Studies of Gamma Efficiencies in Charmonium Decay

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Investigations were carried out regarding the angular dependence of the decay $\chi_c \to J/\psi\gamma$ in the laboratory frame. This determined that the J/ψ and γ are emitted in a cone of small angle, θ. Furthermore, studies were carried out to determine the efficiency of the photon trigger, ε_γ, which was found to be $\varepsilon_\gamma = 37.5\% \pm 3.1\%$.

1 Introduction

1.1 The HERA-B Experiment

HERA-B is a large-aperture, high-rate spectrometer, which is used in studies involving 920GeV protons colliding with a fixed target. The target consists of fixed wires, which are then placed inside the halo of the HERA proton beam. HERA-B's detector was originally designed to study CP-violation, specifically the decay mode

$$B \to J/\psi + K^0. \tag{1}$$

To perform such a task, the detector was designed to be able to identify each of these events from a background of approximately 10^{11} hadronic interactions, occurring at a rate of 40 million interactions per second. Therefore, the design of HERA-B's detector required a large amount of research into radiation-hard technologies. Additional requirements were a sophisticated First Level Trigger (FLT) and the construction of a large data acquisition and high-level trigger system. Figure 1 shows the various components of the HERA-B detector.

The detector consists of three main parts – a silicon vertex detector, micro-strip gas chambers (which comprise the inner tracking region) and honeycomb drift chambers (outer tracking region). A 2.2Tm magnet is positioned in the middle of the spectrometer. Particle identification is aided by a **R**ing **I**maging **CH**erenkov counter (RICH), along with an electromagnetic calorimeter (ECAL) and a muon detector. The inner tracking system provides detector coverage from the beam pipe up to 25cm, providing tracking at small radii along with input for the First Level Trigger. The outer tracker provides coverage from 25cm up to the edges of the spectrometer, and is itself divided into 13 superlayers. The outer tracker consists of honeycomb drift chambers, which comprise the various calorimeters the experiment has.

1.2 Triggering

HERA-B uses various triggers to select events of interest, for example, its J/ψ trigger selects lepton pairs (i.e. $e^\pm e^\mp$ or $\mu^\pm\mu^\mp$) that have a high invariant mass. Triggers are also used to select electrons and muons. The muon trigger only selects muons, for example, which have hits in at least three superlayers of the outer tracker, and have a transverse momentum, $p_\perp > 0.7$GeV/c. For an electron to be accepted by the trigger, it must deposit more than 1GeV/c^2 in the ECAL.

One of the final aims of this project was to calculate the efficiency of the photon trigger, ε_γ. HERA-B has a significantly higher ε_γ than many other experiments, and for comparison, the previously mentioned J/ψ trigger has an efficiency of $\varepsilon_{J/\psi} = 1.4 - 2\%$.

2 Introductory Analysis

This section aims to introduce some of the basic properties of the generated Monte Carlo data, along with the basic equations and formulae used throughout this project.

2.1 Cuts & Equations

For the duration of this project (apart from figure 9) the following 'cuts' were used on the data

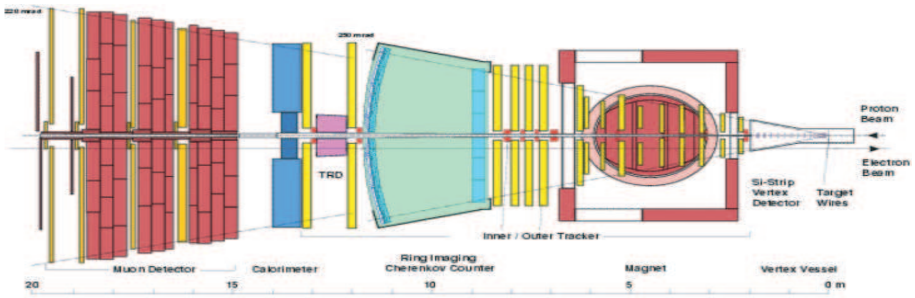


Fig. 1: *The HERA-B detector.*

to make the signal more prominent, and to allow the analysis to be as successful as possible. The cuts used were:

- $E_\gamma > 3\text{GeV}$ – this condition insists that only high energy photons are considered.
- $E_{\gamma\perp} > 0.1\text{GeV}$ – this insists that the photon must have more than 0.1GeV of transverse energy.
- Distance from the beam pipe, $x > 22\text{cm}$.
- Asymmetry > 0.8.
- Reconstructed photons are allowed (i.e. photons that undergo pair production are also counted).
- The J/ψ mass must be in the range $3.01\text{GeV} < M(J/\psi) < 3.17\text{GeV}$, otherwise the event is not accepted.
- Once all of these conditions are passed, the energy/momentum/mass of particles can be calculated.

For all sets of data, variables such as the particles momentum in the x, y and z planes are known, and using this information (along with the particles mass) it is possible to calculate the energy of the particle. Thus the following equations were used throughout this project to determine the energy and momentum of the J/ψ, γ and $\chi_{c1,2}$ along with calculating the $\chi_{c1,2}$ mass:

$$\begin{aligned} p_{J/\psi} &= \sqrt{p^2_{x_{J/\psi}} + p^2_{y_{J/\psi}} + p_z^{2_{J/\psi}}} \\ E_{J/\psi} &= \sqrt{M^2_{J/\psi} + P_{J/\psi}} \\ p_\gamma &= \sqrt{p^2_{x_\gamma} + p^2_{y_\gamma} + p_z^{2_\gamma}} \\ E_\gamma &\equiv p_\gamma \end{aligned} \tag{2}$$

From the above equations, the following can then be calculated for the χ_c:

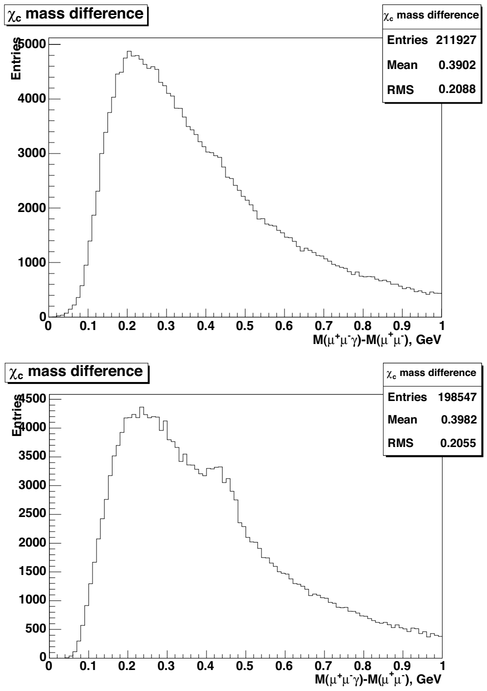
$$\begin{aligned} M_{\chi_c} &= \sqrt{(E_\gamma + E_{J/\psi})^2 - (p_\gamma + p_{J/\psi})^2} \\ E_{\chi_c} &= \sqrt{(E_\gamma + E_{J/\psi})^2} \\ p_{\chi_c} &= \sqrt{(p_\gamma + p_{J/\psi})^2} \end{aligned} \tag{3}$$

2.2 Real versus Monte Carlo Data

This project mainly dealt with the manipulation of a randomly generated Monte Carlo data sample in order to approximate real data as closely as possible. Thus, one of the first tasks was to investigate the variations that occur between the Monte Carlo data and the real data, which it attempts to approximate. The main difference between the two types of data is that the signal is much more prominent in the Monte Carlo data than in the real data (see figure 2).

One of the main problems regarding a real data sample is distinguishing between the different types of charmonium, χ_{c0}, χ_{c1} and χ_{c2}. χ_{c0} has the lowest mass (0.3GeV), however, χ_{c1} and χ_{c2} have much closer masses ($M(\chi_{c2}) - M(\chi_{c1}) \approx 45\text{MeV}$). In this case, the signals from both χ_c's are smeared together – thus, by using a Monte Carlo sample, it should be possible to find the limit of the detectors resolution, i.e. the point where it would be capable of resolving the $\chi_{c1,2}$ peak into two separate peaks.

Since it is possible (with generated data) to select **only** χ_{c1} particles, or **only** χ_{c2}'s, their properties can be plotted and any differences used to distinguish between the two particle types in real data. However, it was found that when plotting the ratio of χ_{c1} momentum/energy to χ_{c2} momentum/energy, the ratio was ≈ 1. Therefore, no major differences were found between the χ_{c1} and χ_{c2}, which could be



a)

b)

Fig. 2: *a) The mass difference spectrum ($M(\chi_c) - M(J/\psi)$) for real detector data. Note the small "bump" which represents the signal amidst the background spectrum; b) the same for the Monte Carlo data – however, the signal "bump" is much larger.*

successfully used to separate the peaks in a real data sample.

3 Lorentz Boosts

Another point of investigation was to examine the angles with which the decay products of charmonium (the J/ψ and γ) are emitted. Since the χ_c is traveling close to the speed of light (i.e. $\beta = \frac{p_{\chi_c}}{E_{\chi_c}} \approx 1$), relativistic effects come into play when you observe the decay products in the lab system.

In the Monte Carlo data, the angles, momenta and energy are all calculated as in the rest frame of the χ_c. This is known as the 'centre of mass' frame. However, a detector observes the particles in the 'lab' frame, and as such the momenta/energy/etc are altered from their 'centre of mass' values. It is possible to calculate the lab frame values from the centre of mass frame values (and vice versa) by using the Lorentz Transformations, which connect one frame of reference to another. Denoting the **centre of mass frame by a prime (′)**, the Lorentz Transformations are (for angles/momenta between the γ and χ_c):

$$
\begin{aligned}
p_{\|_\gamma} &= \frac{p_{x_\gamma} p_{x_\chi} + p_{y_\gamma} p_{y_\chi} + p_{z_\gamma} p_{z_\chi}}{p_\chi} \\
p'_{\|_\gamma} &= \gamma(p_{\|_\gamma} - (\beta E_\gamma)) \\
p_{\perp_\gamma} &= \sqrt{p_\gamma^2 - p_{\|_\gamma}^2} \\
p'_{\perp_\gamma} &= p_{\perp_\gamma} \\
p'_\gamma &= \sqrt{p_{\perp_\gamma}^2 + p'^2_{\|_\gamma}} \\
\cos(\theta_\gamma) &= \frac{p_{\|_\gamma}}{p_\gamma} \\
\cos(\theta') &= \frac{p'_{\|_\gamma}}{p'_\gamma}
\end{aligned}
\tag{4}
$$

where the relativistic factors γ and β are given by:

$$
\begin{aligned}
\gamma &= \frac{E_{\chi_c}}{M_{\chi_c}} \\
\beta &= \frac{p_{\chi_c}}{E_{\chi_c}}
\end{aligned}
\tag{5}
$$

The physical effect of the boost is shown in figure 4. Thus, when the particle is boosted from the rest frame of the decay into the lab frame (where it is observed), the angle between it and its mother particle decreases, and the decay products are therefore emitted in a narrow cone.

3.1 Applying the Lorentz Boost

Figure 5 shows the effect of the Lorentz boost when moving from the centre of mass frame into the lab frame. For example, figure 5b) shows the relationship between $\cos(\theta')$ in the centre of mass frame, to $\cos(\theta)$ in the lab frame, calculating the value of γ from the momentum and energy of the decaying χ_c. It can be seen that although the photon is emitted from the χ_c at a large range of angles (though never at 180°, when the particle is boosted into the lab frame, the angles are confined to a relatively small region. The same is true of the angle between the J/ψ and the χ_c.

The remaining plots (figures 5c, d, e) are the result of fixing the value of γ to different values (and therefore calculating β from γ). In this case, $\gamma = 1$ means that there is no boost (and thus $\cos(\theta') \equiv \cos(\theta)$) and $\gamma = 20$ is the maximum value possible for this case. Thus, as γ increases, the plots increasingly approximate the non-fixed plot.

It was also necessary to calculate the maximum possible value which θ could take on in the lab frame. This was done by minimising the equation,

$$\tan(\theta_L) = \frac{p' \sin(\theta_C)}{\gamma(p' \cos(\theta_C) + \beta E')}, \quad (6)$$

which allows you to calculate θ in the lab frame, given θ in the centre of mass frame (i.e. θ'). Thus, the maximum value of θ in the lab frame is given by,

$$\begin{aligned} \frac{\partial \tan(\theta_L)}{\partial \theta_L} &= \frac{\partial}{\partial \theta_L} \frac{p' \sin(\theta_C)}{\gamma(p' \cos(\theta_C) + \beta E')} = 0 \\ \Rightarrow p'^2 \gamma &= -p' E' \beta \gamma \cos(\theta_C) \\ \Rightarrow \cos(\theta_C) &= -\frac{\beta'}{\beta}. \quad (7) \end{aligned}$$

Figure 6 shows the result of plotting this maximum θ for the J/ψ particle. This confirms the result from figure 5a), showing that the J/ψ is emitted in a relatively small angle with respect to the χ_c when it decays.

4 Calculating the Gamma Efficiency

The final goal of this project was to calculate the gamma efficiency, ε_γ, as given by the Monte Carlo data. This is given by the following relation

$$\varepsilon_\gamma = \frac{N^{\text{recon}}_{\chi_c}}{N^{\chi_c}_{J/\psi}}, \quad (8)$$

where $N^{\text{recon}}_{\chi_c}$ is the total number of reconstructed χ_c's in an event, and $N^{\chi_c}_{J\psi}$ is the total number of J/ψ's that come from a χ_c. The procedure by which these values are found is called 'event mixing'.

4.1 Event Mixing

During the event mixing process, a J/ψ from one event is 'mixed' with photons from several events on either side with the same multiplicity. The resulting mixed data sample then contains these 'mixed' particles that come from a χ_c decay, but not necessarily from that event. Thus, the mixed data approximates the original data, with the exception that it has lost some of the kinematical details (since momentum may not be conserved if the particles are technically from different events).

Once the mixed sample was created, a pure signal sample (i.e. all photons and χ_c's come from the same event) was also generated from the Monte Carlo data. The types of events that each sample contains are

$$\begin{aligned} \text{SE} &= \Phi_{J/\psi} F_\gamma, F_{J/\psi} F_\gamma, \Phi_{J/\psi\gamma} \\ \text{ME} &= F_{J/\psi} F_\gamma, F_{J/\psi} \Phi_\gamma, \Phi_{J/\psi} F_\gamma, \Phi_{J/\psi} \Phi_\gamma, \end{aligned}$$

where SE is the signal sample, ME is the mixed sample, $\Phi_{J/\psi}$ means that there is a **true** J/ψ particle in the event, and $F_{J/\psi}$ means that there is a **false** J/ψ in the event (i.e. it does not come from a χ_c). This shows the main difference between the signal and mixed samples. For example, in the signal sample, it is possible to have a J/ψ and a γ which come from the same χ_c – however, this configuration does not appear in the mixed sample (i.e. there is no $\Phi_{J/\psi\gamma}$). This is exploited by using the mixing technique to find ε_γ, since the total number of **true** χ_c's is the $\Phi_{J/\psi\gamma}$ part of the signal sample.

Thus, by subtracting the histograms,

$$\begin{aligned} N^{\text{recon}}_{\chi_c} &= \text{Histo(SE)} - \text{Histo(ME)} \\ &\quad - \text{Cor}(F_{J/\psi}\Phi_\gamma, \Phi_{J/\psi}\Phi_\gamma), \quad (9) \end{aligned}$$

and fitting the resulting histogram, it is possible to obtain the total number of reconstructed χ_c's. The final fit is shown in Figure 7, which shows a fit of the background spectrum (blue) and the χ_c signal (red). The total number of χ_c's from this fit is 1647 ± 133.4.

After fitting the mixed events to find the number of χ_c's, the number was double-checked by fitting the χ_c mass difference spectrum straight from the Monte Carlo data. By this method, 1639 ± 43.4 χ_c's were found, which is in agreement with the mixed event result. This fit can be seen in figure 8.

Finally, in order to calculate ε_γ, the total number of J/ψ particles which come from a χ_c had to be found. This was done by exploiting the nature of a Monte Carlo event, and selecting only J/ψ particles which originated from either a χ_{c0}, χ_{c1}, or a χ_{c2}, and then fitting their mass spectrum. This fit can be seen in figure 9, which gives us $N^{\chi_c}_{J/\psi} = 4516 \pm 68.1$. However, the total number of J/ψ within the allowed mass region of 3.01GeV $< M(J/\psi) <$ 3.17GeV is only $N^{\chi_c}_{J/\psi} = 4394.05 \pm 68.1$.

Thus, the gamma efficiency could now be calculated,

$$\begin{aligned} \varepsilon_\gamma &= \frac{N^{\text{recon}}_{\chi_c}}{N^{\chi_c}_{J/\psi}} \\ &= \frac{1647}{4394.05} \\ &= 0.3748 \\ \Rightarrow \varepsilon_\gamma &= 37.5\% \end{aligned} \tag{10}$$

The absolute error in a function, $f(x_i)$, can be calculated as follows:

$$\Delta f(x_i) = \sqrt{\sum_{i=1}^{n} (\frac{\partial f(x_i)}{\partial x_i})^2 \sigma^2_{x_i}}. \tag{11}$$

Therefore, putting $N^{\text{recon}}_{\chi_c} = a$ and $N^{\chi_c}_{J/\psi} = b$ (for simplification),

$$\begin{aligned} \varepsilon_\gamma &= \frac{a}{b} \\ \Rightarrow \Delta\varepsilon_\gamma &= \sqrt{(\frac{1}{b})^2 \Delta a^2 + (-\frac{a}{b^2})^2 \Delta b^2}, \end{aligned} \tag{12}$$

and using $a = 1647$, $\Delta a = 133.4$, $b = 4394.05$ and $\Delta b = 68.1$, we find the absolute error to be

$$\begin{aligned} \Delta\varepsilon_\gamma &= \sqrt{133.4^2(\frac{1}{4394.05})^2 + 68.1^2(-\frac{1647}{4394.05^2})^2} \\ &= 0.031 \\ &= 3.1\% \end{aligned} \tag{13}$$

Therefore, the final value for ε_γ is

$$\varepsilon_\gamma = \mathbf{37.5}\% \pm \mathbf{3.1}\%$$

5 Conclusions

Regarding the separation of the χ_{c1} and χ_{c2} peaks (section 2.2), it appears unlikely that the separation can be made simply by comparison of energy and momentum, since the ratio $\frac{p_{\chi_{c2}}}{p_{\chi_{c1}}} \approx 1$. Investigations into the possibility of discrimination via ECAL region may be of some small use, but further investigation would be required.

By performing a Lorentz Boost (section 3.1), it can be seen that the J/ψ and γ are emitted with a wide range of angles in the centre of mass frame. However, upon being boosted into the laboratory frame, they are confined to a small cone of angle θ. By comparing the Monte Carlo signal and background data in the same way, there is very little difference in the way the particles are boosted.

Finally, the gamma efficiency, ε_γ, was calculated (section 4). Although a smaller error could have been achieved by directly examining the Monte Carlo data, the mixing method was used since it provides a closer approximation to the real data analysis. This resulted in a value of $\varepsilon_\gamma = 37.5\% \pm 3.1\%$.

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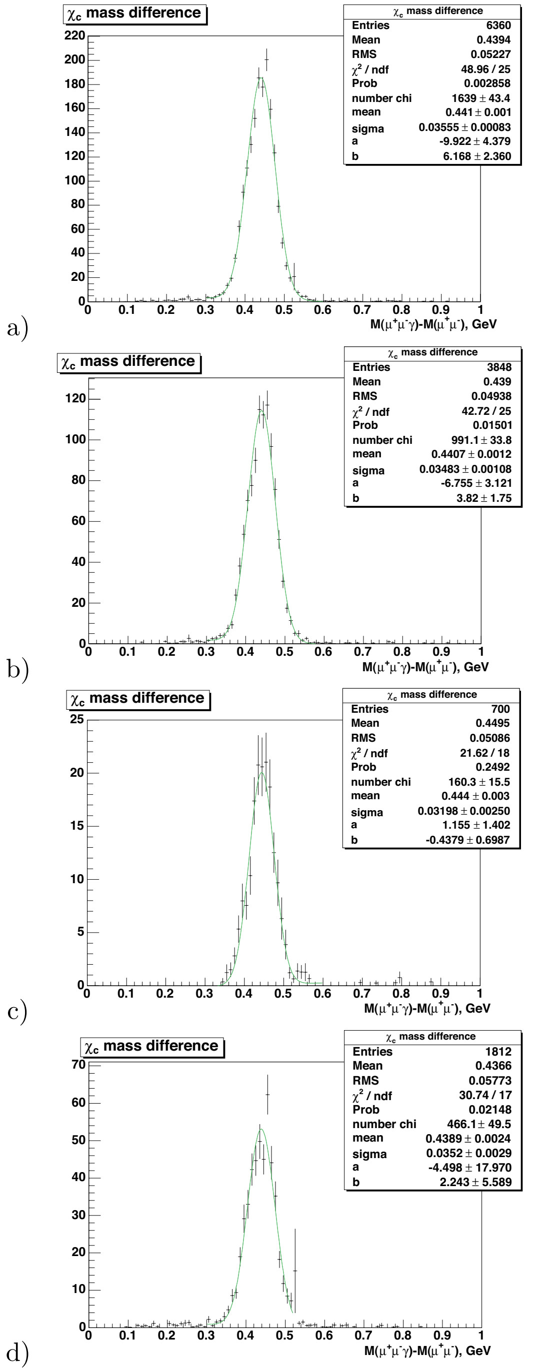

Fig. 3: *Fitted mass difference spectra for χ_{c1} (from Monte Carlo) in a) the entire ECAL, b) the outermost part of the ECAL, c) the middle of the ECAL and d) the innermost part of the ECAL.*

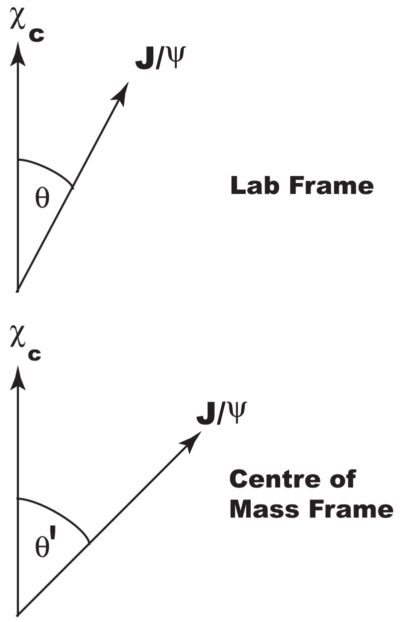

Fig. 4: *The effect of a Lorentz Boost on the angle between the χ_c and the J/ψ emitted during its decay.*

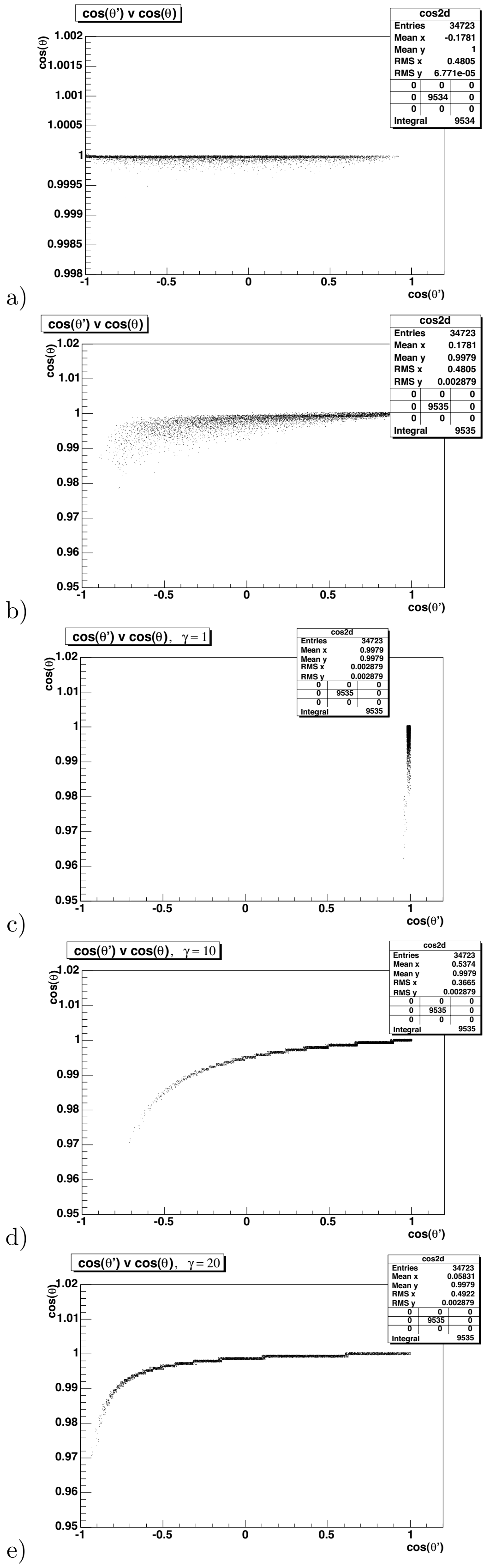

Fig. 5: *Monte Carlo data: a)* $cos\theta^{'}$ *versus* $cos\theta$*, where* $\theta^{'}$ *is the angle between the (boosted)* J/ψ *and the* χ_c*, b) the same for the* γ *and the* χ_c*, c), d), and e) show the result of fixing* $\gamma = 1, 10,$ *and* 20 *respectively for the angle between the* γ *and* χ_c*.*

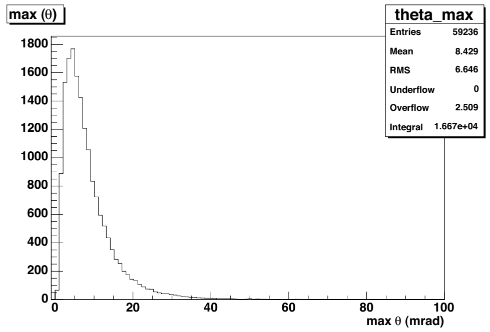

Fig. 6: *This shows the maximum angle,* θ*, with which the* J/ψ *can be emitted from the decay of a* χ_c *(note that the result is the same for both real and Monte Carlo data).*

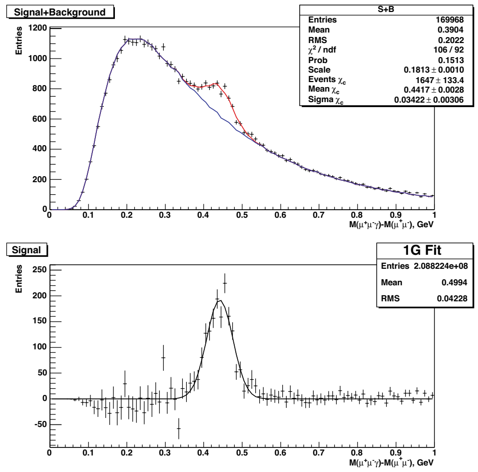

Fig. 7: *The final fitted plot after event mixing. The blue line is the fitted background spectrum, and the red line is the fitted signal.*

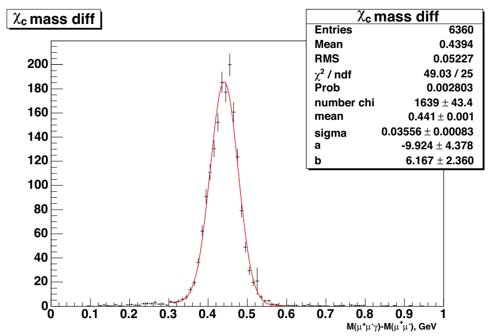

Fig. 8: *This plot shows the fitted* χ_c *mass difference from the non-mixed Monte Carlo data. It is useful to note that the mixed and non-mixed approaches agree within their errors.*

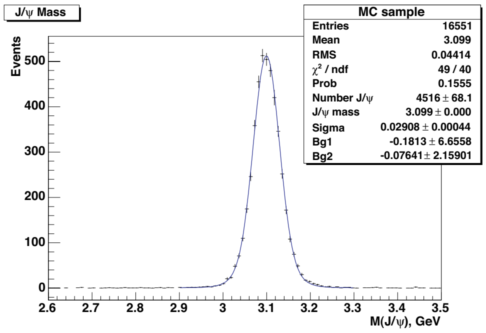

Fig. 9: *This fit gives the total number of J/ψ particles which come from **any** χ_c (i.e. from $\chi_{c0}, \chi_{c1}, \chi_{c2}$). The result is then used to calculate the gamma efficiency, ε_γ.*