Decays of Charmed Hadrons at Belle

V.Balagura (ITEP), EPS HEP 2007, July 19, 2007

1. Measurement of $\mathcal{B}(D_s^+ \to \mu^+\nu_\mu)$.
2. (a) Observation of $D_{s1}(2536)^+ \to D^+\pi^-K^+$,

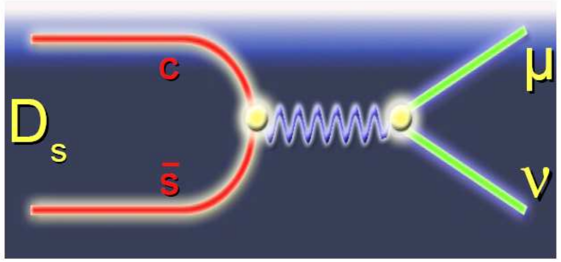
   (b) angular decomposition of S- and D-waves in $D_{s1}(2536)^+ \to D^{*+}K_S^0$.

$D_s^+ \to \mu^+ \nu_\mu$

Latice QCD $\Rightarrow$ f_{B_d} and f_{B_s} $\Rightarrow$ B_d and B_s mixing constraints on CKM unitarity triangle.

Latice QCD can be checked and improved in the charm sector using measured f_D and $f_{D_s^+}$.

$$\Gamma(D_s^+ \to l^+ \nu_l) = \frac{G_F^2}{8\pi} f_{D_s^+}^2 m_l^2 M_{D_s^+} \left(1 - \frac{m_l^2}{M_{D_s^+}^2}\right)^2 |V_{cs}|^2$$



Experimentally $D_s^+ \to \mu^+ \nu_\mu$ is the best mode

$$\Gamma(D_s^+ \to e^+ \nu_e) : \Gamma(D_s^+ \to \mu^+ \nu_\mu) : \Gamma(D_s^+ \to \tau^+ \nu_\tau) \approx 2.5 \cdot 10^{-5} : 1.0 : 9.7.$$

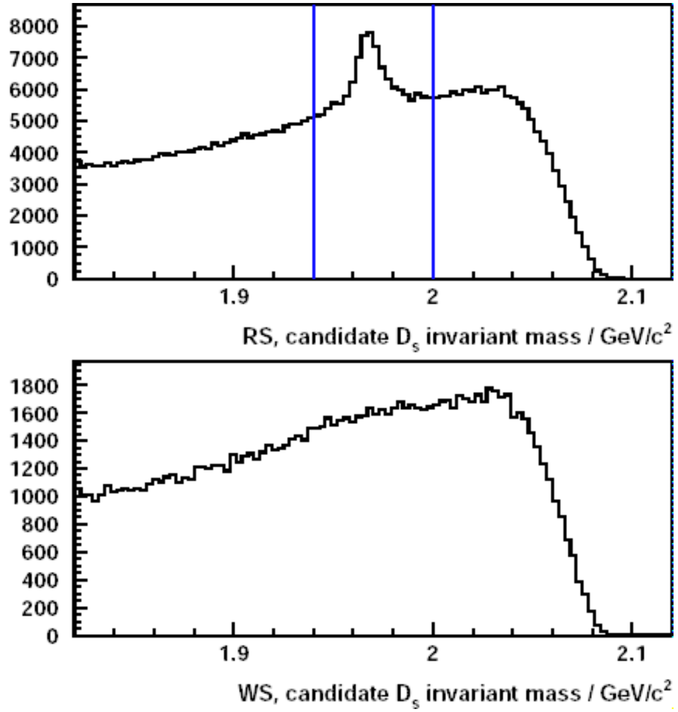
$D_s^+ \to \mu^+ \nu_\mu$

$$e^+e^- \to D_s^{*+}(DKX),\ D_s^{*+} \to D_s^+\gamma, \quad X = k\pi^\pm \text{ or } ((k-1)\pi^\pm)\gamma,$$

$k \leq 5$. Everything in red (DKX and γ from D_s^{*+}) is fully reconstucted,

D_s^+ peak is searched for in the recoil mass spectrum.

$M_{\rm rec}((DKX)\gamma)$, right and wrong sign



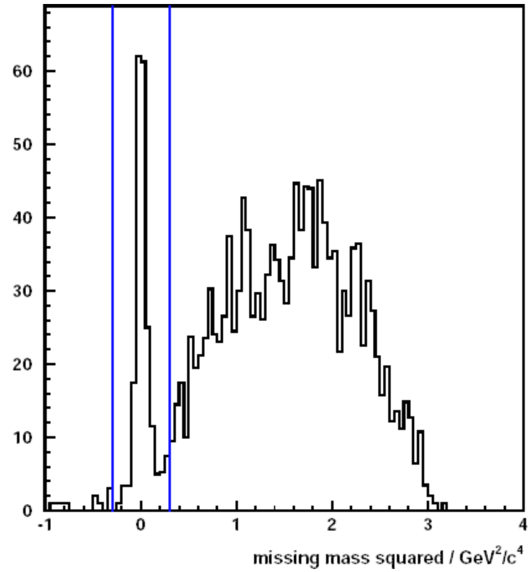
$D^{0,+} \to K_S^{0,-} n\pi^{0,\pm}, \quad n = 1, 2, 3$

$|M_{rec}(DKX) - M_{D_s^{*+}}| < 150$ MeV$/c^2$

$p_D^* > 2, \ p_{D_s^{*+}}^* > 3, \ p_K^* < 2$ GeV$/c^2$

μ^+ is also reconstructed

$$M_{\rm rec}((DKX)\gamma\mu)^2 = M_\nu^2$$



$1.94 < M_{rec}(DKX\gamma) < 2.00$ GeV$/c^2$

$p_\mu > 0.5$ GeV$/c^2$

548 fb^{-1} of data.

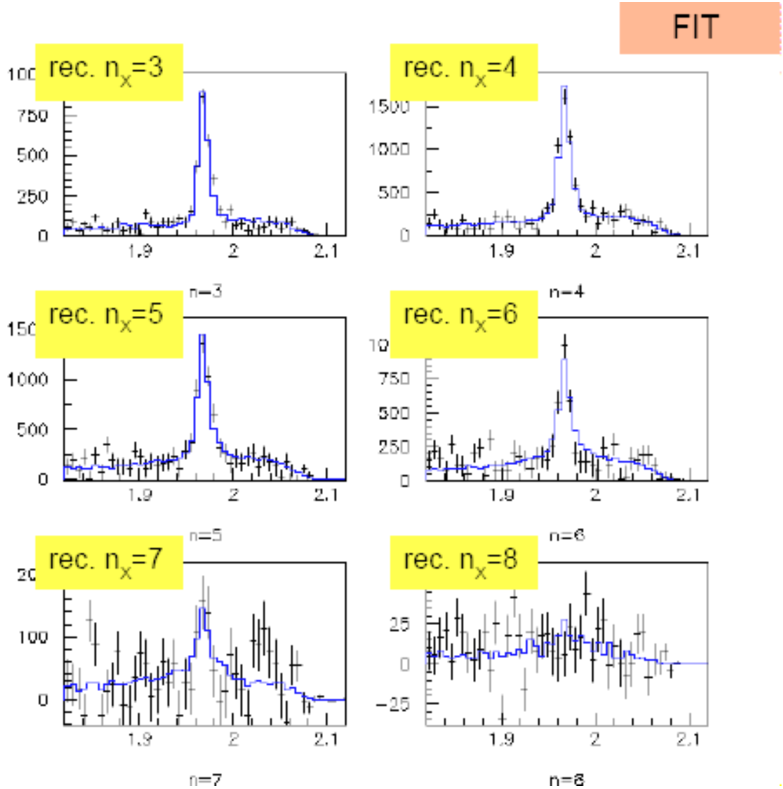
Signal shape and efficiency depend on number of prompt particles $n_X = k + 3 = 3, \dots 8$

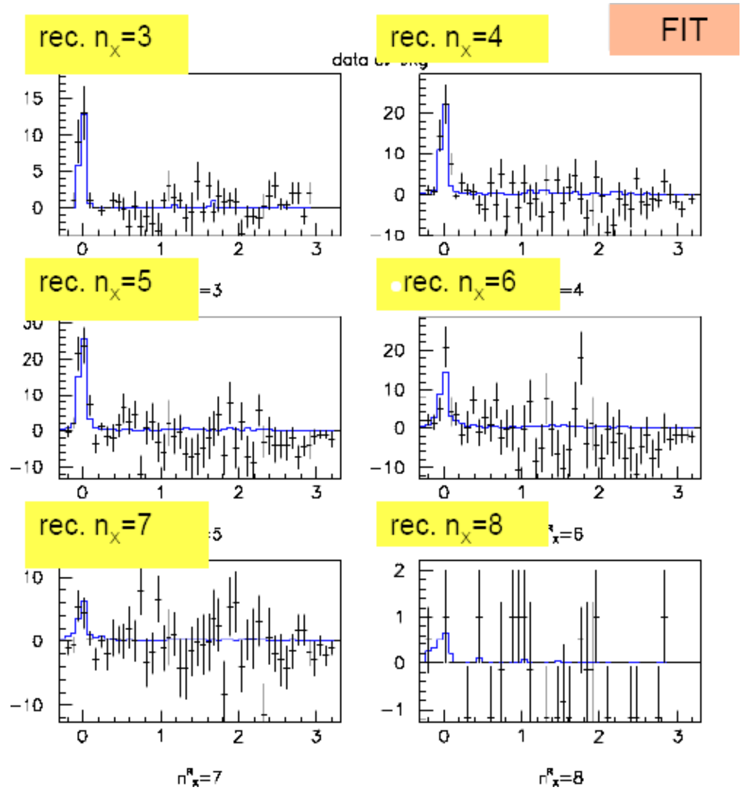
$\Rightarrow$ number of D_s^+'s N is counted in n_X bins, $N = \sum N_{n_X^{rec}}$.

Prompt $\pi^\pm$ or γ may be not reconstructed $\Rightarrow k_{rec} \le k_{true}$, $N_{n_X^{rec}} = \sum M_{n_X^{rec}, n_X^{true}} \times N_{n_X^{true}}$

$\Rightarrow$ cross feeds M between n_X bins is obtained from MC and is taken into account in the fit.

Fitted background is subtracted





background – from WS
or from generic MC to cross check.
$32100 \pm 870 \pm 1210$ ev.

background – by exchanging $\mu^+ \to e^+$,
ratio of μ^+/e^+ efficiencies – from MC.
$169 \pm 16 \pm 8$ ev.

$D_s^+ \to \mu^+ \nu_\mu$

	$B(D_s^+ \to \mu\nu_\mu)$, $\times 10^{-3}$	$f_{D_s^+}$, MeV	
	Preliminary Belle results		
	$6.44 \pm 0.76 \pm 0.52$	$275 \pm 16 \pm 12$	
	Previous results		
PDG'06	6.1 ± 1.9	294 ± 27	
BaBar	$6.74 \pm 0.83 \pm 0.26 \pm 0.66_{\phi\pi}$	$283 \pm 17 \pm 7 \pm 14_{\phi\pi}$	PRL 98, 121801 (2007)
	(last error from $B(D_s^+ \to \phi\pi^+)$)		
CLEO-c	$5.94 \pm 0.66 \pm 0.31$	$264 \pm 15 \pm 7$	hep-ex/0704.0437

$\Rightarrow$ Belle: accuracy is similar to CLEO-c,

direct measurement of absolute $B(D_s^+ \to \mu^+\nu_\mu)$ without norm. channel

C.Davies at EPS-2005: "There has been a revolution in LQCD..."

Unquenched LQCD with $n_f = 2+1$ [PRL 95, 122002 (2005)]: $\boldsymbol{f_{D_s^+} = 249 \pm 3 \pm 16}$ MeV.

Observation of $D_{s1}(2536)^+ \to D^+\pi^- K^+$

$D_{s1}(2536)^+$: $J^P = 1^+$, $j_l = 3/2$; known modes $D^{*+}K_S^0$, $D^{*0}K^+$, $D_s^+\pi^+\pi^-$.

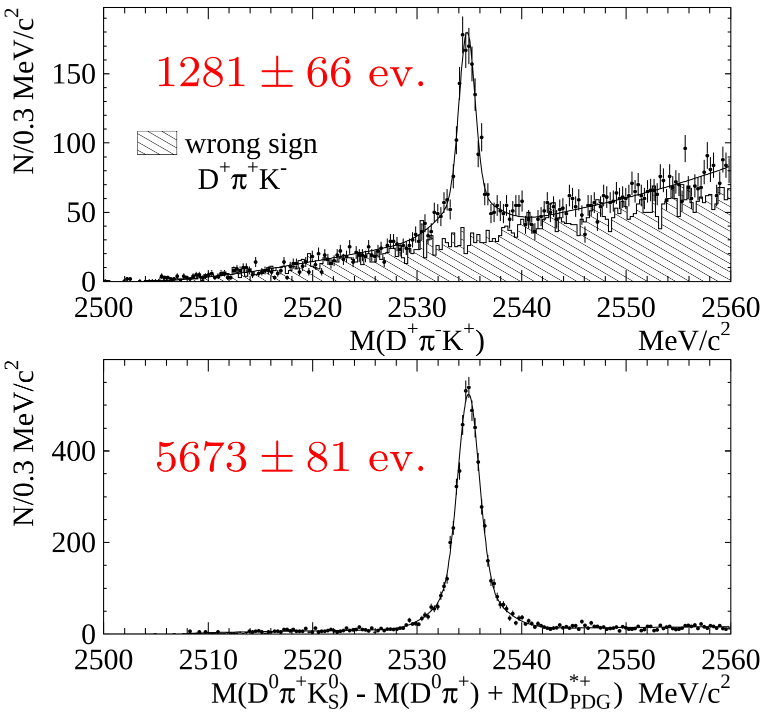
$D^+\pi^-$ cannot come from D^{*0}: $M_{D^0} + M_{\pi^-} > M_{D^{*0}}$.

$x_P = p_{D_{s1}} / \sqrt{s/4 - M^2_{D_{s1}}} > 0.8$,

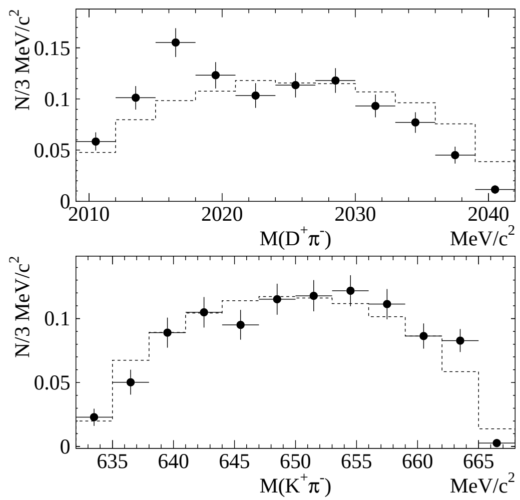
$D^0 \to K^-\pi^+ | K_S^0\pi^+\pi^- | K^-\pi^+\pi^+\pi^-$,
$D^+ \to K_S^0\pi^+ | K^-\pi^+\pi^+$,
$|\Delta M_D| < 20$ MeV/c^2 (99% eff.),

$D^{*+} \to D^0\pi^+$,
$|\Delta M_{D^{*+}}| < 1.5$ MeV/c^2 (98% eff.)

462 fb^{-1} of data



$M_{D^+\pi^-}$ and $M_{K^+\pi^-}$



data (•) vs. ph. space MC

$\longrightarrow$ No visible resonant substructure

$$\frac{B(D_{s1}^+ \to D^+\pi^- K^+)}{B(D_{s1}^+ \to D^{*+}K^0)} = \mathbf{3.17 \pm 0.17 \pm 0.36\%}$$

Partial Wave Analysis (PWA) of $D_{s1}(2536)^+ \to D^{*+}K_S^0$

HQET: $D_{s1}^{(j_l=3/2)} \to D^*K$ D-wave

$(j_l=1/2) \to D^*K$ S-wave (but $D_{s1}(2460)^+ \to D^*K$ is energetically forbidden).

Energy release in $D_{s1}(2536)^+ \to D^*K$ is small $\Rightarrow$ D-wave is suppressed

$\Rightarrow$ small mixing between $j_l=3/2$ and $j_l=1/2$ states

$$|D_{s1}(2460)^+\rangle = \cos\theta\,|(j_l=1/2)\rangle + \sin\theta\,|(j_l=3/2)\rangle$$
$$|D_{s1}(2536)^+\rangle = -\sin\theta\,|(j_l=1/2)\rangle + \cos\theta\,|(j_l=3/2)\rangle$$

can give a sizeable contribution to $D_{s1}(2536)^+$ width.

Belle'03,04: $\frac{B(D_{s1}(2460)\to D_s^{*+}\gamma)}{B(D_{s1}(2460)\to D_s^{+}\gamma)} = \mathbf{0.31 \pm 0.14}$ (B decays and e^+e^- annihilation)

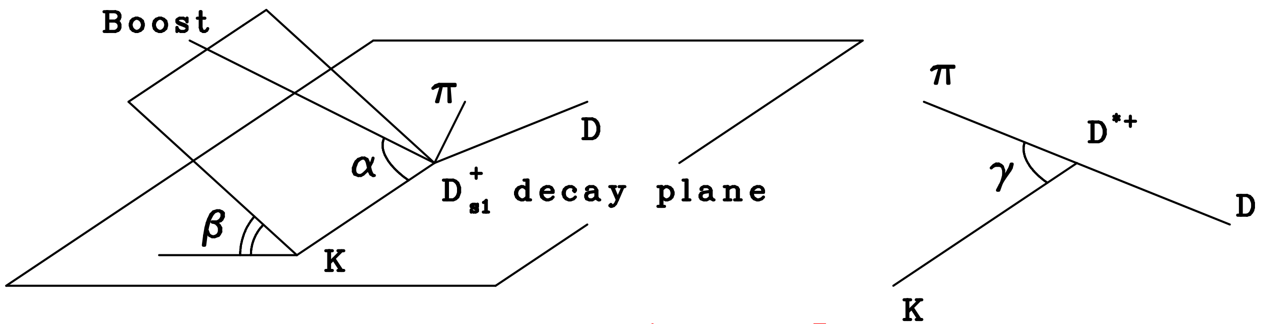
$\Rightarrow$ $\tan^2(\theta+\theta_0) = 0.8 \pm 0.4$, where $\tan^2(\theta_0) = 2$

CLEO'94: first attempt to decompose S- and D-waves in $D_1(2420)^{0,+} \to D^{*+}\pi^-,\ D^0\pi^+$ [PLB **331**, 236; PLB **340**, 194].

Currently no results on $D_{s1}(2536)^+$ exist.

Moreover CLEO method did not allow to perform complete PWA of the decay.

Partial Wave Analysis (PWA) of $D_{s1}(2536)^+ \to D^{*+} K_S^0$



$$\frac{d^3N}{d(\cos\alpha)\ d\beta\ d(\cos\gamma)} = \frac{9}{4\pi(1+2R_\Lambda)} \times \left(\cos^2\gamma\left[\rho_{00}\cos^2\alpha + \frac{1-\rho_{00}}{2}\sin^2\alpha\right] + \right.$$

$$+R_\Lambda \sin^2\gamma\left[\frac{1-\rho_{00}}{2}\sin^2\beta + \cos^2\beta(\rho_{00}\sin^2\alpha + \frac{1-\rho_{00}}{2}\cos^2\alpha)\right]$$

$$\left. + \frac{\sqrt{R_\Lambda}\,(1-3\rho_{00})}{4}\sin 2\alpha \sin 2\gamma \cos\beta \cos\xi \right).$$

ρ_{00} - longitudinal polarization, $\sqrt{\mathbf{R_\Lambda}}\ \exp(i\xi) = \frac{A_{1,0}}{A_{0,0}} = z$,
$A_{1,0}$ and $A_{0,0}$ correspond to D^{*+} helicities ±1 and 0.

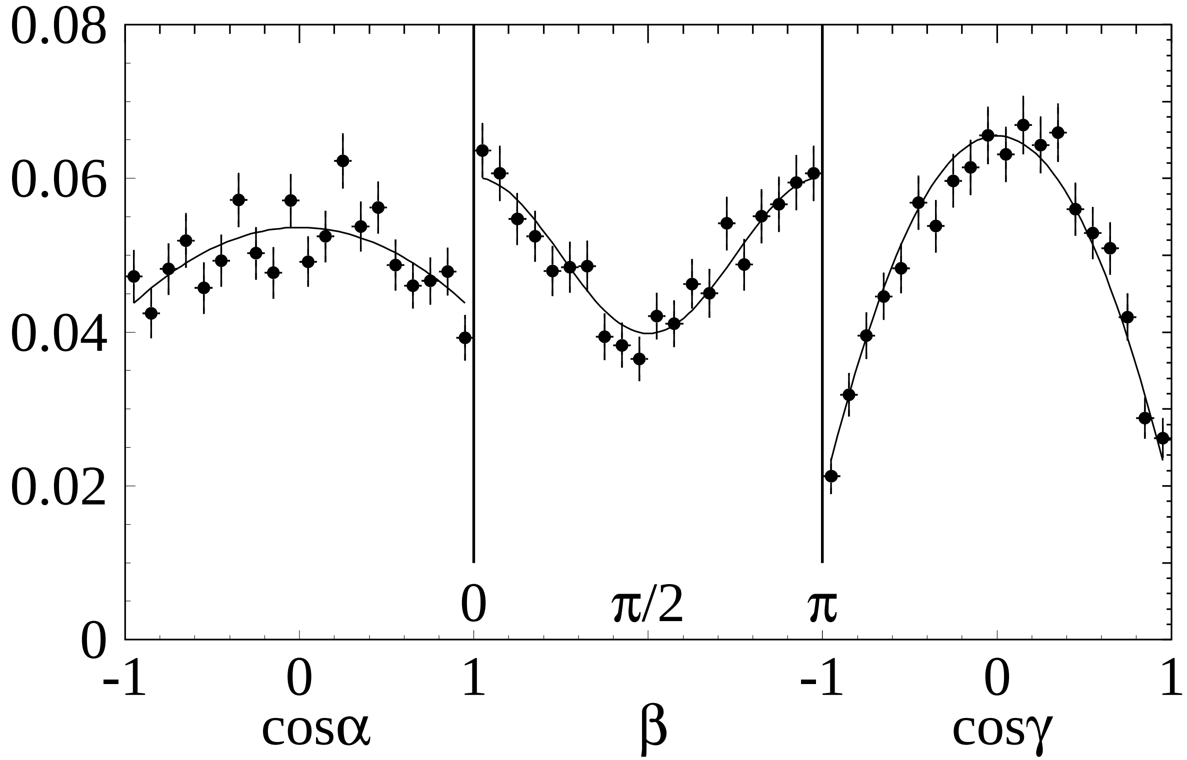
$$\frac{d^3N}{d(\cos\alpha)\ d\beta\ d(\cos\gamma)} \to \rho_{00},\ z = \sqrt{R_\Lambda}\ \exp(i\xi) \to D/S = \sqrt{2}\,(z-1)/(1+2z) = \sqrt{\Gamma_D/\Gamma_S}\ \exp(i\eta).$$

Last interference term with the phase ξ vanishes after integration over any angle. It does not appear in one- and two-dimensional distributions $\frac{dN}{d(\cos\gamma)}$, $\frac{d^2N}{d(\cos\alpha)\,d(\cos\gamma)}$ studied by CLEO in 1994 for $D_1(2420)$ meson.

PDF for 3-D Unbinned ML Fit

$$\mathcal{P}(\alpha,\,\beta,\,\gamma) = (1 - f_b)\cdot\frac{d^3N}{d(\cos\alpha)\;d\beta\;d(\cos\gamma)}\cdot\frac{\epsilon(\alpha,\beta,\gamma)}{\langle\epsilon\rangle_{\rm avr}} + f_b\cdot\mathcal{P}_{bck}(\alpha,\beta,\gamma).$$

Background subtracted and efficiency corrected projections:
data (•) vs. 3-D fit results



χ^2 difference ⇒ goodness-of-fit prob. ~60%.

3-D Fit Quality and Results

PDF is made of $\frac{d^3N}{d(\cos\alpha)\ d\beta\ d(\cos\gamma)} \bigoplus$ efficiency $\bigoplus$ background.

1) $\frac{d^3N}{d(\cos\alpha)\ d\beta\ d(\cos\gamma)}$ depends on fit parameters only *quadratically or linearly*;

2) efficiency is almost flat in all projections: $\epsilon = \text{const} \ \Rightarrow$ results *change by* $\leq 1/3\sigma_{\text{stat}}$;

3) background fraction $f_b = 9\%$ is small;

$\Rightarrow$ **fit is simple.**

Fit of 1000 toy MC samples: *no bias found.* FCN is worse than in data *in 33% of cases.*

$$\boldsymbol{A_{1,0}/A_{0,0} = \sqrt{3.6 \pm 0.3}\,\exp\left(\pm i \cdot (1.27 \pm 0.16)\right)}$$

$$\boldsymbol{D/S = (0.63 \pm 0.07) \cdot \exp\left(\pm i \cdot (0.77 \pm 0.03)\right)}$$

Contrary to HQET, S-wave dominates:

$$\boldsymbol{\Gamma_S/\Gamma_{\text{total}} = 0.72 \pm 0.05}$$

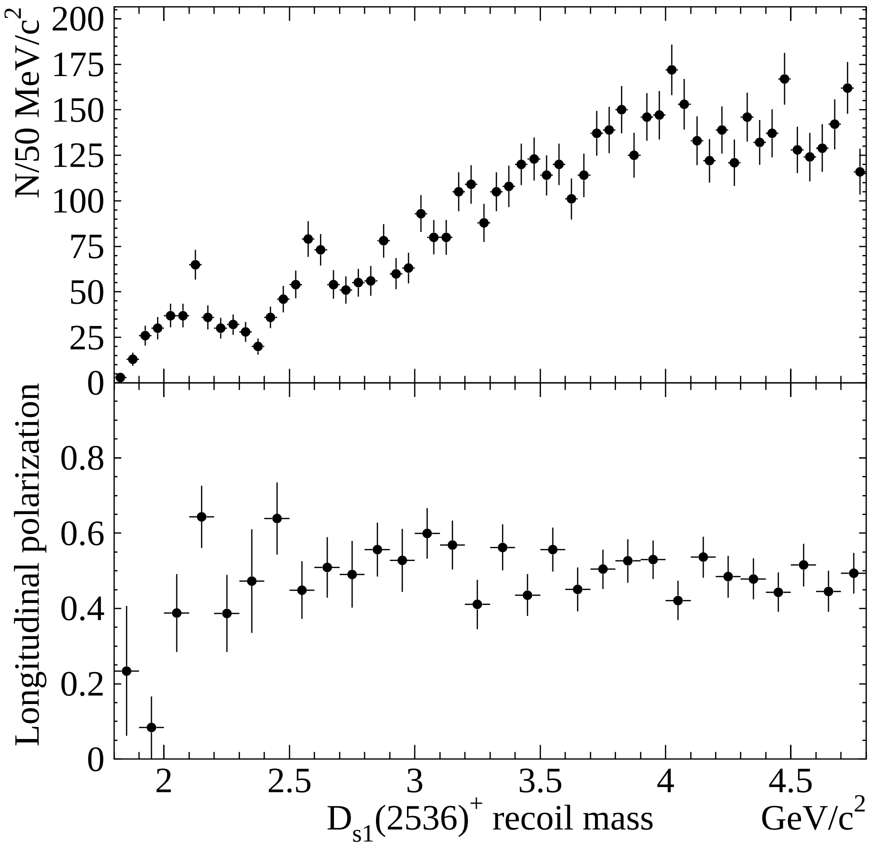
Longitudinal polarization in the region $x_P > 0.8$

$$\boldsymbol{\rho_{00} = 0.490 \pm 0.013}$$

Fit in Bins of D_{s1}^+ Recoil Mass, $M_{\rm rec} = \sqrt{(2E^*_{\rm beam} - E^*_{D_{s1}^+})^2 - (p^*_{D_{s1}^+})^2}$

Parameters R_Λ and ξ are independent of $M_{\rm rec}$ within statistical errors

$\Rightarrow$ fixed to values from overall fit



Resolution: $\sim$70 MeV/c^2 at 2 GeV/c^2, $1/M_{\rm rec}$ dependence.

Indication of two-body $e^+e^- \to D_{s1}^+ X$, $X = D_s^+$, D_s^{*+}, D_s^{**+}.

ρ_{00}: also some structure at low $M_{\rm rec}$; for $e^+e^- \to D_{s1}^+ D_s^+$: low ρ_{00}, rises to ≈ 0.5 at higher $M_{\rm rec}$.

Conclusions

1. **First *preliminary* results on $D_s^+ \to \mu\nu_\mu$; systematics is to be thoroughly evaluated.**

	$B(D_s^+ \to \mu\nu_\mu)$, $\times 10^{-3}$	$f_{D_s^+}$, MeV
Belle	$6.44 \pm 0.76 \pm 0.52$	$275 \pm 16 \pm 12$
PDG'06	6.1 ± 1.9	294 ± 27
BaBar	$6.74 \pm 0.83 \pm 0.26 \pm 0.66_{\phi\pi}$	$283 \pm 17 \pm 7 \pm 14_{\phi\pi}$
CLEO-c	$5.94 \pm 0.66 \pm 0.31$	$264 \pm 15 \pm 7$
Unquen. LQCD	[PRL 95, 122002 (2005)]	$249 \pm 3 \pm 16$

Accuracy is similar to LQCD, statistically limited.

2\. (a) $\frac{\mathcal{B}(D_{s1}^+ \to D^+\pi^- K^+)}{\mathcal{B}(D_{s1}^+ \to D^{*+} K^0)} = (3.17 \pm 0.17 \pm 0.36)\%$, **no clear resonant substructure.**

(b) **$D_{s1}(2536)^+ \to D^{*+} K_S^0$ PWA:**

amplitude ratio $D/S = (0.63 \pm 0.07) \cdot \exp(\pm i \cdot (0.77 \pm 0.03))$

Contrary to HQET, S-wave dominates: $\Gamma_S/\Gamma_{\text{total}} = 0.72 \pm 0.05$

$\Rightarrow$ **mixing with** $j_l = 1/2$ **state** $(D_{s1}(2460)^+)$.

(c) **Spin of** $D_{s1}(2536)^+$ **with** $x_P > 0.8$ **prefers to align**

transverse to momentum: $\rho_{00} = 0.490 \pm 0.013$.

*First measurement for P-wave **c**-meson in fragmentation.*

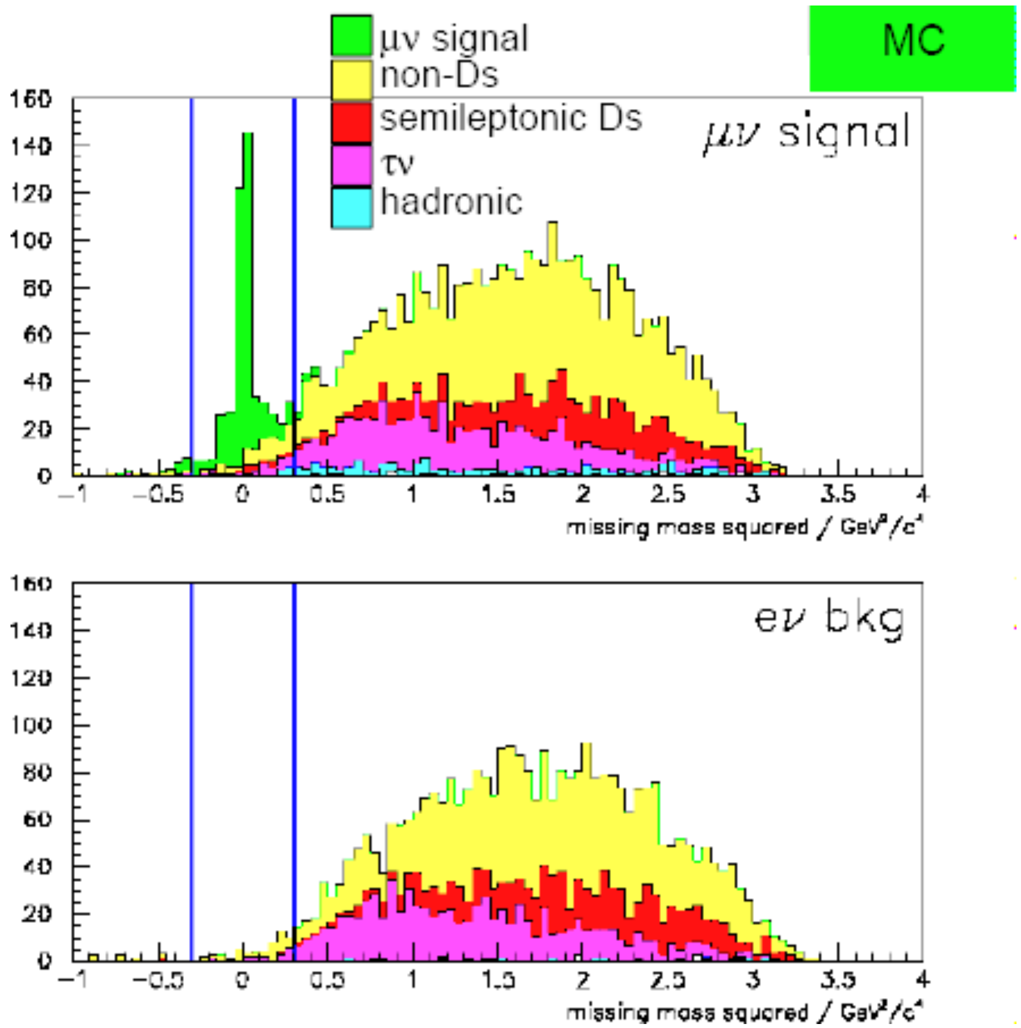
HQET: $\rho_{00} = \frac{2}{3}(1 - w_{3/2})$ **[Phys. Rev. D 49, 3320 (1994)]**

$\Rightarrow$ **Falk–Peskin parameter** $w_{3/2} = 0.266 \pm 0.019$ **for** $x_P > 0.8$

$\Rightarrow$ *predictions for angular distributions of other* $j_l = 3/2$ *meson decays.*

Backup Slides

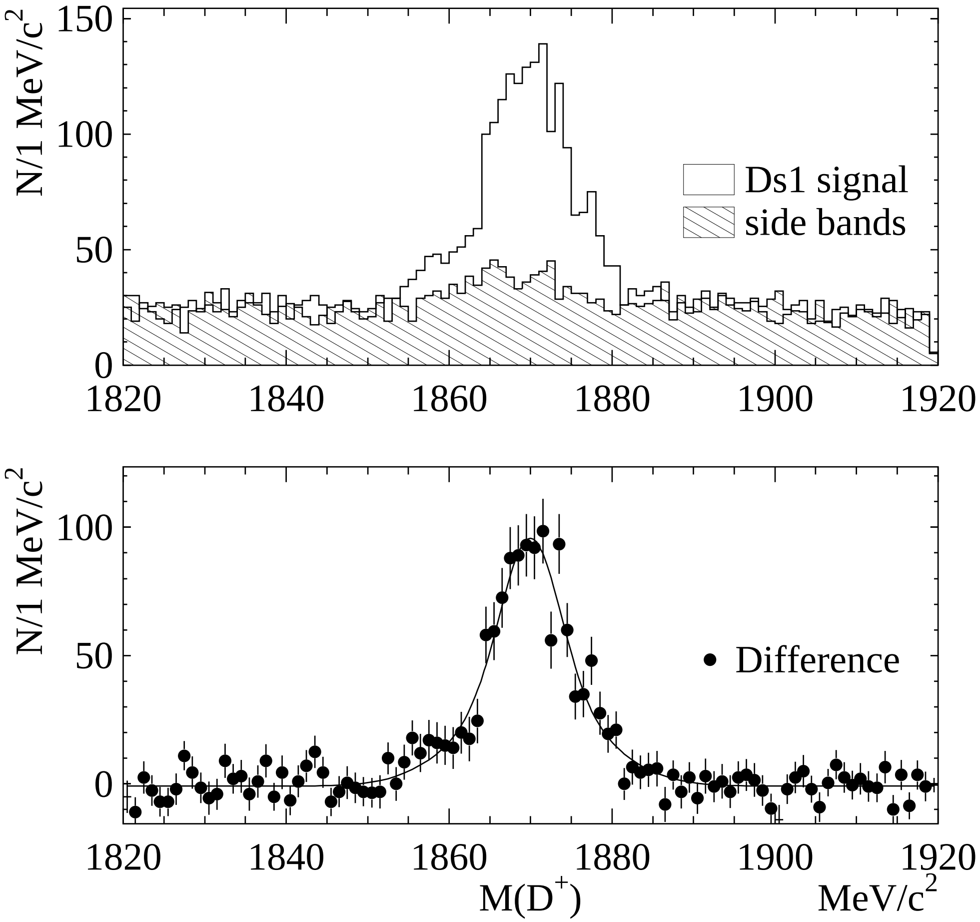
$D_s^+ \rightarrow \mu^+\nu_\mu$ Signal and Background in MC



$D_{s1}(2536)^+ \to D^+\pi^-K^+$ cross check:

D^+ from D_{s1}^+ signal and side bands,

$|\Delta M_{D\pi K}| < 5,\ 10 < |\Delta M_{D\pi K}| < 20$



1249 ± 66 ev. (expected 1262 ± 65)

background level (-0.9 ± 0.8)

Mixing of $j_l = 1/2$ and $j_l = 3/2$ States

Some information on θ is obtained from the ratio of electromagnetic decay rates $D_{s1}(2460) \to D_s^+\gamma$, $D_s^{*+}\gamma$, since only the ${}^1P_1$ state in $D_{s1}(2460)$ undergoes E1 transition to D_s^+ and only the ${}^3P_1$ state to D_s^{*+}. The bases $|j_l\rangle$ and $|{}^{2S+1}P_1\rangle$ are related by the rotation by the angle θ_0, $\tan\theta_0 = -\sqrt{2}$. Therefore the angle between the bases $|D_s^+\rangle$ and $|{}^{2S+1}P_1\rangle$ is $\theta + \theta_0$.

$$|D_s^+\rangle \xrightarrow{\theta} |j_l\rangle \xrightarrow{\theta_0} \left|\begin{matrix} {}^1P_1 \\ {}^3P_1 \end{matrix}\right\rangle \xrightarrow{E1} \left|\begin{matrix} D_s^+\gamma \\ D_s^{*+}\gamma \end{matrix}\right\rangle$$

Belle studied $D_{s1}(2460) \to D_s^+\gamma$, $D_s^{*+}\gamma$ decays using $D_{s1}(2460)$ from both B decays and from e^+e^- annihilation. The ratio of decay rates is found to be 0.4 ± 0.3 and 0.28 ± 0.17, respectively. The average value is $\dfrac{B(D_{s1}(2460) \to D_s^{*+}\gamma)}{B(D_{s1}(2460) \to D_s^+\gamma)} = 0.31 \pm 0.14$. Following Y. Yamada *et.al*, PR C72, 065202 (2005) and taking into account the phase space difference between $D_s^+\gamma$ and $D_s^{*+}\gamma$, this gives the constraint

$$\tan^2(\theta + \theta_0) = 0.8 \pm 0.4.$$

It should be compared with $\tan^2(\theta_0) = 2$ corresponding to the absence of the mixing.

Spin Alignment of D_{s1}^+ from e^+e^- Annihilation

Production of heavy mesons ($Q\bar{q}$) in HQET: A. Falk and M. Peskin, PR D49, 3320 (1994). The fragmentation process is so fast that the color magnetic forces do not have time to act and the spins of Q and $\bar{q}$ are uncorrelated.

Predictions for (D, D^*):

1) D^* mesons are produced unpolarized.

Confirmed by CLEO in 1991, 1998 and checked also by HRS'87, TPC'91, OPAL'97, SLD'97.

2) D^* and D mesons are produced in fragmentation according to the number of helicity states in a 3:1 ratio.

However, average over e^+e^-, hadro-production, photo-production etc. experiments: $P_V = V/(V+P) = 0.594 \pm 0.010 \ll 0.75$ [A. David, PL B644, 224 (2007)].

<u>There are no similar measurements for the P-wave states.</u> Contrary to the (D, D^*) case, HQET predicts that $j_l = 3/2$ doublet can be produced aligned. The probabilities for the light degree of freedom to have helicity $-3/2$, $-1/2$, $1/2$, $3/2$ are expressed via one parameter $w_{3/2}$ as

$$\frac{1}{2}w_{3/2},\ \frac{1}{2}(1-w_{3/2}),\ \frac{1}{2}(1-w_{3/2}),\ \frac{1}{2}w_{3/2},$$

respectively. By adding uncorrelated c-quark spin and resolving the $c\bar{s}$ system into 1^+ and 2^+ states, one can calculate their alignment.

For $j_l = 1/2$ doublets two helicity states should have equal probabilities due to P conservation. As a result all three helicity states of D^* and the fourth state of D should be equally populated.

For $D_{s1}(2536)^+$ the probability of zero helicity is $\rho_{00} = \frac{2}{3}(1 - w_{3/2})$. Perturbative QCD calculations give $w_{3/2} = 29/114 \approx 0.254$ [Y.-Q. Chen and M. Wise, PR D50, 4706 (1994)] and $\rho_{00} \approx 0.497$. ARGUS'89 analysis of angular distributions in $D_2^*(2460) \to D\pi$ decay gives an upper limit $w_{3/2} < 0.24$ at 90% CL. This is the only available experimental number in $j_l = 3/2$ charm sector. Once $w_{3/2}$ is measured, one can make definite predictions for the angular distributions of the remaining $j_l = 3/2$ meson decays (e.g. on the decays of $D_{s2}(2573)^+$ state). $j_l = 3/2$ mesons are the lowest states which can be used to perform first nontrivial tests of HQET in fragmentaion process.