Charm Spectroscopy from *B* factories

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Production of Charm Mesons at B-factories

- *B* factories produce charm mesons directly from $c\bar{c}$ hadronization or from decays of *B* mesons.

Inclusive Production: $e^+e^- \rightarrow c\bar{c} \rightarrow D_{(s)}^{**}\ X$

Exclusive Production: $e^+e^- \rightarrow b\bar{b} \rightarrow B\bar{B},\quad B \rightarrow D_{(s)}^{**}\ X$

where $D_{(s)}^{**}$ can be some excited charm meson.

$\mathcal{L}$ ~ 550 fb^{-1}

→~700 Million $c\bar{c}$

→~550 Million $b\bar{b}$

BELLE

$\mathcal{L}$ ~ 1000 fb^{-1}

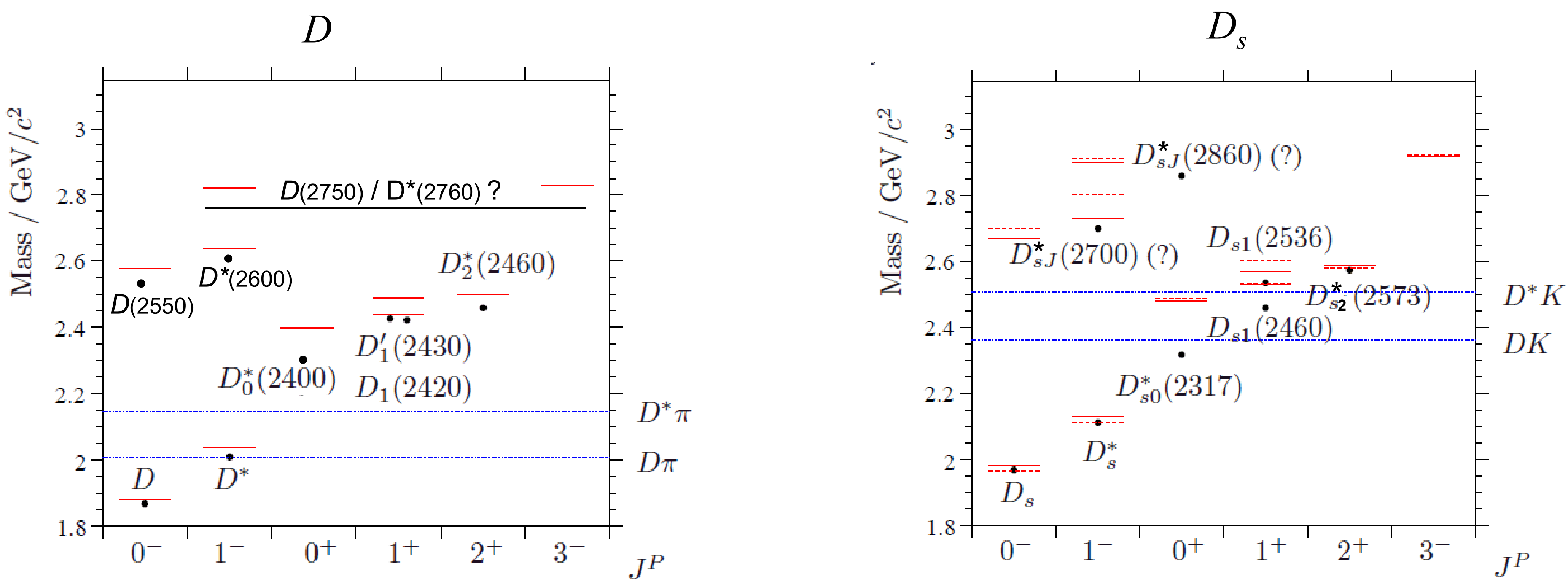
→~1300 Million $c\bar{c}$

→~1000 Million $b\bar{b}$

$e^+e^- \rightarrow$	Cross-section (nb)
$b\bar{b}$	1.05
$c\bar{c}$	1.30
$s\bar{s}$	0.35
$u\bar{u}$	1.39
$d\bar{d}$	0.35
$\tau^+\tau^-$	0.94
$\mu^+\mu^-$	1.16
e^+e^-	~ 40

Predictions for the *D* and D_s states

- Predictions of the *D* and D_s mass eigenstates were performed since 1985 using QCD potential models.
- Recently (2001) the D_s spectrum predictions have been updated.
- The predicted masses of the excited states are generally in qualitative agreement with observations, however, for some states large quantitative differences exist.



— [S. Godfrey and N. Isgur PRD **32**, 189 (1985)] ---- [M. Di Pierro, E. Eichten, PRD **64**, 114004 (2001)]

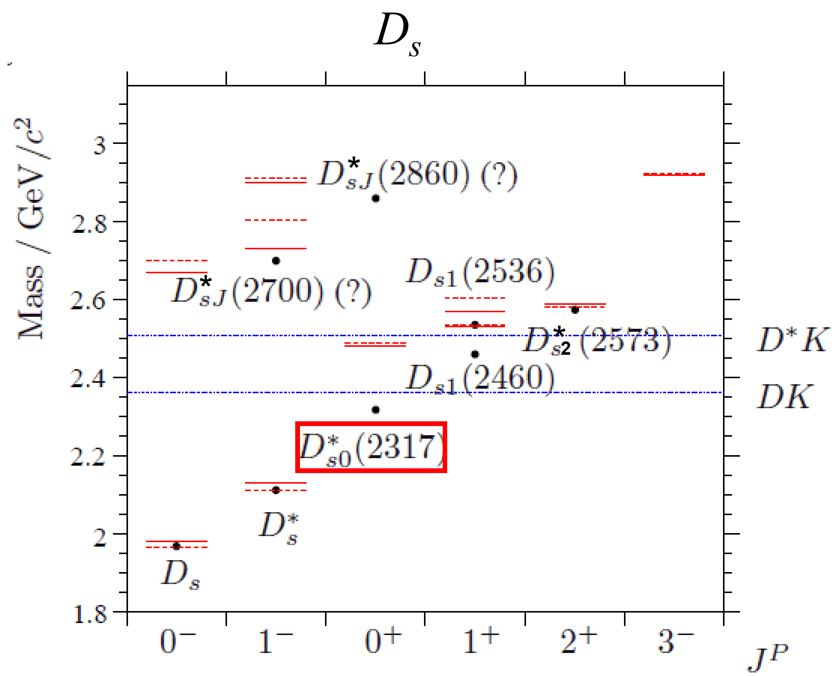
The History

First observations:

D			D_s		
$1^1S_0 : D$	Mark I	1975	$1^1S_0 : D_s$	CLEO	1983
$1^3S_1 : D^*$	Mark I	1977	$1^3S_1 : D_s^*$	TPC	1984
1^3P_1: $D_1(2420)$	ARGUS	1986	1^1P_1: $D_{s1}(2536)$	ARGUS	1989
1^3P_2: $D_2^*(2460)$	TPS	1989	1^3P_2: $D_{s2}^*(2573)$	CLEO2	1994
1^3P_0: $D_0^*(2400)$	BELLE	2004	1^3P_1: $D_{s1}(2460)$	CLEO2	2003
1^1P_1: $D_1(2430)$	BELLE	2004	1^3P_0: $D_{s0}^*(2317)$	BaBar	2003
2^1S_0: $D(2550)$	BaBar	2010	2^3S_1: $D_s^*(2710)$	BaBar	2006
2^3S_1: $D^*(2600)$	BaBar	2010	$1^?D_?$: $D_s^*(2860)$	BaBar	2006
$1^?D_?$: $D(2750)$	BaBar	2010	$??_?$: $D_s(3040)$	BaBar	2009
$1^?D_?$: $D^*(2760)$	BaBar	2010			

Recent studies of these states will be presented in this talk.

The $D_{s0}^{*}(2317)$



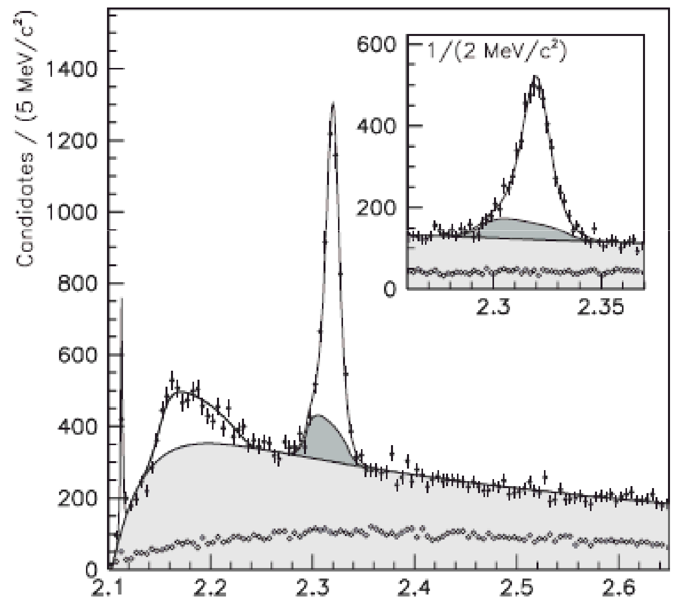
D_s
Mass / GeV / c^2
3
2.8
2.6
2.4
2.2
2
1.8
$D_{sJ}^*(2860)$ (?)
$D_{sJ}^*(2700)$ (?)
$D_{s1}(2536)$
$D_{s2}^*(2573)$
$D_{s1}(2460)$
$D_{s0}^*(2317)$
D_s^*
D_s
D^*K
DK
0^- 1^- 0^+ 1^+ 2^+ 3^-
J^P

The $D_{s0}^*(2317)$

- In an inclusive study of the $D_s\pi^0$ system BaBar discovered the narrow $D_{s0}^*(2317)$ state (2003) [***BaBar 91 fb-1*** *Phys. Rev. Lett.* ***90****, 242001 (2003)].*

- The low unexpected mass of this state triggered many subsequent studies by both BaBar and BELLE including the following:
  - *$B \to D_{s0}^*(2317)$ D*
    [**BELLE ~110 fb^{-1}** Phys. Rev. Lett. 91, 262002 (2003)]
  - *$D_{s0}^*(2317) \to D_s\pi^0$* inclusive
    [**BELLE 87 fb^{-1}** Phys. Rev. Lett. 92, 012002 (2004)]
  - *$B \to D_{s0}^*(2317)$ $D^{(*)}$*
    [**BaBar 113 fb^{-1}** Phys. Rev. Lett. 93, 181801 (2004)]
  - *$B \to D_{s0}^*(2317)$ K*
    [**BELLE 140 fb^{-1}** Phys. Rev. Lett. 94, 061802 (2005)]

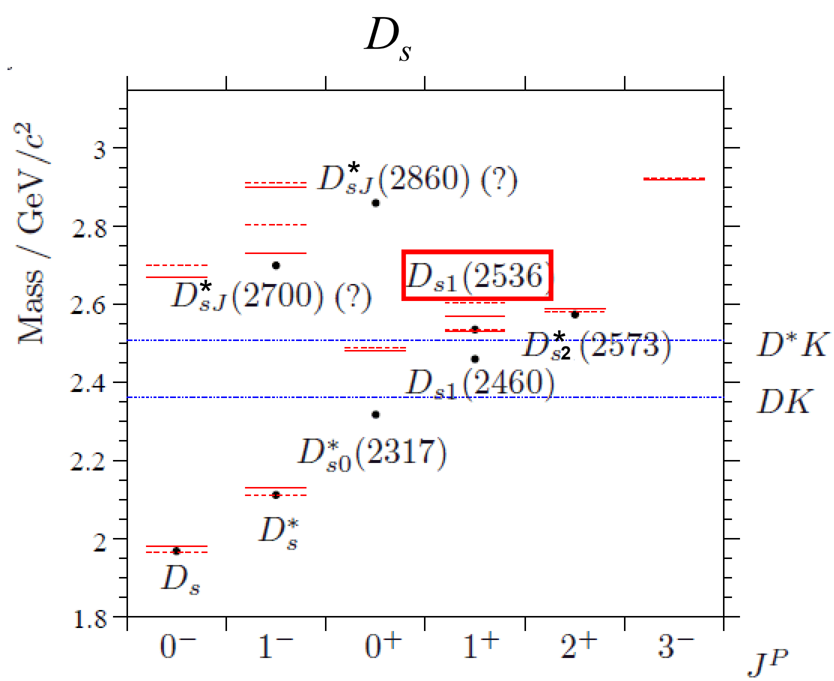
Inclusive $D_{s0}^*(2317) \to D_s\pi^0$



$m(D_s\pi^0)$ (GeV/c^2)

[***BaBar 232 fb-1***
Phys. Rev. D ***72****, 032007 (2006)*]

Precision $D_{s1}(2536)$ Parameters



Precision $D_{s1}(2536)$ Parameters

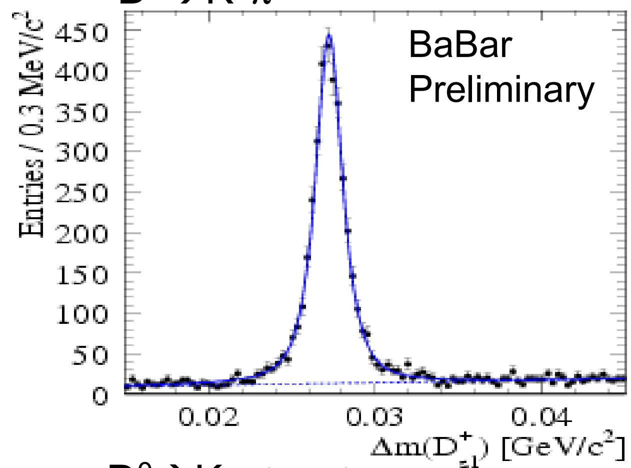
- Preliminary BaBar analysis using 384 fb^{-1} [presented at ICHEP 2010].
- Inclusive reconstruction of
  $D_{s1}(2536)^{+} \rightarrow D^{*+}K_S$
  where $D^{*+} \rightarrow D^0\pi^+$ and $D^0 \rightarrow K^-\pi^+$ or $K^-\pi^+\pi^-\pi^+$
- Parameters determined from the mass difference
  $\Delta m = m(D^*K_S) - m(D^*) - m(K_S)$
  resolution is about 0.26 MeV.
- Preliminary results:

$$m(D_{s1}^{+}) = (2535.10 \pm 0.01 \pm 0.18)\,\mathrm{MeV}/c^2$$

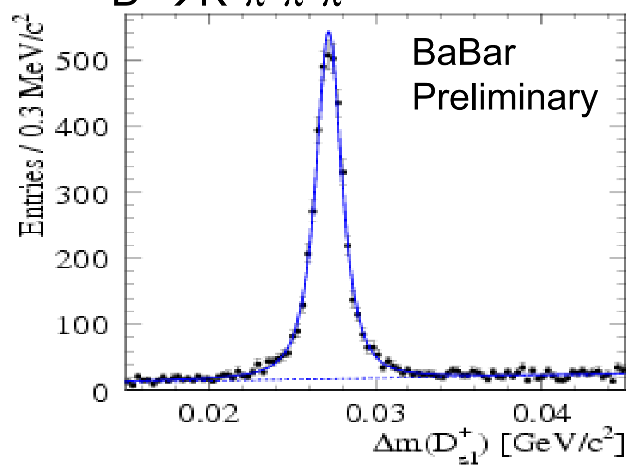
$$\Gamma(D_{s1}^{+}) = (0.92 \pm 0.03 \pm 0.04)\,\mathrm{MeV}$$

- This is the first measurement of the $D_{s1}(2536)$ width.

$D^0 \rightarrow K^-\pi^+$



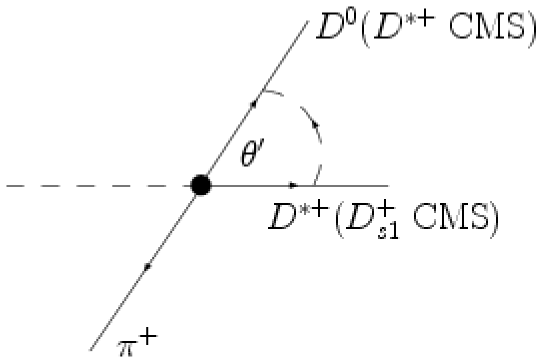
$D^0 \rightarrow K^-\pi^+\pi^-\pi^+$

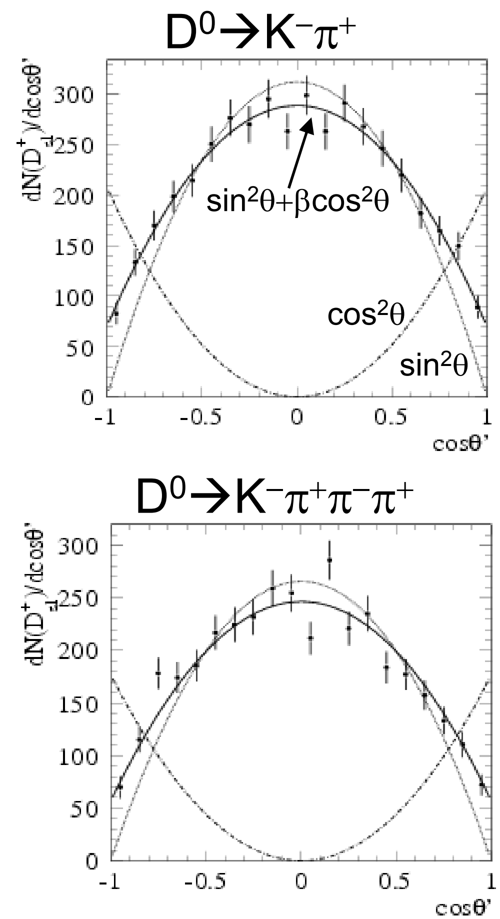


$D_{s1}(2536)$ Angular Analysis

BaBar Preliminary

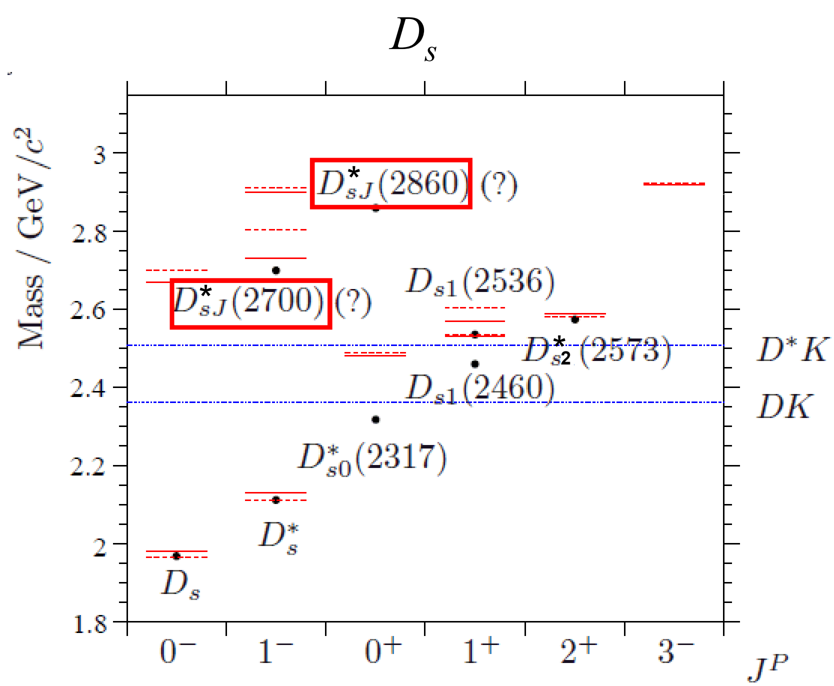
- Signal yield is extracted as a function of the helicity angle θ'.
- Angular distribution indicates un-natural spin-parity.
- Significant *D*-wave contribution is present in the decay.





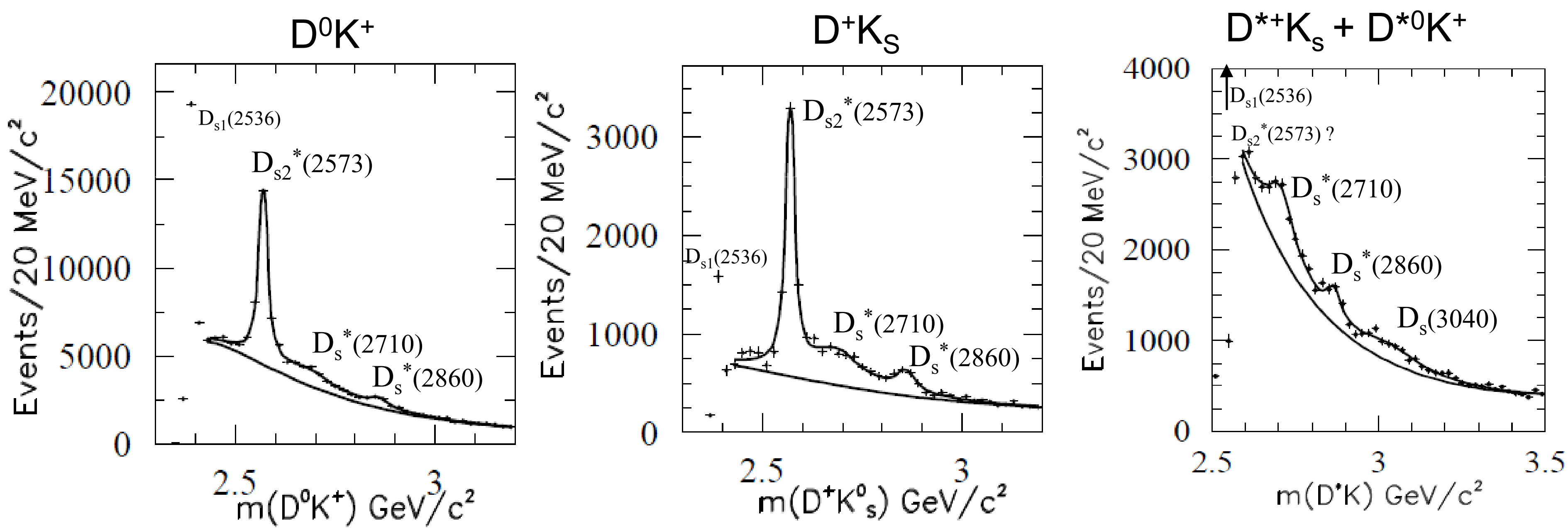
J^P	$dN/d\cos\theta'$	$\chi^2/NDF(K4\pi)$	$\chi^2/NDF(K6\pi)$
0^+	forbidden	–	–
0^-	$\propto \cos^2\theta'$	2142.7/19	2440.8/19
$1^-, 2^+, 3^-, \ldots$	$\propto \sin^2\theta'$	103.2/19	108.8/19
$1^+, 2^-, 3^+, \ldots$ (*S*-wave only)	const	392.1/19	425.1/19
$1^+, 2^-, 3^+, \ldots$ (*S*-, *D*-wave)	$\propto (\sin^2\theta' + \beta\cos^2\theta')$	24.9/18 ($\beta = 0.23 \pm 0.03$)	9.5/18 ($\beta = 0.24 \pm 0.03$)

Inclusive Study of *DK* and *D***K* Systems



Inclusive Study of *DK* and *D*K* Systems

- The following channels have been analyzed:
  - D^0K^+ using $D^0 \to K^-\pi^+$
  - D^+K_S using $D^+ \to K^-\pi^+\pi^+$
  - $D^{*+}K_S$ using $D^{*+} \to D^0\pi^+$, $D^+\pi^0$ ($D \to K^-\pi^+$, $K^-\pi^+\pi^-,\pi^+$, $D^+ \to K^-\pi^+\pi^+$)
  - $D^{*0}K^+$ using $D^{*0} \to D^0\pi^0$ ($D^0 \to K^-\pi^+$)



[**BABAR (470 fb^{-1})** *Phys. Rev. D* ***80****, 092003 (2009)*]

- $D_s^*(2710)$ confirmed by BELLE using $B^+ \to D^0D^0K^+$ [**BELLE 414 fb^{-1}** Phys.Rev.Lett.100, 092001 (2008)].

Parameters of D_{sJ} Structures

- The mass values of the $D_s^*(2710)$ and $D_s^*(2860)$ are close to those of the first radial excitation of the D_s^* and L=2 excited states, respectively.
- The mass of the $D_s(3040)$ is close to that of the second radial excitation predicted in Ref. *[T. Matsuki etal., Eur. Phys. J. A 31, 701 (2007)]*
- The ratios of the D*K over DK branching fractions have been determined.
- For the $D_s^*(2710)$ the ratio is consistent with the value predicted for the first radial excitation. *[P. Colangelo etal., Phys.Rev. D 77, 014012 (2008)]*

$$m(D_{s1}^*(2710)^+) = 2710 \pm 2_{\rm stat}(^{+12}_{-7})_{\rm syst}\ {\rm MeV}/c^2,$$
$$\Gamma = 149 \pm 7_{\rm stat}(^{+39}_{-52})_{\rm syst}\ {\rm MeV},$$

$$m(D_{sJ}^*(2860)^+) = 2862 \pm 2_{\rm stat}(^{+5}_{-2})_{\rm syst}\ {\rm MeV}/c^2,$$
$$\Gamma = 48 \pm 3_{\rm stat} \pm 6_{\rm syst}\ {\rm MeV},$$

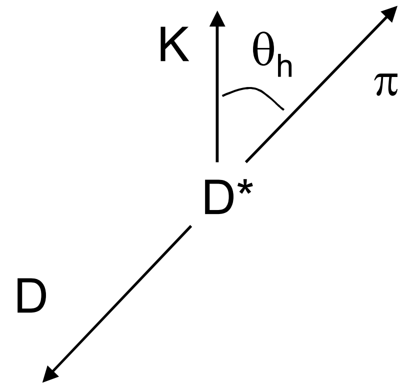
$$m(D_{sJ}(3040)) = 3044 \pm 8_{\rm stat}(^{+30}_{-5})_{\rm syst}\ {\rm MeV}/c^2,$$
$$\Gamma = 239 \pm 35_{\rm stat}(^{+46}_{-42})_{\rm syst}\ {\rm MeV}.$$

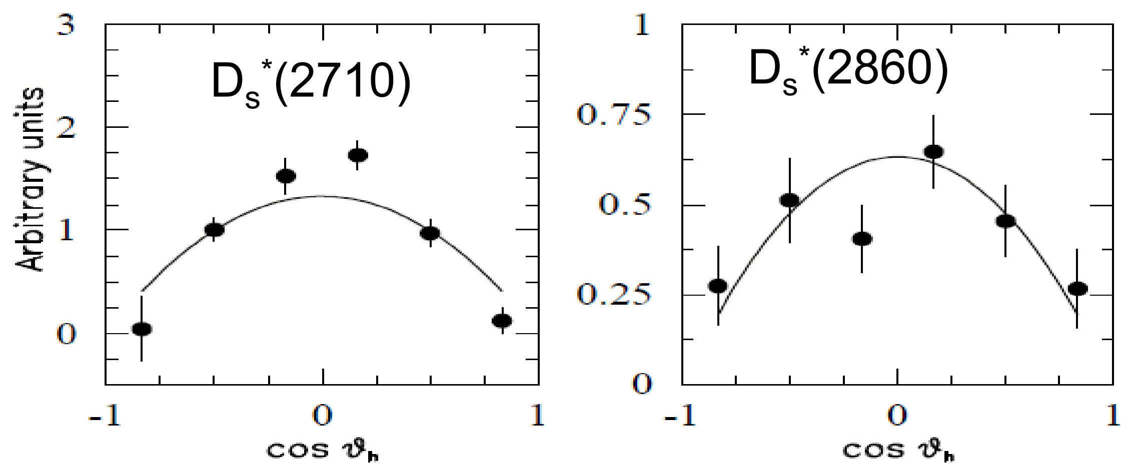
$$\frac{\mathcal{B}(D_{s1}^*(2710)^+ \to D^*K)}{\mathcal{B}(D_{s1}^*(2710)^+ \to DK)} = 0.91 \pm 0.13_{\rm stat} \pm 0.12_{\rm syst},$$

$$\frac{\mathcal{B}(D_{sJ}^*(2860)^+ \to D^*K)}{\mathcal{B}(D_{sJ}^*(2860)^+ \to DK)} = 1.10 \pm 0.15_{\rm stat} \pm 0.19_{\rm syst}.$$

Angular Analysis of the D^*K System

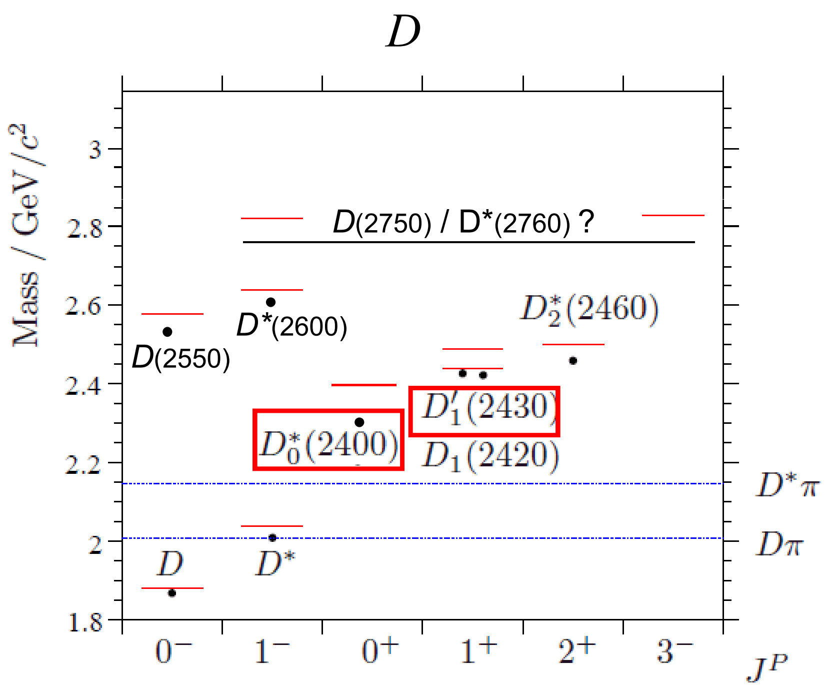
- The helicity angle θ_h defined by the Kaon and pion provides information about the quantum numbers of the resonances.
- For both the $D_s^*(2710)$ and $D_s^*(2860)$, the angular distribution is consistent with natural spin-parity.
- For the $D_s(3040)$ the angular distribution is not conclusive.





[**BABAR (470 fb^{-1})** *Phys. Rev. D **80**, 092003 (2009)*]

Exclusive Studies of Broad D States

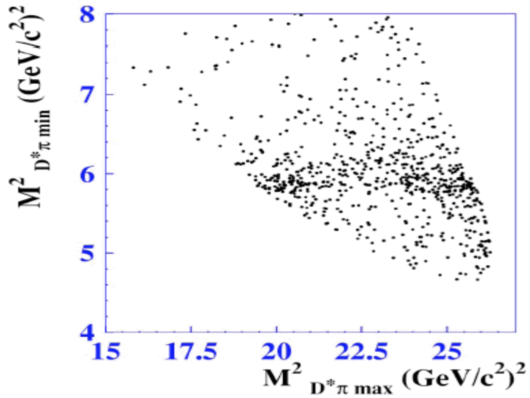


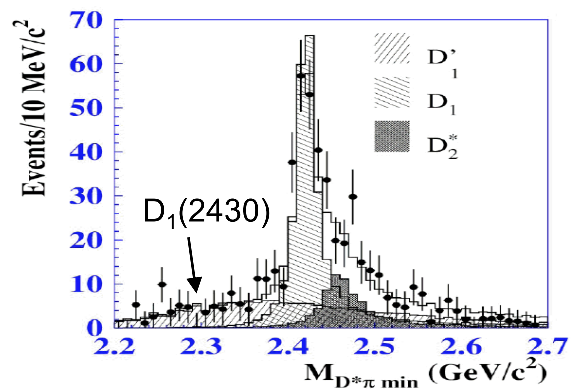
Exclusive Studies of Broad D States

- Parameters of the $D_1(2430)$ determined from a Dalitz plot analysis of $B^+ \to D^{*-}\pi^+\pi^+$:

$$M_{D'^0_1} = 2427 \pm 26 \pm 20 \pm 15 \ \text{MeV}/c^2,$$

$$\Gamma_{D'^0_1} = 384^{+107}_{-75} \pm 24 \pm 70 \ \text{MeV}.$$



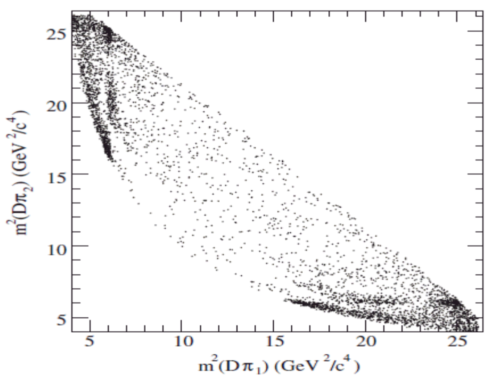


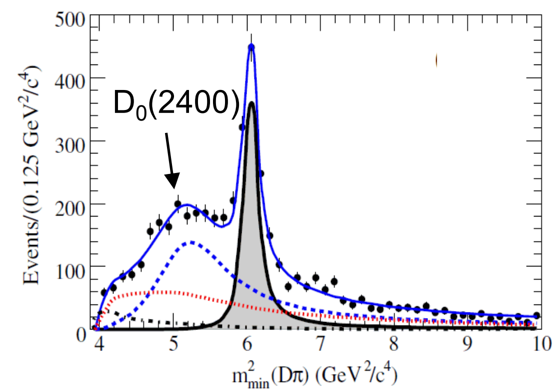
[***BELLE 60 fb***$^{-1}$ *Phys. Rev. D* ***69****, 112002 (2004)*]

- The $D_0^*(2400)$ was confirmed by BaBar and its parameters determined from a Dalitz plot analysis of $B^+ \to D^-\pi^+\pi^+$:

$$m_{D_0^{*0}} = (2297 \pm 8 \pm 5 \pm 19) \ \text{MeV}/c^2$$

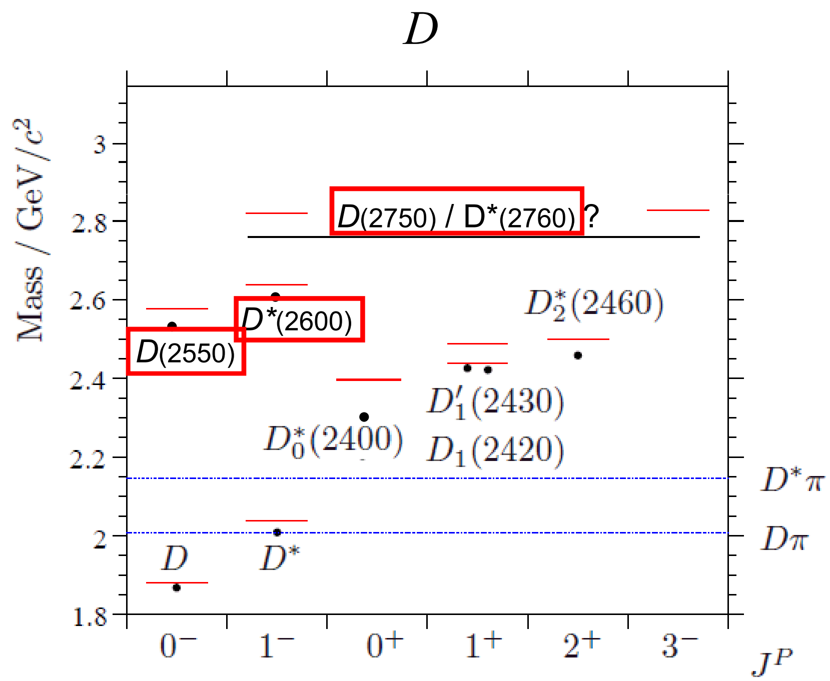
$$\Gamma_{D_0^{*0}} = (273 \pm 12 \pm 17 \pm 45) \ \text{MeV},$$





[***BaBar 350 fb***$^{-1}$ *Phys. Rev. D 79, 112004 (2009)*]

Inclusive Study of Dπ and D*π

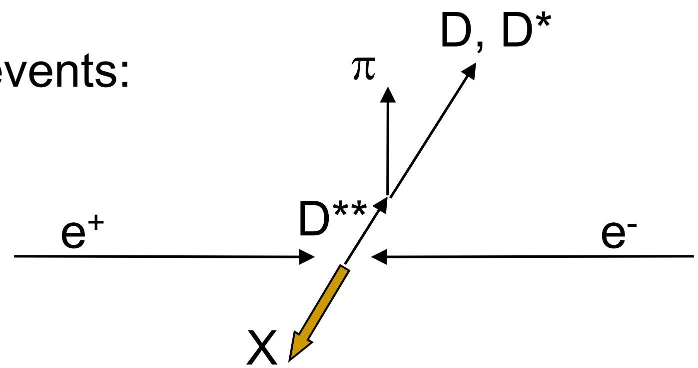


Inclusive Study of Dπ and D*π

- Analysis of Dπ and D*π systems produced from $c\bar{c}$ events:

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

  X represents any additional system.



- The following channels are reconstructed:

  - $D^{**0} \to D^+\pi^-$, $\llcorner K^-\pi^+\pi^+$
  - $D^{**+} \to D^0\pi^+$, $\llcorner K^-\pi^+$
  - $D^{**0} \to D^{*+}\pi^-$, $\llcorner D^0\pi^+$, $\llcorner K^-\pi^+ \text{ or } K^-\pi^+\pi^-\pi^+$

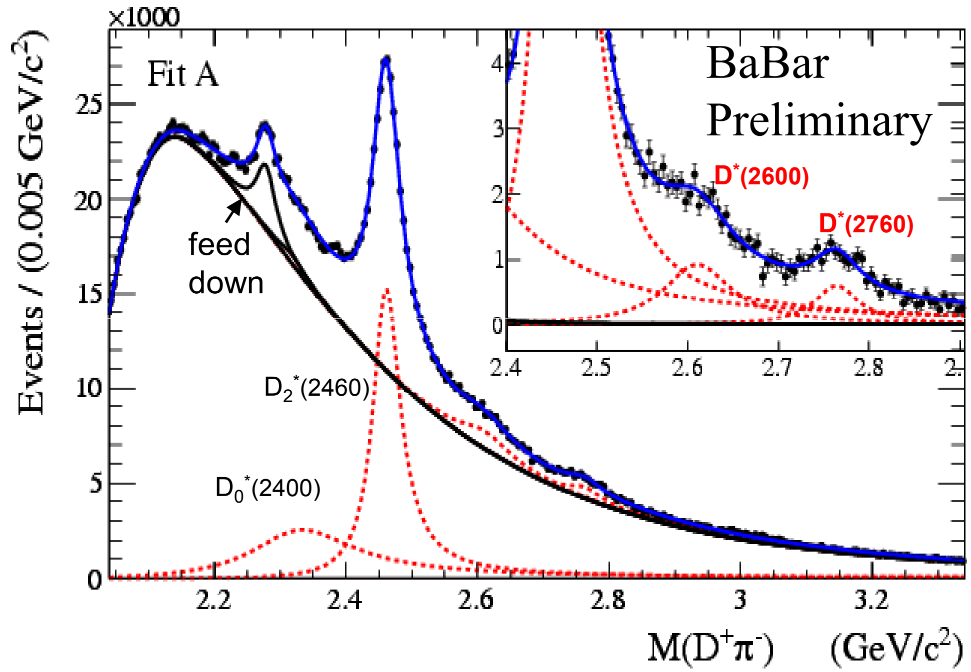
• The data set corresponds to about **10 times** more signal events than the previous study by the CDF collaboration.

[**BABAR (454 fb^{-1})** *arXiv:1009.2076, submitted to PRD-RC (2010)*]

The $D^+\pi^-$ System

BaBar Preliminary

- The mass distribution of the $D^+\pi^-$ final state presents a prominent signal from the $D_2^*(2460)$ as well as two new structures at 2.60 GeV and 2.76 GeV.
- The peaking background at 2.30 GeV is due to $D_2^*(2460)$ and $D_1(2420)$ decaying to $D^*\pi$ where the slow pion is missing.
- The broad $D_0^*(2400)$ improves the fit quality, its parameters are floated within 2σ from the known values.
- The χ^2/NDF of the fit is 281/242.

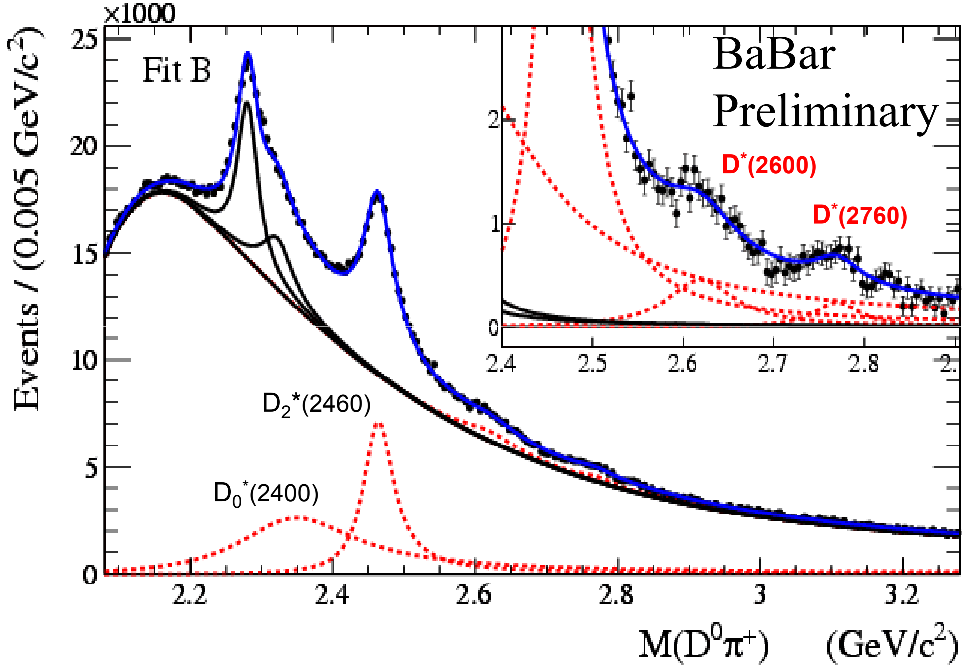


[**BABAR (454 fb^{-1})**
arXiv:1009.2076, submitted to PRD-RC (2010)]

The $D^0\pi^+$ System

BaBar Preliminary

- To confirm the new signals, the $D^0\pi^+$ system is analyzed.
- In this channel the feed-down backgrounds are stronger and the signal statistics of this are smaller so the widths of all signals are fixed to the widths measured in the $D^+\pi^-$.
- The mass values obtained are a few MeV higher than in $D^+\pi^-$, consistent with being the isospin partners.
- The fit quality is χ^2/NDF=278/224.

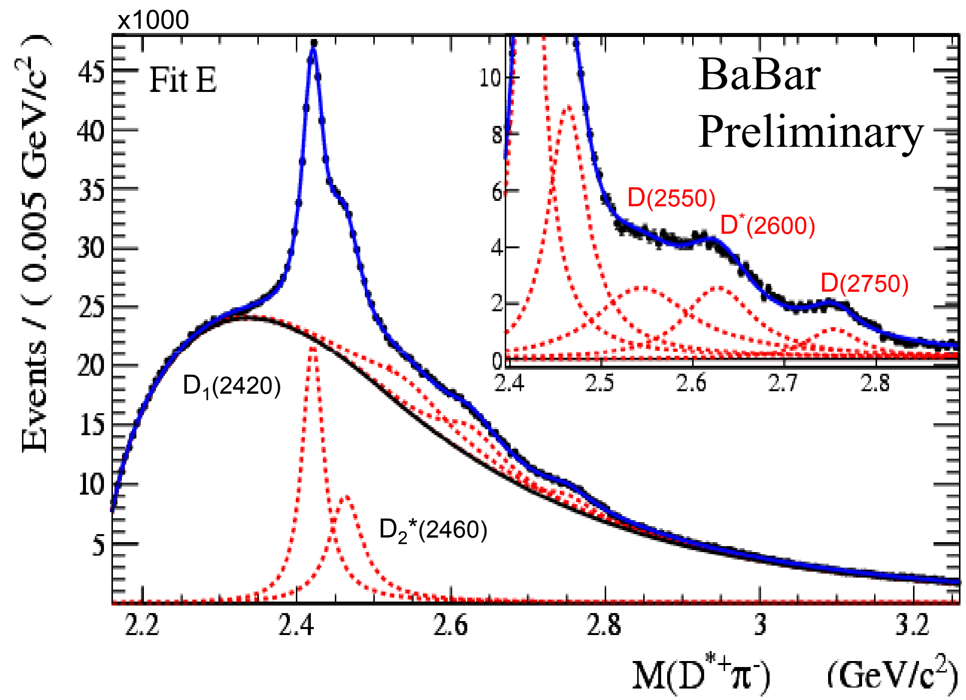


[BABAR (454 fb^{-1})
arXiv:1009.2076, submitted to PRD-RC (2010)]

The $D^{*+}\pi^-$ System

BaBar Preliminary

- The $D^*\pi$ system shows prominent signals of $D_1(2420)$ and $D_2^*(2460)$.
- In addition, there are new structures in the higher mass region. The region at 2.60 GeV is populated by two signals, while at 2.75 GeV there is a signal similar to the $D^*(2760)$ from $D^+\pi^-$.
- The parameters of the $D_2^*(2460)$ and $D^*(2600)$ are fixed to the ones from the $D^+\pi^-$.
- The fit quality is χ^2/NDF=244/207.

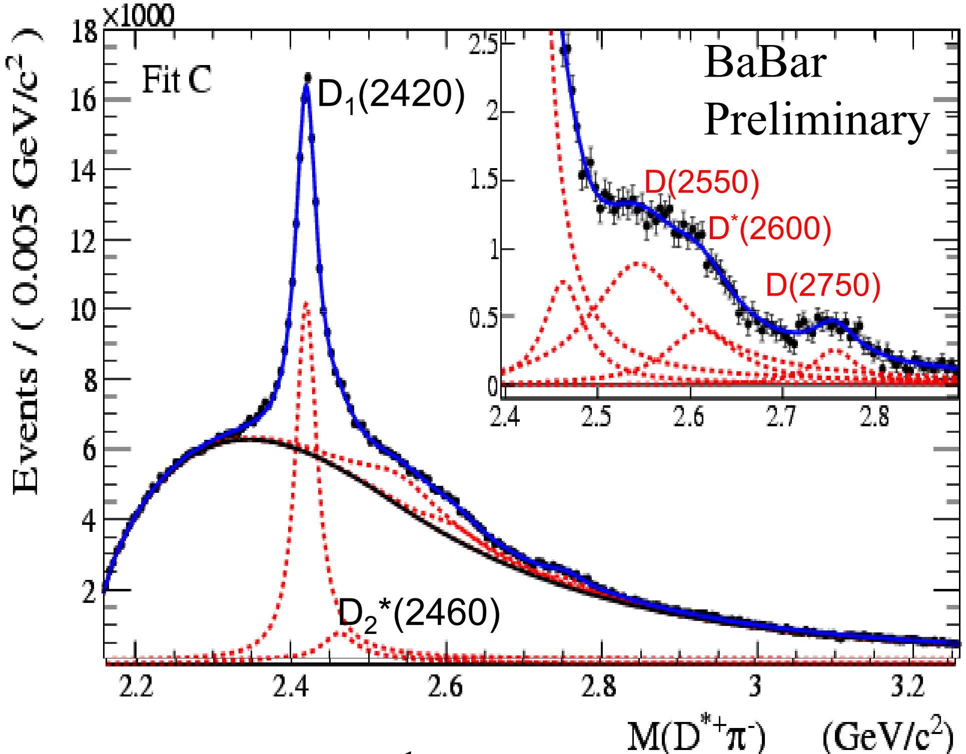


[BABAR (454 fb^{-1})
arXiv:1009.2076, submitted to PRD-RC (2010)]

$D^{*+}\pi^{-}$ with $|\cos\theta_H| > 0.75$

BaBar Preliminary

- The selection $|\cos(\theta_H)|>0.75$ is applied to suppress the resonances with natural spin-parity ($dN/d\cos\theta_H \sim \sin^2\theta_H$).
- This fit allows to determine the parameters of the D(2550) under the assumption that the $D^*(2600)$ is the same signal observed in $D^+\pi^-$.
- The parameters of the $D_2^*(2460)$ and $D^*(2600)$ are fixed to the values from $D^+\pi^-$.
- This fit also determines the parameters of the $D_1(2420)$.
- The fit quality is χ^2/NDF=214/205.

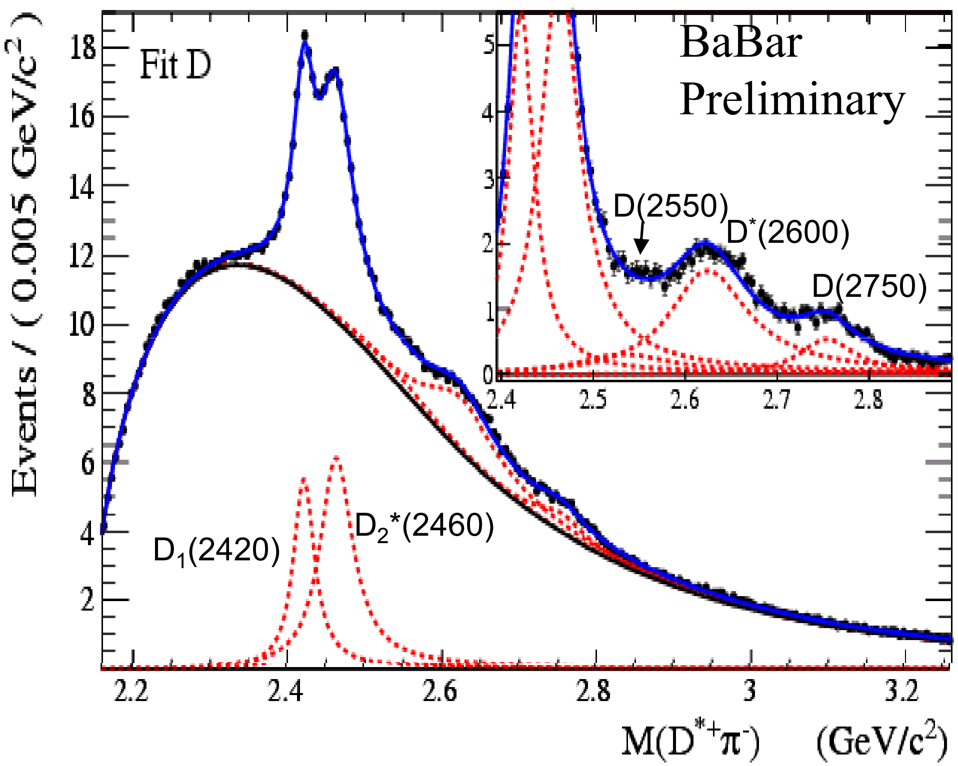


[BABAR (454 fb^{-1})
arXiv:1009.2076, submitted to PRD-RC (2010)]

$D^{*+}\pi^{-}$ with $|\cos\theta_H|<0.5$

BaBar Preliminary

- The selection $|\cos\theta_H|<0.5$ is applied to favor the resonances with natural spin-parity.
- In this fit, the parameters of all signals, except the D(2750), are fixed to the values from the previous fits.
- This fit allows to observe clearly the $D^*(2600)$ signal and shows consistency in the fit model.
- The fit quality is χ^2/NDF=210/209.



[BABAR (454 fb^{-1}) *arXiv:1009.2076, submitted to PRD-RC (2010)*]

Resonance Parameters:

BaBar Preliminary

- The uncertainties on most parameters are dominated by systematic uncertainties.
- The systematic uncertainty includes the following sources: bin size and mass range of the histogram, errors on parameters fixed in the fits, Breit-Wigner shape of the new signals, a possible contribution from the $D_1(2430)$, and background modeling.
- The significance of the new signals is estimated from the yield over its total uncertainty.

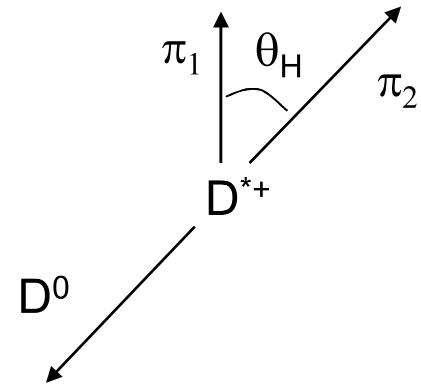
Resonance	Channel(Fit)	Efficiency (%)	Yield (x10^3)	Mass MeV/c^2	Width MeV	Significance
$D_1(2420)^0$	$D^{*+}\pi^-$ (C)		102.8±1.3±2.3	2420.1±0.1±0.8	31.4±0.5±1.3	
	$D^{*+}\pi^-$ (E)	1.09 ± 0.03	214.6±1.2±6.4	2420.1(fixed)	31.4(fixed)	
$D_2^*(2460)^0$	$D^+\pi^-$ (A)	1.29 ± 0.03	242.8±1.8±3.4	2462.2±0.1±0.8	50.5±0.6±0.7	
	$D^{*+}\pi^-$ (E)	1.12 ± 0.04	136±2±13	2462.2(fixed)	50.5(fixed)	
$D(2550)^0$	$D^{*+}\pi^-$ (C)		34.3±6.7±9.2	2539.4±4.5±6.8	130±12±13	3.0σ
	$D^{*+}\pi^-$ (E)	1.14 ± 0.04	98.4±8.2±38	2539.4(fixed)	130(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)		50.2±3.0±6.7	2608.7(fixed)	93(fixed)	7.3σ
	$D^{*+}\pi^-$ (E)	1.18 ± 0.05	71.4±1.7±7.3	2608.7(fixed)	93(fixed)	
$D(2750)^0$	$D^{*+}\pi^-$ (E)	1.23 ± 0.07	23.5±2.1±5.2	2752.4±1.7±2.7	71±6±11	4.2σ
$D^*(2760)^0$	$D^+\pi^-$ (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

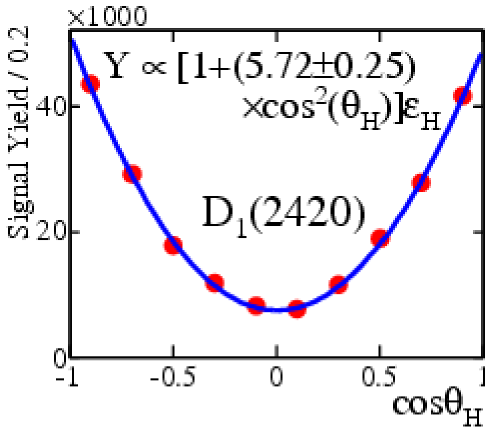
[**BABAR (454 fb^{-1})** *arXiv:1009.2076, submitted to PRD-RC (2010)*]

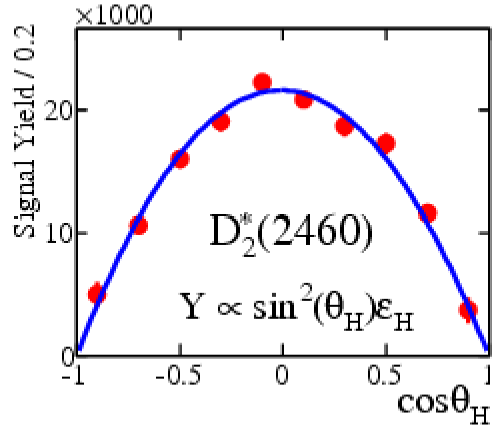
Angular Analysis of $D^{*+}\pi^-$

BaBar Preliminary

- The signal yields have been extracted as a function of $\cos\theta_H$.
- The $D_1(2420)$ shows a $1+A\cos^2\theta_H$ distribution indicating un-natural spin-parity. The value for A indicates a significant S-wave contribution in the decay.
- The $D_2^*(2460)$ shows a $\sin^2\theta_H$ distribution consistent with the natural spin-parity assignment.



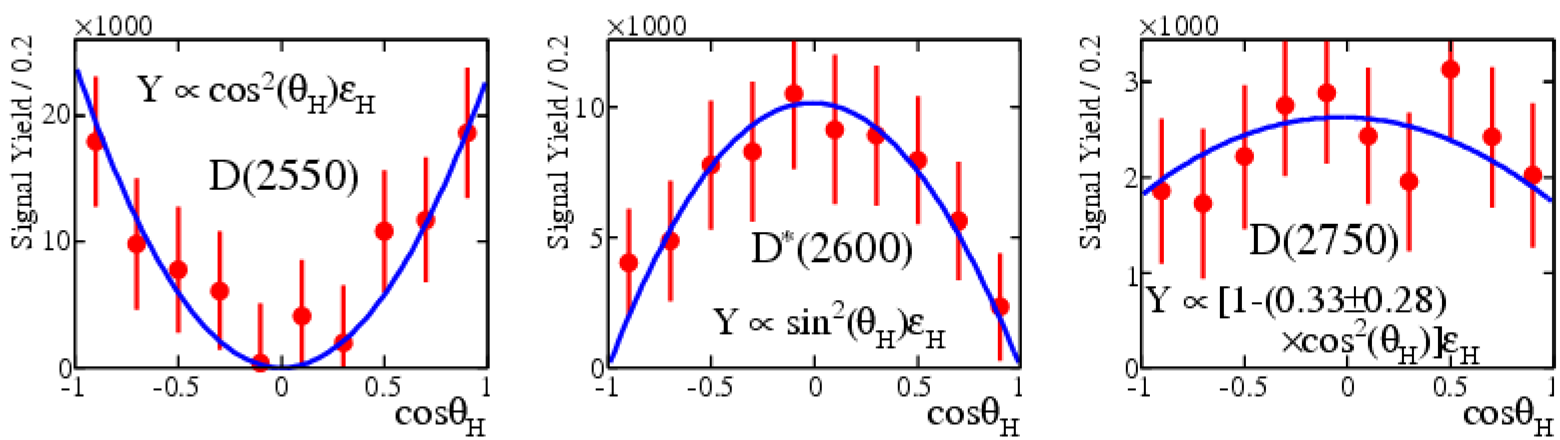




Angular Analysis of $D^{*+}\pi^-$

BaBar Preliminary

- For the signal *D*(2550) a $\cos^2(\theta_H)$ distribution is obtained consistent with a $J^P=0^-$ value.
- For the signal D^*(2600) a $\sin^2(\theta_H)$ distribution is obtained consistent with natural spin-parity.
- For the signal *D*(2750) the interpretation of the distribution is not conclusive.



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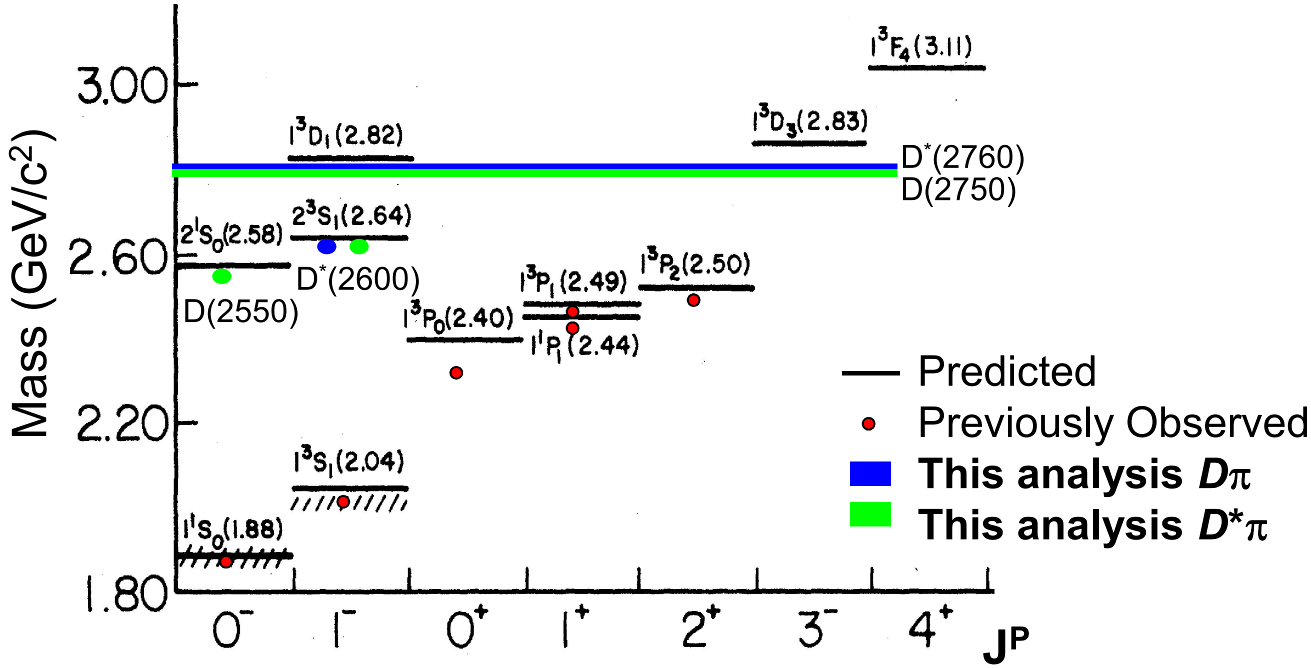
Interpretation of the Dπ and D*π Results

- The $D^{*}(2600)$ signal observed in $D\pi$ and $D^{*}\pi$ has a mass value and helicity distribution consistent with the first radial excitation of the $D^{*}(2010)$.
- Likewise, the $D(2550)$ observed in $D^{*}\pi$ has a mass value and helicity distribution consistent with the first radial excitation of the D^0.
- The $D(2750)$ observed in $D^{*}\pi$ has mass value lower than the $D^{*}(2760)$ observed in $D^{+}\pi^{-}$. The helicity distribution is not conclusive. These two signals may be due to the four L=2 excited states.



Conclusions

- The *B*-factories have large potential for advancing the understanding of the charmed hadron spectrum. In this talk, recent studies of the *D* and D_s mesons have been presented.

- The spectroscopy of charmed mesons has revived in recent years (2009-2010) with the observations by the BaBar of new structures in the *DK*, *D**K*, $D\pi$, and $D^*\pi$ systems. These studies find candidates for the radial and L=2 excited states of the D_s and *D* mesons.

- Precision measurements of the narrow L=1 D_s mesons are possible from the large Data sets. A first measurement of the $D_{s1}(2536)$ decay width has been presented here.

- Charmed mesons obtained from *B* decays allow for the study of the broad L=1 states. However, updated studies of these decays are needed. In particular an analysis of $B^+ \rightarrow D^{*-}\pi^+\pi^+$ might provide much better parameter values for the $D_1(2430)$, and evidence for new the structures observed in the inclusive $D^{(*)}\pi$ analyses.