Non-leptonic B decays to D^{**} at Belle

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for Belle Collaboration

Workshop on B decays into D^{**} and related issues
Paris, November 28, 2012

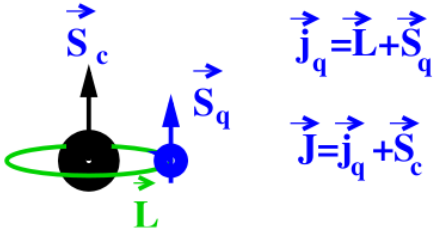
Outline

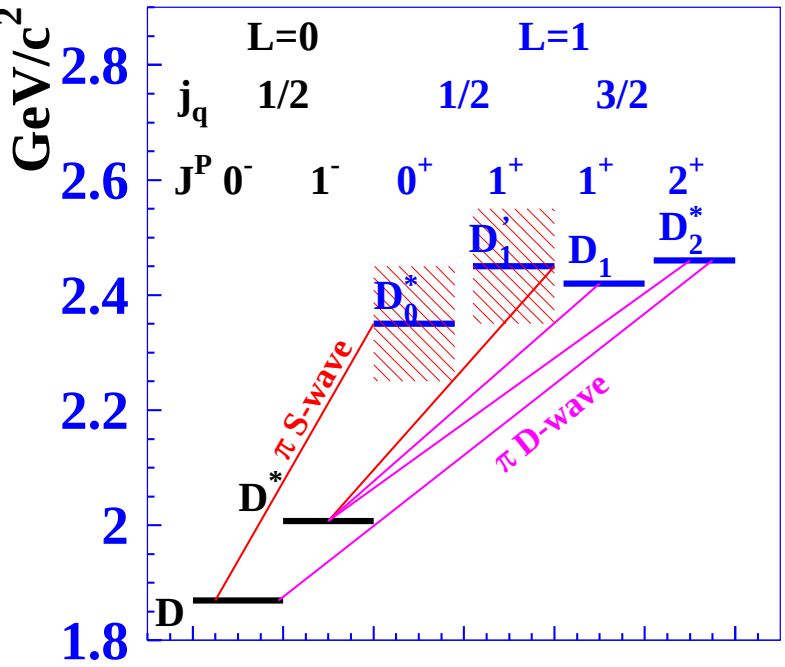
- D^{**} spectroscopy
- Mechanisms of D^{**} production in non-leptonic B-decays
- Experimental environment
- Charm production in B-meson decays
- D^{**} in $B^- \to D^{(*)+}\pi^-\pi^-$ decays
- D^{**} in $\bar{B}^0 \to D^{(*)0}\pi^+\pi^-$ decays
- $D_1(2420)$ decay to $D\pi^+\pi^-$
- D^{**} in $\bar{B}^0 \to D^{*+}\omega\pi^-$ decays
- Summary

Excited states of the D-mesons

- D^{**} are produced with different angular momenta

	$B \to D^{**}\pi$	$B \to D^{**}\omega$
D_0^*	S-wave	P-wave
D_1	P-wave	S, P, D-waves
D_1'	P-wave	S, P, D-waves
D_2^*	D-wave	P, D, F-waves



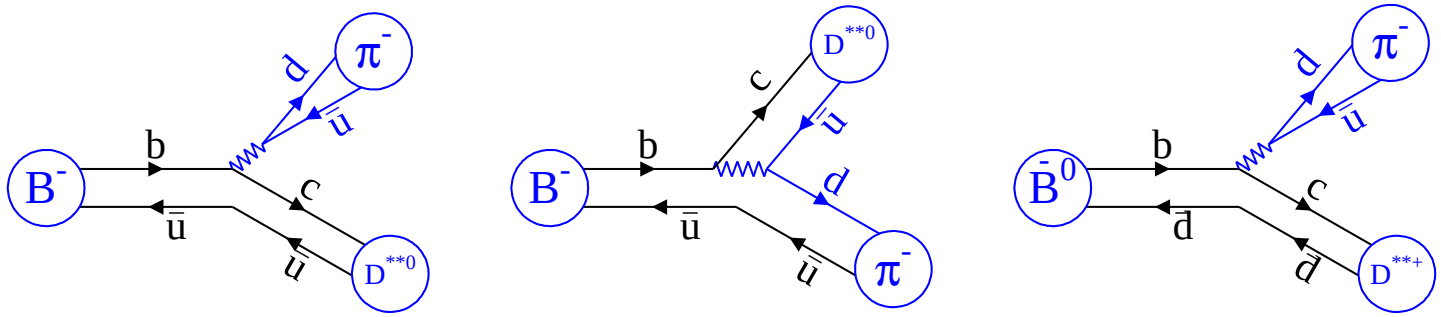


- Spin-parity of the D^{**} determines properties of their decays

$D_2^* \to$	$D\pi$	$D^*\pi$	in D-wave
$D_1 \to$		$D^*\pi$	in D-wave
$D_1' \to$		$D^*\pi$	in S-wave
$D_0^* \to$	$D\pi$		in S-wave

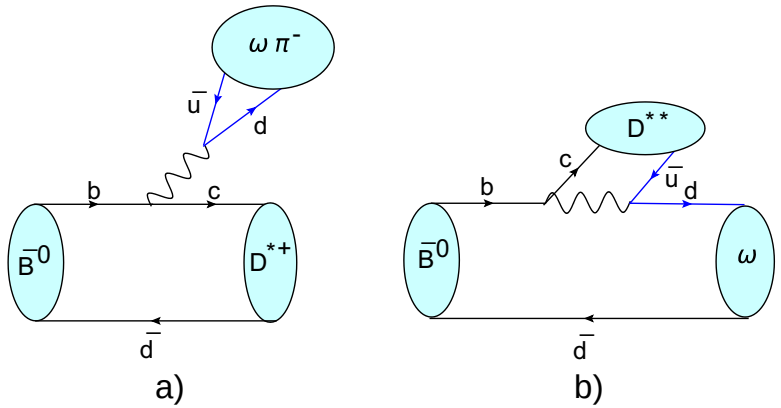
D^{**} production in hadronic B decays

- D^{**} production in the $\bar{B}^0 \to \bar{D}^{(*)0}\pi^+\pi^-$, $B^- \to D^{(*)+}\pi^-\pi^-$ modes.



Diagrams for neutral (a) and charged (b and c) B-decays.

- D^{**} production in the $\bar{B}^0 \to D^{(*)+}\pi^-(\omega, \pi^0)$ mode.

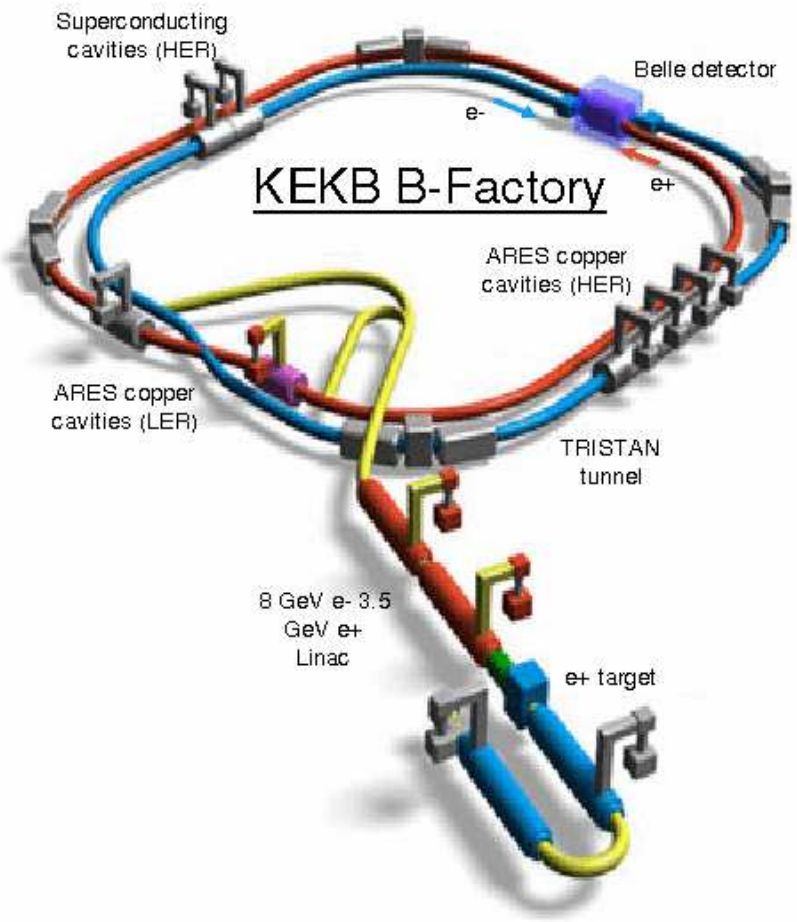


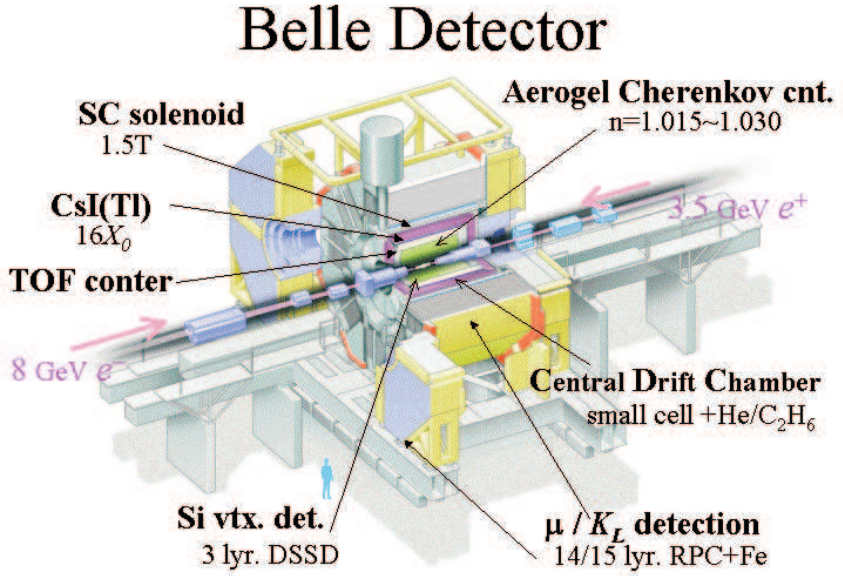
Color-favored (a) and color-suppressed (b) channel for $D^*\omega\pi$ final state.

D^{**} production in hadronic B decays

- Test of HQET predictions.
  The ratio $R = \mathcal{B}(B^- \to D_2^{*0}\pi^-)/\mathcal{B}(B^- \to D_1^0\pi^-)$
  (A.K. Leibovich, Z. Ligetti, I.W. Stewart and M.B. Wise, Phys. Rev. D **57**, 308 (1998), M. Neubert, Phys. Lett. B **418**, 173 (1998))
- QCD sum rules predictions. The suppression of B-decay to the broad D^{**}-states, when the D^{**} production is described by the Isgur-Wise functions. ($\bar{B}^0 \to D^{**+}\pi^-$)
  (A. Le Yaouanc *at al*., Phys. Lett. B **520**, 25 (2001))
- Predictions for the weak decay constants. The dominance of the broad D^{**}-states, when the D^{**} production is described by the W vertex. ($\bar{B}^0 \to D^{**0}\pi^0, D^{**0}\omega$)
  (S. Veseli and I. Dunietz, Phys. Rev. D **54**, 6803 (1996))
- The combined contribution from two different mechanisms of the D^{**} production. ($B^- \to D^{**0}\pi^-$)

Experiment Belle

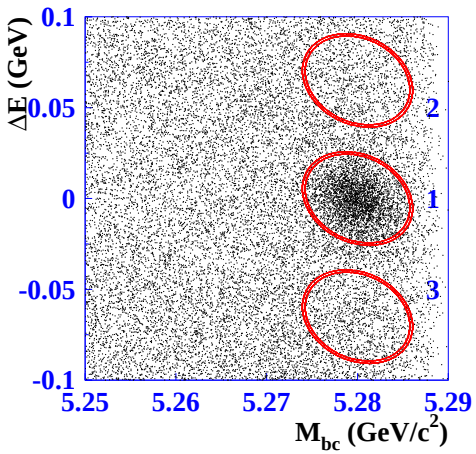


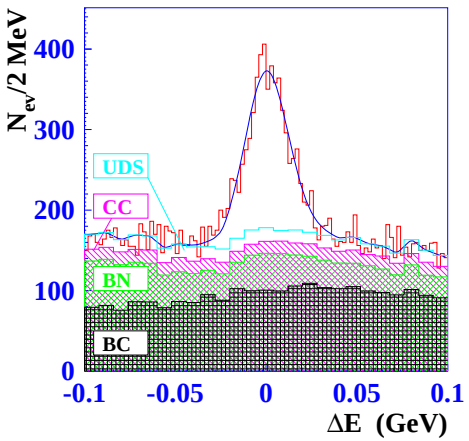


- Maximum differential luminosity: $2.1 \times 10^{34} \mathrm{cm}^{-2} \mathrm{s}^{-1}$.
- Integrated luminosity: 1000 fb^{-1}.
- Number of B pairs: $(771.6 \pm 10.6) \times 10^6$

Charm production in B-meson decays

- Two kinematic variables allow one to select a signal sample with the small background fraction.
  $m_{bc} = \sqrt{(E^{CM}_{beam})^2 - (P^{CM}_B)^2}$
  $\Delta E = E^{CM}_B - E^{CM}_{beam}$
- The fixed quantum numbers of the initial state (B-meson) allow one to describe decay with fixed angular orbital momenta in B and resonance rest frames.
- All the D^{**} are well distinguished by their angular distributions.



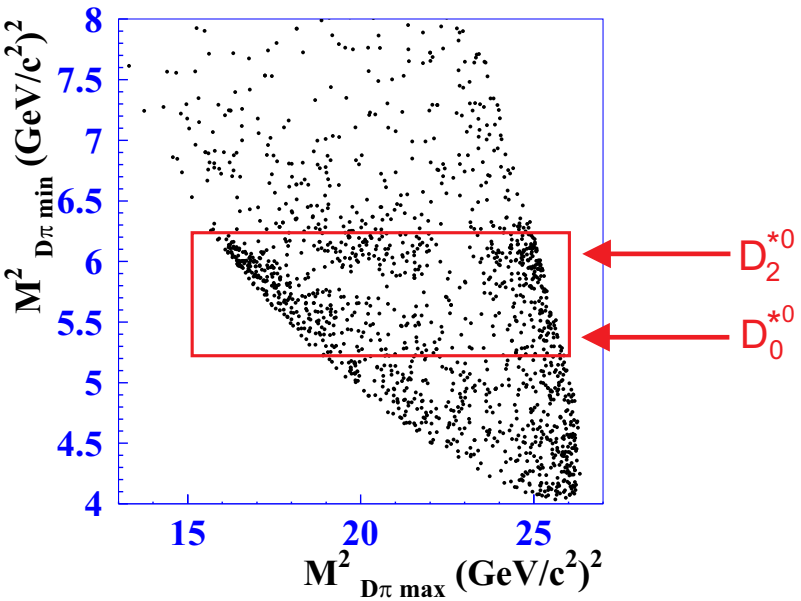


Description of a three-body amplitude

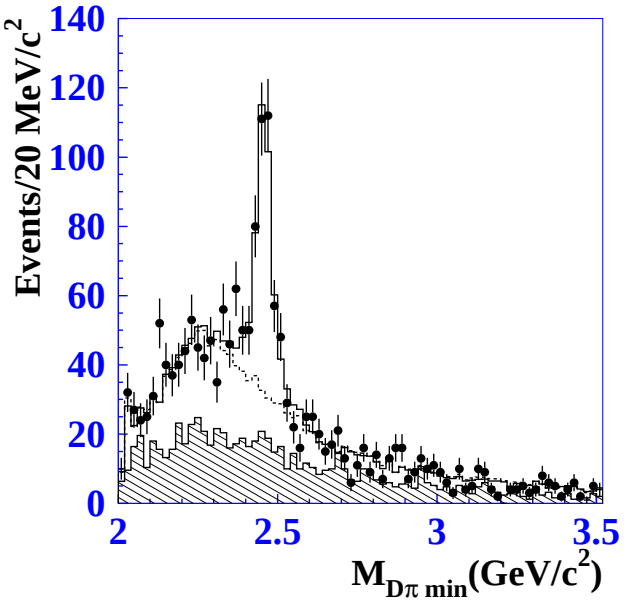
- To describe the dynamics of the D^{**} production and their properties, the signal density function is parameterized.
- An amplitude of the three-body $B \to D^{**}\pi, D^{**}\omega$ decay is written as a sum of the contributions corresponding to quasi-two-body resonances (sum of Breit-Wigner functions).
- Each resonant amplitude is expressed via a set of selected kinematic variables.
- Such approach allows one to distinguish the contributions for narrow and broad resonances (D^{**} and etc.), describe their interference and the effective parameters.

$B^- \to D^+\pi^-\pi^-$

Statistics $\sim 65\, M\, B\bar{B}$



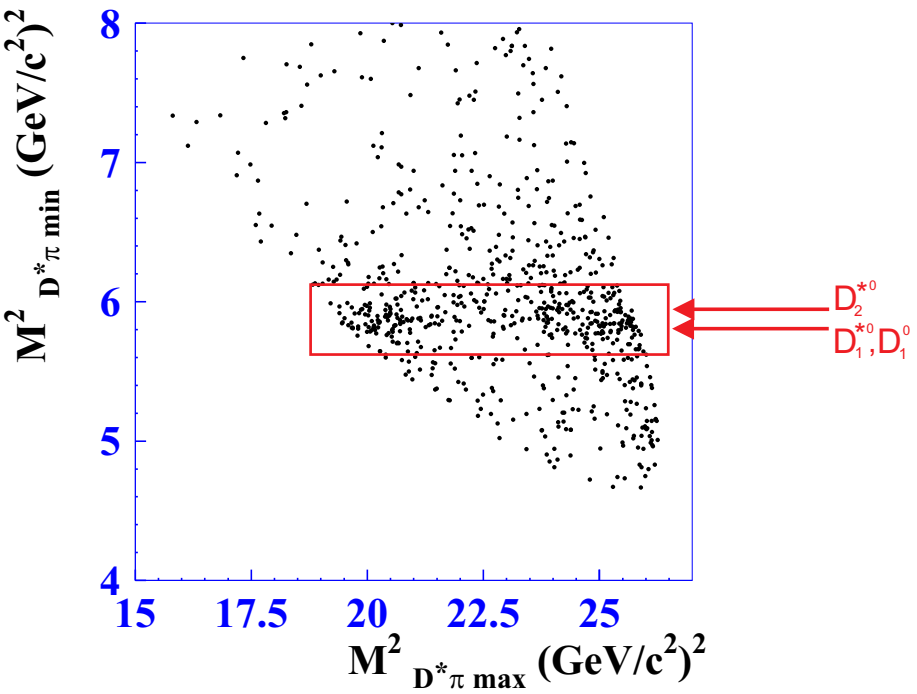
PRD 69, 112002 (2004)



- Only two kinematic variables $M^2_{D\pi\ min}$ and $M^2_{D\pi\ max}$.
- Absence of any two-pion bound state.
- Resonant $D\pi$ structure: D_2^{*0}-narrow state and D_0^{*0}-broad state.
- Off-shell $D\pi$ states: D_V^* ($B^- \to D_V^*\pi^-$, $D_V^* \to D^+\pi^-$) and B_V^* ($B^- \to B_V^*\pi^-$, $B_V^* \to D^+\pi^-$).

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

Statistics $\sim$ 65 $M\,B\bar{B}$



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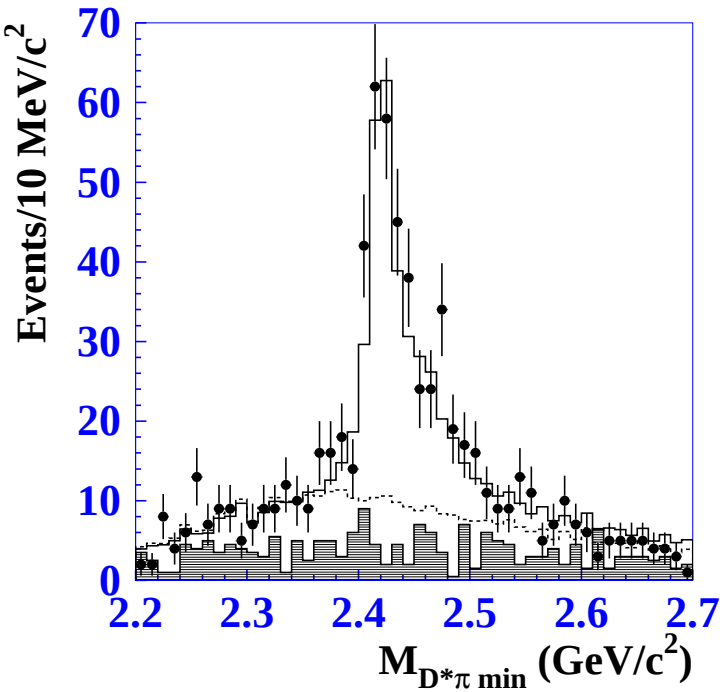
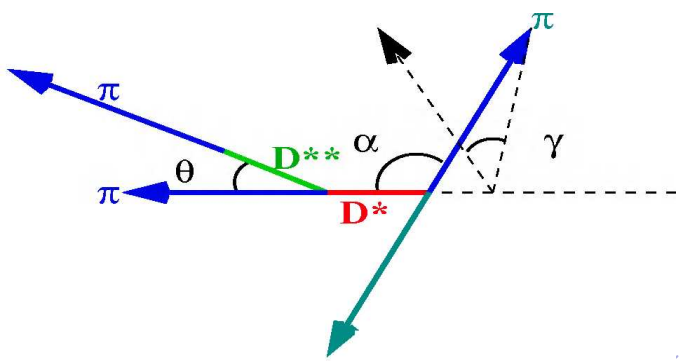
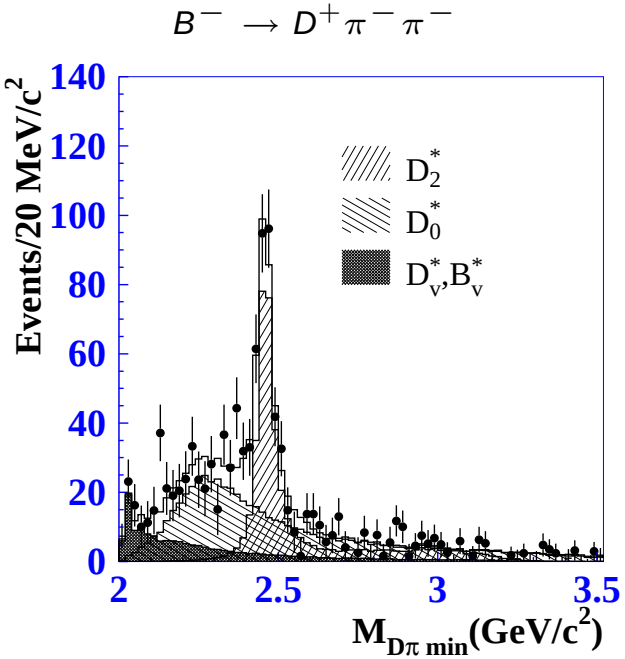
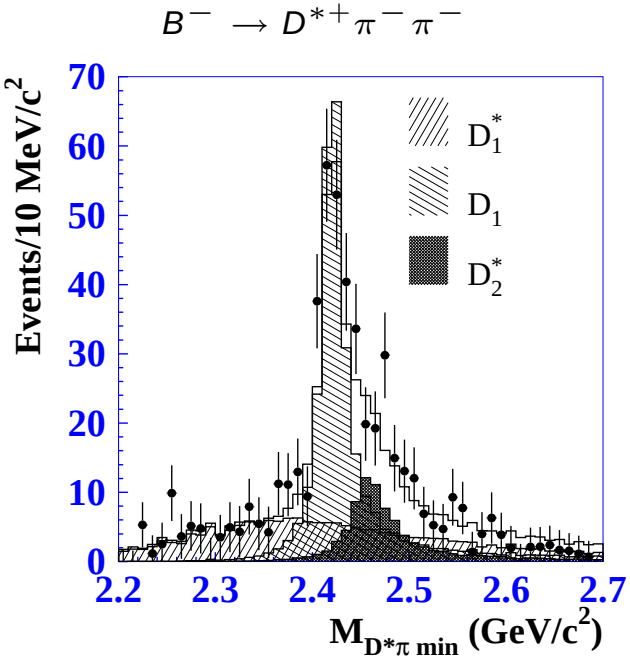


- Kinematic variables: $M^2_{D^*\pi\ min}$, $M^2_{D^*\pi\ max}$ and two additional angles for D^* decay.
- Absence of any two-pion bound state.
- Resonant $D\pi$ structure: D_2^{*0}-narrow state, D_1^0-narrow state and $D_1'^0$-broad state.
- Off-shell $D^*\pi$ states: D_V^* ($B^- \to D_V\pi^-$, $D_V \to D^{*+}\pi^-$) and B_V^* ($B^- \to B_V^*\pi^-$, $B_V^* \to D^{*+}\pi^-$).



Neutral D^{**} production in $B^- \to D^{(*)+}\pi^-\pi^-$





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

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

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

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

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

Neutral D^{**} parameters

All the neutral D^{**} states were observed in $B^- \to D^{(*)+}\pi^-\pi^-$

Since HQET is not exact, the two 1^+ states can be mixed (ϑ — mixing angle, φ — relative phase)

$$D_1^0 = \sin\vartheta\,|j_u = 1/2> + \cos\vartheta\, e^{-i\varphi}\,|j_u = 3/2>$$
$$D_1'^0 = \cos\vartheta\,|j_u = 1/2> - \sin\vartheta\, e^{i\varphi}\,|j_u = 3/2>$$

Mixing angle and phase:

$$\vartheta = 0.10 \pm 0.03 \pm 0.02 \pm 0.02$$
$$\varphi = 0.05 \pm 0.20 \pm 0.04 \pm 0.06$$

Narrow States

$M_{D_2^{*0}} = (2461.6 \pm 2.1 \pm 0.5 \pm 3.3)\,\mathrm{MeV}/c^2$
$\Gamma_{D_2^{*0}} = (45.6 \pm 4.4 \pm 6.5 \pm 1.6)\,\mathrm{MeV}$

$M_{D_1^0} = (2421.4 \pm 2.0 \pm 0.4 \pm 0.8)\,\mathrm{MeV}/c^2$
$\Gamma_{D_1^0} = (23.7 \pm 2.7 \pm 0.2 \pm 4.0)\,\mathrm{MeV}$

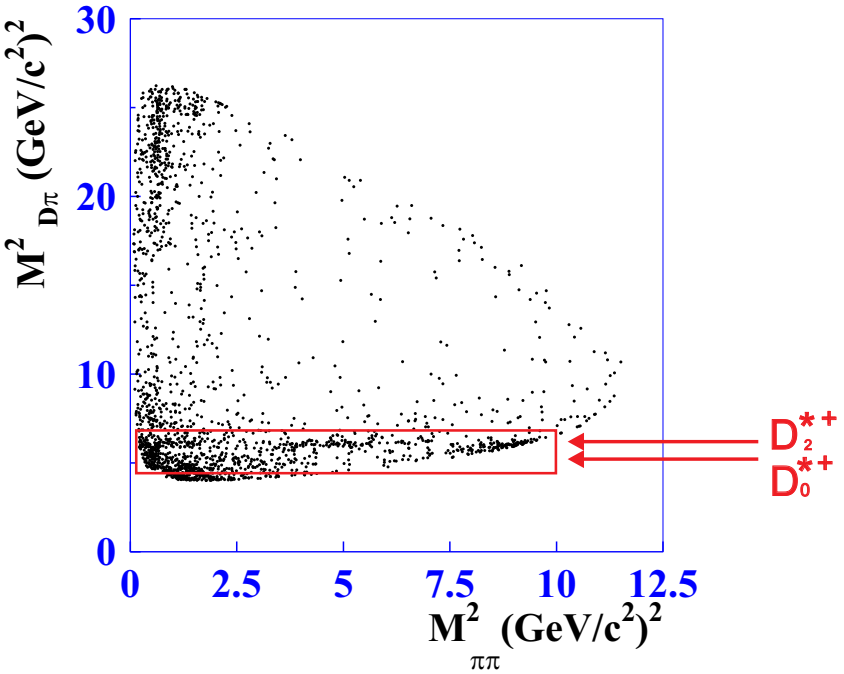
Broad States

$M_{D_0^{*0}} = (2308 \pm 17 \pm 15 \pm 28)\,\mathrm{MeV}/c^2$
$\Gamma_{D_0^{*0}} = (276 \pm 21 \pm 18 \pm 60)\,\mathrm{MeV}$

$M_{D_1'^0} = (2427 \pm 26 \pm 20 \pm 15)\,\mathrm{MeV}/c^2$
$\Gamma_{D_1'^0} = (384^{+107}_{-75} \pm 24 \pm 70)\,\mathrm{MeV}$

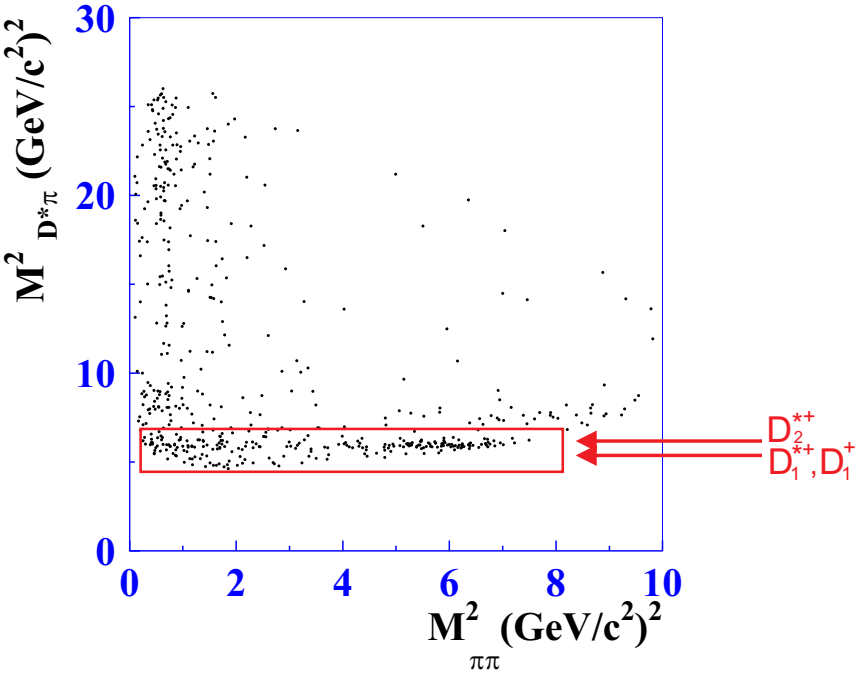
$\bar{B}^0 \to D^{(*)0}\pi^-\pi^+$

Statistics $\sim 386\, M\, B\bar{B}$
PRD 76, 012006 (2007)



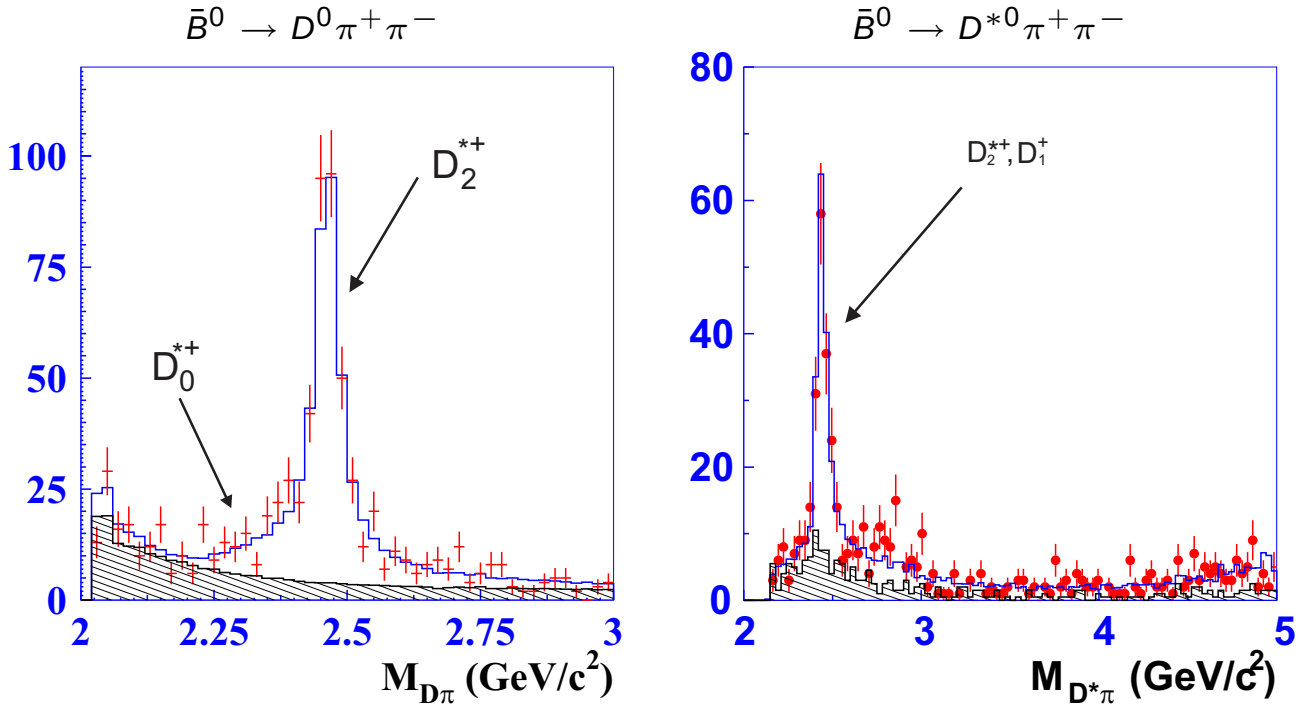
- Only two kinematic variables: $M^2_{D\pi}$ and $M^2_{\pi\pi}$.
- Resonant $\pi\pi$ structures: $\rho^0(770)$, $f_0(600)$, $f_0(1370)$, $f_0(980)$, $f_2(1270)$.
- Resonant $D\pi$ structures: D_2^{*+}-narrow state and D_0^{*+}-broad state.
- Off-shell $D\pi$ states: D_V^* ($\bar{B}^0 \to D_V^*\pi^-$, $D_V^* \to D^0\pi^+$).

Statistics $\sim 152 MB\bar{B}$
hep-ex/0412072



- Kinematic variables: $M^2_{D^*\pi}$, $M^2_{\pi\pi}$ and two additional angle in the D^* rest frame.
- Resonant $\pi\pi$ structures: $\rho^0(770)$, $f_0(600)$, $f_2(1270)$.
- Resonant $D^*\pi$ structures: D_2^{*+}-narrow state, D_1^+-narrow state and $D_1^{'+}$-broad state.
- Off-shell $D^*\pi$ states are not included in the fit.

Charged D^{**} production in $\bar{B}^0 \to D^{(*)0}\pi^+\pi^-$



$$\mathcal{B}(\bar{B}^0 \to D_2^{*+}\pi^-) \times \mathcal{B}(D_2^{*+} \to D^0\pi^+) = (2.15 \pm 0.17 \pm 0.29 \pm 0.12) \times 10^{-4}$$

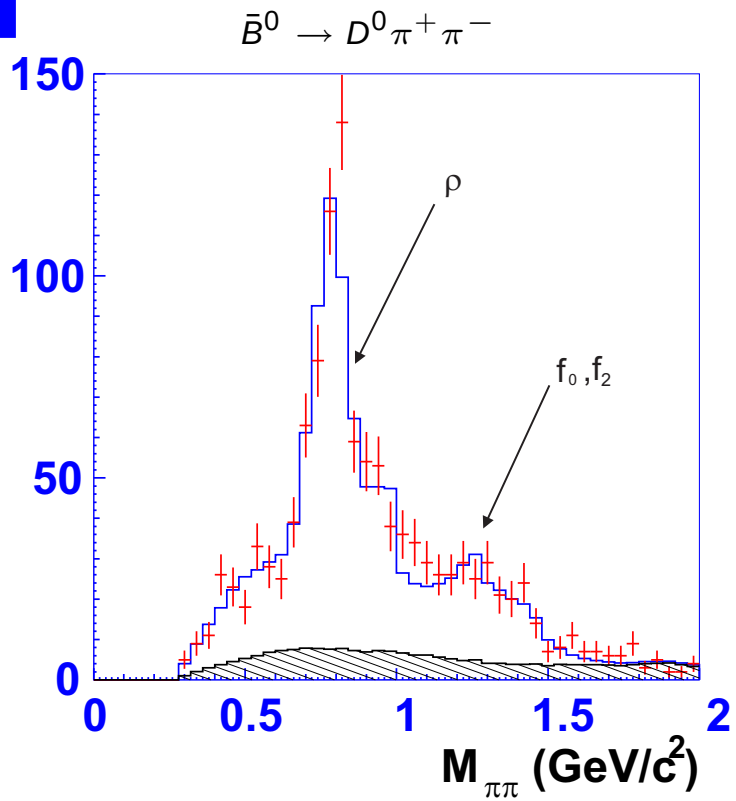
$$\mathcal{B}(\bar{B}^0 \to D_0^{*+}\pi^-) \times \mathcal{B}(D_0^{*+} \to D^0\pi^+) = (0.60 \pm 0.13 \pm 0.15 \pm 0.22) \times 10^{-4}$$

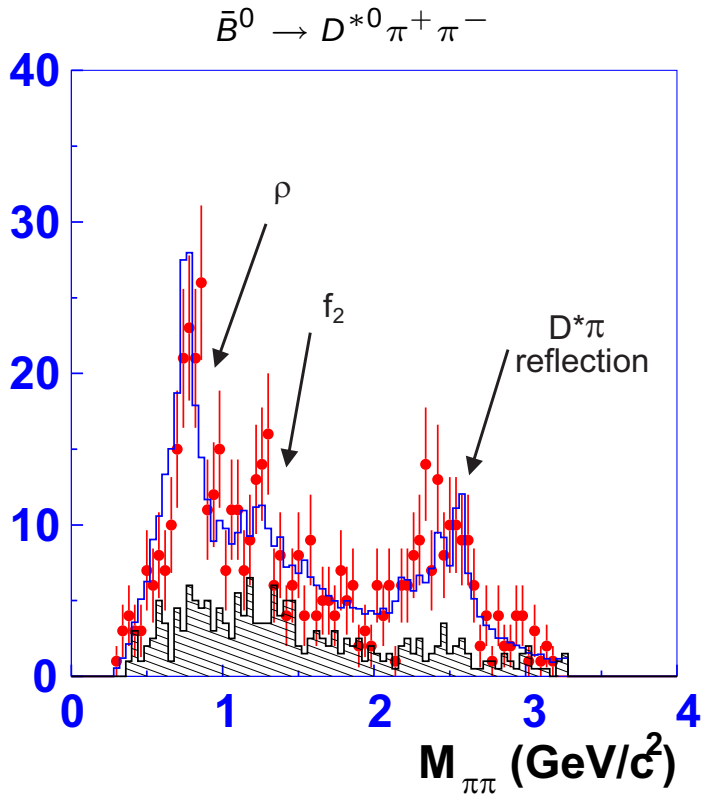
$$\mathcal{B}(\bar{B}^0 \to D_2^{*+}\pi^-) \times \mathcal{B}(D_2^{*+} \to D^{*0}\pi^+) = (2.45 \pm 0.42^{+0.35+0.39}_{-0.45-0.17}) \times 10^{-4}$$

$$\mathcal{B}(\bar{B}^0 \to D_1^{+}\pi^-) \times \mathcal{B}(D_1^{+} \to D^{*0}\pi^+) = (3.68 \pm 0.60^{+0.71+0.65}_{-0.40-0.30} \times 10^{-4}$$

$$\mathcal{B}(\bar{B}^0 \to D_1^{'+}\pi^-) \times \mathcal{B}(D_1^{'+} \to D^{*0}\pi^+) < 0.7 \times 10^{-4} \text{ at } 90\% \text{ C.L.}$$

Two-pion production in $\bar{B}^0 \to D^{(*)0}\pi^+\pi^-$





$\mathcal{B}(\bar{B}^0 \to D^0\rho^0) = (3.19 \pm 0.20 \pm 0.24 \pm 0.38) \times 10^{-4}$

$\mathcal{B}(\bar{B}^0 \to D^0 f_2) = (1.20 \pm 0.18 \pm 0.21 \pm 0.32) \times 10^{-4}$

$\mathcal{B}(\bar{B}^0 \to D^{*0}\rho^0) = (3.73 \pm 0.87 \pm 0.46^{+0.18}_{-0.08}) \times 10^{-4}$

$\mathcal{B}(\bar{B}^0 \to D^{*0} f_2) = (1.86 \pm 0.65 \pm 0.60^{+0.80}_{-0.52}) \times 10^{-4}$

Charged D^{**} parameters

All the narrow charged D^{**} states were observed in $\bar{B}^0 \to D^{(*)0}\pi^+\pi^-$

Narrow States

$$M_{D_2^{*+}} = (2465.7 \pm 1.8 \pm 0.8^{+1.2}_{-4.7})\,\mathrm{MeV}/c^2 \qquad M_{D_1^+} = (2428.2 \pm 2.9 \pm 1.6 \pm 0.6)\,\mathrm{MeV}/c^2$$

$$\Gamma_{D_2^{*+}} = (49.7 \pm 3.8 \pm 4.1 \pm 4.9)\,\mathrm{MeV} \qquad \Gamma_{D_1^+} = (34.9 \pm 6.6^{+4.1}_{-0.9} \pm 4.1)\,\mathrm{MeV}$$

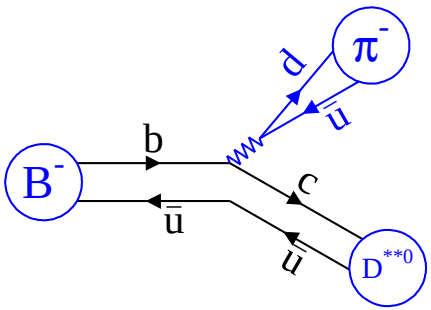
Broad States

- Masses and widths for charged broad states were fixed to those for neutral broad states.

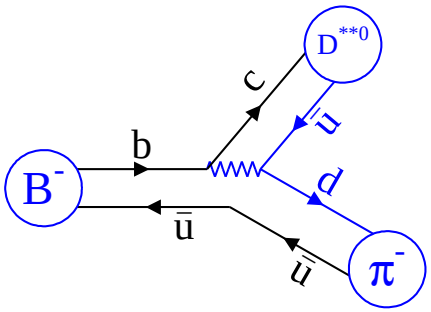
D^{**} production in $B \to D^{(*)}\pi\pi$

	Neutral B	Charged B
$\mathcal{B}(\bar{B} \to D_2^* \pi^-)\mathcal{B}(D_2^* \to D\pi)$	$(2.15 \pm 0.17 \pm 0.29 \pm 0.12) \times 10^{-4}$	$(3.4 \pm 0.3 \pm 0.6 \pm 0.4) \times 10^{-4}$
$\mathcal{B}(\bar{B} \to D_2^* \pi^-)\mathcal{B}(D_2^* \to D^*\pi)$	$(2.45 \pm 0.42^{+0.35+0.39}_{-0.45-0.17}) \times 10^{-4}$	$(1.8 \pm 0.3 \pm 0.3 \pm 0.2) \times 10^{-4}$
$\mathcal{B}(\bar{B} \to D_1 \pi^-)\mathcal{B}(D_1 \to D^*\pi)$	$(3.68 \pm 0.60^{+0.71+0.65}_{-0.40-0.30}) \times 10^{-4}$	$(6.8 \pm 0.7 \pm 1.3 \pm 0.3) \times 10^{-4}$
$\mathcal{B}(\bar{B} \to D_0^* \pi)\mathcal{B}(D_0^* \to D\pi)$	$(0.60 \pm 0.13 \pm 0.15 \pm 0.22) \times 10^{-4}$	$(6.1 \pm 0.6 \pm 0.9 \pm 1.6) \times 10^{-4}$
$\mathcal{B}(\bar{B} \to D_1' \pi^-)\mathcal{B}(D_1' \to D^*\pi)$	$< 0.7 \times 10^{-4}$ at 90 % C.L.	$(5.0 \pm 0.4 \pm 1.0 \pm 0.4) \times 10^{-4}$

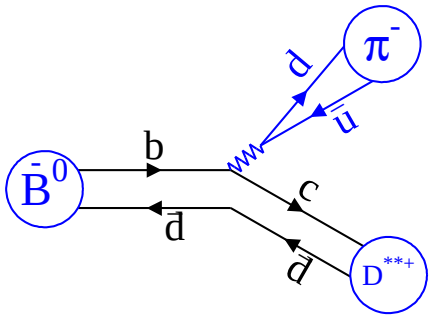
- The production of the narrow D^{**} in B^0 decays is comparable with their production in B^- decays
- The production of the broad D^{**} in B^0 decays is at least five times lower than in B^- decays



$\tau_{3/2} \gg \tau_{1/2}$



$f_{D_{3/2}} \ll f_{D_{1/2}}$



Observation of the $D_1 \to D\pi^+\pi^-$ decays

Statistics $\sim$ 152 M $B\bar{B}$

PRL 94, 221805 (2005)

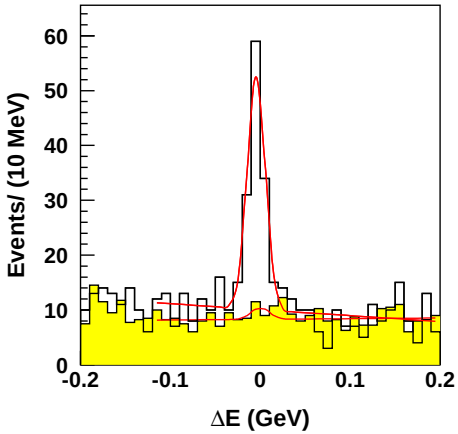
- $B^- \to D^0\pi^+\pi^-\pi^-, D^0 \to K^-\pi^+$
- $D_1^0 \to D^{*+}\pi^- \to D^0\pi^+\pi^-$ decay mode excluded
- Fit of $M_{D\pi\pi}$ distribution by a convolution of a Gaussian with a signal Breit-Wigner function.

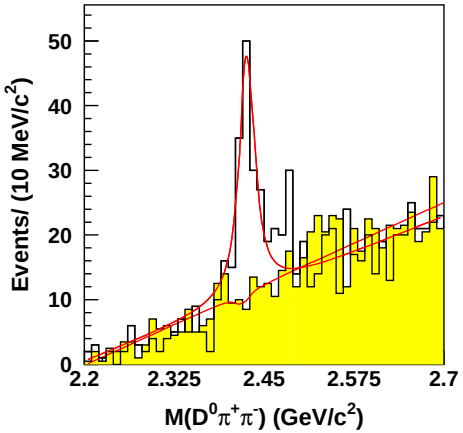
$$M_{D_1^0} = 2426 \pm 3 \pm 1\,\mathrm{MeV}/c^2$$

$$\Gamma_{D_1^0} = 24 \pm 7 \pm 8\,\mathrm{MeV}/c^2$$

- $\mathcal{B}(B^- \to D_1^0\pi^-) \times \mathcal{B}(D_1^0 \to D^0\pi^-\pi^+)$

$(1.85 \pm 0.29 \pm 0.35^{+0.0}_{-0.43}) \times 10^{-4}$





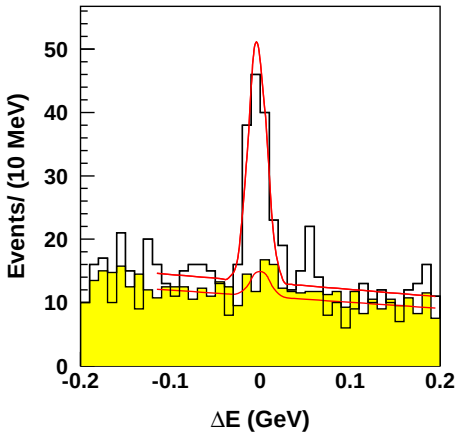
- $\bar{B}^0 \to D^+\pi^-\pi^+\pi^-, D^+ \to K^-\pi^+\pi^+$
- $D_1^+ \to D^{*0}\pi^+ \to D^+\pi^-\pi^+$ decay mode excluded
- Fit of $M_{D\pi\pi}$ distribution by a convolution of a Gaussian with a signal Breit-Wigner function.

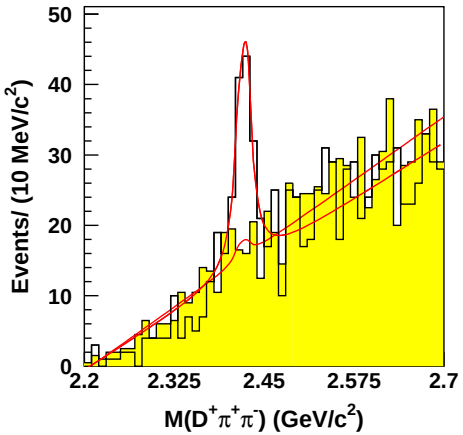
$$M_{D_1^+} = 2421 \pm 2 \pm 1\,\mathrm{MeV}/c^2$$

$$\Gamma_{D_1^+} = 21 \pm 5 \pm 8\,\mathrm{MeV}/c^2$$

- $\mathcal{B}(\bar{B}^0 \to D_1^+\pi^-) \times \mathcal{B}(D_1^+ \to D^+\pi^-\pi^+)$

$(0.89 \pm 0.15 \pm 0.17^{+0.0}_{-0.27}) \times 10^{-4}$





Ratio R

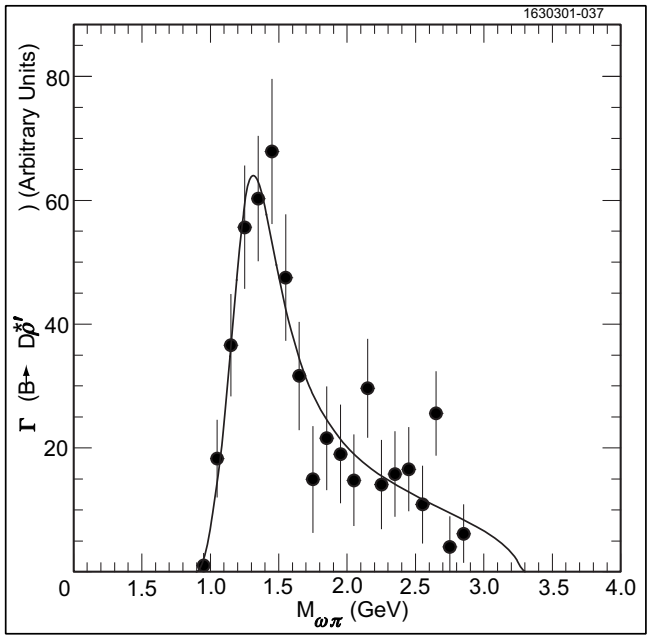
$$R = \frac{\mathcal{B}(B^- \to D_2^{*0}\pi^-)}{\mathcal{B}(B^- \to D_1^0\pi^-)}$$

- Theoretical prediction:
  $R \approx 0.35|(1+\delta_8^{D_2})/(1+\delta_8^{D_1})|^2$, $(\delta_8^{D_2}, \delta_8^{D_1} \ll 1)$
- First CLEO result ($B \to D^*\pi\pi$):
  $R = 1.8 \pm 0.8$
- Belle result ($B^- \to D^{(*)+}\pi^-\pi^-$):
  $R = 0.77 \pm 0.15$
- Belle result ($D_1 \to D\pi\pi$ decays):
  $R = 0.54 \pm 0.18$

$\bar{B}^0 \to D^{*+}\omega\pi^-$

[CLEO Collaboration], Phys. Rev. D **64**, 092001, (2001)

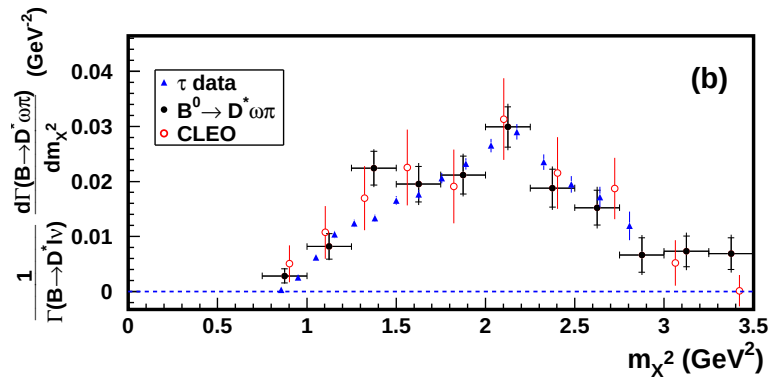
- A study of the $D^{(*)}(4\pi)^-$ decays, which is necessary for knowledge of the hadronic B-meson width.
- Integrated luminosity: 9 fb^{-1}.



- $\mathcal{B}(\bar{B}^0 \to D^{*+}\omega\pi^-)$
  $(2.9 \pm 0.3 \pm 0.4) \times 10^{-3}$

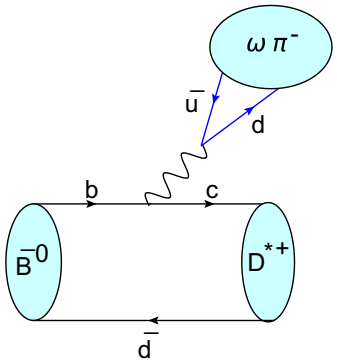
[BaBar Collaboration], Phys. Rev. D **74**, 012001, (2006)

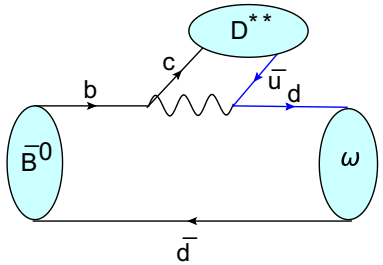
- A study of the factorization approximation.
- Integrated luminosity: 211 fb^{-1}.



- $\mathcal{B}(\bar{B}^0 \to D^{*+}\omega\pi^-)$
  $(2.88 \pm 0.21 \pm 0.31) \times 10^{-3}$.

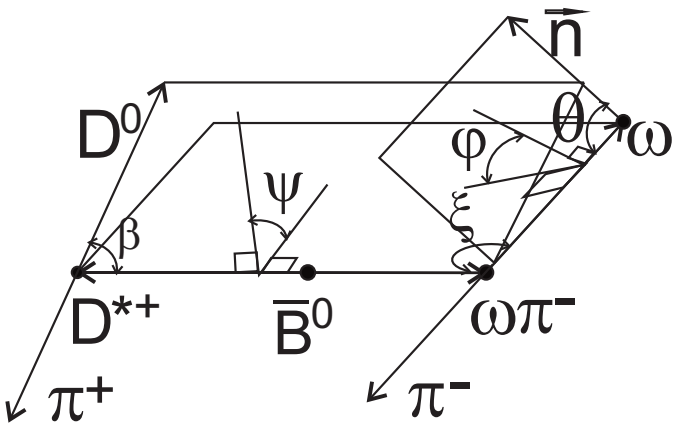
$\bar{B}^0 \to D^{*+}\omega\pi^-$

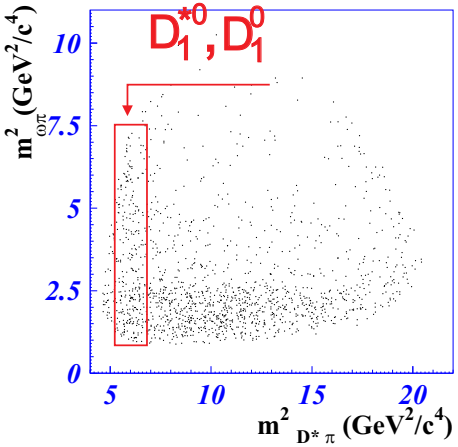




$\omega\pi = \rho_V^-(770),\ \rho^-(1450),\ \rho^-(1700),\ b_1^-(1235), \ldots$ $\quad D^*\pi = D_1^0,\ D_1'^0$

Statistics $\sim 771M\ B\bar{B}$





- $m^2_{D^*\pi}$ and $m^2_{\omega\pi}$ invariant mass squared, two angles in D^* rest frame and two angles in ω rest frame.
- Phase space factor

$$d\Phi = \frac{p_\omega p_{D^*}}{\sqrt{m^2_{\omega\pi}}} dm^2_{\omega\pi}\, d\cos\xi\, d\cos\theta\, d\phi\, d\cos\beta\, d\psi$$

- Different kinematic bases for $\omega\pi$ and $D^*\pi$ sectors

$\bar{B}^0 \to D^{*+}\omega\pi^-$

D.V. Matvienko, A.S. Kuzmin and S.I. Eidelman, JHEP **1109**, 129 (2011)

- The total decay rate for $\omega\pi$ resonance production is as follows:

$$d\Gamma = \frac{6\mathcal{B}_{D^{*+}\to D^0\pi^+}}{(4\pi)^{10}m_B^2}\,\frac{|M|^2\mathbf{pQ}}{\sqrt{q^2}}\,\frac{W(p^2)}{|D_\omega(p^2)|^2}\,dp^2\;(d\cos\theta\,d\phi)\,(d\cos\beta\,d\psi)\,(dq^2\,d\cos\xi)$$

- The matrix element for the $\bar{B} \to D^{*+}\rho(1450)^-$ transition is as follows:

$$\begin{aligned} M_{\bar{B}\to D^*\rho(1450)} = \frac{G_F}{\sqrt{2}}V_{cb}V_{ud}^*\,a_1 f_{\rho(1450)}\Big[& C_P\epsilon^{\mu\nu\rho\sigma}\varepsilon^{'*}_\mu\varepsilon^*_\nu q_\rho Q_\sigma F_P(q^2)+ \\ & + im_B^2 C_S((\varepsilon^{'*}\varepsilon^*) - \frac{1}{f_{P,S}(q^2)}(\varepsilon^{'*}Q)(\varepsilon^* q))F_S(q^2)+ \\ & + iC_D((\varepsilon^{'*}Q)(\varepsilon^* q) - f_{P,D}(q^2)(\varepsilon^{'*}\varepsilon^*))F_D(q^2)\Big] \end{aligned}$$

- The matrix element for the $\rho(1450)^- \to \omega\pi^-$ transition is as follows:

$$M_{\rho(1450)\to\omega\pi} = g\,\epsilon^{\mu\nu\rho\sigma}\varepsilon^{'}_\mu v^*_\nu q_\rho p_\sigma \tilde{F}_P(q^2,p^2)$$

- We move from the covariant amplitudes to the expressions depending on the selected angles, which are defined in the intermediate particle rest frames.

Signal Model

- Non-resonant constant term $\bar{B^0} \to D^{*+}\omega\pi^-$ ($D^*\pi$, $\omega\pi$, $D^*\omega$ S-waves)
- $\bar{B^0} \to \rho(770)^- D^{*+}$
- $\bar{B^0} \to \rho(1450)^- D^{*+}$
- $\bar{B^0} \to D_1^0(2430)\omega$
- $\bar{B^0} \to D_1^0(2420)\omega$

Resonance description

- All resonances are described by relativistic Breit-Wigner functions with energy-dependent widths.
- For energy-dependent widths the following decay modes are used

$$\begin{aligned} \rho(770) &\to \pi\pi + (\rho\omega\pi)\,\text{interaction};\ \ \rho(1450) \to 1/2\pi\pi + 1/2\omega\pi; \\ D_1(2420) &\to D^*\pi;\ \ D_1(2430) \to D^*\pi. \end{aligned}$$

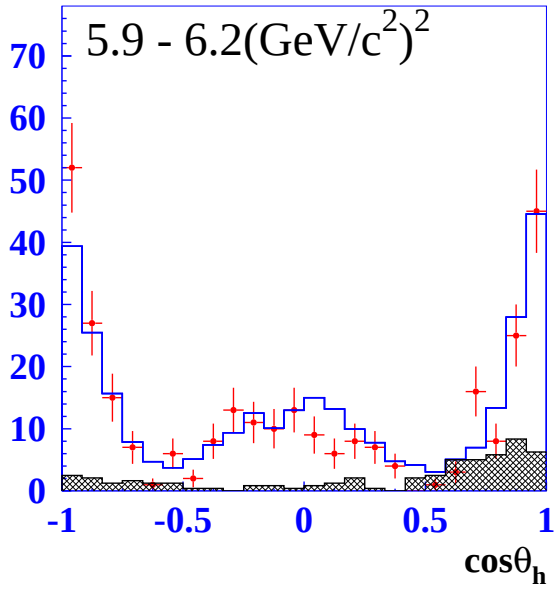
Summary

- The observation of $D_1(2420) \to D\pi^+\pi^-$ decays (with the dominant $D_1 \to D^*\pi$ contribution excluded)
- Observation of all neutral and charged D^{**} states through coherent amplitude analysis in the $B^- \to D^{(*)+}\pi^-\pi^-$ and $\bar{B}^0 \to D^{(*)0}\pi^+\pi^-$ modes.
- The relatively equal production of the broad and narrow D^{**}-states in $B^- \to D^{(*)+}\pi^-\pi^-$ decays. (Color-favored and color-suppressed production channels).
- The dominance of the narrow D^{**}-states production in comparison with the broad D^{**} states production in $\bar{B}^0 \to D^{(*)0}\pi^-\pi^+$ decays. (Color-favored production channel).
- Current study of D^{**} production in $\bar{B}^0 \to D^{*+}\omega\pi^-$ decay at Belle. (Color-suppressed production channel).
- Future study of D^{**} production dynamics in $\bar{B}^0 \to D^+\omega\pi^-$ and $\bar{B}^0 \to D^{(*)+}\pi^0\pi^-$ modes.

Backup

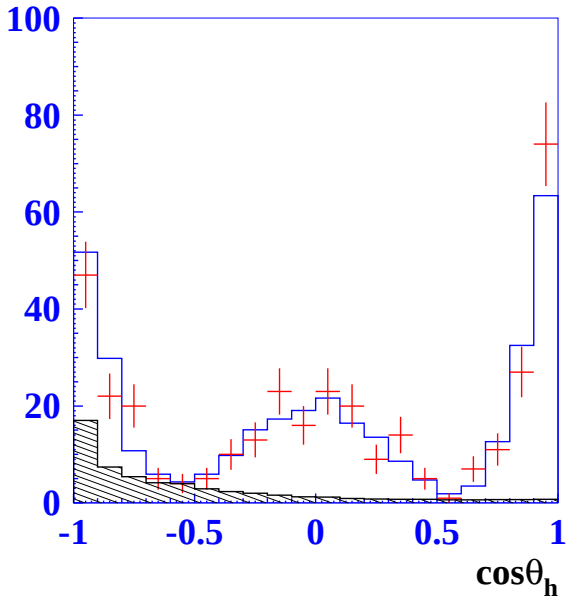
D_2^* helicity distribution

$B^- \to D^+\pi^-\pi^-$



D_2^{*0} region

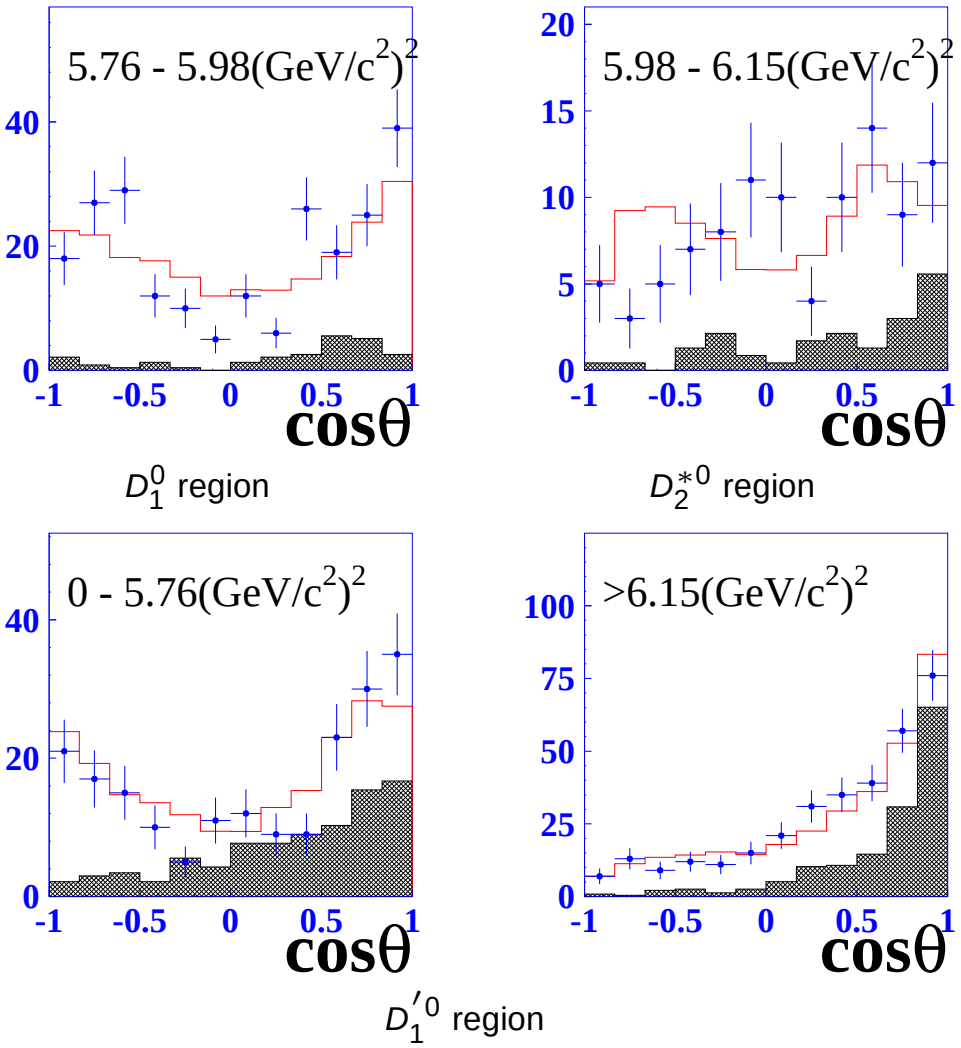
$\bar{B}^0 \to D^0\pi^+\pi^-$



D_2^{*+} region

$|\cos^2\theta_h - 1/3|^2$ D-wave dependence

$B^- \to D^{*+}\pi^-\pi^-$ helicity distributions



D_1^0 region

D_2^{*0} region

$D_1'^0$ region