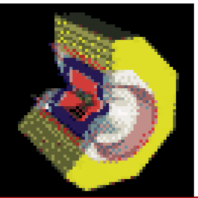


Cornell University
Laboratory for
Elementary-Particle Physics

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

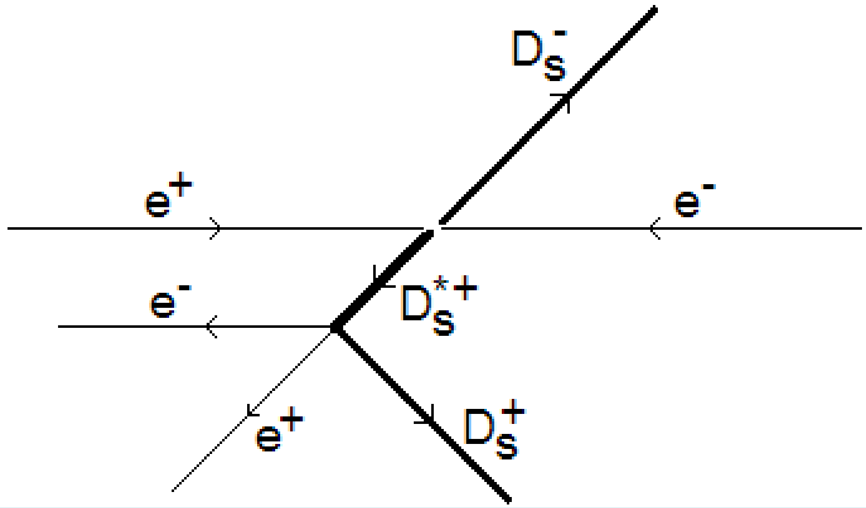
Souvik Das

Cornell University
For the CLEO Collaboration

Contents

8 April 2010

What Are We Looking For?



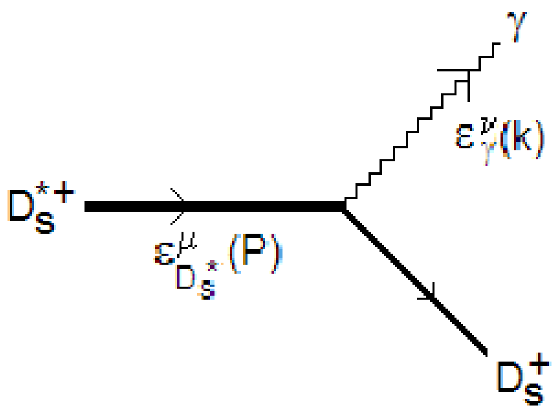
- Searching for $D_s^{*+} \rightarrow D_s^+ e^+ e^-$ with a **blind analysis**.

- Known decay channels are:
  - $D_s^{*+} \rightarrow D_s^+ \gamma$; Branching Fraction = 94.2%
  - $D_s^{*+} \rightarrow D_s^+ \pi^0$; 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 ± 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.

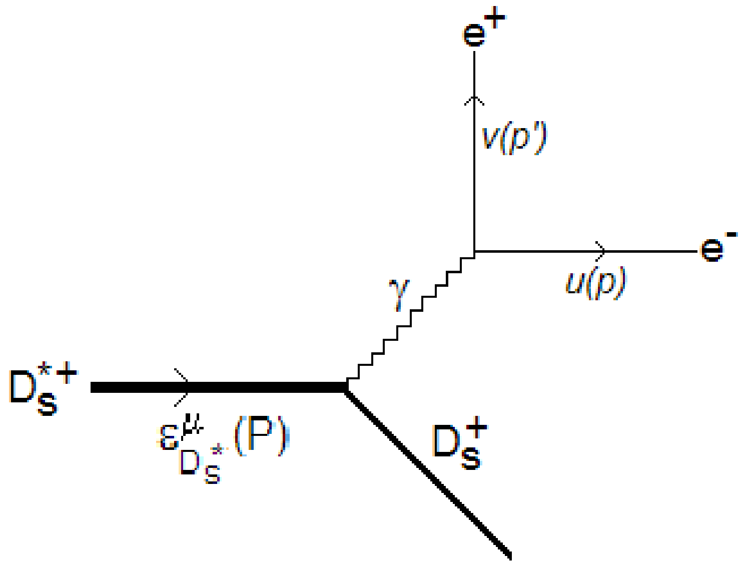
Predicted $D_s^{*\pm} \to D_s^{\pm} e^+ e^-$ Rate



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

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

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



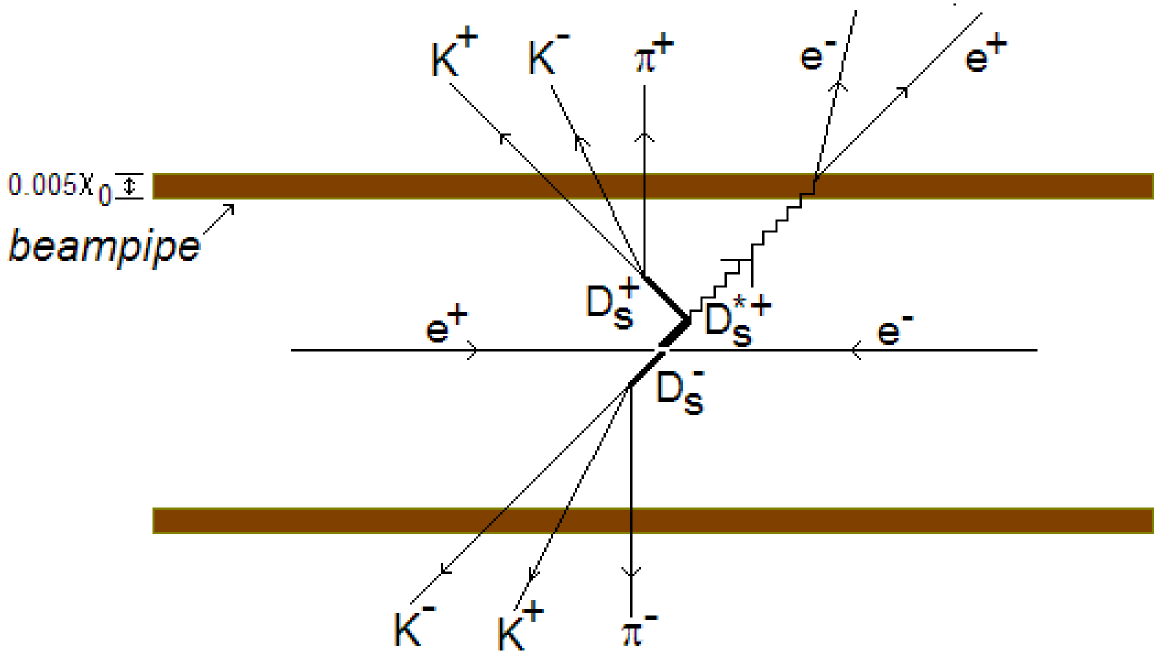
Then we can write the matrix element of the decay to e^+e^- in the form:

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

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

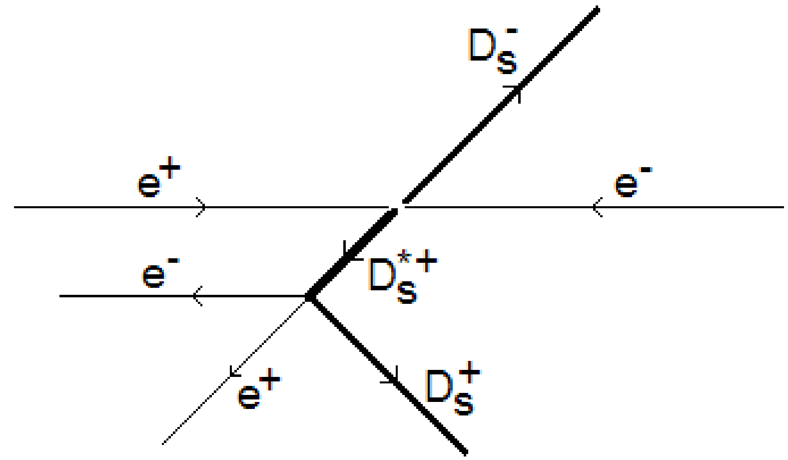
- A background that resembles the signal is expected from D_s^{*+} decaying to $D_s^+ \gamma$ and the γ converting to e^+e^- in the beam-pipe and other material.
- Given that the beam-pipe is ~ 0.5% of a radiation length, we can estimate this conversion background to occur at roughly the same rate as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



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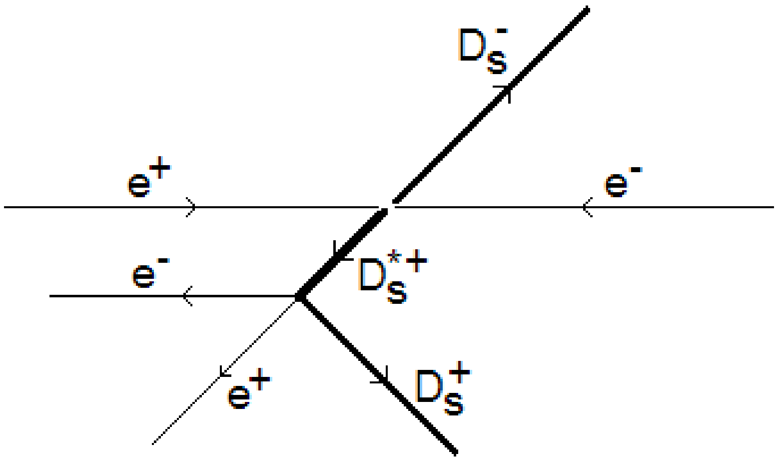

$$D_s^+ \rightarrow K^+K^-\pi^+$$

$$D_s^+ \rightarrow K_S K^+$$

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

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

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Analysis Strategy

•We will fully reconstruct the D_s^*

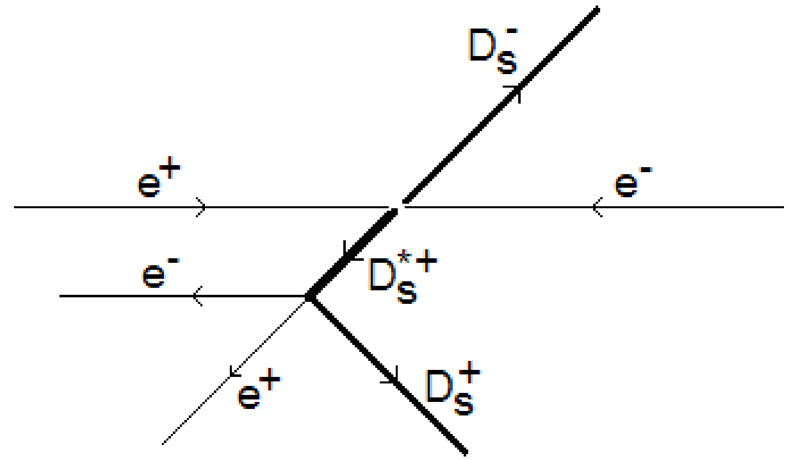
•The D_s *on the side of the* D_s^* is reconstructed through several tagged decay channels:

•The e^+e^- share ~ 144 MeV

•By default CLEO-c does not use electron mass hypothesis in its Kalman Fit

•Pion-mass hypothesis results in significant deviation in momentum < 70 MeV

•Motivated a massive re-reconstruction campaign to include electron hypothesis fit



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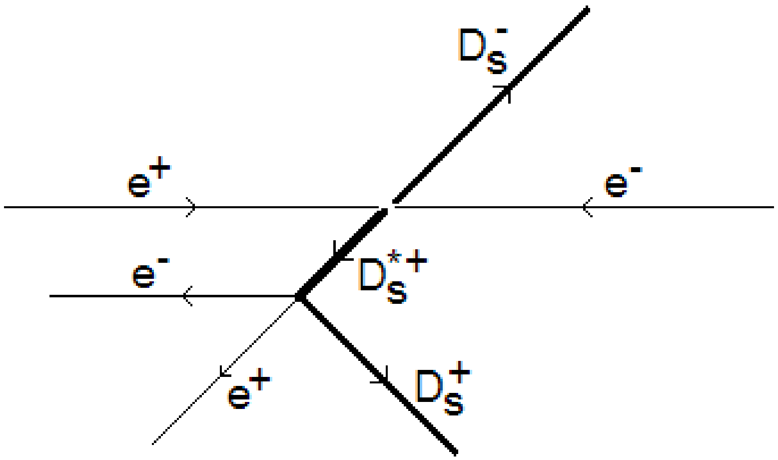

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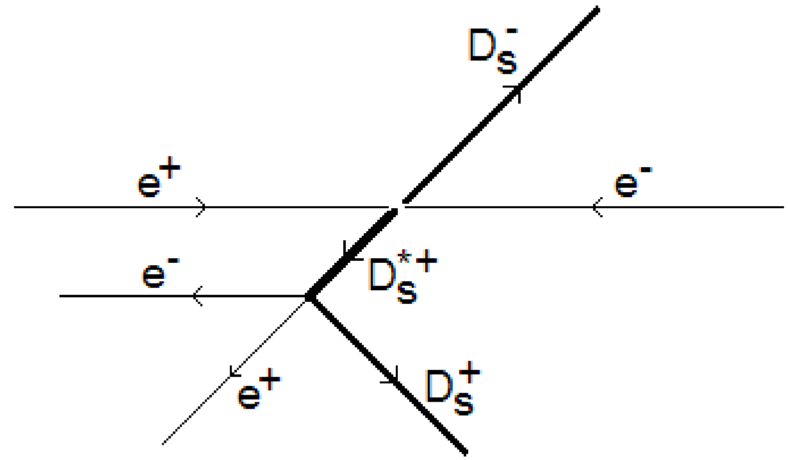
•Criteria based on the *track parameters* of the e^+ and e^- are powerful against the photon conversion background



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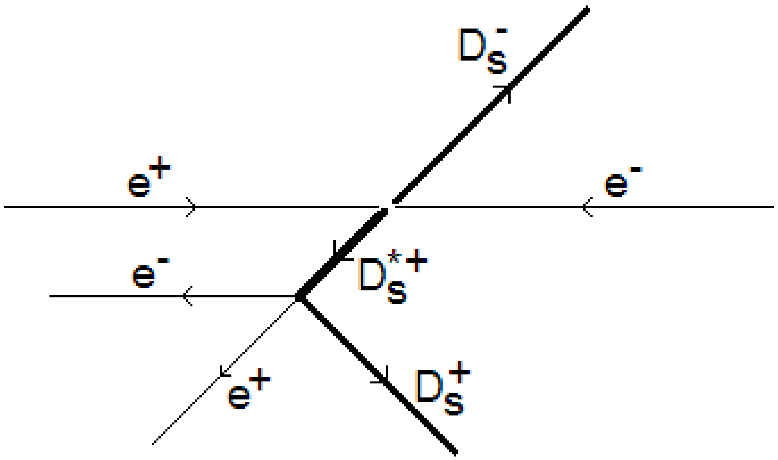
- Selection criteria based on the *invariant masses* of the D_s and D_s^* are used

- Criteria based on the *track parameters* of the e^+ and e^- are powerful against the photon conversion background

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

- This talk will focus only on $\Gamma\left(D_s^{*+} \to D_s^+ e^+ e^-\right)$



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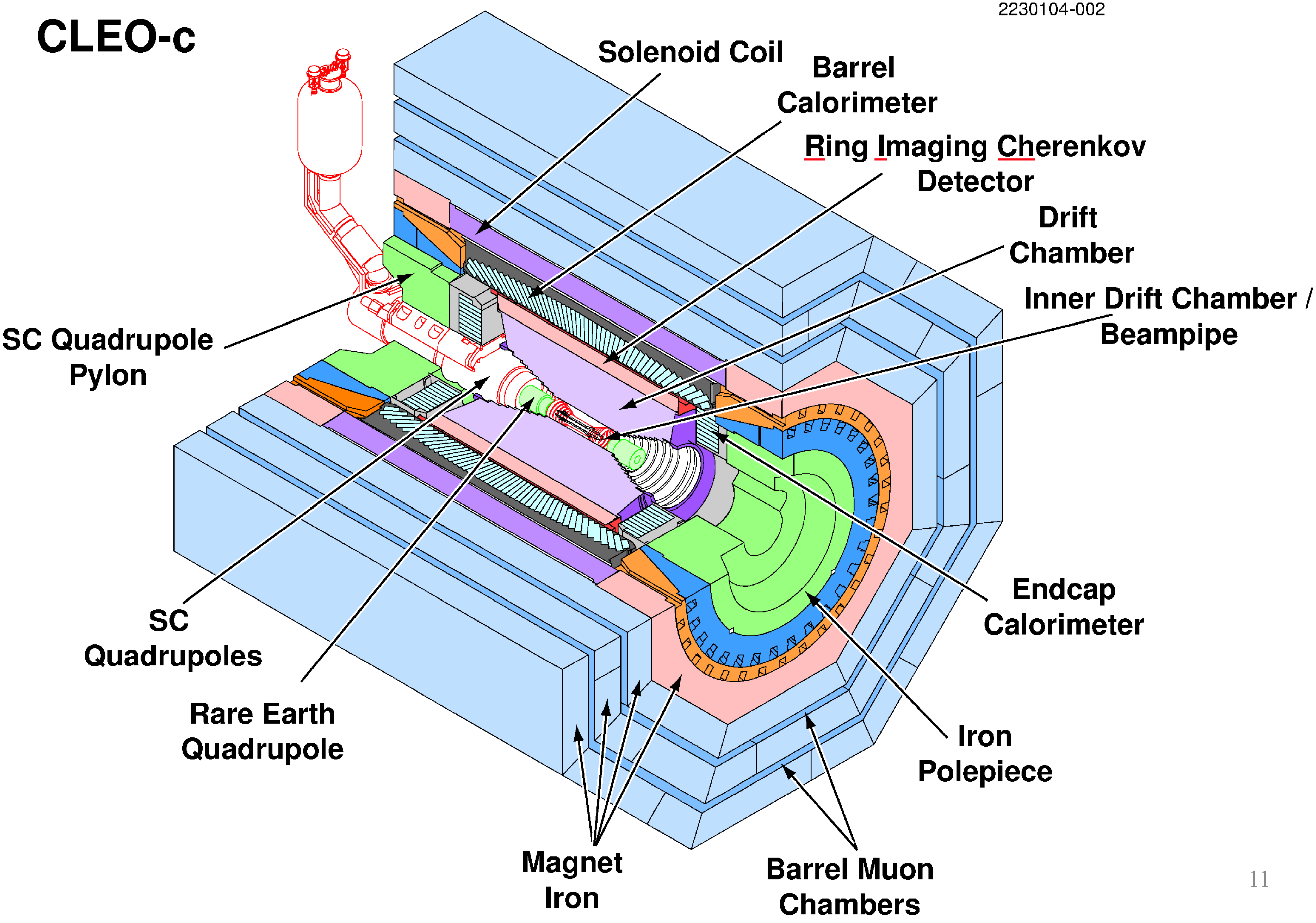
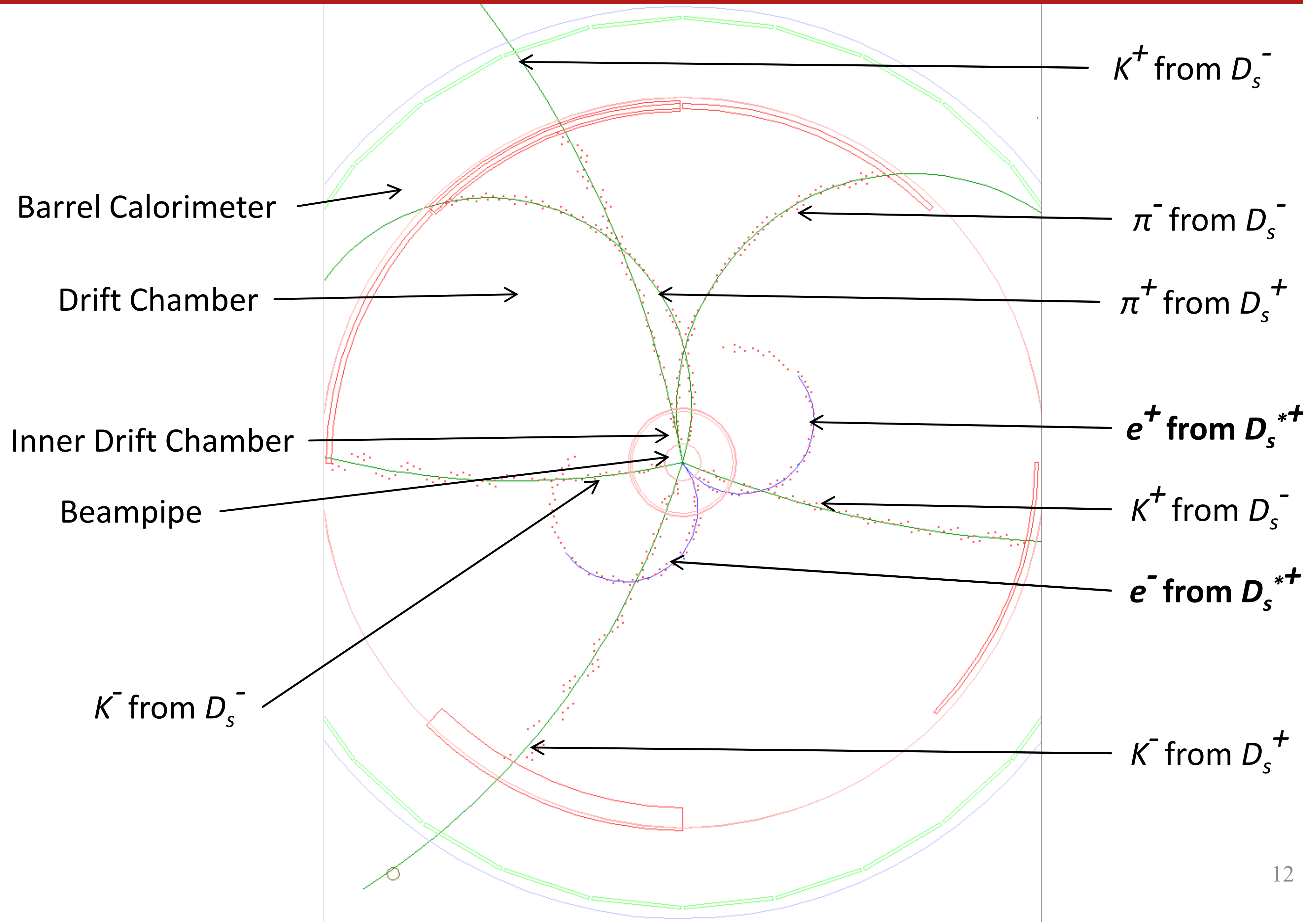
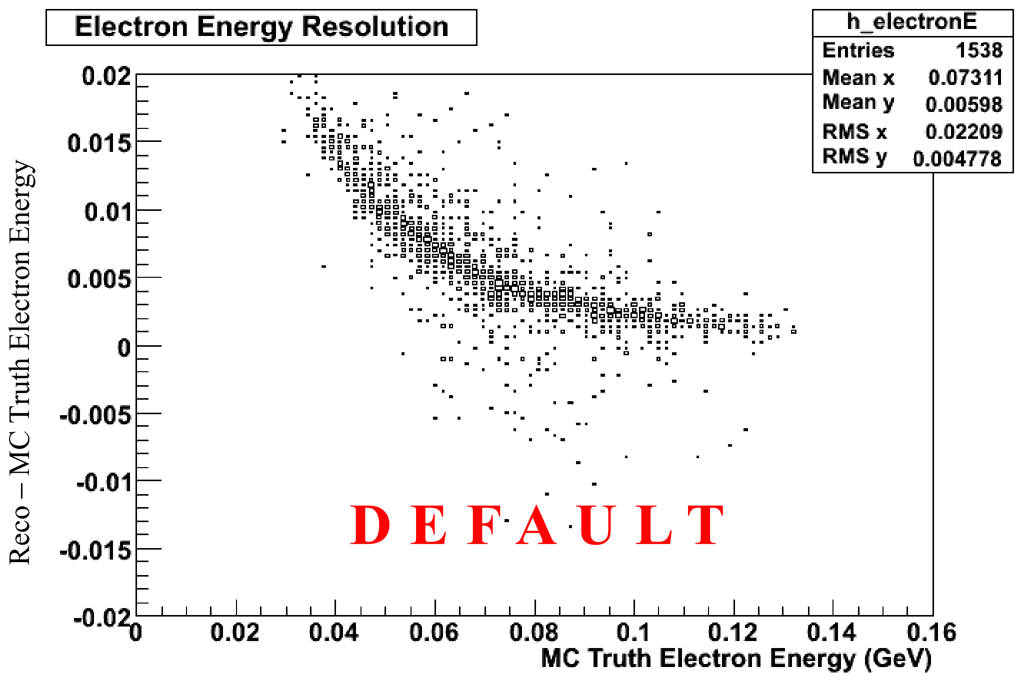
The CLEO-c Detector



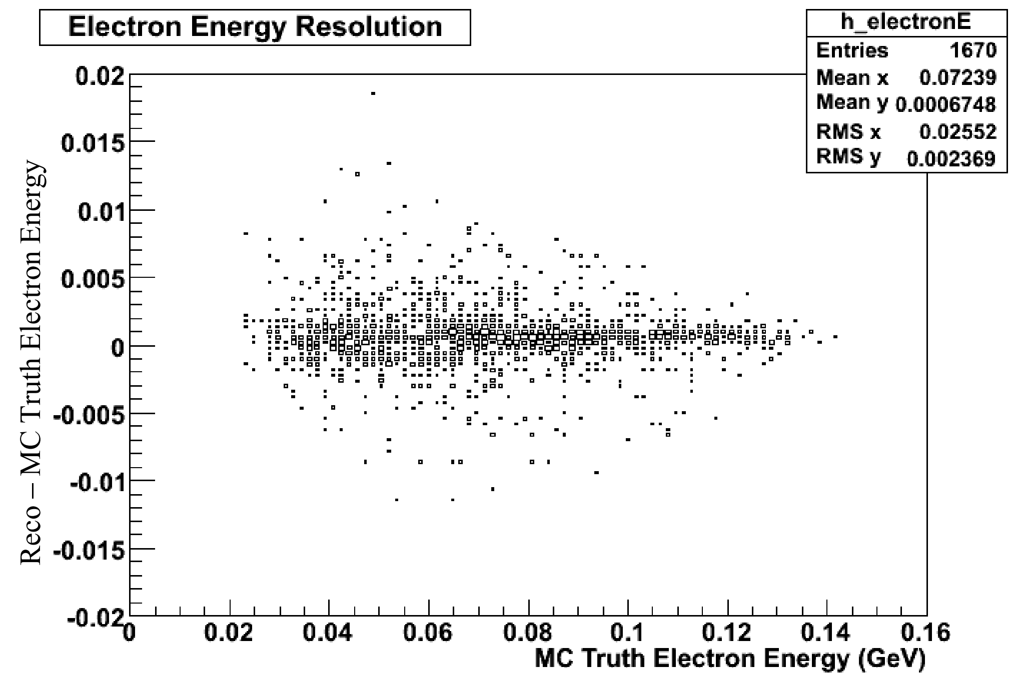
A Simulated Signal Event



Tracking Soft Electrons



Pion fit



Electron fit

- With electron tracks of $p_T < 70$ MeV, fitting to the pion mass hypothesis no longer reliable.
- 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

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.

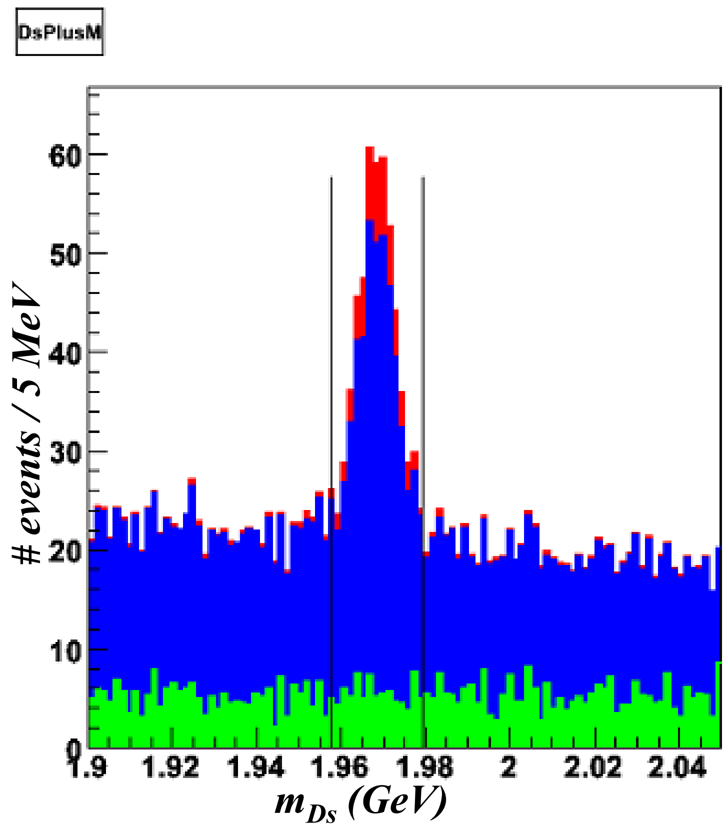
Selection Criteria Common to All D_S^+ Decay Modes

- 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)

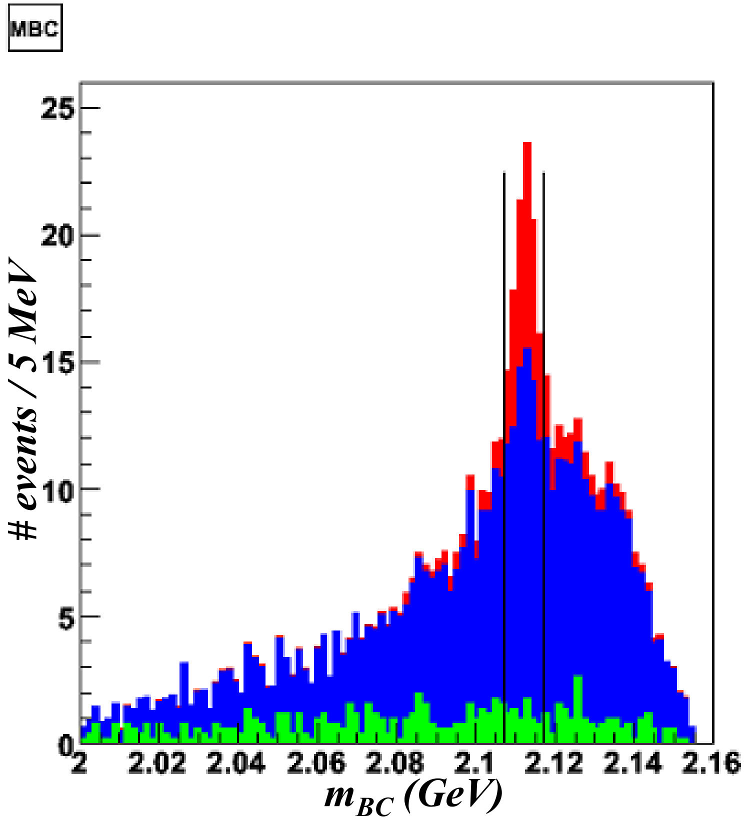
Histograms normalized to 586 pb^{-1}

- 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^*

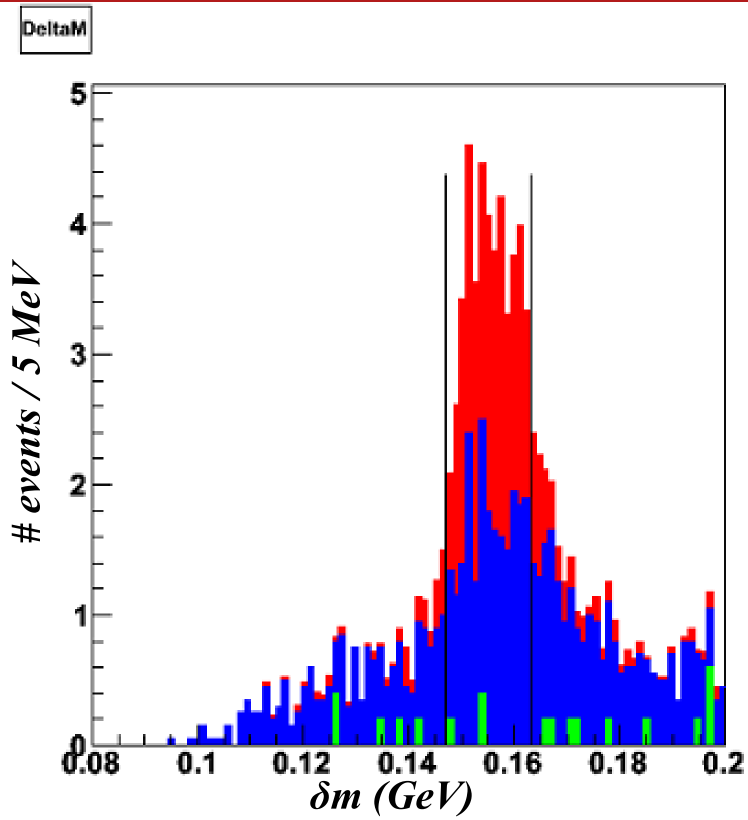
- We define the beam-constrained mass of the D_s^* as:

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

- Selection Criterion for this mode:

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

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}

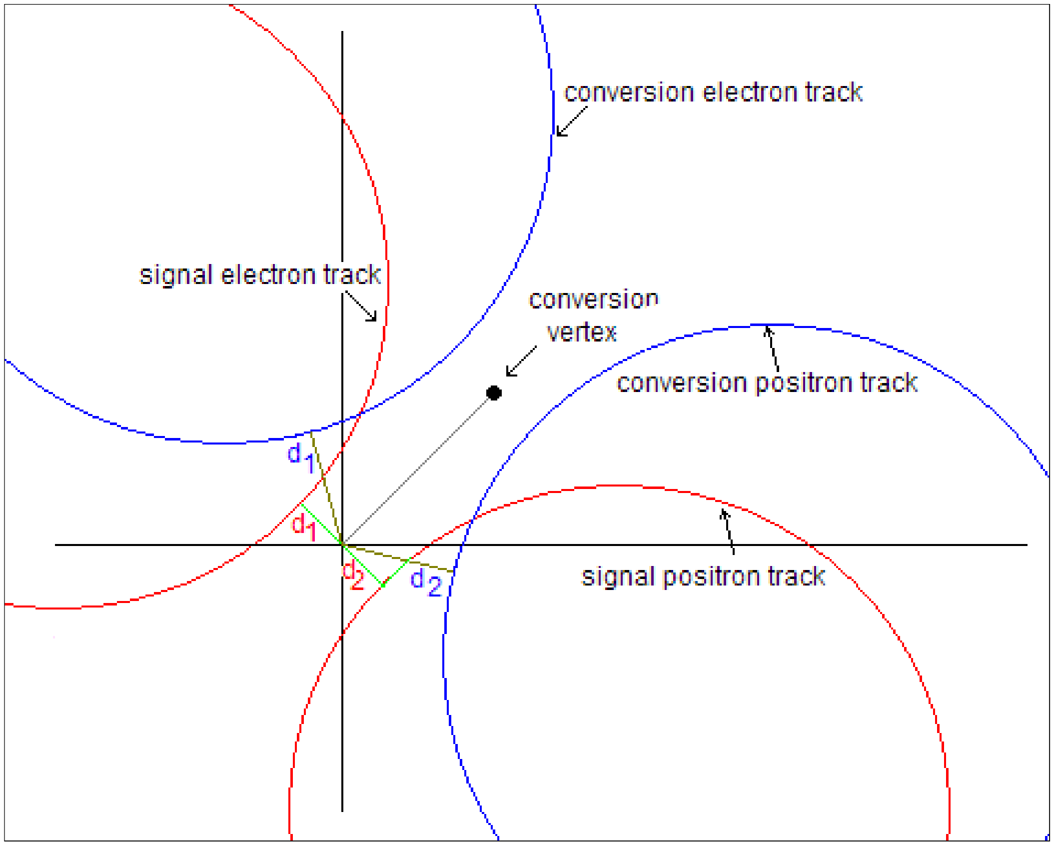
•We define δm as the mass difference the D_s^* and the D_s where both are reconstructed from their daughters:

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

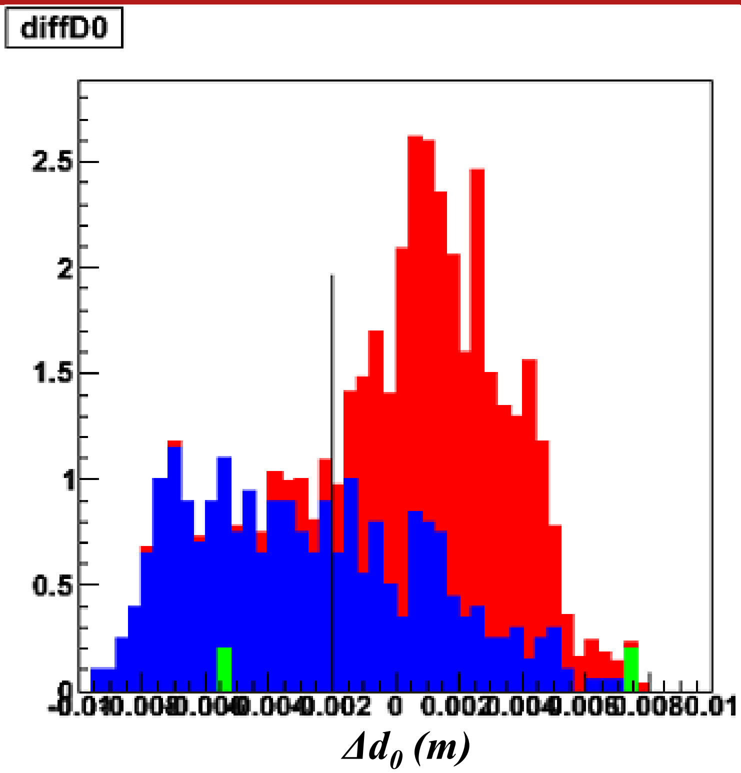
•Selection Criterion for this mode:

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

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



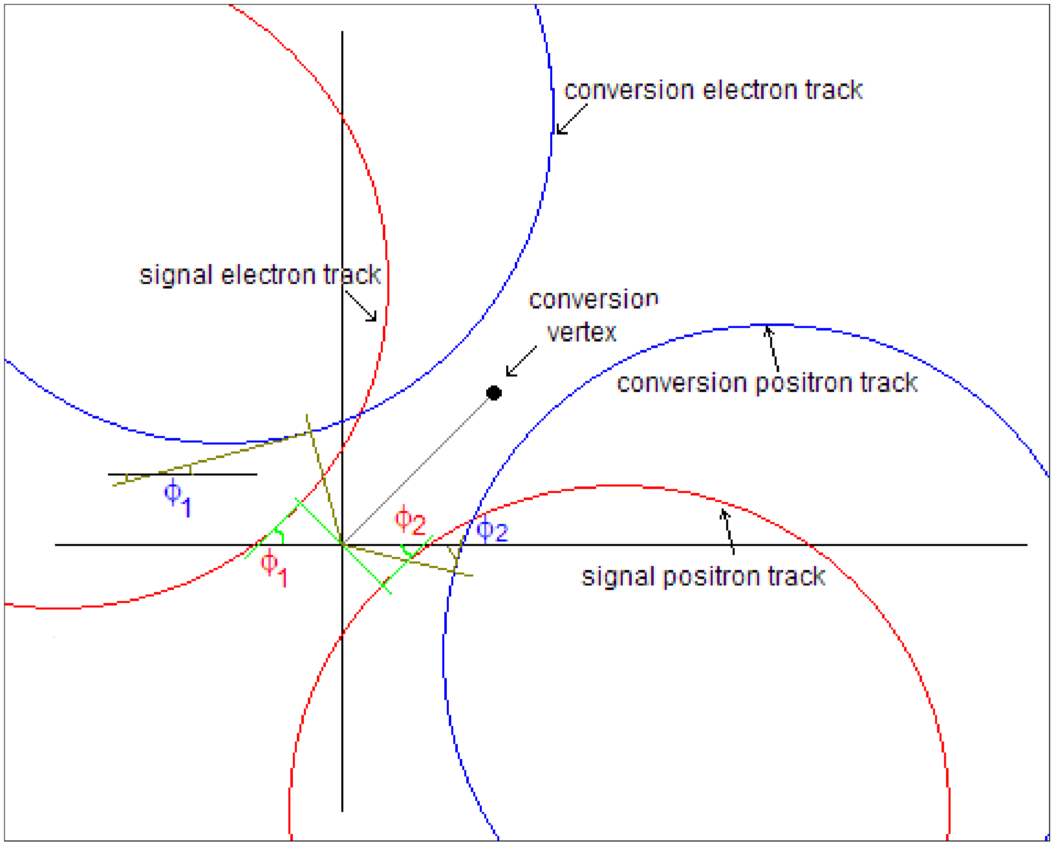
Δd_0 between the electron and positron in the signal (red) and conversion (blue)



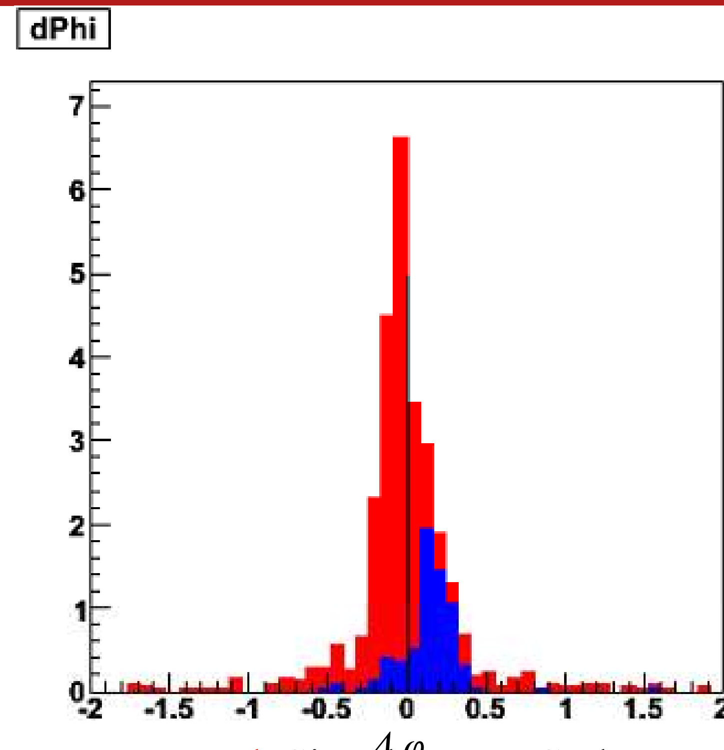
Red: Signal Monte Carlo
Blue: Generic Monte Carlo (heavy quarks)
Green: Continuum Monte Carlo (light quarks)
Histograms normalized to 586 pb^{-1}

- ***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 $\Delta\varphi < 0.1$

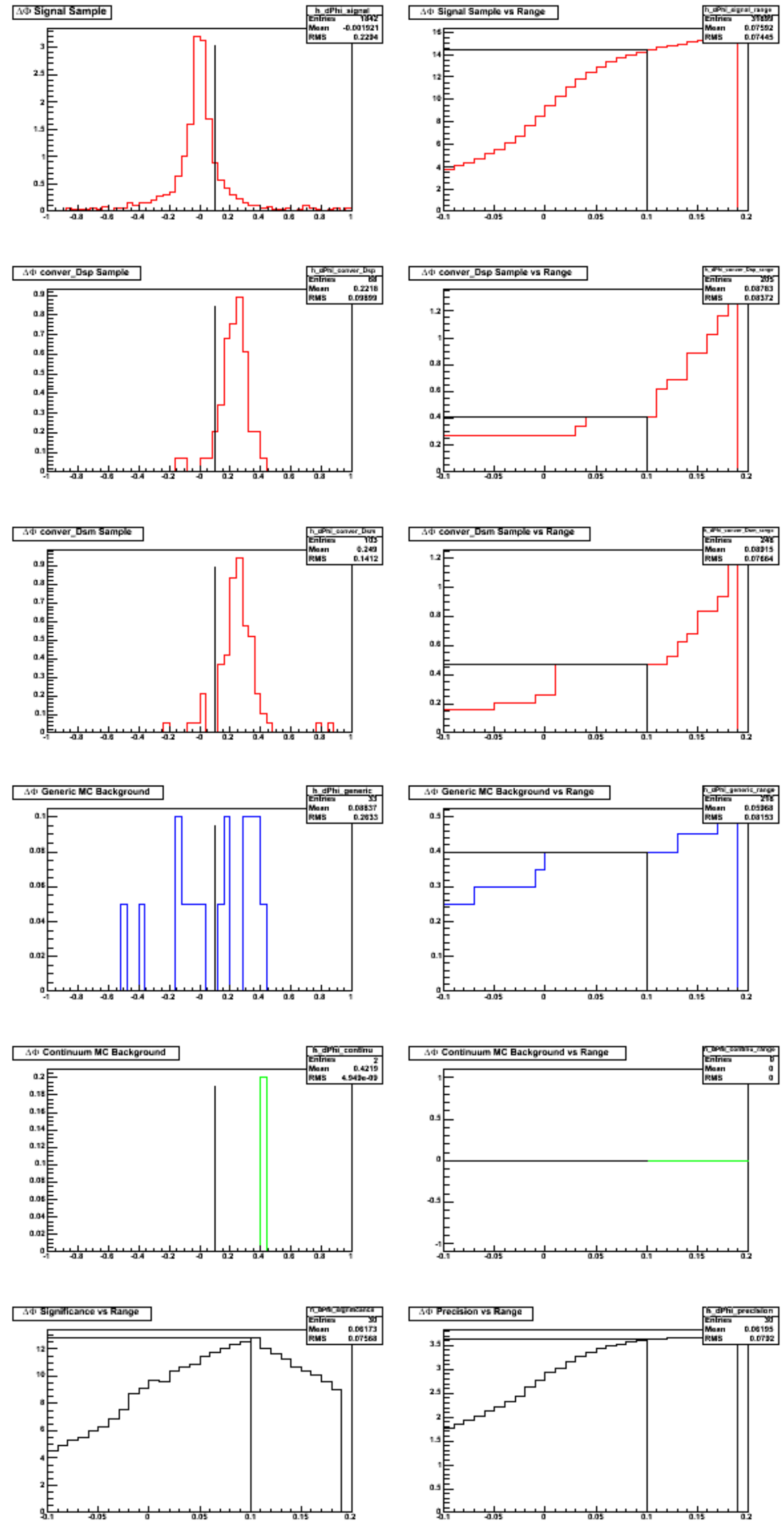
- **A powerful criterion against the photon conversion background.**

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.



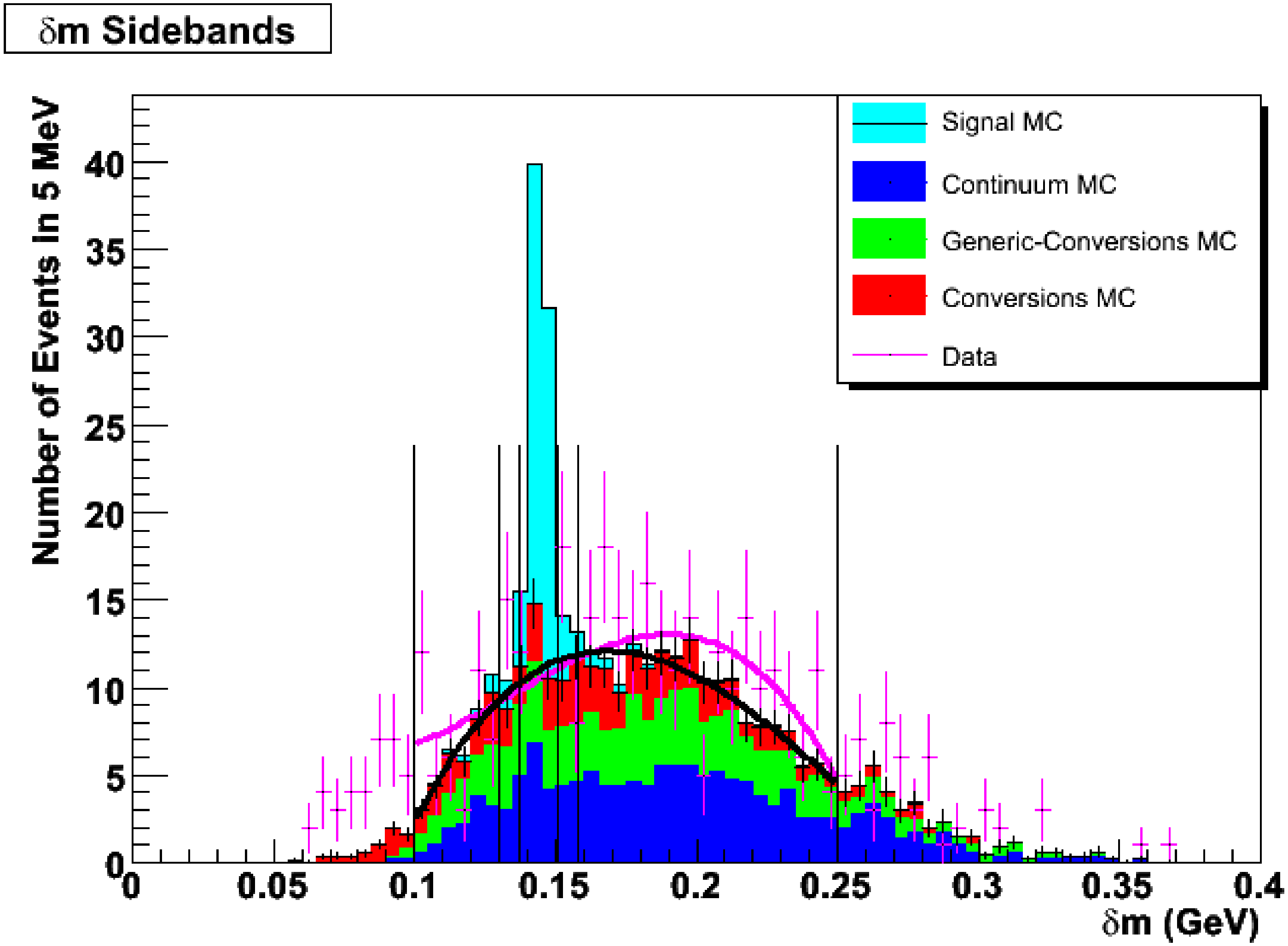
Prediction for Signal from Monte Carlo

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
$\pi^+\eta;\ \eta\to\gamma\gamma$	4.8	0.5
$\pi^+\acute{\eta};\ \acute{\eta}\to\pi^+\pi^-\eta;\ \eta\to\gamma\gamma$	1.2	0.0
$K^+K^-\pi^+\pi^0$	5.1	2.2
$\pi^+\pi^-\pi^+$	3.9	2.1
$K^{*+}K^{*0};\ K^{*+}\to K^0{}_S\pi^+;\ K^{*0}\to K^-\pi^+$	2.1	1.0
$\eta\rho^+;\ \eta\to\gamma\gamma;\ \rho^+\to\pi^+\pi^0$	6.0	2.5
$\acute{\eta}\pi^+;\ \acute{\eta}\to\rho^0\gamma$	2.5	2.3
Total	**42.9**	**12.2**

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

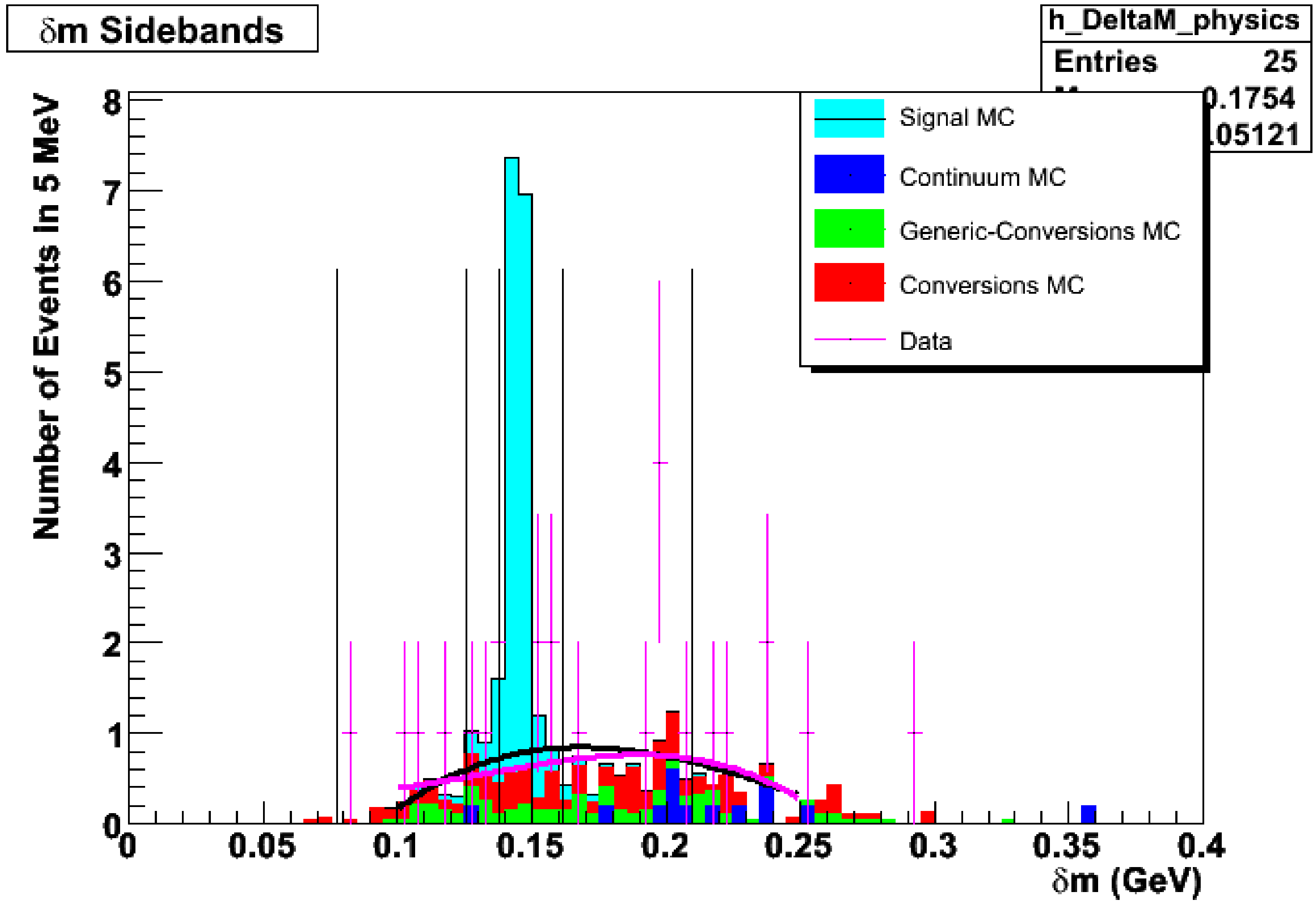
If $D_s^{*+} \to D_s^+e^+e^-$ exists, and our QED based estimation of its rate is correct, **we should see a clear signal over the background for it** in our data on unblinding.

Estimation of Background from δm Sidebands



- δm is plotted with all other cuts applied. δm was chosen as it is the flattest among all the parameters.
- Trying to fit a shape to the individual channels is impossible due to low statistics.
- Add all channels, double the m_{BC} cut width for each channel, and determine a fit shape from
    - Monte Carlo backgrounds (black curve)
    - Data in the sidebands (signal region is still blind!) (pink curve)
- Fit these curves in the individual channels to estimate background in the signal region.

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



- Expected background from the:
  - Monte Carlo shape (black curve): 1.8
  - Data shape (pink curve): 1.5

Prediction for Signal from Monte Carlo and Data Sidebands

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	1.8	1.5
K_sK^+	3.2	0.5	0.39	0.31
$\pi^+\eta;\ \eta\to\gamma\gamma$	4.8	0.5	1.7	1.3
$\pi^+\acute{\eta};\ \acute{\eta}\to\pi^+\pi^-\eta;\ \eta\to\gamma\gamma$	1.2	0.0	0.0	0.0
$K^+K^-\pi^+\pi^0$	5.1	2.2	2.9	2.3
$\pi^+\pi^-\pi^+$	3.9	2.1	2.8	2.2
$K^{*+}K^{*0};\ K^{*+}\to K^0{}_S\pi^+;\ K^{*0}\to K^-\pi^+$	2.1	1.0	2.3	1.8
$\eta\rho^+;\ \eta\to\gamma\gamma;\ \rho^+\to\pi^+\pi^0$	6.0	2.5	3.7	2.9
$\acute{\eta}\pi^+;\ \acute{\eta}\to\rho^0\gamma$	2.5	2.3	2.1	1.7
Total	**42.9**	**12.2**	**17.7**	**14.0**

If $D_s^{*+} \to D_s^+e^+e^-$ 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.

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 are being studied by looking at data in the sideband regions.

- The tracking efficiency for such soft electrons in CLEO is unknown. It will contribute to our systematic uncertainties. This is being estimated by studying the electrons from:

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

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

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5. Peter Onyisi and Werner Sun. Developments in D(s)-tagging. CBX 06-11, 2006.

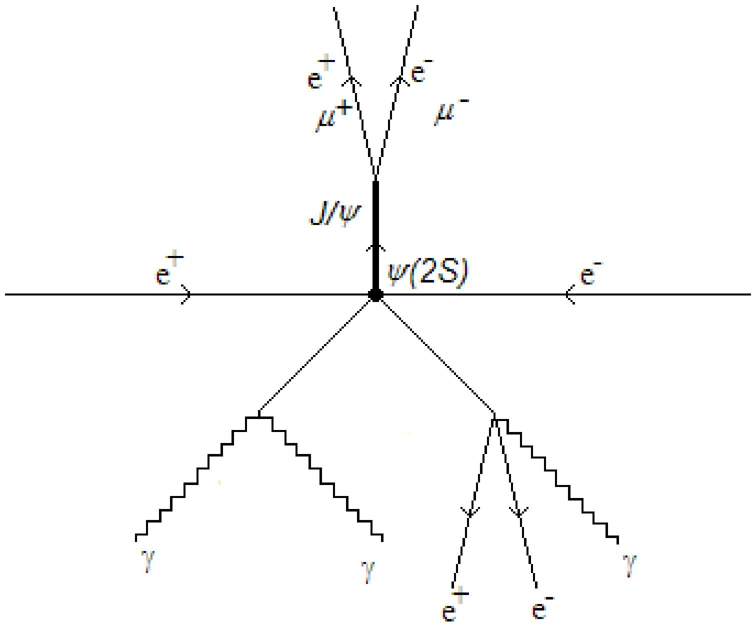
Backup Slides

Datasets Used

Dataset	Integrated Luminosity $\pm$ stat $\pm$ syst
39	$55.1 \pm 0.03 \pm 0.56$ pb^{-1}
40	$123.9 \pm 0.05 \pm 1.3$ pb^{-1}
41	$119.1 \pm 0.05 \pm 1.3$ pb^{-1}
47	$109.8 \pm 0.05 \pm 1.1$ pb^{-1}
48	$178.3 \pm 0.06 \pm 1.9$ pb^{-1}
Total	$586.2 \pm 0.11 \pm 6.1$ 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 ± 6 pb^{-1} of integrated luminosity.

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.

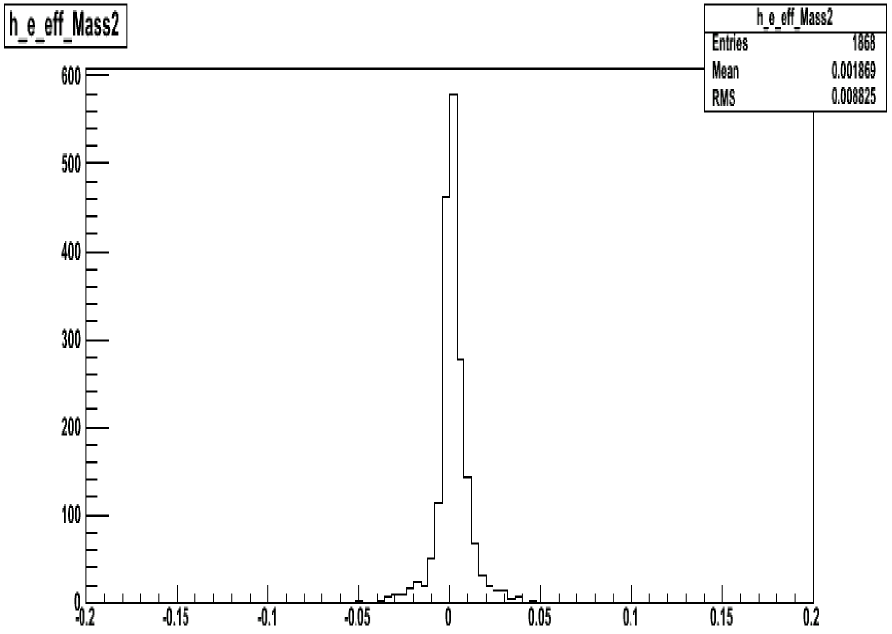
•The J/ψ is reconstructed from e^+e^- or $\mu^+\mu^-$. One π^0 is reconstructed from two showers. The shower and an electron from the other π^0 are reconstructed and the expected 4-vector of the last electron is constructed from the above information.

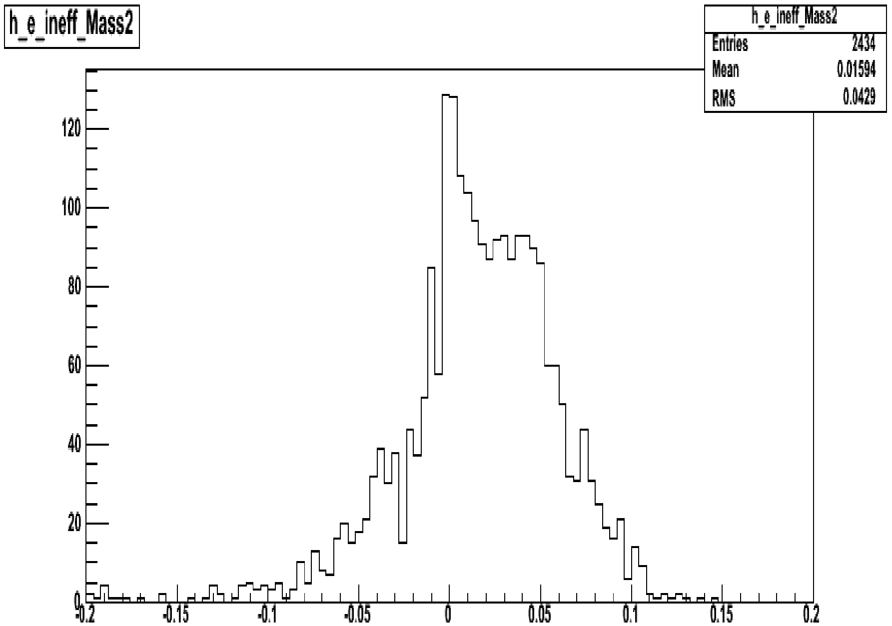
Low Energy Electron Reconstruction Efficiency

- The missing mass of this last electron is split into two plots:
  - the Efficient plot where the *ψ(2S)* is correctly reconstructed (top plot)
  - the Inefficient plot where the *ψ(2S)* is not correctly reconstructed (bottom plot)

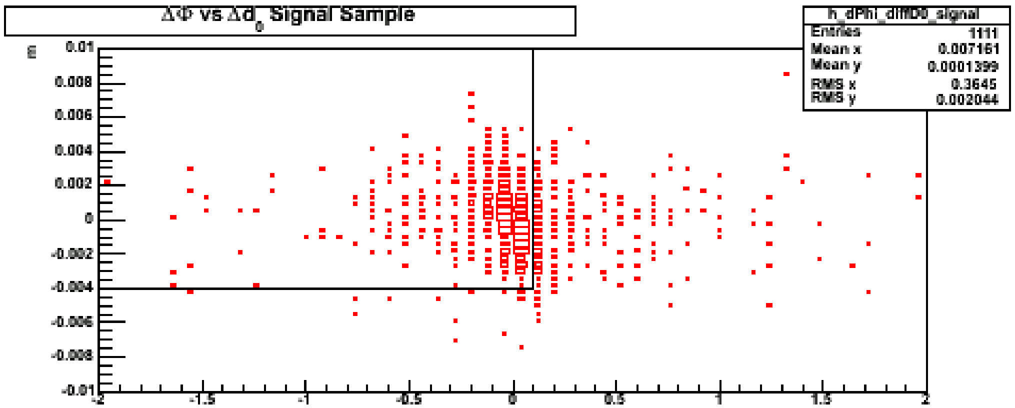
- By cutting and counting, we can roughly estimate the efficiency of electron reconstruction to be ~ 90%

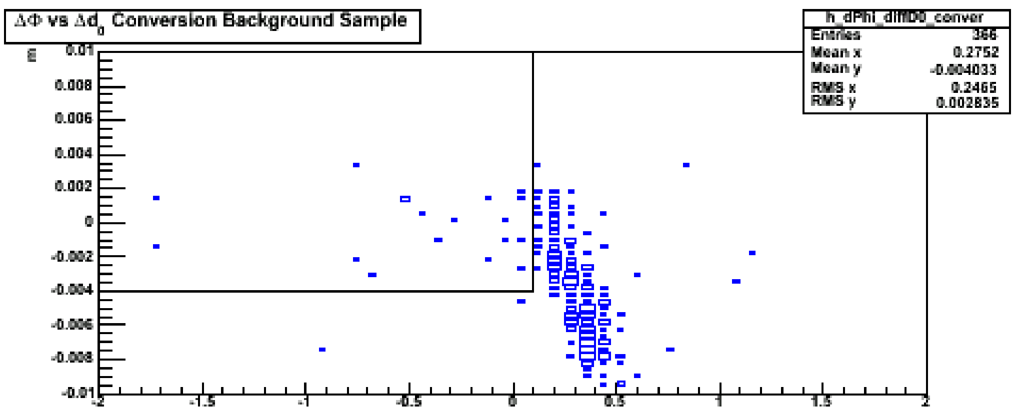
- We will generate Monte Carlo to fit these plots for a more precise measurement.

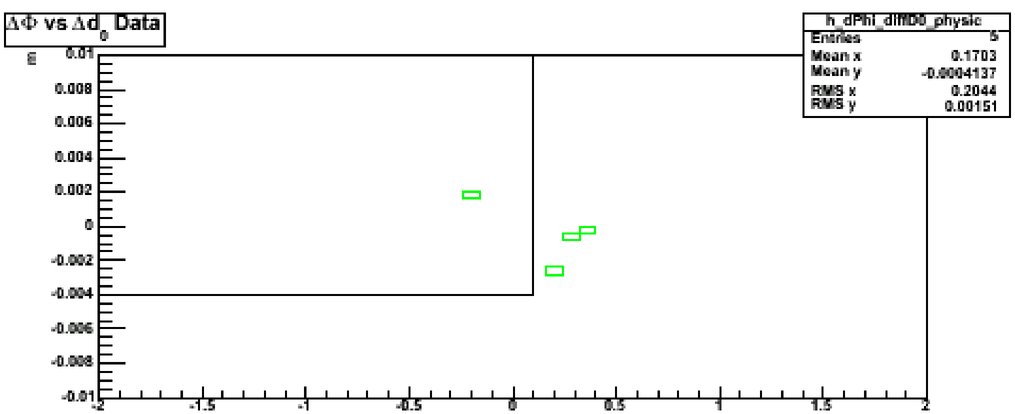


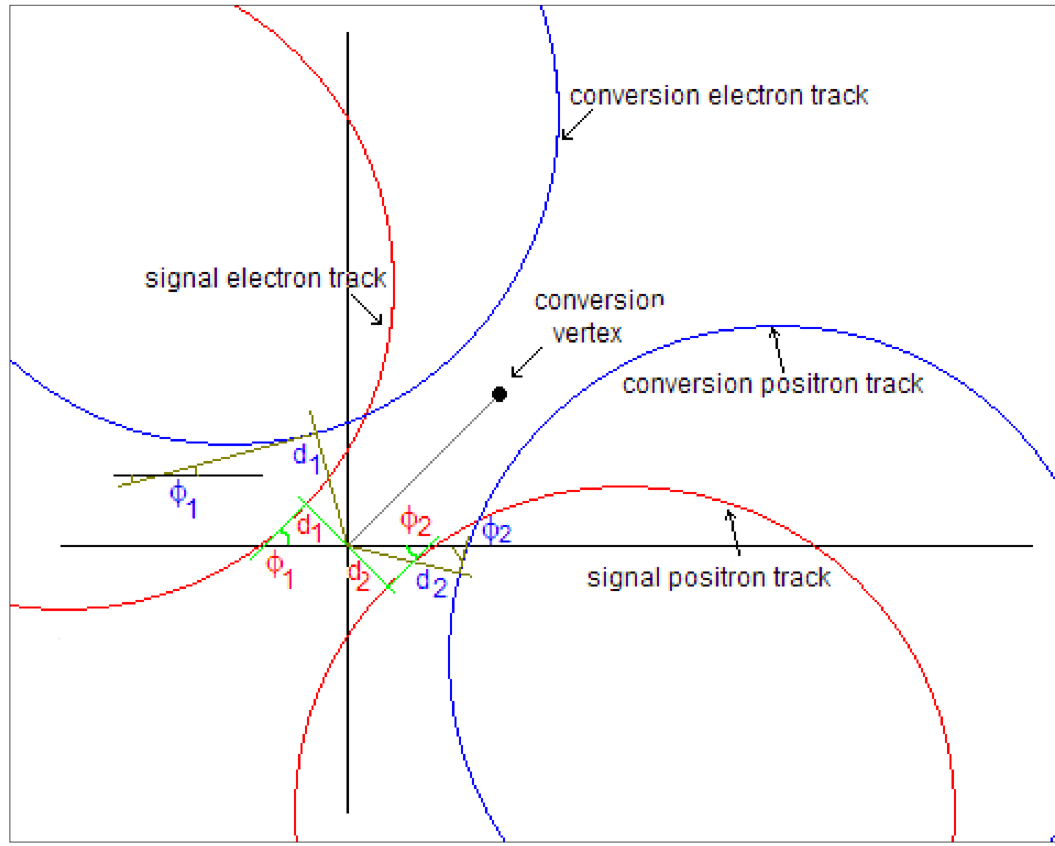


$K^+K^-\pi^+$ Mode $\Delta\Phi$ vs Δd_0









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