Search for the $h_c(2P)$

Using

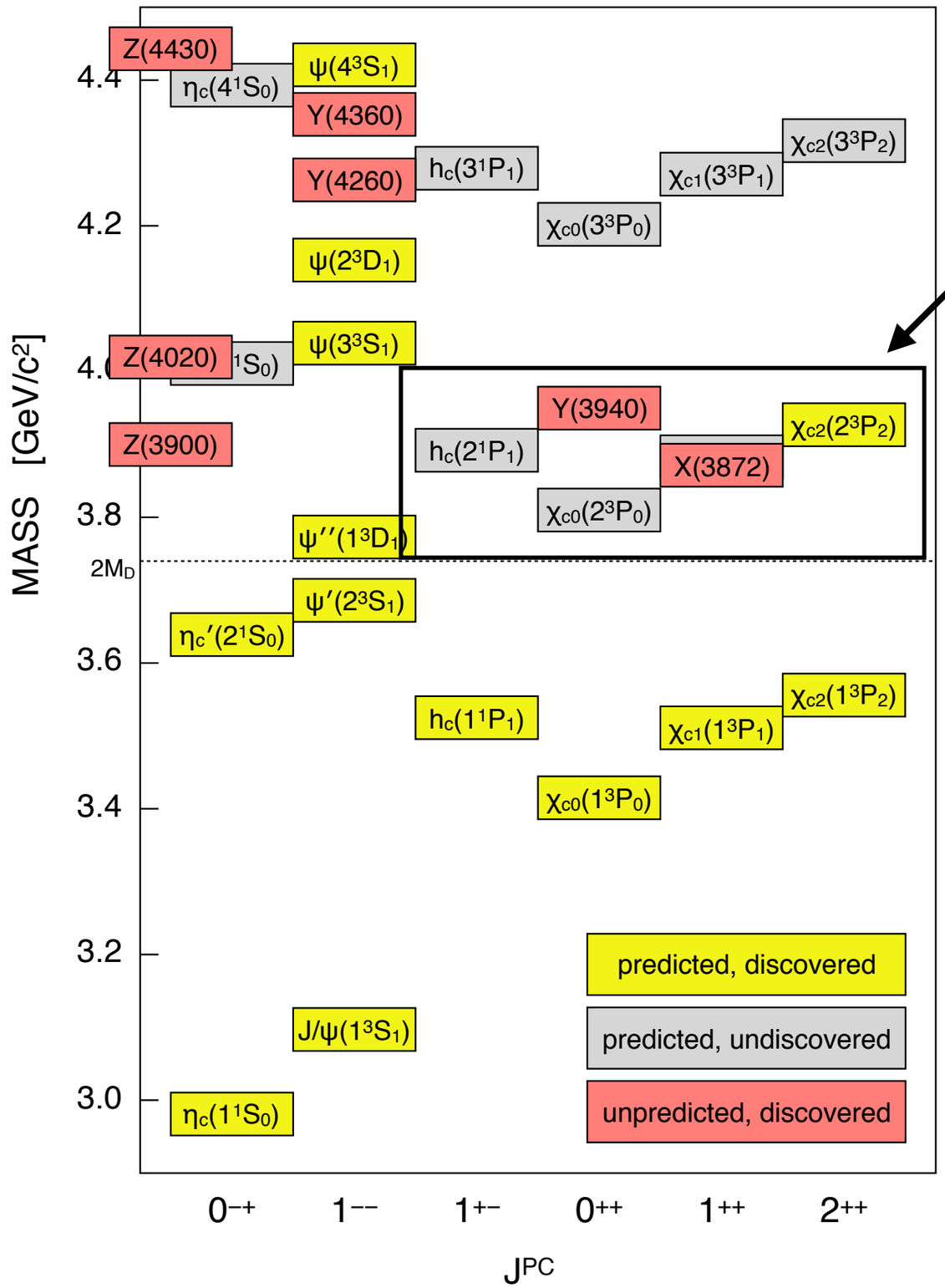
$$e^+e^- \to \pi^+\pi^- h_c(2P)$$

with

$$h_c(2P) \to D^+D^{*-}$$

Ryan Mitchell, Zhentian Sun
Indiana University
June 13, 2017

Overview of the $h_c(2P)$



The region around 3.9 GeV is unclear…
X(3872), X(3915), Y(3940), Z(3930), X(3940)
Which are conventional and which aren't?

Finding the $h_c(2P)$ could bring clarification.

Cross sections for $\pi^+\pi^-\psi(1S,2S)$ and $\pi^+\pi^-h_c(1P)$ are on the order of 50 – 100 pb; we probably expect the same for $\pi^+\pi^-h_c(2P)$.

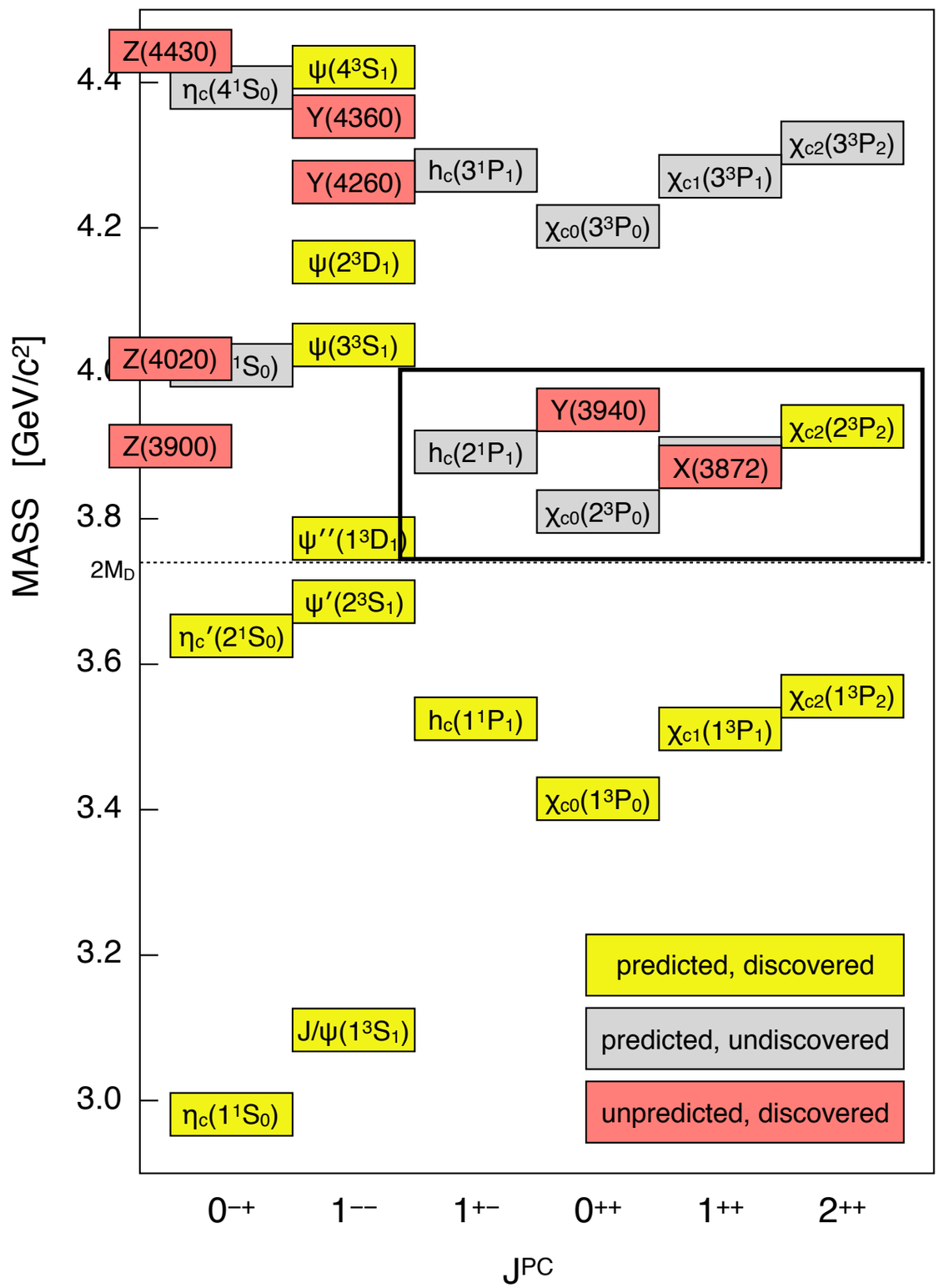
Furthermore, mass and decay width predictions for the $h_c(2P)$ exist:

PHYSICAL REVIEW D **72,** 054026 (2005)

Higher charmonia

T. Barnes,[1,*] S. Godfrey,[2,†] and E. S. Swanson[3,‡]

Overview of the $h_c(2P)$



PHYSICAL REVIEW D **72,** 054026 (2005)

Higher charmonia

T. Barnes,[1,*] S. Godfrey,[2,†] and E. S. Swanson[3,‡]

2P Mass Predictions:

Multiplet	State	Expt.	Input (NR)	Theor. NR	Theor. GI
2P	$\chi_2(2^3P_2)$			3972	3979
	$\chi_1(2^3P_1)$			3925	3953
	$\chi_0(2^3P_0)$			3852	3916
	$h_c(2^1P_1)$			3934	3956

2P DD Decay Width Predictions:

Meson	State	Mode	Γ_{thy} (MeV)	Amps. ($GeV^{-1/2}$)
$\chi_2(3972)$	2^3P_2	DD	42	$^1D_2 = +0.0992$
		DD^*	37	$^3D_2 = -0.1172$
		D_sD_s	0.7	$^1D_2 = +0.0202$
		total	80	
$\chi_1(3925)$	2^3P_1	DD^*	165	$^3S_1 = +0.2883$
				$^3D_1 = -0.0525$
$\chi_0(3852)$	2^3P_0	DD	30	$^1S_0 = +0.1025$
$h_c(3934)$	2^1P_1	DD^*	87	$^3S_1 = -0.1847$
				$^3D_1 = -0.0851$

Strategy

I. Measure the $e^+e^- \to \pi^+\pi^- D^+ D^{*-}$ cross section.

II. Search for $\pi^+\pi^- h_c(2P)$ with $h_c(2P) \to D^+ D^{*-}$.

III. Compare to $e^+e^- \to \pi^-\pi^0 D^+ \bar{D}^{*0}$.

I. Measure the $e^+e^- \to \pi^+\pi^-D^+D^{*-}$ Cross Section

<u>Reconstruct $\pi^+\pi^-D^+$ with $D^+ \to K^-\pi^+\pi^+$ *(and charge conjugate, always implied)*.</u>

Isolate the reaction by finding the D^+ in $K^-\pi^+\pi^+$ and looking for the D^{*-} in the $(K^-\pi^+\pi^+)\pi^+\pi^-$ missing mass. Use all combinations.

Use standard track and angle requirements for all tracks.

Only use PID for the kaon: $P(K) > P(\pi)$ and $P(K) > 10^{-3}$.

<u>Use three classes of data:</u>

SIGNAL MC: Includes $\pi^+\pi^-D^+D^{*-}$ and its charge conjugate.
The charge-conjugate channel is an irreducible background, since $D^{*+} \to \pi^0 D^+$.

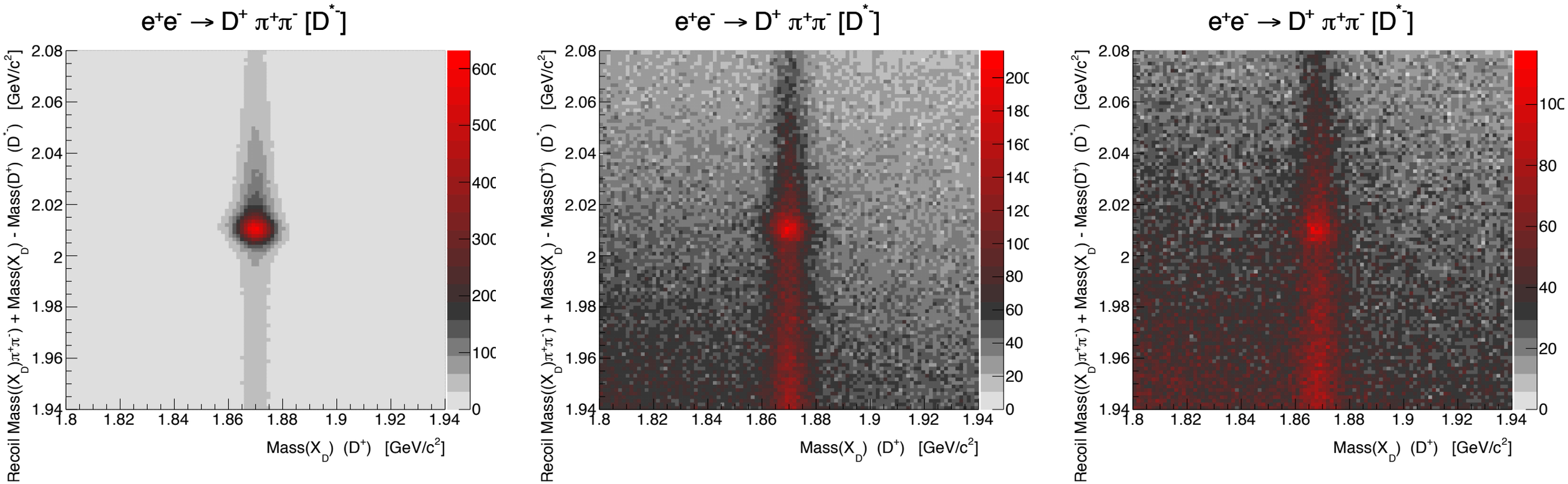
INCLUSIVE MC: (1) Includes full samples of inclusive DDbar MC at 4.42 and 4.60 GeV (*including important channels of the form $\pi D^* D^*$*).
(2) We also add 200 pb each for all charge combinations of the form $\pi\pi DD^*$ (*which includes signal as well as potential peaking backgrounds*).

DATA: Currently use all of the 2014 data: 4420, 4470, 4530, 4575, 4600 MeV (*but should eventually also include the 4360 data from 2013*).

I. Measure the $e^+e^- \rightarrow \pi^+\pi^-D^+D^{*-}$ Cross Section

* Find the D^+ using the $D^+ \rightarrow K^-\pi^+\pi^+$ mass (*x-axis*).

* Find the D^{*-} using the $D^+\pi^+\pi^-$ recoil mass $[RM((K^-\pi^+\pi^+)\pi^+\pi^-) + M(K^-\pi^+\pi^+) - M(D^+)]$ (*y-axis*).

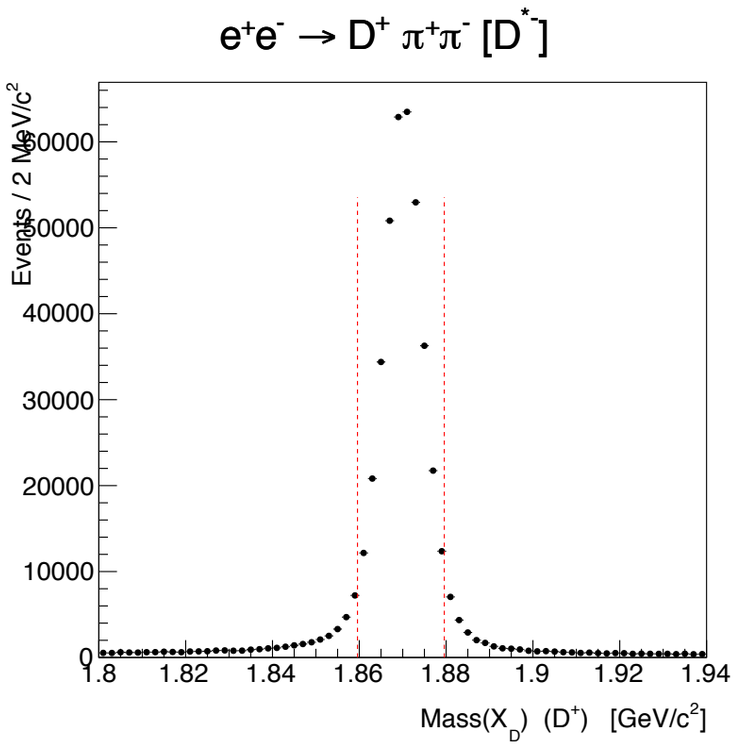


SIGNAL MC **INCLUSIVE MC** **DATA**

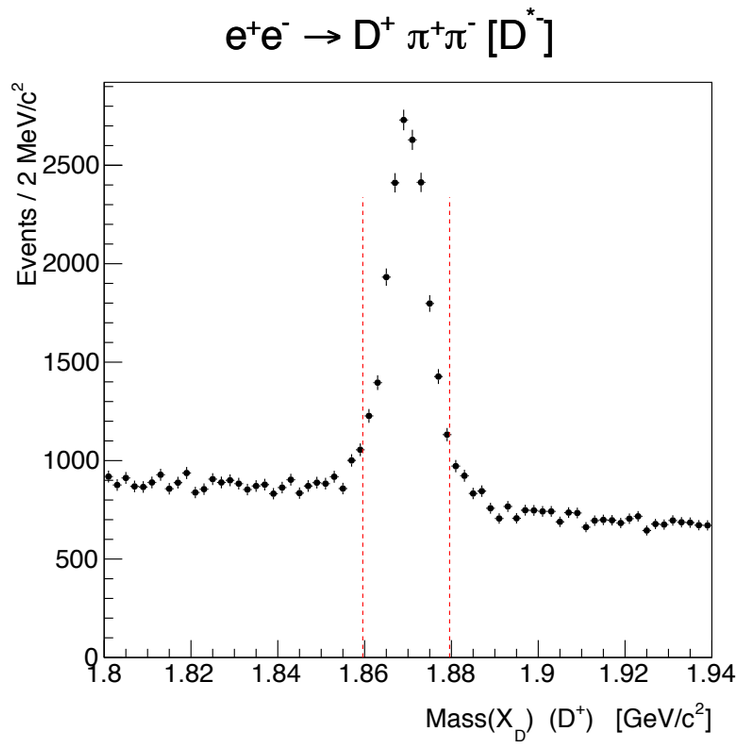
(Using all 2014 data: 4420, 4470, 4530, 4575, 4600.)

I. Measure the $e^+e^- \to \pi^+\pi^- D^+ D^{*-}$ Cross Section

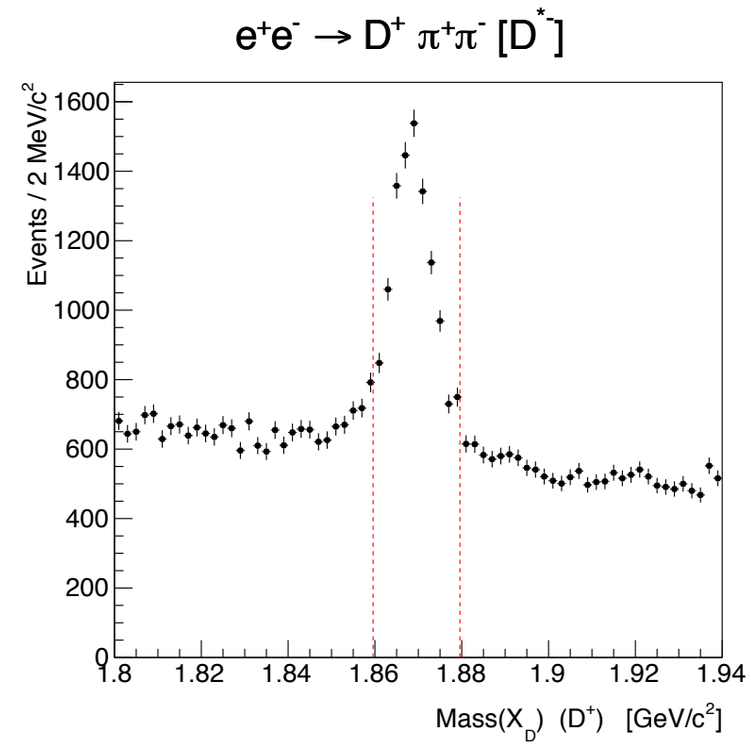
* Select the D^+ by requiring Mass($K^-\pi^+\pi^+$) be within 10 MeV of the D^+ mass.



SIGNAL MC



INCLUSIVE MC



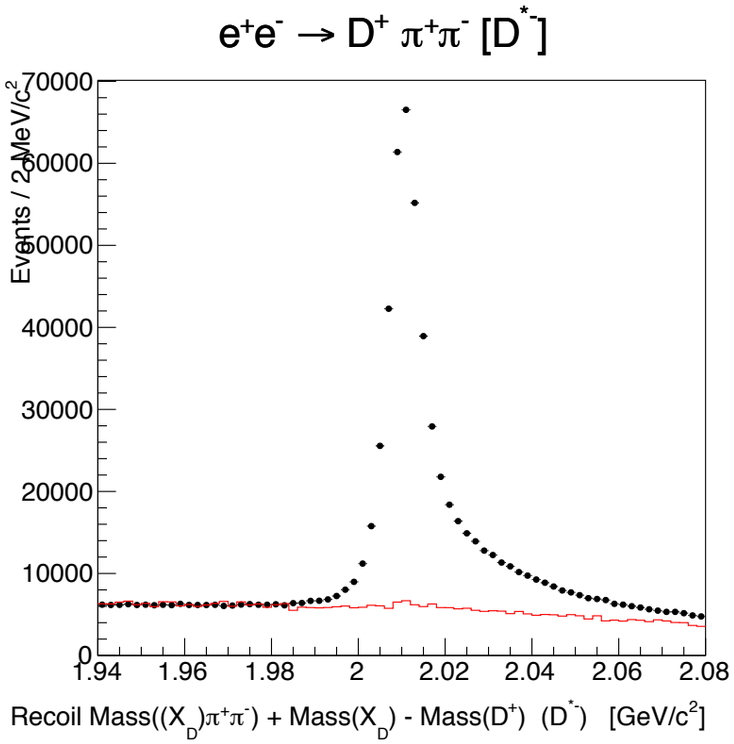
DATA

(Using all 2014 data: 4420, 4470, 4530, 4575, 4600.)

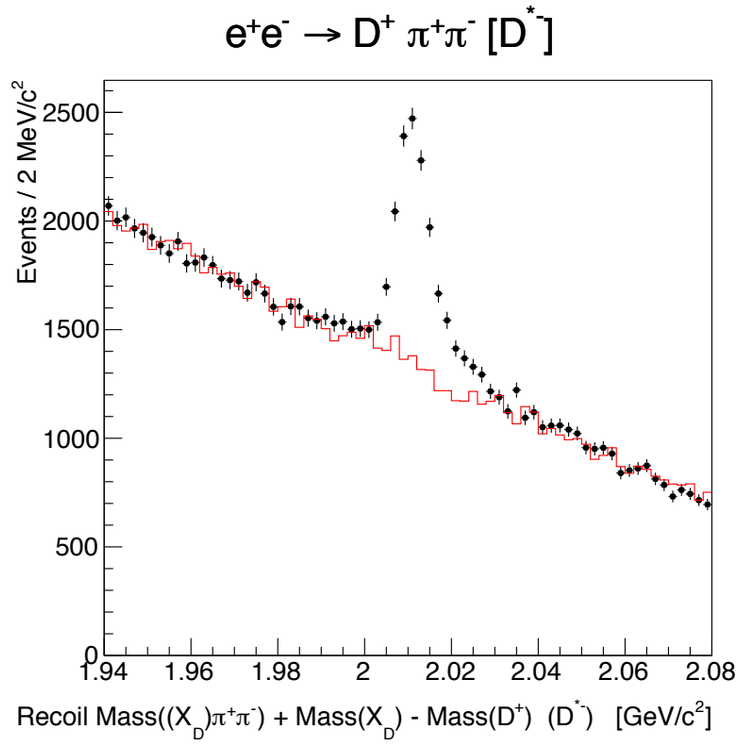
I. Measure the $e^+e^- \to \pi^+\pi^- D^+ D^{*-}$ Cross Section

* After selecting D^+ candidates, there is a clear peak for the D^{*-} in the $D^+\pi^+\pi^-$ recoil mass.

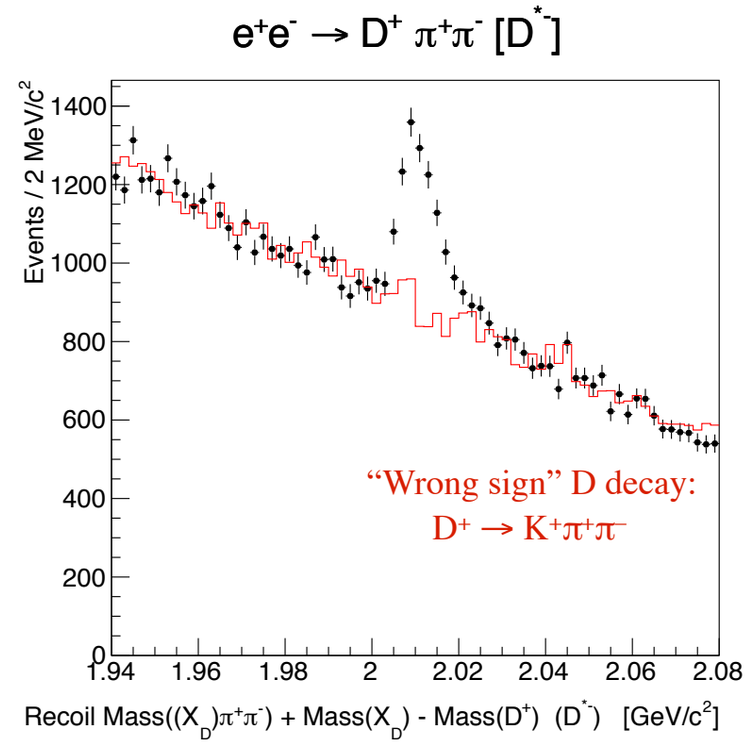
* The "wrong-sign" D^+ decay to $K^+\pi^+\pi^-$ describes the background shape well.



SIGNAL MC



INCLUSIVE MC



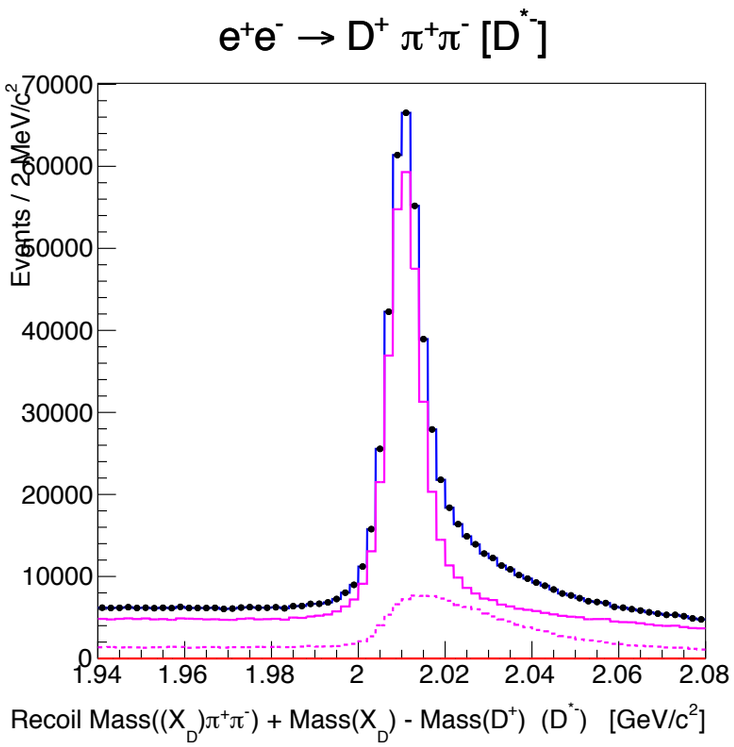
DATA

(Using all 2014 data: 4420, 4470, 4530, 4575, 4600.)

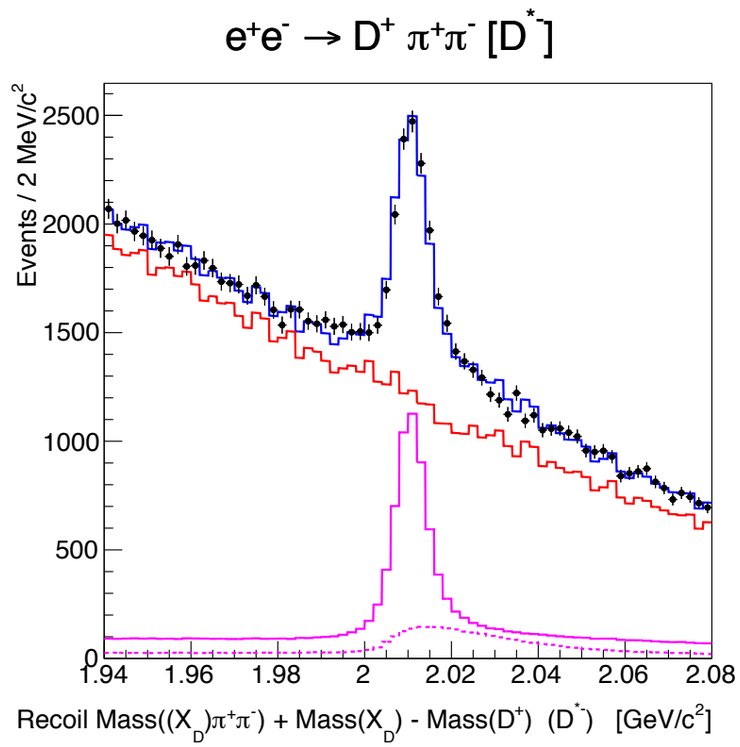
I. Measure the $e^+e^- \to \pi^+\pi^- D^+ D^{*-}$ Cross Section

Fits (*current technique*), three free parameters:

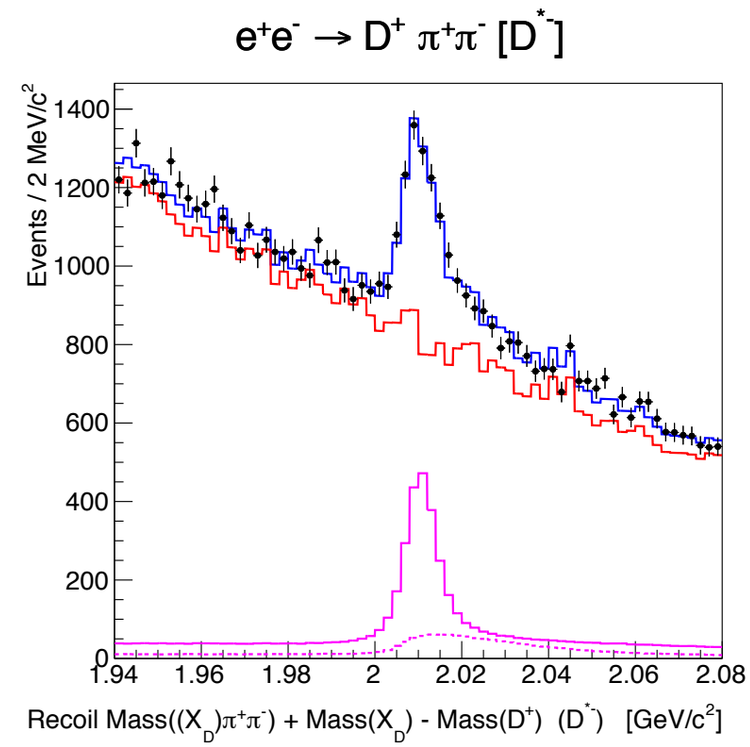
* Take the **signal shape** from signal MC *(there are two components — the charge conjugate is an irreducible background, the ratio is fixed)*.
* Take the **background shape** from the wrong sign D decay and multiply by a 1st order polynomial (*maybe not necessary*).



SIGNAL MC



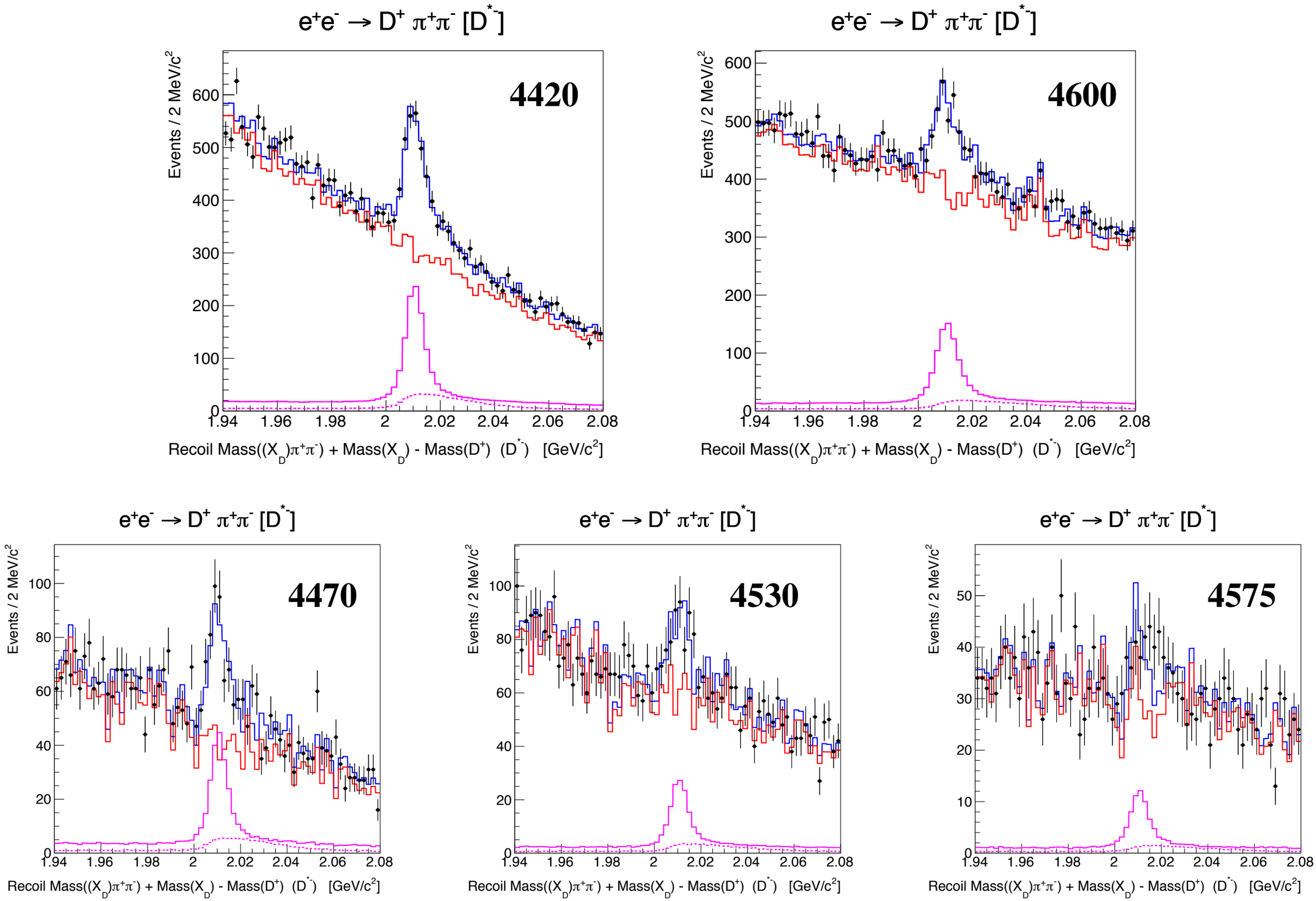
INCLUSIVE MC



DATA

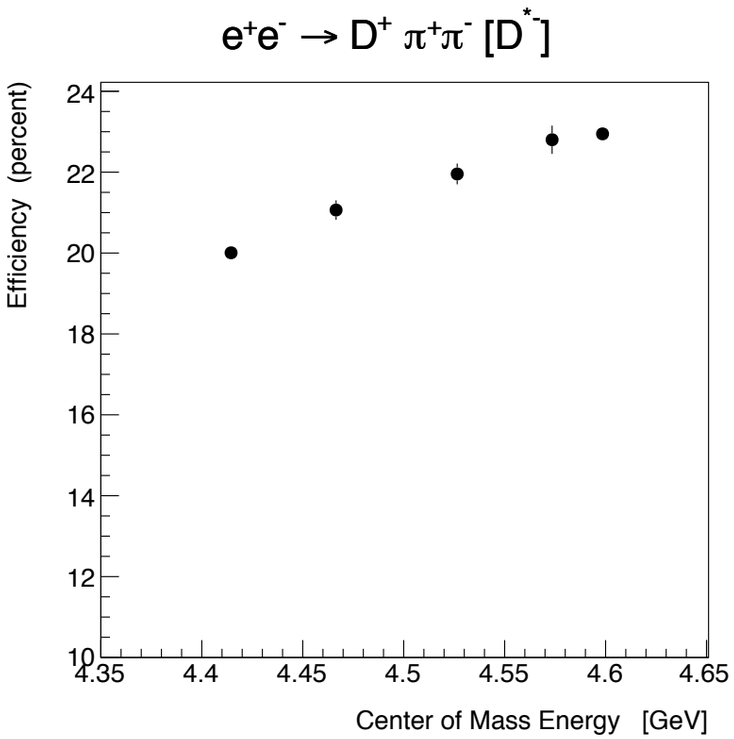
(Using all 2014 data: 4420, 4470, 4530, 4575, 4600.)

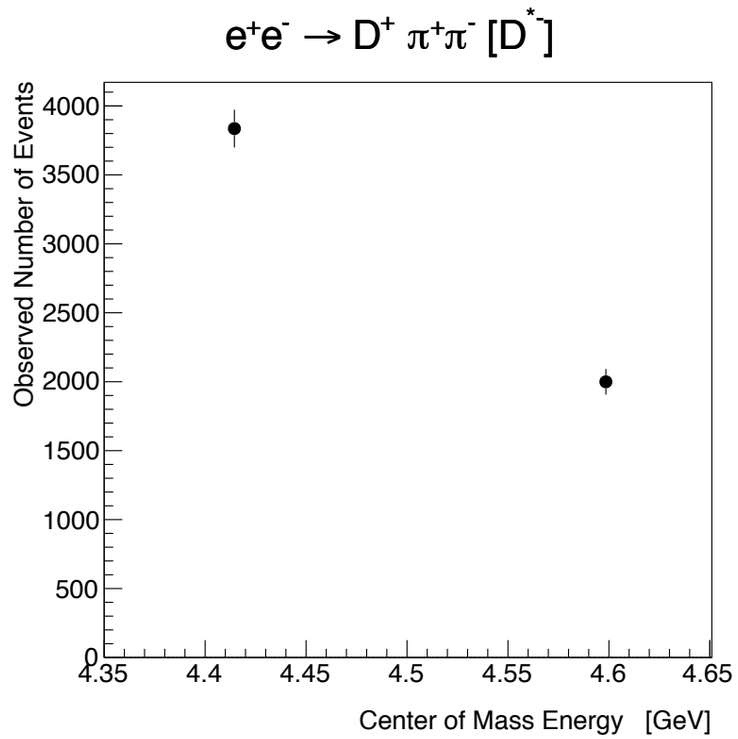
I. Measure the $e^+e^- \to \pi^+\pi^- D^+ D^{*-}$ Cross Section

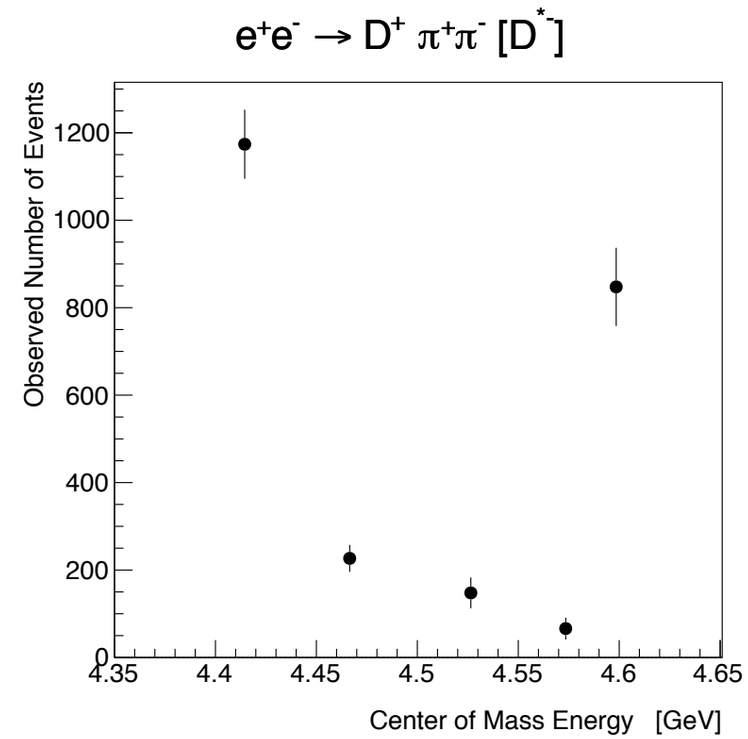


I. Measure the $e^+e^- \rightarrow \pi^+\pi^- D^+ D^{*-}$ Cross Section

* Find the efficiency and number of observed events from the fits.







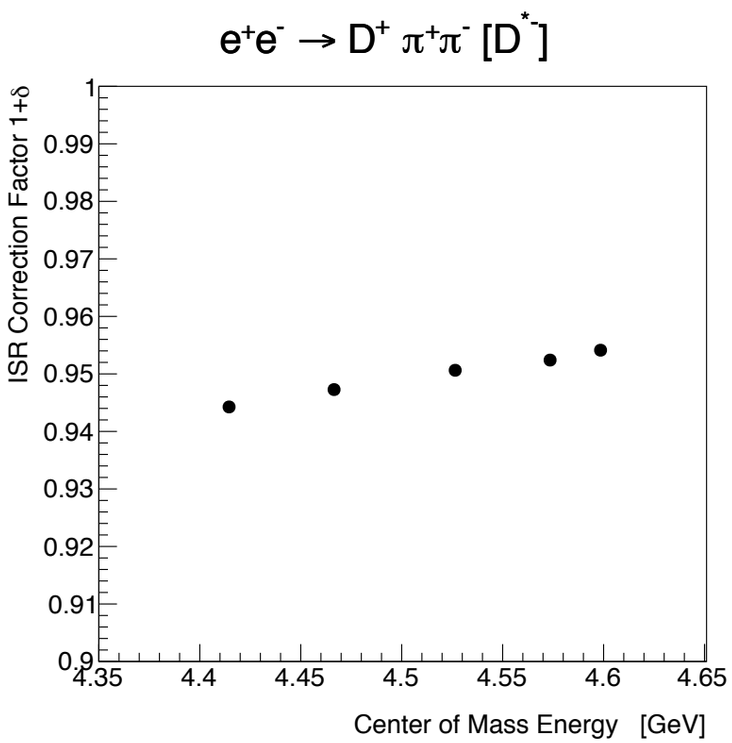
SIGNAL MC
(assuming flat cross section for ISR calculation)

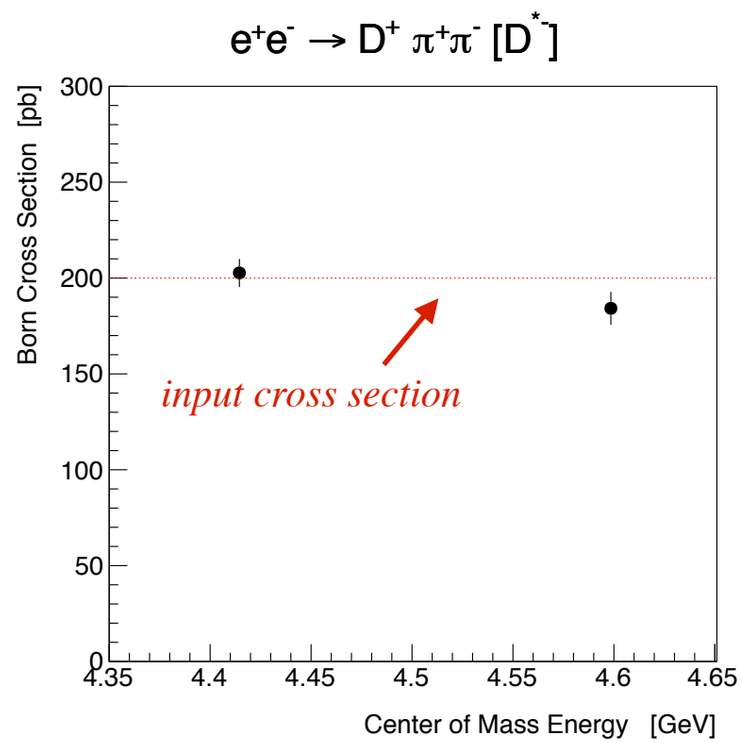
INCLUSIVE MC

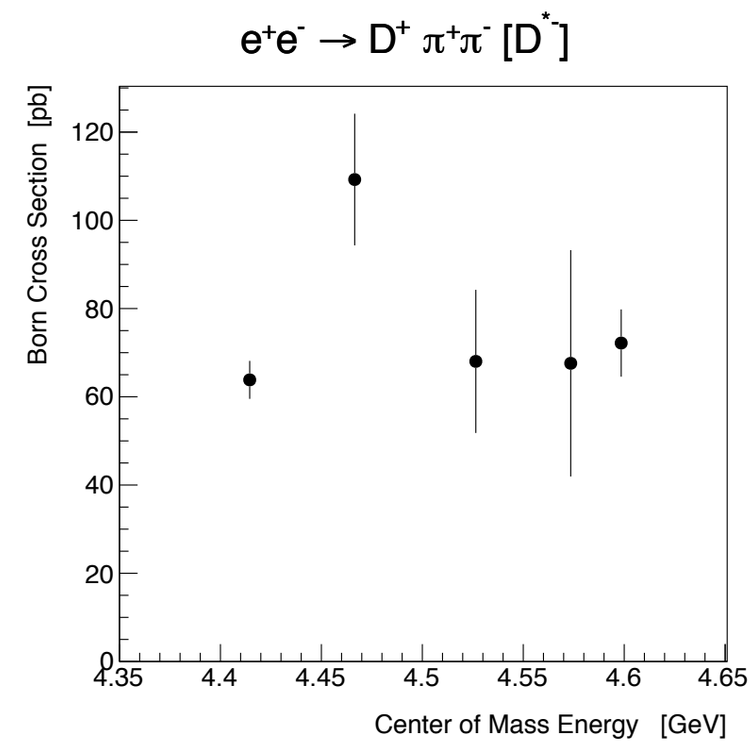
DATA

I. Measure the $e^+e^- \to \pi^+\pi^- D^+ D^{*-}$ Cross Section

* Get the ISR correction factor from SIGNAL MC.
* Divide INCLUSIVE MC and DATA by the efficiency, luminosity, D branching fraction, and ISR correction factor to get the Born Cross Section.







SIGNAL MC

(assuming flat cross section for ISR calculation; threshold = 4.2 GeV)

INCLUSIVE MC

DATA

Strategy

I. Measure the $e^+e^- \to \pi^+\pi^- D^+ D^{*-}$ cross section.

The cross section is ~60 pb, consistent with $\pi^+\pi^-\psi(1S,2S)$ and $\pi^+\pi^- h_c(2P)$.

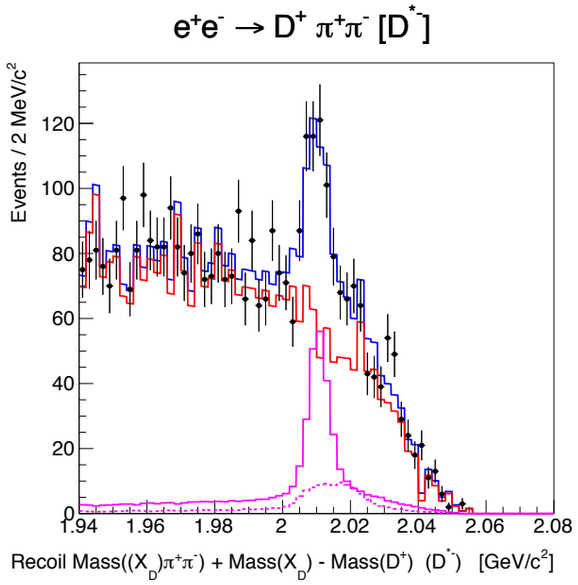
Systematic Errors: luminosity; tracking; fitting; ISR.

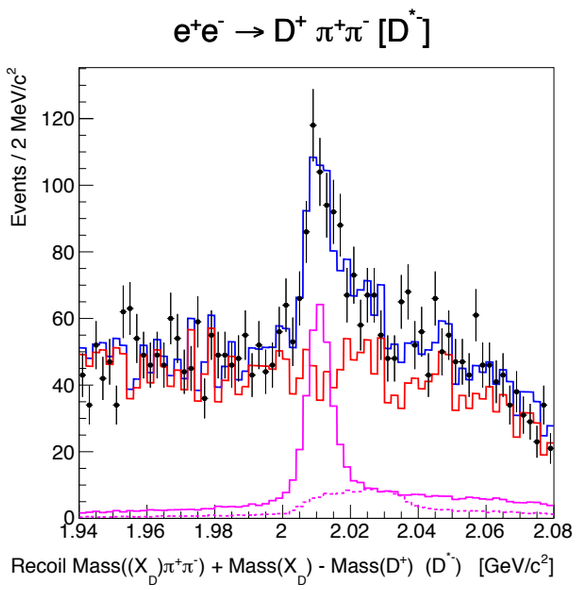
II. Search for $\pi^+\pi^- h_c(2P)$ with $h_c(2P) \to D^+ D^{*-}$.

III. Compare to $e^+e^- \to \pi^-\pi^0 D^+ \bar{D}^{*0}$.

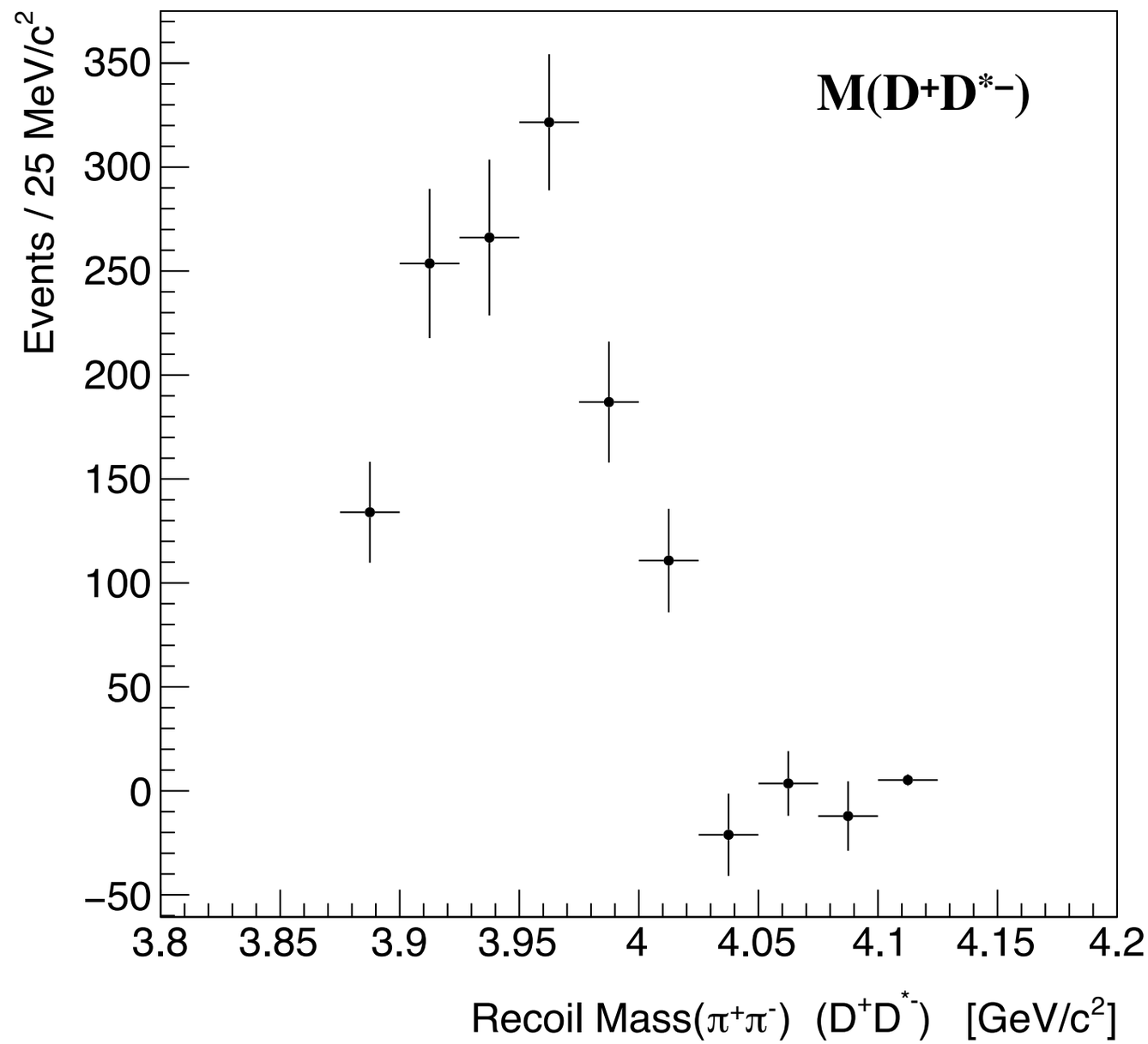
II. Search for $\pi^+\pi^- h_c(2P)$ with $h_c(2P) \to D^+D^{*-}$

Fit the D^{*-} as a function of $M(D^+D^{*-})$…





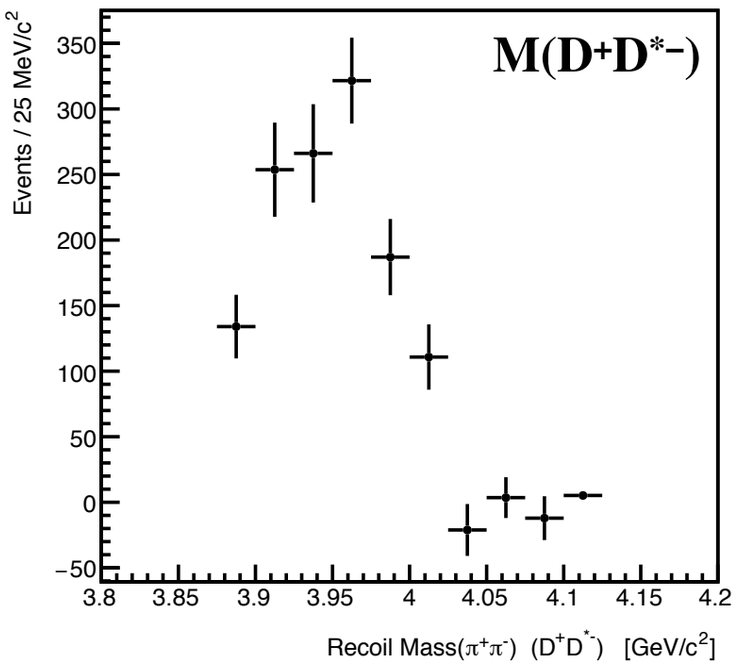
Data at E_{CM} = 4420 MeV



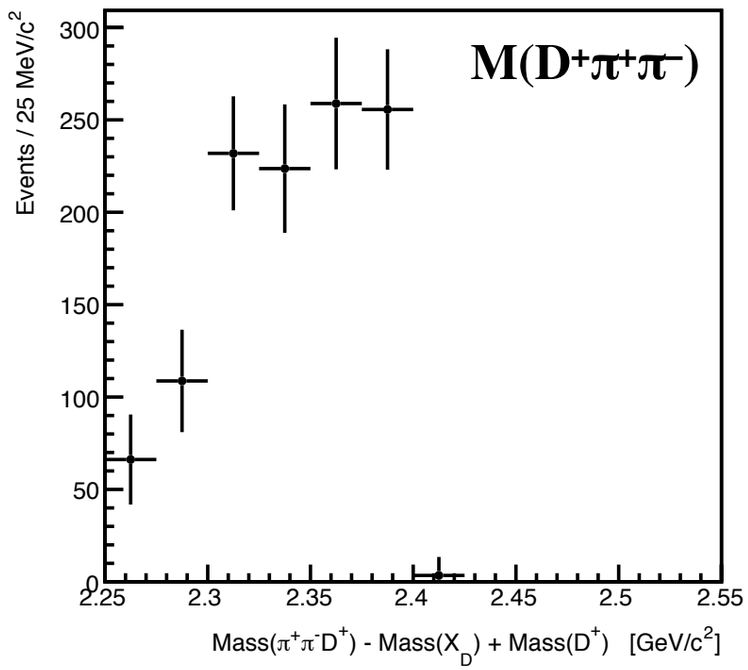
Also look at $M(D^+\pi^+\pi^-)$ (*where there could be a $D_1(2420)$*),
and $\cos\vartheta_{\pi\pi}$ (*which should follow $1 + \cos^2\vartheta_{\pi\pi}$ for the $h_c(2P)$*)…

II. Search for $\pi^+\pi^- h_c(2P)$ with $h_c(2P) \rightarrow D^+D^{*-}$

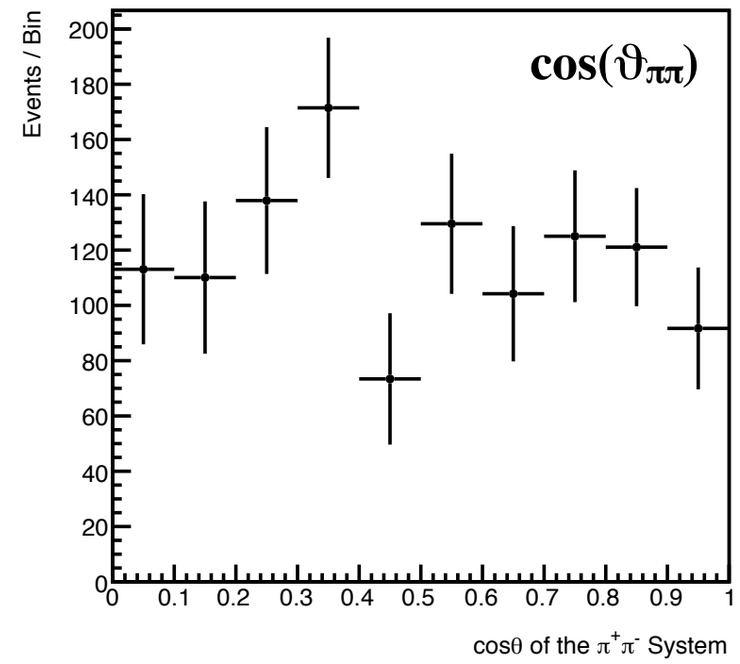
Data at E_{CM} = 4420 MeV



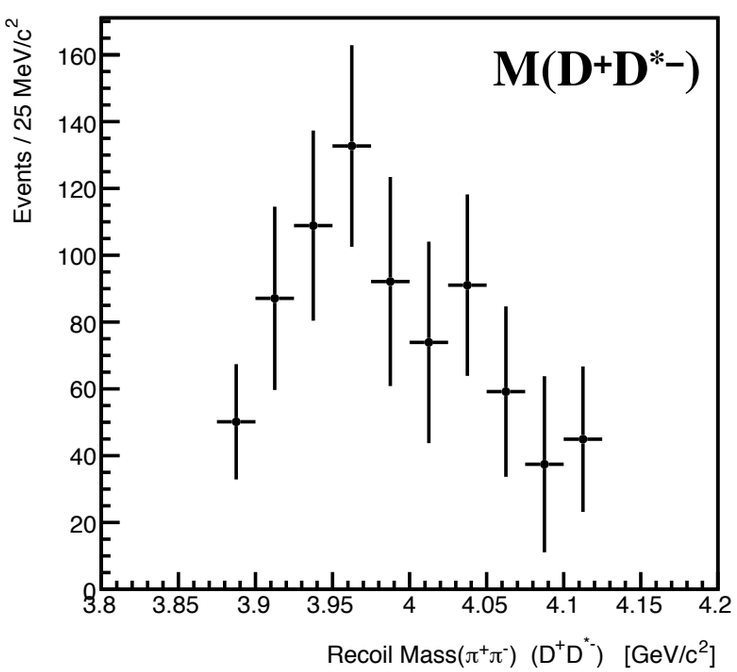
Data at E_{CM} = 4420 MeV



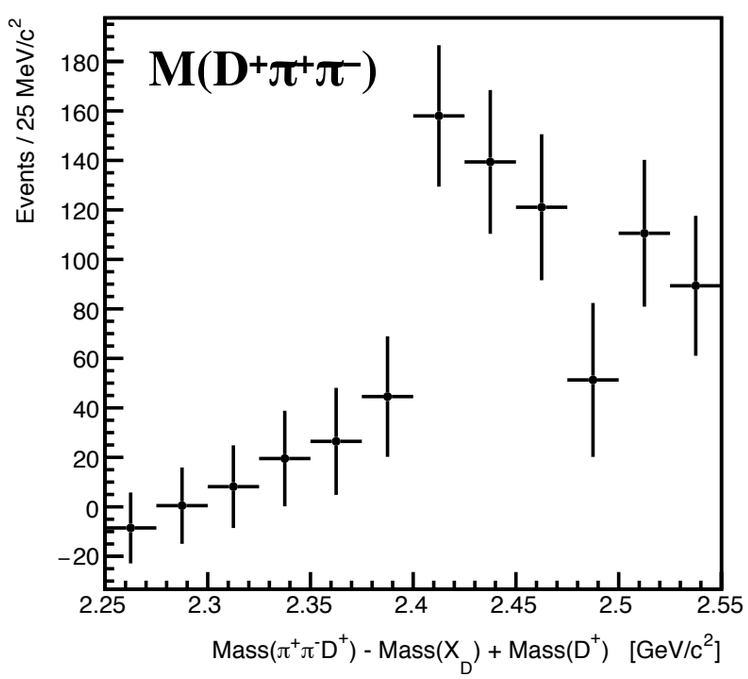
Data at E_{CM} = 4420 MeV



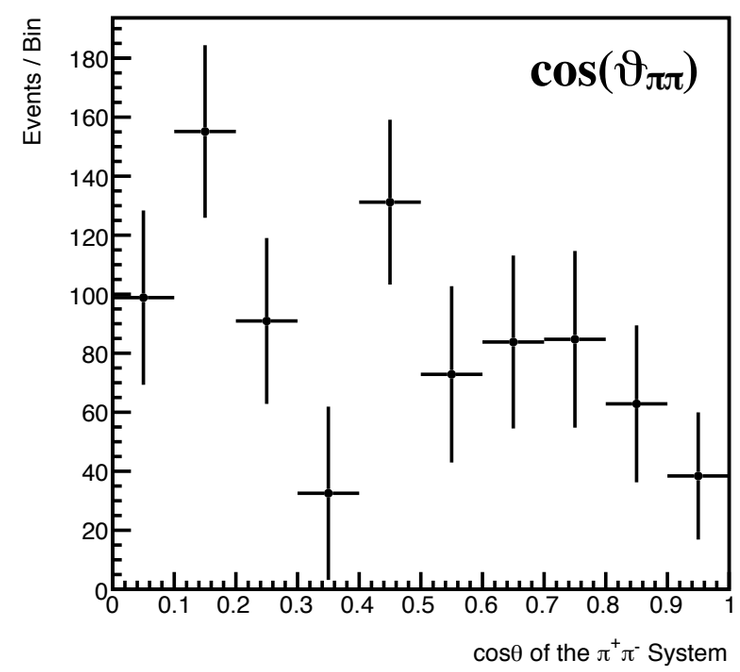
Data at E_{CM} = 4600 MeV



Data at E_{CM} = 4600 MeV



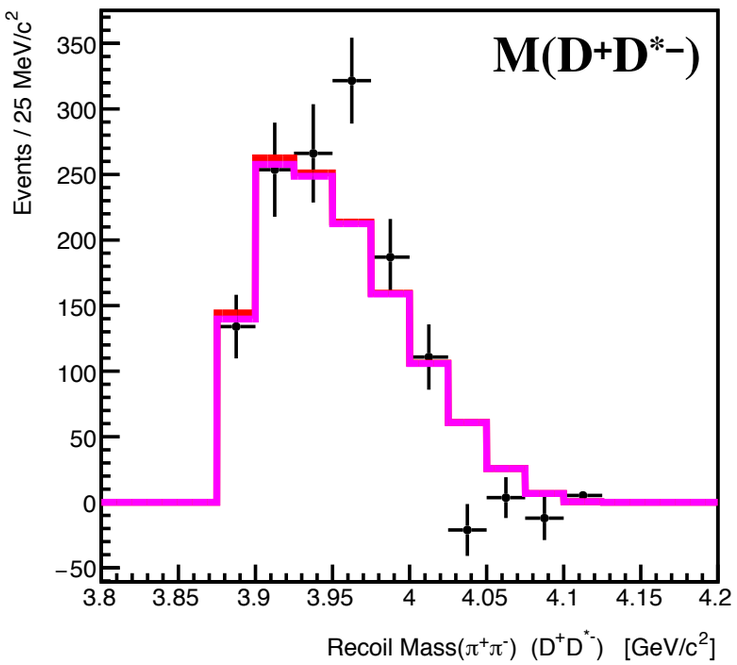
Data at E_{CM} = 4600 MeV



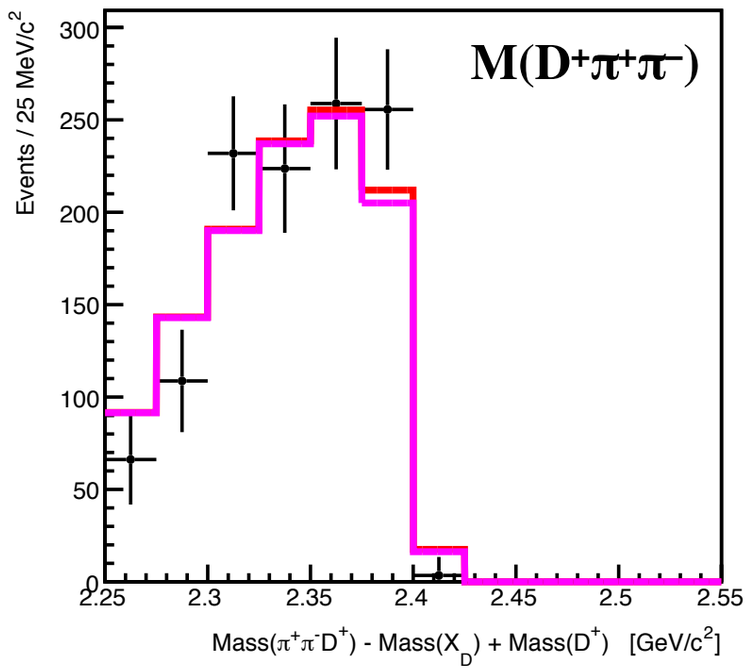
* Distributions for $M(D^+D^{*-})$, $M(D^+\pi^+\pi^-)$, and $\cos(\vartheta_{\pi\pi})$.

II. Search for $\pi^+\pi^- h_c(2P)$ with $h_c(2P) \rightarrow D^+D^{*-}$

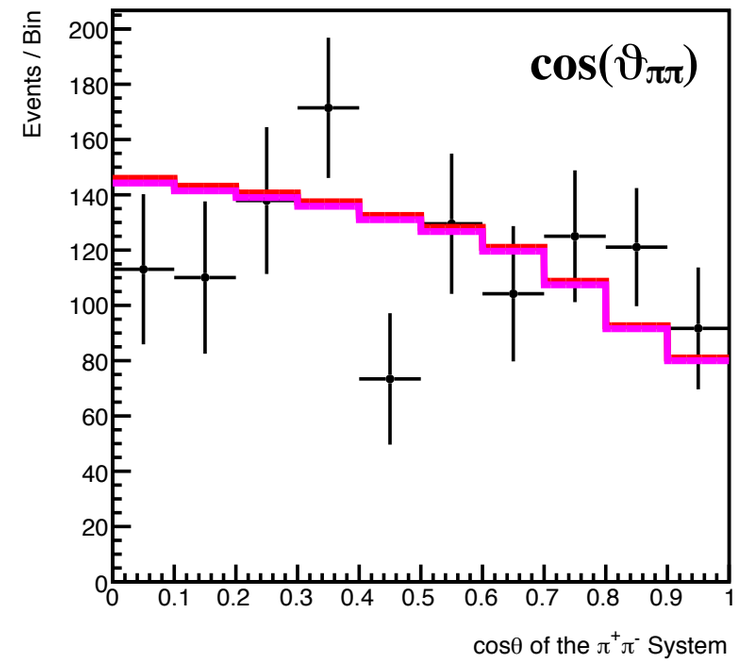
Data at E_{CM} = 4420 MeV



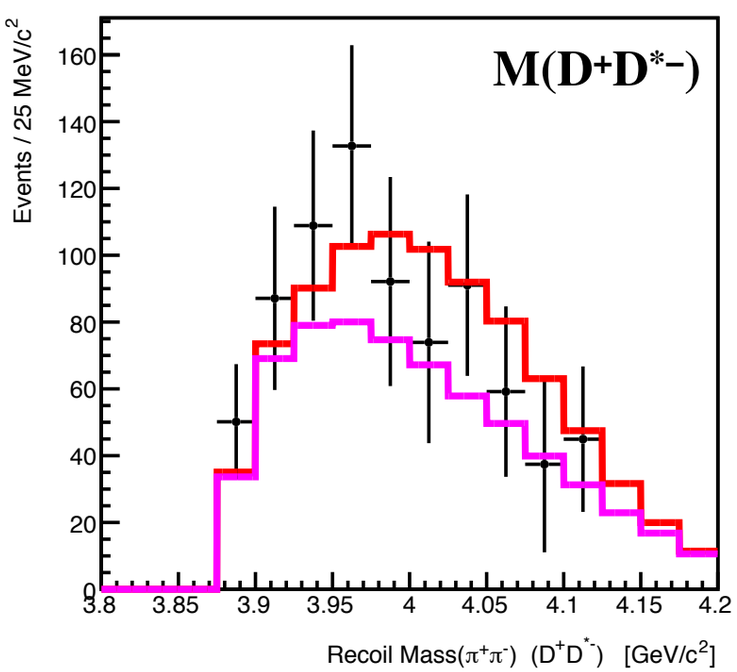
Data at E_{CM} = 4420 MeV



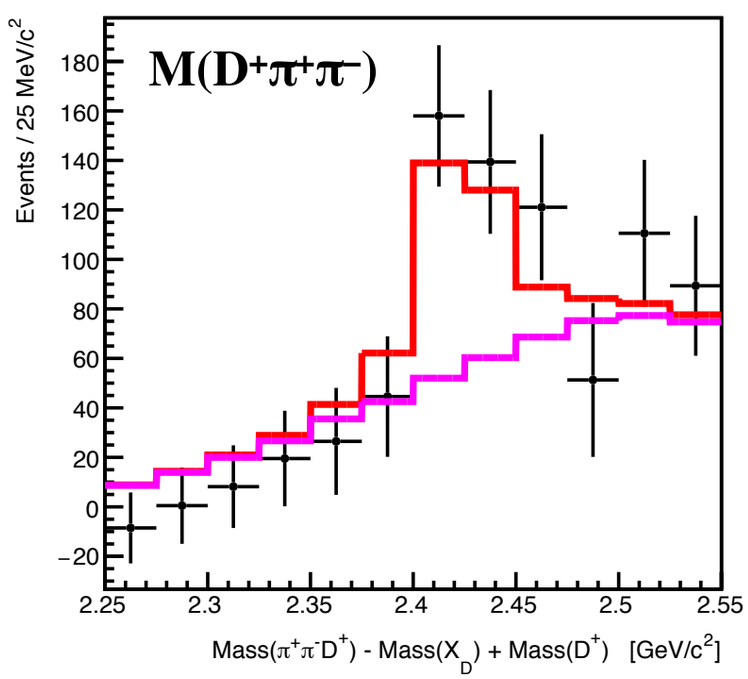
Data at E_{CM} = 4420 MeV



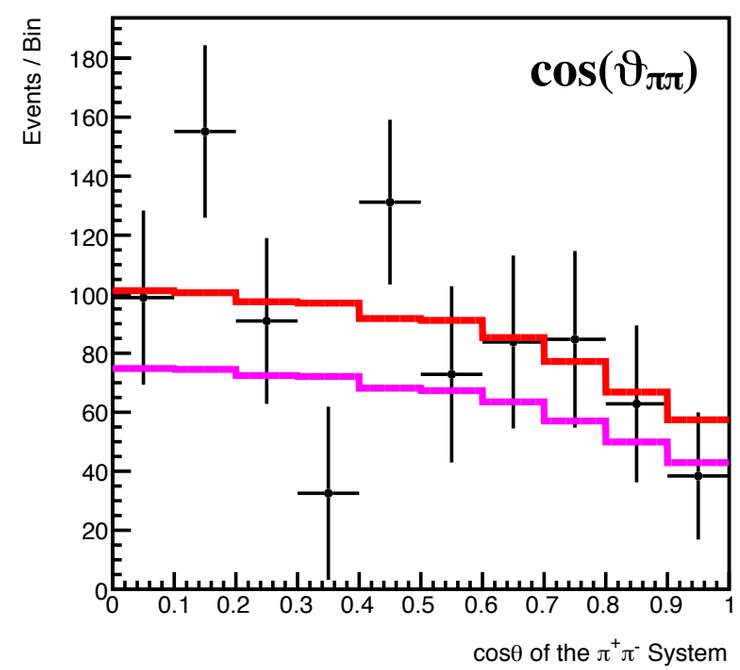
Data at E_{CM} = 4600 MeV



Data at E_{CM} = 4600 MeV



Data at E_{CM} = 4600 MeV

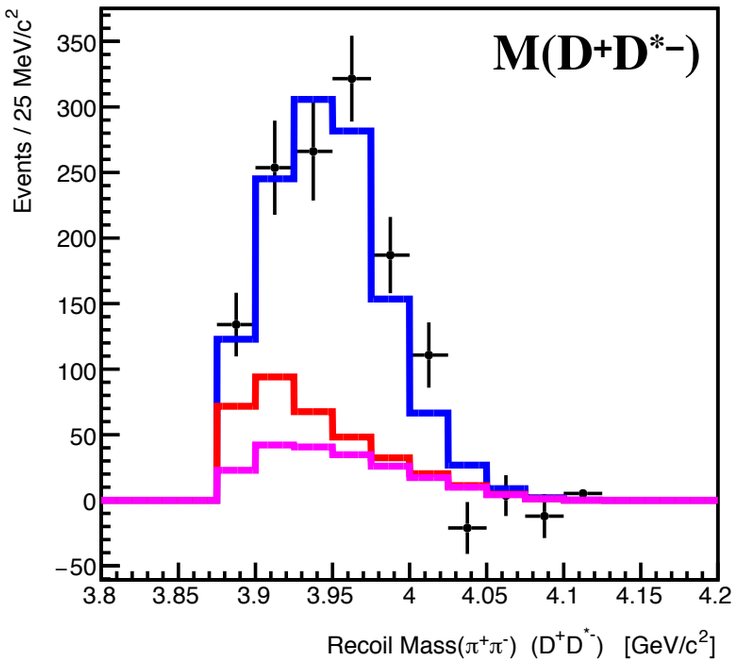


* Perform simultaneous fits at 4420 and 4600 using **Phase Space** and **$D_1^+(2420)D^{*-}$**.

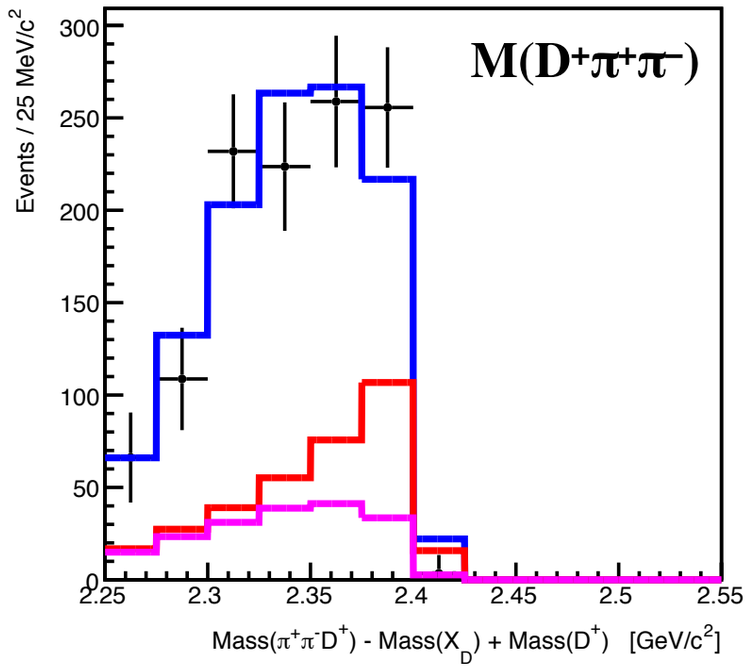
$\chi^2 = 82.7$

II. Search for $\pi^+\pi^- h_c(2P)$ with $h_c(2P) \rightarrow D^+D^{*-}$

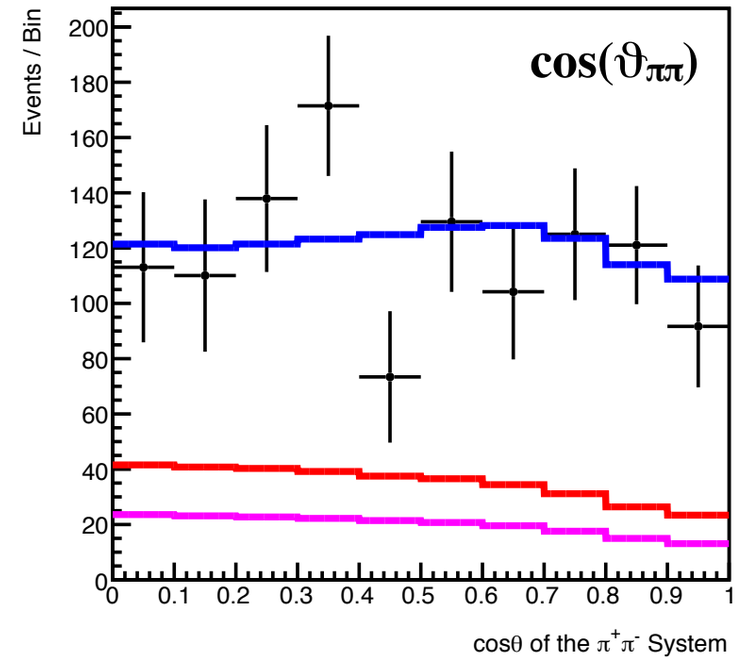
Data at E_{CM} = 4420 MeV



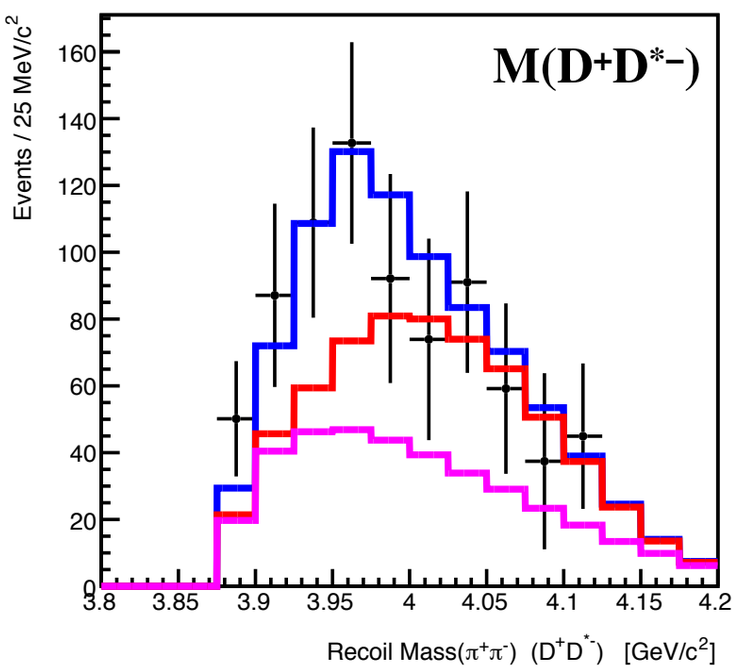
Data at E_{CM} = 4420 MeV



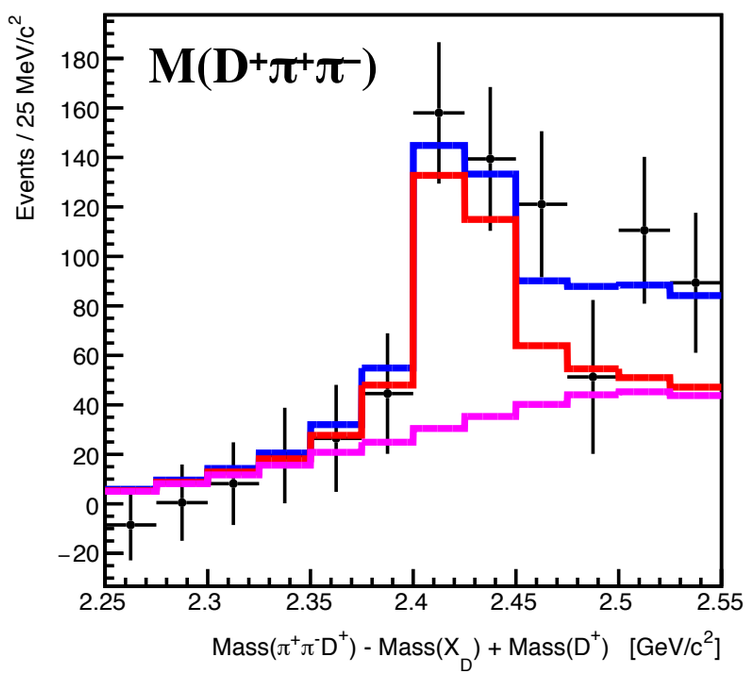
Data at E_{CM} = 4420 MeV



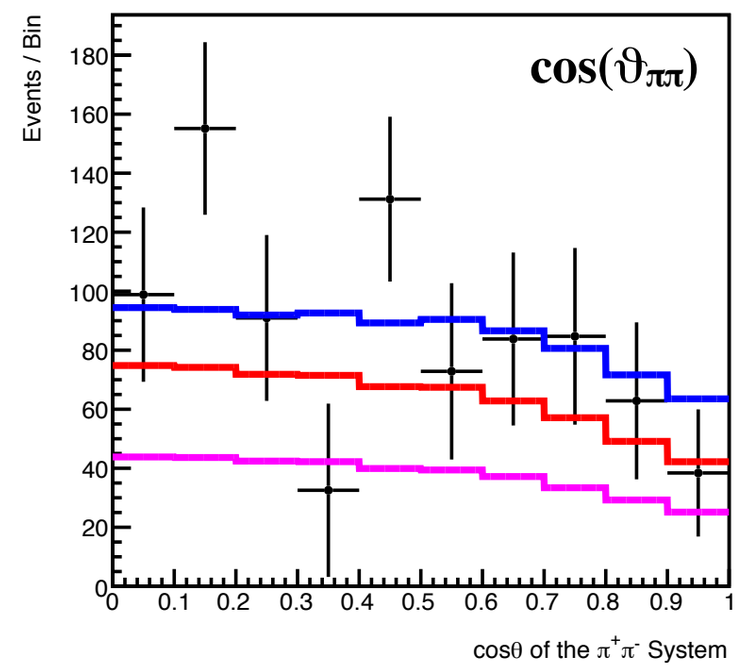
Data at E_{CM} = 4600 MeV



Data at E_{CM} = 4600 MeV



Data at E_{CM} = 4600 MeV

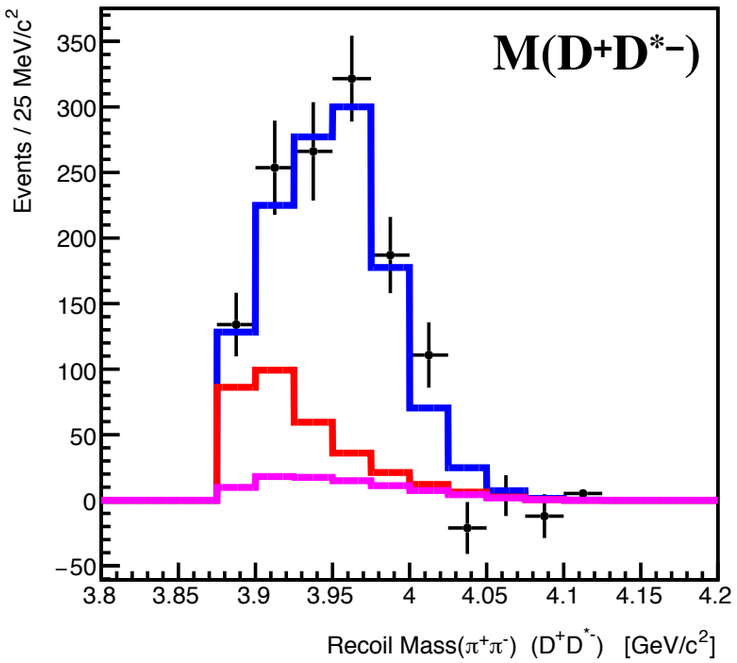


* Use **Phase Space** and **$D_1^+(2420)D^{*-}$** and **$h_c(2P)$** (with parameters from theory).

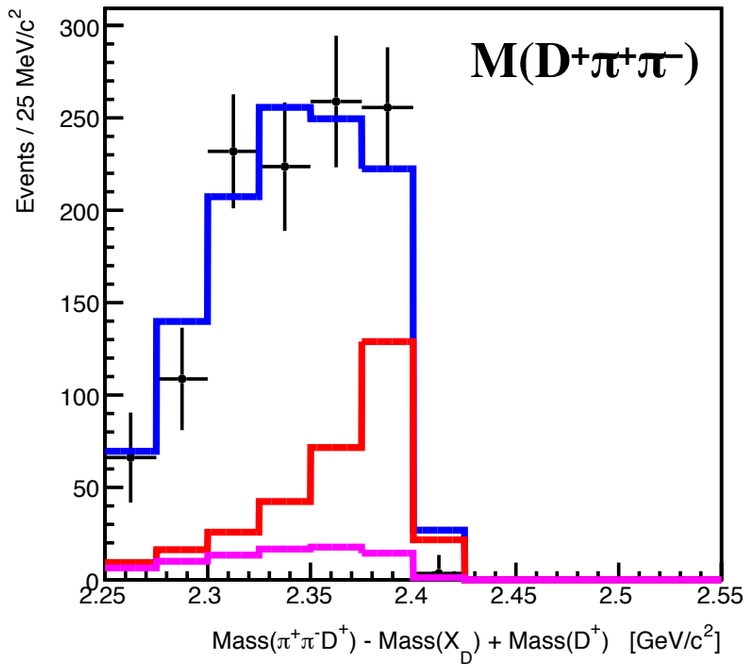
$\chi^2 = 57.4$

II. Search for $\pi^+\pi^- h_c(2P)$ with $h_c(2P) \rightarrow D^+D^{*-}$

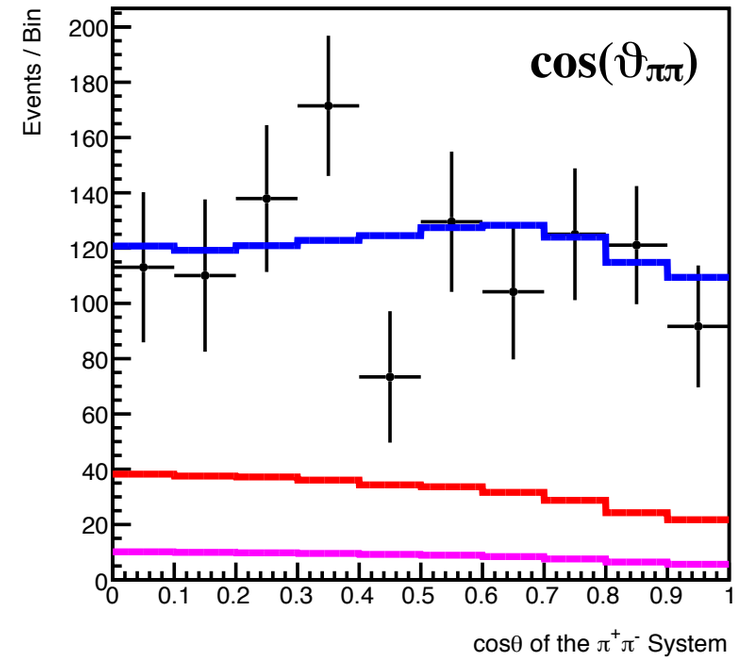
Data at E_{CM} = 4420 MeV



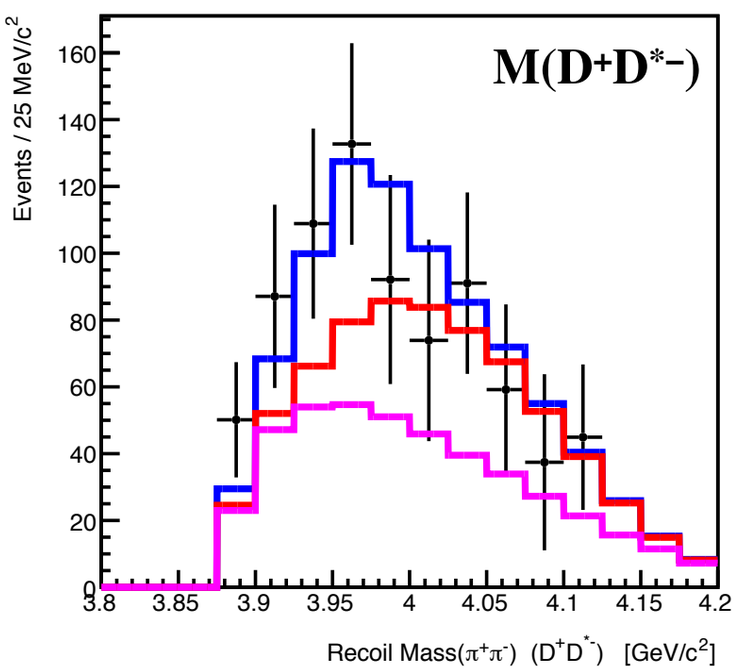
Data at E_{CM} = 4420 MeV



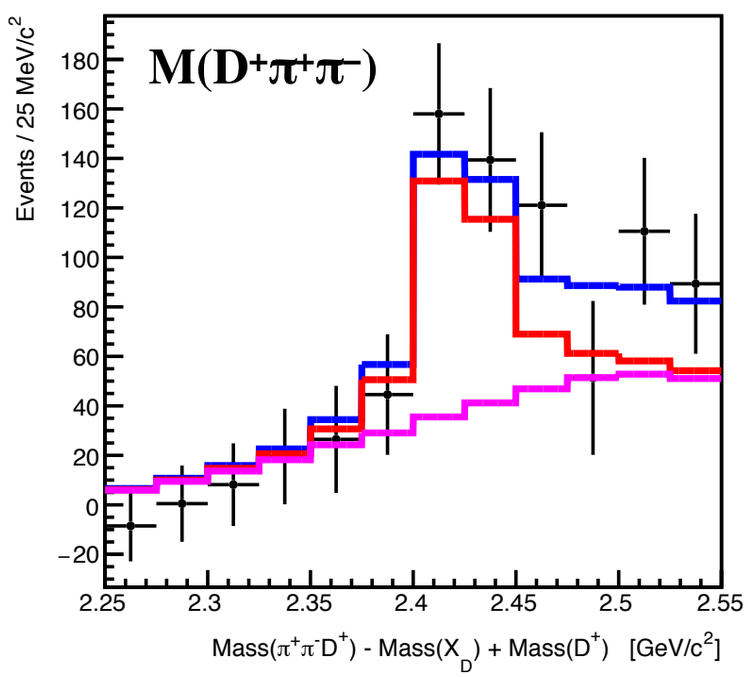
Data at E_{CM} = 4420 MeV



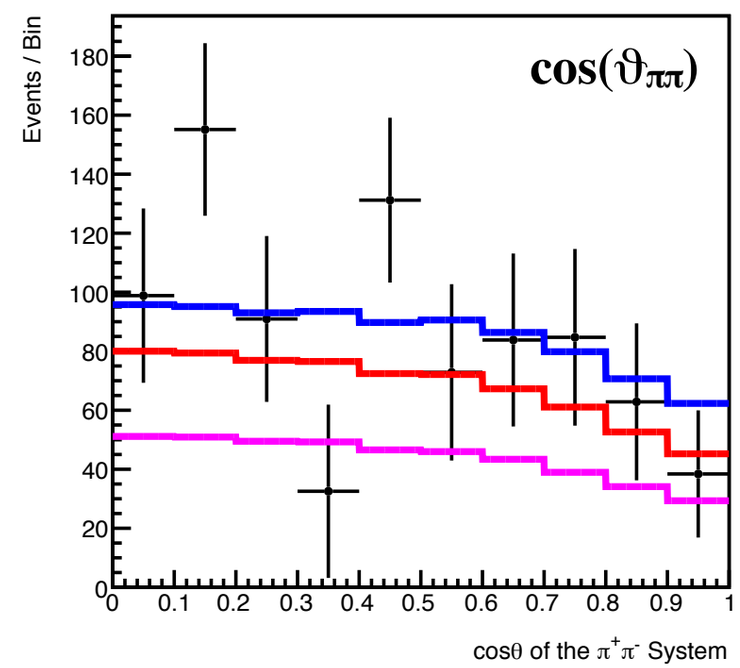
Data at E_{CM} = 4600 MeV



Data at E_{CM} = 4600 MeV



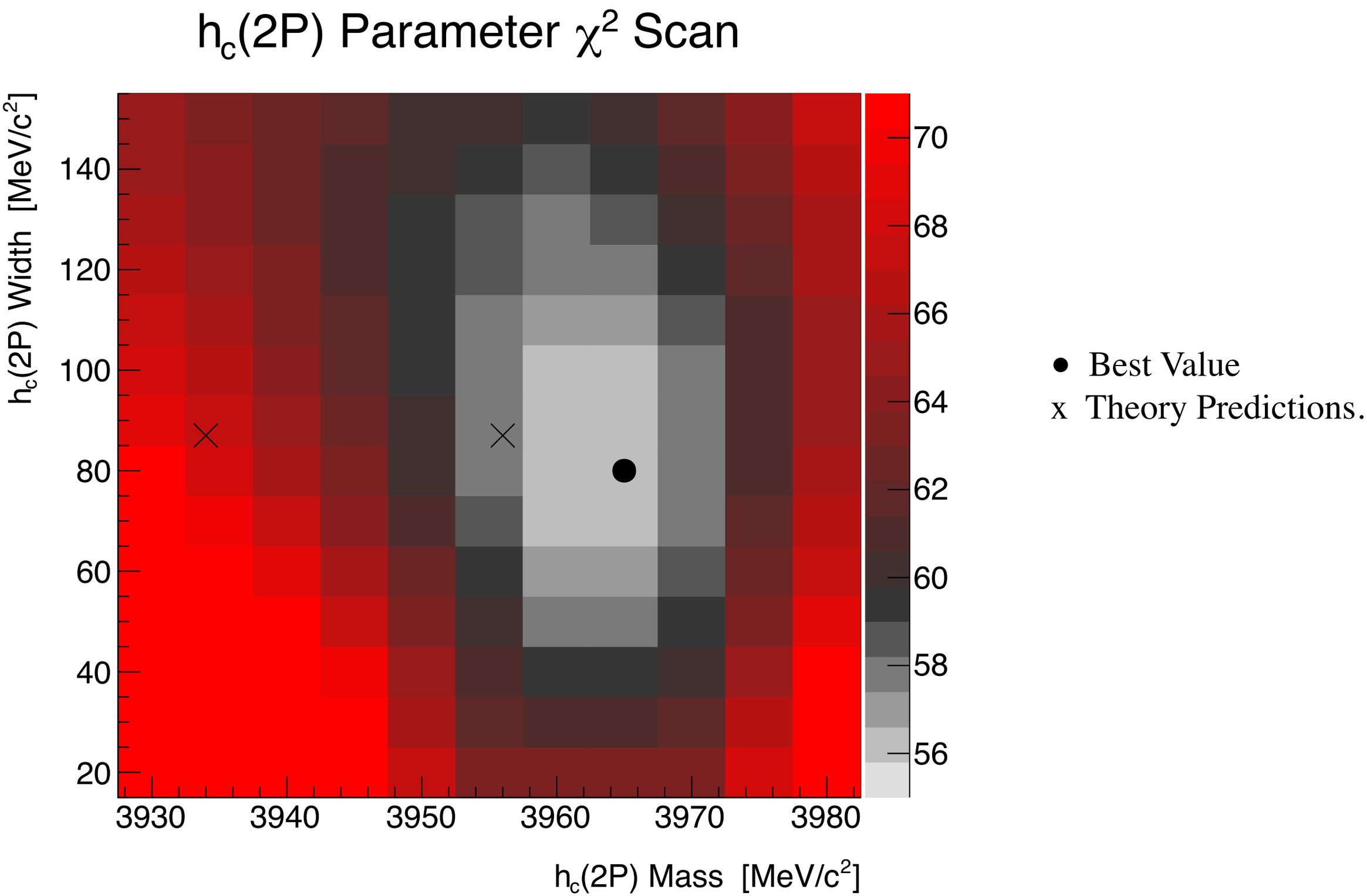
Data at E_{CM} = 4600 MeV



* Use **Phase Space** and **$D_1^+(2420)D^{*-}$** and **$h_c(2P)$** (with best parameters).

$\chi^2 = 56.0$

II. Search for $\pi^+\pi^- h_c(2P)$ with $h_c(2P) \rightarrow D^+D^{*-}$



Strategy

I. Measure the $e^+e^- \to \pi^+\pi^- D^+ D^{*-}$ cross section.

The cross section is ~60 pb, consistent with $\pi^+\pi^-\psi(1S,2S)$ and $\pi^+\pi^- h_c(2P)$.

Systematic Errors: luminosity; tracking; fitting; ISR.

II. Search for $\pi^+\pi^- h_c(2P)$ with $h_c(2P) \to D^+ D^{*-}$.

Including an $h_c(2P)$ signal describes data better than pure phase space and $D_1 D^*$.

The statistical significance calculation requires more thought.

The mass and width are consistent with theoretical expectations.

Systematic Errors: fitting; mass calibration.

III. Compare to $e^+e^- \to \pi^-\pi^0 D^+ \bar{D}^{*0}$.

III. Compare to $e^+e^- \to \pi^-\pi^0 D^+\bar{D}^{*0}$

Isospin Ratios

These ratios always hold:

$$\pi^+\pi^- D^+ D^{*-} : \pi^+\pi^- D^0 \bar{D}^{*0} = 1 : 1$$

$$\pi^-\pi^0 D^+ \bar{D}^{*0} : \pi^+\pi^0 D^0 D^{*-} = 1 : 1$$

$$\pi^0\pi^0 D^+ D^{*-} : \pi^0\pi^0 D^0 \bar{D}^{*0} = 1 : 1$$

For $(\pi\pi)_{I=0}(D\bar{D}^*)_{I=0}$:

$$\pi^+\pi^- D^+ D^{*-} : \pi^-\pi^0 D^+ \bar{D}^{*0} : \pi^0\pi^0 D^+ D^{*-} = 2 : 0 : 1$$

For $(\pi\pi)_{I=1}(D\bar{D}^*)_{I=1}$:

$$\pi^+\pi^- D^+ D^{*-} : \pi^-\pi^0 D^+ \bar{D}^{*0} : \pi^0\pi^0 D^+ D^{*-} = 1 : 2 : 0$$

For $(D\pi)_{I=1/2}(\bar{D}^*\pi)_{I=1/2}$:

$$\pi^+\pi^- D^+ D^{*-} : \pi^-\pi^0 D^+ \bar{D}^{*0} : \pi^0\pi^0 D^+ D^{*-} = 4 : 4 : 1$$

The ratio can tell us something about the isospin composition.

$$\Longrightarrow \quad \frac{\sigma(\pi^-\pi^0 D^+ \bar{D}^{*0})}{\sigma(\pi^+\pi^- D^+ D^{*-})} = 0$$

$$\Longrightarrow \quad \frac{\sigma(\pi^-\pi^0 D^+ \bar{D}^{*0})}{\sigma(\pi^+\pi^- D^+ D^{*-})} = 2$$

$$\Longrightarrow \quad \frac{\sigma(\pi^-\pi^0 D^+ \bar{D}^{*0})}{\sigma(\pi^+\pi^- D^+ D^{*-})} = 1$$

III. Compare to $e^+e^- \to \pi^-\pi^0 D^+ \overline{D}^{*0}$

<u>Use almost the same method as before: Reconstruct $\pi^-\pi^0 D^+$ with $D^+ \to K^-\pi^+\pi^+$</u>

Isolate the reaction by finding the D^+ in $K^-\pi^+\pi^+$ and looking for the D^{*0} in the $(K^-\pi^+\pi^+)\pi^-\pi^0$ missing mass. Use all combinations. Same track selections.

Perform a 1C fit for the π^0 mass; require $\chi^2 < 3$.

<u>Use four classes of data:</u>

SIGNAL MC: Includes $\pi^-\pi^0 D^+ D^{*0}$ and $\pi^-\pi^0 D^0 D^{*+}$.
The latter is an irreducible background, since $D^{*+} \to \pi^0 D^+$.

$\pi D^* D^*$ MC: Since this channel has peaking backgrounds, we generated a larger sample than what is in the DDbar MC. Charge combinations are fixed by isospin.

INCLUSIVE MC: (1) Includes full samples of inclusive DDbar MC at 4.42 and 4.60 GeV (*including important channels of the form $\pi D^* D^*$*).
(2) We also add 200 pb each for all charge combinations of the form $\pi\pi DD^*$ (*which includes signal as well as potential peaking backgrounds*).

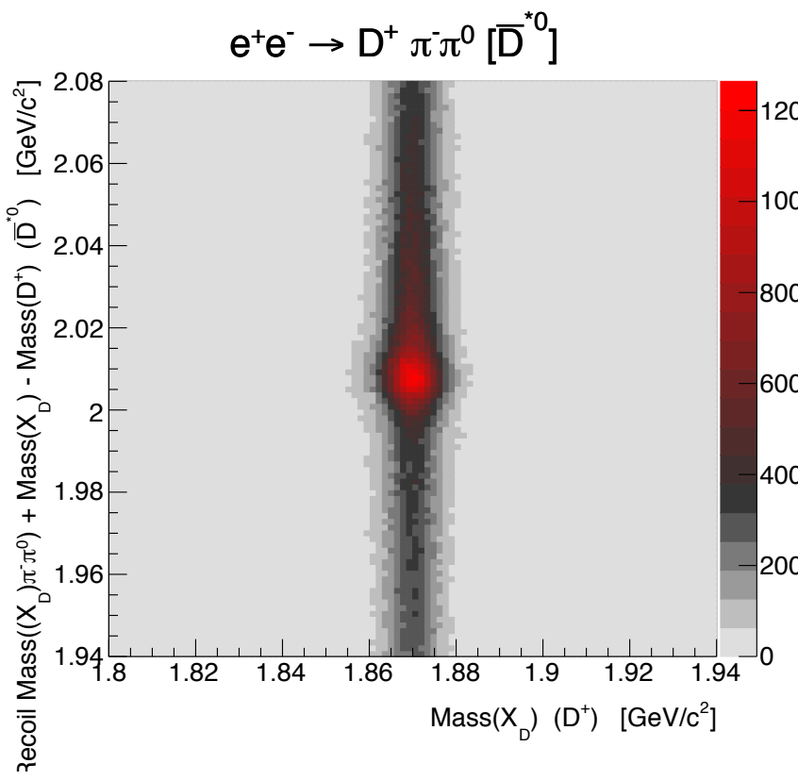
DATA: Currently use all of the 2014 data: 4420, 4470, 4530, 4575, 4600 MeV.

III. Compare to $e^+e^- \to \pi^-\pi^0 D^+\overline{D}^{*0}$

* Find the D^+ using the $D^+ \to K^-\pi^+\pi^+$ mass (*x-axis*).

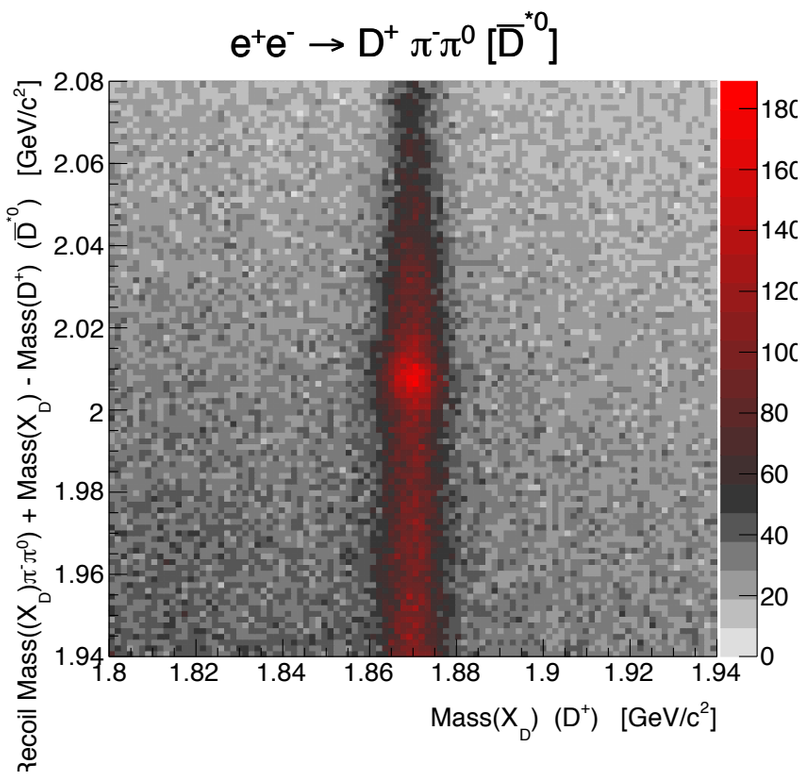
* Find the D^{*0} using the $D^+\pi^-\pi^0$ recoil mass $[RM((K^-\pi^+\pi^+)\pi^-\pi^0) + M(K^-\pi^+\pi^+) - M(D^+)]$ (*y-axis*).

* There are large peaking backgrounds from different combinations of $\pi D^* D^*$.

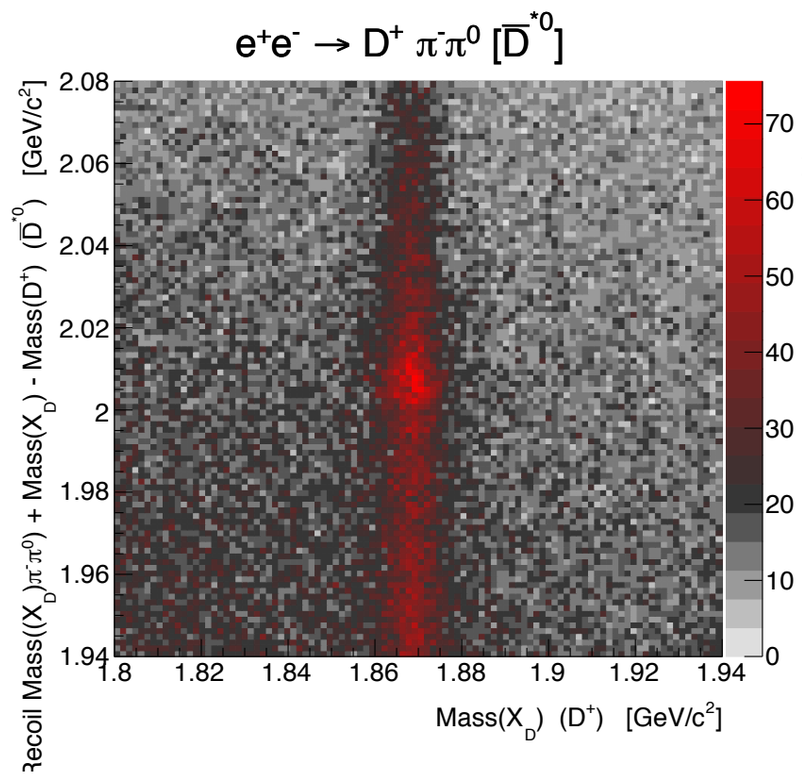


SIGNAL MC

(includes irreducible background from $\pi^-\pi^0 D^0 D^{*+}$)



INCLUSIVE MC



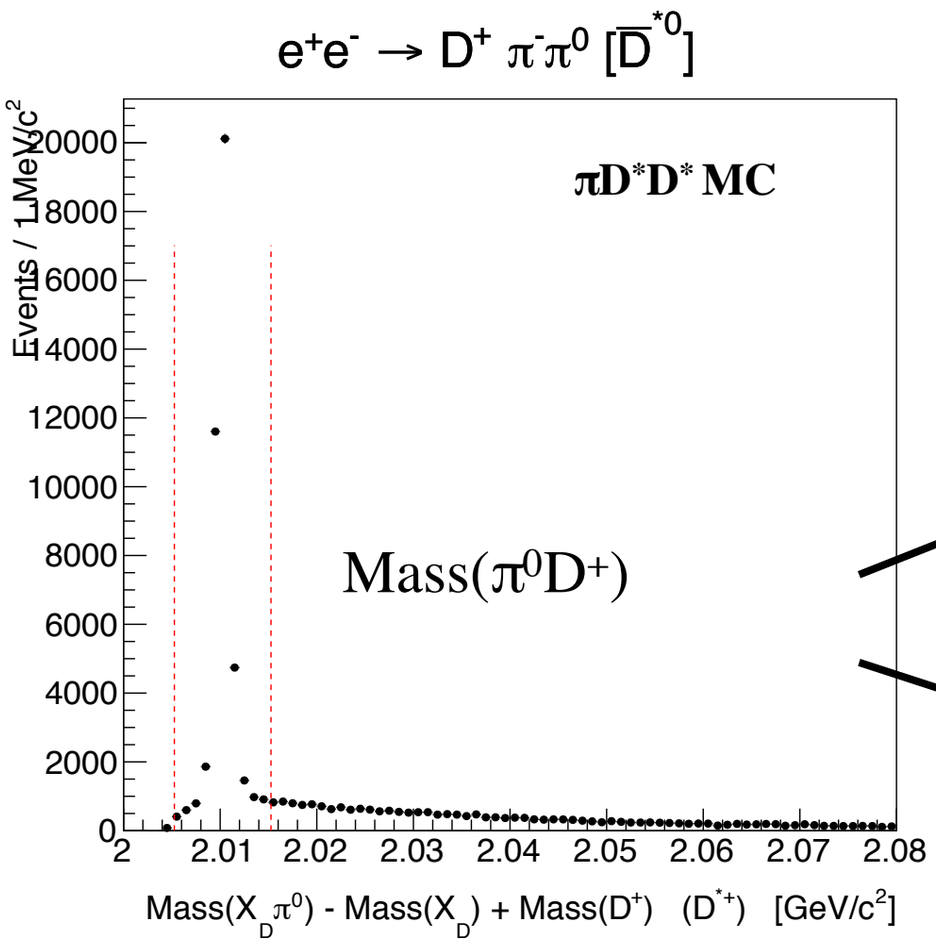
DATA

(Using all 2014 data: 4420, 4470, 4530, 4575, 4600.)

(these plots don't include c.c.)

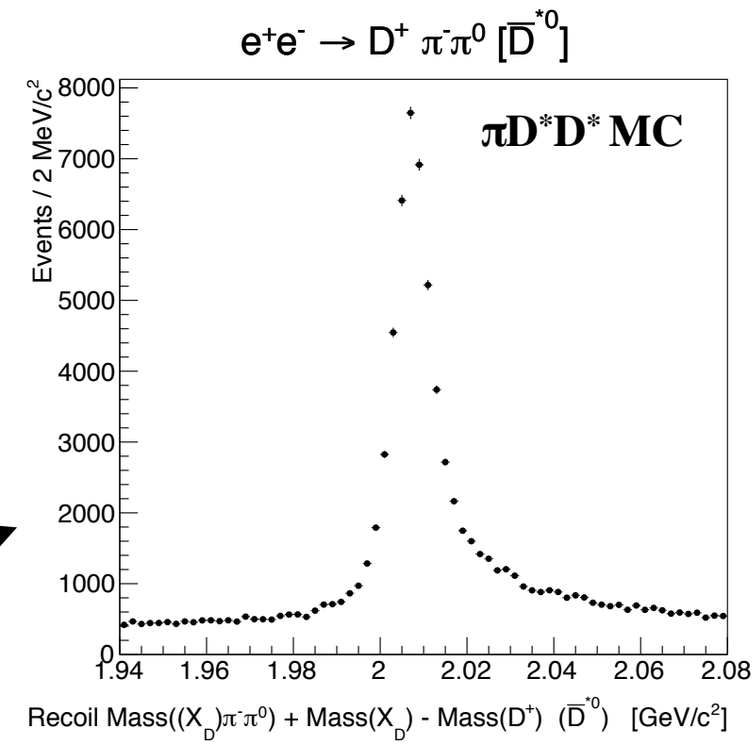
III. Compare to $e^+e^- \to \pi^-\pi^0 D^+ \overline{D}^{*0}$

Use the $\pi D^* D^*$ MC to fix the peaking backgrounds.

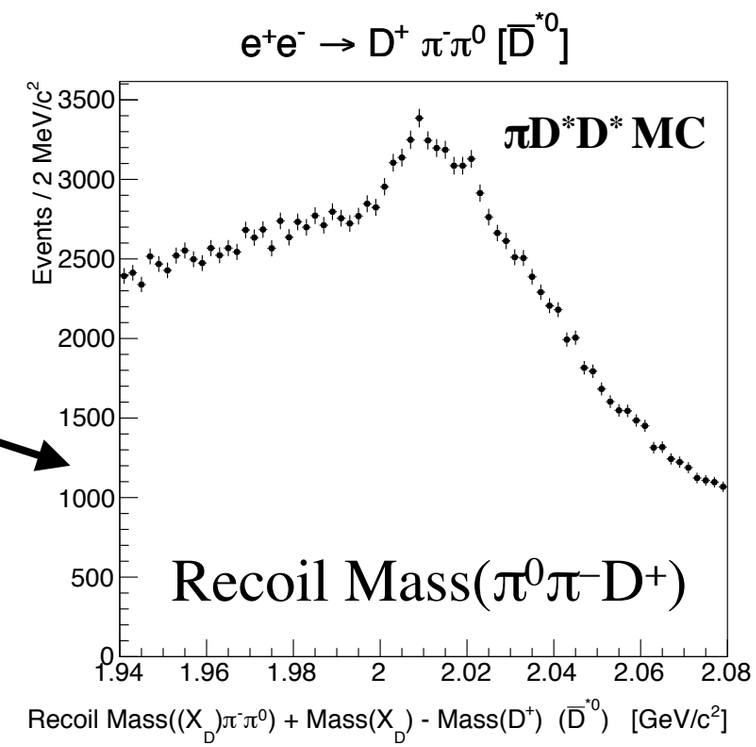


MC FOR $\pi D^* D^*$

Select $D^{*+} \to \pi^0 D^+$ to find the other D^*.



Veto $D^{*+} \to \pi^0 D^+$ to find peaking background.



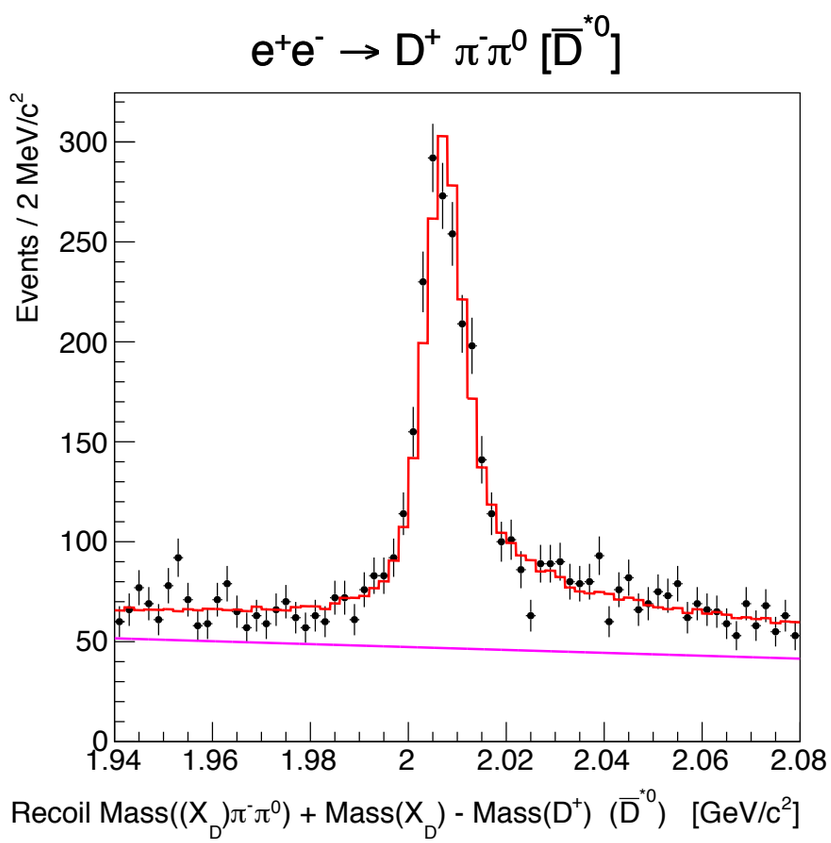
(these plots don't include c.c.)

Use the top to fit the data; then fix the size of the bottom…

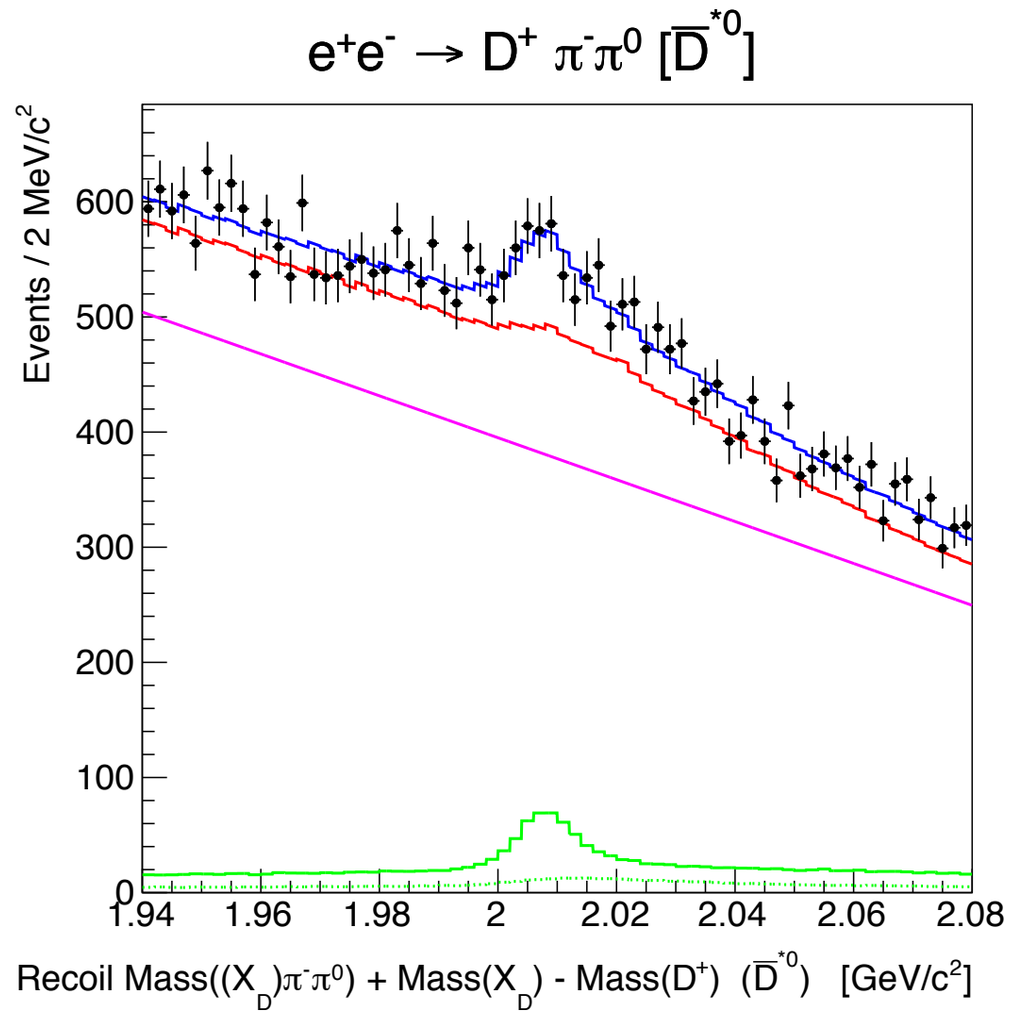
III. Compare to $e^+e^- \to \pi^-\pi^0 D^+ \overline{D}^{*0}$

Fits (current technique), three free parameters:

* Get the **$\pi D^* D^*$ background** shape from MC; fix its size using data.
* Use a **1st order polynomial** for non-peaking backgrounds.
* Take the **signal** shape from signal MC *(there are two components — $\pi^-\pi^0 D^0 D^{*+}$ is an irreducible background)*.



Select $D^{*+} \to \pi^0 D^+$ to fix the size of the $\pi D^* D^*$ background.

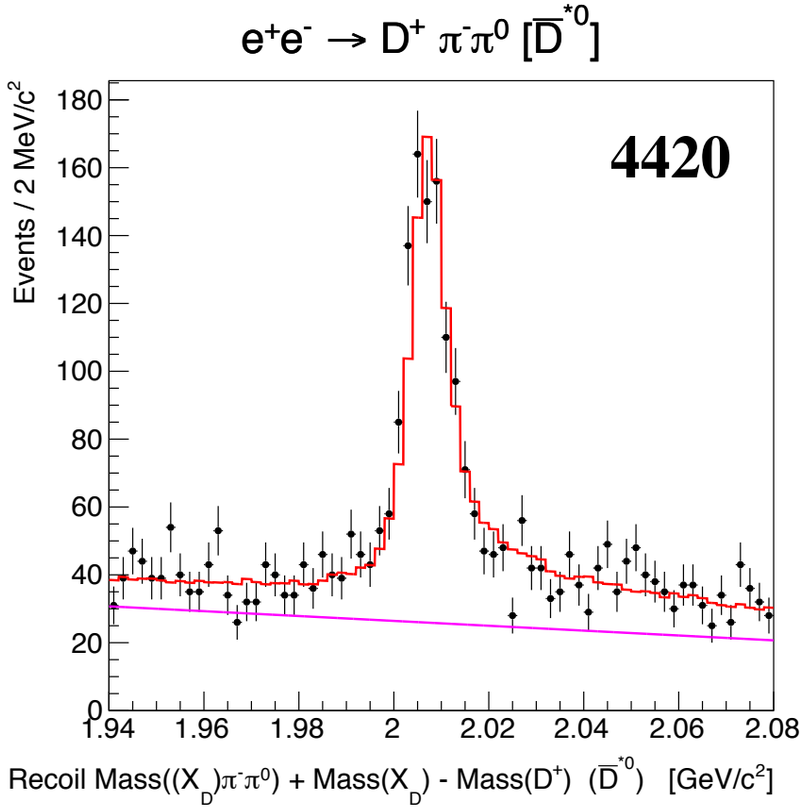


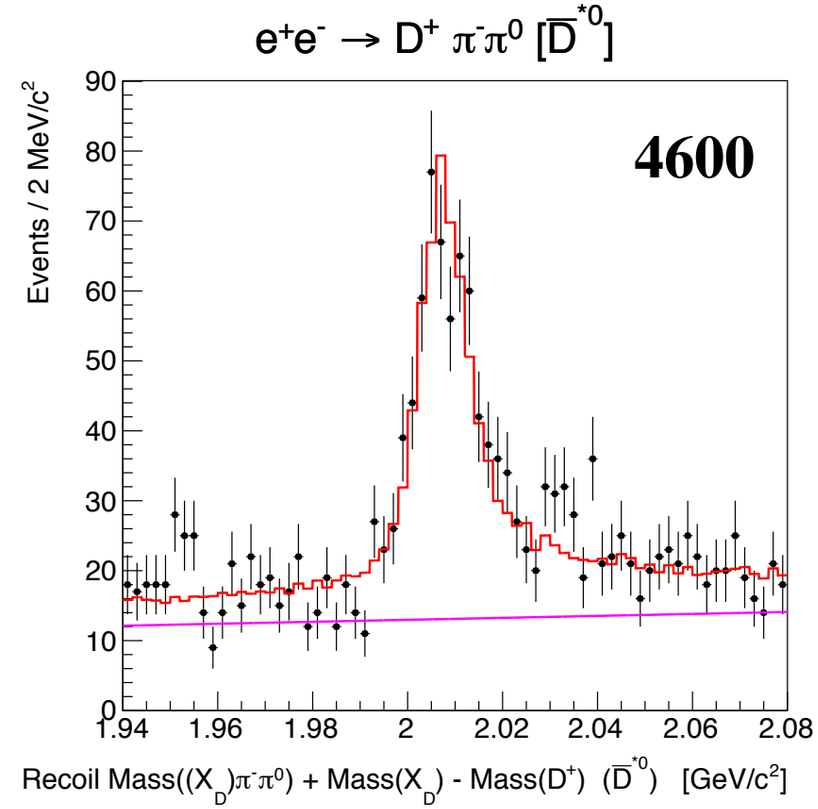
Veto $D^{*+} \to \pi^0 D^+$ with the size of $\pi D^* D^*$ fixed.

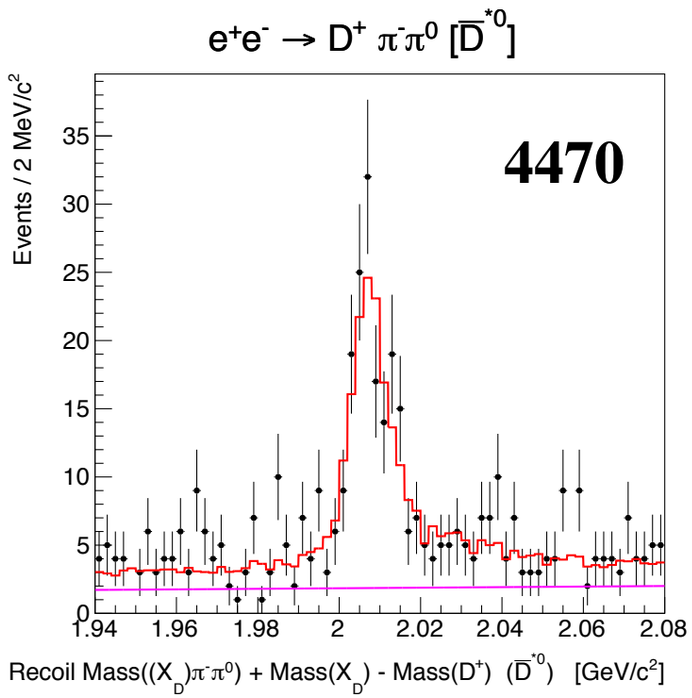
(these plots don't include c.c.)

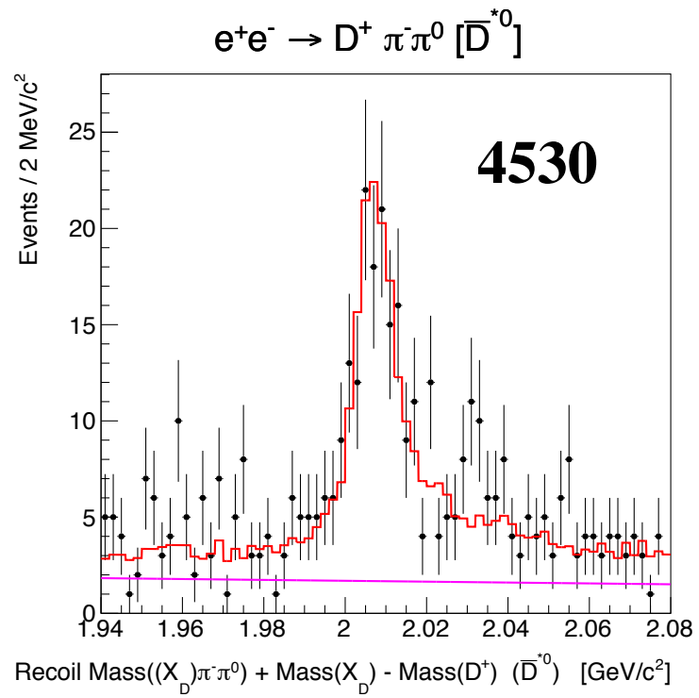
III. Compare to $e^+e^- \to \pi^-\pi^0 D^+ \overline{D}^{*0}$

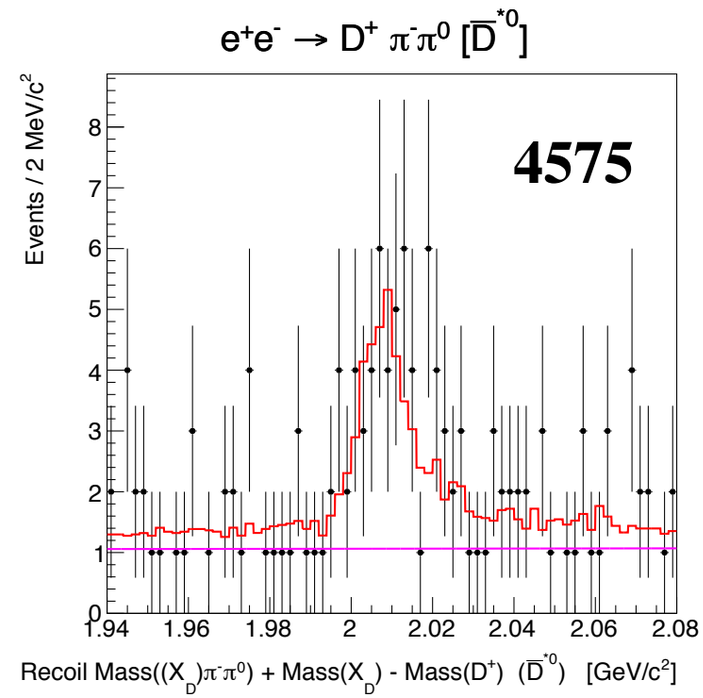
Select $D^{*+} \to \pi^0 D^+$ to fix the size of the background.







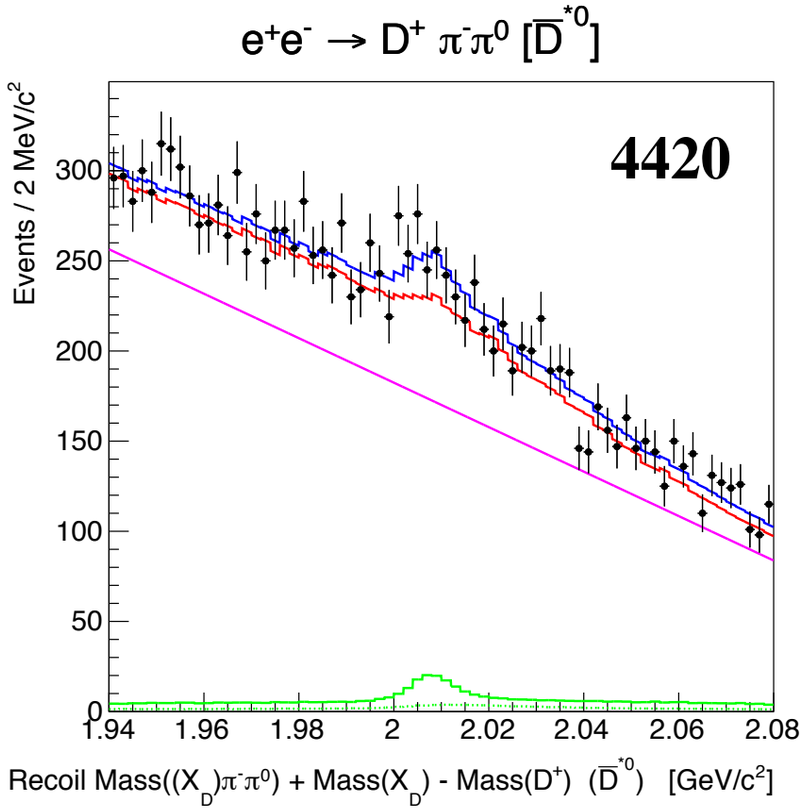


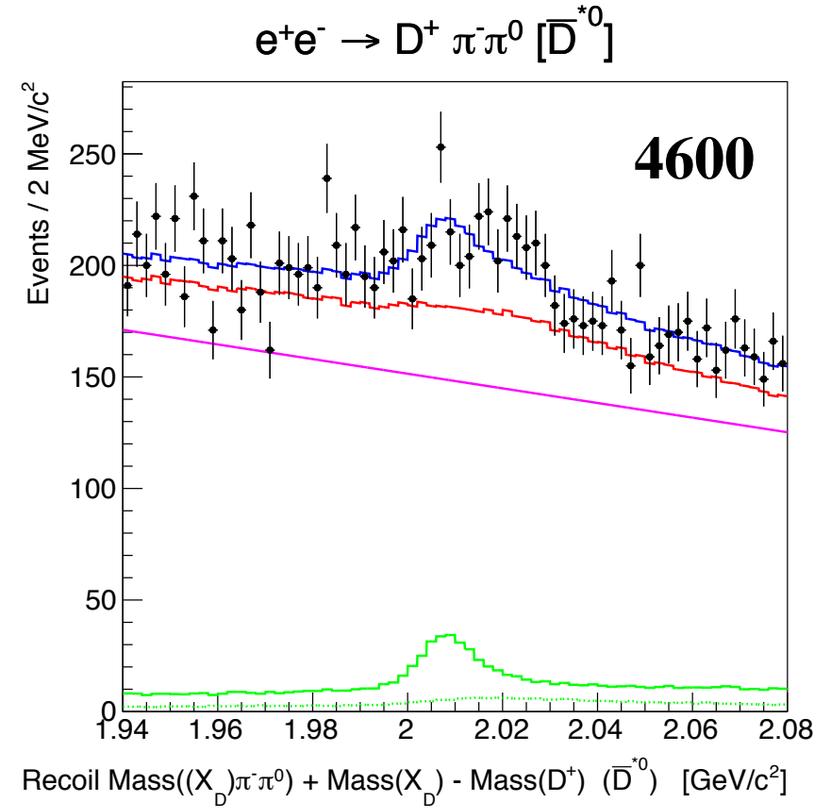


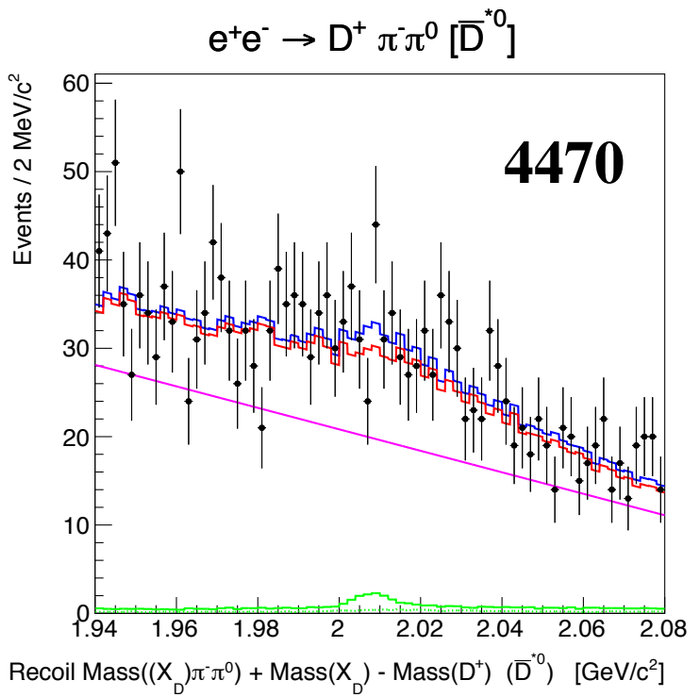
(these plots don't include c.c.)

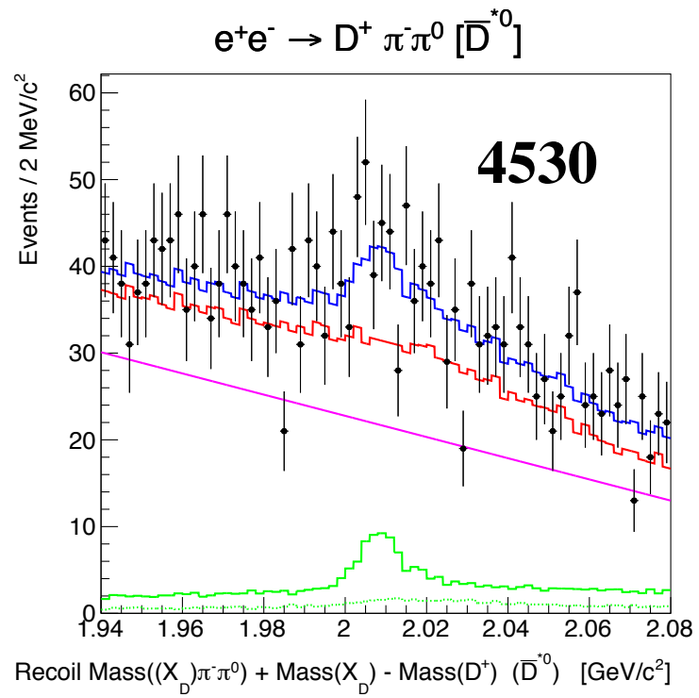
III. Compare to $e^+e^- \to \pi^-\pi^0 D^+ \overline{D}^{*0}$

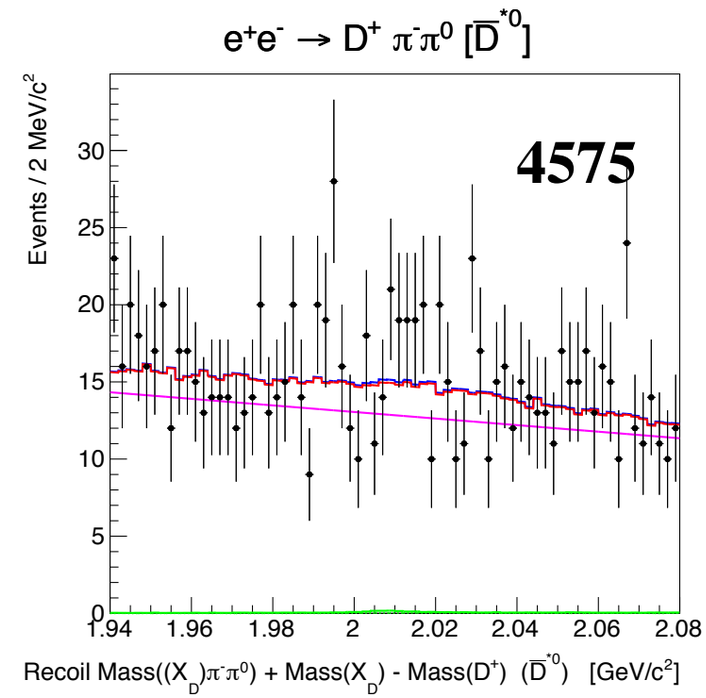
Veto $D^{*+} \to \pi^0 D^+$ to get the size of the signal.







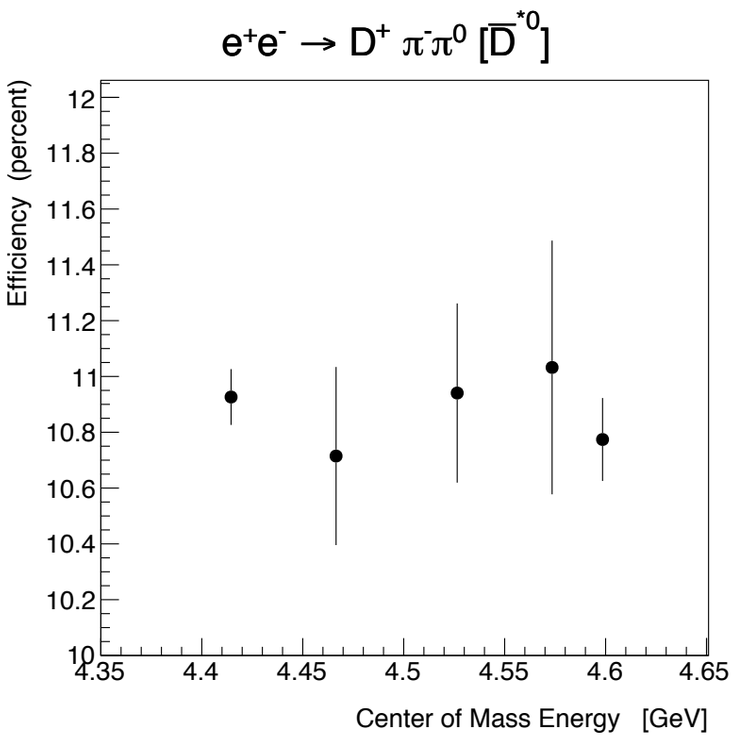


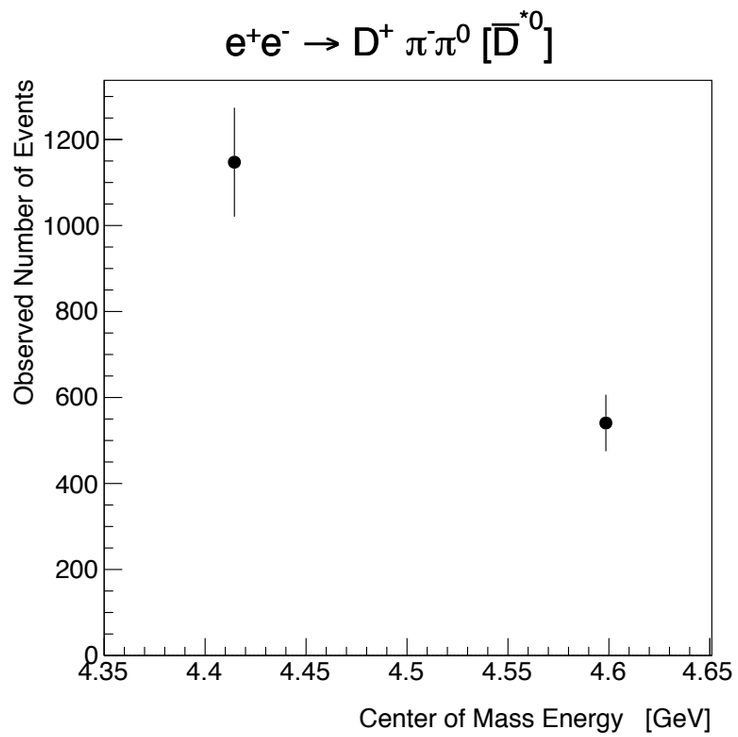


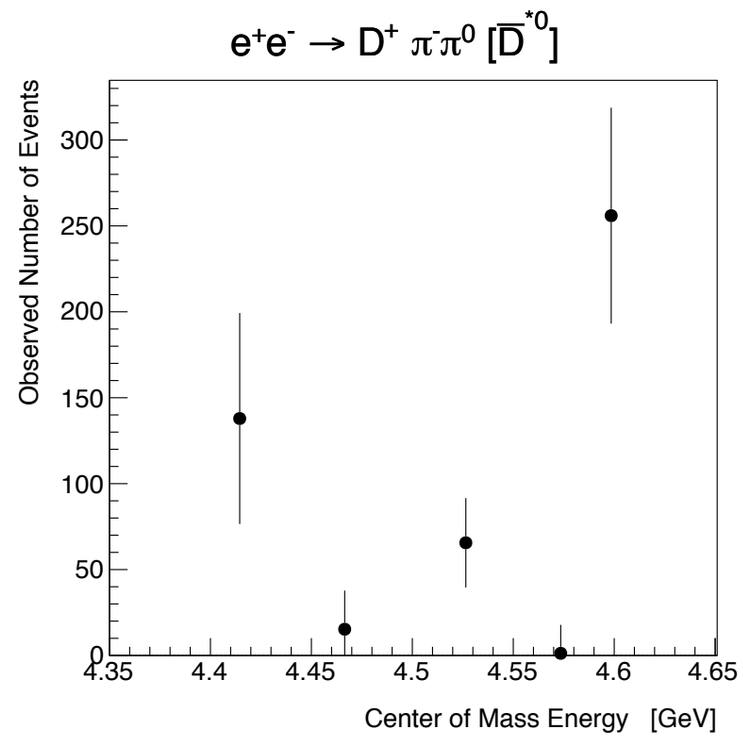
(these plots don't include c.c.)

III. Compare to $e^+e^- \to \pi^-\pi^0 D^+ \overline{D}^{*0}$

* Find the efficiency and number of observed events from the fits.







SIGNAL MC
(assuming flat cross section for ISR calculation)

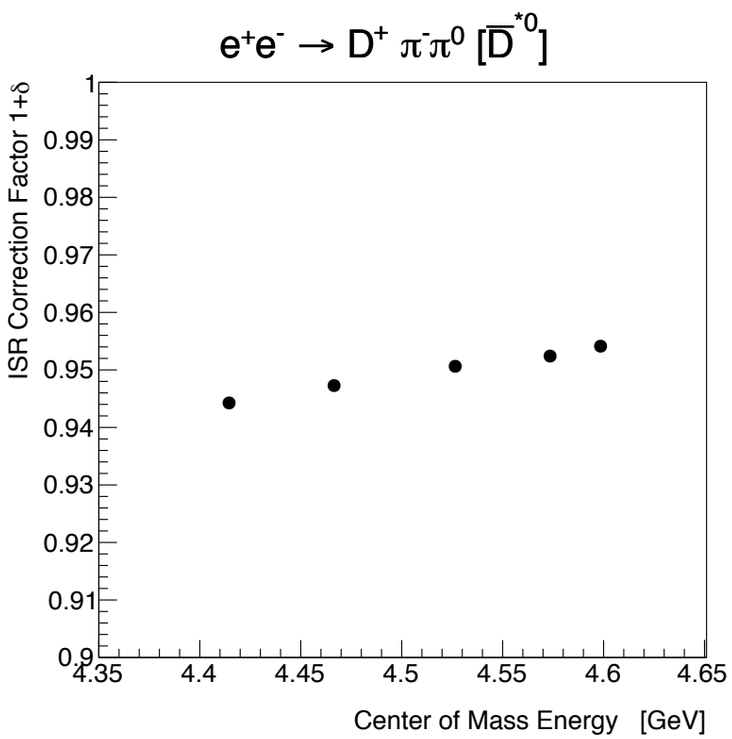
INCLUSIVE MC

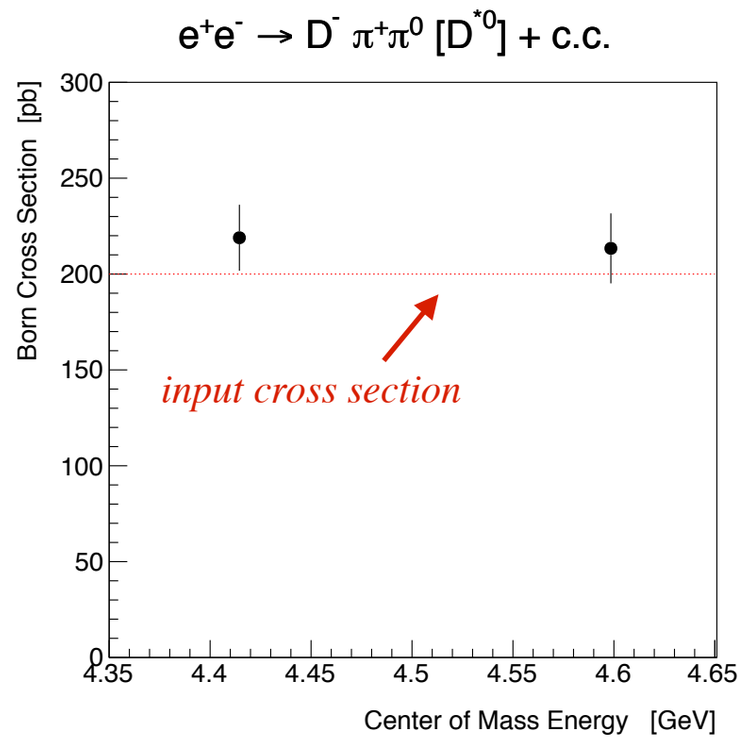
DATA

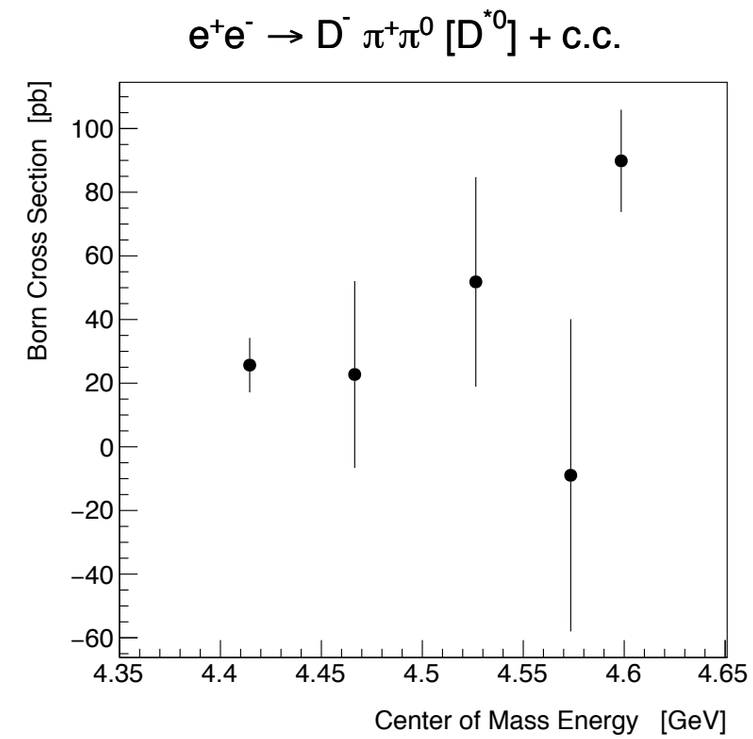
(these plots don't include c.c.)

III. Compare to $e^+e^- \to \pi^-\pi^0 D^+ \overline{D}^{*0}$

* Get the ISR correction factor from SIGNAL MC.
* Divide INCLUSIVE MC and DATA by the efficiency, luminosity, D branching fraction, and ISR correction factor to get the Born Cross Section. Add charge conjugate channels.







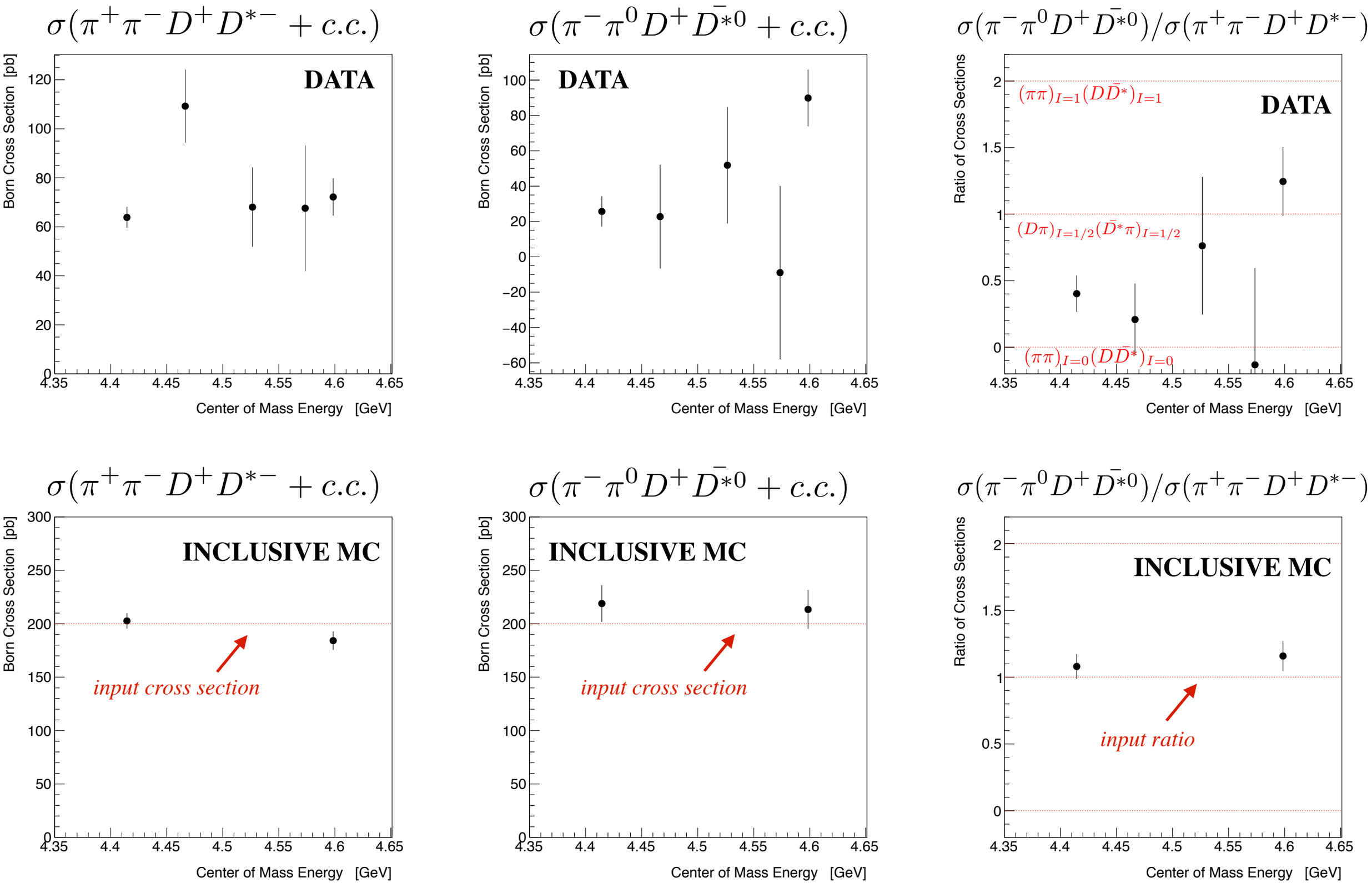
SIGNAL MC

(assuming flat cross section for ISR calculation; threshold = 4.2 GeV)

INCLUSIVE MC

DATA

III. Compare to $e^+e^- \to \pi^-\pi^0 D^+ \bar{D}^{*0}$



Strategy

I. Measure the $e^+e^- \to \pi^+\pi^- D^+ D^{*-}$ cross section.

The cross section is ~60 pb, consistent with $\pi^+\pi^-\psi(1S,2S)$ and $\pi^+\pi^- h_c(2P)$.

Systematic Errors: luminosity; tracking; fitting; ISR.

II. Search for $\pi^+\pi^- h_c(2P)$ with $h_c(2P) \to D^+ D^{*-}$.

Including an $h_c(2P)$ signal describes data better than pure phase space and $D_1 D^*$.

The statistical significance calculation requires more thought.

The mass and width are consistent with theoretical expectations.

Systematic Errors: fitting; mass calibration.

III. Compare to $e^+e^- \to \pi^-\pi^0 D^+ \bar{D}^{*0}$.

The cross section ratio appears to be consistent with predominantly isospin-0 DD* at 4420 MeV and a smaller fraction of isospin-0 at 4600 MeV.

Systematic Errors: luminosity; tracking; fitting; $\pi D^* D^*$ model; ISR.

The $h_c(2P)$ is suggestive! We are also exploring an alternate method. What else can we do??

Backup: Background Channels (I)

1. $\pi^+\pi^-D^+D^{*-}$	1a. $\pi^+\pi^-D^+(\pi^0D^-)$	2a
	1b. $\pi^+\pi^-D^+(\pi^-D^0)$	
2. $\pi^+\pi^-D^-D^{*+}$	2a. $\pi^+\pi^-D^-(\pi^0D^+)$	1a
	2b. $\pi^+\pi^-D^-(\pi^+D^0)$	
3. $\pi^+\pi^-D^0\bar{D}^{*0}$	3a. $\pi^+\pi^-D^0(\pi^0\bar{D}^0)$	2b 4a 4b 6b 8b 13b 13d 14b 14d 15d
	3b. $\pi^+\pi^-D^0(\gamma\bar{D}^0)$	
4. $\pi^+\pi^-\bar{D}^0D^{*0}$	4a. $\pi^+\pi^-\bar{D}^0(\pi^0D^0)$	1b 3a 3b 6b 8b 13b 13d 14b 14d 15d
	4b. $\pi^+\pi^-\bar{D}^0(\gamma D^0)$	
5. $\pi^+\pi^0D^-D^{*0}$	5a. $\pi^+\pi^0D^-(\pi^0D^0)$	1a 2a 6a 10b 13a 13c 15b
	5b. $\pi^+\pi^0D^-(\gamma D^0)$	
6. $\pi^+\pi^0D^0D^{*-}$	6a. $\pi^+\pi^0D^0(\pi^0D^-)$	3a 4a 5a 5b 8b 10b 13a 13b 13c 14b 15b 15d
	6b. $\pi^+\pi^0D^0(\pi^-\bar{D}^0)$	
7. $\pi^-\pi^0D^+\bar{D}^{*0}$	7a. $\pi^-\pi^0D^+(\pi^0\bar{D}^0)$	1a 2a 8a 9b 14a 14c 15c
	7b. $\pi^-\pi^0D^+(\gamma\bar{D}^0)$	
8. $\pi^-\pi^0\bar{D}^0D^{*+}$	8a. $\pi^-\pi^0\bar{D}^0(\pi^0D^+)$	3a 4a 6b 7a 7b 9b 13b 14a 14b 14c 15c 15d
	8b. $\pi^-\pi^0D^0(\pi^+D^0)$	
9. $\pi^0\pi^0D^+D^{*-}$	9a. $\pi^0\pi^0D^+(\pi^0D^-)$	7a 8a 10a 14a 15a 15c
	9b. $\pi^0\pi^0D^+(\pi^-\bar{D}^0)$	
10. $\pi^0\pi^0D^-D^{*+}$	10a. $\pi^0\pi^0D^-(\pi^0D^+)$	5a 6a 9a 13a 15a 15b
	10b. $\pi^0\pi^0D^-(\pi^+D^0)$	
11. $\pi^0\pi^0D^0D^{*0}$	11a. $\pi^0\pi^0D^0(\pi^0D^0)$	5a 6a 10b 12a 12b 13a 15b 16a 16b 16c
	11b. $\pi^0\pi^0D^0(\gamma D^0)$	
12. $\pi^0\pi^0D^0D^{*0}$	12a. $\pi^0\pi^0D^0(\pi^0D^0)$	7a 8a 9b 11a 11b 14a 15c 16a 16b 16c
	12b. $\pi^0\pi^0\bar{D}^0(\gamma D^0)$	

Backup: Background Channels (II)

13. $\pi^+ D^{*-} D^{*0}$	13a. $\pi^+(\pi^0 D^-)(\pi^0 D^0)$	
	13b. $\pi^+(\pi^- D^0)(\pi^0 D^0)$	
	13c. $\pi^+(\pi^0 D^-)(\gamma D^0)$	
	13d. $\pi^+(\pi^- D^0)(\gamma D^0)$	
14. $\pi^- D^{*+} D^{*0}$	14a. $\pi^-(\pi^0 D^+)(\pi^0 D^0)$	
	14b. $\pi^-(\pi^+ D^0)(\pi^0 D^0)$	
	14c. $\pi^-(\pi^0 D^+)(\gamma D^0)$	
	14d. $\pi^-(\pi^+ D^0)(\gamma D^0)$	
15. $\pi^0 D^{*+} D^{*-}$	15a. $\pi^0(\pi^0 D^+)(\pi^0 D^-)$	
	15b. $\pi^0(\pi^+ D^0)(\pi^0 D^-)$	
	15c. $\pi^0(\pi^0 D^+)(\pi^- D^0)$	
	15d. $\pi^0(\pi^+ D^0)(\pi^- D^0)$	
16. $\pi^0 D^{*0} D^{*0}$	16a. $\pi^0(\pi^0 D^0)(\pi^0 D^0)$	
	16b. $\pi^0(\gamma D^0)(\pi^0 D^0)$	
	16c. $\pi^0(\pi^0 D^0)(\gamma D^0)$	
	16d. $\pi^0(\gamma D^0)(\gamma D^0)$	