A study of the combinatorial background description of invariant mass reconstructions on $\pi^0 \to \gamma\gamma$ decay

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Abstract

Microseconds after the Big Bang, the universe consisted of a quark-gluon plasma. When this plasma expanded and cooled down, many different types of particles were created. Some of these particles quickly decayed into other particles. One of these decays is neutral pion decay ($\pi^0 \to \gamma\gamma$). Data from the Electromagnetic Calorimeter (ALICE) obtained from a p-Pb collision experiment at $\sqrt{s_{NN}} = 5.023$ TeV was used to study neutral pion decay. On decay photons that were measured by the calorimeter invariant mass reconstruction was applied to obtain invariant mass distributions for photon pairs. This technique brings a combinatorial background with it, which needs to subtracted from the invariant mass distribution. A method called *event mixing* was used to generate an event mixed background as a representation for the combinatorial background. In the event mixed background the correlations between photons was destroyed. In this research different event mixing methods and ways of subtracting the event mixed background of the invariant mass distribution were investigated and compared to simulation data to determine the most accurate description for the combinatorial background. It was found that both a photon multiplicity event mixing method and a charged track multiplicity event mixing method described the combinatorial background equally well. However, event mixing should be improved further for a more accurate description.

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Contents

1   Introduction

In this research the description of the combinatorial background in invariant mass reconstruction on neutral pion decay was investigated. First of all the reader is introduced to the topic and the motivation for the research is pointed out. In Section 2 the methods used to study the combinatorial background is explained followed by the results of the research in Section 3. In Section 4 the results and improvements for further research are discussed. At last the conclusions of the research are stated and argued in Section 5.

1.1   Quark-gluon plasma

Up to the order of microseconds after the Big Bang, the universe consisted of a very hot and dense substance, called quark-gluon plasma (QGP) [1]. This plasma is made up of quarks and gluons, particles that are the fundamental building blocks of all matter found in the universe. Shortly after the Big Bang, the large amount of available energy caused the particles to move freely in the quark-gluon plasma. It is assumed that this type of phase can only exist at extremely high temperatures and densities and therefore cannot be found on earth naturally.

1.2   Direct and decay photons

One property of quark-gluon plasma that is of main interest is the temperature. This quantity can be determined by measuring the energy of *direct photons* that are coming from the plasma. However, not all particles coming from QGP are direct photons. When the plasma expands and cools down, the quarks and gluons recombine to form many different sorts of particles. Some of these particles have a relatively short lifetime and decay into photons or other particles. Therefore a measurement on direct photons contains a significant amount of decay products including *decay photons*. If the temperature of QGP must be determined, these decay photons must be removed from the total set of photons in order to only have left the direct photons. Nevertheless, the decay photons also contain information which can be useful for studying the characteristics of QGP. One of the decays that is found after QGP has expanded and cooled down is the neutral pion decay ($\pi_0 \to \gamma\gamma$). Almost all neutral pions decay into two photons, with a branching ratio of 98.823 ± 0.034 [2]. These photons can be labeled as decay photons.

1.3   ALICE

At CERN (European Organization for Nuclear Research) heavy-ion collision experiments are performed to recreate the conditions that existed during the very early stages of the universe. ALICE (A Large Ion Collider Experiment) is one of the collaborations that does experiments at CERN on the LHC (Large Hadron Collider) ring (see Figure 1). The ALICE

detector was designed to study strong interactions at extreme conditions [3]. These extreme conditions can be reached by accelerating heavy ions to ultra-relativistic speeds and letting them collide. In the LHC ring, these heavy ions gain energies up to the order of TeV's after which they collide to possibly create a QGP.

Until now, it is assumed that QGP can only be created for a period of $\sim 10^{-23}$ s in heavy-ion collisions [4]. Therefore, lead or gold ions are used for collisions to study the quark gluon plasma. However, collisions with protons only or heavy ions together with protons can be used as a reference for the heavy ions collisions. In these type of collisions, QGP has not occurred yet. In this research, data from a p-Pb collision experiment in ALICE at $\sqrt{s_{NN}} = 5.023$ TeV is used.
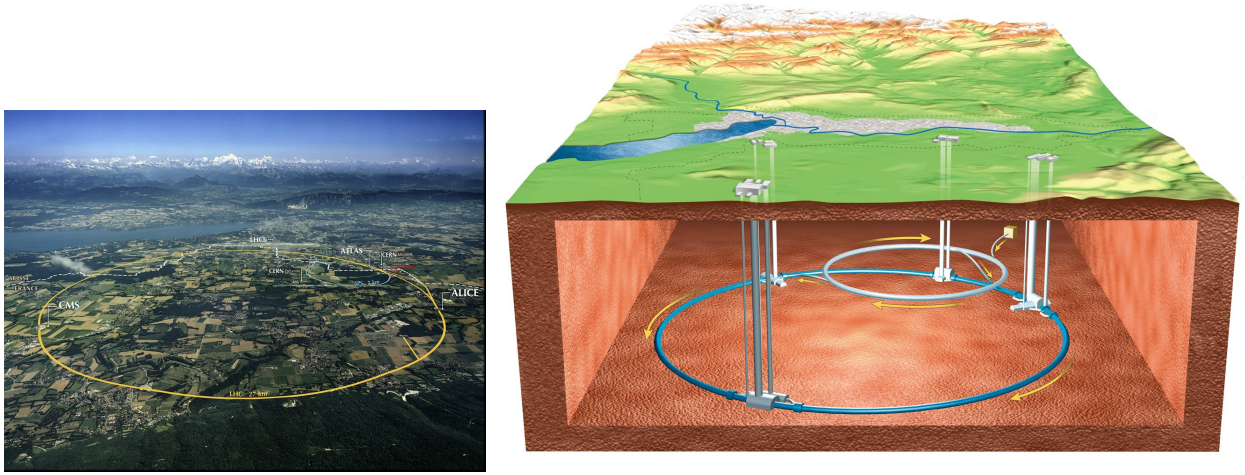

Figure 1 LHC ring near Geneva, Switzerland. The circular accelerator has a circumference of 27 kilometers and is located beneath the ground at a depth of 175 meters [5].

1.4   EMCal

The ALICE detector consist of multiple subdetectors. One of these subdetectors is the Electromagnetic Calorimeter (EMCal) (see Figure 2). It measures the energy of particles created in the heavy-ion collisions. The EMCal is divided into 12,288 so-called towers. Each tower consists of 76 alternating layers of 1.44 mm Pb and 77 layers of 1.76 mm polysterene base. When a particle hits a tower, the energy deposition of the particle in the EMCal is measured. The particles that hit the EMCal are allocated a position relative to the beam axis. In a right-handed coordinate system the beam axis is the Z-axis. In the XY-plane φ is the azimuthal angle with the positive X-direction if $\varphi = 0$ and the positive Y-direction at $\varphi = \pi/2$. The polar angle θ is the angle between the particle and the beam axis ($\theta = 0$). However, instead of using θ, the pseudorapidity η is used, where $\eta = -\ln\tan(\theta/2)$ [6].
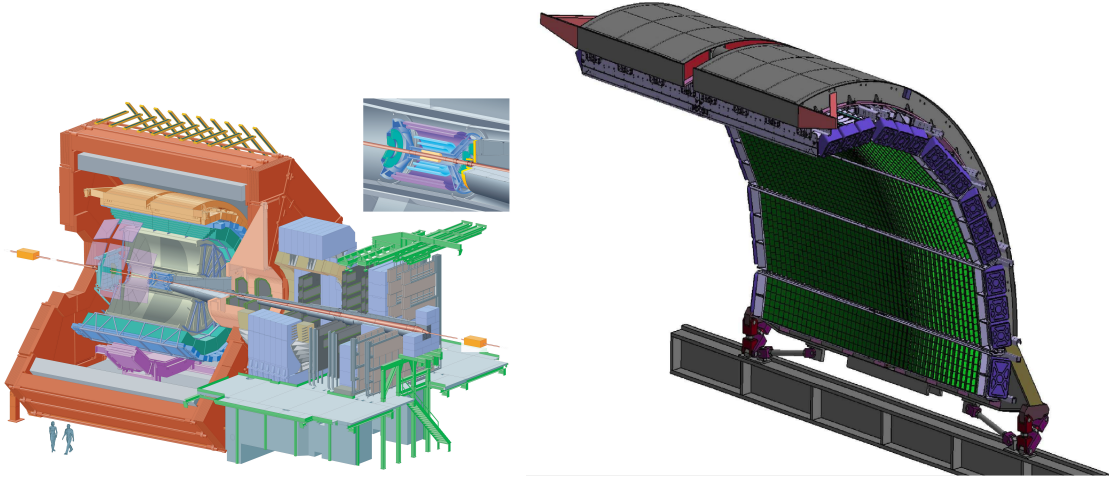
Figure 2 Left: Overview of the ALICE detector. The EMCal is indicated in light orange [7]. Right: Electromagnetic Calorimeter. φ is measured vertically, η horizontally [8]
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1.5   Combinatorial background in invariant mass reconstruction

One item of interest in the p-Pb collision experiment is the number of neutral pions that are created. The number of pions is determined by invariant mass reconstruction based on EMCal data, which will be explained in detail in Section 2. However, invariant mass reconstruction brings a combinatorial background with it, which is undesired. This combinatorial background has to be subtracted from the invariant mass distribution. A method called *event mixing* will be used to generate a representation of the combinatorial background in order to subtract it from the invariant mass distribution. However, it was found that event mixing does not describe the combinatorial background perfectly yet. After subtraction there is still residual background in the signal present. In this research the focus lies on modifying event mixing and the way of subtracting it from the invariant mass distribution in order to obtain a better description of the combinatorial background.

2   Neutral pion reconstruction

In this section the invariant mass reconstruction on neutral pion decay is described from which the combinatorial background originated. Also the event mixing technique is explained. After that the modifications on the event mixing and the way of subtracting it from the invariant mass distribution are listed. At last it is pointed out how the invariant mass reconstruction based on experimental data is compared to a simulation of a Monte Carlo model.

2.1   Photon selection

In heavy-ion collisions a large number of different sorts of particles is created. This almost certainly implies that also other particles than photons will reach the EMCal. Before any invariant mass reconstruction on neutral pion decay can be performed, the decay photons must be extracted from all other sorts of particles. On all particles that are measured by the EMCal, selection cuts are made to sort photons from other particles. Also within the set of photons, selection cuts are made to eventually obtain all photon candidates used for invariant mass reconstruction. For the selection cuts, one is referred to the analysis report of Bock *et al.* [9].

2.2   Clusterization of towers

In the collision experiment, particles collide in the LHC tube. Particles that are created in collisions at the ALICE detector are detected by the subdetectors. When the EMCal is activated for detection, the energy of particles is measured. When the detector measures an energy in a single tower above the threshold (0.5 GeV in this research), this tower is labeled as a *seed tower*. An adjacent tower that contains an energy below the seed tower's energy and above another threshold (0.1 Gev) is connected to the seed tower to form a *cluster*. If a second adjacent tower - that is not adjacent to the seed tower - contains an energy higher than the first adjacent tower - which *is* adjacent to the seed tower - this second adjacent tower is not added to the cluster, yet will be labeled as a new seed tower. A new cluster can be formed using this seed tower. All clusters that are formed during a specified time range together make up an *event*.

2.3   Invariant mass reconstruction

In order to determine how many neutral pions are coming from the p-Pb collision that decayed into two photons, the invariant mass needs to be reconstructed for photon pairs within same events. The invariant mass reconstruction is executed using the remaining photon candidates obtained from the EMCal data after all cuts are applied. All photons

from all clusters are combined with all other photons from the same event and the invariant mass of two photon candidates $M_{\gamma\gamma}$ is calculated using the following relation from relativity

$$M_{\gamma\gamma} = \sqrt{2E_{\gamma 1}E_{\gamma 2}(1 - \cos(\theta_{12}))} \tag{1}$$

where $E_{\gamma 1,2}$ is the energy of a photon and θ_{12} is the opening angle between two photons in the lab frame [6]. In principle, this opening angle is the angle of the momentum vectors of the two decay photons. However, the lifetime of the neutral pion is of the order of $\sim 10^{-16}$ s [10] hence the distance that a pion travels before decaying into photons can be neglected. The resolution of the ALICE detector falls short on these distances and therefore the opening angle is determined using the spatial coordinates of the collision vertex instead of the decay vertex. The invariant mass now can be calculated and a two-dimensional histogram (with $M_{\gamma\gamma}$ and the transverse momentum p_T on the horizontal axes) can be filled (see Figure 3). Here, the transverse momentum is determined using the relation $E = pc$, because the mass of photons is zero. The invariant mass distribution based on pairs from the same event is referred to as the *total signal*.
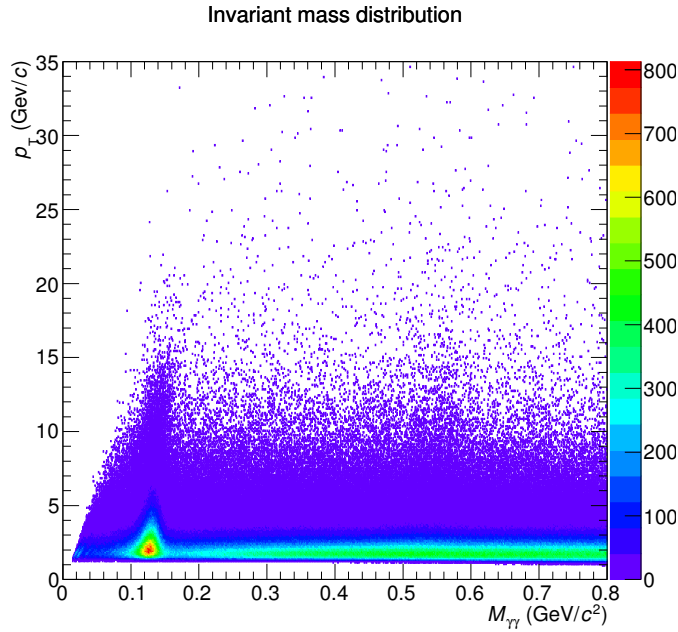

Figure 3 Invariant mass distribution for p_T and $M_{\gamma\gamma}$.

2.4   Combinatorial background

While combining photons into pairs, many combinations of photons form pairs that do not originate from one and the same decay. Yet the invariant mass calculations of these pairs also contribute to the histogram of the invariant mass distribution. This contribution

is combinatorial background and it represents all uncorrelated photon pairs of which the invariant mass is calculated. Only the photon pairs that are coming from one and the same decay are the ones of interest. Therefore this combinatorial background needs to be subtracted from the invariant mass distribution to obtain only the photon pairs coming from one and the same decay. Therefore a combinatorial background will be computed by means of event mixing.

2.5   Event mixed background

The combinatorial background in the invariant mass distribution is approximated by an event mixed background. The representation of the combinatorial background by an event mixed background is based on the assumption that decay photons from different events are totally uncorrelated. Event mixing means that photons from a certain event are combined with photons from all other events. For these photon pairs the invariant mass is calculated. Although the calculated mass could be equal to the mass of the pion, the photon pairs certainly are not coming from one and the same decay for the two photons are uncorrelated. Therefore a pure combinatorial background is obtained by event mixing. This combinatorial background representation is shown in the two dimensional histogram (with M_{inv} and p_T on the horizontal axes), as shown in Figure 4.
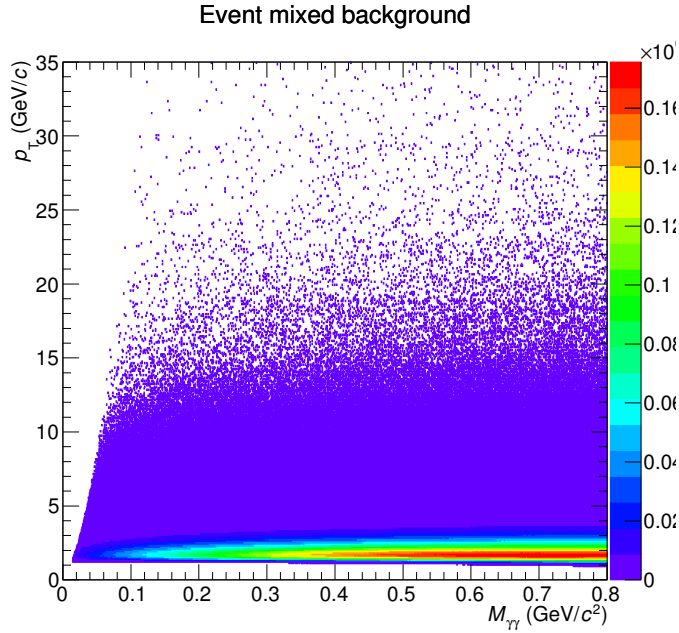

Figure 4 Event mixed background

2.6 Projection for different transverse momenta

Before any further operations on the histograms will be performed, one dimensional projections are extracted from the two-dimensional histograms. The projections are taken along the p_T axis with a range of 0.5 GeV/c. In Figure 5 a projection is shown for p_T = 1.4-1.9 GeV/c extracted from the two-dimensional total signal and event mixed background. For this research three different p_T slices are considered repeatedly: low p_T (1.4-1.9 GeV/c), intermediate p_T (3.9-4.4 GeV/c) and high p_T (6.4-6.9 GeV/c). A first approximation for the maximum of the peak was made using a Gaussian fit (GAUS) together with a first order polynomial (POL1).
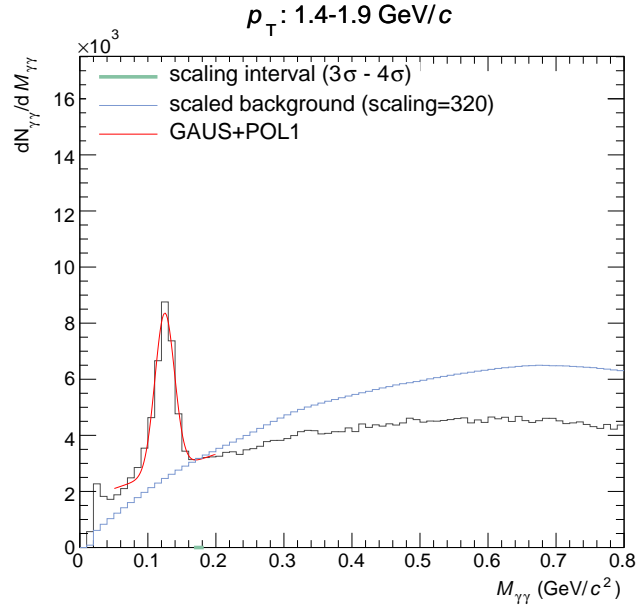
Figure 5 p_T projection of the total signal and scaled event mixed background. The scaling interval is indicated with a turquoise line on the $M_{\gamma\gamma}$-axis.

2.7 Scaling of the combinatorial background

The total number of photon combinations in event mixing $N_{\gamma\gamma}^{\mathrm{mxd}}$ is much larger than the number of photon combinations found in same events $N_{\gamma\gamma}^{\mathrm{same}}$. Therefore the event mixed background must be scaled before it can be subtracted from the total signal. The scaling is performed in the following way:

1. In the total signal histogram a peak is present due to the presence of neutral pions. Just right of the peak an interval of a number of standard deviations is chosen. In Figure 5 the scaling interval is indicated with a turquoise line.

2. On this interval, the integral under the plot for both the total signal as the background is calculated binwise. The scaling factor is the ratio

$$\frac{\text{integral of background}}{\text{integral of total signal}} \tag{2}$$

on the specified interval.

3. The background is scaled by dividing all bin contents of the histogram of the event mixed background by the scaling factor. The scaled background is also shown in Figure 5.

2.8   Subtraction of the background

After scaling, the background is subtracted from the total signal. This is simply done by subtracting the histogram's bin contents of the scaled event mixed background from those of the total signal. In Figure 6 the residual signal is shown. If the subtraction is executed, the residual invariant mass distribution is assumed to be a pure Gaussian function. However, the remaining mass distribution is not a pure Gaussian, due to the fact that the description of the event mixed background is not perfect. Therefore the residual signal is again fitted with a Gaussian function plus a first order polynomial with the linear part of the fit as a correction for this imperfection.
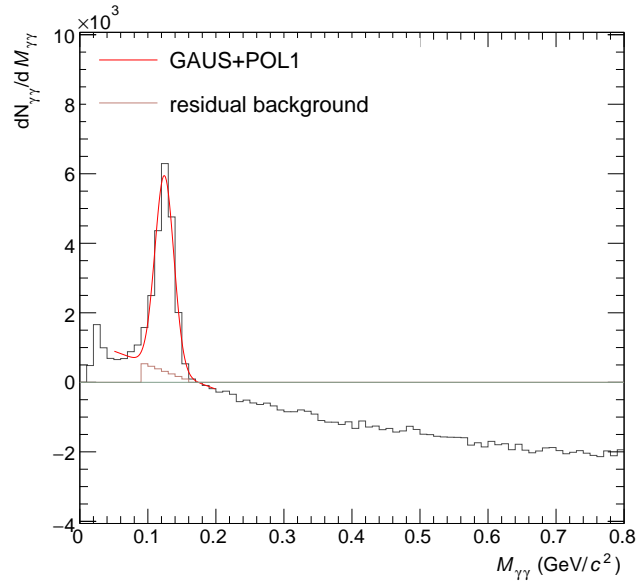
Figure 6 Residual signal after subtraction of the event mixed background

2.9   Quality of the combinatorial background description

To determine the quality of the combinatorial background description by a particular event mixed background, two different methods are considered to quantify this.

2.9.1   Ratio between total signal and background

In order to determine how well the computed event mixed background represents the combinatorial background that is present in the total signal, the ratio between the total signal and the background is considered (see Figure 7). If the event mixed background would describe the combinatorial background from the total signal perfectly, the ratio should have a constant value for the whole invariant mass range, except for the π^0 and η meson peaks around 0.135 and 0.548 GeV/c^2 respectively. The ratio is multiplied by the scaling factor that was calculated for the particular p_T projection for normalization. A perfect description would give a ratio of 1.0 for the whole mass range except for the region of the neutral meson peaks.
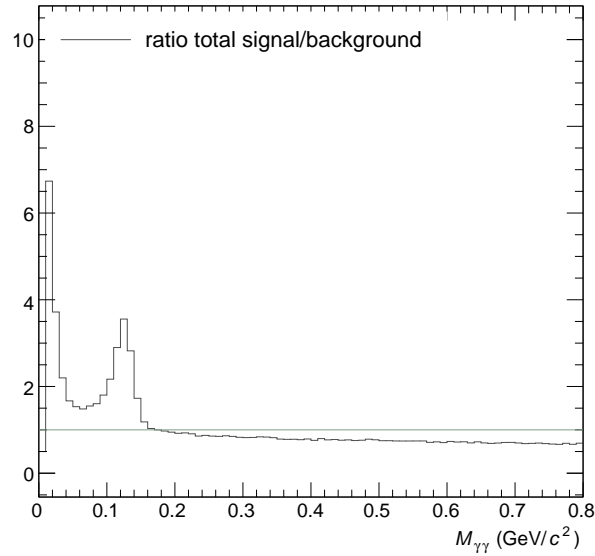
Figure 7 Ratio between total signal and event mixed background

2.9.2   Residual background quantification

The residual peak after subtraction of the background was fitted using a Gaussian function plus a first order polynomial. In the ideal case, the first order polynomial would be zero, for the signal would only be a Gaussian theoretically. The polynomial part of the fit is taken as a measure for the residual background (see Figure 6). The linear part is integrated between three standard deviations from the peak's maximum to obtain an estimate for the residual background. The binwise integration between three standard deviations minus the contribution of the polynomial should eventually give the total number of pions that decayed into two photons. For every p_T slice this will be calculated. From this, histograms are produced with the total number of reconstructed pions, the number of pions in the residual background and the ratio between these two quantities per p_T (see Figure 8). The number of pions in the residual background actually are no real pions coming from the

collision, yet are reconstructed photon pairs that have the same mass as real pions by coincidence. The pions in the residual background can therefore be denoted as fake pions. The total number of pions and the number of pions in the residual background will be divided by the total number of events for normalization. In case of perfect combinatorial background description, the residual background would vanish, resulting in a ratio of zero.
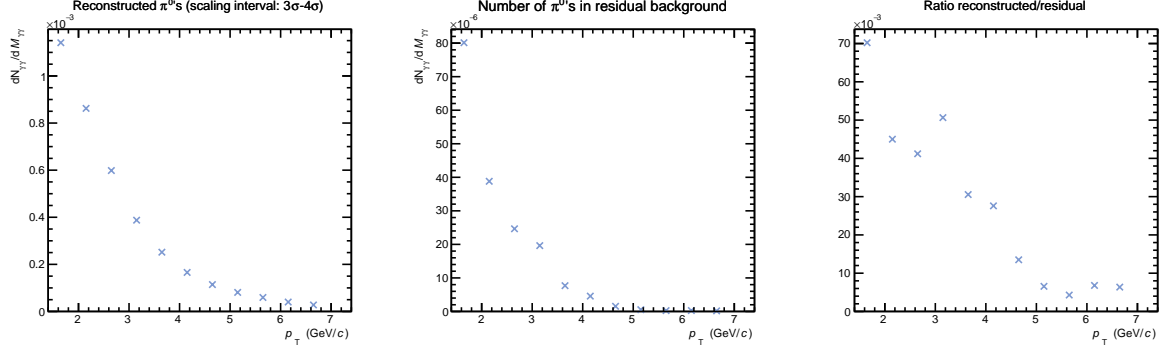

Figure 8 Left: Total number of reconstructed pions per p_T. Center: number of pions in residual background per p_T. Right: ratio between the number of pions in the residual background and the total number of pions per p_T.

2.10   Variations of the combinatorial background description

In order to improve the combinatorial background description, multiple variations regarding the background computation, scaling method and fit function were investigated.

2.10.1   Modification event mixing classes

All events obtained from a collision experiment are stored into several *classes*. Each class has different characteristics. Invariant mass reconstruction and event mixing are performed using events from the same class only. This ensures that the events that are used for the background computation have approximately the same characteristics of the events on which the total signal is based. The characteristics by which the different event mixing classes are distinguished can be chosen. Below the modifications on the event mixing classes are listed (abbreviation of the method is denoted between parentheses).

Standard (STRD) In the standard method, the event mixing classes are distinguished by photon multiplicity and collision vertex position. (See [9] for the in-depth description of the classes.)

Small Radius (SMRAD) In all events, the cluster containing the particle with the highest energy is selected. The position of this cluster on the EMCal in η and φ is identified. The radius R is defined as the square root of the sum of the squared angles $R = \sqrt{(\Delta\varphi)^2 + (\Delta\eta)^2}$. From one single event the position of the cluster with the highest

energetic particle is determined and event mixing is only performed using events that contain their highest energetic particle cluster with a position for which $R < 0.2$ from this position.

Charged Track Multiplicity (CHAR)   In this method the charged track multiplicity is used to define different classes instead of photon multiplicity.

2.10.2   Modification scaling interval

The scaling factor between the event mixed background and the total signal is calculated by dividing the integral of the event mixed background by the integral of the total signal on a given interval just next to the peak. However, the width and position of this interval can be varied. Moreover, the scaling can also be performed far away from the peak. At higher masses, the probability to find a real pion becomes lower for it is unlikely that a pion has a mass at multiple standard deviations from the peak's maximum at $0.135\,\text{GeV}/c$. That implies that at higher masses more pure combinatorial background is found than at masses approximately equal to the pion's mass. On the other hand, the region of the peak is of high interest, not the region far away from the peak. Therefore the following intervals were chosen to execute the scaling:

- 3-4 standard deviations

- 4-5 standard deviations

- 3-13 standard deviations

- 15-40 standard deviations

2.10.3   Modification fit function

The common fit form for the total signal and the residual signal is a Gaussian function together with a first order polynomial (GAUS+POL1). In this research also a Gaussian function together with a second order polynomial (GAUS+POL2) will be fitted through the signals.

2.11   Monte Carlo simulation

The p-Pb collision experiment has been modeled by means of a Monte Carlo simulation. A total signal as well as an event mixed background was built based on the simulation data using the standard method for event mixing. This method is denoted by **MC**. However, from the simulation the exact number of pions that was created in the experiment is known. The MC data is used to check the validity of the event mixing method, scaling method and fit formula for the STRD method. In the ideal case, the number of pions found using operations on the MC data should give the true number of pions that was

extracted afterwards from the simulation. If the numbers are approximately equal, it can be concluded that the event mixed background is a valid description for the combinatorial background of the total signal.

3   Results

In this section the results will be discussed for the different event mixing methods, fit functions and scaling intervals. Some of the figures are shown here. For the full results one is referred to the appendix.

3.1   Standard event mixing (STRD)

The two dimensional histograms for the total signal and the event mixed background computed by the standard method are shown in Figure 9. Clearly a peak in the number of reconstructed neutral pions is visible at an invariant mass of 0.135 GeV/c^2 and at a transverse momentum between 1.4 and 5.0 GeV/c. That means most photon pairs have an invariant mass of 0.135 GeV/c^2 and momenta between 1.4 and 5.0 GeV/c. When comparing the event mixed background with the total signal, one will notice the band for a transverse momentum of 1.4-4 Gev/c and a mass of 0.1-0.8 GeV/c^2, where the number of photon pairs is large. Moreover, a peak that is visible in the total signal is not present in the background, which meets the expectation.
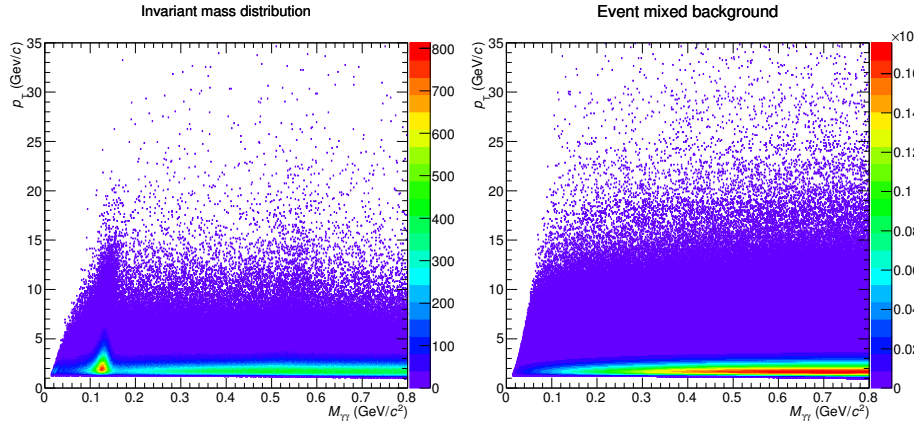
Figure 9 Left: total signal for p_T and M_{inv}. Right: event mixed background

In Figure 10 the results are shown for low p_T and scaling at 3 to 4 standard deviations from the peak's maximum. Whereas the event mixed background follows the total signal in a reasonable way below the peak, far away from the peak the event mixed background fails to describe the combinatorial background appropriately. This causes the tail of the peak at higher masses in the residual signal to drop below 0, which is unphysical. Moreover, the ratio between the total signal and the event mixed background is not constant far away from the peak, yet follows a decreasing trend. With increasing p_T, the description becomes better (see Appendix A) which can be concluded from the fact that the Gaussian peak lies more flat and the tail decreases less than at low p_T. The ratio between the event mixed background and the total signal is very poor at masses lower than 0.05 GeV/c^2. Also at higher masses the ratio does not converge to 1.0.
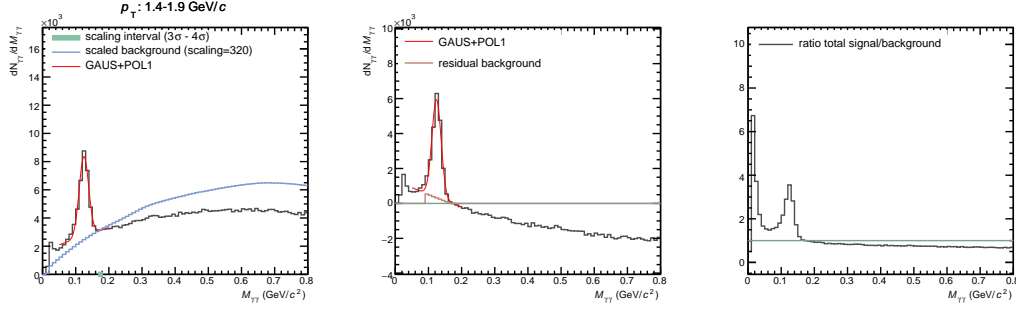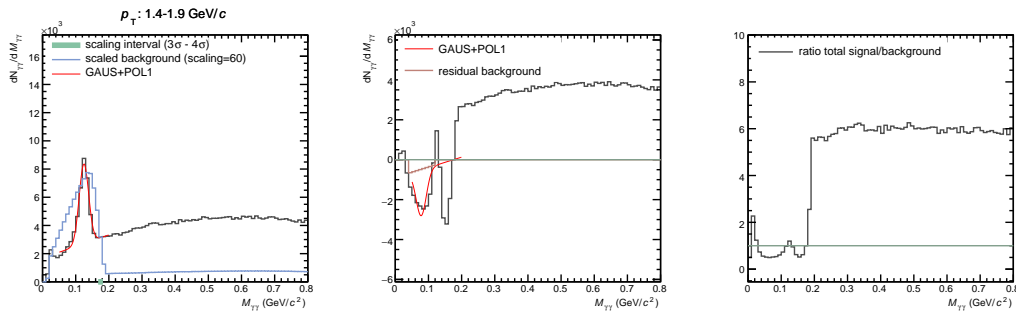
Figure 10 Results for low p_T, POL1, scaling at 3σ-4σ. Left: total signal and scaled background. Center: residual signal and residual background. Right: ratio between total signal and event mixed background.

Figure 11 shows the numbers of pions extracted from the residual signal and also the residual background together with the ratio between the two quantities. Clearly the residual background decreases with higher transverse momentum as well as the ratio. More results shall be considered in order to determine if the already relatively low ratio will be significantly lower when using other methods for describing the combinatorial background.
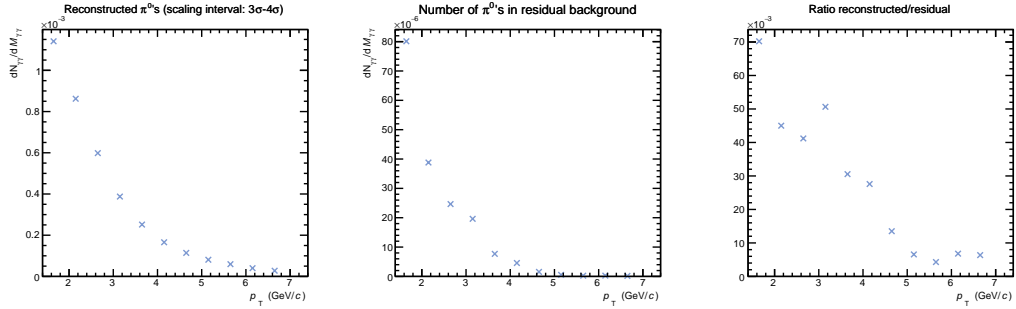
Figure 11 Results per p_T for POL1, scaling at 3σ-4σ. Left: number of reconstructed pions. Center: number of pions in the residual background. Right: ratio between the number of reconstructed pions and number of pions in the residual background

When considering the ratio of the event mixed background to the total signal, improvement can be noticed when scaling far away from the peak in comparison with the results of scaling close to the peak. Especially at higher p_T slices, the ratio is more or less constant except for the peak and at very low masses. However, the combinatorial background description at the peak, which is the region of interest, becomes more poor when scaling far away from the peak.

The results for the other scaling intervals did neither give a significant improvement nor impairment. For fitting the total signal and the residual signal using a Gaussian function together with a second order polynomial caused the residual background to be slightly larger than the case with a first order polynomial.

3.2 Small radius event mixing (SMRAD)

In this method, events were only mixed with other events if the clusters with the highest energetic particle were located relatively close to each other ($R < 0.2$). In Figure 12 the two dimensional background distribution is shown. There is a sharp drop in the number of photon pairs at masses higher than $0.2\,\mathrm{GeV}/c^2$ in contrast to the event mixed background of the standard event mixed method.
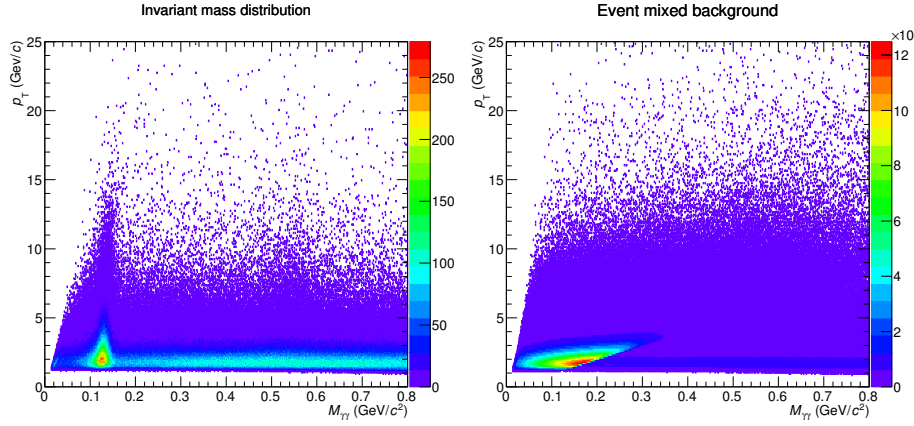
Figure 12 Left: total signal for p_T and M_{inv}. Right: event mixed background (right)

Projections of the two dimensional histograms along the p_T axis were taken which are shown in Figure 13, 14 and 15. The event mixed background contains a large peak in the region of the neutral pion's peak though at higher masses there is too little event mixed background with respect to the combinatorial background. Projections of higher transverse momenta show a better background description than at low momenta. This can particularly be deduced from the ratio between the event mixed background and the total signal (see Figure 15). At low p_T the background description is very poor which causes the ratio to be far from 1.0, where at higher p_T the ratio has a more legit value. However, the ratio diverges again strongly from 1.0 at high masses in the projections of high p_T.
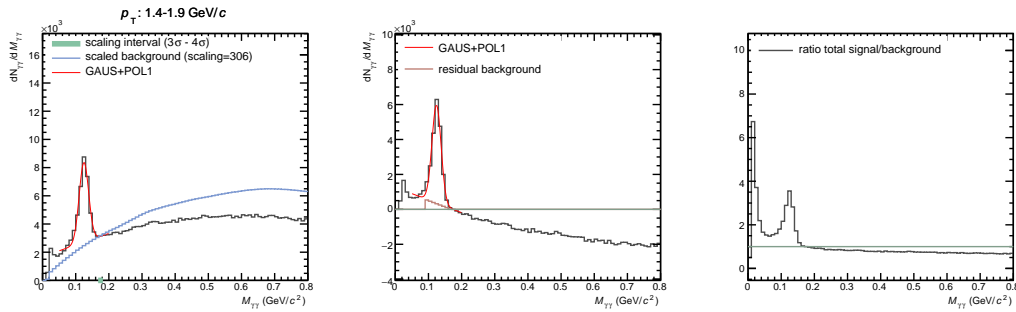

Figure 13 Results for low p_T, POL1, scaling at 3σ-4σ. Left: total signal and scaled background. Center: residual signal and residual background. Right: ratio between total signal and event mixed background.
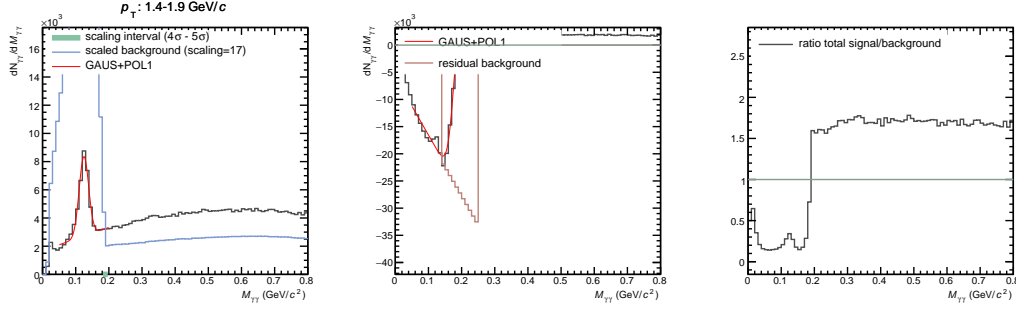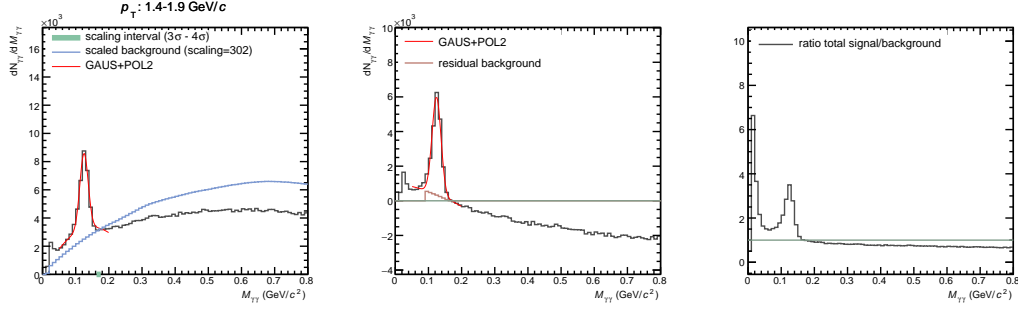
Figure 14 Results for low p_T, POL1, scaling at 4σ-5σ. Left: total signal and scaled background. Center: residual signal and residual background. Right: ratio between total signal and event mixed background.
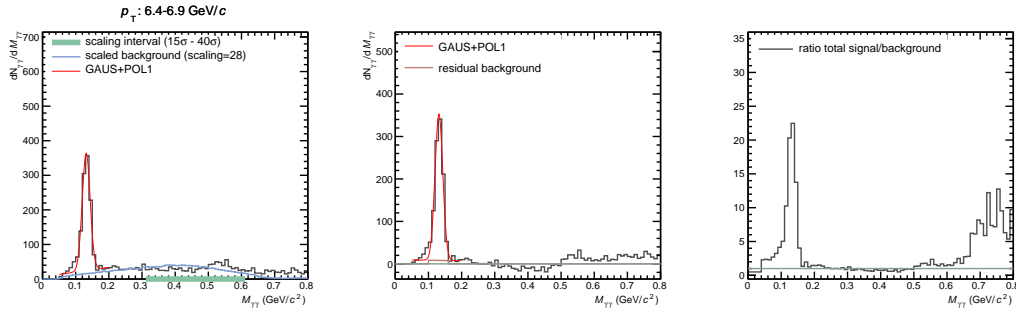
Figure 15 Results for high p_T, POL1, scaling at 15σ-40σ. Left: total signal and scaled background. Center: residual signal and residual background. Right: ratio between total signal and event mixed background.

The peak from the event mixed background causes a large drop of the peak in the residual signal after subtraction of this background, especially at low p_T. The maximum of the pion's peak even drops below the residual combinatorial background. Due to the fact that the residual signal is unphysical, the fit through the peak shows odd behavior for both the first and second order polynomial used to describe the residual background. As a result of the poor description, the total number of pions and the number of pions in the residual background that was found are considered as non-valuable and therefore not shown here, yet are included in Appendix B.

The strange behavior of the background description was also found when the scaling was calculated on a larger interval, whether near of far away from the peak. The fits at low p_T are still meaningless and the ratio between the total signal and the background is far from one.

3.3   Charged track multiplicity event mixing (CHAR)

In this section the results are shown for the charged track multiplicity event mixing method (CHAR). Figure 16 shows the event mixed background
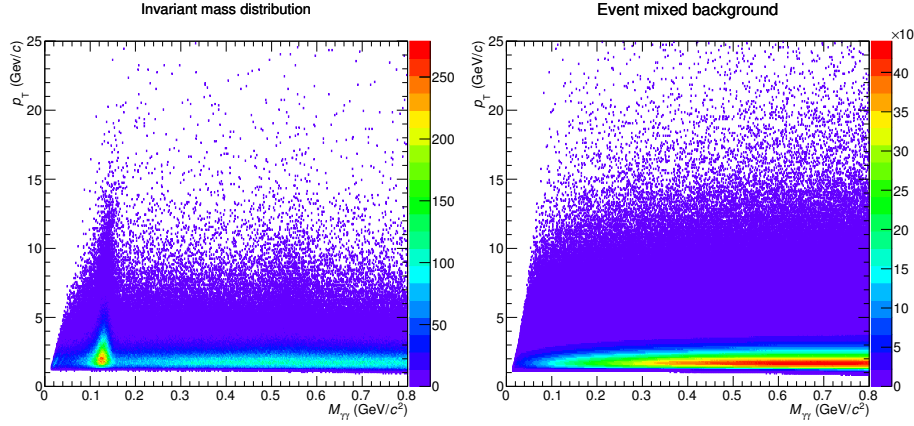
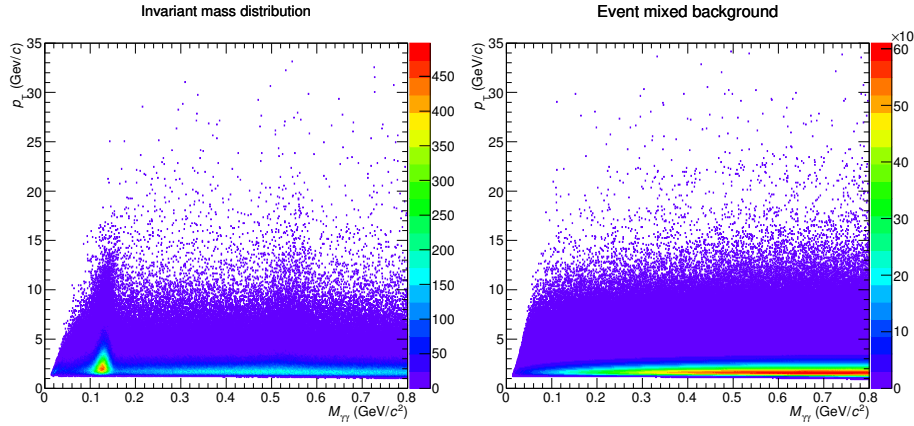**Figure 16** Left: total signal for p_T and M_{inv}. Right: event mixed background

For all p_T the combinatorial background description is acceptable just below the peak. The ratio of the total signal and the scaled background is approximately constant and close to 1.0 as can be seen in Figures 17 and 18 . Only at low transverse momenta and at the lowest masses of the reconstructed photon pairs, the ratio deviates with a factor of the order of $\sim$10.

The differences between the results for the different fit functions that were used are minimal. The residual signal fitted with the Gaussian function together with the first order polynomial caused the peak often to lie slightly more flat than the case using the second order polynomial.

Figure 17 Results for low p_T, POL1, scaling at 3σ-4σ. Left: total signal and scaled background. Center: residual signal and residual background. Right: ratio between total signal and event mixed background.
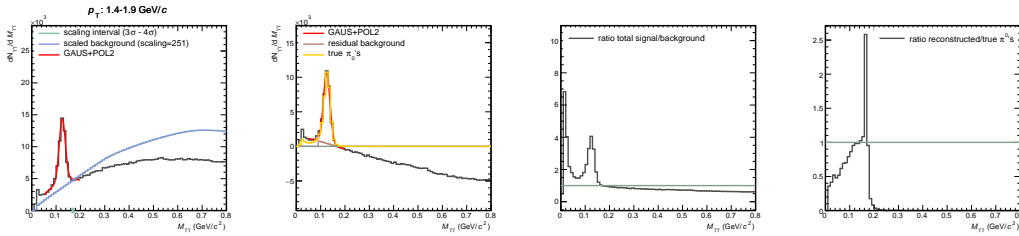
Figure 18 Results for low p_T, POL2, scaling at 3σ-4σ. Left: total signal and scaled background. Center: residual signal and residual background. Right: ratio between total signal and event mixed background.

For the total number of pions and the number of pions in the residual background, the same behavior is found as in the standard event mixing method. The numbers decrease with increasing transverse momentum. Also the ratio between these two quantities of the order of a few percents can be labeled as quite low. The ratio between the number of pions and the number of pions in the residual background is almost the same for all different cases of the STRD and CHAR method. In Figure 19 and 20 the ratios are shown for the STRD method and the CHAR method respectively for the same scaling intervals and fit functions. The CHAR method resulted in slightly smaller ratios than the STRD method.
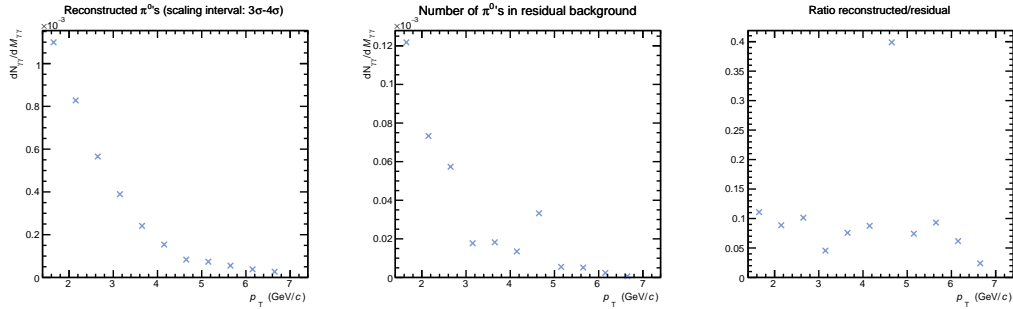
Figure 19 Results per p_T for POL2, scaling at 3σ-4σ. Left: number of reconstructed pions. Center: number of pions in the residual background. Right: ratio between the number of reconstructed pions and number of pions in the residual background
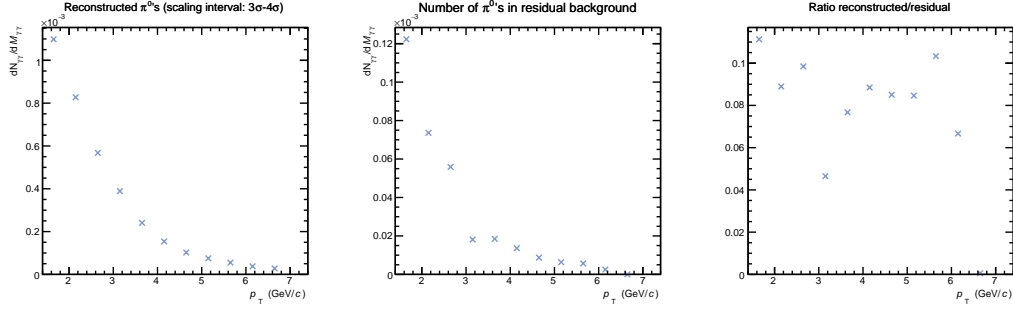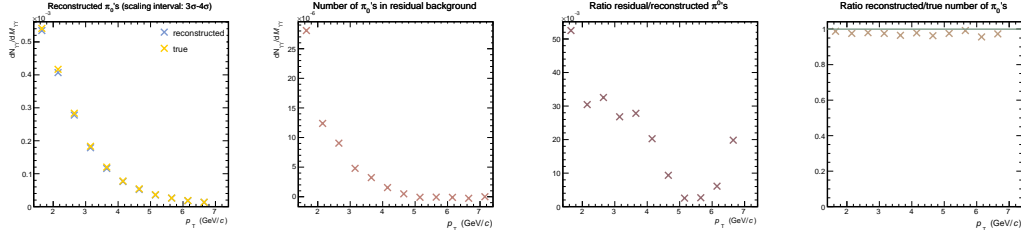
Figure 20 Results per p_T for POL2, scaling at 3σ-4σ. Left: number of reconstructed pions. Center: number of pions in the residual background. Right: ratio between the number of reconstructed pions and number of pions in the residual background

3.4 Monte Carlo (MC)

The p-Pb collision experiment was modeled by a Monte Carlo simulation on which the total signal and event mixed background were based as shown in Figure 21. The mass distribution and event mixed background are quite similar to those of the STRD and CHAR methods.

Figure 21 Left: total signal for p_T and M_{inv}. Right: event mixed background

For all p_T it can be observed that the combinatorial background description is reasonable just below the peak. The ratio of the total signal and the scaled background is approximately constant and close to 1.0. Only at low transverse momenta and at the lowest masses of the reconstructed photon pairs, the ratio deviates with a factor of the order 1-10.
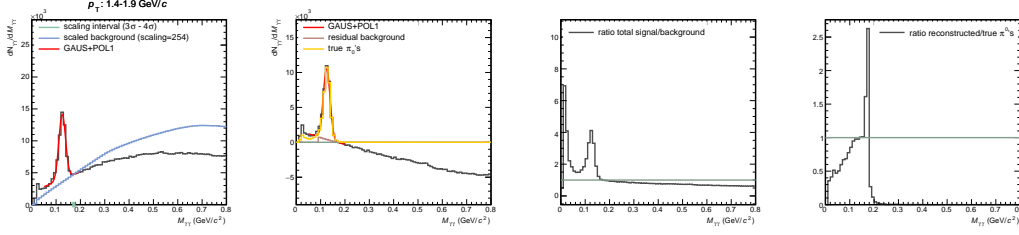
Figure 22 Results for low p_T, POL1, scaling at 3σ-4σ. Left: total signal and scaled background. Center left: residual signal, residual background and true residual signal. Center right: ratio between total signal and event mixed background. Right: ratio between residual signal and true signal.

Figure 23 Results for low p_T, POL2, scaling at 3σ-4σ. Left: total signal and scaled background. Center left: residual signal, residual background and true residual signal. Center right: ratio between total signal and event mixed background. Right: ratio between residual signal and true signal.

Through every residual signal, the true residual signal is plotted which was extracted from the simulation (see Figures 22 and 23). Ideally, the reconstructed peak based on the simulation data is in accordance with the peak of the true pions. That means that in the region of the peak, the ratio between the bin contents of the histograms of the true pions and reconstructed pions should be equal to 1.0. Considering the ratio of the reconstructed pions based on the simulation data and the true found pions, the results are rather unexpected. While the residual signal seems to be largely in accordance with the true pions' histogram in the region of the peak, the ratio between the residual signal and the true residual signal is only equal to 1.0 for a very narrow mass range.

For every p_T slice, the ratio between the reconstructed number of pions and the true number of pions is shown (see most right plots in Figures 24 and 25). When the total number of pions that was reconstructed is compared to the true number of pions for the different p_T slices, the numbers do agree quite well in contrast to the ratio of the bin contents of the different histograms discussed above. For all scaling intervals, it can be seen that the ratio between the reconstructed and true number of pions is close to 1.0. When fitting the histograms with a Gaussian function together with a second order polynomial, it can be seen in Figure 25 that this ratio is a small fraction lower than 1.0.

Figure 24 Results per p_T for POL1, scaling at 3σ-4σ. Left: number of reconstructed pions. Center left: number of pions in the residual background. Center right: ratio between the number of reconstructed pions and number of pions in the residual background. Right: ratio between number of reconstructed pions and number of true pions
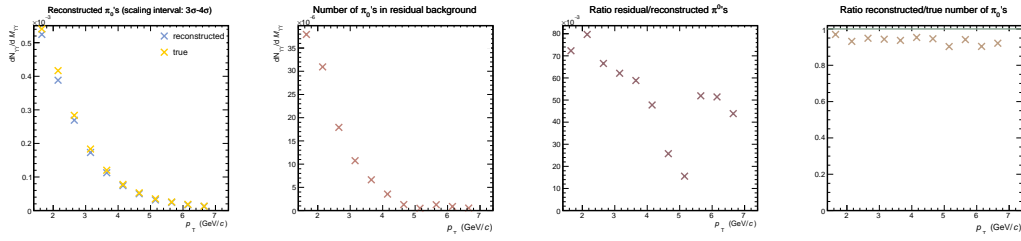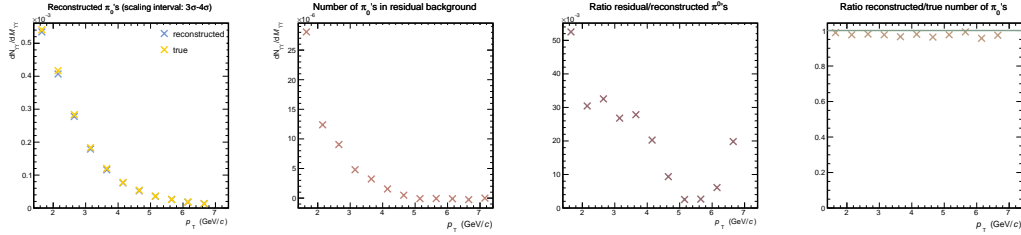

Figure 25 Results per p_T for POL2, scaling at 3σ-4σ. Left: number of reconstructed pions. Center left: number of pions in the residual background. Center right: ratio between the number of reconstructed pions and number of pions in the residual background. Right: ratio between number of reconstructed pions and number of true pions

If the results of the Monte Carlo simulation are compared to the results from the experimental data obtained using the standard method, the results are largely in agreement. The ratio between the total signal and the event mixed background from the Monte Carlo simulation is nearly the same as the ratio based on the experimental data (see Figure 26).
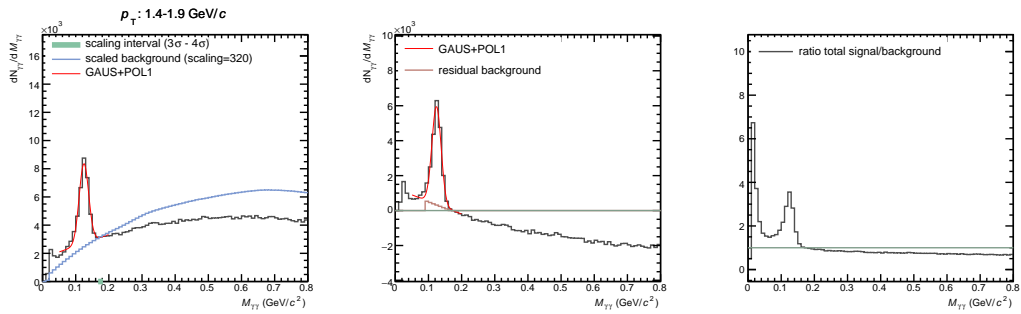
Figure 26 Results from the experimental data for low p_T, POL1, scaling at 3σ-4σ. Left: total signal and scaled background. Center: residual signal and residual background. Right: ratio between total signal and event mixed background. The ratio between the total signal and the event mixed background is approximately similar to the one obtained from the simulation data (see Figure 22).

Whereas the residual signals of the simulation and the experimental data are largely in agreement, the fraction of the number of pions found in the residual background to the total number of pions rather differs for both the experimental as the Monte Carlo data, which can be seen from Figures 27 and 28. Also for other scaling intervals and the POL2 fit function, these ratios differ.
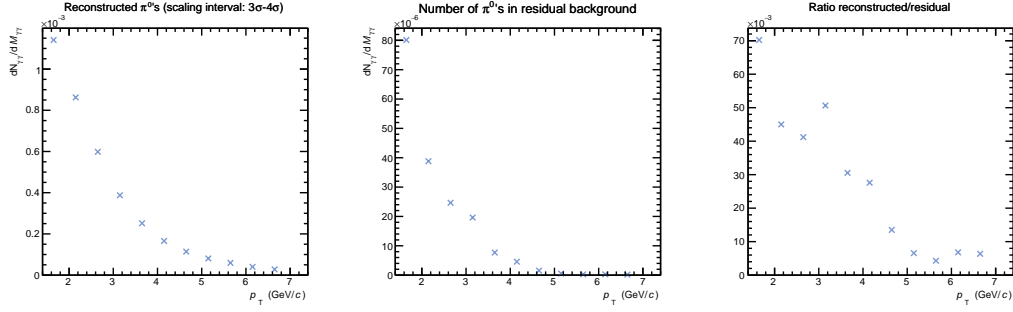
Figure 27 Results per p_T for POL1, scaling at 3σ-4σ. Left: number of reconstructed pions. Center: number of pions in the residual background. Right: ratio between the number of reconstructed pions and number of pions in the residual background

Figure 28 Results per p_T for POL1, scaling at 3σ-4σ. Left: number of reconstructed pions. Center: number of pions in the residual background. Right: ratio between the number of reconstructed pions and number of pions in the residual background

4   Discussion

From the study on the description of the combinatorial background it can be observed that the results are not unambiguous for all possible modifications of event mixing and variations for scaling. The results differ significantly for different p_T slices and therefore no perfect method of the background description was found. However, an overall conclusion was drawn which is discussed in Section 5.

The scaling was performed at different intervals. The interval of 15 to 40 standard deviations was often located below the η meson peak. This caused a relatively small deviation from 1.0 in the ratio between the total signal and the background. For the overall results, this deviation had no major consequences.

The event mixed background of the SMRAD method showed an odd behavior. A sharp cut-off in the number of photon pairs for which $M_{\gamma\gamma} > \sim 0.2\,\mathrm{GeV}/c^2$ was found. In the SM-RAD method, only events that have a cluster with the highest energy for which $R < 0.2$ were used to compute the event mixed background. That means that also the opening angles of two photons is constrained, due to the fact that photons will not be mixed if the angle between the highest energetic clusters is larger than 0.2. However, there is a relation between the energy of the pion and the opening angle of the decay photons. If the energy of the pion is high, the opening angle between the photons is larger. Hence a constraint on the opening angle means a constraint on the energy of the pion. Therefore few photon pairs with a high energy are taken into account when filling the two dimensional histogram of the event mixed background due to the fact that the absence of pions with a high energy means an absence of photon pairs with a high invariant mass. This is the reason the sharp cut-off was found in the event mixed background at a mass of ~ 0.2 GeV/c^2.

For this research data from EMCal was used. Also data from other subdetectors of the ALICE detector could be used. One point of interest is the angular coverage of the collision vertex by the EMCal. Ideally the collision vertex is fully covered by a spherical detector to detect all particles created in the collision. Of course, full spherical coverage is not possible, yet cylindrical coverage is. However the angle that is covered by the EMCal is only a relatively small part of a cylinder which limits the measurement of the collision experiment.

To find a more accurate description of the combinatorial more research is needed. First of all other event mixing classes should be considered. The modifications on the event mixing classes in this research did not result in a description of the combinatorial that was well enough. Also other scaling intervals should be investigated. Furthermore other fit functions can be used to describe the residual background.

5   Conclusion

Considering the results of the different event mixing methods, fit functions and scaling intervals, it can be concluded that the combinatorial background description by the charged track multiplicity event mixing method was just as good as the description by the standard event mixing method. This is based on the fact that the ratio between the total signal and the background was close to 1.0 except for the region of the peak for both methods. Also at relatively high masses the ratio was kept close to 1.0 in contrast to the ratio of the SMRAD method. Furthermore, when the ratio between the residual signal and the total number of reconstructed pions was studied, the CHAR method provided results that are approximately similar to the results of the STRD method for all scaling intervals and both used fit functions. No significant differences were found considering all different cases of the transverse momentum slices, scaling intervals and fit functions.

The total signal of the Monte Carlo simulation was very similar to that of the total signal built on the experimental data. Also the MC event mixed background agreed with both the STRD as well as the CHAR event mixed background. Due to the fact that the STRD method in the Monte Carlo simulation provided results that were in accordance with the true findings of the simulation, it can be concluded that the STRD method gives sufficient results. It was shown that the CHAR method provided similar results as the STRD method on the experimental data and together with the results from the simulation it can be concluded that the CHAR method and STRD method describe the combinatorial background in the most appropriate manner.

The variations in scaling turned out that the scaling intervals of 3-13 and 15-40 standard deviation from the peak's maximum provided a slightly more accurate description of the combinatorial background, based on the ratio between the total signal and the scaled event mixed background. The ratio for all different scaling intervals at the region of the peak is approximately equal, yet far away from the peak the ratio remains closer to 1.0 if the scaling was performed at the intervals that are mentioned above. However, the background description near the peak was better if the scaling was performed at 3-4 or 4-5 standard deviations.

For all possible modifications that were applied on event mixing and the way of subtracting the event mixed background from the invariant mass distribution, the fit function of the Gaussian together with a first order polynomial turned out to give the most accurate description of the combinatorial background. When the fit function of the Gaussian together with the second order polynomial was used, the residual background remained larger than in the case of the first order polynomial.

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Appendices

A   STRD

STRD — POL1 — Scaling: 3-4
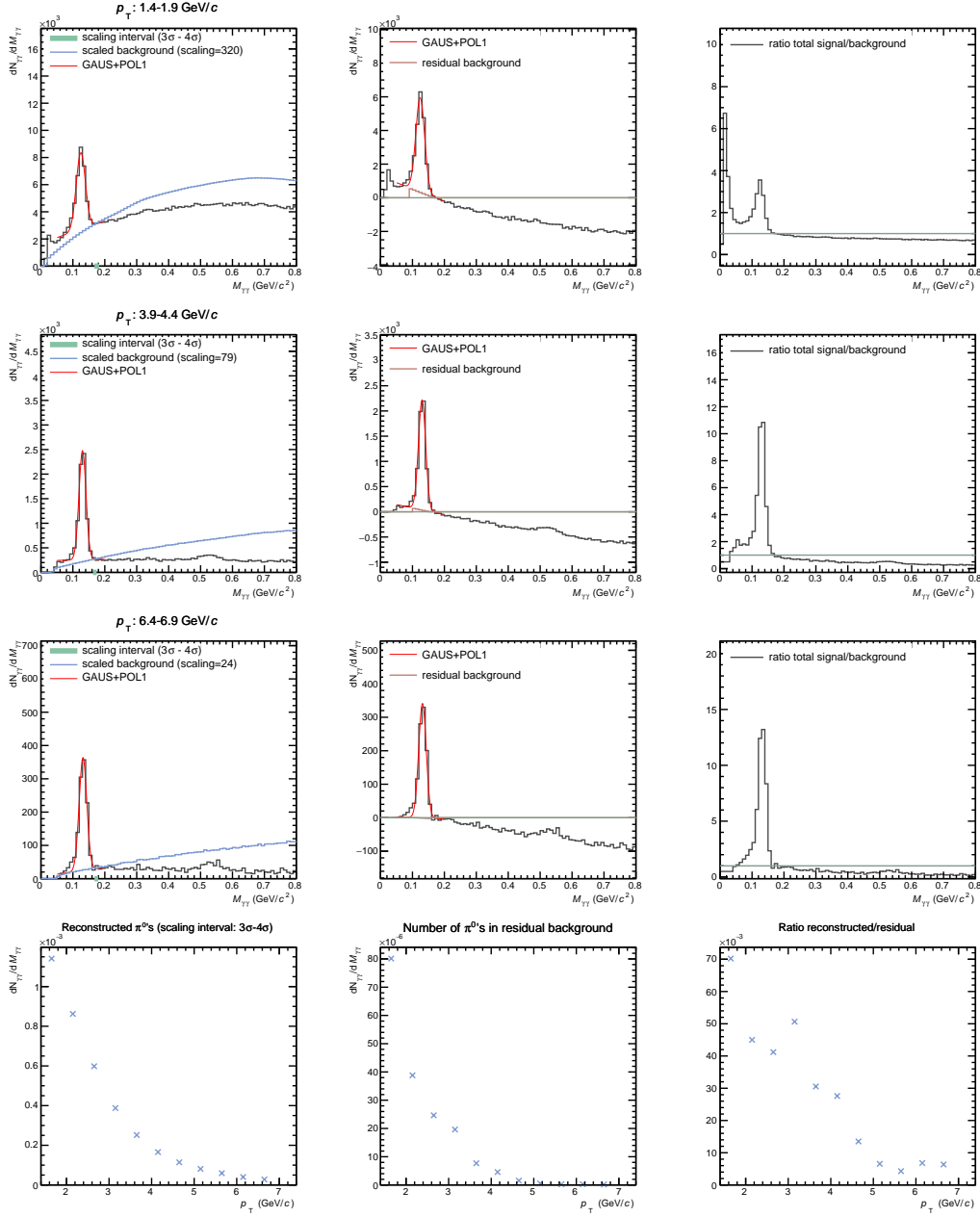
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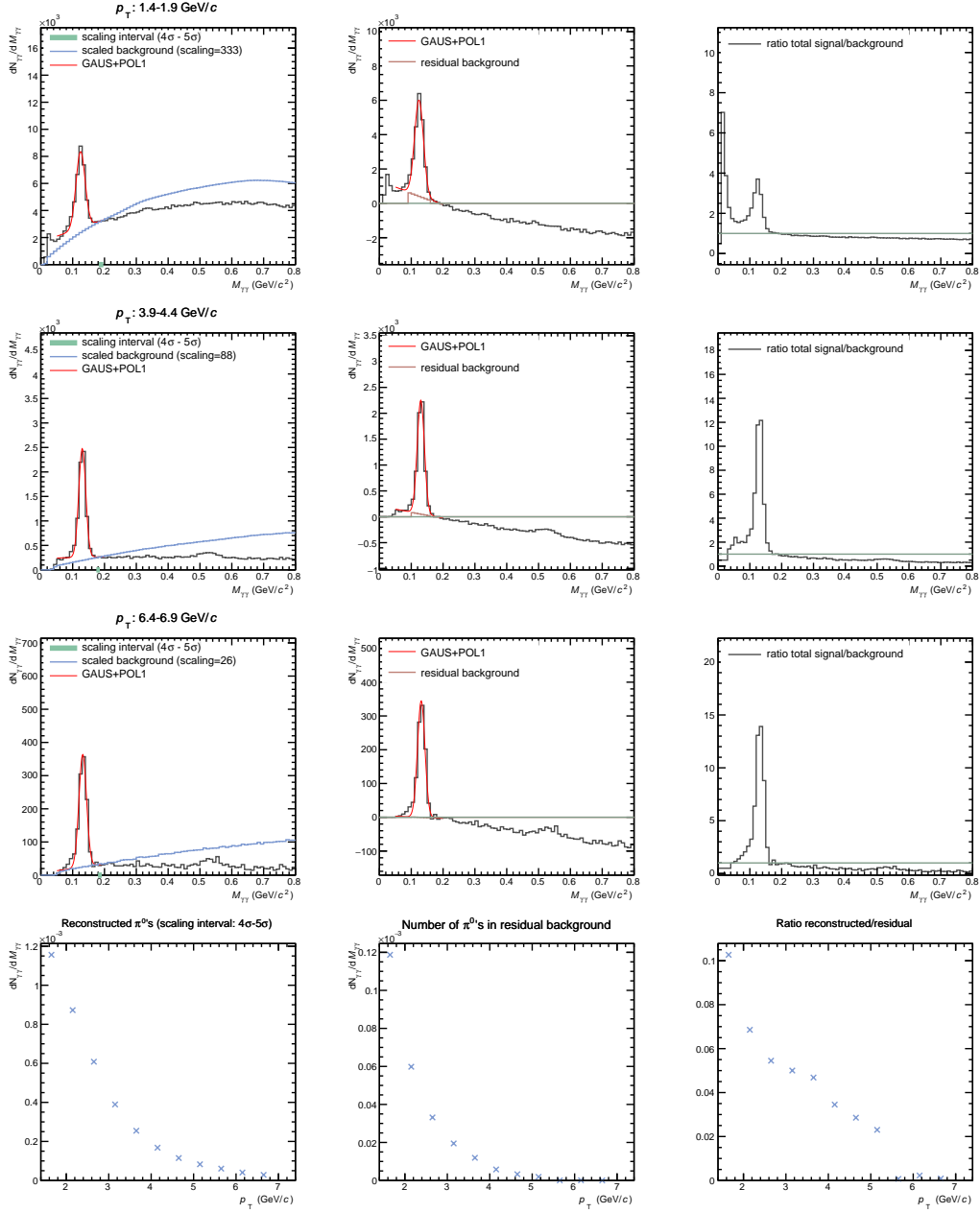
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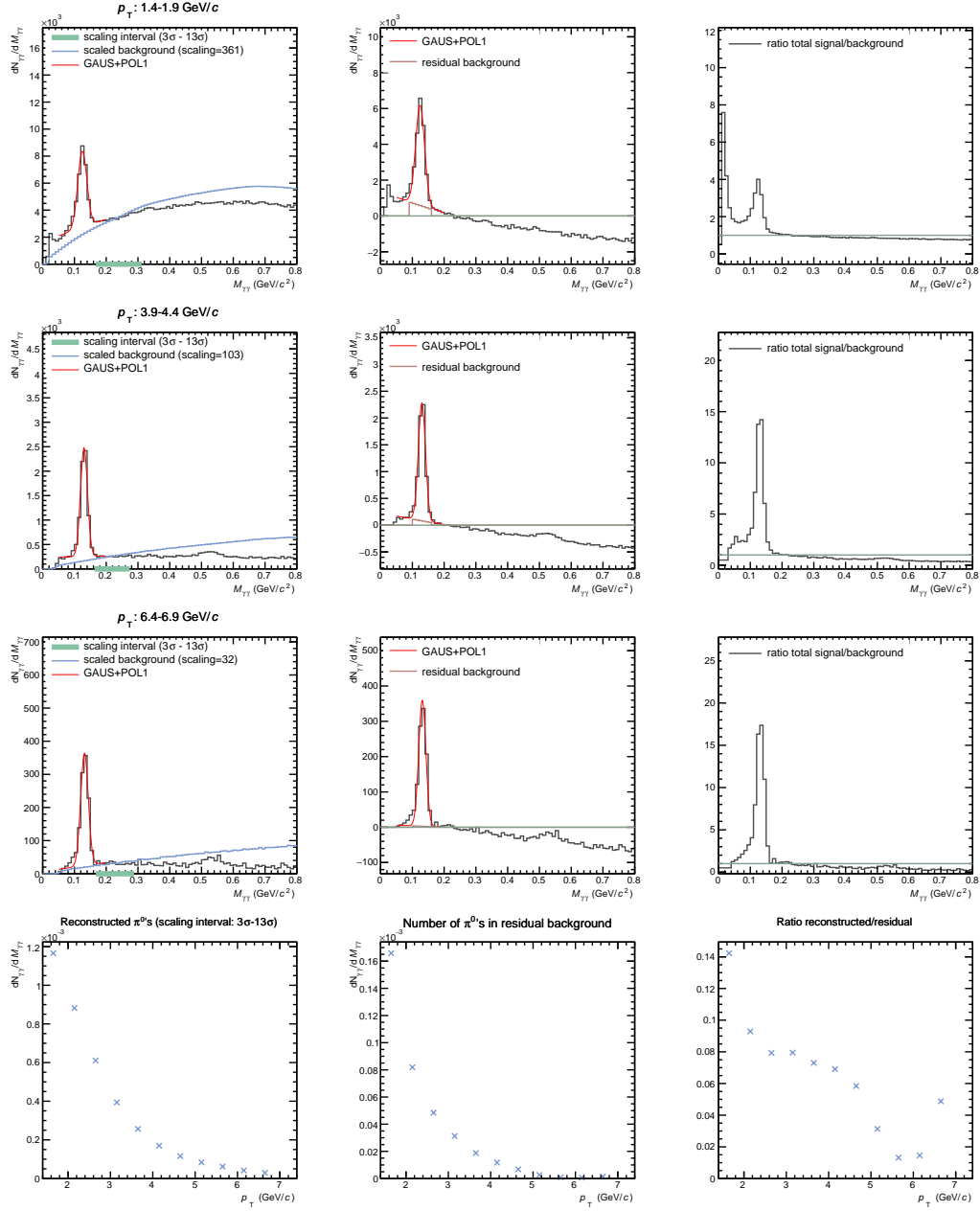
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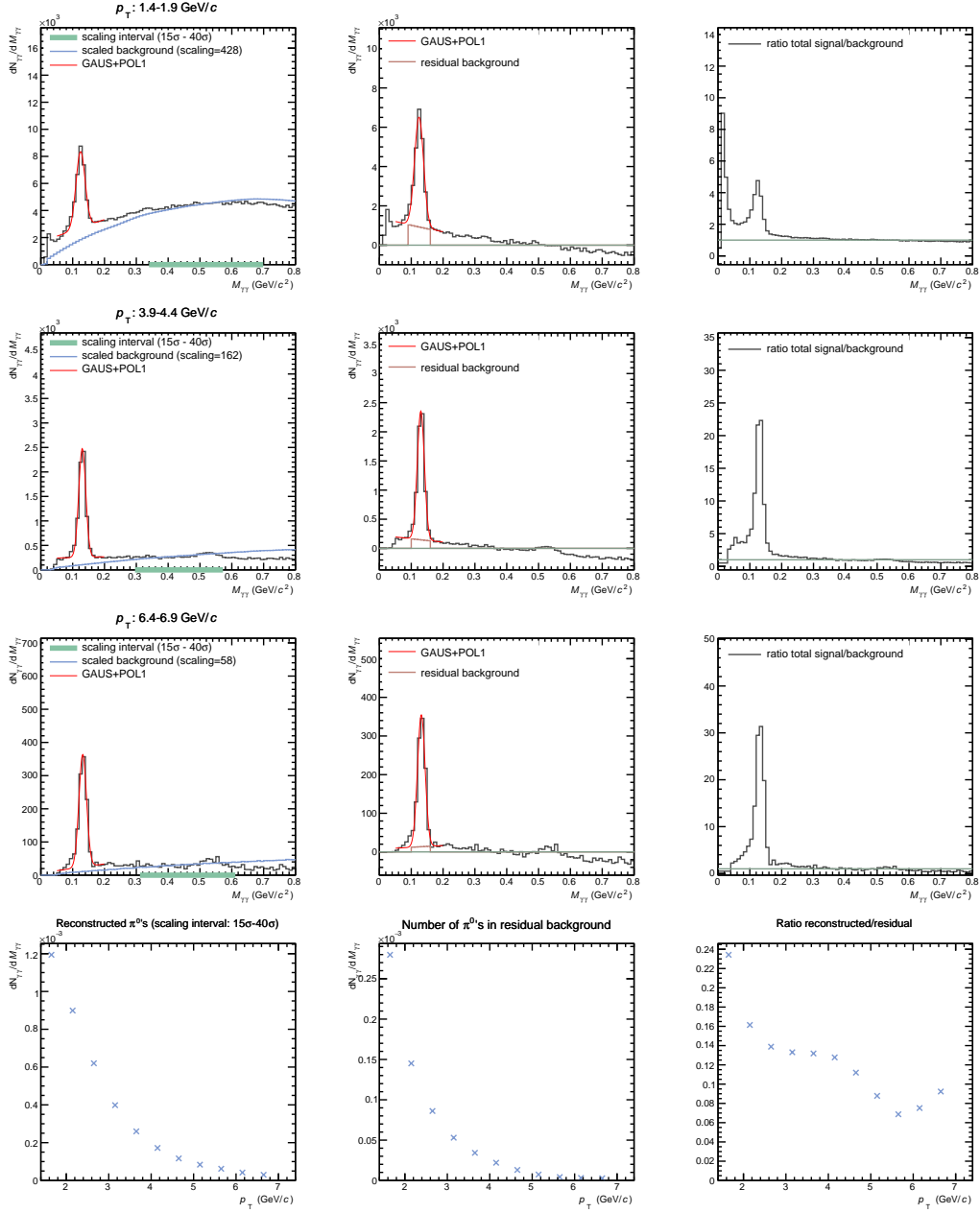
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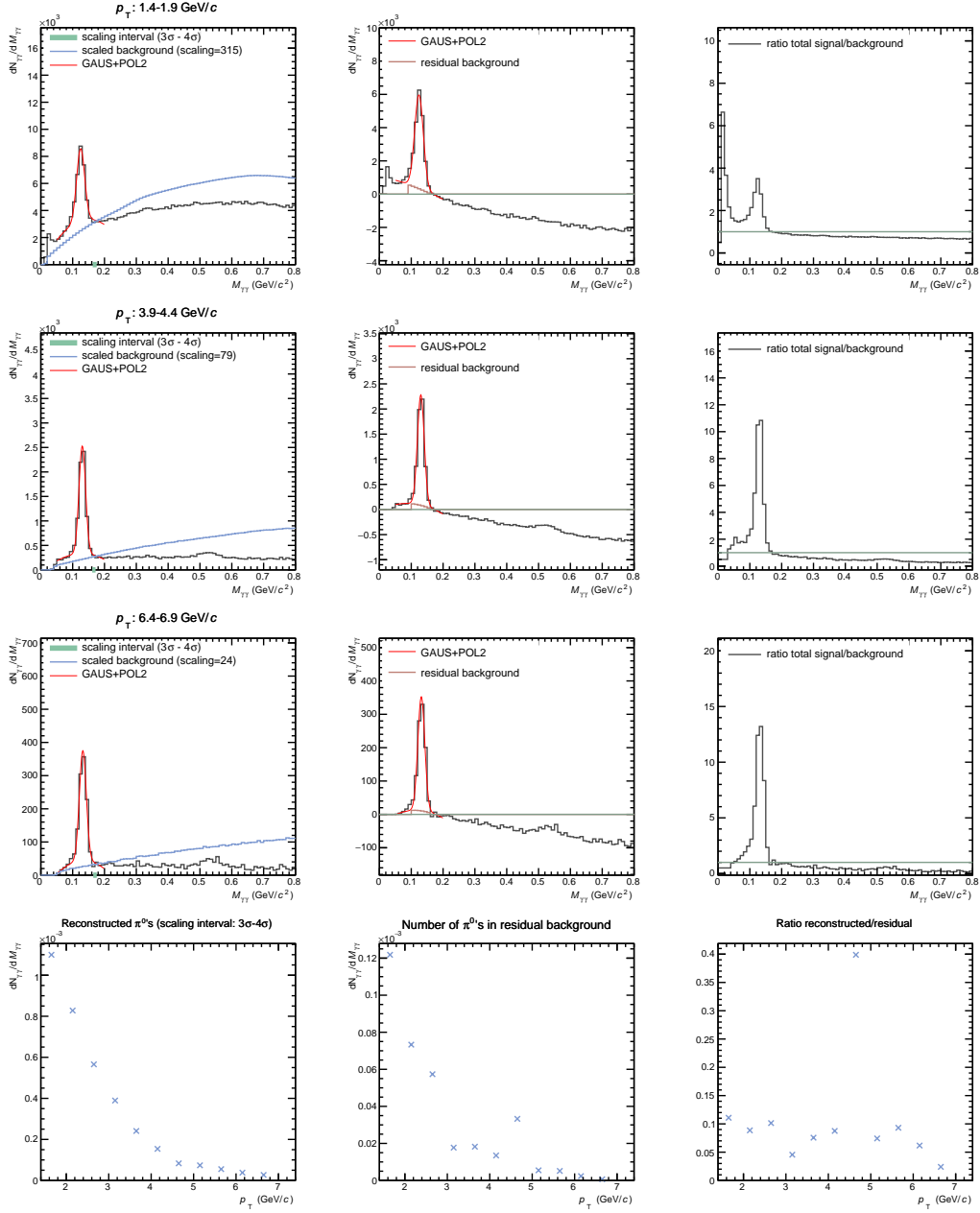
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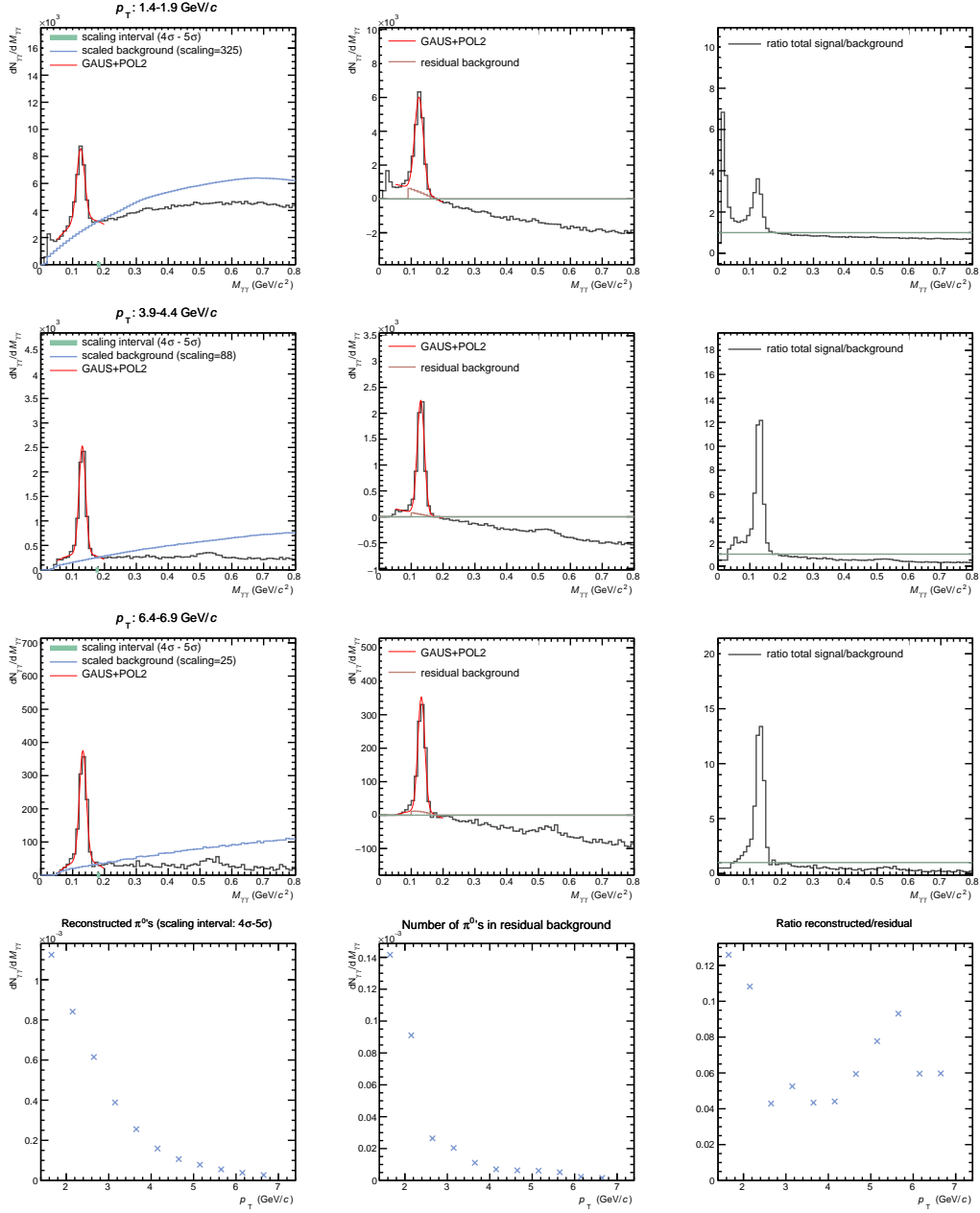
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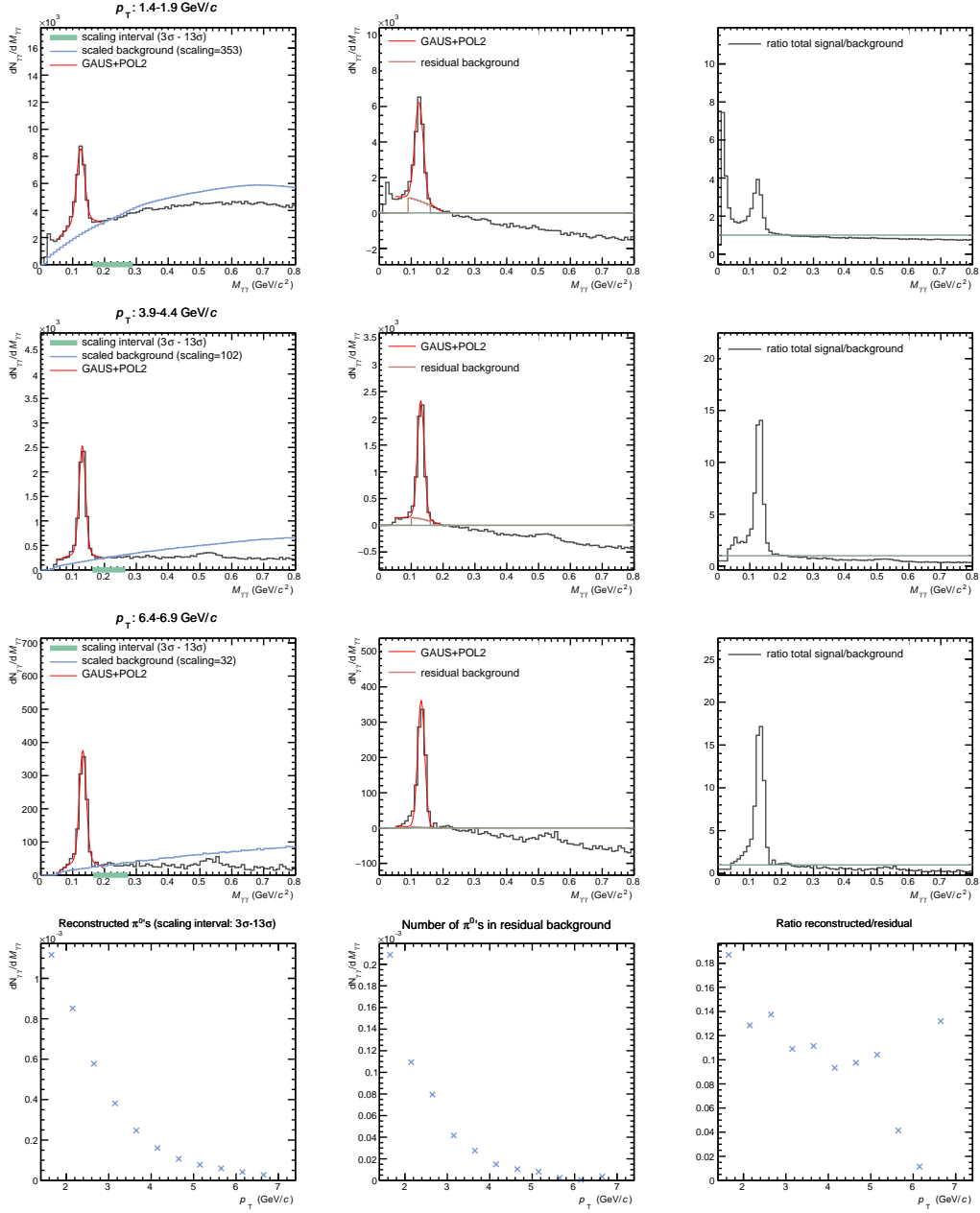
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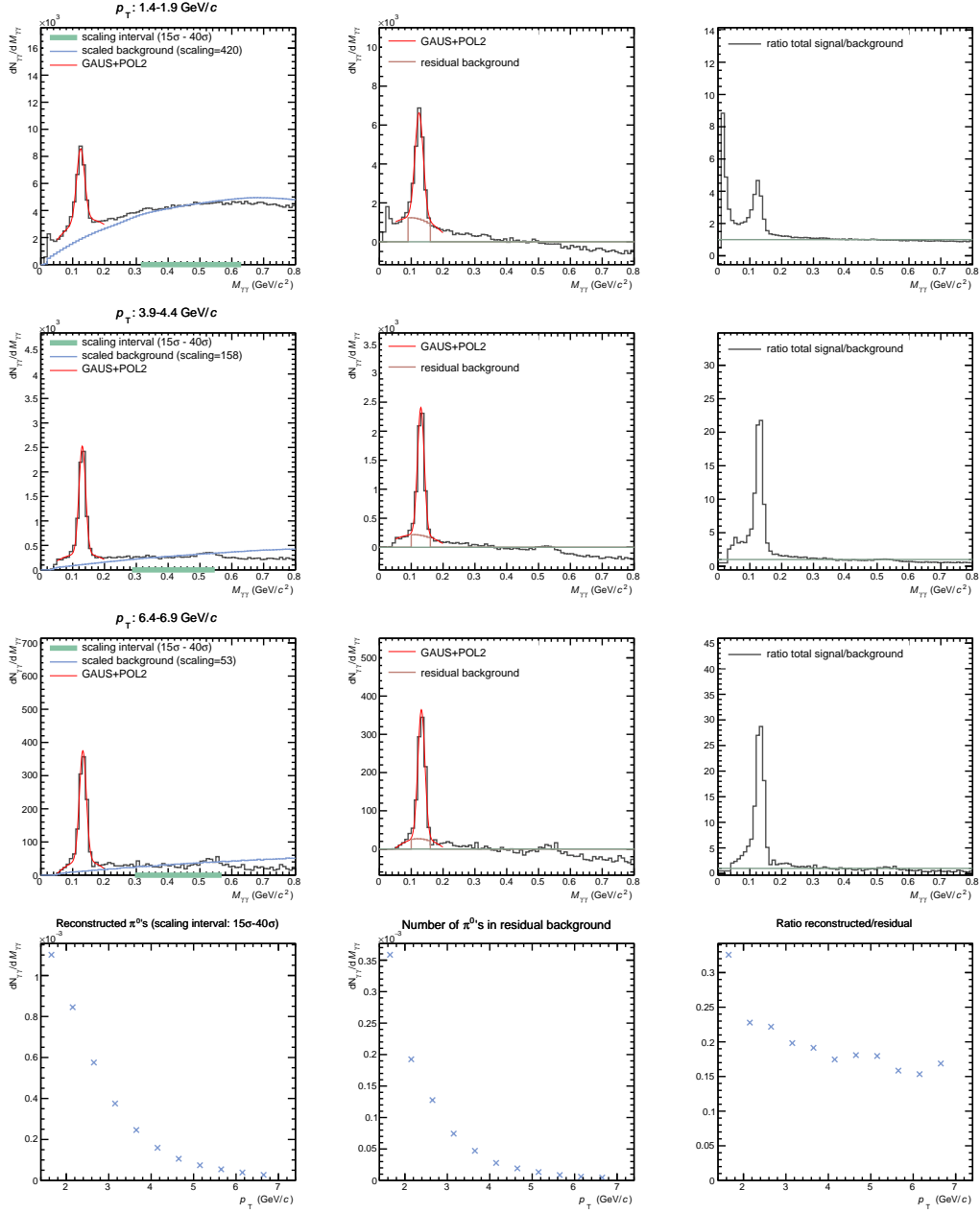
B   SMRAD

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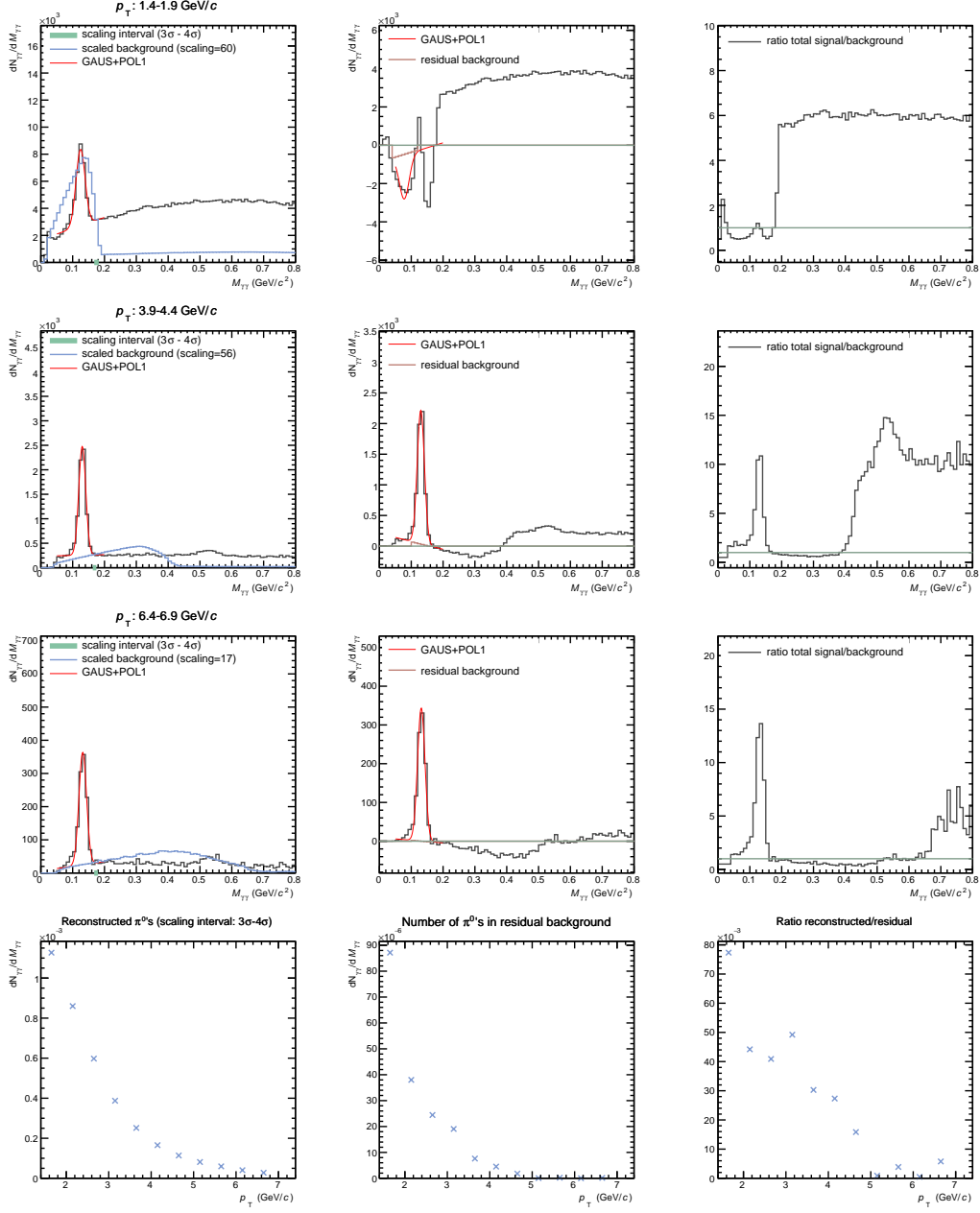
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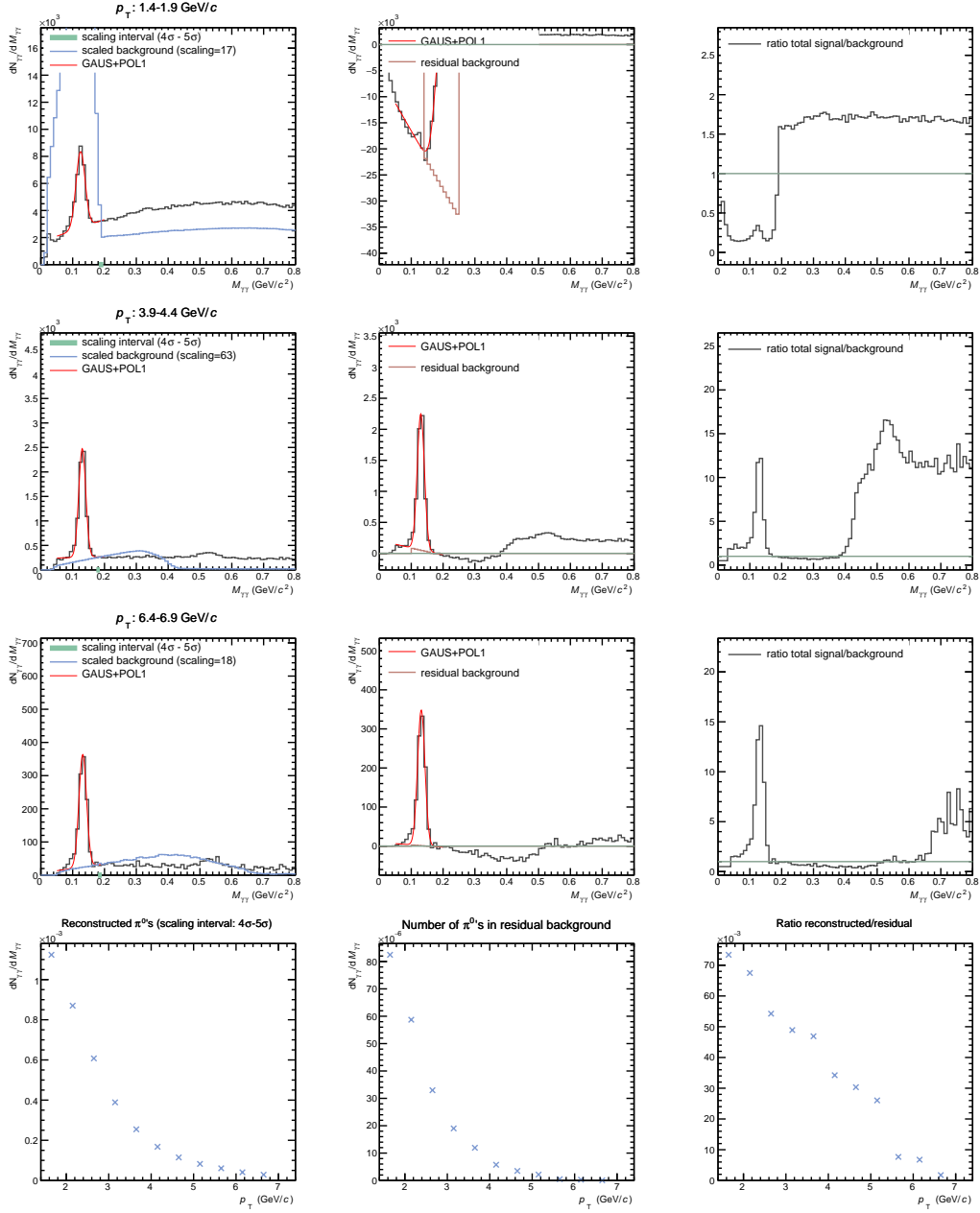
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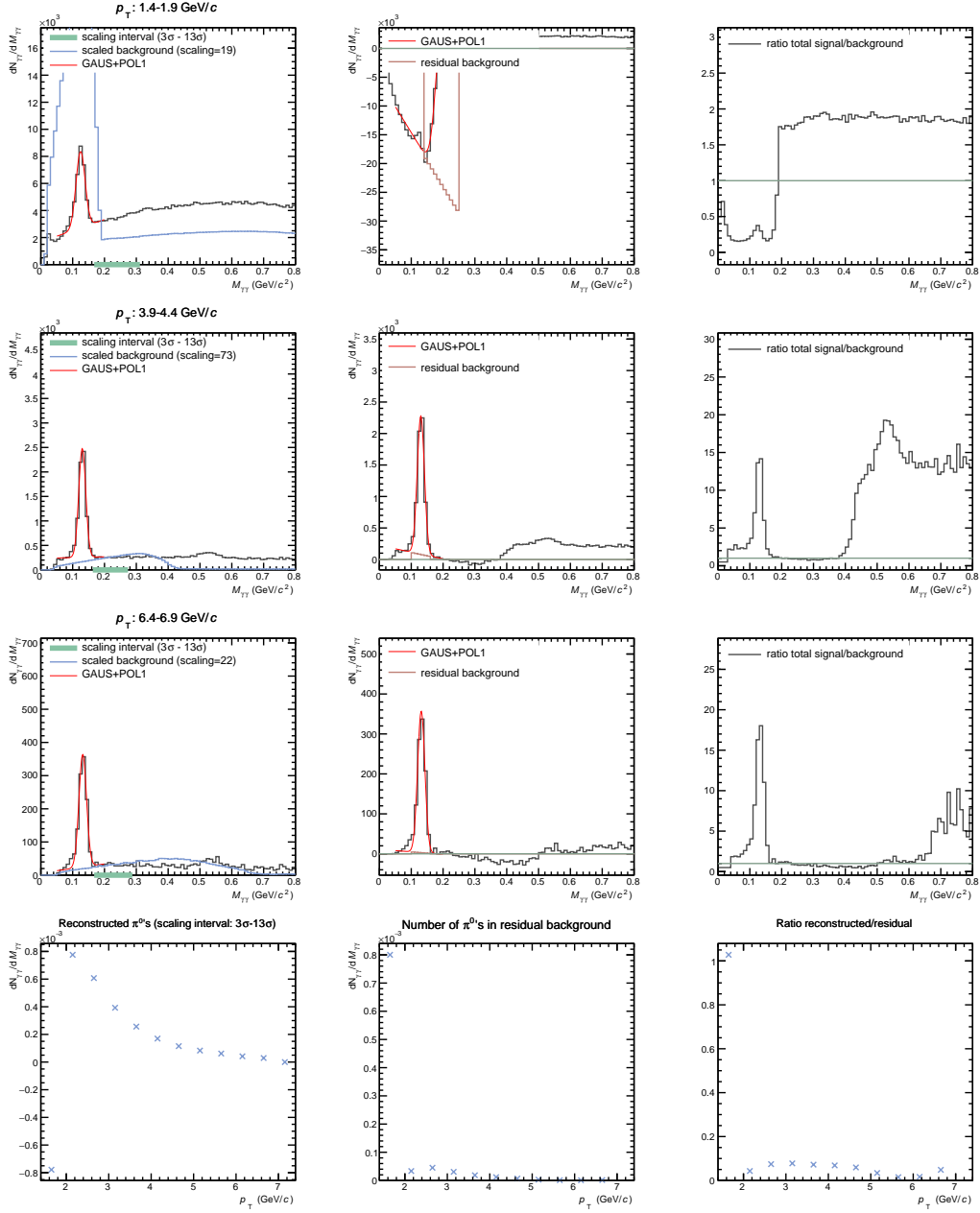
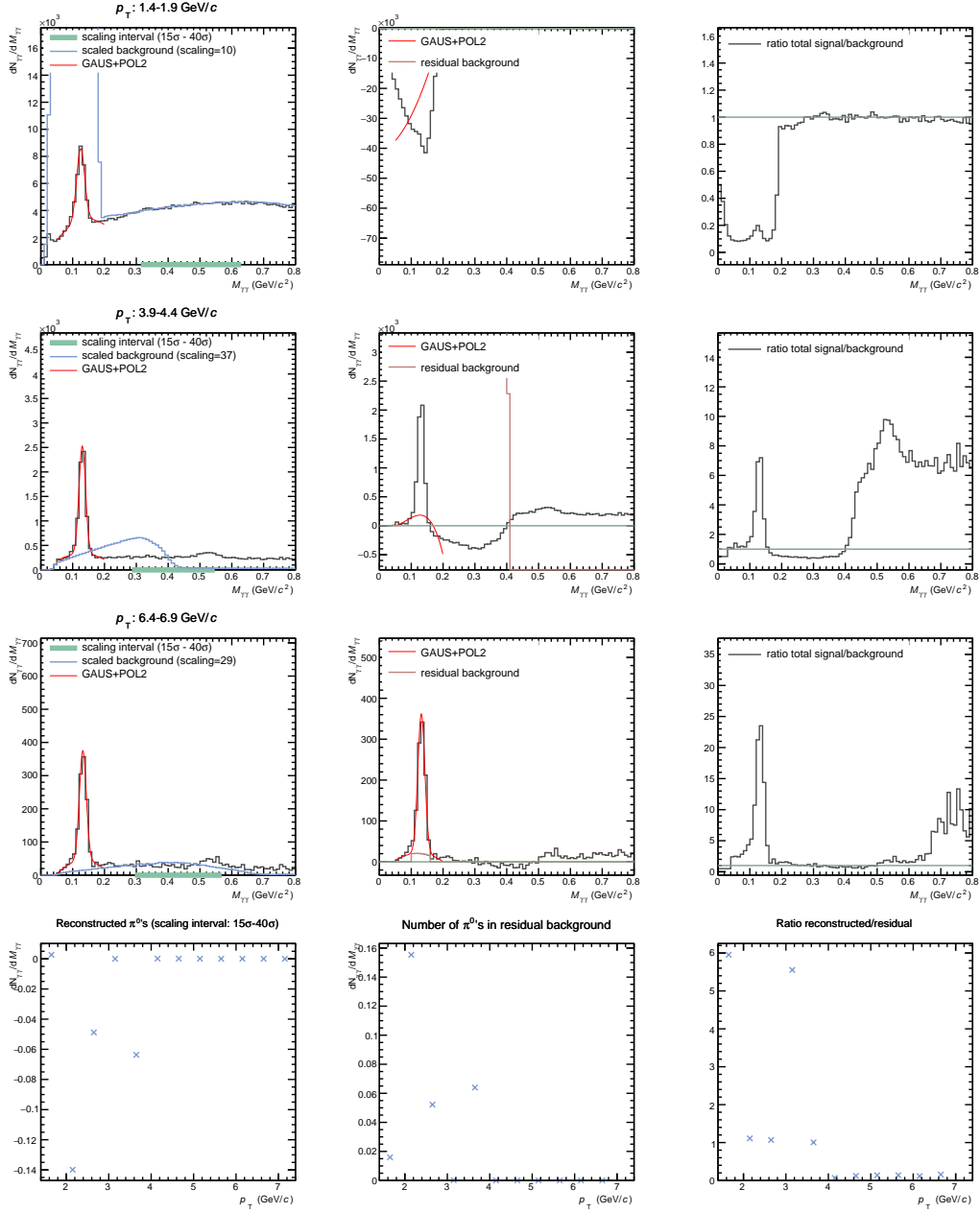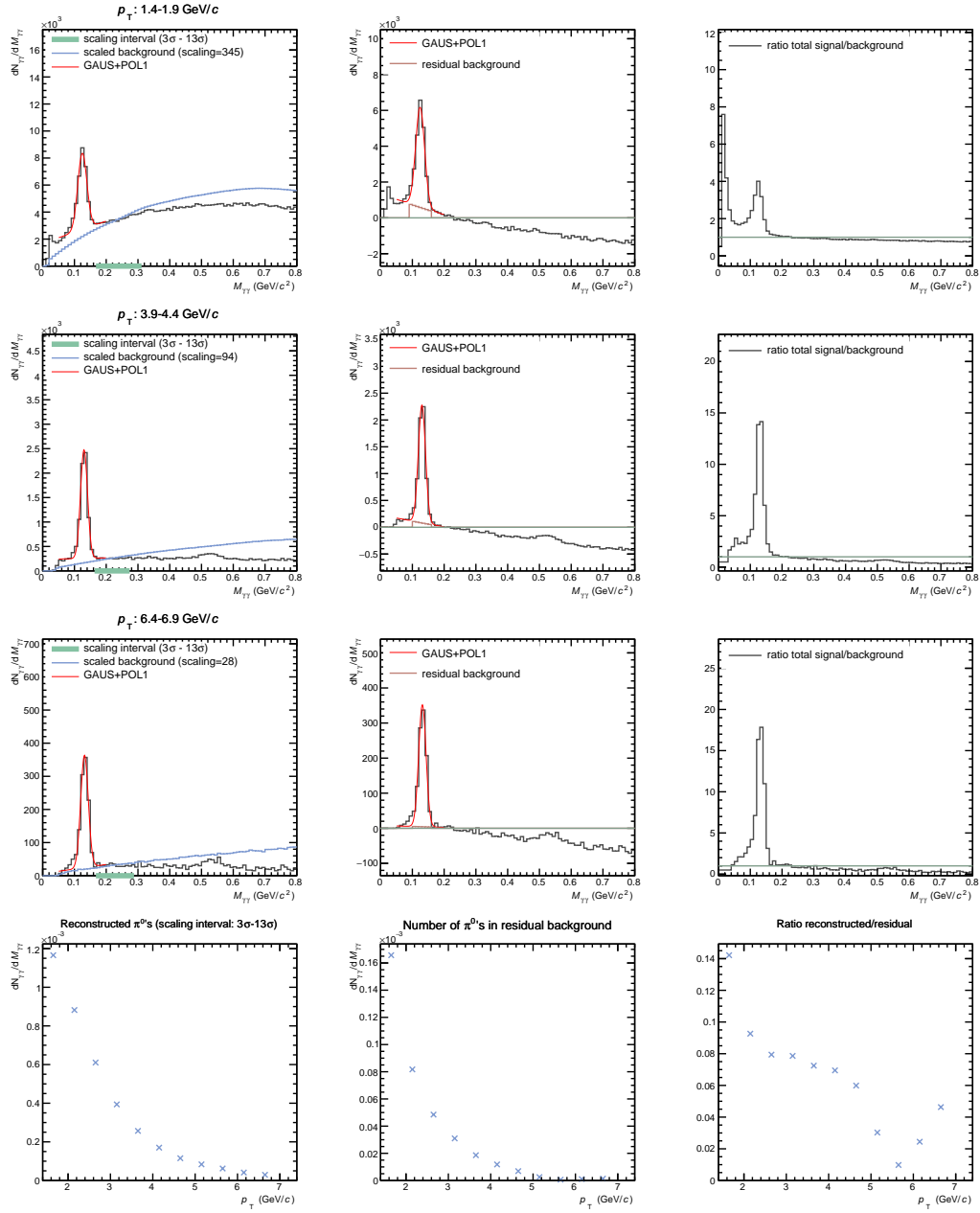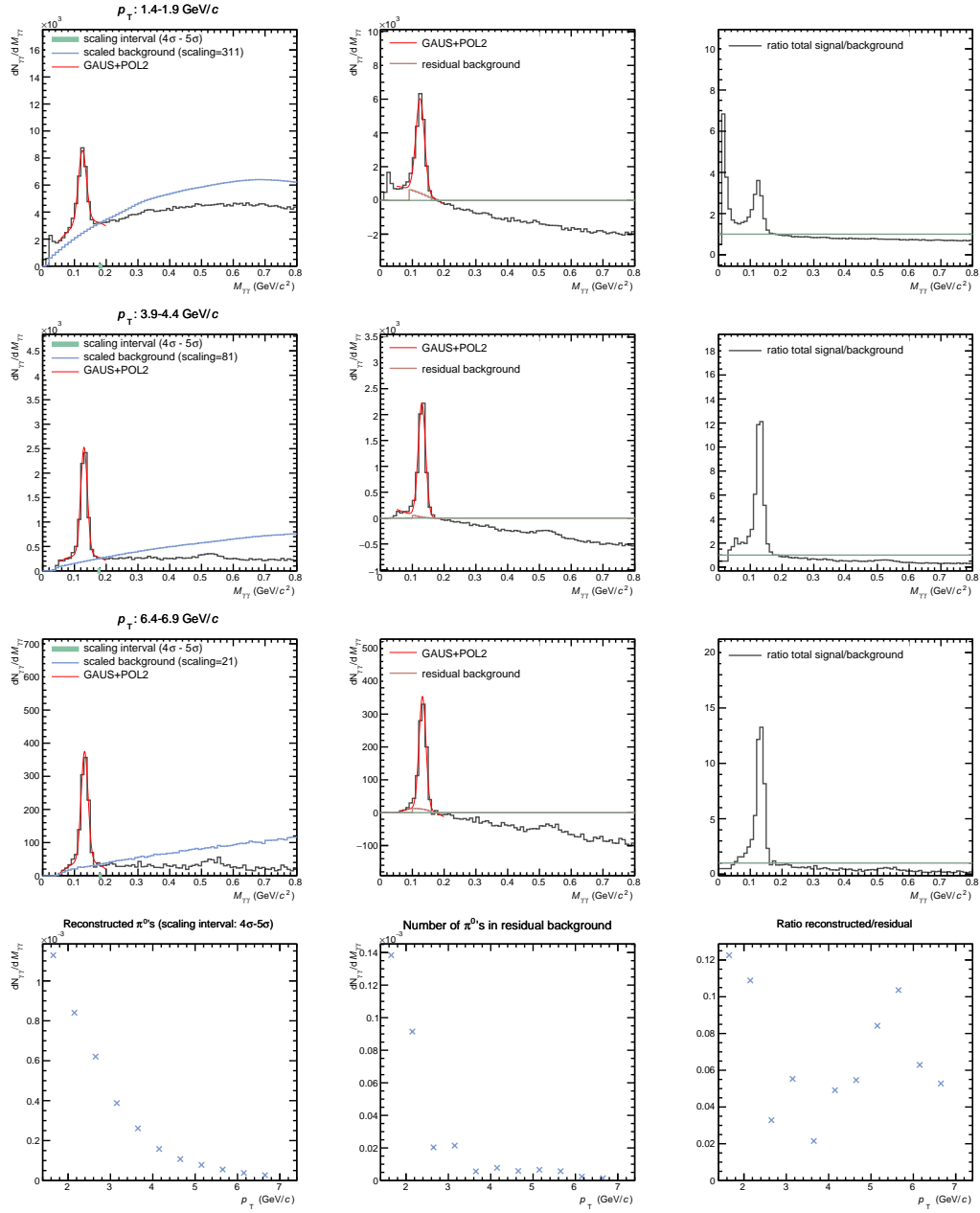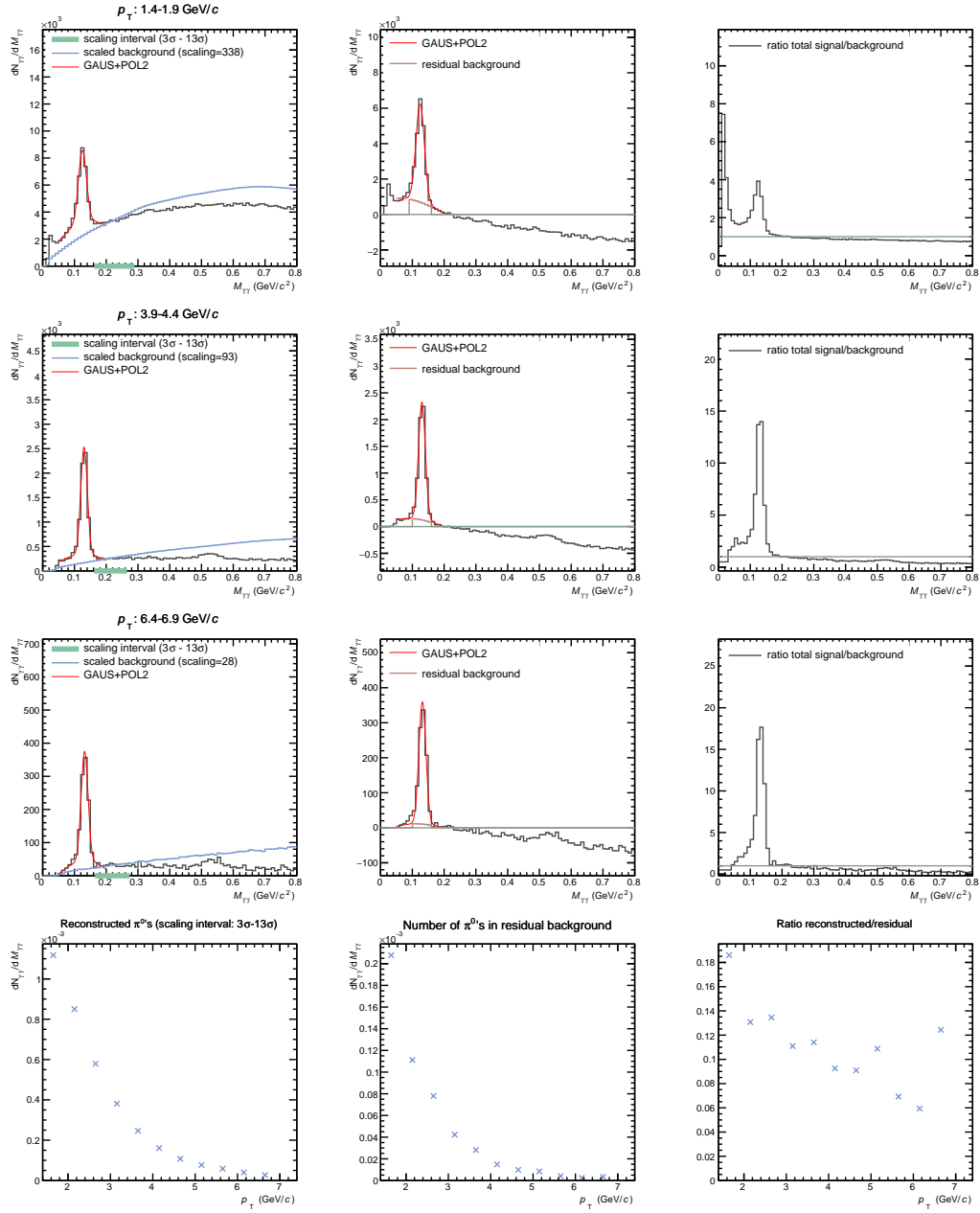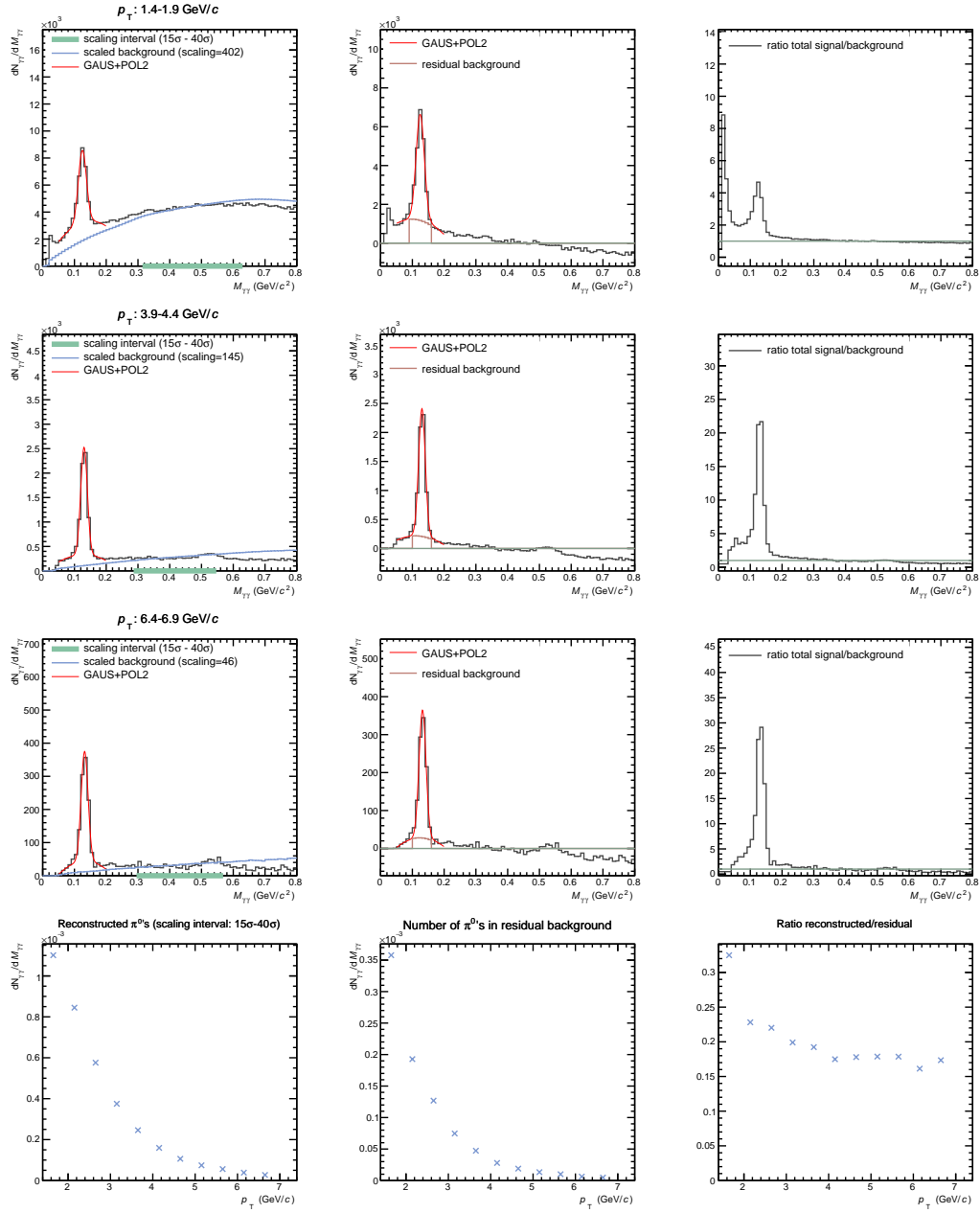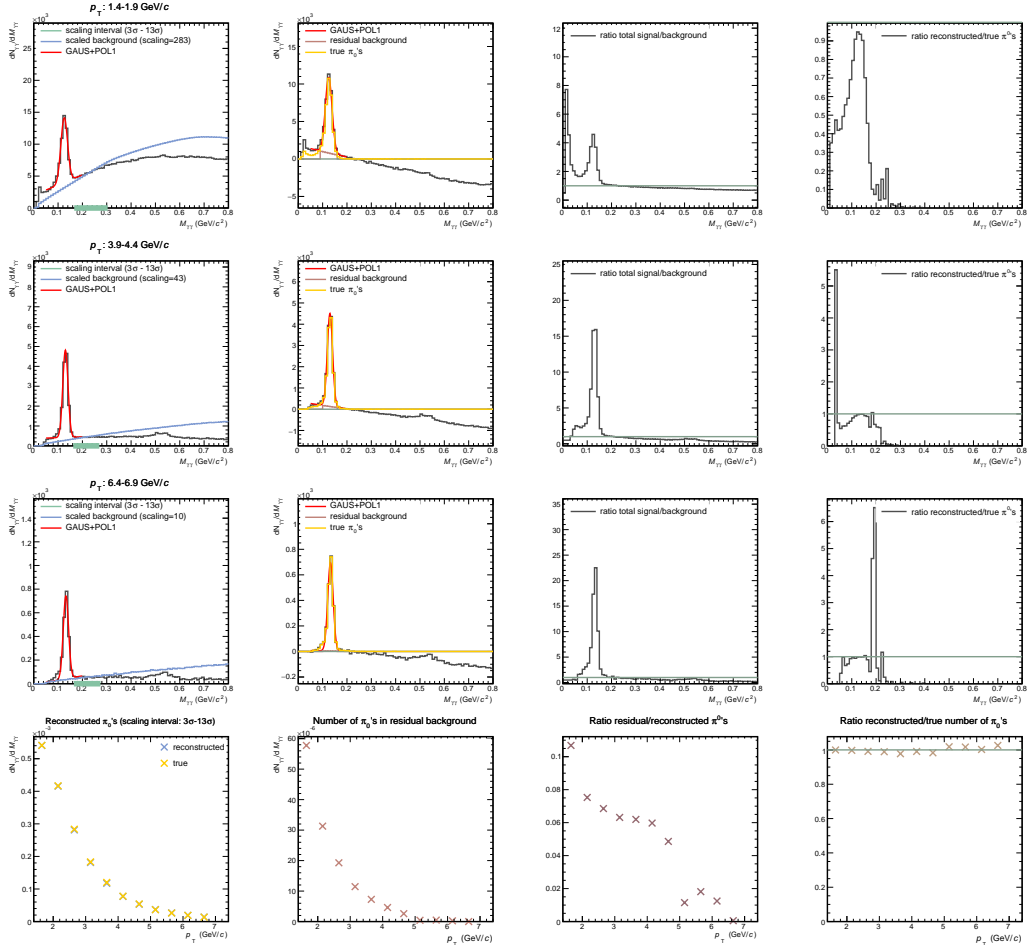# SMRAD — POL1 — Scaling: 15-40
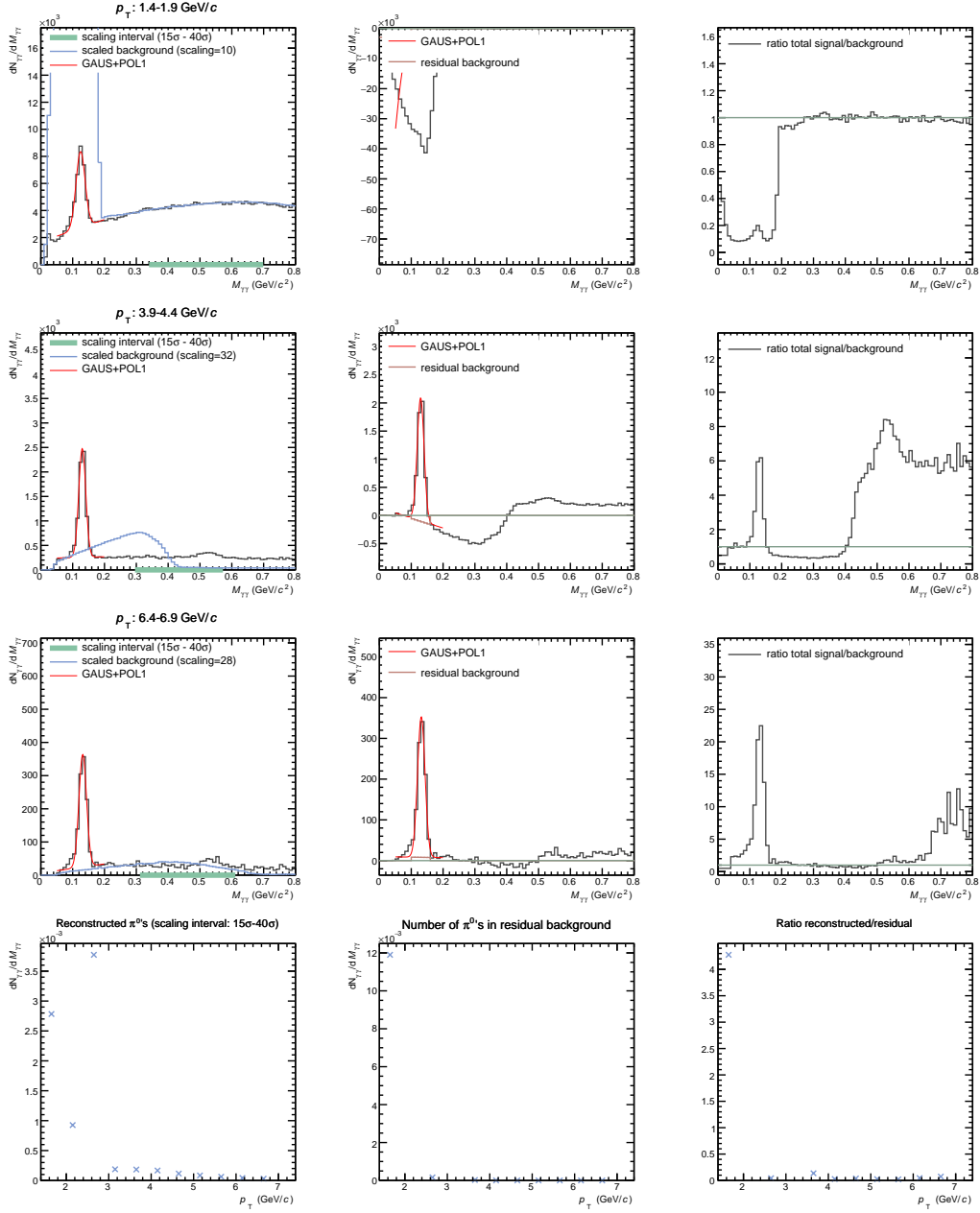
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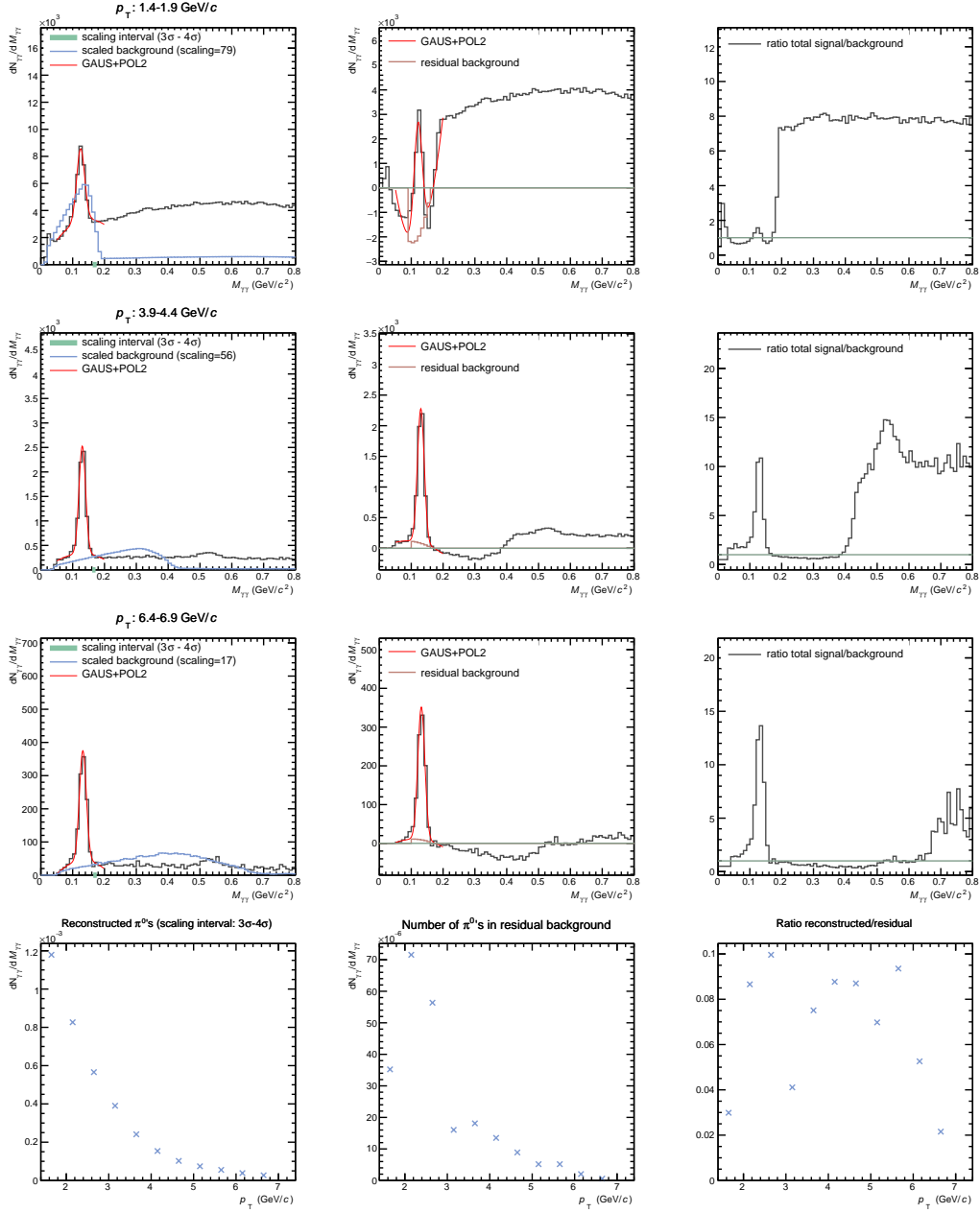
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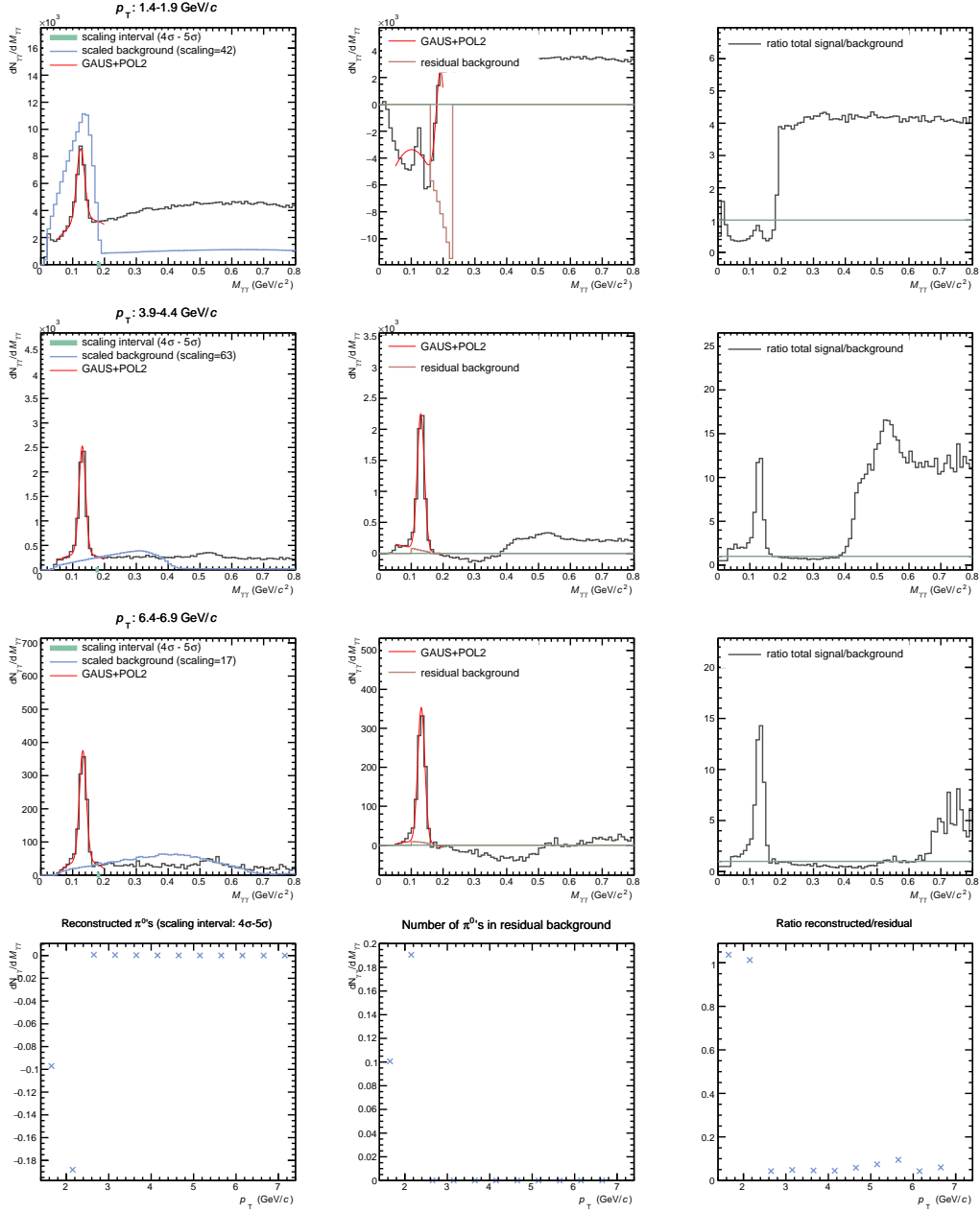
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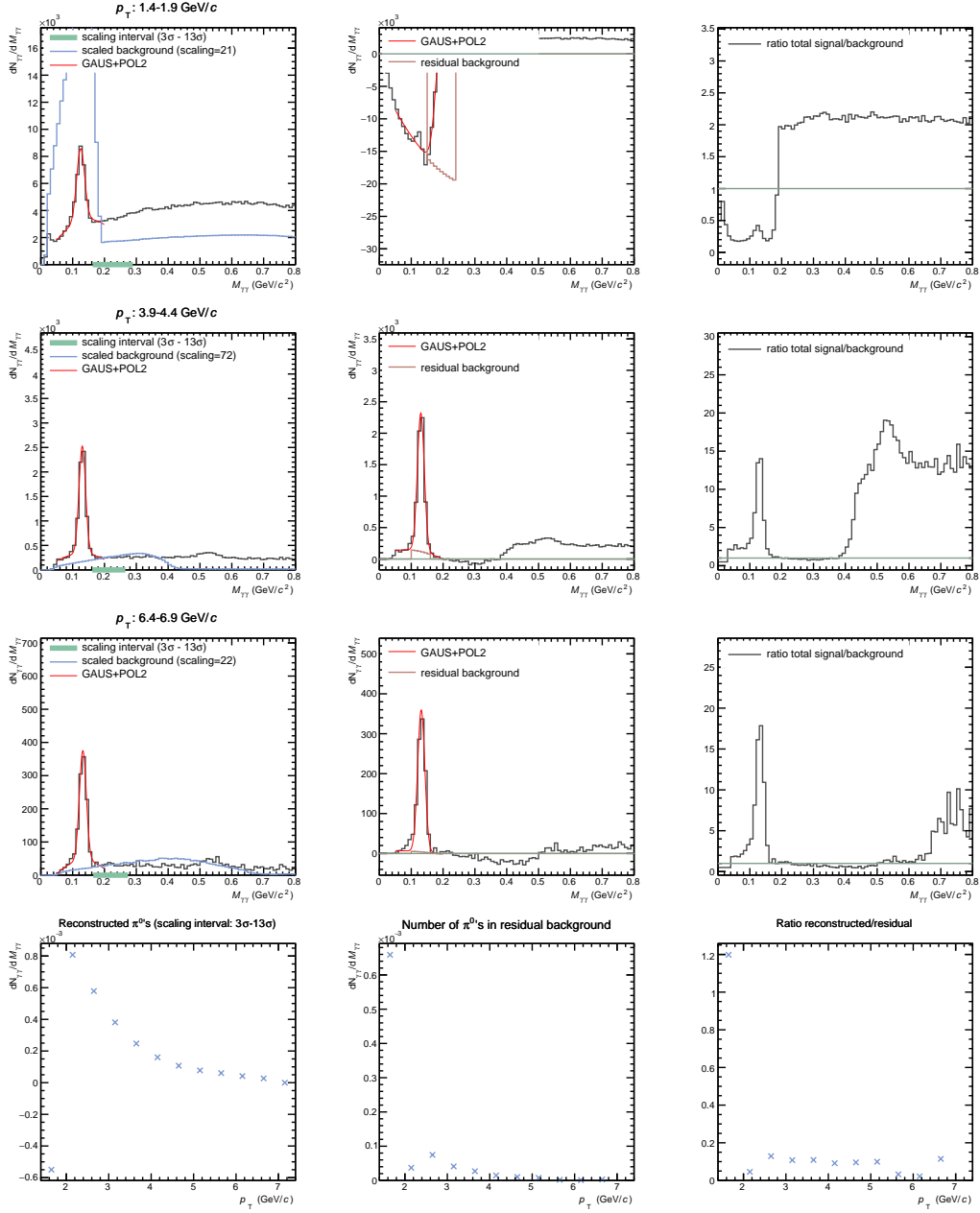
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C CHAR

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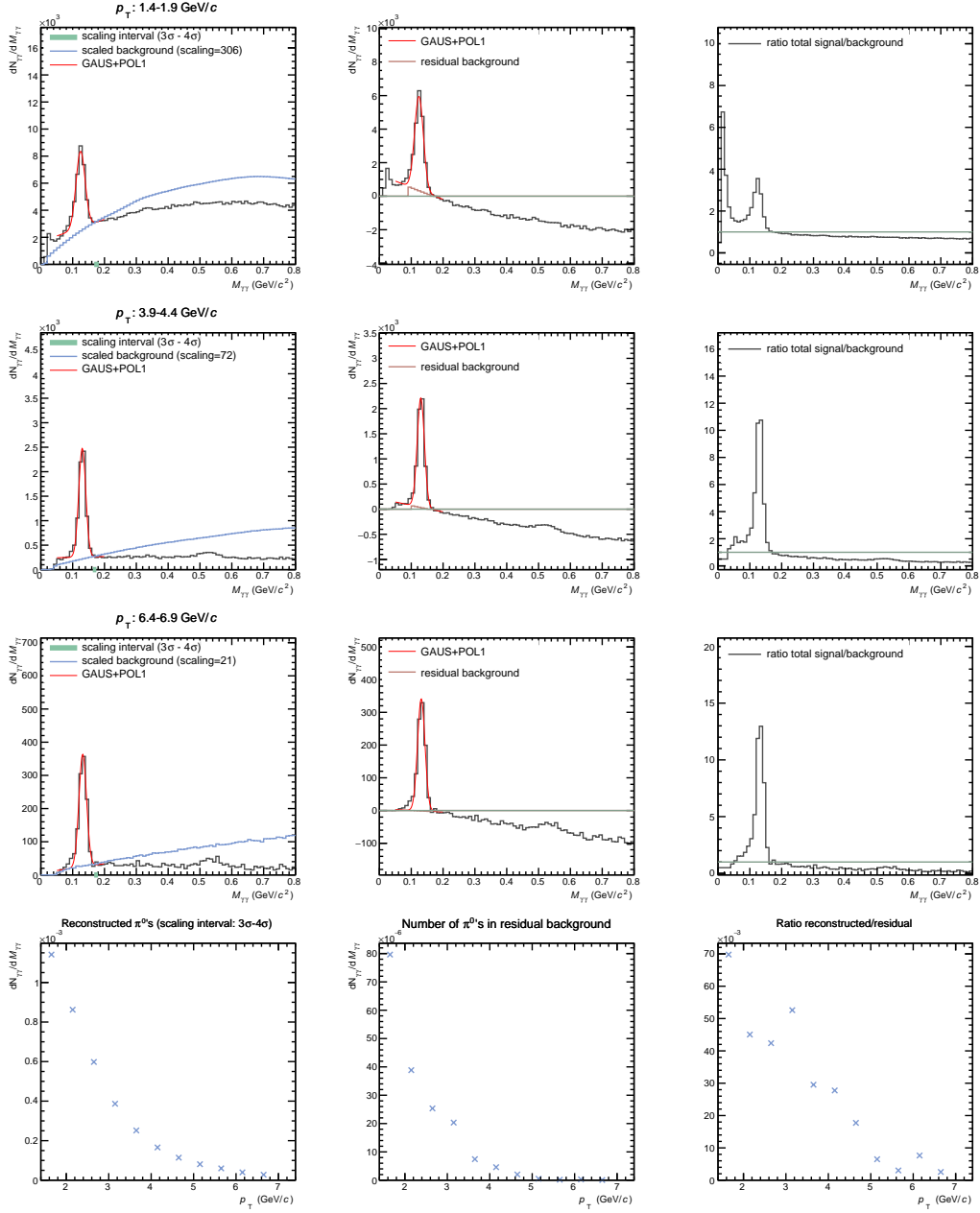
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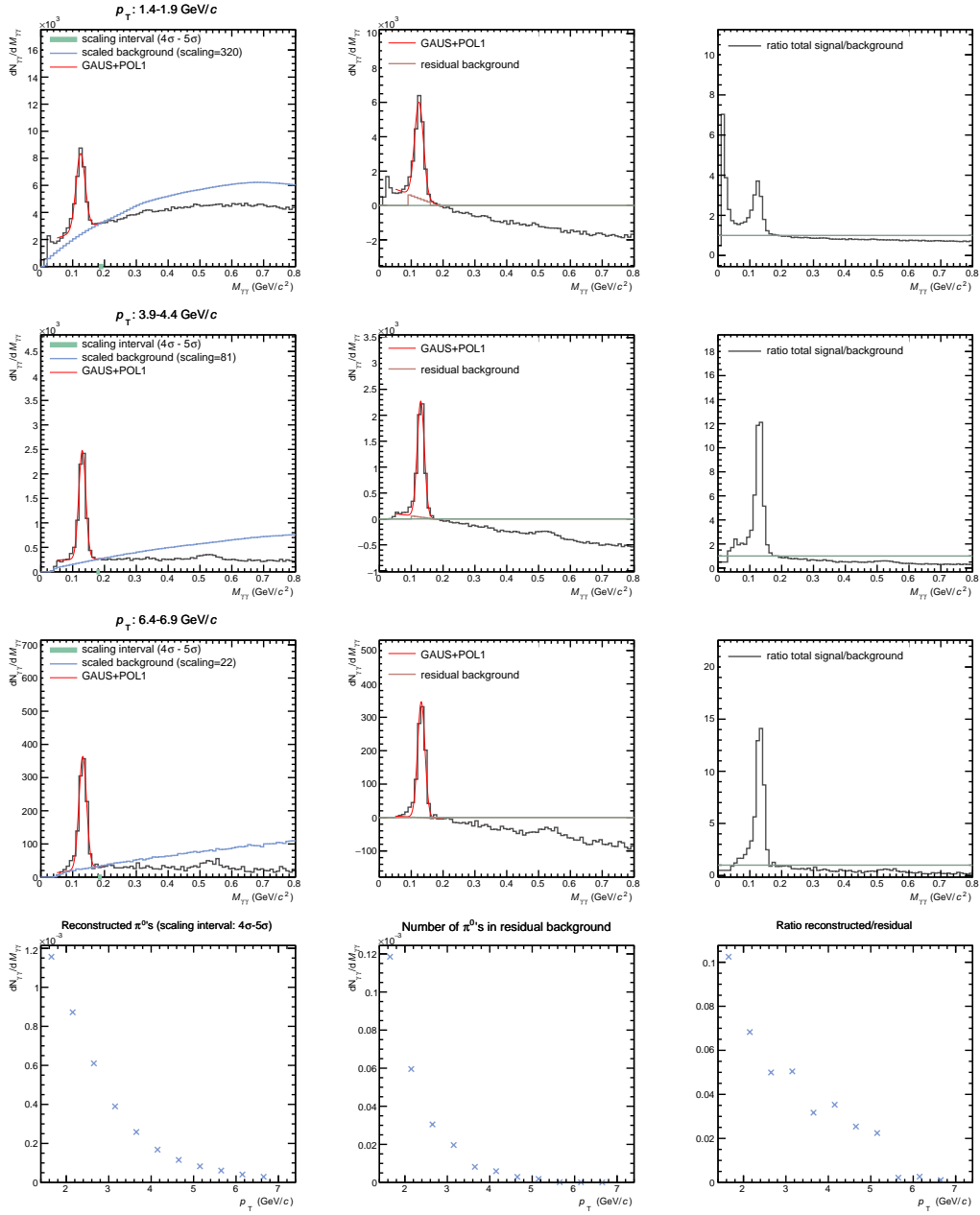
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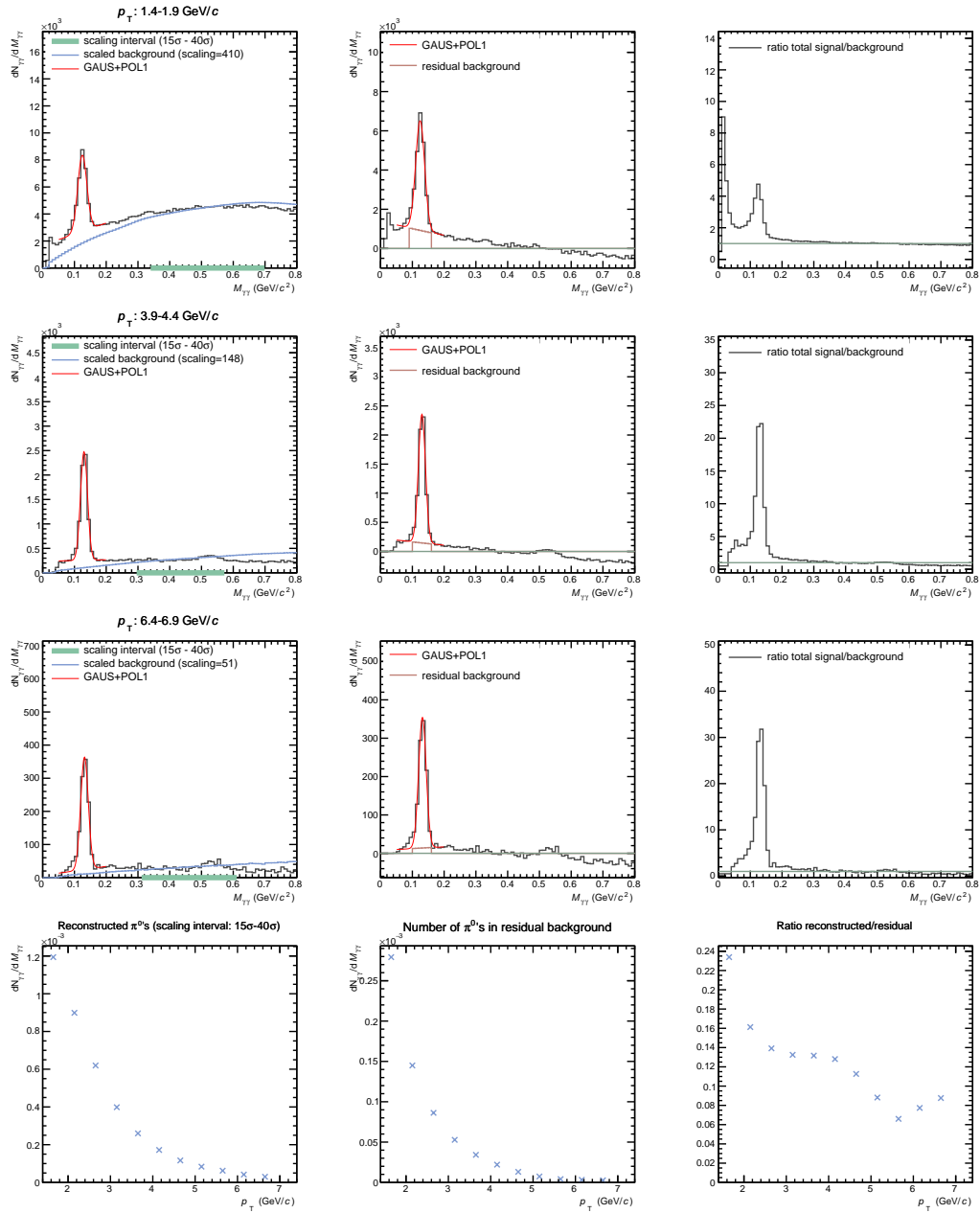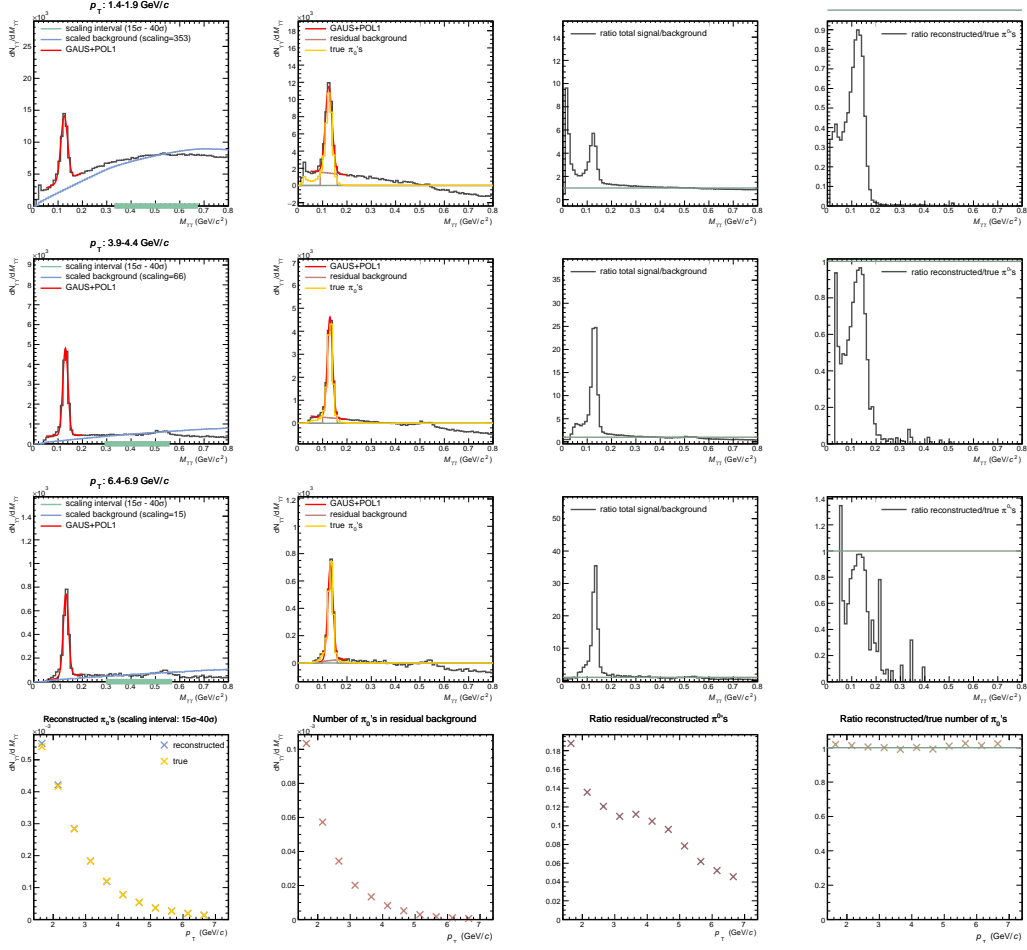
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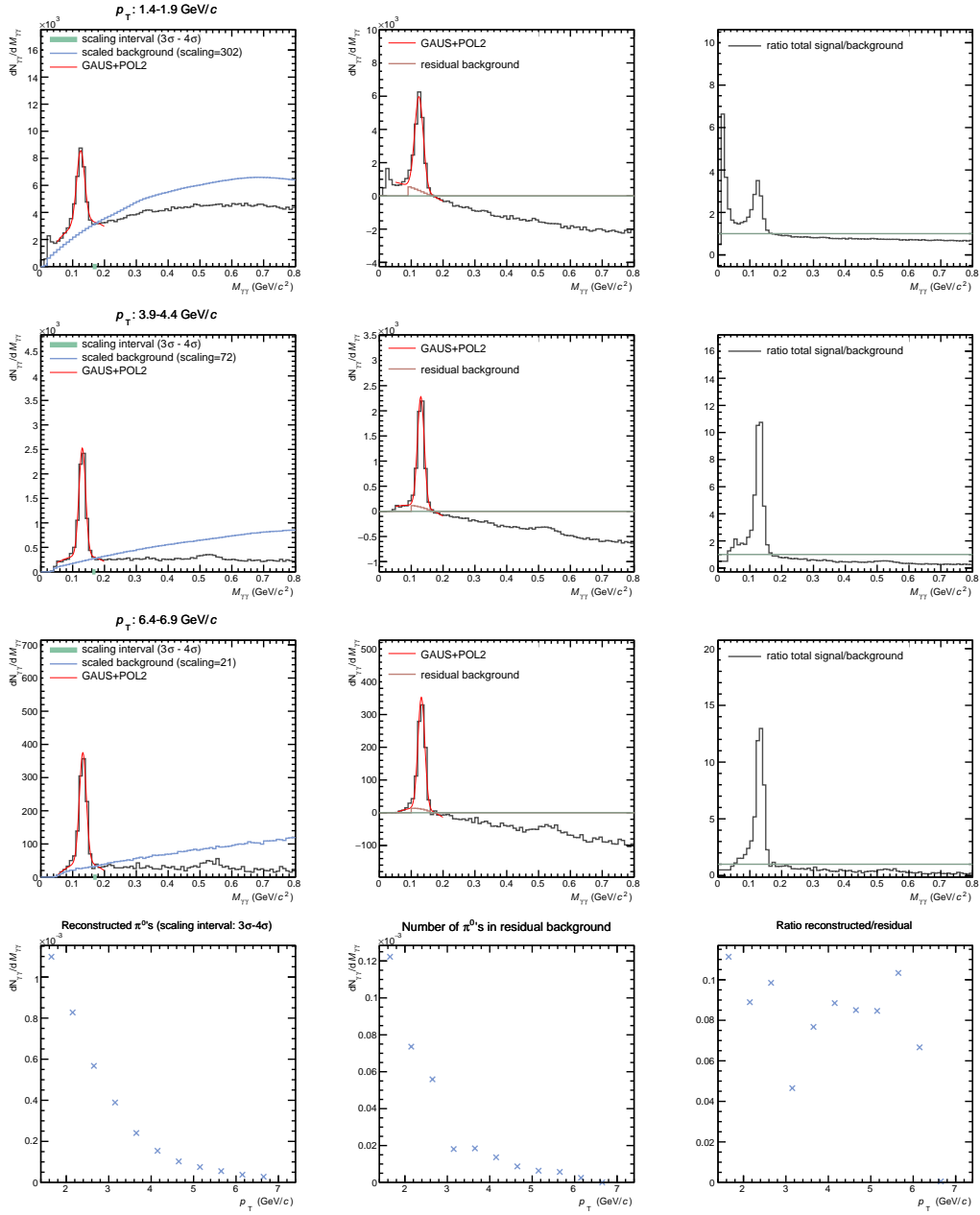
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CHAR — POL2 — Scaling: 3-13

CHAR — POL2 — Scaling: 15-40

D MC

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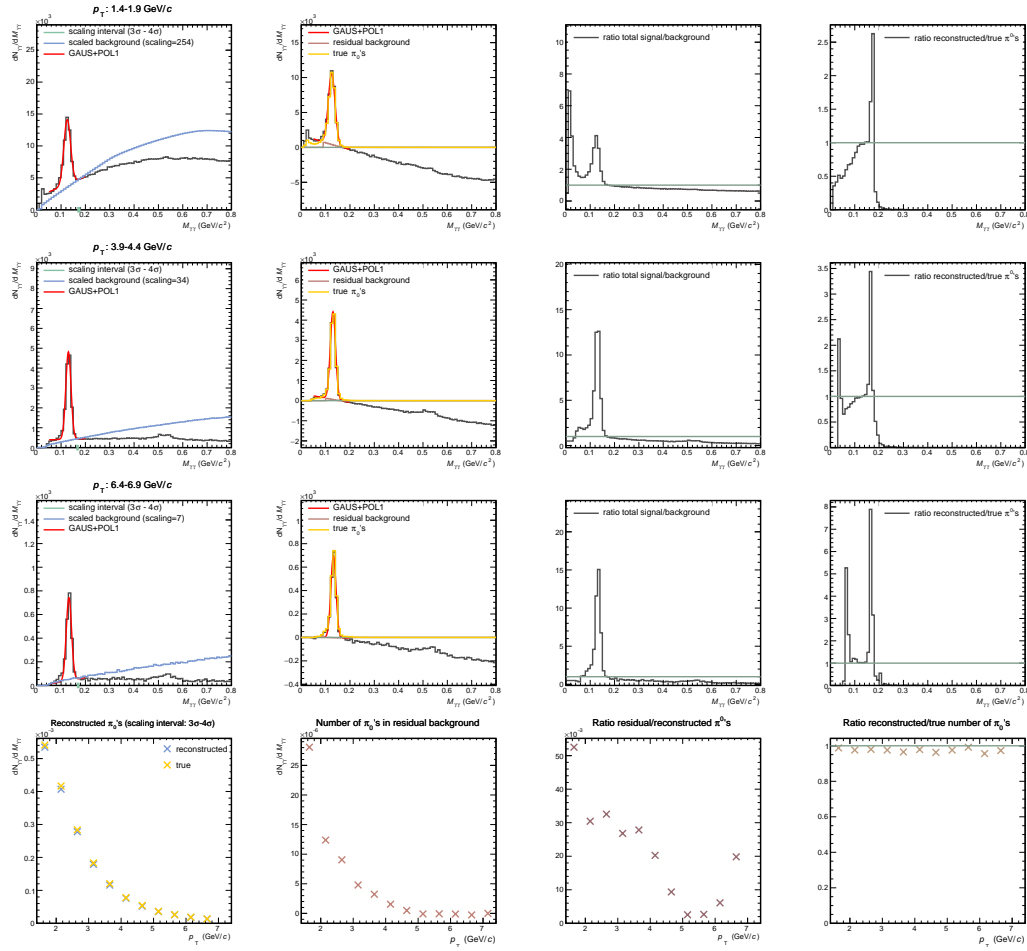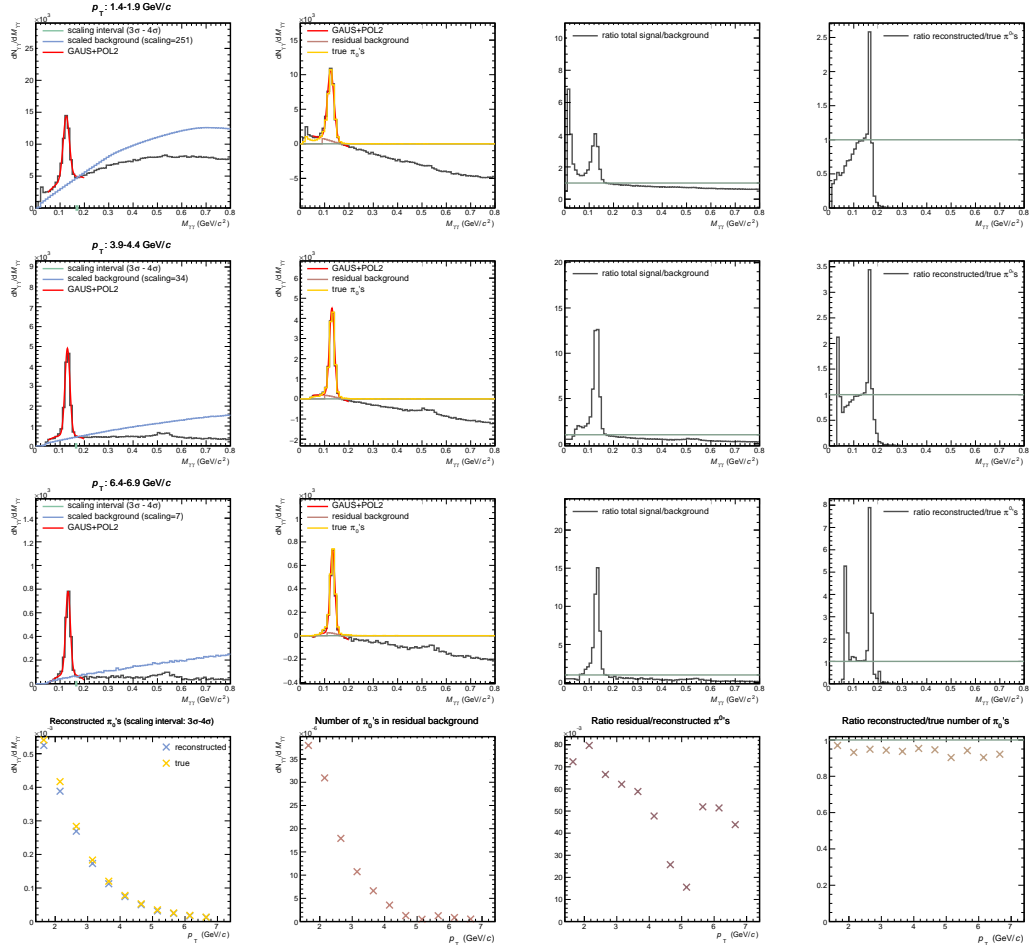
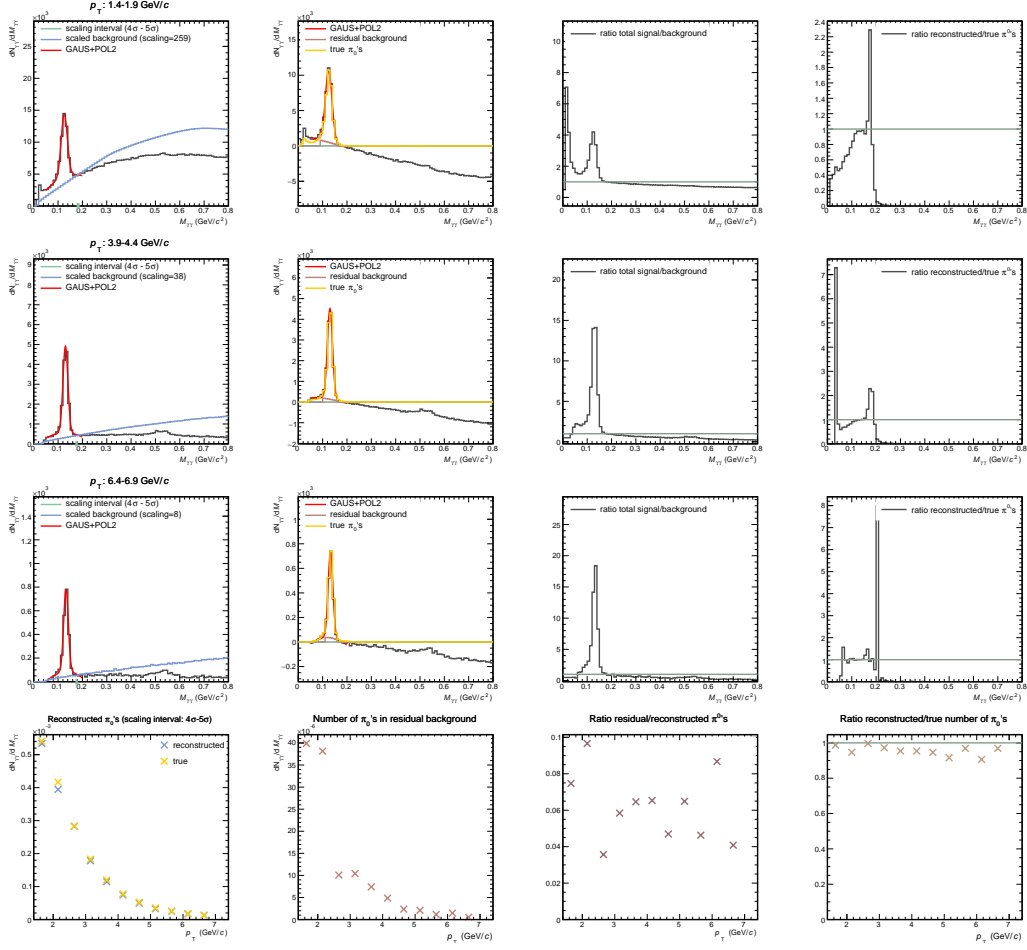# MC — POL1 — Scaling: 4-5
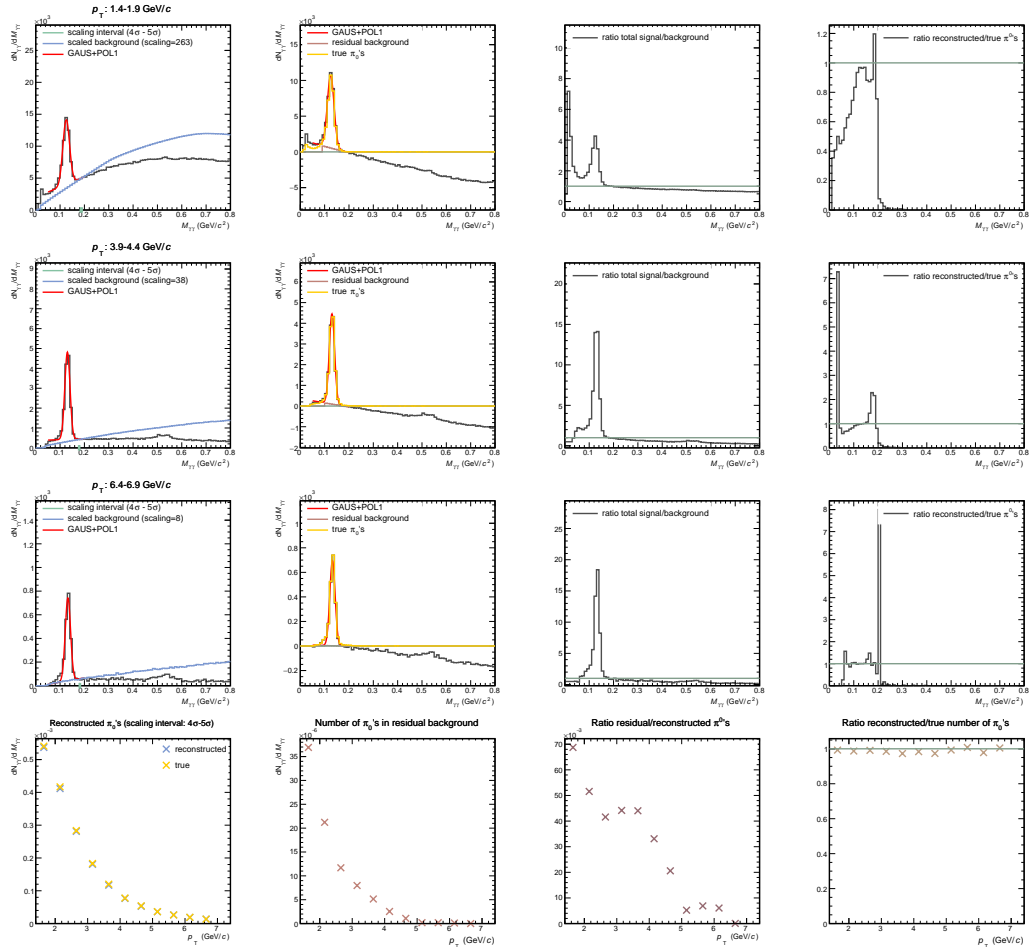
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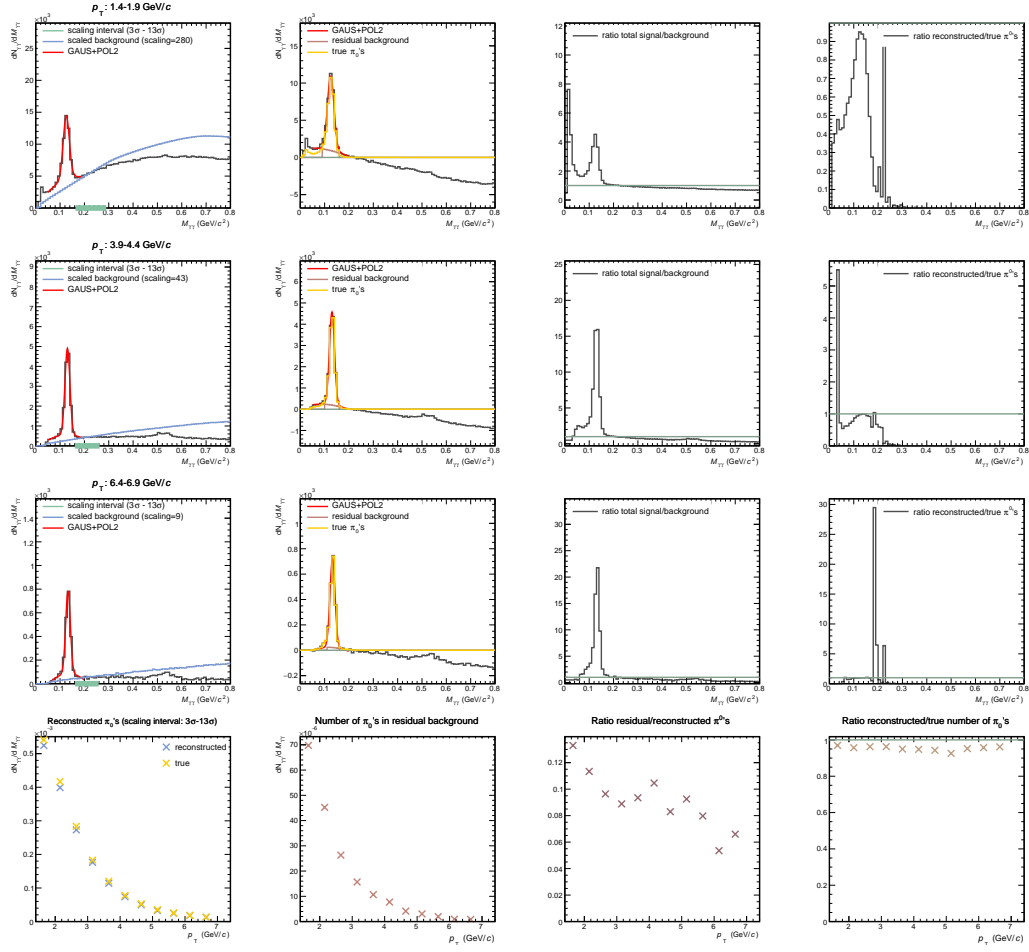
MC — POL1 — Scaling: 15-40

MC — POL2 — Scaling: 3-4

MC — POL2 — Scaling: 4-5

MC — POL2 — Scaling: 3-13

MC — POL2 — Scaling: 15-40