Observation of New Resonances Decaying to $D\pi$ and $D^*\pi$

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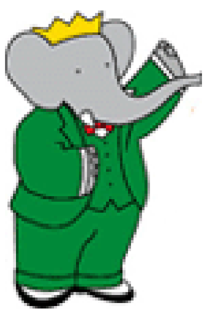
for the BABAR Collaboration



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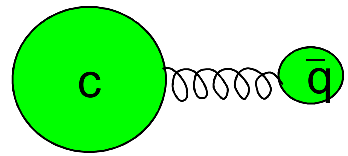
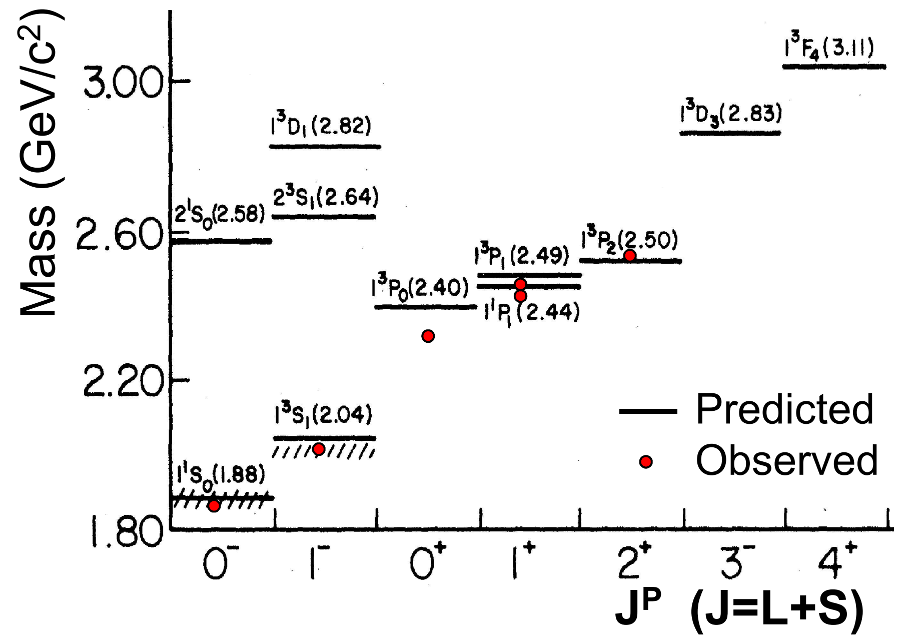
The spectrum of charmed mesons

- The spectroscopy of D mesons is poorly known.
- The bound states of a *c* quark and an *u* or *d* quark were predicted using QCD potential models in 1985.
- Only the ground states D and D* and the narrow L=1 states are well known.
- Observations of higher states have been hindered by poor statistics and their relatively large widths.

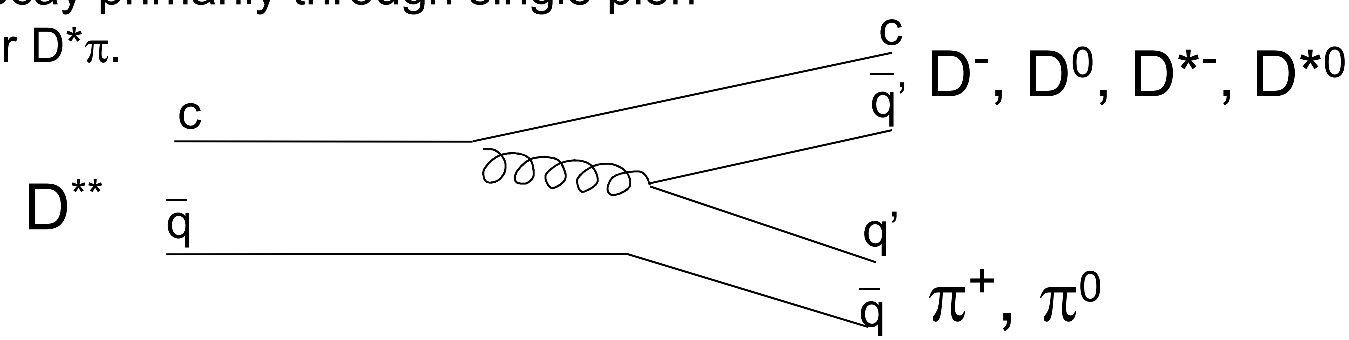


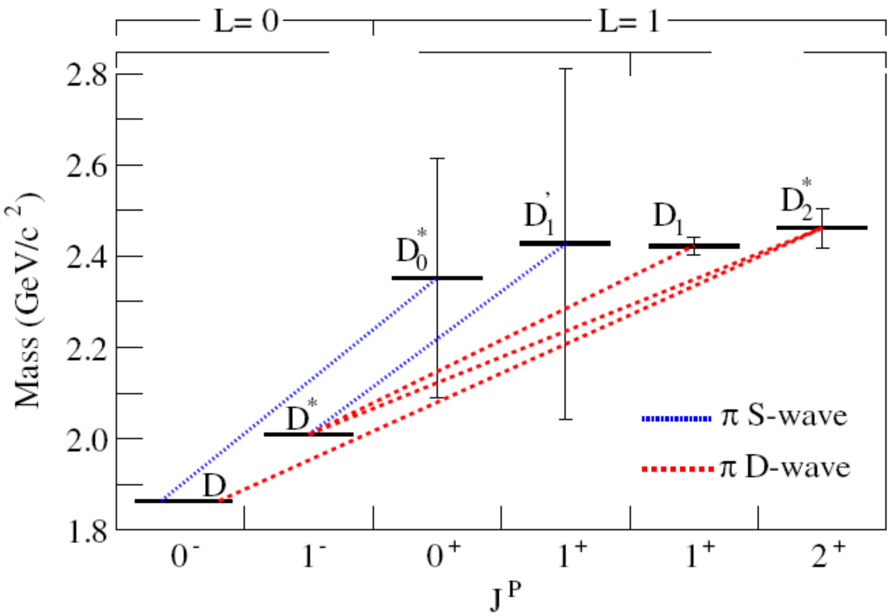


[S. Godfrey and N. Isgur PRD **32**, 189 (1985)]

Decay Properties of the Excited States

- Excited states decay primarily through single pion emission to Dπ or D*π.



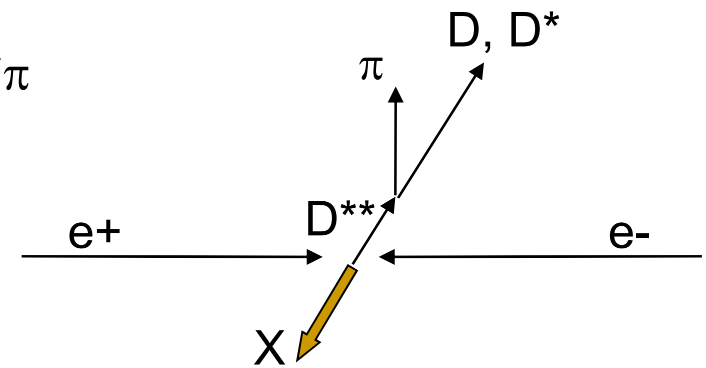


- Four states are known with L=1.
- Two decay through a D-wave and are “narrow” (~40 MeV): D_2*(2460) and D_1(2420).
- Two decay through a S-wave and have very large widths (~300 MeV): D_0(2400) and D_1(2430).

Analysis overview

- Perform an inclusive reconstruction of Dπ and D*π produced from c $\bar{c}$ events:

$$e^+e^- \rightarrow c\bar{c} \rightarrow D^{**}X \rightarrow D^{(*)}\pi X$$



X represents any additional system.

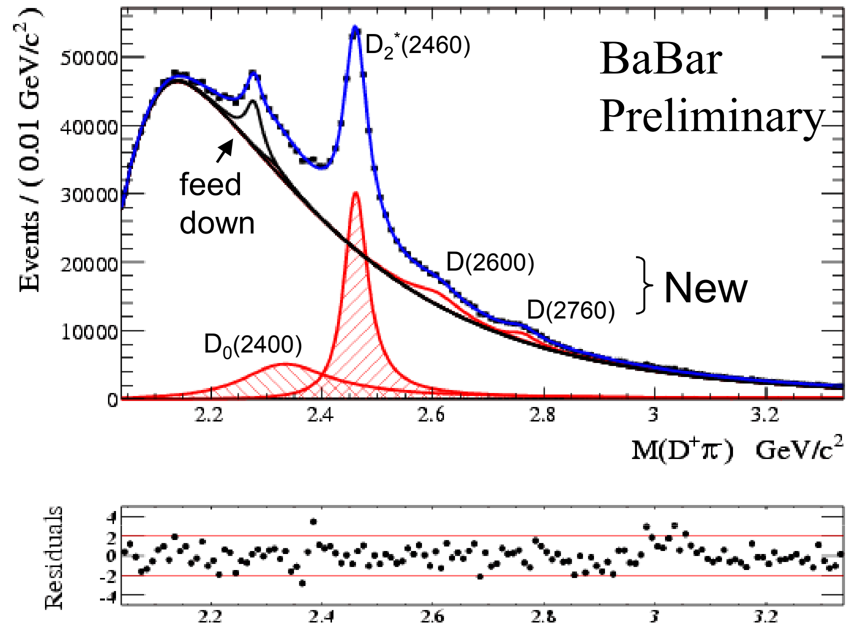
- The following channels are reconstructed:
  - $D^{**0} \rightarrow D^+\pi^-$, $D^+ \rightarrow K^-\pi^+\pi^+$
  - $D^{**+} \rightarrow D^0\pi^+$, $D^0 \rightarrow K^-\pi^+$
  - $D^{**0} \rightarrow D^{*+}\pi^-$, $D^{*+} \rightarrow D^0\pi^+$, $D^0 \rightarrow K^-\pi^+$ or $K^-\pi^+\pi^-\pi^+$

• The data set consists of 454 fb^{-1} (~590 Million $e^+e^- \rightarrow c\,\bar{c}$ events)

• For the known resonances we obtain **10 times** more signal events than the previous study by CDF.

$D^+\pi^-$ mass spectrum

- The known signals are modeled using Breit-Wigner functions corrected with angular momentum form and phase-space factors. Simple Breit-Wigners for the new signals.
- Resolution as well as efficiency shape corrections are applied.
- The broad $D_0(2400)$ is floated within 2σ from the known values.
- The χ^2/NDF of the fit is140/112.

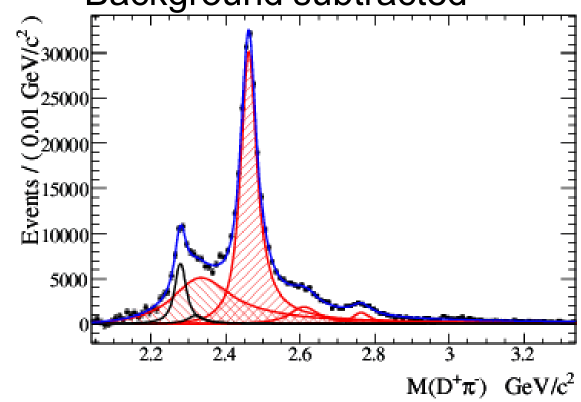


Fit results. Errors are statistical only.

Resonance	Yield ($\times 10^3$)	M (MeV/c^2)	Γ (MeV/c^2)
$D_0^*(2400)$	143.2± 4.7	2338.0± 1.0	195.0±5.9
$D_2^*(2460)$	242.8± 1.8	2462.2± 0.1	50.5± 0.6
$D(2600)$	26.0± 1.4	2608.7± 2.4	93± 6
$D(2760)$	11.3± 0.8	2763.3± 2.3	60.9± 5.1

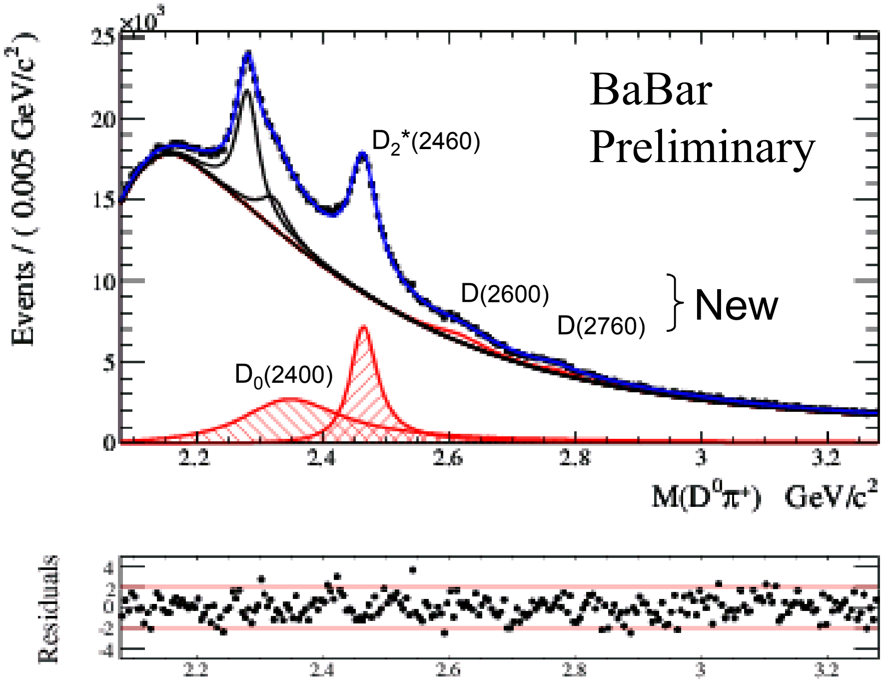
BaBar Preliminary

Background subtracted



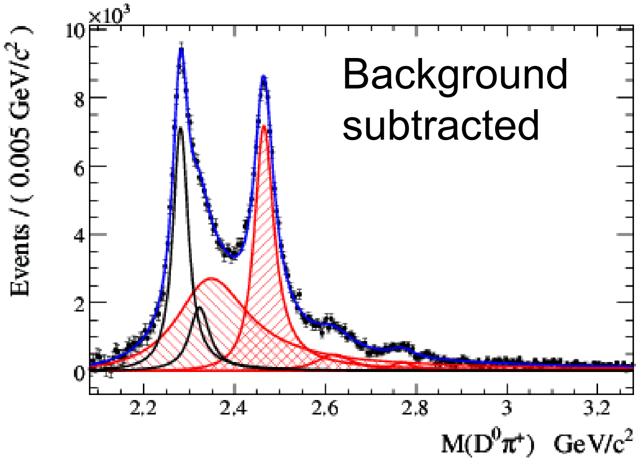
$D^0\pi^+$ mass spectrum

- We observe similar additional signals.
- In this channel the feed-down backgrounds are stronger and the statistics of this channel are smaller so the widths of all signals are fixed to the widths measured in the $D^+\pi^-$.
- We obtain mass values a few MeV higher than in $D^+\pi^-$ consistent with being the isospin partners.
- We obtain a χ^2/ndf=278/224.



Fit results:

Resonance	Yield ($\times 10^3$)	Mass (MeV)	Width (MeV)
$D_0^*(2400)^+$	252.4± 23.7	2342.0± 5.4	264.8± 16.8
$D_2^*(2460)^+$	110.8± 1.3	2465.4± 0.2	50.5
$D(2600)^+$	13.0± 1.3	2621.3± 3.7	93
$D(2760)^+$	5.7± 0.7	2769.7± 3.8	60.9



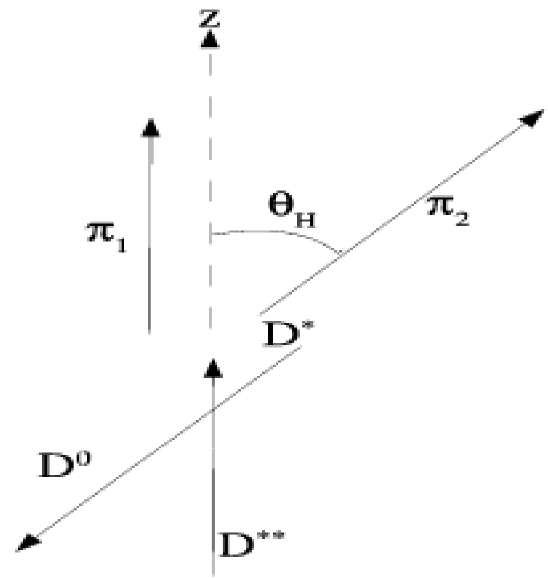
BaBar Preliminary

Analysis of $D^{*}\pi$

Definition of the helicity variable:

- In addition to analyzing the mass spectra we extract the angular distributions in the helicity angle defined in the figure.

- In this reference frame the D^{*+} spin state cannot have z-component. As a result different values of J^P of the parent resonance are distinguished in the intensity of the signal a a function of the helicity angle.

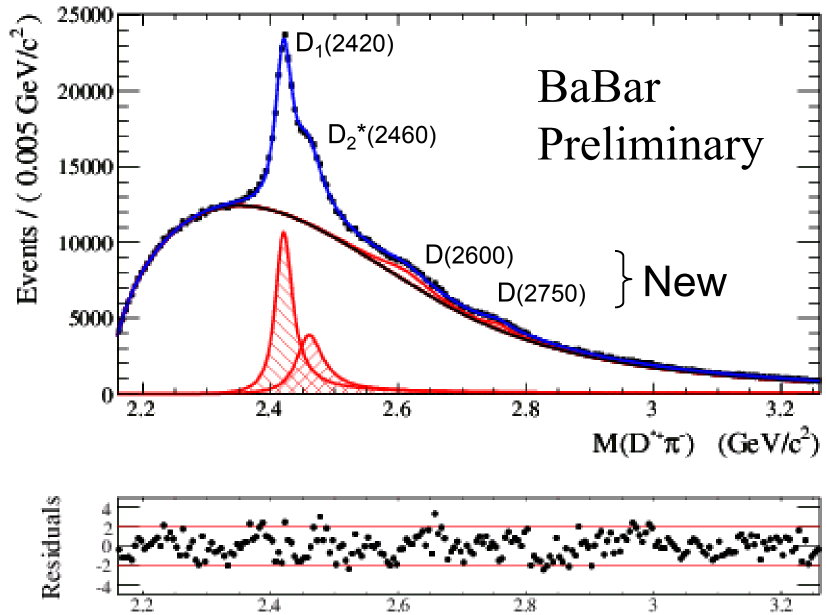


Helicity distributions for the predicted states:

Label $D_J^{2S+1}(nL)$	PDG Name	J^P	$D^*\pi$ Partial Waves	$D^*\pi$ Helicity Distribution
$D_1^1(1P)$	$D_1(2420)$	1^+	S,D	$\propto 1 + Acos^2(\theta)$
$D_0^3(1P)$	$D_0^*(2400)$	0^+	-	-
$D_1^3(1P)$	$D_1'(2430)$	1^+	S,D	$\propto 1 + Acos^2(\theta)$
$D_2^3(1P)$	$D_2^*(2460)$	2^+	D	$\propto sin^2(\theta)$
$D_2^1(1D)$		2^-	P,F	$\propto 1 + Acos^2(\theta)$
$D_1^3(1D)$		1^-	P	$\propto sin^2(\theta)$
$D_2^3(1D)$		2^-	P,F	$\propto 1 + Acos^2(\theta)$
$D_3^3(1D)$		3^-	F	$\propto sin^2(\theta)$
$D_0^1(2S)$		0^-	P	$\propto cos^2(\theta)$
$D_1^3(2S)$		1^-	P	$\propto sin^2(\theta)$

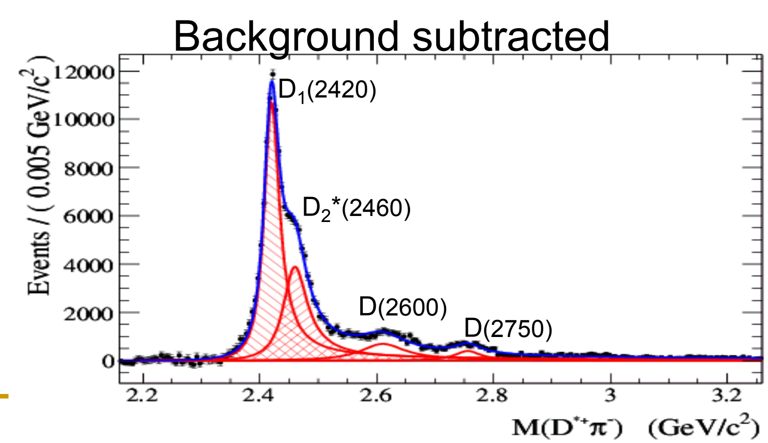
Preliminary fit to $D^{*+}\pi^{-}$ Data

- The fit uses the same background model as in the $D^{+}\pi^{-}$ fit.
- The parameters of the $D_2^*(2460)$ are fixed from the $D^{+}\pi^{-}$ results.
- Two new signals, D(2600) and D(2750), are included in this preliminary fit.



Fit results: **BaBar Preliminary**

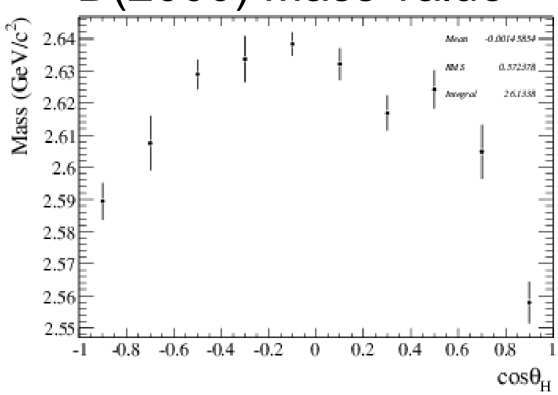
Resonance	Yield ($\times 10^3$)	M (MeV)	Γ (MeV)
$D_1(2420)$	114.9 ± 0.9	2421.2 ± 0.1	30.6 ± 0.1
$D_2^*(2460)$	67.9 ± 1.3	2462.2	50.5
$D(2600)$	31.6 ± 6.1	2616.2 ± 2.6	115.2 ± 13.2
$D(2750)$	6.9 ± 0.9	2756.7 ± 2.7	54.4 ± 6.4

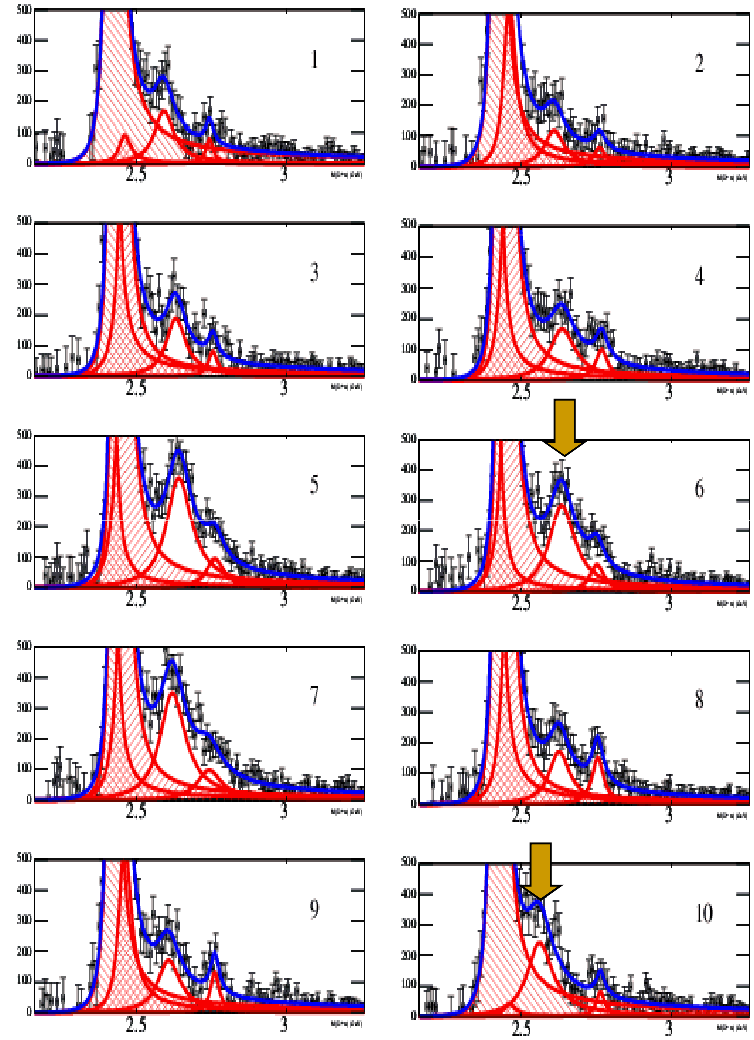


Problem with Preliminary Fit Model

- When we try to fit the spectrum as a function of the helicity angle the mass of the “D(2600)” peak shifts as a function of the angle.
- The other signals are stable.
- This implies this peak is composed of two signals.

D(2600) Mass value



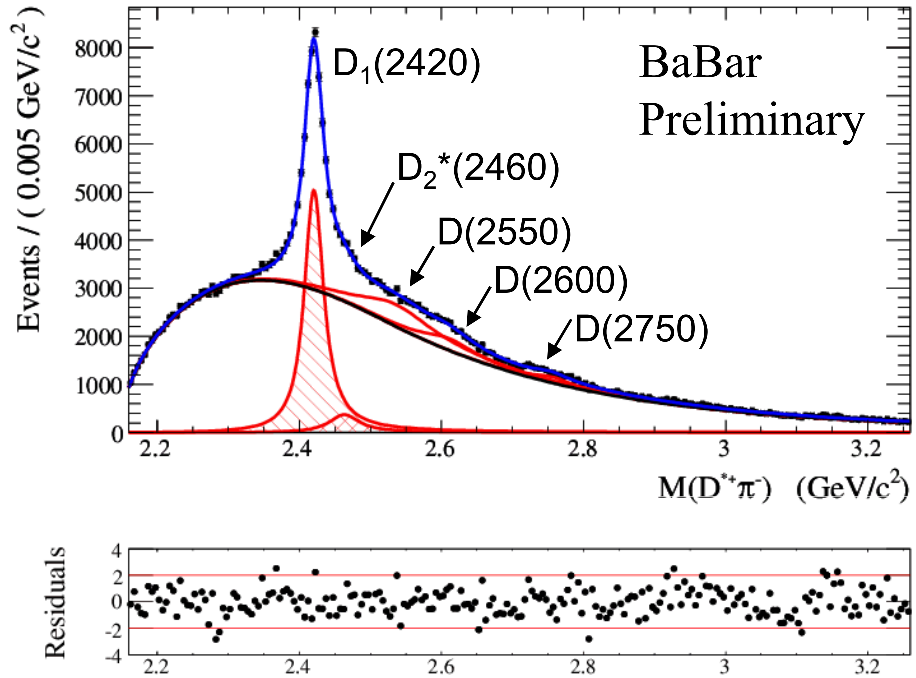


Data divided as a function of the helicity angle.

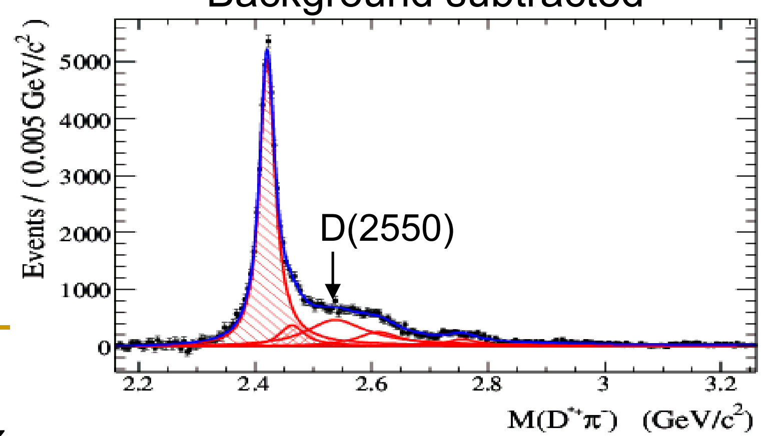
- Strategy to fix the preliminary model:
  - Introduce another signal D(2550)
  - Assume D(2600) is same as observed in $D^+\pi^-$ and fix the parameters.
  - Apply helicity cut $|\cos\theta_H|>0.75$ to enhance the D(2550) and determine its parameters.

Extraction of D(2550) signal

- A cut requiring $|\cos(\theta_H)|>0.75$ is applied to the Data.
- We fit the spectrum now including one more signal around 2.55 GeV.
- The parameters of the $D_2^*(2460)$ and D(2600) are fixed to the ones from $D^+\pi^-$.



Background subtracted



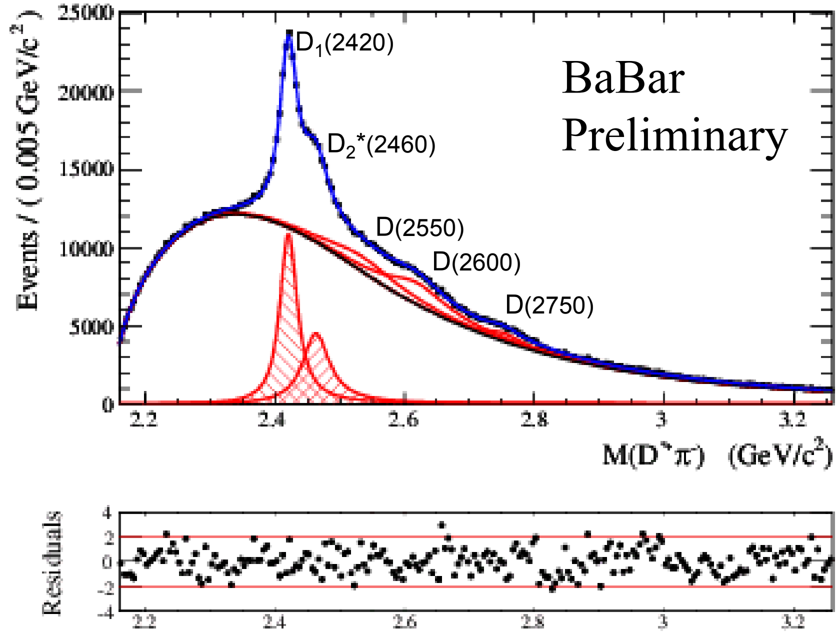
Fit parameters

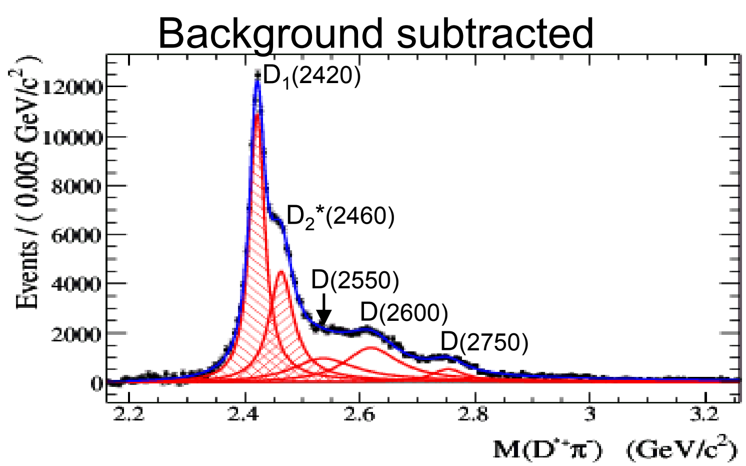
BaBar Preliminary

Resonance	Yield ($\times 10^3$)	M (MeV)	Γ (MeV)
$D_1(2420)$	50.4± 0.9	2420.1± 0.1	31.0± 0.6
$D_2^*(2460)$	73.3± 1.6	2462.2	50.5
$D(2550)$	17.4± 4.5	2533.0± 5.5	127.6± 19.9
$D(2600)$	6.9 ± 1.3	2608.7	92.9
$D(2750)$	2.4 ± 0.5	2754.5 ± 4.7	64.2 ± 11.7

Final fit to $D^{*+}\pi^-$

- The total $D^*\pi$ mass distribution is fit using the final model.
- The parameters of the $D_1(2420)$ and D(2550) are fixed to the ones found in the fit with the helicity cut.
- The parameters of the $D_2^*(2460)$ and D(2600) are constrained to the ones from the $D^+\pi^-$.
- We obtain final parameters for the D(2750) from this fit.
- We obtain a χ^2/ndf=244/207.



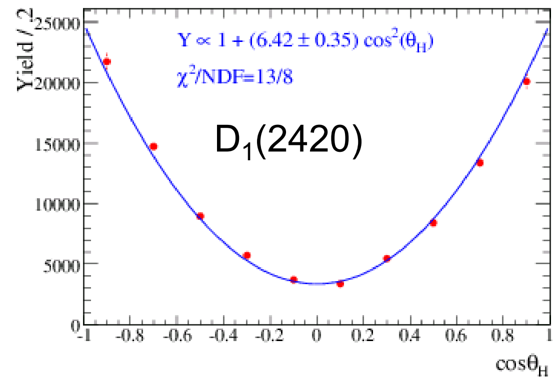


Fit parameters **BaBar Preliminary**

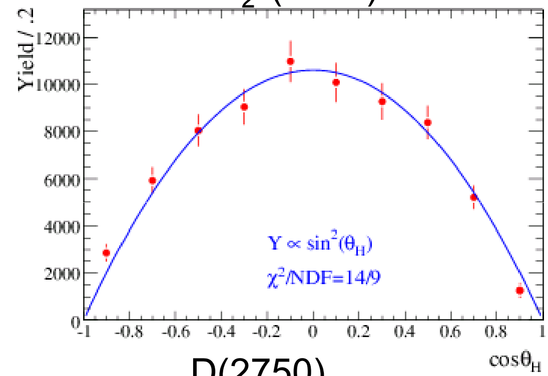
Resonance	Yield ($\times 10^3$)	M (MeV)	Γ (MeV)
$D_1(2420)$	108.4± 0.9	2420.1	31.0
$D_2^*(2460)$	73.3± 1.6	2462.2	50.5
$D(2550)$	47.0± 5.7	2533.0	127.6
$D(2600)$	39.7± 1.3	2619.0	92.9
$D(2750)$	14.5± 1.8	2747.7± 2.5	83.9± 8.9

Helicity distributions:

- The helicity distribution for the known resonances $D_1(2420)$ and $D_2^*(2460)$ are as expected for their J^P values.
- For the signal D(2550) a $\cos^2(\theta_H)$ distribution is obtained consistent with the radial excitation of the D^0
- For the signal D(2600) a $\sin^2(\theta_H)$ is obtained consistent with the radial excitation of the D^{*0}
- For the signal D(2750) the distribution is not simple. This can be consistent with being a composite peak; the L=2 states are candidates.

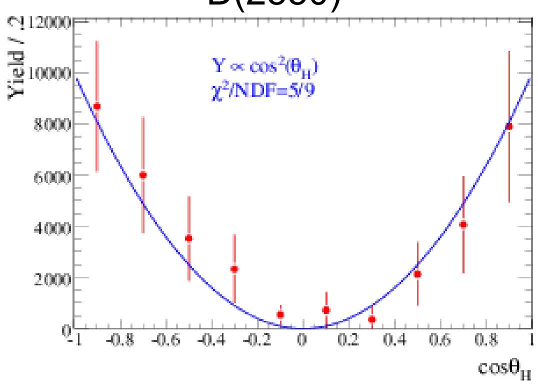


D2*(2460)

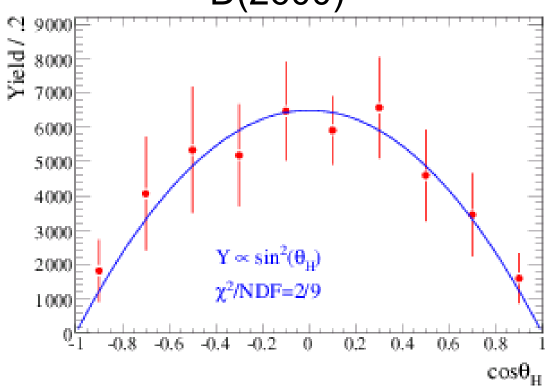


BaBar Preliminary

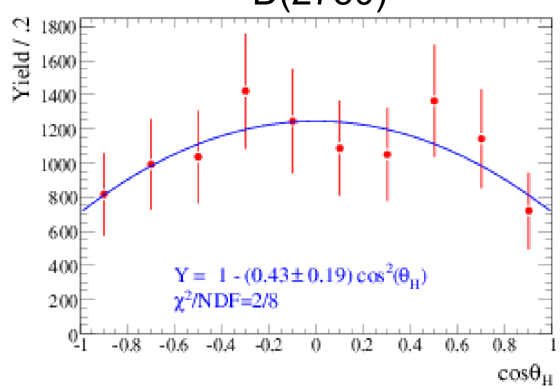
D(2550)



D(2600)



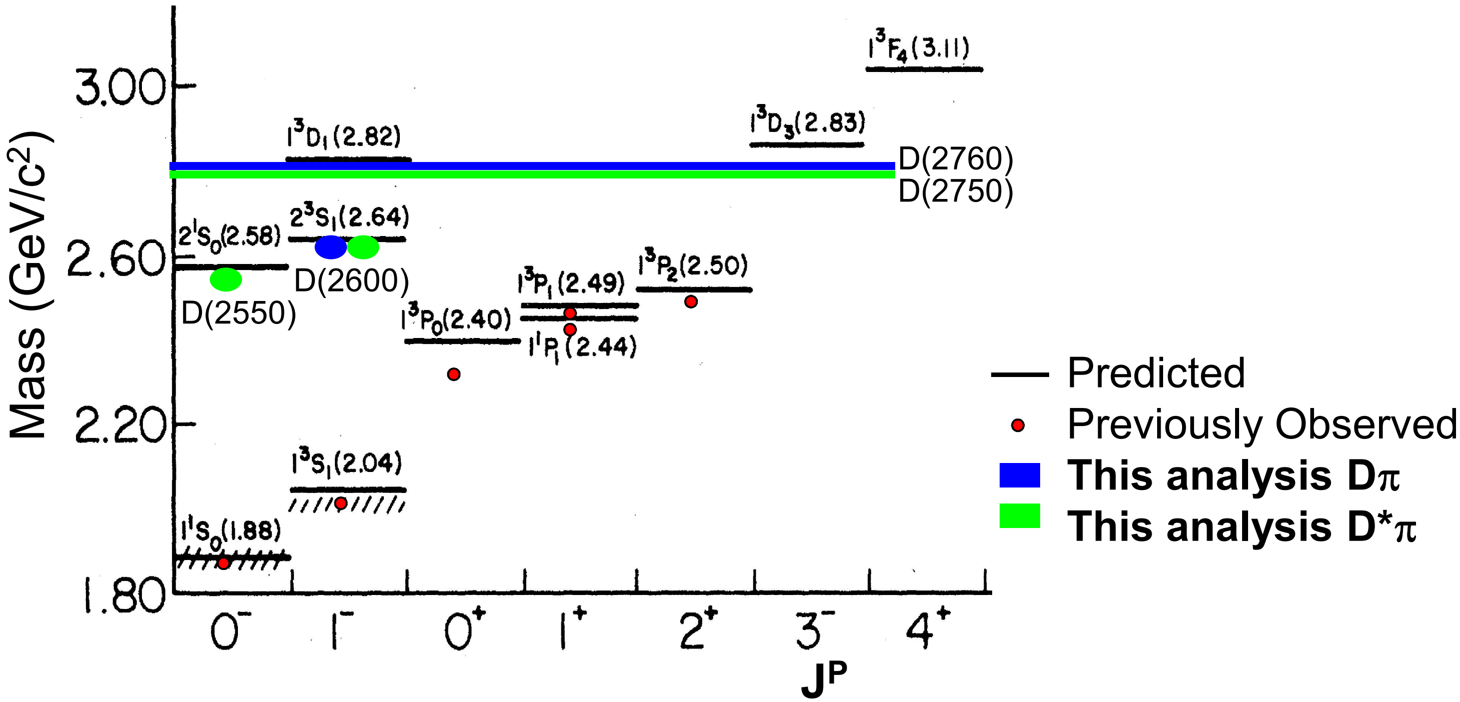
D(2750)



Overview of Results

BaBar Preliminary

- These results fill important gaps in the knowledge of excited D meson states.
- The signals observed in this analysis are shown in the plot and are qualitatively consistent with the predictions.



Summary and Conclusions

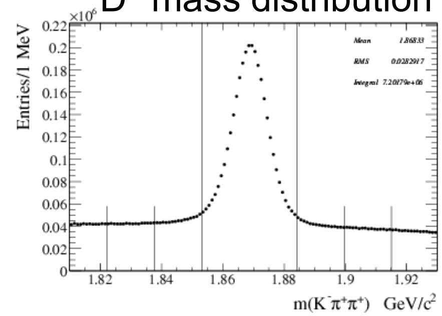
- We have analyzed the inclusive final states $D^+\pi^-$, $D^0\pi^+$, and $D^{*+}\pi^-$ in search for unobserved excited D mesons.
- In $D^+\pi^-$ we find two new signals with masses at about 2610 MeV/c^2 and 2760 MeV/c^2. The isospin partner signals are confirmed in $D^0\pi^+$.
- In $D^{*+}\pi^-$ we find three new signals at about 2530 MeV/c^2, 2610 MeV/c^2 and 2750 MeV/c^2. We assume the signal at 2610 MeV is the same as in $D^+\pi^-$.
- The helicity distributions indicate that the signal at 2530 MeV may be identified as the radial excitation of the D^0. Similarly, the signal at 2610 MeV may be identified as the radial excitation of the D^{*0}. Finally, the helicity distribution of the signal at 2750 GeV indicates this signal may be composite, with the L=2 excitations being the most likely candidates.
- The mass values are similar to the predicted states.

Back-up Slides

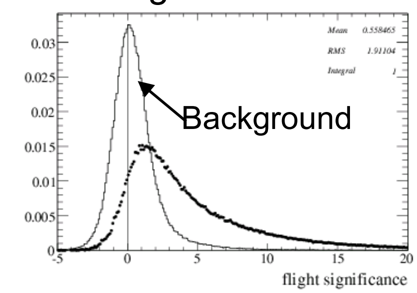
Reconstruction and Selection

- **For all final states:**
  - Apply PID requirements on the tracks.
  - Apply a vertex fit to the tracks requiring to originate from the e^+e^- interaction region.
  - Require the c.m. momentum of the $D^{(*)}\pi$ to be greater than 3 GeV.
  - Require $\cos(\theta_\pi)$ > -0.8 to remove π's from opposite jet.
- **For $D^+\pi^-$:**
  - Require $|m(D^+)$ -1.8686 GeV$|$ < 2.5σ
  - Require D^+ Flight significance > 0 .
- **For $D^0\pi^+$:**
  - Require $|m(D^0)$ -1.8648 GeV$|$ < 2.5σ
  - Require cosine of the angle between K and D^0 direction > -0.9
  - Veto $D^{*+}\rightarrow D^0\pi^+$ and $D^{*0}\rightarrow D^0\pi^0$
- **For $D^{*+}\pi^-$:**
  - Require $|m(D^0)$-1.8648 GeV$|$< 30 MeV
  - Require $|\Delta m$-145.4 MeV$|$ < 2 MeV

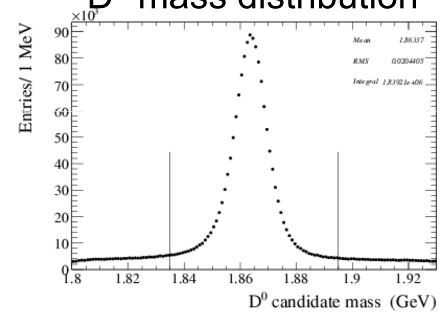
D^+ mass distribution



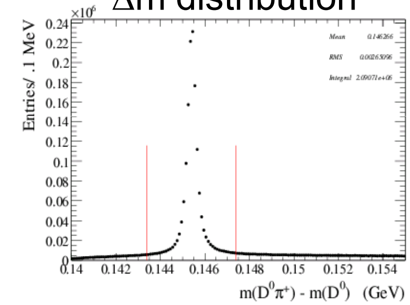
D^+ Flight distribution



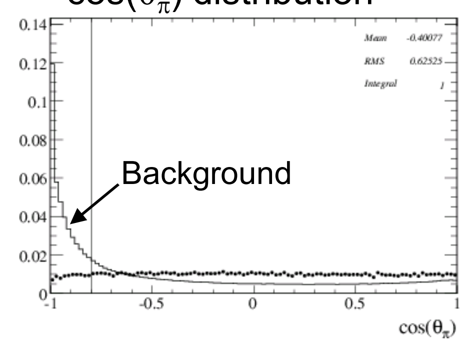
D^0 mass distribution



Δm distribution



$\cos(\theta_\pi)$ distribution



Current Knowledge of Excited States

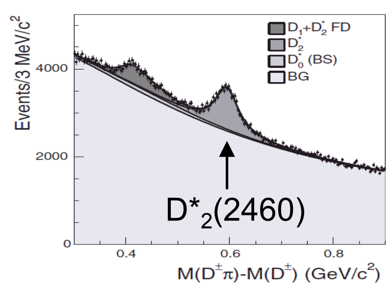
- The narrow L=1 states have been observed with largest statistics by CDF.

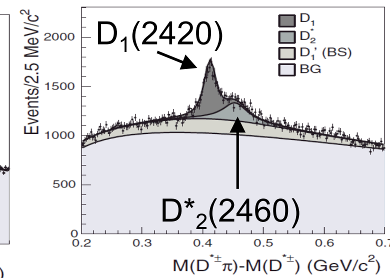
  [CDF Collab. PRD 73, 051104 (2006)]

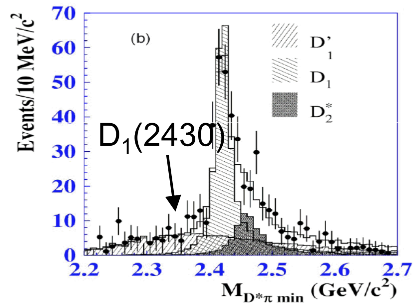
- The wide L=1 states have been measured in *B* decays by BaBar and Belle.

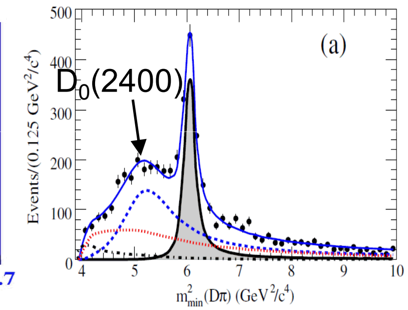
  [Belle Collab. PRD 69, 112002 (2004)]

  [BaBar Collab. PRD 79, 112004 (2009)]





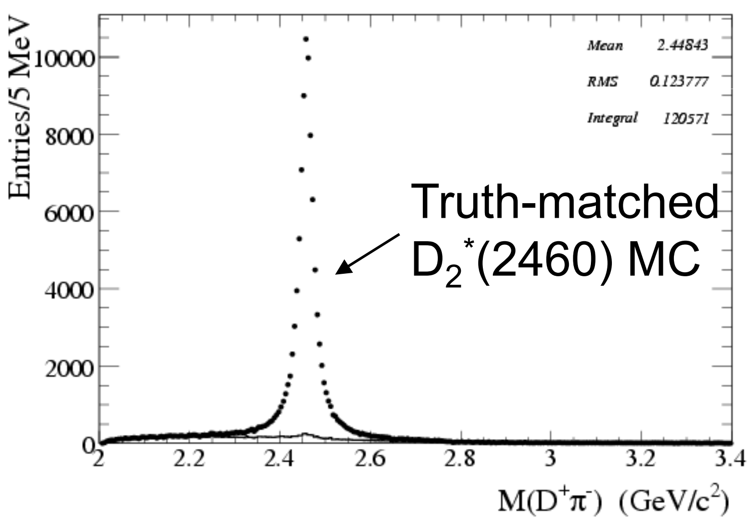


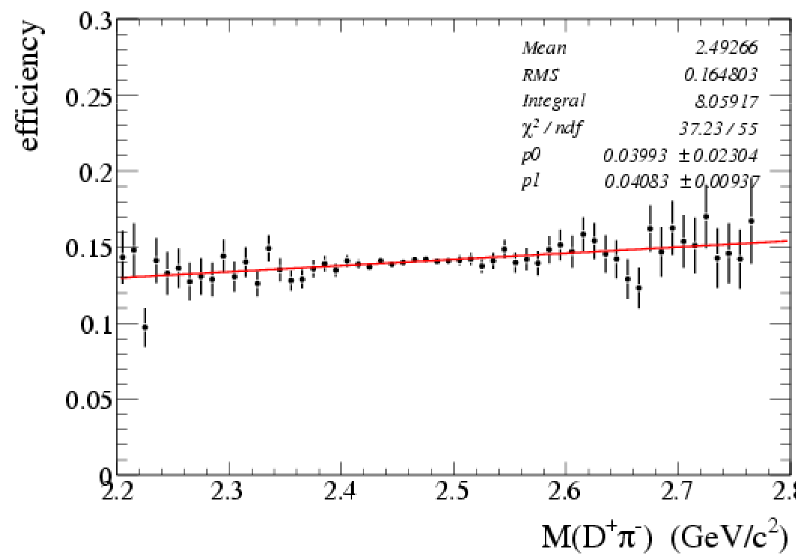


PDG Name	J^P	$D\pi$ Partial Waves	$D^*\pi$ Partial Waves	Expected Mass (GeV)	Observed Mass (MeV)	Observed Width (MeV)
$D_1(2420)$	1^+	-	S,D	2.420	2422 ± 2	20 ± 2
$D_0^*(2400)$	0^+	S	-	2.380	2297 ± 21	273 ± 50
$D_1'(2430)$	1^+	-	S,D	2.469	2427 ± 30	380 ± 100
$D_2^*(2460)$	2^+	D	D	2.479	2460.4 ± 2.5	41.8 ± 3.8

Reconstruction Efficiency

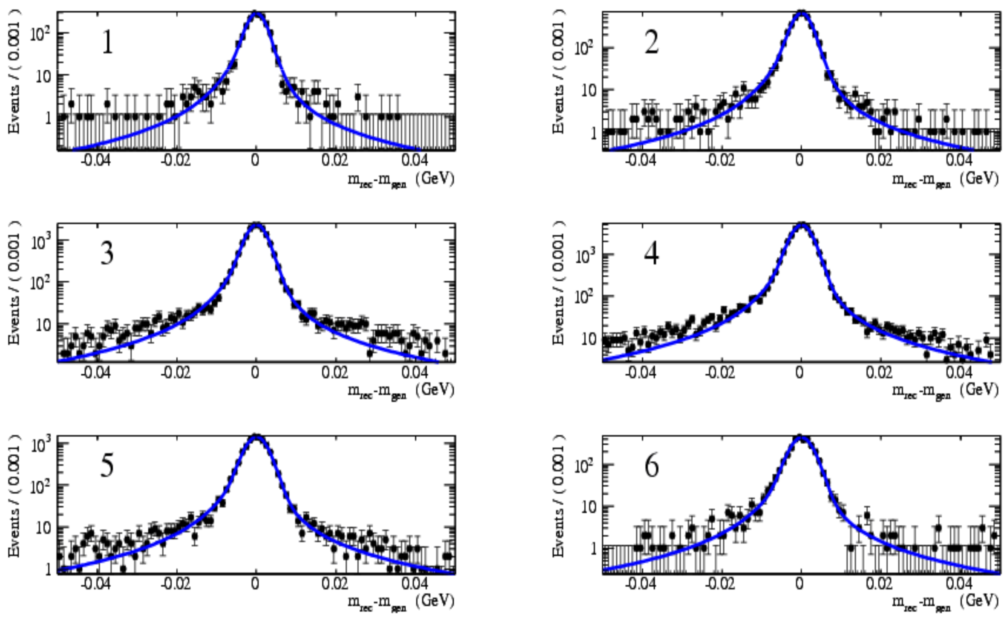
- Truth-matched signal Monte Carlo (MC) is used to determine the efficiency and resolution as a function of $M(D^+\pi^-)$



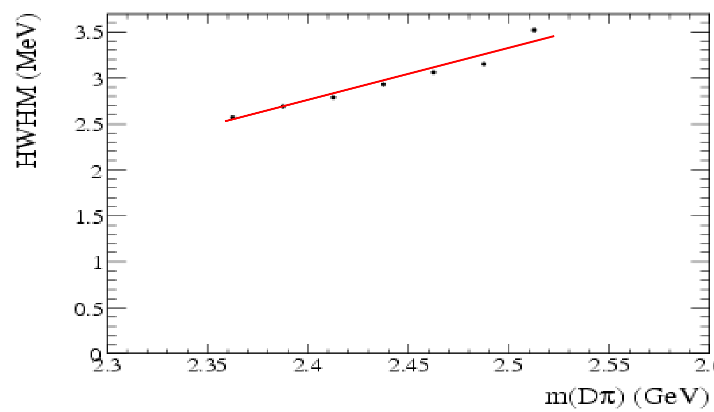


Mass Resolution

- The signal MC is divided in bins of 25 MeV and for each sample we determine the resolution.
- The resolution degrades as a function of $M(D^{+}\pi^{-})$.

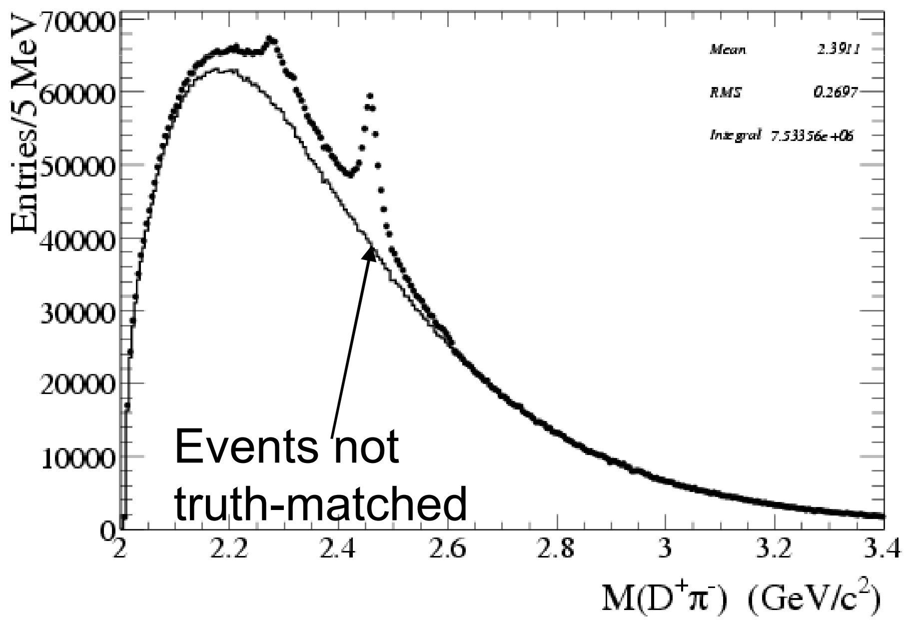


The resolution is about 3 MeV and increases linearly with mass.

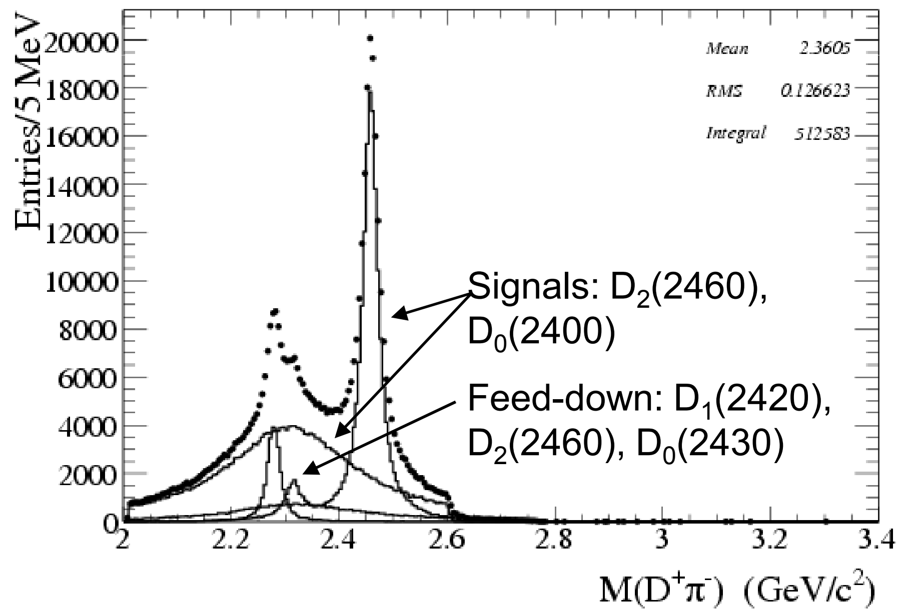


Generic MC Simulation

- The generic MC contains all of the known L=1 resonances: $D_1(2420)$, $D_2(2460)$, $D_0(2400)$, and $D_1(2430)$.
- Besides the signals $D_2(2460)$ and $D_0(2400)$ there is feed-down from $D_1(2420)$, $D_2(2460)$, $D_1(2430)$ decaying to $D^{*+}\pi^-$ where the D^{*+} decays to $D^+\pi^0$ and the π^0 is not reconstructed.
- The broad resonances contain an artificial mass cut-off at about 2.6 GeV.



Truth-matched resonances



Background Model

- We model the smooth background using an exponential function and a threshold factor.

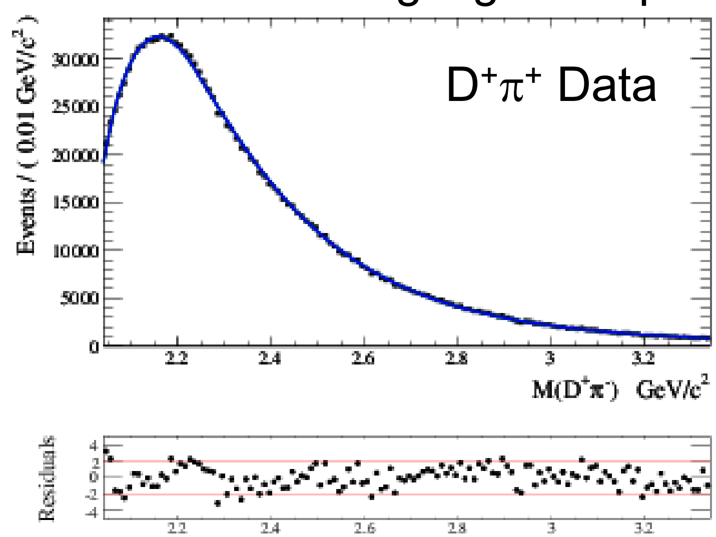
- The background model is tested using the MC and wrong-sign ($D^+\pi^+$) samples.

- The fit to the wrong-sign Data sample shows non-flat residuals. This residual shape is used to estimate the systematic error.

$$F_B(x) \propto P(x) \begin{cases} e^{c_1 x + c_2 x^2} & \text{for } x < x_0 \\ e^{d_0 + d_1 x + d_2 x^2} & \text{for } x > x_0 \end{cases}$$

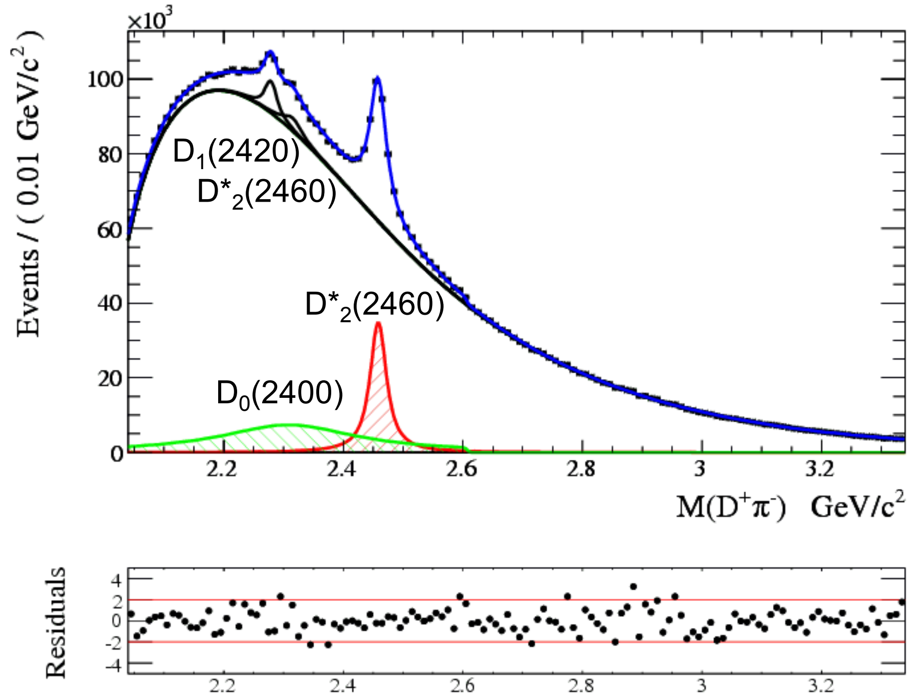
$$P(x) \equiv \frac{1}{2x}\sqrt{[x^2 - (m_{D^+} + m_\pi)^2][x^2 - (m_{D^+} - m_\pi)^2]}$$

Fit to the Wrong-sign Sample



Fit to the Generic MC

- A binned fit is performed in the mass range starting about 30 MeV above threshold. The behavior near threshold is very hard to model.
- The the fitted parameters are in good agreement with the true values.

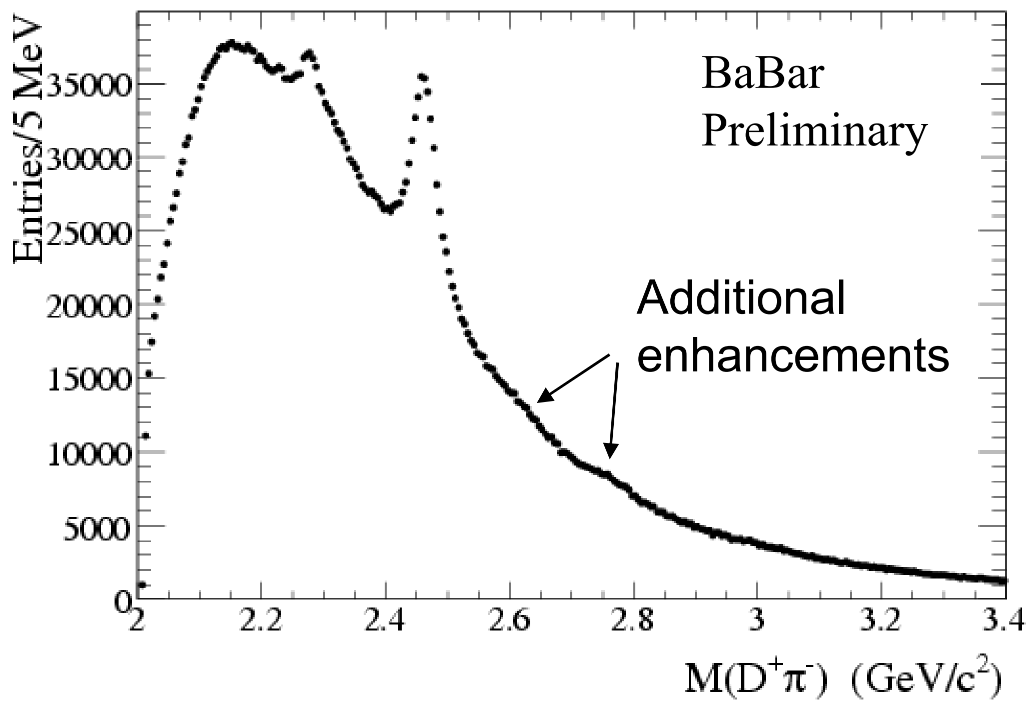


Fit results. Errors are statistical only .

Resonance	Yield ($\times 10^3$)	M (MeV)	Γ (MeV)	Generated Yield ($\times 10^3$)	Generated M (MeV)	Generated Γ (MeV)
$D_2^*(2460)$	173.9 ± 3.1	2458.5 ± 0.1	30.8 ± 0.6	188.8	2459.0	30.0
$D_0^*(2400)$	228.2 ± 16.6	2308.0 ± 0.0	276.0 ± 0.0	246.8	2308.0	276.0
$D_1(2420)_{Feed}$	30.4 ± 1.3	2422.0 ± 0.0	19.0 ± 0.0	30.7	2422.0	19.0
$D_2^*(2460)_{Feed}$	18.4 ± 1.8	2458.5 ± 0.1	30.8 ± 0.6	Included above	2459.0	30.0

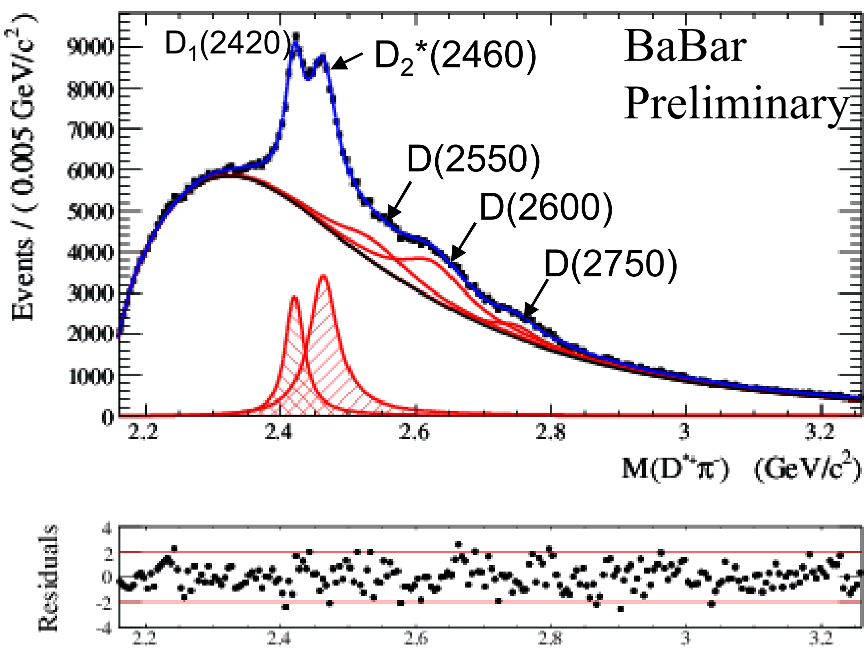
$D^+\pi^-$ Reconstructed Data

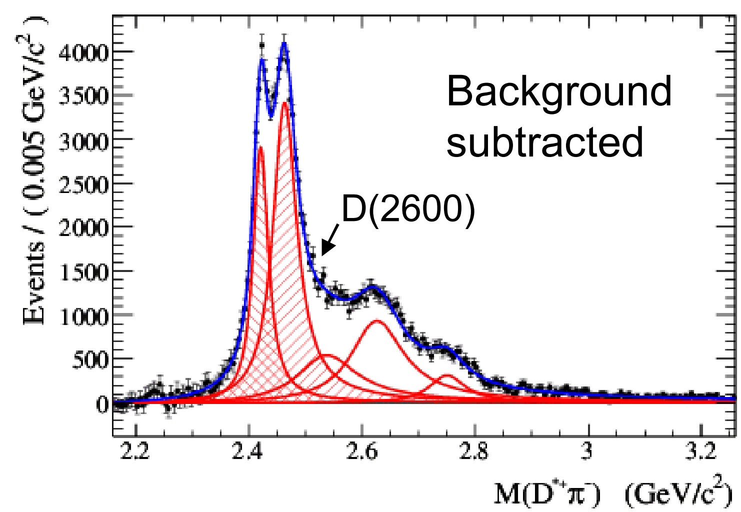
- The $D^+\pi^-$ Data shows both the feed-down and signal $D_2(2460)$.
- Two additional enhancements are observed at ~2.6 GeV and ~2.75 GeV.
- We checked D^+ sideband data to make sure that the additional enhancements are due to true D^+.



Fit to $D^*\pi$ with $|\cos\theta_H|<0.5$

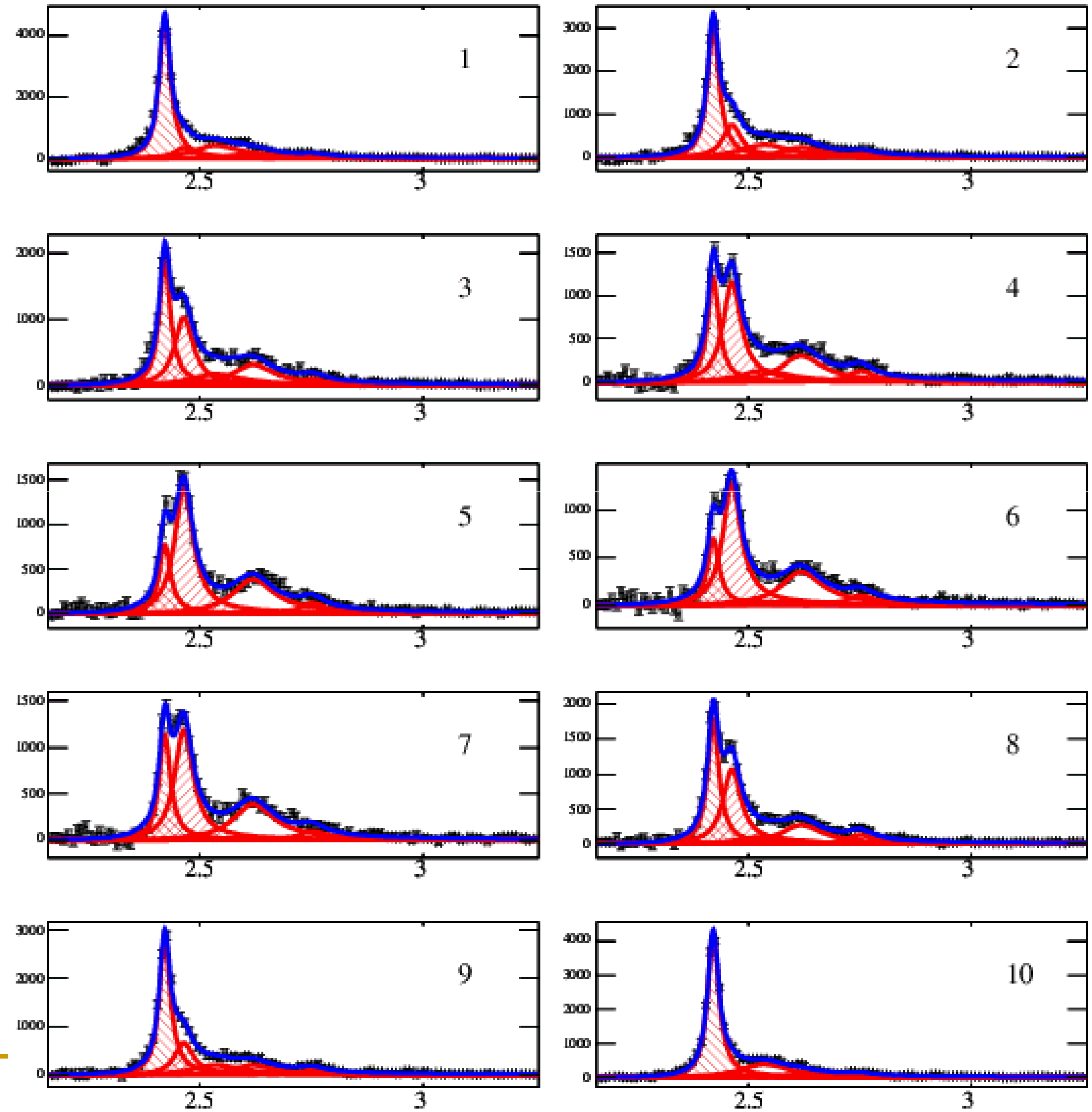
- The complimentary fit with $|\cos\theta_H|<0.5$ is performed.
- In this fit the signals with natural spin-parity are enhanced.





Extraction of the helicity distributions:

- The Data is now divided in bins of 0.2 as a function of the helicity angle.
- A fit is performed in each bin while fixing the mass and width parameters to their final values.
- Only the yield for each signal is allowed to float.



Summary of parameters

TABLE I: Summary of the results. The first errors are statistical and the second are systematic; "fixed" indicates the parameters were fixed to the values from Fit A or C. The significance is defined as the yield divided by the total error.

Resonance	Channel(Fit)	Efficiency (%)	Yield (x10^3)	Mass MeV/c^2	Width MeV/c^2	Significance
$D_1(2420)^0$	$D^{*+}\pi^-$ (C)		50.4±0.9±1.3	2420.1±0.1±0.8	31.0±0.6±1.1	
	$D^{*+}\pi^-$ (E)	1.09 ± 0.03	108.4±0.9±2.2	2420.1(fixed)	31.0(fixed)	
$D_2^*(2460)^0$	$D^+\pi^-$ (A)	1.29 ± 0.03	242.8±1.8±3.4	2462.2±0.1±0.8	50.5±0.6±0.7	
	$D^{*+}\pi^-$ (E)	1.11 ± 0.04	73.3±1.6±4.6	2462.2(fixed)	50.5(fixed)	
$D(2550)^0$	$D^{*+}\pi^-$ (C)		17.4±4.5±5.6	2533.0±5.5±8.3	128±20±13	2.4σ
	$D^{*+}\pi^-$ (E)	1.14 ± 0.04	47±6±32	2533.0(fixed)	128(fixed)	
$D(2600)^0$	$D^+\pi^-$ (A)	1.35 ± 0.05	26.0±1.4± 6.6	2608.7±2.4±2.5	93±6±13	3.9σ
	$D^{*+}\pi^-$ (D)		31.6±0.9±5.3	2608.7(fixed)	93(fixed)	5.9σ
	$D^{*+}\pi^-$ (E)	1.18 ± 0.05	40±1±13	2608.7(fixed)	93(fixed)	
$D(2750)^0$	$D^{*+}\pi^-$ (E)	1.24 ± 0.07	14.5±1.8±3.3	2747.7±2.5±4.5	84±9±11	3.8σ
$D(2760)^0$	$D^+\pi^-$ (A)	1.41 ± 0.09	11.3±0.8±1.0	2763.3±2.3±2.3	60.9±5.1±3.6	8.9σ
$D_2^*(2460)^+$	$D^0\pi^+$ (B)		110.8±1.3±7.5	2465.4±0.2±1.1	50.5(fixed)	
$D(2600)^+$	$D^0\pi^+$ (B)		13.0±1.3±4.5	2621.3±3.7±4.2	93(fixed)	2.8σ
$D(2760)^+$	$D^0\pi^+$ (B)		5.7±0.7±1.5	2769.7±3.8±1.5	60.9(fixed)	3.5σ