Spectroscopy and Charm Quark Fragmentation

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For the Belle collaboration
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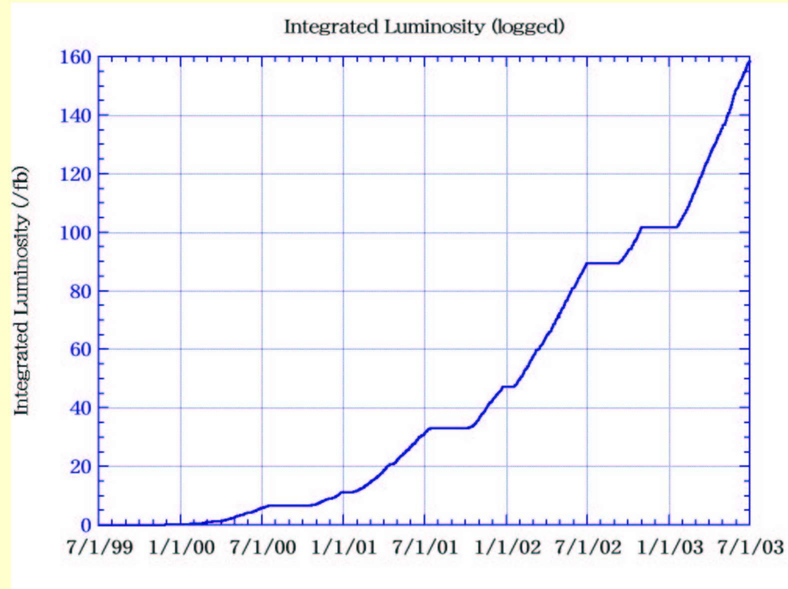
Introduction

production mechanism of charmed mesons unclear

- What mesons are produced / do exist ?
- determine their properties
- test and improve model predictions
- charm mesons in B decays
  how often are they produced
- charm mesons in annihilation
  how often / what's their momentum
  $\rightarrow$ fragmentation function



Belle logged luminosity

b-factories well equipped for charm physics:

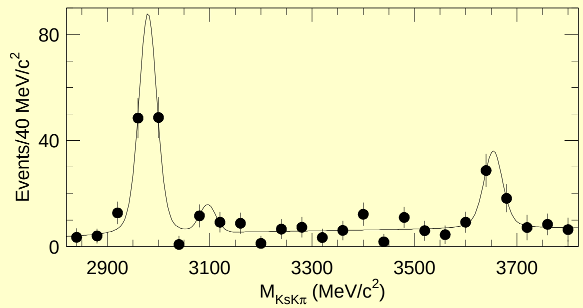
- dominant decay product of b mesons
- $\mathrm{e^+e^-} \rightarrow \mathrm{c\bar{c}}$ about same x-section as $\mathrm{e^+e^-} \rightarrow \Upsilon(4\mathrm{S}) \rightarrow B\bar{B}$

$\rightarrow$ lots of data to analyse

all results presented here are preliminary

Charmonium - $\eta_c(2S)$

1st observation in exclusive $B \to K K_s^0 K^- \pi^+$ decays:

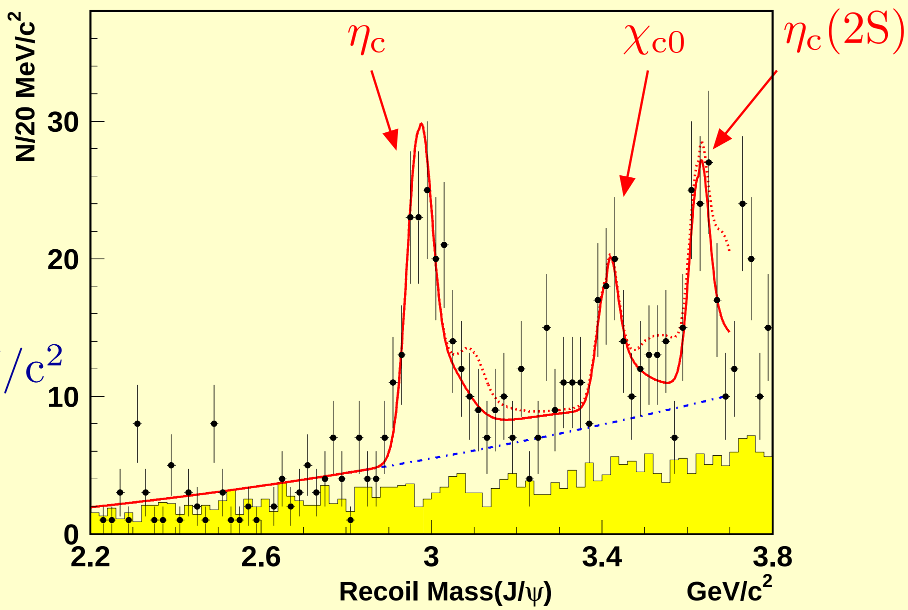


$M_{\eta_c(2S)} = (3654 \pm 6 \pm 8)$ MeV/c^2 (Belle)
$M_{\eta_c(2S)} = (3594 \pm 5)$ MeV/c^2 (Crystal Ball)

now observed in Belle also in double $c\bar{c}$ production (→talk by T.Uglov in HFP(2))

$\mathcal{L} = 101.8 \text{fb}^{-1}$

$M_{\eta_c(2S)} = (3630 \pm 8)$ MeV/c^2



$M_{\eta_c(2S)} = (3639 \pm 6)$ MeV/c^2 (Belle, weighted average)

Charmed Baryons - Ω_c^0

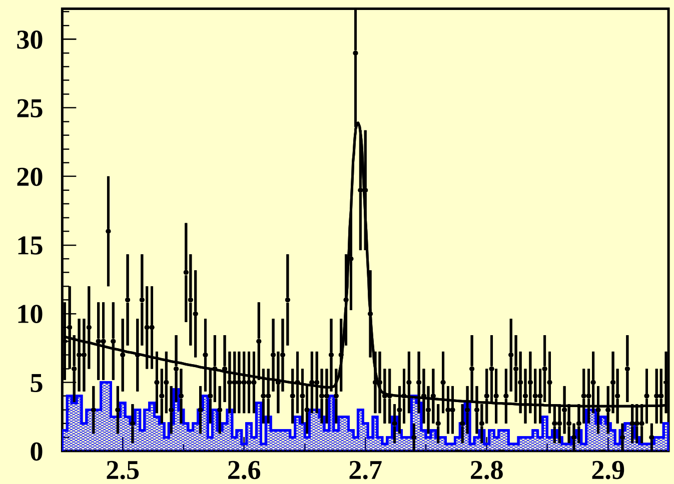
$\Omega_c^0 = css$ baryon

properties only poorly known

PDG : $M_{\Omega_c^0} = (2697.5 \pm 2.6)$ MeV/c^2

$\Omega_c^0 \to \Omega^- \pi^+, \ \Omega^- \to \Lambda^0 K^-$

$\mathcal{L} = 87.1 \mathrm{fb}^{-1}$

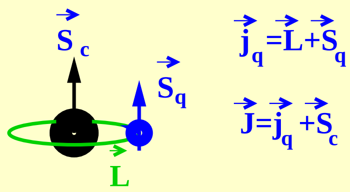


$$M_{\Omega_c^0} = (2693.9 \pm 1.1 \pm 1.4) \ \mathrm{MeV/c^2}$$

production cross section : $\sigma(e^+e^- \to \Omega_c^0 X) \times \mathcal{B}(\Omega_c^0 \to \Omega^- \pi^+) = (19.1 \pm 9.0)$ fb

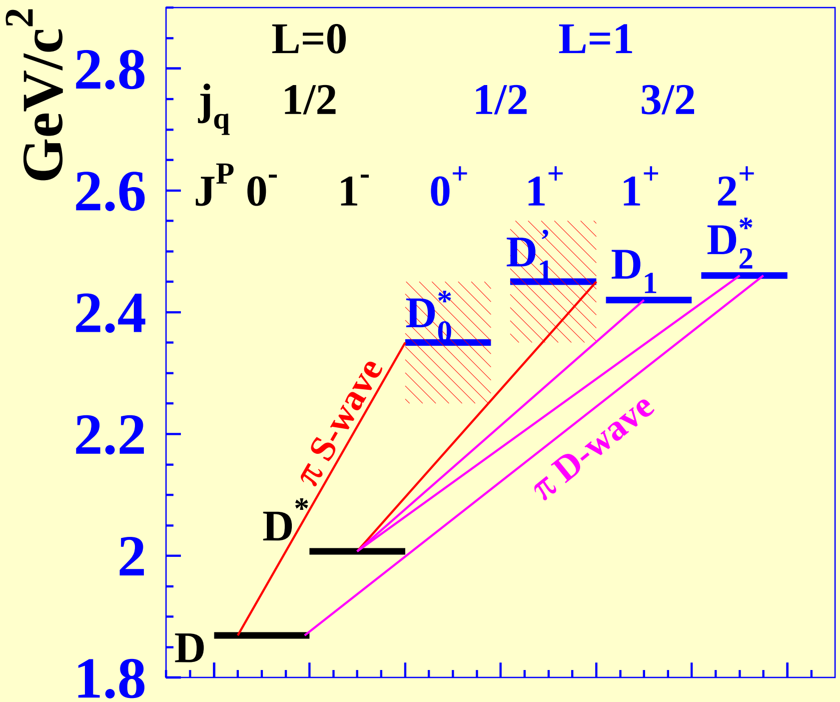
semi-leptonic decays observed $\frac{\mathcal{B}(\Omega_c^0 \to \Omega^- \pi^+)}{\mathcal{B}(\Omega_c^0 \to \Omega^- \ell^+ \nu)} = 0.8 \pm 0.2$ (CLEO :$0.40 \pm 0.19 \pm 0.04$)

Spectroscopy of D-mesons



spin-parity J^P

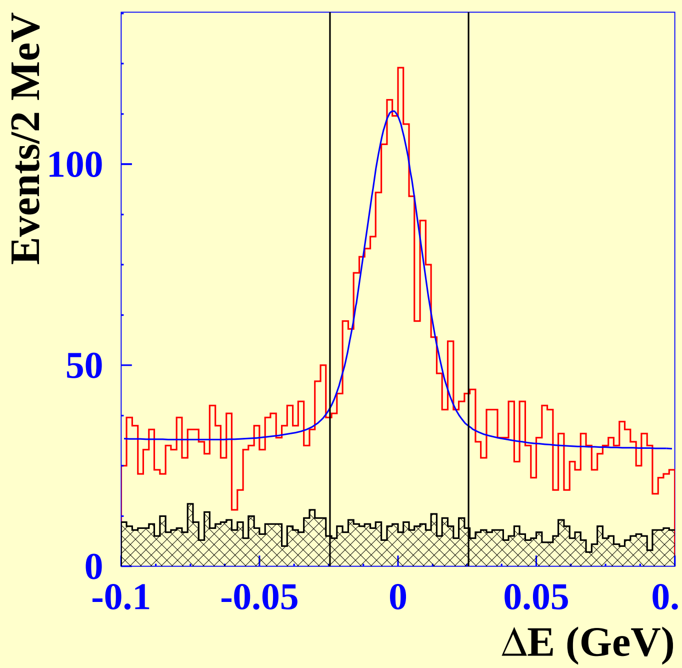
light quark angular momentum j_q



D^{**} mesons in B decays

fully reconstruct $B^- \to D^{(*)+}\pi^-\pi^-$ (in sample of 65×10^6 $B\bar{B}$)

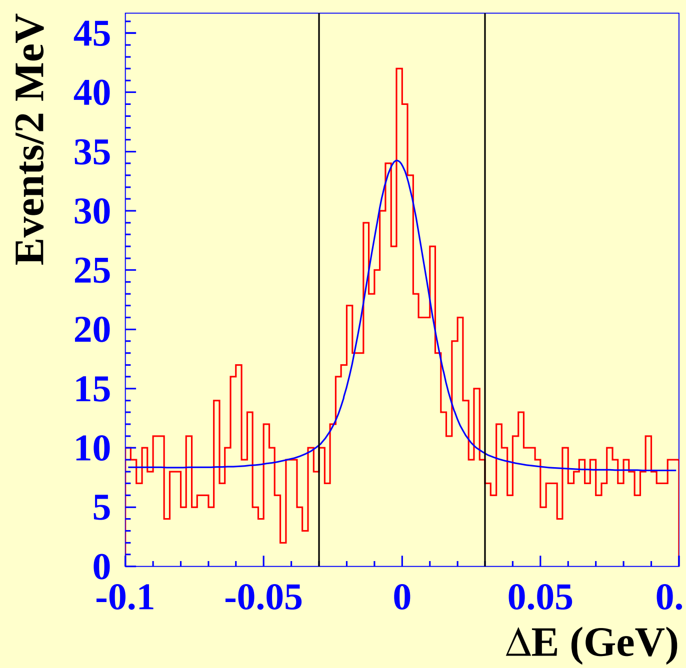
$N(D^+\pi^-\pi^-) = 1101 \pm 46$ ev.



$$\mathcal{B}(B^- \to D^+\pi^-\pi^-) = (1.02 \pm 0.04 \pm 0.15) \times 10^{-3}$$

1st observation

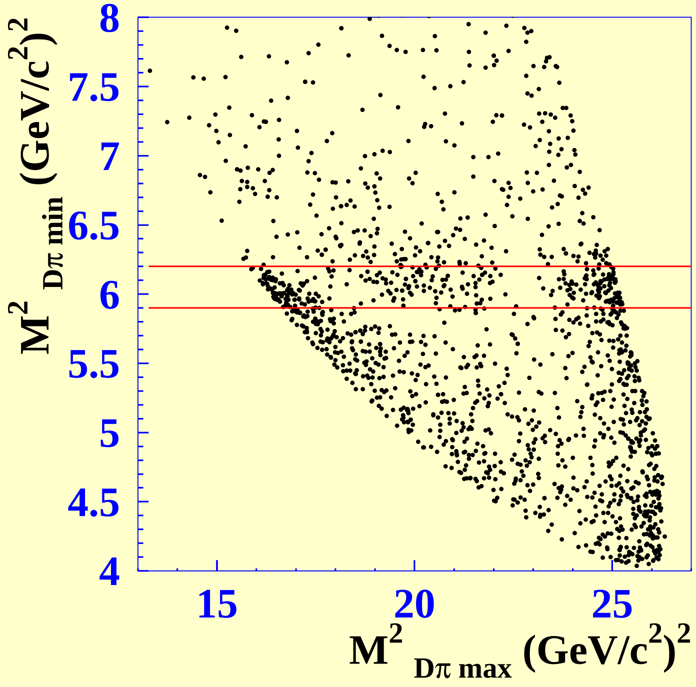
$N(D^{*+}\pi^-\pi^-) = 578 \pm 30$ ev.

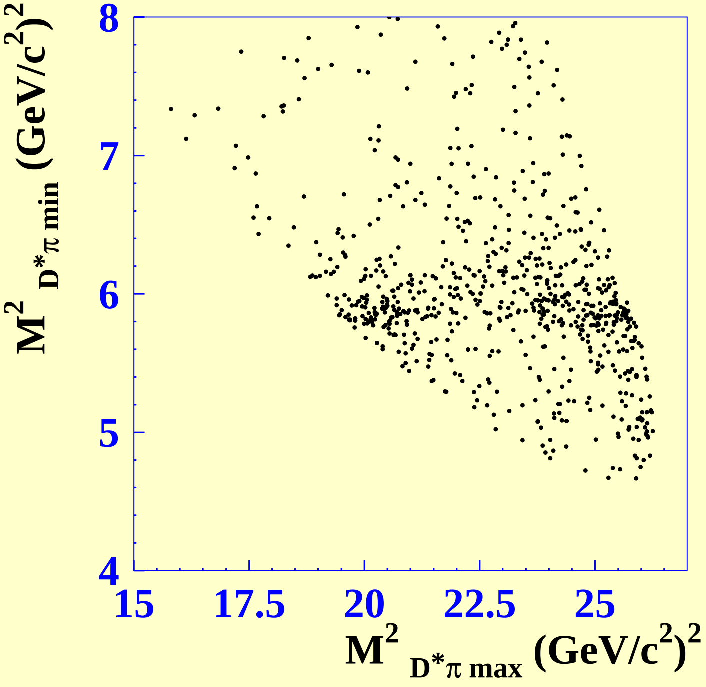


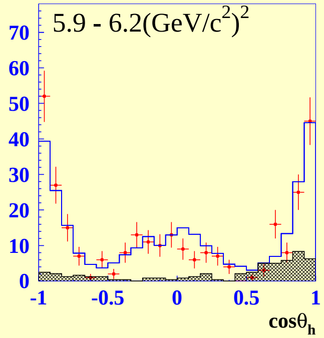
$$\mathcal{B}(B^- \to D^{*+}\pi^-\pi^-) = (1.25 \pm 0.08 \pm 0.22) \times 10^{-3}$$

$(2.1 \pm 0.6) \times 10^{-3}$ (PDG)

Dalitz plot analysis





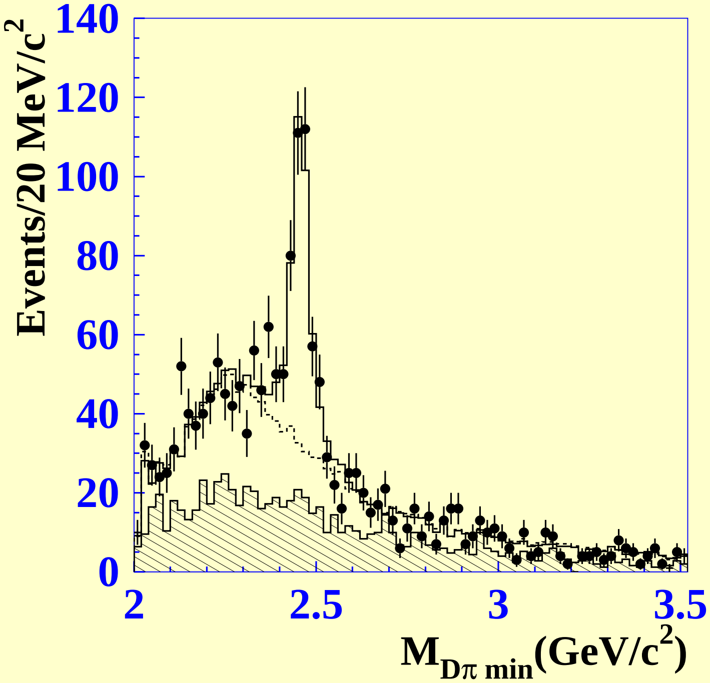


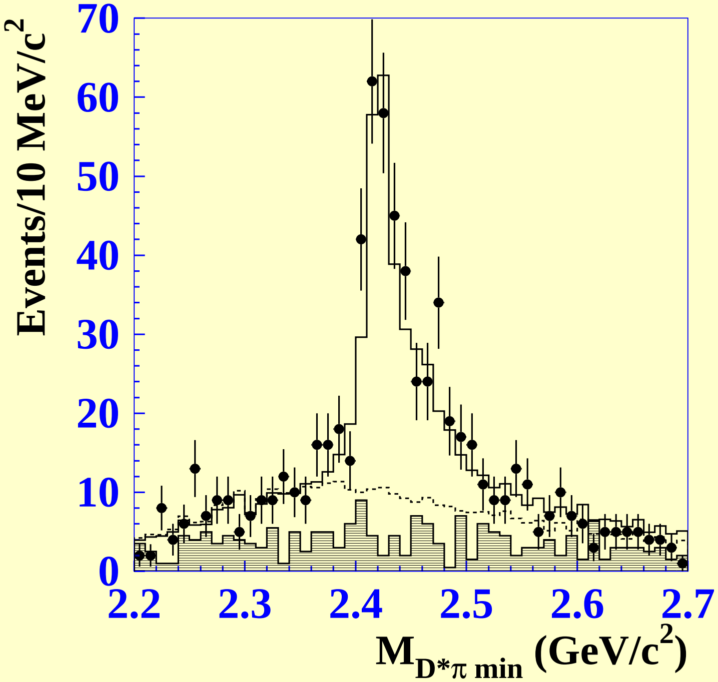
$J^P = 2^+$
D_2^{*0}

New Broad Resonances

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

$M_{D_1^0} = (2421.4 \pm 1.5 \pm 0.4 \pm 0.8)\ \mathrm{MeV/c^2}$
$\Gamma_{D_1^0} = (23.7 \pm 2.7 \pm 0.2 \pm 4.0)\ \mathrm{MeV}$





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

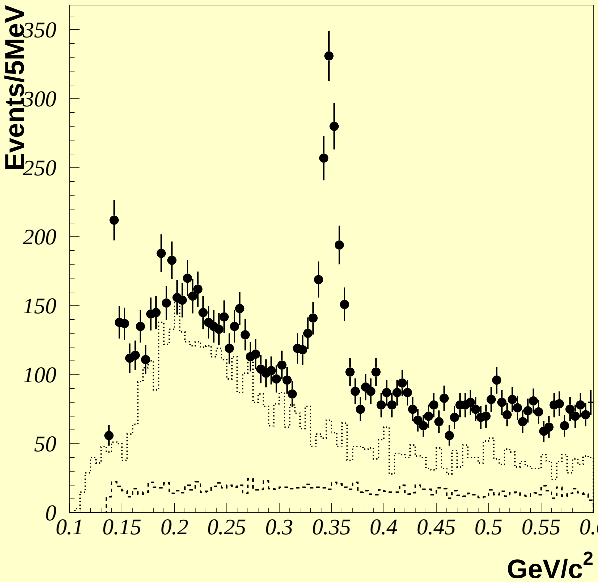
1st observation

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

1st observation

New $c\bar{s}$ State

2 new $c\bar{s}$ states discovered by BaBar and CLEO in $\mathrm{D_s^{(*)}}\pi^0$



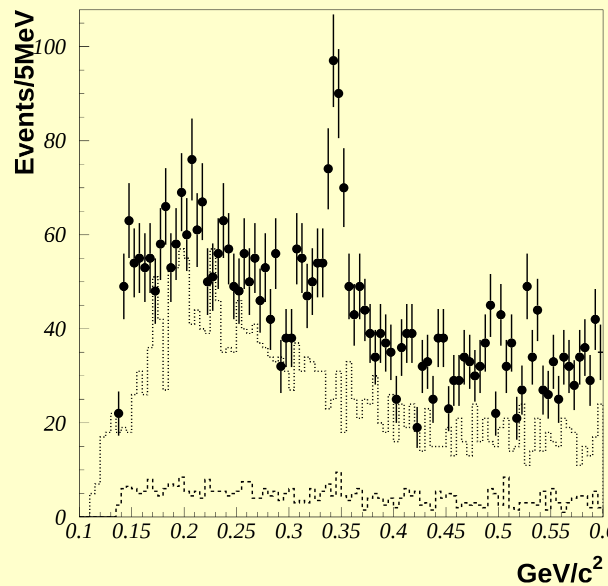
$\mathrm{M(D_s\pi^0) - M(D_s)}$

$\mathrm{D_{sJ}(2320)}$in $\mathrm{D_s\pi^0}$ only

	N	M $[\mathrm{MeV/c^2}]$
Belle	761 ± 44	$2317.2 \pm 0.5 \pm 0.9$
BaBar	1948 ± 104	2316.8 ± 0.4
CLEO	155 ± 23	$2318.6 \pm 1.2 \pm 1.0$

$\mathrm{D_{sJ}(2460)}$in $\mathrm{D_s^*\pi^0}$ only:

	N	M $[\mathrm{MeV/c^2}]$
Belle	126 ± 25	$2456.5 \pm 1.3 \pm 1.1$
BaBar	140 ± 22	2457 ± 1
CLEO	41 ± 12	$2463 \pm 1.7 \pm 1.0$

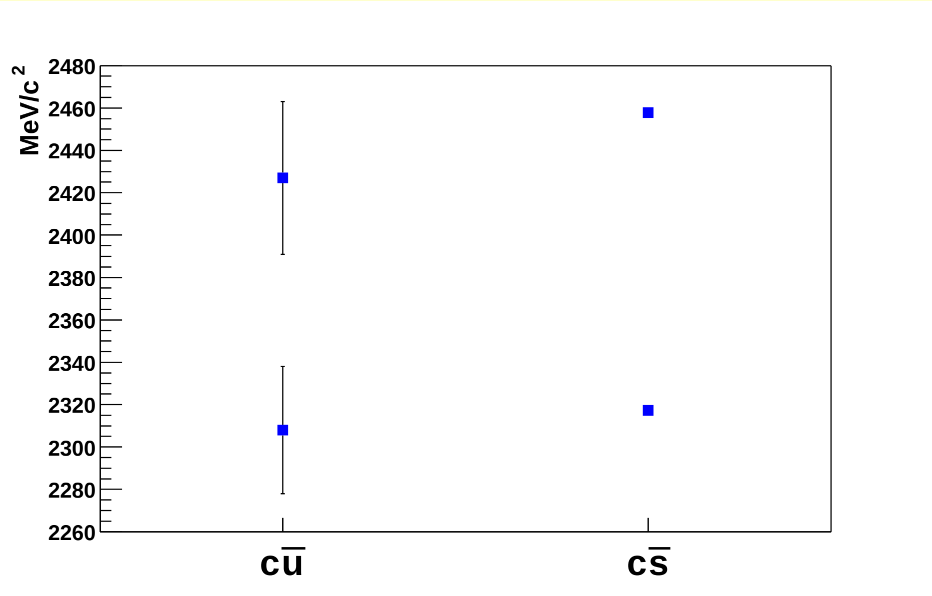


$\mathrm{M(D_s^*\pi^0) - M(D_s^*)}$

$\rightarrow$Belle confirms existence of $\mathrm{D_{sJ}(2320)}$ and $\mathrm{D_{sJ}(2460)}$

Masses in the $c\bar{q}$ System

D^{**} D_{sJ}



	$c\bar{u}$	$c\bar{s}$	
$D_1^{'0}$	2427 ± 36	$2456.5 \pm 1.3 \pm 1.1$	$D_{sJ}(2460)$
D_0^{*0}	2308 ± 30	$2317.2 \pm 0.5 \pm 0.9$	$D_{sJ}(2320)$

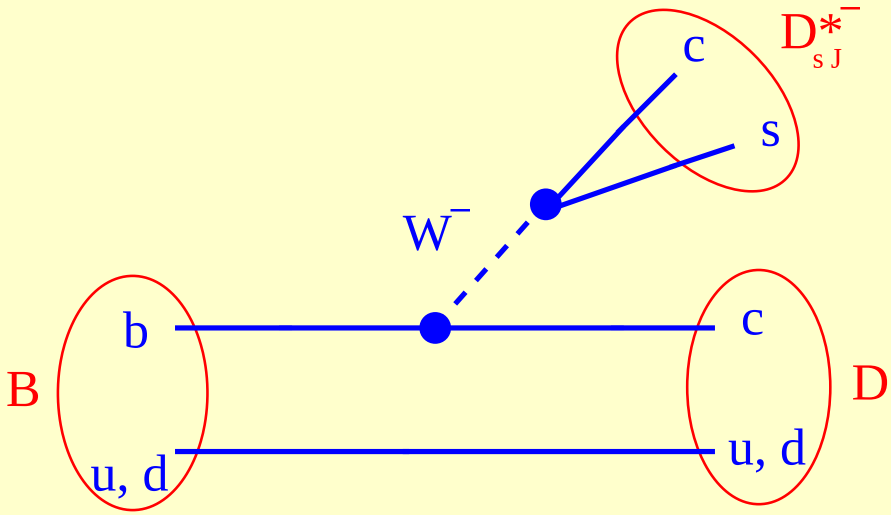
→ground states almost same mass

→mass difference almost same

D_{sJ} in exclusive B Decays

need to determine quantum numbers and branching ratios

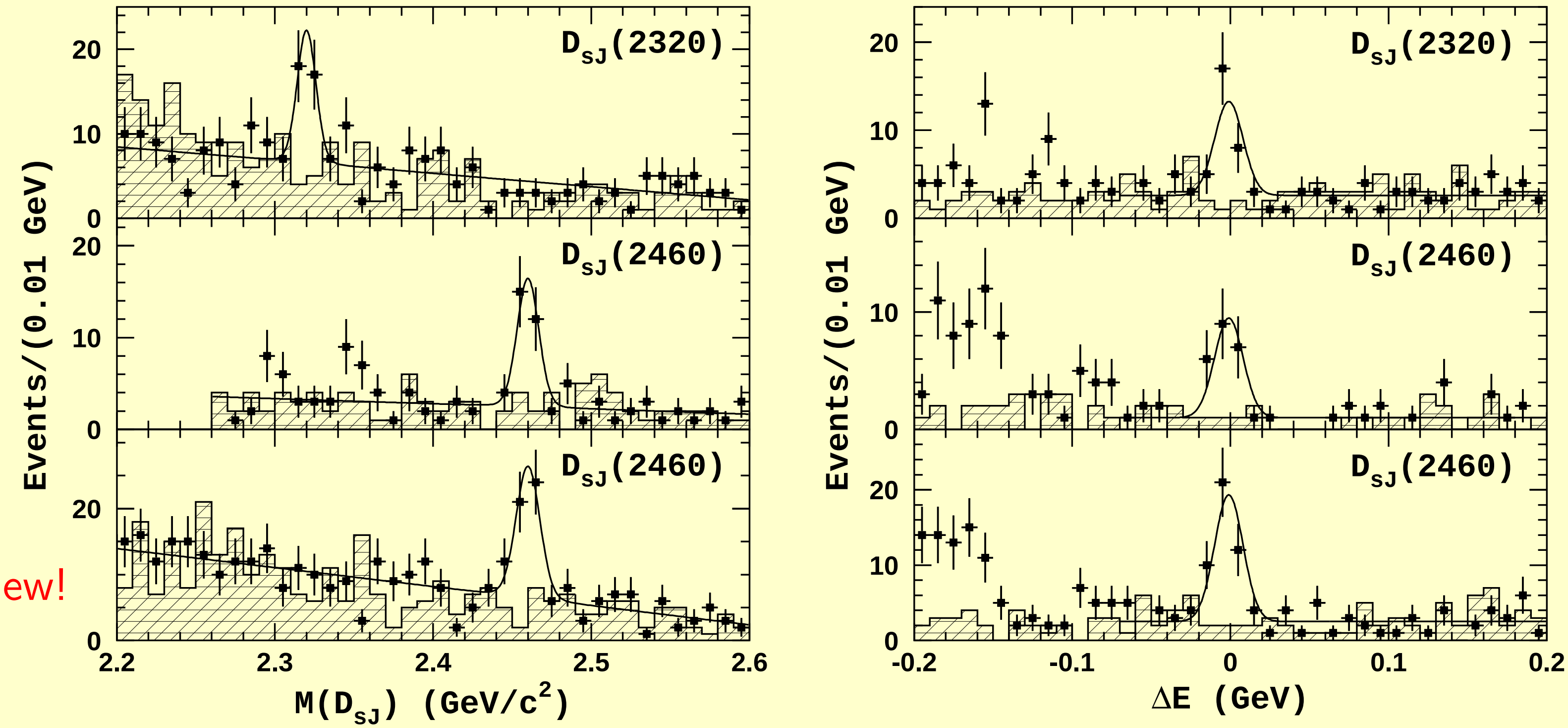
examine $B \to DD_{sJ}(2320)$, $B \to DD_{sJ}(2460)$:



apply angular analysis to reveal quantum numbers

D_{sJ} in $B \to D D_{sJ} \pi^0/\gamma$

123×10^6 $B\bar{B}$



new!

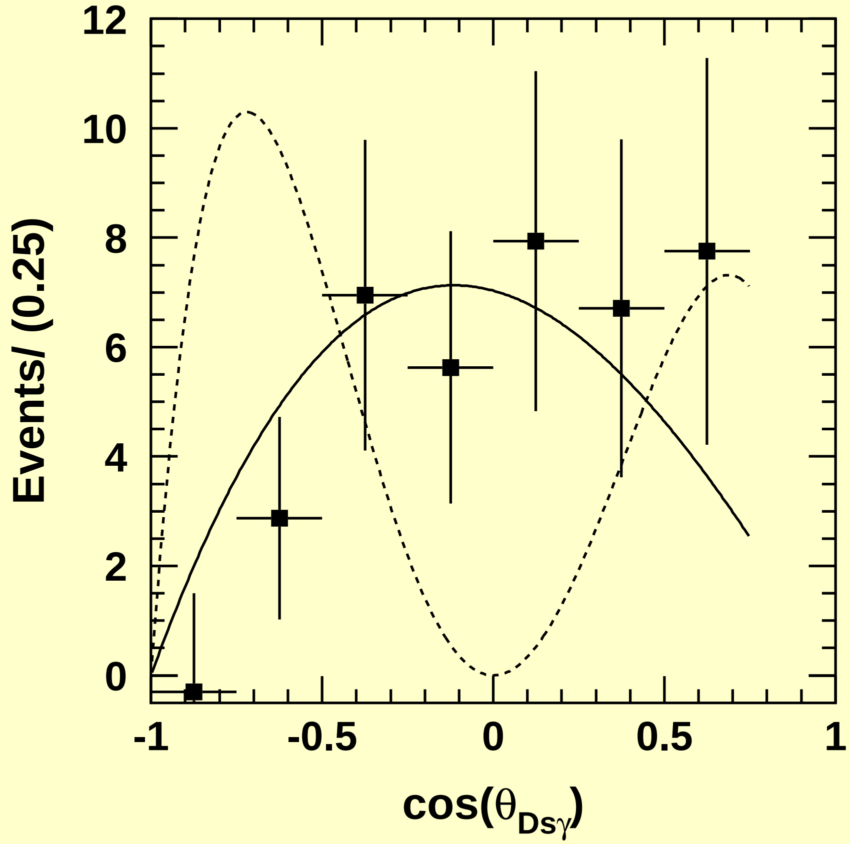
new!

$B \to D D_{sJ}(2320),\ D_{sJ}(2320) \to D_s \pi^0$	$M = (2319.8 \pm 2.1 \pm 2.0)\ \mathrm{MeV}/c^2$	6.1σ
$B \to D D_{sJ}(2460),\ D_{sJ}(2460) \to D_s^* \pi^0$	$M = (2459.4 \pm 1.9 \pm 2.0)\ \mathrm{MeV}/c^2$	6.4σ
$B \to D D_{sJ}(2460),\ D_{sJ}(2460) \to D_s \gamma$	$M = (2458.8 \pm 2.7 \pm 2.0)\ \mathrm{MeV}/c^2$	7.4σ

$D_{sJ}(2460) \to D_s \gamma \quad \to \quad J^P \neq 0^+$

helicity distribution for $\mathrm{D_{sJ}(2460) \to D_s \gamma}$

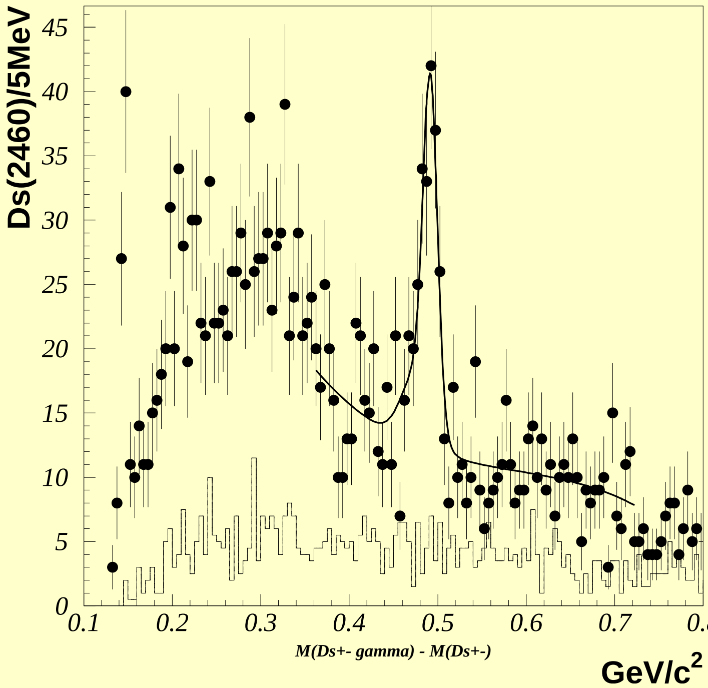
Helicity angle $\theta_{\mathrm{D_s}\gamma}$ defined as the angle between $\mathrm{D_{sJ}(2460)}$ momentum in the B meson rest frame and the $\mathrm{D_s}$ momentum in the $\mathrm{D_{sJ}(2460)}$ rest frame



consistent with $\sin^2\theta$ $\rightarrow$ expected if 1^+

D_{sJ} in e^+e^- Annihilation

confirm $D_{sJ}(2460) \to D_s\gamma$ in continuum



$\to$excludes $D_{sJ}(2460)$ being 0^-

no hint for $D_{sJ}(2320) \to D_s\gamma$ $\to$ consistent with $D_{sJ}(2320)$ being 0^+

$$\frac{\mathcal{B}(D_{sJ}(2320) \to D_s\gamma)}{\mathcal{B}(D_{sJ}(2320) \to D_s\pi^0)} \leq 0.05 \qquad @90\%CL$$

Branching Ratios of $B \to DD_{sJ}$

decay channel	$\mathcal{B},\ 10^{-4}$	significance
$B \to DD_{sJ}(2320), D_{sJ} \to D_s\pi^0$	$8.5^{+2.1}_{-1.9} \pm 2.6$	6.1σ
$B \to DD_{sJ}(2320), D_{sJ} \to D_s^*\gamma$	$< 5.8\ (2.5^{+2.0}_{-1.8})$	1.8σ
$B \to DD_{sJ}(2460), D_{sJ} \to D_s^*\pi^0$	$17.8^{+4.5}_{-3.9} \pm 5.3$	6.4σ
$B \to DD_{sJ}(2460), D_{sJ} \to D_s\gamma$	$6.7^{+1.3}_{-1.2} \pm 2.0$	7.4σ
$B \to DD_{sJ}(2460), D_{sJ} \to D_s^*\gamma$	$< 5.6\ (2.7^{+1.8}_{-1.5})$	2.1σ
$B \to DD_{sJ}(2460), D_{sJ} \to D_s\pi^+\pi^-$	< 1.2	
$B \to DD_{sJ}(2460), D_{sJ} \to D_s\pi^0$	< 1.2	

in b-decays:

$$\frac{\mathcal{B}(B \to DD_{sJ}(2460), D_{sJ} \to D_s\gamma)}{\mathcal{B}(B \to DD_{sJ}(2460), D_{sJ} \to D_s^*\pi^0)} = 0.38 \pm 0.11 \pm 0.04$$

in e^+e^- annihilation:

$$\frac{\mathcal{B}(D_{sJ}(2460) \to D_s\gamma)}{\mathcal{B}(D_{sJ}(2460) \to D_s^*\pi^0)} = 0.63 \pm 0.15 \pm 0.15$$

Branching Ratios, cont'd

Belle weighted average:

$$\frac{\mathcal{B}(\mathrm{D_{sJ}}(2460) \to \mathrm{D_s}\gamma)}{\mathcal{B}(\mathrm{D_{sJ}}(2460) \to \mathrm{D_s^*}\pi^0)} = 0.43 \pm 0.09 \pm 0.04$$

good agreement with predictions:	Bardeen et al :	0.24
	Godfrey :	0.62

Belle also determined $\mathcal{B} \times \sigma$ ($\mathcal{L} = 86.9\mathrm{fb}^{-1}$) in $\mathrm{e^+e^-} \to \mathrm{c\bar{c}}$:

$$\frac{\mathcal{B}(\mathrm{D_{sJ}}(2460) \to \mathrm{D_s^*}\pi^0)}{\mathcal{B}(\mathrm{D_{sJ}}(2320) \to \mathrm{D_s}\pi^0)} \times \frac{\sigma(\mathrm{e^+e^-} \to \mathrm{D_{sJ}}(2460)\mathrm{X})}{\sigma(\mathrm{e^+e^-} \to \mathrm{D_{sJ}}(2320)\mathrm{X})} = 0.26 \pm 0.05 \pm 0.06$$

and

$$\frac{\mathcal{B}(\mathrm{D_{sJ}}(2460) \to \mathrm{D_s}\pi^0)}{\mathcal{B}(\mathrm{D_{sJ}}(2320) \to \mathrm{D_s}\pi^0)} \times \frac{\sigma(\mathrm{e^+e^-} \to \mathrm{D_{sJ}}(2460)\mathrm{X})}{\sigma(\mathrm{e^+e^-} \to \mathrm{D_{sJ}}(2320)\mathrm{X})} < 0.06 \quad (@ = 90\%\mathrm{CL})$$

taking the ratio

$$\frac{\mathcal{B}(\mathrm{D_{sJ}}(2460) \to \mathrm{D_s}\pi^0)}{\mathcal{B}(\mathrm{D_{sJ}}(2460) \to \mathrm{D_s^*}\pi^0)} < 0.22 \quad (@ = 90\%\mathrm{CL})$$

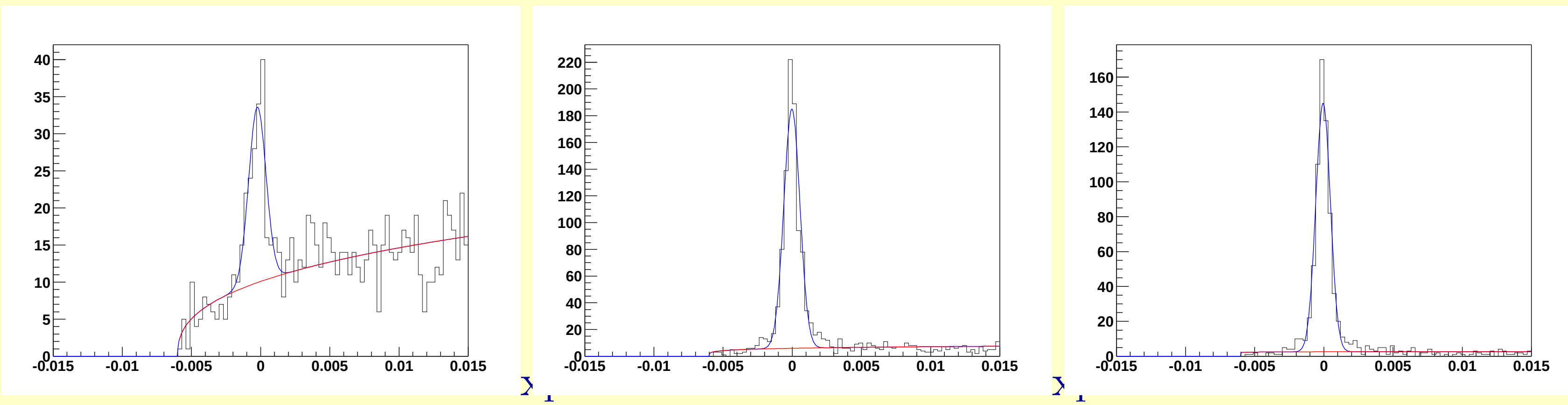
Charm Fragmentation into D^{*+}

fragmentation function: PDF that (heavy) quark Q with momentum p
fragments into (heavy) meson w momentum $z \cdot p$

basically a momentum distribution

LEP/SLD disfavours Peterson et al. fragmentation function
for c quarks $\mathcal{B} \times \epsilon$ small →huge data sample

method: $D^{*+} \to D^0\pi^+,\ D^0 \to K^-\pi^+$
determine scaled momentum $x_P \equiv |\vec{p}_{CMS}(D^*)|/|\vec{p}_{MAX}(D^*)|$

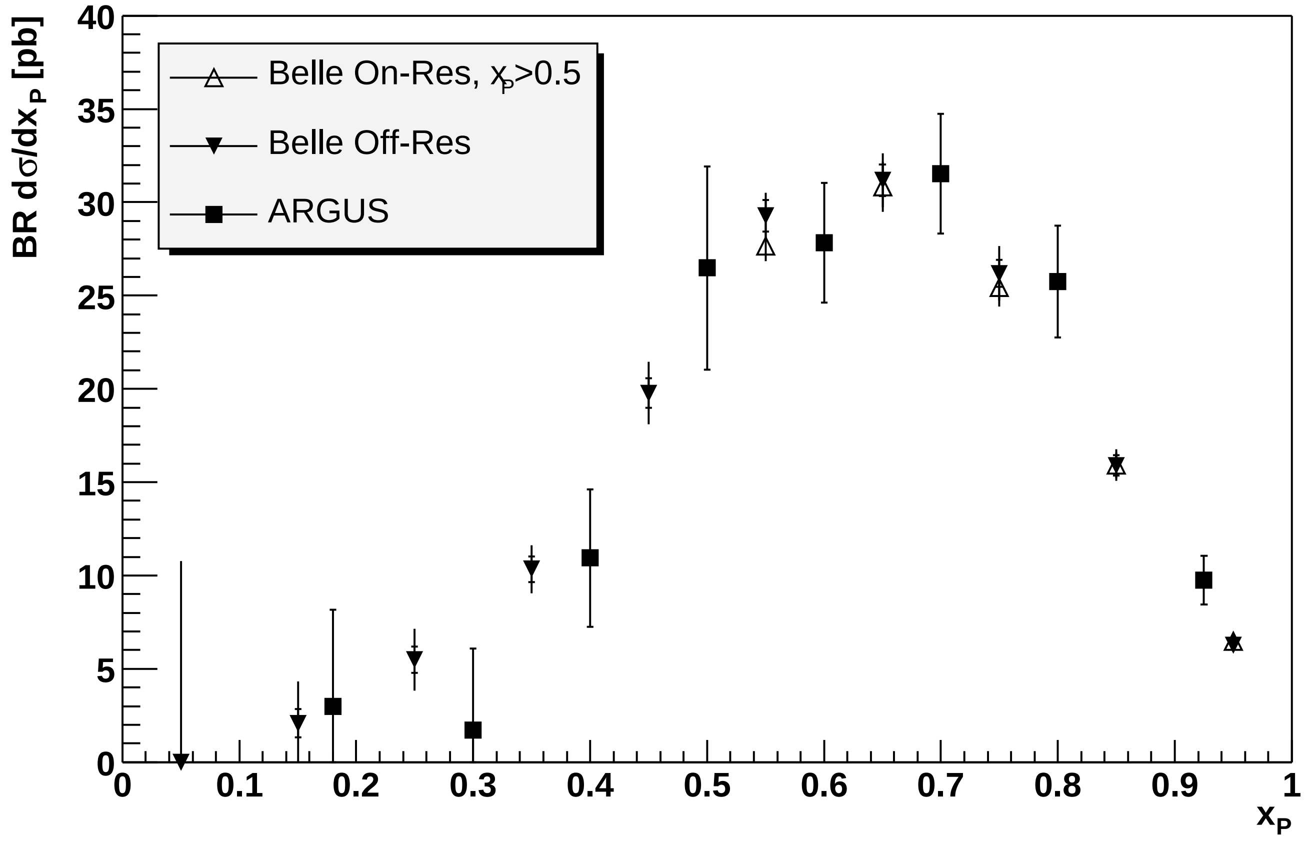


$0.28 < x_P < 0.30$ $\quad$ $0.58 < x_P < 0.60$ $\quad$ $0.78 < x_P < 0.80$

$\mathcal{L} = 3.65\mathrm{fb}^{-1}$ off-resonance, $\mathcal{L} = 25.53\mathrm{fb}^{-1}$ on-resonance

Comparison with existing Measurements

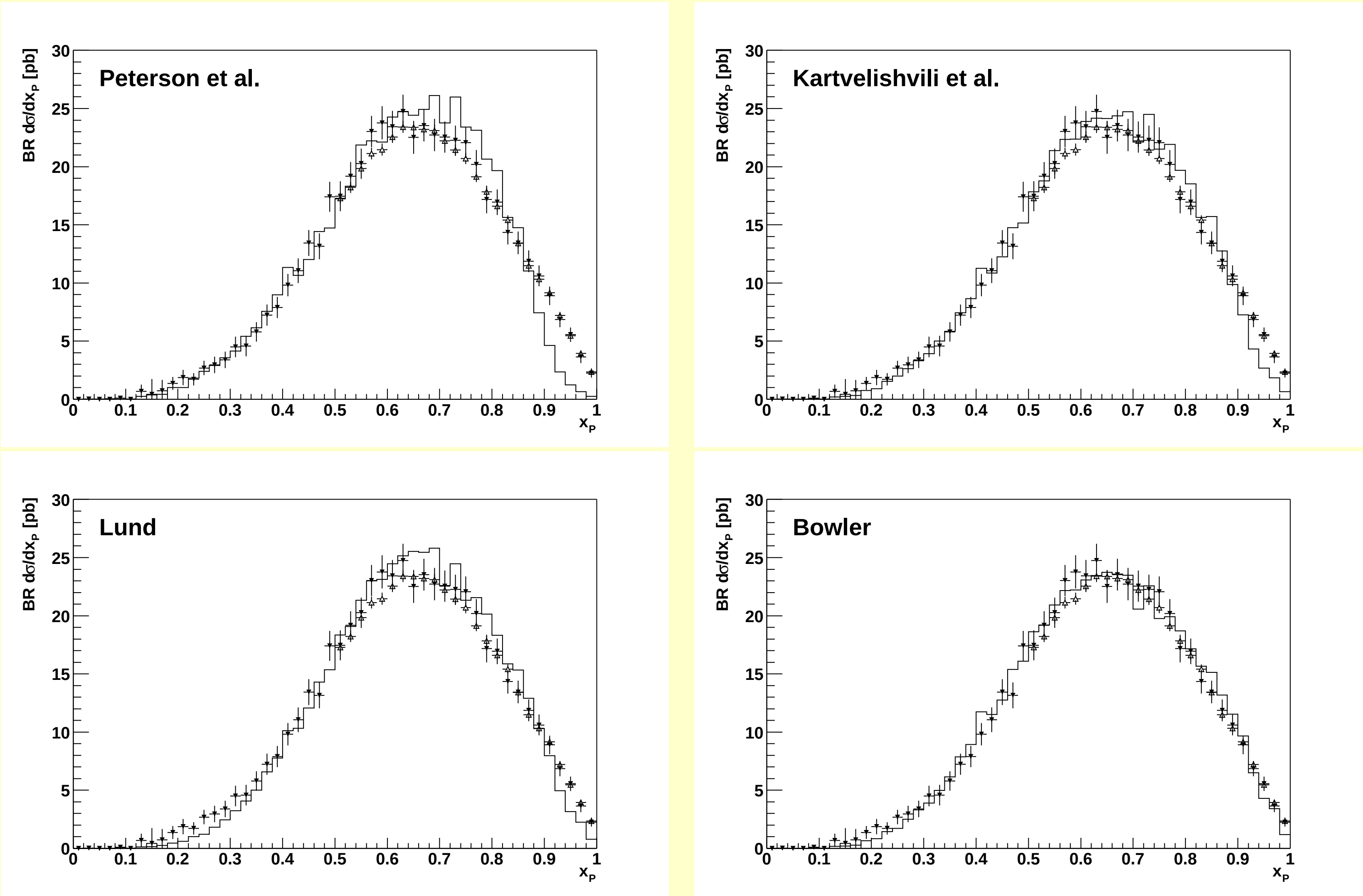
(CLEO used different variable)



reduced no. bins

$$\langle x_P(D^{*\pm})\rangle = 0.612 \pm 0.003(\mathrm{stat.}) \pm 0.004(\mathrm{syst.}).$$

Comparison with several Models



distributions not efficiency corrected

Results

fragmentation fct	functional form	$\chi^2_{\rm min}/{\rm d.o.f.}$	data
Bowler	$N\frac{1}{z^{1+bm^2}}(1-z)^a\exp(-\frac{bm_\perp^2}{z})$	59.2/48	off-r
		166.8/23	on-r
Lund	$N\frac{1}{z}(1-z)^a\exp(-\frac{bm_\perp^2}{z})$	110.6/48	off-r
		517.0/23	on-r
Kartvelishvili et al.	$Nz^{\alpha_c}(1-z)$	122.2/49	off-r
		1050.7/24	on-r
Collins-Spiller	$N(\frac{1-z}{z}+\frac{(2-z)\varepsilon_c}{1-z})(1+z^2)(1-\frac{1}{z}-\frac{\varepsilon_c}{1-z})^{-2}$	185.44/49	off-r
		736.9/24	on-r
Peterson et al.	$N\frac{1}{z}(1-\frac{1}{z}-\frac{\varepsilon_c}{1-z})^{-2}$	300.6/49	off-r
		1613.1/24	on-r

Bowler best agreement over full $\rm x_P$ range
Lund ok, but parameters off
Kartvelishvili et al., problems at high $\rm x_P$
Peterson et al. worst agreement in peak and high $\rm x_P$

Conclusion

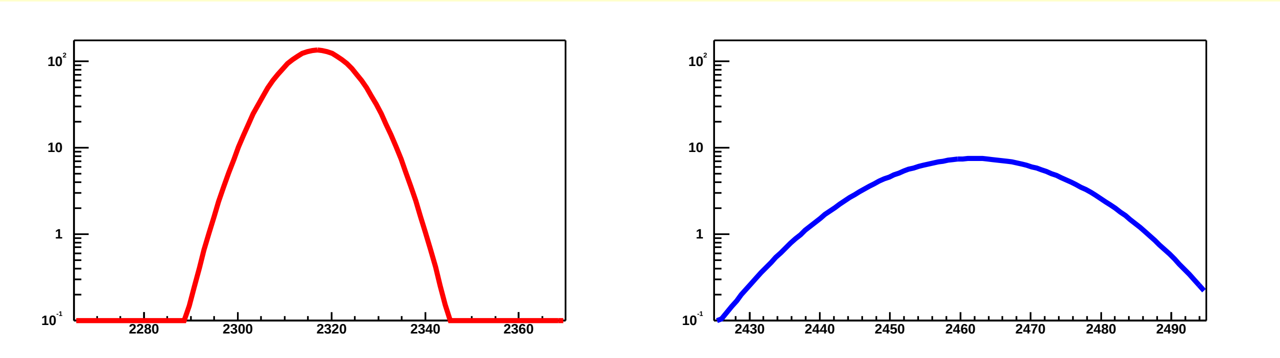
- $\eta_c(2S)$ now also seen in double $c\bar{c}$ production
- new mass determination of Ω_c^0
- all P-wave D^{**} observed, resonance parameters measured
- $D_{sJ}(2320)$ and $D_{sJ}(2460)$ in B decays and e^+e^- annihilation are in agreement with being P-wave $c\bar{s}$ states with $j_q = 1/2$
  $D_{sJ}(2460) \to D_s\gamma$ observed in B decays and e^+e^- annihilation
- charm quark fragmentation into D^{*+} disfavours Peterson et al. model, supports Bowler model

Backup: MC Study: X-Feed btw. D_{sJ} States

detailed MC study:

$D_{sJ}(2320) \to D_s\pi^0$ $\quad M_{D_{sJ}(2320)} = 2317\ \mathrm{MeV}/c^2$

peak @ nominal mass	$\sigma = (7.4 \pm 0.4)\ \mathrm{MeV}/c^2$	signal
peak @ $M_{D_{sJ}(2460)} + 5\ \mathrm{MeV}/c^2$	$\sigma = (12.3 \pm 1.8)\ \mathrm{MeV}/c^2$	random photon



$D_{sJ}(2460) \to D_s^*\pi^0$ $\quad M_{D_{sJ}(2460)} = 2459\ \mathrm{MeV}/c^2$

peak @ nominal mass	$\sigma = (6.5 \pm 0.5)\ \mathrm{MeV}/c^2$	signal
broad peak	$\sigma = (19.5 \pm 3.6)\ \mathrm{MeV}/c^2$	random photon
peak @ $M_{D_{sJ}(2460)} - 2\ \mathrm{MeV}/c^2$	$\sigma = (14.9 \pm 0.8)\ \mathrm{MeV}/c^2$	missed photon