New resonances at Belle (and CLEO)

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Plan:

1. Heavy-light mesons
   - D_{SJ} productions in $e^+e^- \to c\bar{c}$ continuum
   - D_{SJ} productions in exclusive B decays
   - D^{**} in $B \to D^{(*)}\pi^+\pi^-$
2. Heavy-heavy mesons
   - η_c'
   - $X(3872)$

Heavy-Light Mesons $Q\bar{q}$ (e.g. $c\bar{u}$)

In the heavy-quark limit, Q decouples from the rest.

$\vec{j}_l = \vec{L} + \vec{s}_q$: angular momentum of the light degree of freedom

$\vec{J} = \vec{j}_l + \vec{s}_Q$: total spin of the meson

$\text{Parity} = -(-)^L$ (L : orbital angular momentum of $Q\bar{q}$)

- $L = 0$ Parity$-$
  - $j_l = 1/2 \rightarrow J = 0\ (D),\ J = 1\ (D^*)$
- $L = 1$ Parity$+$
  - $j_l = 1/2 \rightarrow J = 0\ (D_0^*),\ J = 1\ (D_1')$
  - $j_l = 3/2 \rightarrow J = 1\ (D_1),\ J = 2\ (D_2^*)$

Main decay of $(L = 1)$ would be:

$(L = 1) \rightarrow D^{(*)}\pi$ light degree of freedom : $(j_l) \rightarrow (\frac{1}{2}) + \pi$

$\rightarrow$ expect $j_l = 1/2$: broad (S-wave π emission)
$j_l = 3/2$: narrow (No S-wave π emission)

BaBar observed a narrow $D_S(2317) \to D_S\pi^0$

$(\to J^P(2317) = 0^+, 1^-, 2^+ \cdots)$

Also a peak at 2.46 GeV in $D_S^*\pi^0$: if it is real,

$$\pi^0 \longleftarrow (2317) \longrightarrow D_S$$

$E_{\pi^0} =$ 372 MeV/c (in D_S frame)

$$\pi^0 \longleftarrow (2460) \longrightarrow D_S^*$$

$$D_S^* \to D_S\gamma$$

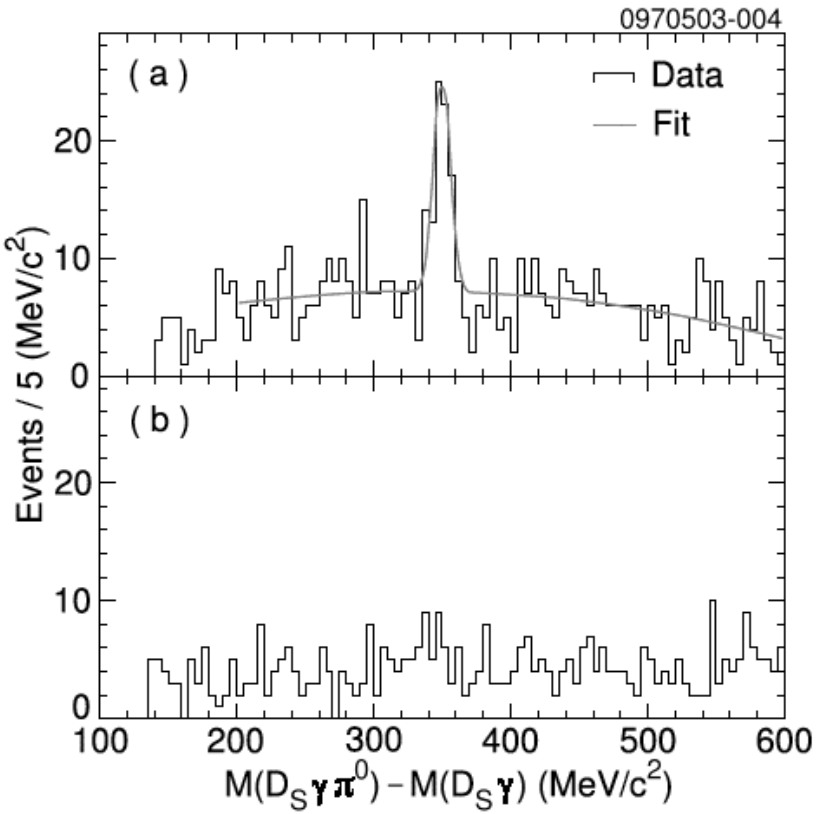
$E_{\pi^0} =$ 374 MeV/c (in D_S^* frame)

$\vec{v}(D_S) \sim 0$ in D_S^* frame.

π^0 and D_S in (2460) decay have invariant mass of (2317).

Adding soft γ to (2317) to form D_S^* will look like (2460).

CLEO Establishes $D_{SJ}(2463)$ (continuum)



Combine $D_S\gamma\pi^0$
(13.5 fb^{-1})

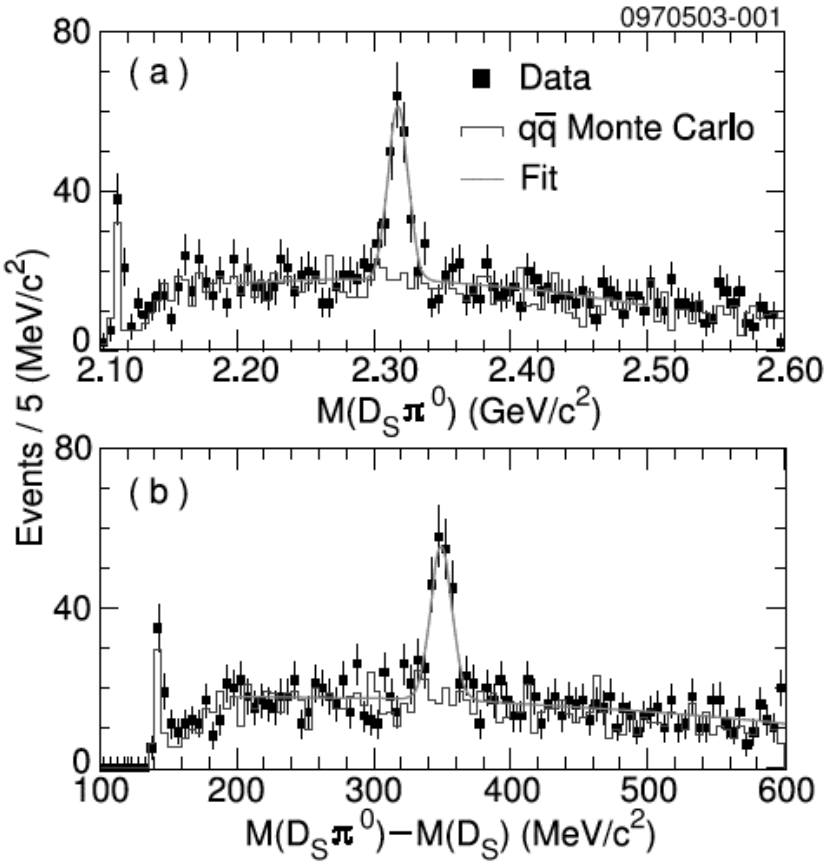
(a) D_S^*, (b) D_S^* side-band

$M(D_S^*\pi^0) - M(D_S^*)$
$=351.2 \pm 1.7 \pm 1.0$ MeV
($M = 2463.6$ MeV)

$\Gamma < 7$ MeV (90% c.l.)

$$\frac{\sigma \cdot B}{\sigma(D_S)} = (3.5 \pm 0.9 \pm 0.2) \times 10^{-2}$$

CLEO Comfirms $DsJ(2317)$



Combine $D_S\pi^0$

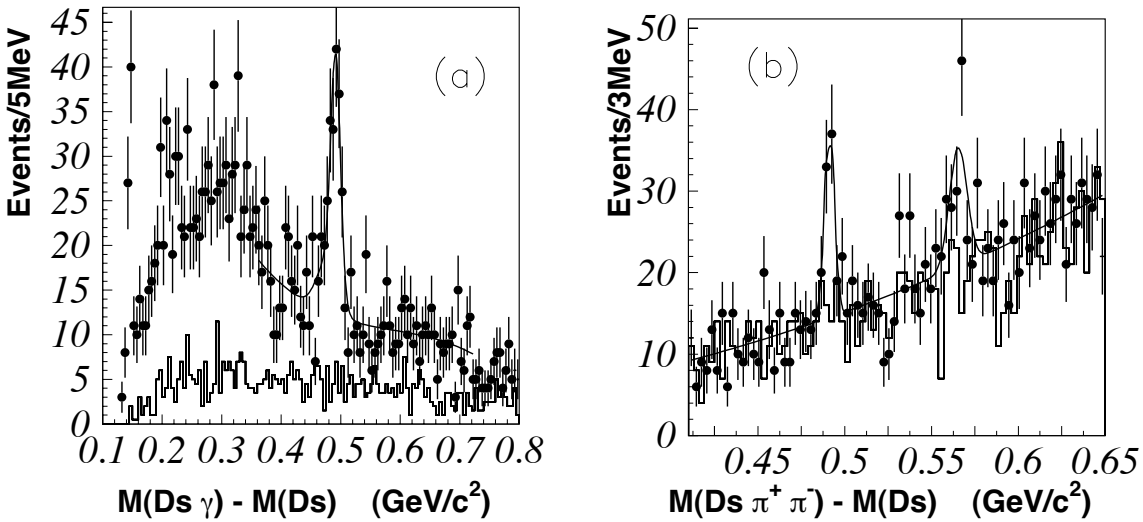
$M(D_S\pi^0) - M(D_S)$
$=350.0 \pm 1.2 \pm 1.0$ MeV
$(M = 2318.5$ MeV)

$\Gamma < 7$ MeV (90% c.l.)

$$\frac{\sigma \cdot B}{\sigma(D_S)} = (7.9 \pm 1.2 \pm 0.4) \times 10^{-2}$$

(The sharp peak on the left: $D_S^* \to D_S\pi^0$)

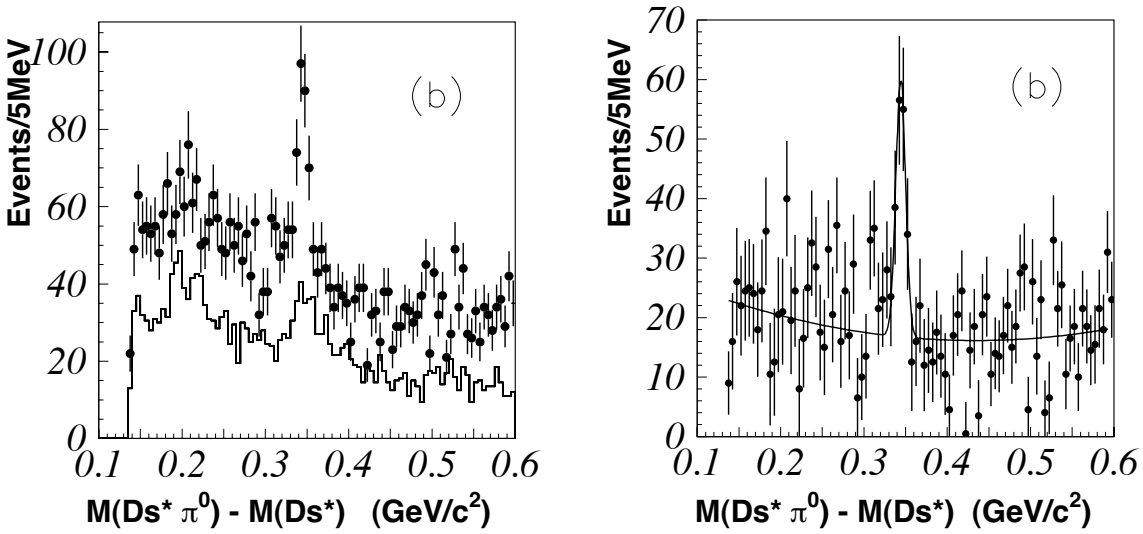
Belle sees $D_{SJ}(2456) \to D_S\gamma, D_S\pi^+\pi^-$ (87 fb^{-1}) (continuum)



$$\frac{Br(2457 \to D_S\gamma)}{Br(2457 \to D_S^*\pi^0)} = 0.55 \pm 0.13 \pm 0.08$$

$$\frac{Br(2457 \to D_S\pi^+\pi^-)}{Br(2457 \to D_S^*\pi^0)} = 0.14 \pm 0.04 \pm 0.02$$

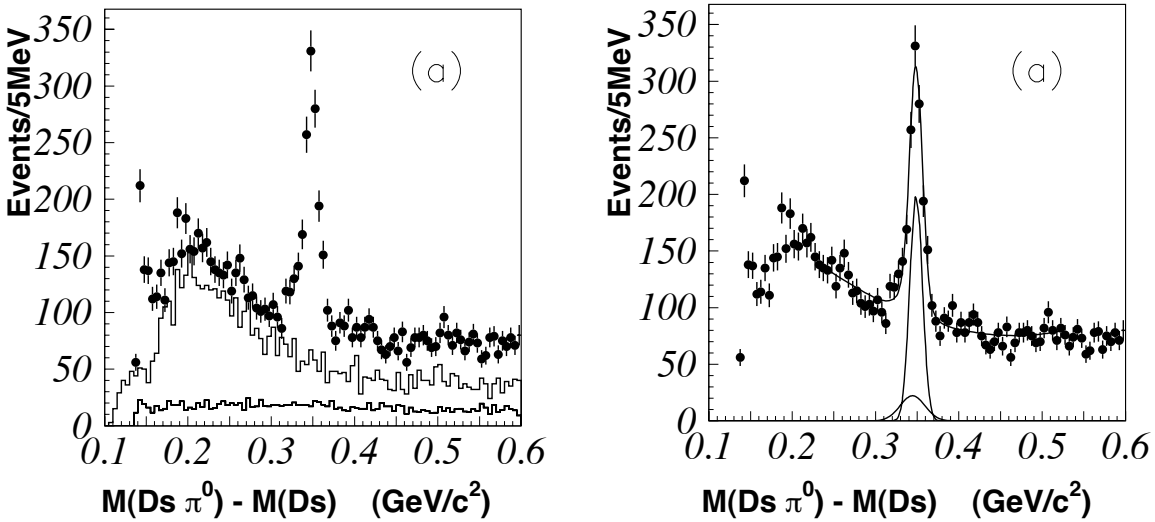
Belle confirms $D_{SJ}(2457)$ (87 fb^{-1})



D_S^* sideband subtraction removes the 'feedup' from (2317)
as well as $(2457) \to D_S^*\pi^0$, $D_S^* \to D_S\gamma(\text{lost}) + \gamma(\text{random})$

$$M(2457) = 2456.5 \pm 1.3 \pm 1.3 \text{ MeV}$$
$$\Gamma(2457) < 5.5 \text{ MeV (90\% c.l.)}$$

Belle confirms $D_{SJ}(2317)$ (87 fb^{-1})



'Feed-down' estimated by MC

$$M(2317) = 2317.2 \pm 0.5 \pm 0.9 \text{ MeV}$$
$$\Gamma(2317) < 4.6 \text{ MeV (90\% c.l.)}$$

Belle (continuum) 87 fb^{-1}

$$\frac{\sigma \cdot B(2457 \to D_S^* \pi^0)}{\sigma \cdot B(2317 \to D_S \pi^0)} = 0.29 \pm 0.06 \pm 0.03$$

$$\frac{Br(2317 \to D_S \gamma)}{Br(2317 \to D_S \pi^0)} < 0.05 \text{ (90\% c.l.)}$$

$$\frac{Br(2317 \to D_S^* \gamma)}{Br(2317 \to D_S \pi^0)} < 0.18 \text{ (90\% c.l.)}$$

$$\frac{Br(2457 \to D_S^* \gamma)}{Br(2457 \to D_S^* \pi^0)} < 0.31 \text{ (90\% c.l.)}$$

$$\frac{Br(2457 \to D_S \pi^0)}{Br(2457 \to D_S^* \pi^0)} < 0.21 \text{ (90\% c.l.)}$$

Belle (continuum) 87 fb^{-1}

$$\frac{\sigma \cdot B(2536 \to D_S \pi^+ \pi^-)}{\sigma \cdot B(2457 \to D_S \pi^+ \pi^-)} = 1.05 \pm 0.32 \pm 0.06$$

$$\frac{Br(2317 \to D_S \pi^+ \pi^-)}{Br(2317 \to D_S \pi^0)} < 0.004 \text{ (90\% c.l.)}$$

- $(2457) \to D_S \gamma$ means (2457) cannot have $J = 0$

  Conservation of angular momentum ($-J \leq \lambda_1 - \lambda_2 \leq J$)

- $(2457) \to D_S \pi^+ \pi^-$ means (2457) cannot be 0^+

  $P(D_S \pi^+ \pi^-) = (-)^{L_{Ds,\pi\pi}} P(D_S) P(\pi^+ \pi^-)$

  $P(\pi^+ \pi^-) = (-)^{L_{\pi,\pi}}$; $L_{Ds,\pi\pi} = L_{\pi,\pi}$ for $J = 0$.

  $\to$ $P(D_S \pi^+ \pi^-) = P(D_S) = -$ for $J = 0$. : Parity violation.

$B \to \bar{D} D_{SJ}$ Exclusive Decays

Full-reconstruction of B decays at $\Upsilon(4S)$

$$B \to f_1, f_2 \cdots f_n$$

Energy-momentum conservation in $\Upsilon(4S)$ frame
($E_B = E_{\rm beam}$ and $|\vec{P}_B| \sim 350$ MeV/c)

For the signal,

$$\Sigma_i^n E_i = E_B, \quad |\Sigma_i^n \vec{P}_i| = P_B$$

Use the equivalent parameters

$$\Delta E \equiv \Sigma_i^n E_i - E_B, \quad M_{bc} \equiv \sqrt{E_B^2 - |\Sigma_i^n \vec{P}_i|^2}$$

M_{bc} **: 'beam-constrained' mass**

$D_{SJ}(2317)$, (2457) in Exclusive B Decays

(Belle 115 fb^{-1})

Reconstruct

$$B^+ \to \bar{D}^0 D_{SJ}^+, \quad B^0 \to D^- D_{SJ}^+$$

using the modes

$$D_{SJ}^+ \to D_S^+ \pi^0, D_S^{*+} \pi^0, D_S^+ \gamma$$

with

$$D^0 \to K^- \pi^+, K^+ \pi^+ \pi^- \pi^+, K^- \pi^- \pi^0, \quad D^+ \to K^- \pi^+ \pi^+$$

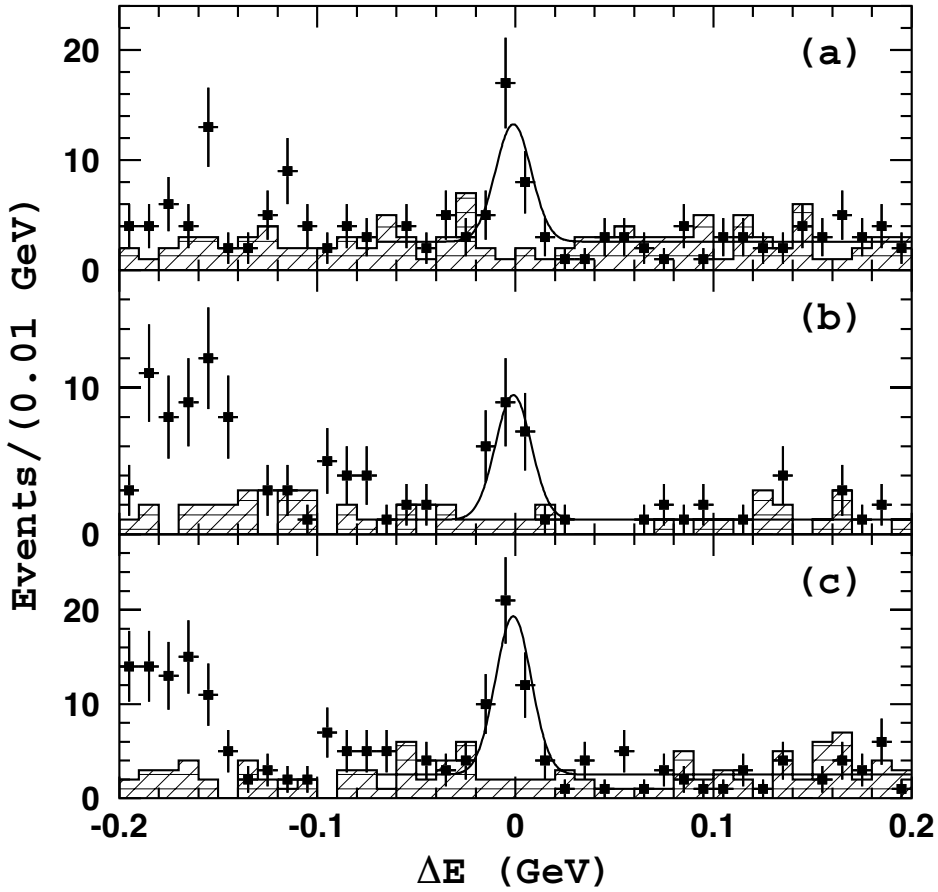
$$D_S^+ \to \phi \pi^+, \bar{K}^{*0} K^+, K_S K^+, \quad \phi \to K^+ K^-, \bar{K}^{*0} \to K^- \pi^+$$

Cut on M_{bc} and D_{SJ} masses and plot ΔE

$D_S\pi^0$

$D_S^*\pi^0$

$D_S\gamma$

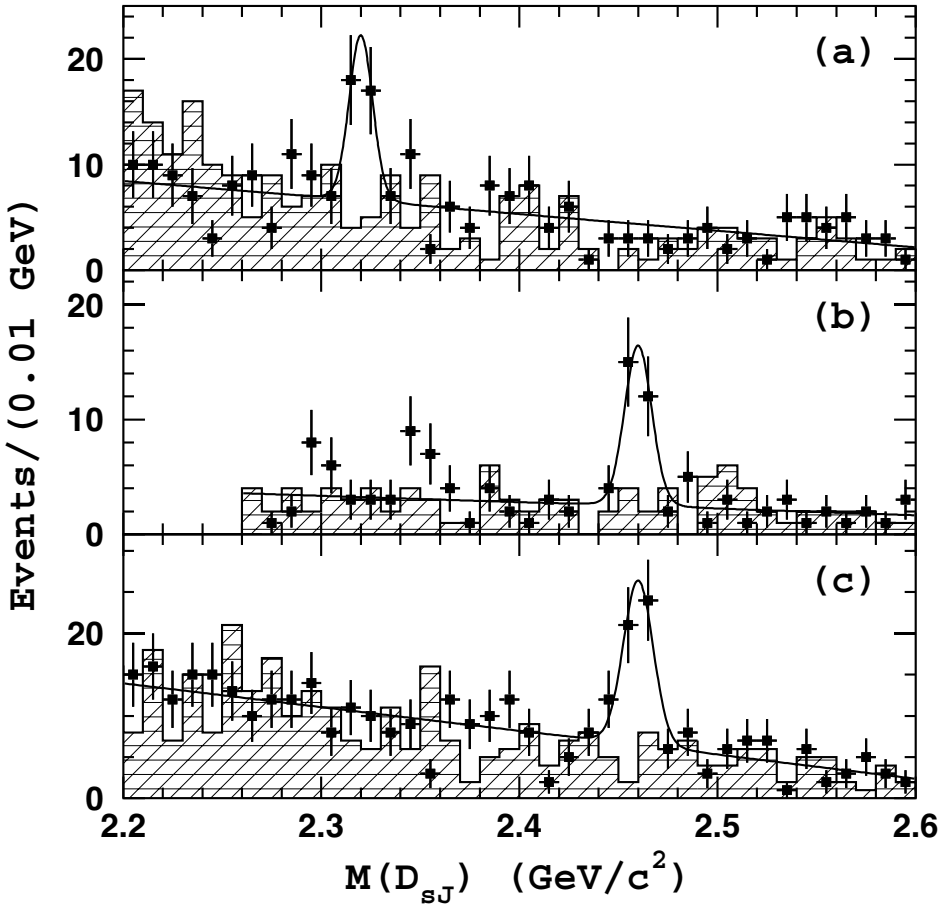


Cut on ΔE and M_{bc} and plot D_{SJ} masses

$D_S\pi^0$

$D_S^*\pi^0$

$D_S\gamma$



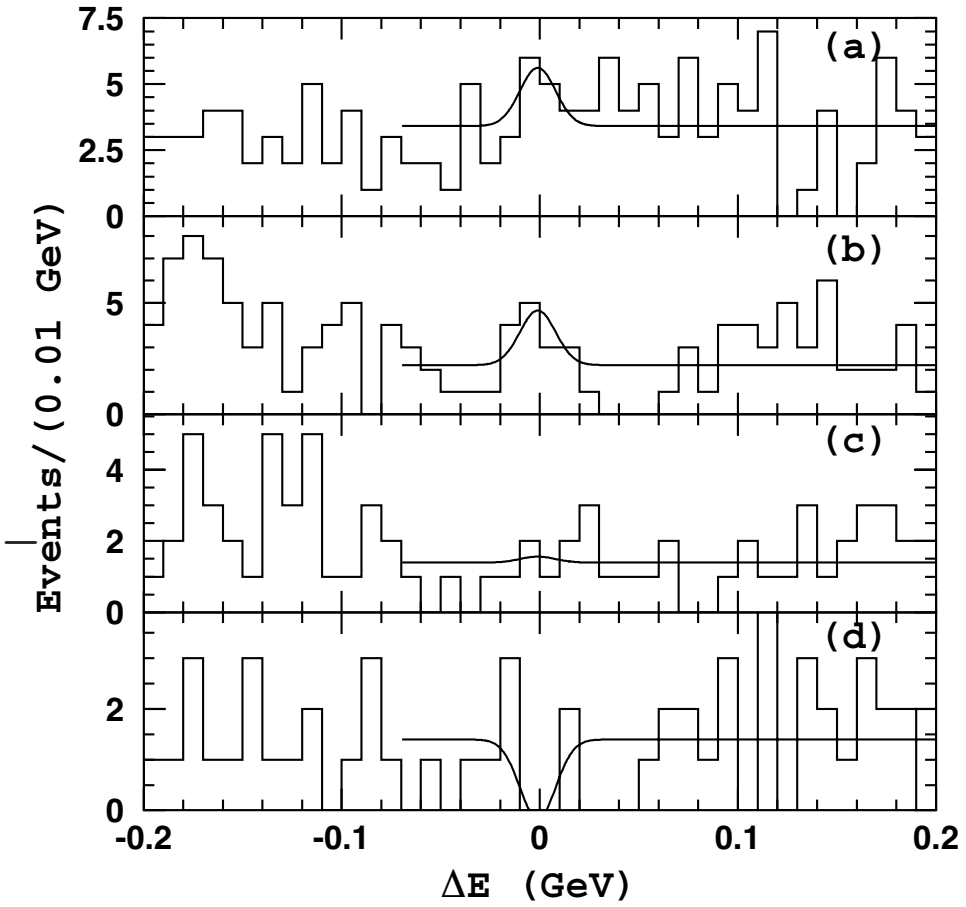
Cut on M_{bc} and D_{SJ} masses and plot ΔE

$(2317)D_S^*\gamma$

$(2457)D_S^*\gamma$

$(2457)D_S\pi^+\pi^-$

$(2457)D_S\pi^0$



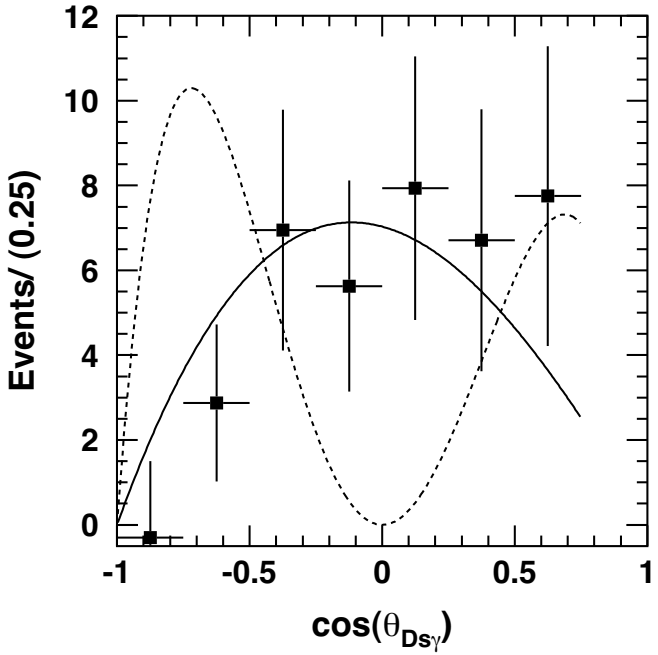
Combine isospin related modes (B^0 and B^+)

$\bar{D}D_{SJ}$	$Br(\times 10^{-4})$	significance
$2317(D_S\pi^0)$	$8.5^{+2.1}_{-1.9} \pm 2.6$	6.1σ
$2317(D_S^*\gamma)$	$2.5^{+2.0}_{-1.8}\ (< 7.5)$	1.8σ
$2457(D_S^*\pi^0)$	$17.8^{+4.5}_{-3.9} \pm 5.3$	6.4σ
$2457(D_S\gamma)$	$6.7^{+1.3}_{-1.2} \pm 2.0$	7.4σ
$2457(D_S^*\gamma)$	$2.7^{+1.8}_{-1.5}\ (< 7.3)$	2.1σ
$2457(D_S\pi^+\pi^-)$	(< 1.6)	
$2457(D_S\pi^0)$	(< 1.8)	

The systematic errors dominated by the 25% error on $Br(D_S \to \phi\pi)$

Helicity angle of $2457 \to D_S\gamma$ in $B \to \bar{D}D_{SJ}$ (not corrected for efficiency)

D_{SJ} is polarized as $|J0\rangle \to \sum_{\lambda=\pm1} |d^J_{0\lambda}(\theta)|^2$



Consistent with $J = 1$ ($\chi^2/df = 5/6$)

Inconsistent with $J = 2$ ($\chi^2/df = 44/6$)

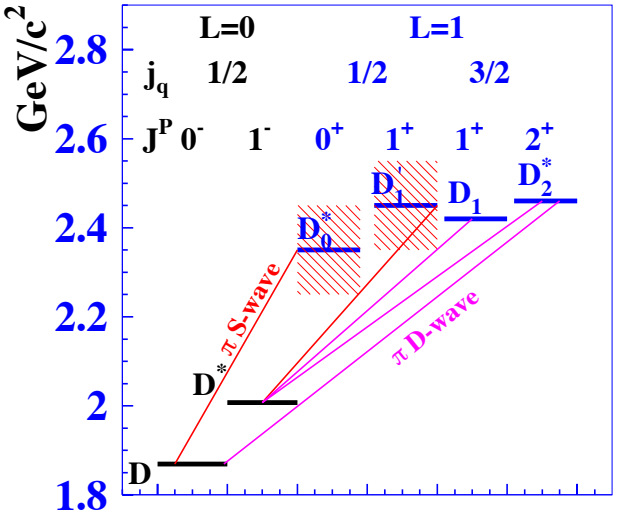
Why are (2317) and (2457) so narrow?

- $(2317)0^+ \to DK$: below threshold.
- $(2317)0^+ \to D_S\pi$ ('main' mode) : isospin breaking
- $(2317)0^+ \to D_S\pi\pi$: parity violating
- $(2317)0^+ \to D_S\gamma$: angular momentum

- $(2457)1^+ \to DK$: parity violating
- $(2457)1^+ \to D_S\pi$: parity violating
- $(2457)1^+ \to D_S^*\pi$ ('main' mode) : isospin breaking
- $(2457)1^+ \to D_S^{(*)}\gamma$: EM
- $(2457)1^+ \to D_S\pi\pi$: phase space (OZI?)

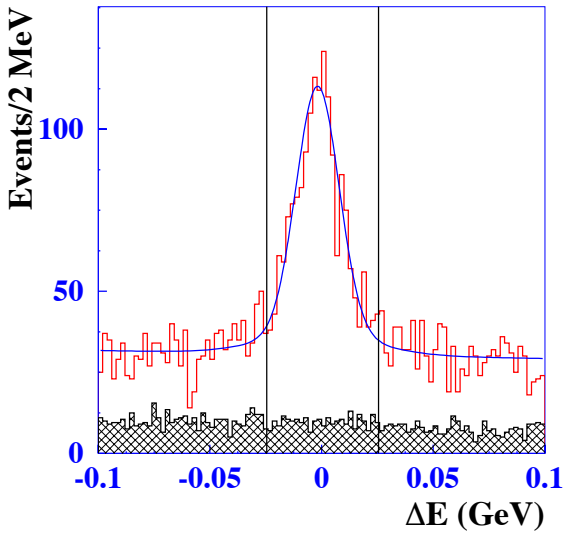
$B^- \to D^{**0}\pi^-$ (Belle 60 fb^{-1})

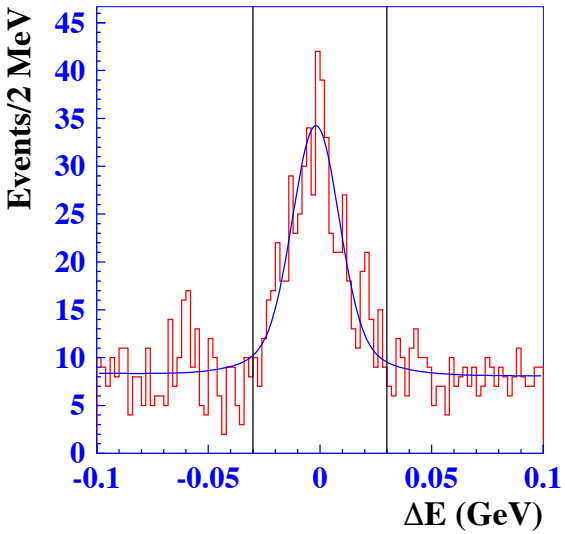
$$D^{**0} \to D^+\pi^-, \quad D^{*+}\pi^-$$



Two narrow states D_1, D_2^* had been found by CLEO.

Cut on M_{bc}, plot ΔE

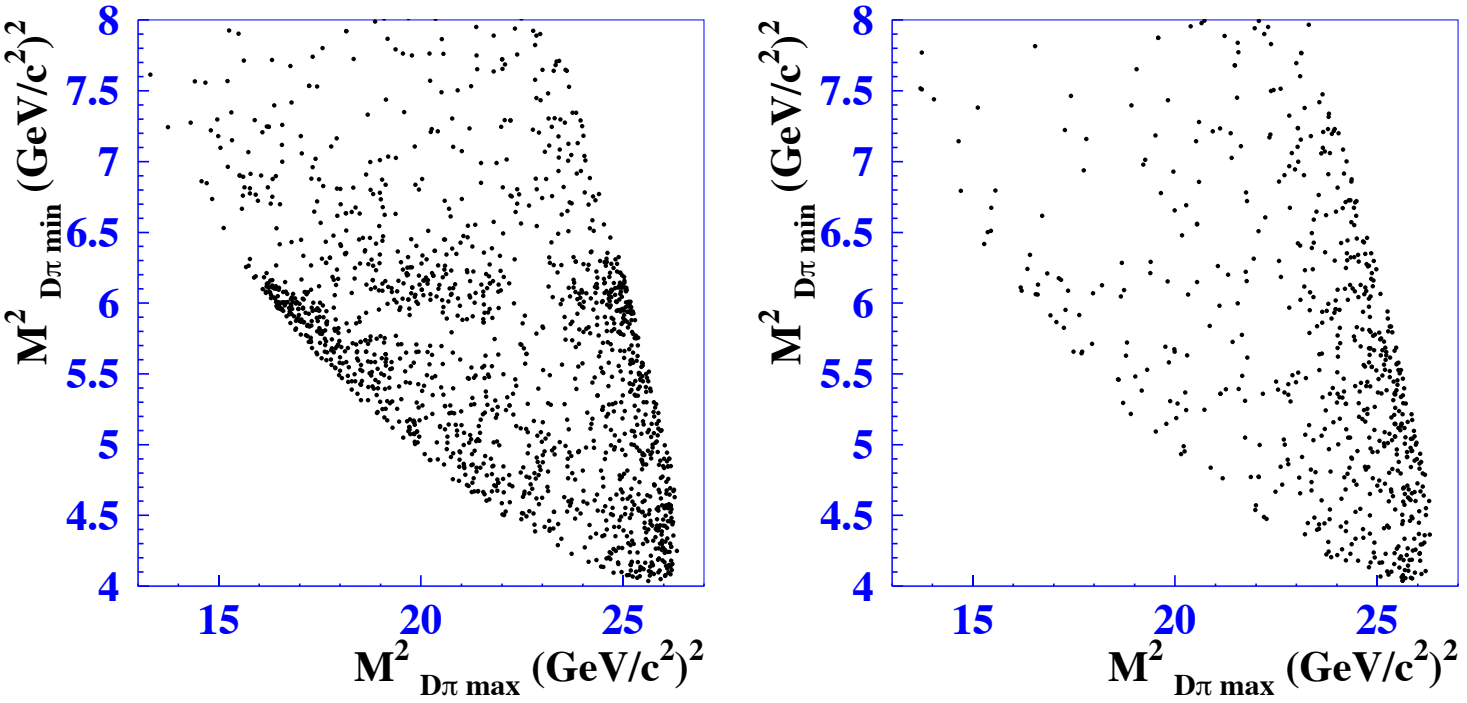




$D^+\pi^-\pi^-$ $D^{*+}\pi^-\pi^-$

$$Br(B^- \to D^+\pi^-\pi^-) = (1.02 \pm 0.04 \pm 0.15) \times 10^{-3}$$
$$Br(B^- \to D^{*+}\pi^-\pi^-) = (1.25 \pm 0.08 \pm 0.22) \times 10^{-3}$$

$D^+\pi^-\pi^-$ Dalitz plot



signal region

ΔE side-band

Fit of $D^+\pi^-\pi^-$ Dalitz plot

$$Amp(q_1^2, q_2^2) = \sum_i a_i e^{i\phi_i} A_i(q_1^2, q_2^2) + a_0 e^{i\phi_0}$$

i: resonances ($i = 0$: phase space term)

$$A_i(q_1^2, q_2^2) = F^i_{BD^{**}}(p_1) \frac{T^i(q_1, q_2)}{q_1^2 - M_i^2 + iM_i\Gamma_i(q_1^2)} F^i_{D^{**}D}(p_2) + (q_1 \leftrightarrow q_2)$$

$$T^i(q_1, q_2) = \begin{cases} 1 & (L_i = 0) \\ \frac{1}{\sqrt{q_1^2}} M_B p_1 p_2 \cos\theta & (L_i = 1) \\ \frac{1}{q_1^2} M_B^2 p_1^2 p_2^2 (\cos^2\theta - \frac{1}{3}) & (L_i = 2) \end{cases}$$

L_i : spin of the resonance

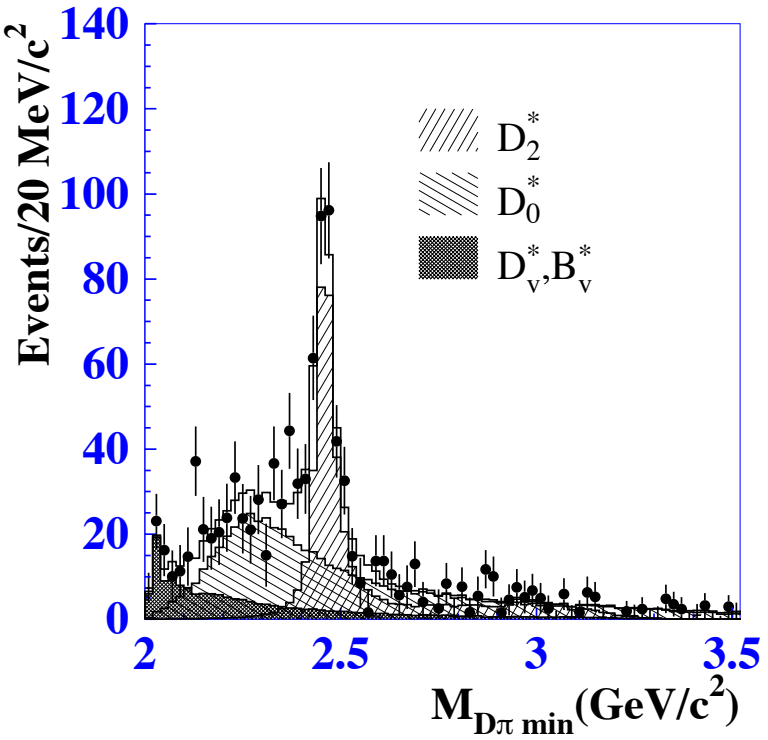
Fit components for $D^+\pi^-\pi^-$ Dalitz plot

$1^+ \not\to D\pi$: drop D_1 and D_1'

1. D_2^* (narrow)
2. D_0^* (broad)
3. D_v^* : virtual hadron of a higher mass
   $D_v^* \to D^+\pi^-$
4. B_v^* : intermediate B state
   $B \to B_v^*\pi$, $B_v^* \to D\pi$

The phase space term does not improve χ^2 much.
Not included for the final result.

$D^+\pi^-\pi^-$ Dalitz plot projection



Each contribution shown are incoherent.

The fit curve is coherent.

$D^+\pi^-\pi^-$ Dalitz plot fit results

(NEW)

$$M_{D_0^{*0}} = 2308 \pm 17 \pm 15 \pm 28\text{MeV}$$
$$\Gamma_{D_0^{*0}} = 276 \pm 21 \pm 18 \pm 60\text{MeV}$$

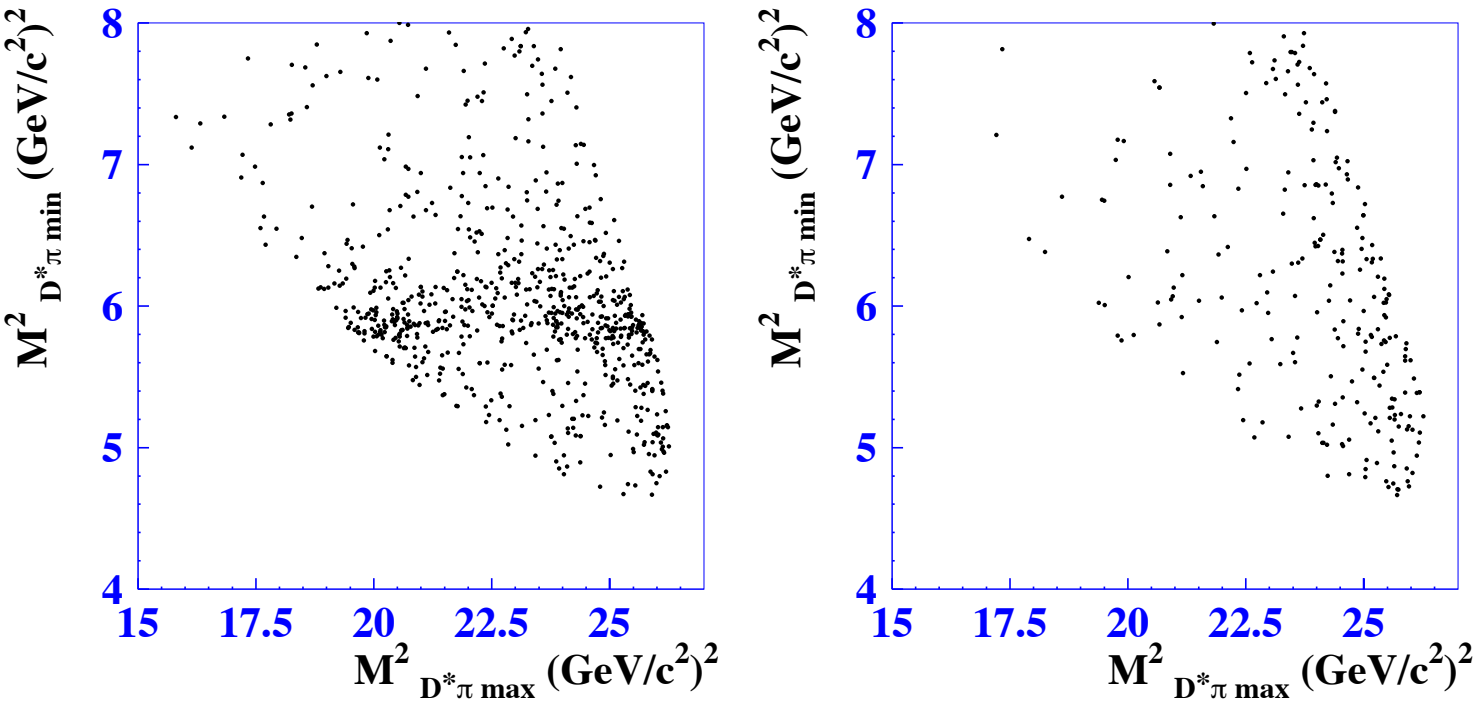
$$M_{D_2^{*0}} = 2461.6 \pm 2.1 \pm 0.5 \pm 3.3\text{MeV}$$
$$\Gamma_{D_2^{*0}} = 45.6 \pm 4.4 \pm 6.5 \pm 1.6\text{MeV}$$

$$Br(B^- \to D_2^{*0}\pi^-)Br(D_2^{*0} \to D^+\pi^-) = (3.4 \pm 0.3 \pm 0.6 \pm 0.4) \times 10^{-4}$$

$$Br(B^- \to D_0^{*0}\pi^-)Br(D_0^{*0} \to D^+\pi^-) = (6.1 \pm 0.6 \pm 0.9 \pm 1.6) \times 10^{-4}$$

Last errors are model-dependence of the Dalitz fit.

$D^{*+}\pi^-\pi^-$ Dalitz plot

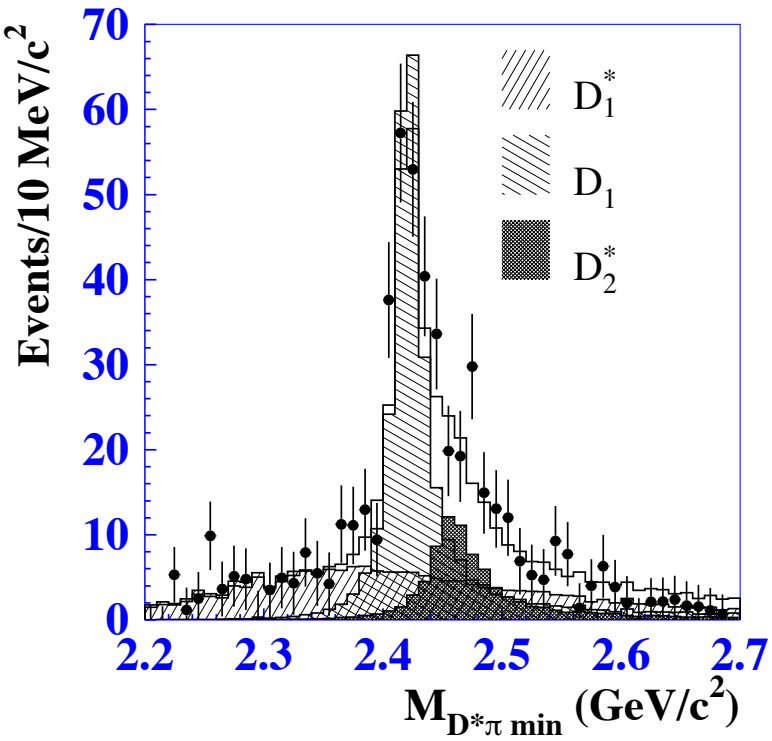


signal region

ΔE side-band

$D^{*+}\pi^-\pi^-$ Dalitz plot projection

Include the D^* decay helicity angle in the fit.



M and Γ of D_2^* are fixed to the values of $D\pi\pi$ fit.

$D^{*+}\pi^-\pi^-$ fit results

$$M_{D_1^0} = 2421.4 \pm 1.5 \pm 0.4 \pm 0.8\text{MeV}$$
$$\Gamma_{D_1^0} = 23.7 \pm 2.7 \pm 0.2 \pm 4.0\text{MeV}$$

(NEW)

$$M_{D_1'^0} = 2427 \pm 26 \pm 20 \pm 15\text{MeV}$$
$$\Gamma_{D_1'^0} = 384^{+107}_{-75} \pm 24 \pm 70\text{MeV}$$

$$Br(B^- \to D_1^0\pi^-)Br(D_1^0 \to D^{*+}\pi^-) = (6.8 \pm 0.7 \pm 1.3 \pm 0.3) \times 10^{-4}$$

$$Br(B^- \to D_1'^0\pi^-)Br(D_1'^0 \to D^{*+}\pi^-) = (5.0 \pm 0.4 \pm 1.0 \pm 0.4) \times 10^{-4}$$

$$Br(B^- \to D_2^{*0}\pi^-)Br(D_2^{*0} \to D^{*+}\pi^-) = (1.8 \pm 0.3 \pm 0.3 \pm 0.2) \times 10^{-4}$$

Do the masses make sense?

Compare mesons of the same configuration with $s \leftrightarrow u$ only.
Expect $M(c\bar{s}) - M(c\bar{u}) \sim 100$ MeV :

$$(L = 0, j_l = 1/2)$$

$$(0^-) \quad M(D_s) - M(D^0) = 113.2 \pm 2.0 \text{ MeV}$$
$$(1^-) \quad M(D_s^*) - M(D^{*0}) = 110.8 \pm 3.9 \text{ MeV}$$

$$(L = 1, j_l = 3/2)$$

$$(1^+) \quad M(D_{s1}) - M(D_1^0) = 104.0 \pm 0.8 \text{ MeV}$$
$$(2^+) \quad M(D_{s2}) - M(D_2^0) = 105.7 \pm 0.9 \text{ MeV}$$

But, for $(L = 1, j_l = 1/2)$

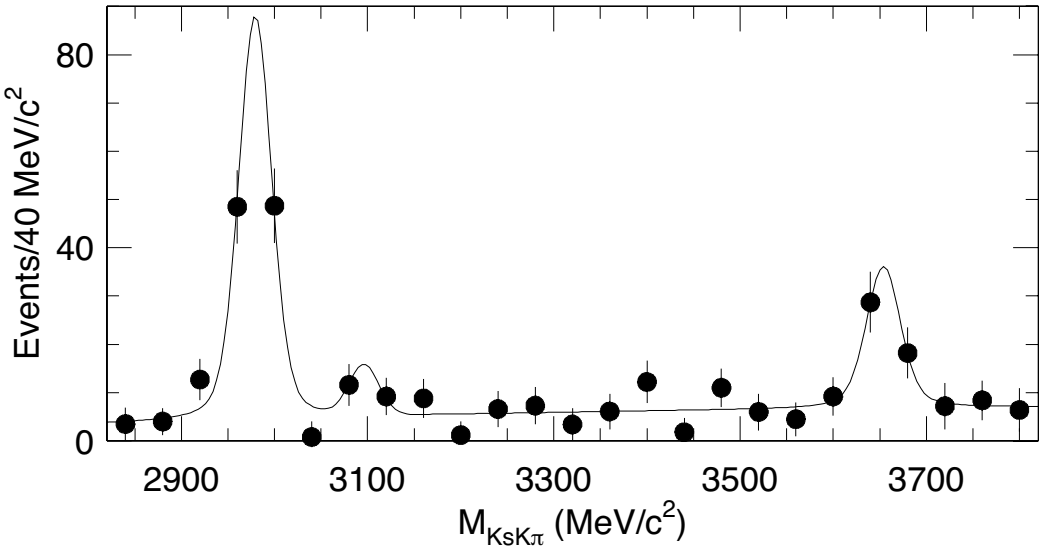
$$(0^+) \quad M(D_s(2317)) - M(D_0^*) = 9 \pm 36 \text{ MeV}$$
$$(1^+) \quad M(D_s(2457)) - M(D_1') = 30 \pm 36 \text{ MeV}$$

Chiral symmetry ($0^- \leftrightarrow 0^+$, $1^- \leftrightarrow 1^+$ in $j_l = 1/2$) ?

$B \to \eta_c' K^+/K_s$ (Belle 41.8 fb^{-1})

$$\eta_c' \to K_s K^- \pi^+ + c.c.$$

$\eta_c'(0^-)$, $h_c(1^+)$: last 2 $(c\bar{c})$'s expected below $D\bar{D}$ threshold.



Fit B signal in each $M(K_s K\pi)$ bin

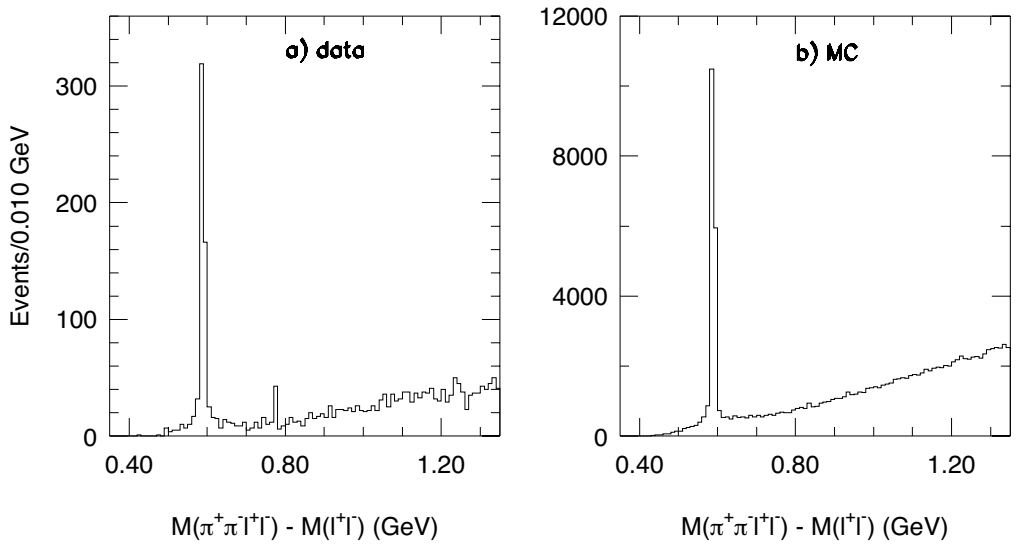
$M(\eta_c') = 3654 \pm 6 \pm 8\text{MeV}$ (near upper end of pot. model)
$\Gamma(\eta_c') = 15^{+24}_{-15}$ MeV (< 55 MeV 90% c.l.)

$\mathcal{B}(B \to \eta_c' K)\mathcal{B}(\eta_c' \to K_s K\pi)/(\eta_c' \to \eta_c) = 0.38 \pm 0.12 \pm 0.05$
(consistent with η_c')

$B^- \to X(3872)K^-$ (Belle 140 fb^{-1})

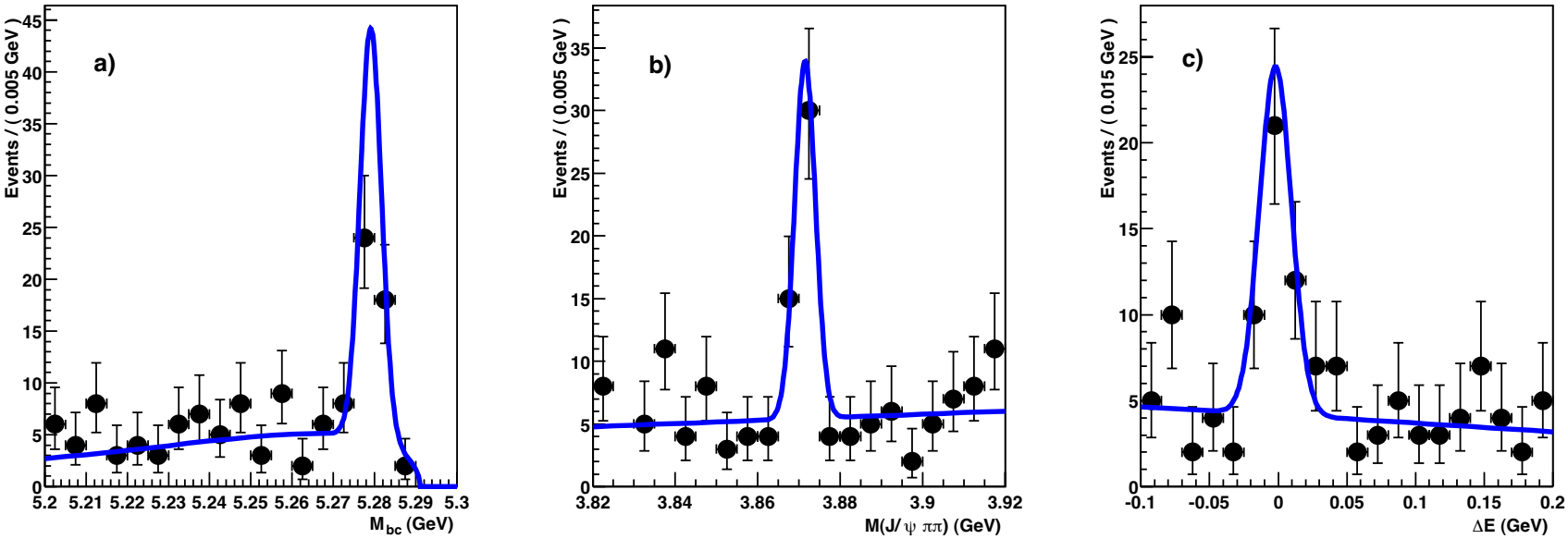
$$X(3872) \to J/\Psi\pi^+\pi^-$$

Cut on ΔE and M_{bc} and plot $M(J/\Psi\pi^+\pi^-)$



$B^- \to X(3872)K^-,\ X(3872) \to J/\Psi\pi^+\pi^-$

$(\Delta E,\ M_{bc},\ M(J/\Psi\pi^+\pi^-))$:
cut on others except oneself



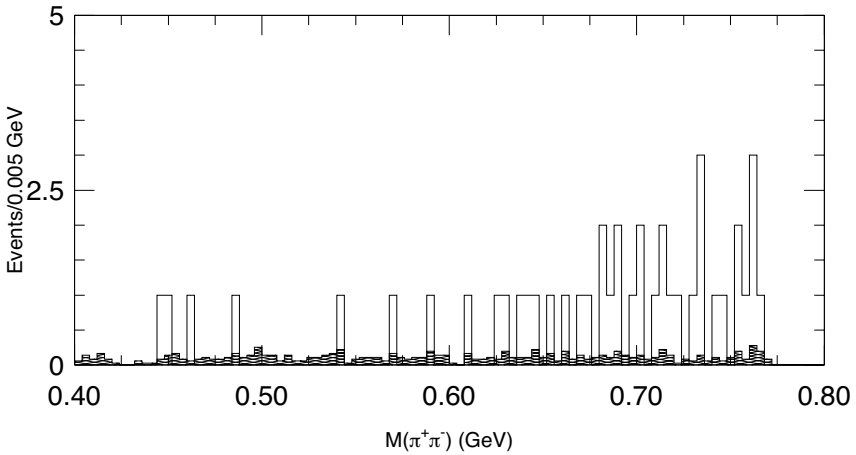
After cutting on $X(3872)$, clear signal in ΔE and M_{bc}

35.7 ± 6.8 events

$$M_X = 3872.0 \pm 0.6 \pm 0.5 \text{ MeV}, \quad \Gamma_X < 2.3\text{MeV (90\% c.l.)}$$

$$\frac{\mathcal{B}(B \to X(3872)K)\mathcal{B}(X(3872) \to J/\Psi\pi\pi)}{(X(3872) \to \Psi')} = 0.063 \pm 0.012 \pm 0.007$$

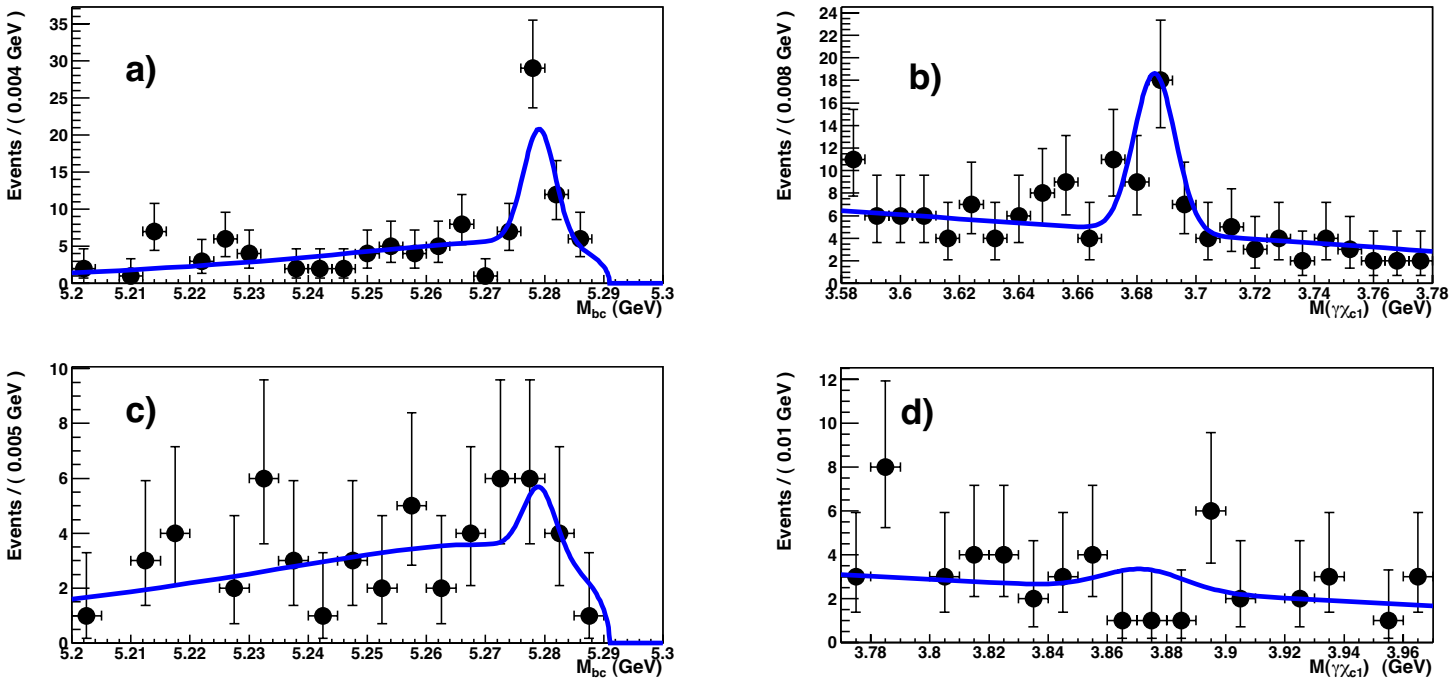
$M_{\pi^+\pi^-}$ in $X(3872) \to J/\Psi\pi^+\pi^-$



The shaded area : ΔE-M_{bc} side-band
$M_{\pi^+\pi^-}$ is quite high.

$M_D + M_{D^*} = 3875\text{MeV}$: DD^* molecule? hybrid?

$X(3872) \to \chi_{c1}\gamma$?



(a),(b): Ψ', (c),(d): χ_{c1}

$$\frac{\Gamma(X(3872) \to \chi_{c1}\gamma)}{\Gamma(X(3872) \to J/\Psi\pi^+\pi^-)} < 0.89\ (90\%\ c.l.)$$

Summary

B-factory is an extremely rich hadron factory.
Both in continuum and B decays.

The kinamatic constraint of B decay is a powerful tool
for background suppression as well as determination
of quantum numbers.