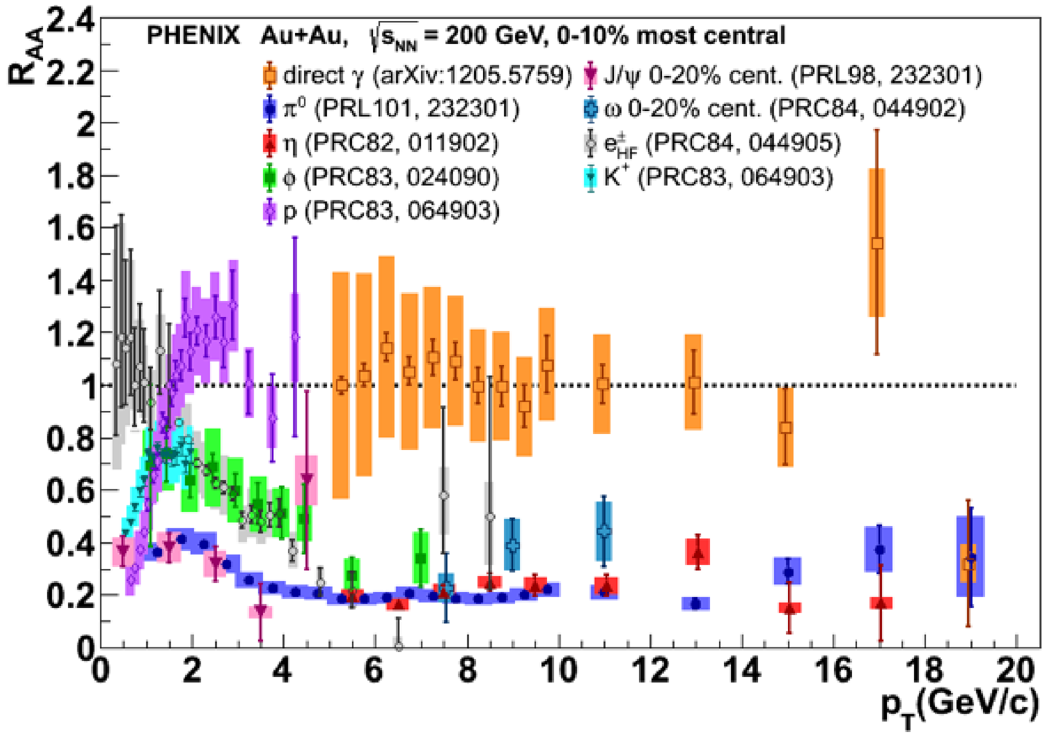

Figure 1: The PHENIX "T-shirt plot": nuclear modification factors in 200 GeV AuAu for various hadrons (all suppressed at high p_{T}) and photons (not suppressed).

for all kinds of hadrons, and for the photon, in the most central (I mean experimentally, i.e. in the highest multiplicity class) events. For moderate to high p_{T} *all* hadrons are suppressed, because they are fragmentation products of hard-scattered, colored partons, which then traversed the *colored* QGP strongly interacting with it and losing energy as compared to the case ($p+p$) when they would immediately find themselves in the vacuum and hadronize (at their original p_{T}). Since the p_{T} spectra are rapidly falling, this means that observing a particle at, say, 10 GeV/c is less probable in an Au + Au event than in N_{coll} $p+p$ events [2] (and remember, R_{AB} shows the ratio at the same p_{T}). – Now look at the photons! They are also produced in initial hard scattering, but they are *blind to the strong interaction*, so even if a QGP is formed, they sail through it. (I know, quarks are charged and photons interact electromagnetically, but the coupling is 1/137, negligible in comparison to strong coupling, their mean free path in the QGP is 2-300 fm, while the QGP is no greater than 10-20 fm.) – And here a circle is closed. Photons are expected to have R_{AB} =1 from purely theoretical (and well founded!) reasons. But this R_{AB} was calculated using the Glauber-model based mapping of b (centrality) to observed multiplicities, and some of the steps were "leap of faith". Now you can turn around and say: since using this somewhat shaky mapping gave the expected result, the mapping works, after all! The unity of the photon R_{AB} (not only here, in all centrality bins) proves that the calculated N_{coll} is sane. **At least**

[2] Think again of "equivalent nucleon-nucleon luminosity": whatever comes out of a *single* Au + Au collision is compared to the *total* particle production from N_{coll} $p+p$ events

in Au + Au.

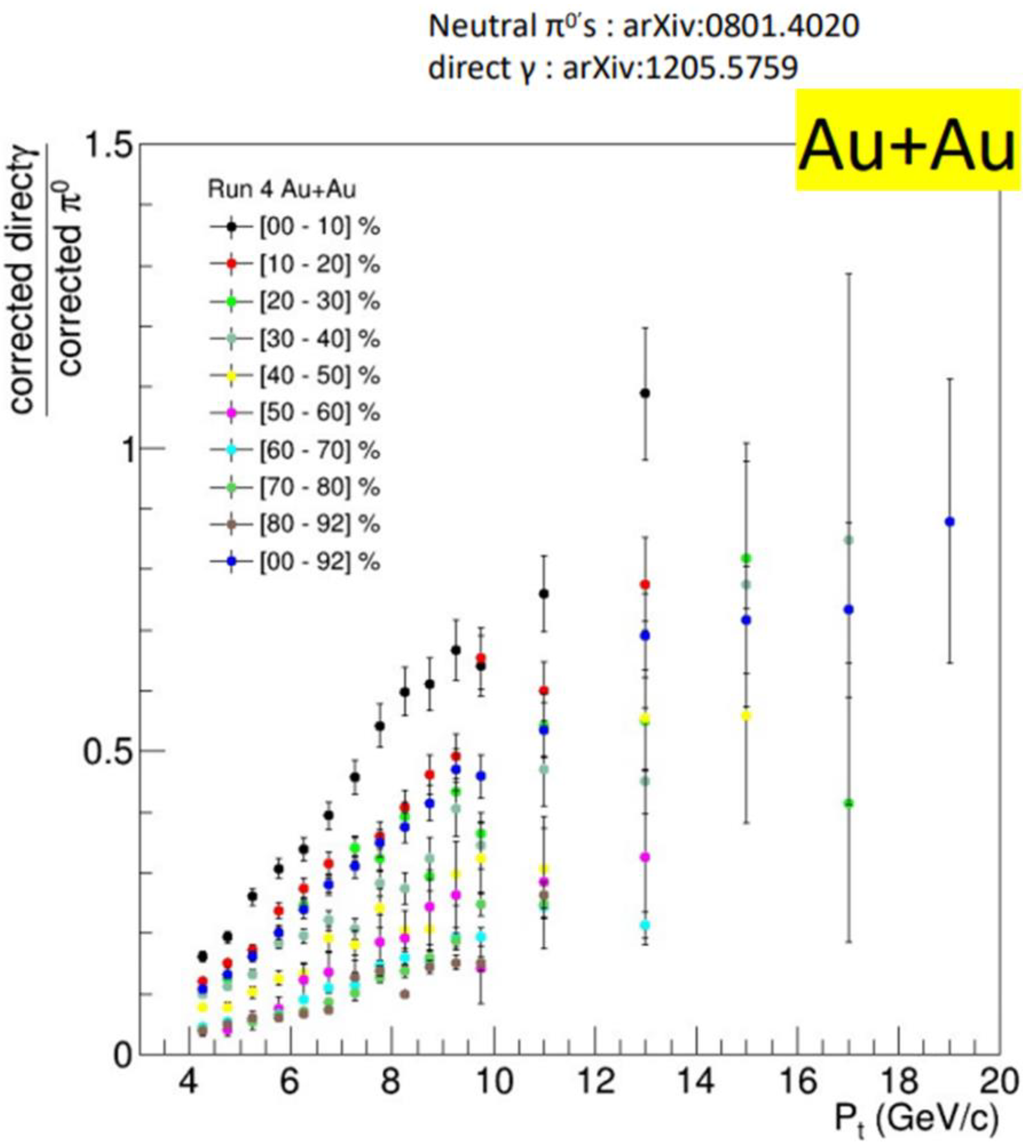

Figure 2: The ratios γ/π^0 vs p_T for different centrality classes in Au + Au.

We know that in Au + Au at high p_T π^0 are suppressed, more in central, less in peripheral collisions (smaller QGP to slow the hard parton down). Since photons are not suppressed (QGP or not), their R_AB is unity for any centrality. So if you now plot the γ/π^0 ratio as a function of p_T, you would expect that the curves separate for different centralities: photons are always proportional to N_coll, pions (the denominator) are more and more suppressed with respect to it, so the ratios will be smallest for peripherals (small suppression) and highest for central collisions (large suppression). This is indeed the case, as shown in Fig. 2.

2 p+p

As discussed above, collision centrality is determined from the multiplicity of low p_T particles produced at forward rapidities (BBC), and there can be many of them in an average event, since low p_T means that only a small fraction of the total proton momentum has been used up. But what if the event is not "average", but one of those (rare!) ones that produce a high p_T particle at mid-rapidity? High p_T means high momentum transfer from the proton to the new, produced particle. Taking the absolute extreme, if a 100GeV/c proton produced a 100GeV/c π^0 at mid-rapidity, there's zero momentum left for forward particle production, i.e. the BBC would be empty (and the event wouldn't be triggered on, at least not with the "minimum bias" trigger based on BBC charge). While this never actually happens [3], obviously if we go sufficiently high in p_T at mid-rapidity, at some point low p_T particle production forward **has to decrease**. (You might as well call it conservation of energy...) The only question is quantitative: **when** does this depletion of forward multiplicity begin? Well, surprisingly early.

In Fig. 3 the average charge in the BBC is shown as a function of the highest p_T π^0 seen at mid-rapidity. The blue dashed line corresponds to the average (minimum bias) events, where only particles of a few hundred MeV/c are produced (that's, say, 99+% of all events...). The black line is the average charge for *triggered* events, where there is a cluster of at least 1.5 GeV in the calorimeter. The red circles are the average charge forward as a function of the highest p_T measured at mid-rapidity. It should be noted that

1. the average charge in triggered events is about 50% higher than in minimum bias, but
2. since the p_T spectra in this region fall exponentially, even in the triggered events the average charge is dominated by events with only 1.5-2.5GeV/c
3. such momentum transfer between the scattered partons means they already got pretty close (0.1 fm to be compared to the 0.8 fm size of the proton), so chances that other, smaller momentum fraction partons also interact, and produce low momentum particles forward, increases
4. however, a significant, monotonic decrease of the average charge starts already at 5 GeV/c, and at 20 GeV/c it is already in the minimum bias range
5. no matter how "excited" the proton is, spending 20% of its momentum on a single particle reduces its forward activity to the minimum bias levels
6. such high p_T events are extremely rare (one in a million or even less)
7. If we defined "centrality" in $p+p$ collisions using the charge produced forward, higher p_T events would automatically be pushed toward lower "centrality" bins (less charge forward); of course not all of them, due to large natural fluctuations, but still on the average that's what would happen

[3] It would mean that a single valence quark carries all the momentum of the proton.

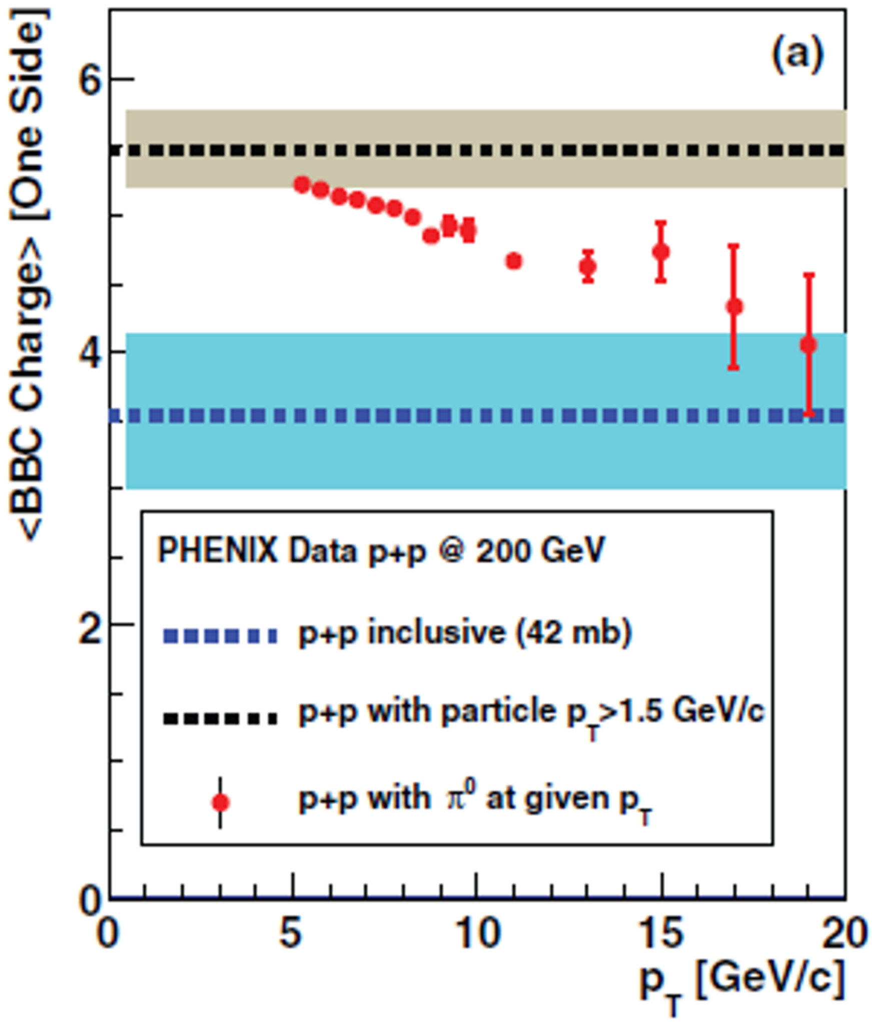

Figure 3: Average charge in the BBC ($-3.9 < \eta < -3.0$) as a function of the highest p_{T} π^0 at mid-rapidity.

At this point you might ask, that if the change in forward charge is so dramatic, how come the Glauber-mapping and centrality works so well in Au + Au? The answer is that because the high p_{T} processes are rare, and even if they happen in a collision, they involve only one pair of mucleons (from the two ions), all the other nucleon-nucleon encounters are average, low momentum exchange. Add the large fluctuations, and it turns out that "loss of production" from single pair is simply unnoticeable – except maybe in the very peripheral collisions where only a few nucleons participate in the collision from both sides. In fact, a possible bias in those most peripheral R_{AB}-s has already been pointed out 2017 – not the least inspired by the upheaval around d+Au collisions, to be discussed next.

3 d+Au

Contrary to Au + Au, where formation of the QGP and, as a consequence, suppression of high p_T hadrons has been expected, in d+Au and other "small system" collisions it was initially thought that the conditions are insufficient for QGP formation. However, measurements at RHIC and LHC since 2012 appeared to contradict this. A recent result is shown in Fig. 4. In central collisions not only d+Au, but even p+Au and ^{3}He+Au shows a suppression – not as dramatic, as in Au + Au, but statistically clearly significant. Even more surprising, in the most peripheral collisions there is an apparent *enhancement*, which simply cannot be explained in any current theory. So even if you accept, that despite earlier expectations QGP can indeed be formed in small systems as well, you are still left with the puzzle of anomalous enhancement in peripherals.

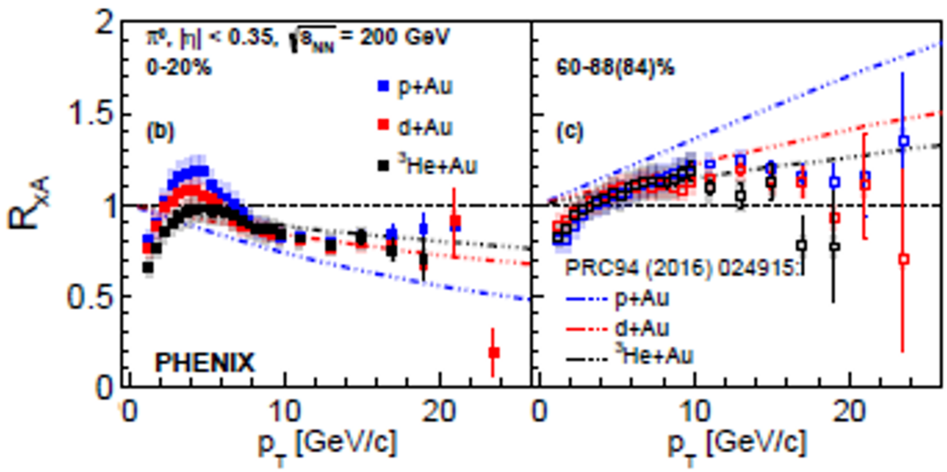

Figure 4: Nuclear modification factors in "small system" collisions, most central and most peripheral.

Before claiming discovery, it's always useful to revisit **all** assumptions used in your analysis. One of them is the Glauber-type mapping of the impact parameter b to the measured forward multiplicity (or charge). Is it possible that the method that works in Au + Au fails (maybe only in extreme circumstances) in d+Au? – Remember, in $p+p$ we've already seen a hint of this: in extreme events the charge produced forward decreased rapidly and proportionally with p_T, as compared to the vast number of "average" (albeit already triggered) events. But the effect may be even more pronounced in d+Au.

Also, it is worth seeing what is the net effect of fluctuations in the soft particle production in each (low p_T transfer) nucleon-nucleon collision. In Fig. 5 the N_{coll} distribution is shown for different, forward multiplicity-based centrality classes in d+Au, based on the customary Glauber-mapping. It is barely an exaggeration that essentially *any experimentally defined centrality class can contain events with any* N_{coll}. Yes, the scale is logarithmic, but it is "only" three orders of magnitude, while the rare events with high p_T have a probability in the 10^{-6} range. While this is not a proof that things necessarily go wrong at high p_{T}, it certainly is a serious warning. [4]

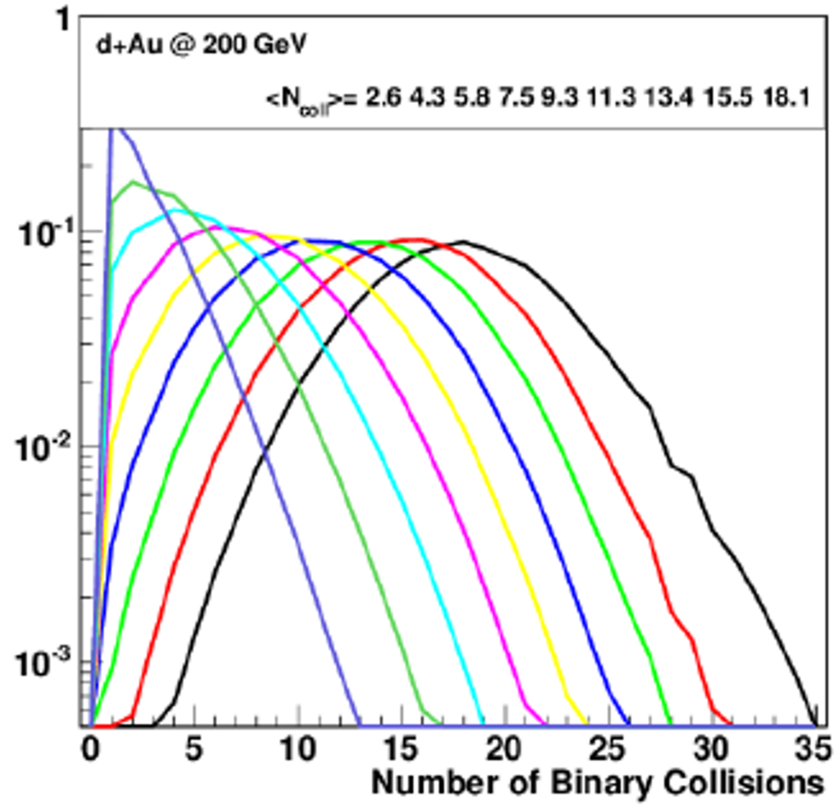

FIG. 3. Extracted distribution of the number of binary collisions in each of the nine centrality quantiles: 0-5%, 5-10%, 10-20%, 20-30%, 30-40%, 40-50%, 50-60%, 60-70%, and 70-88%.

Figure 5: Distribution of the number of binary collisions in d+Au for different, multiplicity-based centrality classes.

For simplicity, let's look at the p+Au case, i.e. just one single nucleon on one side ("projectile"), but many nucleons on the other ("target"). What happens in average events (based on which centrality is mapped, since it needs huge statistics). As the collision becomes more central, the projectile goes through more and more nuclear material, so it gets close to more nucleons of the target – but since each of those encounters is still almost always low-momentum transfer (low p_{T} particles produced), the total charge/multiplicity is still loosely proportional to N_{coll}. Due to the fluctuations the experimental centrality definition is by far not that crisp as in Au + Au but still sort of OK.

[4] Risking being repetitive, let's state again: even in those extreme events with very high p_{T} we classify the (centrality of the) event based on the multiplicity distribution in *average* events. But, as seen in Fig. 5, the multiplicity distribution on those high p_{T} events differs from the average!

But what happens in the rare case when a high p_T particle is produced? In Au + Au no sweat - even if the nucleon in question is unable to produce much charge forward, there are dozens of nucleons on both side to make up for it. But in p+Au there is **only one nucleon in the projectile**! So if it gets "incapacitated" to produce charge forward, it simply will not be produced. As a consequence, the event will easily be classified less central than it really is.

Qualitatively this explains what's seen in Fig. 4: some of the events with high p_T that in reality (b-wise) are central, based on forward charge end up being classified as less central. So if you now look at the events that are *classified* as central, some high p_T yield that would b-wise belong there, is missing! This makes the R_AB sink below unity, even if there was no QGP, no real energy loss, no nuclear modification. – At the other end, the most peripheral case the opposite happens: events from more central collisions are pushed into it, their high p_T yield shows up here, as an excess, and R_AB goes above unity. – Again, qualitatively this is true; whether it explains all the effect seen in Fig. 4 is a different question.

If you think back what we said in connection with the "T-shirt plot" you may ask: if the photons scale perfectly with N_coll, why bother at all mapping the theoretical b in a painful process to multiplicities and calculate N_coll? Why not just scale your pion (or other) spectra with the photons? Indeed, that's part of the idea behind PPG248... In Fig. 2 we plotted γ/π^0 ratios for Au + Au for historical reasons, but might as well plotted π^0/γ i.e. the π^0 yields normalized by γ as a proxy for *the true* N_coll– the message would be the same: the curves for different centralities clearly separate, reflecting the increasing degree of π^0 suppression.

The same plot for d+Au is shown in panel (c) of Fig. 7 and looks very different. While the uncertainties are sizeable, the points follow the same trend except for the green ones, which is the 0-5% most central. While there still appears to be a suppression in this most extreme class, all others are on top of each other. Whatever made the π^0-s be suppressed or enhanced as a function of centrality, affected the photons the same way. But since photons are "blind" to the QGP (no energy loss), it could not be a QGP effect. Most likely it is then a bias in the Glauber-classification of d+Au events in which very high p_T particles were produced.

In fact, you can even go a step further, and instead of the γ/π^0 or π^0/γ ratio make improved R_AB for the π^0 alone. Just look at Eq. 1 and think of photons, where it always is unity. You can then say, that if it is indeed always unity for γ, I can simply express the "experimental" N_coll as

$$N_\mathrm{coll,exp}(p_\mathrm{T}) = \frac{Y_{AB}(p_\mathrm{T})}{Y_{pp}(p_\mathrm{T})}, \tag{2}$$

i.e. the ratio of photon yields in A+B and $p+p$. This is a big thing for two reasons. First, instead of the complicated (and sometimes questionable) theory-to-experiment mapping we now have a direct experimental "measure" of N_coll. Second, this quantity is easily made into a p_T-dependent one, which in reality it is (we just didn't investigate it in PPG248 because of the relatively poor statistics at high p_T).

This write-up is intended to be a general introduction to the topic.

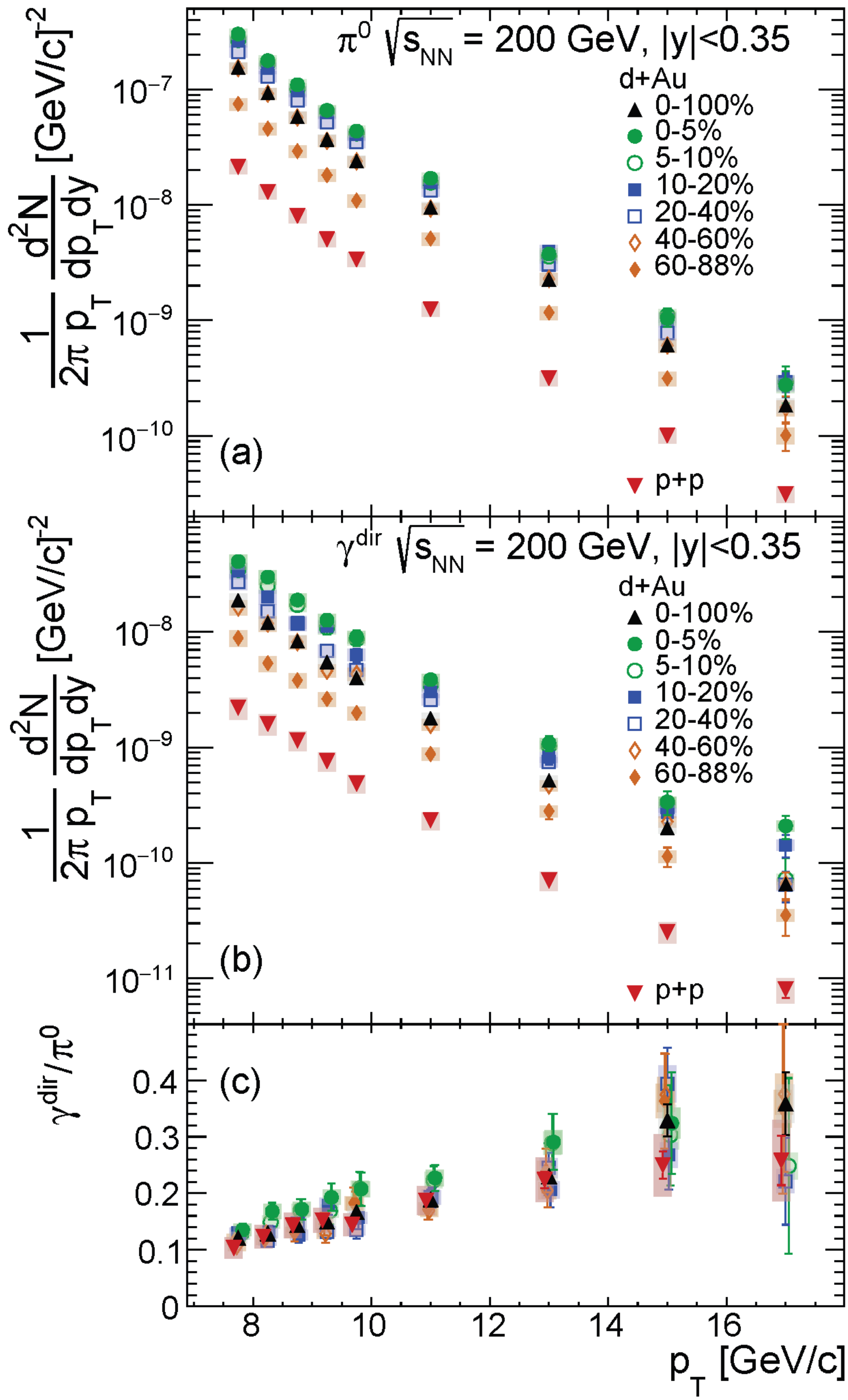

Figure 6: (a) Invariant yield of π^0 in different centrality classes, d+Au. (b) Invariant yield of direct photons in different centrality classes. (c) The ratios γ/π^0 vs p_T for different centrality classes in d+Au. Compare it to Fig. 2 to appreciate the difference.

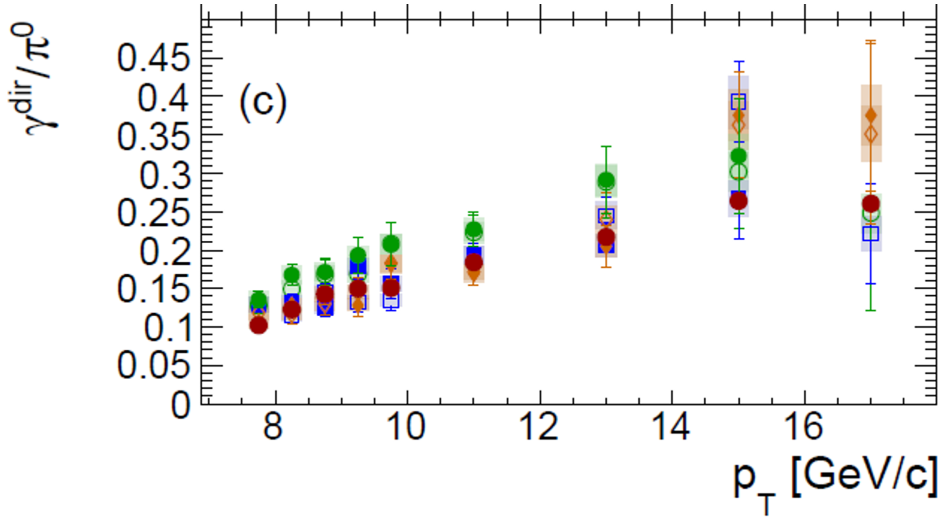

Figure 7: The ratios γ/π^0 vs p_T for different centrality classes in d+Au.