CHARM MESON SPECTROSCOPY AT

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On behalf of the BaBar Collaboration

BABAR
B AND c-FACTORY

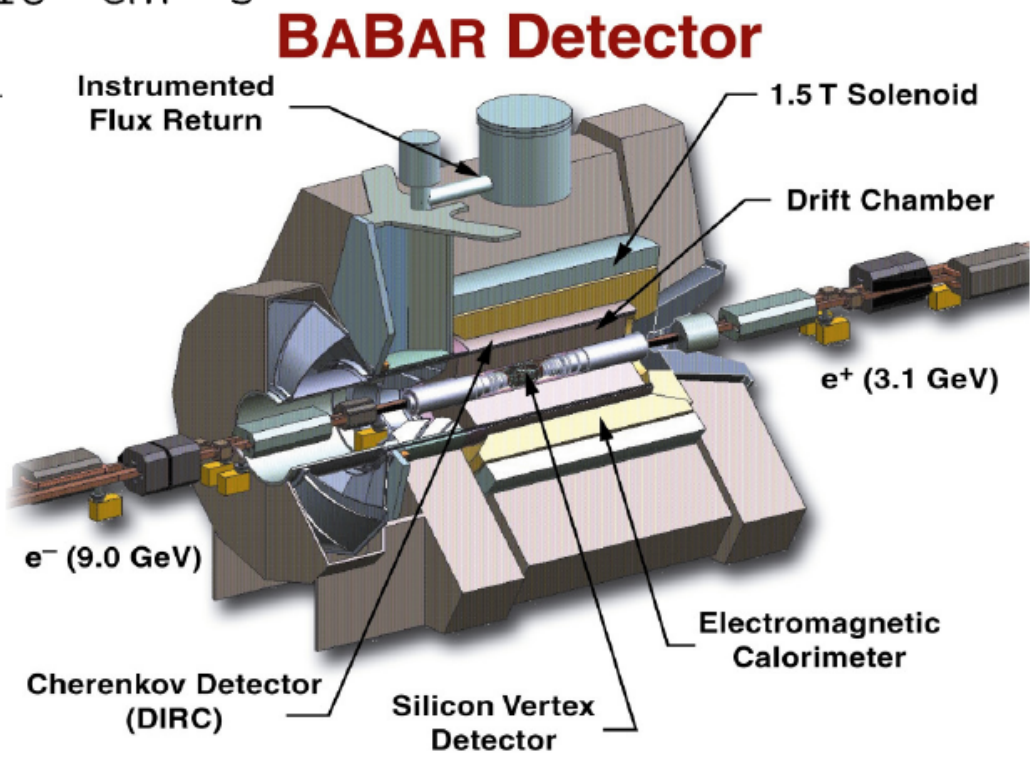
Electron-Positron Collider: PEP-II / SLAC
CM energy 10.58 GeV
Peak Luminosity $1.21 \cdot 10^{34} \mathrm{cm}^{-2}\mathrm{s}^{-2}$
Integrated Luminosity
(10/99-07/07) $447 \mathrm{fb}^{-1}$

$$\sigma(b\bar{b}) = 1.05\mathrm{nb}$$
$$\sigma(c\bar{c}) = 1.30\mathrm{nb}$$

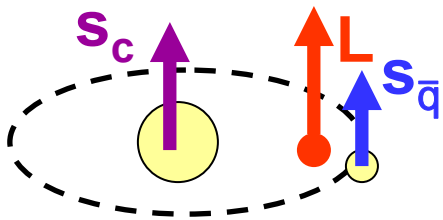
$$\Downarrow$$

$$N(b\bar{b}) = 469 \cdot 10^6$$
$$N(c\bar{c}) = 581 \cdot 10^6$$

Good PID, Tracking and Vertexing



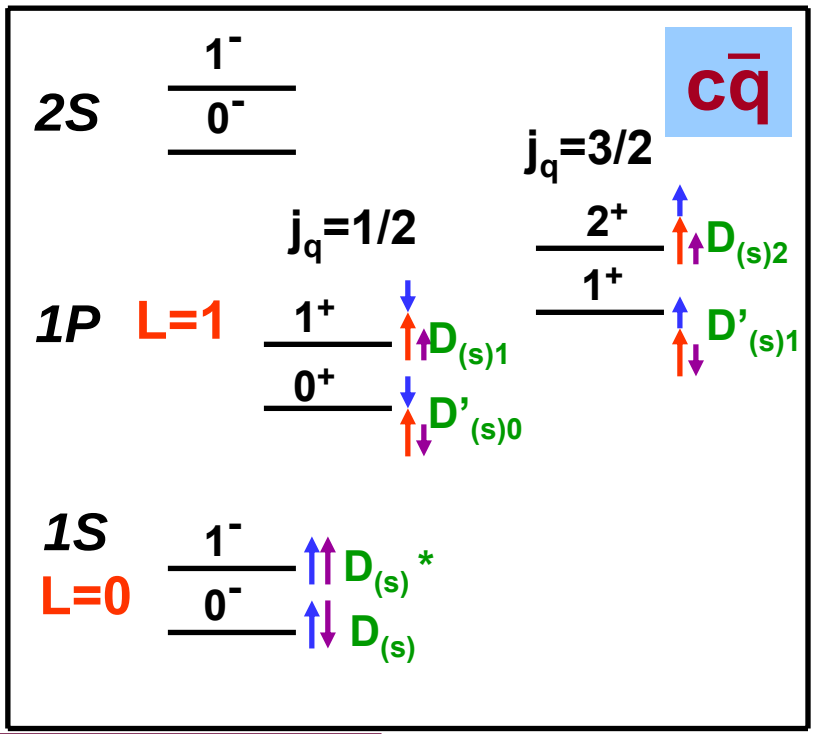
Expected Mass splitting



j_q

$(L\ S_{\bar{q}})\ S_c$

j_q is a good quantum number => separated $D_{(s)}$ meson spin-doublets: (0-,1-), (0+,1+), (1+,2+).

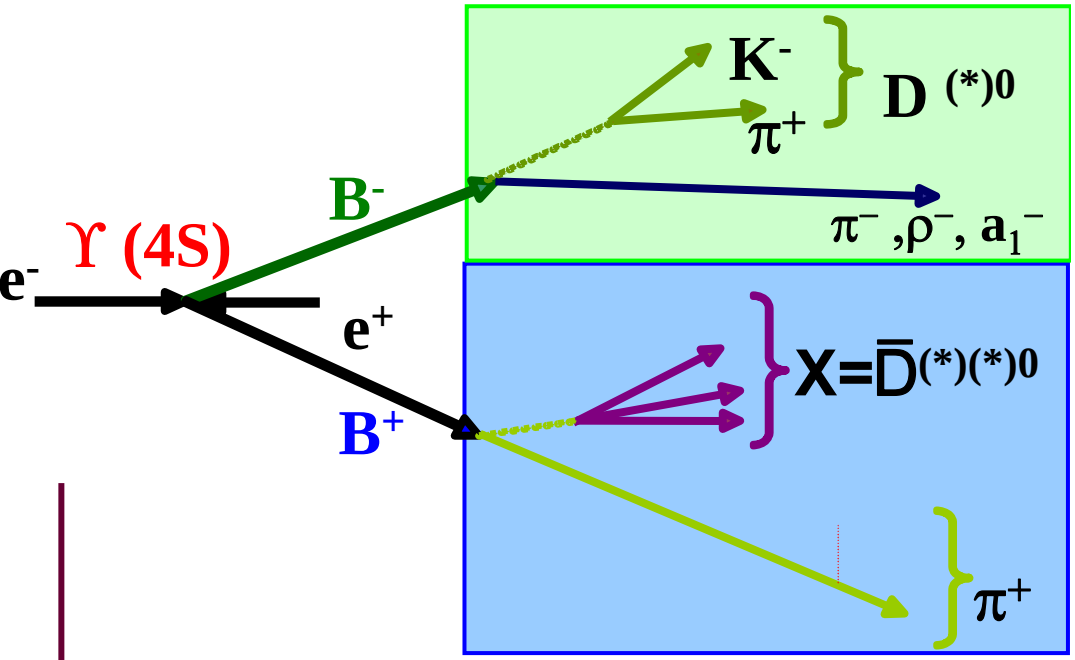


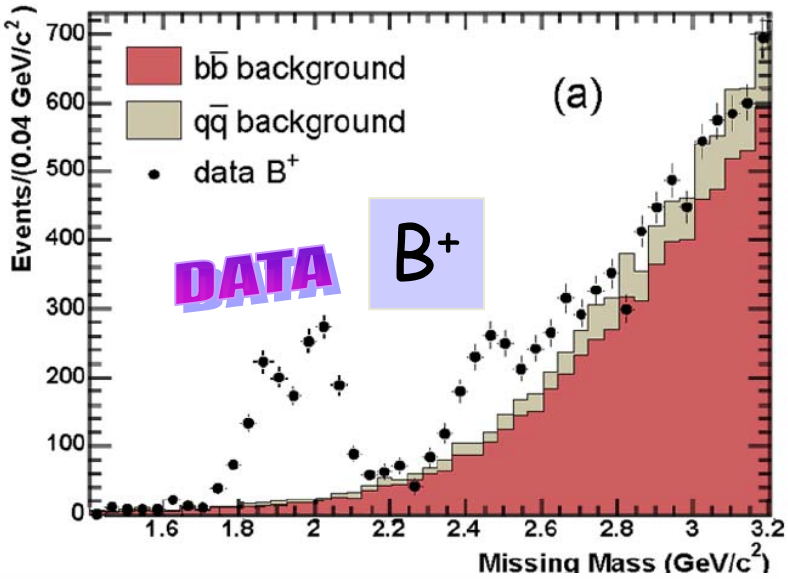
$c\bar{q}$ ($\bar{q}=\bar{u},\bar{d}$) MESONS

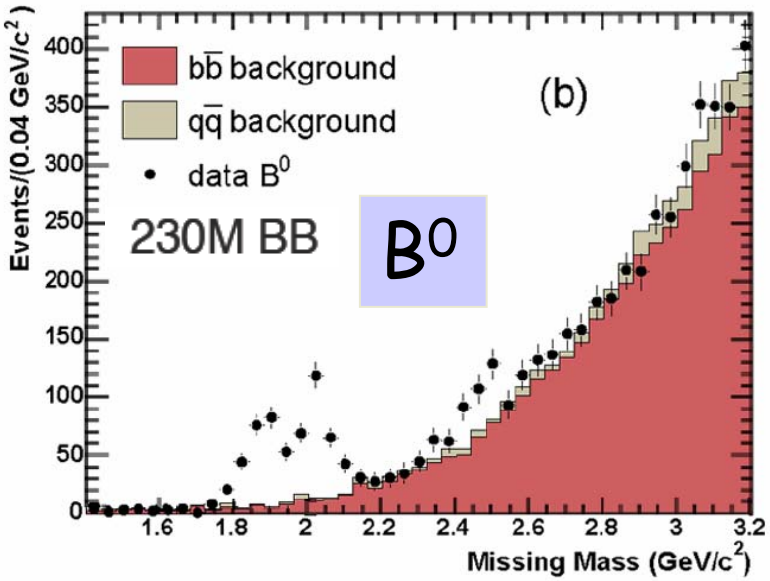
WHAT IS NEW FOR $D^{(*)(*)}$ STATES?

Absolute BF of D $^{(*)(*)}$ with Y(4S) events

1) Reconstruct one B meson fully
2) Reconstruct other B partially: B → π X
3) Deduce invariant mass of X system & plot



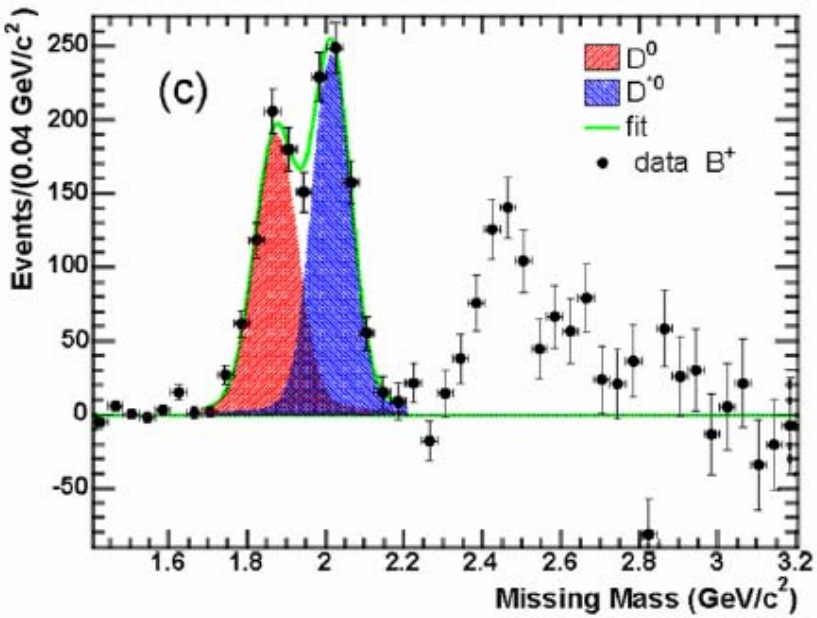


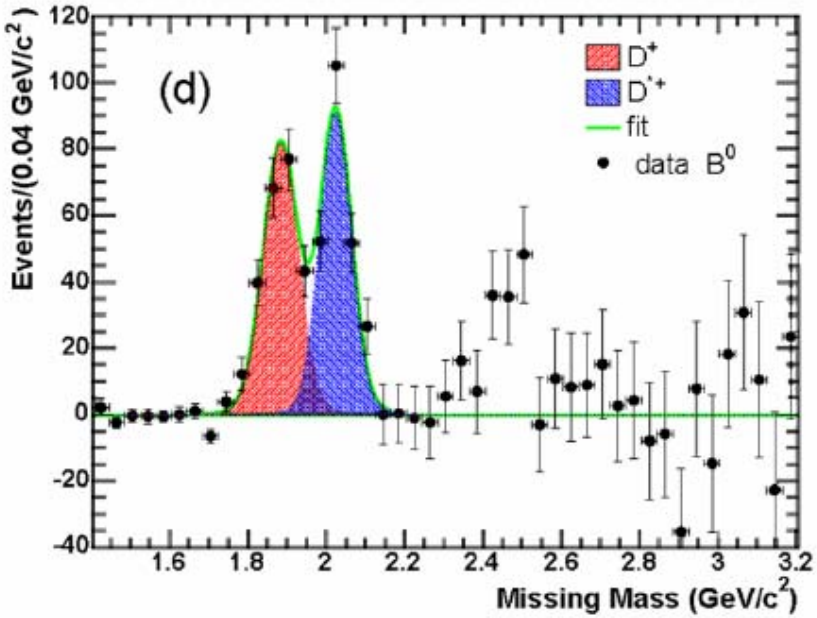


BABAR: Phys. Rev. D74 (2006) 111102

Absolute BF of D $^{(*)(*)}$ with Y(4S) events

BABAR: Phys. Rev. D74 (2006) 111102





230M BB

Decay mode	Yield	$\mathcal{B}(10^{-3})$
$B^- \to D^0\pi^-$	677 ± 32	$4.49 \pm 0.21 \pm 0.23$
$B^- \to D^{*0}\pi^-$	774 ± 33	$5.13 \pm 0.22 \pm 0.28$
$B^- \to$ "D^{**0}"π^-	829 ± 78	$5.50 \pm 0.52 \pm 1.04$
$\bar{B}^0 \to D^+\pi^-$	248 ± 19	$3.03 \pm 0.23 \pm 0.23$
$\bar{B}^0 \to D^{*+}\pi^-$	245 ± 19	$2.99 \pm 0.23 \pm 0.24$
$\bar{B}^0 \to$ "D^{**+}"π^-	192 ± 54	$2.34 \pm 0.65 \pm 0.88$

Absolute BF ratios

Phys. Rev. D74 (2006) 111102
Missing mass Method

Phys. Rev. D75 (2007) 031101
Exclusive method

mode	$\mathcal{B}$ $(\times 10^{-3})$	$\mathcal{B}$ $(\times 10^{-3})$	PDG *BF*
$\overline{B}^0 \to D^+\pi^-$	$3.03 \pm 0.23 \pm 0.23$	$2.63 \pm 0.05 \pm 0.22$	***2.83±0.25 x10^{-3}***
$\overline{B}^0 \to D^{*+}\pi^-$	$2.99 \pm 0.23 \pm 0.24$	$2.79 \pm 0.08 \pm 0.18$	***2.83±0.21 x10^{-3}***
$B^- \to D^0\pi^-$	$4.49 \pm 0.21 \pm 0.23$	$4.90 \pm 0.08 \pm 0.23$	***4.92±0.29 x10^{-3}***
$B^- \to D^{*0}\pi^-$	$5.13 \pm 0.22 \pm 0.28$	$5.52 \pm 0.17 \pm 0.43$	***4.6±0.4 x10^{-3}***

$$\mathcal{B}(B^- \to D^{*0}\pi^-)/\mathcal{B}(B^- \to D^0\pi^-) = 1.14 \pm 0.07 \pm 0.04$$

1.126±0.035±0.091

$$\mathcal{B}(B^- \to D^{**0}\pi^-)/\mathcal{B}(B^- \to D^0\pi^-) = 1.22 \pm 0.13 \pm 0.23$$

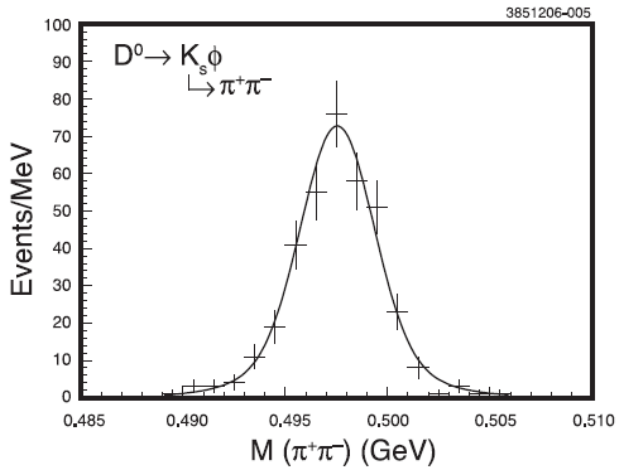
$$\mathcal{B}(\overline{B}^0 \to D^{*+}\pi^-)/\mathcal{B}(\overline{B}^0 \to D^+\pi^-) = 0.99 \pm 0.11 \pm 0.08$$

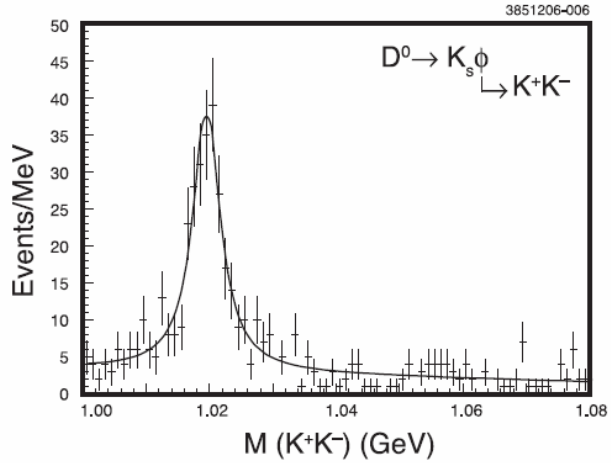
1.061±0.034±0.106

$$\mathcal{B}(\overline{B}^0 \to D^{**+}\pi^-)/\mathcal{B}(\overline{B}^0 \to D^+\pi^-) = 0.77 \pm 0.22 \pm 0.29$$

Precision measurement of D^0 mass from CLEO-c

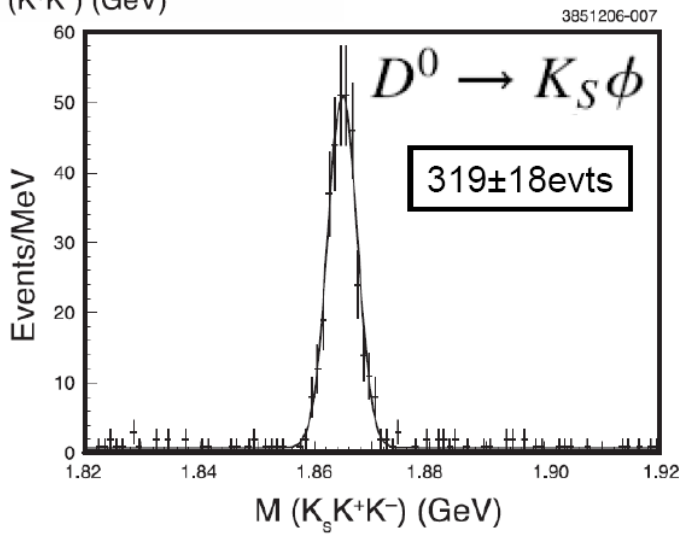
PRL **98,** 092002 (2007)

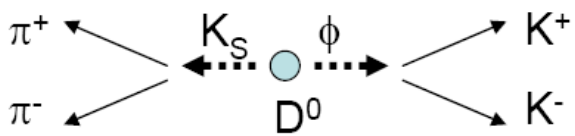




PDG: M(D^0)=1864.5±0.4MeV
- average of LGW, MARK II, NA32
- Measured in $D^0 \rightarrow K\pi$, $K\pi\pi\pi$

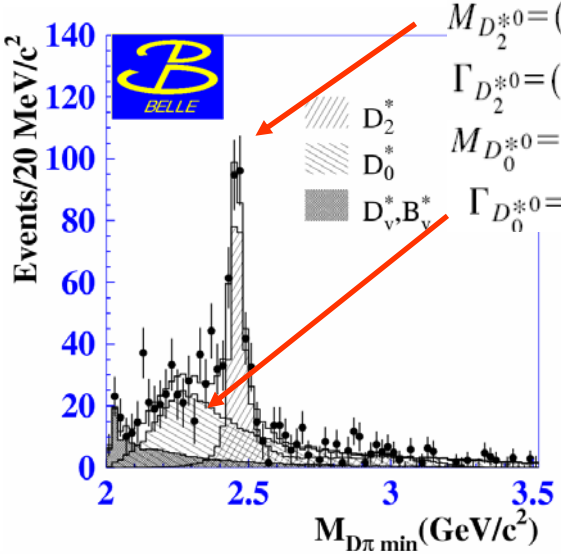
CLEO-c, 281pb^{-1}, use $D^0 \rightarrow K_S\varphi$:
- $M(D^0)-M(\varphi)-M(K_S)$=347MeV
- p(K), p(π) <600MeV range
- Cross-check: $M(\psi(2S) \rightarrow \pi^+\pi^- J/\psi)$





$$M(D^0) = 1864.847 \pm 0.150(\text{stat}) \pm 0.095(\text{syst}) \text{ MeV}.$$

Orbitally excited D^{**0} and D^{**+} mesons (exclusive in B decays)

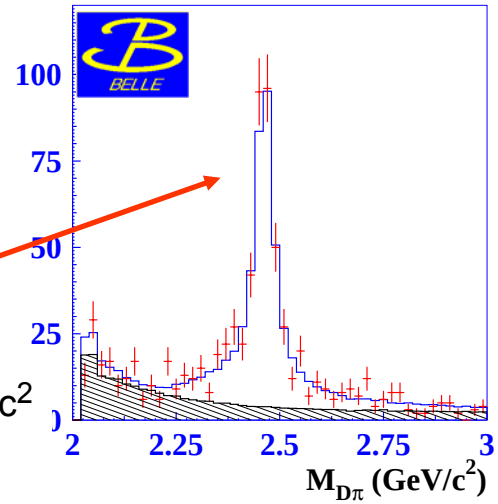


$M_{D_2^{*0}} = (2461.6 \pm 2.1 \pm 0.5 \pm 3.3)$ MeV/c^2

$\Gamma_{D_2^{*0}} = (45.6 \pm 4.4 \pm 6.5 \pm 1.6)$ MeV.

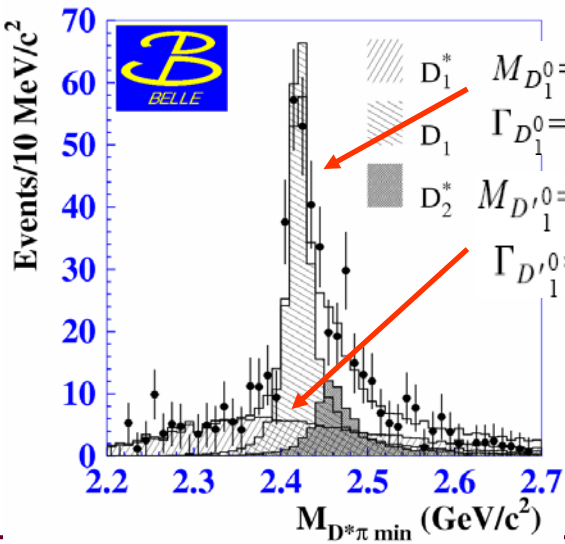
$M_{D_0^{*0}} = (2308 \pm 17 \pm 15 \pm 28)$ MeV/c^2

$\Gamma_{D_0^{*0}} = (276 \pm 21 \pm 18 \pm 60)$ MeV.



$M_{D_2^{*+}} = (2465.7 \pm 1.8 \pm 0.8 \pm {}^{1.2}_{4.7})$ MeV/c^2

$\Gamma_{D_2^{*+}} = (49.7 \pm 3.8 \pm 4.1 \pm 4.9)$ MeV



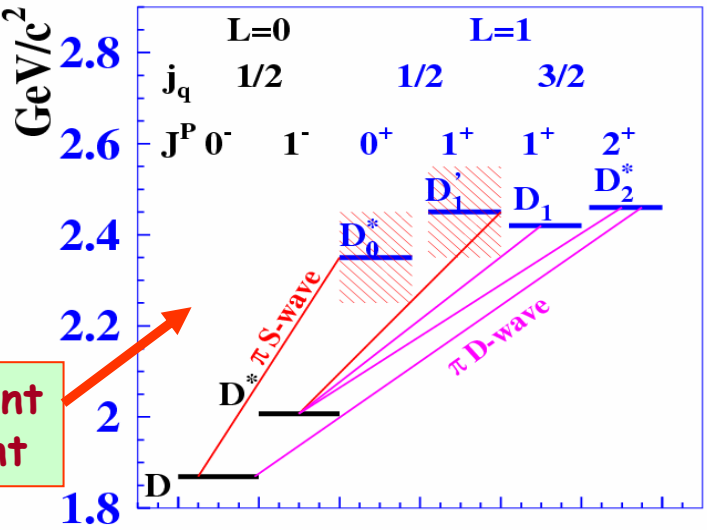
$M_{D_1^0} = 2421.4 \pm 1.5 \pm 0.4 \pm 0.8$ MeV/c^2

$\Gamma_{D_1^0} = 23.7 \pm 2.7 \pm 0.2 \pm 4.0$ MeV.

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

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

Theory and experiment are in good agreement

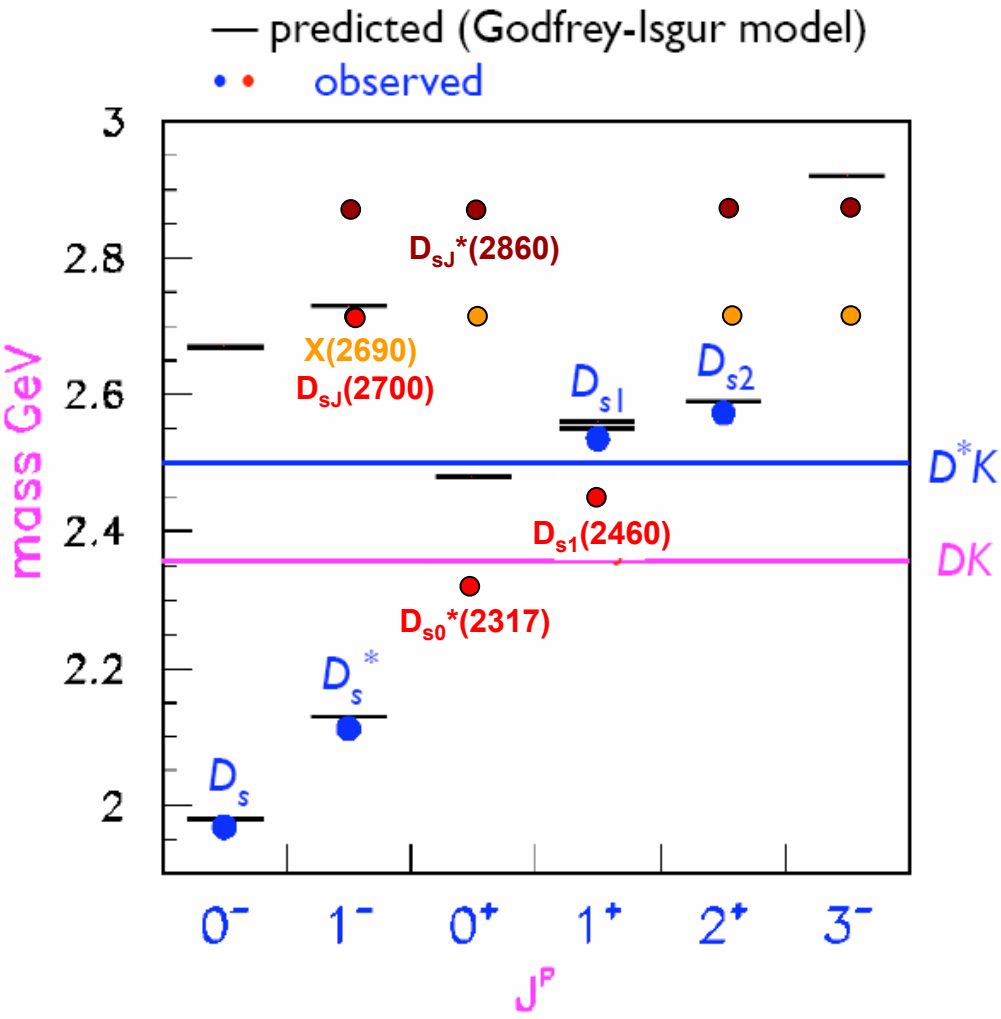


$c\bar{s}$ MESONS

mini-review

- **$D_{s0}^*(2317)$** and **$D_{s1}(2460)$**: surprising states
- **$D_{s1}(2536)$** and **$D_{s2}(2573)$:** precision measurements
- **$D_{sJ}^*(2860)$**: new state
- **X(2690)** and **$D_{sJ}(2700)$**: even more new states, or are they the same state?

CURRENT SITUATION

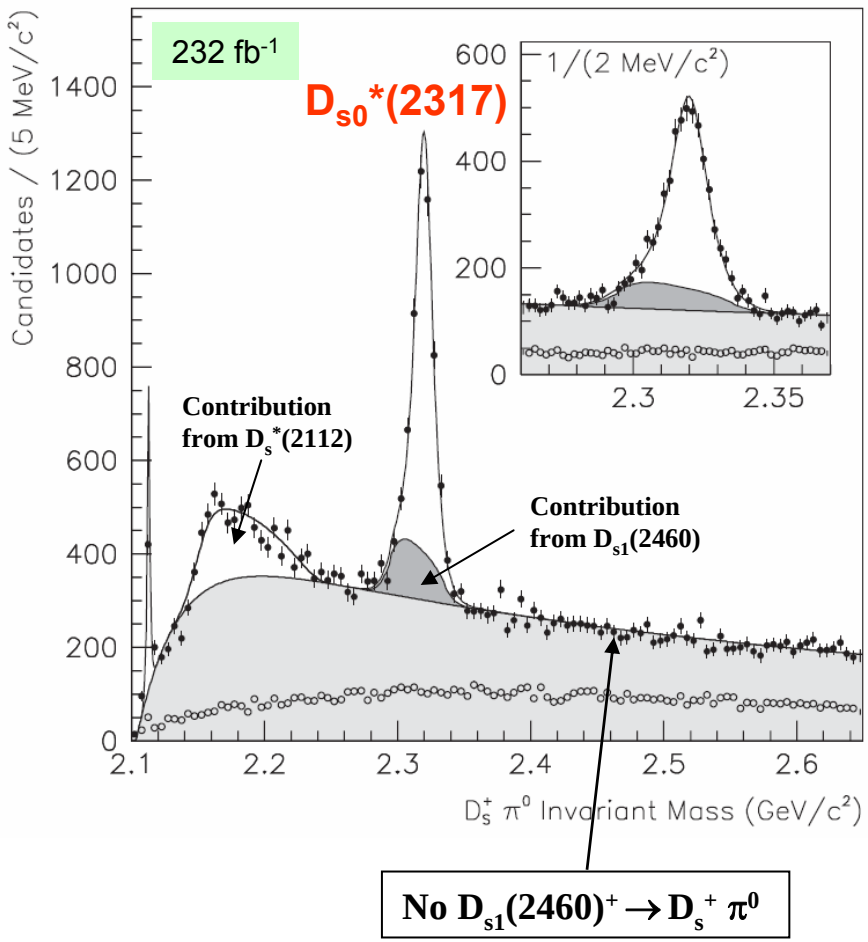


- Prior to B-factories, only 4 states observed: $D_s(1968)$,$D_s^*(2112)$,$D_{s1}(2536)$ and $D_{s2}(2573)$
- $D_{s0}^*(2317)^+$, Apr. 2003: unexpected observation of a narrow resonance in **BaBar**
- $D_{s1}(2460)^+$, May 2003: **CLEO, BaBar** observed a new narrow resonance
- $D_{sJ}^*(2860)^+$, Jul. 2006: new state discovered by **BaBar**
- $X(2690)^+$, Jul. 2006: broad enhancement seen in **BaBar**
- $D_{sJ}(2700)^+$, Jul. 2006: new state discovered by **Belle** (≡ X(2690)?)

$D_{s0}^*(2317)$ IN INCLUSIVE DATA

- Study of $e^+e^- \to c\bar{c}$ events
  - Resonance in $D_s^+\pi^0$
- Complex kinematics with competing contributions and mutual cross-feed
- Properties
  - M = (2319.6 ± 0.2 ± 1.4) MeV/c^2
  - Γ < 3.8 MeV at 95% CL
- No decay to $D_s^+\pi^+$ or $D_s^+\pi^-$
  - No indication of **isospin partners**

$D_s^+\pi^0$ final states

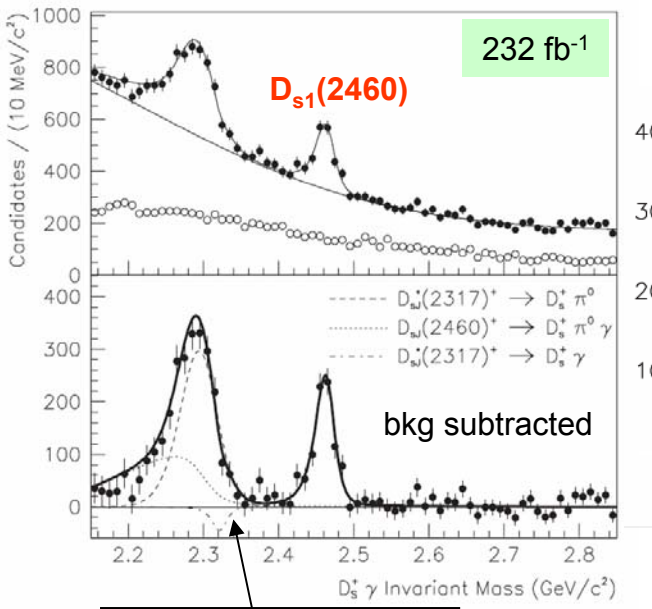


BaBar: Phys. Rev. D74 (2006) 032007

$D_{s1}(2460)$ IN INCLUSIVE DATA

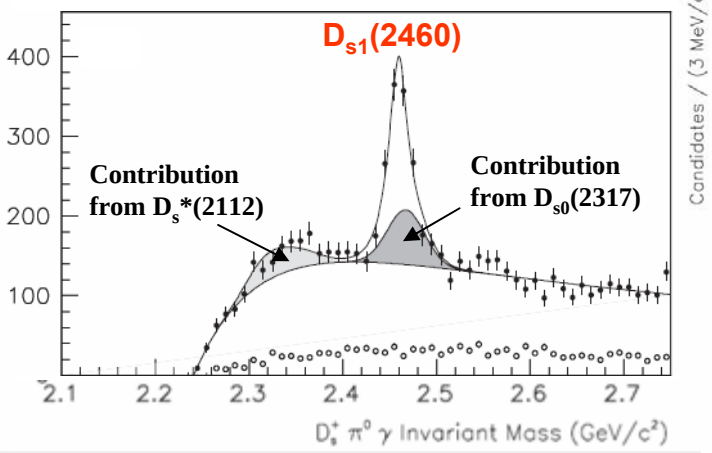
- $D_{s1}(2460)$ observed in 3 decay final states

$D_s^+ \gamma$ final states

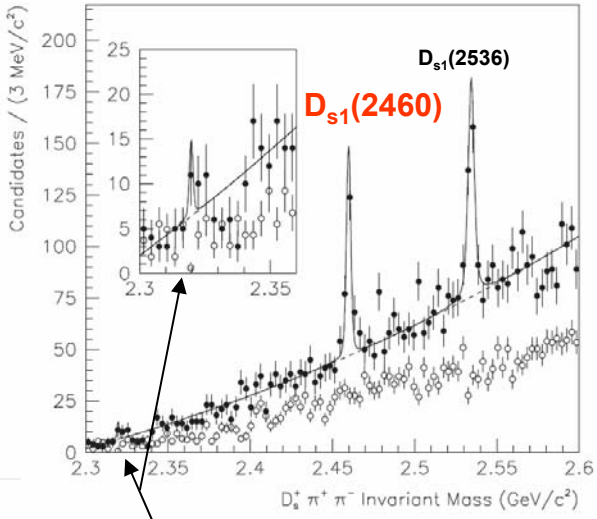


No $D_{s0}^*(2317)^+ \to D_s^+ \gamma$

$D_s^+ \pi^0 \gamma$ final states



$D_s^+ \pi^+ \pi^-$ final states



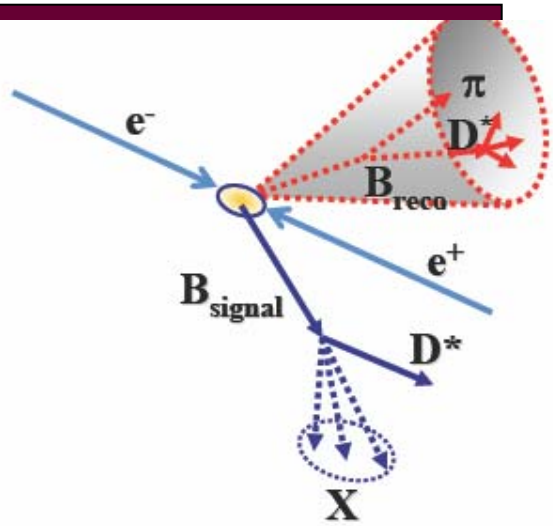
No $D_{sJ}^*(2317)^+ \to D_s^+ \pi^+ \pi^-$

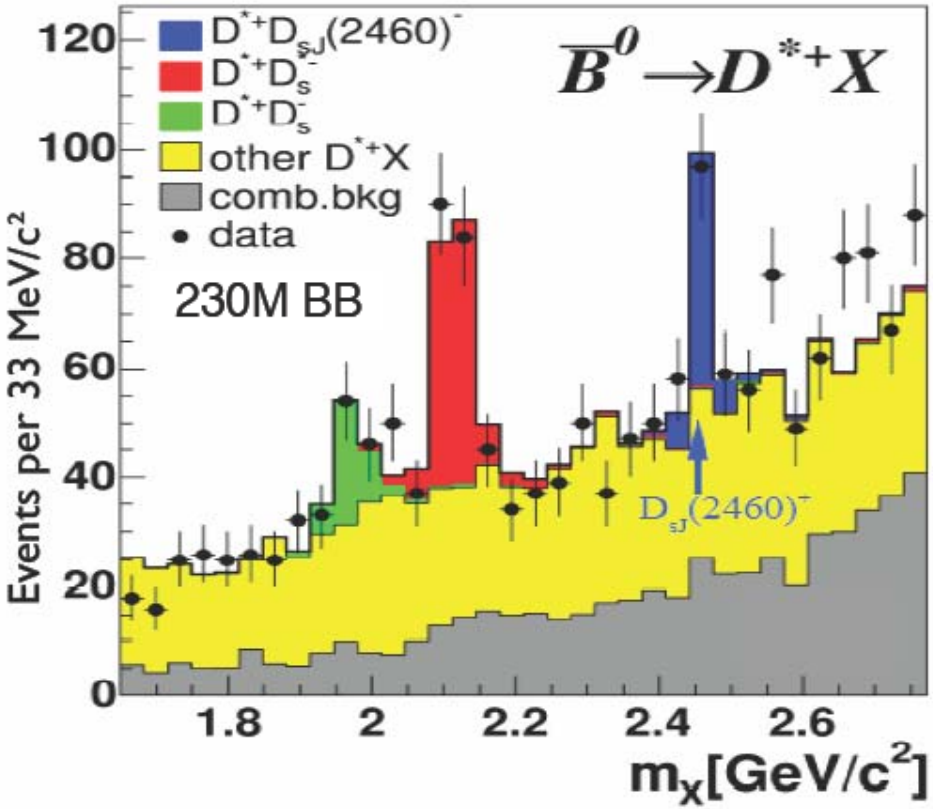
- Properties
  - M = (2460.1 ± 0.2 ± 0.8) MeV/c²
  - Γ < 3.5 MeV at 95% CL

BaBar: Phys. Rev. D74 (2006) 032007

Absolute BF of $D_{sJ}(2460)$ with Y(4S) events

1) Reconstruct one B meson fully
2) Reconstruct other B partially: $B \rightarrow D^{(*)} X$
3) Deduce invariant mass of X system & plot





Combine with previous studies of fully exclusive reconstruction:

$$\mathcal{B}\left(D_{sJ}^*(2460)^+ \rightarrow D_s^*(2112)^+\pi^0\right) = (56 \pm 13 \pm 9)\,\%$$
$$\mathcal{B}\left(D_{sJ}^*(2460)^+ \rightarrow D_s^+\gamma\right) = (16 \pm 4 \pm 3)\,\%$$
$$\mathcal{B}\left(D_{sJ}^*(2460)^+ \rightarrow D_s^+\pi^+\pi^-\right) = (4 \pm 1)\,\%$$

Sum of known modes: (76 ± 20)%
(assuming $\mathcal{B}(D_s^+ \rightarrow \phi\pi^+) = 4.62 \pm 0.36 \pm 0.50\%$)

BABAR: Phys.Rev. D74 (2006) 031103

$D_{s0}^*(2317)$ AND $D_{s1}(2460)$ UPDATE

- Discovered 4 years ago in $e^+e^- \rightarrow c\bar{c}$ events, observed in B decays
- $D_{s0}^*(2317)$ and $D_{s1}(2460)$ very well established and known experimentally
  - **Masses** and **widths**
  - Natural $\mathbf{J^P}$: 0^+ for $D_{s0}^*(2317)$ and 1^+ for $D_{s1}(2460)$
  - **decay modes** and **branching fractions**
- Interpretation of these new states still unclear!
  - One possibility: identify these 2 states as the **0^+ and 1^+ $c\bar{s}$ states**
    - However strong difficulties within the potential model
  - **Other** possibilities
    - 4 quark states? DK molecule? $D\pi$ atom? Chiral symmetry?
- More unexpected? Yes!

Belle: Phys. Rev. Lett. 91 (2003) 262001
BaBar: Phys. Rev. D74 (2006) 032007
Belle: Belle-Conf-0461 (2006)
BaBar: Phys. Rev. D74 (2006) 031103

Analysis of $D_{s1}(2536) \to D^* K_s$

- High precision measurement of $D_{s1}(2536)$ mass and decay width

PDG 06: $m(D_{s1}) = 2535.35 \pm 0.34 \pm 0.5 \text{MeV}/c^2$
$m(D_{s1}) - m(D^*) = 525.3 \pm 0.6 \pm 0.1 \text{MeV}/c^2$
$\Gamma(D_{s1}) < 2.3 \text{MeV}$

- 2 decay modes: $D_{s1}^{\pm} \longrightarrow D^{*\pm} K_S^0$ $\quad$ $D_{s1}^{\pm} \longrightarrow D^{*\pm} K_S^0$

p*(D*K$_s$)>2.7 GeV/c

$K_S^0 \to \pi^+\pi^-$ $\quad$ $K_S^0 \to \pi^+\pi^-$

$D^{*\pm} \to D^0\pi^{\pm}$ $\quad$ $D^{*\pm} \to D^0\pi^{\pm}$

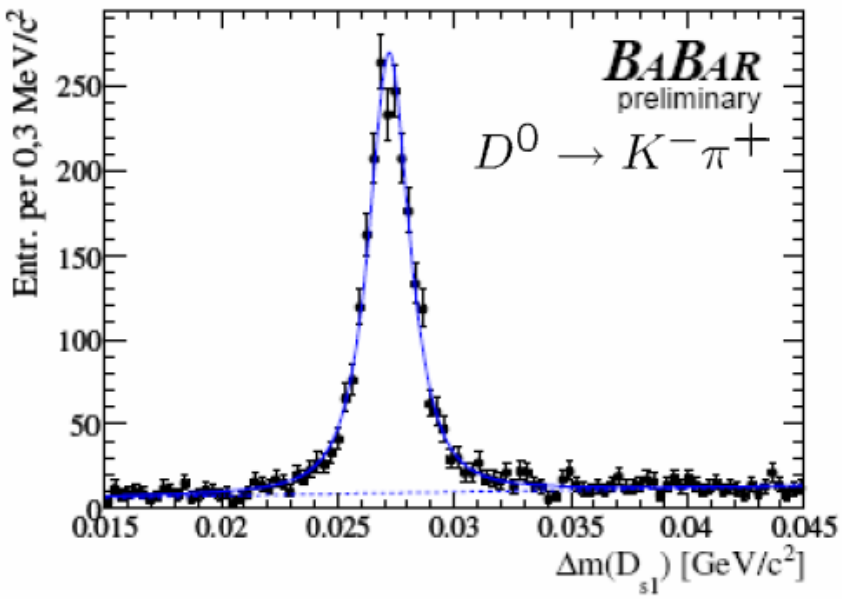
$D^0 \to K^{\mp}\pi^{\pm}$ $\quad$ $D^0 \to K^{\mp}\pi^{\pm}\pi^{\pm}\pi^{\mp}$

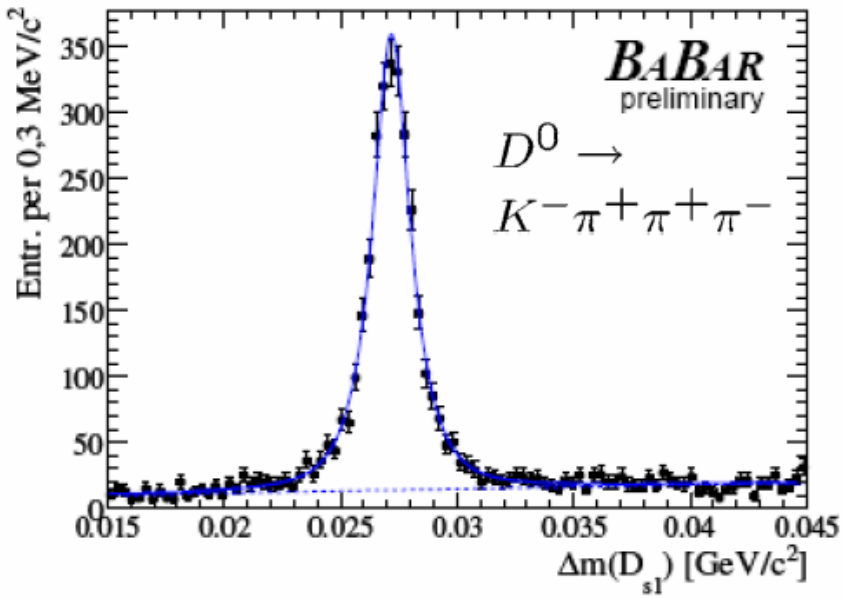
- measure $\Delta m(D_{s1}) = m(D_{s1}) - m(D^*) - m(K_S^0)$
  to reduce systematics and improve resolution
- Systematic studies
  Detector: tracking, momentum and angular dependence
  MC, fit model

Data: 232 fb^{-1}

hep-ex/0607084 (preliminary)

Analysis of $D_{s1}(2536) \rightarrow D^* K_s$





$m(D_{s1}) = 2534.85 \pm 0.02 \pm 0.40$ MeV/c²

$m(D_{s1}) - m(D^*) = 524.85 \pm 0.02 \pm 0.04$ MeV/c²

$\Gamma(D_{s1}) = 1.03 \pm 0.05 \pm 0.12$ MeV

mass difference improvement by factor of 14 compared with PDG

Data: 232 fb^{-1}

hep-ex/0607084 (preliminary)

next: measure J^P

Inclusive study of DK - $D_{s2}(2573)$

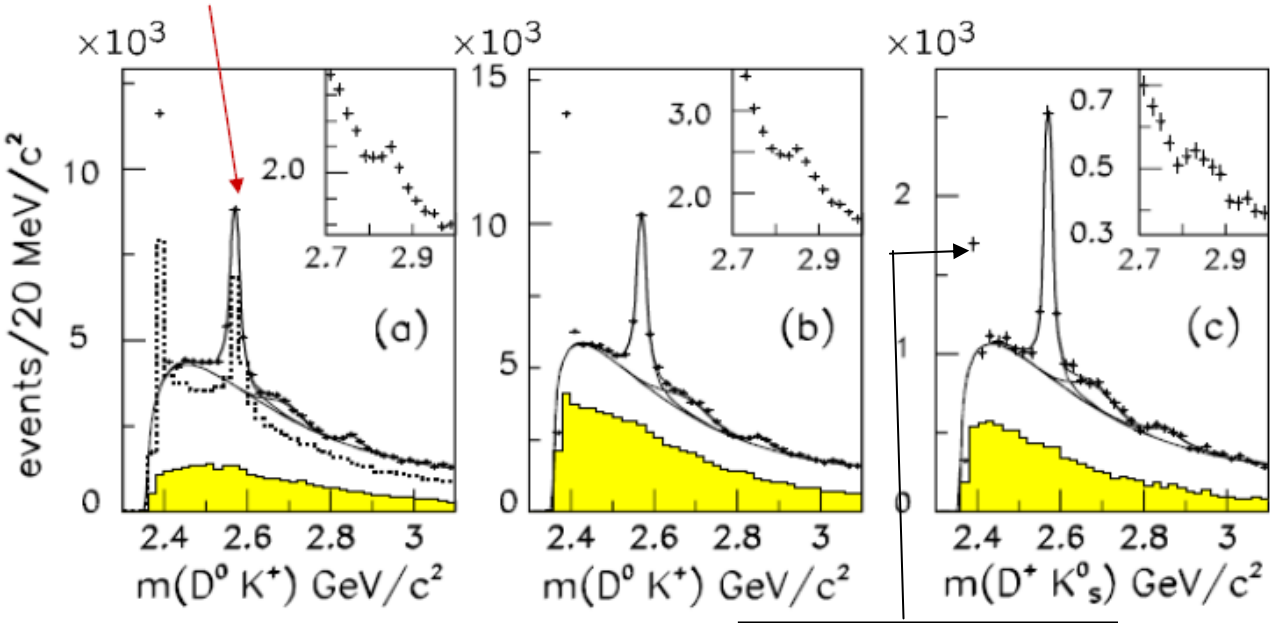
D^0K^+ / $D^+K^0_S$

PDG: $m(D_{s2}(2573)) = 2573.5 \pm 1.7 \text{MeV}/c^2$
$\Gamma(D_{s2}(2573)) = 15 \pm 5 \text{MeV}/c^2$

final state DK → natural spin-parity
→ $J^P = 0^+, 1^-, 2^+ \ldots$

- improvement for $D_{s2}(2573)$

$m(D_{s2}(2573)) = 2572.2 \pm 0.3 \pm 1.0 \text{MeV}/c^2$ (fit to all decay modes)
$\Gamma(D_{s2}(2573)) = 27.1 \pm 0.6 \pm 5.6 \text{MeV}$



$p^*(DK) > 3.5 \text{GeV}/c$

Data: 240 fb^{-1}

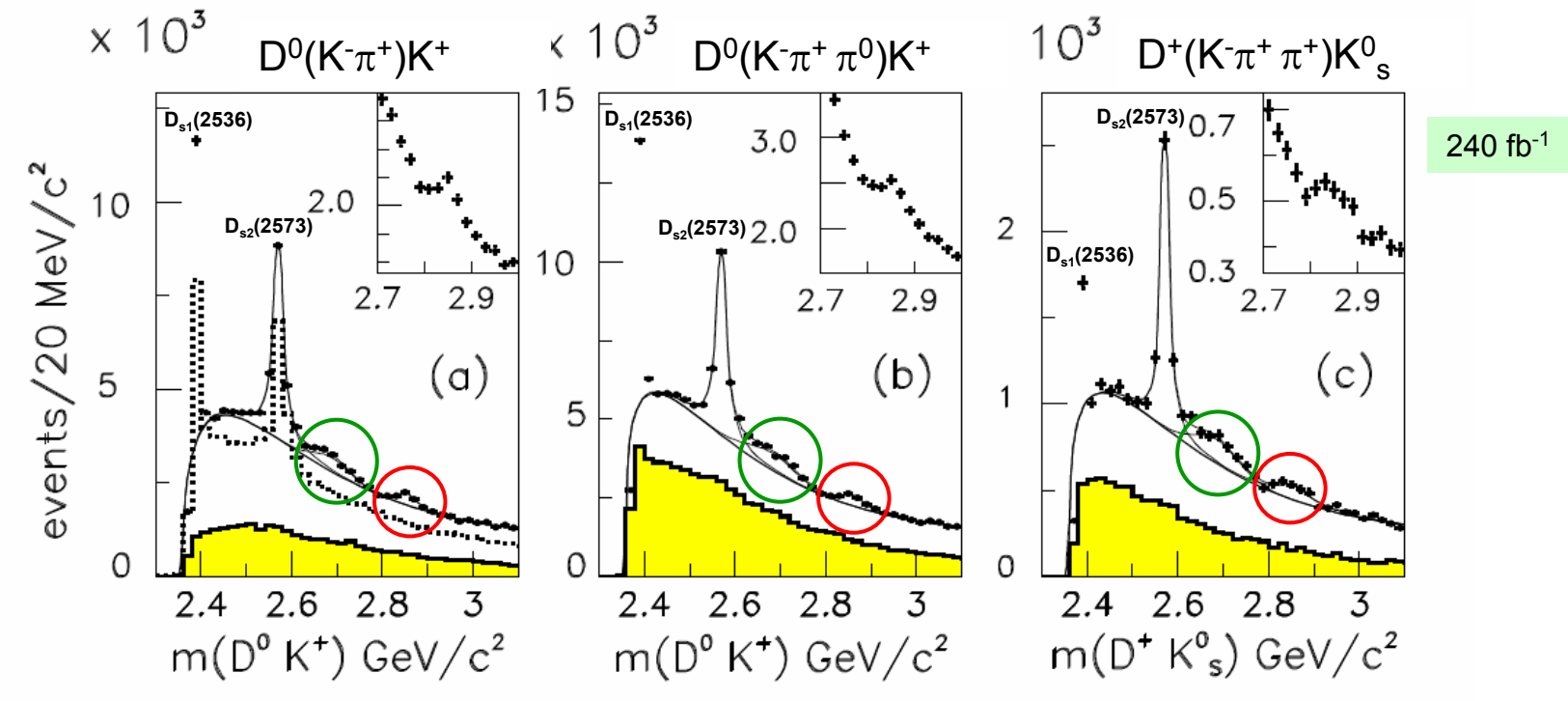
BaBar: PRL97(2006),222001

$c\bar{s}$ MESONS

WHAT IS NEW FOR D_{sJ} STATES?

$D_{sJ}^*(2860)$: NEW STATE

- Looking in the $c\bar{c}$ continuum: $e^+e^- \to D^0_{(K^-\pi^+,K^-\pi^+\pi^0)}K^+X$ and $e^+e^- \to D^+_{(K^-\pi^+\pi^+)}K^0_sX$



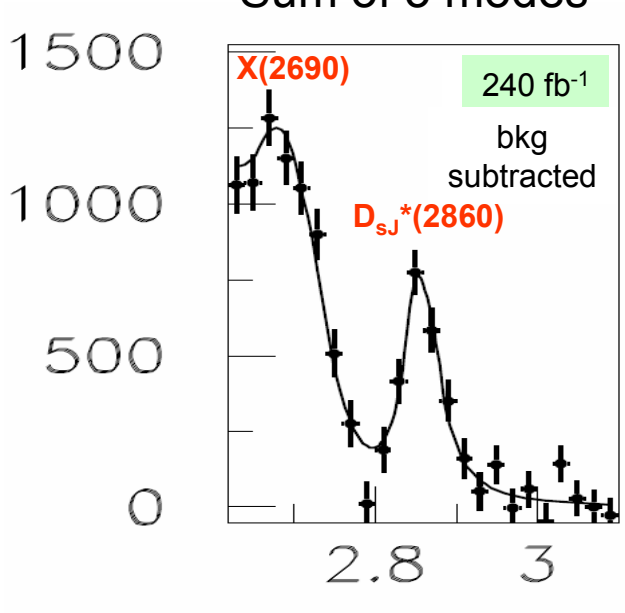
- ◯ New state at 2860 MeV/c^2!
- ◯ Bump at 2690 MeV/c^2?

BaBar: Phys. Rev. Lett. 97 (2006) 222001

$D_{sJ}^*(2860)$ AND… X(2690)?

- Combining the 3 modes
  - M = (2856.6 ± 1.5 ± 5.0) MeV/c^2
  - Γ = (47 ± 7 ± 10) MeV
  - J^P = **0^+, 1^-, 2^+**, …
    - Final state is DK, i.e. two pseudoscalars
    - not seen in D*K
- Interpretation?
  - **Radial excitation** of $D_{s0}^*(2317)$? hep-ph/0606110
  - $c\bar{s}$ with J^P = **3^-**? hep-ph/0607245
  - $c\bar{s}$ with J^P = **0^+**? hep-ph/0608139

Sum of 3 modes



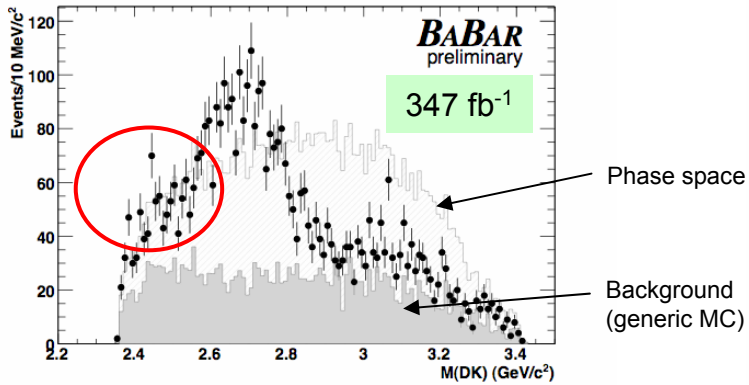
- Another structure at 2690 MeV/c^2?
  - M = (2688 ± 4 ± 3) MeV/c^2
  - Γ = (112 ± 7 ± 36) MeV
- Needs confirmation by other experiments…

BaBar: Phys. Rev. Lett. 97 (2006) 222001

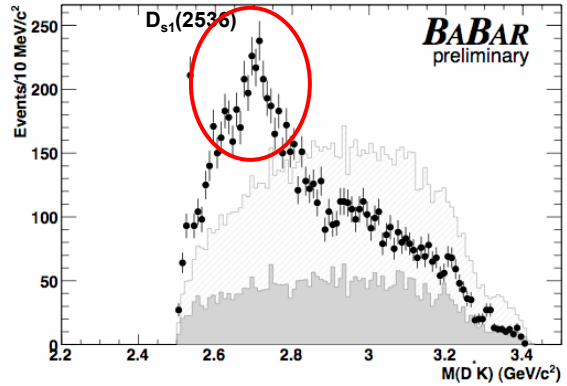
EVEN MORE STATES: $D_{sJ}(2700)$

- Study of $B \to \bar{D}^{(*)}D^{(*)}K$ decays in BaBar (22 modes)
  - Looking at 8 DK + 8 D*K invariant masses, adding **15 decay modes** wrt Belle

Summing all 8 DK modes

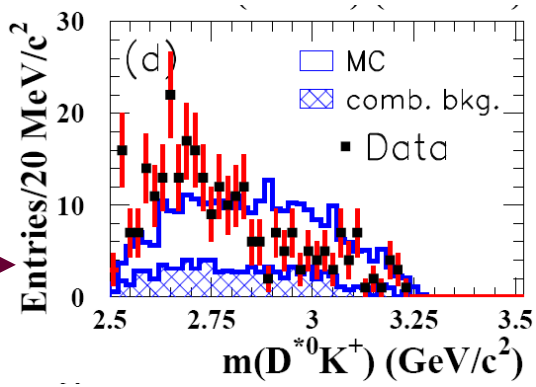


Summing all 8 D*K modes



New result preliminary

- Enhancement observed around 2700 MeV/c^2 in DK and D*K
- Additional $c\bar{s}$ surprise? Maybe!
  - **Low mass enhancement** in DK?
    - Belle sees it and uses an exponential
  - **One or two resonances** around 2.6-2.7 GeV/c^2 in D*K? already there in PRD68(2003)092001



- Need to perform a full Dalitz plot analysis
  - Takes into account **interferences**

BaBar: preliminary

SUMMARY

- Almost no new resonant states in more than 20 years
- Many new ones since 1999, start of Belle and BaBar!

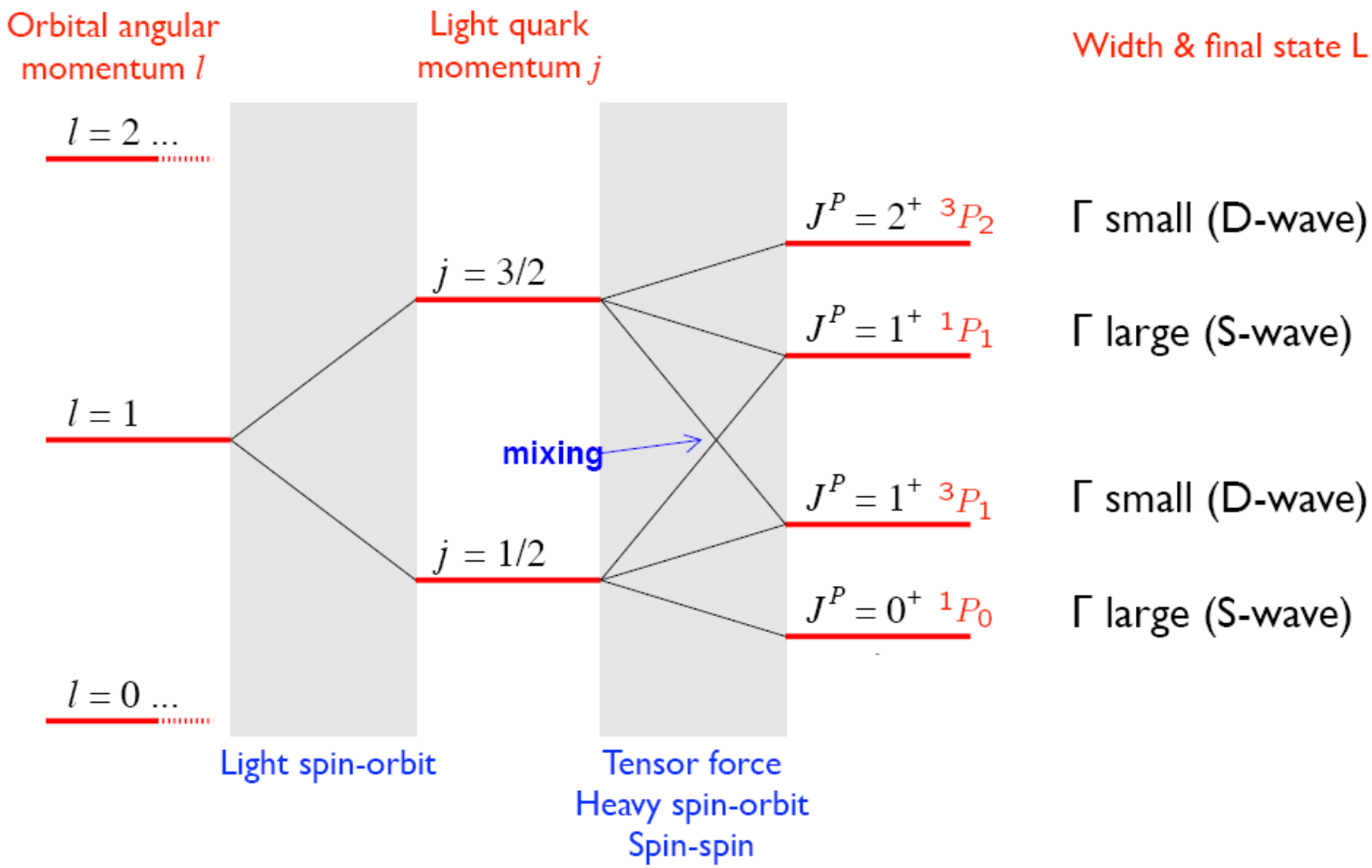
  - **New open charm discovered: $D_{sJ}^{*}(2860)$**,
  - Next: Confirm **X(2690)** (?=**$D_{sJ}(2700)$**) experimentally and theoretically
  - **Precise measurement of D_{sJ} parameters :**
    - **$D_{s0}^{*}(2317)$**, **$D_{s1}(2460)$**: **mass**
    - **$D_{s1}(2536)$: mass, width**

Experimental status:

- Lots of on-going analyses with the current dataset
  - More **decay modes** investigated to understand these resonances
- Belle and BaBar are taking data till end of 2008
- Lots of new data to analyse!

ADDITIONAL SLIDES

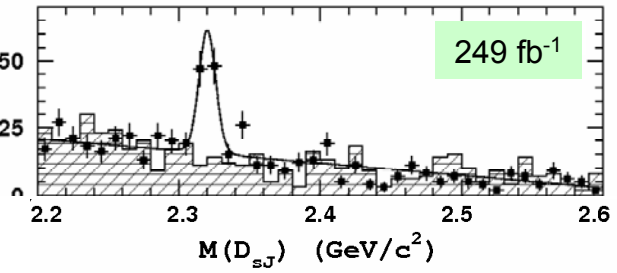
Potential models and Energy-splitting

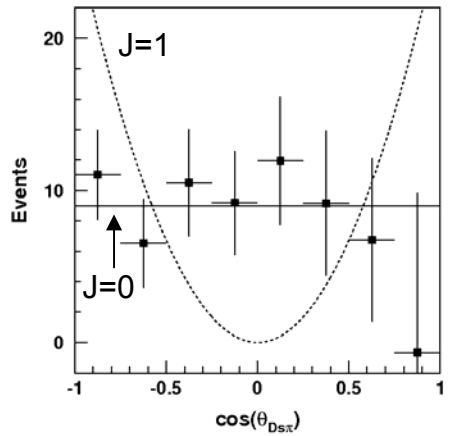


J^P OF $D_{s0}^*(2317)$ AND $D_{s1}(2460)$

- D_{sJ} in B decays: $B \to D_{sJ}^+ \bar{D}^{(*)}$

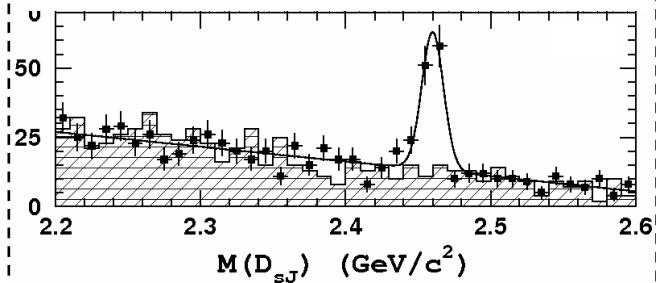
$D_{s0}^*(2317)^+ \to D_s^+ \pi^0$

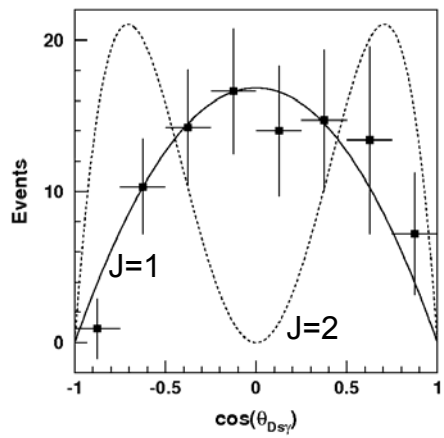




$J^P \Rightarrow 0^+$

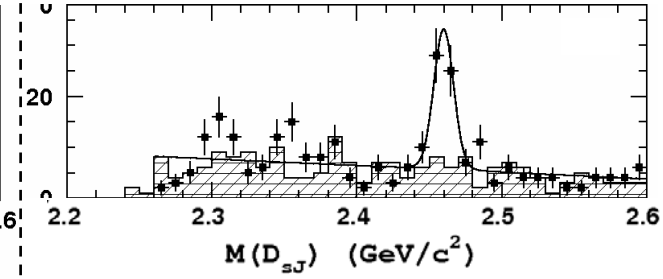
$D_{s1}(2460)^+ \to D_s^+ \gamma$

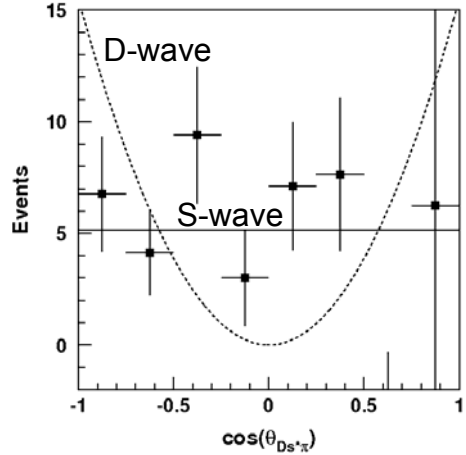




$J \Rightarrow 1$

$D_{s1}(2460)^+ \to D_s^{*+} \pi^0$





J^P 1^- excluded

$J^P \Rightarrow 1^+$

- Natural J^P: 0^+ for $D_{s0}^*(2317)$ and 1^+ for $D_{s1}(2460)$
- Confirmed by pattern of decay modes

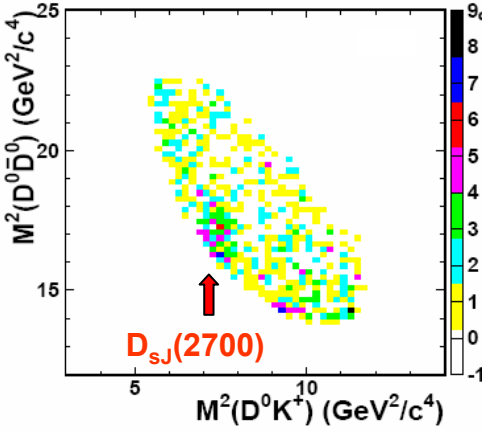
Belle: Belle-Conf-0461 (2006)
BaBar: PRL 93, 181801 (2004)

EVEN MORE STATES: $D_{sJ}(2700)$

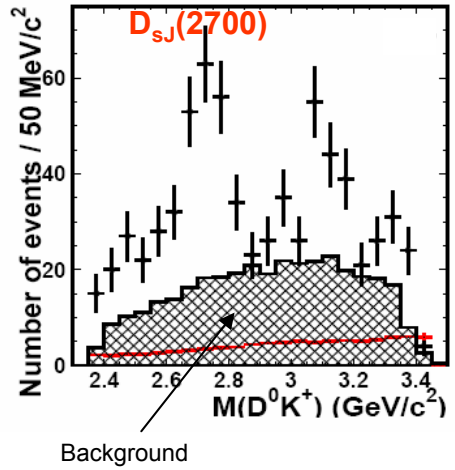
- Study of $B^+ \to \bar{D}^0 D^0 K^+$
  - Looking at the **Dalitz plot** and the **D^0K^+** projection
- New resonance decaying to D^0K^+
  - $B^+ \to \bar{D}^0 D_{sJ}$, $D_{sJ} \to D^0K^+$
  - $M = (2715 \pm 11\ ^{+11}_{-14})$ MeV/c^2
  - $\Gamma = (115 \pm 20\ ^{+36}_{-32})$ MeV
  - $J^P = 1^-$ favored
- Same resonance as seen by BaBar in continuum, X(2690)?
  - Mass and width consistent, same decay mode
- Interpretation?
  - $c\bar{s}$ state $\mathbf{2^3S_1}$?
    - expected mass at 2720 MeV/c^2
  - **Chiral symmetry**: 1^+ - 1^- doublet paired with $D_{s1}(2536)$?

Phys.Polon. B 35, 2377 (2004)

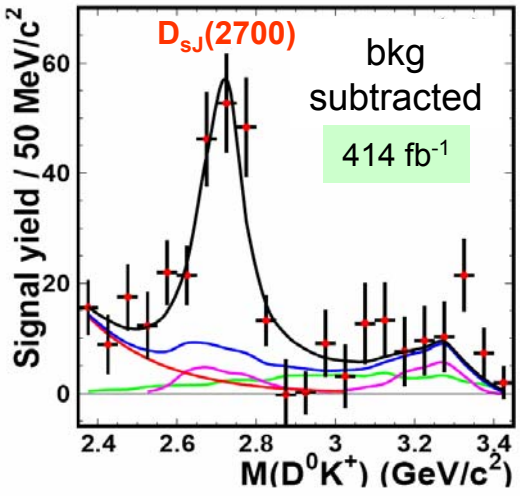
Dalitz plot

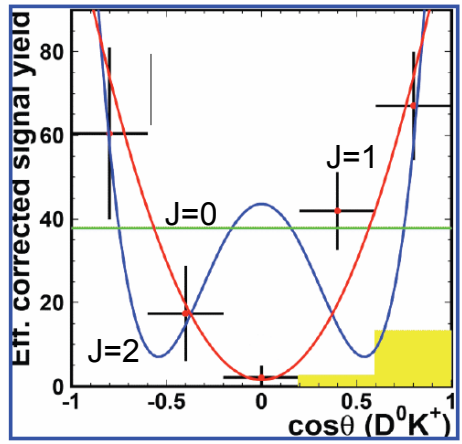


D^0K^+ projection



D^0K^+ projection





Belle: hep-ex/0608031

Charm Strange mesons

New potential model (2006) reproduces data better:

Close,Thomas, Lakina, Swanson (hep-ph/0608139)

other models:
van Beveren, Rupp (hep-ph/0606110)
Colangelo (hep-ph/0607245)