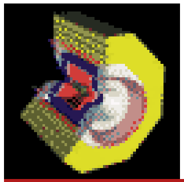

Cornell University
Laboratory for
Elementary-Particle Physics

OBSERVATION OF THE DECAY $D_s^{*+} \to D_s^+ e^+ e^-$ AND MEASUREMENT OF THE RATIO OF BRANCHING FRACTIONS $B(D_s^{*+} \to D_s^+ e^+ e^-)/B(D_s^{*+} \to D_s^+ \gamma)$ AT THE CLEO-c EXPERIMENT

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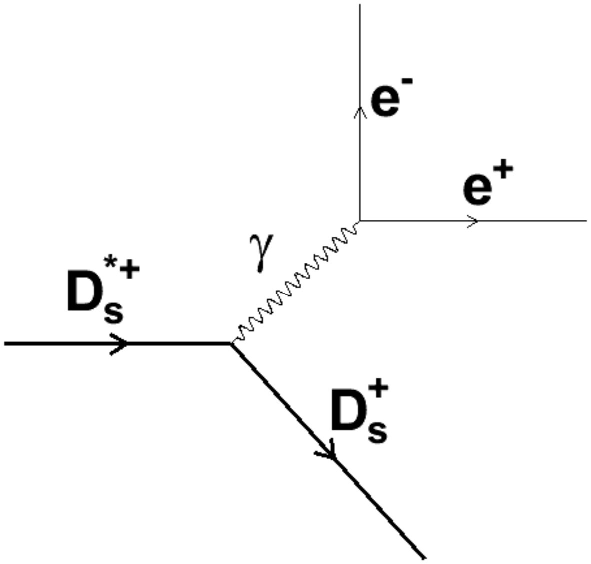
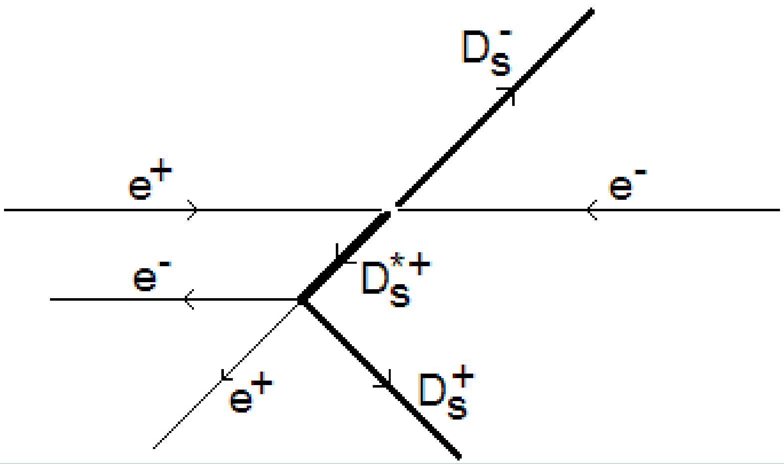


10 December 2010

What Are We Looking For?



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

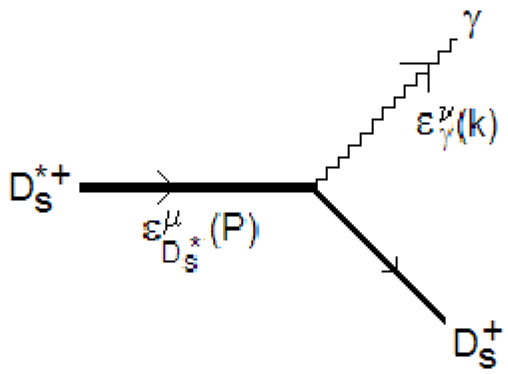
•Known decay channels are:

- $D_s^{*+} \rightarrow D_s^+ \gamma$; 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 ~ 555,000 events to work with.

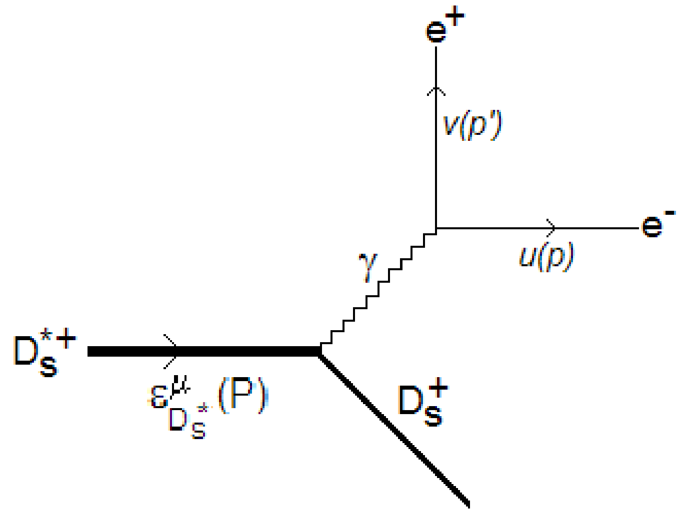
Predicted $D_s^{*\pm} \rightarrow D_s^{\pm} e^+ e^-$ Rate



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.



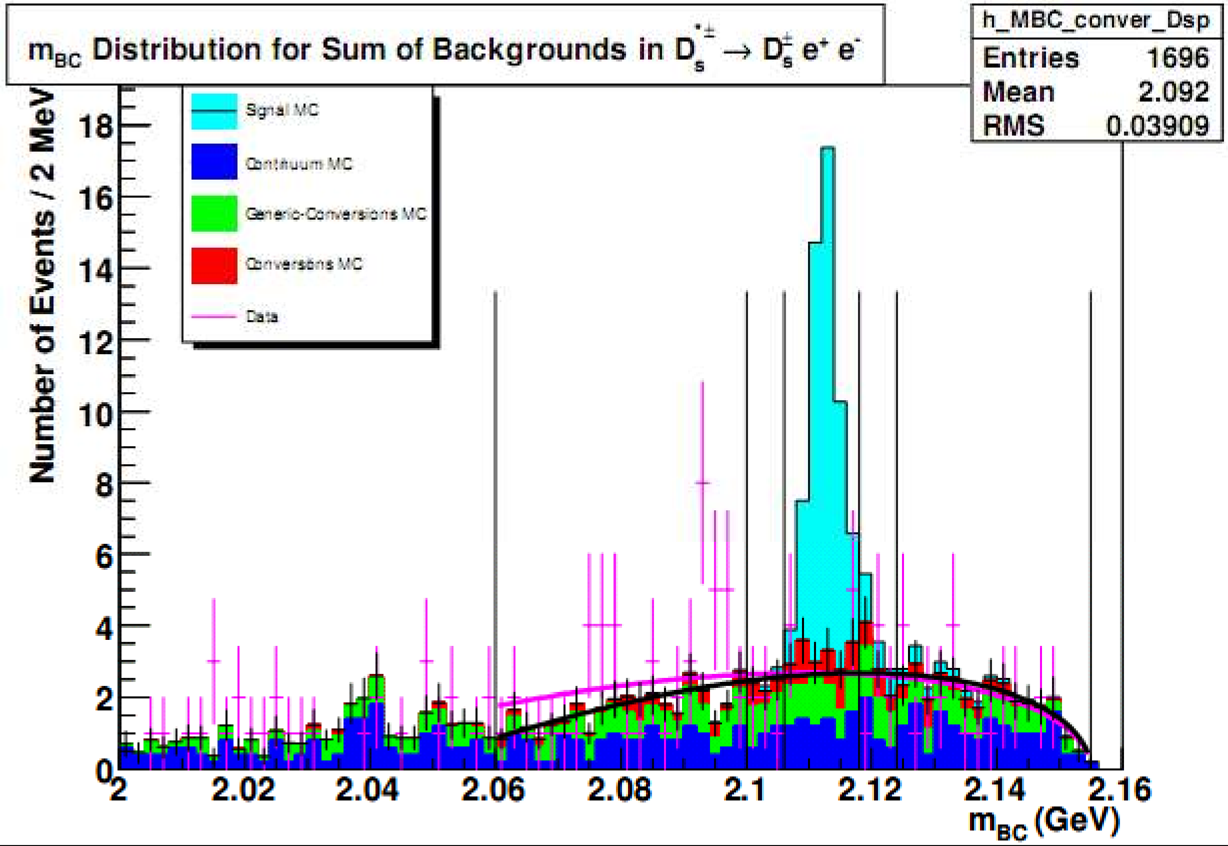
Then we can write the matrix element of the decay to e^+e^- in the form:

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

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 branching fractions:

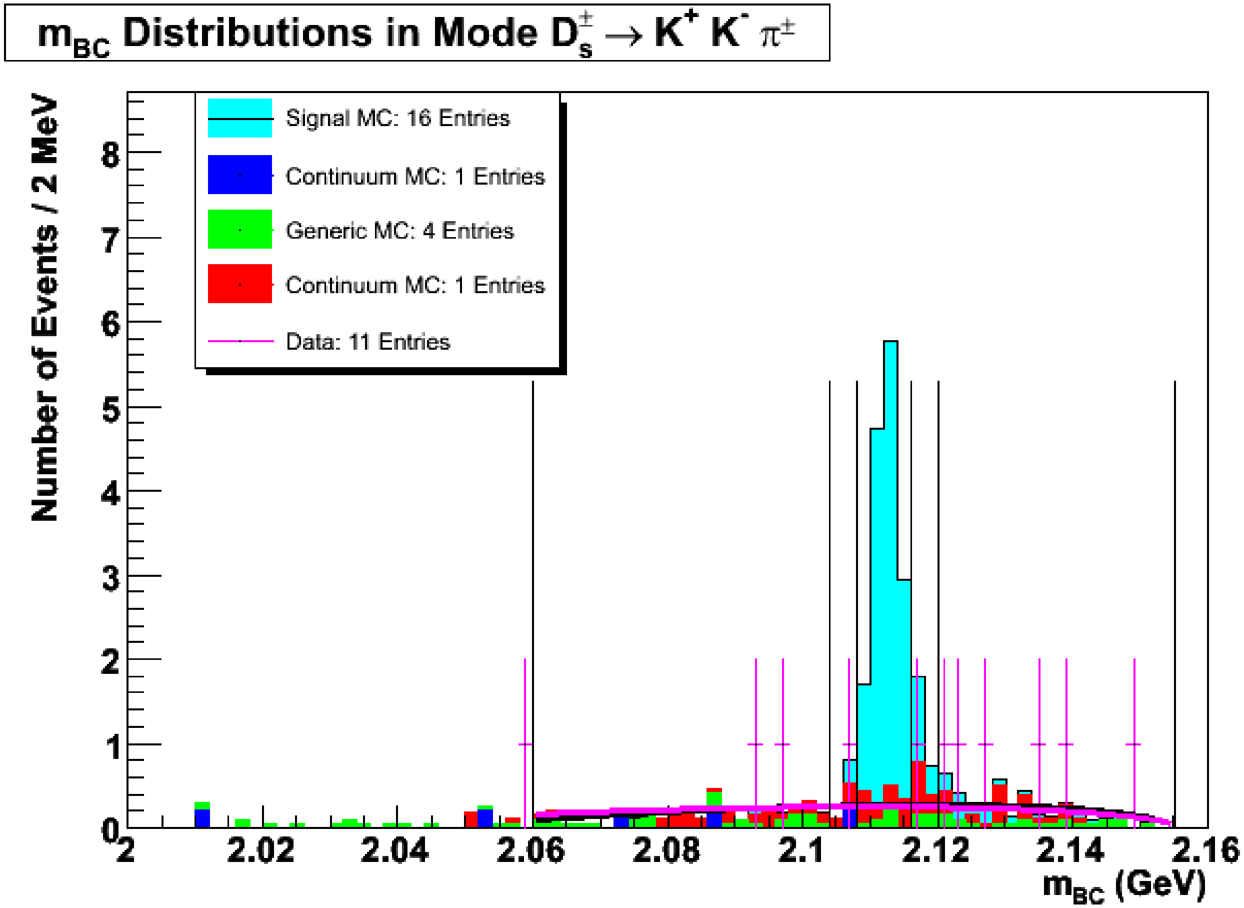
$$\frac{B\left(D_s^{*+} \rightarrow D_s^+ e^+ e^-\right)}{B\left(D_s^{*+} \rightarrow D_s^+ \gamma\right)} = 0.65\% = 0.89\alpha$$

Estimation of Background from m_{BC} Sidebands



- We try to be as Monte Carlo independent as possible. Extrapolate data from sidebands into signal region. Trying to fit a shape to the individual modes is impossible due to low statistics.
- We add all modes and plot the m_{BC} as shown.
- 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 m_{BC} Sidebands in the $K^+K^-\pi^+$ Mode



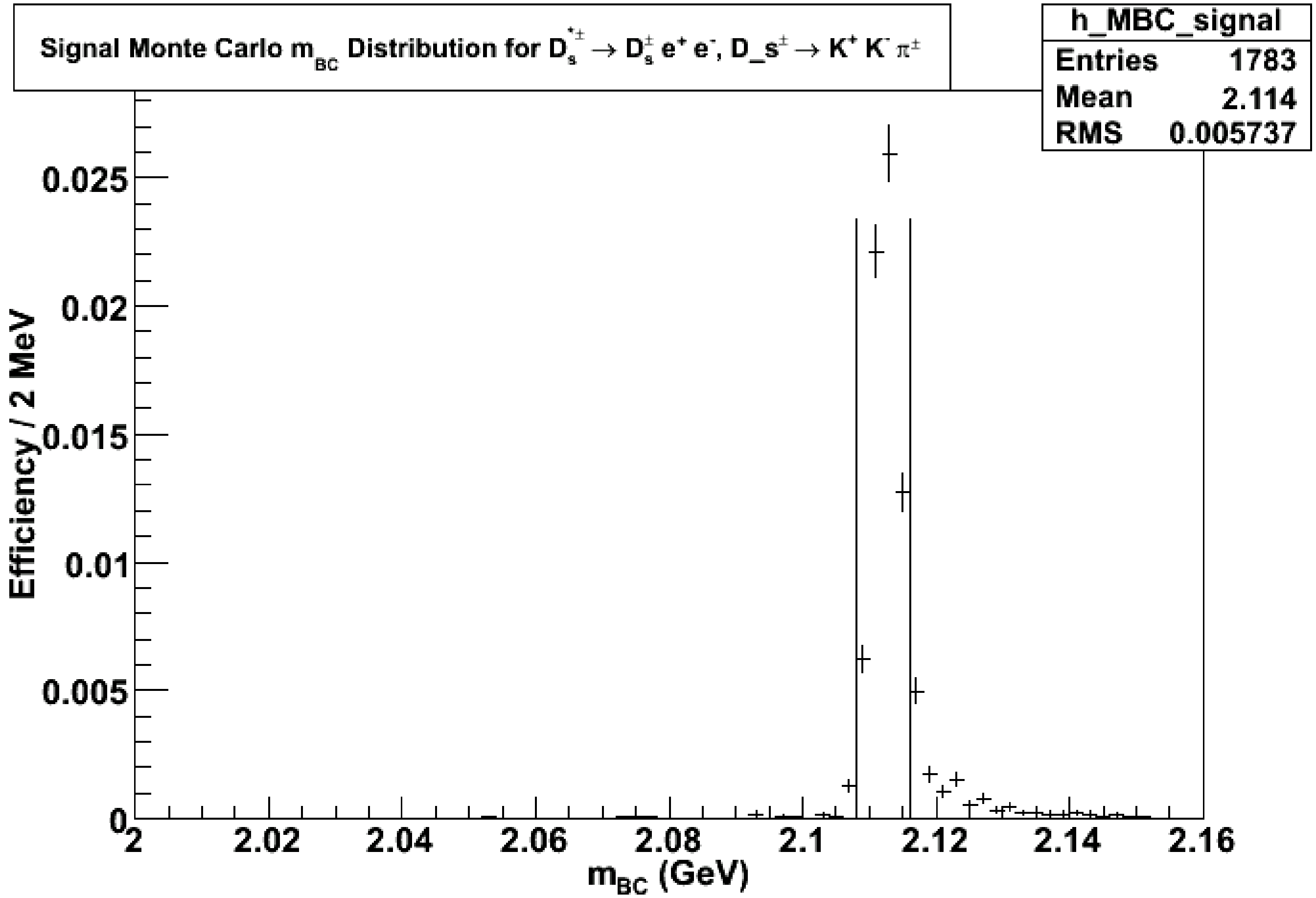
- Expected background from the:
  - Monte Carlo shape (black curve): 1.10 ± 0.39 (stat) events
  - Data shape (pink curve): 1.0 ± 0.35 (stat) events
  - Average: 1.05 ± 0.37 (stat) events. Quoted as estimated background.
- Repeat procedure with δm distributions to obtain systematic uncertainty:
  - 1.05 ± 0.37 (stat) ± 0.79 (syst)

Prediction for Signal from Monte Carlo and Data Sidebands

Decay Mode of the D_S^+	Expected Yield in 586 pb^{-1} (Signal + Background)	Expected Background in 586 pb^{-1}
$K^+K^-\pi^+$	14.70	$1.05 \pm 0.37 \pm 0.79$
K_sK^+	3.87	$0.85 \pm 0.43 \pm 0.74$
$\pi^+\eta;\ \eta\rightarrow\gamma\gamma$	3.21	$1.40 \pm 0.70 \pm 0.49$
$\pi^+\acute{\eta};\ \acute{\eta}\rightarrow\pi^+\pi^-\eta;\ \eta\rightarrow\gamma\gamma$	1.20	$0.00 + 0.63 + 0.00$
$K^+K^-\pi^+\pi^0$	6.55	$1.70 \pm 0.47 \pm 0.56$
$\pi^+\pi^-\pi^+$	5.32	$1.57 \pm 0.45 \pm 0.59$
$K^{*+}K^{*0};\ K^{*+}\rightarrow K^0_S\pi^+;\ K^{*0}\rightarrow K^-\pi^+$	3.57	$1.58 \pm 0.53 \pm 0.40$
$\eta\rho^+;\ \eta\rightarrow\gamma\gamma;\ \rho^+\rightarrow\pi^+\pi^0$	8.11	$2.62 \pm 0.59 \pm 0.23$
$\acute{\eta}\pi^+;\ \acute{\eta}\rightarrow\rho^0\gamma$	4.26	$1.84 \pm 0.49 \pm 0.25$
Total	**50.79**	**$12.61 \pm 1.58 \pm 1.53$**

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.

Signal Selection Efficiencies



•What fraction of produced signal events are retained by our selection criteria? This was calculated from the signal region in the m_{BC} distribution.

Calculating the Ratio of Branching Fractions

For the i^{th} decay mode of the $D_s^{\,+}$, we may write an expression for the signal yield N^i_{e+e-}

$$L\sigma B(D_s^{*+} \to D_s^+ e^+ e^-) B(D_s^+ \to i) \varepsilon^i_{D_s e+e-} = N^i_{e+e-}$$

Where L is the integrated luminosity of data used (586 pb^{-1}), σ is the production cross section of $D_s^{\,*+} D_s^{\,-}$ at 4170 MeV (948 pb), and ε^i_{Dse+e-} is the selection efficiency of criteria for the i^{th} mode.

We can write a similar expression for the $D_s^{\,*+} \to D_s^{\,+} \gamma$ channel:

$$L\sigma B(D_s^{*+} \to D_s^+ \gamma) B(D_s^+ \to i) \varepsilon^i_{D_s \gamma} = N^i_\gamma$$

We will evaluate the ratio of branching fractions with all modes considered together:

$$K = \frac{B(D_s^{*+} \to D_s^+ e^+ e^-)}{B(D_s^{*+} \to D_s^+ \gamma)} = \left(\frac{\sum_i N^i_{e+e-}}{\sum_i N^i_\gamma} \right) \left(\frac{\sum_i \varepsilon^i_{D_s \gamma} B(D_s^+ \to i)}{\sum_i \varepsilon^i_{D_s e+e-} B(D_s^+ \to i)} \right)$$

Signal Selection Efficiencies

To see the contribution of uncertainties to this measure of *K*, we may write it as

$$K = \left(\frac{\sum_i N^i_{e+e-}}{\sum_i N^i_\gamma} \right) \left(\frac{\varepsilon_\gamma}{\varepsilon_{e+e-}} \right) \left(\frac{\sum_i \varepsilon^i_{D_s} B(D_s^+ \to i)}{\sum_i \varepsilon^i_{D_s} B(D_s^+ \to i)} \right) \Rightarrow K = \left(\frac{\sum_i N^i_{e+e-}}{\sum_i N^i_\gamma} \right) \left(\frac{\varepsilon_\gamma}{\varepsilon_{e+e-}} \right)$$

To be fair, the ε^i_{Ds} in the numerator and denominator are not exactly equal because slightly different selection criteria are used for reconstructing $D_s^{*+} \to D_s^+ e^+ e^-$ and $D_s^{*+} \to D_s^+ \gamma$ but they are close enough to assume the last term to be 1.

The uncertainties in *K* may be broken down as follows.

$$\left(\frac{\Delta K(stat)}{K} \right)^2 = \frac{\sum_i \left(\Delta N^i_{e+e-}(stat) \right)^2}{\left(\sum_i N^i_{e+e-} \right)^2} + \frac{\sum_i \left(\Delta N^i_\gamma(stat) \right)^2}{\left(\sum_i N^i_\gamma \right)^2}$$

$$\left(\frac{\Delta K(syst)}{K} \right)^2 = \frac{\sum_i \left(\Delta N^i_{e+e-}(syst) \right)^2}{\left(\sum_i N^i_{e+e-} \right)^2} + \frac{\sum_i \left(\Delta N^i_\gamma(syst) \right)^2}{\left(\sum_i N^i_\gamma \right)^2} + \left(\frac{\Delta\left(\varepsilon_\gamma / \varepsilon_{e^+e^-} \right)}{\varepsilon_\gamma / \varepsilon_{e^+e^-}} \right)^2$$

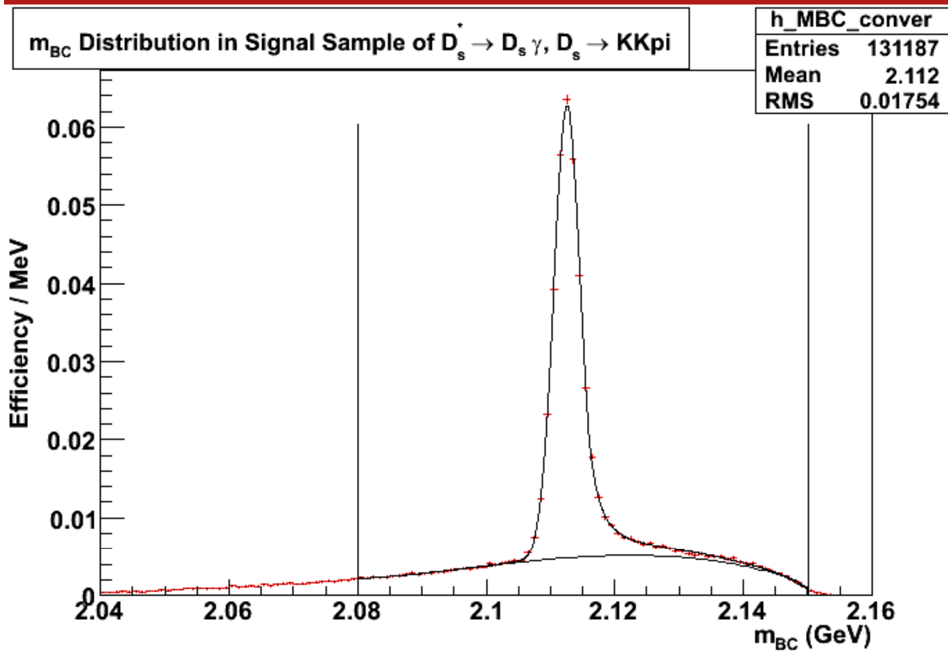
Criteria to Select $D_s^{*+} \rightarrow D_s^+ \gamma$ Events

- We also measure the signal yields and efficiencies for the $D_s^{*+} \rightarrow D_s^+ \gamma$ channel since we have set out to measure the ratio of branching fractions

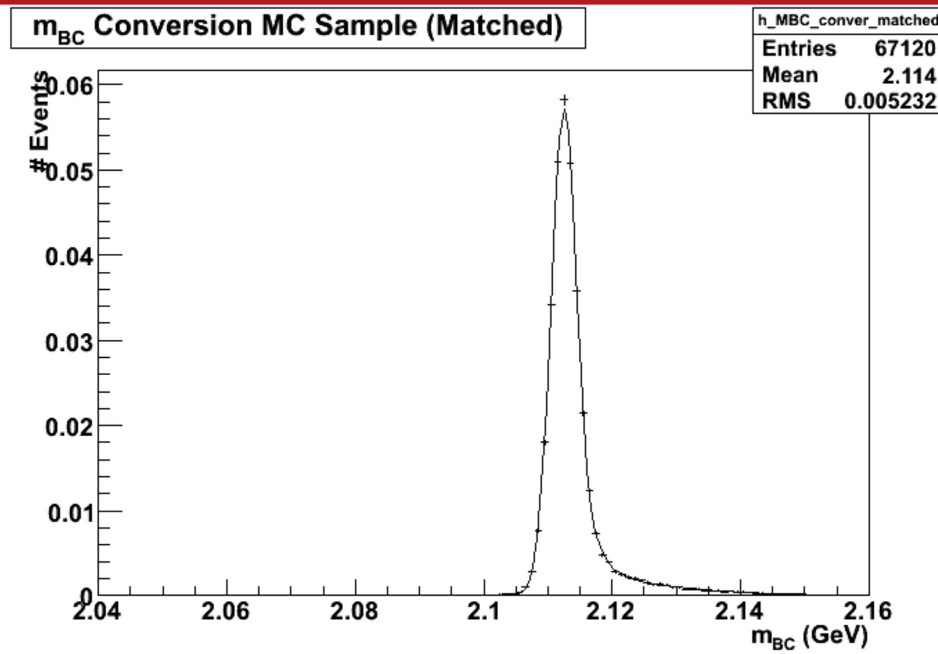
$$B(D_s^{*+} \rightarrow D_s^+ e^+ e^-) / B(D_s^{*+} \rightarrow D_s^+ \gamma)$$

- We reconstruct the D_s^{*+} through the D_s^+ and the γ
- The D_s^+ is reconstructed through the 9 hadronic decay modes
- Criteria on the e^+e^- inapplicable. Instead, criteria on the electromagnetic shower of the photon in the calorimeter are applied.
    - 10 MeV < Shower Energy < 2.0 GeV
    - No tracks leading to or in the vicinity of the shower
    - Known noisy calorimeter crystals discarded
    - Electromagnetic shower shape
- The m_{BC} criterion is discarded in favor of a fit to extract yield.

Criteria to Select $D_s^{*+} \to D_s^+ \gamma$ Events where $D_s^+ \to K^+K^-\pi^+$



Distribution of m_{BC} in the signal Monte Carlo sample of $D_s^{*+} \to D_s^+\gamma$ events where $D_s^+ \to K^+K^-\pi^+$. The plot is normalized so as to directly read out the efficiency of the m_{BC} selection criterion.



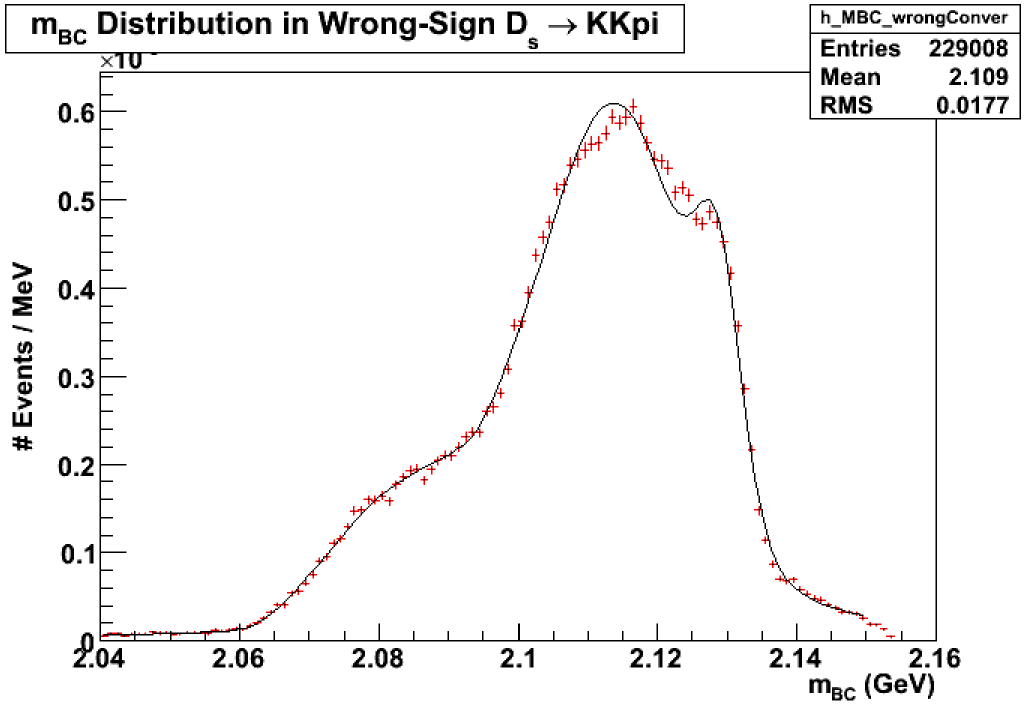
Distribution of m_{BC} in signal MC where the D_s^+ and the γ have been MC matched.

- Shape of the peak determined from events where both the Ds+ and photon are MC matched. Used a Crystal Ball function with power law on high side with soft Gaussian on high shoulder.

- Fitted peak on top of: $f(x; x_0, p, C_0, C_1, C_2, C_3) = (C_0 + C_1 x + C_2 x^2 + C_3 x^3)(x - x_0)^p; \quad 0 < p < 1$

- Extracted signal efficiency

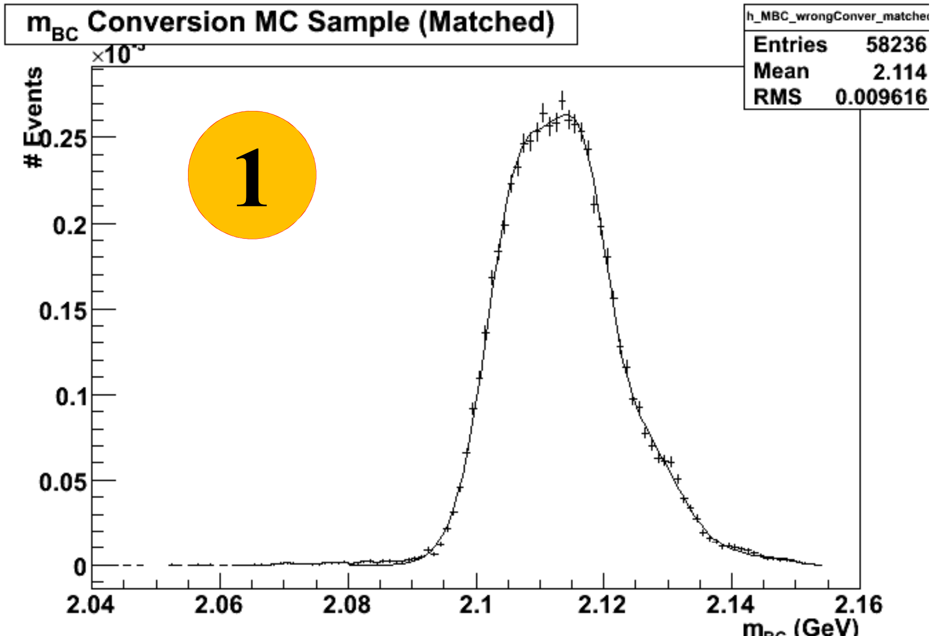
Criteria to Select $D_s^{*+} \to D_s^+ \gamma$ Events where $D_s^+ \to K^+K^-\pi^+$



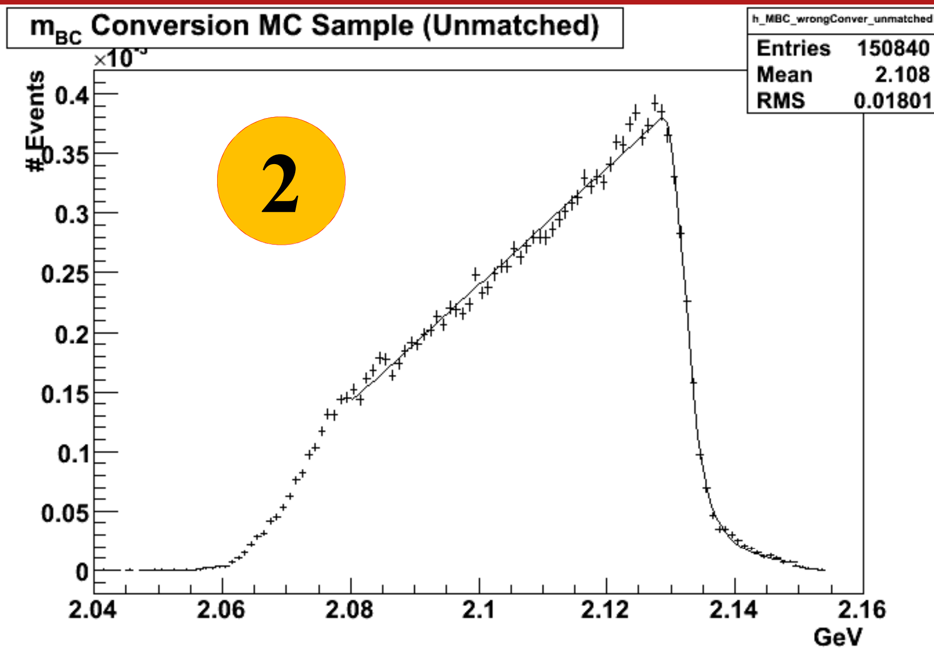
Peaking background in the Monte Carlo m_{BC} distribution from incorrectly reconstrucing the D_s^{*+} out of the D_s^- and the γ in an event.

•Incorrectly reconstructed D_s^{*+} mesons from the combination of D_s^- and γ exhibit a double-humped structure in the m_{BC} distribution.

Criteria to Select $D_s^{*+} \rightarrow D_s^+ \gamma$ Events where $D_s^+ \rightarrow K^+K^-\pi^+$



Combinatorial background structured in m_{BC} consisting of wrongly reconstructed D_s^{*+} where the D_s^- and the γ have been MC matched.



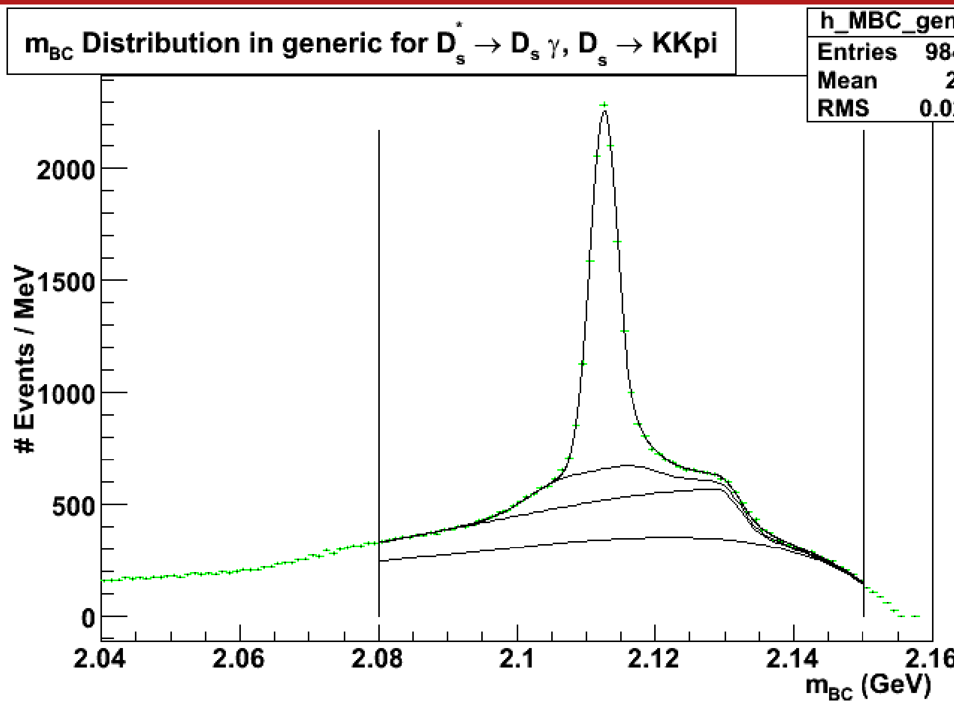
Combinatorial background structured in m_{BC} consisting of wrongly reconstructed D_s^{*+} where the D_s^- has been MC matched but the γ has failed MC matching.

•Shape 1 was fitted to a Gaussian on the left, a Crystal Ball function on the right with its power law on the high side and another soft Gaussian on the high shoulder.

•Shape 2 was fitted to a Crystal Ball function with its power law on the high side and analytically continued into a straight line on the low side.

•The amplitudes of these shapes were fitted independently to data and generic MC.

Criteria to Select $D_s^{*+} \rightarrow D_s^+ \gamma$ Events where $D_s^+ \rightarrow K^+K^-\pi^+$



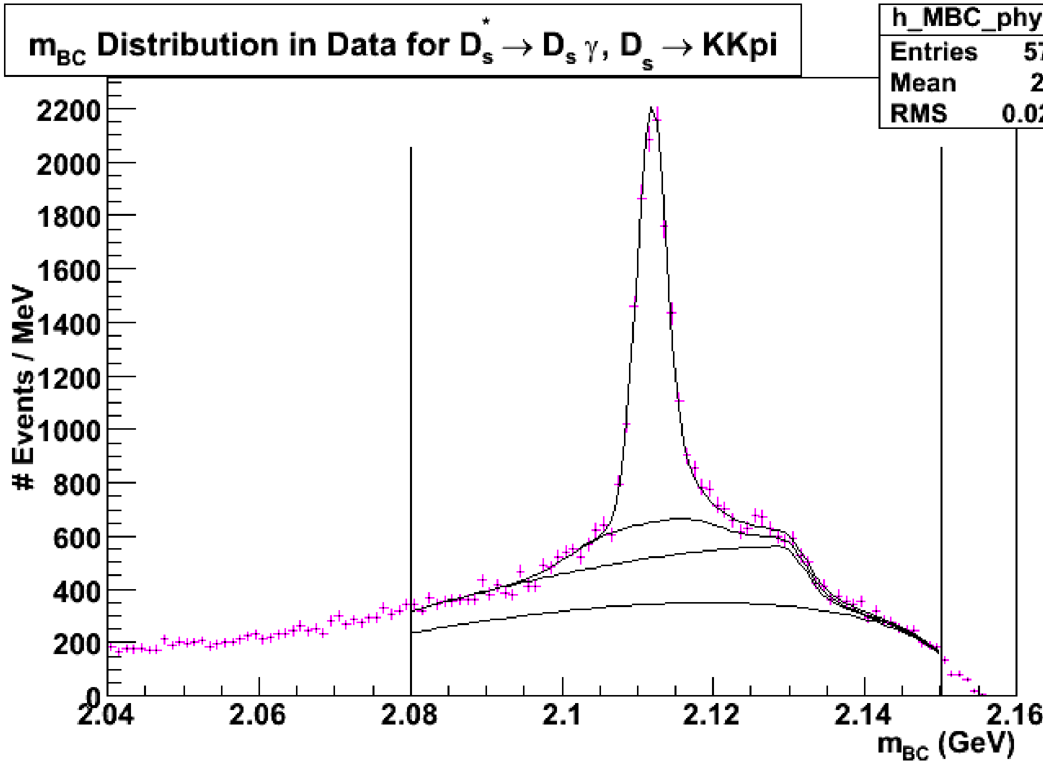
Distribution of m_{BC} of $D_s^{*+} \rightarrow D_s^+ \gamma$ where $D_s^+ \rightarrow K^+K^-\pi^+$ in 586 pb^{-1} of Generic Monte Carlo

- Try fit Generic MC to see if we can recover $B(D_s^{*+} \rightarrow D_s^+ \gamma)$

- Fits from bottom to top:
  1. Featureless combinatorial background modeled by an Argus function.
  2. Scaled shape 2, wrongly reconstructed D_s^{*+} using a matched D_s^- and a matched photon
  3. Scaled shape 1 ,wrongly reconstructed D_s^{*+} using a matched D_s^- and a random photon
  4. Scaled peak shape recovered from signal MC where D_s^+ and the photon were matched

- $B(D_s^{*+} \rightarrow D_s^+ \gamma) = 0.926 \pm 0.006$. [Systematics arising from inconsistencies between models used for signal and generic MC not estimated.]

Criteria to Select $D_s^{*+} \rightarrow D_s^+ \gamma$ Events where $D_s^+ \rightarrow K^+K^-\pi^+$



Distribution of m_{BC} of $D_s^{*+} \rightarrow D_s^+ \gamma$ where $D_s^+ \rightarrow K^+K^-\pi^+$ in 586 pb^{-1} of data

- Signal selection efficiency = 0.339 ± 0.002
- Signal yield = 9114 ± 110 ± 201
- $B(D_s^{*+} \rightarrow D_s^+ \gamma) = 0.880 \pm 0.011^{[1]} \pm 0.045^{[2]} \pm 0.035^{[3]} \pm 0.019^{[4]}$
  - [1] is the statistical uncertainty from the fit
  - [2] is the systematic uncertainty from the uncertainty in $B(D_s^+ \rightarrow K^+K^-\pi^+)$.
  - [3] encapsulates the systematic uncertainty from the signal efficiency, the integrated luminosity and production cross section of $D_s^{*+}D_s^-$
  - [4] is the systematic uncertainty from the fit. Evaluated using an alternative fitting method.
- Our measurement of $B(D_s^{*+} \rightarrow D_s^+ \gamma)$ is 1σ away from the accepted value of 0.942 ± 0.007

Yields, Efficiencies and Unblinding Data

•The yields and efficiencies for $D_s^{*+} \to D_s^+ \gamma$ in the 9 hadronic decay modes of the Ds+ are recorded. Will be presented in final calculation of

$$\frac{B(D_s^{*+} \to D_s^+ e^+ e^-)}{B(D_s^{*+} \to D_s^+ \gamma)}$$

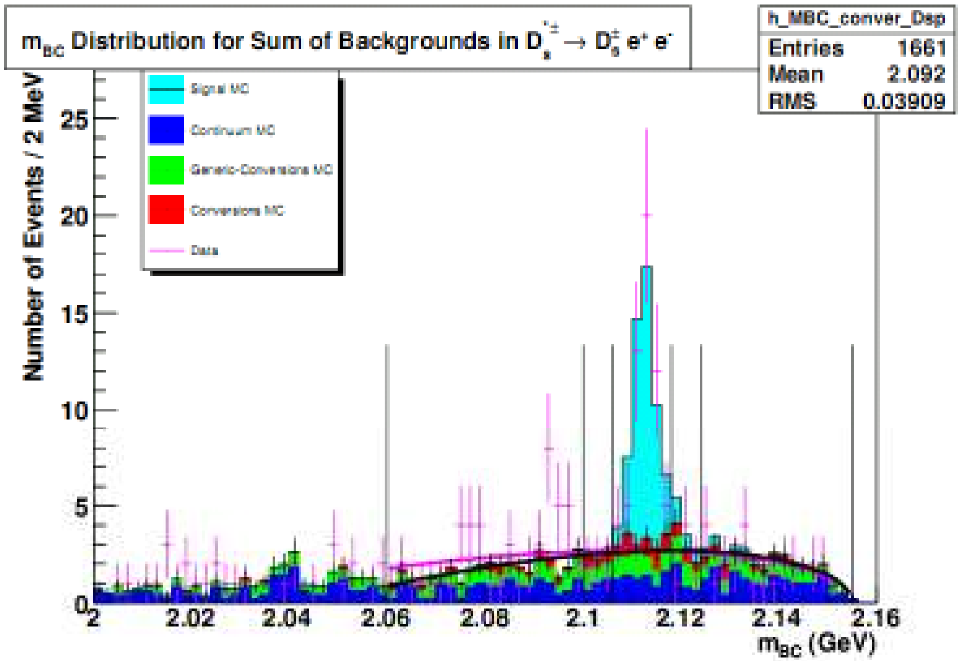
where systematic uncertainties in the reconstruction of Ds+ mesons would have canceled.

But now we unblind the signal region for $D_s^{*+} \to D_s^+ e^+ e^-$

So buckle your seat belts!

Unblinding Data in the m_{BC} Signal Region of $D_s^{*+} \rightarrow D_s^+ e^+ e^-$

Decay Mode of the D_S^+	Expected Yield from MC in 586 pb^{-1}	Observed Yield in 586 pb^{-1}
$K^+K^-\pi^+$	14.70	14
K_sK^+	3.87	1
$\pi^+\eta;\ \eta\rightarrow\gamma\gamma$	3.21	4
$\pi^+\acute{\eta};\ \acute{\eta}\rightarrow\pi^+\pi^-\eta;\ \eta\rightarrow\gamma\gamma$	1.20	4
$K^+K^-\pi^+\pi^0$	6.55	6
$\pi^+\pi^-\pi^+$	5.32	7
$K^{*+}K^{*0};\ K^{*+}\rightarrow K^0{}_S\pi^+;\ K^{*0}\rightarrow K^-\pi^+$	3.57	4
$\eta\rho^+;\ \eta\rightarrow\gamma\gamma;\ \rho^+\rightarrow\pi^+\pi^0$	8.11	7
$\acute{\eta}\pi^+;\ \acute{\eta}\rightarrow\rho^0\gamma$	4.26	4
Total	**50.79**	**51**



- Distribution of m_{BC} in data after unblinding all modes.

- Magenta curve extrapolates to estimate background using the data shape. Black curve extrapolates data using the MC shape.

Results from Unblinding Data

Decay Mode of the D_S^+	Branching Fraction (RPP 2008) %	$D_s^{*+} \rightarrow D_s^+ e^+ e^-$		$D_s^{*+} \rightarrow D_s^+ \gamma$		$K = \frac{B(D_s^{*+} \to D_s^+ \pi^0)}{B(D_s^{*+} \to D_s^+ \gamma)}$
		Background Subtracted Yield	Selection Efficiency	Background Subtracted Yield	Selection Efficiency	
$K^+K^-\pi^+$	0.055 ± 0.0028	12.95 ± 3.76 ± 0.79	0.0730 ± 0.0019	9114 ± 110 ± 201	0.339 ± 0.002	0.0066 ± 0.0019 ± 0.0005
K_sK^+	0.0149 ± 0.0009	0.15 ± 1.09 ± 0.74	0.0597 ± 0.0017	1902 ± 57 ± 45	0.2573 ± 0.0004	0.0003 ± 0.0025 ± 0.0017
$\pi^+\eta;\ \eta\rightarrow\gamma\gamma$	0.0062 ± 0.0008	2.60 ± 2.12 ± 0.49	0.0855 ± 0.0021	1037 ± 46 ±37	0.3310 ± 0.0015	0.0097 ± 0.0079 ± 0.0019
$\pi^+\acute{\eta};\ \acute{\eta}\rightarrow\pi^+\pi^-\eta;\ \eta\rightarrow\gamma\gamma$	0.0067 ± 0.0007	4.00 ± 2.10 ± 0.00	0.0530 ± 0.0016	691 ± 34 ±40	0.2101 ± 0.0013	0.023 ± 0.0123 ± 0.0015
$K^+K^-\pi^+\pi^0$	0.056 ± 0.005	4.30 ± 2.49 ± 0.56	0.0255 ± 0.0011	3592 ± 118 ± 72	0.1225 ± 0.0010	0.0058 ± 0.0033 ± 0.0008
$\pi^+\pi^-\pi^+$	0.0111 ± 0.0008	5.43 ± 2.68 ± 0.59	0.0992 ± 0.0022	2745 ± 93 ± 52	0.4583 ± 0.0018	0.0091 ± 0.0045 ± 0.0010
$K^{*+}K^{*0};\ K^{*+}\rightarrow K^0{}_S\pi^+;\ K^{*0}\rightarrow K^-\pi^+$	0.0164 ± 0.0012	2.42 ± 2.07 ± 0.40	0.0356 ± 0.0013	1570 ± 74 ± 13	0.1913 ± 0.0012	0.0083 ± 0.0071 ± 0.0014
$\eta\rho^+;\ \eta\rightarrow\gamma\gamma;\ \rho^+\rightarrow\pi^+\pi^0$	0.0511 ± 0.0087	4.38 ± 2.71 ± 0.23	0.0316 ± 0.0013	3170 ± 161 ± 313	0.1839 ± 0.0013	0.0080 ± 0.0050 ± 0.0010
$\acute{\eta}\pi^+;\ \acute{\eta}\rightarrow\rho^0\gamma$	0.0112 ± 0.0012	2.16 ± 2.06 ± 0.25	0.064 ± 0.0018	1531 ± 80 ± 122	0.3171 ± 0.0015	0.0070 ± 0.0067 ± 0.0010
Sum of Modes		38.39 ± 7.32 ±1.53		25351 ± 280		**0.0072 ± 0.0014 ± 0.0003**

Result

•We observe a signal for $D_s^{*+} \rightarrow D_s^+ e^+ e^-$ with a signal significance of 6.39 σ

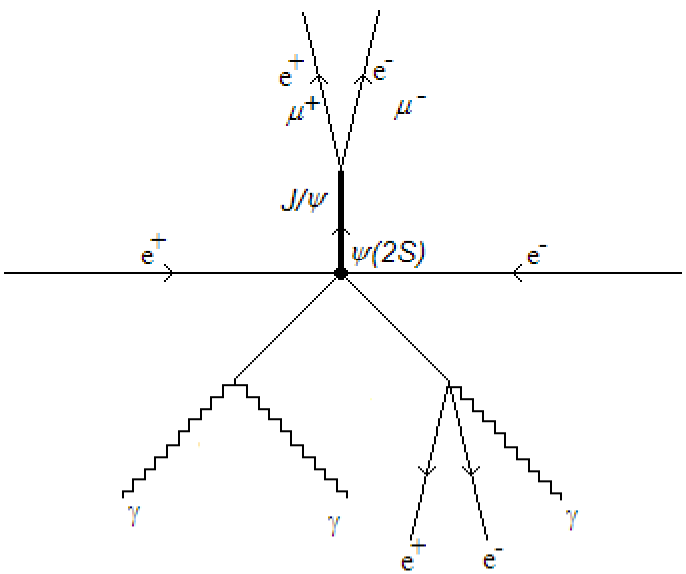
•We measure the ratio of branching fractions from the table:

$$K = \frac{B(D_s^{*+} \rightarrow D_s^+ e^+ e^-)}{B(D_s^{*+} \rightarrow D_s^+ \gamma)} = (0.72 \pm 0.14(stat) + 0.03(syst))\%$$

•However, the multiplicative systematic from the last term of ΔK(syst) on Slide 9 has not been included. The fractional error from this term is measured by an independent study to be 6.51%. 6.51% of 0.72% is 0.047% and when added in quadrature to the other systematics, we arrive at the final result

$$\boxed{\frac{B(D_s^{*+} \rightarrow D_s^+ e^+ e^-)}{B(D_s^{*+} \rightarrow D_s^+ \gamma)} = (0.72 \pm 0.14(stat) + 0.06(syst))\%}$$

Systematic Uncertainties from Tracking Soft Electrons and Photons



•The systematic uncertainty stemming from uncertainties in tracking soft electrons and photons will contribute multiplicatively:

$$\Delta K = K \frac{\Delta\left(\varepsilon_\gamma / \varepsilon_{e^+e^-}\right)}{\varepsilon_\gamma / \varepsilon_{e^+e^-}}$$

•We estimate this by measuring B($\pi^0 \rightarrow e^+e^-\gamma$) within the energy range of our analysis. Discrepancies between this measurement and the currently accepted value is related to the systematic uncertainty we are trying to establish.

$$\frac{\Delta\left(\varepsilon_\gamma / \varepsilon_{e^+e^-}\right)}{\varepsilon_\gamma / \varepsilon_{e^+e^-}} = \frac{\Delta B(\pi^0 \rightarrow e^+e^-\gamma)}{B(\pi^0 \rightarrow e^+e^-\gamma)}$$

•To study these π^0, we look at $\psi(2S) \rightarrow J/\psi\pi^0\pi^0$ events.

- •We call events where one of the π^0 Dalitz decays to $\pi^0 \rightarrow \gamma e^+e^-$ *Type I* events
- • Events where both $\pi^0 \rightarrow \gamma\gamma$ (*Type II* events)

$$\frac{n_I}{n_{II}} = \frac{2B(\pi^0 \rightarrow e^+e^-\gamma)}{B(\pi^0 \rightarrow \gamma\gamma)}$$

Systematic Uncertainties from Tracking Soft Electrons and Photons

•We employ two methods to estimate B($\pi^0 \to e^+e^-\gamma$) in order to assign a systematic uncertainty to our measurement.

METHOD 1

•We set up selection criteria to reconstruct the $\psi(2S)$ from Type I events.
•Selection efficiency to keep Type I events from an MC sample is called ε_s. Efficiency to keep Type II events from an MC sample is called ε_c.
•The yield in data, y, is related to the numbers of produced Type I and II by

$$n_I \varepsilon_s + n_{II} \varepsilon_c = y$$

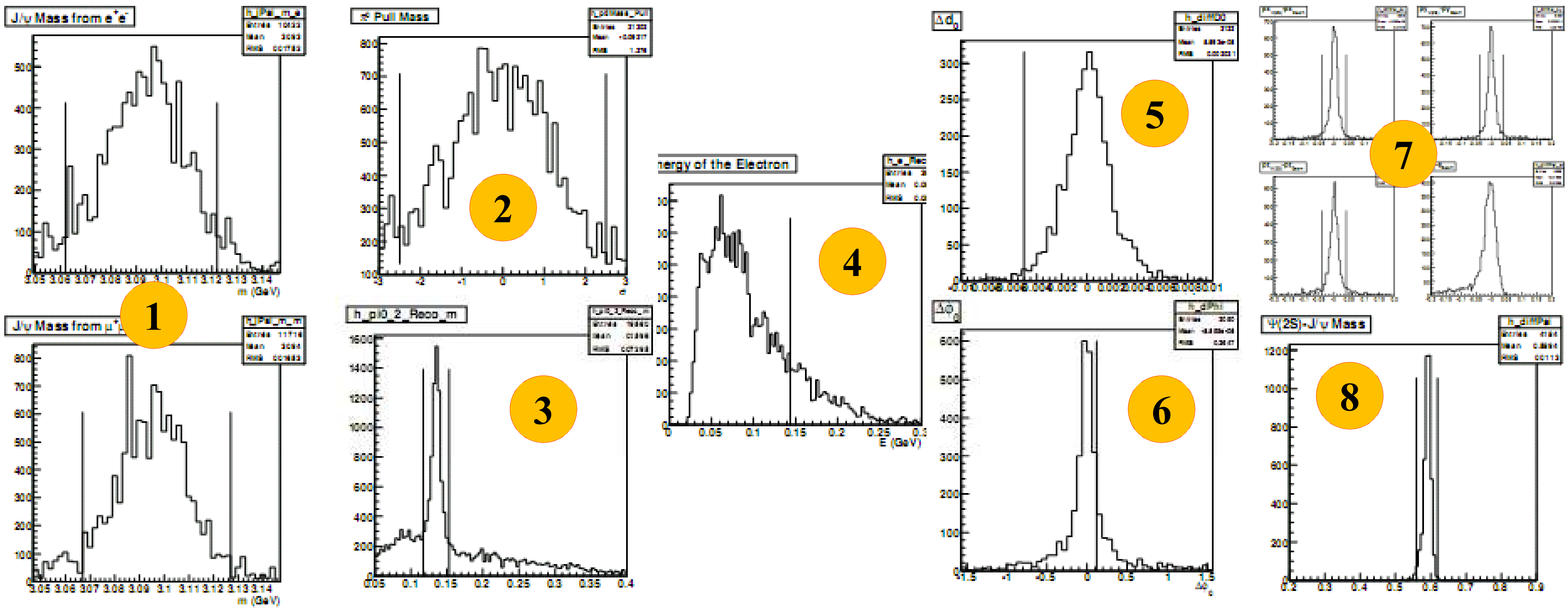
•We solve for n_I keeping in mind the currently accepted ratio of n_I and n_{II}

•We set up selection criteria to reconstruct the $\psi(2S)$ from Type I events.
•Applying them to our data, we find their signal yield and directly estimate the number of Type II events in our data.

•Having found n_I and n_{II}, we calculate B($\pi^0 \to \gamma e^+e^-$) from

$$\frac{n_I}{n_{II}} = \frac{2B(\pi^0 \to e^+e^-\gamma)}{B(\pi^0 \to \gamma\gamma)}$$

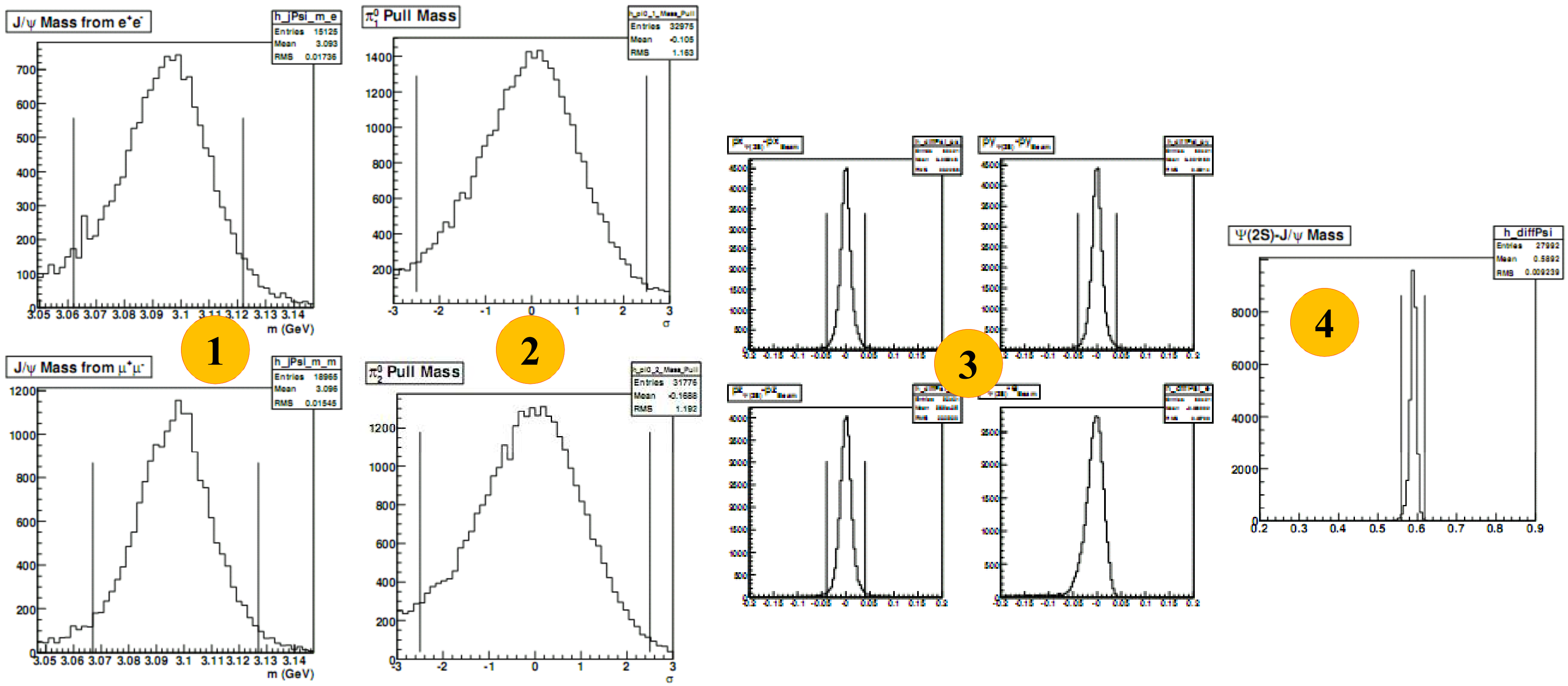
Selection Criteria for Type I Events



1. The J/ψ is reconstructed from e^+e^- or $\mu^+\mu^-$
2. First π^0 reconstructed from two photons. Criterion on pull mass
3. Second π^0 reconstructed from one photon and a soft e^+e^- pair
4. The energy of the e+e- are restricted to within 144 MeV.
5. Δd_0 cuts applied on the soft e+e- pair
6. $\Delta\varphi_0$ cuts applied on the soft e+e- pair
7. The $\psi(2S)$ is required to be within a range of the collision lab 4-momentum
8. $m_{\psi(2S)}$ - $m_{J/\psi}$ is required to be within a range.

•We find ε_s and ε_c using these on MC and apply them on data to record the yield, y.

Selection Criteria for Type II Events



1. The J/ψ is reconstructed from e^+e^- or $\mu^+\mu^-$
2. Both π^0 reconstructed from two photons. Criterion on pull mass
3. The $\psi(2S)$ is required to be within a range of the collision lab 4-momentum
4. $m_{\psi(2S)} - m_{J/\psi}$ is required to be within a range.

- We find the efficiency of keeping Type II events using these.
- We record the yield in data.

Systematic Uncertainties from Tracking Soft Electrons and Photons

METHOD 1

- Solving for n_I and n_{II}, we get

$$\frac{n_I}{n_{II}} = \frac{8447 \pm 554}{341607 \pm 2555} = \frac{2B(\pi^0 \rightarrow e^+ e^- \gamma)}{(98.823 \pm 0.034) \times 10^{-2}}$$

- This gives us $B(\pi^0 \rightarrow e^+ e^- \gamma) = 0.01222 \pm 0.00081$ (stat)

Systematic Uncertainties from Tracking Soft Electrons and Photons

METHOD 2

•We set up selection criteria to reconstruct the $\psi(2S)$ from Type II events where the photon likely converted to an e^+e^-. This is done by accepting events which were formerly rejected by the Δd_0 or $\Delta\varphi_0$ selection criteria.

•Selection efficiency to keep Type I events from an MC sample is called ε'_s. Efficiency to keep Type II events from an MC sample is called ε'_c. The yield in data, y', is related to the numbers of produced Type I and II by

$$n_I \varepsilon'_s + n_{II} \varepsilon'_c = y'$$

•Using this equation simultaneously with that on Slide 21, we solve for n_I. We use numbers for n_{II} as derived before.

$$\frac{n_I}{n_{II}} = \frac{8437 \pm 342}{341607 \pm 2555} = \frac{2B(\pi^0 \to e^+e^-\gamma)}{(98.823 \pm 0.034) \times 10^{-2}}$$

•From this we get $B(\pi^0 \to e^+e^-\gamma) = 0.01220 \pm 0.00050$ (stat)

Systematic Uncertainties from Tracking Soft Electrons and Photons

- Combining Method 1 & 2, B($\pi^0 \rightarrow e^+e^-\gamma$) = 0.01222 ± 0.00081 (stat) ± 0.00002 (syst)

- Currently accepted value B($\pi^0 \rightarrow e^+e^-\gamma$) = 0.01174 ± 0.00035

- Difference between our result and current value is 0.00046. Of the same order of magnitude as the uncertainties, and therefore added in quadrature to get a total uncertainty of 0.00077.

- Now we can write

$$\frac{\Delta\left(\varepsilon_\gamma / \varepsilon_{e^+e^-}\right)}{\varepsilon_\gamma / \varepsilon_{e^+e^-}} = \frac{\Delta B(\pi^0 \rightarrow e^+e^-\gamma)}{B(\pi^0 \rightarrow e^+e^-\gamma)} = \frac{0.00077}{0.01174} = 0.0651$$

and this is what we propagate into the systematic error for *K*

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

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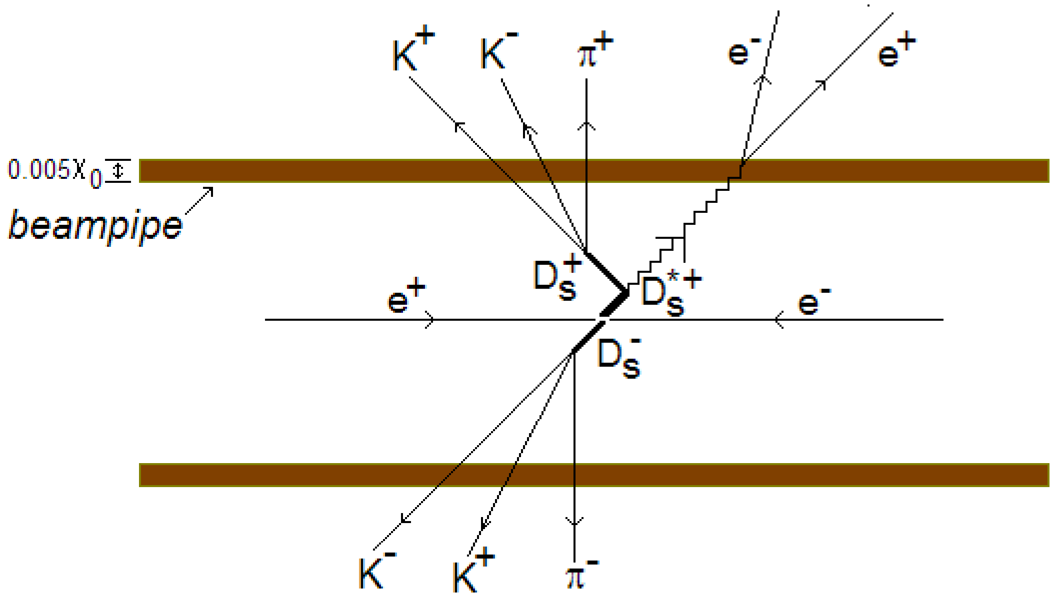
- I would like to thank Anders Ryd for suggesting and guiding me through this entire project. And for being an excellent and **extremely** involved advisor.
- David Cassel and Jim Alexander for providing me with brilliant advice at various junctures of this analysis.
- Dan Riley for helping me reprocess CLEO-c datasets.
- Werner Sun for helping me familiarize myself with CLEO-c software, reprocess data, and offering me general physics advice when sought.
- Peter Onyisi for answering all my questions about D_s^+ mesons.
- Brian Heltsley for help with reprocessing data, answering my questions about CLEO-c calorimetry and taking so much care in reading our note and offering interesting and useful suggestions.
- Matthew Shepherd for the feedback on our note.
- Paras Naik for fielding random questions about the detector and software at equally random times of the day or night.

Backup Slides

Typical Background Processes



Photon Conversion Background

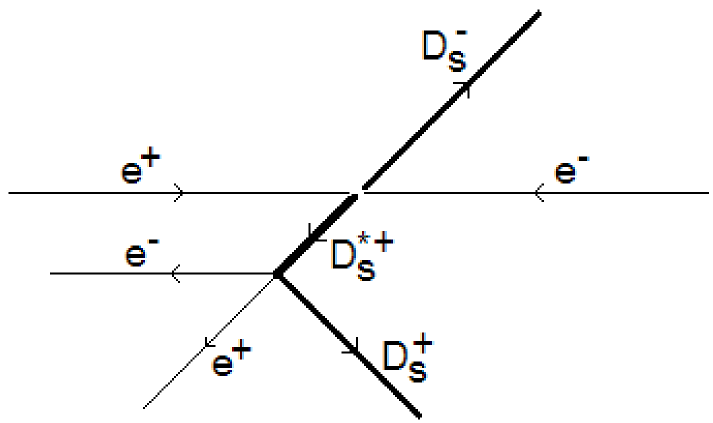
- A background that resembles the signal is expected from D_s^{*+} decaying to $D_s^+ \gamma$ and the γ converting to e^+e^- in the beam-pipe and other material.
- Given that the beam-pipe is ~ 0.5% of a radiation length, we can estimate this conversion background to occur at roughly the same rate as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

Analysis Strategy

- Employ a blind analysis search for the $D_s^{*+} \to D_s^+ e^+ e^-$
- Fully reconstruct the D_s^{*+} through the D_s^+ and e^+e^-.
- The D_s^+ is reconstructed through 9 hadronic decay modes
- Selection criteria based on the *invariant masses* of the D_s^+ and D_s^{*+} are optimized
- Criteria based on the *track parameters* of the e^+ and e^- are powerful against the photon conversion background
- The e^+e^- are extremely soft (~144 MeV total) and accuracy required by tracking motives a data reprocessing campaign.
- Estimate the number of background events we will see in the signal region after our selection.
- Use selection criteria to measure the rate of $D_s^{*+} \to D_s^+ \gamma$
- Unblind data in the signal region for $D_s^{*+} \to D_s^+ e^+ e^-$. Compute $\dfrac{B(D_s^{*+} \to D_s^+ e^+ e^-)}{B(D_s^{*+} \to D_s^+ \gamma)}$



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

$D_s^+ \to K_S K^+$

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

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

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

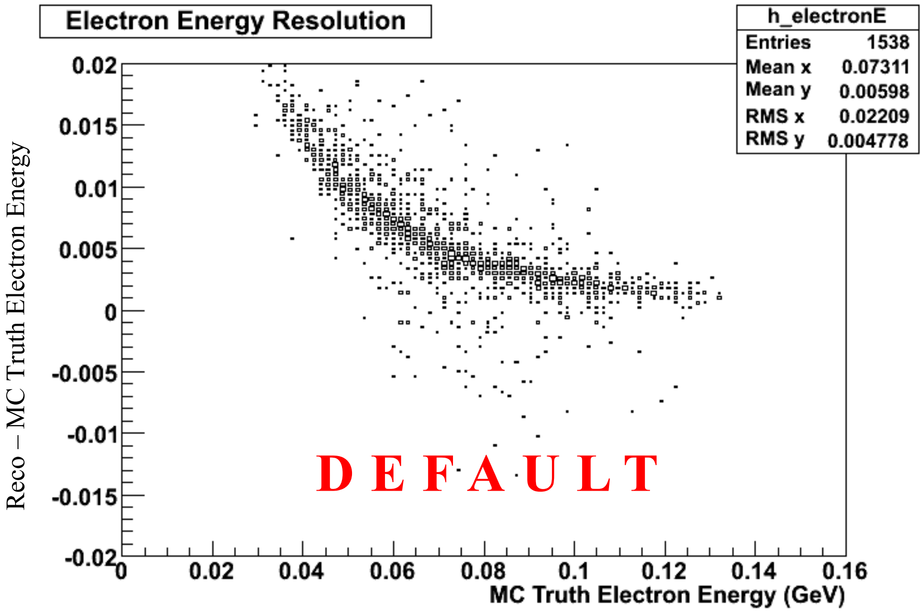
$D_s^+ \to \pi^+ \pi^+ \pi^-$

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

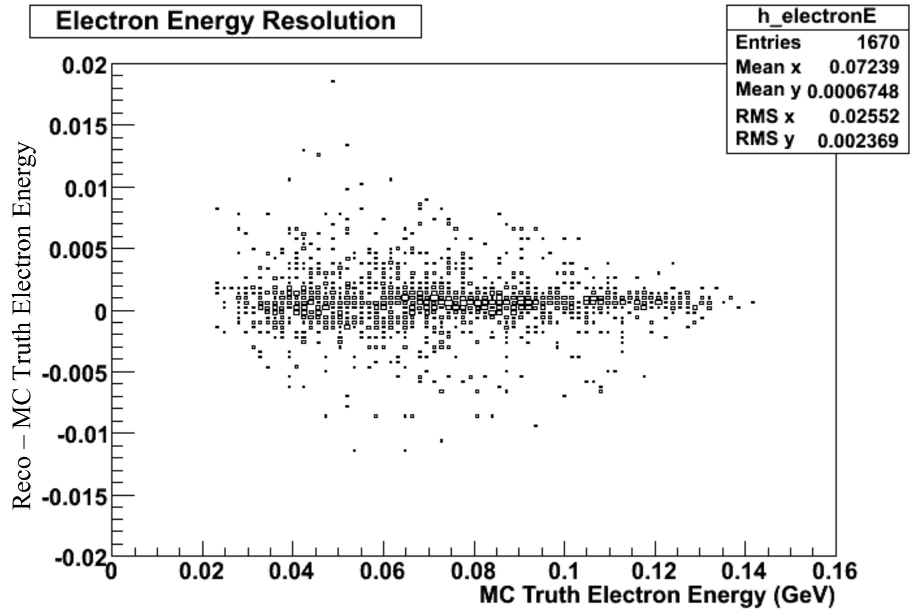
$D_s^+ \to \eta \rho^+; \eta \to \gamma\gamma; \rho^+ \to \pi^+ \pi^0$

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

Tracking Soft Electrons



Pion mass hypothesis fit in Signal MC samples



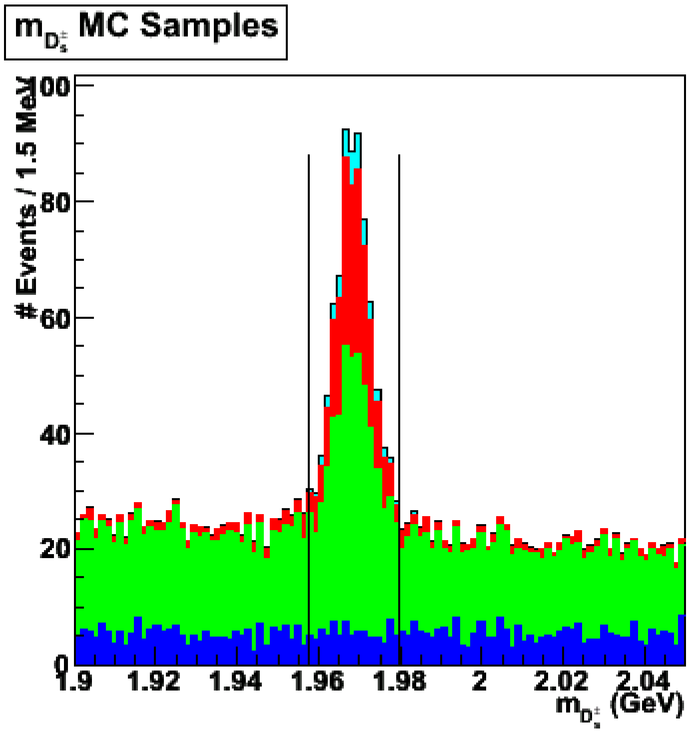
Electron mass hypothesis fit in Signal MC samples

- Studies with privately generated Monte Carlo samples indicate significantly better performance of analysis with electron mass hypothesis fitted data.
- Motivated a campaign to reprocess datasets containing 4170 MeV collision data to include such tracks.

Electron Track Selection Criteria

- Electron tracks must pass track quality cuts:
  - 10 MeV < Track Energy < 150 MeV
  - $|z_0| < 5$ cm. Tracks pass within 5 cm of the interaction point in dimension parallel to beam axis.
  - $|d_0| < 5$ mm. Tracks pass within 5 mm of the interaction point in dimensions perpendicular to the beam axis.
  - *dE/dx* within 3.0σ of that expected for an electron.

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



Cyan: Signal Monte Carlo
Red: Conversion Monte Carlo
Green: Generic Monte Carlo (c<u>c</u> production)
Blue: Continuum Monte Carlo (light quarks)

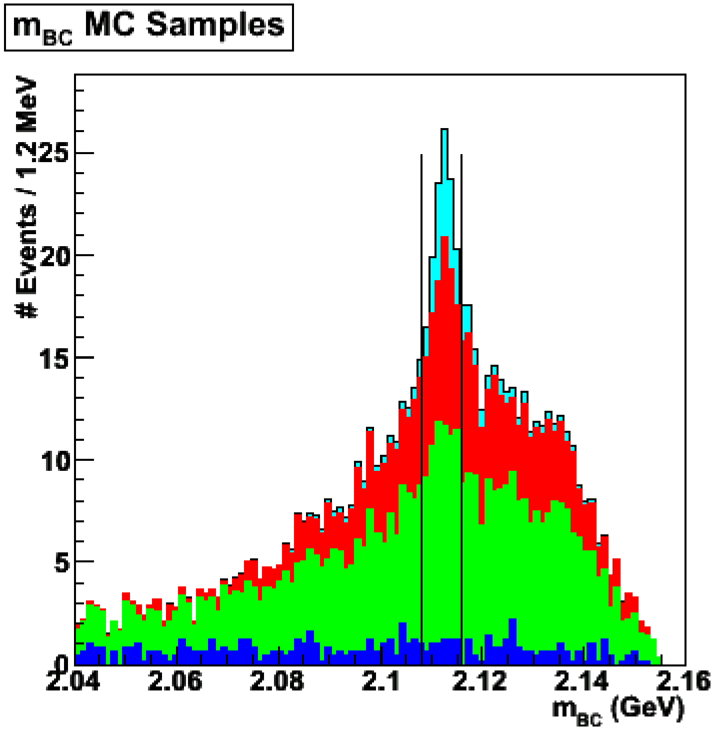
Histograms normalized to 586 pb^{-1} of data

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

•Selection Criterion for this mode:

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

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



Cyan: Signal Monte Carlo
Red: Conversion Monte Carlo
Green: Generic Monte Carlo (cc production)
Blue: 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^{*+}

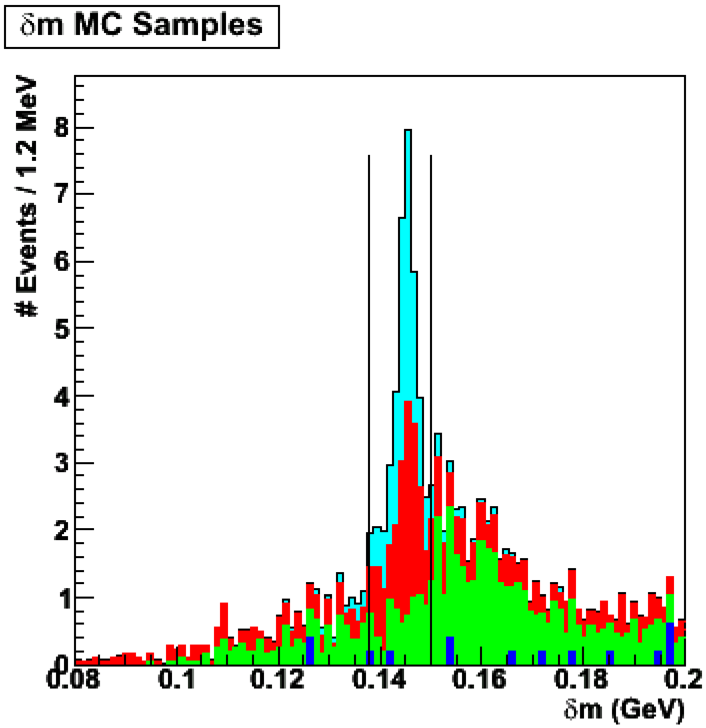
•We define the beam-constrained mass of the D_s^{*+} as:

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

•Selection Criterion for this mode:

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

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



Cyan: Signal Monte Carlo
Red: Conversion Monte Carlo
Green: Generic Monte Carlo (cc production)
Blue: Continuum Monte Carlo (light quarks)

Histograms normalized to 586 pb^{-1}

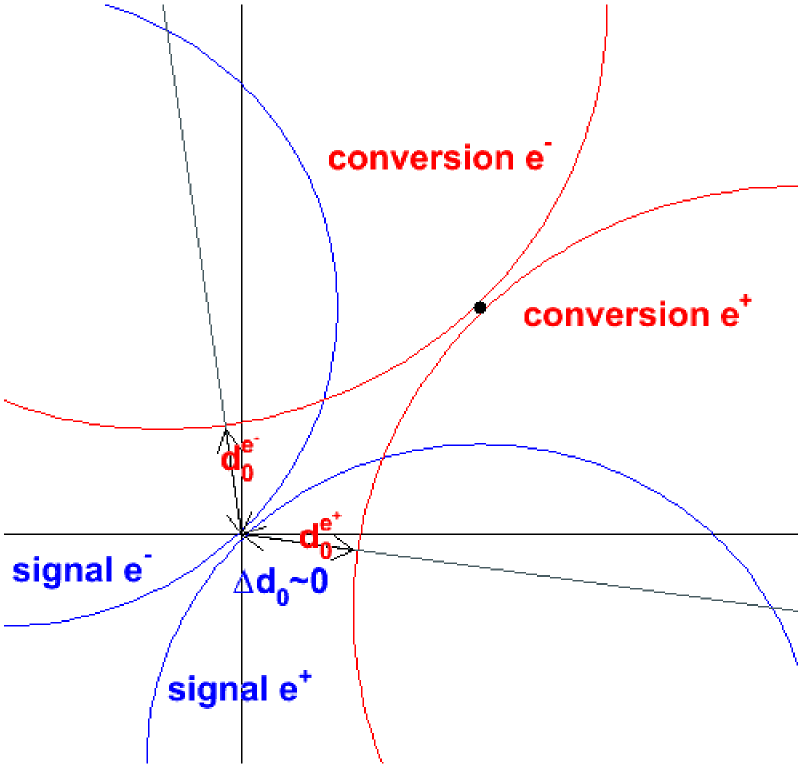
- We define δm as the mass difference the D_s^{*+} and the D_s^+ where both are reconstructed from their daughters:

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

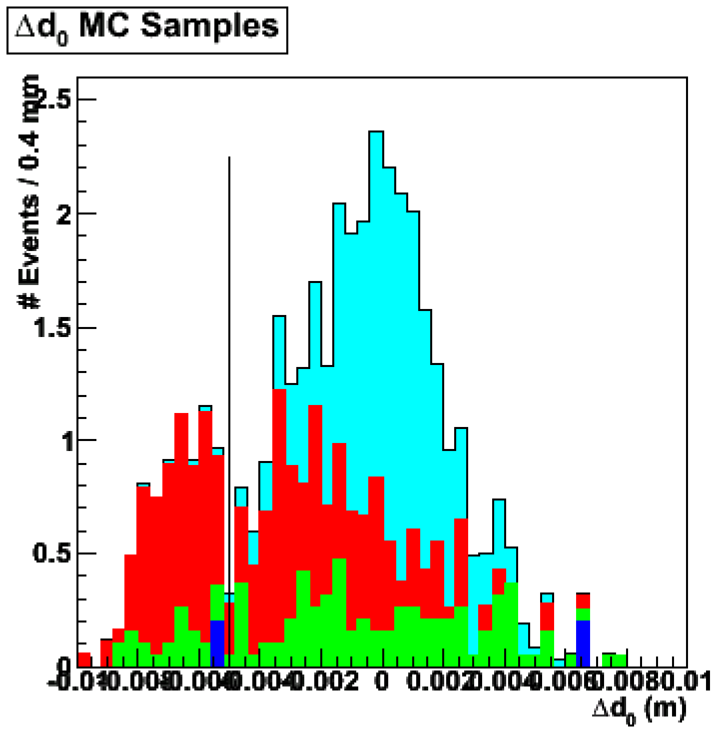
- Selection Criterion for this mode:

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

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



Δd$_0$ between the electron and positron in the signal (blue) and conversion (red)

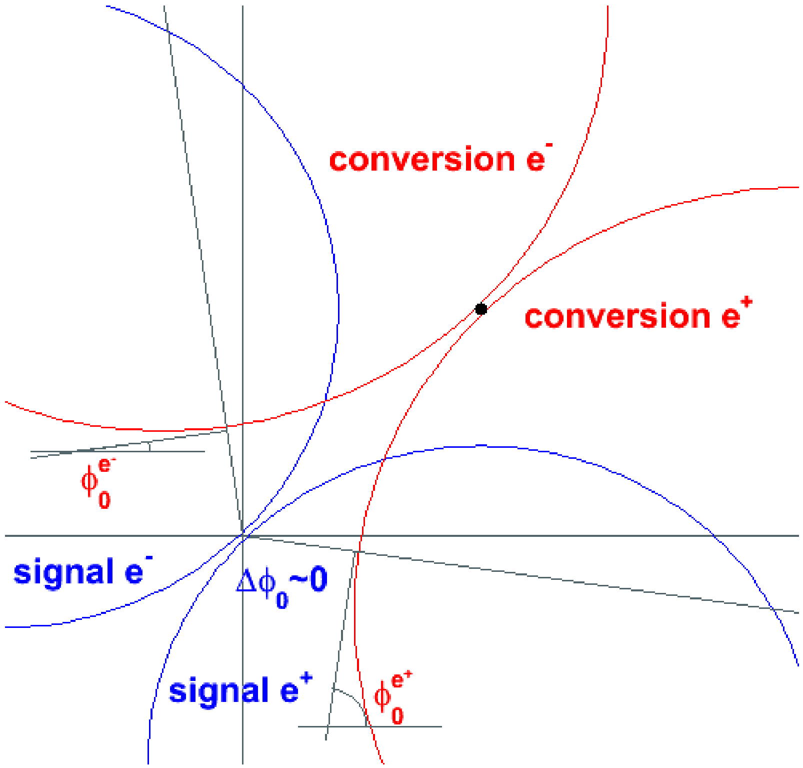


•$\boldsymbol{d_0}$: Signed distance of closest approach to the beamline [4]

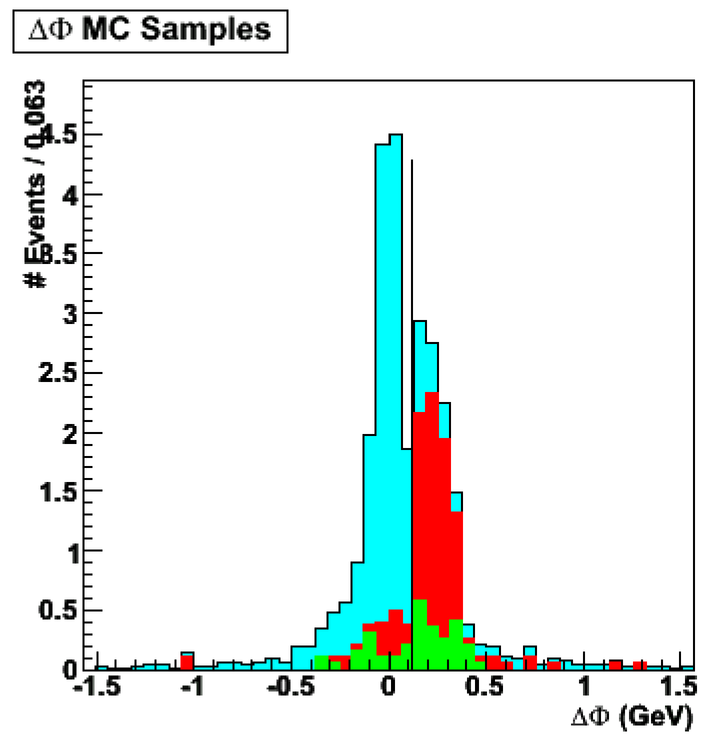
•The $\Delta d_0 = d_0^{e-} - d_0^{e+}$ is centered around 0 for the signal and offset from 0 for conversion backgrounds

•We require Δd_0 > -5 mm

$\Delta\varphi_0$ Selection Criterion for the $K^+K^-\pi^+$ Mode



$\Delta\varphi_0$ between the electron and positron in the signal (blue) and conversion (red) samples



•φ_0: Azimuth of track at the point of closest approach to beamline [4]

•$\Delta\varphi_0 = \varphi_0^{e-} - \varphi_0^{e+}$ is centered around 0 for the signal and offset for the conversion background. We require $\Delta\varphi < 0.12$

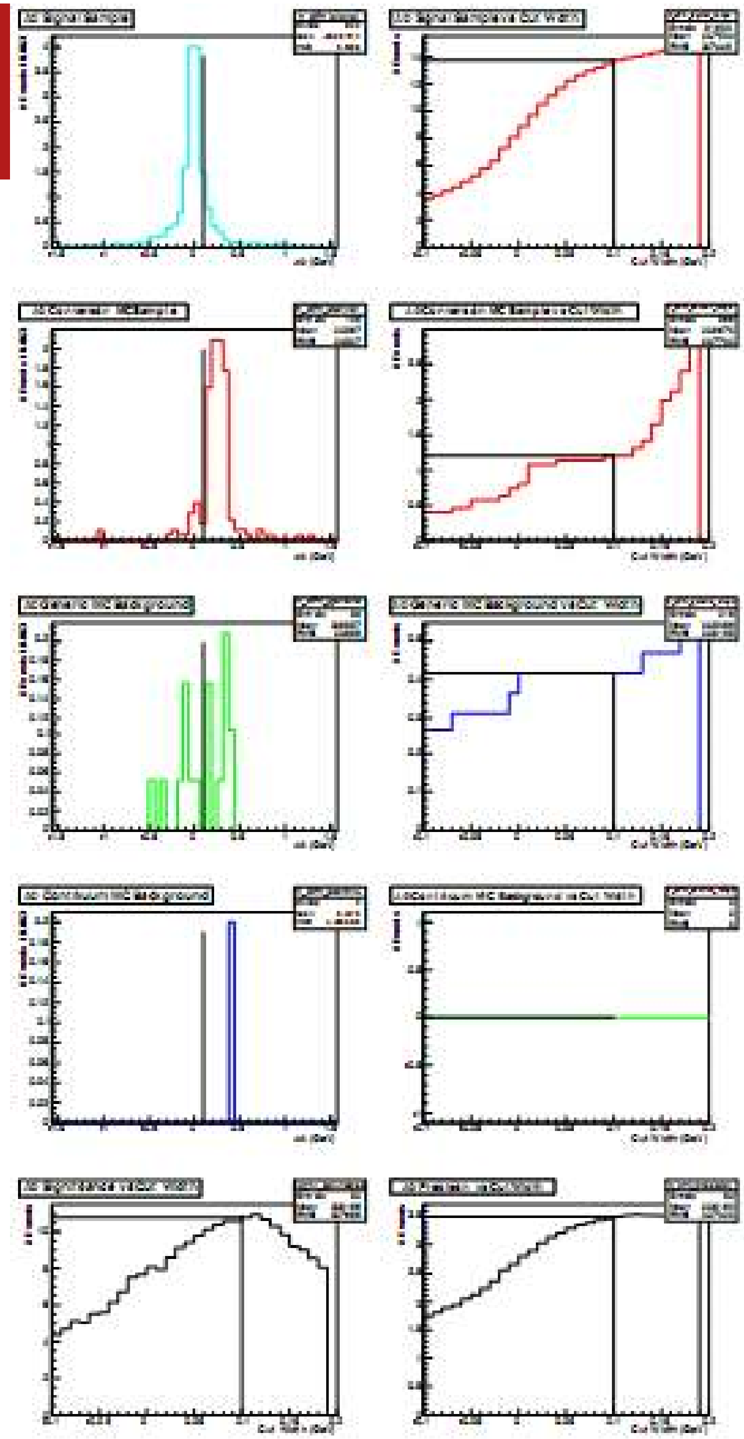
•**Δd_0 and $\Delta\varphi_0$ constitute powerful criterion against the photon conversion background.**

Optimizing Selection Criteria

•We went channel by channel, criterion by criterion. (Example of $\Delta\Phi_0$ Selection Criterion for the $K^+K^-\pi^+$ Mode on the right)

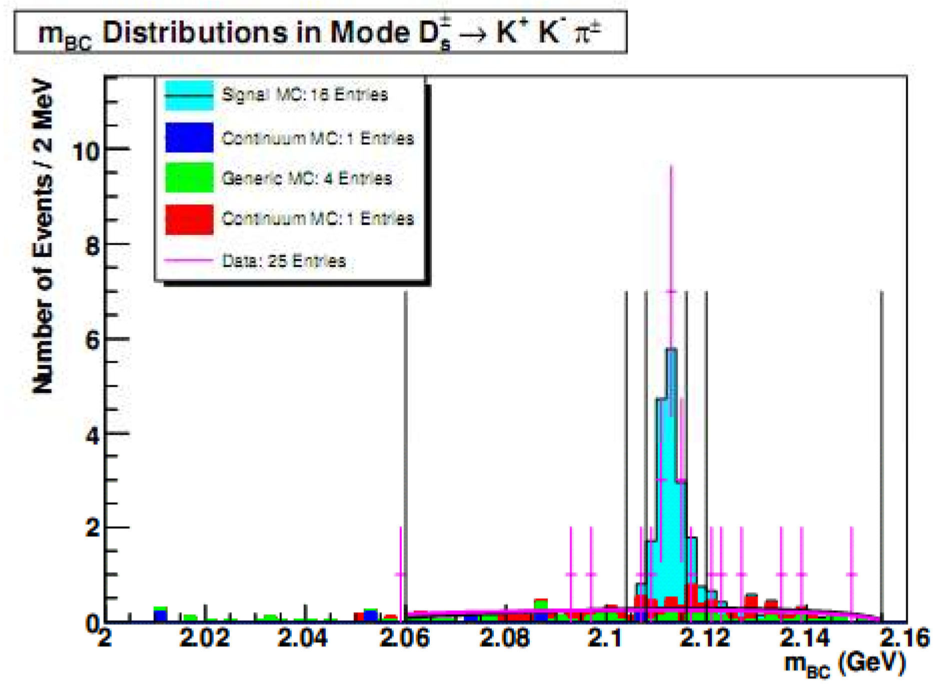
•Plotted the signal MC, conversion MC, generic without conversion MC, and continuum MC vs variation in the cut.

•Optimized for significance [$s/\sqrt{b}$] for low-statistics modes and precision [$s/\sqrt{(s+b)}$] for high-statistics modes.



Unblinding Data in the m_{BC} Signal Region of $D_s^{*+} \rightarrow D_s^+ e^+ e^-$

Decay Mode of the D_S^+	Expected Yield from MC in 586 pb^{-1}	Observed Yield in 586 pb^{-1}
$K^+K^-\pi^+$	14.70	14
K_sK^+	3.87	
$\pi^+\eta;\ \eta\rightarrow\gamma\gamma$	3.21	
$\pi^+\acute{\eta};\ \acute{\eta}\rightarrow\pi^+\pi^-\eta;\ \eta\rightarrow\gamma\gamma$	1.20	
$K^+K^-\pi^+\pi^0$	6.55	
$\pi^+\pi^-\pi^+$	5.32	
$K^{*+}K^{*0};\ K^{*+}\rightarrow K^0{}_S\pi^+;\ K^{*0}\rightarrow K^-\pi^+$	3.57	
$\eta\rho^+;\ \eta\rightarrow\gamma\gamma;\ \rho^+\rightarrow\pi^+\pi^0$	8.11	
$\acute{\eta}\pi^+;\ \acute{\eta}\rightarrow\rho^0\gamma$	4.26	
Total	**50.79**	

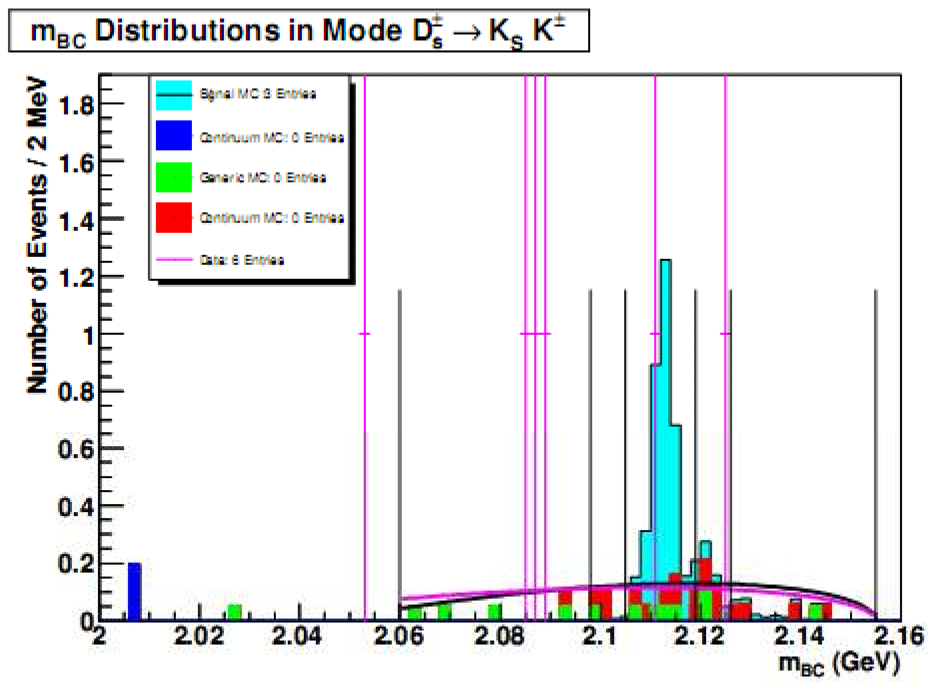


- Distribution of m_{BC} in data after unblinding in the $K^+K^-\pi^+$ mode

- Magenta curve extrapolates to estimate background using the data shape. Black curve extrapolates data using the MC shape.

Unblinding Data in the m_{BC} Signal Region of $D_s^{*+} \rightarrow D_s^+ e^+ e^-$

Decay Mode of the D_S^+	Expected Yield from MC in 586 pb^{-1}	Observed Yield in 586 pb^{-1}
$K^+K^-\pi^+$	14.70	14
K_sK^+	3.87	1
$\pi^+\eta;\ \eta\rightarrow\gamma\gamma$	3.21	
$\pi^+\acute{\eta};\ \acute{\eta}\rightarrow\pi^+\pi^-\eta;\ \eta\rightarrow\gamma\gamma$	1.20	
$K^+K^-\pi^+\pi^0$	6.55	
$\pi^+\pi^-\pi^+$	5.32	
$K^{*+}K^{*0};\ K^{*+}\rightarrow K^0{}_S\pi^+;\ K^{*0}\rightarrow K^-\pi^+$	3.57	
$\eta\rho^+;\ \eta\rightarrow\gamma\gamma;\ \rho^+\rightarrow\pi^+\pi^0$	8.11	
$\acute{\eta}\pi^+;\ \acute{\eta}\rightarrow\rho^0\gamma$	4.26	
Total	**50.79**	

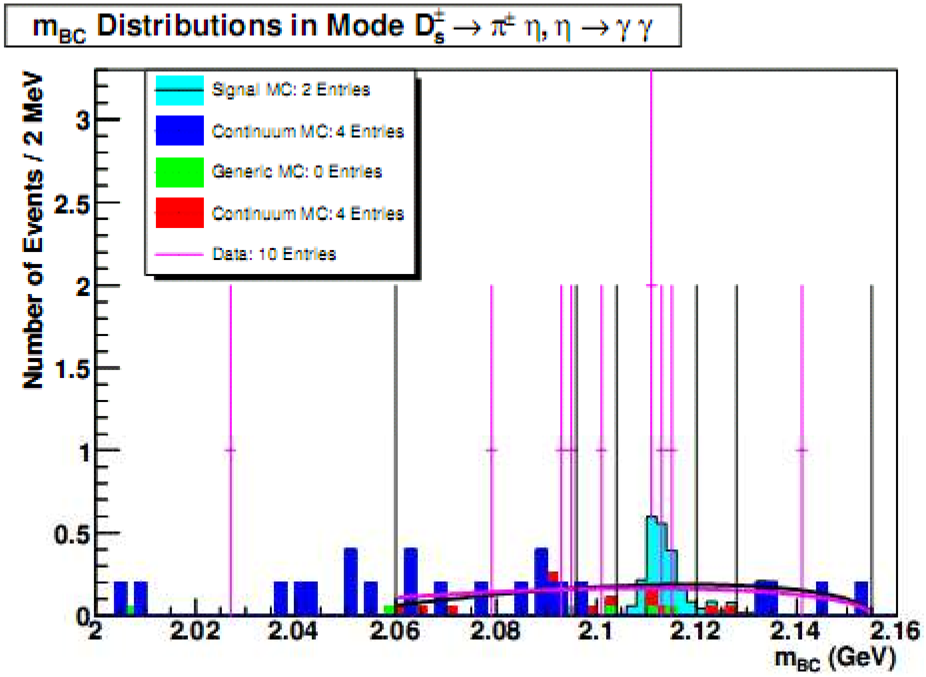


•Distribution of m_{BC} in data after unblinding in the K_sK^+mode

•Magenta curve extrapolates to estimate background using the data shape. Black curve extrapolates data using the MC shape.

Unblinding Data in the m_{BC} Signal Region of $D_s^{*+} \rightarrow D_s^+ e^+ e^-$

Decay Mode of the D_S^+	Expected Yield from MC in 586 pb^{-1}	Observed Yield in 586 pb^{-1}
$K^+K^-\pi^+$	14.70	14
K_sK^+	3.87	1
$\pi^+\eta;\ \eta\rightarrow\gamma\gamma$	3.21	4
$\pi^+\acute{\eta};\ \acute{\eta}\rightarrow\pi^+\pi^-\eta;\ \eta\rightarrow\gamma\gamma$	1.20	
$K^+K^-\pi^+\pi^0$	6.55	
$\pi^+\pi^-\pi^+$	5.32	
$K^{*+}K^{*0};\ K^{*+}\rightarrow K^0{}_S\pi^+;\ K^{*0}\rightarrow K^-\pi^+$	3.57	
$\eta\rho^+;\ \eta\rightarrow\gamma\gamma;\ \rho^+\rightarrow\pi^+\pi^0$	8.11	
$\acute{\eta}\pi^+;\ \acute{\eta}\rightarrow\rho^0\gamma$	4.26	
Total	**50.79**	

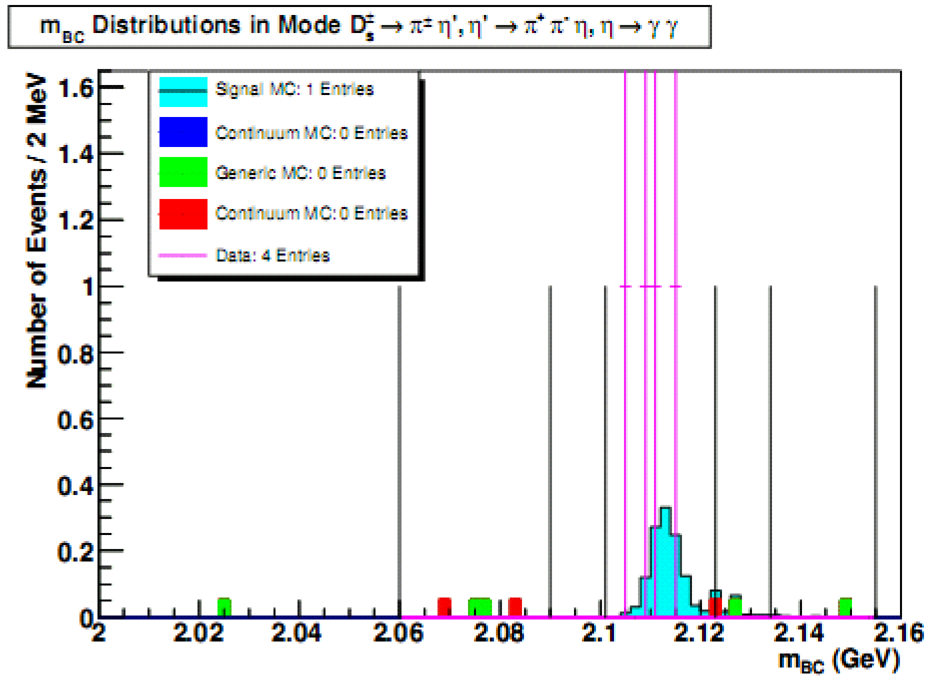


•Distribution of m_{BC} in data after unblinding in the $\pi^+\eta;\ \eta\rightarrow\gamma\gamma$ mode

•Magenta curve extrapolates to estimate background using the data shape. Black curve extrapolates data using the MC shape.

Unblinding Data in the m_{BC} Signal Region of $D_s^{*+} \rightarrow D_s^+ e^+ e^-$

Decay Mode of the D_S^+	Expected Yield from MC in 586 pb^{-1}	Observed Yield in 586 pb^{-1}
$K^+K^-\pi^+$	14.70	14
K_sK^+	3.87	1
$\pi^+\eta;\ \eta\rightarrow\gamma\gamma$	3.21	4
$\pi^+\acute{\eta};\ \acute{\eta}\rightarrow\pi^+\pi^-\eta;\ \eta\rightarrow\gamma\gamma$	1.20	4
$K^+K^-\pi^+\pi^0$	6.55	
$\pi^+\pi^-\pi^+$	5.32	
$K^{*+}K^{*0};\ K^{*+}\rightarrow K^0{}_S\pi^+;\ K^{*0}\rightarrow K^-\pi^+$	3.57	
$\eta\rho^+;\ \eta\rightarrow\gamma\gamma;\ \rho^+\rightarrow\pi^+\pi^0$	8.11	
$\acute{\eta}\pi^+;\ \acute{\eta}\rightarrow\rho^0\gamma$	4.26	
Total	**50.79**	

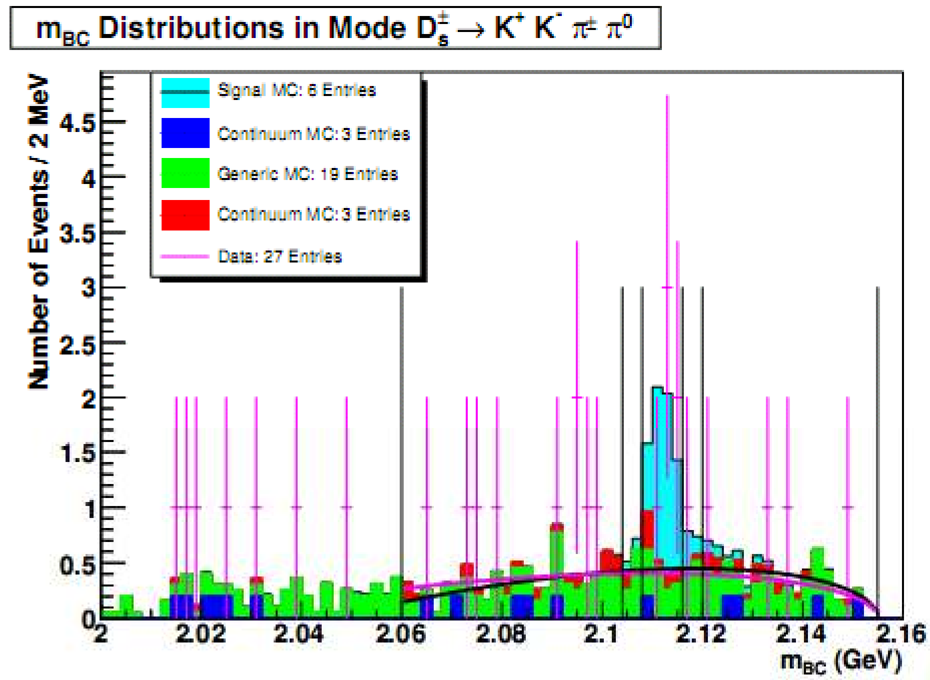


•Distribution of m_{BC} in data after unblinding in the $\pi^+\acute{\eta};\ \acute{\eta}\rightarrow\pi^+\pi^-\eta;\ \eta\rightarrow\gamma\gamma$

•Magenta curve extrapolates to estimate background using the data shape. Black curve extrapolates data using the MC shape.

Unblinding Data in the m_{BC} Signal Region of $D_s^{*+} \longrightarrow D_s^+ e^+ e^-$

Decay Mode of the D_S^+	Expected Yield from MC in 586 pb^{-1}	Observed Yield in 586 pb^{-1}
$K^+K^-\pi^+$	14.70	14
K_sK^+	3.87	1
$\pi^+\eta;\ \eta\rightarrow\gamma\gamma$	3.21	4
$\pi^+\acute{\eta};\ \acute{\eta}\rightarrow\pi^+\pi^-\eta;\ \eta\rightarrow\gamma\gamma$	1.20	4
$K^+K^-\pi^+\pi^0$	6.55	6
$\pi^+\pi^-\pi^+$	5.32	
$K^{*+}K^{*0};\ K^{*+}\rightarrow K^0{}_S\pi^+;$ $K^{*0}\rightarrow K^-\pi^+$	3.57	
$\eta\rho^+;\ \eta\rightarrow\gamma\gamma;\ \rho^+\rightarrow\pi^+\pi^0$	8.11	
$\acute{\eta}\pi^+;\ \acute{\eta}\rightarrow\rho^0\gamma$	4.26	
Total	**50.79**	

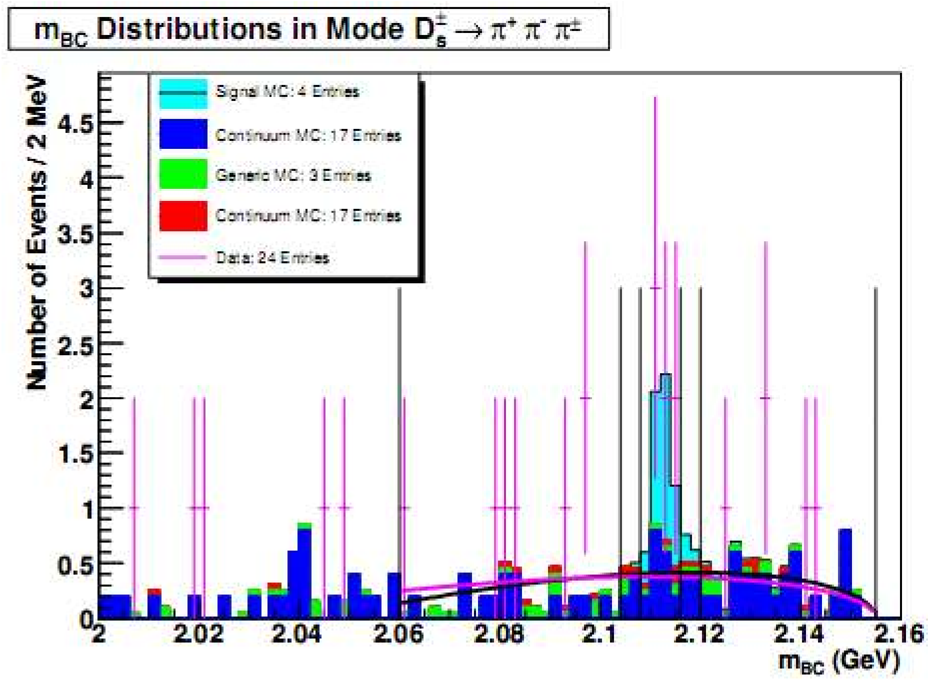


- Distribution of m_{BC} in data after unblinding in the $K^+K^-\pi^+\pi^0$ mode

- Magenta curve extrapolates to estimate background using the data shape. Black curve extrapolates data using the MC shape.

Unblinding Data in the m_{BC} Signal Region of $D_s^{*+} \to D_s^+ e^+ e^-$

Decay Mode of the D_S^+	Expected Yield from MC in 586 pb^{-1}	Observed Yield in 586 pb^{-1}
$K^+K^-\pi^+$	14.70	14
K_sK^+	3.87	1
$\pi^+\eta;\ \eta\to\gamma\gamma$	3.21	4
$\pi^+\acute{\eta};\ \acute{\eta}\to\pi^+\pi^-\eta;\ \eta\to\gamma\gamma$	1.20	4
$K^+K^-\pi^+\pi^0$	6.55	6
$\pi^+\pi^-\pi^+$	5.32	7
$K^{*+}K^{*0};\ K^{*+}\to K^0{}_S\pi^+;$ $K^{*0}\to K^-\pi^+$	3.57	
$\eta\rho^+;\ \eta\to\gamma\gamma;\ \rho^+\to\pi^+\pi^0$	8.11	
$\acute{\eta}\pi^+;\ \acute{\eta}\to\rho^0\gamma$	4.26	
Total	**50.79**	

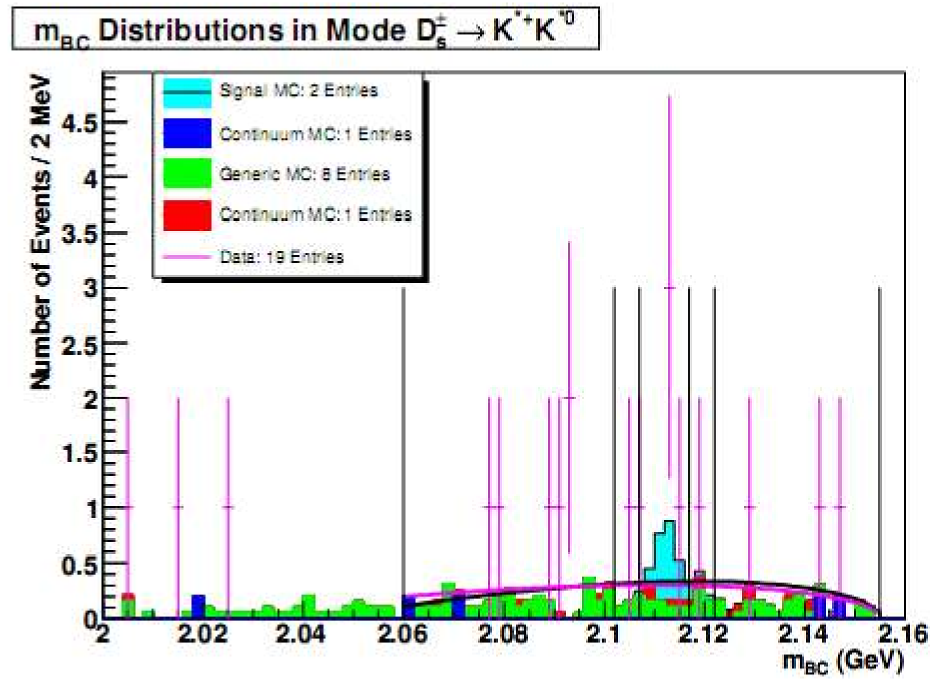


•Distribution of m_{BC} in data after unblinding in the $\pi^+\pi^-\pi^+$ mode

•Magenta curve extrapolates to estimate background using the data shape. Black curve extrapolates data using the MC shape.

Unblinding Data in the m_{BC} Signal Region of $D_s^{*+} \to D_s^+ e^+ e^-$

Decay Mode of the D_S^+	Expected Yield from MC in 586 pb^{-1}	Observed Yield in 586 pb^{-1}
$K^+K^-\pi^+$	14.70	14
K_sK^+	3.87	1
$\pi^+\eta;\ \eta\to\gamma\gamma$	3.21	4
$\pi^+\acute{\eta};\ \acute{\eta}\to\pi^+\pi^-\eta;\ \eta\to\gamma\gamma$	1.20	4
$K^+K^-\pi^+\pi^0$	6.55	6
$\pi^+\pi^-\pi^+$	5.32	7
$K^{*+}K^{*0};\ K^{*+}\to K^0{}_S\pi^+;\ K^{*0}\to K^-\pi^+$	3.57	4
$\eta\rho^+;\ \eta\to\gamma\gamma;\ \rho^+\to\pi^+\pi^0$	8.11	
$\acute{\eta}\pi^+;\ \acute{\eta}\to\rho^0\gamma$	4.26	
Total	**50.79**	

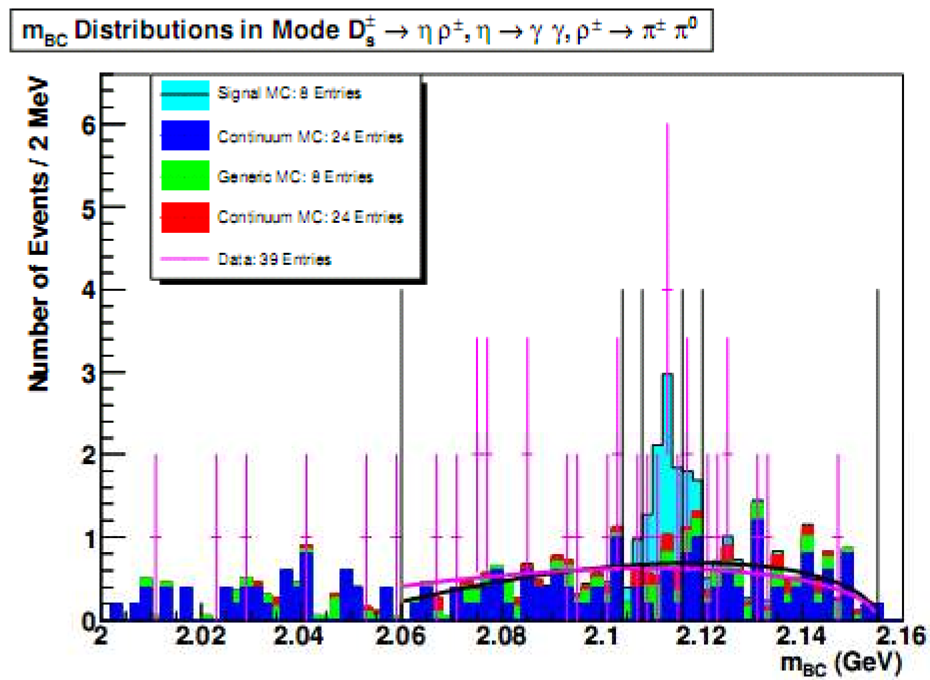


- Distribution of m_{BC} in data after unblinding in the $K^{*+}K^{*0};\ K^{*+}\to K^0{}_S\pi^+;\ K^{*0}\to K^-\pi^+$ mode

- Magenta curve extrapolates to estimate background using the data shape. Black curve extrapolates data using the MC shape.

Unblinding Data in the m_{BC} Signal Region of $D_s^{*+} \rightarrow D_s^+ e^+ e^-$

Decay Mode of the D_S^+	**Expected Yield from MC in 586 pb^{-1}**	**Observed Yield in 586 pb^{-1}**
$K^+K^-\pi^+$	14.70	14
K_sK^+	3.87	1
$\pi^+\eta;\ \eta\rightarrow\gamma\gamma$	3.21	4
$\pi^+\acute{\eta};\ \acute{\eta}\rightarrow\pi^+\pi^-\eta;\ \eta\rightarrow\gamma\gamma$	1.20	4
$K^+K^-\pi^+\pi^0$	6.55	6
$\pi^+\pi^-\pi^+$	5.32	7
$K^{*+}K^{*0};\ K^{*+}\rightarrow K^0{}_S\pi^+;\ K^{*0}\rightarrow K^-\pi^+$	3.57	4
$\eta\rho^+;\ \eta\rightarrow\gamma\gamma;\ \rho^+\rightarrow\pi^+\pi^0$	8.11	7
$\acute{\eta}\pi^+;\ \acute{\eta}\rightarrow\rho^0\gamma$	4.26	
Total	**50.79**	



•Distribution of m_{BC} in data after unblinding in the $\eta\rho^+;\ \eta\rightarrow\gamma\gamma;\ \rho^+\rightarrow\pi^+\pi^0$ mode

•Magenta curve extrapolates to estimate background using the data shape. Black curve extrapolates data using the MC shape.

Significance of Observation

Question: What is the probability that 12.61 ± 1.58 ± 1.53 background events fluctuated up to the 51 events we observed?

Answer: 1.7×10^{-10}

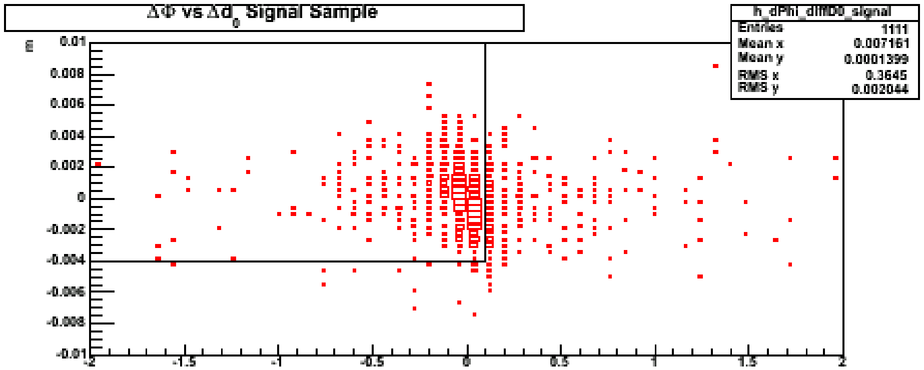
- Assume the estimated background fluctuates as a Gaussian with mean (b) = 12.61 and standard deviation (σ) = 2.20

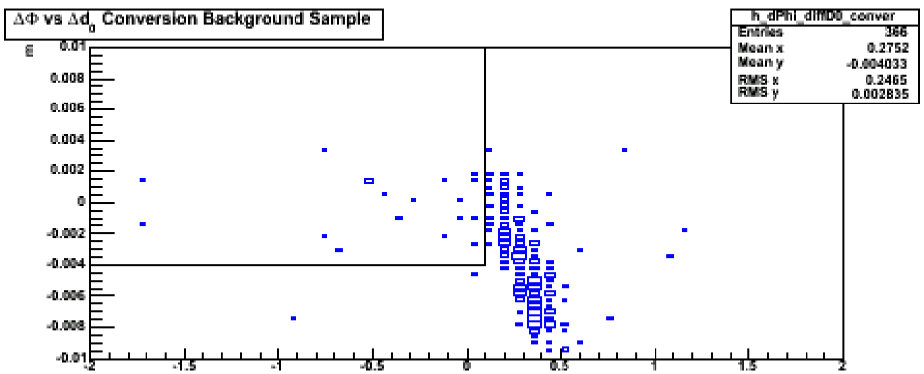
- Convolute it with a Poisson fluctuation to 51 events (n) or higher to find the probability.

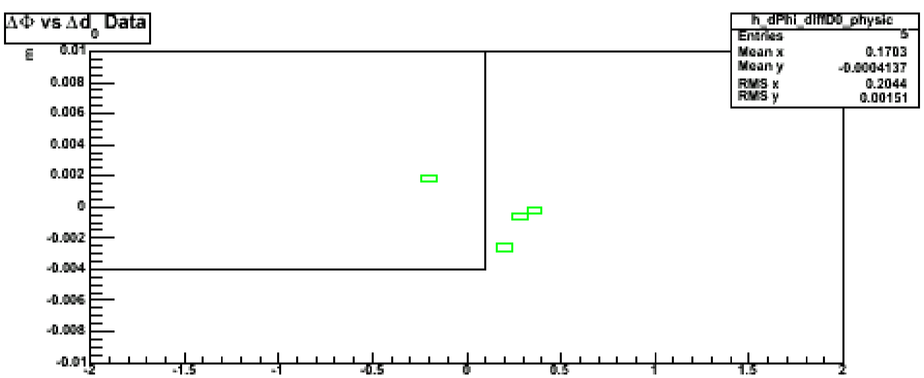
$$P(b,\sigma,n) = \frac{\sum_{i=n}^{i=\infty} \int_{x=0}^{x=\infty} \frac{x^i}{i!} e^{-[x+\frac{1}{2}(\frac{x-b}{\sigma})^2]} dx}{\int_{x=0}^{x=\infty} e^{-\frac{1}{2}(\frac{x-b}{\sigma})^2} dx}$$

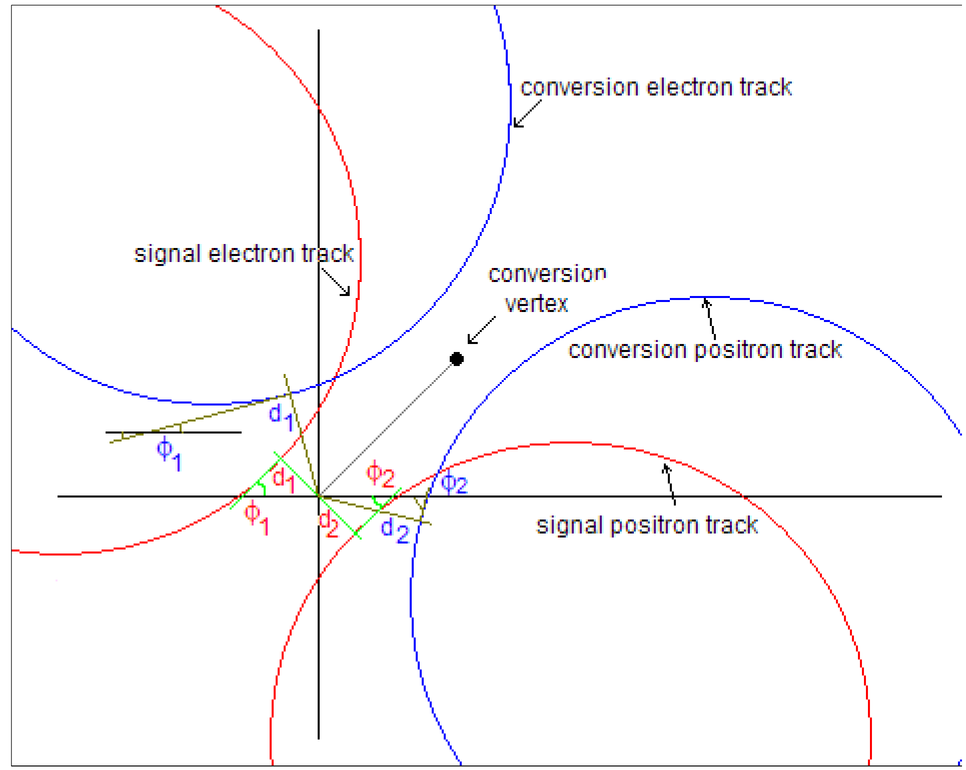
- In high energy physics, we express such small probabilities in terms of standard deviations of a Gaussian we need to eliminate to be left with that probability. 1.7×10^{-10} corresponds to 6.39 σ

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









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

Background Monte Carlo Samples

- The generic and continuum MC samples that come with the CLEO-c datasets do not have electron mass fitted tracks either!

- We do not bother reprocessing them. Instead we remove events in the generic MC that have $D_s^{*+} \to D_s^+ \gamma$ at the level of event generation. We replace these events with privately produced $D_s^{*+} \to D_s^+ \gamma$ where electron mass fitted tracks are stored.

- This complicates plots, hence not shown.

- However, such a separation of backgrounds is used for optimizing our selection criteria.

Criteria to Select $D_s^{*+} \to D_s^+ \gamma$ Events

•Now we measure the yields and efficiencies for the $D_s^{*+} \to D_s^+ \gamma$ channel since we have set out to measure the ratio of branching fractions

$$B(D_s^{*+} \to D_s^+ e^+ e^-) / B(D_s^{*+} \to D_s^+ \gamma)$$

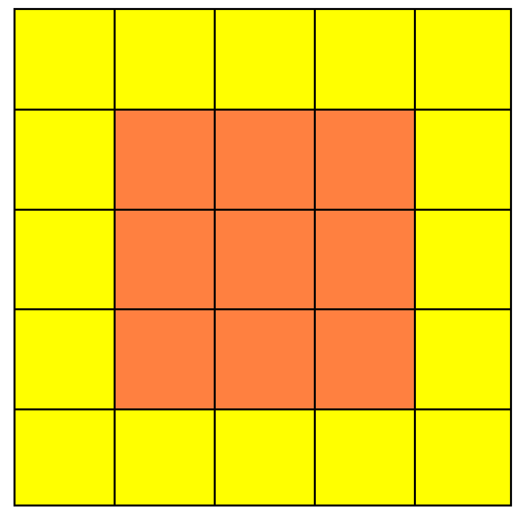
•We reconstruct the D_s^{*+} through the D_s^+ and the γ

•The D_s^+ is reconstructed through the 9 hadronic decay modes

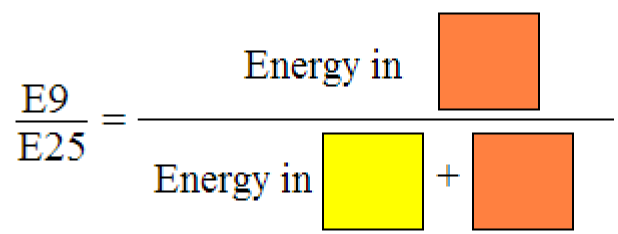
•Criteria on the e^+e^- inapplicable. Instead, criteria on the electromagnetic shower of the photon in the calorimeter are applied.

- •10 MeV < Shower Energy < 2.0 GeV
- •No tracks leading to or in the vicinity of the shower
- •Known noisy calorimeter crystals discarded
- •EM shower shape ensured with *E9/E25*

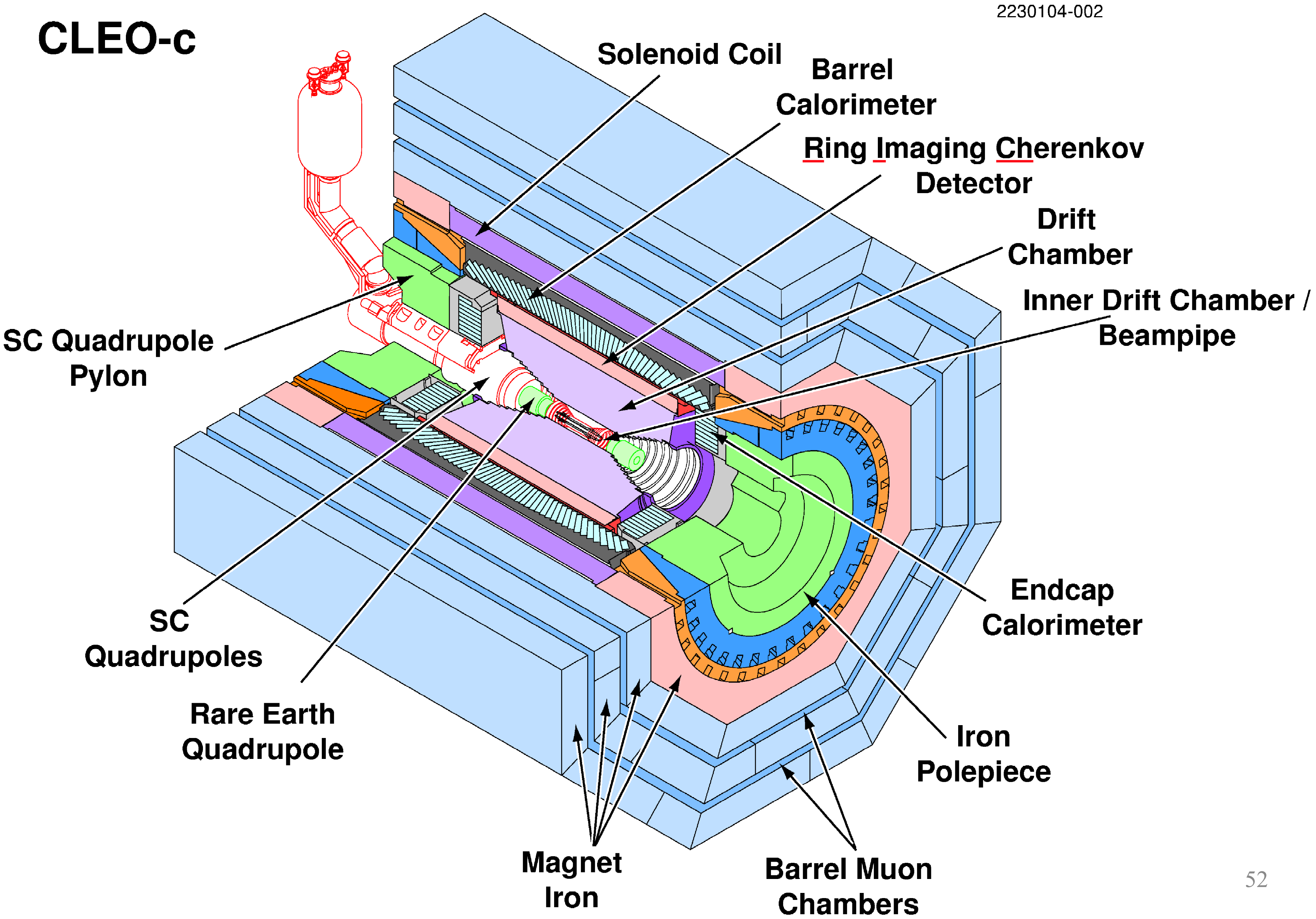
•The m_{BC} criterion is discarded in favor of a fit to extract yield.



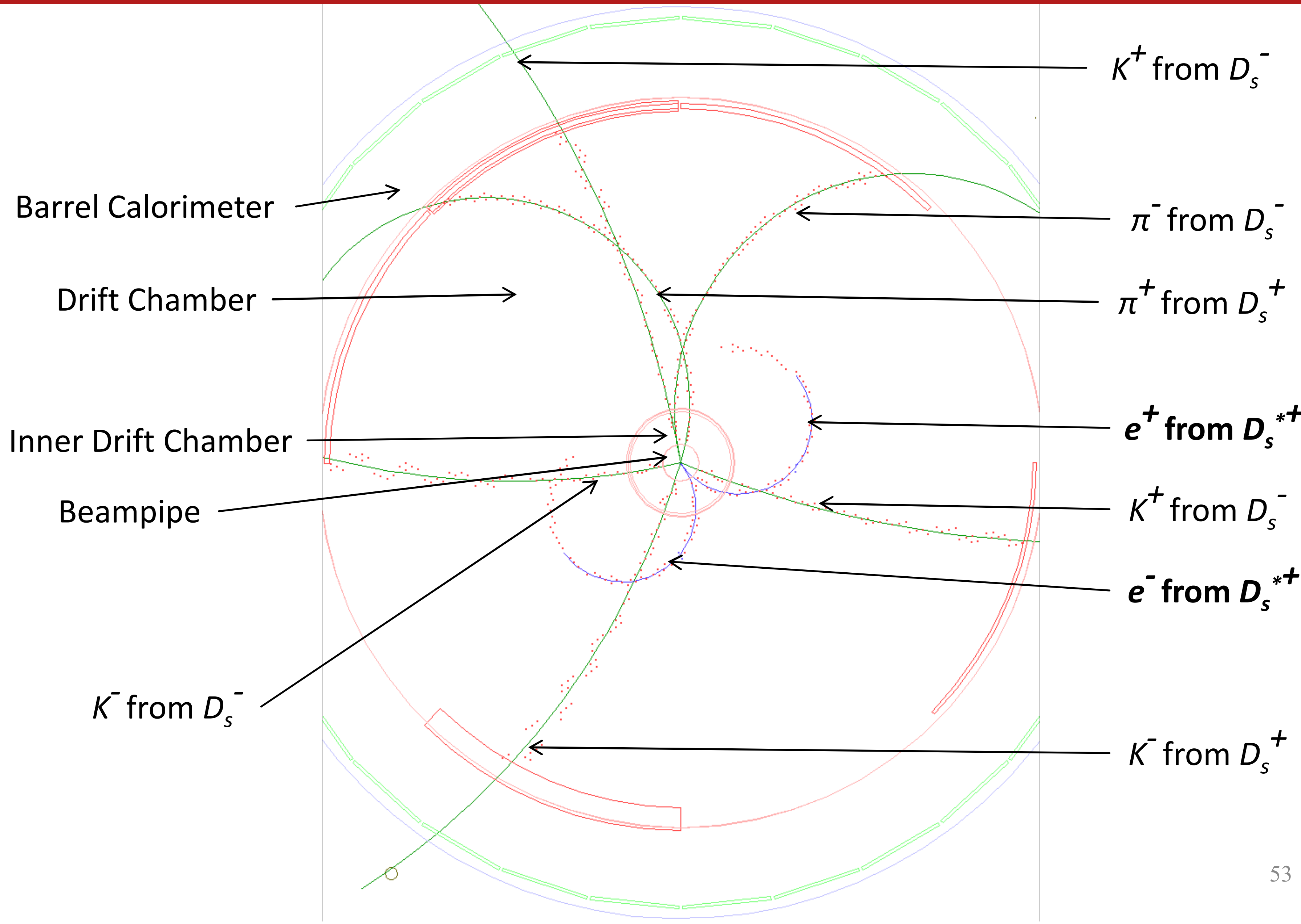
25 CsI crystals surrounding the center of an EM shower



The CLEO-c Detector



A Simulated Signal Event of $D_s^{*\pm} \rightarrow D_s^{\pm} e^+ e^-; D_s^{*\pm} \rightarrow K^+ K^- \pi^+$



The Problem with Soft Electrons

- Hits in the CLEO-c drift chamber are fitted to a track with a Kalman filter

- Kalman filter depends on models of energy loss of charged particle in material

- Given a certain momentum, the energy loss depends on the mass of the particle

- Tracks associated with electrons in the standard CLEO-c dataset were Kalman fitted with the $\pi^{\pm}$ mass. Fits with the $e^{\pm}$ mass were computed but discarded in the interest of disk space.

- This works fine in reconstructing electrons above ~ 200 MeV, but we are working with electrons ~ 70 MeV each.

- The Kalman filter over-compensates the energy of electron tracks. Hurts our analysis.