The D and D_s Spectrum

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Charm 09
Leimen
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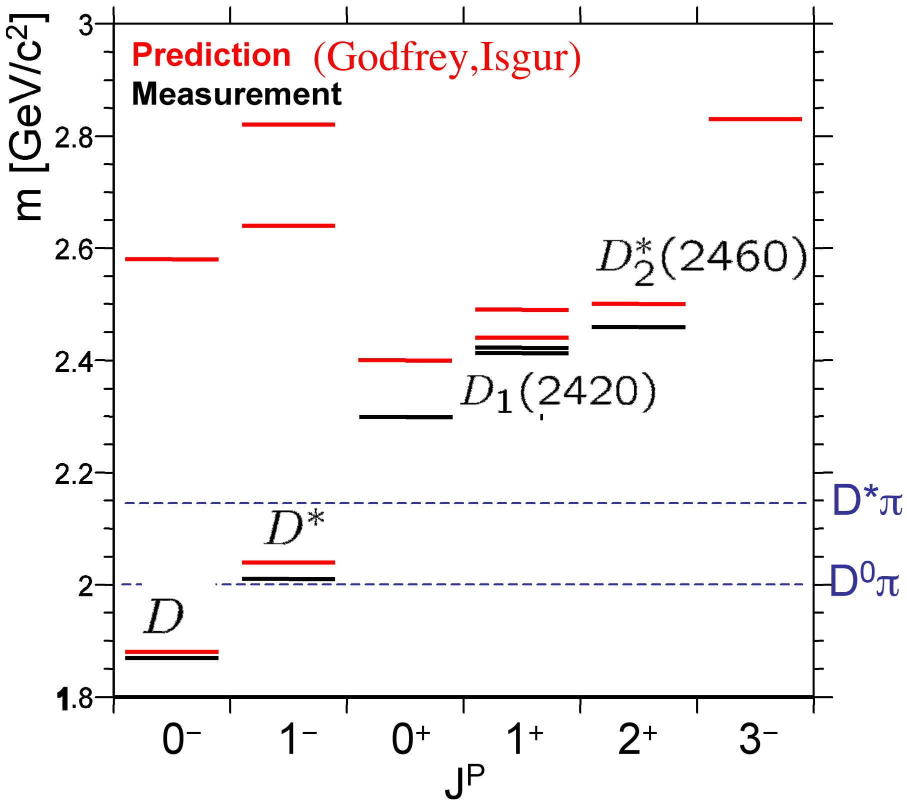
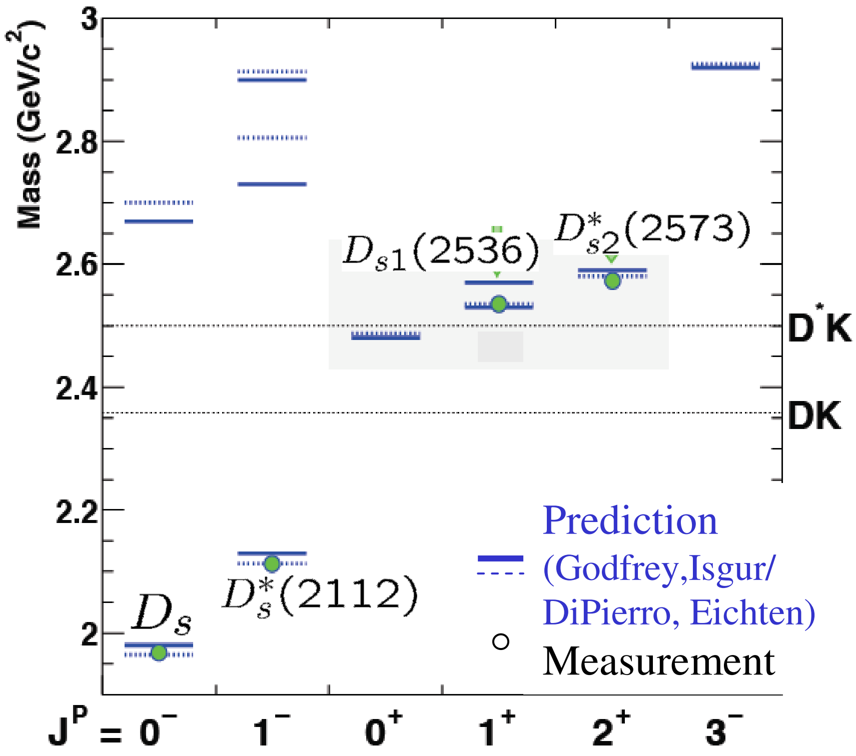
Overview

- Motivation
- Charm Production at *B*-Factories
- *D* Meson Spectrum and its Candidates
- D_s Meson Spectrum and its Candidates
- Outlook

Motivation

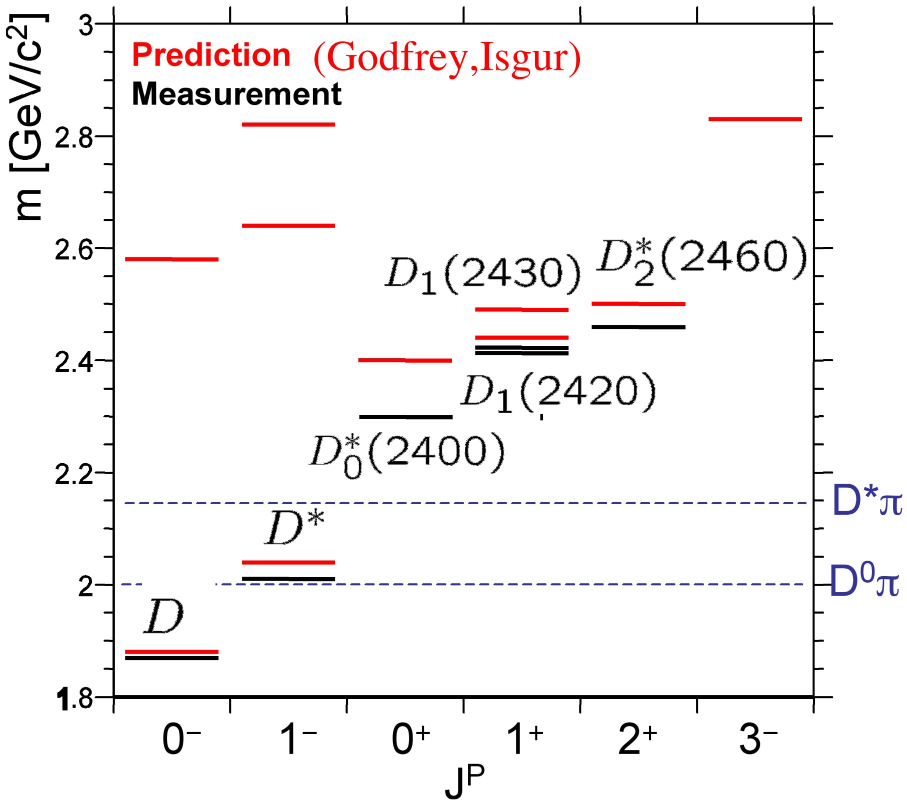
- Until 2003: D/D_s spectra not very exciting



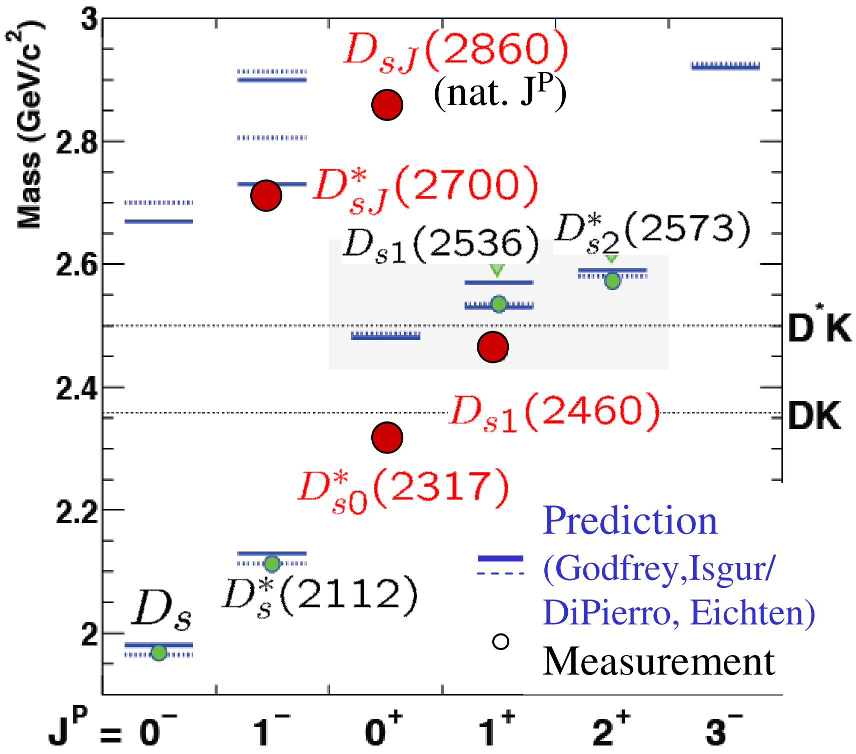


Motivation

- After 2003: Further states, partly very narrow (D_s system)
- Not consistent with theoretical expectations [$D^*_{s0}(2317)$, $D_{s1}(2460)$]



Evidence for 2 new states



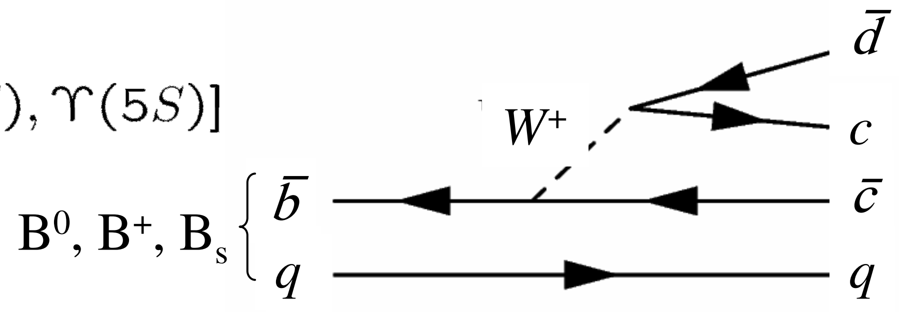
4 new states

Motivation

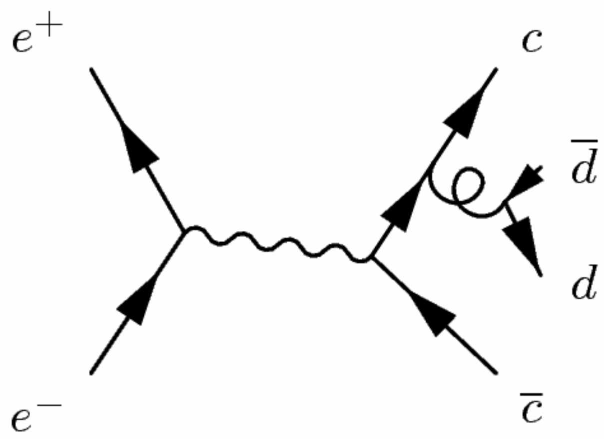
- Nature of the recently found states?
  - $c\bar{u}/c\bar{d}$, $c\bar{s}$ states
  - Tetraquark states
  - Molecular states (near threshold)
- Experimental observables
  - Masses
  - Total Widths
  - Spin-Parity
  - Isospin
  - Partial decay widths
  - Mixing angles

Charm Production at *B*-Factories

- Resonant $\Upsilon(4S)$ [$\Upsilon(2S)$, $\Upsilon(3S)$, $\Upsilon(5S)$]
  $e^+e^- \to \gamma^* \to b\bar{b}$
  favored decay: $b \to c\, W^-$



- non-resonant $q\bar{q}$ production: $e^+e^- \to \gamma^* \to q\bar{q}$
  $c\bar{c}$-events rich source for D and D_s mesons



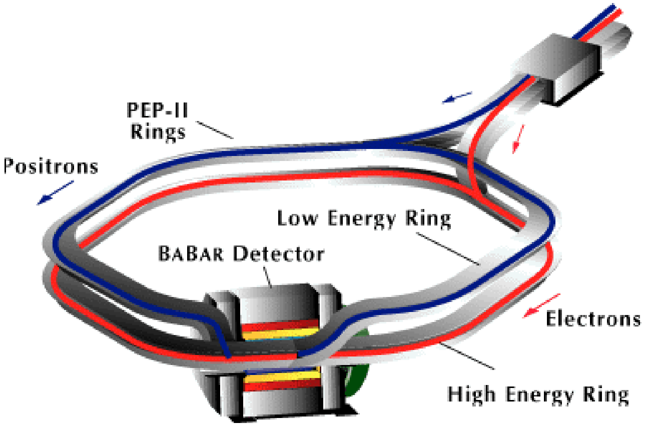
$e^+e^- \to$	σ [nb]
$b\bar{b}$	1,05
$c\bar{c}$	1,30
$s\bar{s}$	0,35
$d\bar{d}$	0,35
$u\bar{u}$	1,39

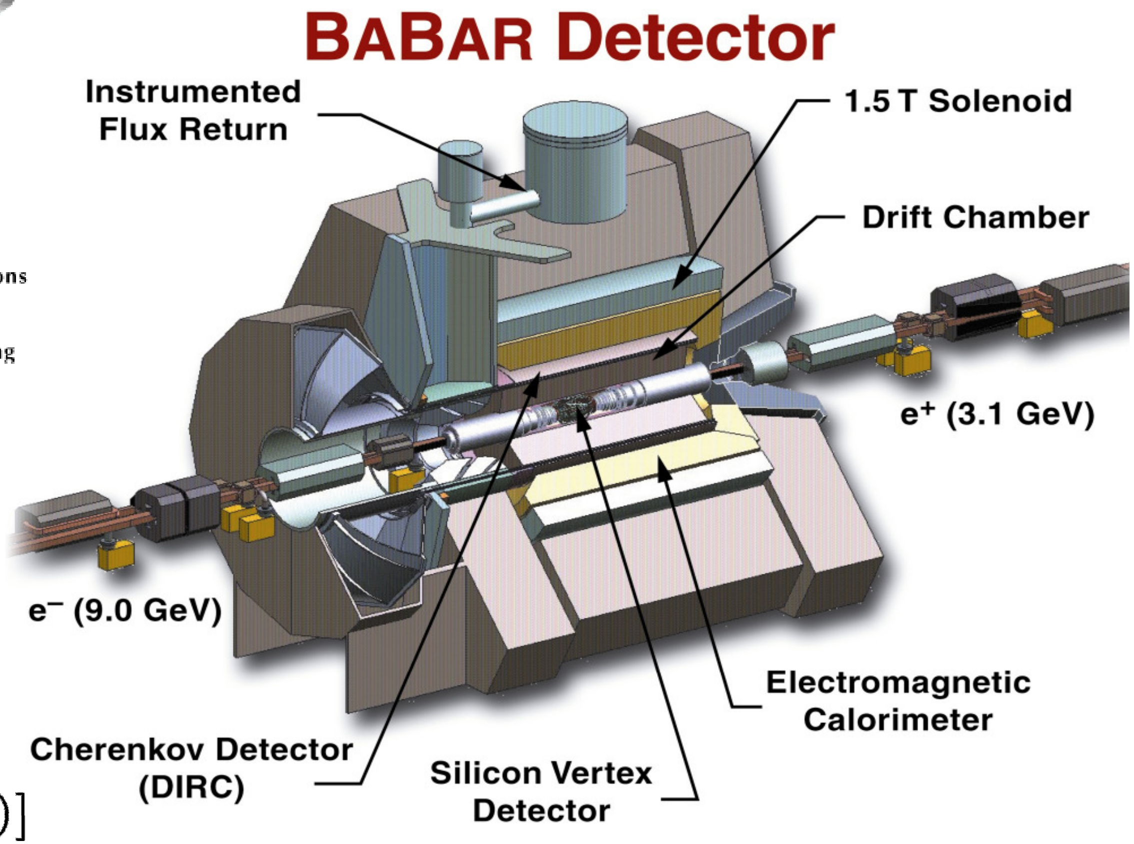
BABAR integrated luminosity
531 fb^{-1}
$\to 558 \cdot 10^6$ $b\bar{b}$ pairs
$\to 690 \cdot 10^6$ $c\bar{c}$ pairs
Belle integrated luminosity 921 fb^{-1}

B-factories $\to$ Charm physics studies

Experimental Overview

Electron-Positron Collider: PEP-II / SLAC



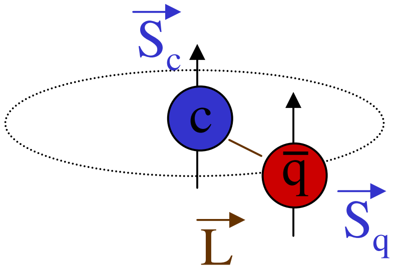


Very good PID, Tracking and Vertexing

PEP-II
e^+e^- CMS energy
$\rightarrow \Upsilon(4S)\ [\Upsilon(2S), \Upsilon(3S)]$
max. lum. > $1.2 \cdot 10^{34}$ $cm^{-2}s^{-1}$

D Meson Spectrum

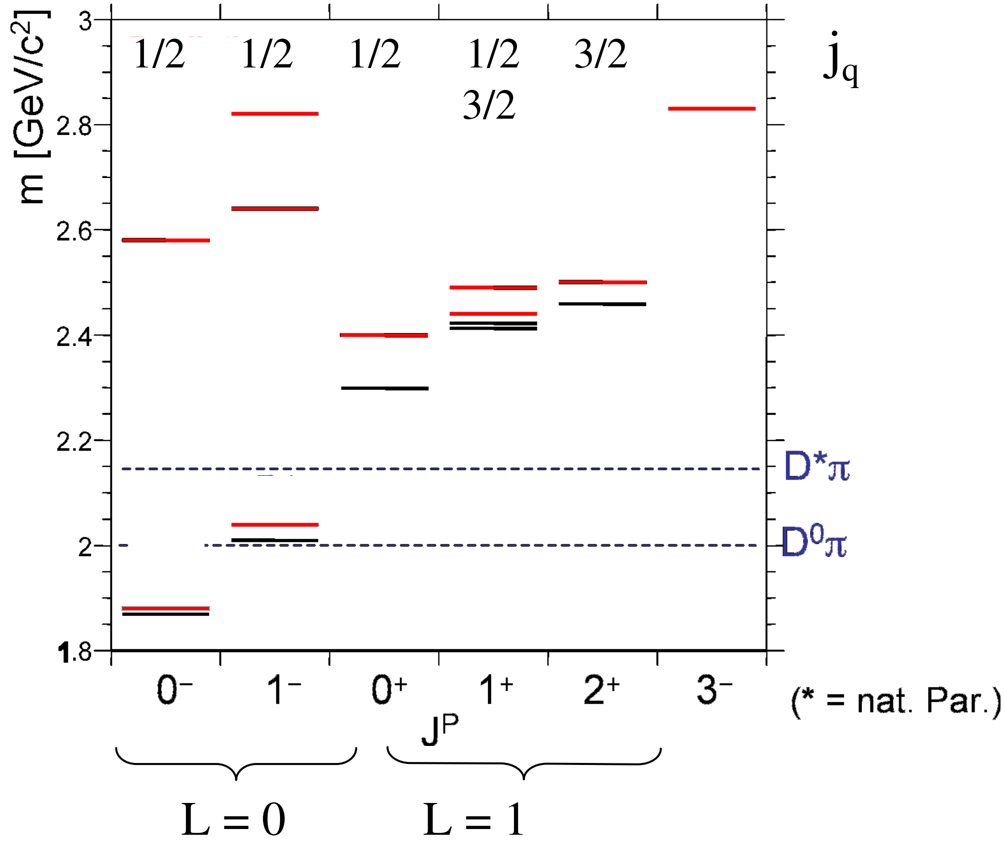
$c\bar{u}$, $c\bar{d}$ (= $D^{0(*)}$, $D^{+(*)}$) and c.c.



$j_q = L + S_q$
$J = j_q + S_c$

angular momentum L

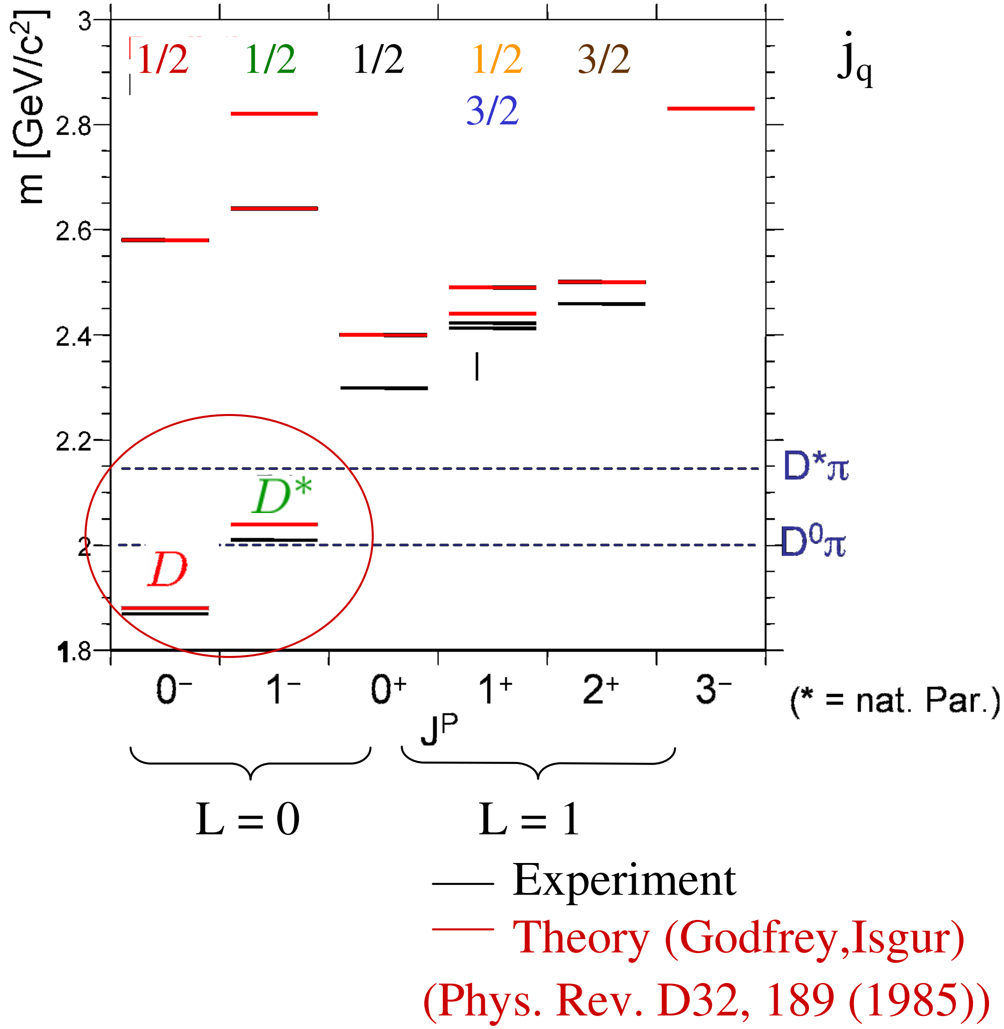
Heavy-light quark system
HQET: spin S_c decouples
j_q good quantum number



— Experiment
— Theory (Godfrey,Isgur)
(Phys. Rev. D32, 189 (1985))

D Meson Spectrum

- S-wave states (L=0)
  $D^0/D^\pm$ (Mark I, 1975)
  $D^{*0}/D^{*\pm}$ (Mark I, 1975)

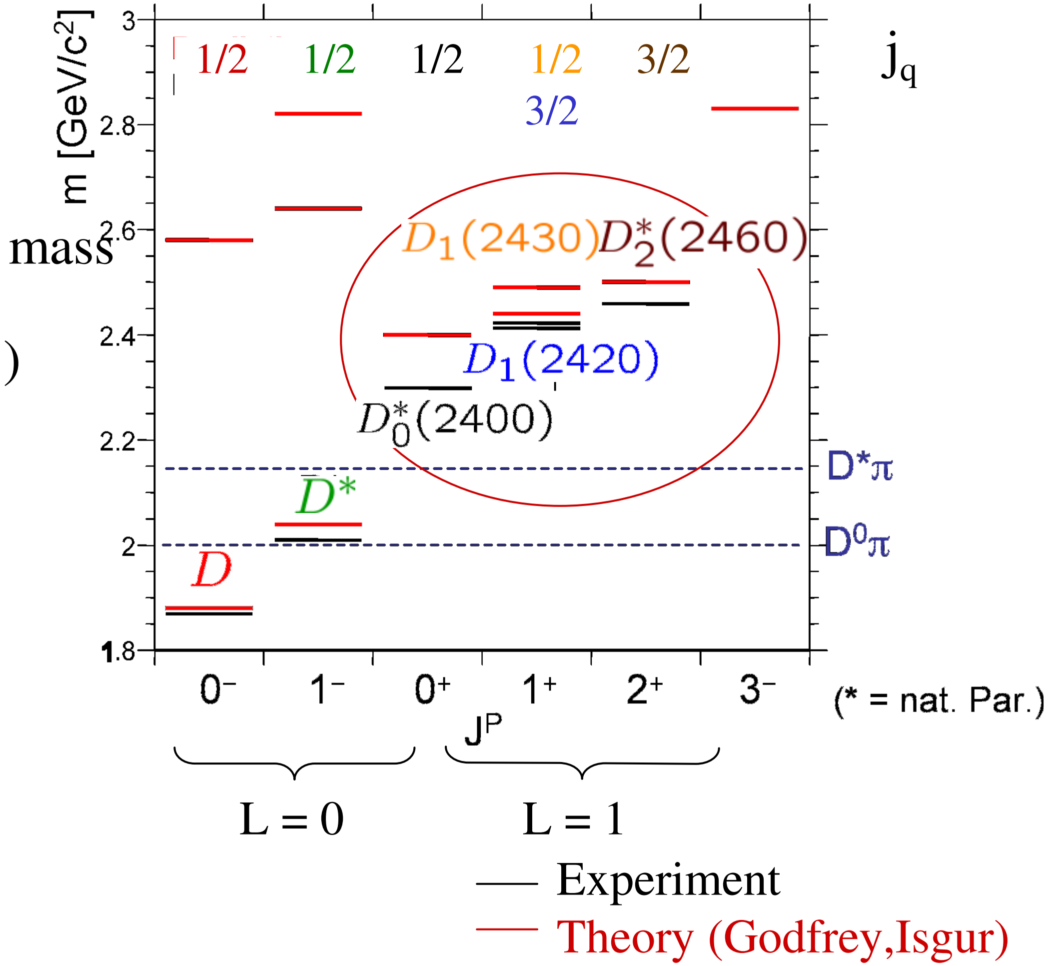


D Meson Spectrum

- S-wave states (L=0)
  - $D^0/D^\pm$ (Mark I, 1975)
  - $D^{*0}/D^{*\pm}$ (Mark I, 1975)

- P-wave state candidates (L=1)
  - $D_0^*(2400)$ (Belle, 2004)
  - $D_1(2420)$ (Argus, 1986)
  - $D_1'(2430)$ (Belle, 2004)
  - $D_2^*(2460)$ (E691, 1989)

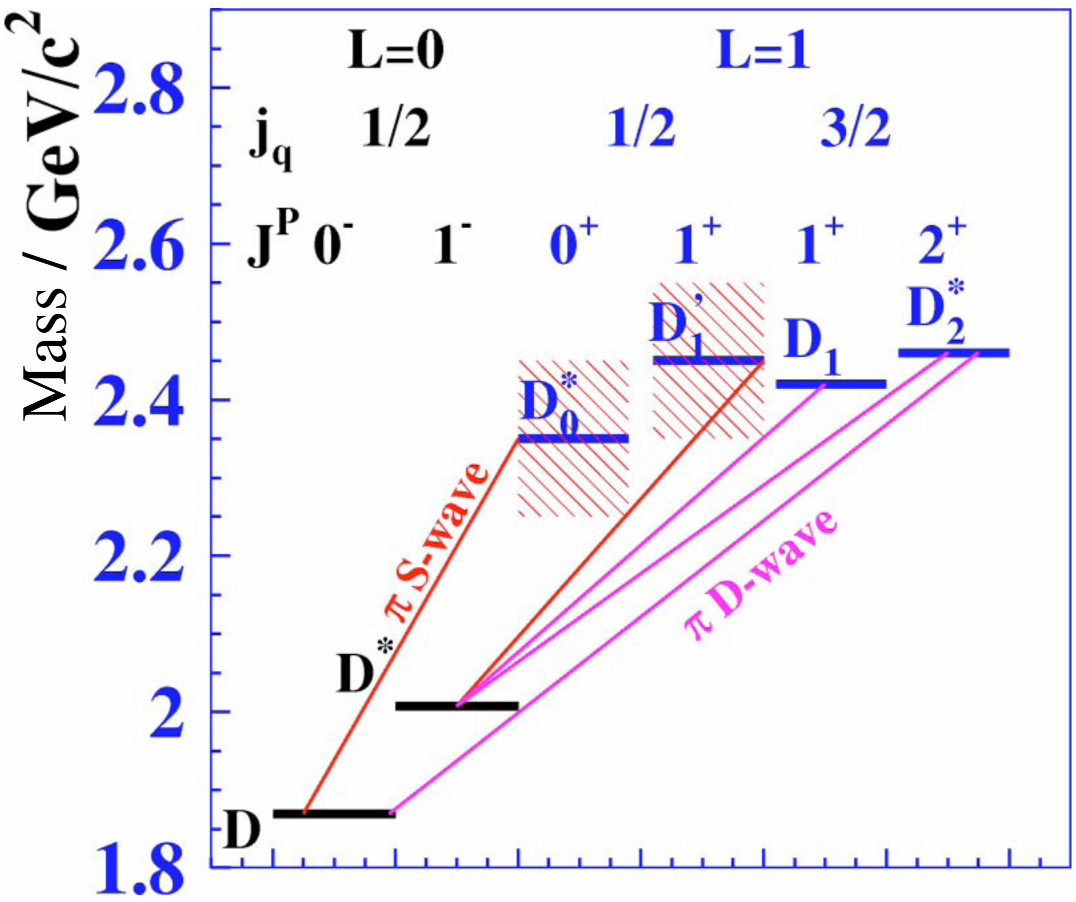
Neutral and charged states



(Phys. Rev. D32, 189 (1985))

D Meson Spectrum

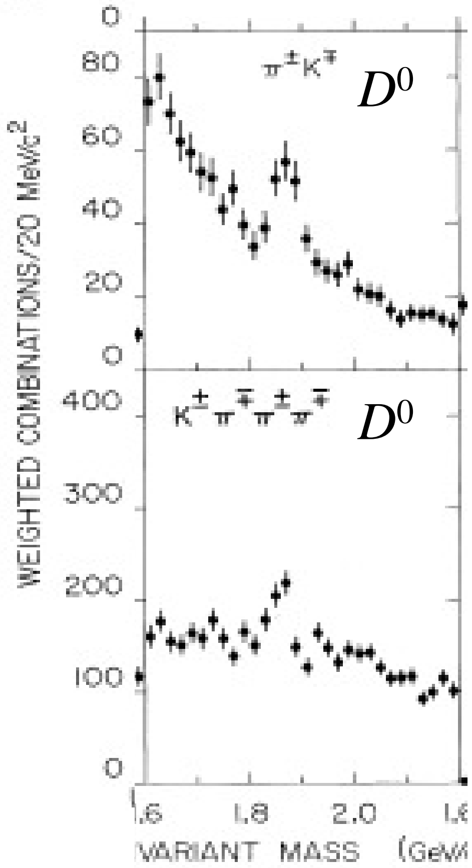
Predicted: broad narrow



Decay S-wave, D-wave
$\propto q^{2L+1}$

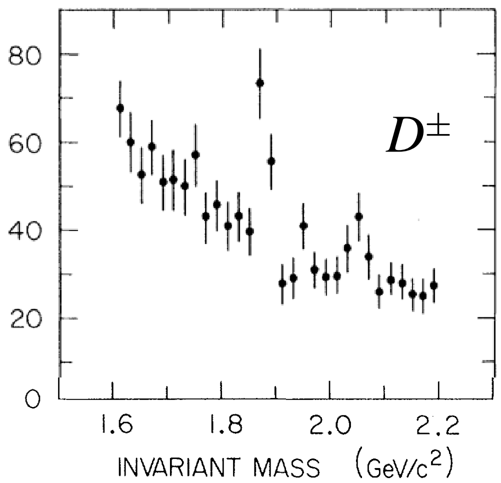
(q breakup momentum)

First seen in continuum events

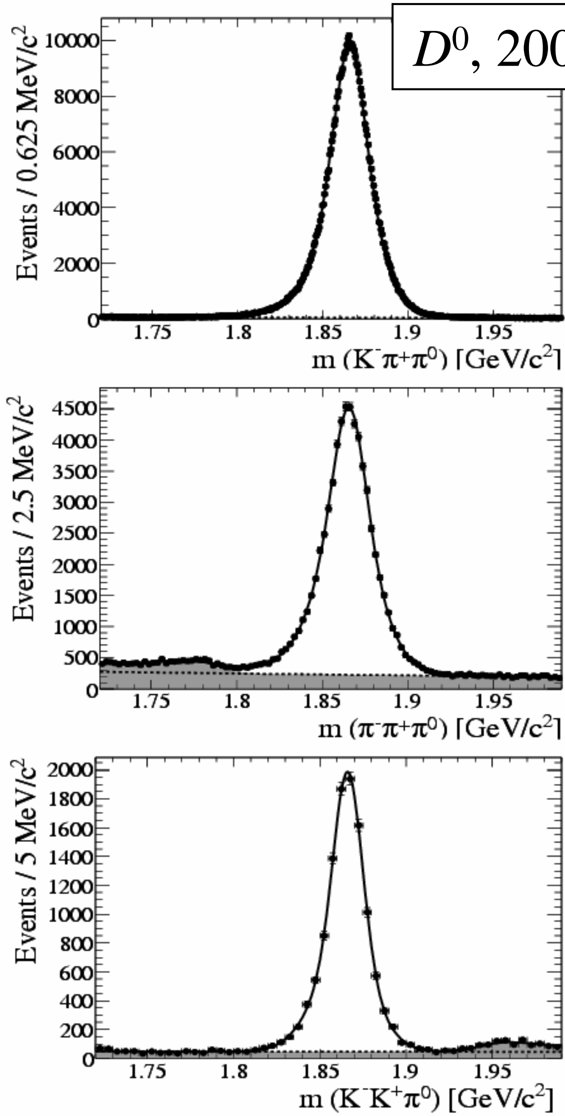


232 fb^{-1}
Phys. Rev. D74 091102 (2006)

Mark I, 1975



D^0, 2006



D^0, $D^{\pm}$ - Parameters and Decays

D^0 m = 1864.84 ± 0.17 MeV/c^2
cτ = 122.9 μm

$D^{\pm}$ m = 1869.62 ± 0.20 MeV/c^2
cτ = 311.8 μm

$J^P = 0^-$ Consistent with angular distributions

D Ground state 1^1S_0

200 decay modes studied
Study of weak decays
D^0-$\overline{D}^0$ Mixing
See other talks on various *D* studies

(PDG 08)

Topological modes

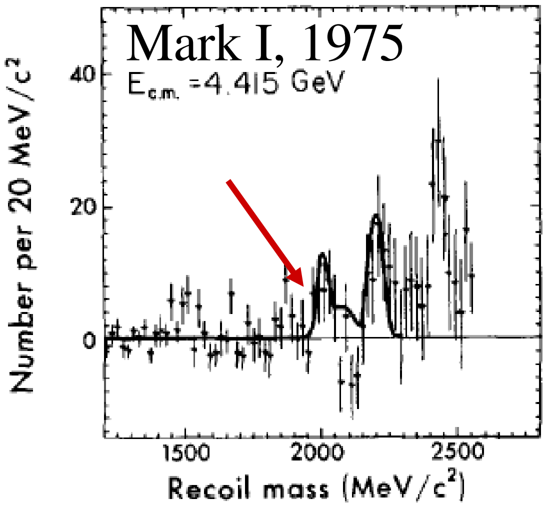
0-prongs	[vv]	(15 ± 6) %
2-prongs		(71 ± 6) %
4-prongs	[ww]	(14.6 ± 0.5) %
6-prongs		$(1.2\ ^{+1.3}_{-0.7}) \times 10^{-3}$

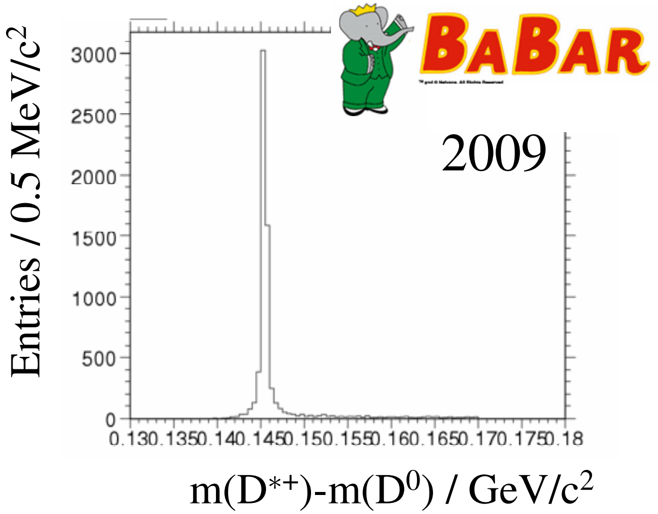
Inclusive modes

e^+ anything	[xx]	(6.53 ± 0.17) %
μ^+ anything		(6.7 ± 0.6) %
K^- anything		(54.7 ± 2.8) %
$\overline{K}^0$ anything + K^0 anything		(47 ± 4) %
K^+ anything		(3.4 ± 0.4) %
$K^*(892)^-$ anything		(15 ± 9) %
$\overline{K}^*(892)^0$ anything		(9 ± 4) %
$K^*(892)^+$ anything		< 3.6 %
$K^*(892)^0$ anything		(2.8 ± 1.3) %
η anything		(9.5 ± 0.9) %
η' anything		(2.48 ± 0.27) %
ϕ anything		(1.05 ± 0.11) %

$D^*(2007)^0$/ $D^*(2010)^\pm$ Parameters, Decays …

First seen in continuum





$D^*(2007)^0$ DECAY MODES	Fraction (Γ_i/Γ)
$D^0\pi^0$	(61.9 ± 2.9) %
$D^0\gamma$	(38.1 ± 2.9) %

$D^*(2010)^\pm$ DECAY MODES	Fraction (Γ_i/Γ)
$D^0\pi^+$	(67.7 ± 0.5) %
$D^+\pi^0$	(30.7 ± 0.5) %
$D^+\gamma$	$(\ 1.6\pm0.4)$ %

D^{*0} m = 2006.97 ± 0.19 MeV/c²
$\Gamma < 2.1$ MeV

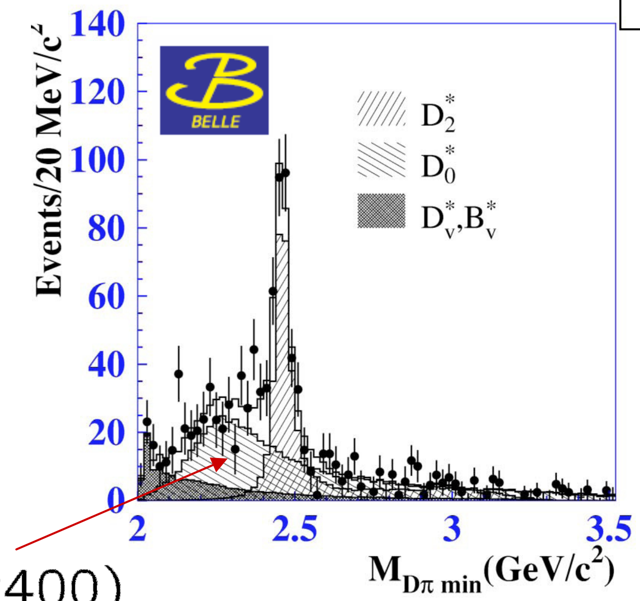
$D^{*\pm}$ 2010.27 ± 0.17 MeV/c²
$\Gamma = 96 \pm 22$ keV

$J^P = 1^-$ Consistent with
1^3S_0 angular distributions

$D_0^*(2400)$ – Production, Parameters

First observed in
$B \to (D\pi)\pi$

62 fb^{-1}
Phys. Rev. D69 112002 (2004)



$D_0^*(2400)$
m = 2308 ± 17 ± 22 MeV/c^2
Γ =276 ± 21 ± 63 MeV

Only decay mode $D\pi$
$J^P = 0^+$ favored 1^1P_0

Use decay pattern for indirect J^P measurement
Allowed decay modes for
$J^P = 0^+$ $D\pi$
1^+ $D^*\pi$
2^+ ($D\pi$, $D^*\pi$)

Focus (seen in γA)

$D_0^*(2400)^0$ m = 2407 ± 21 ± 35 MeV/c^2
Γ = 240 ± 55 ± 59 MeV

$D_0^*(2400)^\pm$ m = 2403 ± 14 ± 35 MeV/c^2
Γ = 283 ± 24 ± 34 MeV

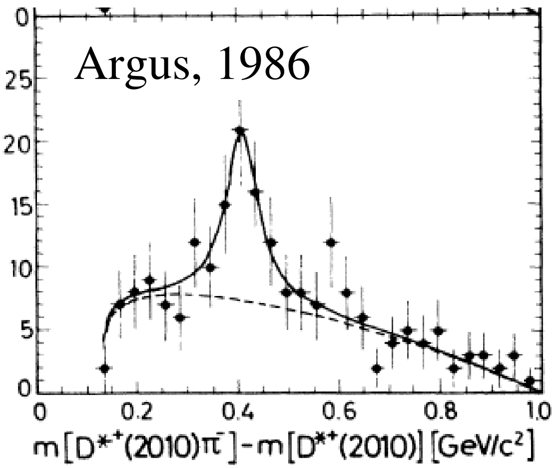
100 MeV difference

Phys. Lett. B586, 11 (2004)

$D_1(2420)$ – Production and Decays

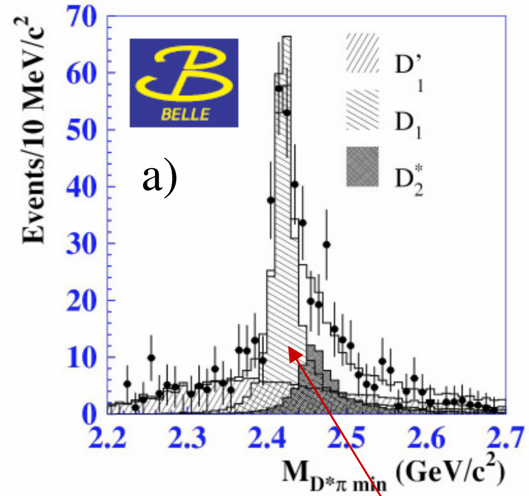
First observed in continuum

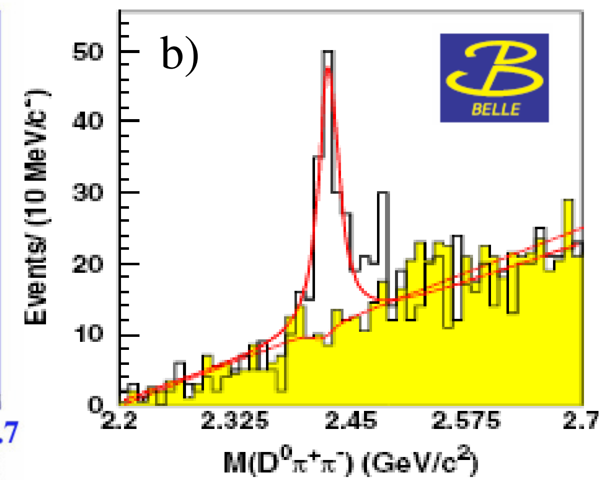
$e^+e^- \to (D^*\pi)X,\ D^* \to D\pi$



B-Decays

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



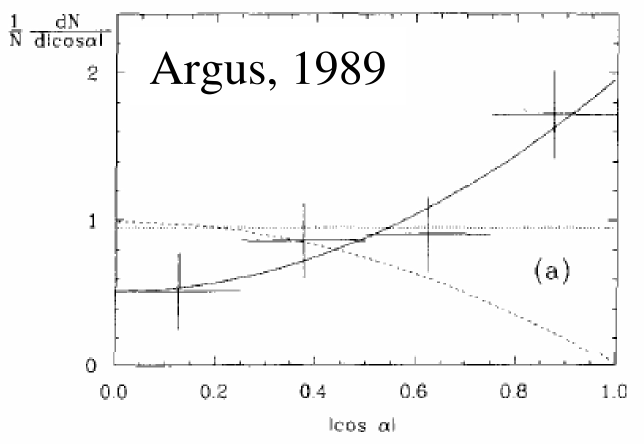


$D_1(2420)^0$ DECAY MODES	Fraction (Γ_i/Γ)
$D^*(2010)^+\pi^-$	seen
$D^0\pi^+\pi^-$	seen
$D^+\pi^-$	not seen
$D^{*0}\pi^+\pi^-$	not seen

a) 62 fb-1
Phys. Rev. D69 112002 (2004)

b) 145 fb^{-1}
Phys. Rev. Lett. 94 221805 (2005)

D_1(2420) – Parameters, Test of Nature



Angular analysis consistent with spin 1

Phys. Lett. B232, 398 (1989)

Seen in $D^*\pi$, not in $D\pi$
Decay pattern rules out 0^+, 2^+

D_1^0	m = 2422.3 ± 1.3 MeV/c^2 Γ = 20.4 ± 1.7 MeV	
$D_1^\pm$	m = 2423.4 ± 3.1 MeV/c^2 Γ = 25 ± 6 MeV	$J^P = 1^+$

Not seen in color suppressed decays.

Two $J^P = 1^+$ states
Mixing with D_1(2430)

62 fb^{-1}
Phys. Rev. D69 112002 (2004)

Dalitzplot →
Mixing angle $\theta \approx$ -0.10 ±0.03 ± 0.02 rad

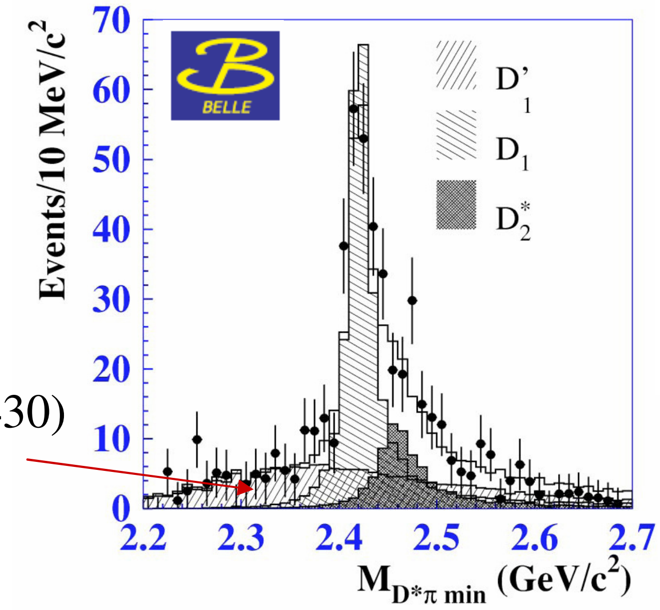
$D_1(2430)$ – Production, Parameters…

First seen in B decays

62 fb^{-1}
Phys. Rev. D69
112002 (2004)

$B^{\pm} \rightarrow (D^{*}\pi)\pi$
Color favored

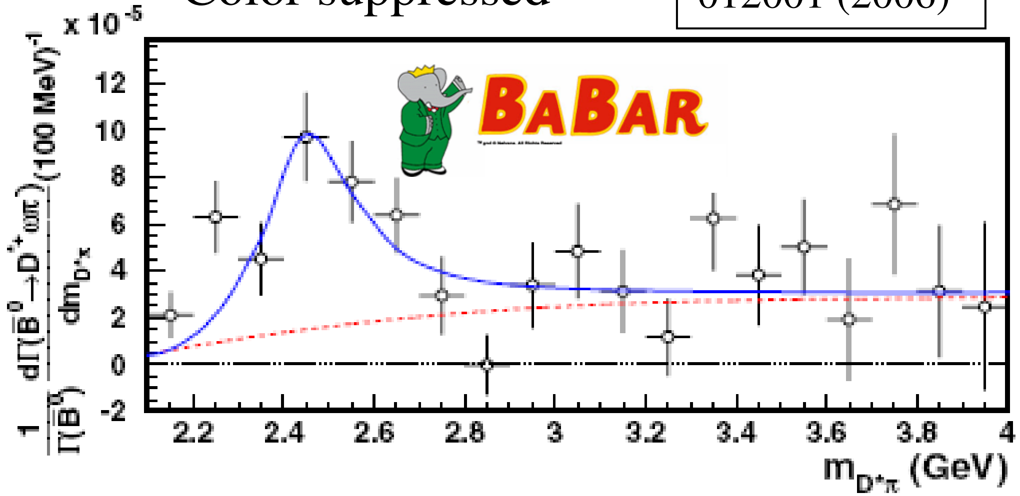
$D_1(2430)$



M = 2427 ± 36 MeV/c^2
Γ = 384 ± 117 MeV

$\bar{B}^0 \rightarrow (D^{*+}\pi^-)\omega$
Color suppressed

221 fb^{-1}
Phys. Rev. D74
012001 (2006)



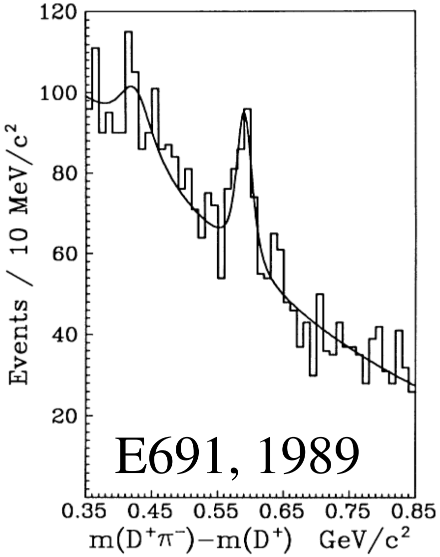
No evidence for the narrow resonances at 2420 and 2460 MeV/c^2 ?

M = 2477 ± 28 MeV/c^2
Γ = 266 ± 97 MeV

Only decay mode $D^*\pi$
$J^P = 1^+$ favored

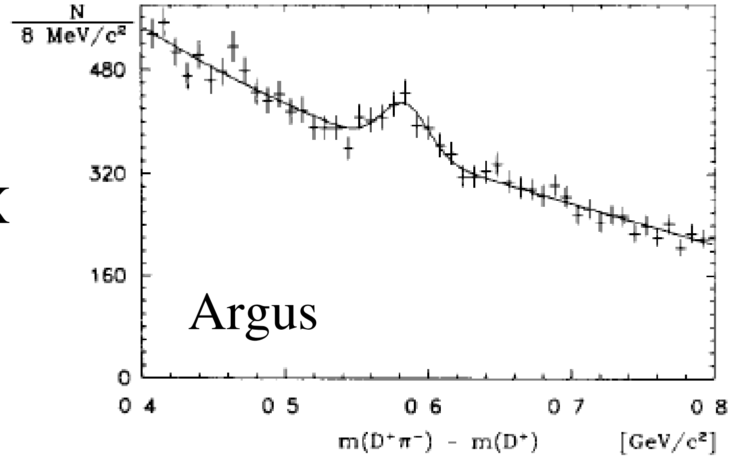
D_2*(2460) - Production

First observed in $\gamma N \rightarrow (D\pi)X$



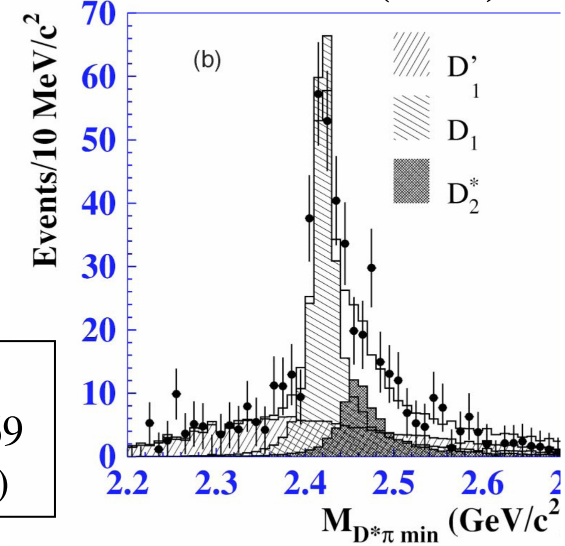
In continuum

$e^+e^- \rightarrow (D\pi)X$

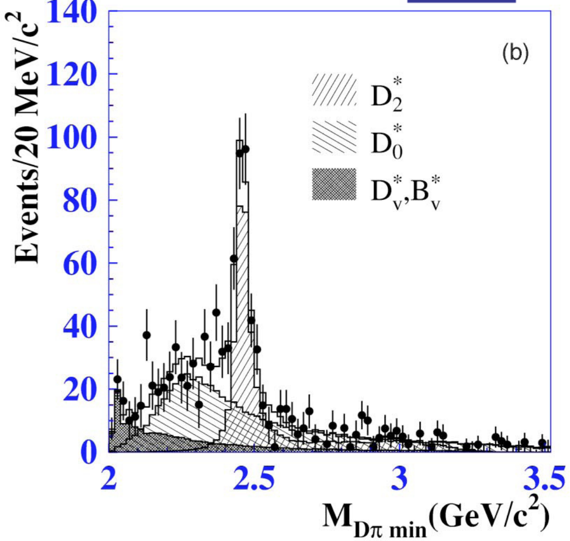


In B decays

$B \rightarrow (D^*\pi)\pi$



$B \rightarrow (D\pi)\pi$

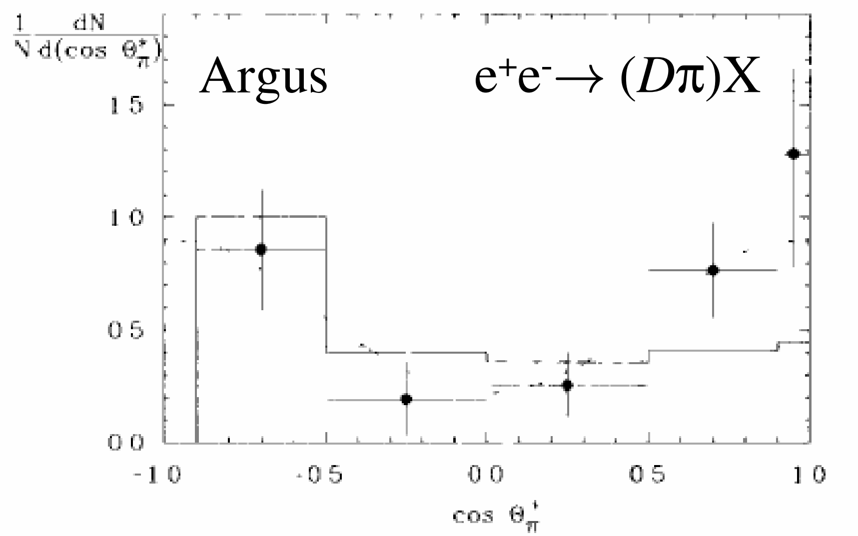


62 fb^{-1}
Phys. Rev. D69
112002 (2004)

$D_2^*(2460)$ – Parameters and Decays

$D_2^*(2460)^0$ DECAY MODES	Fraction (Γ_i/Γ)
$D^+\pi^-$	seen
$D^*(2010)^+\pi^-$	seen
$D^0\pi^+\pi^-$	not seen
$D^{*0}\pi^+\pi^-$	not seen

$D_2^*(2460)^\pm$ DECAY MODES	Fraction (Γ_i/Γ)
$D^0\pi^+$	seen
$D^{*0}\pi^+$	seen
$D^+\pi^+\pi^-$	not seen
$D^{*+}\pi^+\pi^-$	not seen



Consistent with spin 2
(0 flat, 1 not allowed)

Decay pattern

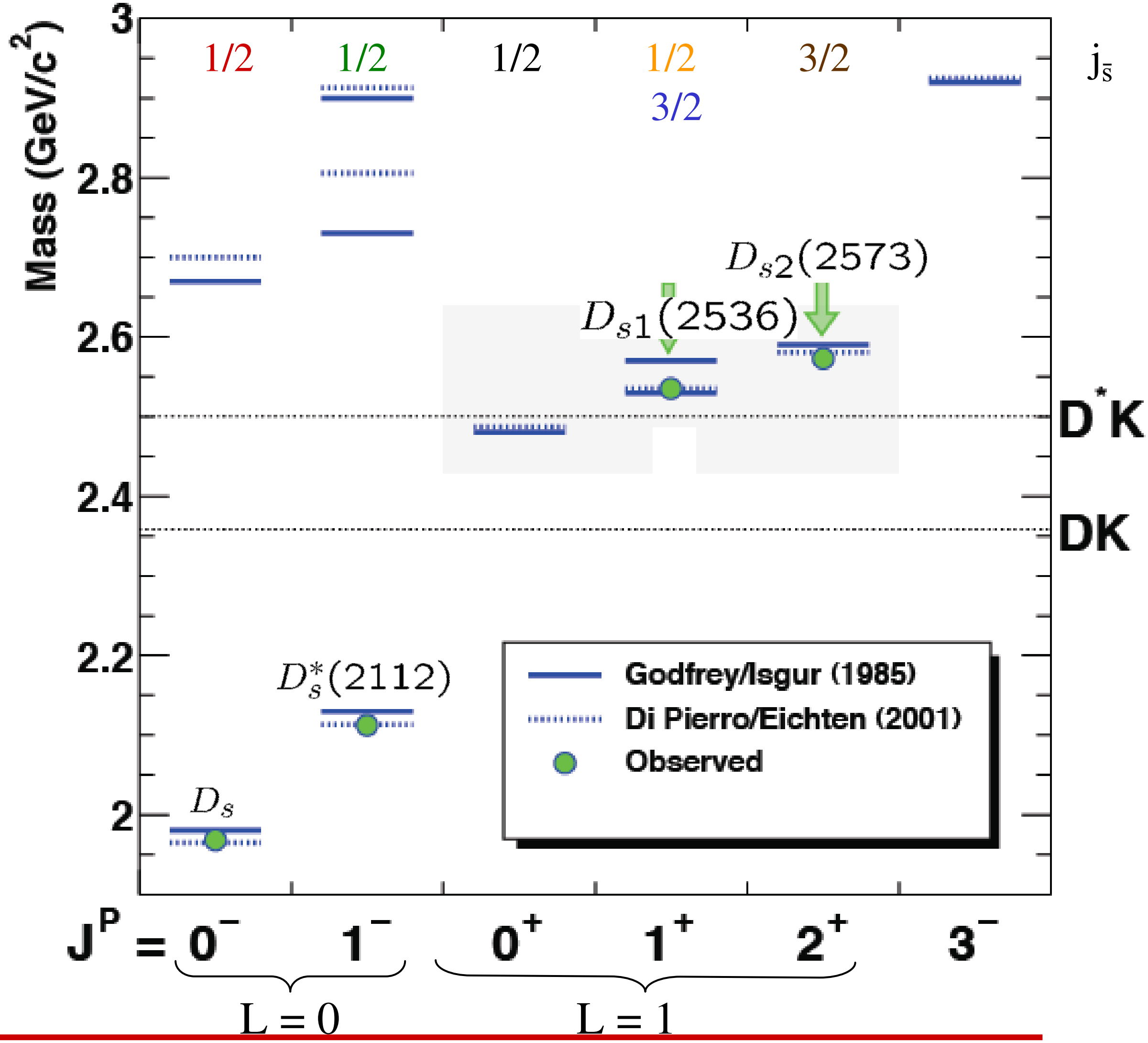
D_2^{*0}	m = 2461.1 ± 1.6 MeV/c^2 Γ = 43 ± 4 MeV	
$D_2^{*\pm}$	m = 2460.1 ± 3.0 MeV/c^2 Γ = 37 ± 6 MeV	$J^P = 2^+$ 1^3P_2

D_s Meson Spectrum

$c\bar{s}$ and c.c.

States known until 2003

D_s	(CLEO, 1983)
$D_s^*(2112)$	(PEP4, 1984)
$D_{s1}(2536)$	(Argus, 1989)
$D_{s2}(2573)$	(Cleo, 1994)



D_s Meson Spectrum

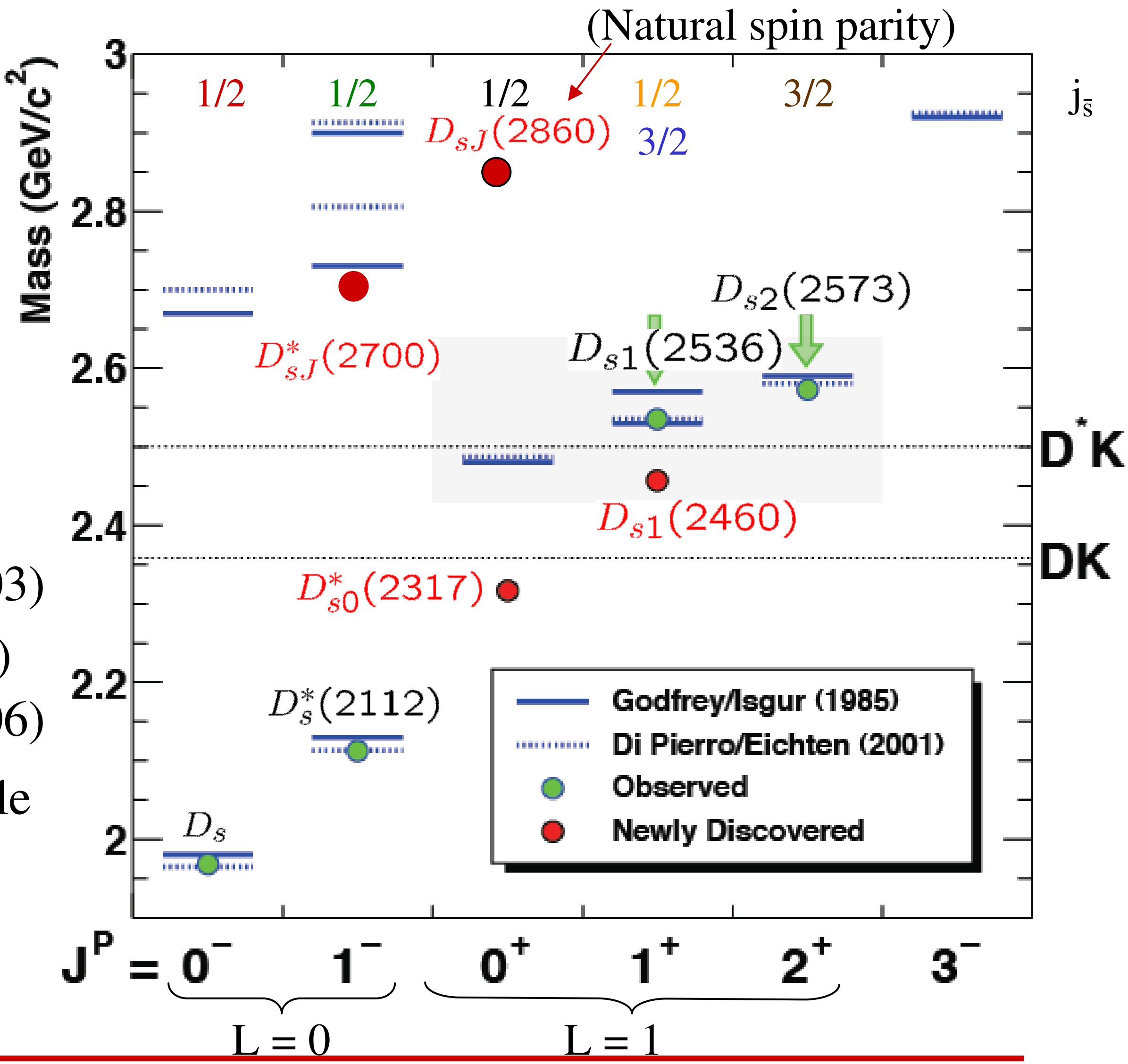
$c\bar{s}$ and c.c.

States known until 2003

D_s	(Cleo, 1983)
$D_s^*(2112)$	(Slac, 1984)
$D_{s1}(2536)$	(Argus, 1989)
$D_{s2}(2573)$	(Cleo, 1994)

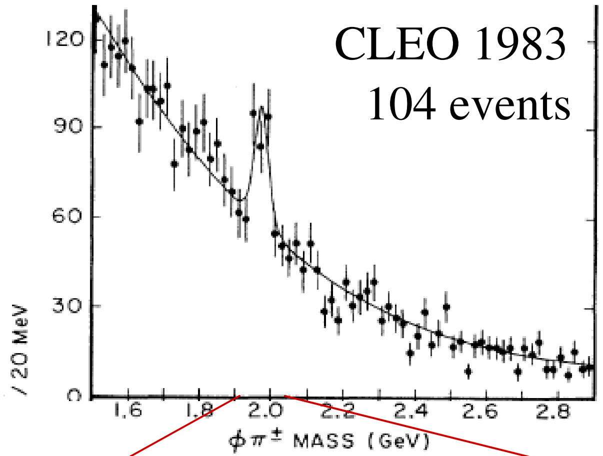
Discovered after 2003

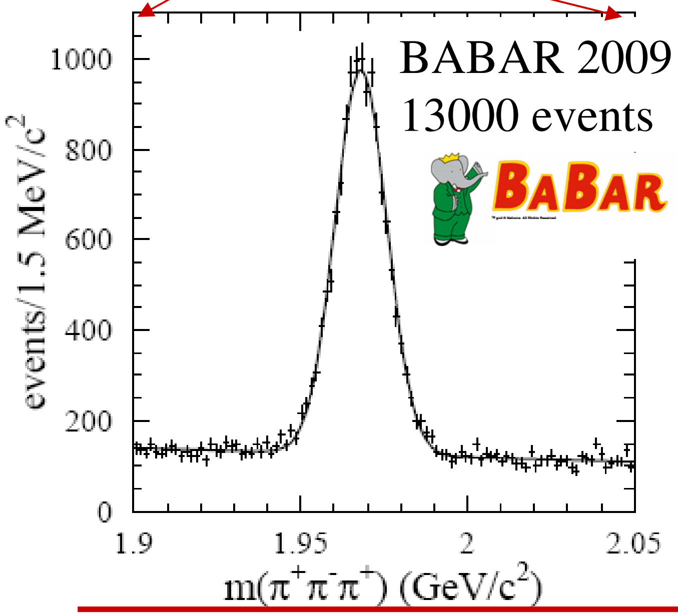
$c\bar{s}$?	$D_{s0}^*(2317)$	(BaBar, 2003)
	$D_{s1}(2460)$	(Cleo, 2003)
	$D_{sJ}(2860)$	(BaBar, 2006)
	$D_{sJ}^*(2700)$	(BaBar/Belle 2006)



D_s^+ – Parameters and Decays

First seen in continuum $e^+e^- \to \phi\pi X$





$m = 1968.49 \pm 0.34$ MeV/c^2
$c\tau = 149.9$ μm

(PDG 08)

Ground state 1^1S_0
$J^P=0^-$

(Spin assignment from angular analysis of $\phi\pi$, $K\bar{K}^*$)

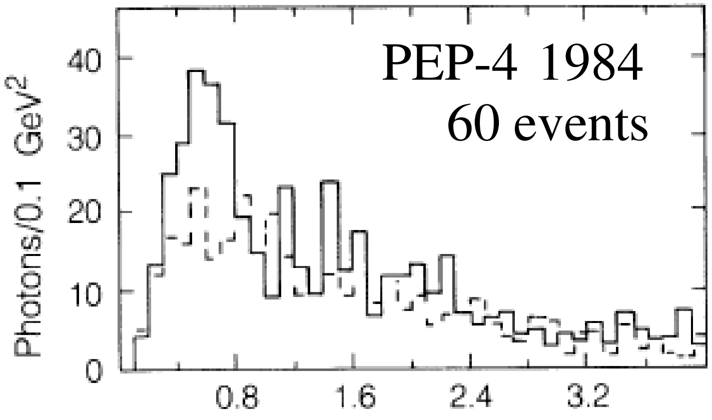
$\approx$ 100 decay modes studied: hadronic, (semi)leptonic $\to$ Dalitz Plot Analyses

D_s^+ DECAY MODES		Fraction (Γ_i/Γ)
Inclusive modes		
K^- anything		$(13\ ^{+14}_{-12})$ %
$\overline{K}^0$ anything + K^0 anything		(39 ± 28) %
K^+ anything		$(20\ ^{+18}_{-14})$ %
(non-$K\overline{K}$) anything		(64 ± 17) %
η anything	[ddd]	(24 ± 4) %
η' anything		(8.7 ± 2.1) %
ϕ anything		(16.1 ± 1.6) %
e^+ anything		$(8\ ^{+6}_{-5})$ %

See other talks for details

D_s^{*+} – Parameters and Decays

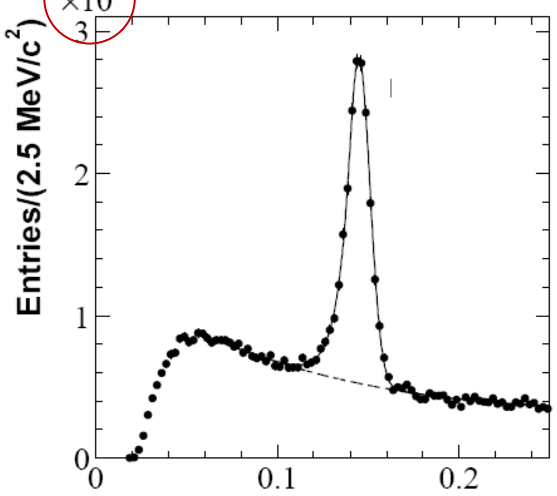
First seen in $e^+e^- \to D_s\gamma X, D_s \to KK\pi$



ΔM^2 in GeV^2 = $M^2(KK\pi\gamma)-M^2(KK\pi)$

D_s^{*+} DECAY MODES	Fraction (Γ_i/Γ)
$D_s^+\gamma$	(94.2 ± 0.7) %
$D_s^+\pi^0$	(5.8 ± 0.7) %

(PDG 08)



Δm [GeV/c²] = $M(KK\pi\gamma)-M(KK\pi)$

2003
15600 events

BABAR

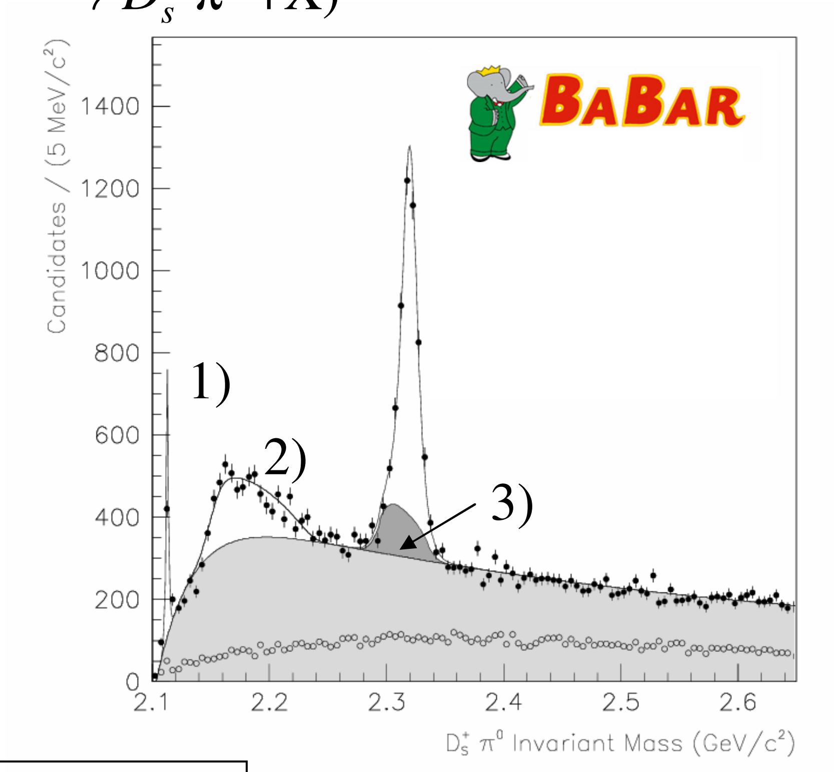
$m = 2112.3 \pm 0.5$ MeV/c²
$\Gamma < 1.9$ MeV

Natural J^P,
decay modes consistent with $J^P = 1^-$
$\to 1^3S_1$

$D_{s0}^*(2317)^+$ - Production

<u>$c\bar{c}$ continuum events</u>

(first observation of this state by BaBar in $e^+e^- \to D_s^+\pi^0 + X$)

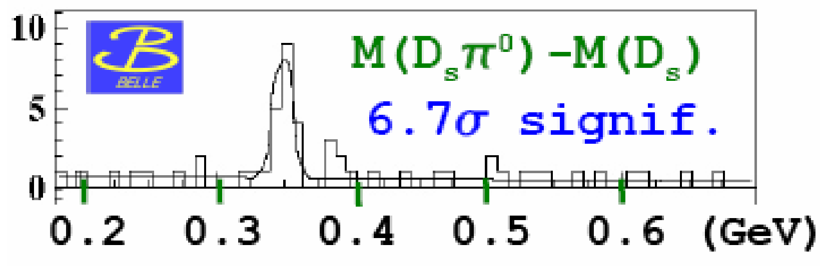


232 fb^{-1}
Phys. Rev. D74 032007 (2006)

Backgr.: 1) $D_s^* \to D_s\pi^0$
2) $D_s^*(\to D_s\gamma)$+wrong γ
3) $D_{s1}(2460)$ $(\to D_s\pi_0)$-missing γ

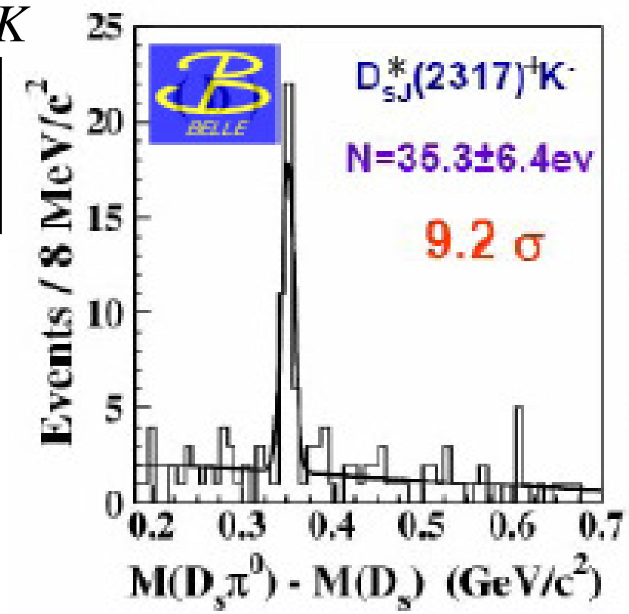
<u>*B* decays</u>

(first seen in *B* decays by Belle $B \to D_{s0}^*(2317)D$, $D_{s0}^* \to D_s\pi^0$



$B \to D_{s0}^*(2317)K$

368 fb^{-1}
hep-ex/0507064



$D_{s0}^*(2317)^+$ – Parameters and Decays

Mass m = 2317.8 ± 0.6 MeV/c^2 Decay width Γ < 3.8 MeV	(PDG 08) Very narrow

Observations

- Mass too low compared with old potential models
  (Godfrey, Dipierro)
  New models work better
- Mass lies below *DK* threshold
  → only isospin-violating and
  electromagnetic decays possible
  → Explanation of small width

$D_{s0}^*(2317)^{\pm}$ DECAY MODES	Fraction (Γ_i/Γ)
$D_s^+ \pi^0$	seen
$D_s^+ \pi^0 \pi^0$	not seen

$D_{s0}^*(2317)^+$ – Parameters

Decay pattern

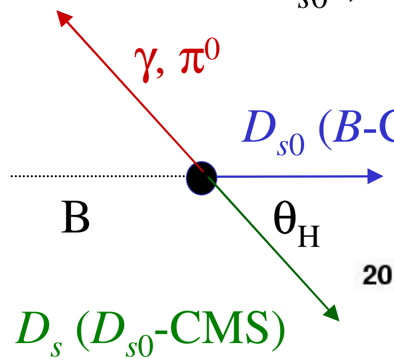
$D_{s0}^*(2317)$^+ $\rightarrow$ Final state	$D_{sJ}^*(2317)^+$ if $J^P = 0^+$	
$D_s^+\pi^0$	⇑	△
$D_s^+\gamma$	⇓	▽
$D_s^+\pi^0\gamma$	⇑	
$D_s^*(2112)^+\pi^0$	⇓	▽
$D_s^+\pi^0\pi^0$	⇓	▽
$D_s^+\gamma\gamma$	⇑	▽
$D_s^*(2112)^+\gamma$	⇑	▽
$D_s^+\pi^+\pi^-$	⇓	▽

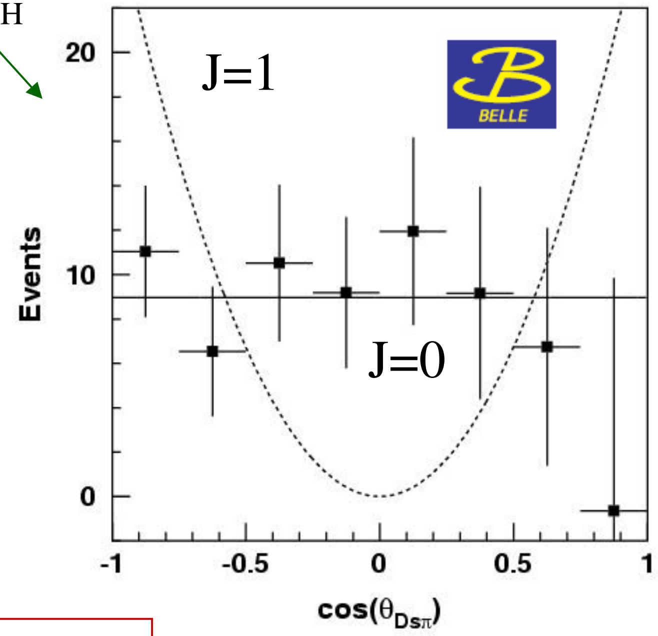
⇑ allowed, ⇓ forbidden
△ observed, ▽ not observed

Angular distribution

$B \rightarrow \bar{D}D_{s0}^*,\ D_{s0}^* \rightarrow D_s\gamma$

261 fb^{-1}
Belle Conf 0461
(2004)



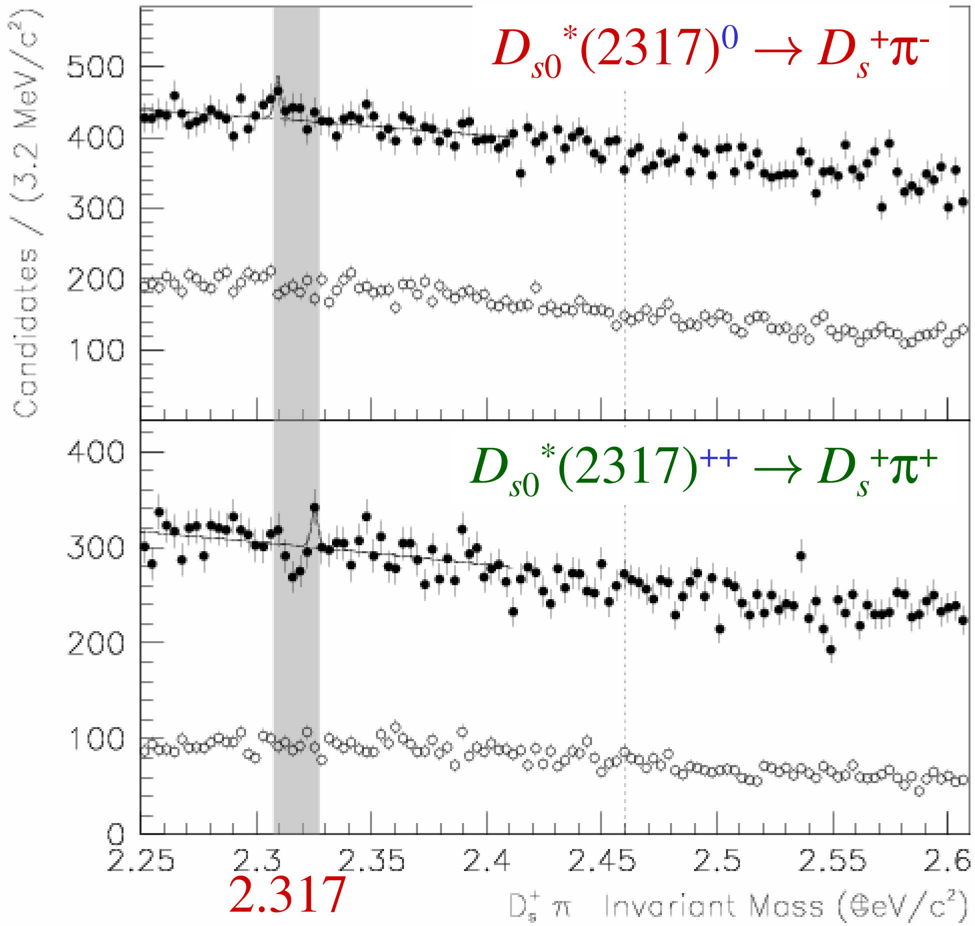


→ Spin-Parity $J^P = 0^+$

$D_{s0}^*(2317)^+$ – Nature of State

- Molecule state?
  Search for $D_{s0}^*(2317)^0$ and $D_{s0}^*(2317)^{++}$ companions

- no signal in $D_s^+\pi^-$ and $D_s^+\pi^+$
  ⇩
  Isospin = 0
  compatible with $c\bar{s}$ state



232 fb^{-1}
Phys. Rev. D74 032007 (2006)

$D_{s0}^{*}(2317)^{+}$ – Nature of State

$$\frac{\mathcal{B}(B^0 \to D^- D^*_{s0}(2317)^+)}{\mathcal{B}(B^0 \to D^- D_s^+)} \approx 0.1$$

(in constrast to HQET ≈ 1)

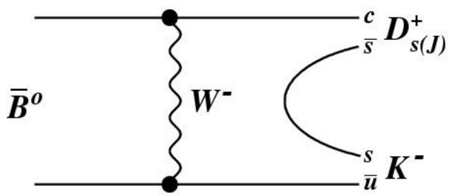
Phys. Rev. Lett. 94
061802 (2005)
140 fb^{-1}

Belle: $B^0 \to D_{s0}^{*}(2317)^{-} K^{+}$

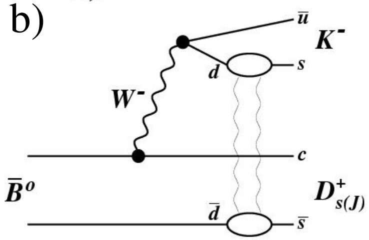
- Strange process: Both initial quarks undergo weak decay ($b\bar{d} \to cs\bar{s}\bar{u}$)
- Possible diagrams:
  - a) PQCD factorization
  - b) W exchange tree with FSI
  - c) Exotic: Tetraquark

$$\frac{\mathcal{B}(B^0 \to D^*_{s0}(2317)^- K^+)}{\mathcal{B}(B^0 \to D_s^- K^+)} \approx 1$$

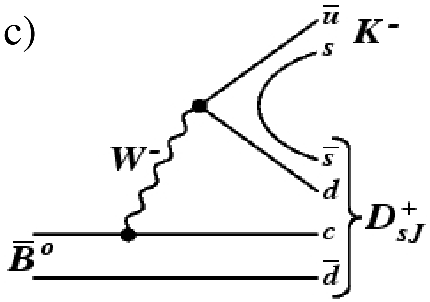
a)



b)



c)

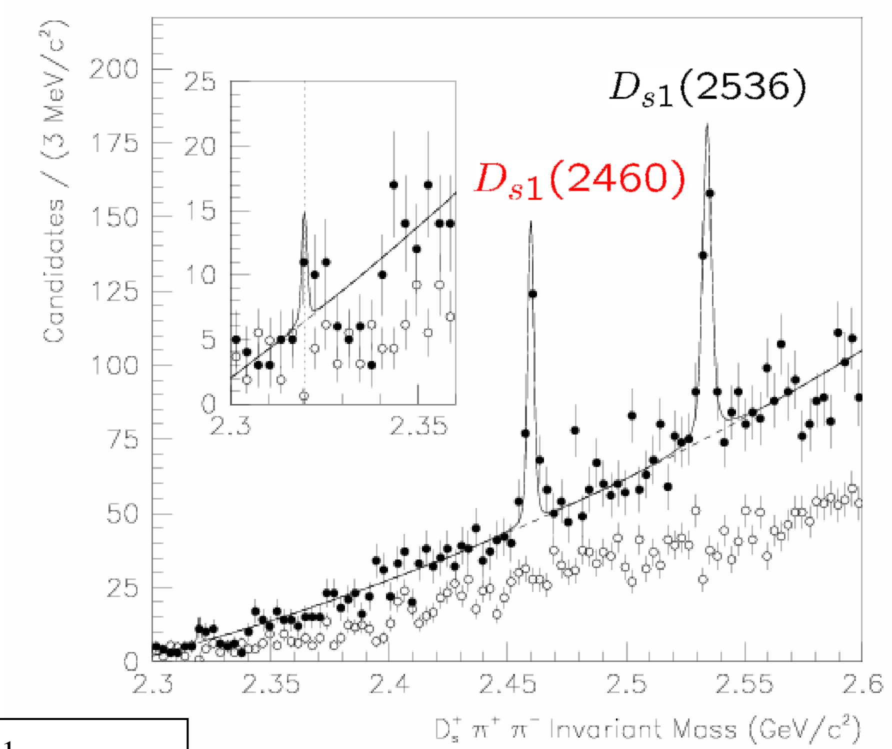


Conclusion: $c\bar{s}$ state,
but other explanations not excluded

$D_{s1}(2460)^+$ - Production

<u>$c\bar{c}$ continuum events</u>

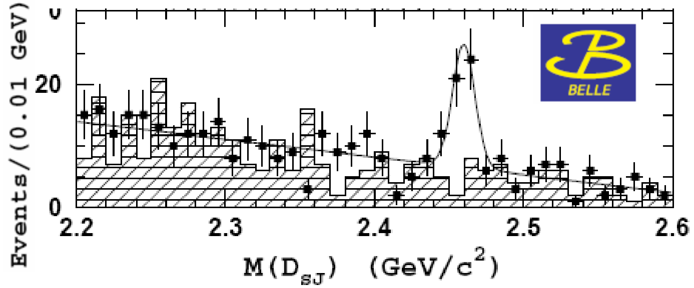
(first observation of this state by CLEO in $e^+e^- \rightarrow D_s^*\pi^0 + X$)



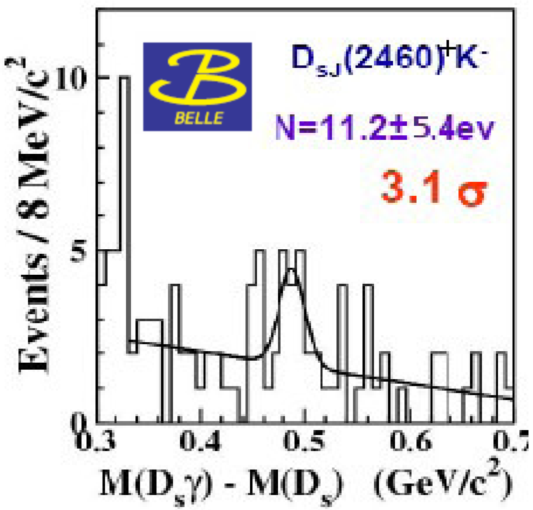
232 fb^{-1}
Phys. Rev. D74 032007 (2006)

<u>B decays</u>

(first seen in B decays by Belle $B \rightarrow D_{s1}(2460)D$)



$B \rightarrow D_{s1}(2460)K$



368 fb^{-1}
hep-ex/0507064

$D_{s1}(2460)^+$ – Parameters and Decays

Mass m = 2459.6 ± 0.6 MeV/c^2
Decay width Γ < 3.5 MeV

(PDG 08)

Observations

-Mass too low compared with old potential models (Godfrey, Dipierro)
New models work better

- Mass lies below *D*K* threshold

$D_{s1}(2460)^+$ DECAY MODES	Fraction (Γ_i/Γ)
$D_s^{*+}\pi^0$	(48 ± 11) %
$D_s^+\gamma$	(18 ± 4) %
$D_s^+\pi^+\pi^-$	(4.3 ± 1.3) %
$D_s^{*+}\gamma$	< 8 %
$D_{s0}^*(2317)^+\gamma$	$(3.7^{+5.1}_{-2.4})$ %

Decay pattern

Final state	$D_{sJ}(2460)^+$ if $J^P = 1^+$	
$D_s^+\pi^0$	⇓	▽
$D_s^+\gamma$	⇑	△
$D_s^+\pi^0\gamma$	⇑	
$D_s^*(2112)^+\pi^0$	⇑	△
$D_{sJ}^*(2317)^+\gamma$	⇑	▽
$D_s^+\pi^0\pi^0$	⇑	▽
$D_s^+\gamma\gamma$	⇑	▽
$D_s^*(2112)^+\gamma$	⇑	△
$D_s^+\pi^+\pi^-$	⇑	△

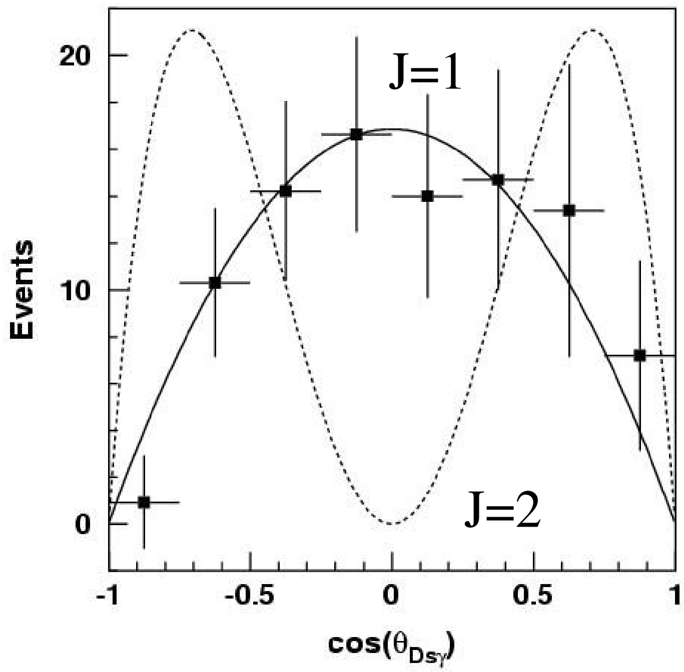
⇑ allowed, ⇓ forbidden
△ observed, ▽ not observed

(Missing modes: more statistic needed)

$D_{s1}(2460)^+$ – Parameters

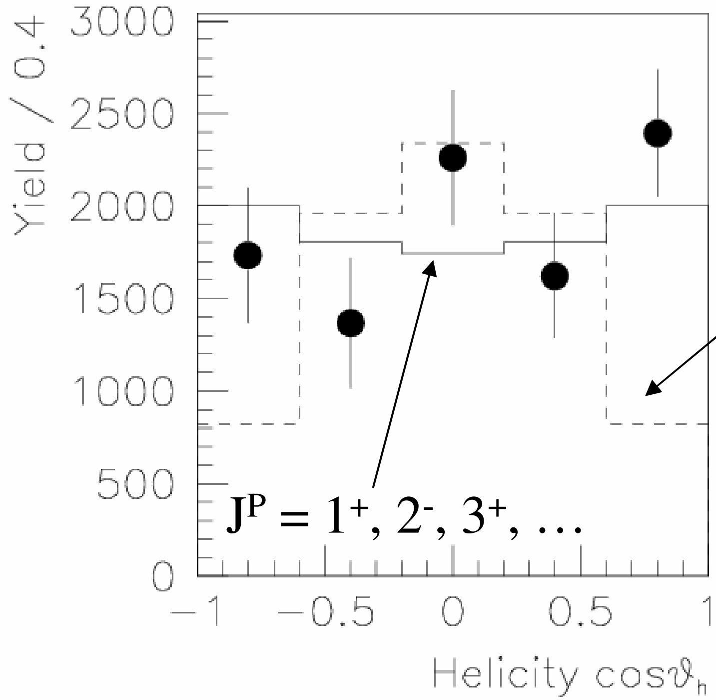
Angular distribution

$B \to \bar{D} D_{s1}$ $D_{s1} \to D_s\gamma$



→ J=1

Continuum, $D_{s1} \to D_s^{*}\pi^0$



261 fb^{-1}
Belle Conf 0461
(2004)

→ Spin-Parity $J^P = 1^+$

232 fb^{-1}
Phys. Rev. D74
032007 (2006)

$D_{s1}(2460)^+$ – Nature of State

Relative Branching fractions

Decay mode	Yield $\Delta M(D_{sJ})$	Yield ΔE	Efficiency (10^{-4})	Product $\mathcal{B}(\overline{B}^0 \to D_{sJ}^+ K^-)\times$ $\mathcal{B}(D_{sJ} \to D_s\pi^0(\gamma))$ (10^{-5})	Signif. σ
$D_{sJ}^*(2317)^+K^-$	35.3 ± 6.4	34.1 ± 6.6	21.9 ± 0.6	$4.4 \pm 0.8 \pm 0.6 \pm 1.1$	9.2
$D_{sJ}(2460)^+K^-$	11.2 ± 5.4	10.2 ± 5.4	59.5 ± 1.4	$0.53 \pm 0.20^{+0.16}_{-0.15}$ < 0.86 (90% C.L.)	3.1

Different branching fractions → Not from same spin doublet

Mixing angle

There are two 1^+ states, ($D_{s1}(2460)^+$, $D_{s1}(2536)^+$)

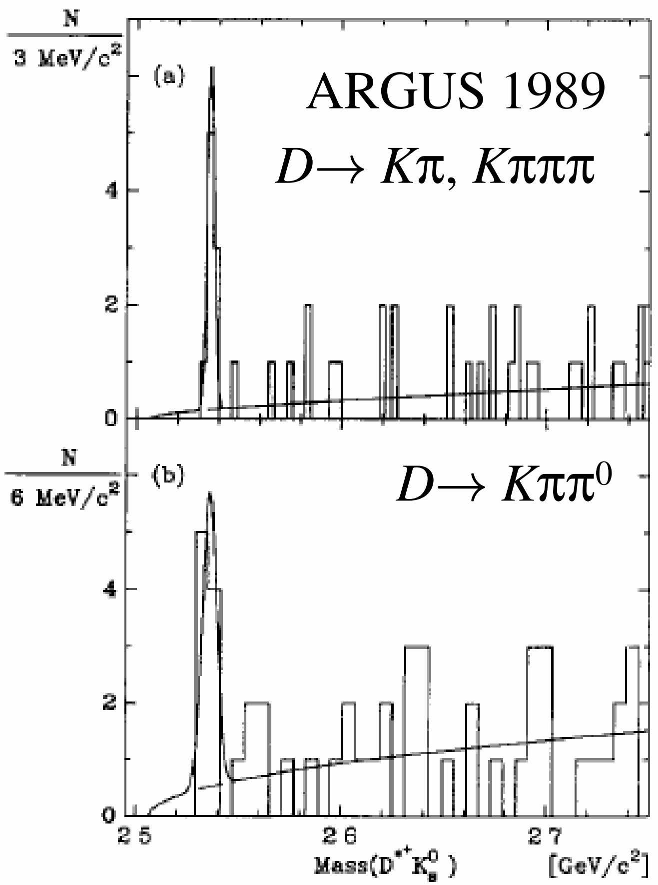
mass difference $\Delta m \approx 76$ MeV

→ investigation of mixing: see $D_{s1}(2536)^+$

$D_{s1}(2536)^+$ - Production

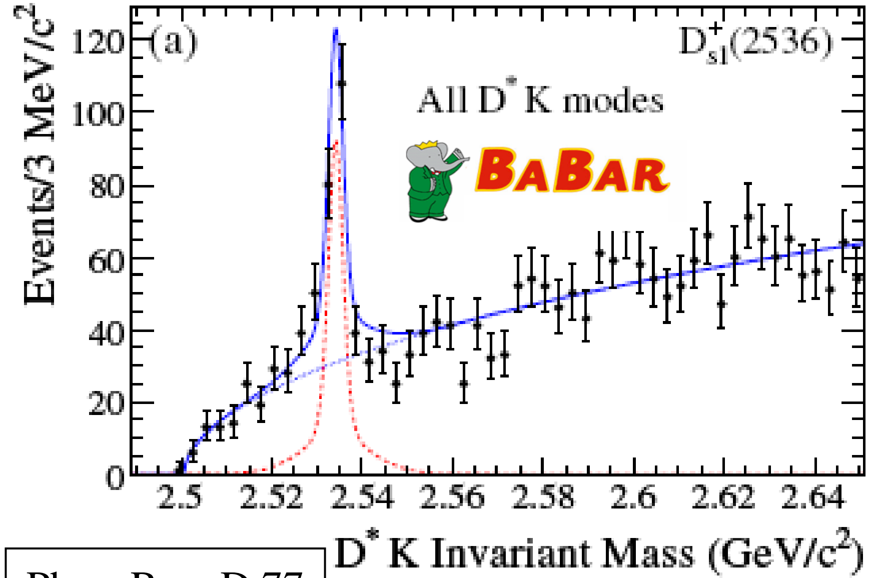
<u>$c\bar{c}$ continuum events</u>

(first seen in $e^+e^- \to D^*K$, $D^* \to D\pi$)



<u>*B* decays</u>

(first seen in B decays by BaBar $B \to D^{(*)}D^{(*)}K$)

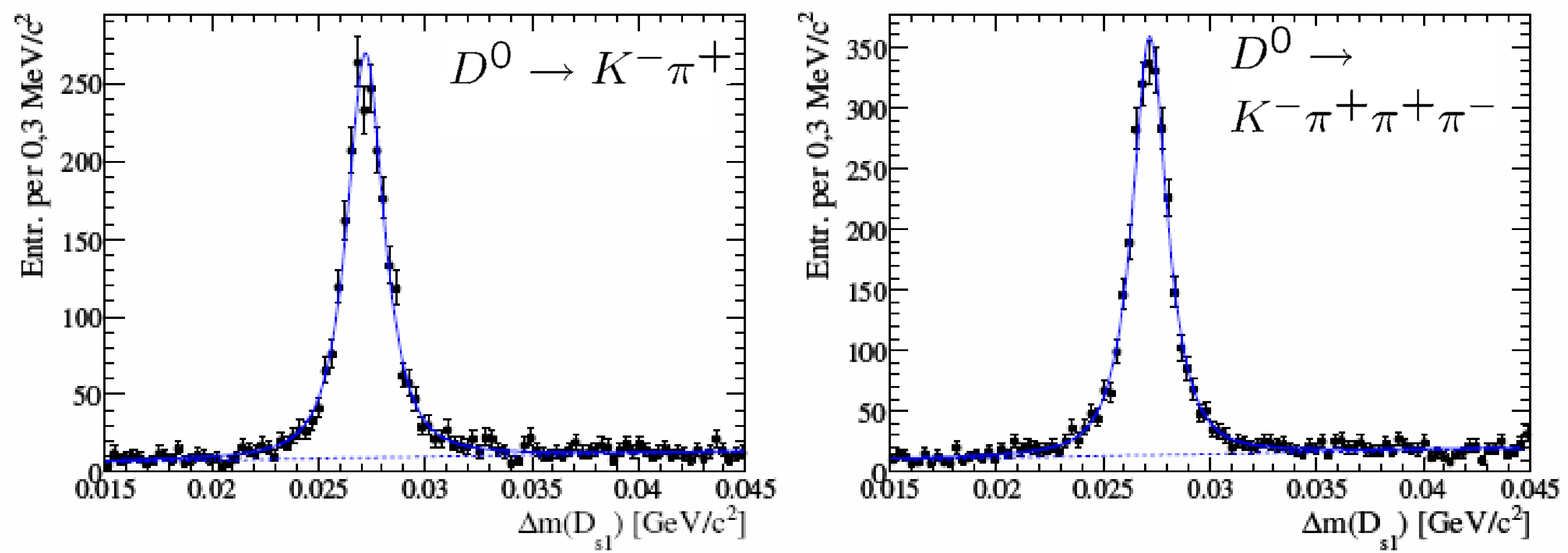


Phys. Rev. D 77 011102 (2008)
347 fb^{-1}

Large signals observed → very precise Measurements of mass and width possible

$D_{s1}(2536)^+$ - Parameters

Continuum events $e^+e^- \to (D^{*+}K)X$, $D^{*+} \to D^0\pi^+$



Large signals → Precise measurement of mass, width

$$m(D_{s1})-m(D^*) = 524.85 \pm 0.02 \pm 0.04 \text{ MeV}/c^2$$

PDG: $525.3 \pm 0.6 \pm 0.1$ MeV/c²

First measurement of $D_{s1}(2536)$ decay width:

$$\Gamma(D_{s1}) = 1.03 \pm 0.05 \pm 0.12 \text{ MeV}$$

232 fb^{-1}
hep-ex/0607084 (preliminary)

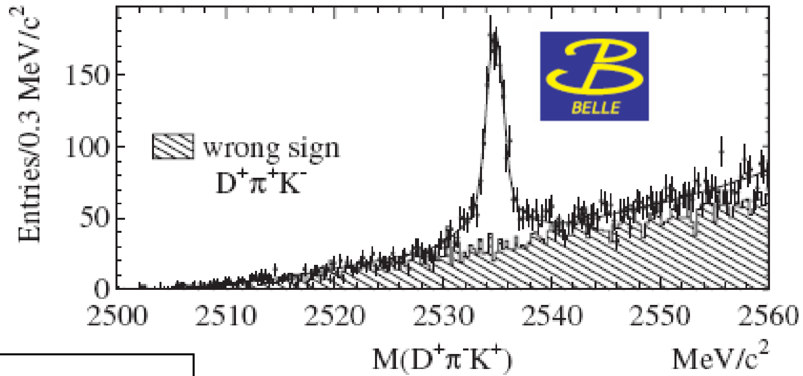
$D_{s1}(2536)^+$ – Decays, Parameters

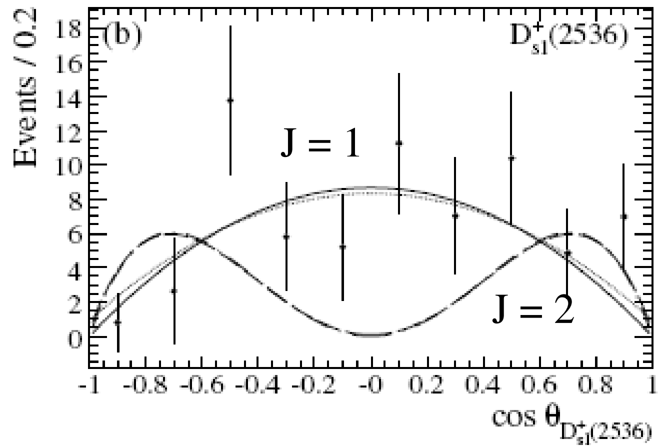
$D_{s1}(2536)^+$ DECAY MODES	Fraction (Γ_i/Γ)
$D^*(2010)^+ K^0$	seen
$D^*(2007)^0 K^+$	seen
$D^+ K^0$	not seen
$D^0 K^+$	not seen
$D_s^{*+} \gamma$	possibly seen
$D_s^+ \pi^+ \pi^-$	seen

Phys. Rev. D 77 011102 (2008) 347 fb^{-1}

BABAR

First observation of $D_{s1}(2536)^+ \to D^+\pi^- K^+$ (no D^*)
only 2nd three-body decay mode





Angular analysis
Consistent with J = 1

Phys. Rev. D 77 032001 (2008) 426 fb^{-1}

No signal in *DK*
→ Unnatural spin parity

→ Spin-Parity $J^P = 1^+$

$D_{s1}(2536)^+$ – Nature of State

1^+ Mixing angle

Phys. Rev. D77 032001 (2008)

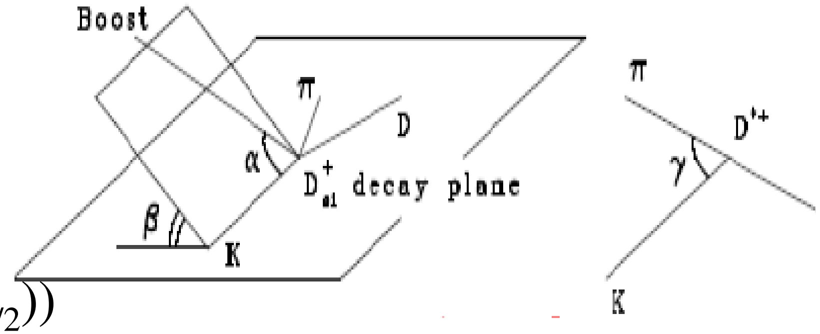
Belle: $D_{s1}(2536)^+ \rightarrow D^{*+}K_S^0$, $D^{*+} \rightarrow D^0\pi^+$

D_{s1} is produced in e^+e^- continuum processes with (small) polarization

Observables: 3 angles (α,β,γ)

Fit to 3-dimensional angular distribution $\frac{d^3N}{dcos\alpha d\beta dcos\gamma}$

as function of polarization ($\rho_{00} = 2/3(1-w_{3/2})$) and D/S-wave ratio



(SLAC-PUB-6311)

Results:

$\rho_{00} = 0.49 \pm 0.012 \pm 0.004$ (corresponds to HQET prediction)

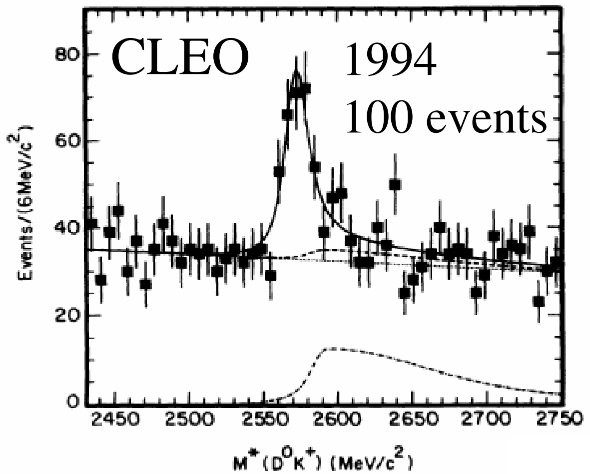
$D/S = 0.63 \pm 0.07 \pm 0.02 \times \exp[\pm i(0.76 \pm 0.03 \pm 0.01)]$

$\rightarrow$ mixing angle (theoretical input)

S-wave dominates contribution to total width ($\Gamma_S/\Gamma_{total} = 0.72 \pm 0.05 \pm 0.01$) in contrast to HQET prediction

$D_{s2}^*(2573)^+$ – Production and Decays

First seen in $c\bar{c}$ continuum



$D_{s2}(2573)^+$ DECAY MODES	Fraction (Γ_i/Γ)
$D^0 K^+$	seen
$D^*(2007)^0 K^+$	not seen

No angular distribution measured

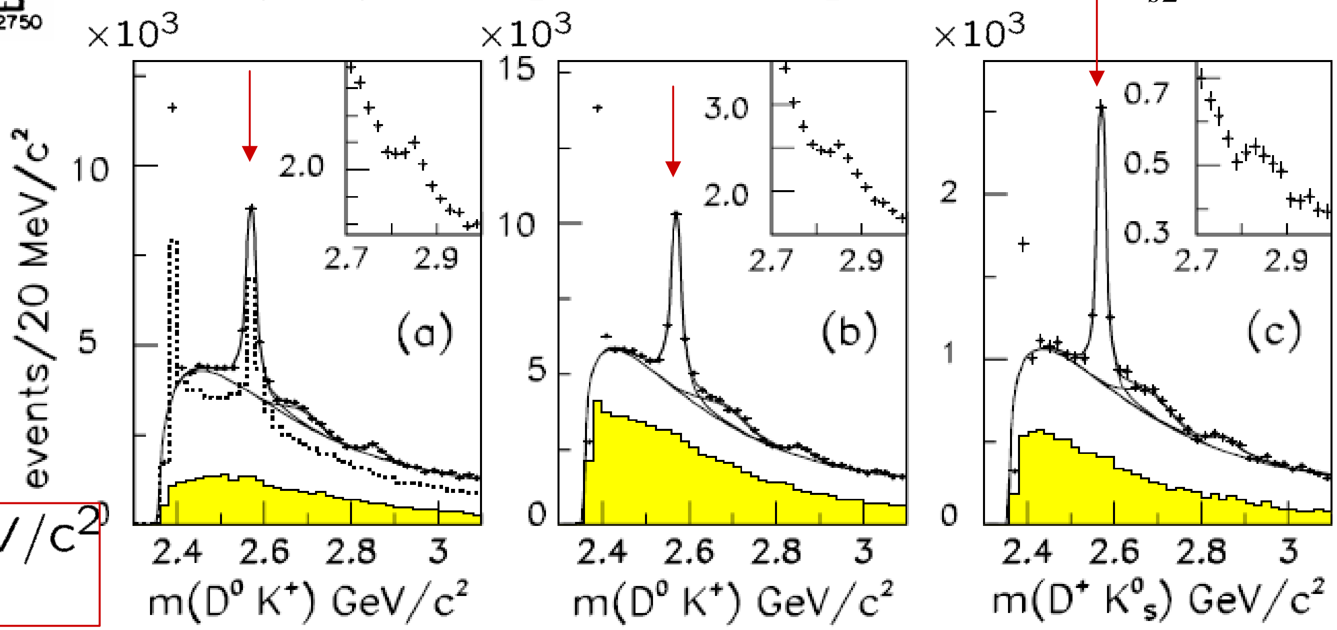
Decay mode consistent with 2^+ 1^3P_2

Inclusive study of $e^+e^- \to (DK)X$

Large signal: Improvement in precision for $D_{s2}(2573)$

BABAR

Phys. Rev. Lett. 97 222001 (2006) 240 fb^{-1}



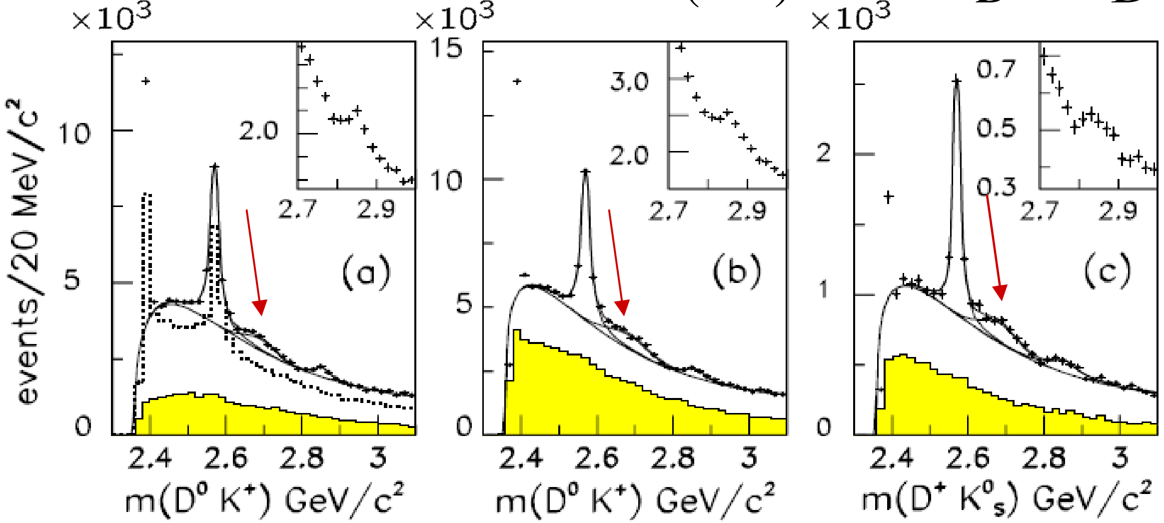
$m = 2572.2 \pm 0.9$ MeV/c²

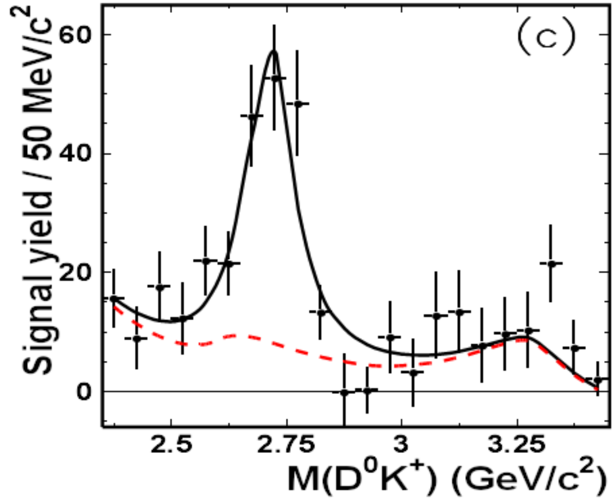
$\Gamma = 20 \pm 5$ MeV

$D_{sJ}{}^*(2700)^+$ - Production

Seen by Babar in $c\bar{c}$ continuum
Inclusive study of $e^+e^- \to (DK)X$

Seen by Belle in
$B^+ \to \bar{D}^0 D_{sJ}(2700)^+$, $D_{sJ}(2700)^+ \to D^0 K^+$





$$m = 2688 \pm 4 \pm 3 \text{ MeV}/c^2$$
$$\Gamma = 112 \pm 7 \pm 36 \text{ MeV}$$

$$m = 2708 \pm 9 \pm 10 \text{ MeV}/c^2$$
$$\Gamma = 108 \pm 23 \pm 33 \text{ MeV}$$

Phys. Rev. Lett. 97 222001 (2006)
240 fb^{-1}

BABAR

Same state?

BELLE

Phys. Rev. Lett. 100 092001(2008)
414 fb^{-1}

$D_{sJ}^*(2700)^+$ – Parameters

final state → natural spin-parity
$J^P = 0^+, 1^-, 2^+ \ldots$

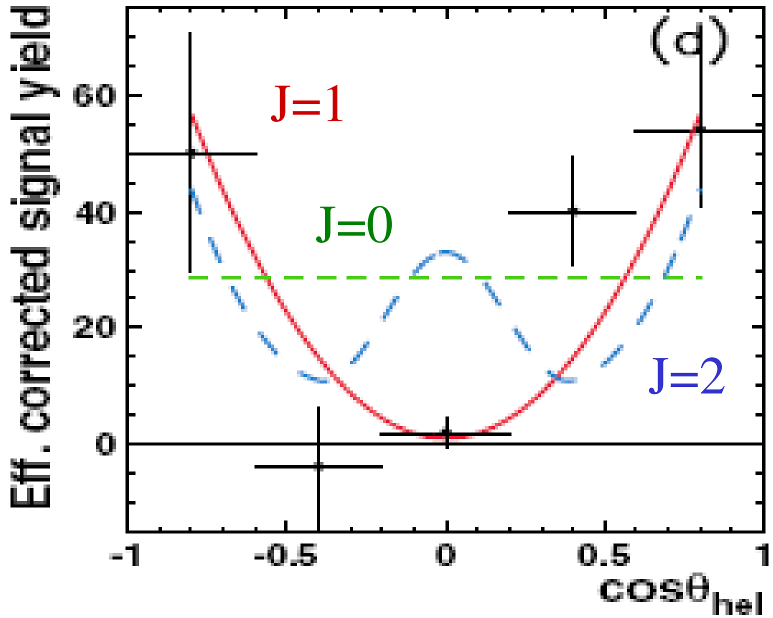
Angular distribution
Preferred: $J^P=1^-$

Possible interpretations:
- Radially excited 2^3S_1 (excited D_s^*)
  predicted mass ~2720 MeV/c² [1]
- Chiral doublet 1^- state to
  1^+ $D_{s1}(2536)^+$
  predicted (2721 ± 10) MeV/c² [2]

Confirmation needed

prozess

Phys. Rev. Lett. 100
092001(2008)
414 fb^{-1}



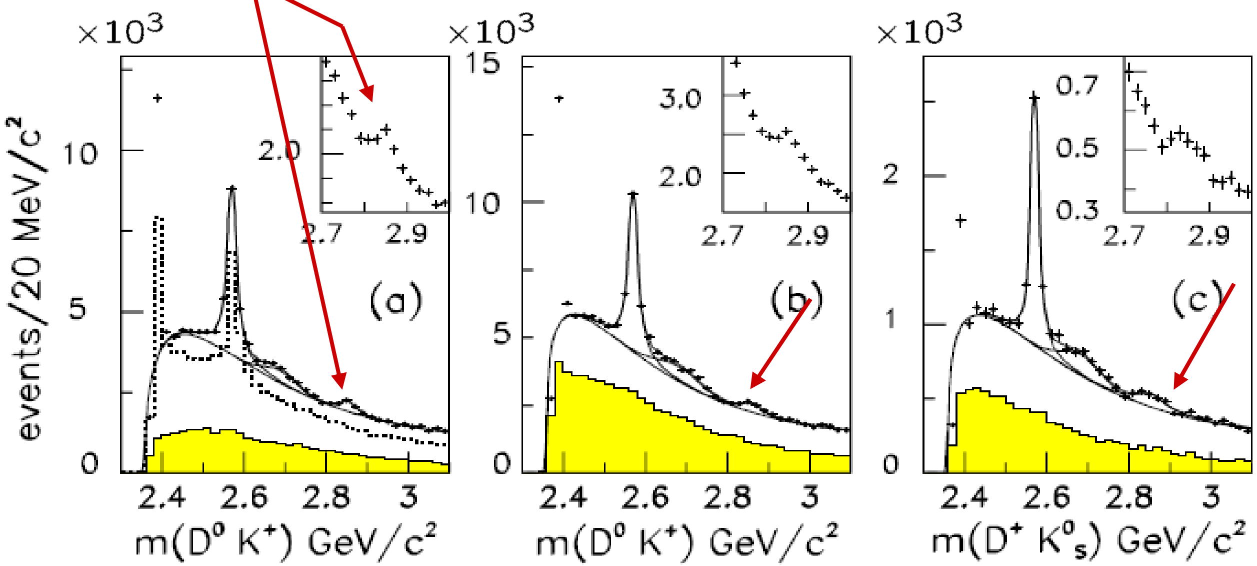
1) Godfrey, Isgur PRD 32, 189 (1985)
Close et al., PLB 647, 159 (2007)
2) Nowak et al.,
Acta Phys. Pol. B 35, 2377 (2004)

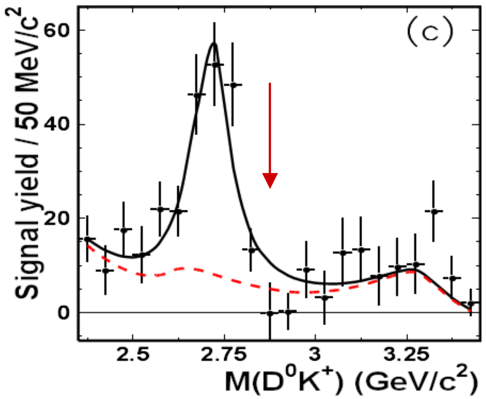
$D_{sJ}^{*}(2860)^{+}$ - Production, Parameters …

First observed in $e^{+}e^{-} \rightarrow (DK)X$

Phys. Rev. Lett. 97
222001 (2006)
240 fb^{-1}

$D_{sJ}^{*}(2860)$





Phys. Rev. Lett. 100
092001(2008)
414 fb^{-1}

$$m = 2856.6 \pm 1.5 \pm 5.0 \text{ MeV}/c^2$$
$$\Gamma = 47 \pm 7 \pm 10 \text{ MeV}$$

final state → natural spin-parity $J^P = 0^+, 1^-, 2^+ \ldots$

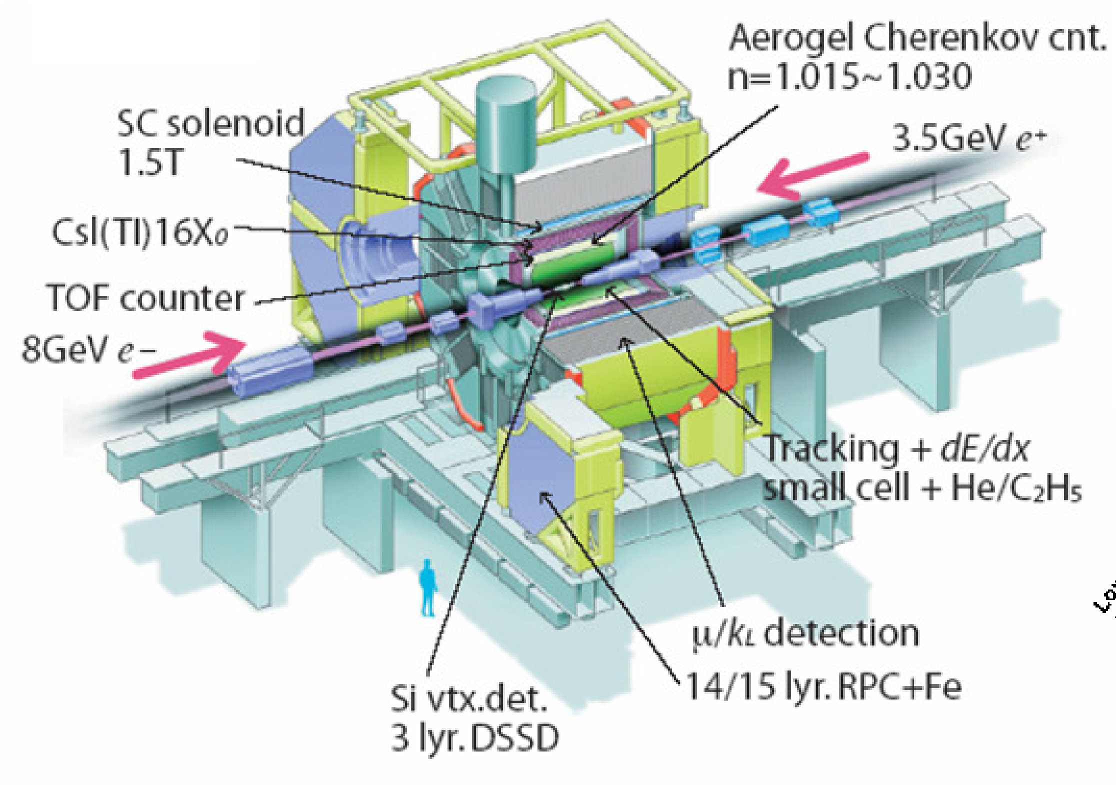
- $D_{sJ}^{*}(2860)$ not seen in B decays.
  → high spin for this meson ?
  production suppressed in *B* decays?

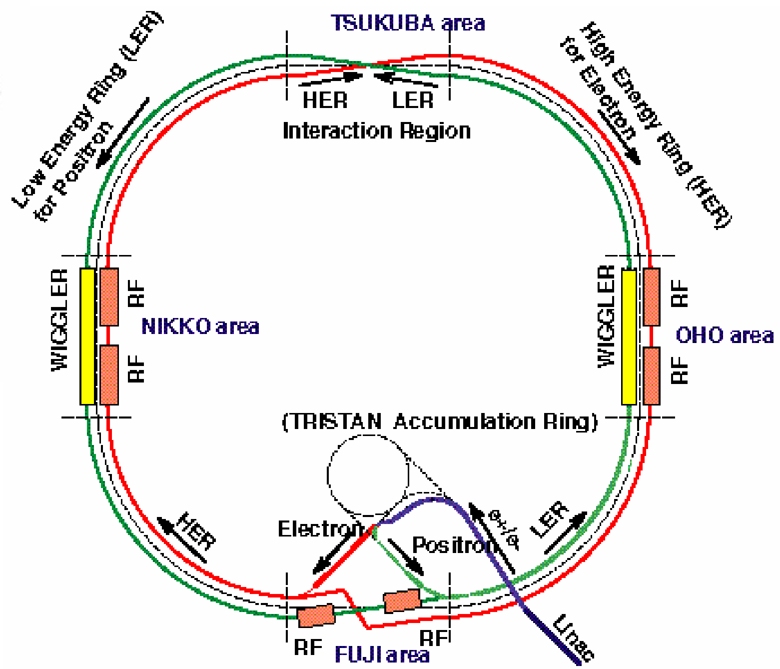
Outlook

- Necessary ingredients to differentiate among models
  - Accurate total width measurements
  - Hadronic and radiative transitions to $D_{s0}^*(2317)/D_{s1}(2460)$ from higher mass states
  - Partial decay widths
  - Test of mixing schemes for 1^+ (2^+) states
- Tools
  - Ongoing BaBar / Belle / Cleo / CDF / D0 analyses
  - High luminosity *B*-factories
  - LHCb (B_s decays)
  - Charm production with $\bar{p}p$, FAIR (High precision widths)

Backup Slides

The Belle Experiment





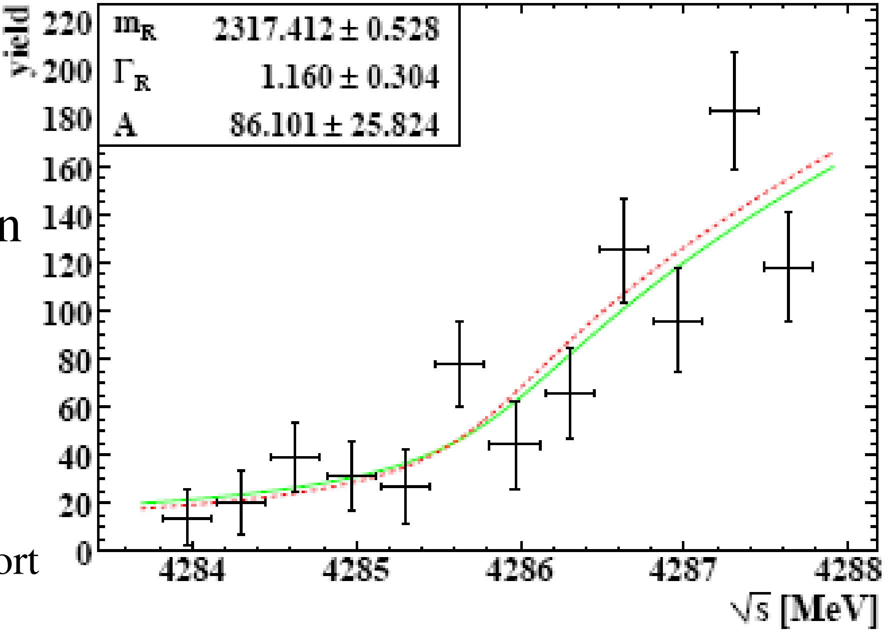
KEK-B (Tsukuba)
E(HER/LER): 8,0/3,5 GeV
I(HER/LER): 1300/1600 A
max. Lum > $16 \cdot 10^{33}$ $cm^{-2}s^{-1}$

Outlook: D_{sJ} widths at PANDA

$D_{s0}^*(2317)^+/D_{s1}(2460)^+$ decay widths constrained by upper limits based on detector resolution

PANDA approach

- width of a narrow resonance can be determined in a measurement of the energy dependence of the production cross section around the energy threshold
- calculate energy dependence model-independently
  $\rightarrow$ sensitive to width
- no need to include detector resolution
- $\delta p/p \approx 10^{-5}$
  $\rightarrow$ threshold scan $\bar{p}p \rightarrow \bar{D}_s D_{sJ}$
- Measure width as small as 100 keV.



PANDA Physics Performance Report
arXiv 0903.3905

Theoretical Background (1)

Polarization/alignment of heavy quark mesons in continuum production

- HQET framework (Falk, Peskin: SLAC-PUB-6311 (1993))

  Fragmentation process so rapid that color magnetic forces have no time to act

  $\rightarrow$ Spin of light antiquark in the produced meson uncorrelated with that of the heavy quark

- Prediction

  $D_{(s)}$(j=1/2) are produced unploarized

  $D_{(s)}$(j=3/2) can be produced polarized

  (both confirmed by experiment)

Theoretical Background (2)

Polarization/alignment of heavy quark mesons in continuum production

- Definition of $w_{3/2}$
  Probabilites for the light degrees of freedom to have helicities
  -3/2,-1/2,1/2,3/2 are (z-axis: direction of heavy quark)
  $\frac{1}{2}(w_{3/2})$, $\frac{1}{2}(1-w_{3/2})$, $\frac{1}{2}(1-w_{3/2})$, $\frac{1}{2}(w_{3/2})$
  $\rightarrow$ Polarization alignment of $Q\bar{q}$-meson
- Probability for helicity 0:
  $\rho_{00}=2/3(1-w_{3/2})$ (helicity density matrix element)
  Probability for helicity ± 1:
  $\rho_{11}=\rho_{-1-1}=1/2(1-\rho_{00})$
- Example: $D_{s1}(2536)^{+}$
  HQET prediction: $w_{3/2} = 0.254 \rightarrow \rho_{00\ x} \approx 0.50$
  (in agreement with experiment)

Note: When $w_{3/2}$ is known for one decay mode, it's the same for the other decay modes

Theoretical Background – S/D-ratio (Mixing angle)

Radiative transitions of D_{sJ} (P-wave charmed-strange mesons)

- E1: $$\Gamma(i \to f + \gamma) = \frac{4e_Q^2}{27} k^3 (2J_f + 1) |< f|r|i >|^2 S_{if}$$

  (Phys. Lett. B66, 286)

  With e_Q = effective charge = $(m_1 e_2 - m_2 e_1)/(m_1 + m_2)$

  k = momentum of emitted photon = $(M_i^2 - M_f^2)/2M_i$

  S_{if} = { 1 for transition between triplett states; 3 for transition between singulett states }

- For D_{sJ}: $$\frac{\Gamma(D_{sJ} \to D_s^* \gamma)}{\Gamma(D_{sJ} \to D_s \gamma)} = \left(\frac{322.7}{442.0}\right)^3 \tan^2 \theta$$

  $({}^3P_1 \to D_s^* \gamma, \not\to D_s \gamma \;/\; {}^1P_1 \to D_s \gamma, \not\to D_s^* \gamma)$

Theoretical Background – S/D-ratio (Mixing angle)

Mixing angle (S/D) from polarized meson decay

Example $D_{s1}(2536)^+ \to D^{*+}K_S^0$, $D^{*+} \to D^0\pi$ (Helicity formalism)

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

Dependence on three variables ρ_{00}, R_Λ, ξ

$A_{1,0}$, $A_{0,0}$ helicity amplitudes corresponding to D^{*+} helicities $\pm 1,0$

$$A_{1,0} = \frac{1}{\sqrt{3}}(S + \frac{1}{\sqrt{2}}D),\ A_{0,0} = \frac{1}{3}(S - \sqrt{2}D)$$

S,D = S/D-wave amplitudes in $D_{s1}(2536)^+$ decay

$R_\Lambda^{1/2}e^{i\xi} = A_{1,0}/A_{0,0} = z$ (complex numbers)

ρ_{00} = helicity density matrix element

$$D/S = \sqrt{2}(z-1)/(1+2z) = \sqrt{\frac{\Gamma_D}{\Gamma_S}}e^{i\eta}$$

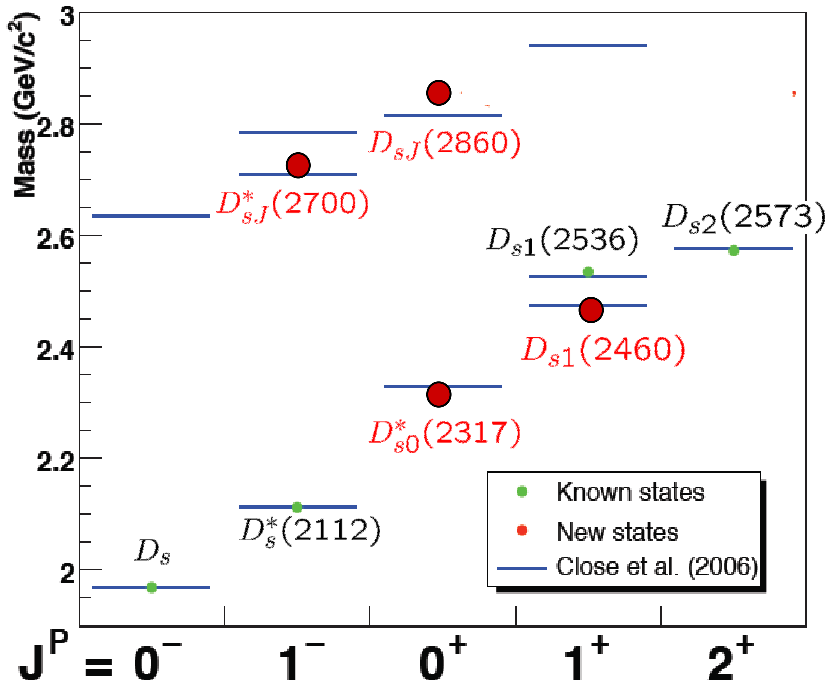
$\Gamma_{D,S}$ = partial widths of $D_{s1}(2536)^+$, η = phase between D/S-amplitudes

Fit of (1) to data $\to \rho_{00}$, z, D/S

Theoretical Background – Potential Models

- Godfrey (Phys. Rev. D32, 189)
  Non-spin-dependent potential
  with linear confinement
  - one gluon exchange
  - relativistic corrections (small effects)

- DiPierro, Eichten:
  (Phys. Rev. D64, 114004)
  also include mixing
  (D_{s1} states)



New potential models (2006) reproduce D_{sJ} data better:

- Close, Thomas, Lakina, Swanson (hep-ph/0608139)

- van Beveren, Rupp (hep-ph/0606110)
- Colangelo, De Facio (hep-ph/0607245)