Quarkonium: New Developments

Chris Quigg · La Thuile 2004

A puzzling new state

A new charmonium spectroscopy?

A new quarkonium spectroscopy

Open issues for theory & experiment

Exciting times for hadron spectroscopy: many new narrow states

$\star\ \eta_c'$ in $B \to K K_S K^{\mp}\pi^{\pm}$

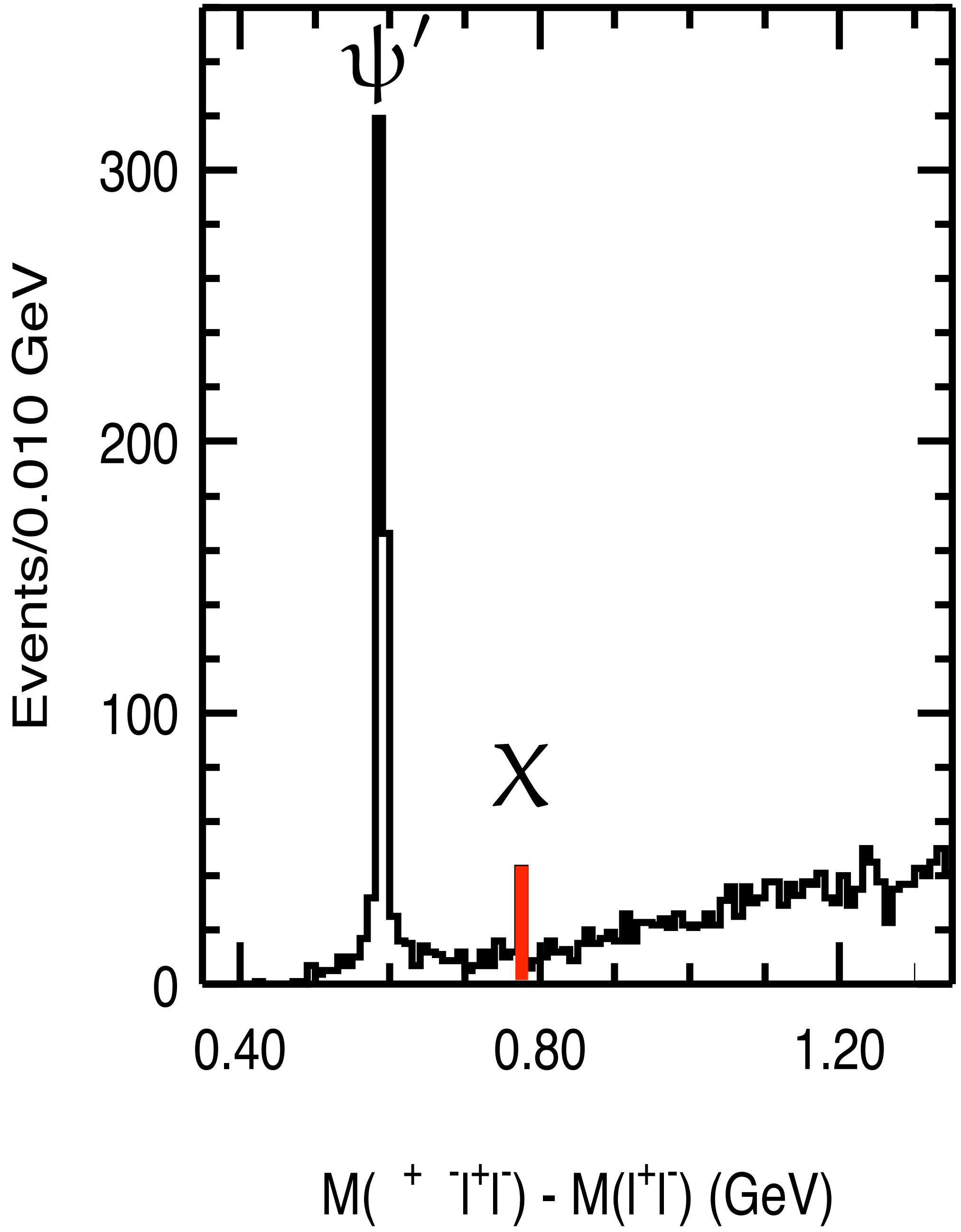
$\star$ Narrow D_s levels $(0^{++}, 1^{++})$

$\star$ Pentaquark $K^+n : \Theta^+(1540)$

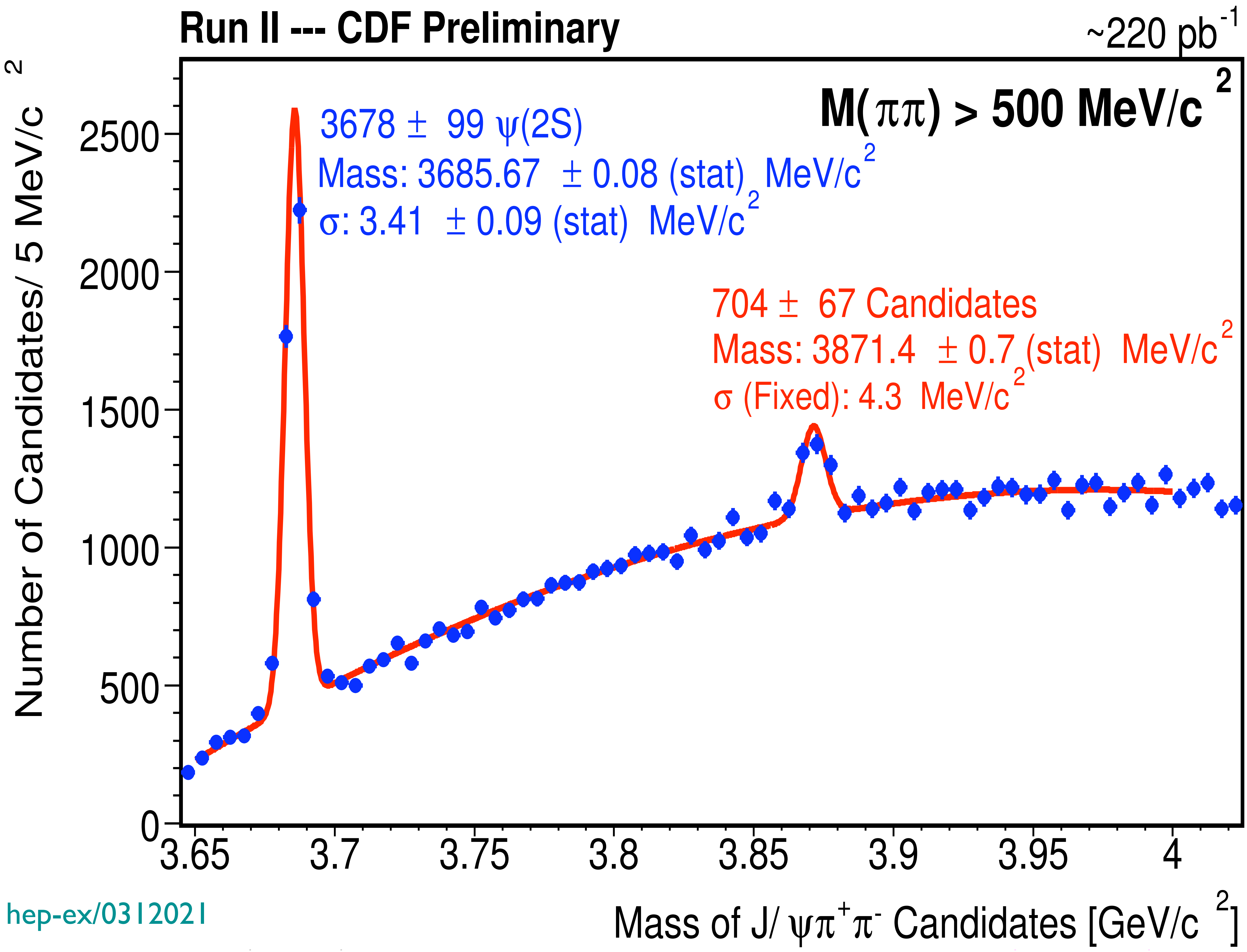
$\boxed{\star\ X(3872) \to \pi^+\pi^- J/\psi}$

Each raises questions of interpretation, and offers opportunities.

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



Phys. Rev. Lett. 91, 262001 (2003)



3678 ± 99 ψ(2S)

Mass: 3685.67 ± 0.08 (stat) MeV/c^2

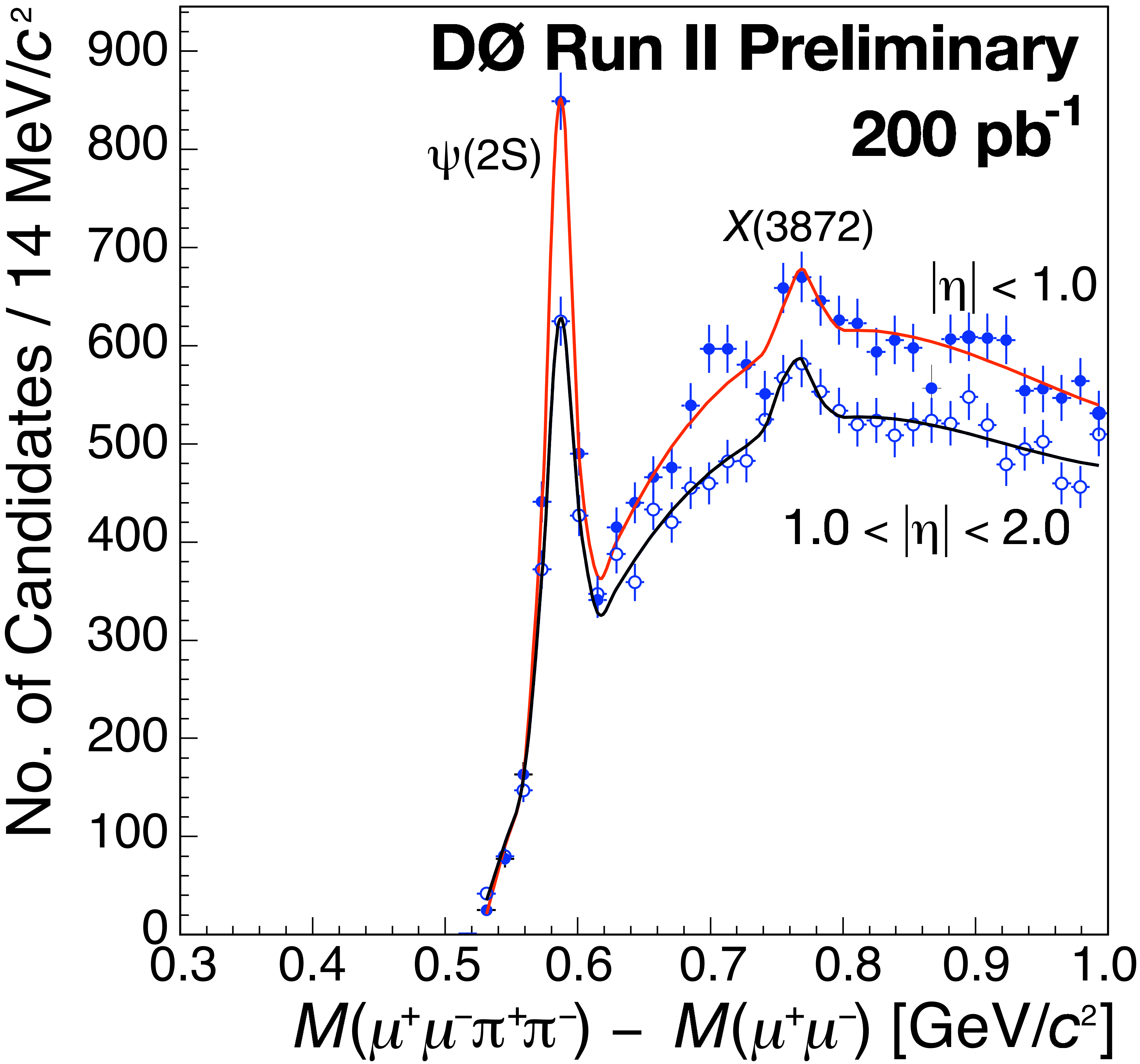
σ: 3.41 ± 0.09 (stat) MeV/c^2

704 ± 67 Candidates

Mass: 3871.4 ± 0.7 (stat) MeV/c^2

σ (Fixed): 4.3 MeV/c^2

hep-ex/0312021



http://www-d0.fnal.gov/Run2Physics/ckm/Moriond_2003/X_conf_note_v9.ps

Issues:

η_c': small splitting from ψ'

$D_s(2317)$ and $D_s(2463)$:
surprisingly light; chiral symmetry?

$\Theta^+(1540)$: chiral soliton?
uncorrelated quarks? $3^\star$ diquark picture?

$X(3872)$: Mass; radiative decays?
$D^0\bar{D}^{*0}$ threshold?

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 quarkonium spectroscopy.

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

In the wake of the η_c' news ...

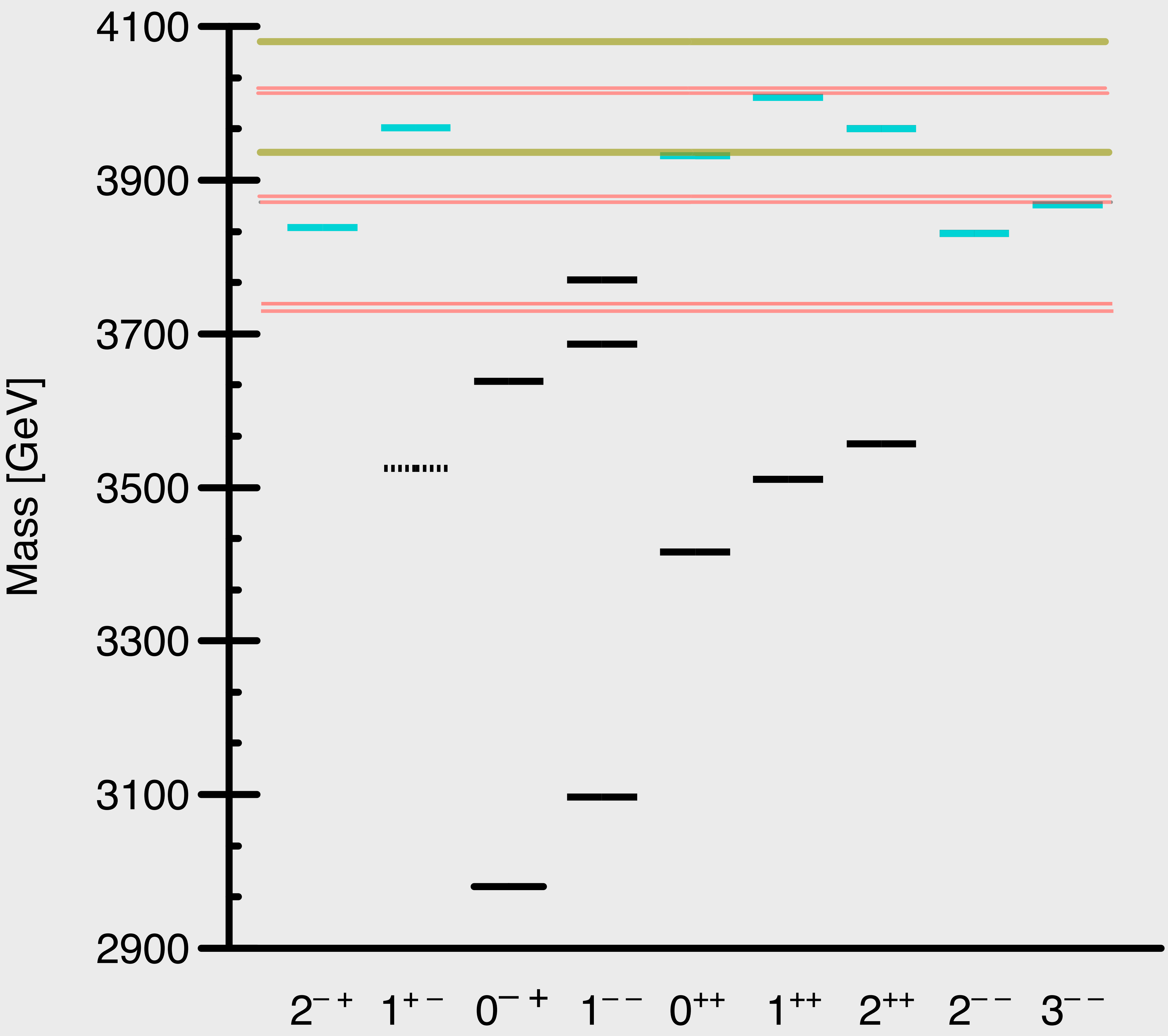
E-L-Q: *B*-Meson Gateways to Missing Charmonium Levels, PRL 89, 162002 (2002)

$\eta_c'(2^1S_0)$ 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)


4100
3900
3700
3500
3300
3100
2900
Mass [GeV]
2^{-+}
1^{+-}
0^{-+}
1^{--}
0^{++}
1^{++}
2^{++}
2^{--}
3^{--}

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

ELQ 2002

$c\bar{c}$ state		$\Gamma(B \to (c\bar{c}) + X)/\Gamma(B \to \text{all})$ (%)
$1^1\mathrm{S}_0$	η_c	$\approx 0.53^{a}$
$1^3\mathrm{S}_1$	J/ψ	$0.789 \pm 0.010 \pm 0.034^{b\,c}$
$1^1\mathrm{P}_1$	h_c	0.132 ± 0.060^{d}
$1^3\mathrm{P}_0$	χ_{c0}	0.029 ± 0.012^{d}
$1^3\mathrm{P}_1$	χ_{c1}	$0.353 \pm 0.034 \pm 0.024^{b\,e}$
$1^3\mathrm{P}_2$	χ_{c2}	$0.137 \pm 0.058 \pm 0.012^{b}$
$2^1\mathrm{S}_0$	η_c'	$\approx 0.18^{a}$
$2^3\mathrm{S}_1$	ψ'	$0.275 \pm 0.020 \pm 0.029^{b}$
$1^1\mathrm{D}_2$	η_{c2}	0.23^{f}
$1^3\mathrm{D}_1$	ψ	0.28^{f}
$1^3\mathrm{D}_2$	ψ_2	0.46^{f}
$1^3\mathrm{D}_3$	ψ_3	0.65^{f}

Expect roughly similar BRs

ELQ 2002

Expect small hadronic widths

1^1D_2	3815	$\eta_{c2} \to gg$	$110\ \text{keV}^e$	
		$\eta_{c2} \to \pi\pi\eta_c$	$\approx 45\ \text{keV}^d$	
1^3D_1	3770	$\psi \to ggg$	$216\ \text{keV}^f$	
		$\psi \to \pi\pi J/\psi$	$43 \pm 15\ \text{keV}^g$	→ ~~140 keV~~
1^3D_2	3815	$\psi_2 \to ggg$	$36\ \text{keV}^f$	80 ± 32 ± 21 keV (BES)
		$\psi_2 \to \pi\pi J/\psi$	$\approx 45\ \text{keV}^d$	< 55 keV, 90% CL (CLEO)
1^3D_3	3815	$\psi_3 \to ggg$	$102\ \text{keV}^f$	
		$\psi_3 \to \pi\pi J/\psi$	$\approx 45\ \text{keV}^d$	

Radiative rates not small!

ELQ 2002

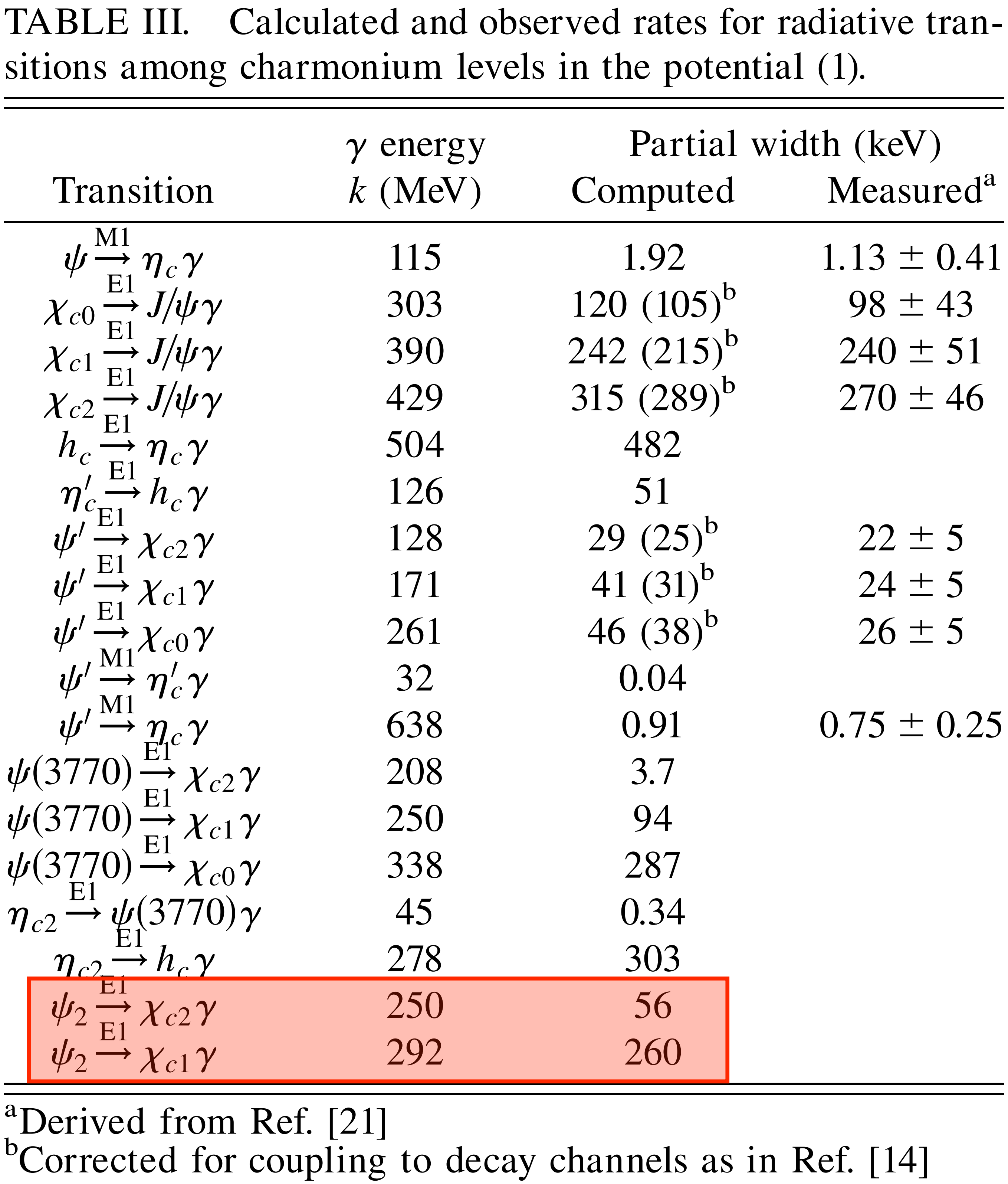


TABLE III. Calculated and observed rates for radiative transitions among charmonium levels in the potential (1).

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

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

What we expected: prominent radiative decays

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

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

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

+ useful rates for ππ cascades

What we know about X(3872)

Mass higher than simplest expectation;
lies at DD* threshold
3871.7 ± 0.6 MeV (3815 MeV)

In CDF & DØ, prompt production not negligible

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

No sign yet of radiative cascades to 1P states

$$\frac{\Gamma(X \to \gamma\chi_{c1,2})}{\Gamma(X \to \pi^+\pi^- J/\psi)} < 0.9, 1.1$$

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

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

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

Possibly enhanced decay rate to $\eta J/\psi$

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

Coupling to open-charm channels

Phenomenological approach:

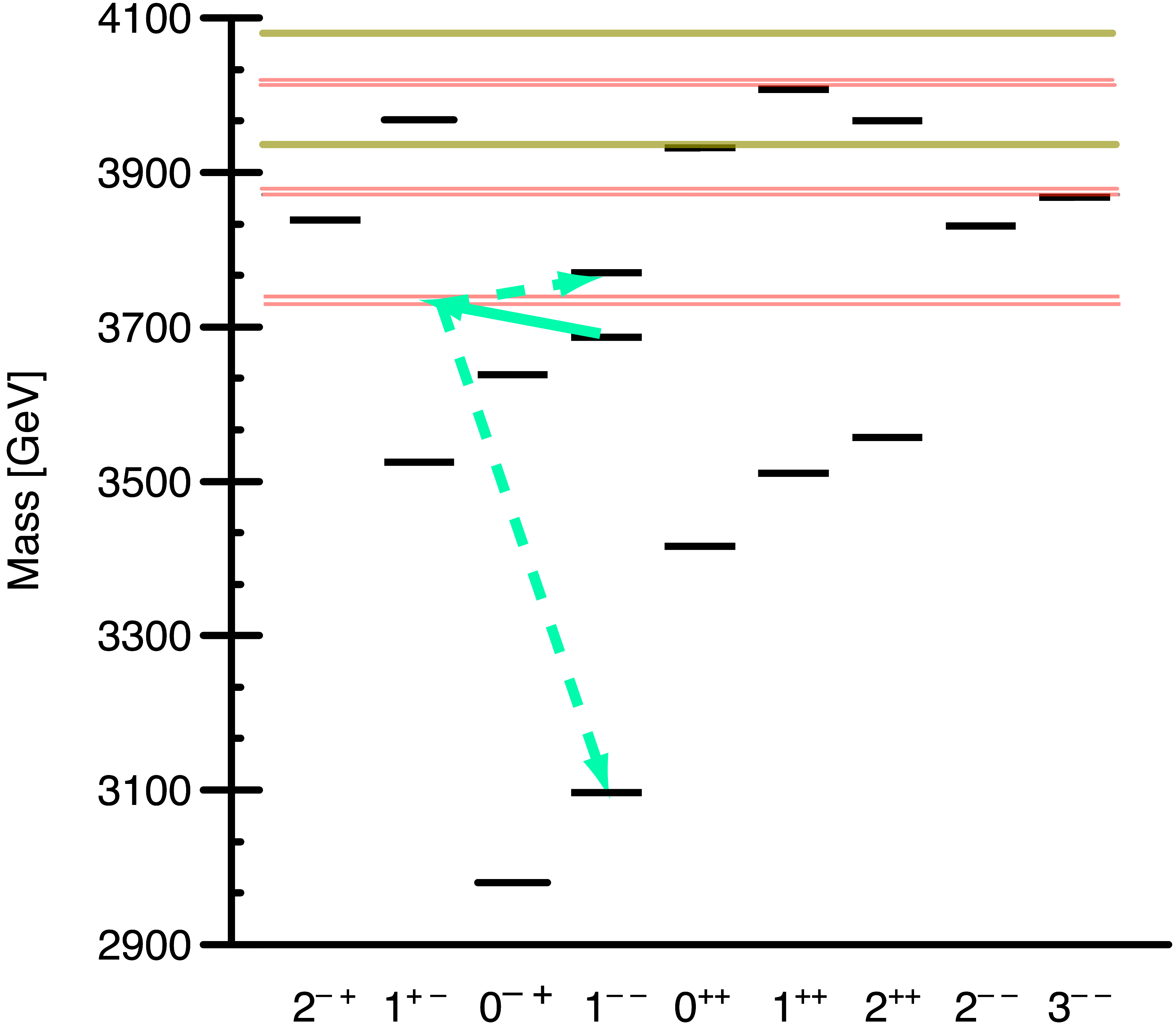
$$\text{Evaluate } \langle n^3S_1|\mathcal{H}_{\text{int}}|D\bar{D}\rangle, \text{ etc.}$$

$$\mathcal{H}_{\text{int}} = \frac{3}{8}\int d\vec{x}d\vec{y}\; J_{0a}(\vec{x})V(|\vec{x}-\vec{y}|)J_0^a(\vec{y})$$

$$J_0^a = \bar{c}\gamma_0 t^a c + \bar{q}\gamma_0 t^a q$$

Calculate pair-creation amplitudes,
solve coupled-state system

Eichten, Gottfried, Kinoshita, Lane, Yan, PRD 21, 203 (1980)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3900
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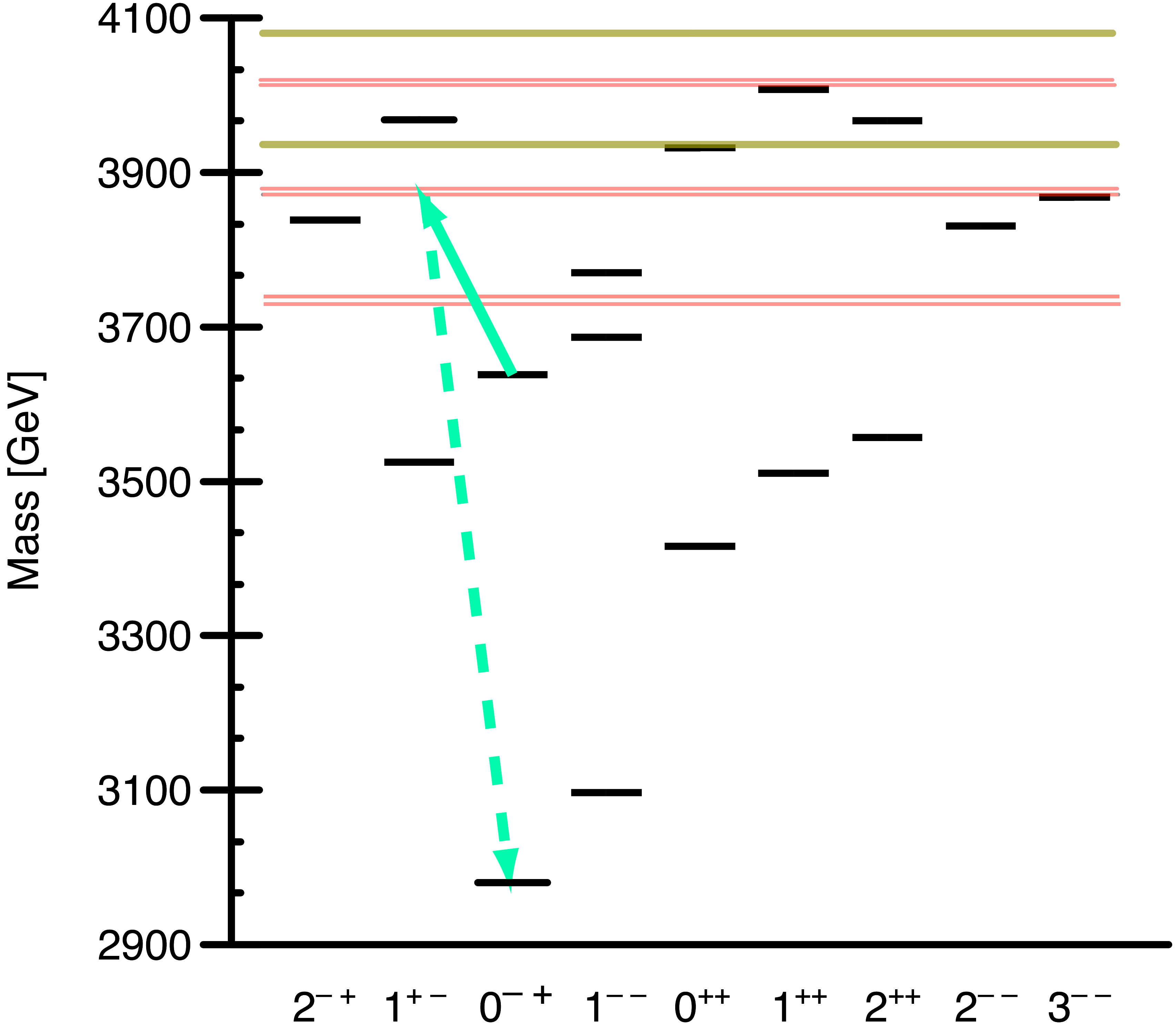
3100
2900
Mass [GeV]
2^{-+}
1^{+-}
0^{-+}
1^{--}
0^{++}
1^{++}
2^{++}
2^{--}
3^{--}


4100
3900
3700
3500
3300
3100
2900
Mass [GeV]
2^{-+}
1^{+-}
0^{-+}
1^{--}
0^{++}
1^{++}
2^{++}
2^{--}
3^{--}

Effects on the spectrum

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

State	Mass	Centroid	Splitting (Potential)	Splitting (Induced)
1^1S_0	2 979.9[a]	3 067.6[b]	−90.5	+2.8
1^3S_1	3 096.9[a]		+30.2	−0.9
1^3P_0	3 415.3[a]	3 525.3[c]	−114.9[e]	+5.9
1^3P_1	3 510.5[a]		−11.6[e]	−2.0
1^1P_1	3 525.3		+1.5[e]	+0.5
1^3P_2	3 556.2[a]		−31.9[e]	−0.3
2^1S_0	3 637.7[a]	3 673.9[b]	−50.4	+15.7
2^3S_1	3 686.0[a]		+16.8	−5.2
1^3D_1	3 769.9[a b]	(3 815)[d]	−40	−39.9
1^3D_2	3 830.6		0	−2.7
1^1D_2	3 838.0		0	+4.2
1^3D_3	3 868.3		+20	+19.0
2^3P_0	3 931.9	3 968[d]	−90	+10
2^3P_1	4 007.5		−8	+28.4
2^1P_1	3 968.0		0	−11.9
2^3P_2	3 966.5		+25	−33.1

ELQ, hep-ph/0401210

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

Hyperfine splitting:

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

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

$$\boxed{\Rightarrow M(\psi') - M(\eta_c') = 67 \text{ MeV}}$$

$(48.3 \pm 4.4 \text{ MeV observed})$

20.9 MeV induced shift ⇒ agrees

Suppression of radiative decay rates

(reduced overlap between initial & final states)

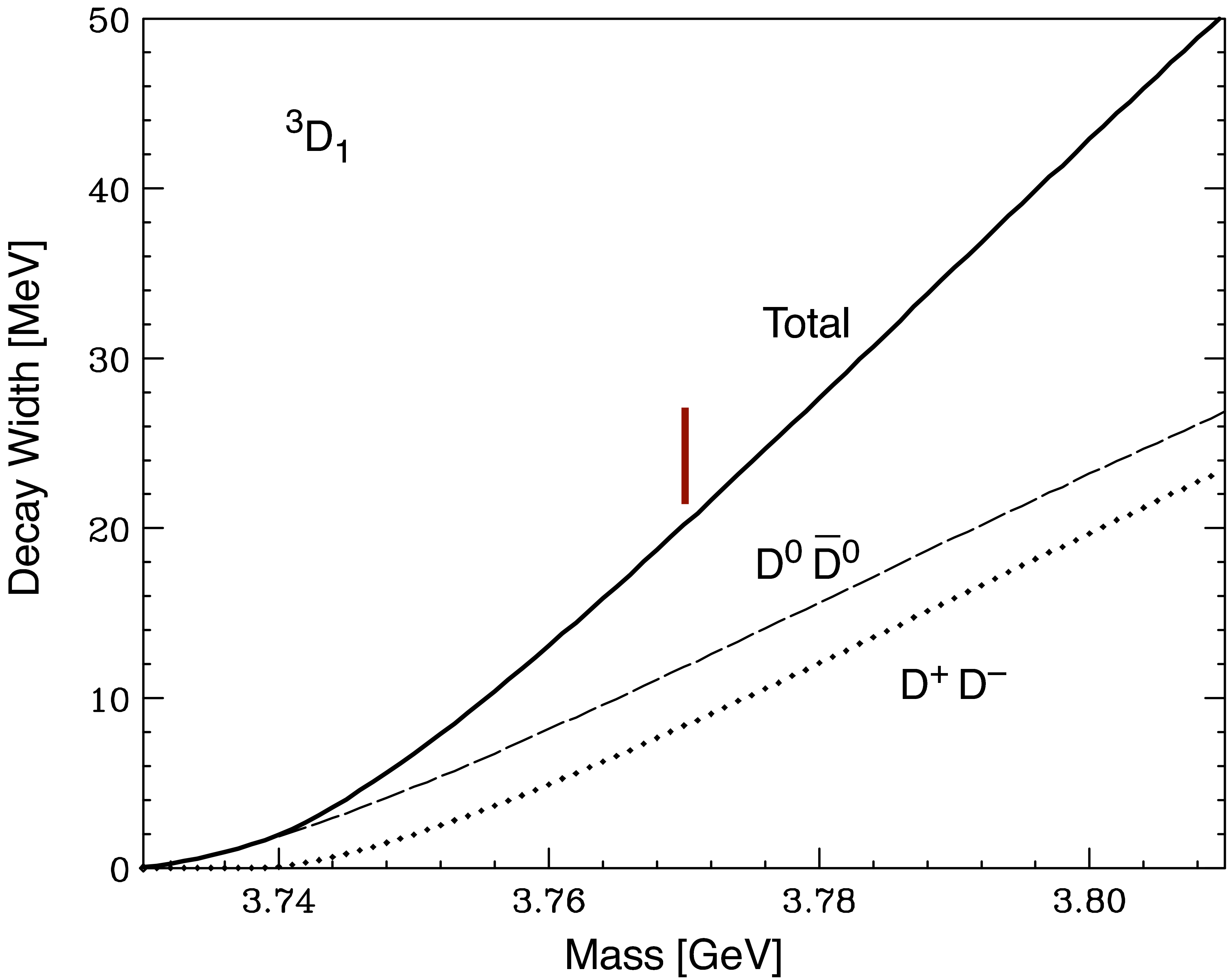
$$\Psi(1^3\mathrm{S}_1) = 0.983\,|1^3\mathrm{S}_1\rangle - 0.050\,|2^3\mathrm{S}_1\rangle - 0.009\,|3^3\mathrm{S}_1\rangle + \ldots;\ 96.8\%(c\bar{c})$$

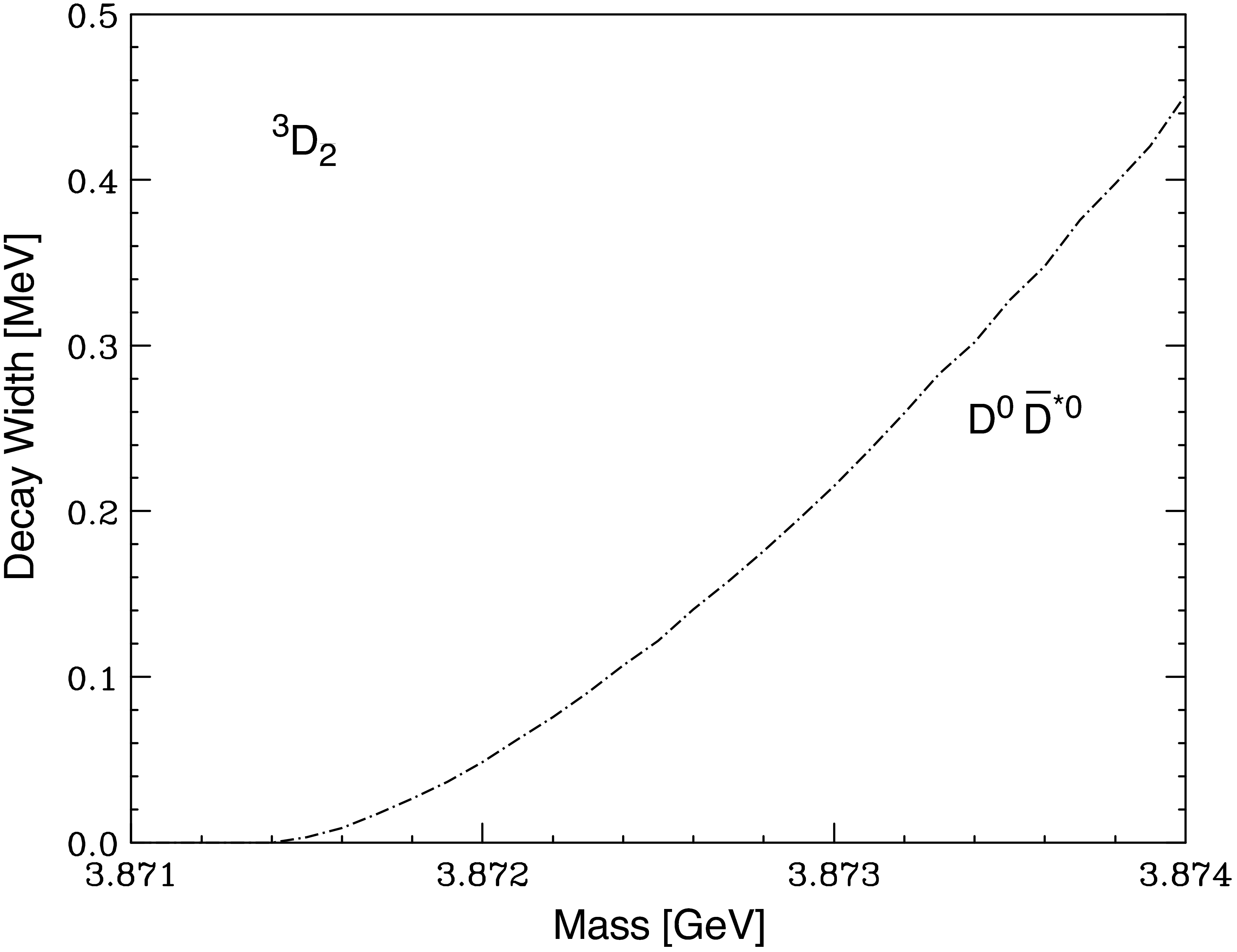
$$\Psi(1^3\mathrm{P}_1) = 0.914\,|1^3\mathrm{P}_1\rangle - 0.075\,|2^3\mathrm{P}_1\rangle - 0.015\,|3^3\mathrm{P}_1\rangle + \ldots;\ 84.1\%(c\bar{c})$$

$$\Psi(1^3\mathrm{D}_2) = 0.754\,|1^3\mathrm{D}_2\rangle - 0.084\,|2^3\mathrm{D}_2\rangle - 0.011\,|3^3\mathrm{D}_2\rangle + \ldots;\ 57.6\%(c\bar{c})$$

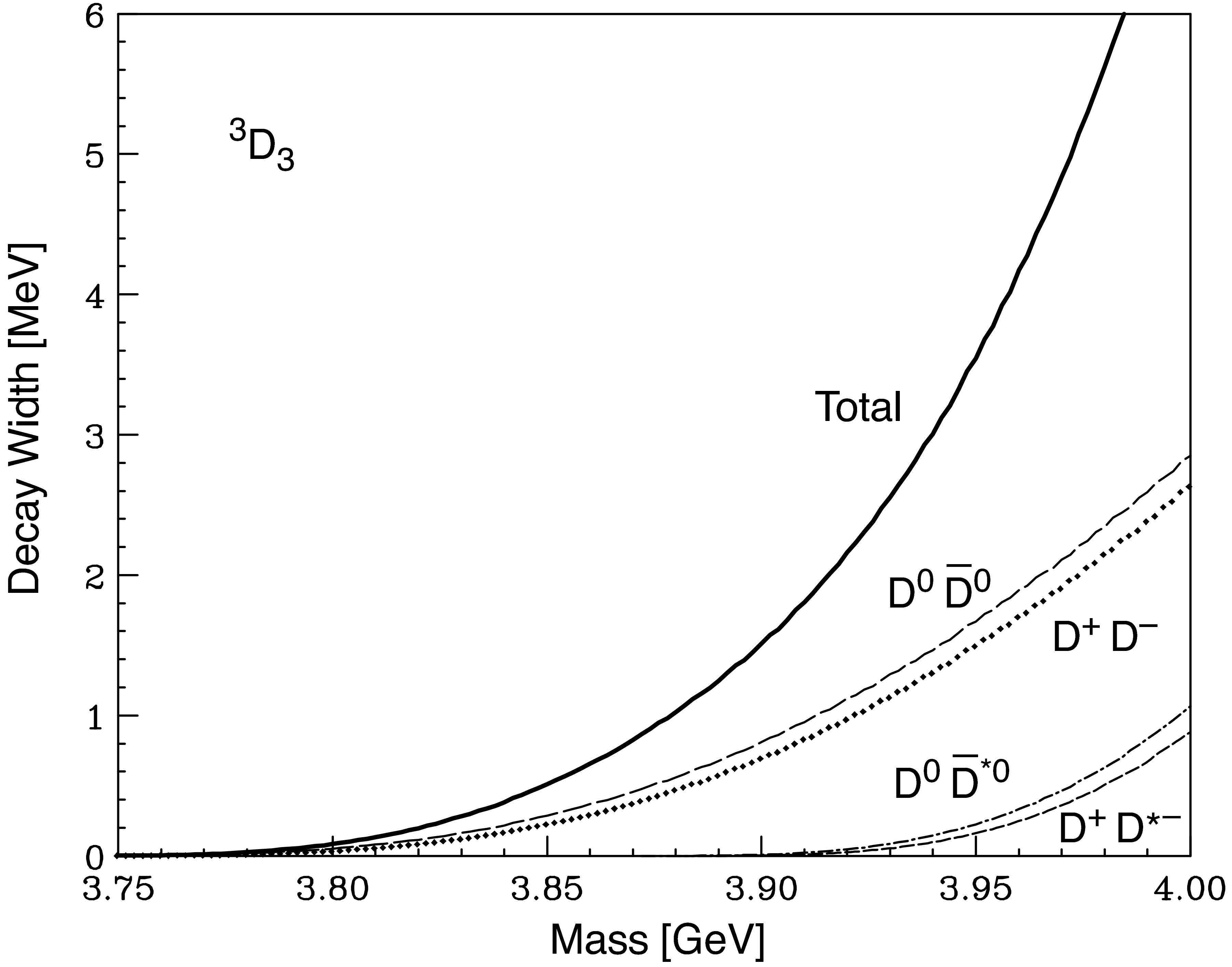
Transition (γ energy in MeV)	Partial width (keV) Computed
$1^3\mathrm{D}_1(3770) \rightarrow \chi_{c0}\,\gamma(338)$	$\mathit{254} \rightarrow 225$
$1^3\mathrm{D}_2(3831) \rightarrow \chi_{c2}\,\gamma(266)$	$\mathit{59} \rightarrow 45$
$1^3\mathrm{D}_2(3831) \rightarrow \chi_{c1}\,\gamma(308)$	$\mathit{264} \rightarrow 212$
$1^3\mathrm{D}_2(3872) \rightarrow \chi_{c2}\,\gamma(303)$	$\mathit{85} \rightarrow 45$
$1^3\mathrm{D}_2(3872) \rightarrow \chi_{c1}\,\gamma(344)$	$\mathit{362} \rightarrow 207$
$1^3\mathrm{D}_3(3868) \rightarrow \chi_{c2}\,\gamma(303)$	$\mathit{329} \rightarrow 286$
$1^3\mathrm{D}_3(3872) \rightarrow \chi_{c2}\,\gamma(304)$	$\mathit{341} \rightarrow 299$

Decays into open charm





0.5
0.4
0.3
0.2
0.1
0.0
Decay Width [MeV]
$^3D_2$
$D^0\,\bar{D}^{*0}$
3.871
3.872
3.873
3.874
Mass [GeV]


$^3D_3$
Total
$D^0\,\bar{D}^0$
$D^+\,D^-$
$D^0\,\bar{D}^{*0}$
$D^+\,D^{*-}$
Decay Width [MeV]
0
1
2
3
4
5
6
Mass [GeV]
3.75
3.80
3.85
3.90
3.95
4.00

Near 3872 MeV

$$\Gamma(1^3\mathrm{D}_2 \to \mathrm{D}^0\bar{\mathrm{D}}^{*0}) \approx \Gamma(1^3\mathrm{D}_2 \to \pi\pi J/\psi)$$

$$\Gamma(1^3\mathrm{D}_3 \to \pi^+\pi^- J/\psi) \leq \tfrac{1}{4}\Gamma(1^3\mathrm{D}_3 \to \mathrm{D}\bar{\mathrm{D}})$$

$$\Gamma(1^3\mathrm{D}_3 \to \gamma\chi_{c2}) \approx \tfrac{1}{3}\Gamma(1^3\mathrm{D}_3 \to \mathrm{D}\bar{\mathrm{D}})$$

Belle:

$$\mathcal{B}(\mathrm{X} \to \mathrm{D}^0\bar{\mathrm{D}}^0) \leq 4\mathcal{B}(\mathrm{X} \to \pi^+\pi^- J/\psi)$$

$$\mathcal{B}(\mathrm{X} \to \mathrm{D}^+\mathrm{D}^-) \leq 3\mathcal{B}(\mathrm{X} \to \pi^+\pi^- J/\psi)$$

Sensitivity already approaches interesting range

Could X(3872) be 2^1P_1?

Radiative decay would be hindered M1

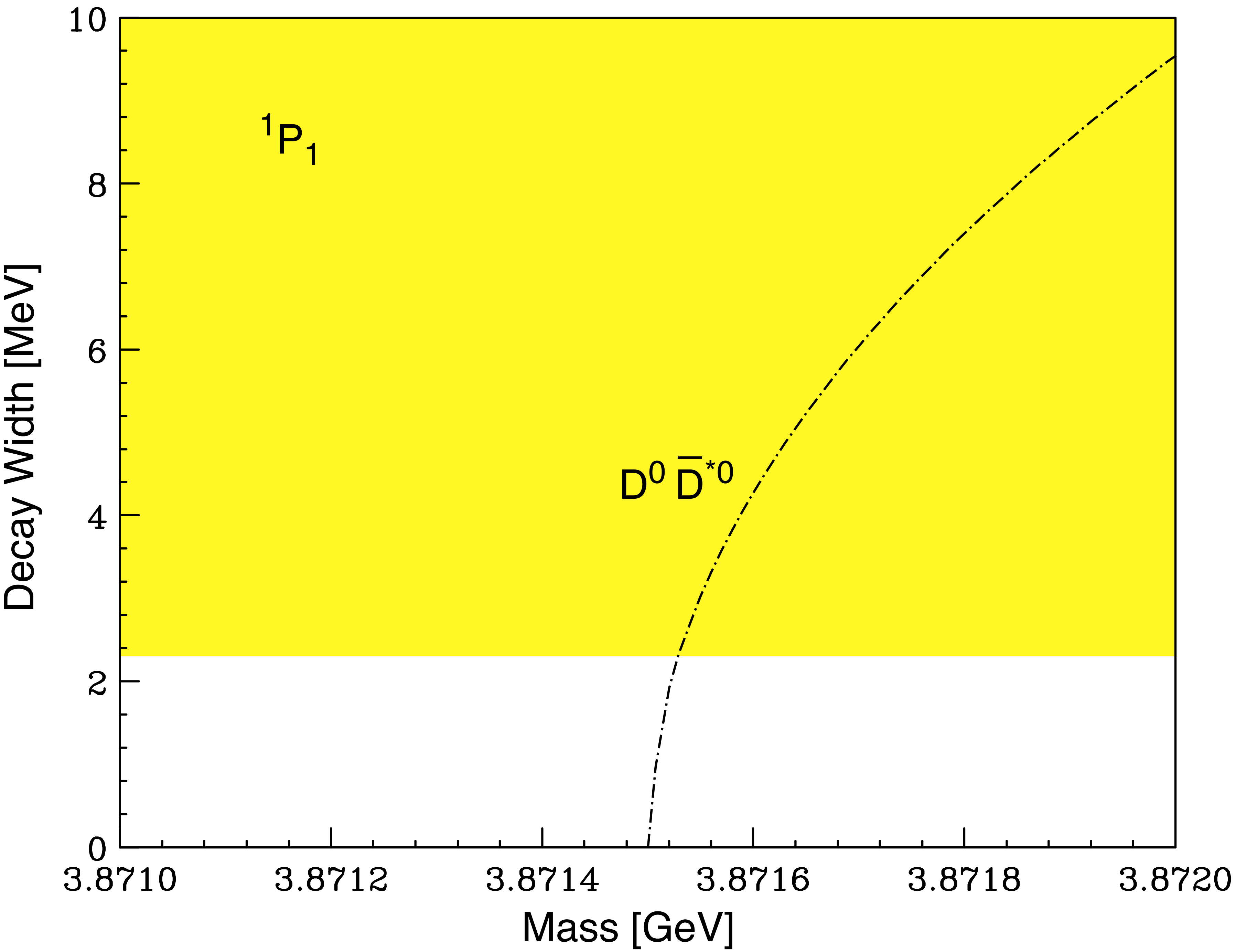
(Could explain small radiative BR)

Belle: decay angular distribution disfavors

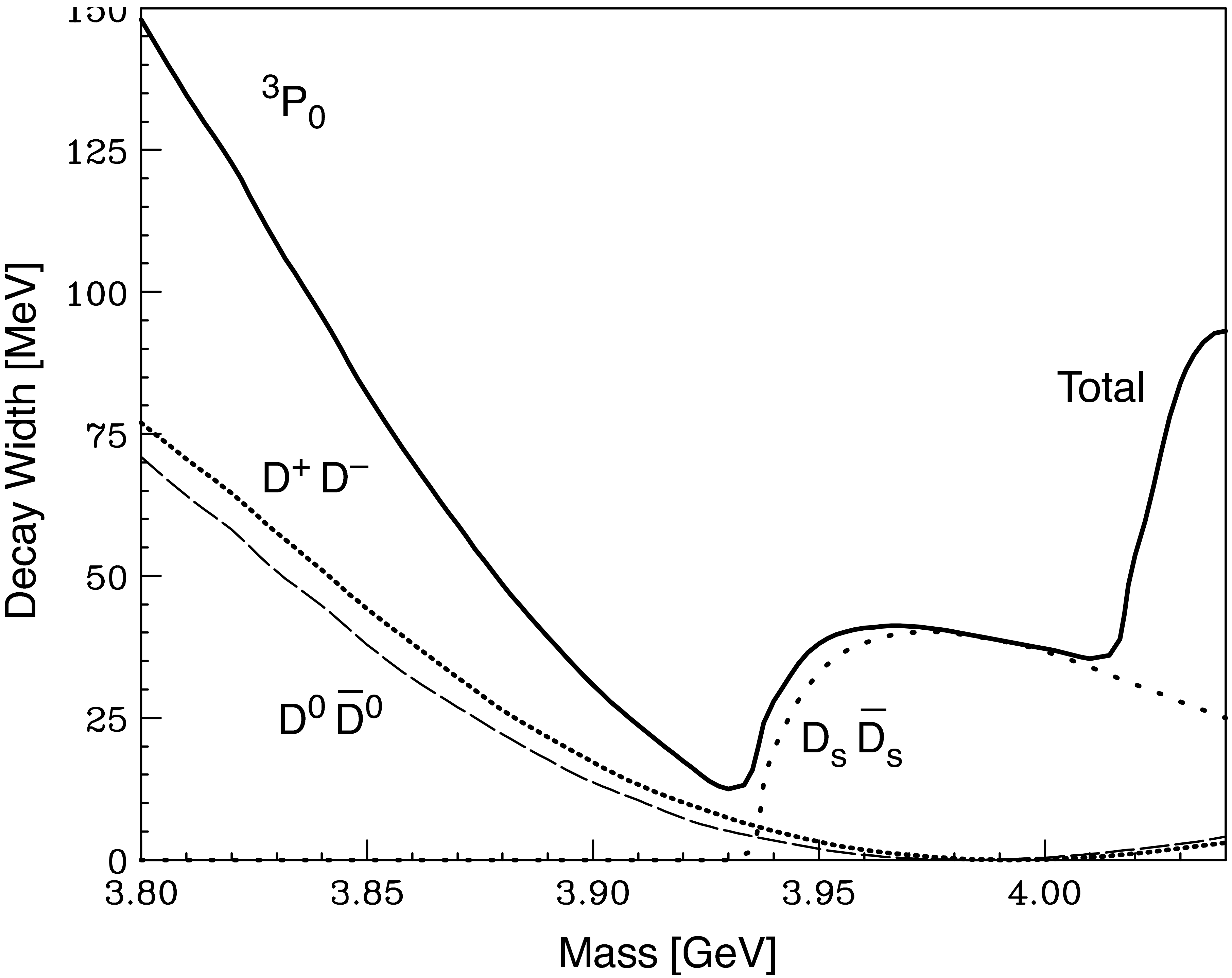
Strong cascade: s-wave ππ by L=1 (not 2)

Seems improbable: 100 MeV above $D^0\bar{D}^{*0}$ in coupled-channel model;

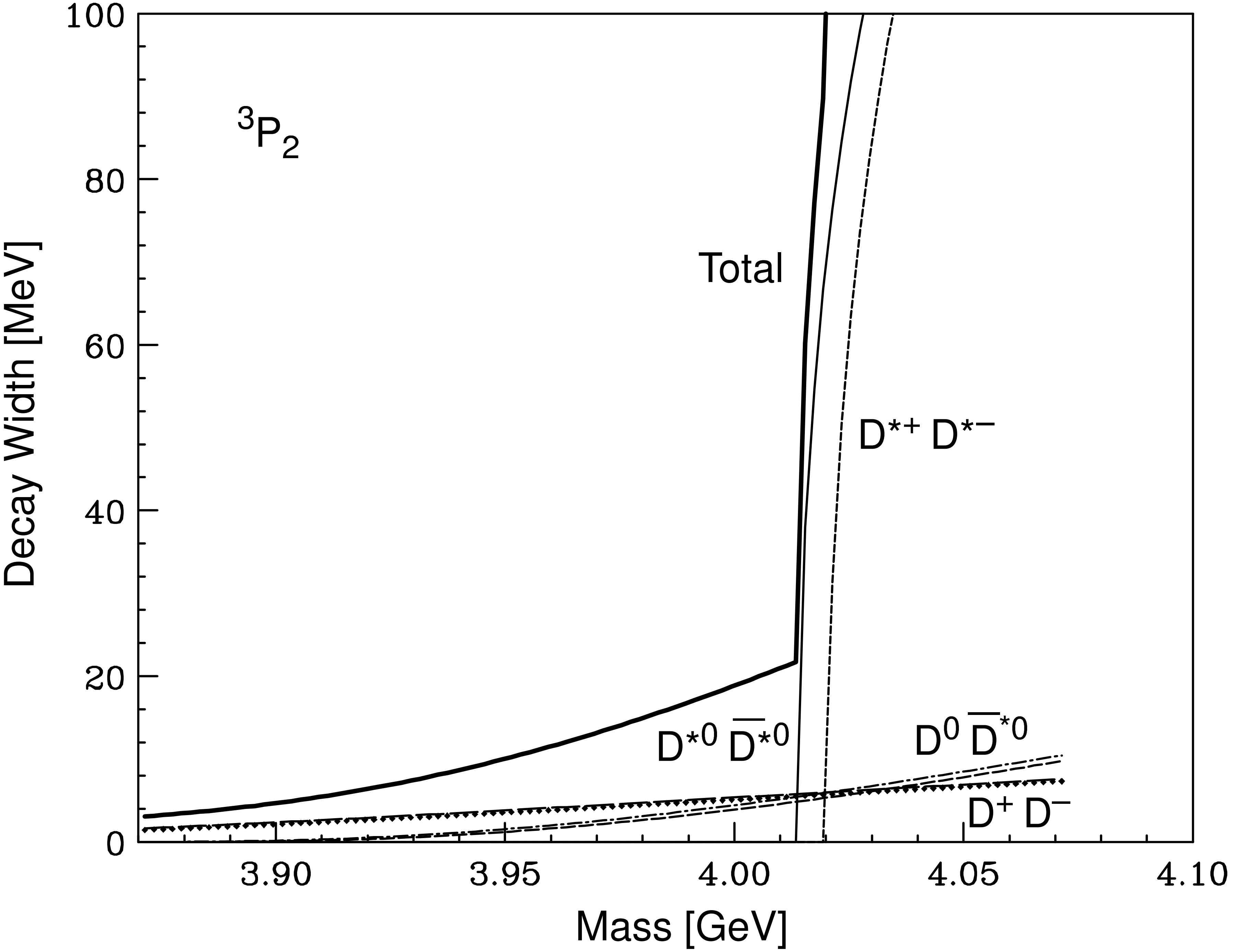
Likely to be too broad if DD* open

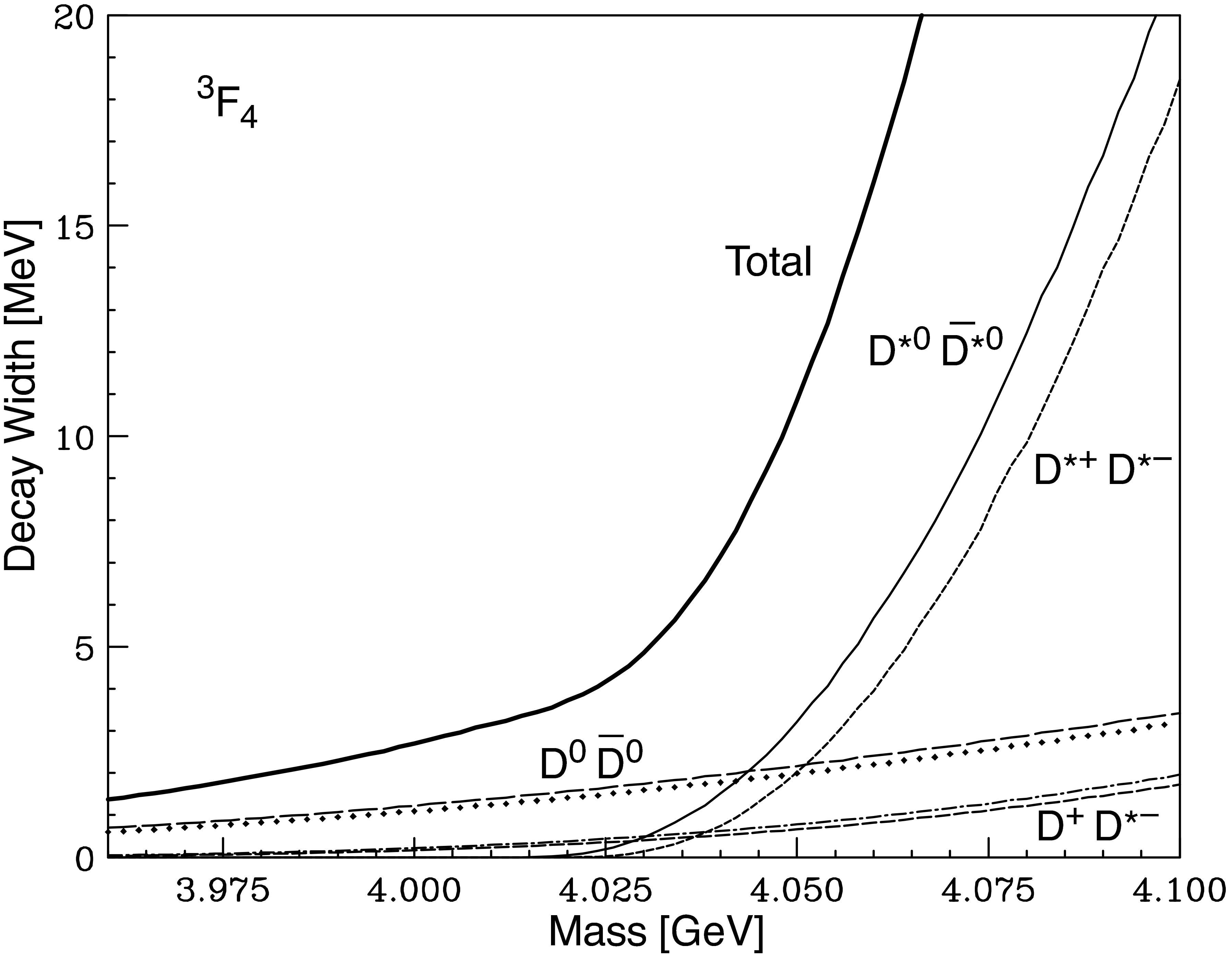


Decay Width [MeV]
10
8
6
4
2
0
$^1P_1$
$D^0\,\bar{D}^{*0}$
3.8710
3.8712
3.8714
3.8716
3.8718
3.8720
Mass [GeV]

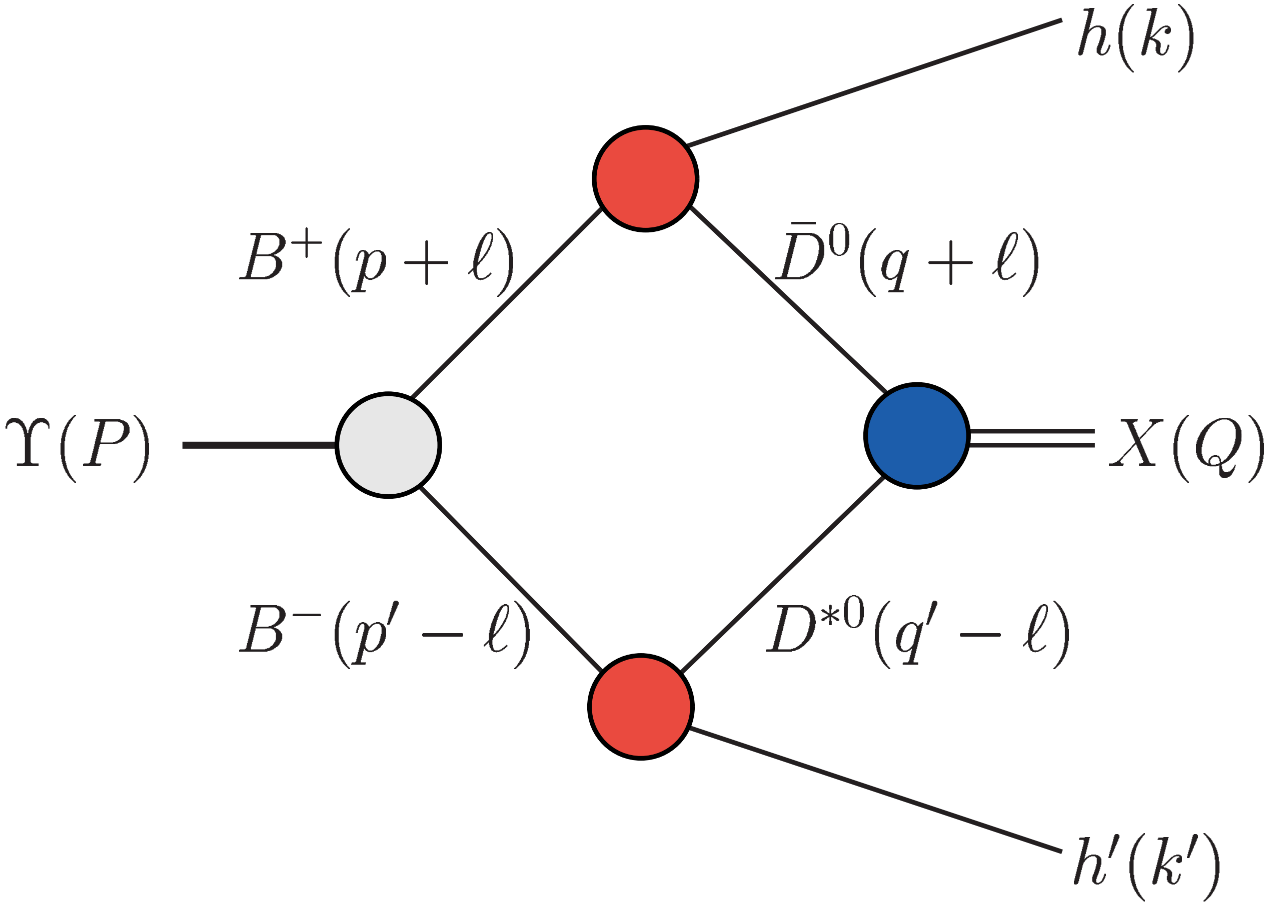


Decay Width [MeV]
150
125
100
75
50
25
0
3.80
3.85
3.90
3.95
4.00
Mass [GeV]
$^3P_0$
Total
$D^+ D^-$
$D^0 \bar{D}^0$
$D_s \bar{D}_s$


$^3P_2$
Total
$D^{*+}D^{*-}$
$D^{*0}\bar{D}^{*0}$
$D^0\bar{D}^{*0}$
D^+D^-
Decay Width [MeV]
0
20
40
60
80
100
Mass [GeV]
3.90
3.95
4.00
4.05
4.10


$^3F_4$
Total
$D^{*0}\,\bar{D}^{*0}$
$D^{*+}\,D^{*-}$
$D^0\,\bar{D}^0$
$D^+\,D^{*-}$
Decay Width [MeV]
Mass [GeV]
20
15
10
5
0
3.975
4.000
4.025
4.050
4.075
4.100

Production of DD* molecule by fusion



$$\frac{\Gamma(\Upsilon(4S) \to X h h')}{\Gamma(\Upsilon(4S) \to D^0 \bar{D}^{*0} h h') + \Gamma(\Upsilon(4S) \to \bar{D}^0 D^{*0} h h')} \approx 10^{-24}$$

Braaten & Kusunoki, hep-ph/0402177

Following up X(3872)

Verify I=0: look for charged partner, check dipion angular distribution, see $\pi^0\pi^0$

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

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

Measure prompt vs *B*-decay at CDF, DØ

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 $J/\psi + (\pi^\pm, \eta, K^\pm, K_S, p, \Lambda, \ldots)$

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

Similar studies in $b\bar{b}$

Theoretical work needed

Charmonium: understand threshold influence ✔

understand production

improve understanding of hadron cascades

compare Υ family

Theoretical work needed

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

Molecular charmonium: production rates, decay patterns

Lattice: surpass the potential model

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

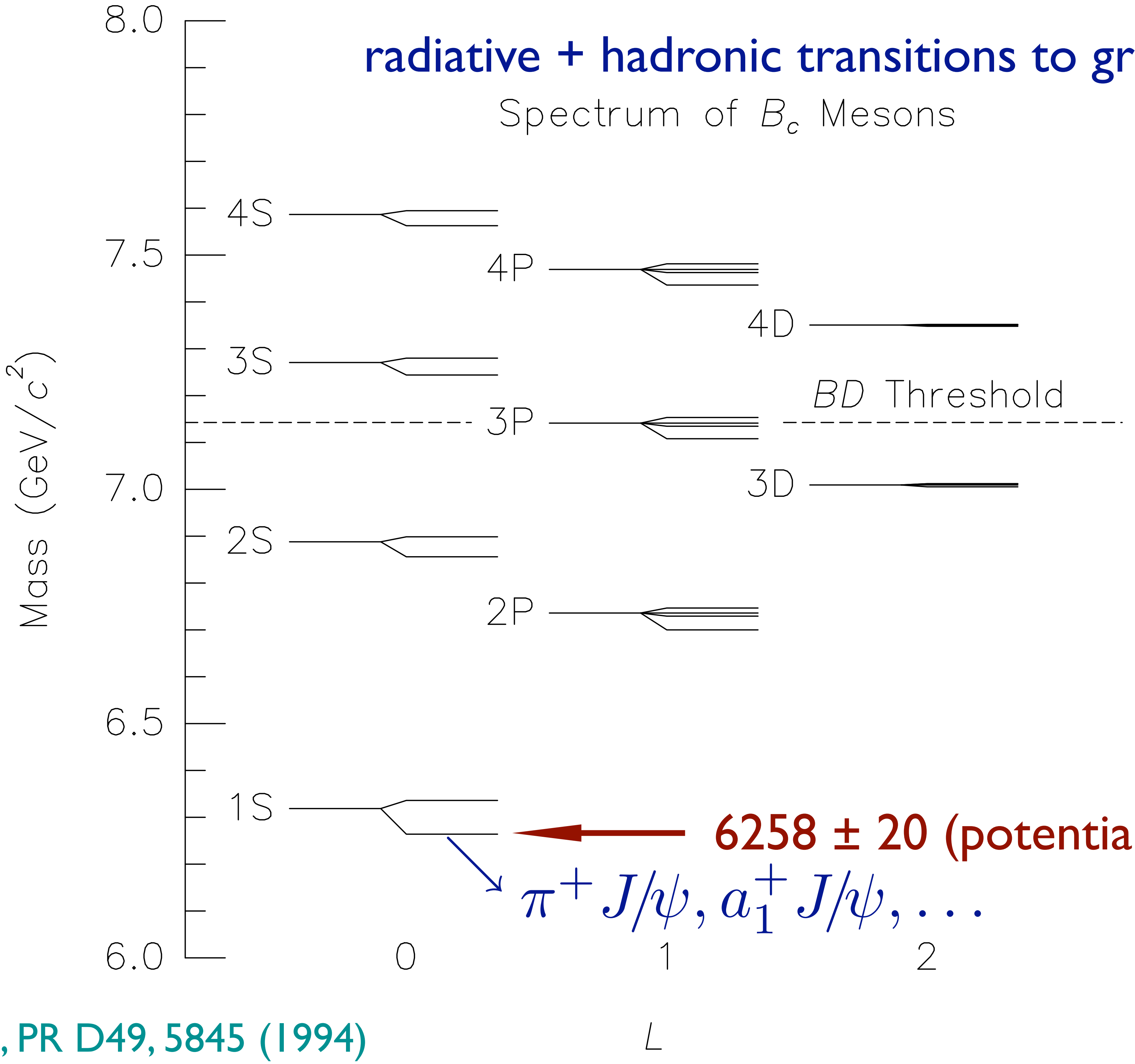
If charmonium, find other states,
advance beyond one-channel NRQM

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

If not charmonium, a new kind of spectroscopy

(Charmonium states still await discovery)

The Next Wave: $b\bar{c}$ Spectroscopy



radiative + hadronic transitions to ground state

6258 ± 20 (potential model)

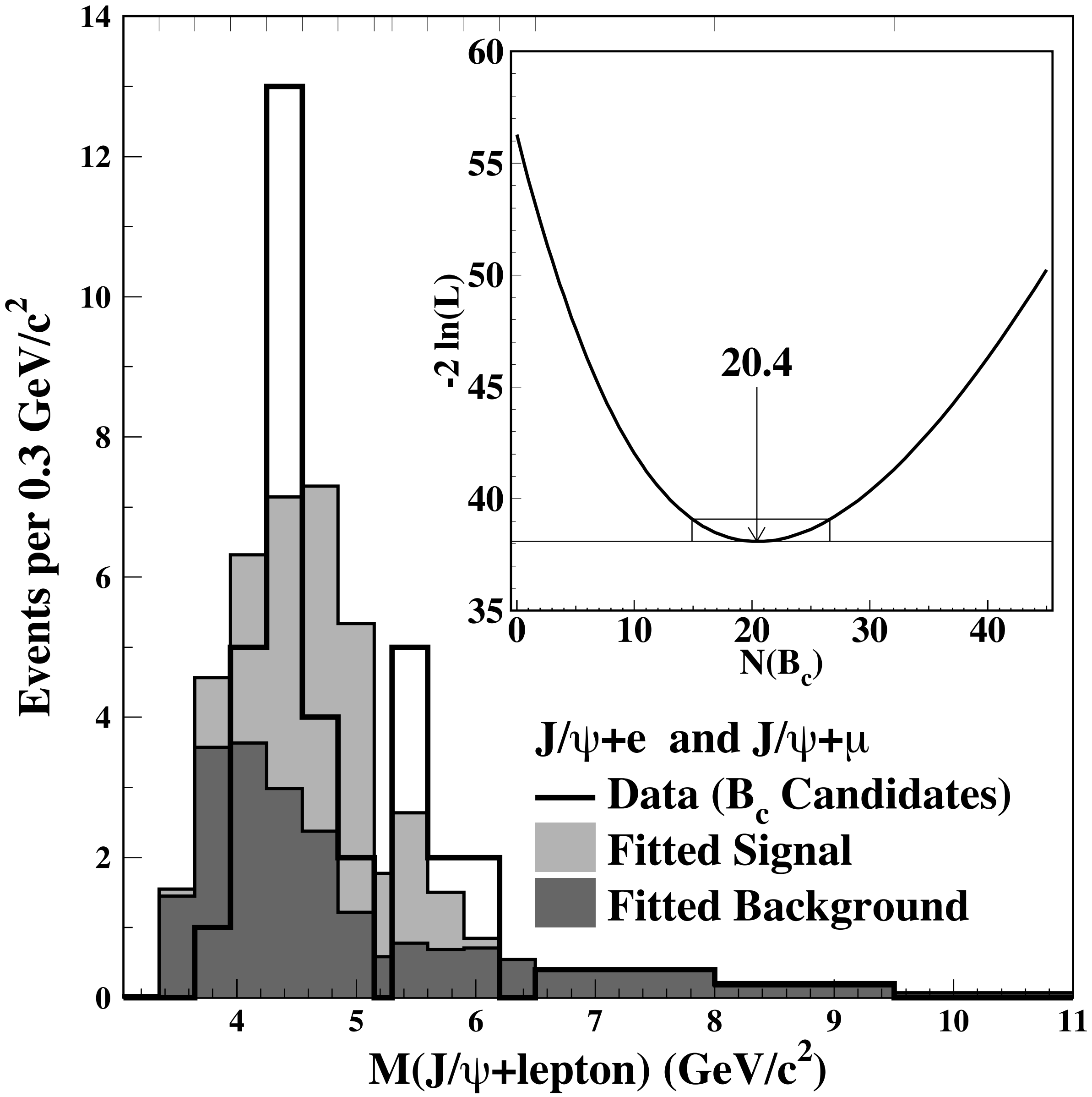
$\pi^+ J/\psi, a_1^+ J/\psi, \ldots$

Eichten & Quigg, PR D49, 5845 (1994)

Reasons for Interest …

- Experimental tour-de-force
- Third quarkonium system
- Intermediate between heavy-heavy and heavy-light mesons
- Sensitive to relativistic effects, configuration mixing
- Rich pattern of weak decays (*b* decay, *c* decay, annihilation)

CDF: $B_c \to J/\psi\ell(\nu)$

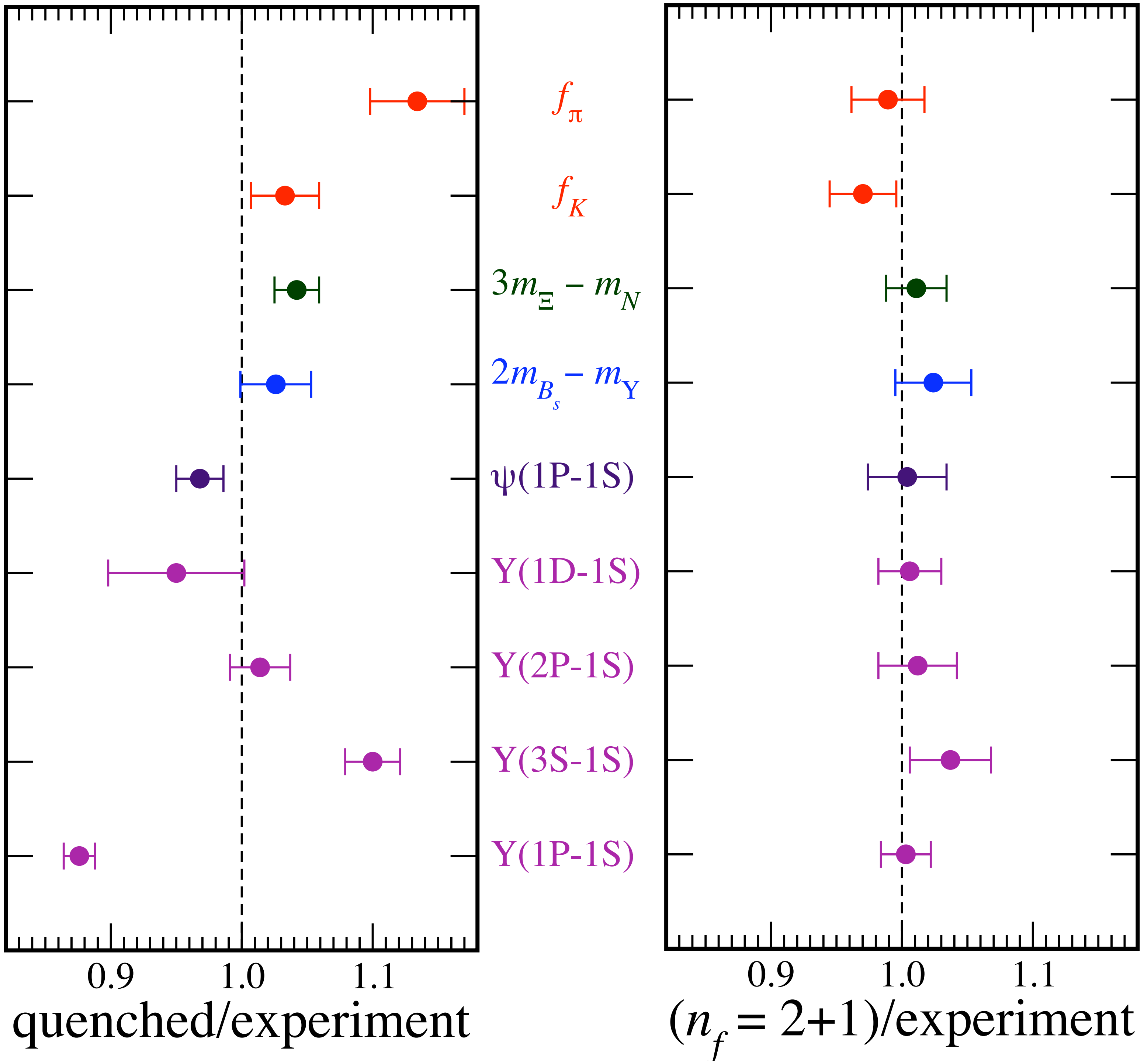


$$M(B_c) = 6.40 \pm 0.39(\text{stat.}) \pm 0.13(\text{sys.})\ \text{GeV}/c^2$$

Phys. Rev. Lett. 81, 2432 (1998)

Lattice QCD: including dynamical quarks

Davies et al., hep-lat/0304004



HPQCD [Glasgow/Fermilab]

- with quarkonium baseline (preliminary)
  - $m_{B_c} = 6.307 \pm 0.002^{+0.000}_{-0.010}$ GeV
  - systematic dominated by the B_c Darwin correction
- with heavy-light baseline (preliminary)
  - $m_{B_c} = 6.253 \pm 0.017^{+0.030\sim50}_{-0.000}$ GeV
  - systematic dominated by the D_s Darwin correction
- Further study of m^{sea} & a dependence underway

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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: Barnes & Godfrey, hep-ph/0311162; ELQ, hep-ph/0401210