Charm Physics at Belle

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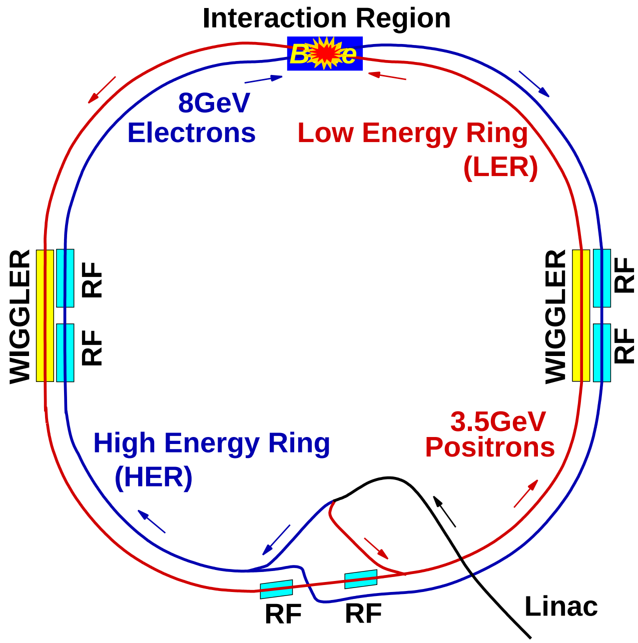
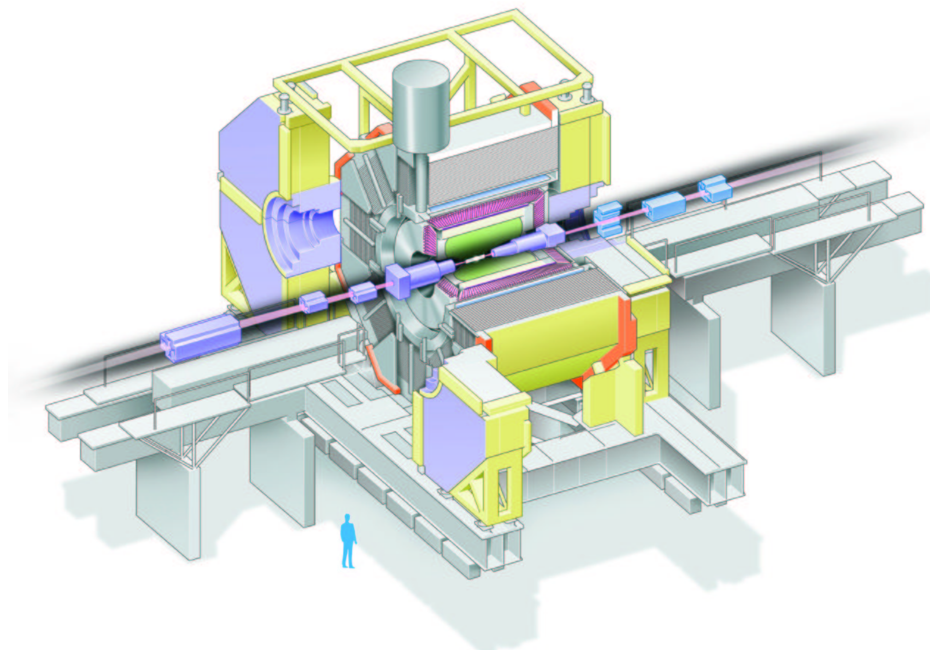
XIX Rencontres de Physique de La Vallee d'Aoste

Outline:

- Introduction
- $D^0 - \overline{D}^0$ mixing in $D^0 \to K^+\pi^-$
- $D^0 - \overline{D}^0$ mixing in $D^0 \to K^+e^-\bar{\nu}_e$
- D^{**} study in B decay
- $B \to D_{sJ}K/\pi$ results
- Double charm production
- Summary

KEKB, Belle detector





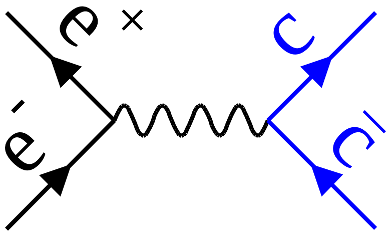
- 3.5 GeV e^+ $\times$ 8.0 GeV e^-.
- $\mathcal{L} = 1.5 \times 10^{34} cm^{-2} s^{-1}$
- Continuous injection 1.1 fb^{-1}/day.
- $\int \mathcal{L} dt \approx 360\ fb^{-1}$

$\rightarrow$

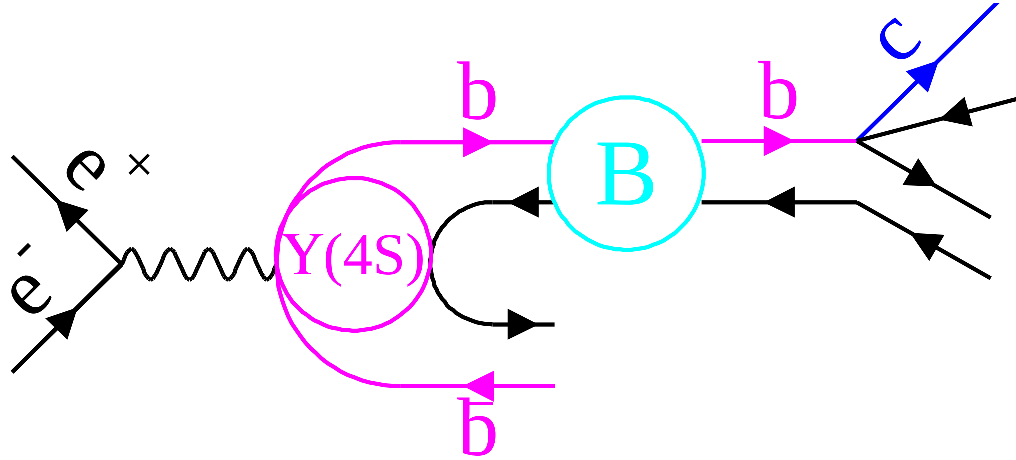
- **Sil.VD: 3(4) layers DSSD**
- **CDC : small cells** $He + C_2H_5$
- **TOF counters.**
- **Aerogel CC:**$n = 1.015 \sim 1.030$
- **CsI(Tl) 16** X_0
- **SC solenoid 1.5 T**
- $\mu K_L detection$ **14-15 layers RPC+Fe**

Charm production

$e^+e^- \to c\bar{c}$



$e^+e^- \to \Upsilon(4s) \to B\bar{B}$



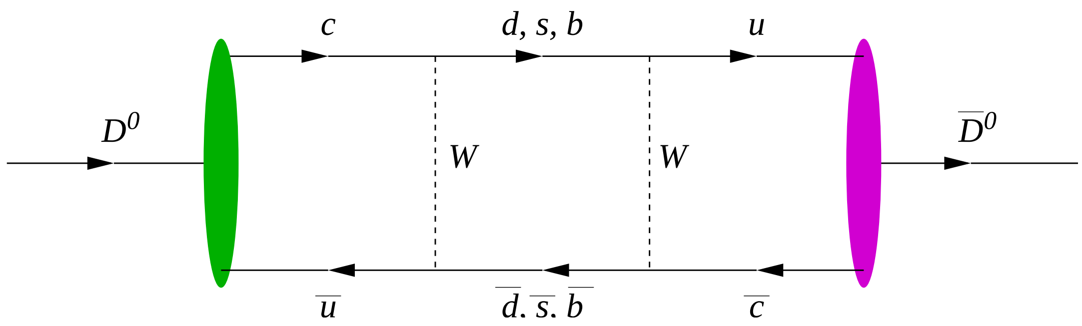
- $E_c = E_e$
- $\sigma \sim 1.3\,nb$
- **Both at $\Upsilon(4s)$ and in continuum**

- $E_B = E_e$
- $\sigma \sim 1\,nb$
- **Fixed initial state (B) angular momenta.**

Charm studies

- $D^0 - \overline{D}^0$ **mixing.**
- **Rare decays of D.**
- **Study of charmonia production**
- **Excited D^{**} and D_{sJ} spectroscopy and production from B decay.**
- **Charm baryons**

$D^0 - \overline{D}^0$ mixing



- **Neutral D mass eigenstates are $D^0 - \overline{D}^0$ combinations with masses $m_1, \ m_2$.**

$$x = \frac{m_1 - m_2}{(\Gamma_1 + \Gamma_2)/2}, \qquad y = \frac{\Gamma_1 - \Gamma_2}{\Gamma_1 + \Gamma_2}$$

- **Highly suppressed in SM: $x, y = O(10^{-10} - 10^{-9})$**
  Long distance effects $\rightarrow x, y = O(10^{-3} - 10^{-2})$
- **New Physics can provide additional box diagrams**

Way to measure.

- **Lifetime in different D decay modes $K^+K^-, \ \pi^+\pi^-, \ K\pi$.**
- **Wrong-sign decay $D^0 \rightarrow K^+\pi^-$ - time evolution.**
- **Wrong-sign decay amplitude $D^0 \rightarrow K^+l^-\nu$.**

$D^0 - \overline{D}^0$ mixing in $D^0 \to K^+\pi^-$.

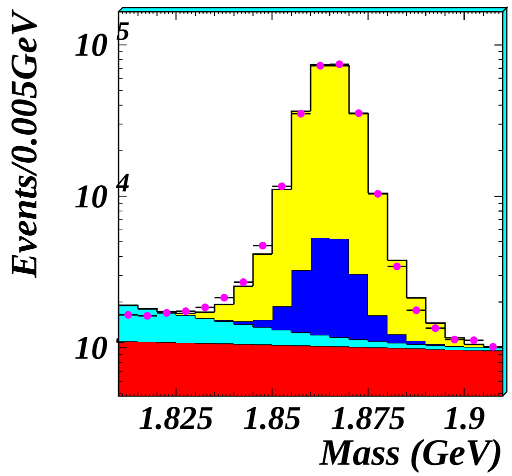
$\int \mathcal{L}dt = 90\ \mathrm{fb}^{-1}$ | $m_{K\pi}$ | $Q = m_{K\pi\pi_{slow}} - m_{K\pi} - m_\pi$

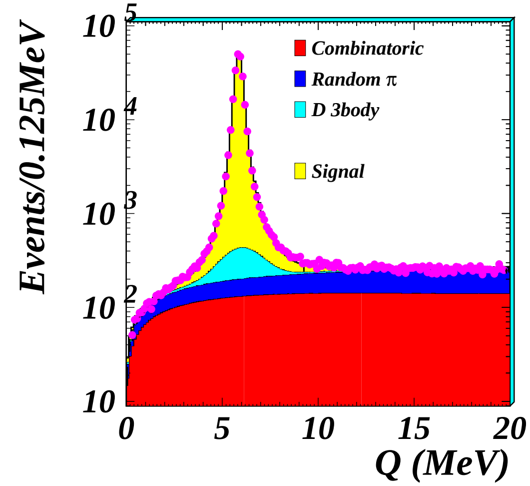
D flavor – sign of π from $D^{*+} \to D^0\pi^+$.

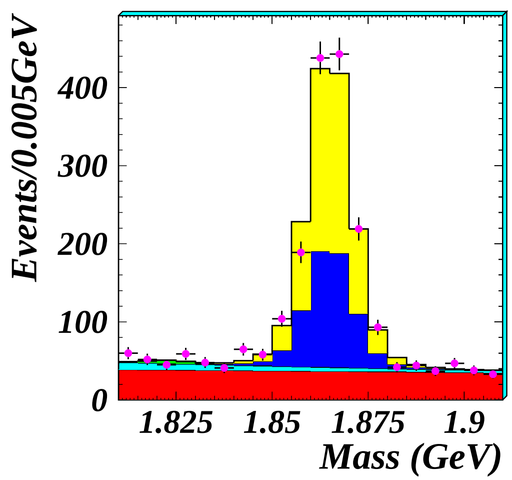
Wrong sign:

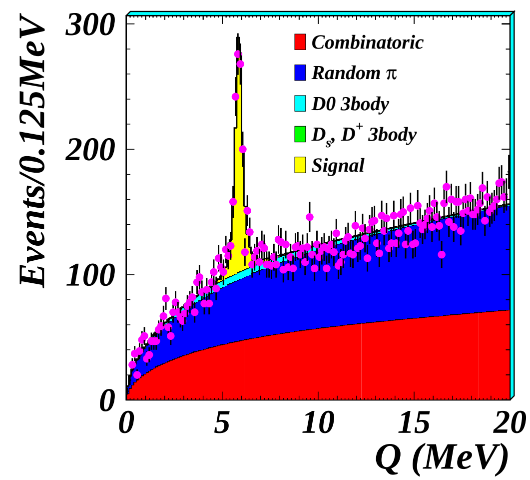
Double-Cabibbo Suppressed

mixing+Cabibbo-favored









- *Combinatoric*
- *Random π*
- *D0 3body*
- *D_s, D^+ 3body*
- *Signal*

$R_{WS} = \frac{\Gamma(D^0 \to K^+\pi^-)}{\Gamma(D^0 \to K^-\pi^+)}$
$= (0.371 \pm 0.018)\%$
(statistical errors only)

$D^0 - \overline{D}^0$ mixing in $D^0 \to K^+\pi^-$.

Wrong sign decay rate depends on DCS and CF amplitude + mixing:

$$R_D = \frac{|A_{DCS}|}{|A_{CF}|},$$

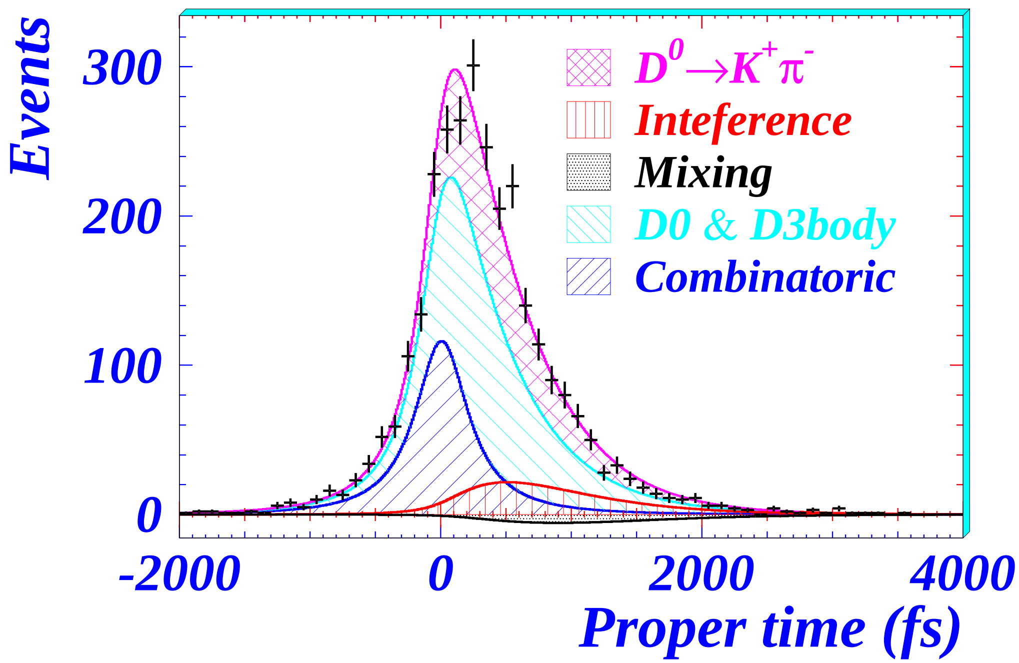
$$x' = x\cos\delta_{K\pi} + y\sin\delta_{K\pi}$$

$$y' = -x\sin\delta_{K\pi} + y\cos\delta_{K\pi}$$

$$\frac{dN}{dt} \propto e^{-\bar{\Gamma}t}(R_D + \sqrt{R_D}y'\bar{\Gamma}t + \frac{x'^2+y'^2}{4}(\bar{\Gamma}t)^2)$$

DCSD **interference** **mixing**

Unbinned likelihood fit $pdf(t, m, Q)$.



In the case of CPV: $\{R_D^+, x'^{+2}, y'^+\}$ **for** D^0 **and** $\{R_D^-, x'^{-2}, y'^-\}$ **for** $\overline{D}^0$

CP violation is parametrized by the asymmetries:

$A_D = (R_D^+ - R_D^-)/(R_D^+ + R_D^-)$ **and** $A_M = (R_M^+ - R_M^-)/(R_M^+ + R_M^-)$,

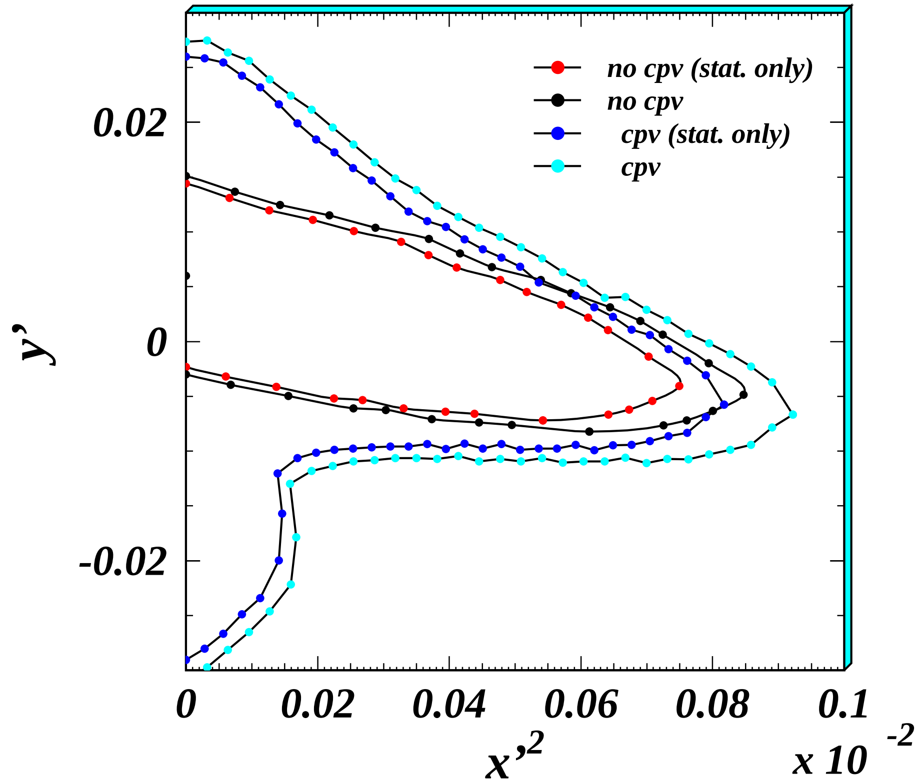
where $R_M^\pm = \left(x'^{\pm 2} + y'^{\pm 2}\right)/2$.

$D^0 - \overline{D}^0$ mixing in $D^0 \to K^+\pi^-$.

95 % C.L. region.

Fit results

Fit Case	**Parameter**	**Fit Result** ($\times 10^{-3}$)
No CPV	x'^2	$-1.53\,^{+0.80}_{-1.00}$
	y'	$25.4\,^{+11.1}_{-10.2}$
	R_D	2.87 ± 0.37
No CPV $x'=0$ **(fixed)**	y'	6.0 ± 3.3
	R_D	3.43 ± 0.26
CPV **allowed**	A_D	-80 ± 77
	A_M	$987\,^{+13}_{-380}$



hep-ex/0408125 , PRL, 94, N7, p.071801

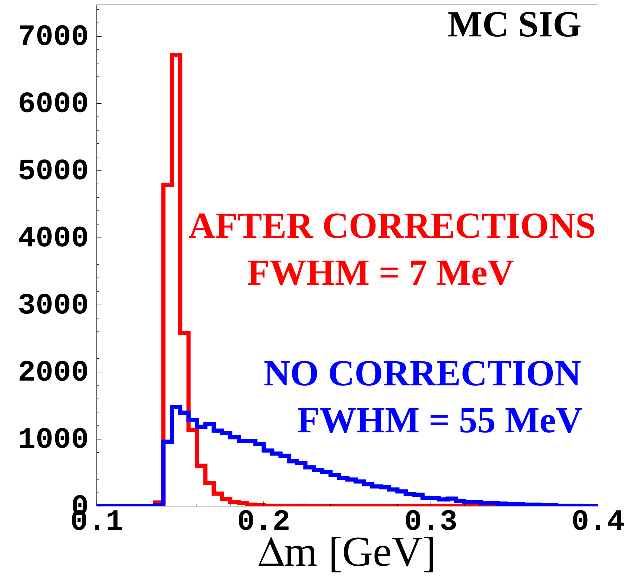
$D^0 \to K^+ e^- \bar{\nu}_e$ decay.

$\int \mathcal{L} dt = 140 \text{ fb}^{-1}$

- **No DCSD: only mixing amplitude:**

$$\frac{dN}{dt} \propto e^{-\bar{\Gamma}t} \left(\frac{x'^2 + y'^2}{4} (\bar{\Gamma}t)^2 \right)$$

- **background from CF decay**
- **No amplification $\sim \sqrt{R_D}$**
- **Presence of ν**

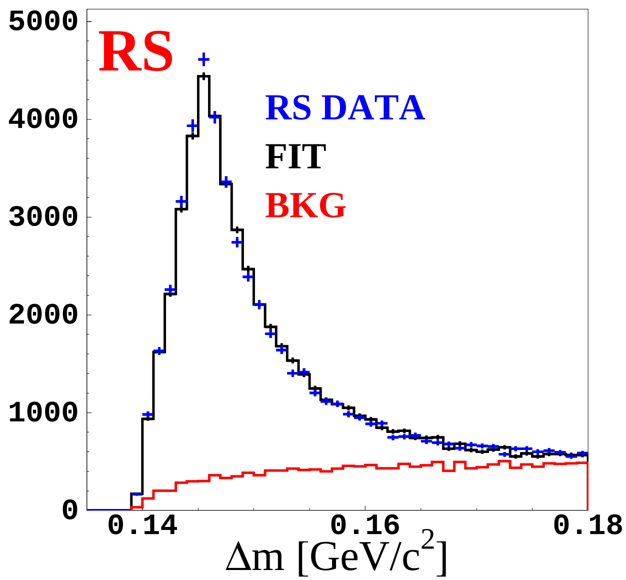


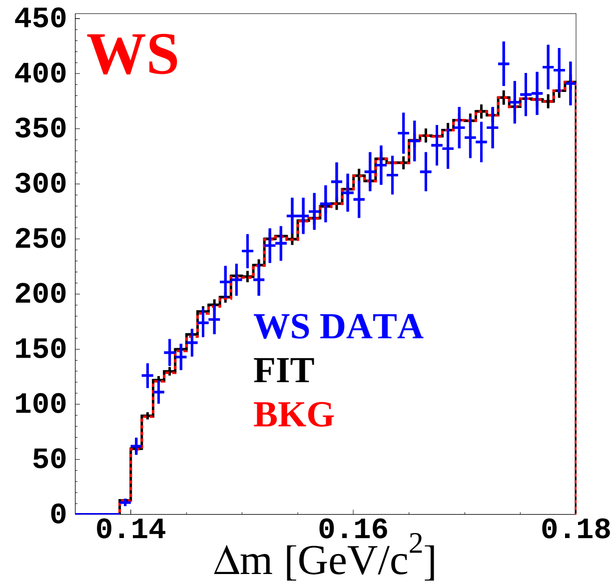
Reconstruction:

- **Use simple cut on $t > 1.5\tau_D$ to suppress D^0 mistag background**
- **Use constraints to improve ν reconstruction for m_{D^*}, m_ν**
- **The background shapes are estimated from the data, with a small MC-derived correction.**

$D^0 \to K^+ e^- \bar{\nu}_e$.

Right sign | **Wrong sign**





$N_{RS} = 40198 \pm 329$ $\qquad$ $N_{WS} = 19 \pm 67$

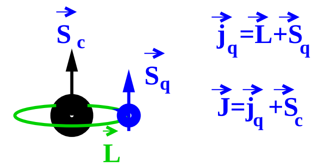
$$r_D = \frac{D^0 \to e^- K^+ \bar{\nu}_e}{D^0 \to e^+ K^- \nu_e} = \frac{x^2 + y^2}{2} = (0.20 \pm 0.70 \pm 0.11) \times 10^{-3}$$

$r_D < 1.4 \times 10^{-3}$ **at 90% C.L.**

hep-ex/0408125

update, with twice the statistics, is in preparation

D^{**} are p-wave excitations of D mesons.



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

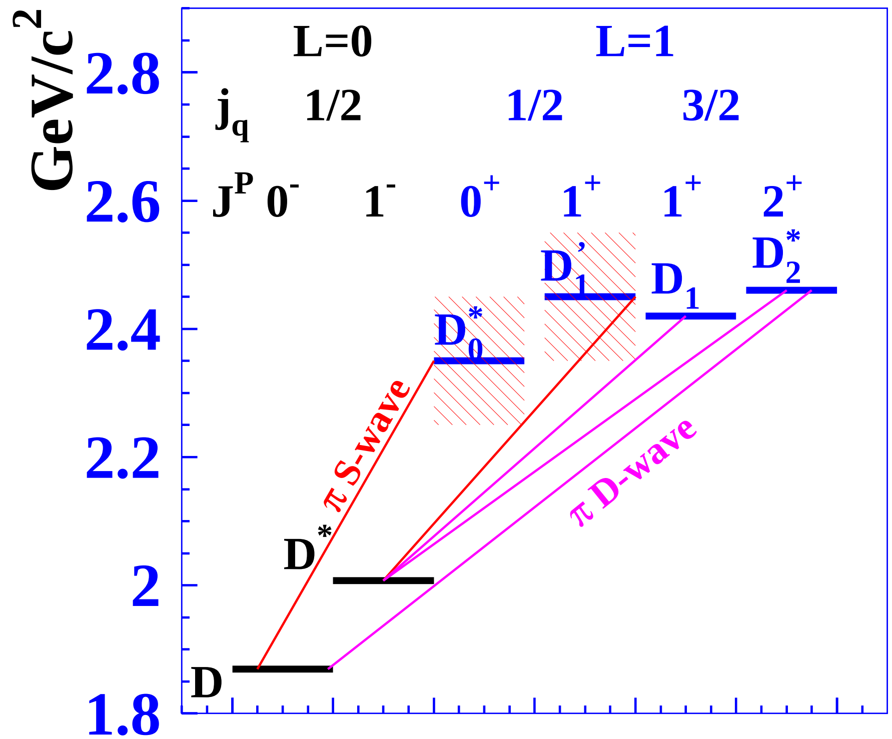
$D^{**} \to D^{(*)}\pi$ **have different dependences**

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

In B decay fixed initial state spin 0.

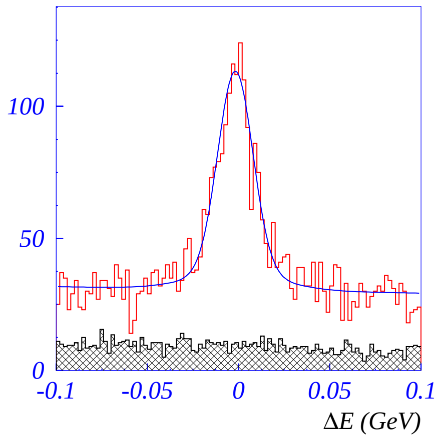
$B \to D_2^*\pi$	**D-wave**
$B \to D_1\pi$	**P-wave**
$B \to D_1'\pi$	**P-wave**
$B \to D_0^*\pi$	**S-wave**

All D^{**} states can be distinguished using Dalitz plot analysis



Test of HQET and QCD sum rule predictions.

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



$\sim 65\ MB\bar{B}$

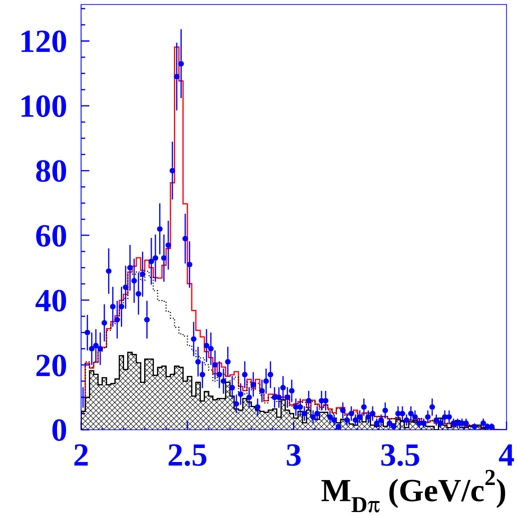
$D^+ \to K^-\pi^+\pi^+$, $D^{*+} \to D^0\pi^+$

$D^0 \to K^-\pi^+$ and $D^0 \to K^-\pi^+\pi^-\pi^+$

Unbinned likelihood fit of Dalitz plot for $D\pi\pi$.

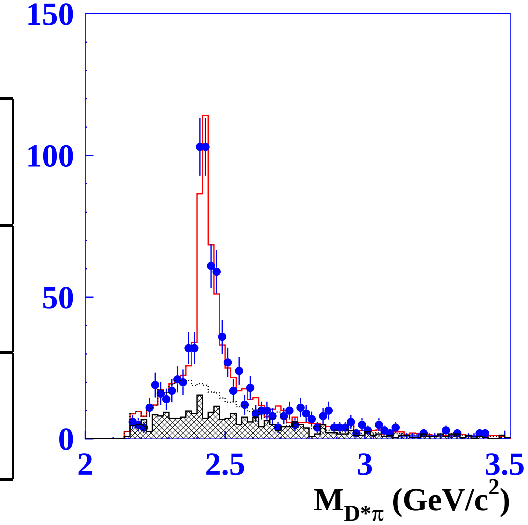
2 more angles for D^* decay.

Unbinned likelihood fit of 4-D plot for $D^*\pi\pi$.



All 4 neutral D^{**} have been observed.

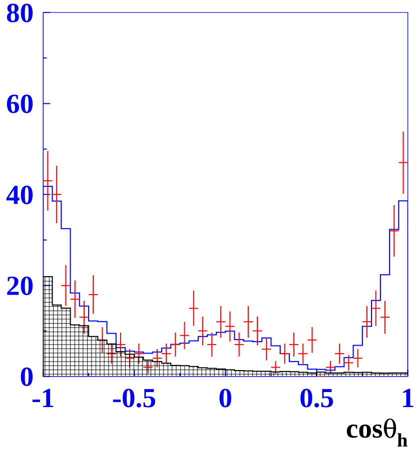
D^{**}	products of branching fractions 10^{-4}	
	$B(B \to D^{**}\pi)B(D^{**} \to D\pi)$	$B(B \to D^{**}\pi)B(D^{**} \to D^*\pi)$
D_2^*	$3.4 \pm 0.3 \pm 0.6 \pm 0.4$	$1.8 \pm 0.3 \pm 0.3 \pm 0.2$
D_1		$6.8 \pm 0.7 \pm 1.3 \pm 0.2$
D_0^*	$6.1 \pm 0.6 \pm 0.9 \pm 1.6$	
D_1'		$5.0 \pm 0.4 \pm 1.0 \pm 0.4$



Masses and widths of all neutral D^{**}'s have been measured.
First observation of D_0^* and D_1'.

PRD 69, 112002,2004

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

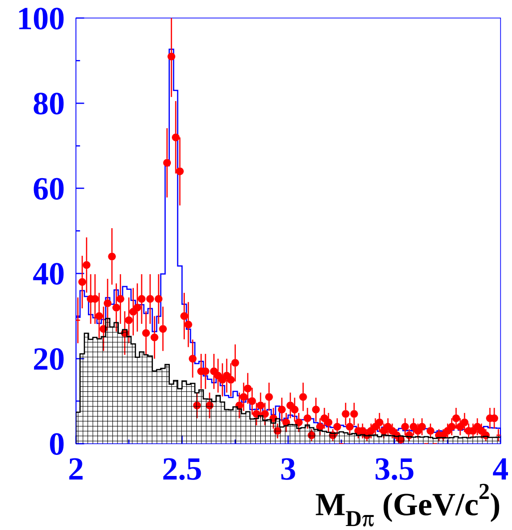


$\sim 152\ MB\bar{B}$

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

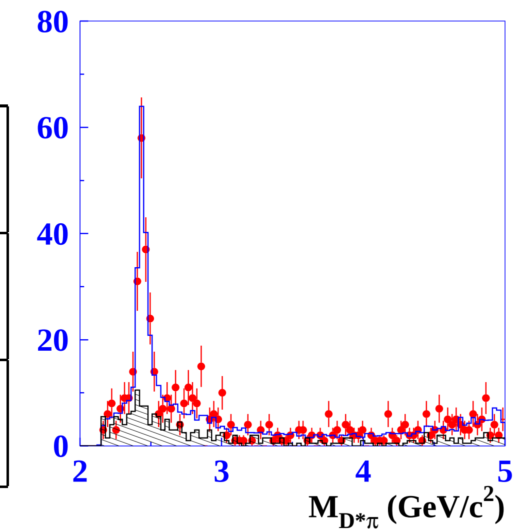
$D^0 \to K^-\pi^+$ **and** $D^0 \to K^-\pi^+\pi^-\pi^+$

Unbinned likelihood fit of 2(4-D) distribution to extract D^{**}'s contributions.



Both neutral narrow D^{**} have been observed.

D^{**}	products of branching fractions 10^{-4}	
	$B(B \to D^{**}\pi)B(D^{**} \to D\pi)$	$B(B \to D^{**}\pi)B(D^{**} \to D^*\pi)$
D_2^*	$3.08 \pm 0.33 \pm 0.09^{+0.15}_{-0.02}$	$2.45 \pm 0.42^{+0.35+0.39}_{-0.45-0.17}$
D_1		$3.68 \pm 0.60^{+0.71+0.65}_{-0.40-0.30}$
D_0^*	< 1.2 at 90 % C.L.	
D_1'		< 0.7 at 90 % C.L.



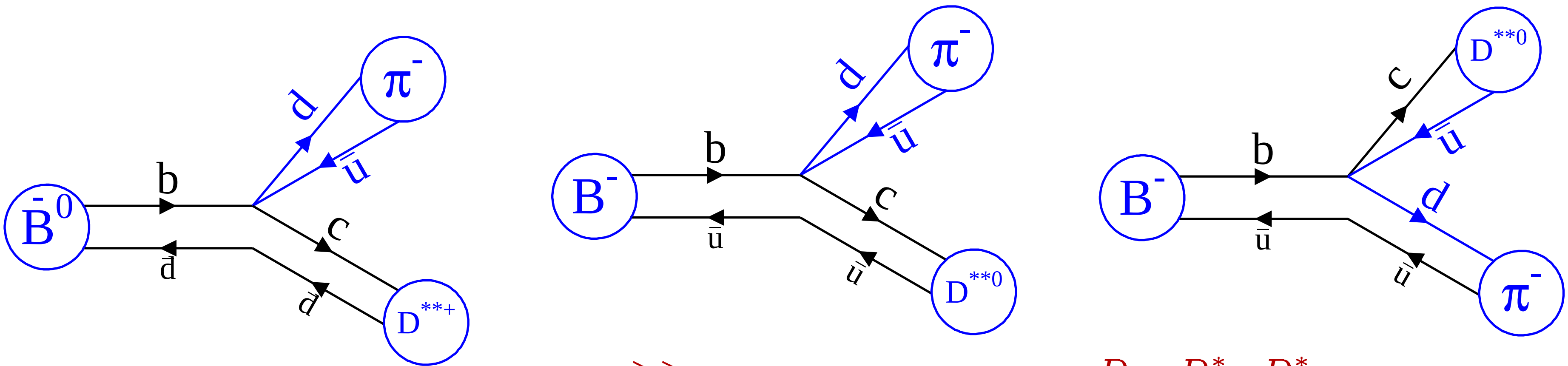
Broad D^{**} production is suppressed.

hep-ex/0412072

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

The production of $D^{**+}_{j=3/2}\pi^-$ in B^0 decay is comparable with $D^{**0}_{j=3/2}\pi^-$ in B^+ decay.

$D^{**+}_{j=1/2}\pi^-$ production in B^0 decay is at least 5 times lower than in B^+ decay.



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

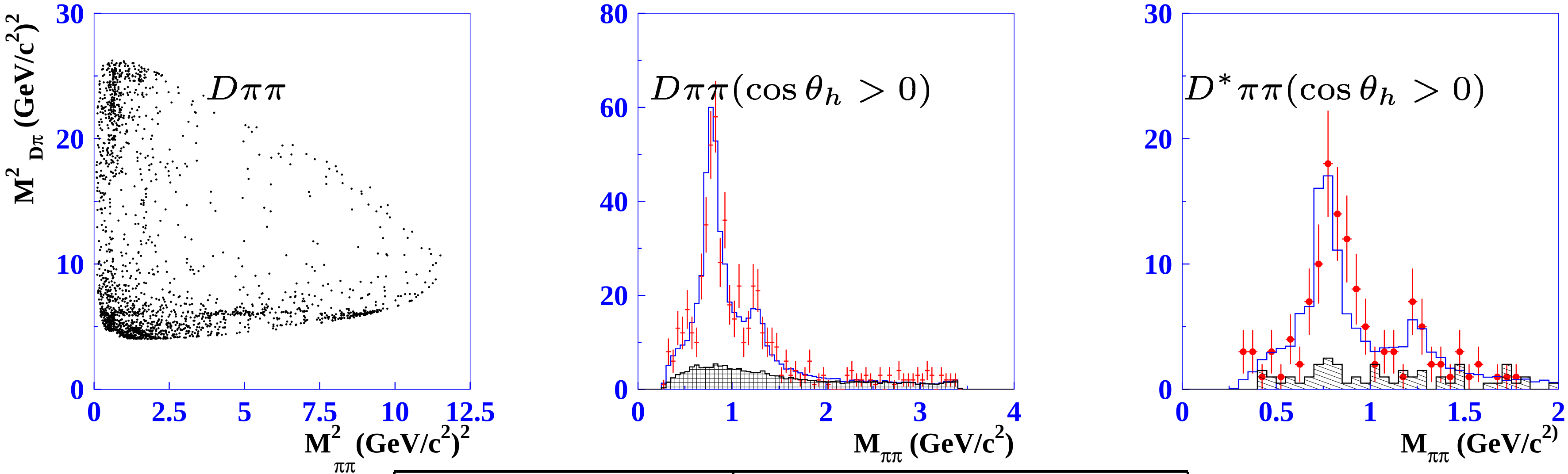
$D_1,\ D_1^*,\ D_0^*$

- **Tree $B \to D^{**}$ diagram:** $\tau_{3/2} >> \tau_{1/2}$
- **Color suppressed diagram** $f_{D_{3/2}} << f_{D_{1/2}}$

For broad D^{**} production Color suppressed amplitude dominates.

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

- $\bar{B}^0 \to D^{(*)0}\pi^+\pi^-$ **includes** $\bar{B}^0 \to D^{(*)0}h^0$
- $D^{(*)}\rho$, $D^{(*)}f_2(1270)$ **and** $D^{(*)}f_0(600)$ **are included in the fit amplitude.**



decay	BF 10^{-4}
$B(\bar{B}^0 \to D^0\rho)$	$2.91 \pm 0.28 \pm 0.33^{+0.08}_{-0.54}$
$B(\bar{B}^0 \to D^0 f_2)$	$1.95 \pm 0.34 \pm 0.38^{+0.32}_{-0.02}$
$B(\bar{B}^0 \to D^{*0}\rho)$	$3.73 \pm 0.87 \pm 0.46^{+0.18}_{-0.08}$
$B(\bar{B}^0 \to D^{*0} f_2)$	$1.86 \pm 0.65 \pm 0.60^{+0.80}_{-0.52}$

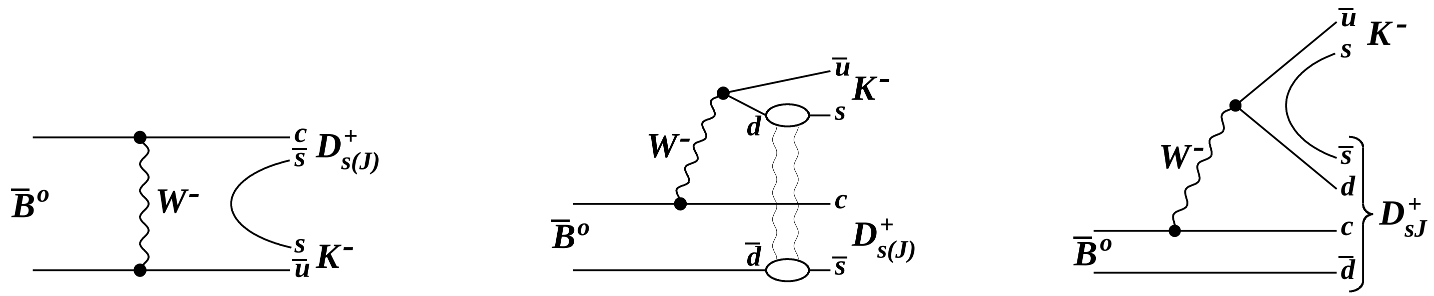
Preliminary

hep-ex/0412072

$\bar{B}^0 \to D_{sJ}^+ K^-$, $\bar{B}^0 \to D_{sJ}^- \pi^+$ decays.

- Narrow $D_{sJ}(2317)$ and $D_{sJ}(2460)$ were observed by BaBar, CLEO and Belle.
  - Masses significantly lower than potential model expectations.
  - Widths of the resonances are consistent with zero.
  - The quantum numbers are consistent with 0^+ and 1^+.
- Decays $B \to D_{sJ}\bar{D}$ were observed by BaBar and Belle with branching fractions one order magnitude smaller than for $B \to D_s\bar{D}$ decay.
- Studies of decays $\bar{B}^0 \to D_{sJ}^+ K^-$, $\bar{B}^0 \to D_{sJ}^- \pi^+$ are important to understand nature of D_{sJ}

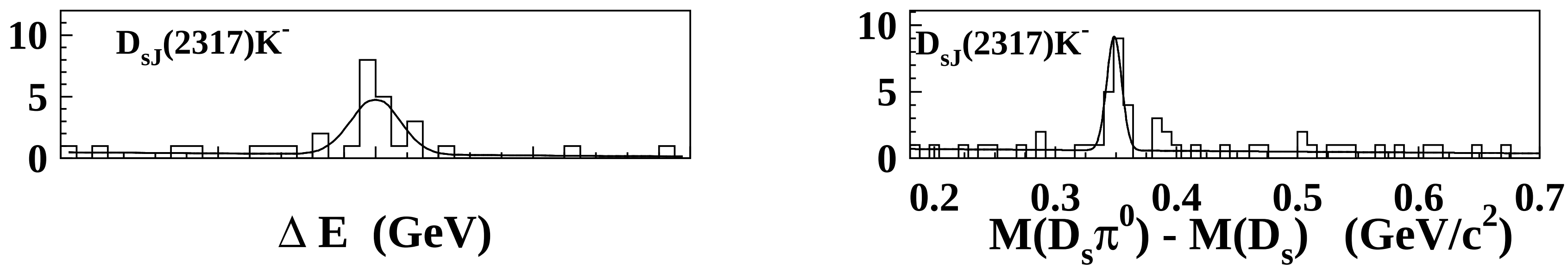
W-exchange diagram | Final state interaction | Tree, 4-quark D_{sJ}



$\bar{B}^0 \to D_{sJ}^+ K^-$, $\bar{B}^0 \to D_{sJ}^+ \pi^-$ decays.

152×10^6 $B\bar{B}$ **pairs**

$D_{sJ}(2317)^+ \to D_s^+ \pi^0$, $D_{sJ}(2460)^+ \to D_s^+ \gamma$, $D_s^+ \to \phi\pi^+,\ K^{*0}K^+,\ K_s K^+$,



Fit mass difference $\Delta m = m_{D_{sJ}} - m_{D_s}$

Decay mode	Yield $\Delta M(D_{sJ})$	Product $\mathcal{B}(\bar{B}^0 \to D_{sJ} h) \times \mathcal{B}(D_{sJ} \to D_s \pi^0(\gamma))$ (10^{-5})	Significance σ
$\bar{B}^0 \to D_{sJ}^*(2317)^+ K^-$	$16.6^{+4.6}_{-4.1}$	$5.3^{+1.5}_{-1.3} \pm 0.7 \pm 1.4$	**6.8**
$\bar{B}^0 \to D_{sJ}^*(2317)^- \pi^+$	$2.9^{+3.3}_{-2.8}$	$<$**2.5 (90%** C.L.)	
$\bar{B}^0 \to D_{sJ}(2460)^+ K^-$	$2.0^{+2.9}_{-2.2}$	$<$**0.94 (90%** C.L.)	
$\bar{B}^0 \to D_{sJ}(2460)^- \pi^+$	$-1.9^{+3.1}_{-2.6}$	$<$**0.40 (90%** C.L.)	

$\bar{B}^0 \to D_{sJ}^*(2317)^+ K^-$ **branching fraction is of the same order as** $\bar{B}^0 \to D_s^+ K^-$ **and at least a factor of 2 larger than the** $\bar{B}^0 \to D_{sJ}(2460)^+ K^-$.

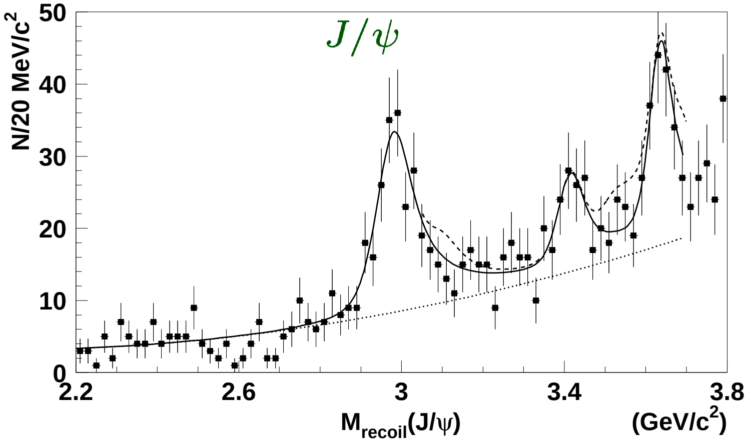
No significant signal from $\bar{B}^0 \to D_{sJ}^- \pi^+$

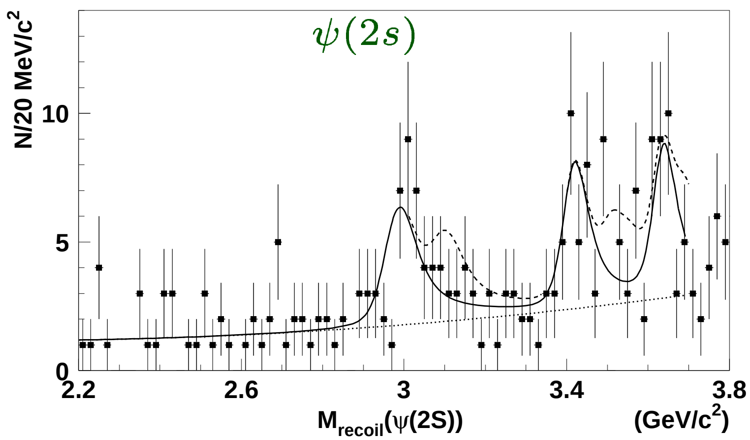
hep-ex/0409026, PRL 94, N6, p.061802

Double charmonium production

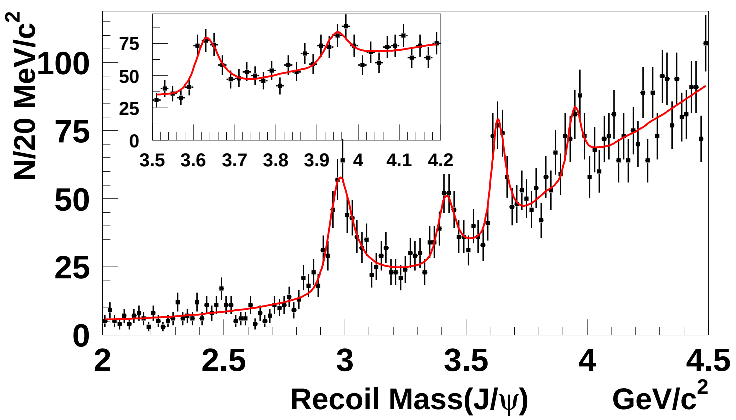
$\int \mathcal{L}dt = 155\ \text{fb}^{-1}$

Study of recoil mass against $J/\psi(\psi(2S))$: $M_{rec} = \sqrt{(E_{\text{CM}} - E^*_{J/\psi})^2 - p^{*\,2}_{J/\psi}}$





$280\ \text{fb}^{-1}$



- **Production of η_c, χ_{c0}, η_c' observed**
- **$\psi\eta_c$ yield is very much larger than predicted by theory**
- **No J/ψ, χ_{c1} , χ_{c2}, $\psi(2S)$ rule out double virtual photon annihilation**
- **angular analysis rule out $J/\psi+$ glueball production**
- **Evidence of $X(3940)$ with new data.**

hep-ex/0407009, Phys. Rev. D 70, 071102(R) (2004)

Summary

- Sensitivity to $D^0 - \bar{D}^0$ mixing has reached a 10^{-3} level.
- Accuracy is close to the level to search CPV in these decays.
- The branching fractions of $B^- \to D^{**0}\pi^-$ have been measured both for narrow and for broad states. Masses and widths of D^{**} have been measured.
- Significantly smaller branching fractions of $\bar{B}^0 \to D^{**+}\pi^-$ for the broad states has been observed.
- $\bar{B}^0 \to D^{*+}_{sJ} K^-$ and $\bar{B}^0 \to D_{sJ} - \pi^+$ decays were studied for the first time.
- The branching fraction of $\bar{B}^0 \to D^*_{sJ}(2317)^+ K^-$ is of the same order as $\bar{B}^0 \to D^{*+}_s K^-$ and at least a factor of 2 larger than the $\bar{B}^0 \to D_{sJ}(2460)^+ K^-$.
- No significant signal from $\bar{B}^0 \to D_{sJ} - \pi^+$
- Double charmonia production has been observed.

Backup slides

$D^0 - \overline{D}^0$ mixing in $D^0 \to K^+\pi^-$.

Fit Case	Parameter	Fit Result ($\times 10^{-3}$)	95% CL interval ($\times 10^{-3}$)
No CPV	x'^2	$-1.53^{+0.80}_{-1.00}$	$x'^2 < 0.81$
	y'	$25.4^{+11.1}_{-10.2}$	$-8.2 < y' < 16$
	R_D	2.87 ± 0.37	$2.7 < R_D < 4.0$
	R_M	–	$R_M < 0.42$
No CPV $x'=0$ (fixed)	y'	6.0 ± 3.3	–
	R_D	3.43 ± 0.26	–
CPV allowed	A_D	-80 ± 77	$-250 < A_D < 110$
	A_M	987^{+13}_{-380}	$-991 < A_M < 1000$
	x'^2	–	$x'^2 < 0.89$
	y'	–	$-30 < y' < 27$
	R_M	–	$R_M < 0.46$
No mixing or CPV	R_D	$3.81 \pm 0.17\,(\text{stat.})^{+0.08}_{-0.16}\,(\text{syst.})$	

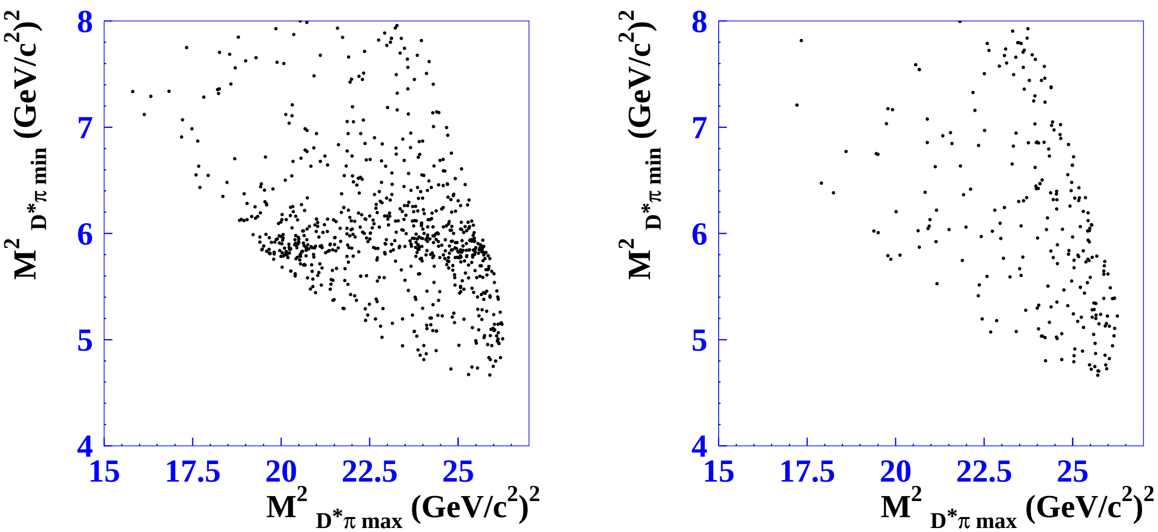
Masses

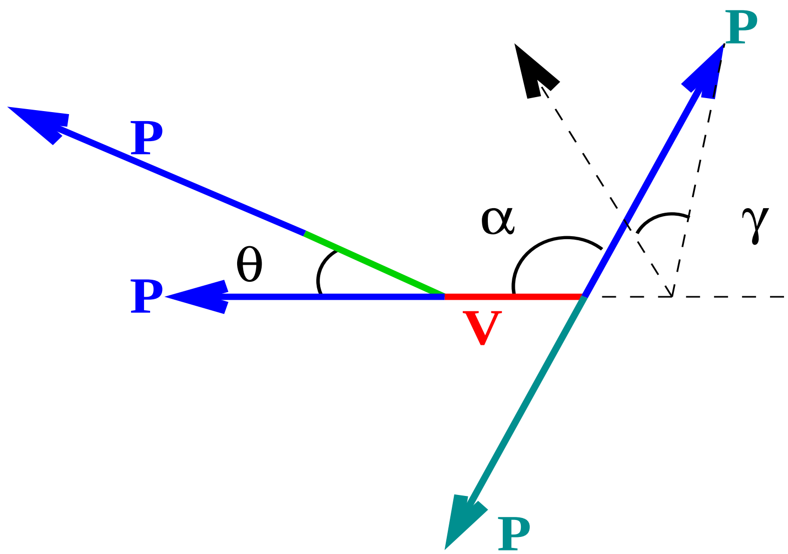
- Masses and widths of D^{**} have been measured.

$$M_{D_2^{*+}} = (2459.5 \pm 2.3 \pm 0.7^{+4.9}_{-0.5})\mathrm{MeV}/c^2, \quad \Gamma_{D_2^{*+}} = (48.9 \pm 5.4 \pm 4.2 \pm 1.9)\mathrm{MeV}.$$
$$M_{D_1^{+}} = (2428.2 \pm 2.9 \pm 1.6 \pm 0.6)\,\mathrm{MeV}/c^2, \quad \Gamma_{D_1^{+}} = (34.9 \pm 6.6^{+4.1}_{-0.9} \pm 4.1)\,\mathrm{MeV}.$$
$$M_{D_2^{*0}} = (2461.6 \pm 2.1 \pm 0.5 \pm 3.3)\,\mathrm{MeV}/c^2, \quad \Gamma_{D_2^{*0}} = (45.6 \pm 4.4 \pm 6.5 \pm 1.6)\,\mathrm{MeV},$$
$$M_{D_0^{*0}} = (2308 \pm 17 \pm 15 \pm 28)\,\mathrm{MeV}/c^2, \Gamma_{D_0^{*0}} = (276 \pm 21 \pm 18 \pm 60)\,\mathrm{MeV}.$$
$$M_{D_1^{0}} = (2421.4 \pm 1.5 \pm 0.4 \pm 0.8)\,\mathrm{MeV}/c^2, \quad \Gamma_{D_1^{0}} = (23.7 \pm 2.7 \pm 0.2 \pm 4.0)\,\mathrm{MeV},$$
$$M_{D_1^{\prime 0}} = (2427 \pm 26 \pm 20 \pm 15)\,\mathrm{MeV}/c^2, \quad \Gamma_{D_1^{\prime 0}} = (384^{+107}_{-75} \pm 24 \pm 70)\,\mathrm{MeV}.$$

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

Mass constrain fit to M_B, M_{D^*} and M_D.





B decays to 2 pseudoscalars and vector $\mathbf{B \to PPV}$

$V \to PP$ decay gives information about polarization.

$$\mathbf{d\Gamma = \frac{|A|^2}{256\pi^3 M_B^3} \frac{p_{3*}}{M_*} dm_{13}^2 dm_{12}^2 d} \cos\alpha \mathbf{d}\gamma,$$

$$D_2^* \quad 2^+_{3/2} \quad A^{(2)} \sim \sin\alpha \sin\theta \sin\gamma$$

$$D_{3/2} \quad 1^+_{3/2} \quad A_D^{(1)} \sim \sin\alpha \sin\theta \cos\gamma + 2\cos\theta\cos\alpha$$

$$D_{1/2} \quad 1^+_{1/2} \quad A_S^{(1)} \sim \sin\alpha \sin\theta \cos\gamma - \cos\theta\cos\alpha$$

Since c-quark has finite mass the two 1^+ states can be mixed:

$$D_1 = (D_{3/2}\cos\omega + D_{1/2}e^{i\psi}\sin\omega)$$

$$D_1^* = (D_{1/2}\cos\omega - D_{3/2}e^{-i\psi}\sin\omega)$$

$$A_\Sigma = (a_d A_D^{(1)}\cos\omega + a_s A_S^{(1)}\sin\omega e^{i\psi}) BW_{M_{D_1}\Gamma_{D_1}}(q^2)$$

$$+(a_s A_S^{(1)}\cos\omega - a_d A_D^{(1)}\sin\omega e^{-i\psi}) BW_{M_{D_1'}\Gamma_{D_1'}}(q^2) +$$

$$a_2 A^{(2)} BW_{M_{D_2^*}\Gamma_{D_2^*}}(q^2) + a_{D_v} A^{(D_v)} BW_{D_v}(q^2) + a_{B_v^*} A^{(B_v^*)} BW_{B_v^*}(q^2)$$