Charmonium: the Next Wave

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SLAC Experimental Seminar

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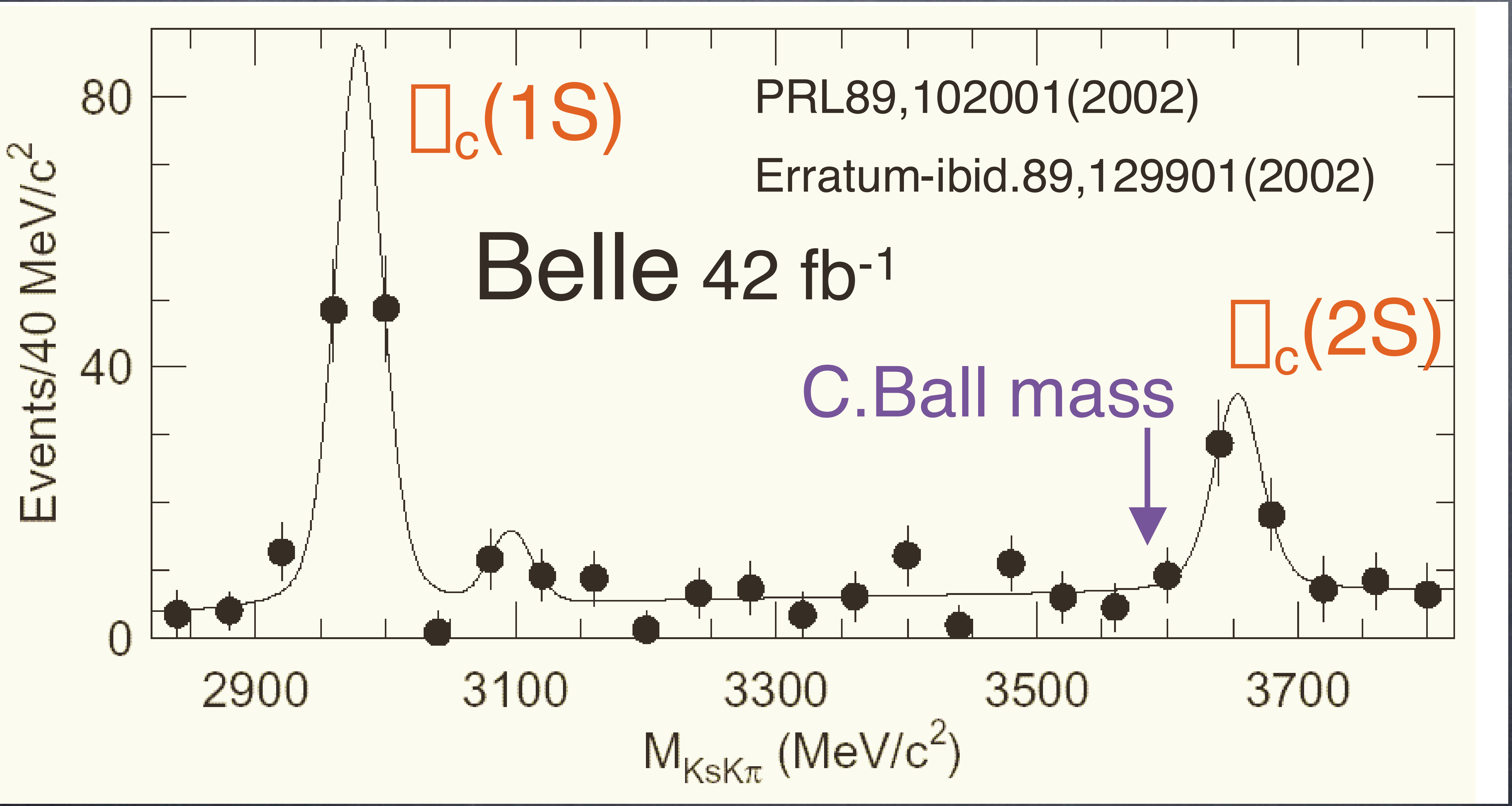
Exciting times for hadron spectroscopy

many new narrow states

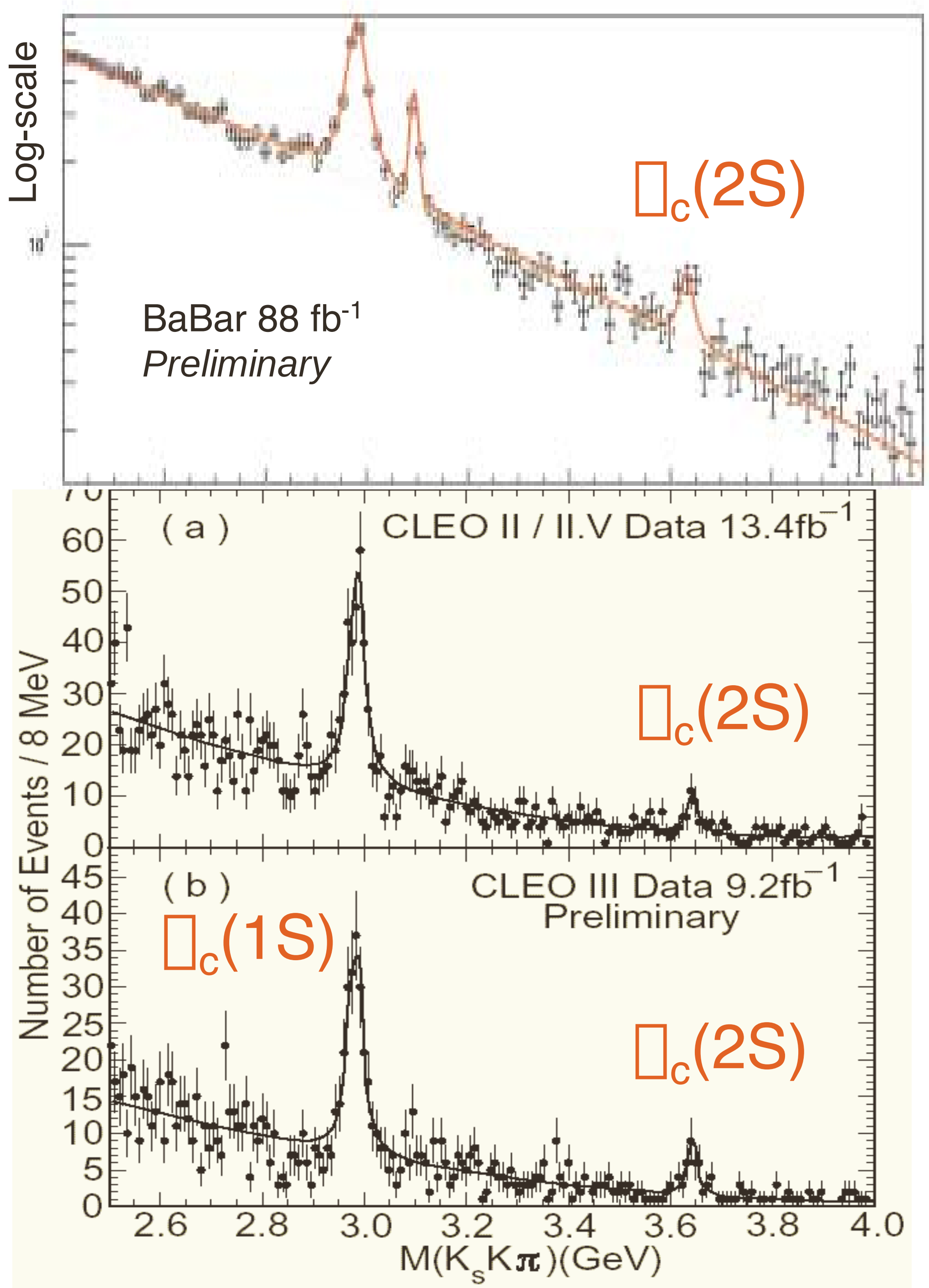
- ⋆ η_c' in $B \to K K_S K^- \pi^+$
- ⋆ Narrow D_s levels $(0^{++}, 1^{++})$
- ⋆ Pentaquark $K^+ n$: $\Theta^+(1540)$
- ⋆ $X(3872) \to \pi^+\pi^- J/\psi$

Each one raises questions of interpretation, and offers opportunities.

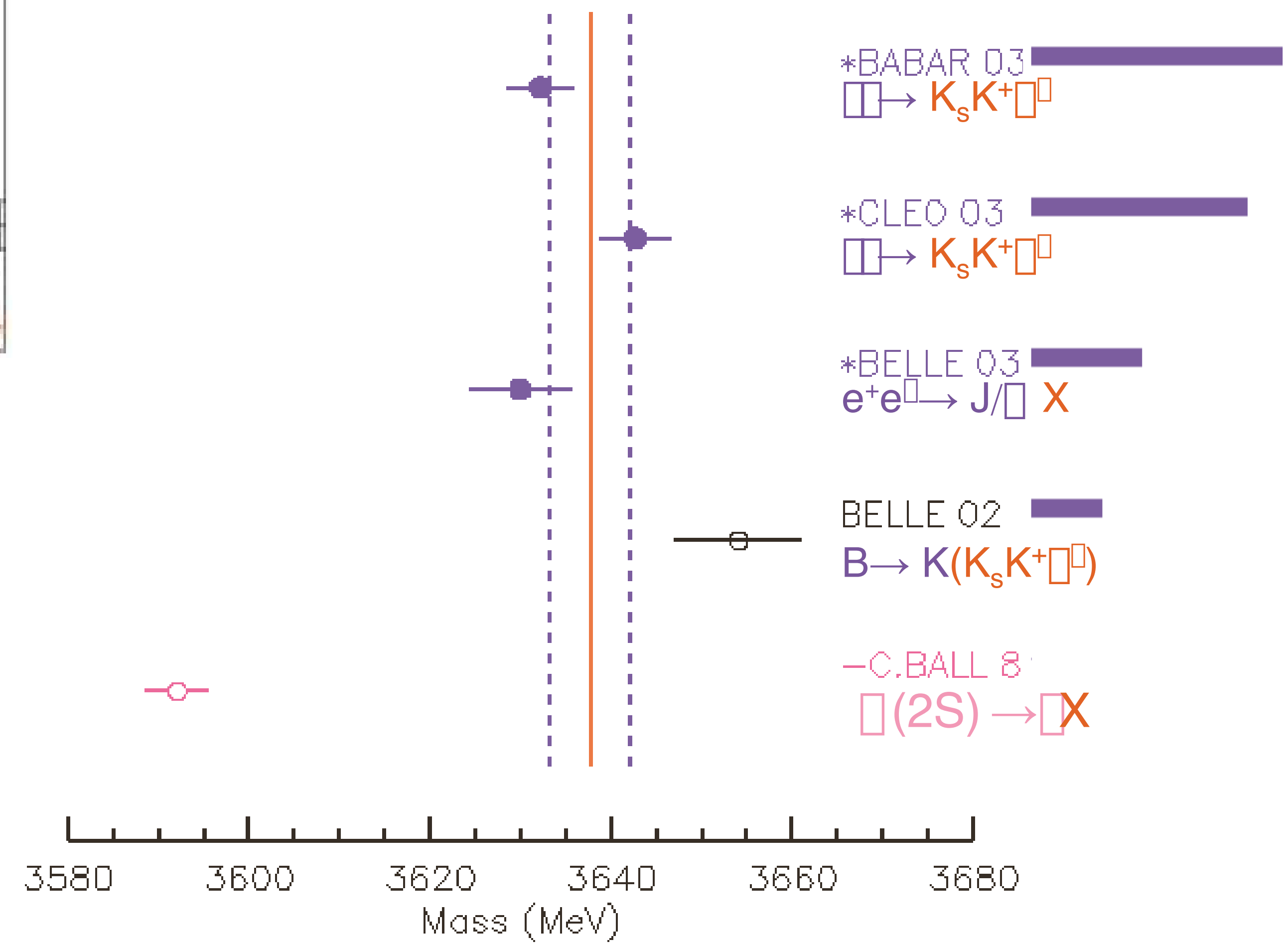
Belle: B-meson gateways to charmonium



Confirmation of $\eta_c(2^1S_0)$ in $\gamma\gamma$-collisions



3637.7±4.4 MeV



$$\frac{\Gamma_{\gamma\gamma}(\eta_c')\times B(\eta_c'\to K_SK\pi)}{\Gamma_{\gamma\gamma}(\eta_c)\times B(\eta_c\to K_SK\pi)} = 0.17^{+0.07}_{-0.06}(stat)\ \pm 0.04(syst)$$

CL=14% scale factor=1.3

New measurements of mass are consistent

$\Gamma_{tot}(\eta_c(2S))$ = (19±10) MeV

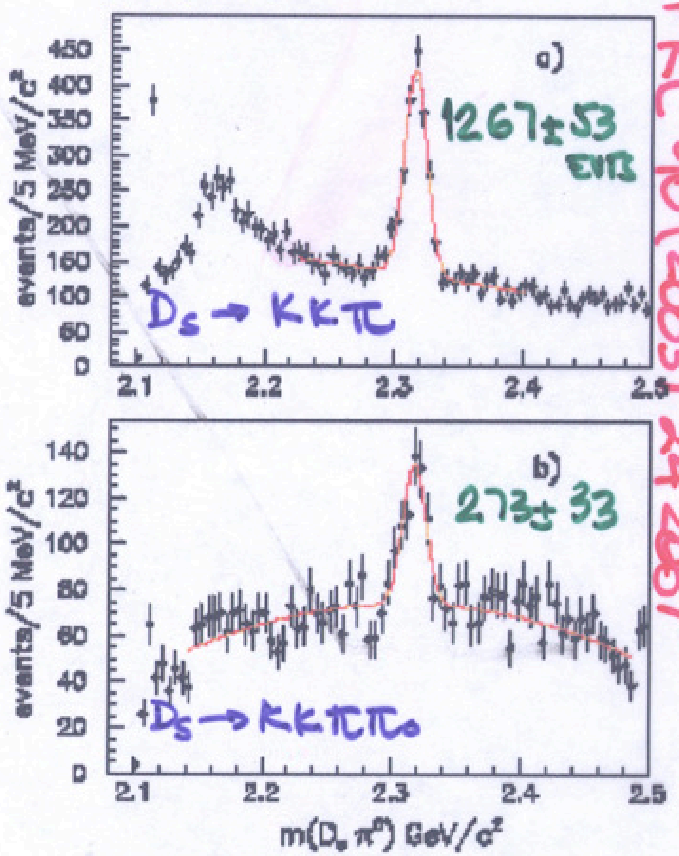
$D_{sJ}^{*}(2317)^{\pm}$

$\hookrightarrow D_s^+\pi^0$

(F. PORTER EPS 07/2003)

BABAR

PRL 90 (2003) 242001



CLEO

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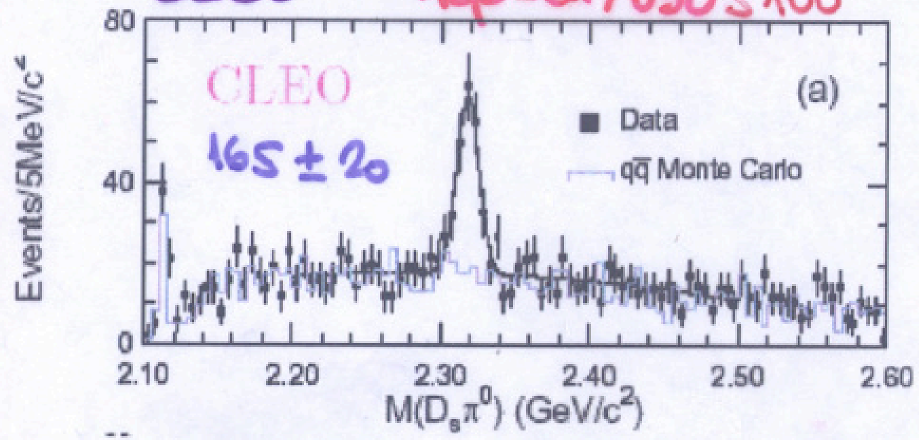

BELLE PREL.

hep-ex 0307052
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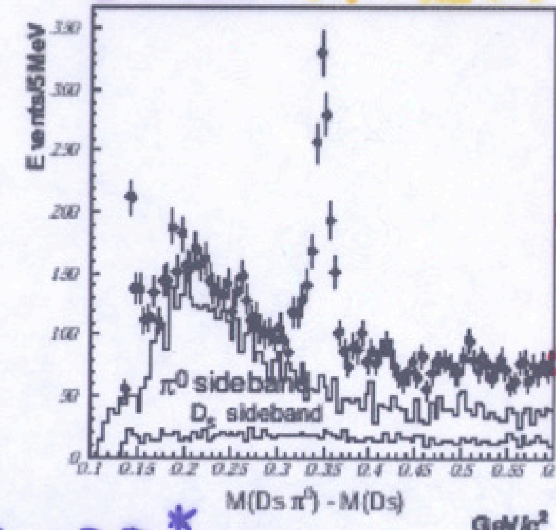
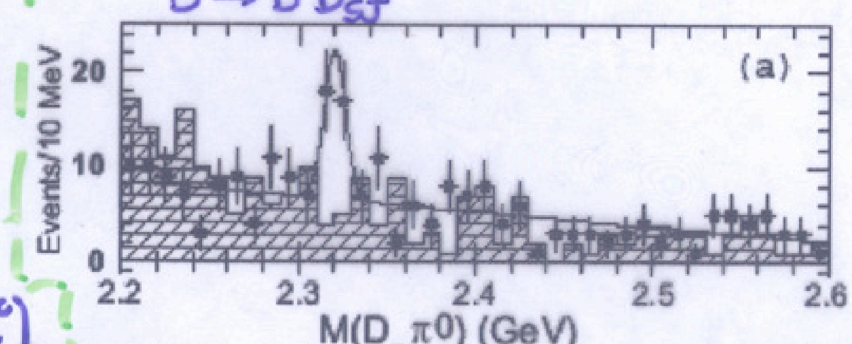


$B \to D D_{sJ}^*$



- FROM $D_s \to \phi\pi^+$
  $\to K^{*0} K^+$
- $m = 2316.8 \pm 0.4 \pm 3$ MeV
- $\Gamma \lesssim 10$ MeV

- $N(D_s\pi^0, D_s \to \phi\pi^+) = 155 \pm 23$
- $m = 2318.5 \pm 1.2 \pm 1.1$ MeV
- $\Gamma < 7$ MeV
- $BR(D_{sJ}^* \to [\ ])/BR(D_{sJ}^* \to D_s^+\pi^0)$
  - $[D_s^+\gamma] < 0.052$ (90% CL)
  - $[D^{*+}\gamma] < 0.059$
  - $[D_s^+\pi^+\pi^-] < 0.019$
  - $[D_s^{*+}\pi_0] < 0.11$

- YIELDS:
  - $D_s \to \phi\pi$: 761 ± 44 EVTS
  - $B^+ \to \bar{D}^0 D_{sJ}^{*+}$: $13.4^{+6.2}_{-5.4}$
  - $B^0 \to D^- D_{sJ}^{*+}$: $10.8^{+4.2}_{-3.6}$
- $m = 2317.2 \pm 0.5 \pm 0.9$
- $\Gamma \to$ RESOLUTION
- $BR(\to D_s^+\gamma)/BR(\to D_s^+\pi_0) < 0.05$ 90% CL

▷ ALL WIDTHS CONSISTENT WITH DETECTOR RESOLUTION

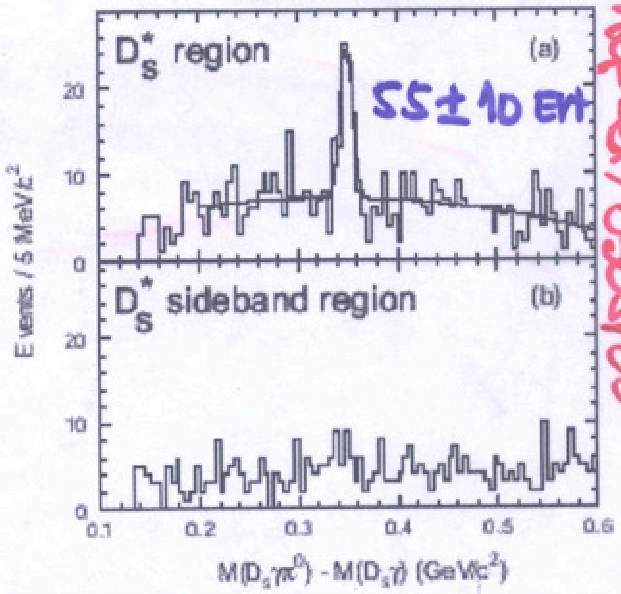
▷ FEED DOWN FROM $D_{sJ}(2460)$ (BY NEGLECTING γ IN $D_s^*(2112) \to D_s\gamma$) CONSIDERED

$D_{sJ}^*(2463)^\pm$

$\hookrightarrow D_s^{*+}\pi_0$

$\hookrightarrow D_s^+\gamma$

CLEO



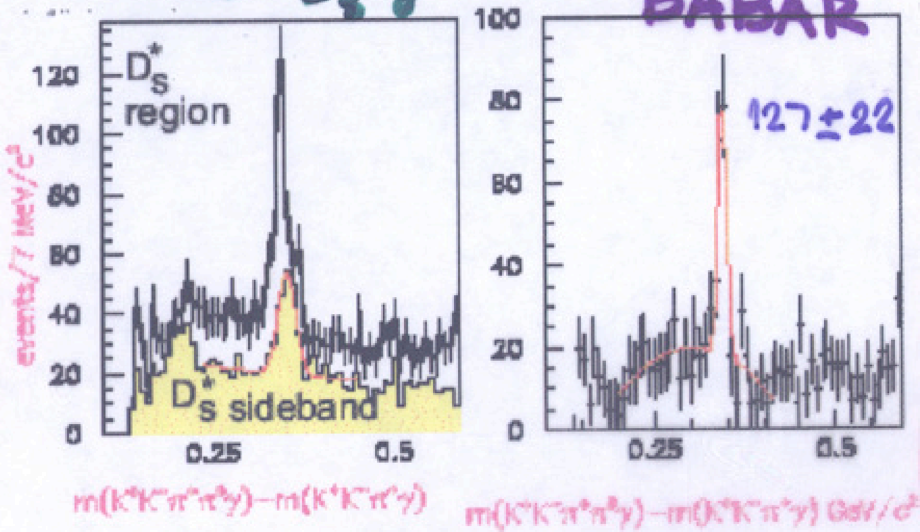
• $N(D_s^*\pi^0, D_s^* \to D_s\gamma) = 41 \pm 12$

• $m = 2463.6 \pm 1.7 \pm 1.2$

• $\Gamma \lesssim 7$

.PREL.

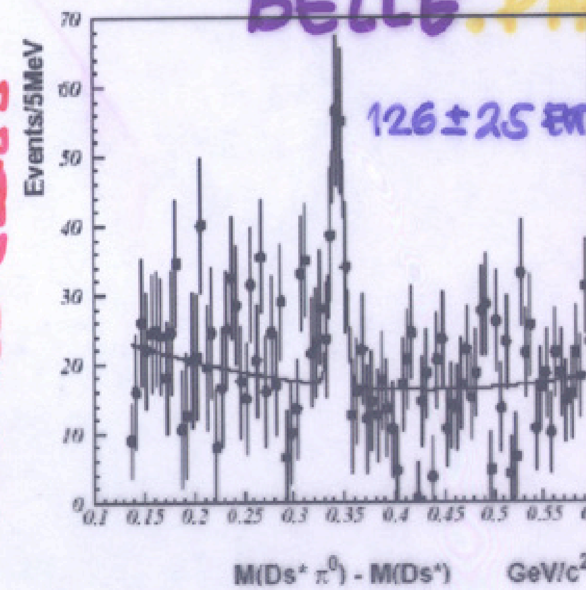
BABAR

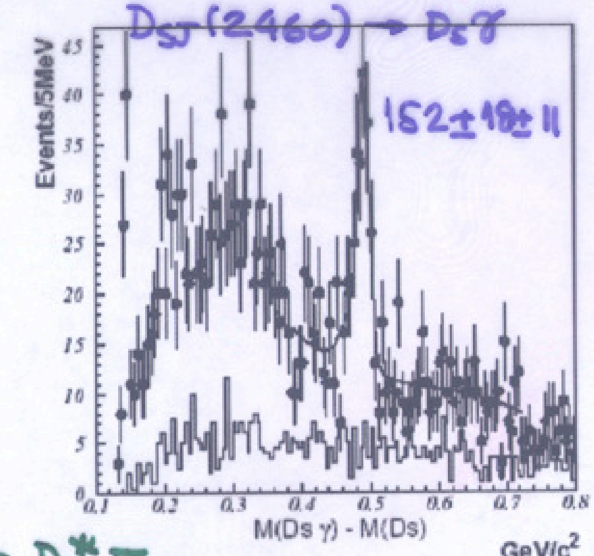


• $m = 2457.0 \pm 1.4 \pm 3$

• $\Gamma \to$ RESOLUTION

BELLE .PREL.





→ FEED UP FROM $D_{sJ}(2317)$ (BY ADDING A RANDOM γ TO D_s) CONSIDERED

• $D_{sJ}^{*+} \to D_s^*\pi_0$

• $m = 2456.5 \pm 1.3 \pm 1.1$ MeV

• $D_{sJ}^* \to D_s\gamma$

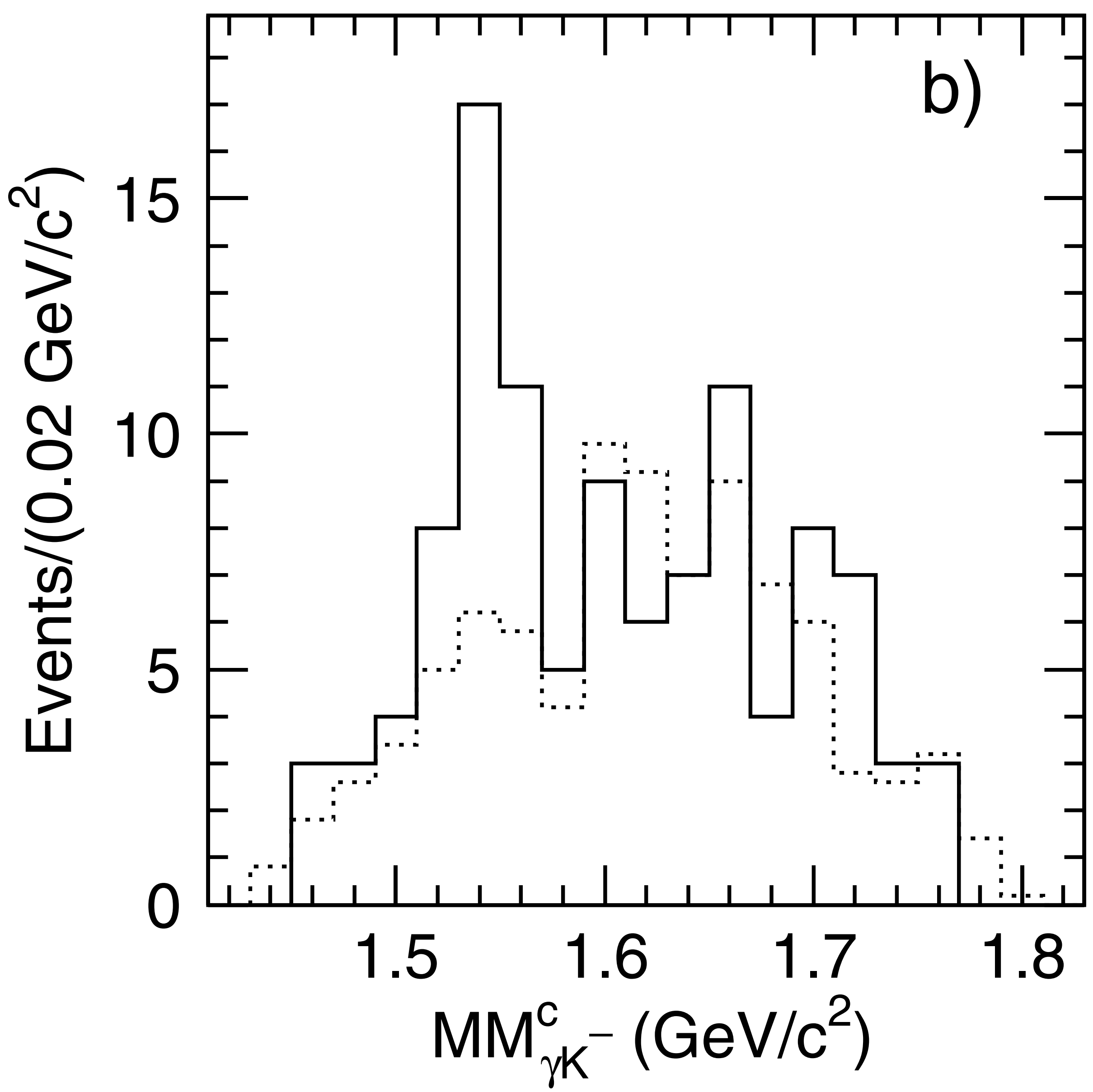
• $m = 2459.5 \pm 1.3$

• $BR(\to D_s\gamma)/BR(\to D_s^{*+}\pi_0) = 0.63 \pm .15$

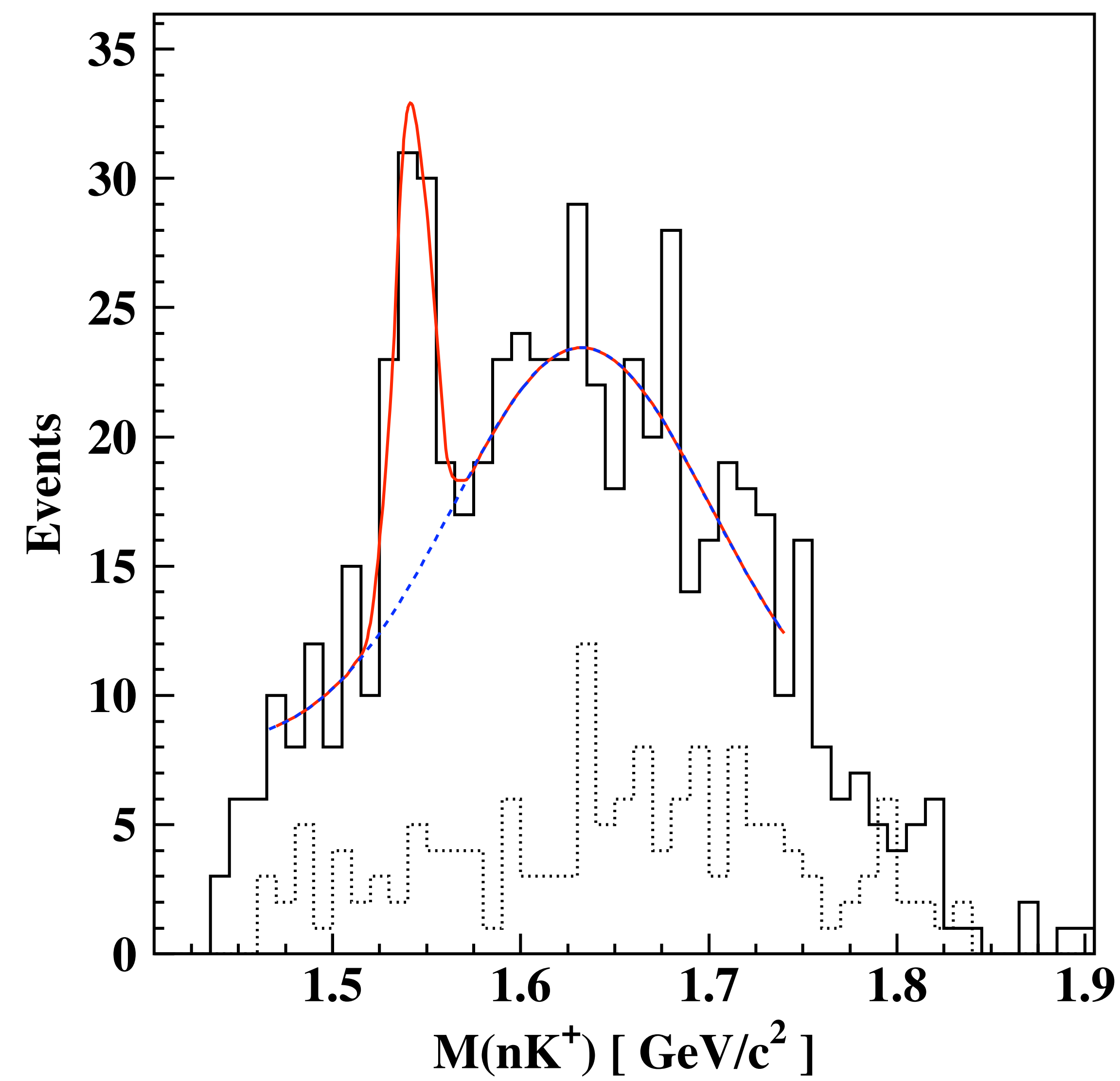
• + EXCLUSIVE B DECAYS (hep-ex/0307041)

$\Theta^+(1540) \to K^+n$

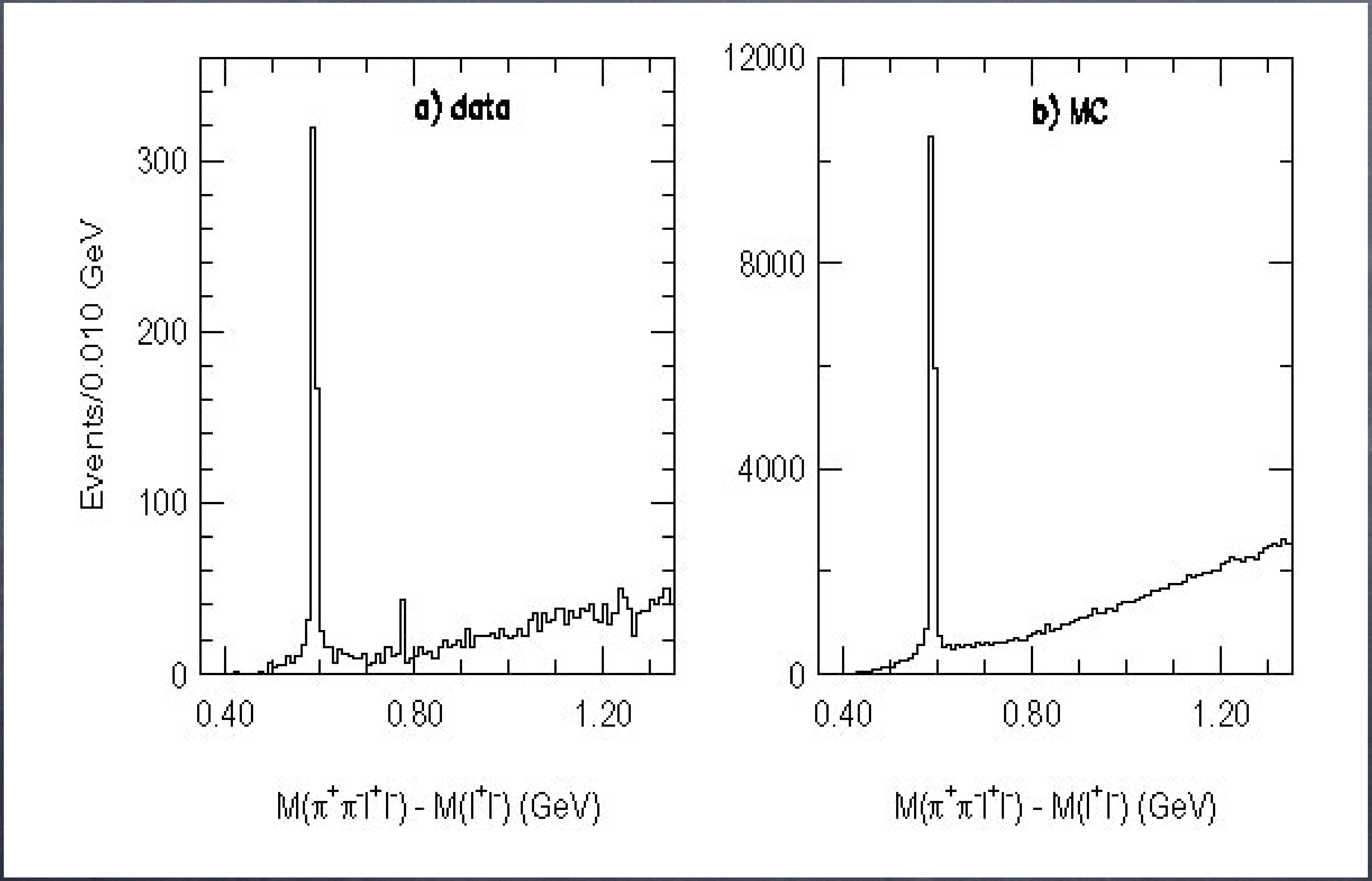
Spring8



CLAS (JLab)



Belle $B^{\pm} \to K^{\pm}\pi^{+}\pi^{-}J/\psi$



Belle $B^{\pm} \to K^{\pm}\pi^{+}\pi^{-} J/\psi$ ...

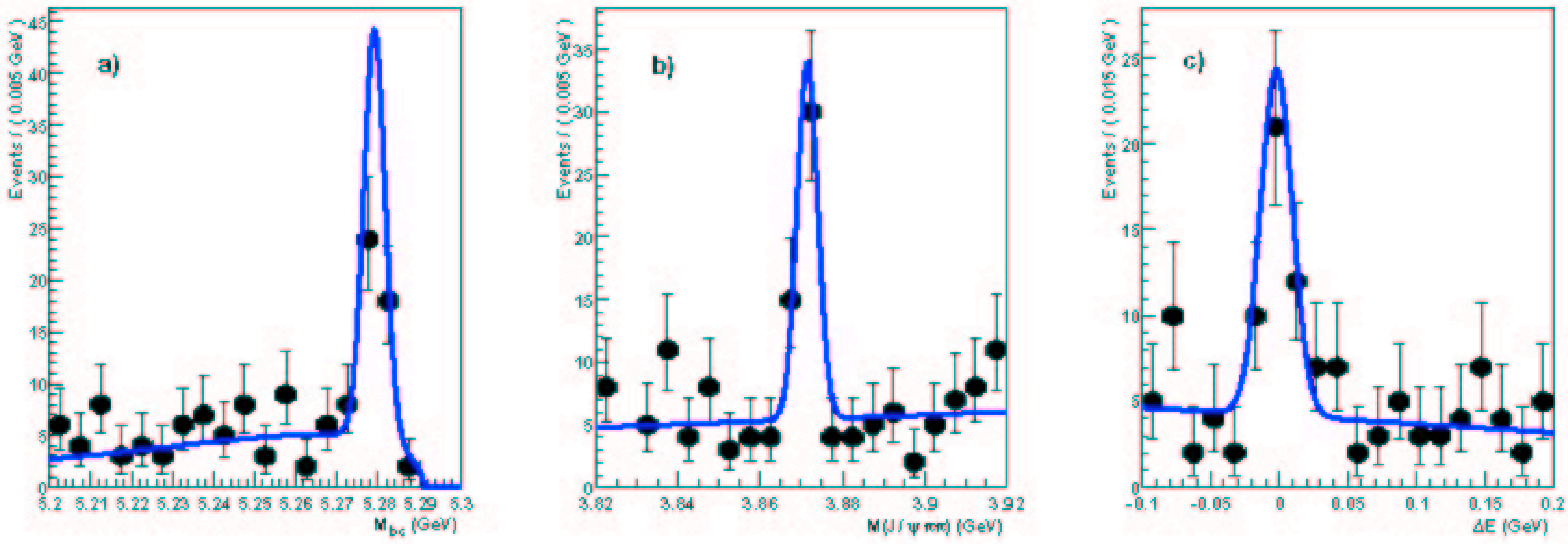
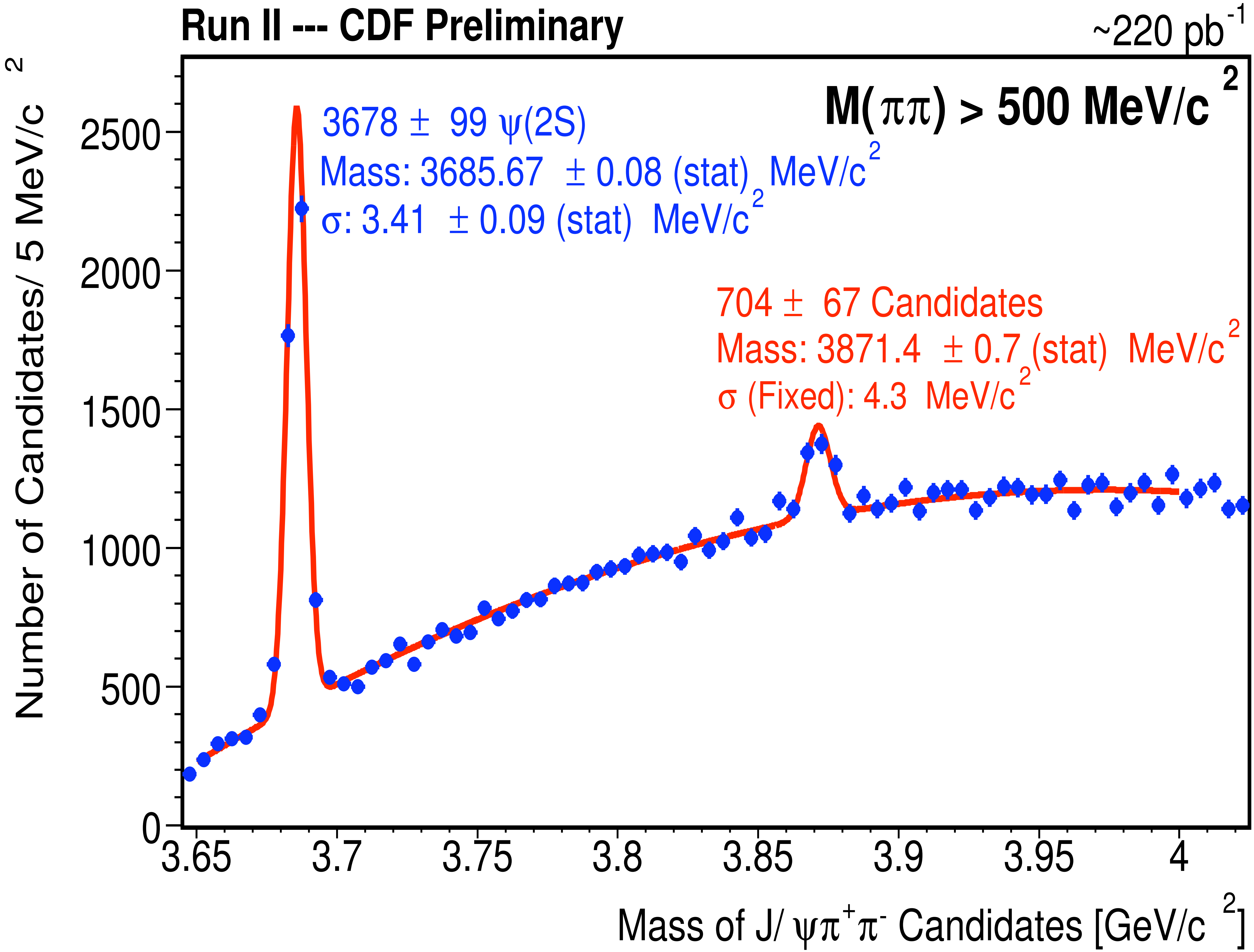


FIG. 2: Signal-band projections of (a) $M_{\rm bc}$, (b) $M_{\pi^+\pi^- J/\psi}$ and (c) ΔE for the $X(3872) \to \pi^+\pi^- J/\psi$ signal region with the results of the unbinned fit superimposed.



Run II --- CDF Preliminary
~220 pb^{-1}
M(ππ) > 500 MeV/c^2
3678 ± 99 ψ(2S)
Mass: 3685.67 ± 0.08 (stat) MeV/c^2
σ: 3.41 ± 0.09 (stat) MeV/c^2
704 ± 67 Candidates
Mass: 3871.4 ± 0.7 (stat) MeV/c^2
σ (Fixed): 4.3 MeV/c^2
Number of Candidates/ 5 MeV/c^2
Mass of J/ψπ$^+$π$^-$ Candidates [GeV/c^2]
0
500
1000
1500
2000
2500
3.65
3.7
3.75
3.8
3.85
3.9
3.95
4

Issues:

η_c' : small splitting from ψ'

$D_s(2317)$ and $D_s(2463)$:

surprisingly light; chiral symmetry?

$\Theta^+(1540)$: chiral soliton?

uncorrelated quarks? $q^4\bar{q}$

3* diquark picture? $[ud]^2\bar{s}$

$X(3872)$: Splitting from $\psi''(3770)$;

radiative decays? $D^0\bar{D}^{*0}$ threshold

Additional experimental stimulus:

Many changes to charmonium properties

$\Gamma(\eta_c) \times (2.5 - 3)$

$\psi(3770) \to \pi^+\pi^- J/\psi$

refined charm masses

$h_c\ (^1P_1)$ status?

General reasons for interest ...

Many charmonium levels: 9 or 10 narrow states, plus ~60 states within 800 MeV of threshold

Potential models give a good account of the spectrum, but cannot be the whole story

Lattice QCD is increasingly capable for charmonium spectroscopy

New states seen in e^+e^-, B decay, 2-photon, hadronic production: new J^{PC} accessible

... reasons for interest

Hope to investigate QCD in all its richness: degrees of freedom beyond

NR $c\bar{c}$ bound in a potential

$c\bar{c}g$ hybrid states

$(cq)(\bar{c}\bar{q})$ diquark · diquark states

$(c\bar{q})(\bar{c}q)$ molecules

Comparison with Υ, B_c

In the wake of the η_c' news ...

E-L-Q: B-Meson Gateways to Missing Charmonium Levels, PRL 89, 162002 (2002)

$\eta_c'(2^1S_0)$ and $h_c(1^1P_1)$ below $D\bar{D}$ threshold

$\eta_{c2}\ (1^1D_2,\ 2^{-+})$ and $\psi_2\ (1^3D_2,\ 2^{--})$ between $D\bar{D}$ threshold and $D\bar{D}^*$

long-anticipated narrow states

(related work by Ko-Lee-Song, Suzuki)

E735 : $\bar{p}p \to h_c(3526) \to \pi^0 J/\psi$

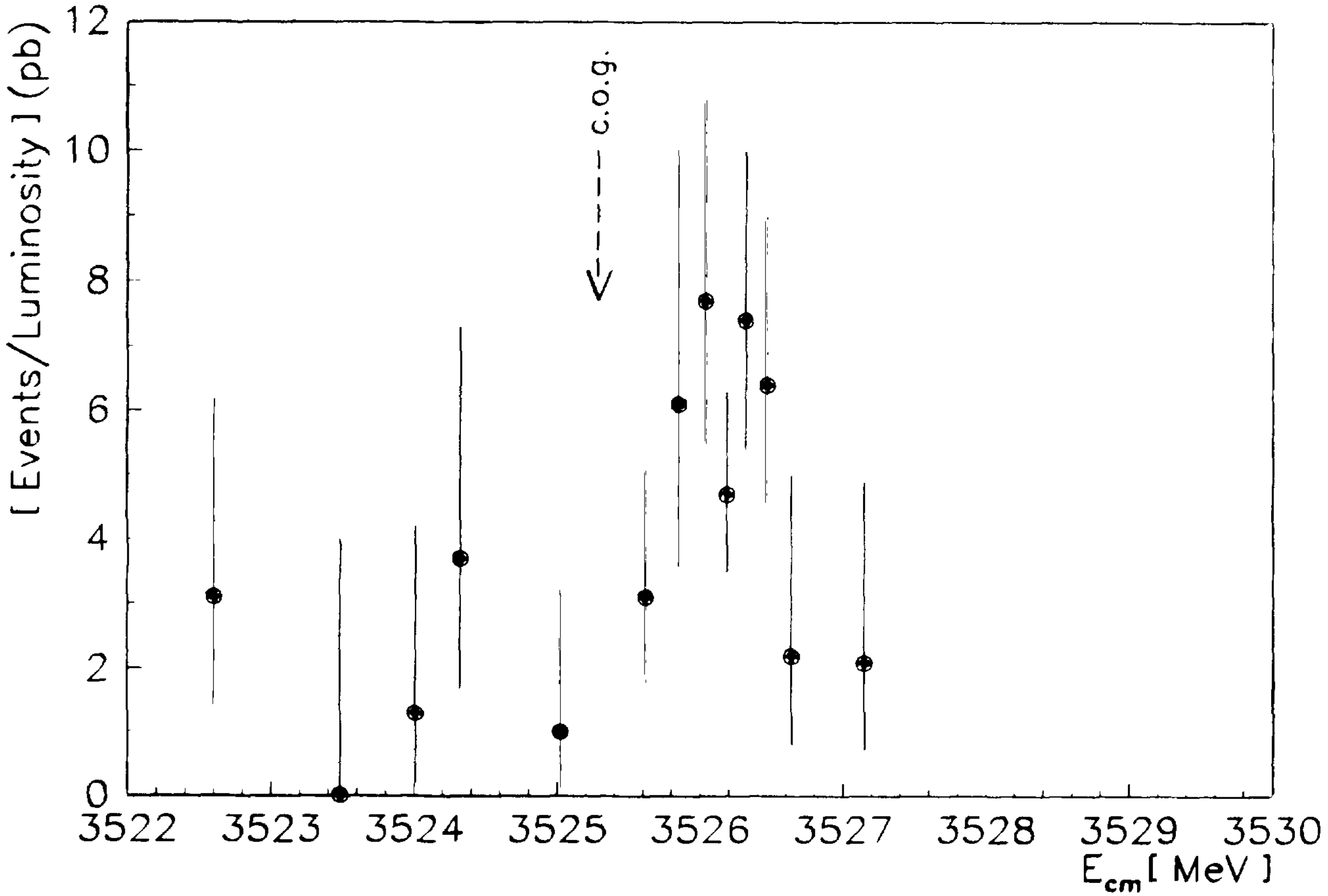
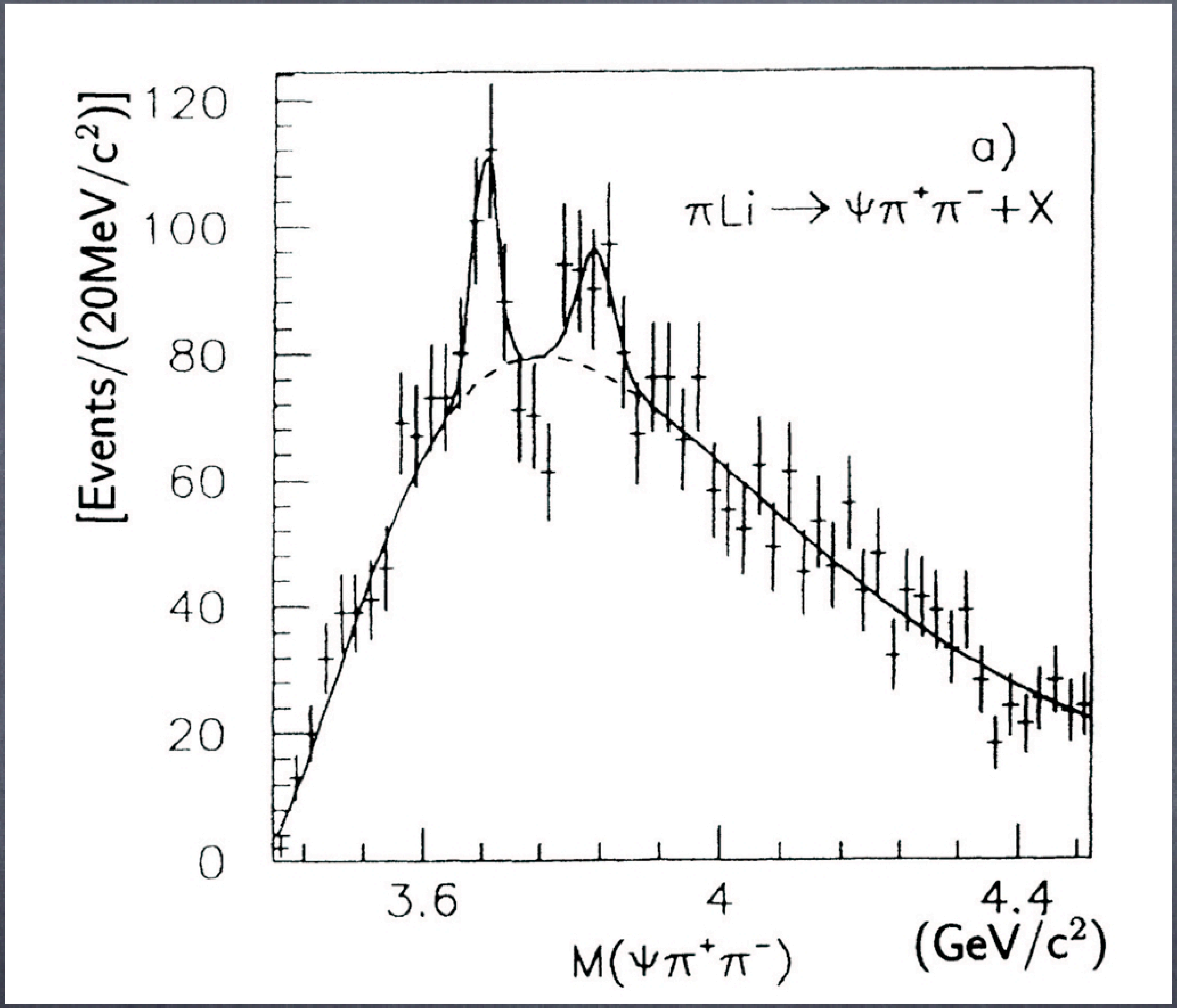


FIG. 2. Number of events per integrated luminosity vs center-of-mass energy; data are binned in 150-keV intervals in the average center-of-mass energy.

Fermilab E705 300 GeV π^- Li (1994)



"Tentative observation" of ψ_2 $(^3D_2)$: 3836 ± 13 MeV

$b \to (c\bar{c})_1 + \ldots$ or $b \to (c\bar{c})_8 + \ldots$

TABLE IV. Measured and estimated branching fractions for B decays to quarkonium levels.

$c\bar{c}$ State		$\Gamma(B \to (c\bar{c}) + X)/\Gamma(B \to \text{all})$ (%)
1^1S_0	η_c	≈ 0.53[a]
1^3S_1	J/ψ	$0.789 \pm 0.010 \pm 0.034$[b,c]
1^1P_1	h_c	0.132 ± 0.060[d]
1^3P_0	χ_{c0}	0.029 ± 0.012[d]
1^3P_1	χ_{c1}	$0.353 \pm 0.034 \pm 0.024$[b,e]
1^3P_2	χ_{c2}	$0.137 \pm 0.058 \pm 0.012$[b]
2^1S_0	η_c'	≈ 0.18[a]
2^3S_1	ψ'	$0.275 \pm 0.020 \pm 0.029$[b]
1^1D_2	η_{c2}	0.23[f]
1^3D_1	ψ	0.28[f]
1^3D_2	ψ_2	0.46[f]
1^3D_3	ψ_3	0.65[f]

[a] Scaled from $^3S_1$ rate.
[b] Data from Refs. [32,33].
[c] Known feed-down from $2S$ state removed.
[d] Scaled from $^3P_{1,2}$ rates using Eq. (6).
[e] Known feed-down from $2S$ and $1P$ states removed.
[f] Computed; see Ref. [34].

Not much guidance yet from measurements!

Expect small hadronic widths

TABLE II. Hadronic decay widths of charmonium states.

$c\bar{c}$ State	Decay	Partial Width
1^1S_0	$\eta_c \to gg$	17.4 ± 2.8 MeV [20]
1^3S_1	$J/\psi \to ggg$	52.8 ± 5 keV [21]
1^1P_1	$h_c \to ggg$	720 ± 320 keV[a]
1^3P_0	$\chi_{c0} \to gg$	14.3 ± 3.6 MeV[b]
1^3P_1	$\chi_{c1} \to ggg$	0.64 ± 0.10 MeV[b]
1^3P_2	$\chi_{c2} \to gg$	1.71 ± 0.21 MeV[b]
2^1S_0	$\eta_c' \to gg$	8.3 ± 1.3 MeV[c]
	$\eta_c' \to \pi\pi\eta_c$	160 keV[d]
2^3S_1	$\psi' \to ggg$	23 ± 2.6 keV [21]
	$\psi' \to \pi\pi J/\psi$	152 ± 17 keV [21]
	$\psi' \to \eta J/\psi$	6.1 ± 1.1 keV [21]
1^1D_2	$\eta_{c2} \to gg$	110 keV[e]
	$\eta_{c2} \to \pi\pi\eta_c$	≈ 45 keV[d]
1^3D_1	$\psi \to ggg$	216 keV[f]
	$\psi \to \pi\pi J/\psi$	43 ± 15 keV[g]
1^3D_2	$\psi_2 \to ggg$	36 keV[f]
	$\psi_2 \to \pi\pi J/\psi$	≈ 45 keV[d]
1^3D_3	$\psi_3 \to ggg$	102 keV[f]
	$\psi_3 \to \pi\pi J/\psi$	≈ 45 keV[d]

[a] Computed from ^3P_J rates using formalism of [22]; also see [23].
[b] Compilation of data analyzed by Maltoni (Ref. [22]).
[c] Scaled from $\Gamma(\eta_c \to gg)$.
[d] Computed using Eq. (3.5) of Ref. [19].
[e] Computed using Eq. (3).
[f] Computed using Eq. (2).
[g] From rates compiled in Table X of Ref. [19].

Radiative rates not negligible

TABLE III. Calculated and observed rates for radiative transitions among charmonium levels in the potential (1).

Transition	γ energy k (MeV)	Partial width (keV) Computed	Measured[a]
$\psi \xrightarrow{\text{M1}} \eta_c \gamma$	115	1.92	1.13 ± 0.41
$\chi_{c0} \xrightarrow{\text{E1}} J/\psi \gamma$	303	120 (105)[b]	98 ± 43
$\chi_{c1} \xrightarrow{\text{E1}} J/\psi \gamma$	390	242 (215)[b]	240 ± 51
$\chi_{c2} \xrightarrow{\text{E1}} J/\psi \gamma$	429	315 (289)[b]	270 ± 46
$h_c \xrightarrow{\text{E1}} \eta_c \gamma$	504	482	
$\eta'_c \xrightarrow{\text{E1}} h_c \gamma$	126	51	
$\psi' \xrightarrow{\text{E1}} \chi_{c2} \gamma$	128	29 (25)[b]	22 ± 5
$\psi' \xrightarrow{\text{E1}} \chi_{c1} \gamma$	171	41 (31)[b]	24 ± 5
$\psi' \xrightarrow{\text{E1}} \chi_{c0} \gamma$	261	46 (38)[b]	26 ± 5
$\psi' \xrightarrow{\text{M1}} \eta'_c \gamma$	32	0.04	
$\psi' \xrightarrow{\text{M1}} \eta_c \gamma$	638	0.91	0.75 ± 0.25
$\psi(3770) \xrightarrow{\text{E1}} \chi_{c2} \gamma$	208	3.7	
$\psi(3770) \xrightarrow{\text{E1}} \chi_{c1} \gamma$	250	94	
$\psi(3770) \xrightarrow{\text{E1}} \chi_{c0} \gamma$	338	287	
$\eta_{c2} \xrightarrow{\text{E1}} \psi(3770) \gamma$	45	0.34	
$\eta_{c2} \xrightarrow{\text{E1}} h_c \gamma$	278	303	
$\psi_2 \xrightarrow{\text{E1}} \chi_{c2} \gamma$	250	56	
$\psi_2 \xrightarrow{\text{E1}} \chi_{c1} \gamma$	292	260	

[a]Derived from Ref. [21]
[b]Corrected for coupling to decay channels as in Ref. [14]

What we expected: prominent radiative decays

$$\mathcal{B}(h_c \to \eta_c \gamma) \approx \frac{2}{5}$$

$$\mathcal{B}(\eta_{c2} \to h_c \gamma) \approx \frac{2}{3}$$

$$\mathcal{B}(\psi_2 \to \chi_{c1,2} \gamma) \approx \frac{4}{5}, \text{ of which } \mathcal{B}(\psi_2 \to \chi_{c1} \gamma) \approx \frac{2}{3}$$

+ useful rates for ππ cascades

What we know about X(3872)

Mass higher than simplest expectation; lies at DD* threshold

In CDF, prompt production not negligible

$$\frac{\Gamma(X(3872) \to \gamma\chi_{c1})}{\Gamma(X(3872) \to \pi^+\pi^- J/\psi)} < 0.89$$

$$\frac{\mathcal{B}(B^+ \to K^+X) \cdot \mathcal{B}(X \to \pi^+\pi^- J/\psi)}{\mathcal{B}(B^+ \to K^+\psi') \cdot \mathcal{B}(\psi' \to \pi^+\pi^- J/\psi)} = 0.063 \pm 0.014$$

Alternatives to charmonium: deusons

deuteron-like "molecules" formed by attractive π exchange between

D^0 and $\bar{D}^{*0}$

Most attractive : $I = 0, \; J^{PC} = 0^{-+}, 1^{++}$

Parity forbids decay into $(\pi\pi)_{I=0} J/\psi$

Hadronic cascade must be $(\pi\pi)_{I=1} J/\psi$

dissociation : $X \to (D^0\bar{D}^{*0})_{virtual} \to D^0\bar{D}^0\pi^0$

Alternatives to charmonium: hybrid mesons

Expected levels: anything but 2^{--}

$$\text{Chromoelectric flux tubes}: (0,1,2)^{++}, 1^{+-}$$

$$\text{Chromomagnetic flux tubes}: (0,1,2)^{-+}, 1^{--}$$

Estimated masses 4.1 ± 0.2 GeV

Decay angular distributions

Spin-2 X(3872) decaying through s-wave ππ:

angular distribution of $J/\psi \propto \sin^2\theta \cos^2\theta$

θ : X line of flight *vs* J/ψ direction

$J/\psi \to \ell^+\ell^-$ angular distribution $\propto 1 + \cos^2\vartheta$

ϑ : angle of ℓ^+ *wrt* J/ψ flight direction

The classic: J. D. Jackson, Les Houches, 1965

also see Pakvasa & Suzuki, hep-ph/0309294

(ππ angular distribution)

Another ππ diagnostic

Isospin of dipion: charmonium + other contenders interpret X(3872) as I=0

$$\mathcal{R}_0 \equiv \Gamma(X \to \pi^0\pi^0 J/\psi)/\Gamma(X \to \pi^+\pi^- J/\psi)$$

measures dipion isospin

$$\Gamma_I \equiv \Gamma(X \to (\pi^+\pi^-)_I J/\psi) : \mathcal{R}_0 = \tfrac{1}{2}/(1 + \Gamma_1/\Gamma_0)$$

Deviations from 1/2 signal I-violating decay of an isoscalar, or I-conserving decay of an isovector

Charmonium: Comparison with Experiment (1980)

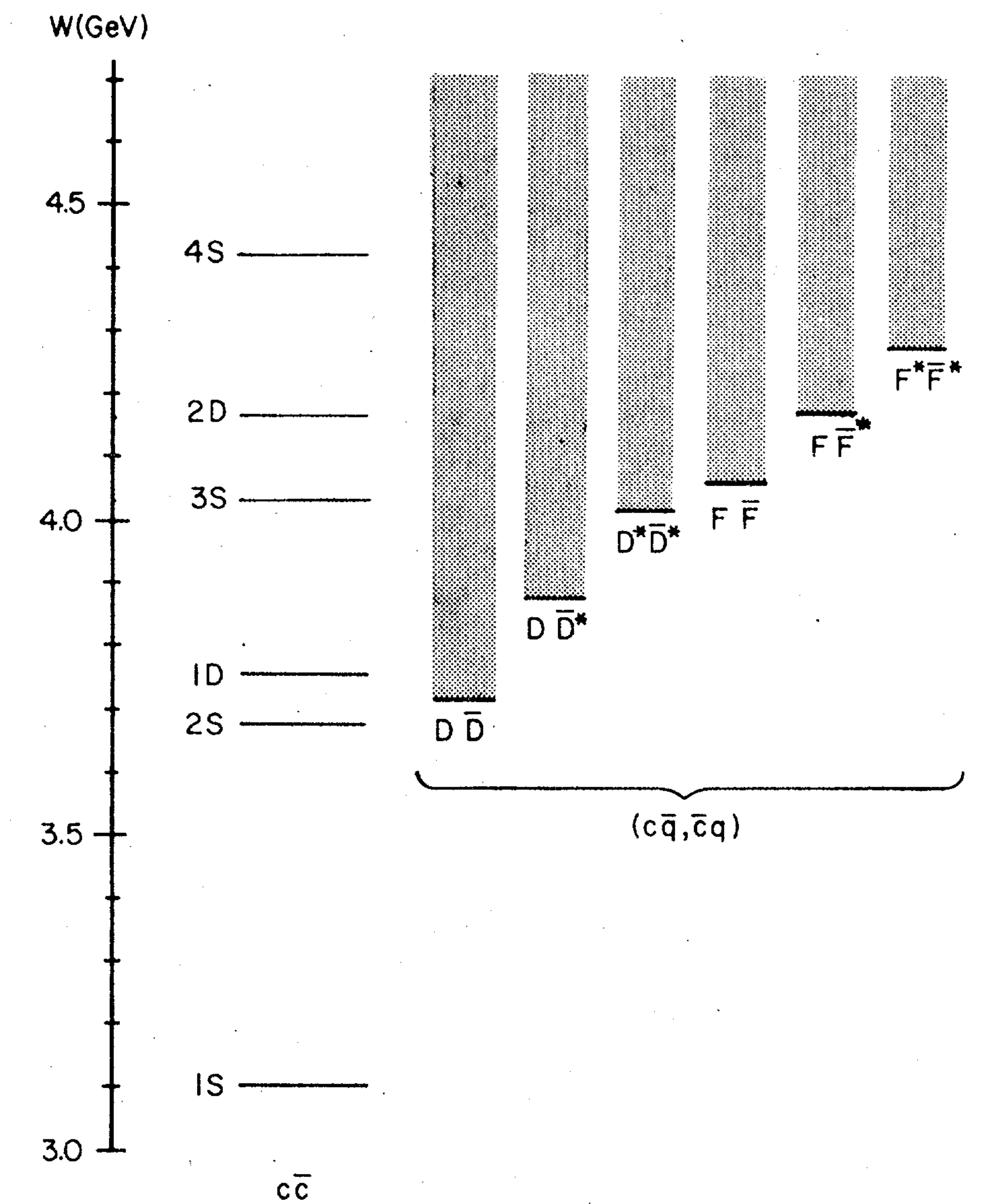


FIG. 5. The spectra of the $c\bar{c}$ system, and of the lowest-lying charmed-meson decay channels.

Eichten, Gottfried, Kinoshita, Lane, Yan, PRD 21, 203 (1980)

Coupling to open-charm channels

Phenomenological approach:

$$\text{Evaluate } \langle n^3S_1|\mathcal{H}_{int}|D\bar{D}\rangle, \text{ etc.}$$

$$\mathcal{H}_{int} = \frac{3}{8}\int d\vec{x}d\vec{y}\; J_{0a}(\vec{x})V(|\vec{x}-\vec{y}|)J^a_o(\vec{y})$$

$$J^a_0 = \bar{c}\gamma_0 t^a c + \bar{q}\gamma_0 t^a q$$

Calculate pair-creation amplitudes, solve coupled-state system

Effects on the spectrum

Coupling to virtual channels induces spin-dependent forces in charmonium near threshold, because $M(D^*) > M(D)$

Effects on partial widths

Radiative transitions suppressed (how much?) by reduced overlap between 1D and 1P states

Also studying effect on hadronic transitions

Anticipate small strong decay width for $\psi_2(3872)$

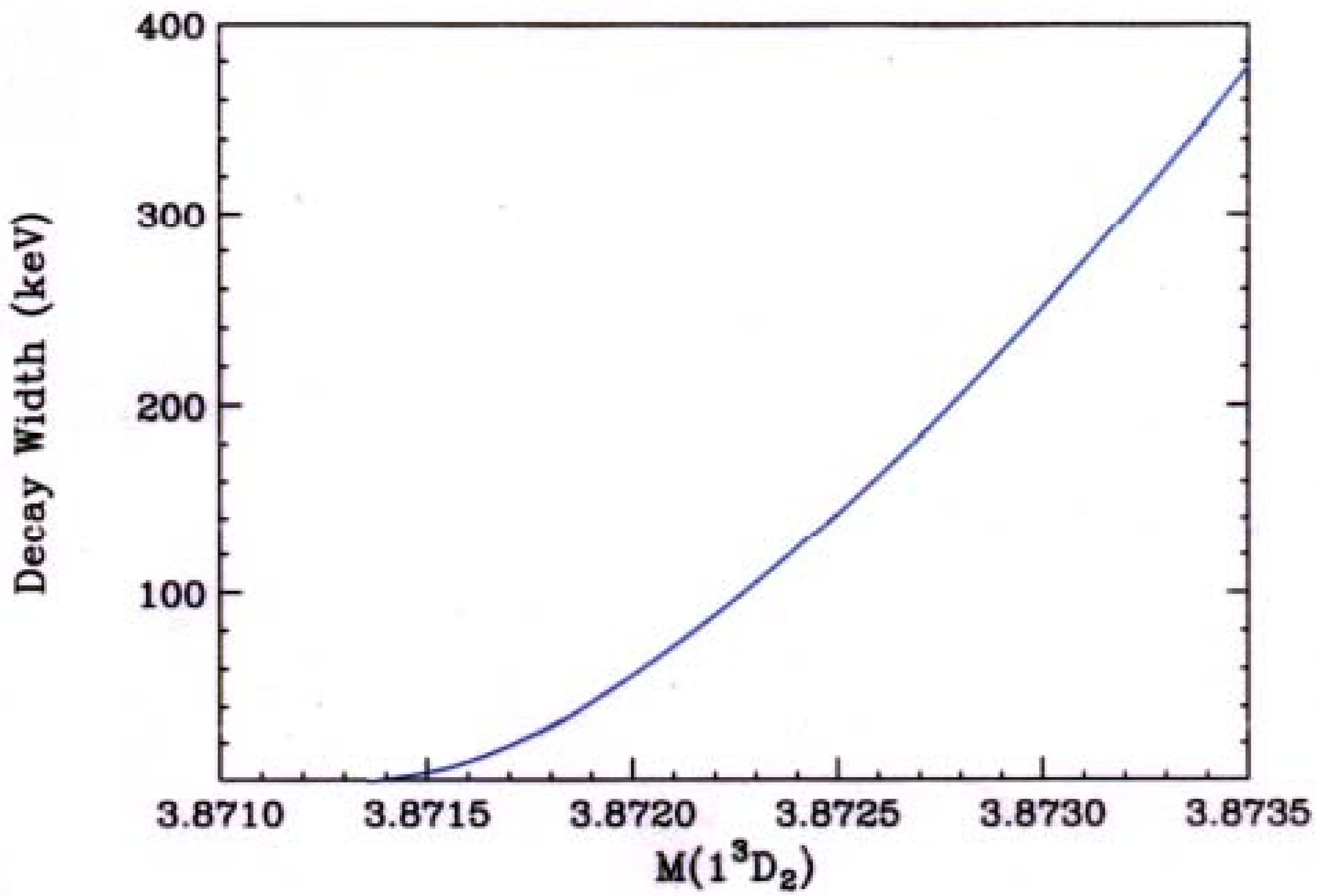


Figure 4: Decay Width $^3D_2 \to D^0\bar{D}^{*0}$ versus mass M.

State		Raw Mass	Observed Mass	Shift
1^1S_0	η_c	3067.	2979.9 ± 1.0	+1.6
1^3S_1	J/ψ		3096.87 ± 0.04	−0.5
1^1P_1	h_c	3526.		+0.1
1^3P_0	χ_{c0}	3526.	3415.3 ± 0.4	+0.5
1^3P_1	χ_{c1}		3510.51 ± 0.12	−2.3
1^3P_2	χ_{c2}		3556.18 ± 0.13	+1.2
2^1S_0	η_c'	3678.	3637.7 ± 4.4	+13.2
2^3S_1	ψ'		3685.96 ± 0.09	−4.2
1^1D_2	η_{c2}	3815.	$\not\to D\bar{D}$ (parity)	+5.6
1^3D_1	ψ	3815.	3769.9 ± 2.5	−54.7
1^3D_2	ψ_2		3871.7 ± 0.6	−7.2
1^3D_3	ψ_3		$\to D\bar{D}$	+28.5
2^1P_1	h_c'	3968.		+24.9
2^3P_0	χ_{c0}'	3968.		+14.9
2^3P_1	χ_{c1}'			+39.5
2^3P_2	χ_{c2}'			−26.7
1^1F_3	h_{c3}	4054.		−2.9
1^3F_2	χ_{c2}	4054.		−0.5
1^3F_3	χ_{c3}			+0.3
1^3F_4	χ_{c4}			−0.4

$$M(\eta_c') = 3637.7 \pm 4.4$$

Hyperfine splitting:

$$M(\psi') - M(\eta_c') = 32\pi\alpha_s|\Psi(0)|^2/9m_c^2$$

Normalize to $M(J/\psi) - M(\eta_c) = 117\ \text{MeV}$

Hyperfine splitting

$$M(\psi') - M(\eta_c') = \begin{cases} 79 \text{ MeV} & \text{Tuned Cornell (ELQ)} \\ 75 \text{ MeV} & \text{Cornell} \\ 78 \text{ MeV} & \text{Buchmueller}-\text{Tye} \\ 65 \text{ MeV} & \text{power}-\text{law} \\ 60 \text{ MeV} & \text{logarithmic} \end{cases}$$

... all larger than observed 48.3 ± 4.4 MeV

2S shifts reduce splitting by 17.7 MeV

substantially improves agreement

First indication of open-charm influence?

Coupled-channel influence on 1D masses:

d-wave spin splittings small in NRQM picture

$^3\mathrm{D}_2, {}^3\mathrm{D}_1 \approx$ degenerate

Coupling to open charm depresses $1^3\mathrm{D}_1$ 55 MeV

Leaves $1^3\mathrm{D}_2$ 50 MeV higher

Doesn't fully account for observed

$$\mathrm{M}(\mathrm{X}(3872)) - \mathrm{M}(\psi(3770)) = 102 \ \mathrm{MeV}$$

but makes $1^3\mathrm{D}_2$ assignment plausible

Could X(3872) be 2^1P_1?

Seems improbable: 100 MeV above $D^0\bar{D}^{*0}$ in potential model;
coupling to open charm raises by 25 MeV

Radiative decay would be hindered M1

Strong cascade: *s*-wave ππ by L=1 (not 2)

(Could explain small radiative BR)

E1 decay to η_c'

Coming soon:

Radiative rates — new masses, effects of mixing with open-charm states

Hadronic rates — new masses, some new inputs

Charmonium wave functions beyond $c\bar{c}$

Tests for influence of open channels?

Search for structures in charm-anticharm mesons

State		Mass (MeV)	Width (MeV)
1^1D_2	η_{c2}	3884.	3.4
1^3D_1	ψ	3770.	18.7
1^3D_2	ψ_2	3872.	-
1^3D_3	ψ_3	3920.	2.4
2^1P_1	h'_c	3968.	36.5
2^3P_0	χ'_{c0}	3968.	23.8
2^3P_1	χ'_{c1}	3968.	74.2
2^3P_2	χ'_{c2}	3968.	8.6
1^1F_3	h_{c3}	4054.	14.6
1^3F_2	χ_{c2}	4054.	30.6
1^3F_3	χ_{c3}	4054.	11.0
1^3F_4	χ_{c4}	4054.	5.6
		Thresholds	
$D^0\bar{D}^0$		3729.4	
D^+D^-		3738.8	
$D^0\bar{D}^{*0}$ or $D^{*0}\bar{D}^0$		3871.5	
$D^\pm D^{*\mp}$		3879.5	
$D_s^+D_s^-$		3936.2	
$D^{*0}\bar{D}^{*0}$		4013.4	
$D^{*+}D^{*-}$		4020.0	
$D_s^+\bar{D}_s^{*-}$ or $D_s^{*+}\bar{D}_s^-$		4080.0	
$D_s^{*+}D_s^{*-}$		4223.8	

Following up X(3872)

Verify I=0: look for charged partner, check dipion angular distribution

Determine (or at least restrict) J^{PC}

Look for radiative decays: $\gamma\chi_{c1}, \gamma\chi_{c2}$

Measure prompt vs B-decay at CDF

Look for $D^0\bar{D}^0\pi^0$ and $D^0\bar{D}^0\gamma$

Following up X(3872)

Measure ππ mass distribution

Look for structure in $D\bar{D}, D\bar{D}^*, D^*\bar{D}^*$

Find structures or set limits on other $\pi^+\pi^- J/\psi$

Examine $\eta\ J/\psi$

Measure rates for $b \to (c\bar{c}) + \text{anything}$

Similar studies in $b\bar{b}$

Theoretical work needed

Charmonium: understand threshold influence

Hybrid mesons: make some specific predictions, sketch a decision tree

Molecular charmonium: production rates

Lattice: surpass the potential model

Whatever X(3872) turns out to be, much to do

If charmonium, find other states, advance beyond one-channel NRQM

Molecular states and hybrid mesons may still exist — how to form them?

If not charmonium, a new spectroscopy

(Charmonium states still await discovery)

X-theory papers

General diagnostics: S. Pakvasa & M. Suzuki, hep-ph/0309294; F. E. Close & P. R. Page, hep-ph/0309253.

Charm Molecules: N. A. Törnqvist, hep-ph/0308277; M. Voloshin, hep-ph/0309307.

Hybrid mesons: F. E. Close & S. Godfrey, hep-ph/0305285.

Charmonium: Eichten, Lane, Quigg (soon!)