Search for $D_s^{*+} \to D_s^+ e^+ e^-$

Anders Ryd (*ryd@lepp.cornell.edu*)
Souvik Das (*sd259@cornell.edu*)
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Abstract

This short note outline initial steps in a search for the decay $D_s^{*+} \to D_s^+ e^+ e^-$

1 Introduction

The idea is to look for the process $D_s^{*+} \to D_s^+ e^+ e^-$. The largest D_s^{*+} decay is $D_s^{*+} \to D_s^+ \gamma$. This decay channel has a branching fraction of about 94other known decay is $D_s^{*+} \to D_s \pi^0$. It is assumed that these final states accounts for all decays. (Souvik, explain why the strong $D_s^{*+} \to D_s \pi^0$ is smaller than the electromagnetic decay $D_s^{*+} \to D_s^+ \gamma$. And: Isospin suppression. The pion has isospin of 1 while everything other particle has isospin of 0.)

2 Analysis strategy

There are potentially more than one way to look for this signal. I'll outline one approach below that I think would be the most promising.

We will use e^+e^- data collected at $E_{\rm cm} = 4170$ MeV. At this energy we have a cross-section of about 1 nb to produce $D_s^{*+} D_s^-$ + charge conj. CLEO-c has recorded 602 pb^{-1} of data at this energy. (How many D_s^*'s do we have in the data sample.)

Pick a decay of the D_s that is easy to reconstruct; I suggest to use $D_s^+ \to \phi \pi^+$ where the $\phi \to K^+ K^-$. I.e. we have a final state with K^+, K^-, and π^+. (In what I write here and below the charge conjugate is implied.)

Require that the $K^+ K^- \pi^+$ invariant mass is consistent with the D_s mass. Next, look for two charged particles, the e^+ and e^- candidates, with opposite charge. Combine the $K^+ K^- \pi^+$ four-momentum with the $e^+ e^-$ system four-momentum to get the D_s^* four-momentum.

Here, I think that the best way to look for the signal would be to calculate three kinematic quantities:

- $\Delta E = E(K^+ K^- \pi^+ e^+ e^-) - E(D_s^*)$
- $m_{BC} = \sqrt{E(D_s^*)^2 - P(K^+ K^- \pi^+ e^+ e^-)^2}$
- $\delta m = M(K^+ K^- \pi^+ e^+ e^-) - M(K^+ K^- \pi^+)$

Where $E(D_s^*)$ is the energy of the D_s^* that can be calculated from the known beam energy and the mass of the D_s and D_s^* mesons. I think you would apply a cut on one (or two) of these variables and plot the other(s) to look for a signal.

This analysis has a lot of kinematic constraints, so I would think that backgrounds are not the main problem. Rather the challenge is the soft electrons in this mode. (Is there a background from $D_s^{*+} \to D_s^+ \pi^0$ with $\pi^0 \to e^+e^-$.)

I would start by simulating events like

$$\begin{aligned} e^+e^- &\to D_s^{*+} D_s^- \\ D_s^{*+} &\to D_s^+ e^+ e^- \\ D_s^+ &\to \phi \pi^+ \\ \phi &\to K^+ K^- \end{aligned}$$

and write an analyzer that would reconstruct this decay chain. For the decay $D_s^{*+} \to D_s^+ e^+ e^-$ I would first just use a simple phase space model; but I'm sure that later we would need to investigate a more realistic model for this decay.

After establishing that this analyzer works on the signal Monte Carlo I would run over the data sample and blind the signal region in the variables ΔE, m_{BC}, and δm to see what the backgrounds are in the sideband regions. (I hope they would be small!) At this point we can estimate what our sensitivity is.

At this point we can 'unblind' and see if we have a signal. I think that this would be useful to do in this case to establish that we are seeing a signal.

3 Alternative analysis strategy

In the previous section an analysis was described where we reconstruct the D_s the comes from the decay of the D_s^*. In principle we can double the statistics if we can also look at the other D_s in the event. (There will be a small overlap that we will ignore for now.)

I will denote the decay chain $D_s^+ D_s^{*-}$, with $D_s^{*-} \to D_s^- e^+ e^-$. (Of course the charge conjugate mode is also analyzed.) In this analysis the D_s^+ is fully reconstructed. Similar, to what was done above we can form

$$\begin{aligned} \Delta E &= E_{\rm cand} - E(D_s), \\ m_{\rm BC} &= \sqrt{E^2(D_s) - P^2_{\rm cand}}, \end{aligned}$$

where $E(D_s)$ is the energy the D_s candidate is predicted to have given the known beam energy. Next the e^+e^- pair is added. If we denote by p_{ee} the four-momentum of the e^+e^- system we can form the missing mass

$$MM^2 = (p_{\rm cm} - p_{\rm cand} - p_{ee}.$$

This should peak that the D_s mass for correctly reconstructed signal events. There might be other kinematic quantities we can calculate, but these are the once that are obvious to me.

4 Future steps

Then to get a real result there are several things to consider. Some of these issues are

- Better Monte Carlo model of $D_s^{*+} \to D_s^+ e^+ e^-$.
- Adding additional modes in which we reconstruct the D_s.
- Optimize cuts.
- Systematic errors; here in particular the efficiency for finding the slow electrons and positrons will be an issue.

5 Theory

For the decay $D_s^{*+} \to D_s^+ \gamma$ we can write this amplitude as

$$A(D_s^{*+} \to D_s^+ \gamma) = \varepsilon^{\mu}_{D_s^*} \varepsilon^{*\nu}_{\gamma} T_{\mu\nu}(P,k)$$

where P is the four-momentum of the D_s^{*+} and k is the photon four-momentum. We can write T on the form

$$T_{\mu\nu}(P,k) = A g_{\mu\nu} + B k_\mu P_\nu + C \epsilon_{\mu\nu\alpha\beta} P^\alpha k^\beta$$

This is a $1^- \to 0^- 1^-$ decay. The relative orbital angular momentum can be 0, 1, or 2. But in order to conserve parity we have to have $L = 1$. This means that we have to have

$$T_{\mu\nu}(P,k) = C \epsilon_{\mu\nu\alpha\beta} P^\alpha k^\beta$$

Now instead of just considering a photon in the final state we can consider the case where we have a virtual photon and couple it to the electron positron pair. I.e. something like

$$A(D_s^{*+} \to D_s^+ e^+ e^-) = \varepsilon^{\mu}_{D_s^*} T_{\mu\nu}(P,k) \frac{-ig^{\nu\alpha}}{k^2} \langle \bar{u}(p) | ie\gamma_\alpha | v(p') \rangle,$$

where p and p' are the four-momenta of the electron and positron respectively. Try to keep the A and B terms as well, though I think that you will see that they will not contribute to the rate when you consider parity conservation as the two electrons couple to the the virtual photon via a vector coupling and this forces the virtual photon to be in a 1^- state.

If you evaluate the rate for the $D_s^{*+} \to D_s^+ \gamma$ and $D_s^{*+} \to D_s^+ e^+ e^-$ you can calculate the ratio and then the constant C will cancel out. This should give us a fairly good prediction for the branching fraction. In principle C can depend on the 'q^2' of this process, i.e. the invariant mass squared of the electron-positron system. This is equivalent to the momentum of the produced D_s^+. Now as the recoil is fairly small in this process, I think that the approximation that C is just a constant should be pretty good.

We should also plot the kinematic distributions of the electron and positron. One useful plot would be to plot q^2 versus the energy of the electron.

6 Rate for $D_s^{*+} \to D_s^+\gamma$

From above we have the amplitude for this process given as

$$\mathcal{M} = \varepsilon^{\mu}_{D_s^*}\varepsilon^{*\nu}_{\gamma} C\epsilon_{\mu\nu\alpha\beta}P^{\alpha}k^{\beta}.$$

Squaring this we get

$$|\mathcal{M}^2| = |C^2|\varepsilon^{\mu}_{D_s^*}\varepsilon^{*\nu}_{\gamma}\epsilon_{\mu\nu\alpha\beta}P^{\alpha}k^{\beta}\varepsilon^{*\mu'}_{D_s^*}\varepsilon^{*\nu'}_{\gamma}\epsilon_{\mu'\nu'\alpha'\beta'}P^{\alpha'}k^{\beta'}.$$

Summing over final state polarizations and averaging over initial polarizations we ge

$$\begin{aligned}
\overline{|\mathcal{M}^2|} &= \frac{|C^2|}{3}g^{\nu\nu'}\left(g^{\mu\mu'} - \frac{P^{\mu}P^{\mu'}}{M^2_{D_s^*}}\right)\epsilon_{\mu\nu\alpha\beta}P^{\alpha}k^{\beta}\epsilon_{\mu'\nu'\alpha'\beta'}P^{\alpha'}k^{\beta'} \\
&= \frac{|C^2|}{3}\epsilon^{\mu\nu}{}_{\alpha\beta}\epsilon_{\mu\nu\alpha'\beta'}P^{\alpha}k^{\beta}P^{\alpha'}k^{\beta'} \\
&= -\frac{|C^2|}{3}(2g_{\alpha\alpha'}g_{\beta\beta'} - 2g_{\alpha\beta'}g_{\alpha'\beta'})P^{\alpha}k^{\beta}P^{\alpha'}k^{\beta'} \\
&= -\frac{2|C^2|}{3}(P^2k^2 - (P\cdot k)^2) \\
&= -\frac{2|C^2|}{3}(P^2k^2 - (P\cdot k)^2) \\
&= \frac{2|C^2|}{3}M^2_{D_s^*}E^2_{\gamma}
\end{aligned}$$

For a two-body decay we can write the rate as

$$d\Gamma = \frac{1}{32\pi^2}\overline{|\mathcal{M}^2|}\frac{|P_{\gamma}|}{M^2_{D_s^*}}d\Omega.$$

After integrating over $d\Omega$ we have

$$\Gamma = \frac{1}{8\pi}\overline{|\mathcal{M}^2|}\frac{|E_{\gamma}|}{M^2_{D_s^*}}d\Omega.$$

And putting in the form of the matrix element we have for $D_s^{*+} \to D_s^+\gamma$ we find

$$\Gamma = \frac{|C^2|}{12\pi}E^3_{\gamma}.$$

7 Rate for $D_s^{*+} \to D_s^+ e^+ e^-$

The rate for $D_s^{*+} \to D_s^+ e^+ e^-$ is a bit more involved as it is a three body decay. We will proceed in the same way. First we will calculate $\overline{|\mathcal{M}^2|}$. We start with the amplitude which is given by

$$A(D_s^{*+} \to D_s^+ e^+ e^-) = \varepsilon^{\mu}_{D_s^*} C \epsilon_{\mu\nu\alpha\beta} P^{\alpha} k^{\beta} \frac{-ig^{\nu\rho}}{k^2} \bar{u}(p)|ie\gamma_{\rho}|v(p').$$

Next we square this

$$|\mathcal{M}^2| = |C^2| \varepsilon^{\mu}_{D_s^*} \varepsilon^{*\mu'}_{D_s^*} \epsilon_{\mu\nu\alpha\beta} P^{\alpha} k^{\beta} \epsilon_{\mu'\nu'\alpha'\beta'} P^{\alpha'} k^{\beta'} \frac{g^{\nu\rho} g^{\nu'\rho'}}{k^4} \bar{u}(p)|e\gamma_{\rho}|v(p')\bar{v}(p')|e\gamma_{\rho'}|u(p).$$

Summing over final states and averaging over initial states allow us to write

$$\begin{aligned}
\overline{|\mathcal{M}^2|} &= \frac{4e^2|C^2|}{3k^4} \epsilon^{\mu}{}_{\nu\alpha\beta} \epsilon_{\mu\nu'\alpha'\beta'} P^{\alpha} k^{\beta} P^{\alpha'} k^{\beta'} \left[p^{\nu} p'^{\nu'} + p'^{\nu} p^{\nu'} - g^{\nu\nu'}(p \cdot p' + m^2) \right] \\
&= \frac{4e^2|C^2|}{3k^4} \left[m^2 k^4 - k^2 (P \cdot k)^2 - 2X^2 \right],
\end{aligned}$$

where

$$X^{\mu} \equiv \epsilon^{\mu}{}_{\nu\alpha\beta} P^{\alpha} p'^{\beta} p^{\nu}.$$

The evaluation of X^2 that I used first was rather awkward, and it is possible that I got something wrong there. So instead, one can use

$$\begin{aligned}
\epsilon^{\mu\alpha\beta\gamma} \epsilon_{\mu\alpha'\beta'\gamma'} &= g^{\alpha}_{\alpha'} g^{\beta}_{\beta'} g^{\gamma}_{\gamma'} + g^{\alpha}_{\beta'} g^{\beta}_{\gamma'} g^{\gamma}_{\alpha'} + g^{\alpha}_{\gamma'} g^{\beta}_{\alpha'} g^{\gamma}_{\beta'} - \\
& \quad g^{\alpha}_{\alpha'} g^{\beta}_{\gamma'} g^{\gamma}_{\beta'} - g^{\alpha}_{\gamma'} g^{\beta}_{\beta'} g^{\gamma}_{\alpha'} - g^{\alpha}_{\beta'} g^{\beta}_{\alpha'} g^{\gamma}_{\gamma'}
\end{aligned}$$

This then gives

$$\begin{aligned}
X^2 &= P^2 p'^2 p^2 + 2P \cdot p' p' \cdot p P \cdot p - P^2 (p \cdot p')^2 - m^2 ((P \cdot p')^2 + (P \cdot p)^2) \\
&= M^2_{D_s^*} m^4 + q^2 (P \cdot p')(P \cdot p) - M^2_{D_s^*} (m^2 - k^2/2)^2 - m^2 (P \cdot k)^2 \\
&= q^2 (P \cdot p')(P \cdot p) - M^2_{D_s^*} (m^2 - q^2/2)^2 - \frac{m^2}{4} (M^2_{D_s^*} - M^2_{D_s} + q^2)^2
\end{aligned}$$

where I have used

$$p \cdot p' = q^2/2 - m^2$$

and

$$P \cdot k = (M^2_{D_s^*} - M^2_{D_s} + q^2)/2.$$

The next task is to express $P \cdot p'$ and $P \cdot p$ in a more convenient form. Denote by a * quantities evaluated in the e^+e^- restframe. Let θ^* be the angle the electron makes with the direction opposite to the D_s in the e^+e^- frame. This means that

$$\begin{aligned}
P \cdot p &= E^*_{D_s^*} E^*_e - |P^*_{D_s^*}||P^*_e| \cos\theta^*, \\
P \cdot p' &= E^*_{D_s^*} E^*_e + |P^*_{D_s^*}||P^*_e| \cos\theta^*.
\end{aligned}$$

But the energy in the e^+e^- restframe, $E^*_{D_s^*}$, can be written

$$E^*_{D_s^*} = \frac{P \cdot k}{\sqrt{q^2}}$$

as in this frame $k^\mu = (\sqrt{q^2}, 0, 0, 0)$. Similarly we can express the electron energy as

$$E^*_e = \frac{p \cdot k}{\sqrt{q^2}}$$

Putting this together we get

$$\begin{aligned} P \cdot p &= \frac{P \cdot k}{\sqrt{q^2}} \frac{p \cdot k}{\sqrt{q^2}} + \sqrt{\frac{(P \cdot k)^2}{q^2} - M^2_{D_s^*}} \sqrt{\frac{(p \cdot k)^2}{q^2} - m^2} \cos\theta^* \\ P \cdot p' &= \frac{P \cdot k}{\sqrt{q^2}} \frac{p \cdot k}{\sqrt{q^2}} - \sqrt{\frac{(P \cdot k)^2}{q^2} - M^2_{D_s^*}} \sqrt{\frac{(p \cdot k)^2}{q^2} - m^2} \cos\theta^* \end{aligned}$$

Using $p \cdot k = q^2/2$ gives

$$(P \cdot p)(P \cdot p') = (P \cdot k)^2/4 - \left(\frac{(P \cdot k)^2}{q^2} - M^2_{D_s^*}\right)\left(\frac{q^2}{4} - m^2\right)\cos^2\theta^*.$$

Putting this together we get

$$X^2 = q^2 \frac{(P \cdot k)^2}{4} - \left((P \cdot k)^2 - q^2 M^2_{D_s^*}\right)\left(\frac{q^2}{4} - m^2\right)\cos^2\theta^* - M^2_{D_s^*}(m^2 - \frac{q^2}{2})^2 - \frac{m^2}{4}(M^2_{D_s^*} - M^2_{D_s} + q^2)^2.$$

Using $A = M^2_{D_s^*} - M^2_{D_s} + q^2$ we get

$$\overline{|\mathcal{M}^2|} = \frac{4e^2|C^2|}{3q^4}\left[q^4 m^2 - \frac{3A^2}{8}q^2 + 2\left(\frac{A^2}{4} - M^2_{D_s^*}\right)\left(\frac{q^2}{4} - m^2\right)\cos^2\theta^* + 2M^2_{D_s^*}\left(m^2 - \frac{q^2}{2}\right)^2 + \frac{m^2}{2}A^2\right]$$

For a three-body decay we can write

$$d\Gamma = \frac{1}{(2\pi)^3} \frac{1}{16 M^2_{D_s^*}} \overline{|\mathcal{M}^2|} dE_e dq^2$$

Now using

$$dE_e = \frac{P_{D_s}}{2} d\cos\theta^*$$

(this form assumes $m = 0$) and integrating over $\cos\theta$ we get

$$\frac{d\Gamma}{dq^2} = \frac{2P_{D_s} e^2 |C^2|}{3(2\pi)^3 16 M^2_{D_s^*} q^4}\left[2q^4 m^2 - \frac{3A^2}{4}q^2 + \frac{4}{3}\left(\frac{A^2}{4} - M^2_{D_s^*}\right)\left(\frac{q^2}{4} - m^2\right) + 4M^2_{D_s^*}\left(m^2 - \frac{q^2}{2}\right)^2 + m^2 A^2\right]$$

We can do this integral numerically (and we should!) but to estimate the rate we note that the largest contribution to the rate is at small values of q^2 as we have a singularity at $q^2 = 0$. Note however, that $q^2 > 4m^2$. So for small q^2 values we can approximate this expression with

$$\frac{d\Gamma}{dq^2} = \frac{2P_{D_s}e^2|C^2|}{3(2\pi)^3 16 M_{D_s^*}^2}\left[-\frac{3(M_{D_s^*}^2 - M_{D_s}^2)^2}{4q^2}\right]$$

Integrating this from $q^2 = 4m^2$ to about $q^2 = 100^2$ MeV^2 we have

$$\Gamma \simeq \frac{2P_{D_s}e^2|C^2|}{3(2\pi)^3 16 M_{D_s^*}^2}\left[-\frac{3(M_{D_s^*}^2 - M_{D_s}^2)^2}{4}\right]\left[\ln q^2\right]_{4m^2}^{100^2\ \mathrm{MeV}^2}$$

I have an overall minus sign wrong. I lost this in the sum over the polarization vectors. We can write this as

$$\Gamma \simeq \frac{1}{16\pi^2}P_{D_s}^3\alpha|C^2|\ln(100)$$

Now we can take the ratio of the two rates

$$\frac{\Gamma(D_s^{*+}\to D_s^+e^+e^-)}{\Gamma(D_s^{*+}\to D_s^+\gamma)} \simeq \frac{3\alpha}{4\pi}\ln 100 \simeq \alpha$$

Where we have used that for small q^2 we have $P_{D_s} \simeq E_\gamma$.

This shows that the the naive expectation of this ratio being α is approximately correct.

8 Selection Criteria for the Various D_s^+ Decay Modes

For this analysis, we focus on the D_S^+ that decayed from the D_s^{*+} and reconstruct it via nine decay modes listed below. We reconstruct D_s^{*+} candidates from the Lorentz vector of the D_S^+ candidates and the tracks of electrons and positrons observed in each event.

The electron and positrons in the signal and conversion background samples are fitted to the electron hypothesis, while those in the data are fitted to the pion hypothesis. This will be corrected for later.

8.1 Criteria Common to All Decay Modes

Electron and positron tracks are required to have:

- 10 MeV ¡ p_T ¡ 2 GeV
- χ^2 ¡ 100,000
- $|d_0| < 5mm$
- $|z_0| < 5cm$
- dE/dx within 3σ of that expected for an electron.

The DTag tools apply their default criteria for reconstructing the nine modes of D_s^+ decay investigated in the following sub-sections.

8.2 $K^+K^-\pi^+$

We select reconstructed D_S^+ candidates with an invariant mass within $|m_{D_S^+} - 1.96849GeV| < 0.011GeV$ as shown in Figure 1.

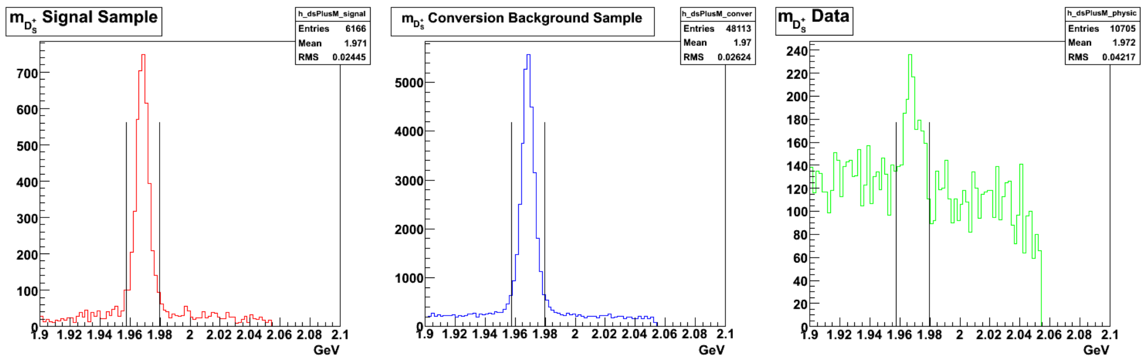

Figure 1: Reconstructed mass of the D_S^+ in the signal sample (left plot), conversion sample (middle), and 109.8 pb^{-1} of data (right).

We define $\Delta E = E(K^+K^-\pi^+e^+e^-) - E(D_s^*)$ and cut on $|\Delta E| < 0.019GeV$ as shown in Figure 2.

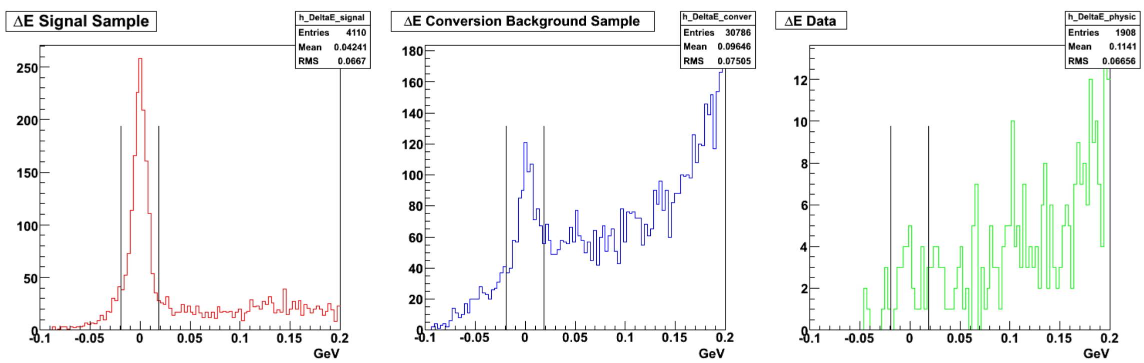

Figure 2: Distribution of ΔE in the signal (left plot), conversion sample (middle), and 109.8 pb^{-1} of data (right).

We define $m_{BC} = \sqrt{E(D_s^*)^2 - P(K^+K^-\pi^+e^+e^-)^2}$ and cut on $|m_{BC} - 2.112GeV| < 0.008GeV$ as shown in Figure 3.

We define $\delta m = M(K^+K^-\pi^+e^+e^-) - M(K^+K^-\pi^+)$ and cut on $|\delta m - 0.1455GeV| < 0.0085GeV$ as shown in Figure 4.

The conversion of the real photon into an e^+e^- pair in the conversion sample is expected to occur within the beam-pipe material. The Dalitz decay of the $D_s^{*+} \to D_s^+e^+e^-$ via a virtual photon, will on the other hand, produce e^+e^- tracks that come from the interaction point.

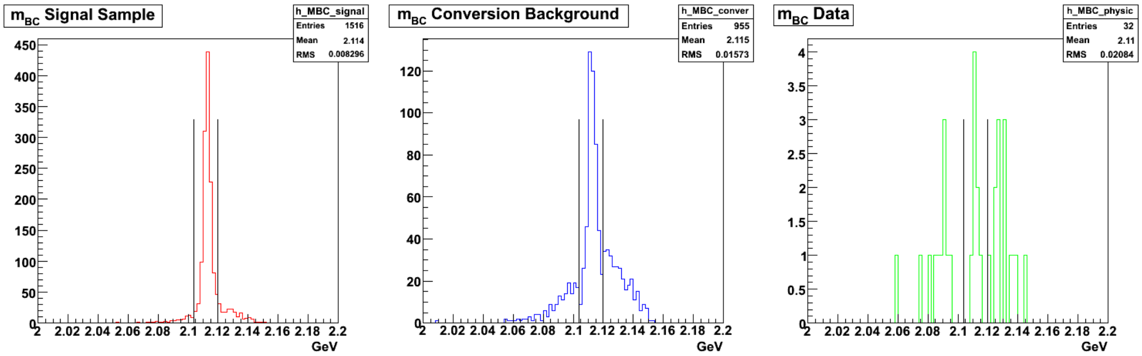

Figure 3: Distribution of m_{BC} in the signal (left plot), conversion sample (middle), and 109.8 pb^{-1} of data (right).

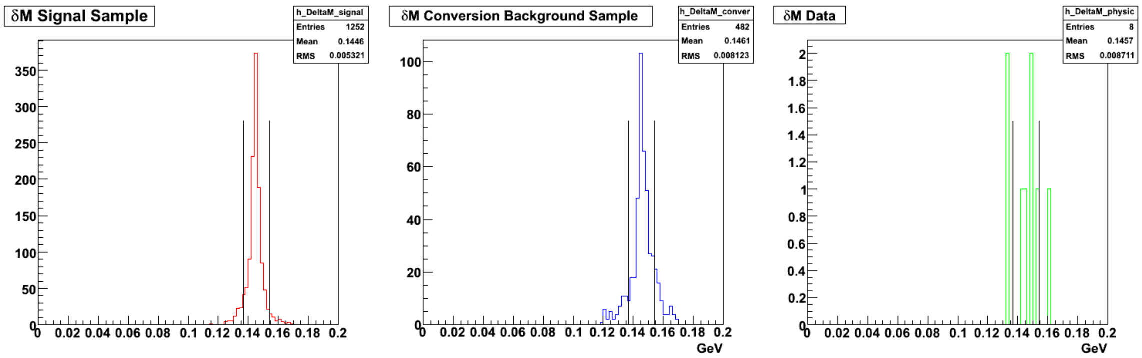

Figure 4: Distribution of δm in the signal (left plot), conversion sample (middle), and 109.8 pb^{-1} of data (right).

The impact parameter, d_0, of the electron and positron tracks are therefore expected to be larger in the conversion sample than in the signal sample. This is illustrated in Figure **??**. Given that the CLEO sign convention for d_0 factors in the charge of the particle being tracked, we can infer that $d_0^{e+} - d_0^{e-}$ will be centered around 0 for the signal and offset from 0 for the conversion background. This is what we notice in the distributions of this quantity plotted in Figure 5. We require $d_0^{e+} - d_0^{e-} > -4mm$.

The azimuthal angle, ϕ, of the electron and positron tracks are expected to be nearly equal in events of the signal sample and systematically unequal in events of the conversion sample. This is illustrated in Figure **??**. $\phi^{e+} - \phi^{e-}$ is expected to be centered around 0 in the signal sample and offset from 0 in the conversion sample and this is what we see in the distributions plotted in Figure 6. We require $\phi^{e+} - \phi^{e-} < 0.1$.

We are left with 815/9988 events in the signal sample and 21/646387 events in the conversion sample that pass our selection criteria listed above. Given that:

- the cross-section of $D_s^{*+} D_s^- + c.c.$ production from e^+e^- collisions at $E_{\rm cm} = 4170$ MeV is $\simeq 1$ nb,

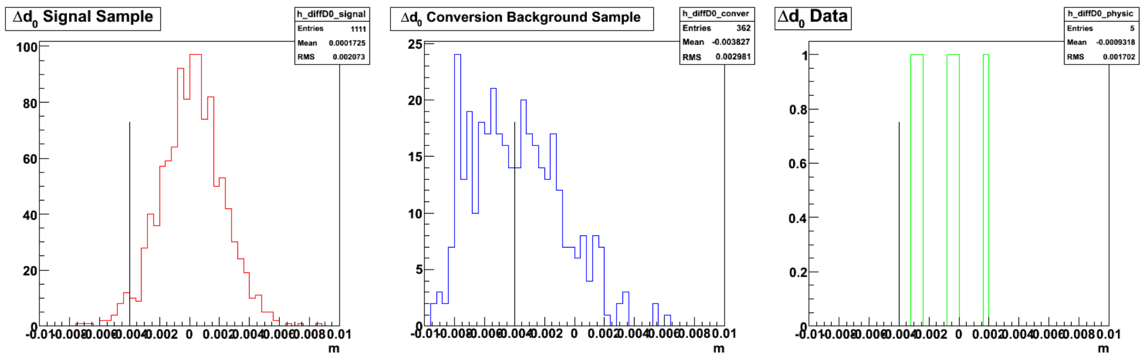

Figure 5: Distribution of $d_0^{e+} - d_0^{e-}$ in the signal (left plot), conversion sample (middle), and 109.8 pb^{-1} of data (right).

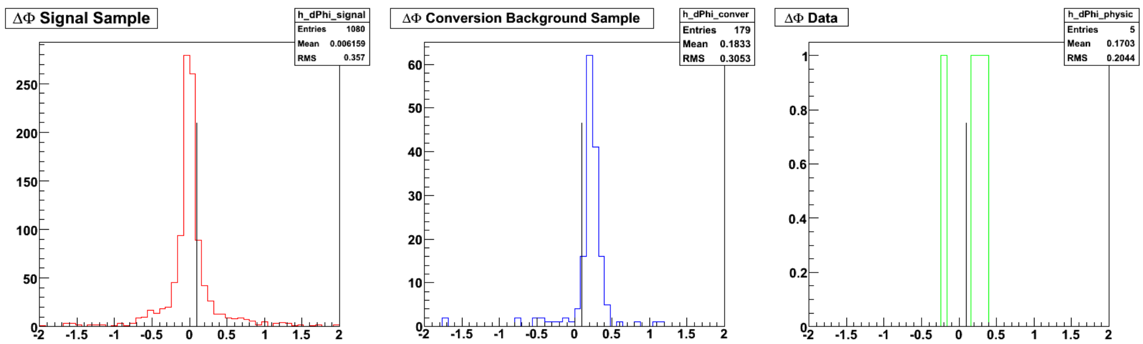

Figure 6: Distribution of $\phi^{e+} - \phi^{e-}$ in the signal (left plot), conversion sample (middle), and 109.8 pb^{-1} of data (right).

- the branching fraction of $D_s^{*+} \to D_s^+\gamma$ is $\simeq 94.2\%$,
- the predicted branching fraction of $D_s^{*+} \to D_s^+ e^+ e^-$ is $94.2\% \times 1.4\alpha = 0.96\%$
- the branching fraction of $D_s^+ \to K^+K^-\pi^+$ is $\simeq 5.50\%$,

we can calculate the number of expected signal events in $109.8 pb^{-1}$ to be:

$$109.8pb^{-1} \times 1000pb \times 5.50\% \times 94.2\% \times 1.4\alpha \times 815/9988 = 4.74 \tag{1}$$

and the number of expected conversion background events in $109.8pb^{-1}$ to be:

$$109.8pb^{-1} \times 1000pb \times 5.50\% \times 94.2\% \times 21/646387 = 0.19 \tag{2}$$

We observe 2 events in $109.8pb^{-1}$ of data that pass all our selection criteria.

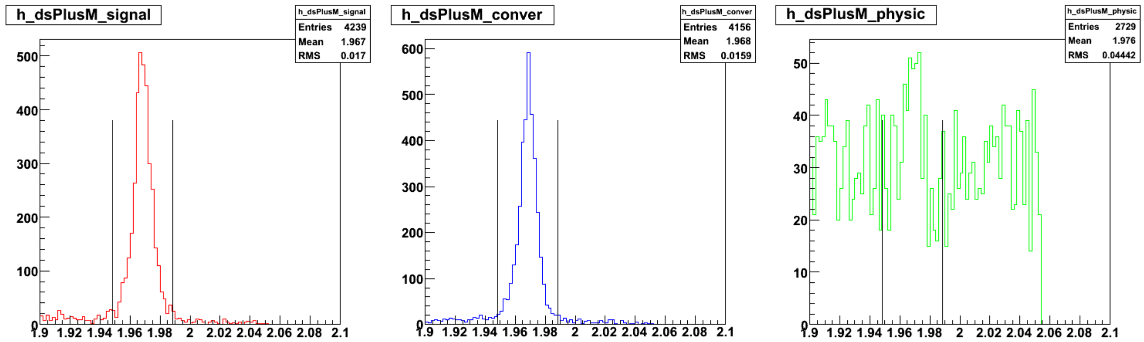

Figure 7: Reconstructed mass of the D_S^+ in the signal sample (left plot), conversion sample (middle), and 109.8 pb^{-1} of data (right).

8.3 $K_S K^+$

We select reconstructed D_S^+ candidates with an invariant mass within $|m_{D_S^+} - 1.96849GeV| < 0.02GeV$ as shown in Figure 7.

We select candidates with $|\Delta E| < 0.019GeV$ as shown in Figure 8.

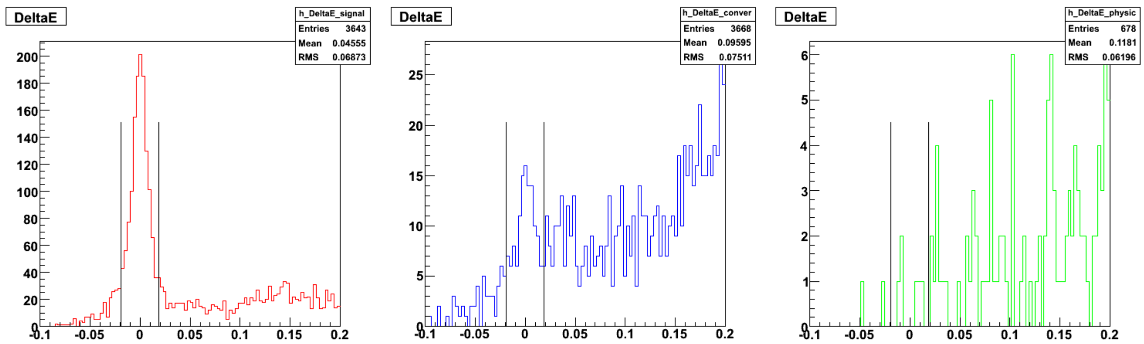

Figure 8: Distribution of ΔE in the signal (left plot), conversion sample (middle), and 109.8 pb^{-1} of data (right).

We select candidates with $|m_{BC} - 2.112GeV| < 0.008GeV$ as shown in Figure 9.

We select candidates with $|\delta m - 0.1455GeV| < 0.0085GeV$ as shown in Figure 10.

We require $d_0^{e+} - d_0^{e-} > -4mm$ as shown in Figure 11.

We require $\phi^{e+} - \phi^{e-} < 0.1$ as shown in Figure 12.

We are left with 712/9988 events in the signal sample and 3/99880 events in the conversion sample that pass our selection criteria listed above. Given that the branching fraction of $D_s^+ \to K_S K^+$ is $\simeq 1.49\%$, we can calculate the number of expected signal events in $109.8pb^{-1}$ to be:

$$109.8pb^{-1} \times 1000pb \times 1.49\% \times 94.2\% \times 1.4\alpha \times 712/9988 = 1.12 \tag{3}$$

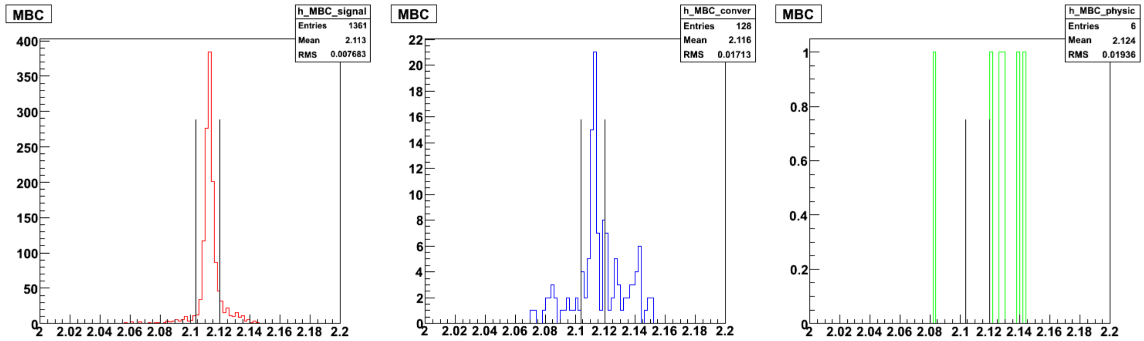

Figure 9: Distribution of m_{BC} in the signal (left plot), conversion sample (middle), and 109.8 pb^{-1} of data (right).

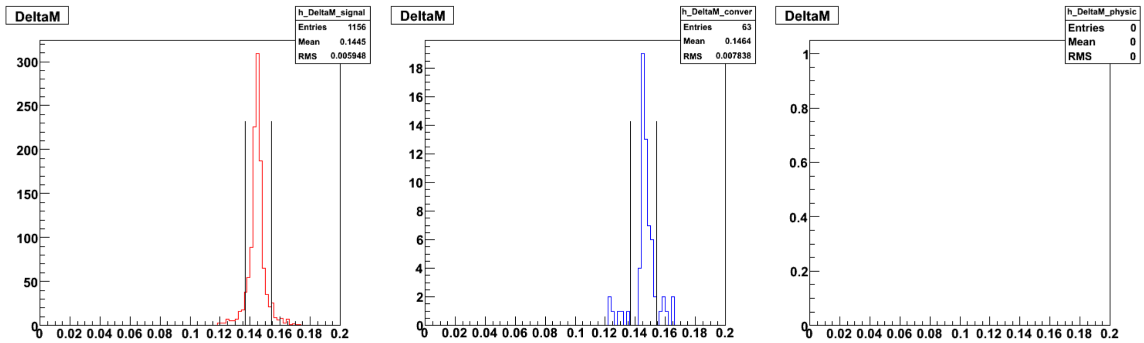

Figure 10: Distribution of δm in the signal (left plot), conversion sample (middle), and 109.8 pb^{-1} of data (right).

and the number of expected conversion background events in $109.8pb^{-1}$ to be:

$$109.8pb^{-1} \times 1000pb \times 1.49\% \times 94.2\% \times 3/99880 = 0.046 \tag{4}$$

We observe 0 events in $109.8pb^{-1}$ of data that pass all our selection criteria.

8.4 $\eta\pi^+; \eta \to \gamma\gamma$

We select reconstructed D_S^+ candidates with an invariant mass within $|m_{D_S^+} - 1.96849GeV| < 0.02GeV$ as shown in Figure 13.

We select candidates with $|\Delta E| < 0.019GeV$ as shown in Figure 14.

We select candidates with $|m_{BC} - 2.112GeV| < 0.008GeV$ as shown in Figure 15.

We select candidates with $|\delta m - 0.1455GeV| < 0.0085GeV$ as shown in Figure 16.

We require $d_0^{e+} - d_0^{e-} > -4mm$ as shown in Figure 17.

We require $\phi^{e+} - \phi^{e-} < 0.07$ as shown in Figure 18.

We are left with 839/9988 events in the signal sample and 2/99880 events in the conversion sample that pass our selection criteria listed above. Given that:

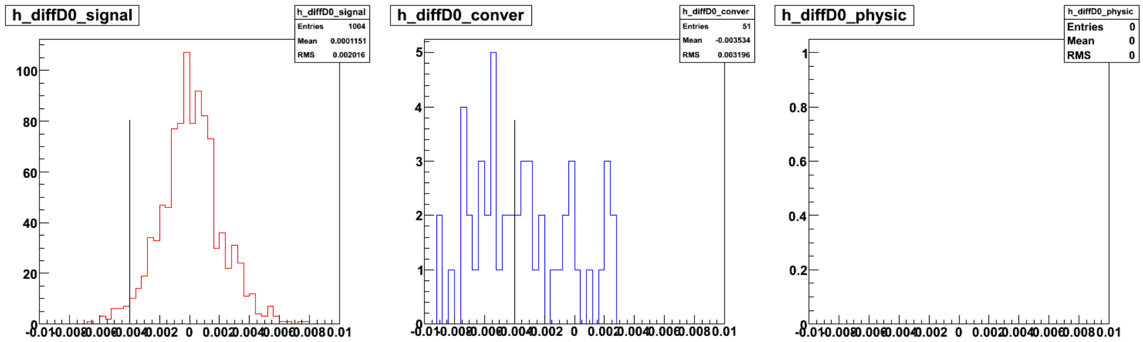

Figure 11: Distribution of $d_0^{e+} - d_0^{e-}$ in the signal (left plot), conversion sample (middle), and 109.8 pb^{-1} of data (right).

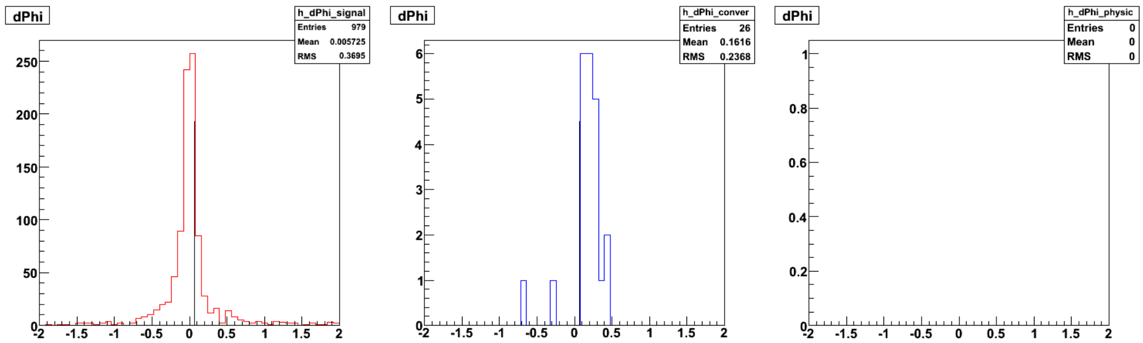

Figure 12: Distribution of $\phi^{e+} - \phi^{e-}$ in the signal (left plot), conversion sample (middle), and 109.8 pb^{-1} of data (right).

- the branching fraction of $D_s^+ \to \eta\pi^+$ is $\simeq 1.58\%$, and
- the branching fraction of $\eta \to \gamma\gamma$ is $\simeq 39.31\%$,

we can calculate the number of expected signal events in $109.8pb^{-1}$ to be:

$$109.8pb^{-1} \times 1000pb \times 1.58\% \times 39.31\% \times 94.2\% \times 1.4\alpha \times 839/9988 = 0.55 \quad (5)$$

and the number of expected conversion background events in $109.8pb^{-1}$ to be:

$$109.8pb^{-1} \times 1000pb \times 1.58\% \times 39.31\% \times 94.2\% \times 2/99880 = 0.013 \quad (6)$$

We observe 0 events in $109.8pb^{-1}$ of data that pass all our selection criteria.

8.5 $\eta'\pi^+; \eta' \to \pi^+\pi^-\eta; \eta \to \gamma\gamma$

We are left with 504/9988 events in the signal sample and 1/99880 events in the conversion sample that pass our selection criteria listed above. Given that:

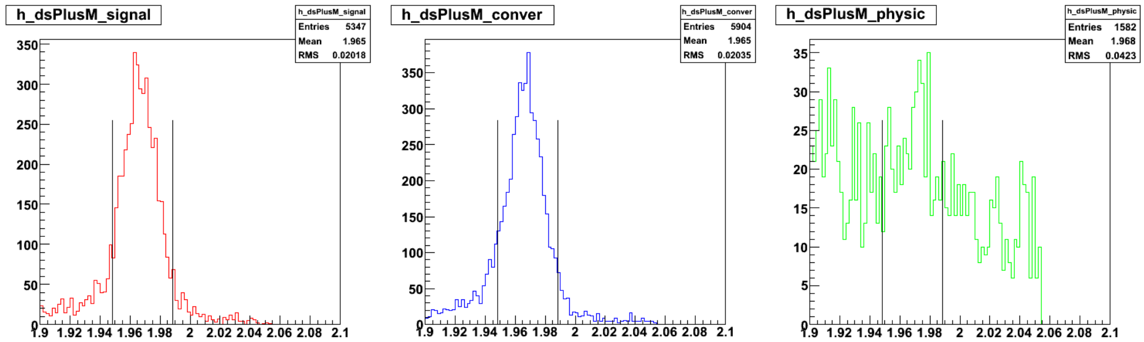

Figure 13: Reconstructed mass of the D_S^+ in the signal sample (left plot), conversion sample (middle), and 109.8 pb^{-1} of data (right).

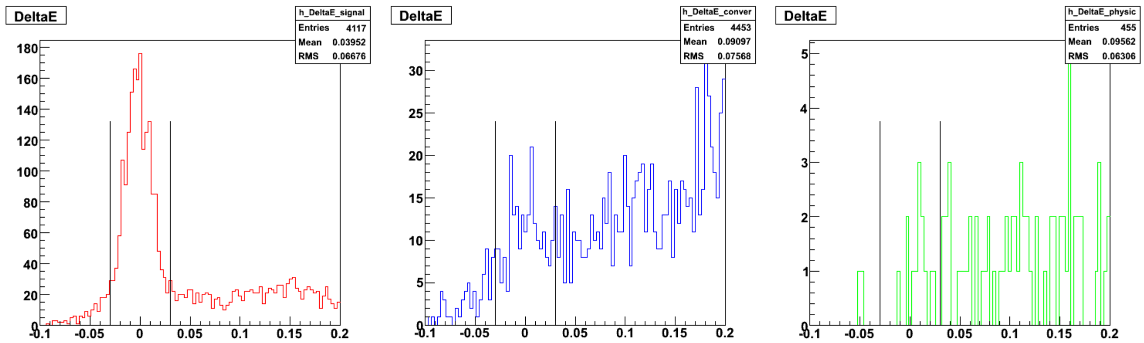

Figure 14: Distribution of ΔE in the signal (left plot), conversion sample (middle), and 109.8 pb^{-1} of data (right).

- the branching fraction of $D_s^+ \to \eta'\pi^+$ is $\simeq 3.8\%$, and
- the branching fraction of $\eta' \to \pi^+\pi^-\eta$ is $\simeq 44.6\%$,
- the branching fraction of $\eta \to \gamma\gamma$ is 39.31%,

we can calculate the number of expected signal events in $109.8pb^{-1}$ to be:

$$109.8pb^{-1} \times 1000pb \times 3.8\% \times 44.6\% \times 39.31\% \times 94.2\% \times 1.4\alpha \times 504/9988 = 0.36 \tag{7}$$

and the number of expected conversion background events in $109.8pb^{-1}$ to be:

$$109.8pb^{-1} \times 1000pb \times 3.8\% \times 44.6\% \times 39.31\% \times 94.2\% \times 1/99880 = 0.007 \tag{8}$$

We observe 0 events in $109.8pb^{-1}$ of data that pass all our selection criteria.

8.6 $K^+K^-\pi^+\pi^0$

Technical problem – Pythia Jetset starts up!

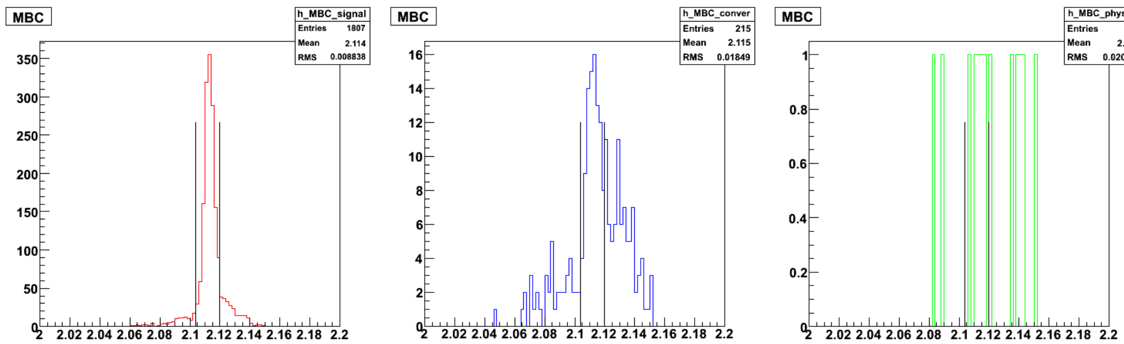

Figure 15: Distribution of m_{BC} in the signal (left plot), conversion sample (middle), and 109.8 pb^{-1} of data (right).

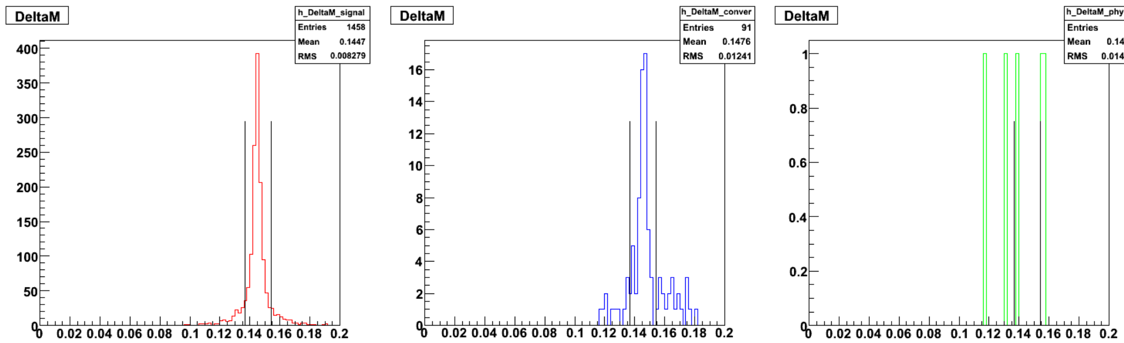

Figure 16: Distribution of δm in the signal (left plot), conversion sample (middle), and 109.8 pb^{-1} of data (right).

8.7 $\pi^+\pi^-\pi^+$

We are left with 1200/9988 events in the signal sample and 2/99880 events in the conversion sample that pass our selection criteria listed above. Given that the branching fraction of $D_s^+ \to \pi^+\pi^-\pi^+$ is $\simeq$ 1.11%, we can calculate the number of expected signal events in $109.8pb^{-1}$ to be:

$$109.8pb^{-1} \times 1000pb \times 1.11\% \times 94.2\% \times 1.4\alpha \times 1200/9988 = 1.4 \qquad (9)$$

and the number of expected conversion background events in $109.8pb^{-1}$ to be:

$$109.8pb^{-1} \times 1000pb \times 1.11\% \times 94.2\% \times 2/99880 = 0.02 \qquad (10)$$

We observe 2 events in $109.8pb^{-1}$ of data that pass all our selection criteria.

8.8 $K_S^0\pi^+K^-\pi^+(K^{*+}K^{*0}; K^{*+} \to K_S^0\pi^+, K^{*0} \to K^-\pi^+)$

We are left with 453/9988 events in the signal sample and 2/99880 events in the conversion sample that pass our selection criteria listed above. Given that the branching fraction of

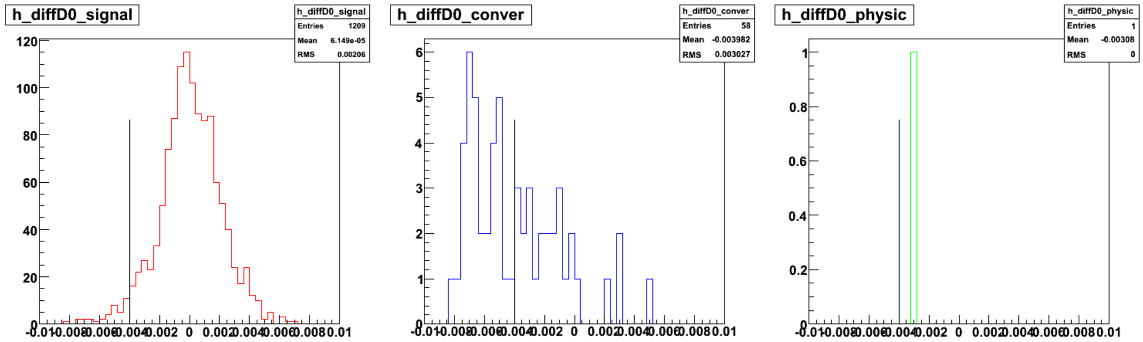

Figure 17: Distribution of $d_0^{e+} - d_0^{e-}$ in the signal (left plot), conversion sample (middle), and 109.8 pb^{-1} of data (right).

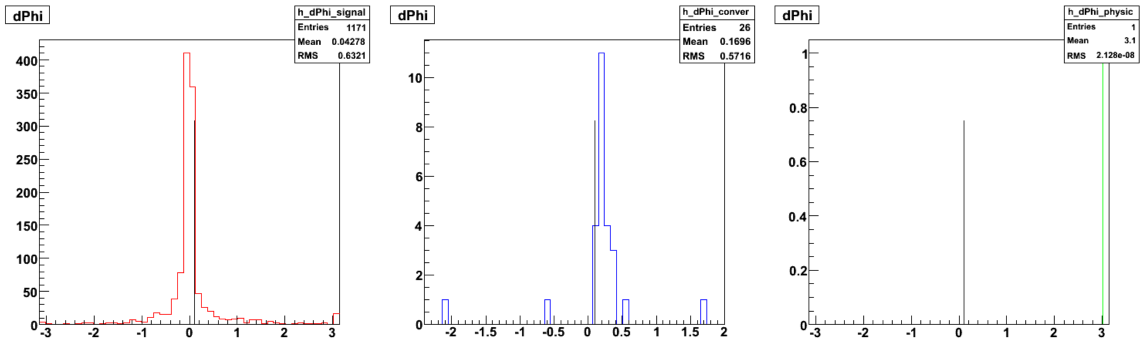

Figure 18: Distribution of $\phi^{e+} - \phi^{e-}$ in the signal (left plot), conversion sample (middle), and 109.8 pb^{-1} of data (right).

$D_s^+ \to K_S^0 \pi^+ K^- \pi^+$ is $\simeq 1.64\%$, we can calculate the number of expected signal events in $109.8pb^{-1}$ to be:

$$109.8pb^{-1} \times 1000pb \times 1.64\% \times 94.2\% \times 1.4\alpha \times 453/9988 = 0.79 \tag{11}$$

and the number of expected conversion background events in $109.8pb^{-1}$ to be:

$$109.8pb^{-1} \times 1000pb \times 1.64\% \times 94.2\% \times 2/99880 = 0.03 \tag{12}$$

We observe 2 events in $109.8pb^{-1}$ of data that pass all our selection criteria.

8.9 $\eta\rho^+; \eta \to \gamma\gamma; \rho^+ \to \pi^+\pi^0$

We are left with 641/9988 events in the signal sample and 8/99880 events in the conversion sample that pass our selection criteria listed above. Given that:

- the branching fraction of $D_s^+ \to \eta\rho^+$ is $\simeq 13.0\%$, and

- the branching fraction of $\rho^+ \rightarrow \pi^+\pi^0$ is $\simeq 100$ %,
- the branching fraction of $\eta \rightarrow \gamma\gamma$ is $\simeq 39.31\%$,

we can calculate the number of expected signal events in $109.8pb^{-1}$ to be:

$$109.8pb^{-1} \times 1000pb \times 13.0\% \times 39.31\% \times 94.2\% \times 1.4\alpha \times 641/9988 = 3.49 \qquad (13)$$

and the number of expected conversion background events in $109.8pb^{-1}$ to be:

$$109.8pb^{-1} \times 1000pb \times 13.0\% \times 39.31\% \times 94.2\% \times 8/99880 = 0.43 \qquad (14)$$

We observe 6 events in $109.8pb^{-1}$ of data that pass all our selection criteria.

8.10 $\eta'\pi^+; \eta' \rightarrow \rho^0\gamma$

We are left with 875/9988 events in the signal sample and 8/99880 events in the conversion sample that pass our selection criteria listed above. Given that:

- the branching fraction of $D_s^+ \rightarrow \eta'\pi^+$ is $\simeq 3.8\%$, and
- the branching fraction of $\eta' \rightarrow \rho^0\gamma$ is $\simeq 29.4\%$,

we can calculate the number of expected signal events in $109.8pb^{-1}$ to be:

$$109.8pb^{-1} \times 1000pb \times 3.8\% \times 29.4\% \times 94.2\% \times 1.4\alpha \times 875/9988 = 1.03 \qquad (15)$$

and the number of expected conversion background events in $109.8pb^{-1}$ to be:

$$109.8pb^{-1} \times 1000pb \times 3.8\% \times 29.4\% \times 94.2\% \times 8/99880 = 0.09 \qquad (16)$$

We observe 0 events in $109.8pb^{-1}$ of data that pass all our selection criteria.