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# Direct Photons in Au-Au Collisions: The Case for the Shower Maximum Detector

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## 1 Introduction

Direct photons (i.e. photons that are not from decays of hadrons, e.g. $\pi^0 \to \gamma\gamma$) can be an informative probe of nuclear matter. Because photons do not feel the strong force, they provide both an undisturbed picture of the collision at very short times, and a comparison sample for understanding the interaction between quarks and gluons and the surrounding nuclear matter.

This note does not focus on the details of the physics of direct photons in Au+Au collisions. Rather, it assumes that we want to reconstruct them, and attempts to summarize what we know about this task from other experiments, the design of the EMC, and various Monte Carlo studies.

## 2 Direct Photon Lore

### 2.1 Backgrounds

The background to high $p_T$ direct photons arises from jets. Between about a quarter and a third of the particles in a jet are $\pi^0$'s, which decay into two photons. Sometimes a $\pi^0$ carries a large fraction of the jet energy, and sometimes it decays in such a way that the two photons are not resolvable: either by having the two photons too close to be resolved, or by having one photon too low in energy to be identified.

In fixed target and $p\overline{p}$ colliders, a common technique is to require that the direct photon candidate be isolated: that the energy near the shower be less than some amount. Real direct photons will fail this only if the photon happens to randomly overlap with a jet. Fake direct photons that arise from jets, however, can have the rest of the jet energy nearby, so isolation provides a way of distinguishing the two classes of events. It is important to point out, however, that fake photons still tend to be relatively isolated. Because the jet cross section is falling so steeply, it is easier to get a fake direct photon by having a low $E_T$ jet fragment so that most of it's energy is in a single $\pi^0$ or $\eta$ than having a high $E_T$ jet give a smaller fraction of its energy to the neutral meson - there are just so many more low $E_T$ jets than high $E_T$ jets.

A typical isolation cut might be that the energy in a cone of $R(\equiv \Delta\phi^2 + \Delta\eta^2) < 0.3$ be less than 15% of the photon energy. Both the cone size and the energy threshold can be varied, to change the rejection and acceptance of this cut.

## 2.2 Cross Section Calculation

The physics quantity of interest in direct photon physics is the cross section, that is, the rate of direct photon production. To measure this, it is not sufficient to have a low background: it is necessary to have a well-understood background. For the single $\pi^0$ background, the most common technique is to reconstruct as many $\pi^0$'s as one can, and then extrapolate from the ones that are identified to the ones that are not: often the asymmetry $A \equiv (E_1 - E_2)/(E_1 + E_2)$ is used for this.

This sets the scale necessary for the measurement. The mass of two photons of energies $E_1$ and $E_2$ with an angle $\theta$ between them is given by:

$$m = 2\sqrt{E_1 E_2} \sin \frac{\theta}{2}$$

Which is exact.

Casting this in terms of the total energy $E$ and the asymmetry $A$, this becomes:

$$m = \sqrt{1 - A^2} E \sin \frac{\theta}{2}$$

From this, we can determine the scale of angular resolution required to identify $\pi^0$'s from the direct photon signal, both to reject them as background, but also to measure how much background remains. For 10 GeV photons, for example, we need to resolve photons separated by about half a degree, or about .01 in $R$. The following table shows the photon position resolution necessary for the STAR detector (with the photon position detector 220 cm from the beam line) to separate direct photons from $\pi^0$ decays:

| $E_T(\gamma)$ (GeV) | Minimum separation (cm) | Most probable separation (cm) |
|---|---|---|
| 5 | 12.3 | 14.2 |
| 10 | 6.2 | 7.1 |
| 15 | 4.1 | 4.7 |
| 20 | 3.1 | 3.6 |
| 25 | 2.5 | 2.8 |

Without a shower maximum detector, we need a tower resolution that is of order half the average separation between photons. (Because we don't have position information within the towers, the origin of energy in two adjoining towers is ambiguous: it could be from two photons from a $\pi^0$, or it could be from a single photon that hit near a boundary, so the shower is in two towers.) To study photons in the 10-15 GeV range, would therefore require towers roughly 10 times smaller than the present ones, with 100 times as many photomultiplier tubes.

The shower maximum detector, however, has detector elements with resolution comparable to the size of a shower: 1-1.5 cm at these energies. Typically one can measure broadening of the shower shape from two overlapping shower to about this width, so the device is useful to about 40 GeV.

## 2.3 Statistical Reach and Background Rejection

Suppose one can only identify a fraction $x$ of $\pi^0$'s. How does this effect the ultimate statistical precision of the experiment? (Assume $x$ is known exactly; the uncertainty on $x$ is part of the systematic uncertainty.) One can then divide the sample into two statistically independent subsamples, $N_1$ "photon candidates" and $N_2$ "$\pi^0$ candidates. The number of true photons is therefore

$$N_\gamma = N_1 - \frac{1-x}{x} N_2$$

The statistical uncertainty on the number of direct photons is then the $1/\sqrt{N_\gamma}$ for a perfect system, multiplied by a weighting factor:

$$\approx \sqrt{1 + \frac{1}{x}\frac{1}{S/B}}$$

where $S/B$ is the signal to background ratio of the direct photon candidates.

Occasionally the possibility of reconstructing only a small fraction of $\pi^0$'s is discussed: the idea being that there are many $\pi^0$'s, so one can determine the number faking the direct photons quite accurately, even if the absolute reconstruction efficiency is small. A 5% reconstruction efficiency and a $S/B$ ratio of 1:10 give a de-weighting factor of about 14, equivalent to taking only 1/200 as much data. Since in Au-Au collisions we expect a few thousand photon candidates, such a strategy would leave us with the same statistical power of a few dozen.

This idea also relies on the $\pi^0$ background in direct photon candidate events being very similar to that in other events, an assumption that is reasonably good, but not quite perfect. Since the extracted photon signal is the result of the subtraction of two large numbers, the larger those numbers get, the more important the validity of this assumption becomes.

# 3 Photons in Au+Au Collisions

The environment in Au+Au colliding beam experiments has a much larger particle flux than any other direct photon experiment to date. Below some issues unique to Au+Au are explored.

## 3.1 Isolation

In central AuAu events, *nothing* is isolated. The issue relevant to direct photons is whether or not background fluctuations allow us to make any isolation requirement at all.

An AuAu event averages 45 GeV (charged particles + neutral EMC energy deposition) in a cone of $R < 0.4$, with a standard deviation of 6.8 GeV. [1] Therefore a cone of $R < 0.3$ will have 25 GeV, with a standard deviation of 5.1 GeV. A loose 20% isolation cut on even a 20 GeV photon candidate is only 4 GeV, so it's clear that the underlying event fluctuations make this cut far less effective than at other experiments.

Isolation, however, is not worthless. Charged hadrons can deposit a large fraction of their energy in an EM calorimeter, if for example the hadronic shower is rich in $\pi^0$'s. An isolation cut will reject these events: a 10 GeV EM tower is a rare thing in AuAu collisions. So is a 10 GeV track, or even two 5 GeV tracks pointing at the same tower. If a 10 GeV tower has one or more high $p_T$ tracks pointing at it, it is much more likely to be either a hadron-initiated shower or a jet: in either case, background to the true direct photon signal.

## 3.2 Random Overlaps

A Monte Carlo study was done assuming a detector with perfect particle identification and position resolution, and $16\%/\sqrt{E}$ momentum resolution. A direct photon candidate was overlayed on a HIJING AuAu central event, and $\gamma\gamma$ combinations were made, and pairs with masses less than 250 MeV were identified as $\pi^0$'s. 200 events at each energy were generated, and the number of reconstructed $\pi^0$'s are shown below:

| | $E_T(\gamma_1)$ (GeV) | | | |
|---|---|---|---|---|
| $E_T(\gamma_2)$ (MeV) | 5 | 10 | 15 | 20 |
| 500 | 636 | 279 | 225 | 42 |
| 750 | 30 | 18 | 15 | 11 |
| 1000 | 8 | 5 | 4 | 6 |
| 1250 | 4 | 2 | 2 | 2 |
| 1500 | 2 | 0 | 1 | 2 |

Note that it is often possible to find the "other photon" from the $\pi^0$ whether it is there or not, sometimes more than once. It is perhaps more informative to display the fraction of real direct photons that would survive such a requirement, assuming Poisson statistics.

| | $E_T(\gamma_1)$ (GeV) | | | |
|---|---|---|---|---|
| $E_T(\gamma_2)$ (MeV) | 5 | 10 | 15 | 20 |
| 500 | 4.2% | 25% | 32% | 82% |
| 750 | 86% | 91% | 93% | 95% |
| 1000 | 96% | 98% | 98% | 97% |
| 1250 | 98% | 99% | 99% | 99% |
| 1500 | 99% | 99% | 99% | 99% |

From this, it can be concluded that pushing the second photon detection threshold below about 1 GeV doesn't help. There are so many low $E_T$ photons that finding one near a direct photon candidate doesn't provide much rejection against $\pi^0 \to \gamma\gamma$ events.

A charged particle deposits about the same energy in the SMD as a 500 MeV photon. While in principle this background can be removed by taking tracks, extrapolating them to the SMD, and then disregarding the nearest shower, it would be better to have an additional handle on this background, such as the 1 GeV requirement mentioned above. Or, put the other way, since we already need to make a 1 GeV or so cut on the second photon candidate, it is fortunate that this also rejects the charged particle background.

### 3.3 Photon Energy Overlaps

In a detector with $\Delta\eta \times \Delta\phi$ towers of $0.1 \times 0.1$, we find that there is $640 \pm 520$ MeV of underlying event energy per tower. [1] The 520 MeV fluctuation can be treated as a constant term in the resolution: $\Delta E(\mathrm{GeV}) = .16\sqrt{E} \oplus .52$. For photons above about 10 GeV, the $16\%/\sqrt{E}$ term dominates.

## 4 Monte Carlo Studies: Baseline

To get a handle on what sort of signal to noise we expect, we ran PYTHIA and HIJING under various configurations. Direct photons and jets were generated with PYTHIA for 200 GeV *pp* collisions, and when appropriate, overlayed with a central AuAu HIJING event. All quantities are simulated at the particle level, and we assume that the calorimeter has perfect energy response.

### 4.1 Starting Point

We started by generating a sample of direct photons of a given $E_T$ or higher, and a sample of jets 100 times larger, with the same $E_T$ threshold. In each sample, the electromagnetic energy in a tower is summed, and events with a barrel tower energy above the $E_T$ threshold are kept. No energy or position smearing is done; this is still an ideal calorimeter. The number of real and fake candidates is shown below:

| Min. $E_T(\gamma)$ (GeV) | $\sigma(\gamma)/\sigma(\mathrm{jet})$ | Direct Photons | Fake photons | $S/B$ ratio |
|---|---|---|---|---|
| 5 | 4612 | 3748 | 2681 | 1:33 |
| 10 | 2774 | 4846 | 2156 | 1:12.3 |
| 15 | 1793 | 5603 | 2018 | 1:6.5 |
| 20 | 1319 | 6201 | 1723 | 1:3.7 |

It may be instructive to work out one line of the preceeding table. At 5 GeV, out of 10,000 direct photons generated by PYTHIA, 3748 have $E_T > 5$ GeV in the EMC barrel. (The rest are in the endcap, or even further forward) Out of 1,000,000 generated jets, 2681 have have $E_T > 5$ GeV in the EMC barrel. That is, a 5 GeV (or higher) jet is only $7.15 \times 10^{-3}$ times as likely as a photon to deposit 5 GeV in the EMC. However, because the jet cross-section is 4612 times larger than the photon cross section, one makes 33 fake photons (from jets) per real photon.

These numbers come from four separate PYTHIA runs. As a check, we can see if we get the same value at (e.g.) 10 GeV using the 5 GeV sample (which contains a few percent of events above 10 GeV) as we do with the 10 GeV sample. We do.

## 4.2 Isolation

In previous direct photon experiments, it has been found that an isolation cut is a powerful rejector of background. It is unusual that a jet will fragment to just a single $\pi^0$, with no nearby tracks or EM energy. Therefore, the majority of jets can be rejected by a cut such as $E_T(R < 0.7) < 0.2E_T(\gamma)$, where $E_T(R < 0.7)$ is the summed transverse energy, neglecting the photon in a cone of $R(\equiv \sqrt{\Delta\eta^2 + \Delta\phi^2}) < 0.7$ around the photon.

At RHIC, the underlying event background is substantially larger than at previous direct photon experiments. A cone of 0.7 around a random point contains over 100 GeV of energy. Clearly, we need to develop a different isolation algorithm.

A simple isolation algorithm is requiring that there be no tracks with $p_T > 2$ GeV in a cone $R < 0.4$ around the photon candidate. From studies of embedding a PYTHIA direct photon in a generic HIJING central event, we find the following efficiencies for signal and background:

| Min. $E_T$ | Photon Efficiency | Fake Photon Efficiency |
|---|---|---|
| 5 | 65.6% | 51.6% |
| 10 | 65.7% | 42.6% |
| 15 | 65.8% | 40.4% |
| 20 | 65.9% | 38.1% |

While the isolation does improve things somewhat, the improvement is small, especially at low $E_T$'s.

## 4.3 Shower Maximum

The next handle in rejecting background is to use the shower maximum to count high $E_T$ photons. Events with two photons are much more likely to be from $\pi^0 \to \gamma\gamma$ decays than they are to be direct photons. More importantly, these events can be used to estimate the amount of background that remains in the single photon candidate sample:

If the two photons have $E_{T1}$ and $E_{T2}$, the variable $A \equiv (E_{T1} - E_{T_2})/(E_{T1} + E_{T2})$ is flat. This gives a measurement of the $\pi^0$ reconstruction efficiency as a function of $A$, directly from the data, enabling one to extrapolate from the $\pi^0$'s which are identified to the ones that are not. Without this ability, it is extraordinarily difficult to accurately count the number of true direct photons in the direct photon candidate sample.

Here we assume we can reject the event as background if either of the following conditions are met:

- There is another photon with $E_T > 1.5$ GeV in the same tower, further than 3cm in $z$ from the primary photon. $z$ is the direction in which the shower maximum occupancy is lowest.

- There are at least three photons with $E_T > 1$ GeV in that tower. Roughly 10-15% of background events have more than 2 photons in a single tower.

This has not been established yet from either data (obviously!) or a detailed digital Monte Carlo, perhaps based on GEANT. However, it is a reasonable estimate based on typical detector performance: most photons are around 500 MeV, which is also the equivalent EM energy deposited in the SMD by a track. Typical SMD energy resolutions vary between $50\%/\sqrt{E}$ and $100\%/\sqrt{E}$, so to reject these very soft photons, we need to look at photons above about 1.5 GeV. Also, a strip width of 1-1.5 cm implies good shower separation at 2-2.5 strip widths, or about 3 cm. The occupancy of the wire view will be close to 100% in AuAu; while undoubtably we will be able to spot the other photon some fraction of the time in that view, we do not rely on that in this study. The following table shows the improvement in $S/B$ after the SMD information is used. Note that the relative efficiency of the isolation cut is used in the table, although the absolute efficiency is not. (i.e. both the signal and background are 1.5 times larger than they would be in reality)

| Min. $E_T(\gamma)$ (GeV) | Direct Photons | Fake photons | $S/B$ |
|---|---|---|---|
| 5 | 3710 | 1478 | 1:18.4 |
| 10 | 4816 | 838 | 4.8 |
| 15 | 5574 | 739 | 1:2.4 |
| 20 | 6178 | 661 | 1:1.4 |

While the Signal-to-Background ratio is one interesting figure of merit, it suffers from the shortcoming that it doesn't provide much information on the physics capability. Perhaps a better figure of merit would be the increase on the uncertainty on the number of photons relative to the background free ($1/\sqrt{N}$) case.

There are two factors to this. The first is the statistical decrease in precision from subtracting two large numbers. If before the cut the signal-to-background ratio is 1:$\alpha$ and after it is 1:$\beta$, for a perfectly efficient cut, and perfect knowledge of the ratio

$\alpha/\beta$, the statistical uncertainty increase can be derived as follows:

Before the cut, the number of candidates $N_1$ is given by $N_\gamma + (\alpha/\beta)N_B$, where $N_B$ is the number of background events that survive the cut. After the cut, the number of candidates $N_2$ is simply $N_\gamma + N_B$.

The number of background events in terms of the measured quantities $N_1$ and $N_2$ is given by:

$$N_B = \frac{\beta}{\alpha - \beta}(N_1 - N_2)$$

Since $N_\gamma = N_2 - N_B$, we have an expression for the number of real photons, in terms of the two measured quantities and the known factors $\alpha$ and $\beta$:

$$N_\gamma = \frac{\alpha}{\alpha - \beta}N_2 - \frac{\beta}{\alpha - \beta}N_1$$

However, $N_1$ and $N_2$ are not statistically independent quantities: an event counted in $N_2$ *must* be counted in $N_1$ as well. Let us therefore recast the above quantities in terms of $N_P$ (for the number of passing events) and $N_F$ (for the number of failing events), where $N_P \equiv N_2$ and $N_F \equiv N_1 - N_2$.

$$N_B = \frac{\beta}{\alpha - \beta}N_F$$

$$N_\gamma = N_P - \frac{\beta}{\alpha - \beta}N_F$$

Since we have two statistically independent quantities, we can propagate the statistical uncertainties:

$$(\Delta N_\gamma)^2 = (\Delta N_P)^2 + \frac{\beta^2}{(\alpha - \beta)^2}(\Delta N_F)^2$$

From the definitions of the $\alpha$ and $\beta$ parameters, we know that the expectation value of $N_P$ is $(1+\beta)N_\gamma$ and the expectation value of $N_F$ is $(\alpha - \beta)N_\gamma$. That allows us to express the uncertainty on $N_\gamma$ in terms of the true number of direct photons and a prefactor that arises from the background subtraction process:

$$(\Delta N_\gamma)^2 \to (1+\beta)(\Delta N_\gamma)^2 + \frac{\beta^2}{(\alpha-\beta)}(\alpha-\beta)^2(\Delta N_\gamma)^2$$

which reduces to:

$$\Delta N_\gamma \to \sqrt{1+\beta+\frac{\beta^2}{\alpha-\beta}}\Delta N_\gamma$$

The second factor is that since the isolation cut is 65.6%-65.9% percent efficient, the statistical uncertainty is increase by about 23%, just on $1/\sqrt{N}$ grounds.

| Min. $E_T(\gamma)$ (GeV) | $S/B$ (no SMD) | $S/B$ (w/SMD) | $\Delta N$ Increase |
|---|---|---|---|
| 5 | 1:33 | 1:18.4 | 8.1 |
| 10 | 1:12.3 | 4.8 | 3.7 |
| 15 | 1:6.5 | 1:2.4 | 2.7 |
| 20 | 1:3.7 | 1:1.4 | 2.2 |

So, if we expect 3000 direct photons with $E_T > 10$ GeV for a certain period of running, the best we could hope to count them would be to within $3.7/\sqrt{3000}$, or 8%. Systematic uncertainties can worsen this value still further: each 1% of systematic uncertainty on the background uncertainty corresponds to $\beta$% of uncertainty on the signal: to get a 10% systematic uncertainty on the total number of events at 10 GeV requires understanding the systematics to 2.7%.

# 5 Monte Carlo: Beyond the Baseline

While the above numbers seem to allow for some physics to be done, a higher degree of purity and statistical power would be desirable, both for making better measurements of the direct photon cross section and for examining the fragmentation of the recoiling parton. In this section, strategies to improve this are briefly examined.

## 5.1 Isolation

The isolation cut has not been completely optimized. Since the signal-to-background ratio is poor, perhaps the isolation cut could be tightened. The following table shows what happens if the "no track about 2 GeV" cut is relaxed to 1.5 GeV.

| Min. $E_T(\gamma)$ (GeV) | Direct Photons | Fake photons | $S/B$ | $\Delta N$ Increase |
|---|---|---|---|---|
| 5 | 3701 | 1321 | 1:16.5 | 11.9 |
| 10 | 4809 | 720 | 4.2 | 9.3 |
| 15 | 5562 | 641 | 1:2.1 | 4.1 |
| 20 | 6171 | 578 | 1:1.2 | 3.4 |

Note that while there is a small increase in the signal-to-background ratio, the statistical uncertainty gets substantially worse. The reason is that only 24% of the real direct photons pass this cut; the rest are lost when a random track from the underlying event passes too close to the photon. So this cut doesn't select on real vs. fake photons so much as photon candidates that are in a region of low vs. high underlying event activity.

While it is probable that the the isolation requirement can be improved and optimized, it is unlikely that there is a "magic bullet" that will improve the signal-to-background ratio by a large factor.

## 5.2 Calorimeter Improvements

Next, imagine we built the perfect calorimeter. This calorimeter can resolve 500 MeV photons with perfect efficiency, even when they are within as little as 1.5 cm of another photon (in $R\phi - R\eta$ space). Since electromagnetic showers are typically 1-1.5 cm in radius, this is probably about as good as can ever be done. If one repeats the Monte Carlo under these conditions, one obtains the following:

| Min. $E_T(\gamma)$ (GeV) | Direct Photons | Fake photons | $S/B$ |
|---|---|---|---|
| 5 | 3678 | 941 | 1:11.8 |
| 10 | 4782 | 396 | 1:2.3 |
| 15 | 5542 | 298 | 1:1 |
| 20 | 6144 | 244 | 2:1 |

A few things stand out. The first is that the improvement in 5 GeV photons is relatively small: about a third of the background is removed. Recall that this cut is only 4.2% efficient, so in practice a higher energy cut would have to be used instead, which would remove even less background. The background here is from low energy photons from $\pi^0, \eta \to \gamma\gamma$ decays at large angles. There are thousands of such candidates in AuAu collisions.

At large $E_T$'s, the improvement is larger: more than half the background is removed. On average, the second photon from the neutral meson decay is higher energy than in the 5 GeV case, which makes identification and rejection easier. Even in this case, though, the photon candidate sample is about a third background.

# 6 Conclusions

Monte Carlo studies suggest that it is possible to reconstruct direct photons of moderate $E_T$'s in AuAu collisions at STAR. The signal-to-background ratios are quite small, however. The SMD is necessary for this physics, both in reducing this background, but more importantly, for measuring how much background remains in the sample. Without an SMD, this cannot be measured, even with towers half the present size.

The background arises because the very effective isolation cuts used in previous experiments become ineffective in AuAu collisions, because these events are so busy that nothing is particularly isolated. Only the very least isolated fake photons can be identified and removed by this cut. This is independent of detector design: it's true at the generator level.

An interesting source of background is more than two photons in a single tower. While this is only 10-15% of the total background, since the signal-to-background ratio can be 1:20 at the lowest $E_T$'s, this background alone can be 2-3 times as large as the signal. To get a 25% measurement on the cross section requires understanding this background to 10% of itself at the very lowest $E_T$'s. This background can be measured with the SMD. Calculating this background with the inclusive $\pi^0$ spectrum will be difficult, since these $\pi^0$'s are in jets, which introduces position and momentum correlations.

The STAR detector is capable of reconstructing a direct photon signal "as is". While improvements of the detector improve things, the improvements are small, both because the STAR EMC design is based on years of experience with direct photons, and because the new element in heavy ion collisions is real extra energy and particles near the photon: a more accurate picture of this underlying event does not translate into a substantial improvement in the measurement.

The best improvement we can make to the EMC would be to position it at larger radius. This will improve the angular resolution between two showers, and reduce the occupancy. However, since many backgrounds are due to the underlying event occupancy, the relative improvements will be substantially smaller than they would be in present day $p\overline{p}$ collider and fixed-target direct photon experiments. Of course, this is impractical in any event: cost scales as $r^2$, and the TPC and magnet constraints are formidable.

The two most practical improvements would be to a) split the SMD wires, doubling the wire channel count, which halves the occupancy, which in turn improves the ability to detect a second photon from a $pi^0$ whose decay opens in $\phi$, not $\theta$, and b) to instrument the first layer of the EMC separately to use as a preconverter. Since systematic uncertainties enter with a large pre-factor, control over them is of critical importance. Having both a preconverter and a shower maximum detector allows for comparing the two results, and thereby reducing systematic uncertainties. It may be that a tower size of $0.05 \times 0.05$ just for the preconverter may be a highly cost effective distribution of channels. More study on this issue needs to be done.

10 GeV photons look to be possible, provided that the systematics can be brought under control. 5 GeV photons look much harder, because of the very large backgrounds. Below is a table with the total uncertainties for a sample with 3000 10 GeV photons, assuming 5%, 10% and 15% systematic uncertainties in the backgrounds:

| Min. $E_T(\gamma)$ (GeV) | $N(\gamma)$ | $\Delta\sigma$ (5% syst) | $\Delta\sigma$ (10% syst) | $\Delta\sigma$ (15% syst) |
|---|---|---|---|---|
| 5 | 45000 | 92% | 184% | 276% |
| 10 | 3000 | 25% | 48% | 72% |
| 15 | 460 | 16% | 26% | 38% |
| 20 | 100 | 16% | 20% | 25% |

While it appears a direct photon program in heavy ion collisions is possible, such a program will have to pay close attention to background systematic uncertainties. The lower limit on the photon $E_T$ before the signal is washed out in background is somewhere between 5 and 10 GeV, depending on the degree of control over the background systematics.

# References

[1] T. LeCompte and D. Underwood *Jet Quenching using Gamma-Jet Events*, STAR Note 0242.