Hadron Spectroscopies at B-Factories

Hitoshi Yamamoto
Tohoku University

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Plan:

1. D_{SJ} productions in $e^+e^- \to c\bar{c}$ continuum
2. D_{SJ} productions in exclusive B decays
3. D^{**} in $B \to D^{(*)}\pi^+\pi^-$
4. $J/\Psi\pi^+\pi^+$ (3872)

e^+e^- B-Factories

$$e^+e^- \to \Upsilon(4S) \to B^0\bar{B}^0, B^+B^-$$

$$e^+e^- \to u\bar{u}, d\bar{d}, s\bar{s}, c\bar{c} \text{ (continuum)}$$

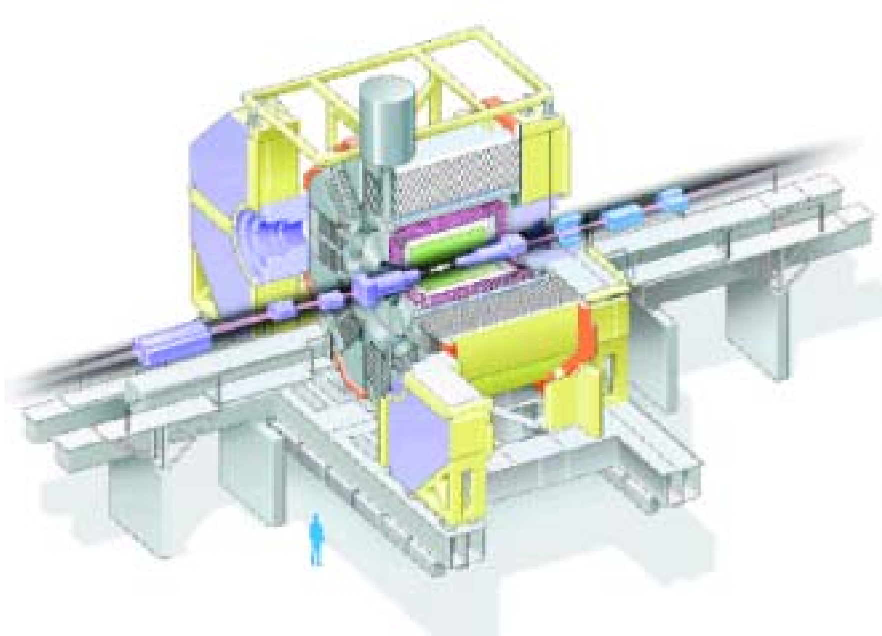
	PEPII(BaBar)	KEKB(Belle)	CESR(CLEO)
type	asymmetric	asymmetric	symmetric
#ring	double	double	single
E_{beam} (GeV)	$9(e^-)/3.1(e^+)$	$8(e^-)/3.5(e^+)$	$5.29(e^\pm)$
$\beta_{\Upsilon(4S)}$ in lab.	0.49	0.39	0
full xing angle	0 mrad	22 mrad	4.6 mrad
$\mathcal{L}_{\max}(\times 10^{33}/\text{cm}^2\text{s})$	7.93	11.35	1.25
$\int \mathcal{L}dt$ (recd. fb^{-1})	167	197	13.7
off resonance	$\sim 10\%$	$\sim 10\%$	$\sim$1/3

Basic design: Vertexing(Si)-Central tracker(DC)-PID-SC coil
-EM calorimeter(CsI)-Muon system(RPC)

BaBar detector

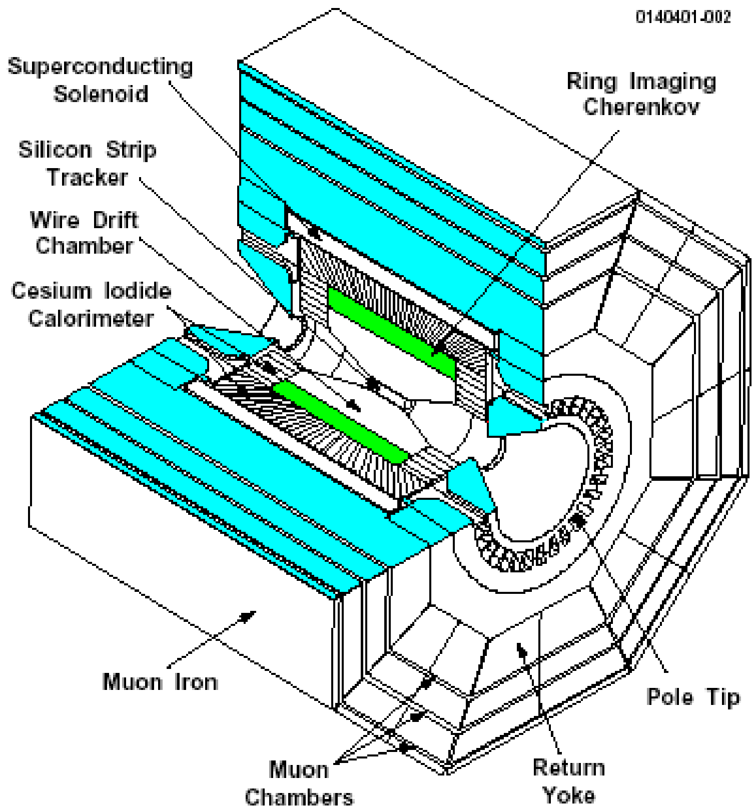
- PID=DIRC(Cerenkov)

Belle detector



- PID=Aerogel+TOF

CLEO detector



- PID=Ring-imaging Cherenkov

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

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

The total angular momentum of the light degree of freedom:

$$\vec{j} = \vec{L} + \vec{s}_q$$

$$\text{Parity} = -(-)^L$$

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

Expect,
$j = 1/2$: broad (S-wave π emission)
$j = 3/2$: narrow (No S-wave π emission)

$$D_{SJ} \to D^{(*)}\pi \;:\; (j) \to (\tfrac{1}{2}) + \pi$$

Suprise by BaBar on $c\bar{s}$ (continuum)

Narrow states had been established by CLEO

$$D_{s1}(2536) \longrightarrow D^{*}K$$
$$D_{s2}(2573) \longrightarrow D^{0}K^{+}$$

Consistent with $j = 3/2$ states 1^{+} and 2^{+}

BaBar looked for $D_{sJ}^{+} \longrightarrow D_{S}^{+}\pi^{0}$ (isospin breaking!)

$$D_{S} \longrightarrow K^{+}K^{-}\pi^{+}, K^{+}K^{-}\pi^{+}\pi^{0}$$

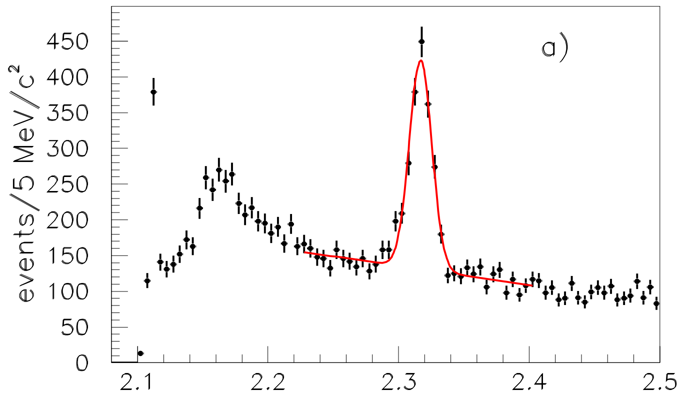
Select $\phi \longrightarrow K^{+}K^{-}$ or K^{*}

$p^{*}(D_{S}^{+}\pi^{0}) > 3.5\mathrm{GeV/c}$ (continuum)

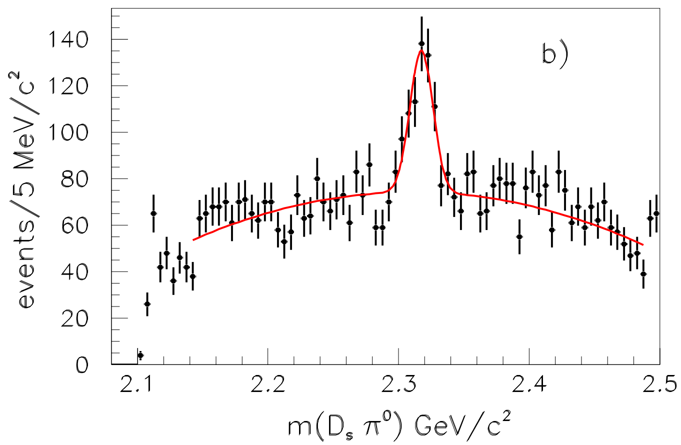
Plot $M(D_S\pi^0)$ with $M(D_S)$ constraint

BaBar (91 fb^{-1})

(a) $D_S \rightarrow K^+K^-\pi^+$



(b) $D_S \rightarrow K^+K^-\pi^+\pi^0$



$M = 2317 \pm 1.3$ MeV

And narrow!

($\Gamma \sim 10$ MeV or less)

Decay to $D_S\pi^0$ means the spin-parity is

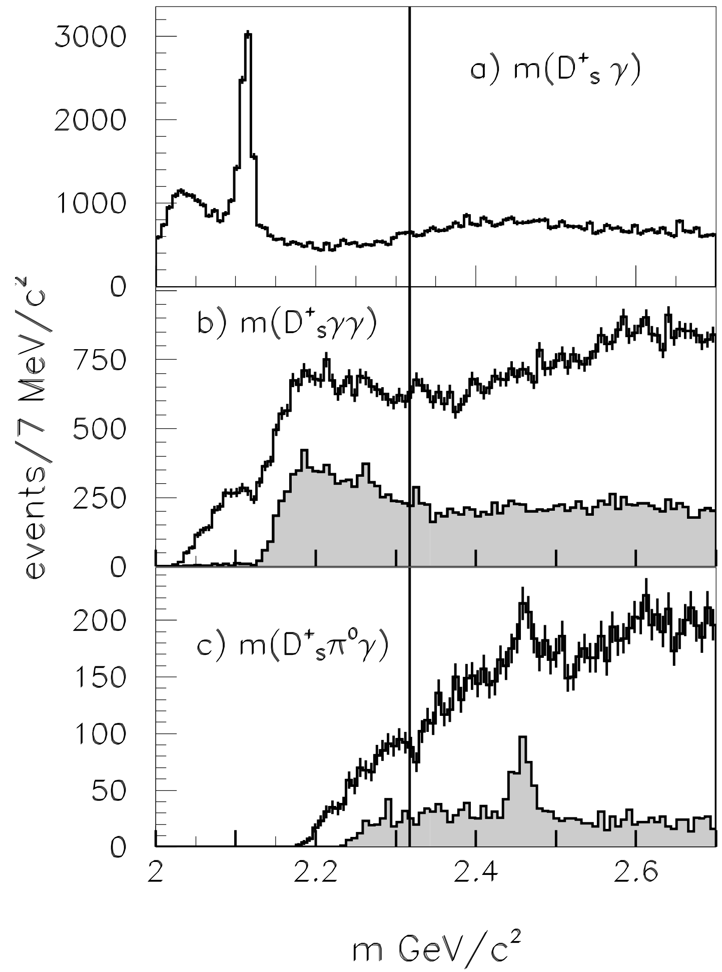
$$J^{(-)^J} = 0^+, 1^-, 2^+, \cdots$$

BaBar (91 fb^{-1})
(b) $\gamma\gamma$ not π^0
(c) $D_S\gamma$ is D_S^*

- **No $(2317) \rightarrow D_S\gamma$**
- **No $(2317) \rightarrow D_S^*\pi^0$**

Consistent with $J = 0$

What is the peak at 2.46 GeV?



If the peak 2.46 GeV is real

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

E_{π^0} = 372 MeV/c (in D_S frame)

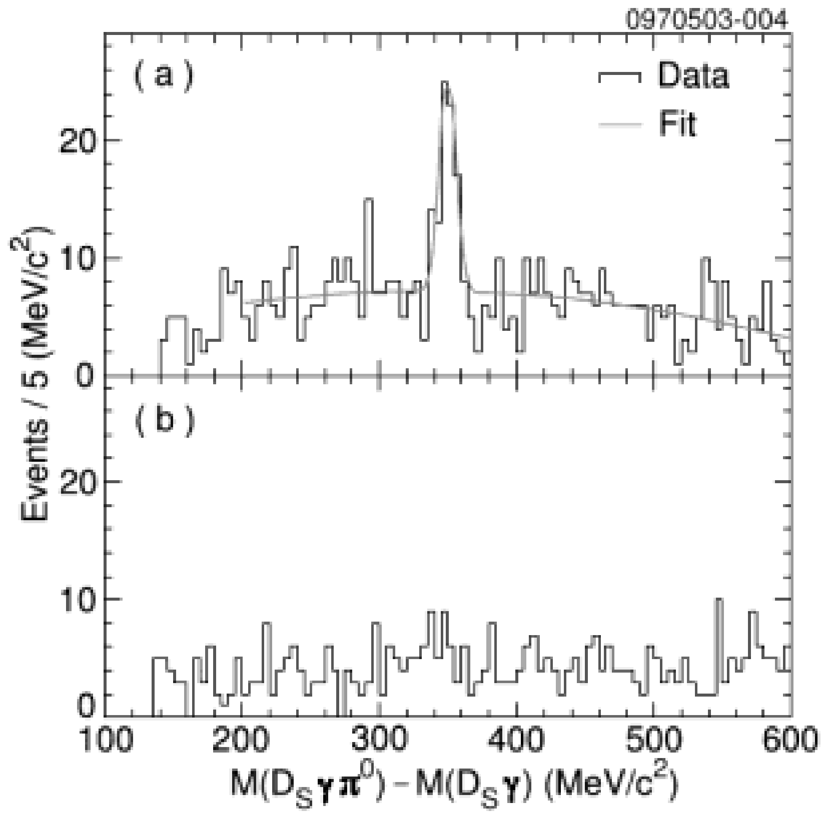
$$\pi^0 \longleftarrow (2460) \longrightarrow D_S^*$$
$$D_S^* \rightarrow D_S\gamma$$

E_{π^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

$M(D_S^*\pi^0) - M(D_S^*)$

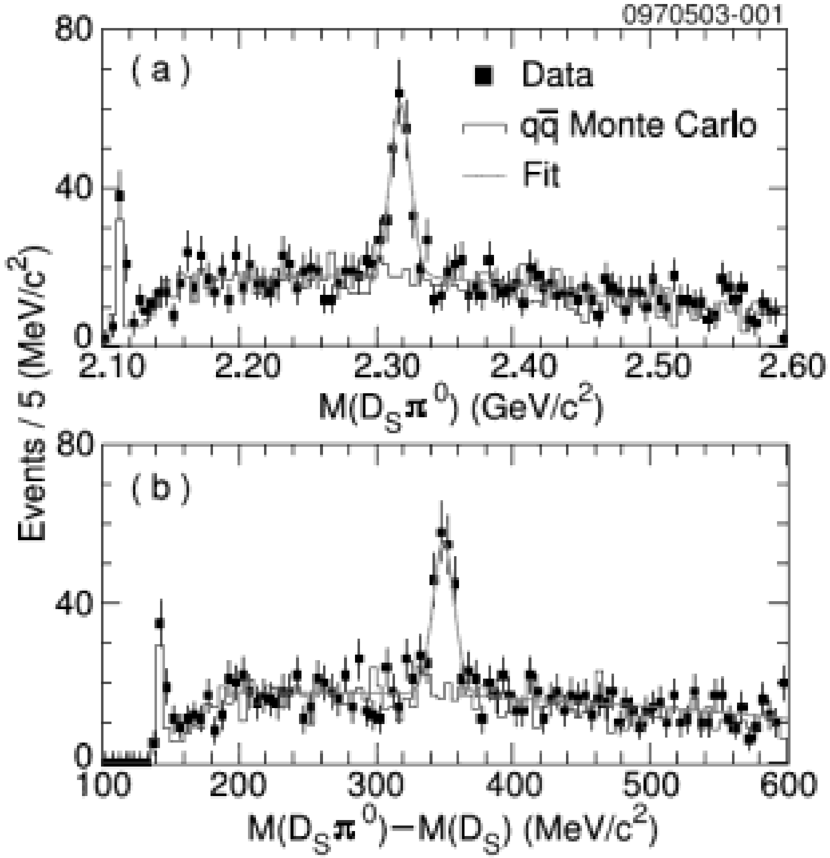
$=351.2 \pm 1.7 \pm 1.0$ MeV

($M = 2463.6$ 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 $D_S\pi^0$

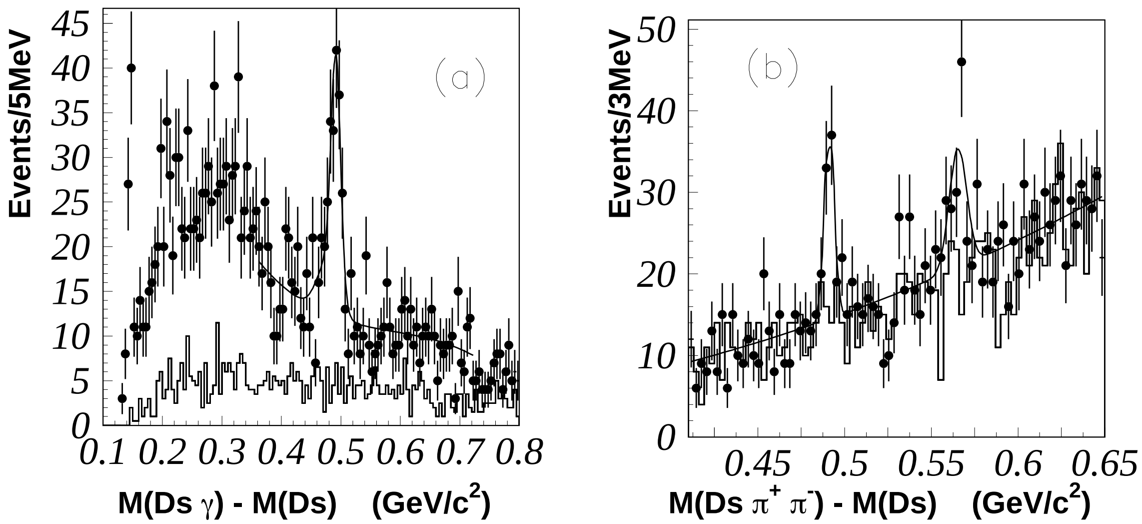
$M(D_S\pi^0) - M(D_S)$
$=350.0 \pm 1.2 \pm 1.0$ **MeV**
$(M = 2318.5$ **MeV)**

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

$$\frac{\sigma \cdot B}{\sigma(D_S)} = (7.9\pm1.2\pm0.4)\times10^{-2}$$

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

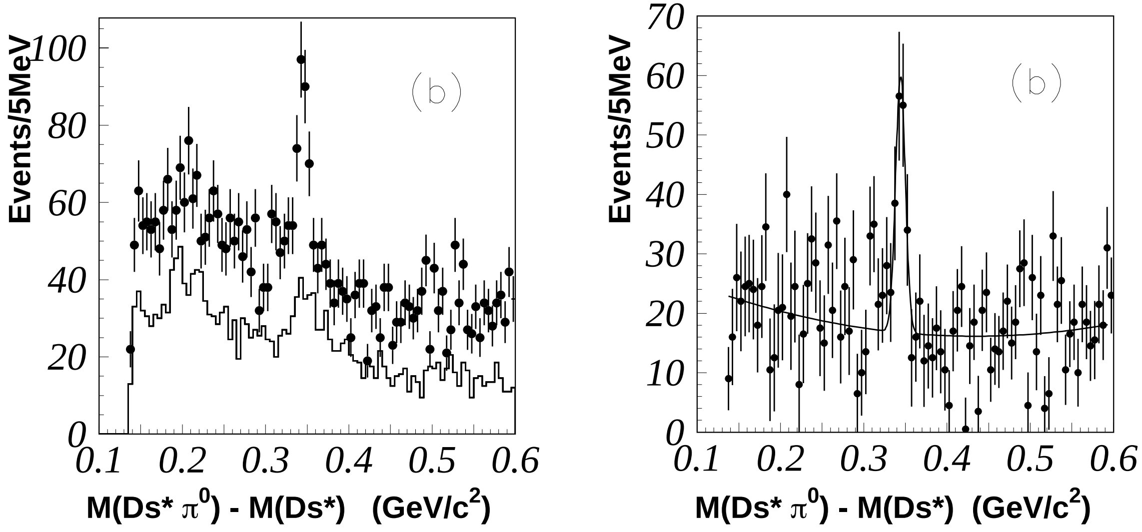
Belle sees $D_{SJ}(2456) \to D_S\gamma, D_S\pi^+\pi^-$ (87 fb^{-1}) (continuum)



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

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

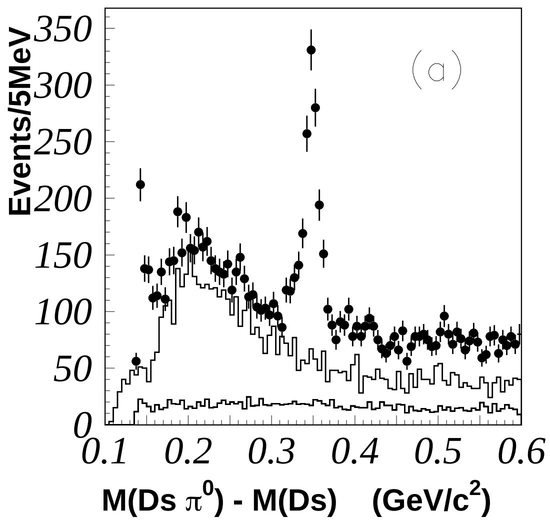
Belle confirms $D_{SJ}(2456)$ (87 fb^{-1})

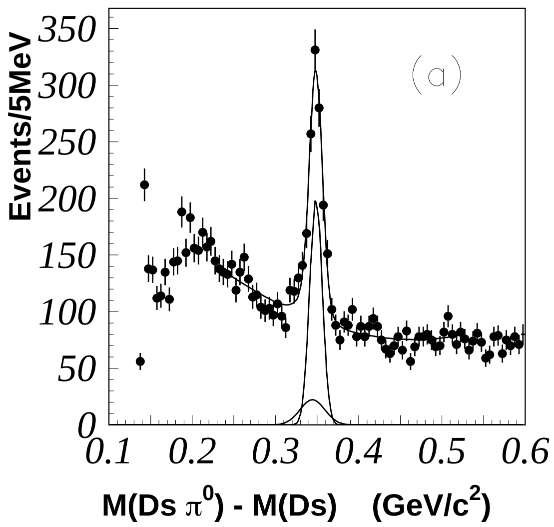


D_S^* sideband subtraction removes the 'feedup' from (2317)
as well as $(2457) \to D_S^* \pi^0$, $D_S^* \to D_S \gamma(\text{lost}) + \gamma(\text{random})$

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

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





'Feed-down' estimated by MC

$$M(2317) = 2317.2 \pm 0.5 \pm 0.9 \text{ MeV}$$

$$\Gamma(2457) < 4.6 \text{ MeV (90\% c.l.)}$$

Belle (continuum) (87 fb^{-1})

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

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

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

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

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

Belle (continuum) (87 fb^{-1})

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

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

- $(2457) \longrightarrow D_S\gamma$ means (2457) cannot have $J = 0$
  Conservation of angular momentum ($-J \leq \lambda_1 - \lambda_2 \leq J$)

- $(2457) \longrightarrow D_S\pi^+\pi^-$ 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 $J = 0$.
  $\longrightarrow$ $P(D_S\pi^+\pi^-) = P(D_S) = -$ for $J = 0$. Parity violation.

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

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

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

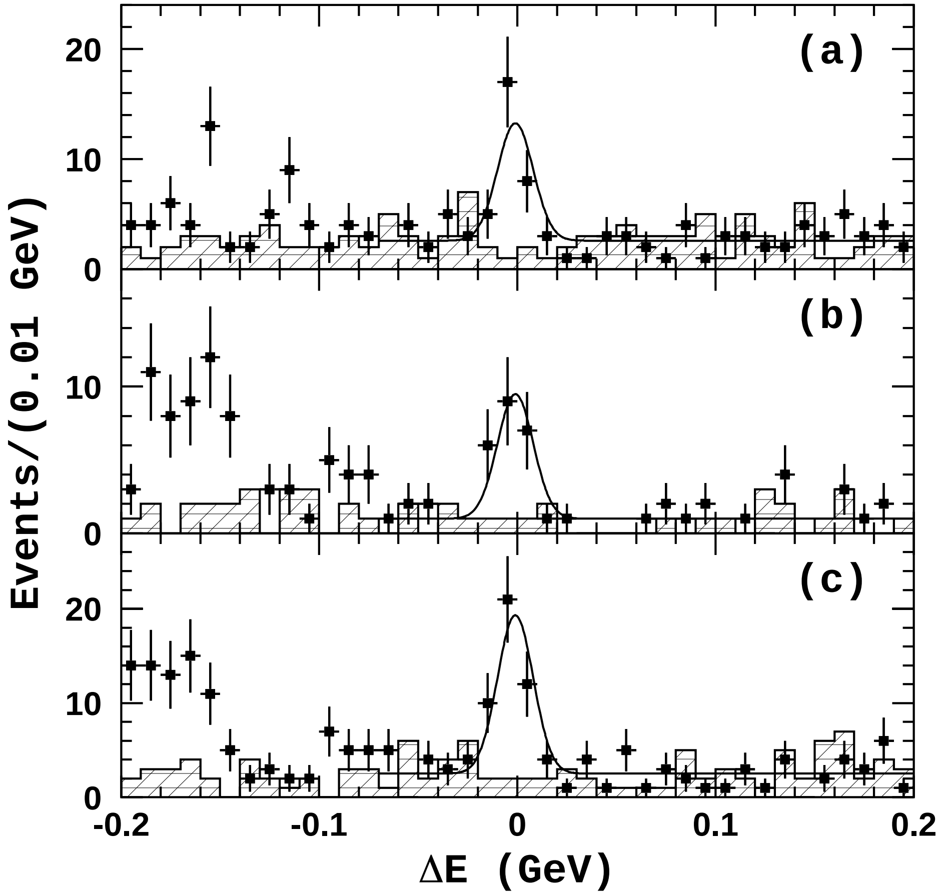
$$D_S^+ \to \phi \pi^+, \bar{K}^{*0} K^+, K_S K^+, \quad \phi \to K^+ K^-, \bar{K}^{*0} \to K^- \pi^+$$

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

$D_S\pi^0$

$D_S^*\pi^0$

$D_S\gamma$

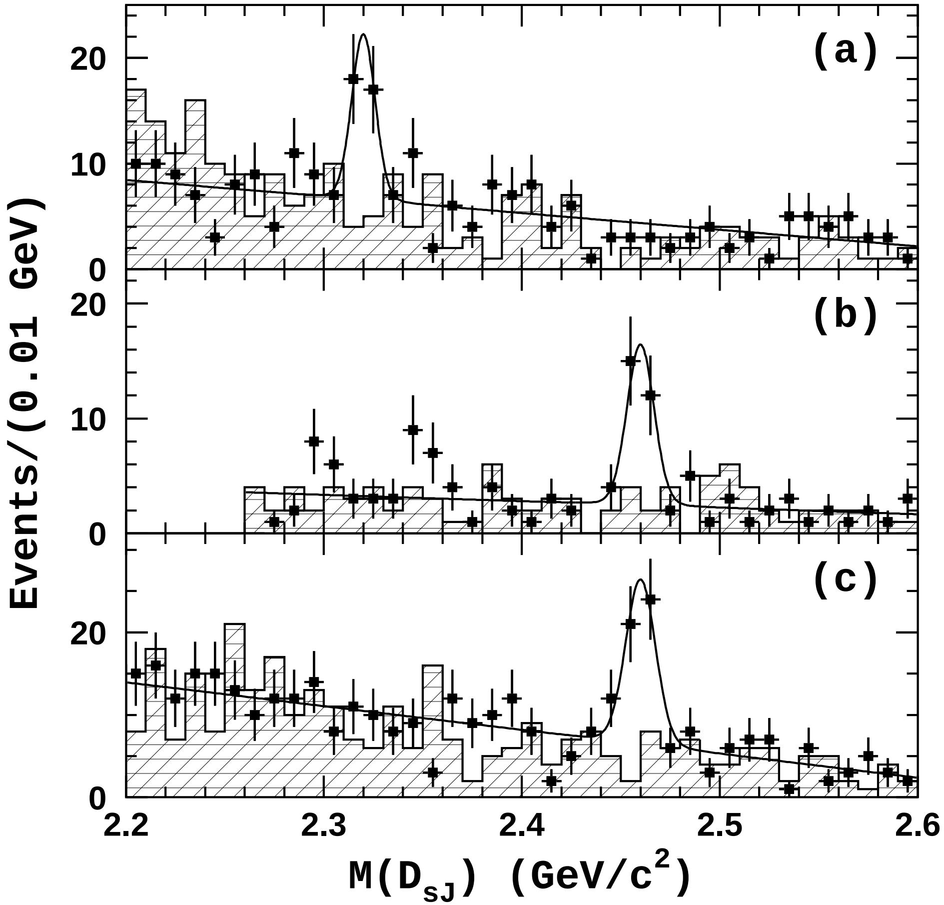


Cut on ΔE and M_{bc} and plot D_{SJ} masses

$D_S\pi^0$

$D_S^*\pi^0$

$D_S\gamma$



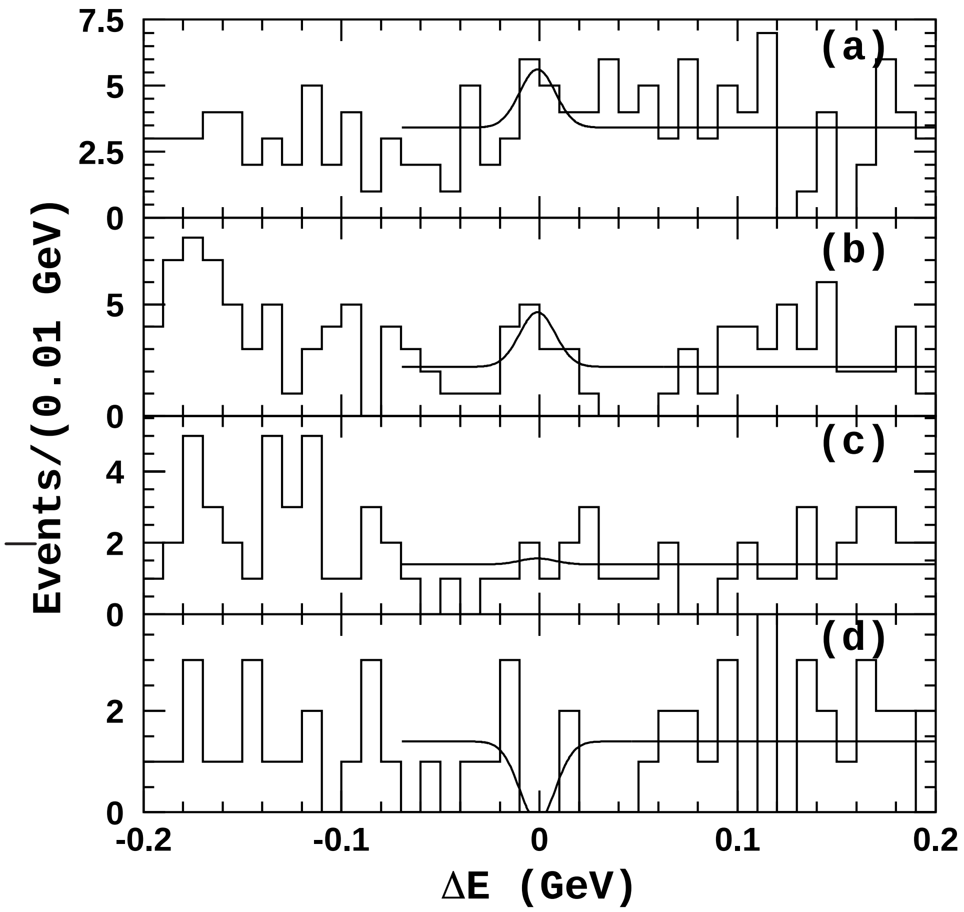
Cut on M_{bc} and D_{SJ} masses and plot ΔE

$(2317)D_S^*\gamma$

$(2457)D_S^*\gamma$

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

$(2457)D_S\pi^0$



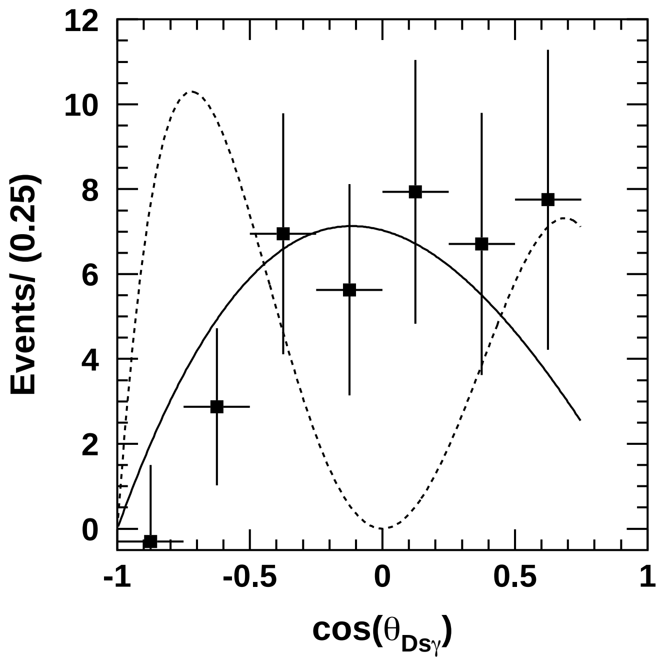
Combine isospin related modes

$\bar{D}D_{SJ}$	$Br(\times 10^{-4})$	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)	7.4σ
$2457(D_S\pi^+\pi^-)$	(< 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 $|J0\rangle \to \sum_{\lambda=\pm 1} |d^J_{0\lambda}(\theta)|^2$



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

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

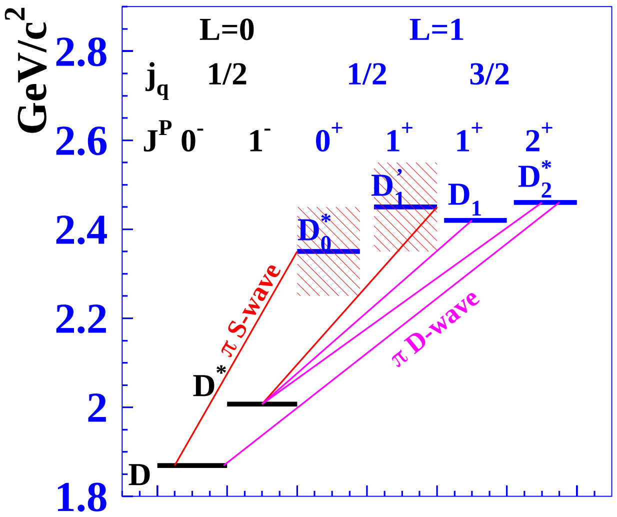
Why are (2317) and (2457) so narrow?

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

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

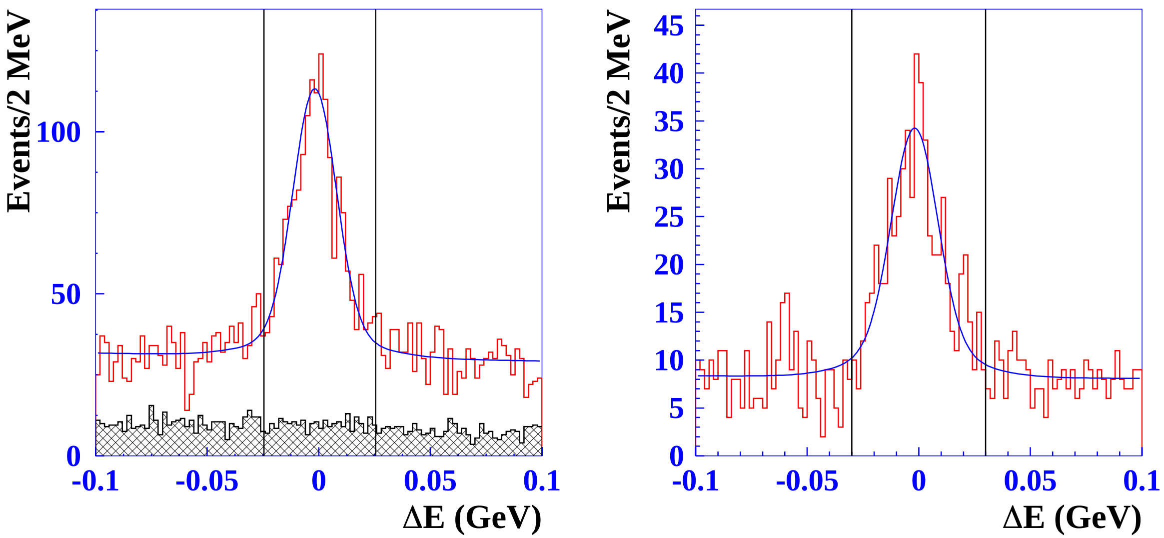
$B^- \to D^{**0}\pi^-$ by Belle (60 fb^{-1})

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



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

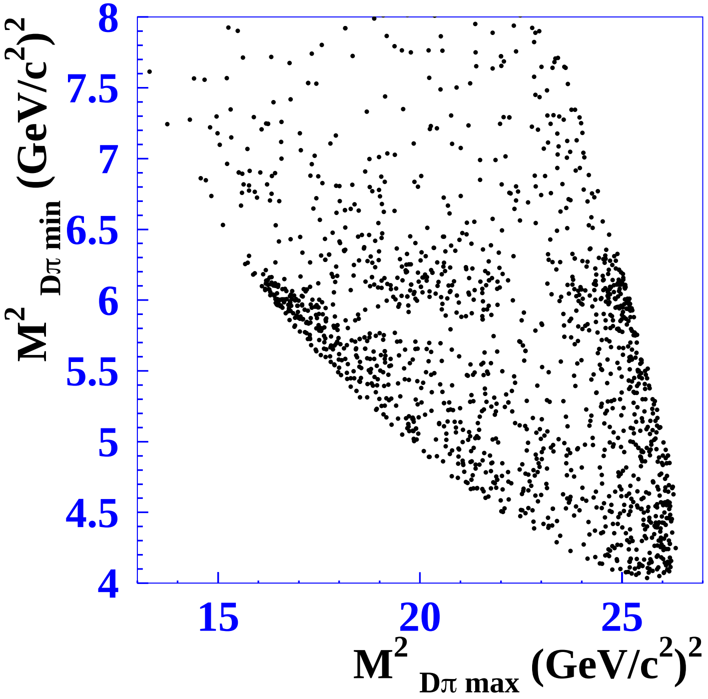
Cut on M_{bc}, plot ΔE

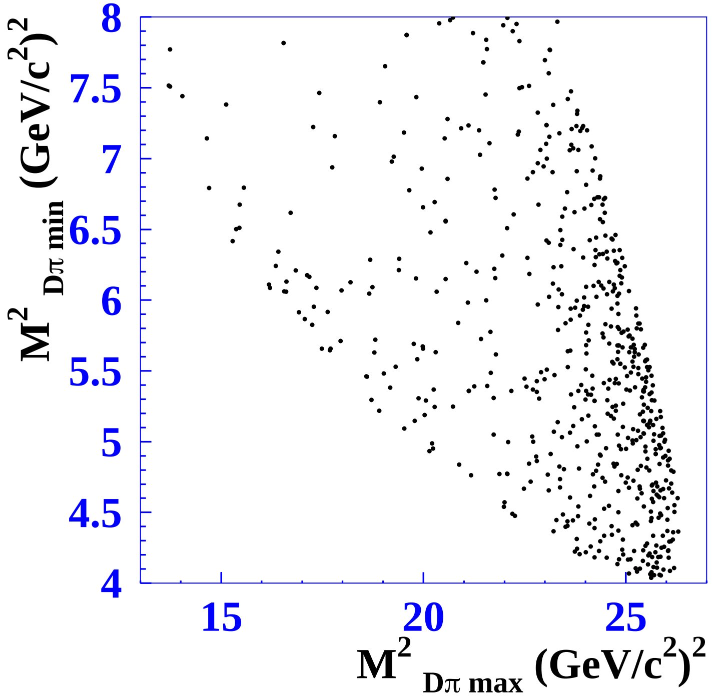


$D^+\pi^-\pi^-$ $\qquad\qquad$ $D^{*+}\pi^-\pi^-$

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

$D^+\pi^-\pi^-$ 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

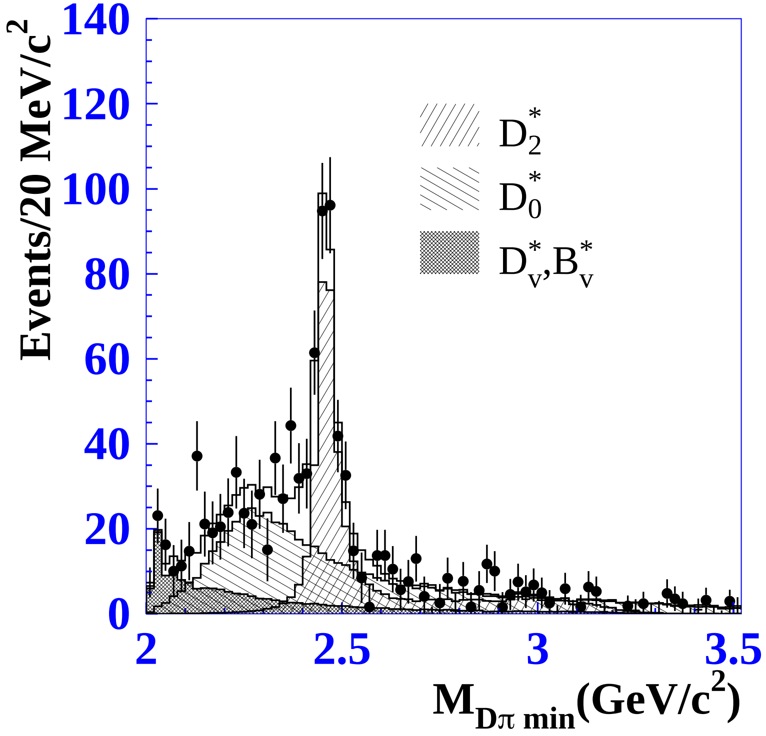
Fit components for $D^+\pi^-\pi^-$ Dalitz plot

$1^+ \not\to D\pi$: 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

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

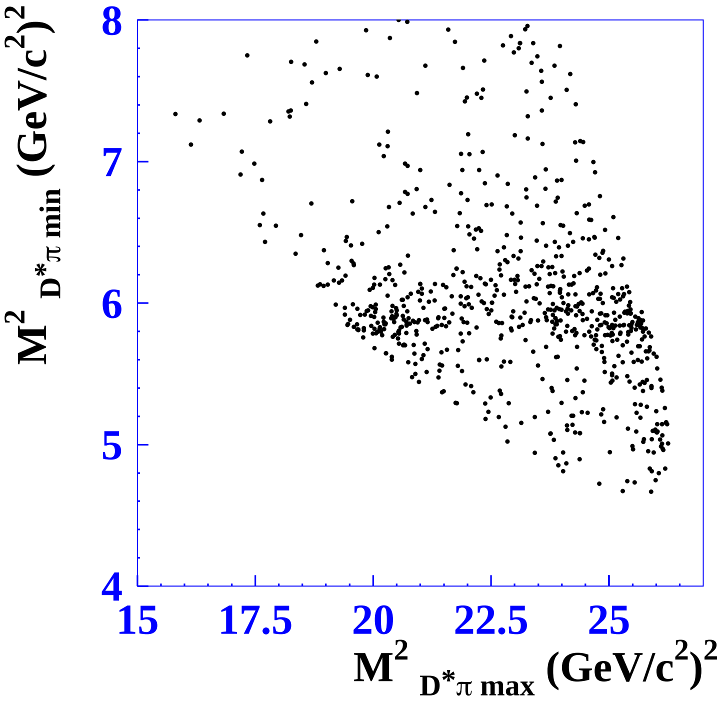
$$M_{D_2^{*0}} = 2461.6 \pm 2.1 \pm 0.5 \pm 3.3 \mathrm{MeV}$$
$$\Gamma_{D_2^{*0}} = 45.6 \pm 4.4 \pm 6.5 \pm 1.6 \mathrm{MeV}$$

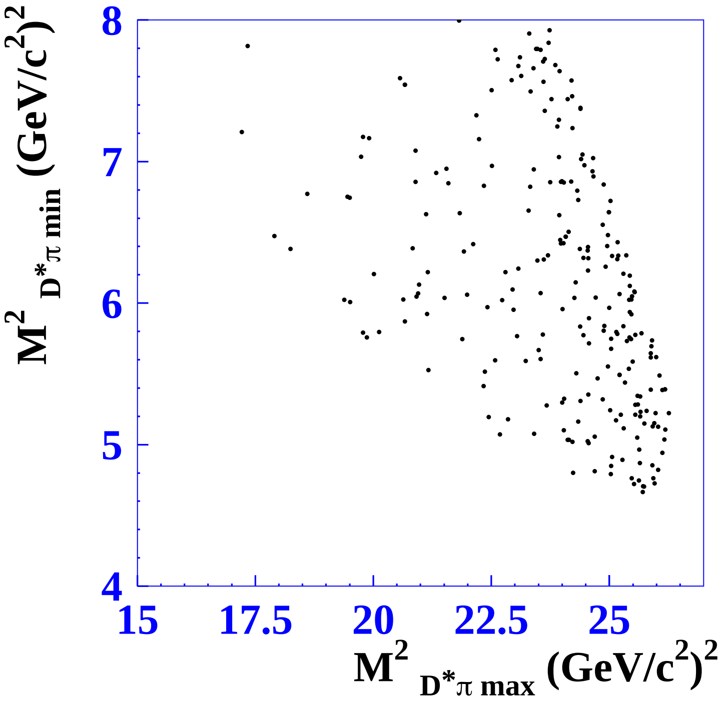
$$Br(B^- \to D_2^{*0}\pi^-)Br(D_2^{*0} \to D^+\pi^-) = (3.4 \pm 0.3 \pm 0.6 \pm 0.4) \times 10^{-4}$$

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

Last errors are model-dependence of the Dalitz fit.

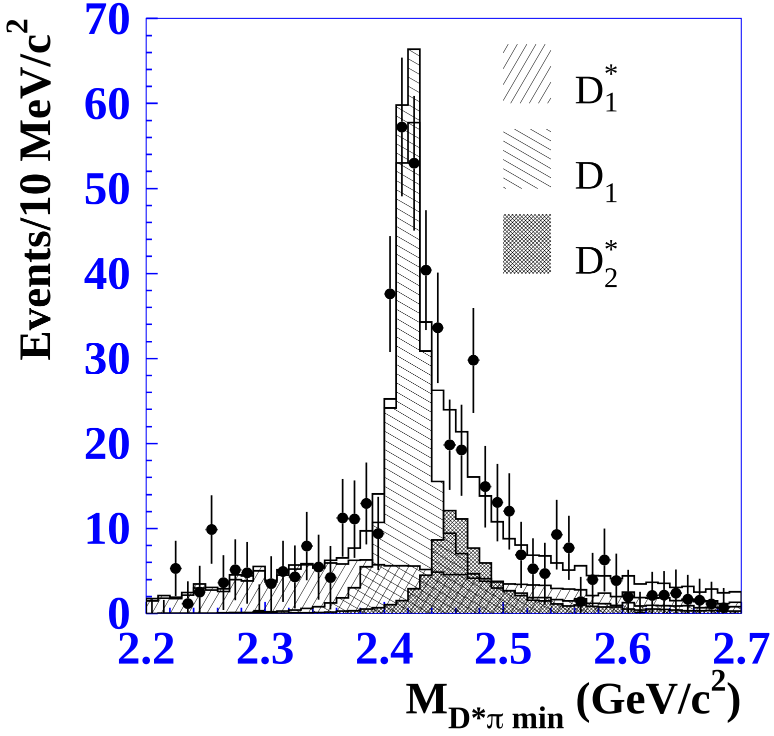
$D^{*+}\pi^-\pi^-$ Dalitz plot





signal region $\quad\quad$ ΔE side-band

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



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

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

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

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

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

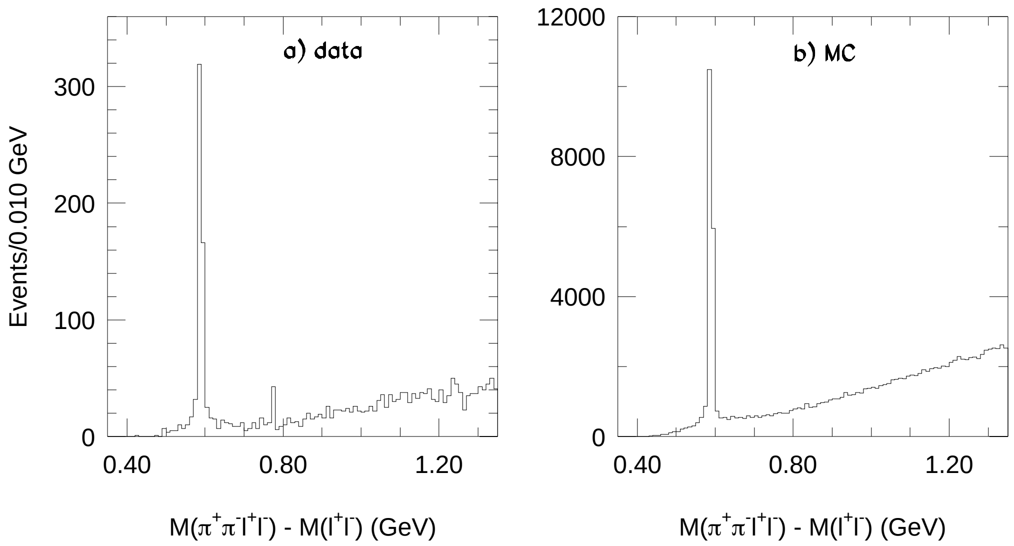
$$Br(B^- \to D_1'^0\pi^-)Br(D_1'^0 \to D^{*+}\pi^-) = (5.0 \pm 0.4 \pm 1.0 \pm 0.4) \times 10^{-4}$$

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

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

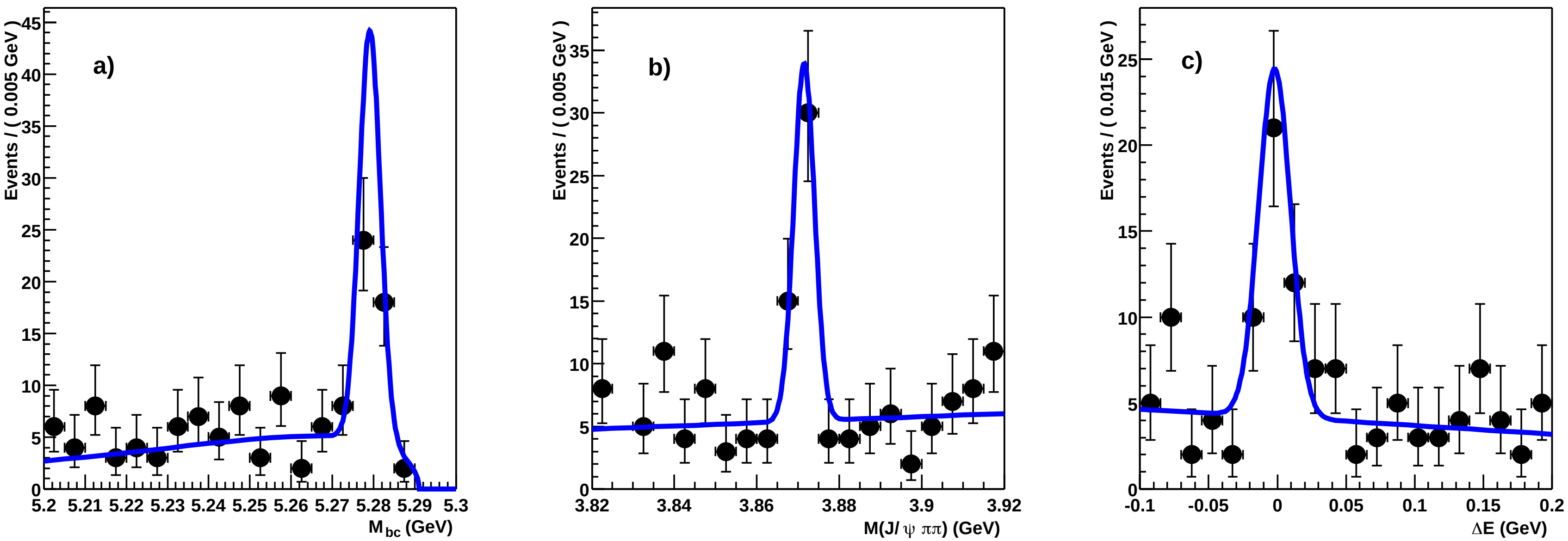
$$X(3872) \to J/\Psi\pi^+\pi^-$$

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



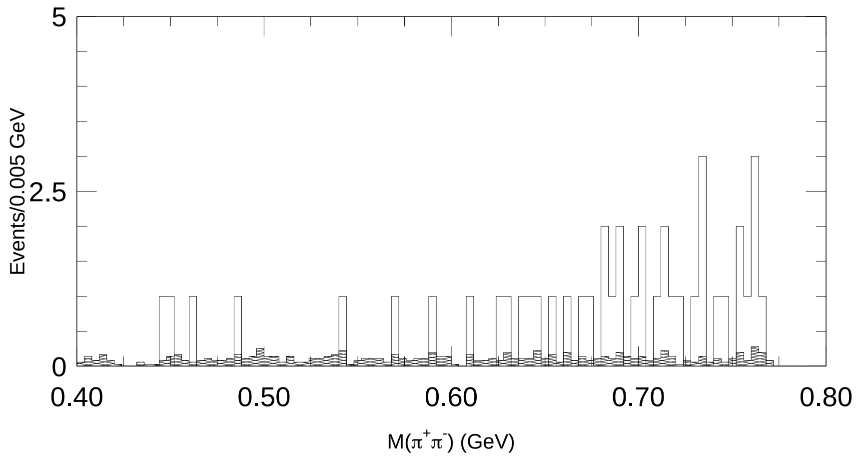
$B^- \to X(3872)K^-, \; X(3872) \to J/\Psi\pi^+\pi^-$

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



After cutting on $X(3872)$, clear signal in ΔE and M_{bc}
35.7 ± 6.8 events

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



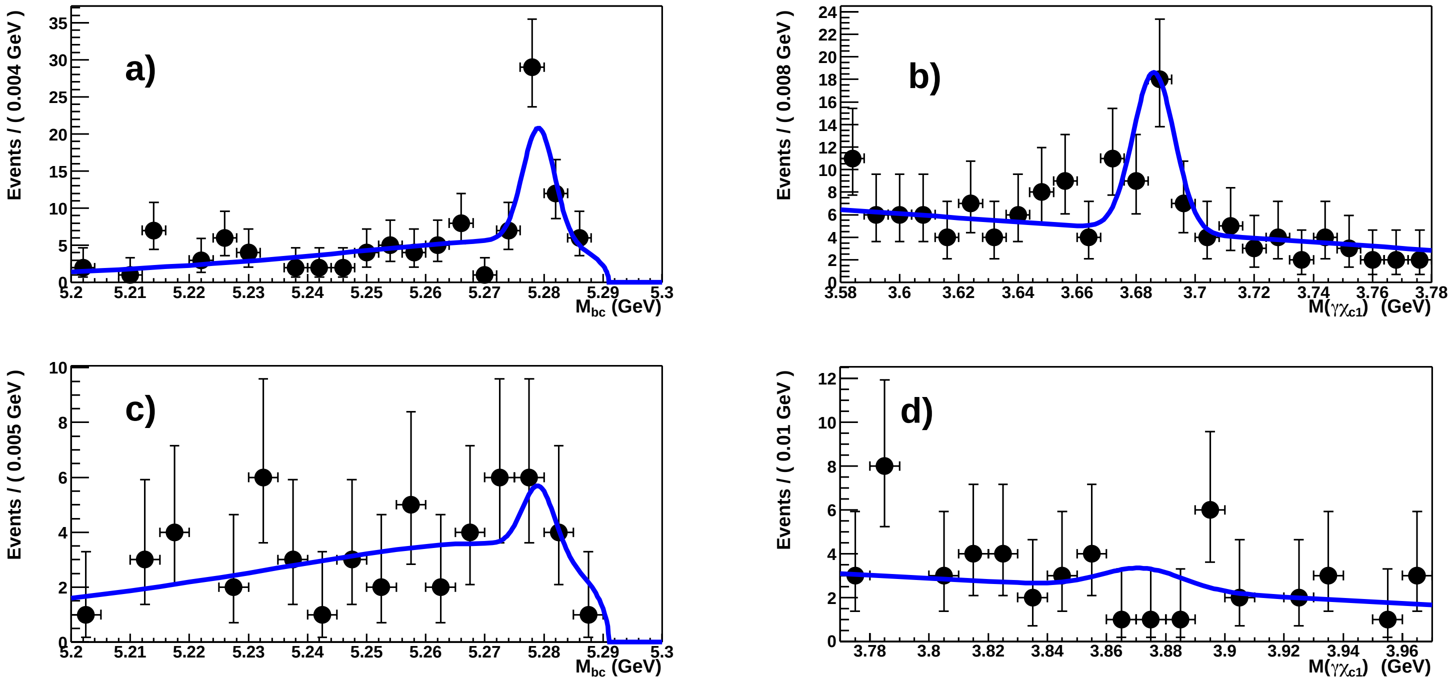
The shaded area : ΔE-M_{bc} side-band

$M_{\pi^+\pi^-}$ is quite high.

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

$M_D + M_{D^*} = 3875\text{MeV}$: 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.