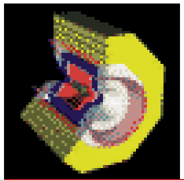


$D_s^{*+} \rightarrow D_s^+ e^+ e^-$

Souvik Das

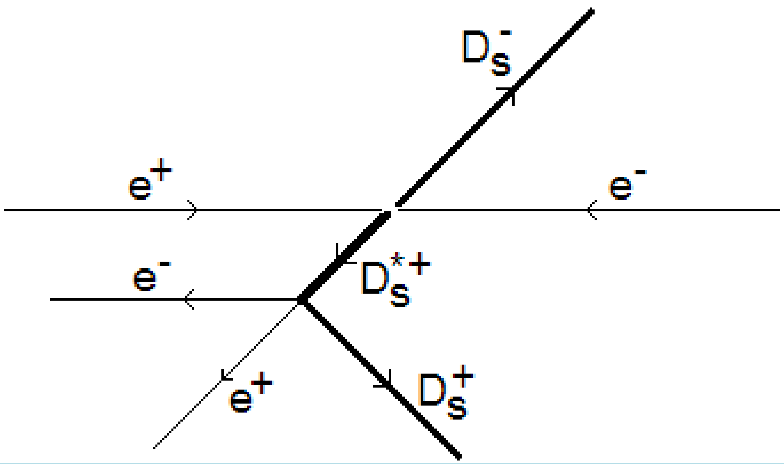
Cornell University
For the CLEO Collaboration

Cornell University
Laboratory for
Elementary-Particle Physics

Contents

8 May 2010

What Are We Looking For?



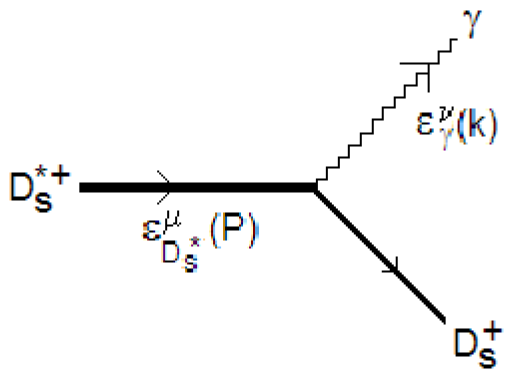
- Searching for $D_s^{*+} \to D_s^+ e^+ e^-$ with a **blind analysis**.

- Known decay channels are:
  - $D_s^{*+} \to D_s^+ \gamma$; Branching Fraction = 94.2%
  - $D_s^{*+} \to D_s^+ \pi^0$; Branching Fraction = 5.8% [1]

- We are using e^+e^- collision data collected by the CLEO-c detector at the Cornell Electron Storage Ring (CESR) operating at $\sqrt{s}$ = 4170 MeV. We have $586 \pm 6\ pb^{-1}$ of data at this energy.

- $D_s^{*\pm} D_s^{\mp}$ Production cross section at this energy is 948 ± 36 pb (combining results from [2] and [3]). This will give us ~ 600,000 events to work with.

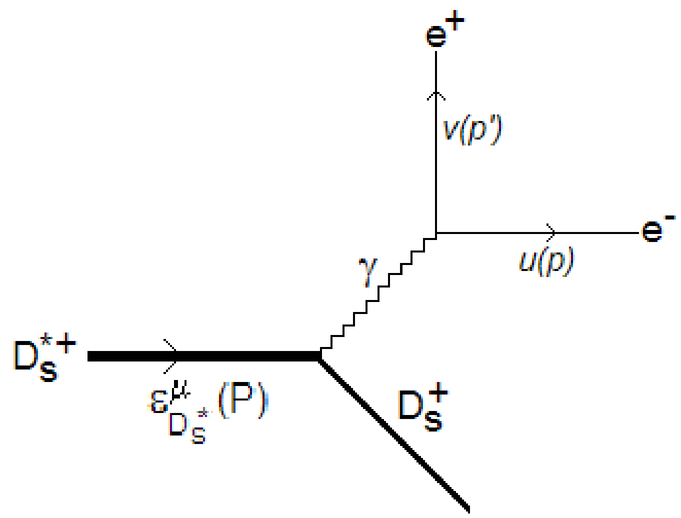
Predicted $D_s^{*\pm} \to D_s^{\pm} e^+ e^-$ Rate



If we write the matrix element of the D_s^* decay to a real photon in the form:

$$M = \varepsilon^{\mu}_{D_S^{*+}} \varepsilon^{*\nu}_{\gamma} T_{\mu\nu}(P,k)$$

Where $T_{\mu\nu}(P,k)$ is a generic form factor coupling the D_s^* with a photon.



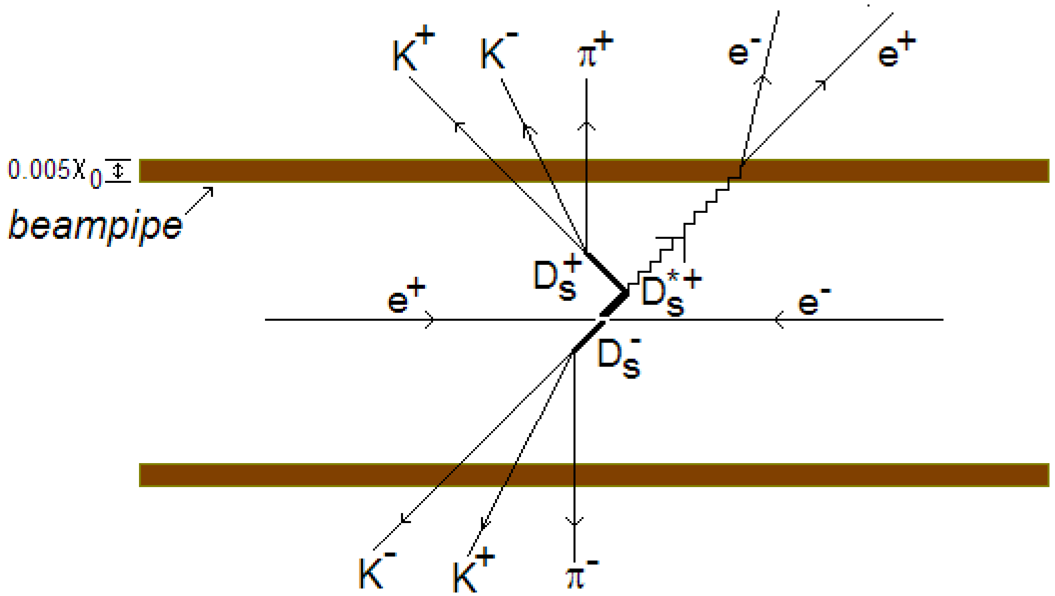
Then we can write the matrix element of the decay to e^+e^- in the form:

$$M = \varepsilon^{\mu}_{D_S^{*+}} T_{\mu\nu}(P,k)\left(\frac{-ig^{\upsilon\sigma}}{k^2}\right)\overline{u}(p)ie\gamma_{\sigma}v(p')$$

Evaluating the spin-average over the initial states and spin-sum over the final states of the invariant amplitudes and integrating over the phase space of daughters, we predict the ratio of decay rates:

$$\boxed{\frac{\Gamma\left(D_s^{*+} \to D_s^+ e^+ e^-\right)}{\Gamma\left(D_s^{*+} \to D_s^+ \gamma\right)} = 0.65\% = 0.90\alpha}$$

Backgrounds



Photon Conversion Background

- A background that resembles the signal is expected from D_s^{*+} decaying to $D_s^+\ \gamma$ and the γ converting to e^+e^- in the beam-pipe and other material.
- Given that the beam-pipe is ~ 0.5% of a radiation length, we can estimate this conversion background to occur at roughly the same rate as the signal

Combinatorial Backgrounds

- Dalitz decay of any $\pi^0 \rightarrow \gamma\ e^+\ e^-$ also give equally soft electrons that appear to come from interaction point
- Fake D_s tags

Analysis Strategy

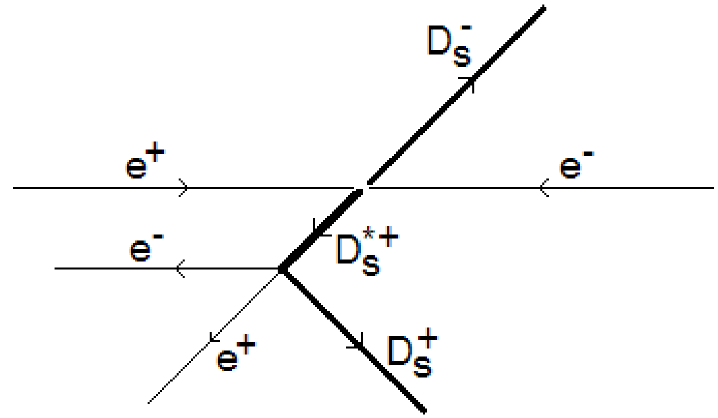
•We're trying to measure the ratio: $\dfrac{\Gamma\left(D_s^{*+} \to D_s^+ e^+ e^-\right)}{\Gamma\left(D_s^{*+} \to D_s^+ \gamma\right)}$

•For selecting $D_s^{*+} \to D_s^+ e^+ e^-$ events, the D_s^+ is reconstructed through several hadronic decay modes:

- •Selection criteria based on the *invariant masses* of the D_s and D_s^* are used
- •Criteria based on the *track parameters* of the e^+ and e^- are powerful against the photon conversion background

•For selecting $D_s^{*+} \to D_s^+ \gamma$ events, the D_s^+ is reconstructed through the same decay modes.

- •Criteria based on the invariant masses of the D_s and D_s^* and the photon momentum are used.



$$D_s^+ \to K^+ K^- \pi^+$$

$$D_s^+ \to K_S K^+$$

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

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

$$D_s^+ \to K^+ K^- \pi^+ \pi^0$$

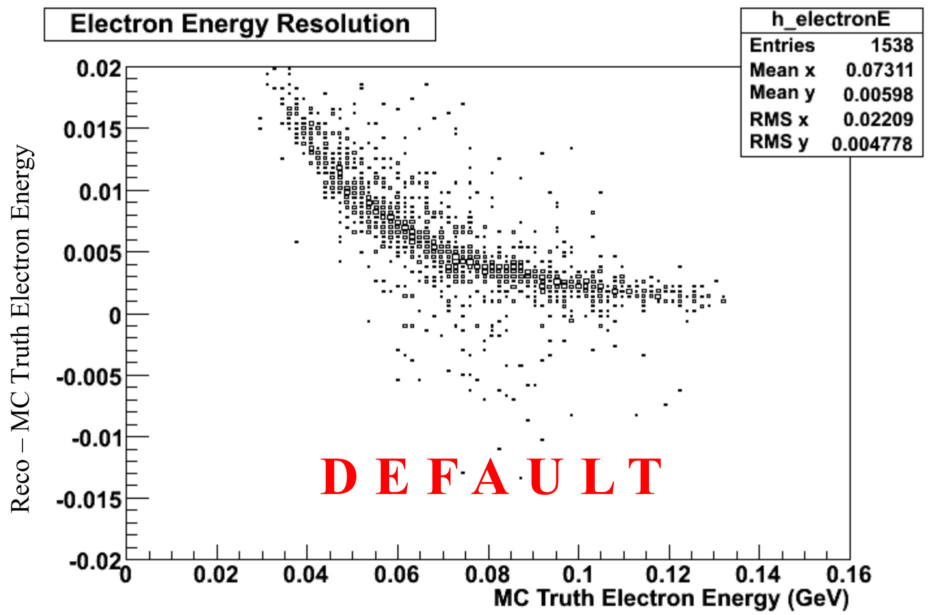
$$D_s^+ \to \pi^+\pi^+\pi^-$$

$$D_s^+ \to K^{*+} K^{*0}; K^{*+} \to K_S^0 \pi^+; K^{*0} \to K^- \pi^+$$

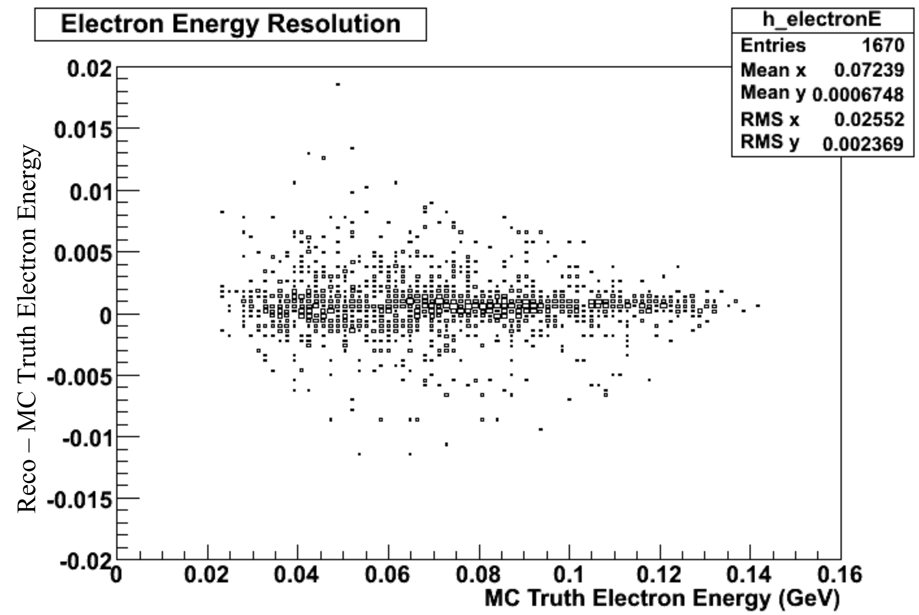
$$D_s^+ \to \eta\rho^+; \eta \to \gamma\gamma; \rho^+ \to \pi^+\pi^0$$

$$D_s^+ \to \eta'\pi^+; \eta' \to \rho^0\gamma$$

Tracking Soft Electrons



Pion fit

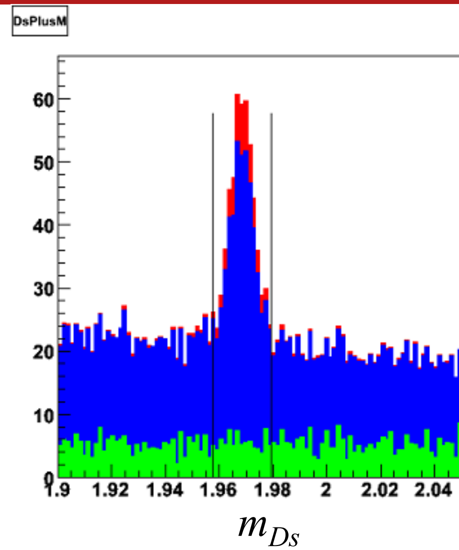


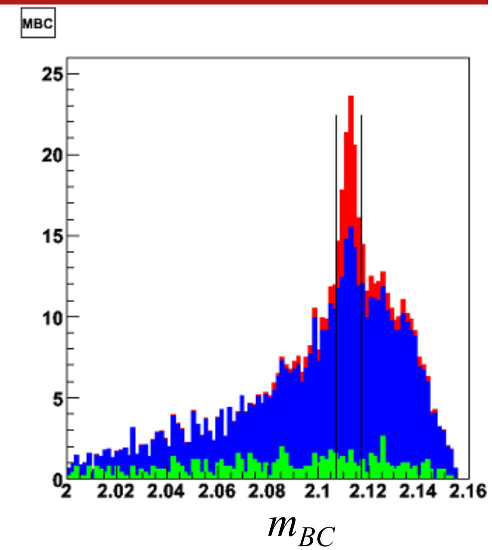
Electron fit

- Fitting to the pion mass hypothesis leads to over-estimation in the reconstructed track momentum below MeV.
- We tried parameterizing deviations. Selection criteria shown to work much better with electron-fitted tracks.
- Motivated us to **re-pass2 datasets** collected at 4170 MeV for events with a D_S-Tag

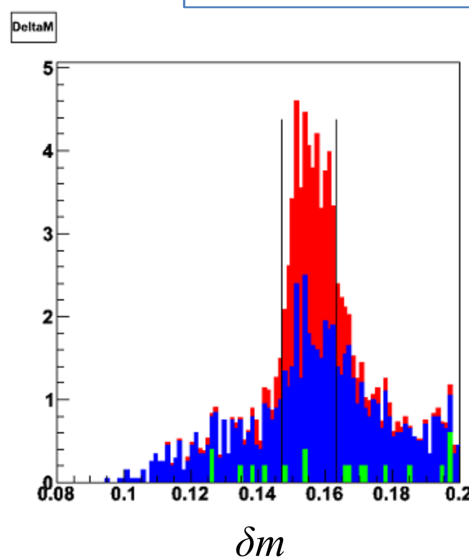
Selection Criteria

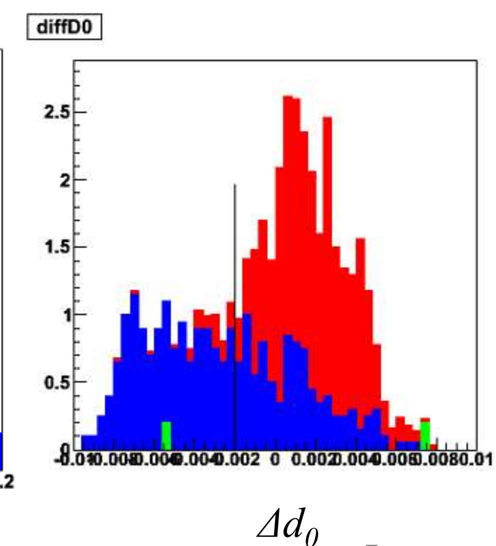
- We have settled on criteria for selecting $D_s^{*+} \to D_s^+ e^+ e^-$ events:
  - Electron track quality cuts
  - m_{Ds} criterion
  - m_{BC} criterion $\quad m_{BC} = \sqrt{E^2(D_S^{*+} beam) - P^2(D_S^{*+} reco)}$
  - δm criterion $\quad \delta m = M(K^+K^-\pi^+e^+e^-) - M(K^+K^-\pi^+)$
  - Δd_0 criterion $\quad \Delta d_0 = d_{0\_e-} - d_{0\_e+}$
  - $\Delta\varphi_0$ criterion $\quad \Delta\varphi_0 = \varphi_{0e-} - \varphi_{0e+}$
- These cuts have been optimized for each of the 9 hadronic modes of the D_s we're studying.
- We are yet to optimize the criteria for $D_s^{*+} \to D_s^+ \gamma$ events.



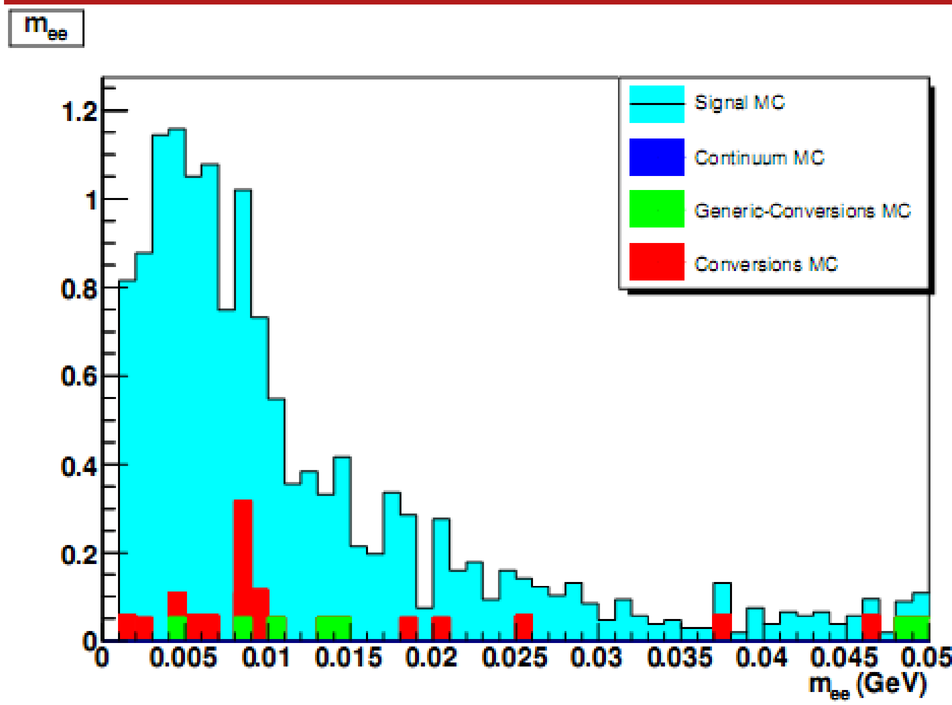


Plots for the $K^+K^-\pi^+$ Mode

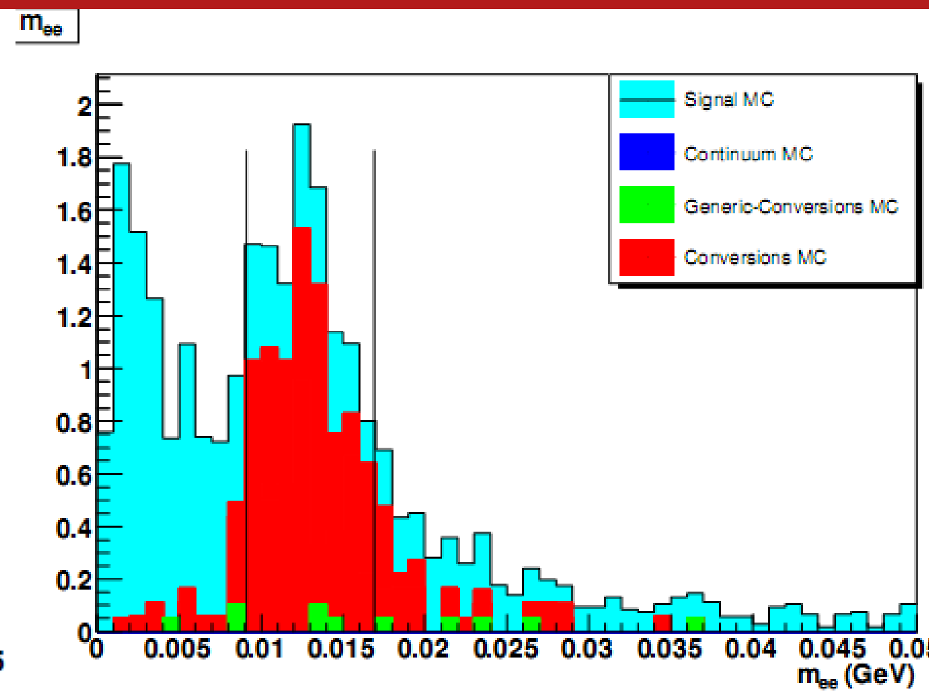




Can Vertex-Constraints & m_{ee} Cut Replace Δd_0 and $\Delta\varphi_0$ Cuts?



Invariant mass of the e^+e^- pair without vertex constraints, with all selection criteria applied.

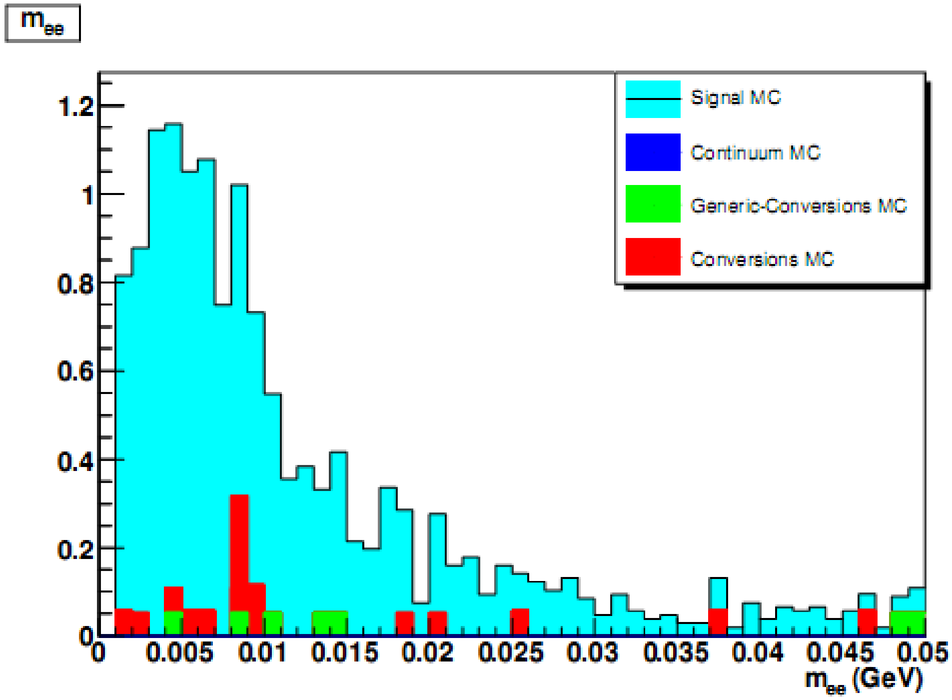


Invariant mass of the e^+e^- pair with vertex constraints, with all selection criteria except the Δd_0 and $\Delta\varphi_0$ cuts applied. m_{ee} cut will be applied in the shown region.

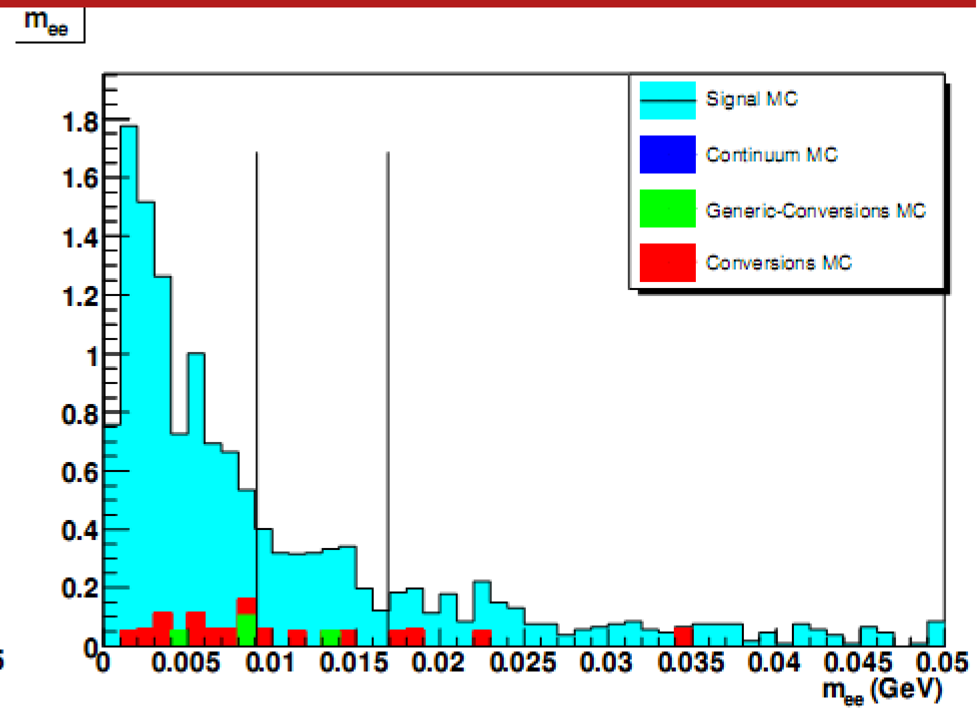
	Signal Yield	Conversions	Vetoed Generic	Continuum	Signal Significance
All criteria without vertex constraints	13.9	1.2	0.4	0.0	11.3
All kinematic criteria with vertex constraints and m_{ee} criterion	14.1	3.8	0.9	0.0	6.5

Does not adequately replace the Δd_0 and $\Delta\varphi_0$ Cuts.

Can Vertex-Constraints & m_{ee} Cut Improve Upon Δd_0 and $\Delta\varphi_0$ Cuts?



Invariant mass of the e^+e^- pair without vertex constraints, with all selection criteria applied.

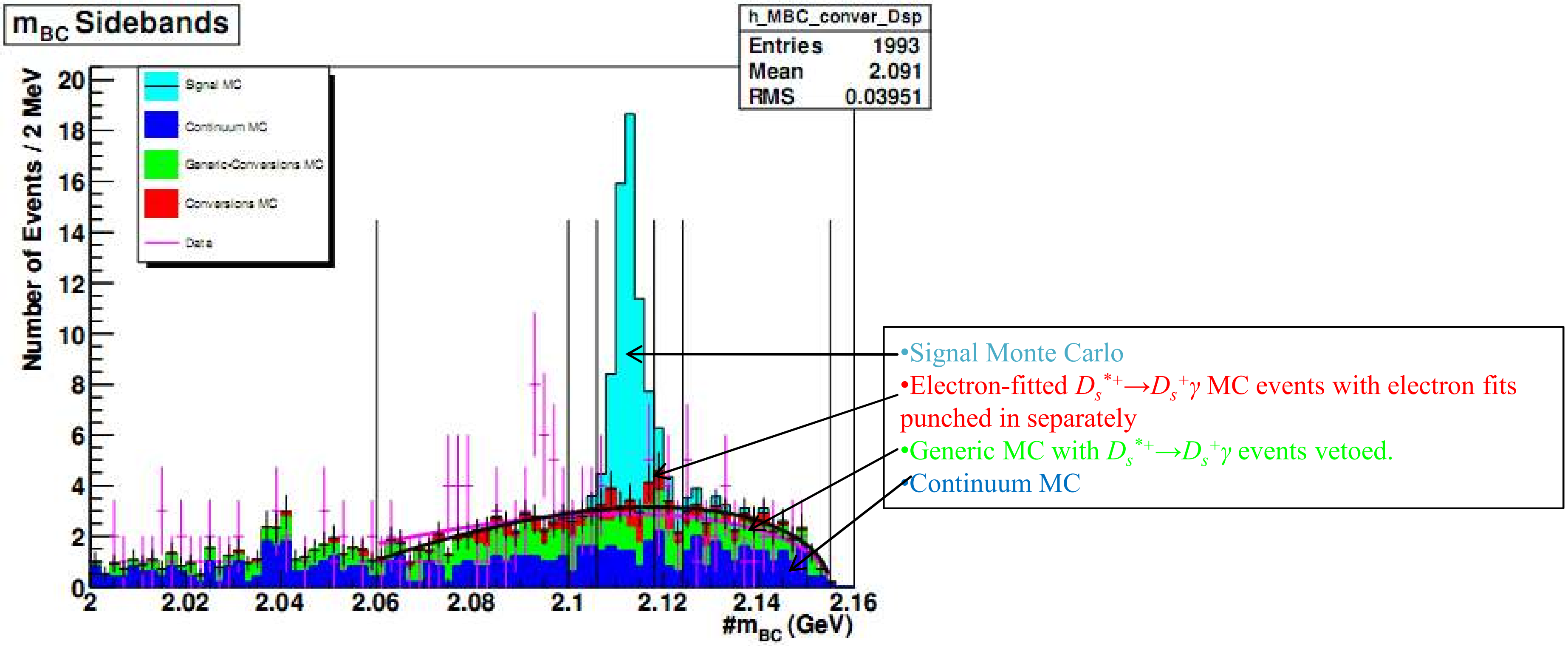


Invariant mass of the e^+e^- pair with vertex constraints, with all selection criteria applied. m_{ee} cut will be applied in the shown region.

	Signal Yield	Conversions	Vetoed Generic	Continuum	Signal Significance
All criteria without vertex constraints	13.9	1.2	0.4	0.0	11.3
All criteria with vertex constraints and mee criterion	11.3	0.9	0.2	0.0	11.2

Does not increase signal/√conversion much for substantial decrease in signal yield.

Estimation of Background Shape from m_{BC} Sidebands



•To estimate the background in the signal region for each channel, we consider the m_{BC} distribution with all other criteria applied.

•Individual modes have low statistics. We add up the m_{BC} distributions in MC and data in all modes.

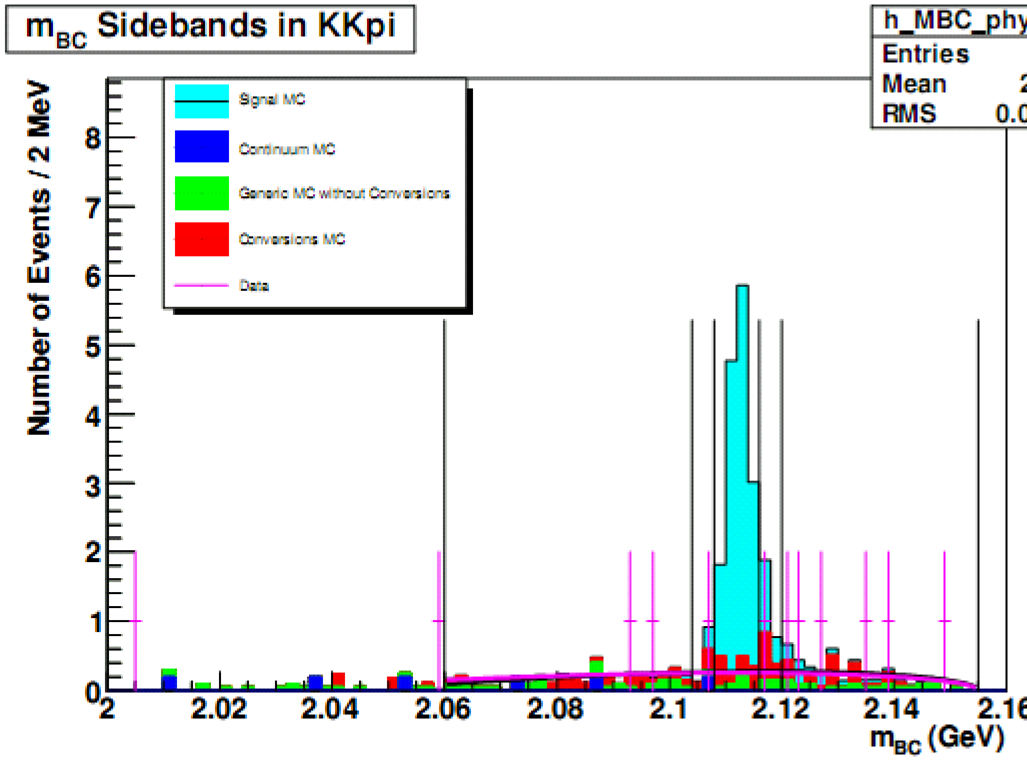
•We fit a curve to the MC background between 2.060 and 2.155 GeV. We call this the *MC shape*.

•We fit a curve to the data in the sidebands 2.060 - 2.100 & 2.124 - 2.155 GeV. This is the *data shape*.

$$N = (p_0 + p_1 m_{MBC})\sqrt{2.155 - m_{BC}}$$

•Fit these shapes back in the individual channels to estimate background in the signal region.

Estimation of Background from m_{BC} Sidebands in the $K^+K^-\pi^+$ Mode

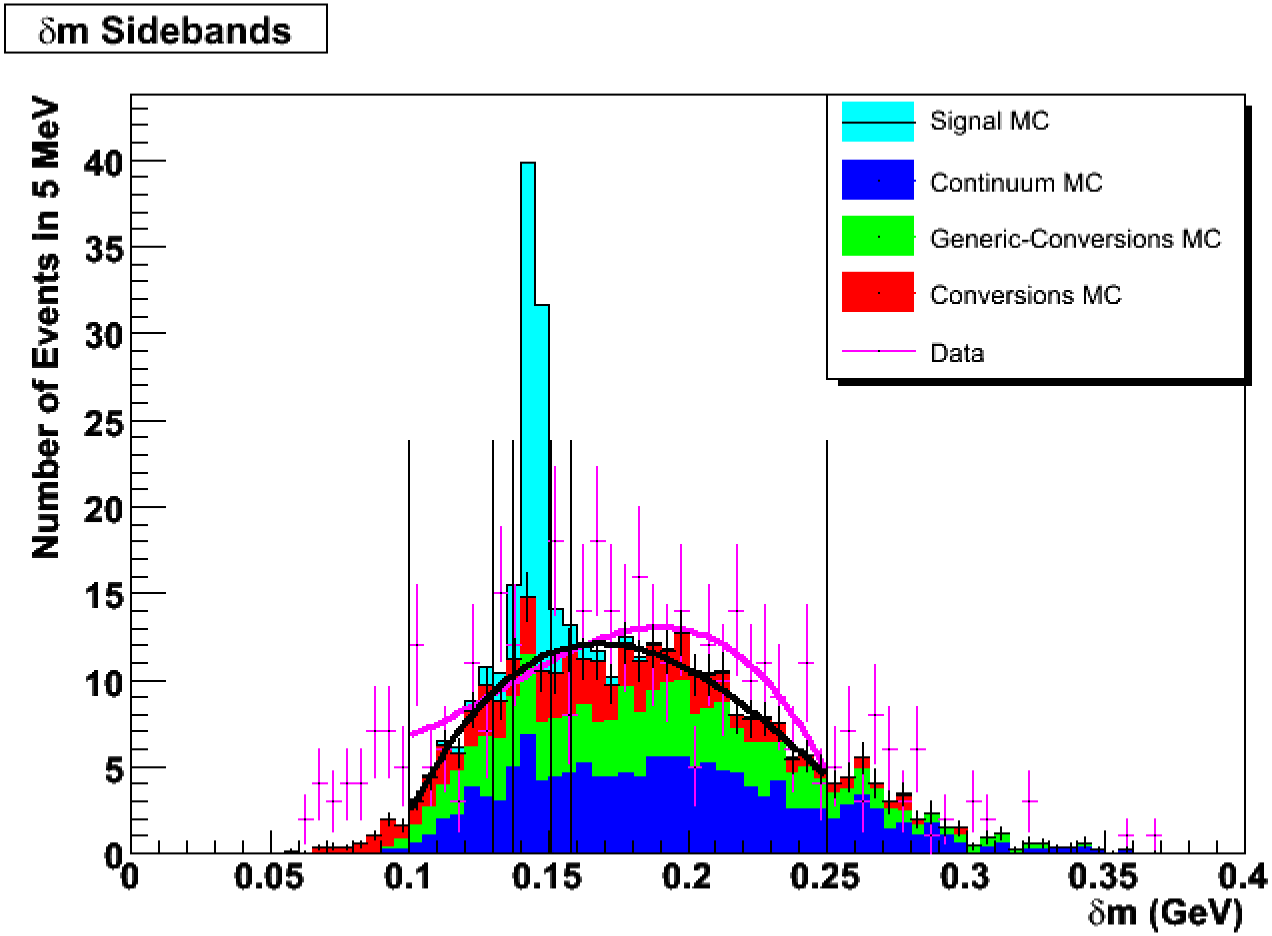


•We fit (scale) the *MC shape* and *Data shape* to the data in the sidebands of the $K^+K^-\pi^+$ (and other) mode.
•We estimate the expected background in the signal region from both shapes. The statistical uncertainty for each fit is:

$$\frac{N_{\exp ectedBackgroundFromFit}}{\sqrt{N_{sidebands}}}$$

•For the $K^+K^-\pi^+$ channel, we estimate 1.1 ± 0.4 events from the *MC shape* and 1.0 ± 0.4 events from the *Data shape*.

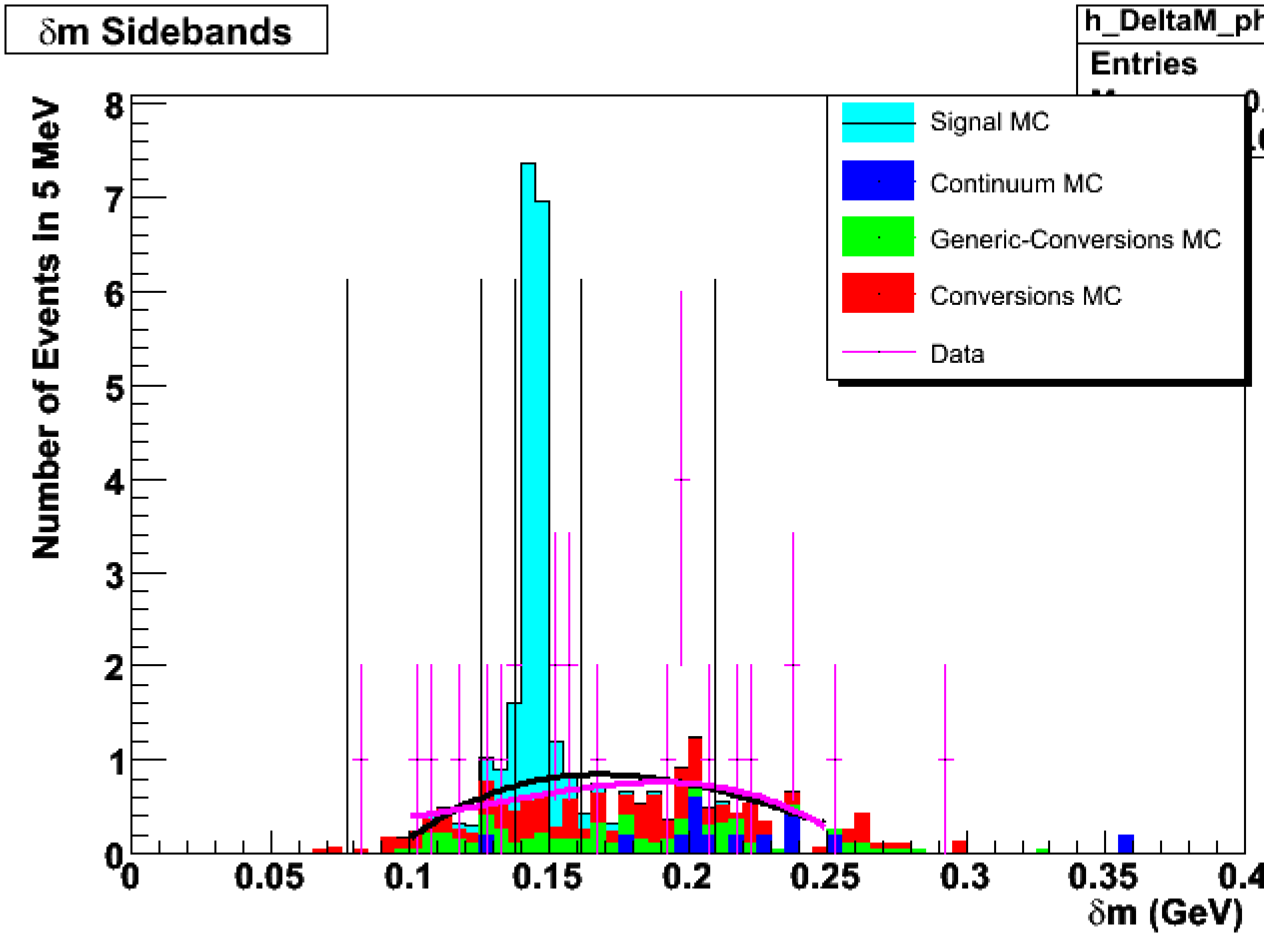
Estimation of Background Shape from δm Sidebands



•To estimate a statistical uncertainty in our estimate from fitting, we repeat our procedure with δm. Two shapes, the *MC shape* and the *Data shape* are extracted.

•We doubled the m_{BC} cut width for each mode to increase statistics.

Estimation of Background from δm Sidebands in the $K^+K^-\pi^+$ Mode



•Repeating the procedure of fitting the shapes to the individual channels, we estimate 2.1 ± 0.5 events from the *MC shape* and 1.6 ± 0.4 events from the *Data shape* in the $K^+K^-\pi^+$ channel.

Statistical Uncertainties in the Estimated Background

- Consider the mean of the *MC shape* and *Data shape* estimates from the m_{BC} distributions as the **primary estimate** because
  - the m_{BC} distribution is less peaked,
  - the difference between two estimates smaller, and
  - we did not loosen other cuts.
- The statistical error of the primary estimate is the mean of the statistical errors from the MC and Data shapes.

- Also calculate the mean of the MC shape and Data shape estimates from the δm distributions as the **secondary estimate**.

- The absolute difference between the primary and secondary estimate is recorded as the systematic uncertainty.

For the $\pi^+\acute{\eta}$; $\acute{\eta}\rightarrow\pi^+\pi^-\eta$; $\eta\rightarrow\gamma\gamma$ mode, we do not have any data points in the sidebands of m_{BC} or δm. To estimate the statistical error, we place a data point "by hand" at the center of the largest sideband in each case, and the statistical error is computed from that.

Prediction for Signal from Monte Carlo and Background from Data

Decay Mode of the D_S^+	Expected Signal Events in 586 pb^{-1}	m_{BC}		δm		Expected Background Events in 586 pb^{-1}
		MC Shape	**Data Shape**	**MC Shape**	**Data Shape**	
$K^+K^-\pi^+$	14.1	1.1 ± 0.4	1.0 ± 0.4	2.1 ± 0.5	1.6 ± 0.4	1.1 ± 0.4 (stat) ± 0.8 (syst)
K_sK^+	3.2	1.2 ± 0.5	1.1 ± 0.5	0.4 ± 0.2	0.3 ± 0.2	1.1 ± 0.5 ± 0.8
$\pi^+\eta;\ \eta\to\gamma\gamma$	4.8	1.5 ± 0.7	1.4 ± 0.7	1.5 ± 0.5	1.2 ± 0.4	1.41 ± 0.71 ± 0.04
$\pi^+\acute{\eta};\ \acute{\eta}\to\pi^+\pi^-\eta;\ \eta\to\gamma\gamma$	1.2	0.0 + 0.6	0.0 + 0.7	0.0 + 0.3	0.0 + 0.3	0.0 + 0.6 + 0.0
$K^+K^-\pi^+\pi^0$	5.1	1.8 ± 0.5	1.7 ± 0.5	2.8 ± 0.6	2.2 ± 0.5	1.7 ± 0.5 ± 0.8
$\pi^+\pi^-\pi^+$	3.9	1.6 ± 0.5	1.5 ± 0.4	2.7 ± 0.6	2.1 ± 0.4	1.6 ± 0.5 ± 0.8
$K^{*+}K^{*0};\ K^{*+}\to K^0{}_S\pi^+;\ K^{*0}\to K^-\pi^+$	2.1	1.8 ± 0.6	1.7 ± 0.5	2.2 ± 0.6	1.8 ± 0.5	1.8 ± 0.6 ± 0.2
$\eta\rho^+;\ \eta\to\gamma\gamma;\ \rho^+\to\pi^+\pi^0$	6.0	2.9 ± 0.6	2.7 ± 0.6	3.4 ± 0.6	2.7 ± 0.5	2.8 ± 0.6 ± 0.3
$\acute{\eta}\pi^+;\ \acute{\eta}\to\rho^0\gamma$	2.5	2.1 ± 0.5	1.9 ± 0.5	2.1 ± 0.6	1.7 ± 0.4	2.0 ± 0.5 ± 0.1
Total	**42.9**	**13.9 ± 2.9**	**12.9 ± 2.4**	**17.1 ± 2.3**	**13.6 ± 1.4**	**13.4 ± 2.7 ± 2.7**

Efficiencies that Need to be Estimated

- Then we can calculate the branching ratio for our signal process as:

$$B(D_s^{*+} \to D_s^+ e^+ e^-) = \frac{\sum_{mode} N_S}{L\sigma_{D_s^{\pm} D_s^{*\mp}} \epsilon_{ee} \sum_{mode} (\epsilon_{mode} \epsilon_{sel1} B(D_s^+ \to mode))}$$

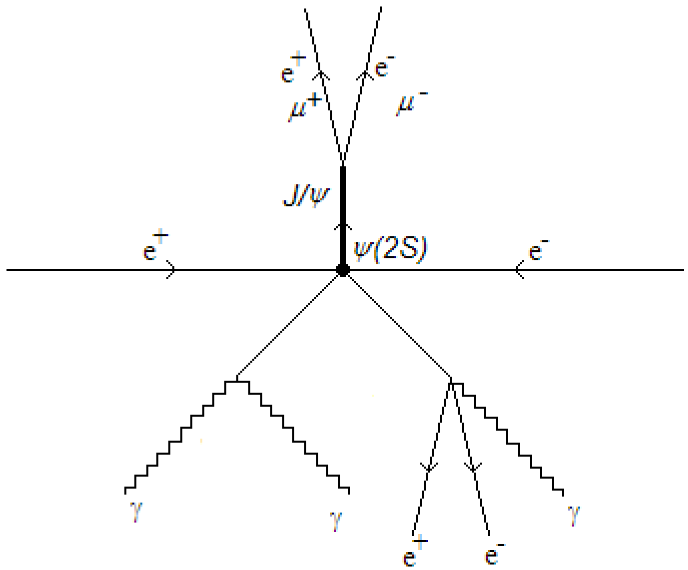
- We can do the same for the Ds* -> Ds \gamma events.

$$B(D_s^{*+} \to D_s^+ \gamma) = \frac{\sum_{mode} N_\gamma}{L\sigma_{D_s^{\pm} D_s^{*\mp}} \epsilon_\gamma \sum_{mode} (\epsilon_{mode} \epsilon_{sel2} B(D_s^+ \to mode))}$$

- Then we can write down the ratio as:

$$\frac{B(D_s^{*+} \to D_s^+ e^+ e^-)}{B(D_s^{*+} \to D_s^+ \gamma)} = \frac{N_S}{N_\gamma} \frac{\epsilon_\gamma}{\epsilon_{ee}} \frac{\sum_{mode} (\epsilon_{mode} \epsilon_{sel2} B(D_s^+ \to mode))}{\sum_{mode} (\epsilon_{mode} \epsilon_{sel1} B(D_s^+ \to mode))}$$

Low Energy Electron Reconstruction Efficiency



$\psi(2S) \rightarrow J/\psi\ \pi^0\ \pi^0$
$J/\psi \rightarrow e^+\ e^-;\ \mu^+\ \mu^-$
$\pi^0 \rightarrow \gamma\ \gamma$
$\pi^0 \rightarrow \gamma\ e^+\ e^-$

- We seek to exploit the electrons from Dalitz decay of the π^0 in this channel to measure the tracking efficiency for soft electrons at CLEO.

- Dataset 42 that has 53 /pb of data at psiprime resonance is used for this study.

- The J/ψ is reconstructed from e^+e^- or $\mu^+\mu^-$. One π^0 is reconstructed from two showers. The shower and an electron from the other π^0 are reconstructed and the missing mass of the last electron is used to measure the reconstruction efficiency.

Conclusion

- In our search for the $D_s^{*+} \rightarrow D_s^+ e^+ e^-$ we have converged on a set of selection criteria that should allow us to extract signal at the estimated level.

- Massive re-reconstruction campaign successful.

- Optimization points for each selection criteria for each channel have been determined.

- Background levels have been estimated for each channel.

- A procedure for estimating the probability that a given number of events is a fluctuation of the background estimation upon un-blinding is being devised.

- The tracking efficiency for soft electrons around 70 MeV is being estimated, which will be incorporated into our branching fraction measurement as a systematic uncertainty or a correction.

- **On the verge of unblinding data.**

If $D_s^{*+} \rightarrow D_s^+ e^+ e^-$ exists, and our QED based estimation of its rate is correct, **we should see a clear signal over the background for it** in our data on un-blinding.

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Backup Slides

Datasets Used

Dataset	Integrated Luminosity $\pm$ stat $\pm$ syst
39	$55.1 \pm 0.03 \pm 0.56\ \mathrm{pb}^{-1}$
40	$123.9 \pm 0.05 \pm 1.3\ \mathrm{pb}^{-1}$
41	$119.1 \pm 0.05 \pm 1.3\ \mathrm{pb}^{-1}$
47	$109.8 \pm 0.05 \pm 1.1\ \mathrm{pb}^{-1}$
48	$178.3 \pm 0.06 \pm 1.9\ \mathrm{pb}^{-1}$
Total	$586.2 \pm 0.11 \pm 6.1\ \mathrm{pb}^{-1}$

The statistical uncertainties are added in quadrature, while the systematic uncertainties are added linearly. Then these two forms of uncertainties are added in quadrature to give us $586 \pm 6\ \mathrm{pb}^{-1}$ of integrated luminosity.

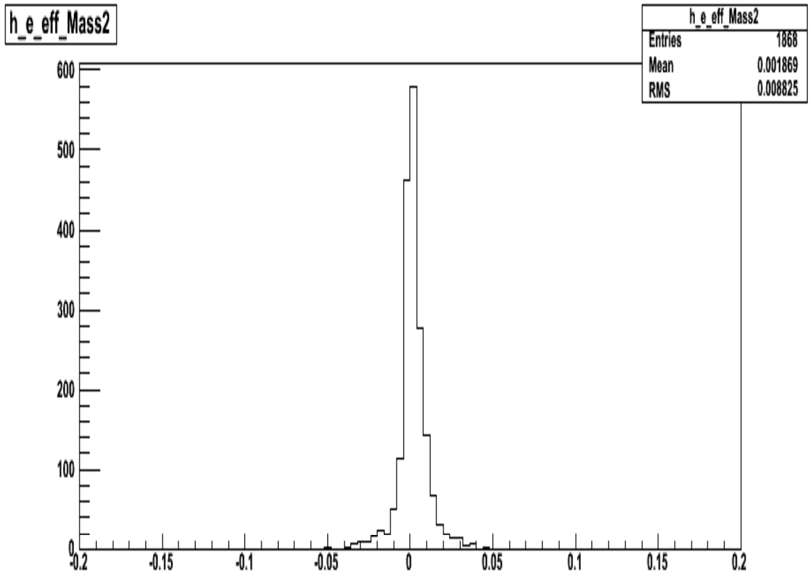
Low Energy Electron Reconstruction Efficiency

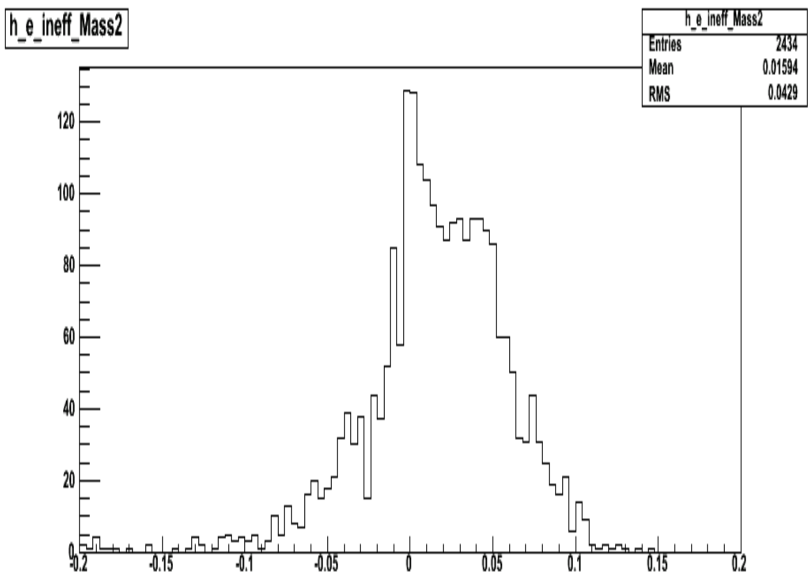
•The missing mass of this last electron is split into two plots:

- •the Efficient plot where the $\psi(2S)$ is correctly reconstructed (top plot)
- •the Inefficient plot where the $\psi(2S)$ is not correctly reconstructed (bottom plot)

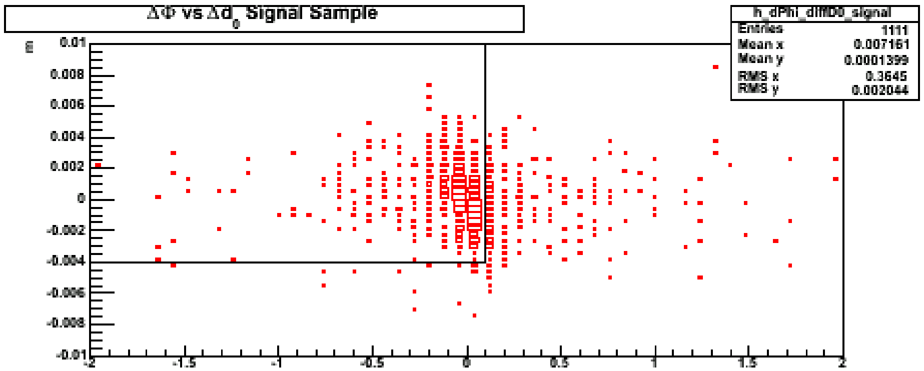
•By cutting and counting, we can roughly estimate the efficiency of electron reconstruction to be ~ 90%

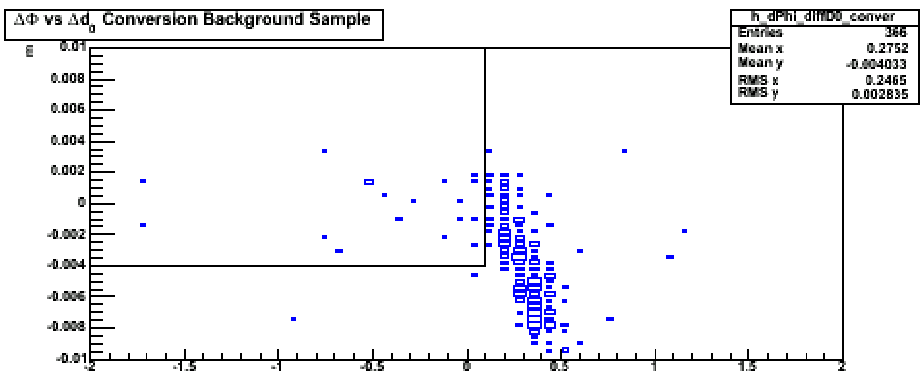
•We will generate Monte Carlo to fit these plots for a more precise measurement.

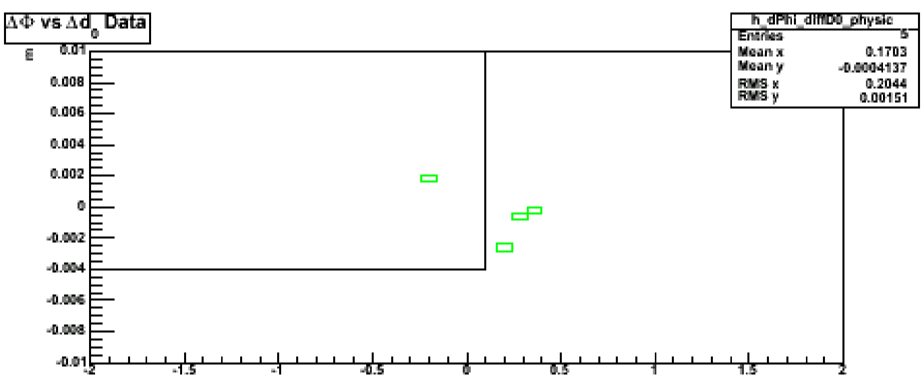


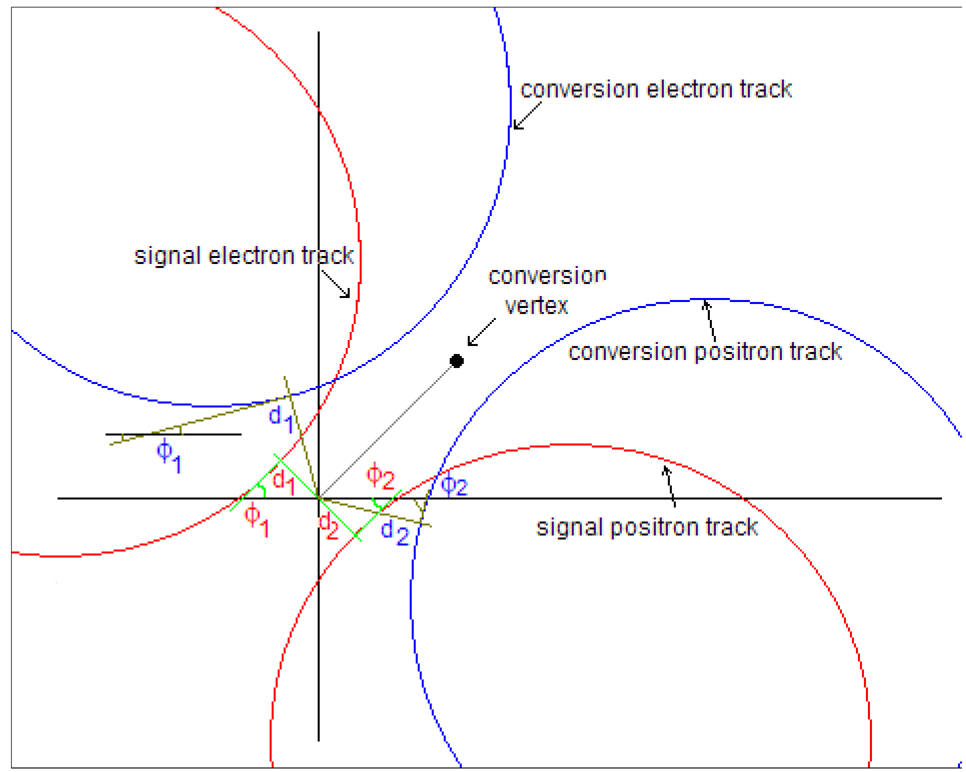


$K^+K^-\pi^+$ Mode $\Delta\Phi$ vs Δd_0









The $\Delta\Phi$ & Δd_0 between the electron and positron in the signal (red) and conversion (blue)

Signal Monte Carlo Samples

- For signal Monte Carlo, we force the e^+e^- collision to produce a $\Psi(4160)$, and that to decay into D_s^{*+} , D_s^{-} $^+$ + c.c.
- We added an EVTGEN plug-in to generate vector (D_s^{*+}) to scalar (D_s^+), lepton (e^-), lepton (e^+) distributions with the invariant amplitude in consideration, apart from the invariant phase space factor.
- The D_s^+ was forced to decay through each of the previously mentioned channels. The D_s^- was allowed to decay generically.
- We fitted electrons to the electron hypothesis as well as the default pion hypothesis.
- We generated 10,000 signal MC events for each decay mode of the D_s^+.

Background Monte Carlo

Continuum Backgrounds

- Combinatoric background from light quark (u, d, s) production. Does dominate in some channels.
- Comes with the datasets. Electrons are pion-fitted.

Generic Backgrounds

- All known physics processes at 4170 MeV involving heavy quark production.
- Comes with the datasets. Electrons are pion-fitted.
- We veto $D_s^{*+} \rightarrow D_s^{+} \gamma$ events from the MC truth and replace them with privately produced and electron fitted conversion MC.

Conversion Background

- For this conversion background Monte Carlo, we force the e^+e^- collision to produce a $\Psi(4160)$, and then that to decay into the D_s^{*+}, D_s^{-}. The D_s^{*+} now decays via D_s^{+},γ . The conversion of the photon to e^+e^- is taken care of in the detector simulation.

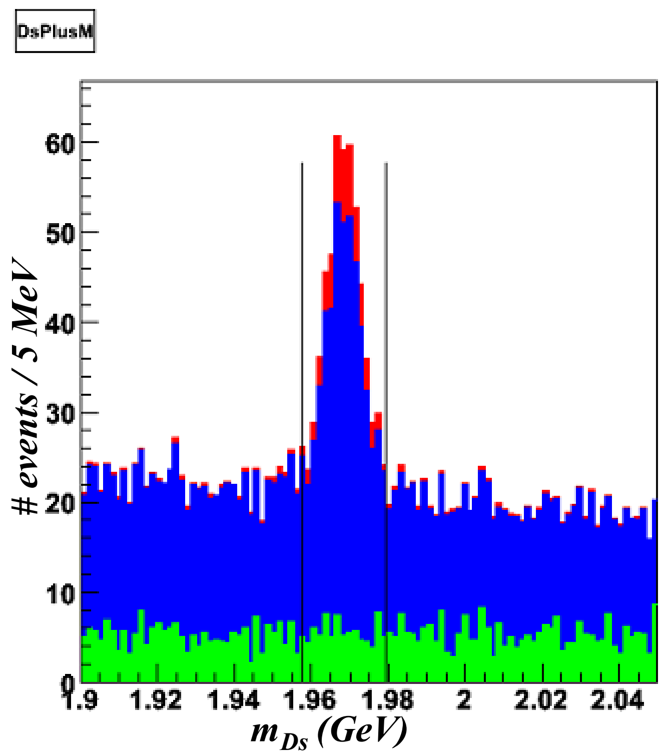
Selection Criteria Common to All D_S^+ Decay Modes

- Electron tracks must pass track quality cuts:
  - 10 MeV < Track Energy < 150 MeV
  - $\chi^2 < 100{,}000$
  - $|d_0| < 5$ mm
  - $|z_0| < 5$ cm
  - *dE/dx* within 3.0σ of that expected for an electron.

- The *DTag* tools applied their default criteria for the nine investigated modes. [5]

- These cuts, and the reconstruction of a D_S^{*+} were required for filling our n-tuples on which we applied subsequent cuts.

m_{Ds} Selection Criterion for the $K^+K^-\pi^+$ Mode



Red: Signal Monte Carlo
Blue: Generic Monte Carlo (c$\underline{c}$ production)
Green: Continuum Monte Carlo (light quarks)

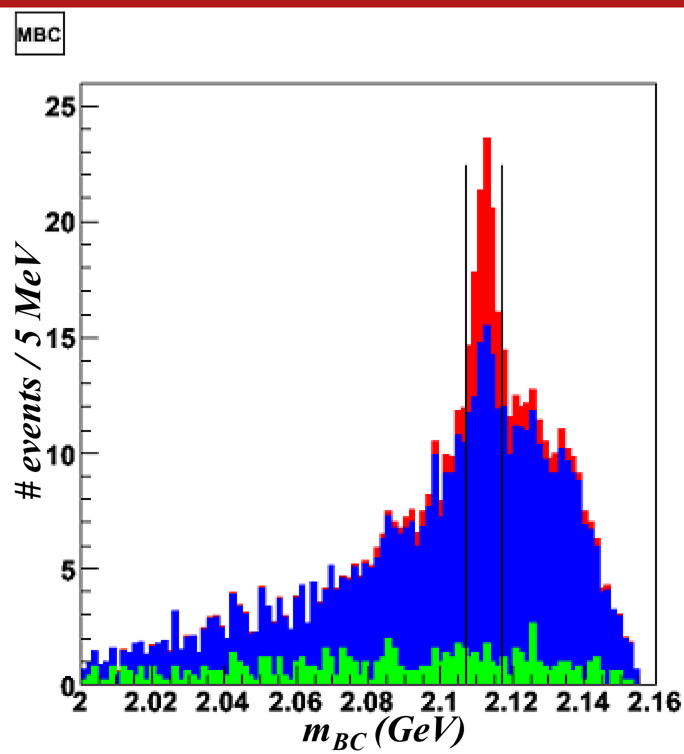
Histograms normalized to 586 pb^{-1}

•We reconstruct the invariant mass m_{D_s} of a D_s from its decay products.

•Selection Criterion for this mode:

$$\left| m_{D_s} - 1.969 GeV \right| < 0.011 GeV$$

m_{BC} Selection Criterion for the $K^{+}K^{-}\pi^{+}$ Mode



Red: Signal Monte Carlo
Blue: Generic Monte Carlo ($c\underline{c}$ production)
Green: Continuum Monte Carlo (light quarks)

Histograms normalized to 586 pb^{-1}

•We know the energy of the CESR beam to high precision. Given the masses of the D_s^* and D_s, we can calculate the energy carried away by the D_s^*

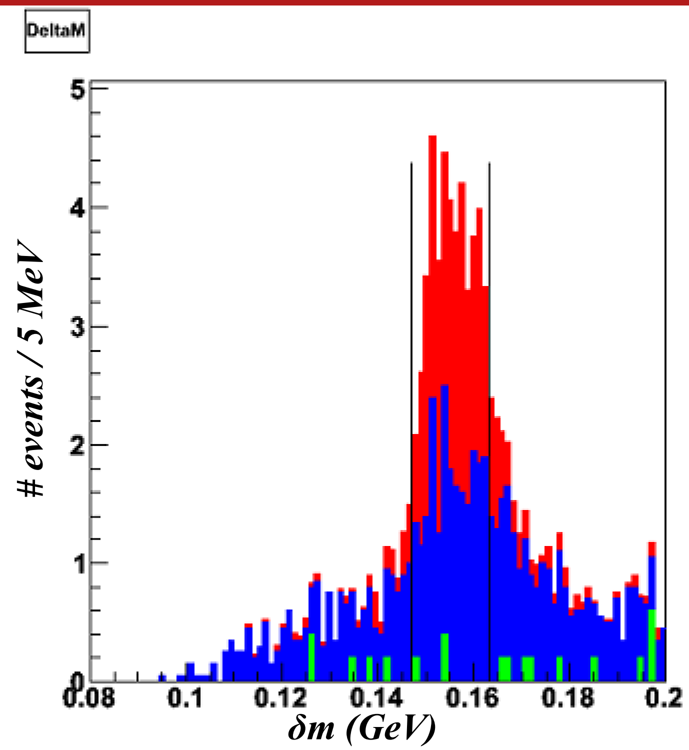
•We define the beam-constrained mass of the D_s^* as:

$$m_{BC} = \sqrt{E^2(D_S^{*+} beam) - P^2(K^+K^-\pi^+e^+e^-)}$$

•Selection Criterion for this mode:

$$|m_{BC} - 2.112 GeV| < 0.004 GeV$$

δm Selection Criterion for the $K^+K^-\pi^+$ Mode



Red: Signal Monte Carlo
Blue: Generic Monte Carlo ($c\underline{c}$ production)
Green: Continuum Monte Carlo (light quarks)

Histograms normalized to 586 pb^{-1}

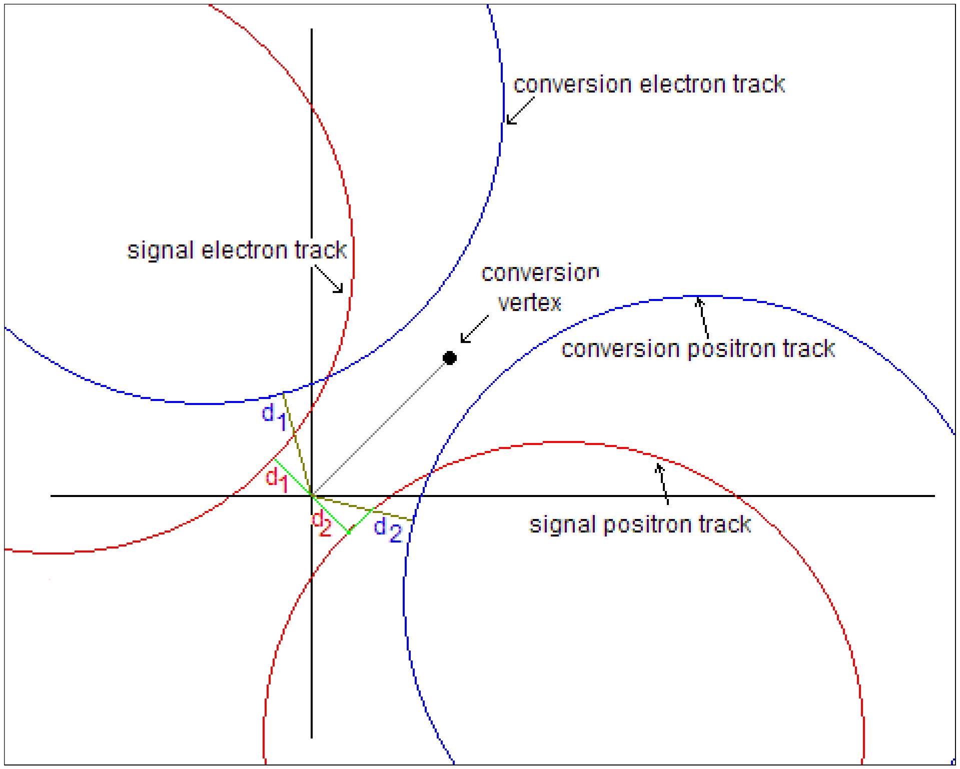
- We define δm as the mass difference the D_s^* and the D_s where both are reconstructed from their daughters:

$$\delta m = M(K^+K^-\pi^+e^+e^-) - M(K^+K^-\pi^+)$$

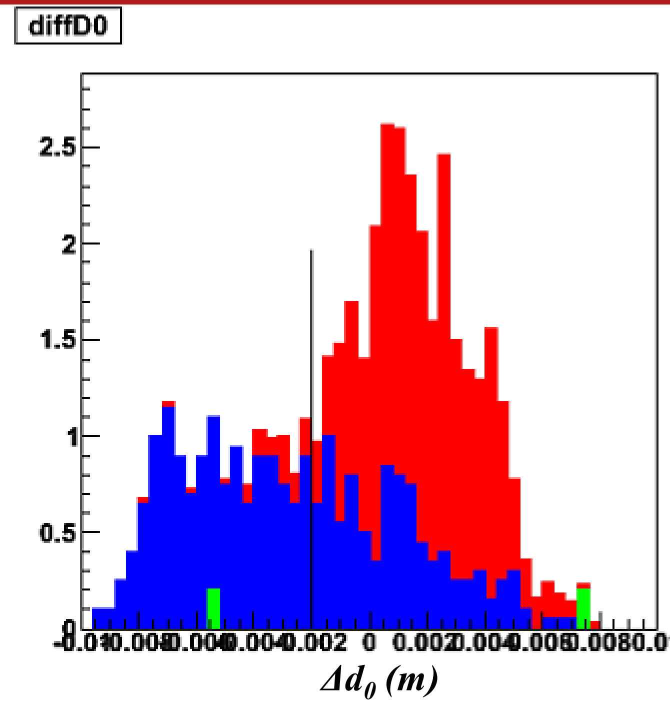
- Selection Criterion for this mode:

$$\left|\delta m - 0.1438 GeV\right| < 0.006 GeV$$

Δd_0 Selection Criterion for the $K^+K^-\pi^+$ Mode



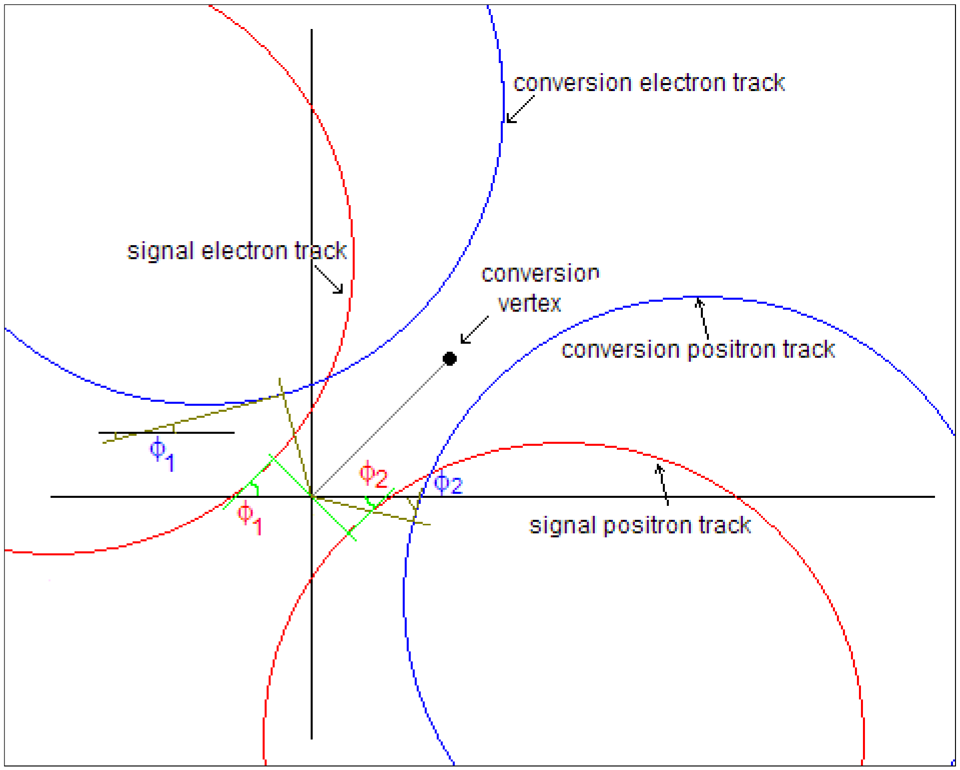
Δd_0 between the electron and positron in the signal (red) and conversion (blue)



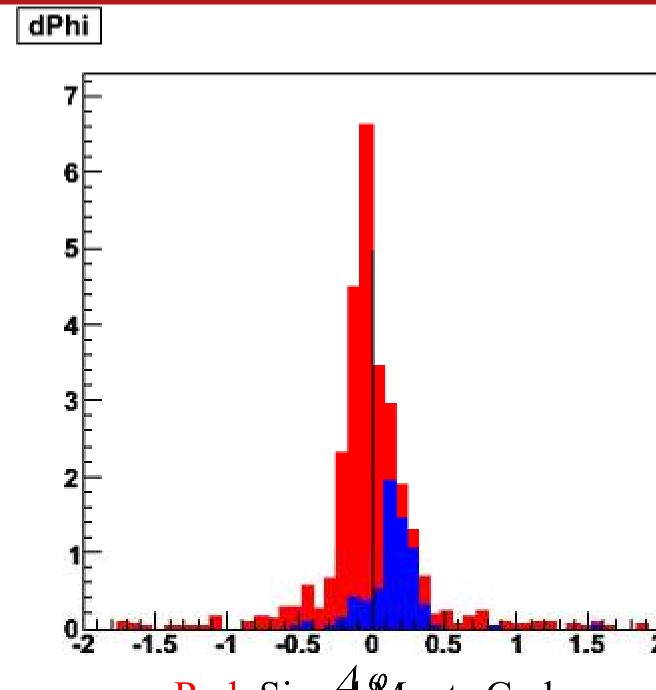
Red: Signal Monte Carlo
Blue: Generic Monte Carlo (heavy quarks)
Green: Continuum Monte Carlo (light quarks)
Histograms normalized to 586 pb^{-1}

- $\boldsymbol{d_0}$: Track's closest distance of approach to the beamline [4]
- The $\Delta d_0 = d_{0\_e-} - d_{0\_e+}$ is centered around 0 for the signal and offset from 0 for conversion backgrounds
- We require $d_1 - d_2 > -6$ mm

$\Delta\varphi$ Selection Criterion for the $K^+K^-\pi^+$ Mode



$\Delta\ \varphi$ between the electron and positron in the signal (red) and conversion (blue)



Red: Signal Monte Carlo
Blue: Generic Monte Carlo (heavy quarks)
Green: Continuum Monte Carlo (light quarks)
Histograms normalized to 586 pb^{-1}

- ***φ***: Azimuth of track at origin [4]

- $\Delta\varphi = \varphi_{e-} - \varphi_{e+}$ is centered around 0 for the signal and offset for the conversion background.
- We require $\Delta\varphi < 0.1$

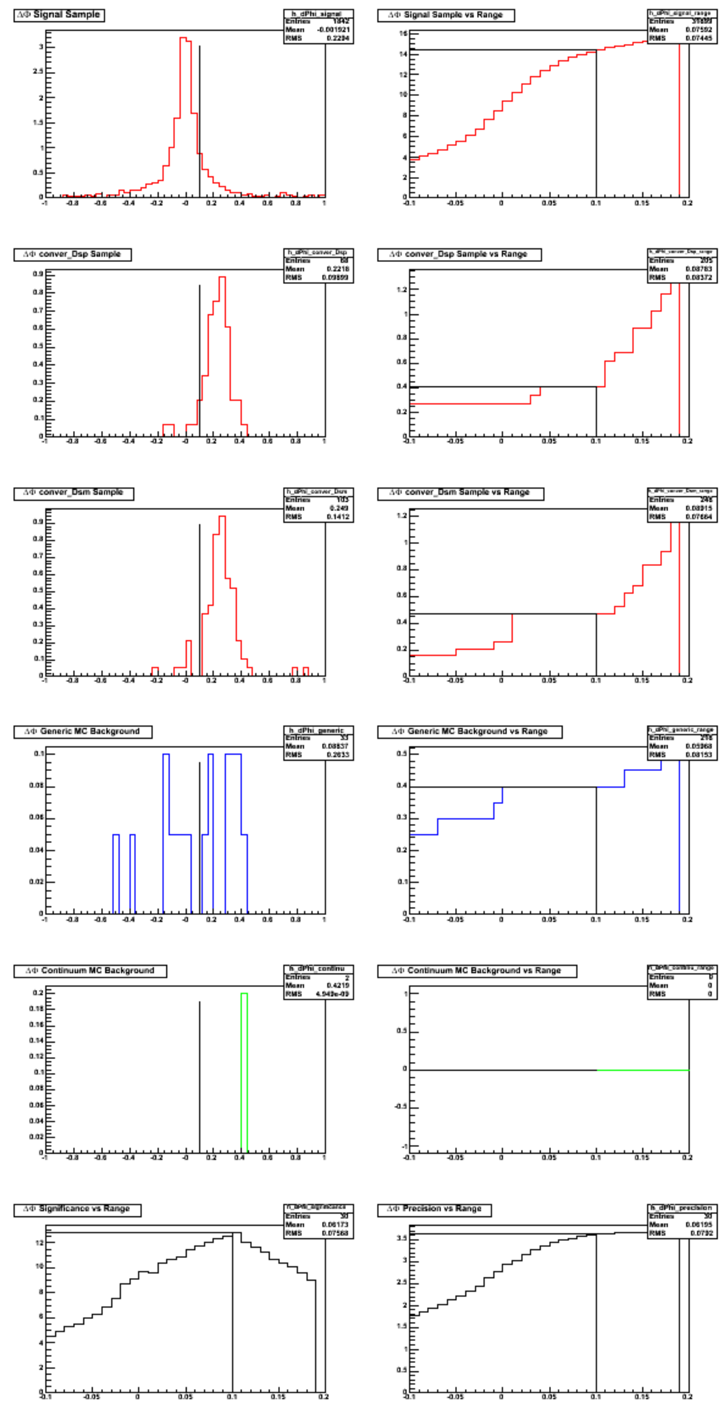
- **A powerful criterion against the photon conversion background.**

Optimizing Selection Criteria

•We went channel by channel, criterion by criterion. (Example of $\Delta\Phi$ Selection Criterion for the $K^+K^-\pi^+$ Mode on the right)

•Plotted the signal MC, conversion MC, generic without conversion MC, and continuum MC vs variation in the cut.

•Optimized for significance [s/√b] for low-statistics channels and precision [s/ √(s+b)] for high-statistics channels.



Prediction for Signal from Monte Carlo

Decay Mode of the D_S^+	Expected Signal Events in 586 pb^{-1}	Expected Background Events in 586 pb^{-1}
$K^+K^-\pi^+$	14.1	1.1
K_sK^+	3.2	0.5
$\pi^+\eta;\ \eta\rightarrow\gamma\gamma$	4.8	0.5
$\pi^+\eta';\ \eta'\rightarrow\pi^+\pi^-\eta;\ \eta\rightarrow\gamma\gamma$	1.2	0.0
$K^+K^-\pi^+\pi^0$	5.1	2.2
$\pi^+\pi^-\pi^+$	3.9	2.1
$K^{*+}K^{*0};\ K^{*+}\rightarrow K^0_S\pi^+;\ K^{*0}\rightarrow K^-\pi^+$	2.1	1.0
$\eta\rho^+;\ \eta\rightarrow\gamma\gamma;\ \rho^+\rightarrow\pi^+\pi^0$	6.0	2.5
$\eta'\pi^+;\ \eta'\rightarrow\rho^0\gamma$	2.5	2.3
Total	**42.9**	**12.2**

signal/√background = **12.3**, would've been **9.1** for pion-fitted data.

If $D_s^{*+} \rightarrow D_s^+e^+e^-$ exists, and our QED based estimation of its rate is correct, **we should see a clear signal over the background for it** in our data on unblinding.