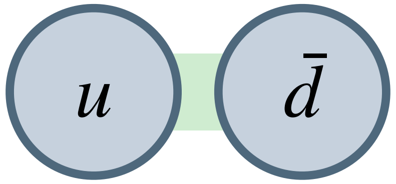
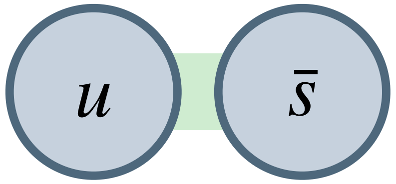
A Field Guide to the Mesons

Mainz Colloquium, April 26, 2023

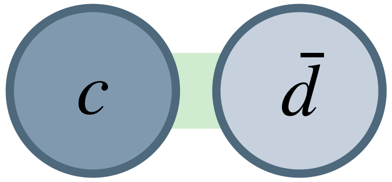
Ryan Mitchell
Indiana University



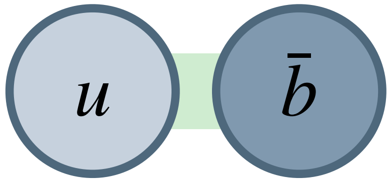
π^+ (pion)
$M \approx 140$ MeV



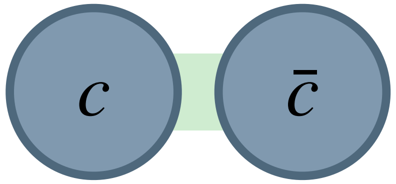
K^+ (kaon)
$M \approx 494$ MeV



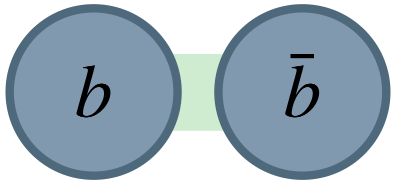
D^+ (D meson)
$M \approx 1870$ MeV



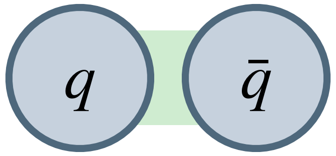
B^+ (B meson)
$M \approx 5279$ MeV



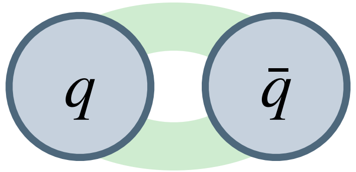
J/ψ (charmonium)
$M \approx 3097$ MeV



$\Upsilon(1S)$ (bottomonium)
$M \approx 9460$ MeV

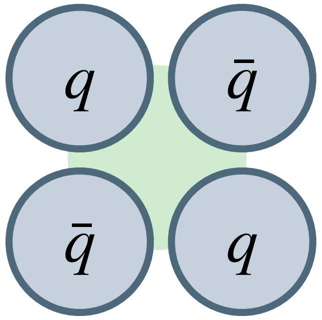


conventional meson

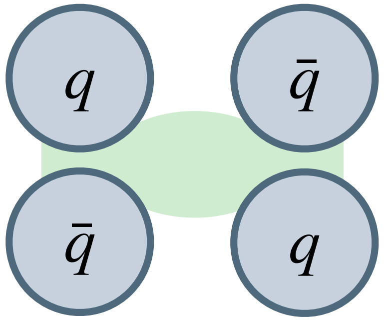


hybrid meson

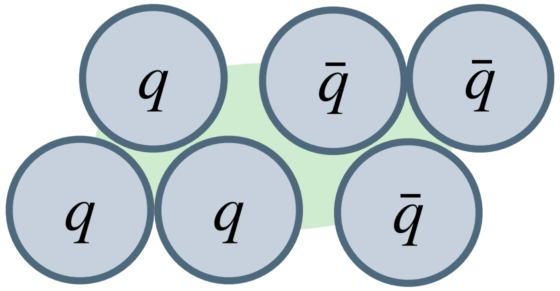
glueball



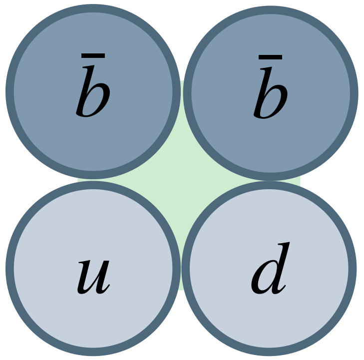
tetraquark



meson molecule

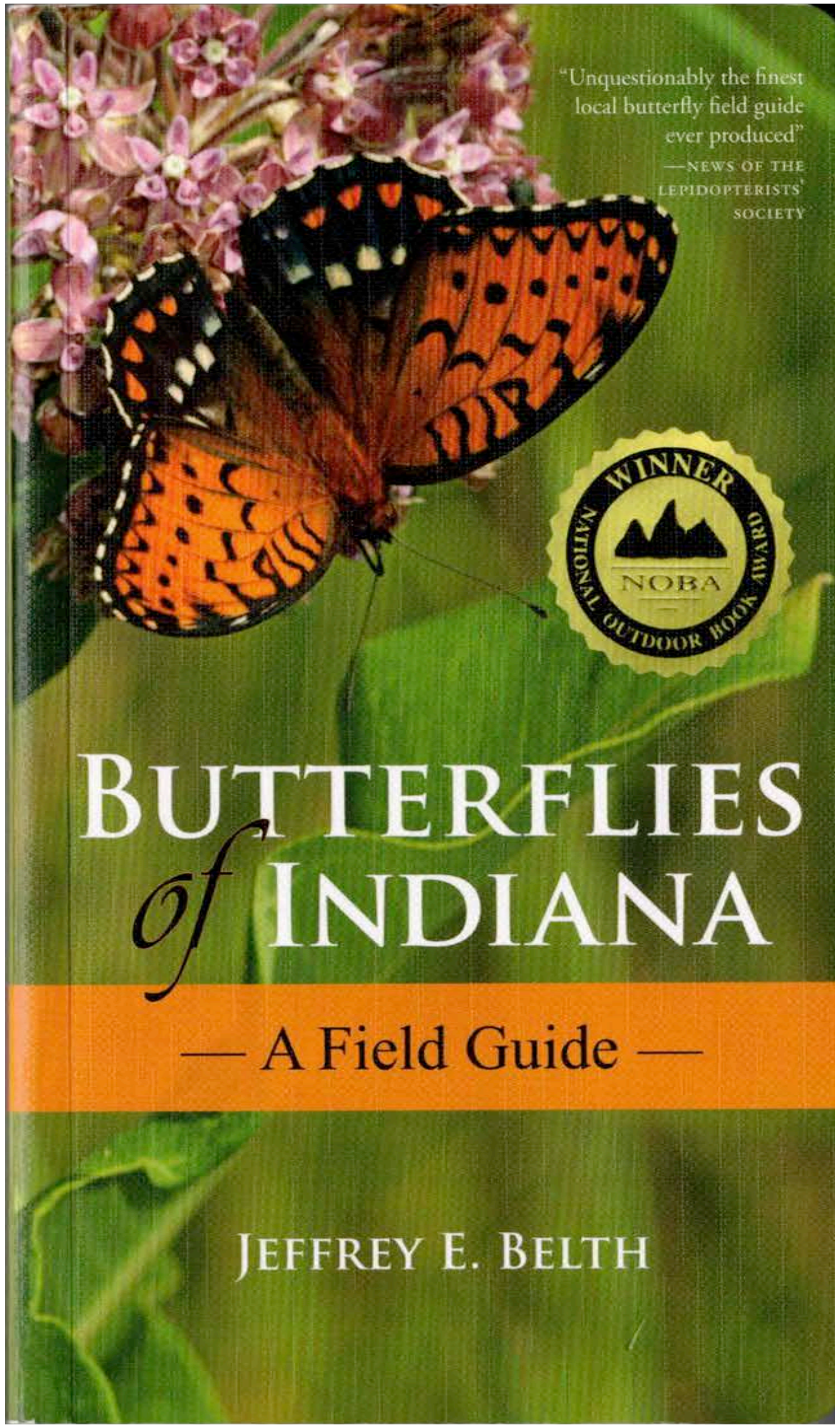


baryonium



double-bottom
tetraquark
$M \approx 10400$ MeV

The Approach of a Field Guide



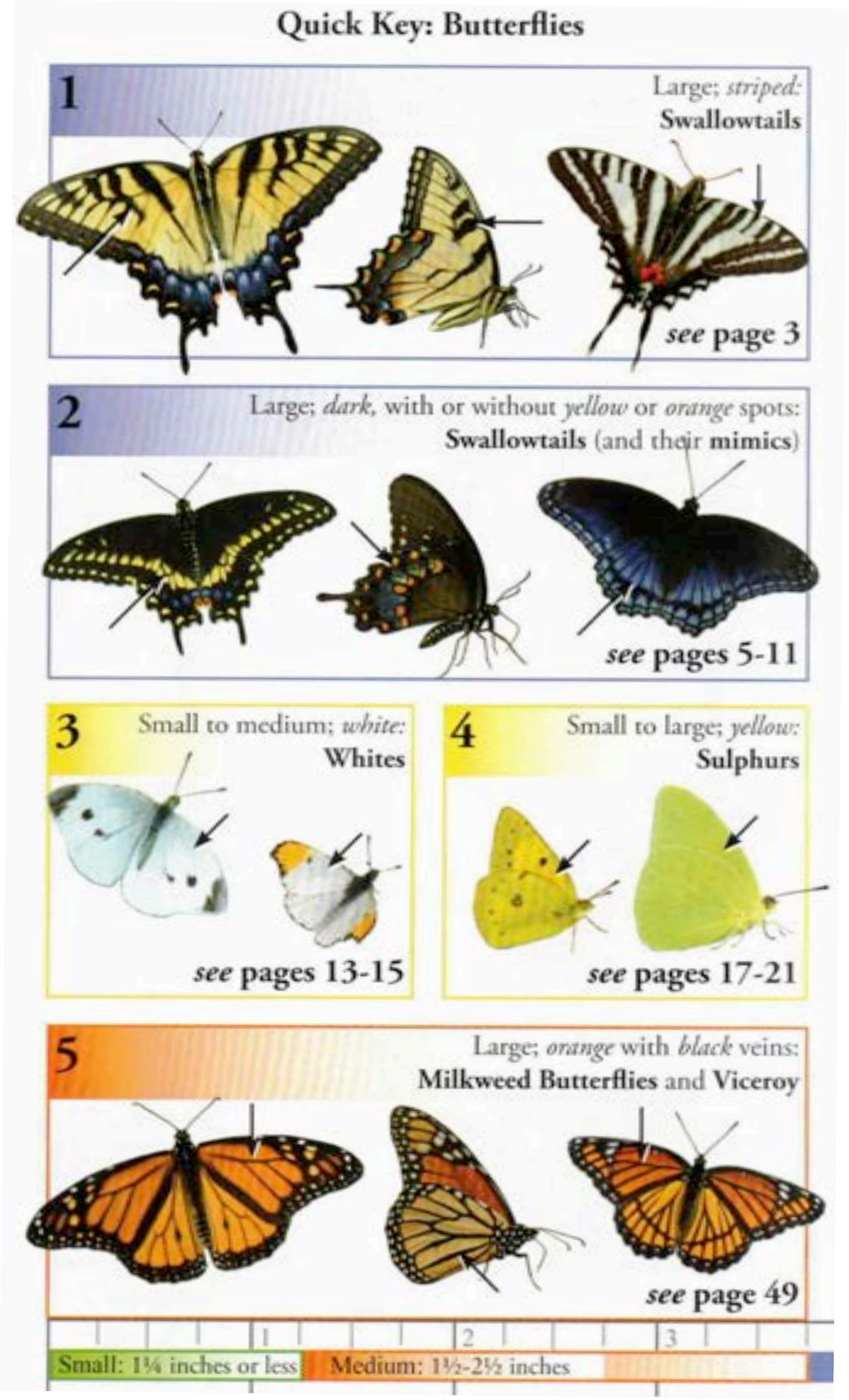
"Unquestionably the finest local butterfly field guide ever produced"
—News of the Lepidopterists' Society

WINNER
NATIONAL OUTDOOR BOOK AWARD
NOBA

BUTTERFLIES *of* INDIANA

— A Field Guide —

JEFFREY E. BELTH



Quick Key: Butterflies

1 Large; *striped:*
Swallowtails
see page 3

2 Large; *dark*, with or without *yellow* or *orange* spots:
Swallowtails (and their **mimics**)
see pages 5-11

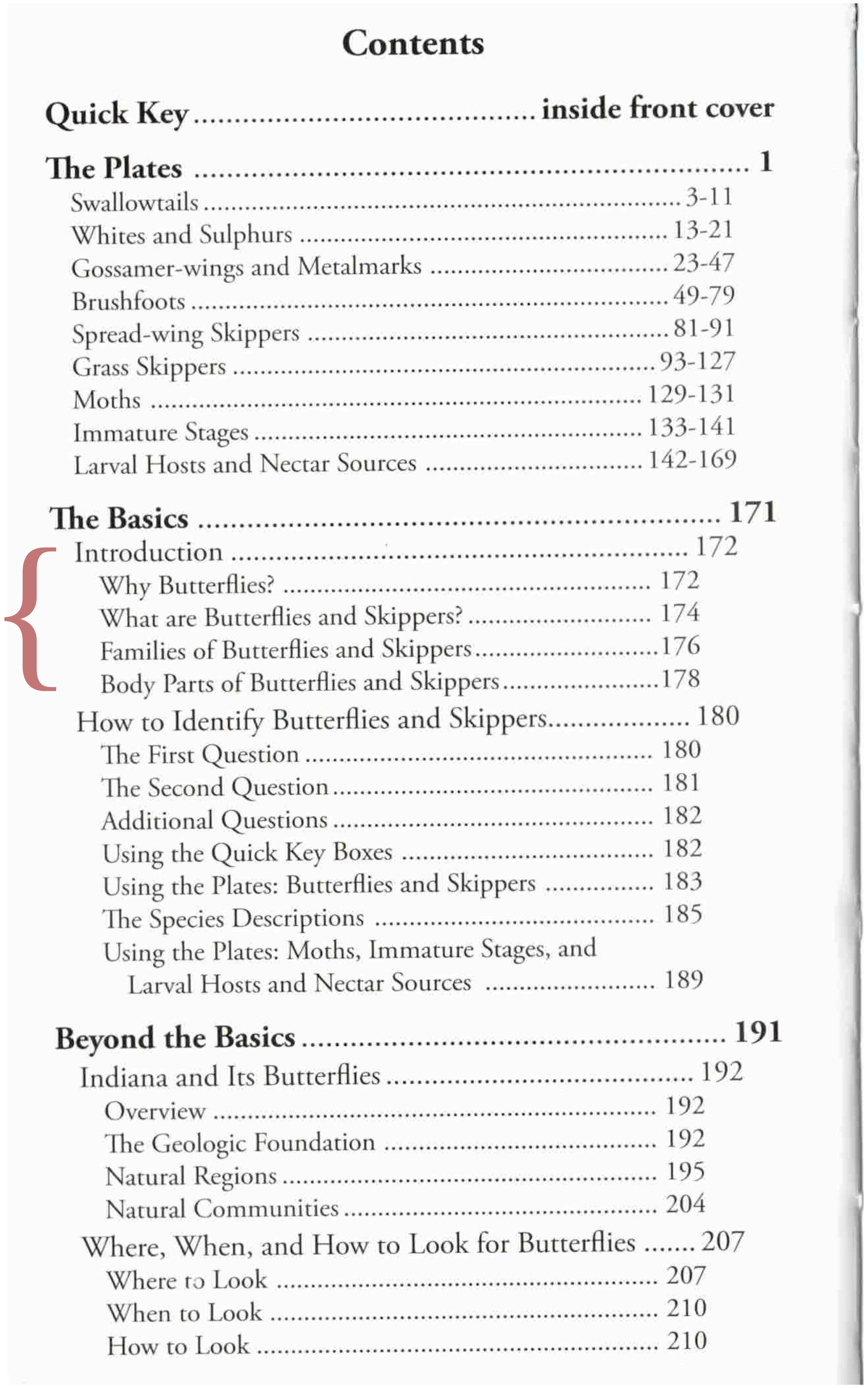
3 Small to medium; *white:*
Whites
see pages 13-15

4 Small to large; *yellow:*
Sulphurs
see pages 17-21

5 Large; *orange* with *black* veins:
Milkweed Butterflies and **Viceroy**
see page 49

Small: 1¼ inches or less
Medium: 1½-2½ inches

The Approach of a Field Guide



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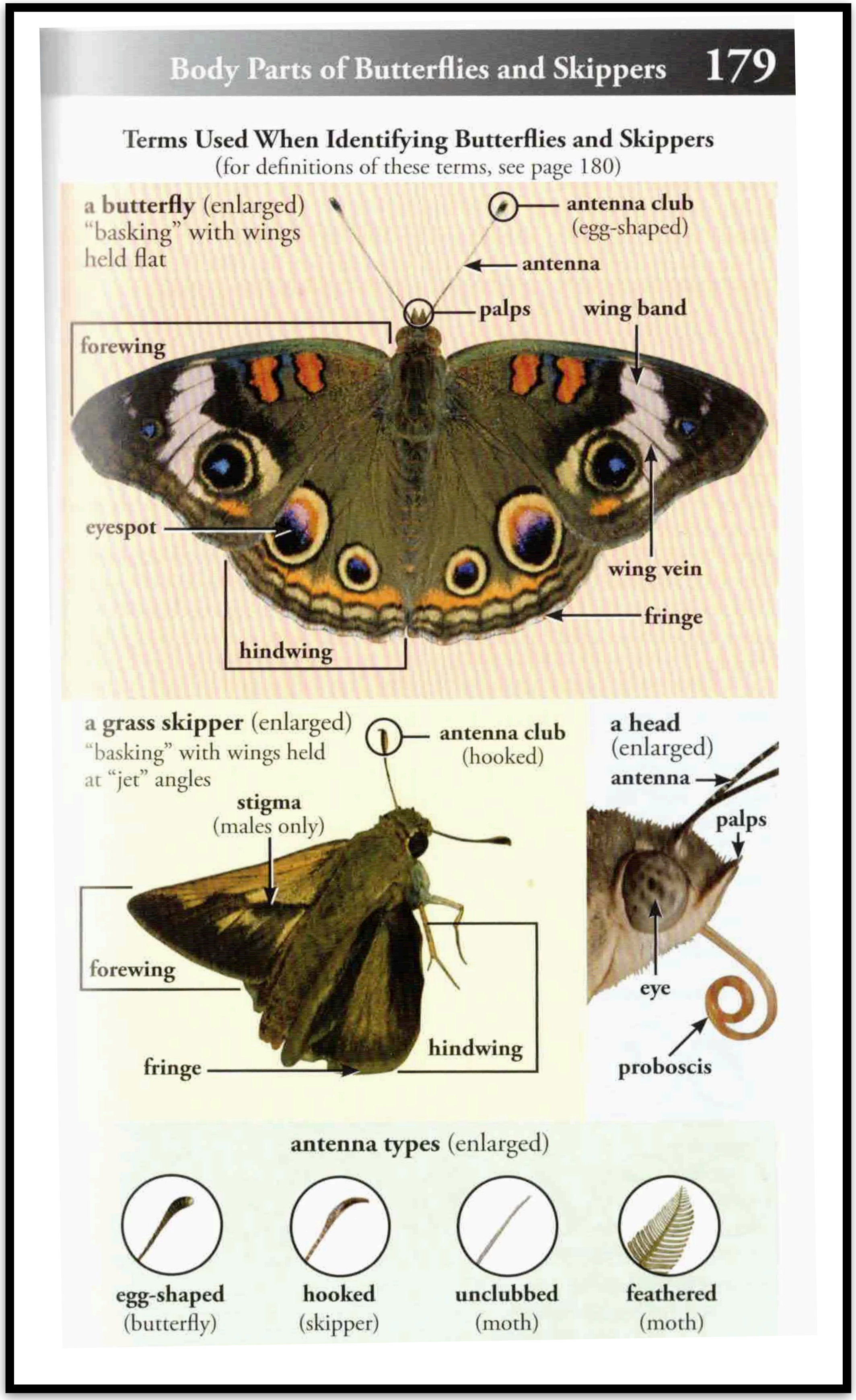
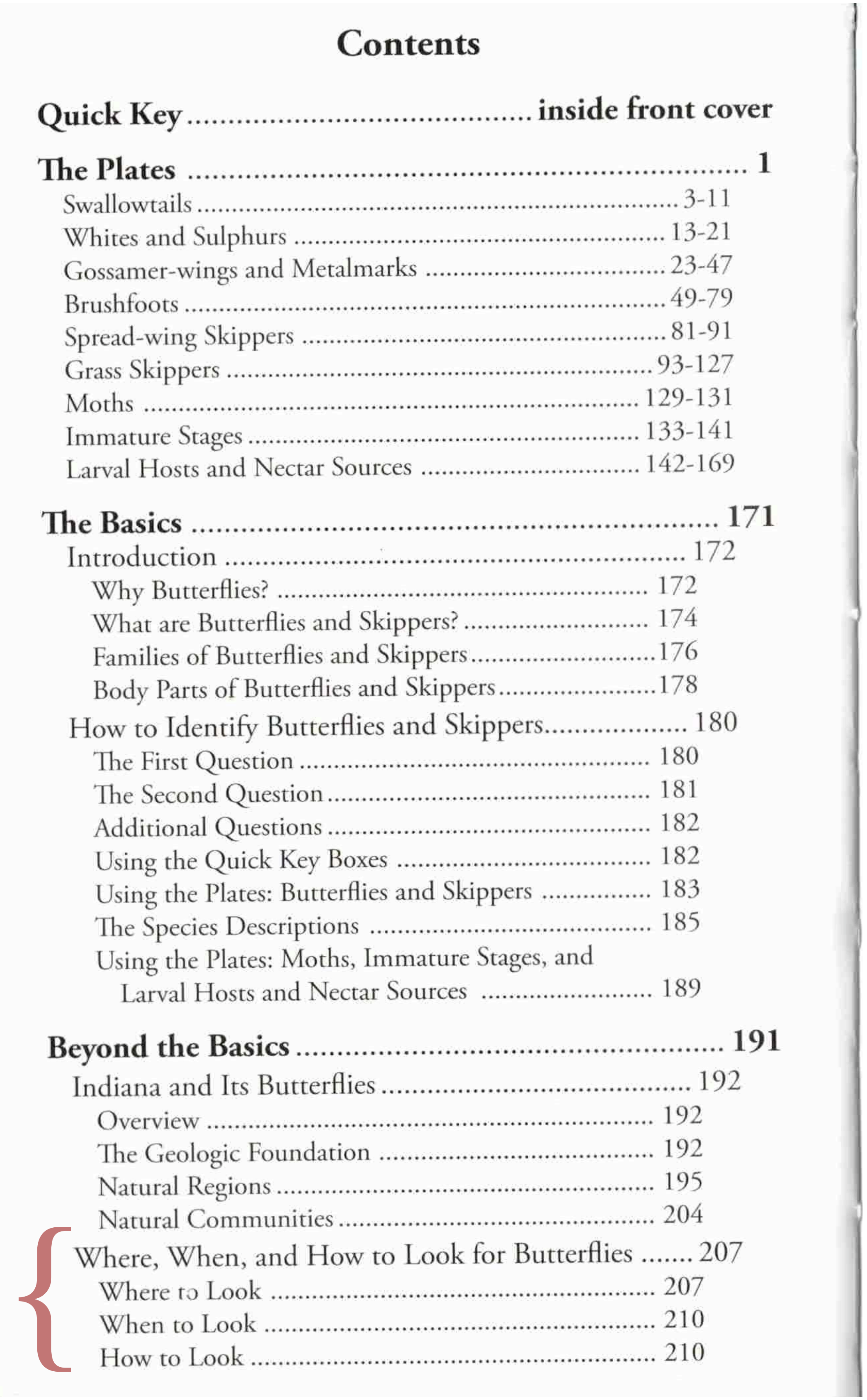


Body Parts of Butterflies and Skippers 179

Terms Used When Identifying Butterflies and Skippers
(for definitions of these terms, see page 180)

The Approach of a Field Guide



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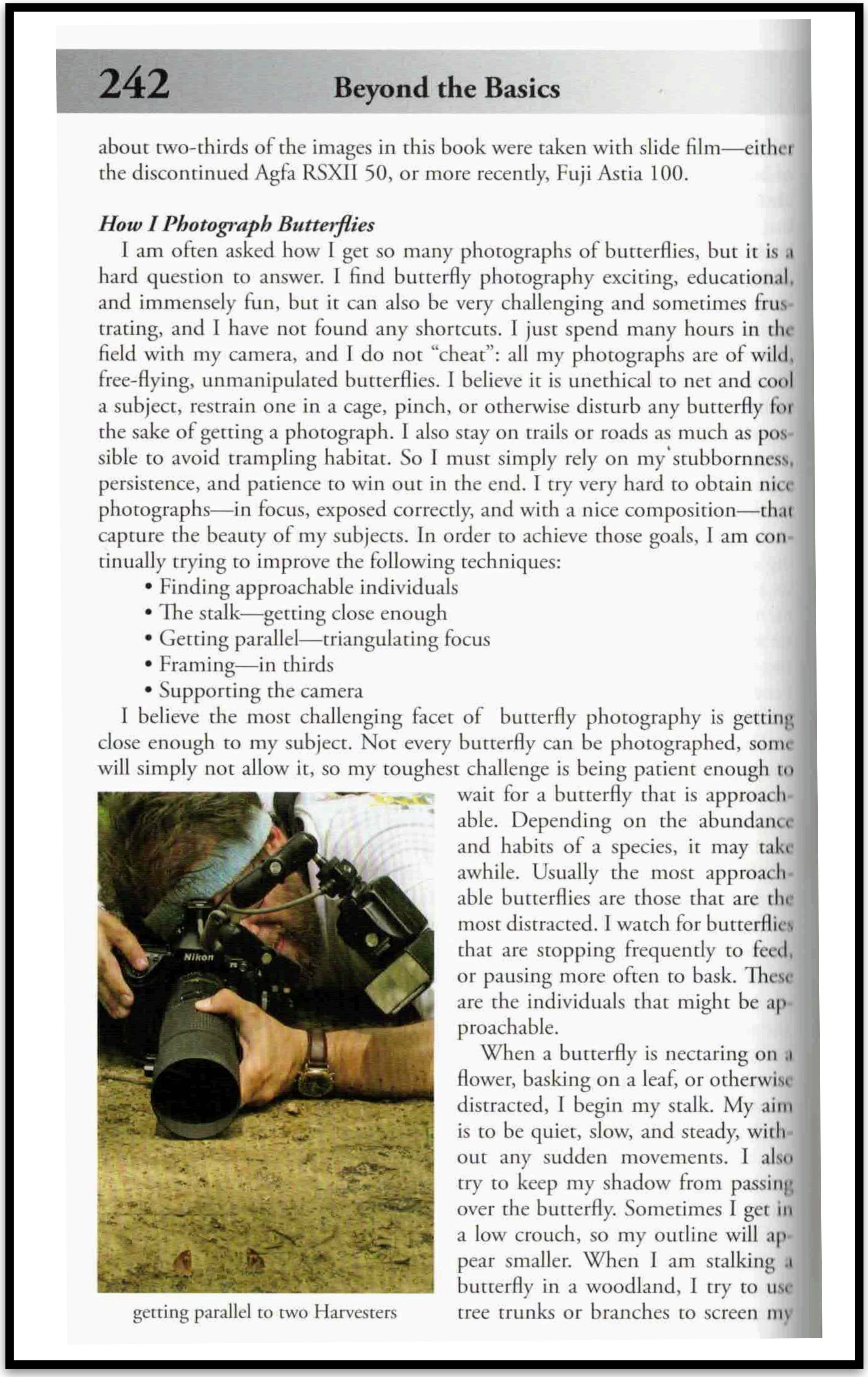


about two-thirds of the images in this book were taken with slide film—either the discontinued Agfa RSXII 50, or more recently, Fuji Astia 100.

How I Photograph Butterflies

I am often asked how I get so many photographs of butterflies, but it is a hard question to answer. I find butterfly photography exciting, educational, and immensely fun, but it can also be very challenging and sometimes frustrating, and I have not found any shortcuts. I just spend many hours in the field with my camera, and I do not "cheat": all my photographs are of wild, free-flying, unmanipulated butterflies. I believe it is unethical to net and cool a subject, restrain one in a cage, pinch, or otherwise disturb any butterfly for the sake of getting a photograph. I also stay on trails or roads as much as possible to avoid trampling habitat. So I must simply rely on my stubbornness, persistence, and patience to win out in the end. I try very hard to obtain nice photographs—in focus, exposed correctly, and with a nice composition—that capture the beauty of my subjects. In order to achieve those goals, I am continually trying to improve the following techniques:

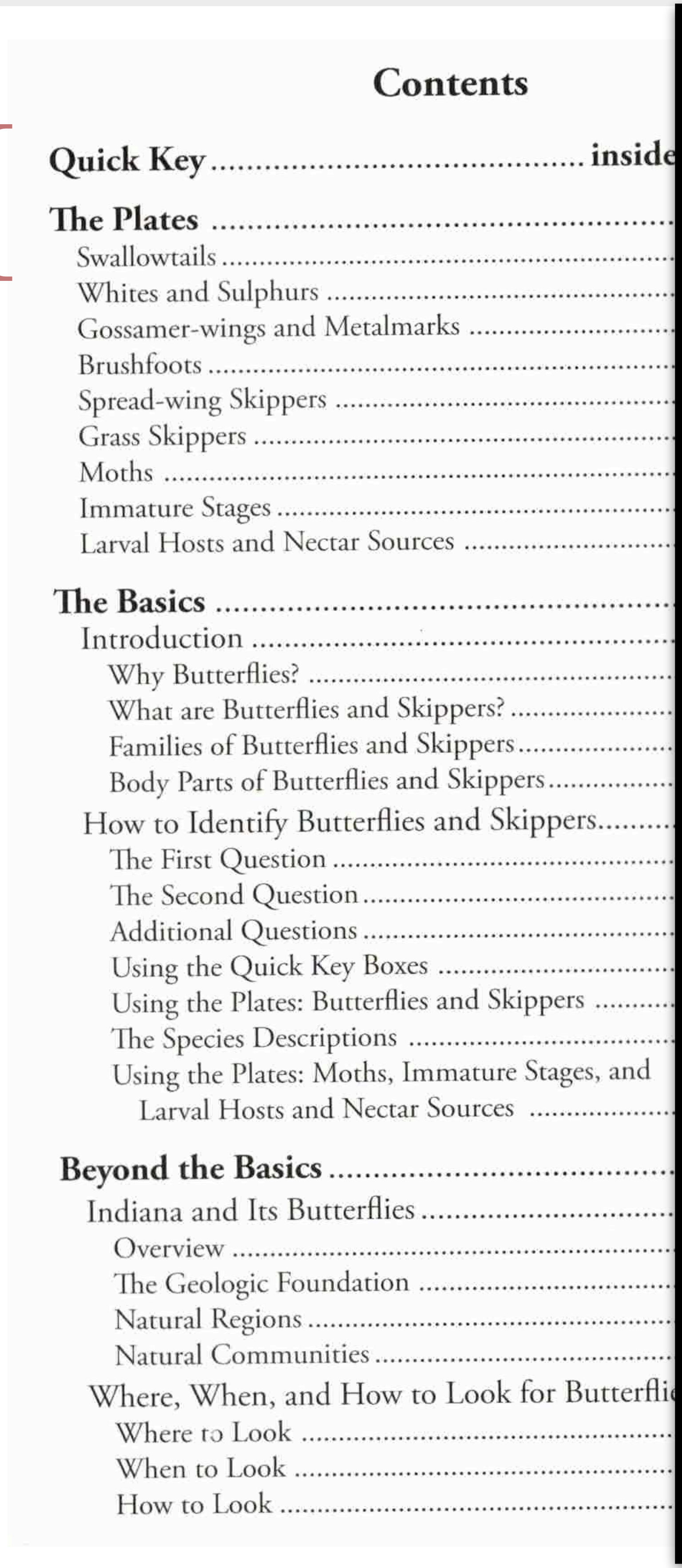
- Finding approachable individuals
- The stalk—getting close enough
- Getting parallel—triangulating focus
- Framing—in thirds
- Supporting the camera

I believe the most challenging facet of butterfly photography is getting close enough to my subject. Not every butterfly can be photographed, some will simply not allow it, so my toughest challenge is being patient enough to wait for a butterfly that is approachable. Depending on the abundance and habits of a species, it may take awhile. Usually the most approachable butterflies are those that are the most distracted. I watch for butterflies that are stopping frequently to feed, or pausing more often to bask. These are the individuals that might be approachable.

When a butterfly is nectaring on a flower, basking on a leaf, or otherwise distracted, I begin my stalk. My aim is to be quiet, slow, and steady, without any sudden movements. I also try to keep my shadow from passing over the butterfly. Sometimes I get in a low crouch, so my outline will appear smaller. When I am stalking a butterfly in a woodland, I try to use tree trunks or branches to screen my

getting parallel to two Harvesters

The Approach of a Field Guide



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4 Small to large; *yellow:* **Sulphurs** — *see* pages 17-21

5 Large; *orange* with *black* veins: **Milkweed Butterflies** and **Viceroy** — *see* page 49

Small: 1¼ inches or less | Medium: 1½-2½ inches

Quick Key: Butterflies

6 Large; *orange* with *dark* spots: **Greater Fritillaries** — *see* pages 51-55

7 Small to medium; *orange* or *black,* with *spots:* **Crescents** and **Lesser Fritillaries** — *see* pages 57-61

8 Medium to Large; with *irregular* wing edges: **Anglewings** and **Tortoiseshells** — *see* pages 63-67

9 Medium; forewing with *white* or *orange spots* or *bands:* **Ladies, Emperors, Buckeyes,** and **Snouts** — *see* pages 69-71

10 Small to large; *tan, gray,* or *brown,* with *eyespots:* **Satyrs** — *see* pages 73-79

Large: 3 inches or larger

Quick Key: Butterflies

11 Small; *blue, dark gray,* or *tan* above, *silvery gray, tan,* or *white* below: **Azures** and **Blues** — *see* pages 23-29

12 Small; *gray, tan,* or *brown* below, with *white* streaks: **Elfins, Harvester,** and **Hairstreaks** — *see* pages 31-39

13 Small; underside *green* or *black* below, with tails: **Hairstreaks** — *see* page 41

14 Small; wings *brown* above and *orange* below: **Metalmarks** — *see* page 47

15 Small; *gray* and *orange* below with *spots; dark* with *orange* above: **Coppers** — *see* pages 43-45

Small: 1¼ inches or less | Medium: 1½-2½ inches

Quick Key: Skippers

16 *either ...* Small to Medium; wings held *flat* or at the *same angle* while basking: **Spread-wing Skippers** — *see* **Quick Key Boxes 17-20 below**

or ... Small; wings held at *different "jet" angles* while basking: **Grass Skippers** — *see* **Quick Key Boxes 21-33 next page**

17 Medium; forewing with *brownish gold* or *gold* bands: — *see* page 81

18 Small to medium; *mottled brown; with* or *without white* spots: **Duskywings** — *see* pages 83-87

19 Medium; *unmottled;* forewing with *white* spots: **Cloudywings** — *see* page 89

20 Small; forewing with *white* spots or *checkered* pattern: — *see* page 91

Large: 3 inches or larger

Quick Key: Grass Skippers (wings closed)

21 Small; hindwing with *bold* or *chevron-shaped* pattern: — *see* pages 93-97

22 Small; hindwing *dark,* with *violet* or *gray* border: — *see* page 99

23 Small; hindwing with *checkered* fringe: — *see* page 101

24 Small; hindwing with *pale stripes* or *highlighted* veins: — *see* pages 103-105

25 Small; hindwing *yellow* or *orange, without* bold pattern: — *see* page 107

26 Small; hindwing *dark brown* or *light gray, without* bold pattern: — *see* page 109

27 Small; hindwing *brown* or *tan, without* bold pattern: — *see* pages 111-113

28 Small to medium; forewing *elongated:* — *see* page 113

Small: 1¼ inches or less | Medium: 1½-2½ inches

Quick Key: Grass Skippers (wings open)

29 Small; forewing *orange,* with *distinct* stigma: — *see* pages 115-117

30 Small; forewing *orange, without* stigma; or stigma *indistinct:* — *see* page 119

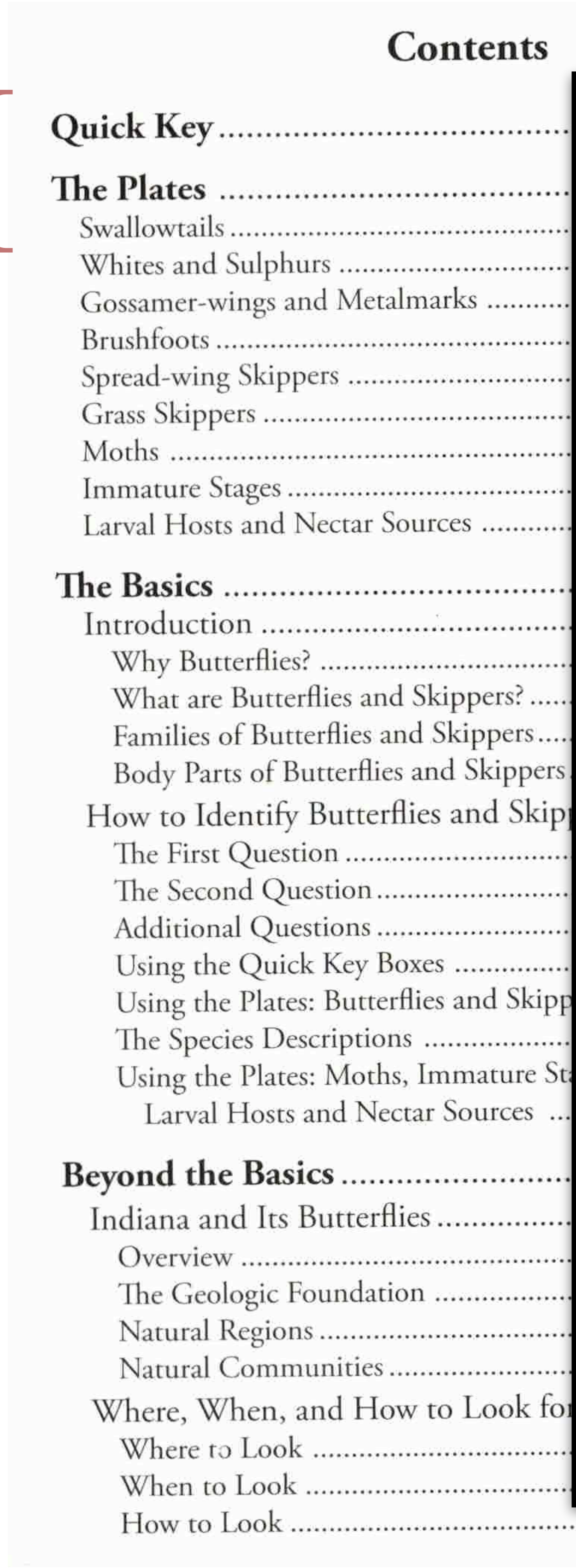
31 Small to medium; forewing with a *diagonal row* of *spots:* — *see* pages 121-123

32 Small; forewing *dark* with *small* spots: — *see* pages 125-127

33 Small; forewing *dark, without* spots: — *see* page 127

Large: 3 inches or larger

The Approach of a Field Guide



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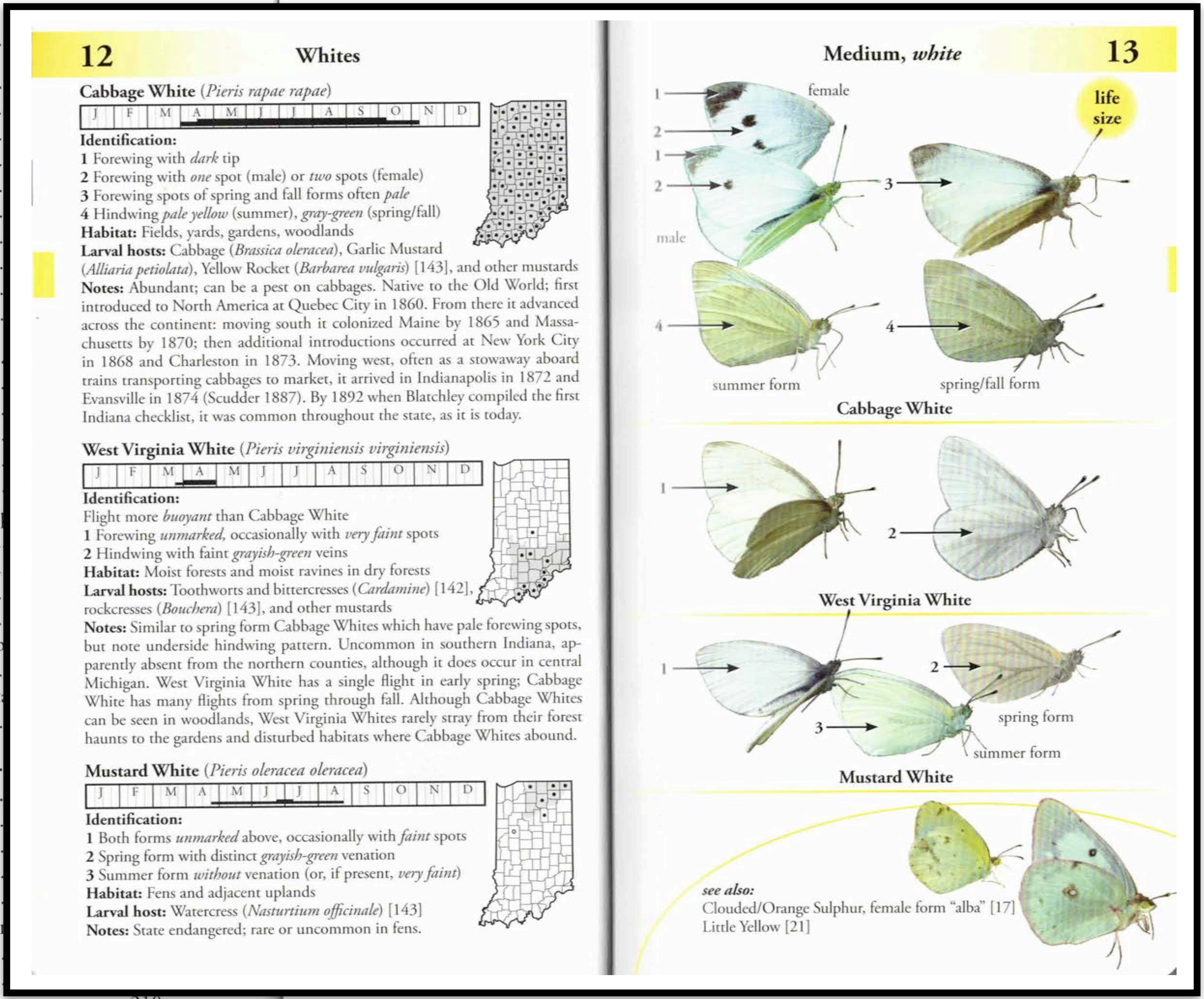


12 Whites

Cabbage White (*Pieris rapae rapae*)

Identification:
1 Forewing with *dark* tip
2 Forewing with *one* spot (male) or *two* spots (female)
3 Forewing spots of spring and fall forms often *pale*
4 Hindwing *pale yellow* (summer), *gray-green* (spring/fall)
Habitat: Fields, yards, gardens, woodlands
Larval hosts: Cabbage (*Brassica oleracea*), Garlic Mustard (*Alliaria petiolata*), Yellow Rocket (*Barbarea vulgaris*) [143], and other mustards
Notes: Abundant; can be a pest on cabbages. Native to the Old World; first introduced to North America at Quebec City in 1860. From there it advanced across the continent: moving south it colonized Maine by 1865 and Massachusetts by 1870; then additional introductions occurred at New York City in 1868 and Charleston in 1873. Moving west, often as a stowaway aboard trains transporting cabbages to market, it arrived in Indianapolis in 1872 and Evansville in 1874 (Scudder 1887). By 1892 when Blatchley compiled the first Indiana checklist, it was common throughout the state, as it is today.

West Virginia White (*Pieris virginiensis virginiensis*)

Identification:
Flight more *buoyant* than Cabbage White
1 Forewing *unmarked,* occasionally with *very faint* spots
2 Hindwing with faint *grayish-green* veins
Habitat: Moist forests and moist ravines in dry forests
Larval hosts: Toothworts and bittercresses (*Cardamine*) [142], rockcresses (*Bouchera*) [143], and other mustards
Notes: Similar to spring form Cabbage Whites which have pale forewing spots, but note underside hindwing pattern. Uncommon in southern Indiana, apparently absent from the northern counties, although it does occur in central Michigan. West Virginia White has a single flight in early spring; Cabbage White has many flights from spring through fall. Although Cabbage Whites can be seen in woodlands, West Virginia Whites rarely stray from their forest haunts to the gardens and disturbed habitats where Cabbage Whites abound.

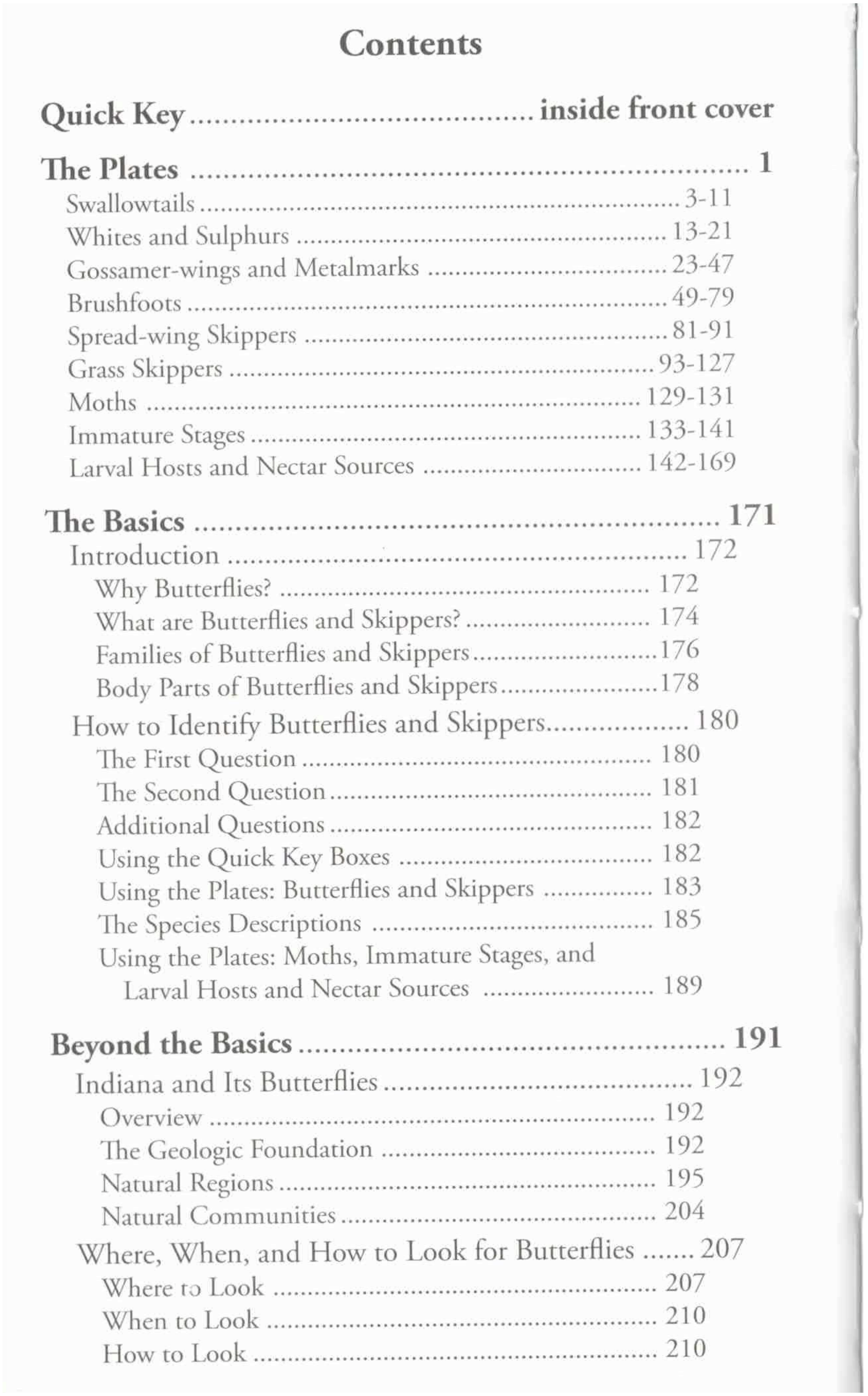
Mustard White (*Pieris oleracea oleracea*)

Identification:
1 Both forms *unmarked* above, occasionally with *faint* spots
2 Spring form with distinct *grayish-green* venation
3 Summer form *without* venation (or, if present, *very faint*)
Habitat: Fens and adjacent uplands
Larval host: Watercress (*Nasturtium officinale*) [143]
Notes: State endangered; rare or uncommon in fens.

Medium, *white* 13

see also:
Clouded/Orange Sulphur, female form "alba" [17]
Little Yellow [21]

A Field Guide to the Mesons



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This Talk:

I. What are Mesons?

II. Families of Mesons

III. Looking for Mesons

IV. The Plates: $c\bar{c}$ and cc mesons

V. The Plates: $b\bar{b}$ and bb mesons

VI. Why Mesons?

I. What are Mesons?

HADRONS: composite particles made from quarks (q), antiquarks ($\bar{q}$), and gluons (g)

$\Longrightarrow$ *strongly interacting particles*

BARYONS: hadrons with three more quarks than antiquarks (*e.g. qqq*)

$\Longrightarrow$ *strongly interacting particles, fermions, baryon number = 1*

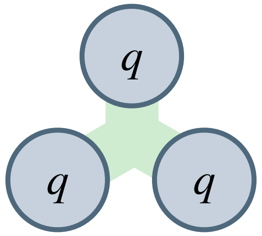
MESONS: hadrons with equal numbers of quarks and antiquarks (*e.g.* $q\bar{q}$)

$\Longrightarrow$ *strongly interacting particles, bosons, baryon number = 0*

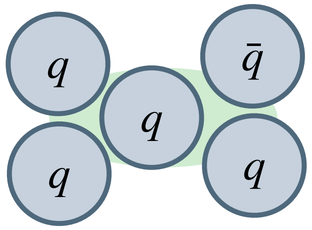
QUARKS

	generations		
electric charge	I	II	III
$+\frac{2}{3}$	u (up)	c (charm)	t (top)
$-\frac{1}{3}$	d (down)	s (strange)	b (bottom)

BARYONS

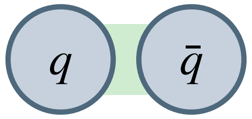


conventional baryon



pentaquark

MESONS



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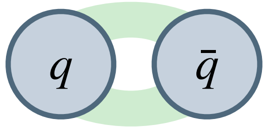
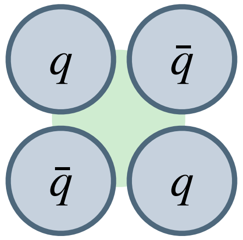


hybrid meson

glueball



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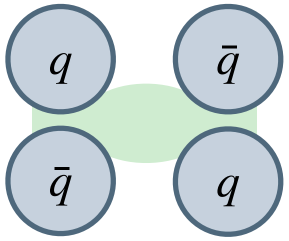
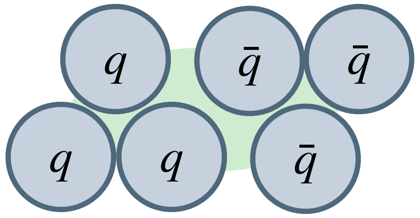


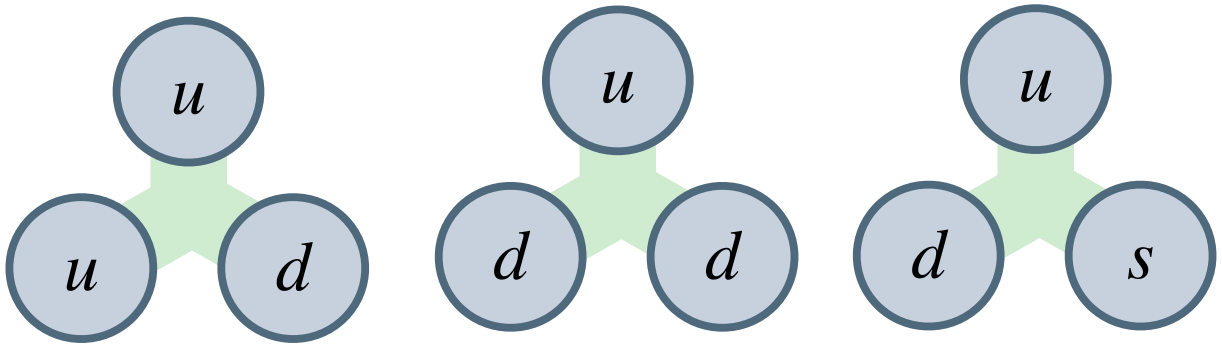
meson molecule



baryonium

I. What are Mesons?

A few famous baryons…

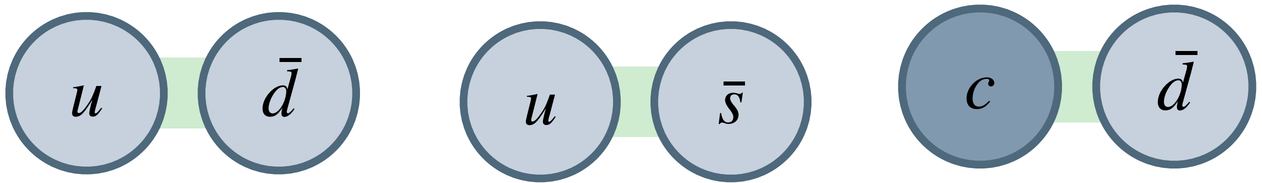


p (proton)
$M \approx 938$ MeV

n (neutron)
$M \approx 940$ MeV

Λ (lambda)
$M \approx 1116$ MeV

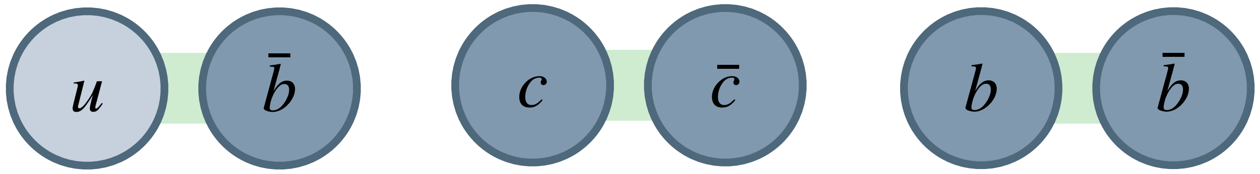
A few famous mesons…



π^+ (pion)
$M \approx 140$ MeV

K^+ (kaon)
$M \approx 494$ MeV

D^+ (D meson)
$M \approx 1870$ MeV



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$\Upsilon(1S)$ (bottomonium)
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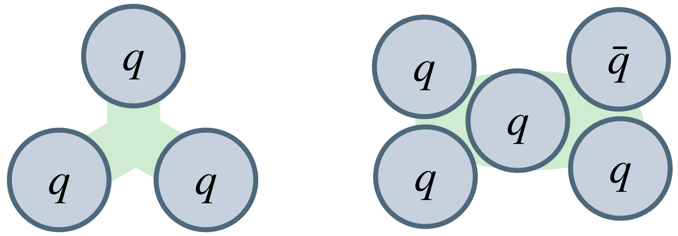
QUARKS

generations

electric charge

	I	II	III
$+\frac{2}{3}$	u (up)	c (charm)	t (top)
$-\frac{1}{3}$	d (down)	s (strange)	b (bottom)

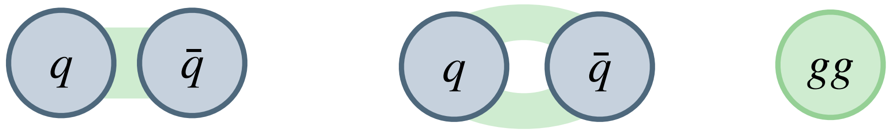
BARYONS



conventional baryon

pentaquark

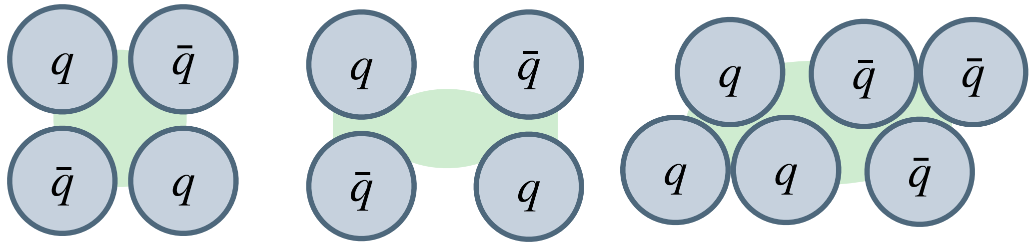
MESONS



conventional meson

hybrid meson

glueball



tetraquark

meson molecule

baryonium

I. What are Mesons?

Why are only these combinations of quarks and gluons allowed?

In Quantum Chromodynamics (QCD) quarks and gluons carry a color charge that follows SU(3) symmetry:

$q\bar{q}$: $3 \otimes \bar{3} = 8 \oplus 1$

$$qqq: \quad 3 \otimes 3 \otimes 3 = (6 \oplus \bar{3}) \otimes 3$$
$$= 10 \oplus 8 \oplus 8 \oplus 1$$

Hadrons are colorless (color singlets).

Compare this to angular momentum, which follows SU(2) symmetry:

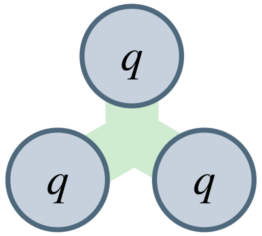
two spin-1/2 particles: $2 \otimes 2 = 3 \oplus 1$

two spin-1 particles: $3 \otimes 3 = 5 \oplus 3 \oplus 1$

QUARKS

	generations		
electric charge	I	II	III
$+\frac{2}{3}$	u (up)	c (charm)	t (top)
$-\frac{1}{3}$	d (down)	s (strange)	b (bottom)

BARYONS



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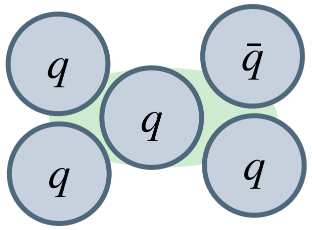
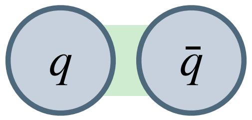
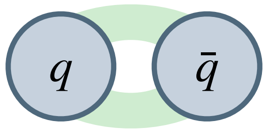


pentaquark

MESONS

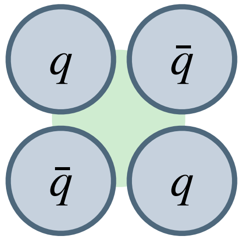


conventional meson

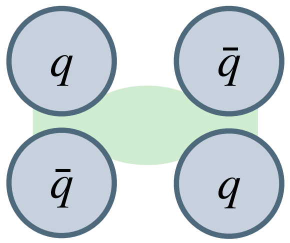


hybrid meson

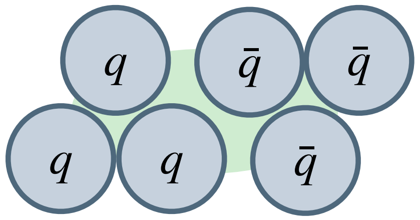
glueball



tetraquark

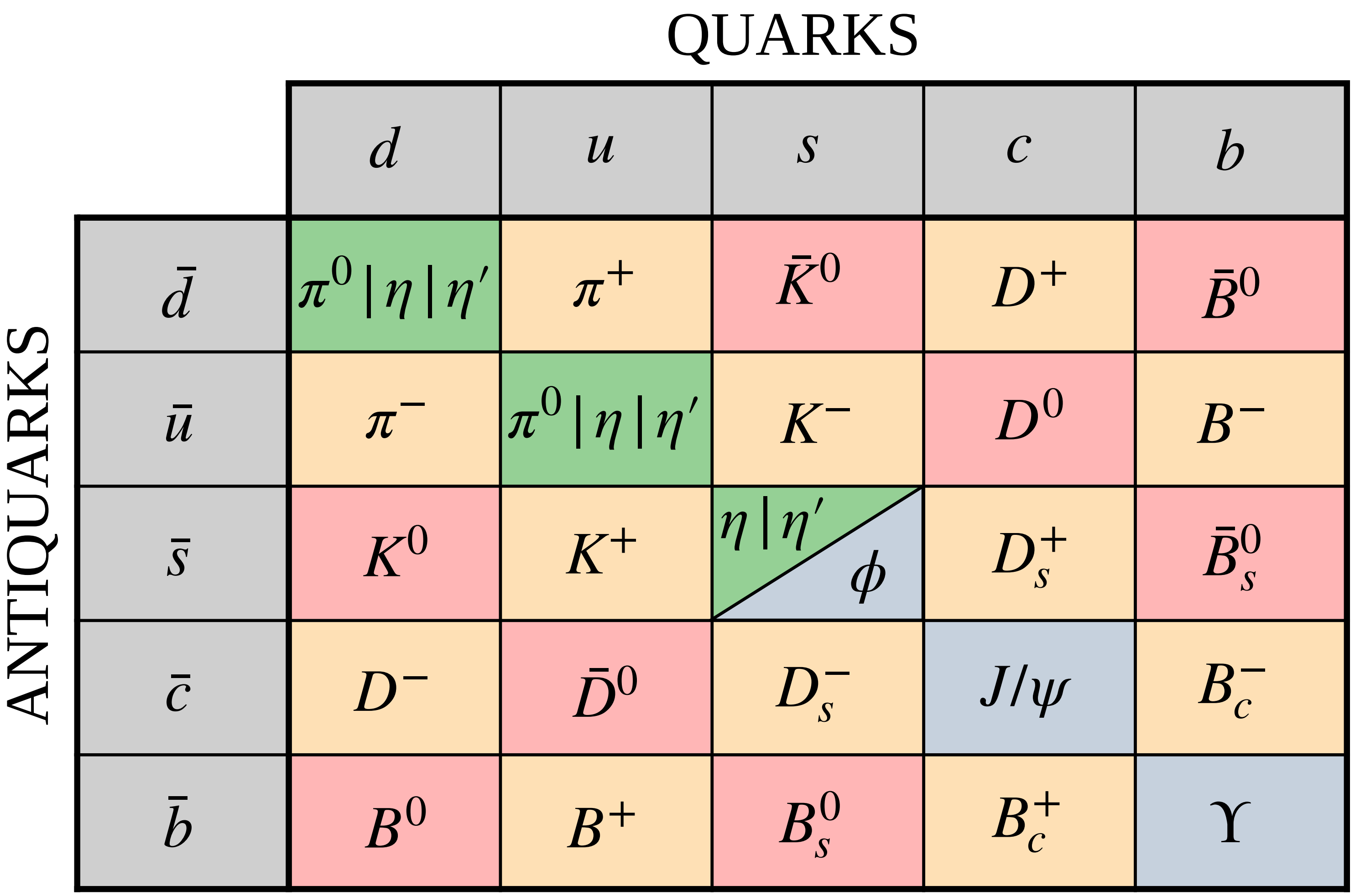


meson molecule



baryonium

II. Families of Mesons



QUARKS

ANTIQUARKS	d	u	s	c	b
$\bar{d}$	$\pi^0 \mid \eta \mid \eta'$	π^+	$\bar{K}^0$	D^+	$\bar{B}^0$
$\bar{u}$	π^-	$\pi^0 \mid \eta \mid \eta'$	K^-	D^0	B^-
$\bar{s}$	K^0	K^+	$\eta \mid \eta'$ ϕ	D_s^+	$\bar{B}_s^0$
$\bar{c}$	D^-	$\bar{D}^0$	D_s^-	J/ψ	B_c^-
$\bar{b}$	B^0	B^+	B_s^0	B_c^+	Υ

K^+ family
(weak decays, no mixing)

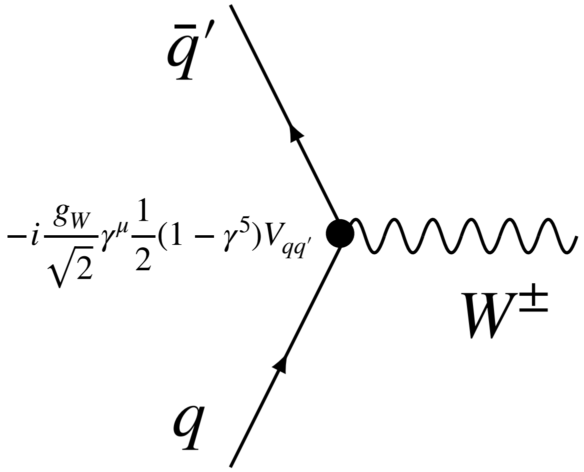
K^0 family
(weak decays, mixing)

π^0 family
(large electromagnetic decays)

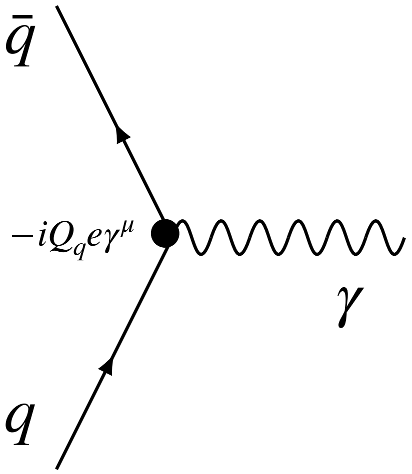
J/ψ family
(strong decays, near or below open flavor threshold)

Meson properties are largely dictated by how they decay.

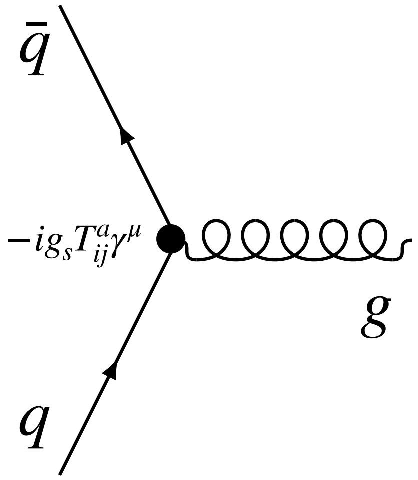
WEAK



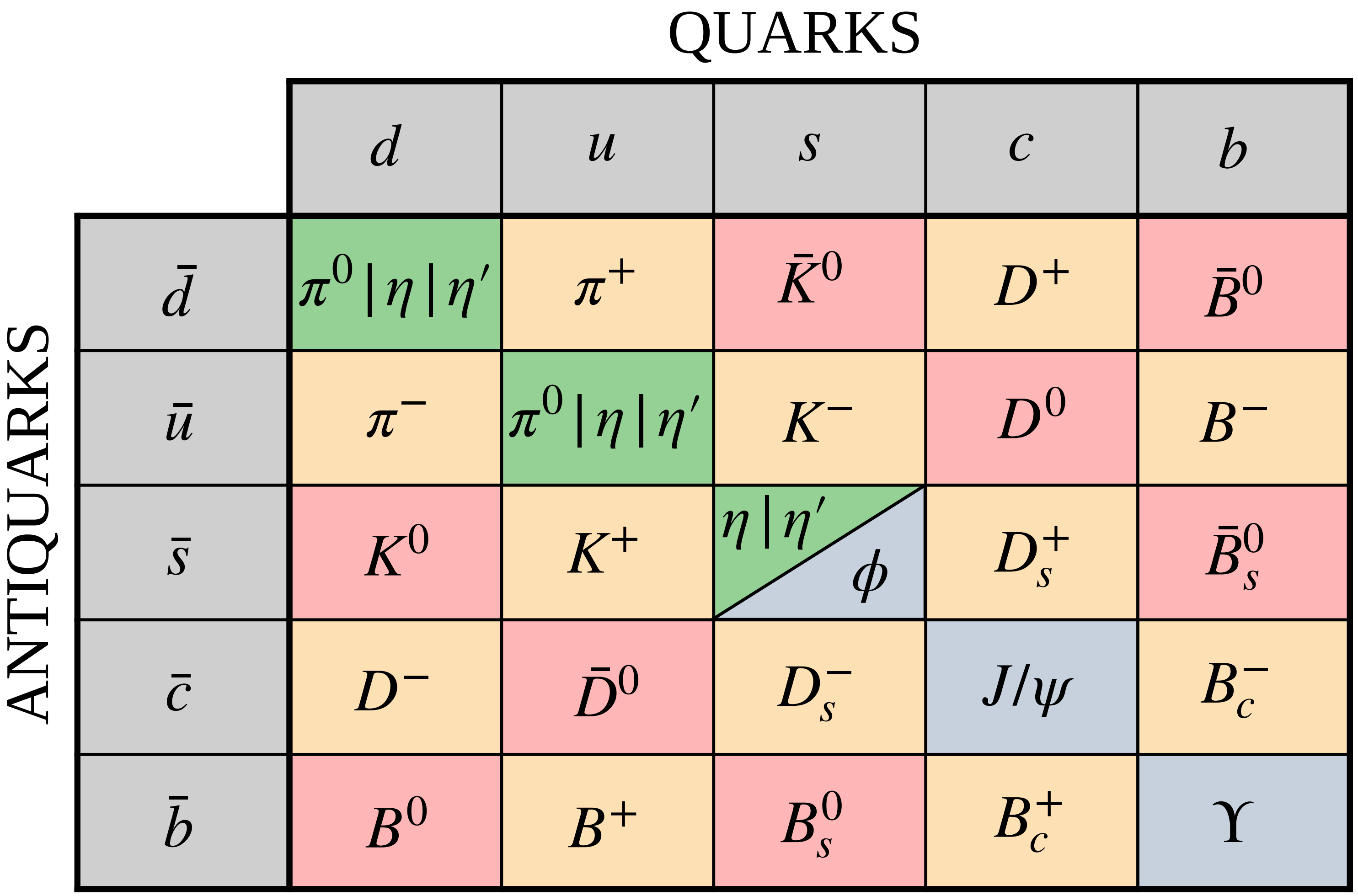
ELECTROMAGNETIC



STRONG



II. Families of Mesons

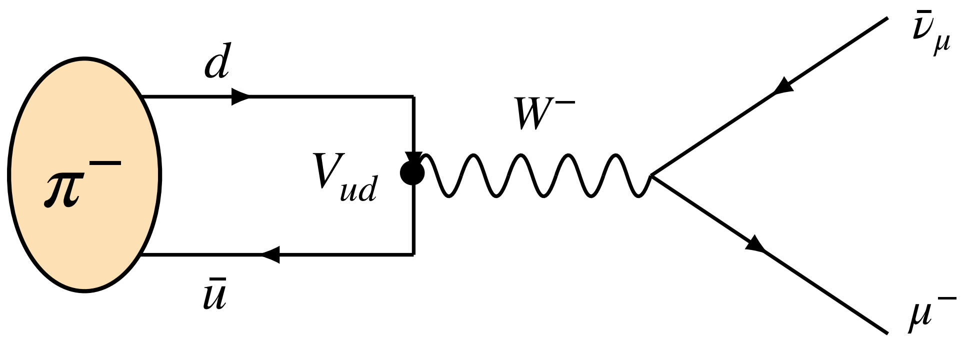


QUARKS

ANTIQUARKS

	d	u	s	c	b
$\bar{d}$	$\pi^0 \mid \eta \mid \eta'$	π^+	$\bar{K}^0$	D^+	$\bar{B}^0$
$\bar{u}$	π^-	$\pi^0 \mid \eta \mid \eta'$	K^-	D^0	B^-
$\bar{s}$	K^0	K^+	$\eta \mid \eta'$ ϕ	D_s^+	$\bar{B}_s^0$
$\bar{c}$	D^-	$\bar{D}^0$	D_s^-	J/ψ	B_c^-
$\bar{b}$	B^0	B^+	B_s^0	B_c^+	Υ

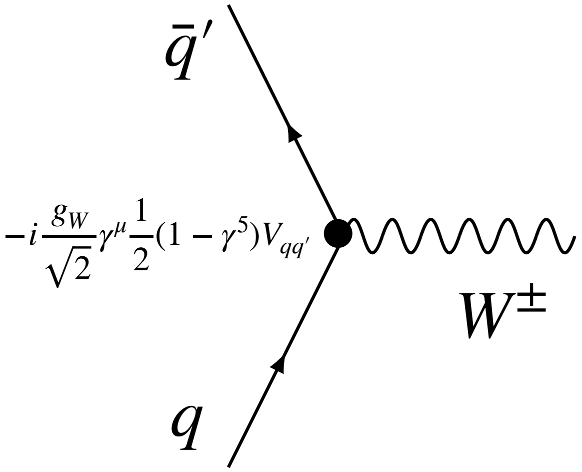
Decays via the weak force are slow:



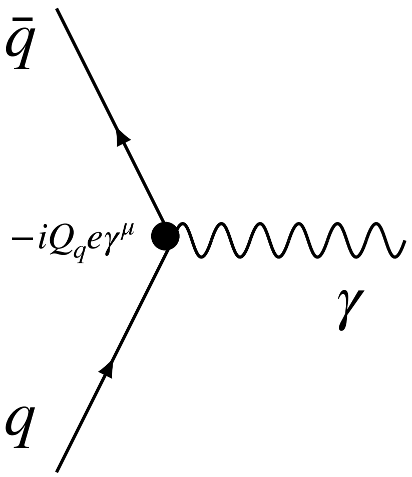
$\tau_\pi = 2.6 \times 10^{-8}$ s $\qquad c\tau_\pi = 7.8$ m

Meson properties are largely dictated by how they decay.

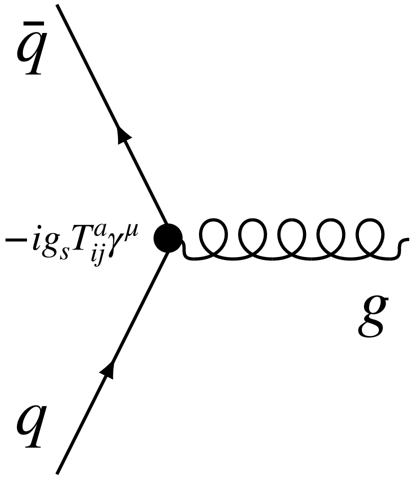
WEAK



ELECTROMAGNETIC



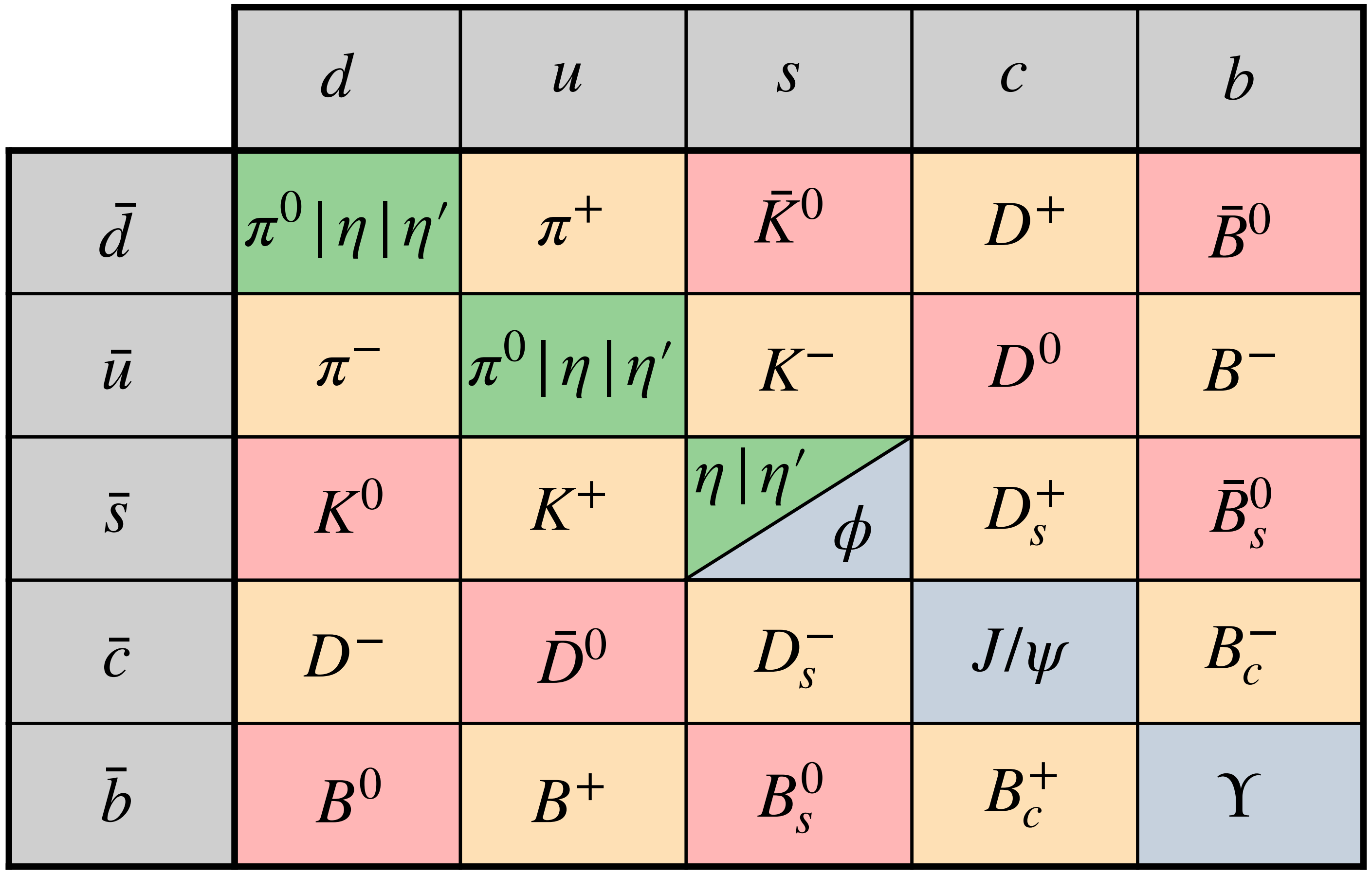
STRONG



II. Families of Mesons

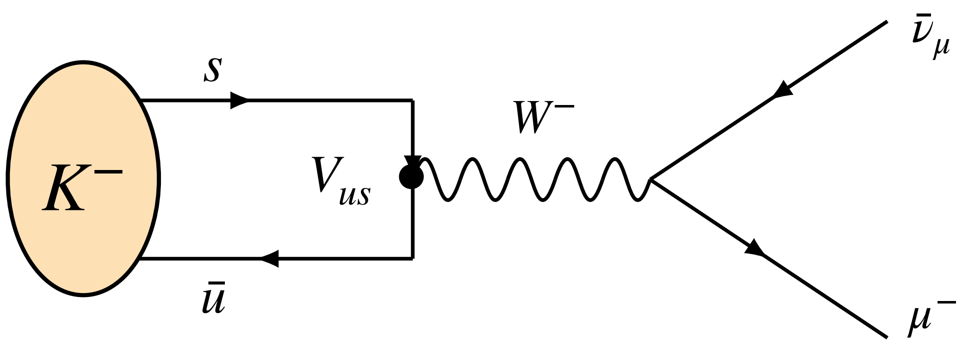
QUARKS

ANTIQUARKS



	d	u	s	c	b
$\bar{d}$	$\pi^0 \vert \eta \vert \eta'$	π^+	$\bar{K}^0$	D^+	$\bar{B}^0$
$\bar{u}$	π^-	$\pi^0 \vert \eta \vert \eta'$	K^-	D^0	B^-
$\bar{s}$	K^0	K^+	$\eta \vert \eta'$ ϕ	D_s^+	$\bar{B}_s^0$
$\bar{c}$	D^-	$\bar{D}^0$	D_s^-	J/ψ	B_c^-
$\bar{b}$	B^0	B^+	B_s^0	B_c^+	Υ

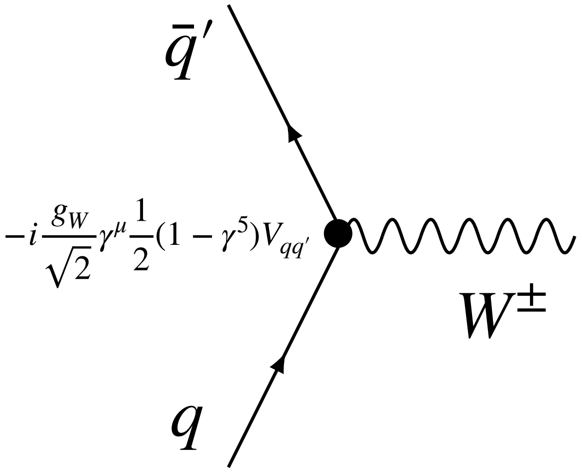
Decays via the weak force are slow:



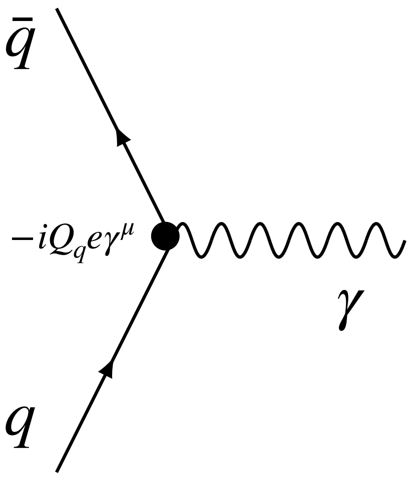
$\tau_K = 1.2 \times 10^{-8}$ s $\qquad c\tau_K = 3.7$ m

Meson properties are largely dictated by how they decay.

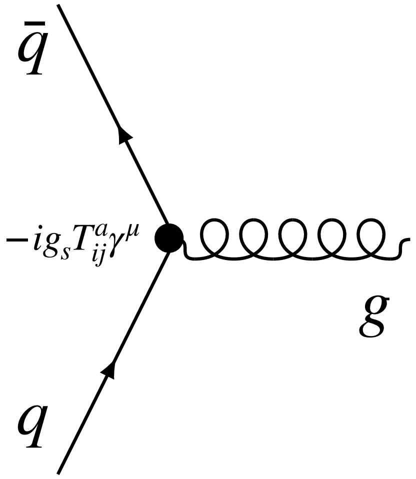
WEAK



ELECTROMAGNETIC



STRONG

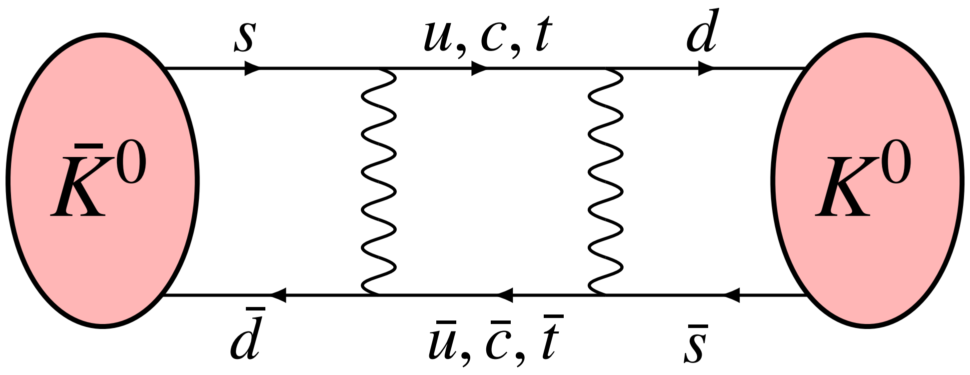


II. Families of Mesons

QUARKS

ANTIQUARKS	d	u	s	c	b
$\bar{d}$	$\pi^0\,\vert\,\eta\,\vert\,\eta'$	π^+	$\bar{K}^0$	D^+	$\bar{B}^0$
$\bar{u}$	π^-	$\pi^0\,\vert\,\eta\,\vert\,\eta'$	K^-	D^0	B^-
$\bar{s}$	K^0	K^+	$\eta\,\vert\,\eta'$ ϕ	D_s^+	$\bar{B}_s^0$
$\bar{c}$	D^-	$\bar{D}^0$	D_s^-	J/ψ	B_c^-
$\bar{b}$	B^0	B^+	B_s^0	B_c^+	Υ

The weak force can cause oscillations:

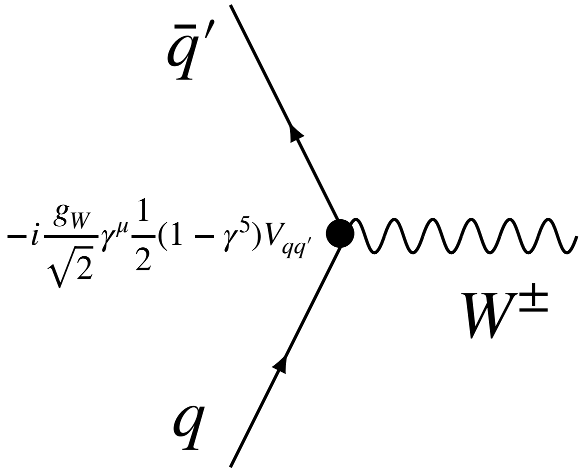


$\tau_{K_S} = 9.0 \times 10^{-11}$ s $\qquad c\tau_{K_S} = 2.7$ cm

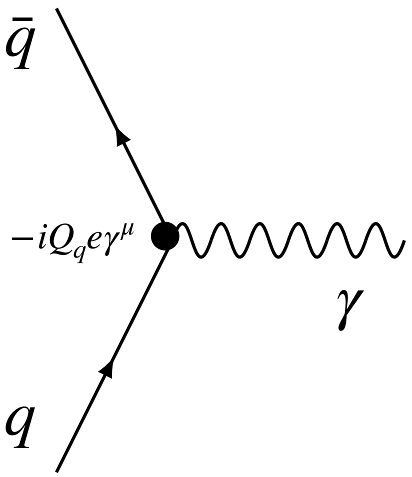
$\tau_{K_L} = 5.1 \times 10^{-8}$ s $\qquad c\tau_{K_L} = 15$ m

Meson properties are largely dictated by how they decay.

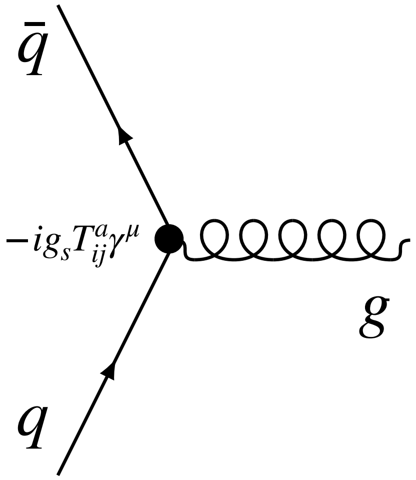
WEAK



ELECTROMAGNETIC



STRONG



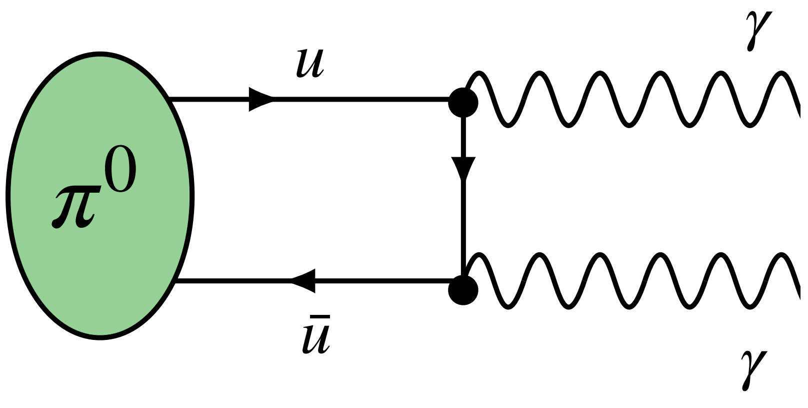
II. Families of Mesons

QUARKS

ANTIQUARKS

	d	u	s	c	b
$\bar{d}$	$\pi^0\,\vert\,\eta\,\vert\,\eta'$	π^+	$\bar{K}^0$	D^+	$\bar{B}^0$
$\bar{u}$	π^-	$\pi^0\,\vert\,\eta\,\vert\,\eta'$	K^-	D^0	B^-
$\bar{s}$	K^0	K^+	$\eta\,\vert\,\eta'$ ϕ	D_s^+	$\bar{B}_s^0$
$\bar{c}$	D^-	$\bar{D}^0$	D_s^-	J/ψ	B_c^-
$\bar{b}$	B^0	B^+	B_s^0	B_c^+	Υ

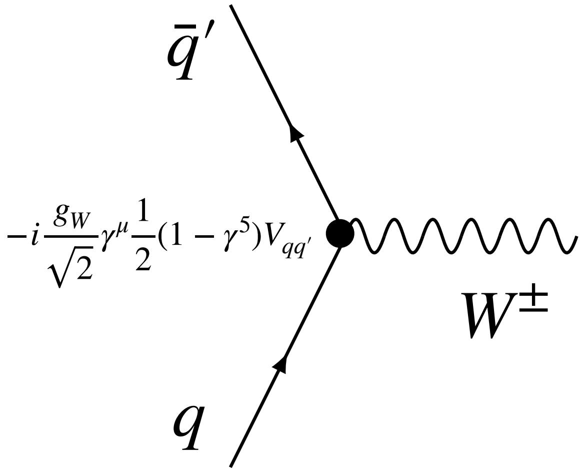
Decays via the electromagnetic force are less slow:



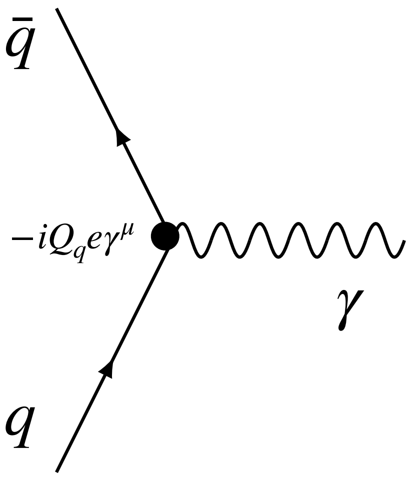
$\tau_{\pi^0} = 8.5 \times 10^{-17}$ s $\qquad c\tau_{\pi^0} = 26$ nm

Meson properties are largely dictated by how they decay.

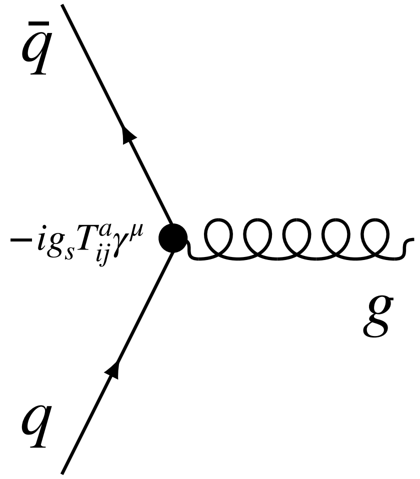
WEAK



ELECTROMAGNETIC



STRONG



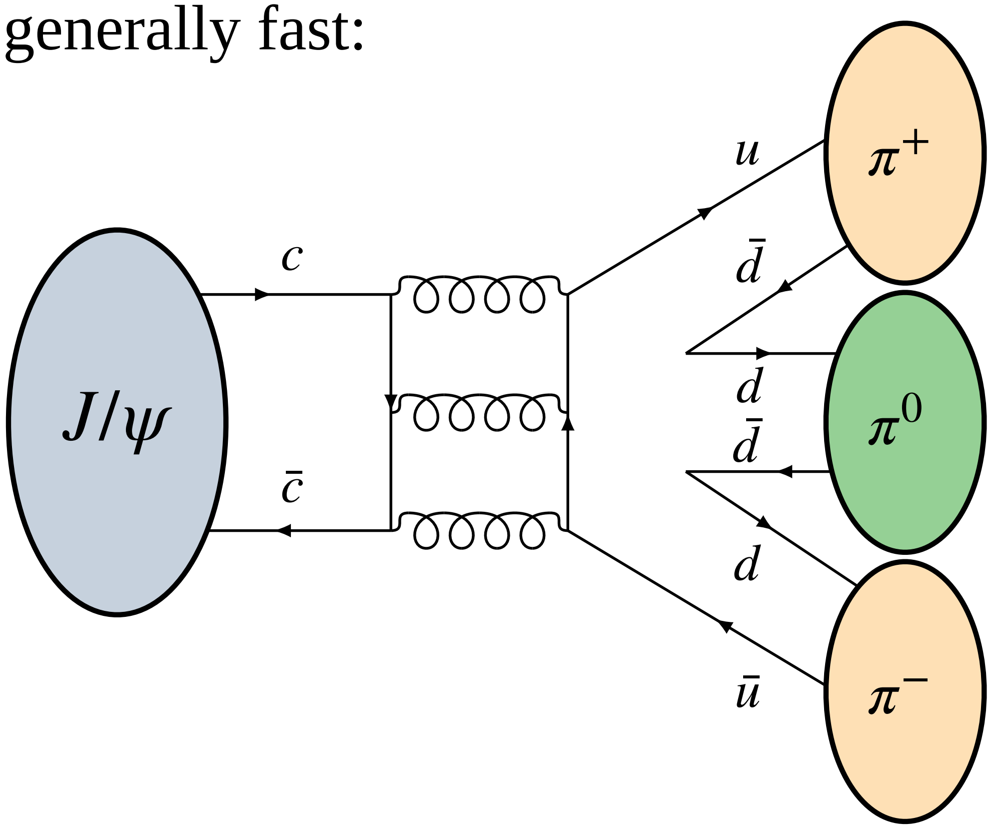
II. Families of M

QUARKS

ANTIQUARKS

	d	u	s	c	b
$\bar{d}$	$\pi^0\,\vert\,\eta\,\vert\,\eta'$	π^+	$\bar{K}^0$	D^+	$\bar{B}^0$
$\bar{u}$	π^-	$\pi^0\,\vert\,\eta\,\vert\,\eta'$	K^-	D^0	B^-
$\bar{s}$	K^0	K^+	$\eta\,\vert\,\eta'$ ϕ	D_s^+	$\bar{B}_s^0$
$\bar{c}$	D^-	$\bar{D}^0$	D_s^-	J/ψ	B_c^-
$\bar{b}$	B^0	B^+	B_s^0	B_c^+	Υ

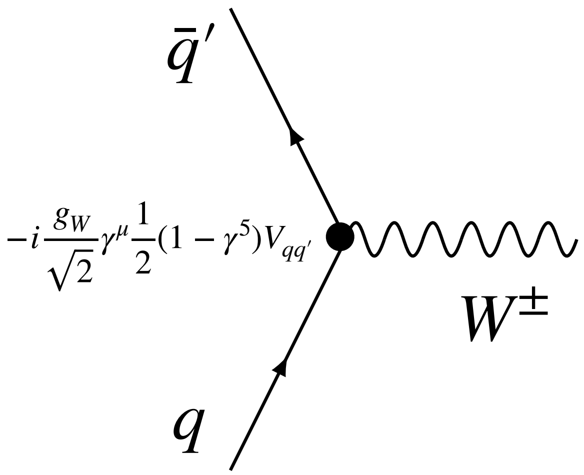
Decays via the strong force are generally fast:



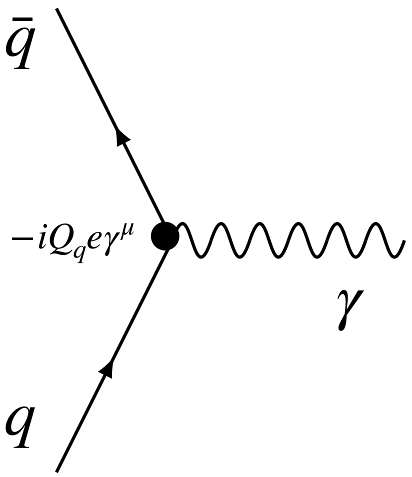
$\tau_{J/\psi} = 7.1 \times 10^{-21}$ s $\quad c\tau_{J/\psi} = 2.1$ pm

Meson properties are largely dictated by how they decay.

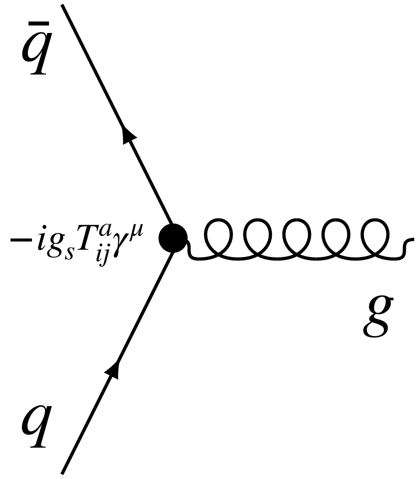
WEAK



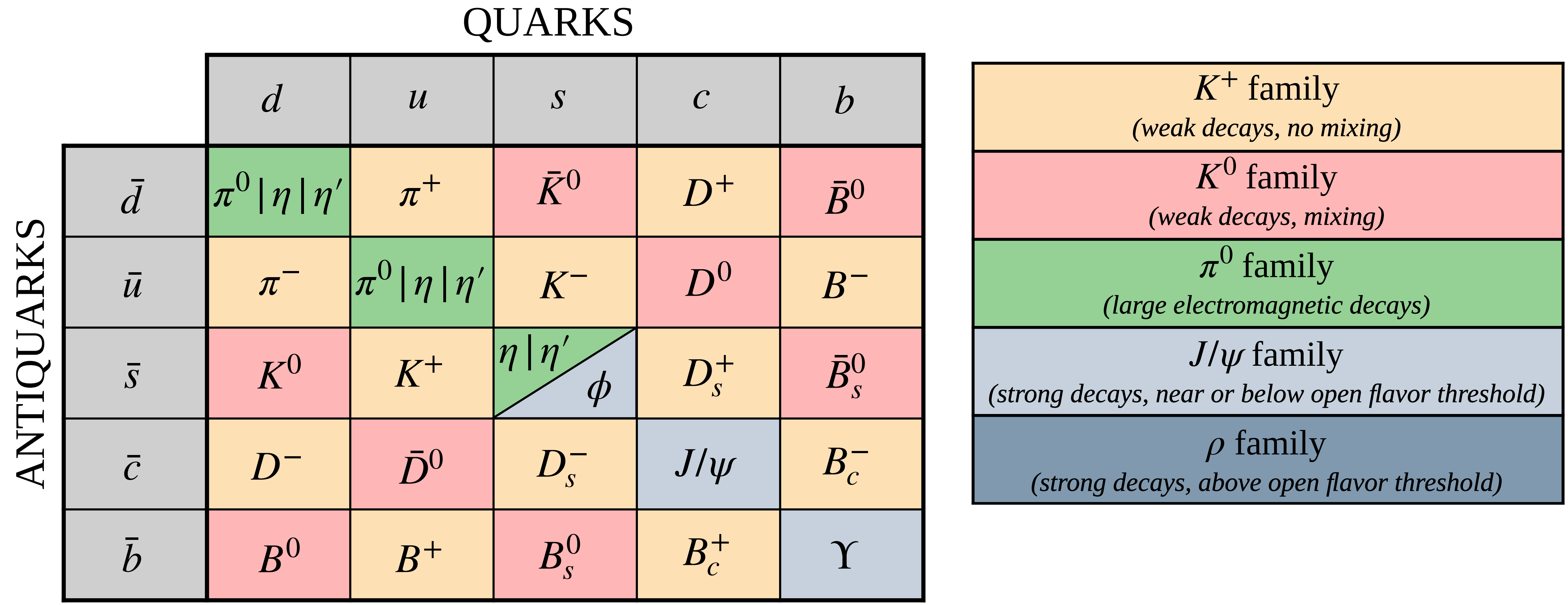
ELECTROMAGNETIC



STRONG



II. Families of Mesons



QUARKS

ANTIQUARKS

	d	u	s	c	b
$\bar{d}$	$\pi^0 \mid \eta \mid \eta'$	π^+	$\bar{K}^0$	D^+	$\bar{B}^0$
$\bar{u}$	π^-	$\pi^0 \mid \eta \mid \eta'$	K^-	D^0	B^-
$\bar{s}$	K^0	K^+	$\eta \mid \eta'$ ϕ	D_s^+	$\bar{B}_s^0$
$\bar{c}$	D^-	$\bar{D}^0$	D_s^-	J/ψ	B_c^-
$\bar{b}$	B^0	B^+	B_s^0	B_c^+	Υ

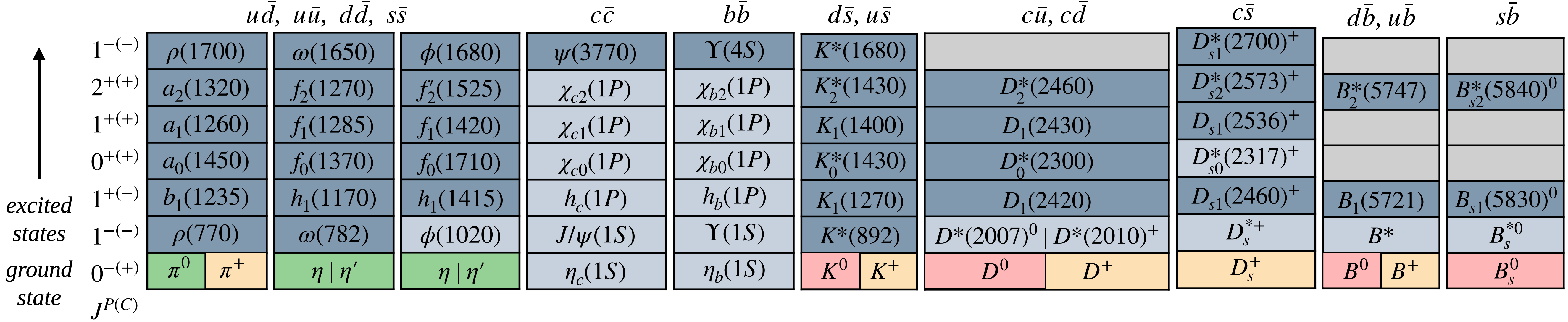
K^+ family
(weak decays, no mixing)

K^0 family
(weak decays, mixing)

π^0 family
(large electromagnetic decays)

J/ψ family
(strong decays, near or below open flavor threshold)

ρ family
(strong decays, above open flavor threshold)



$J^{P(C)}$	$u\bar{d},\ u\bar{u},\ d\bar{d},\ s\bar{s}$			$c\bar{c}$	$b\bar{b}$	$d\bar{s},\ u\bar{s}$	$c\bar{u},\ c\bar{d}$	$c\bar{s}$	$d\bar{b},\ u\bar{b}$	$s\bar{b}$
$1^{-(-)}$	$\rho(1700)$	$\omega(1650)$	$\phi(1680)$	$\psi(3770)$	$\Upsilon(4S)$	$K^*(1680)$		$D_{s1}^*(2700)^+$		
$2^{+(+)}$	$a_2(1320)$	$f_2(1270)$	$f_2'(1525)$	$\chi_{c2}(1P)$	$\chi_{b2}(1P)$	$K_2^*(1430)$	$D_2^*(2460)$	$D_{s2}^*(2573)^+$	$B_2^*(5747)$	$B_{s2}^*(5840)^0$
$1^{+(+)}$	$a_1(1260)$	$f_1(1285)$	$f_1(1420)$	$\chi_{c1}(1P)$	$\chi_{b1}(1P)$	$K_1(1400)$	$D_1(2430)$	$D_{s1}(2536)^+$		
$0^{+(+)}$	$a_0(1450)$	$f_0(1370)$	$f_0(1710)$	$\chi_{c0}(1P)$	$\chi_{b0}(1P)$	$K_0^*(1430)$	$D_0^*(2300)$	$D_{s0}^*(2317)^+$		
$1^{+(-)}$	$b_1(1235)$	$h_1(1170)$	$h_1(1415)$	$h_c(1P)$	$h_b(1P)$	$K_1(1270)$	$D_1(2420)$	$D_{s1}(2460)^+$	$B_1(5721)$	$B_{s1}(5830)^0$
$1^{-(-)}$	$\rho(770)$	$\omega(782)$	$\phi(1020)$	$J/\psi(1S)$	$\Upsilon(1S)$	$K^*(892)$	$D^*(2007)^0 \mid D^*(2010)^+$	D_s^{*+}	B^*	B_s^{*0}
$0^{-(+)}$	$\pi^0 \mid \pi^+$	$\eta \mid \eta'$	$\eta \mid \eta'$	$\eta_c(1S)$	$\eta_b(1S)$	$K^0 \mid K^+$	$D^0 \mid D^+$	D_s^+	$B^0 \mid B^+$	B_s^0

excited states

ground state

For a $q\bar{q}'$ meson: $\vec{J} = \vec{L} + \vec{S}$ and $P = (-1)^{L+1}$ and $C = (-1)^{L+S}$

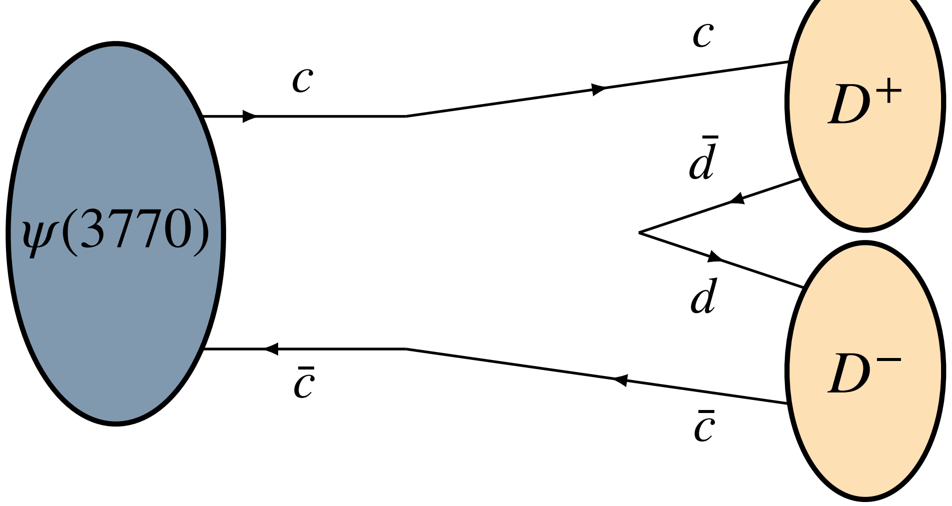
II. Families of M

QUARKS

ANTIQUARKS

	d	u	s	c	b
$\bar d$	$\pi^0\,\vert\,\eta\,\vert\,\eta'$	π^+	$\bar K^0$	D^+	$\bar B^0$
$\bar u$	π^-	$\pi^0\,\vert\,\eta\,\vert\,\eta'$	K^-	D^0	B^-
$\bar s$	K^0	K^+	$\eta\,\vert\,\eta'$ ϕ	D_s^+	$\bar B_s^0$
$\bar c$	D^-	$\bar D^0$	D_s^-	J/ψ	B_c^-
$\bar b$	B^0	B^+	B_s^0	B_c^+	Υ

Decays via the strong force are generally fast:



$$\tau_{\psi(3770)} = 2.4 \times 10^{-23}\ \mathrm{s}$$

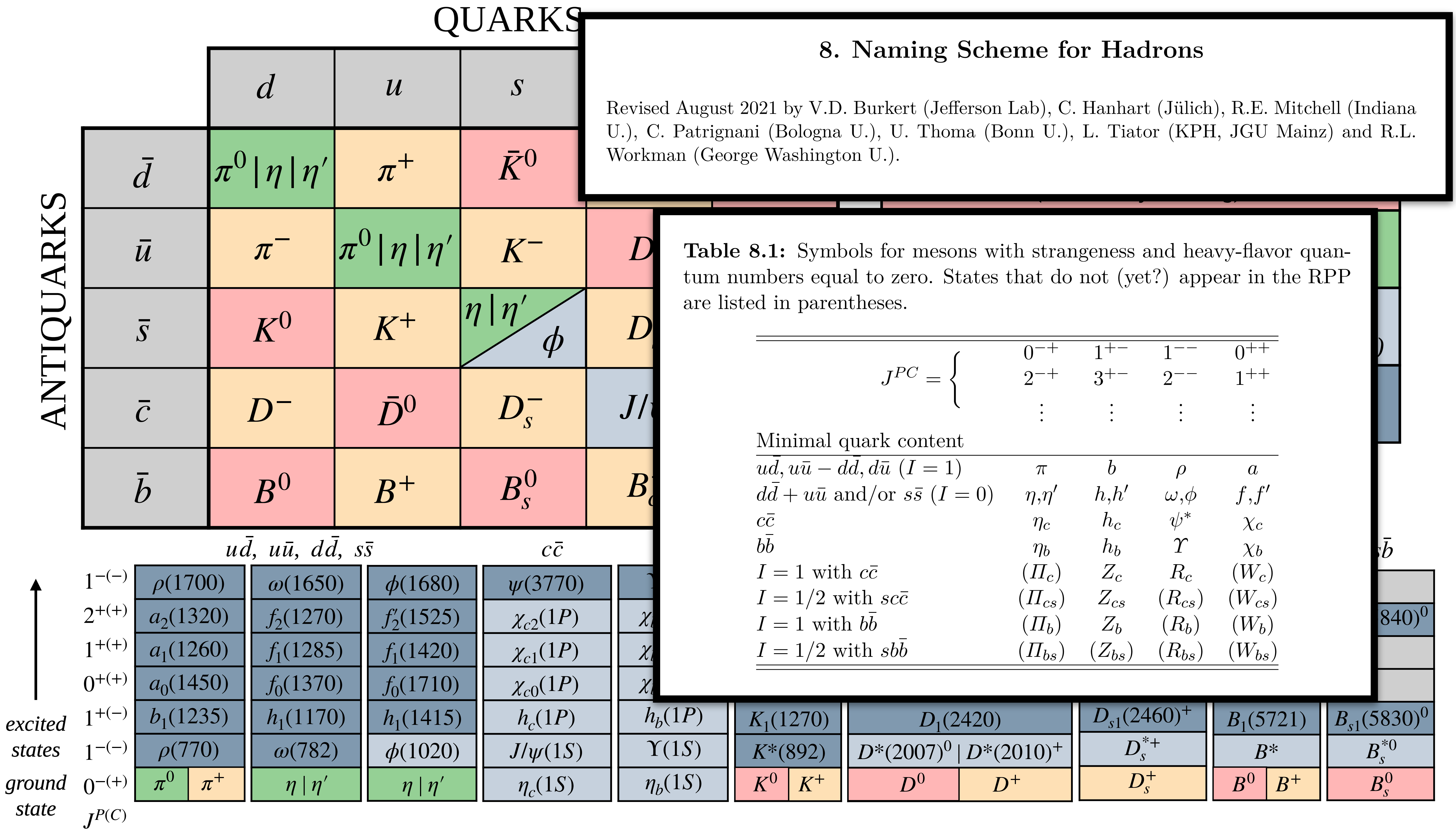
$$c\tau_{\psi(3770)} = 7.2\ \mathrm{fm}$$

$$\Gamma_{\psi(3770)} = 27\ \mathrm{MeV}$$

	$J^{P(C)}$	$u\bar d,\ u\bar u,\ d\bar d,\ s\bar s$			$c\bar c$	$b\bar b$	$d\bar s,\ u\bar s$	$c\bar u,\ c\bar d$	$c\bar s$	$d\bar b,\ u\bar b$	$s\bar b$
↑	$1^{-(-)}$	$\rho(1700)$	$\omega(1650)$	$\phi(1680)$	$\psi(3770)$	$\Upsilon(4S)$	$K^*(1680)$		$D_{s1}^*(2700)^+$		
	$2^{+(+)}$	$a_2(1320)$	$f_2(1270)$	$f_2'(1525)$	$\chi_{c2}(1P)$	$\chi_{b2}(1P)$	$K_2^*(1430)$	$D_2^*(2460)$	$D_{s2}^*(2573)^+$	$B_2^*(5747)$	$B_{s2}^*(5840)^0$
	$1^{+(+)}$	$a_1(1260)$	$f_1(1285)$	$f_1(1420)$	$\chi_{c1}(1P)$	$\chi_{b1}(1P)$	$K_1(1400)$	$D_1(2430)$	$D_{s1}(2536)^+$		
	$0^{+(+)}$	$a_0(1450)$	$f_0(1370)$	$f_0(1710)$	$\chi_{c0}(1P)$	$\chi_{b0}(1P)$	$K_0^*(1430)$	$D_0^*(2300)$	$D_{s0}^*(2317)^+$		
excited states	$1^{+(-)}$	$b_1(1235)$	$h_1(1170)$	$h_1(1415)$	$h_c(1P)$	$h_b(1P)$	$K_1(1270)$	$D_1(2420)$	$D_{s1}(2460)^+$	$B_1(5721)$	$B_{s1}(5830)^0$
	$1^{-(-)}$	$\rho(770)$	$\omega(782)$	$\phi(1020)$	$J/\psi(1S)$	$\Upsilon(1S)$	$K^*(892)$	$D^*(2007)^0\,\vert\,D^*(2010)^+$	D_s^{*+}	B^*	B_s^{*0}
ground state	$0^{-(+)}$	π^0 π^+	$\eta\,\vert\,\eta'$	$\eta\,\vert\,\eta'$	$\eta_c(1S)$	$\eta_b(1S)$	K^0 K^+	D^0 D^+	D_s^+	B^0 B^+	B_s^0

For a $q\bar q'$ meson: $\vec J = \vec L + \vec S$ and $P = (-1)^{L+1}$ and $C = (-1)^{L+S}$

II. Families of Mesons



QUARKS

ANTIQUARKS

	d	u	s	
$\bar d$	$\pi^0 \mid \eta \mid \eta'$	π^+	$\bar K^0$	
$\bar u$	π^-	$\pi^0 \mid \eta \mid \eta'$	K^-	D
$\bar s$	K^0	K^+	$\eta \mid \eta'$ ϕ	D
$\bar c$	D^-	$\bar D^0$	D_s^-	$J/$
$\bar b$	B^0	B^+	B_s^0	B_c

8. Naming Scheme for Hadrons

Revised August 2021 by V.D. Burkert (Jefferson Lab), C. Hanhart (Jülich), R.E. Mitchell (Indiana U.), C. Patrignani (Bologna U.), U. Thoma (Bonn U.), L. Tiator (KPH, JGU Mainz) and R.L. Workman (George Washington U.).

Table 8.1: Symbols for mesons with strangeness and heavy-flavor quantum numbers equal to zero. States that do not (yet?) appear in the RPP are listed in parentheses.

$J^{PC} = \{$	0^{-+}	1^{+-}	1^{--}	0^{++}
	2^{-+}	3^{+-}	2^{--}	1^{++}
	$\vdots$	$\vdots$	$\vdots$	$\vdots$
Minimal quark content				
$u\bar d, u\bar u - d\bar d, d\bar u$ $(I=1)$	π	b	ρ	a
$d\bar d + u\bar u$ and/or $s\bar s$ $(I=0)$	η,η'	h,h'	ω,ϕ	f,f'
$c\bar c$	η_c	h_c	ψ^*	χ_c
$b\bar b$	η_b	h_b	Υ	χ_b
$I=1$ with $c\bar c$	(Π_c)	Z_c	R_c	(W_c)
$I=1/2$ with $sc\bar c$	(Π_{cs})	Z_{cs}	(R_{cs})	(W_{cs})
$I=1$ with $b\bar b$	(Π_b)	Z_b	(R_b)	(W_b)
$I=1/2$ with $sb\bar b$	(Π_{bs})	(Z_{bs})	(R_{bs})	(W_{bs})

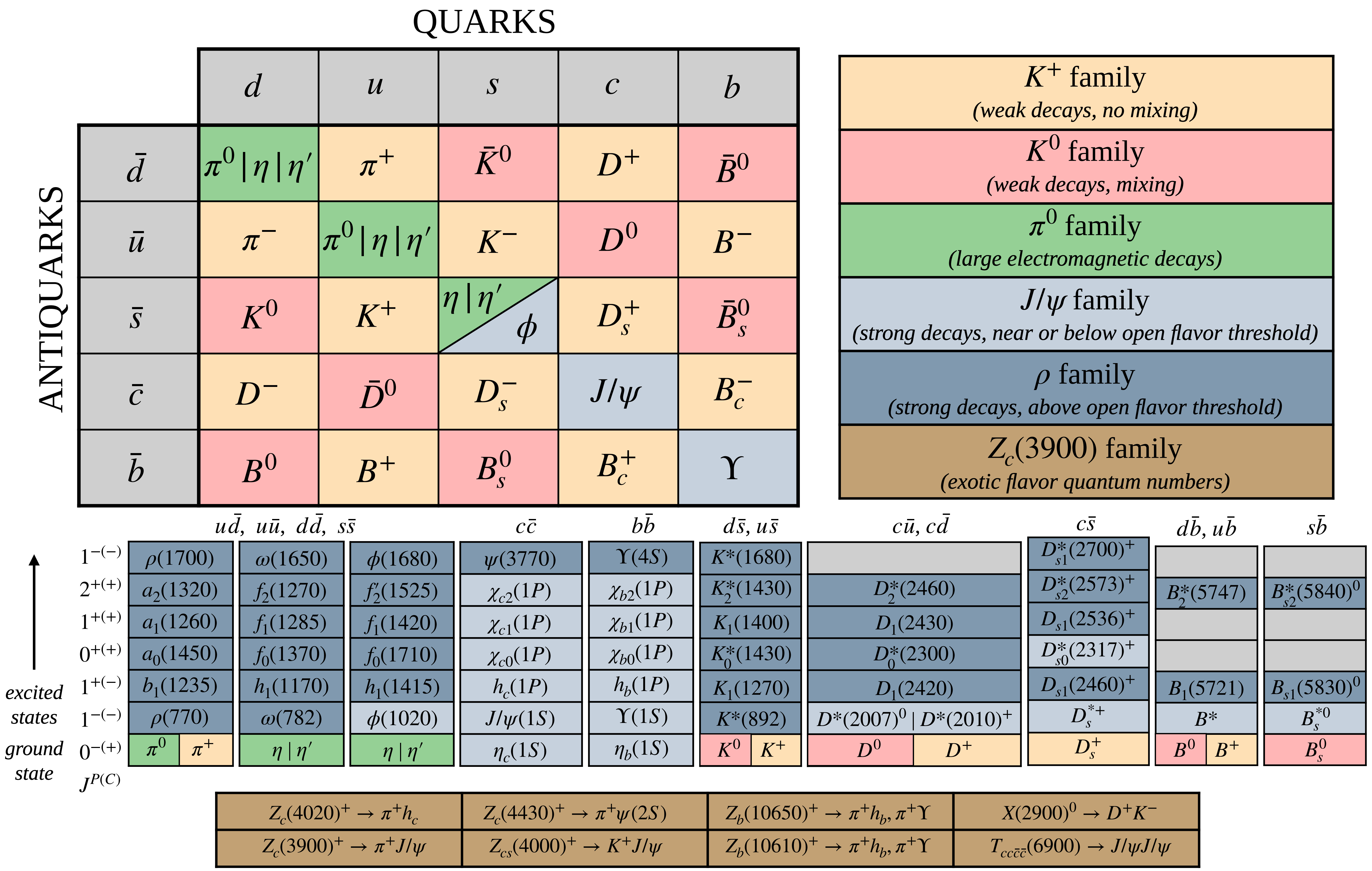
$J^{P(C)}$	$u\bar d$, $u\bar u$, $d\bar d$, $s\bar s$			$c\bar c$						$s\bar b$
$1^{-(-)}$	$\rho(1700)$	$\omega(1650)$	$\phi(1680)$	$\psi(3770)$						
$2^{+(+)}$	$a_2(1320)$	$f_2(1270)$	$f'_2(1525)$	$\chi_{c2}(1P)$	χ					$840)^0$
$1^{+(+)}$	$a_1(1260)$	$f_1(1285)$	$f_1(1420)$	$\chi_{c1}(1P)$	χ					
$0^{+(+)}$	$a_0(1450)$	$f_0(1370)$	$f_0(1710)$	$\chi_{c0}(1P)$	χ					
$1^{+(-)}$	$b_1(1235)$	$h_1(1170)$	$h_1(1415)$	$h_c(1P)$	$h_b(1P)$	$K_1(1270)$	$D_1(2420)$	$D_{s1}(2460)^+$	$B_1(5721)$	$B_{s1}(5830)^0$
$1^{-(-)}$	$\rho(770)$	$\omega(782)$	$\phi(1020)$	$J/\psi(1S)$	$\Upsilon(1S)$	$K^*(892)$	$D^*(2007)^0 \mid D^*(2010)^+$	D_s^{*+}	B^*	B_s^{*0}
$0^{-(+)}$	π^0 π^+	$\eta \mid \eta'$	$\eta \mid \eta'$	$\eta_c(1S)$	$\eta_b(1S)$	K^0 K^+	D^0 D^+	D_s^+	B^0 B^+	B_s^0

excited states

ground state

For a $q\bar q'$ meson: $\vec{J} = \vec{L} + \vec{S}$ and $P = (-1)^{L+1}$ and $C = (-1)^{L+S}$

II. Families of Mesons



QUARKS

ANTIQUARKS

	d	u	s	c	b
$\bar{d}$	$\pi^0 \mid \eta \mid \eta'$	π^+	$\bar{K}^0$	D^+	$\bar{B}^0$
$\bar{u}$	π^-	$\pi^0 \mid \eta \mid \eta'$	K^-	D^0	B^-
$\bar{s}$	K^0	K^+	$\eta \mid \eta'$ ϕ	D_s^+	$\bar{B}_s^0$
$\bar{c}$	D^-	$\bar{D}^0$	D_s^-	J/ψ	B_c^-
$\bar{b}$	B^0	B^+	B_s^0	B_c^+	Υ

K^+ family
(weak decays, no mixing)

K^0 family
(weak decays, mixing)

π^0 family
(large electromagnetic decays)

J/ψ family
(strong decays, near or below open flavor threshold)

ρ family
(strong decays, above open flavor threshold)

$Z_c(3900)$ family
(exotic flavor quantum numbers)

		$u\bar{d}$, $u\bar{u}$, $d\bar{d}$, $s\bar{s}$		$c\bar{c}$	$b\bar{b}$	$d\bar{s}$, $u\bar{s}$	$c\bar{u}$, $c\bar{d}$	$c\bar{s}$	$d\bar{b}$, $u\bar{b}$	$s\bar{b}$
$1^{-(-)}$	$\rho(1700)$	$\omega(1650)$	$\phi(1680)$	$\psi(3770)$	$\Upsilon(4S)$	$K^*(1680)$		$D_{s1}^*(2700)^+$		
$2^{+(+)}$	$a_2(1320)$	$f_2(1270)$	$f_2'(1525)$	$\chi_{c2}(1P)$	$\chi_{b2}(1P)$	$K_2^*(1430)$	$D_2^*(2460)$	$D_{s2}^*(2573)^+$	$B_2^*(5747)$	$B_{s2}^*(5840)^0$
$1^{+(+)}$	$a_1(1260)$	$f_1(1285)$	$f_1(1420)$	$\chi_{c1}(1P)$	$\chi_{b1}(1P)$	$K_1(1400)$	$D_1(2430)$	$D_{s1}(2536)^+$		
$0^{+(+)}$	$a_0(1450)$	$f_0(1370)$	$f_0(1710)$	$\chi_{c0}(1P)$	$\chi_{b0}(1P)$	$K_0^*(1430)$	$D_0^*(2300)$	$D_{s0}^*(2317)^+$		
$1^{+(-)}$	$b_1(1235)$	$h_1(1170)$	$h_1(1415)$	$h_c(1P)$	$h_b(1P)$	$K_1(1270)$	$D_1(2420)$	$D_{s1}(2460)^+$	$B_1(5721)$	$B_{s1}(5830)^0$
$1^{-(-)}$	$\rho(770)$	$\omega(782)$	$\phi(1020)$	$J/\psi(1S)$	$\Upsilon(1S)$	$K^*(892)$	$D^*(2007)^0 \mid D^*(2010)^+$	D_s^{*+}	B^*	B_s^{*0}
$0^{-(+)}$	π^0 π^+	$\eta \mid \eta'$	$\eta \mid \eta'$	$\eta_c(1S)$	$\eta_b(1S)$	K^0 K^+	D^0 D^+	D_s^+	B^0 B^+	B_s^0
$J^{P(C)}$										

excited states

ground state

$Z_c(4020)^+ \to \pi^+ h_c$	$Z_c(4430)^+ \to \pi^+ \psi(2S)$	$Z_b(10650)^+ \to \pi^+ h_b, \pi^+ \Upsilon$	$X(2900)^0 \to D^+ K^-$
$Z_c(3900)^+ \to \pi^+ J/\psi$	$Z_{cs}(4000)^+ \to K^+ J/\psi$	$Z_b(10610)^+ \to \pi^+ h_b, \pi^+ \Upsilon$	$T_{cc\bar{c}\bar{c}}(6900) \to J/\psi J/\psi$

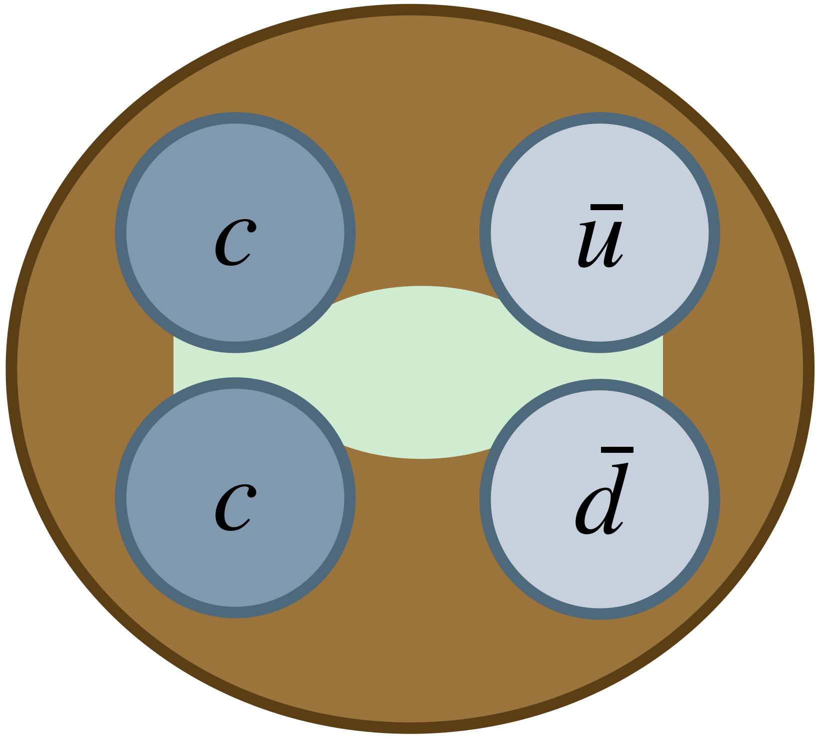
II. Families of Mesons

QUARKS

ANTIQUARKS

	d	u	s	c	b
$\bar{d}$	$\pi^0 \mid \eta \mid \eta'$	π^+	$\bar{K}^0$	D^+	$\bar{B}^0$
$\bar{u}$	π^-	$\pi^0 \mid \eta \mid \eta'$	K^-	D^0	B^-
$\bar{s}$	K^0	K^+	$\eta \mid \eta'$ ϕ	D_s^+	$\bar{B}_s^0$
$\bar{c}$	D^-	$\bar{D}^0$	D_s^-	J/ψ	B_c^-
$\bar{b}$	B^0	B^+	B_s^0	B_c^+	Υ

“T_{cc}^+” tetraquark:



	$J^{P(C)}$	$u\bar{d},\ u\bar{u},\ d\bar{d},\ s\bar{s}$			$c\bar{c}$	$b\bar{b}$	$d\bar{s}, u\bar{s}$	$c\bar{u}, c\bar{d}$	$c\bar{s}$	$d\bar{b}, u\bar{b}$	$s\bar{b}$
	$1^{-(-)}$	$\rho(1700)$	$\omega(1650)$	$\phi(1680)$	$\psi(3770)$	$\Upsilon(4S)$	$K^*(1680)$		$D_{s1}^*(2700)^+$		
	$2^{+(+)}$	$a_2(1320)$	$f_2(1270)$	$f_2'(1525)$	$\chi_{c2}(1P)$	$\chi_{b2}(1P)$	$K_2^*(1430)$	$D_2^*(2460)$	$D_{s2}^*(2573)^+$	$B_2^*(5747)$	$B_{s2}^*(5840)^0$
	$1^{+(+)}$	$a_1(1260)$	$f_1(1285)$	$f_1(1420)$	$\chi_{c1}(1P)$	$\chi_{b1}(1P)$	$K_1(1400)$	$D_1(2430)$	$D_{s1}(2536)^+$		
	$0^{+(+)}$	$a_0(1450)$	$f_0(1370)$	$f_0(1710)$	$\chi_{c0}(1P)$	$\chi_{b0}(1P)$	$K_0^*(1430)$	$D_0^*(2300)$	$D_{s0}^*(2317)^+$		
excited states	$1^{+(-)}$	$b_1(1235)$	$h_1(1170)$	$h_1(1415)$	$h_c(1P)$	$h_b(1P)$	$K_1(1270)$	$D_1(2420)$	$D_{s1}(2460)^+$	$B_1(5721)$	$B_{s1}(5830)^0$
	$1^{-(-)}$	$\rho(770)$	$\omega(782)$	$\phi(1020)$	$J/\psi(1S)$	$\Upsilon(1S)$	$K^*(892)$	$D^*(2007)^0 \mid D^*(2010)^+$	D_s^{*+}	B^*	B_s^{*0}
ground state	$0^{-(+)}$	π^0 π^+	$\eta \mid \eta'$	$\eta \mid \eta'$	$\eta_c(1S)$	$\eta_b(1S)$	K^0 K^+	D^0 D^+	D_s^+	B^0 B^+	B_s^0

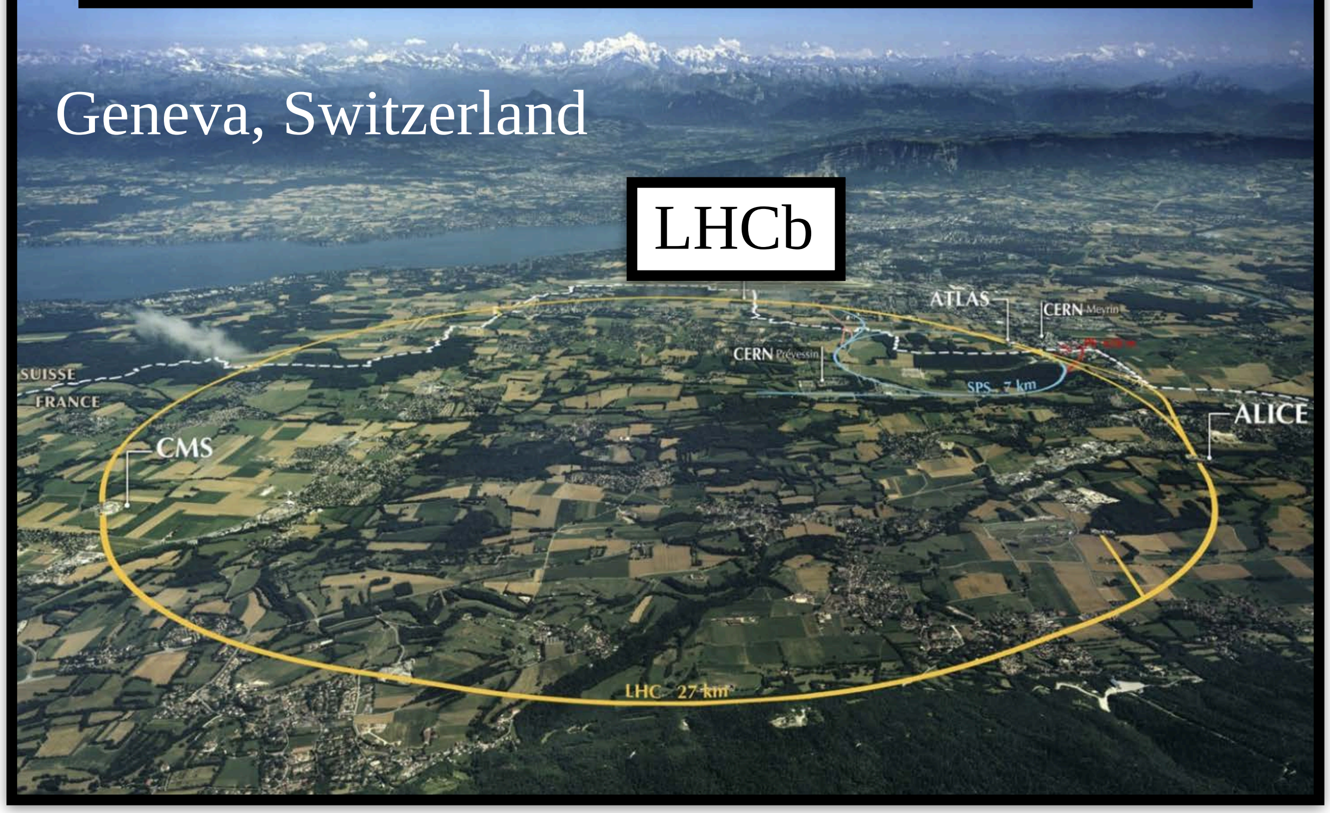
$Z_c(4020)^+ \rightarrow \pi^+ h_c$	$Z_c(4430)^+ \rightarrow \pi^+ \psi(2S)$	$Z_b(10650)^+ \rightarrow \pi^+ h_b, \pi^+ \Upsilon$	$X(2900)^0 \rightarrow D^+ K^-$
$Z_c(3900)^+ \rightarrow \pi^+ J/\psi$	$Z_{cs}(4000)^+ \rightarrow K^+ J/\psi$	$Z_b(10610)^+ \rightarrow \pi^+ h_b, \pi^+ \Upsilon$	$T_{cc\bar{c}\bar{c}}(6900) \rightarrow J/\psi J/\psi$

III. Looking for Mesons

Step 1: Produce mesons…

… using a sledgehammer:

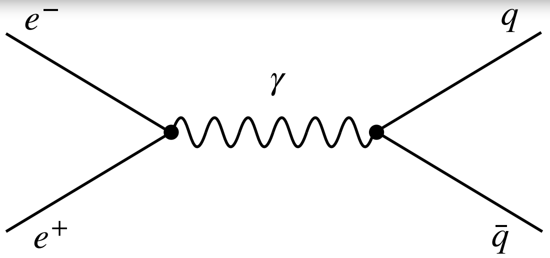
Large Hadron Collider (LHC)
pp collisions at very high energy (7-14 TeV)



$pp \rightarrow$ many many hadrons (baryons and mesons)

… using a scalpel:

Beijing Electron Positron Collider (BEPCII)
e^+e^- *collisions at low energies (2-5 GeV)*



e.g., $e^+e^- \rightarrow J/\psi \rightarrow \pi^+\pi^-\pi^0$

$e^+e^- \rightarrow \psi(3770) \rightarrow D^+D^-$

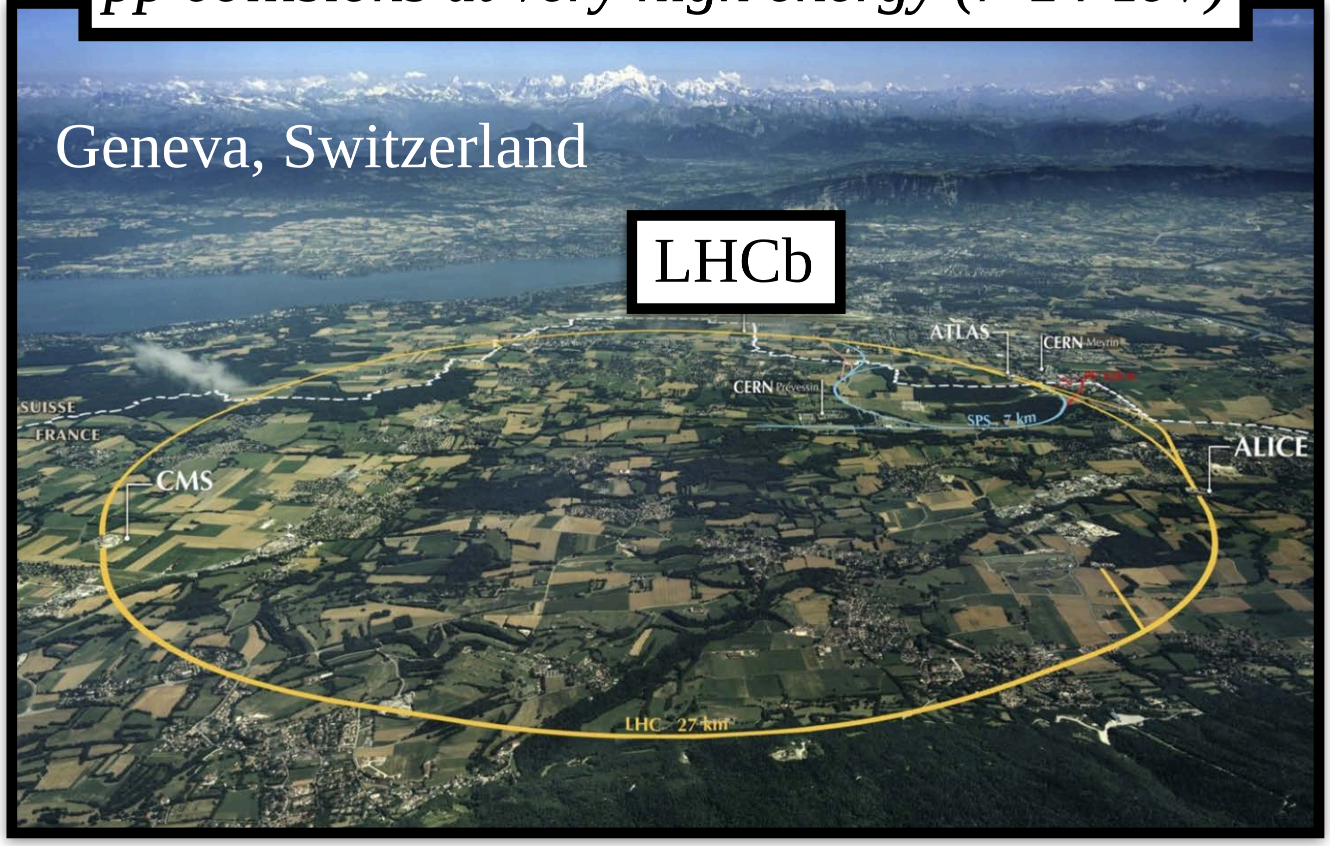
III. Looking for Mesons

Step 1: Produce mesons…

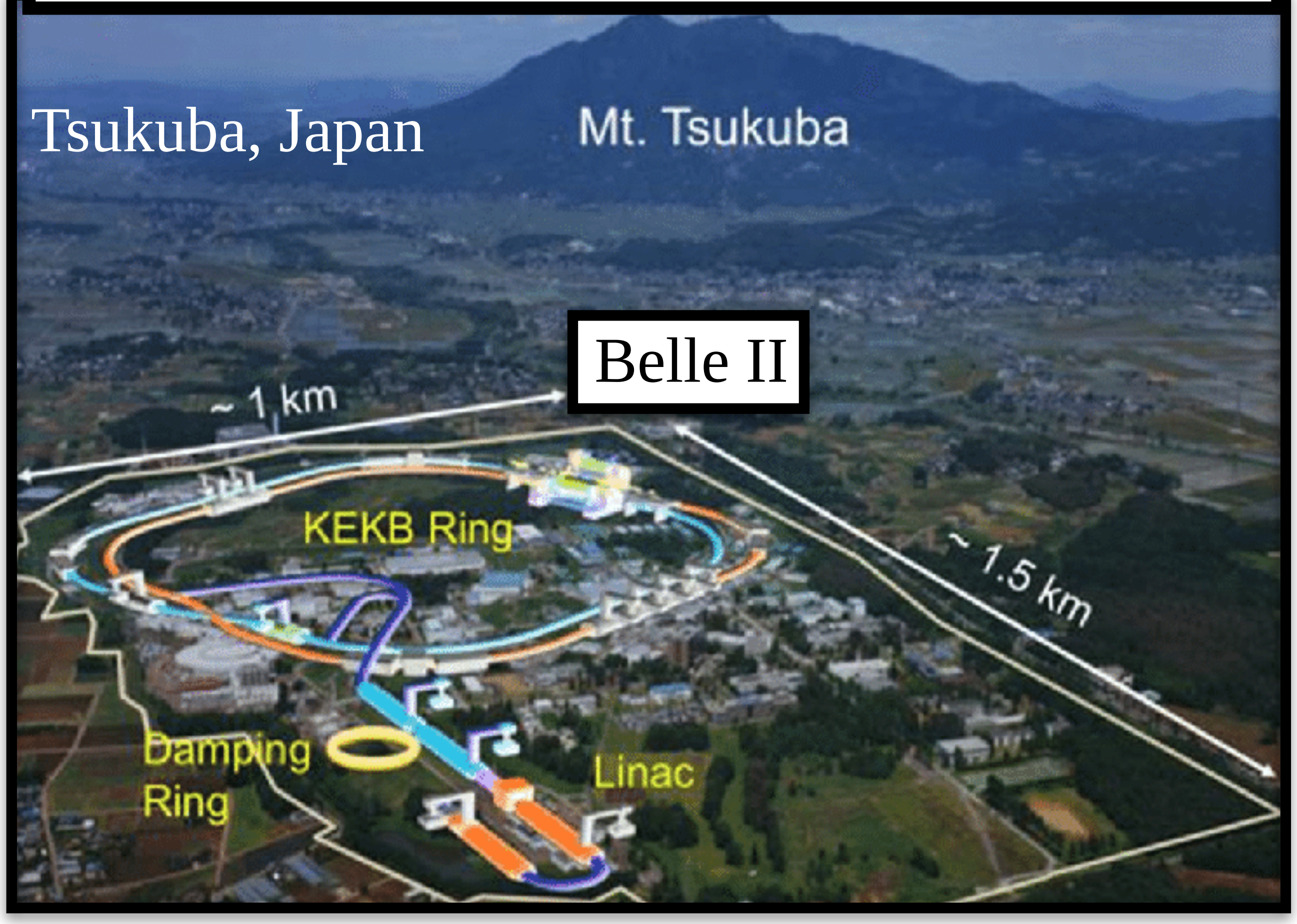
… using a sledgehammer:

… using a scalpel:

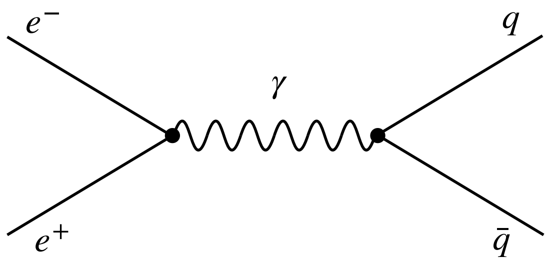
Large Hadron Collider (LHC)
pp collisions at very high energy (7-14 TeV)



SuperKEKB
e^+e^- collisions at higher energies (10.58 GeV)



$pp \to$ many many hadrons (baryons and mesons)

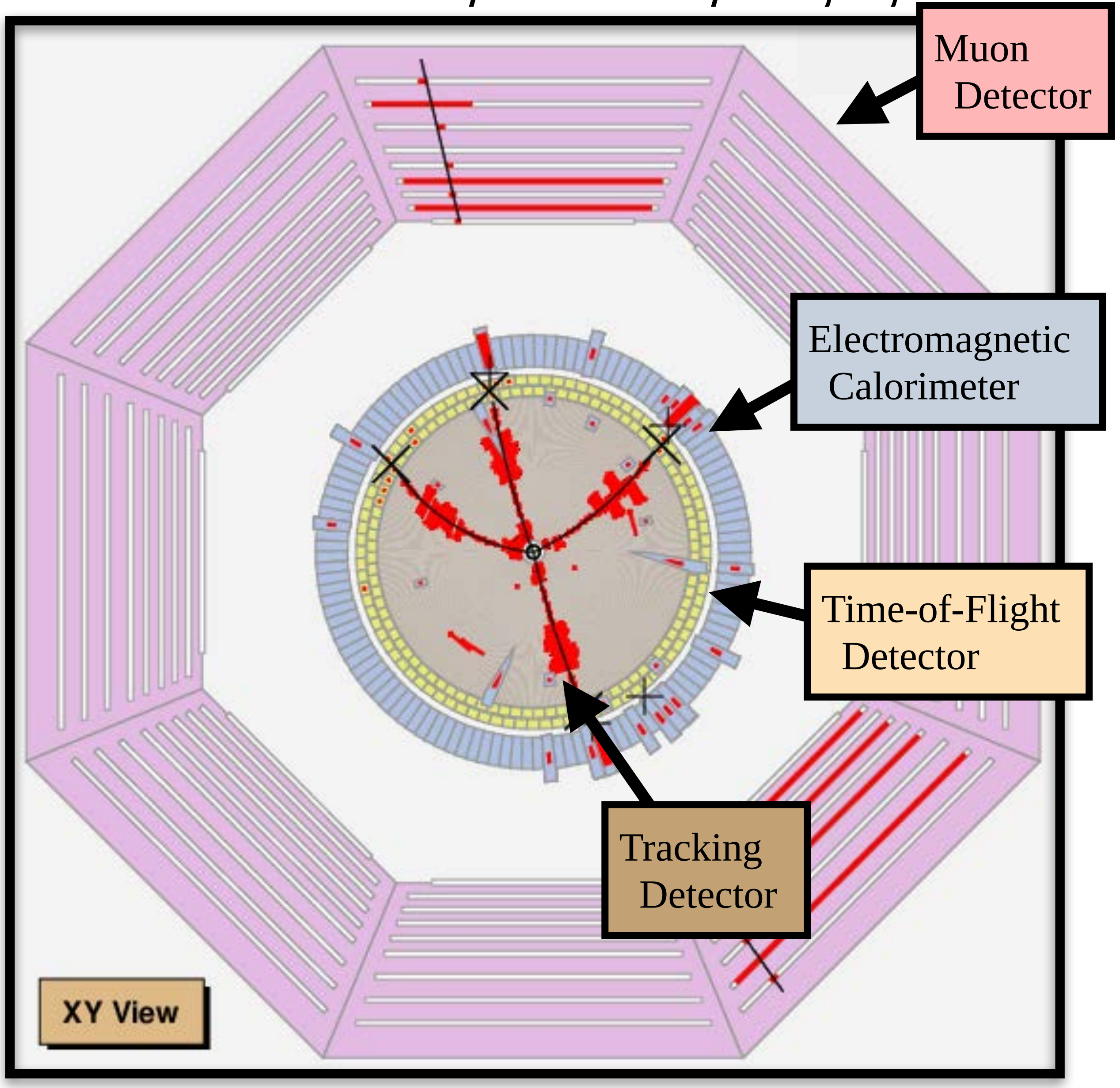


e.g., $e^+e^- \to \Upsilon(4S) \to B^+B^-$

III. Looking for Mesons

Step 2: Detect mesons.

$$e^+e^- \to \pi^+\pi^- J/\psi \text{ with } J/\psi \to \mu^+\mu^-$$



Muon Detector

Electromagnetic Calorimeter

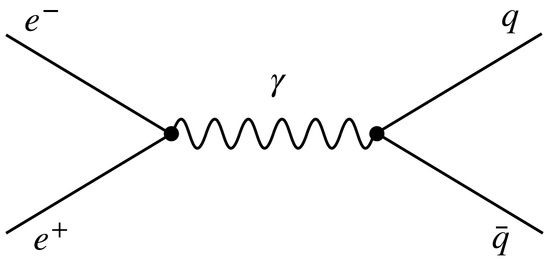
Time-of-Flight Detector

Tracking Detector

Beijing Electron Positron Collider (BEPCII)
e^+e^- collisions at low energies (2-5 GeV)


Beijing, China

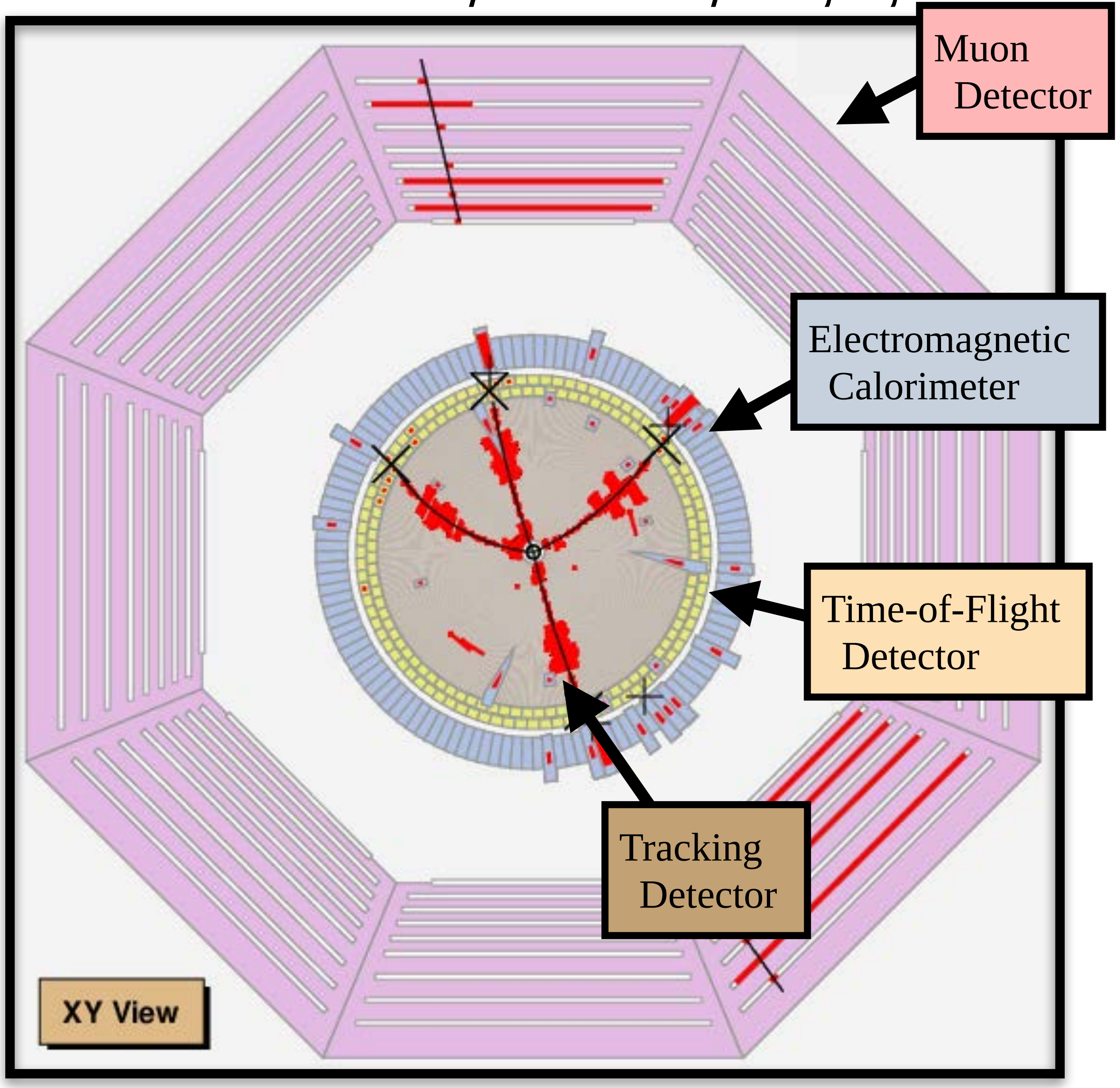
BESIII



III. Looking for Mesons

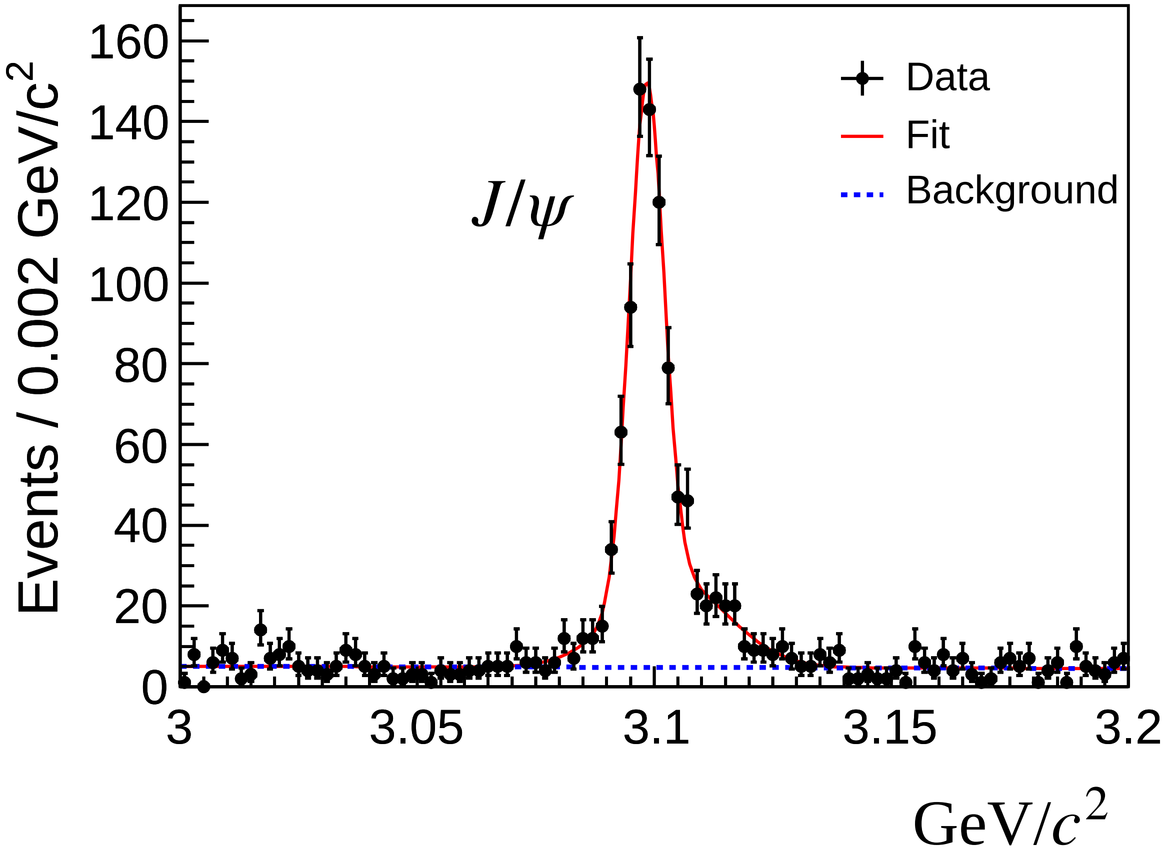
Step 2: Detect mesons.

$e^+e^- \to \pi^+\pi^- J/\psi$ with $J/\psi \to \mu^+\mu^-$



$e^+e^- \to \pi^+\pi^- J/\psi$ with $J/\psi \to \mu^+\mu^-$

BESIII, PRL110, 252001 (2013)



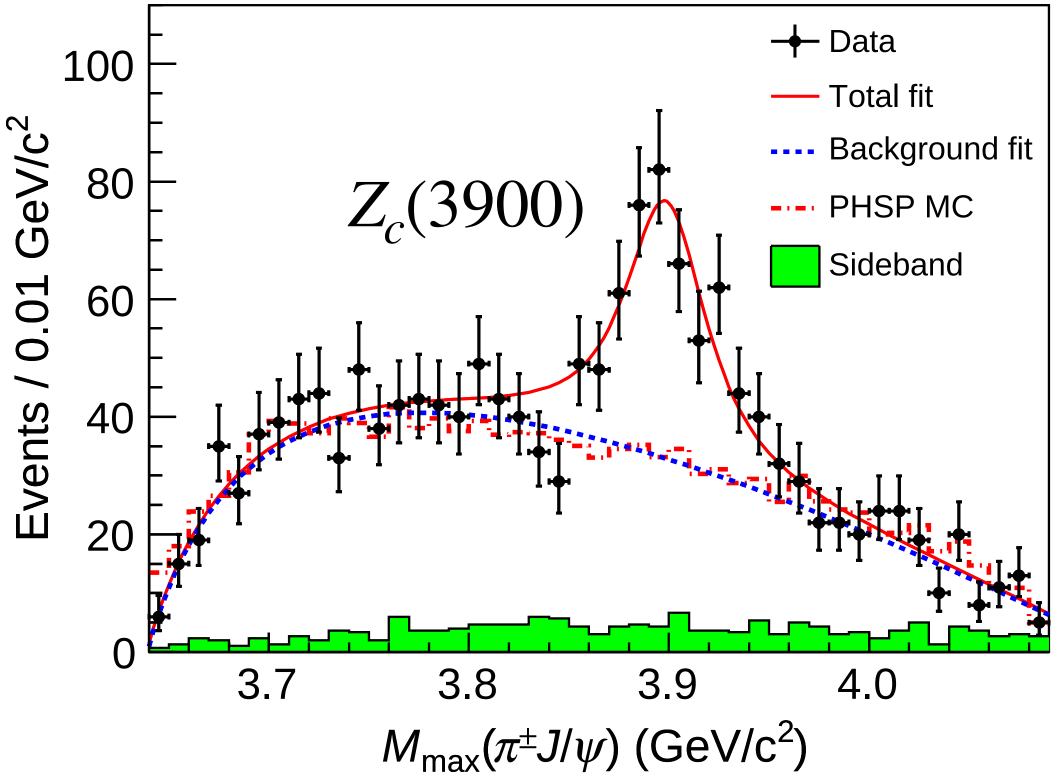
$$M_{\mu\mu} = \sqrt{(E_{\mu^+} + E_{\mu^-})^2 - (\vec{p}_{\mu^+} + \vec{p}_{\mu^-})^2}$$

III. Looking for Mesons

Step 2: Detect mesons.

$$e^+e^- \to \pi^+\pi^- J/\psi \text{ with } J/\psi \to l^+l^-$$

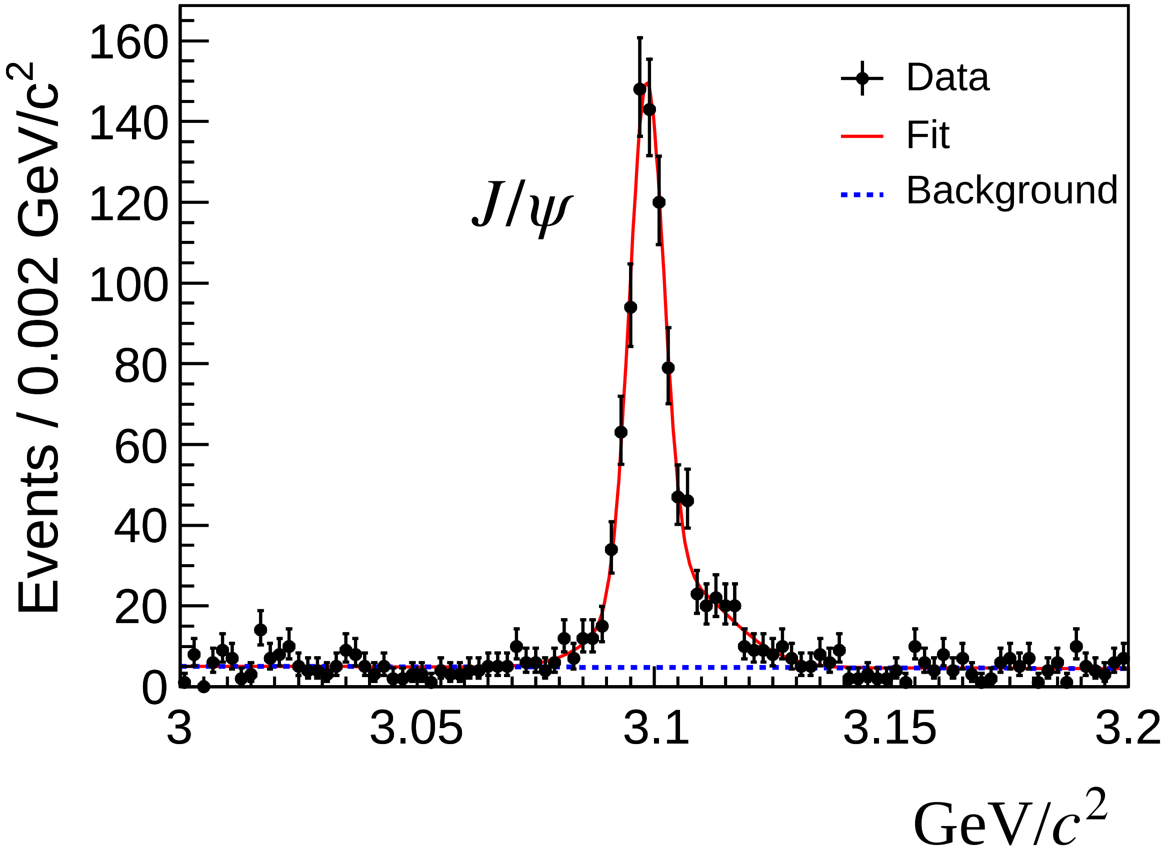
BESIII, PRL110, 252001 (2013)



$$M_{\pi J/\psi} = \sqrt{(E_\pi + E_{ll})^2 - (\vec{p}_\pi + \vec{p}_{ll})^2}$$

$$e^+e^- \to \pi^+\pi^- J/\psi \text{ with } J/\psi \to \mu^+\mu^-$$

BESIII, PRL110, 252001 (2013)

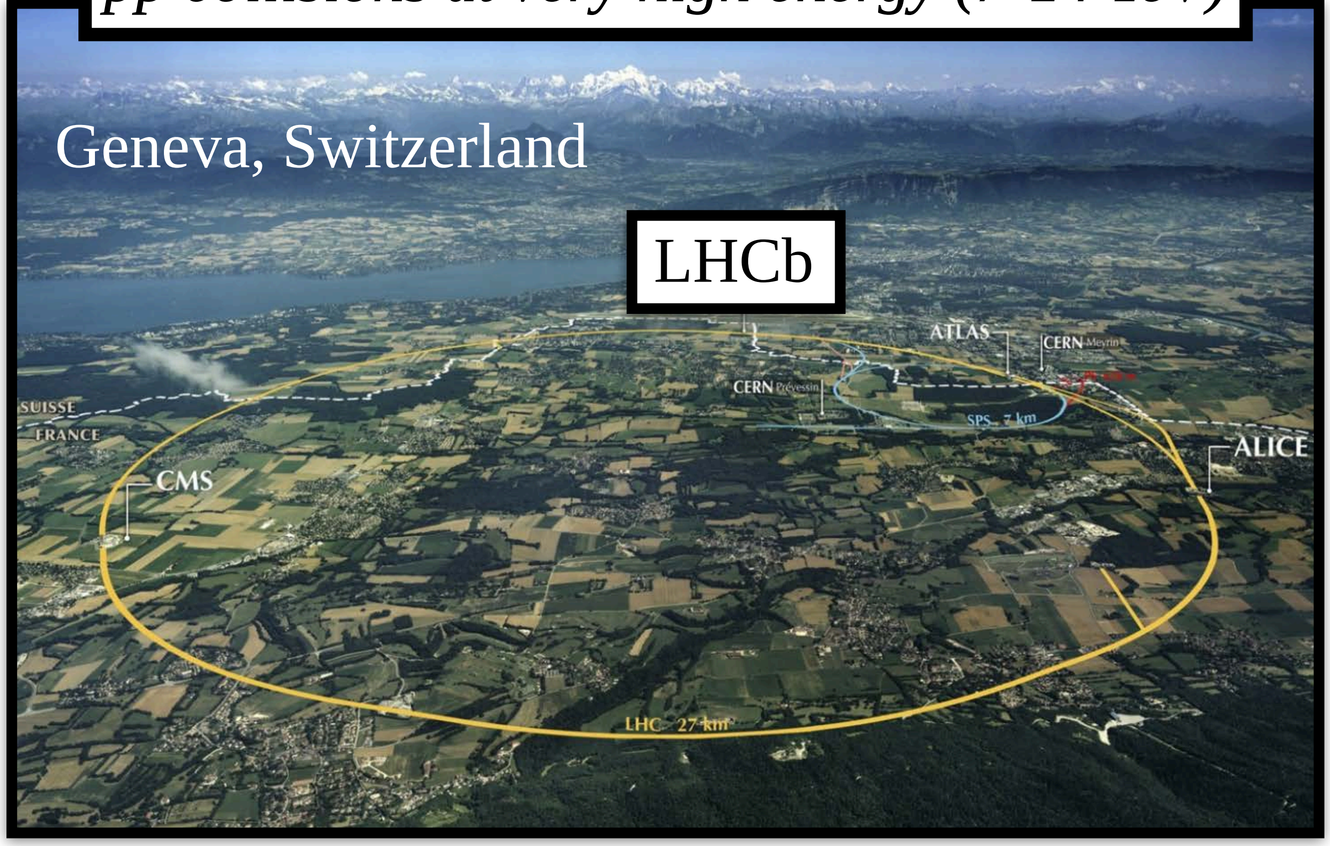


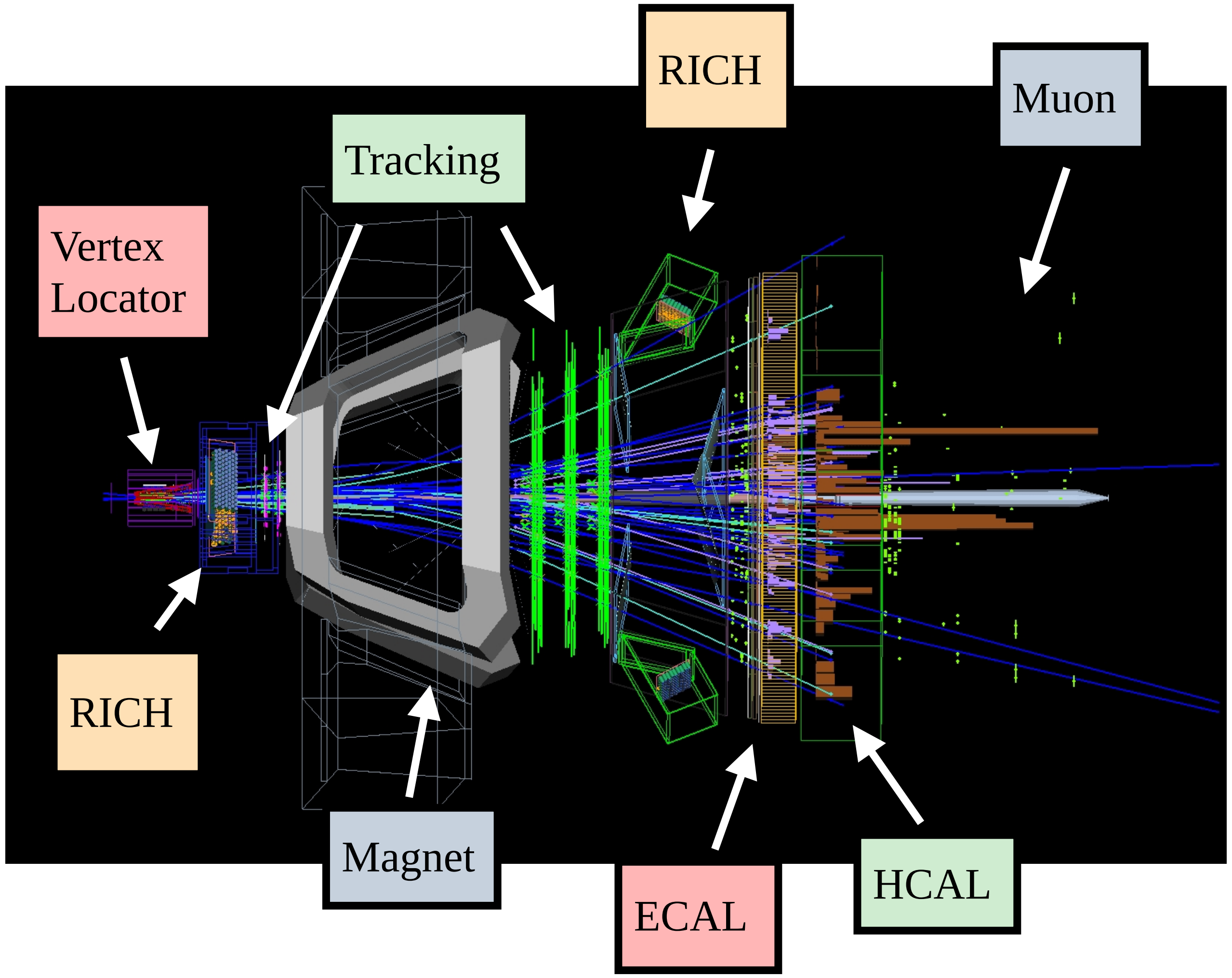
$$M_{\mu\mu} = \sqrt{(E_{\mu^+} + E_{\mu^-})^2 - (\vec{p}_{\mu^+} + \vec{p}_{\mu^-})^2}$$

III. Looking for Mesons

Step 2: Detect mesons.

Large Hadron Collider (LHC)
pp collisions at very high energy (7-14 TeV)



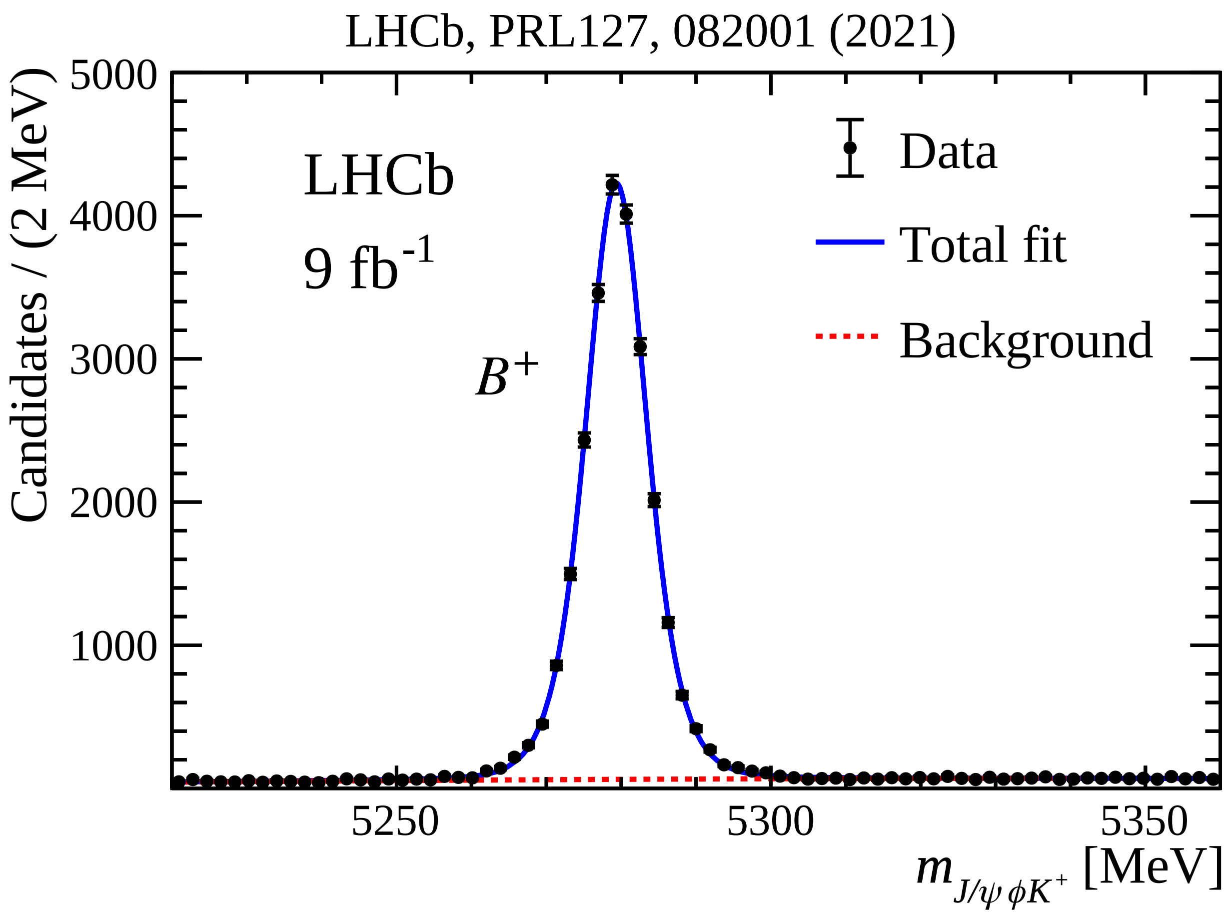


$pp \rightarrow$ many many hadrons (baryons and mesons)

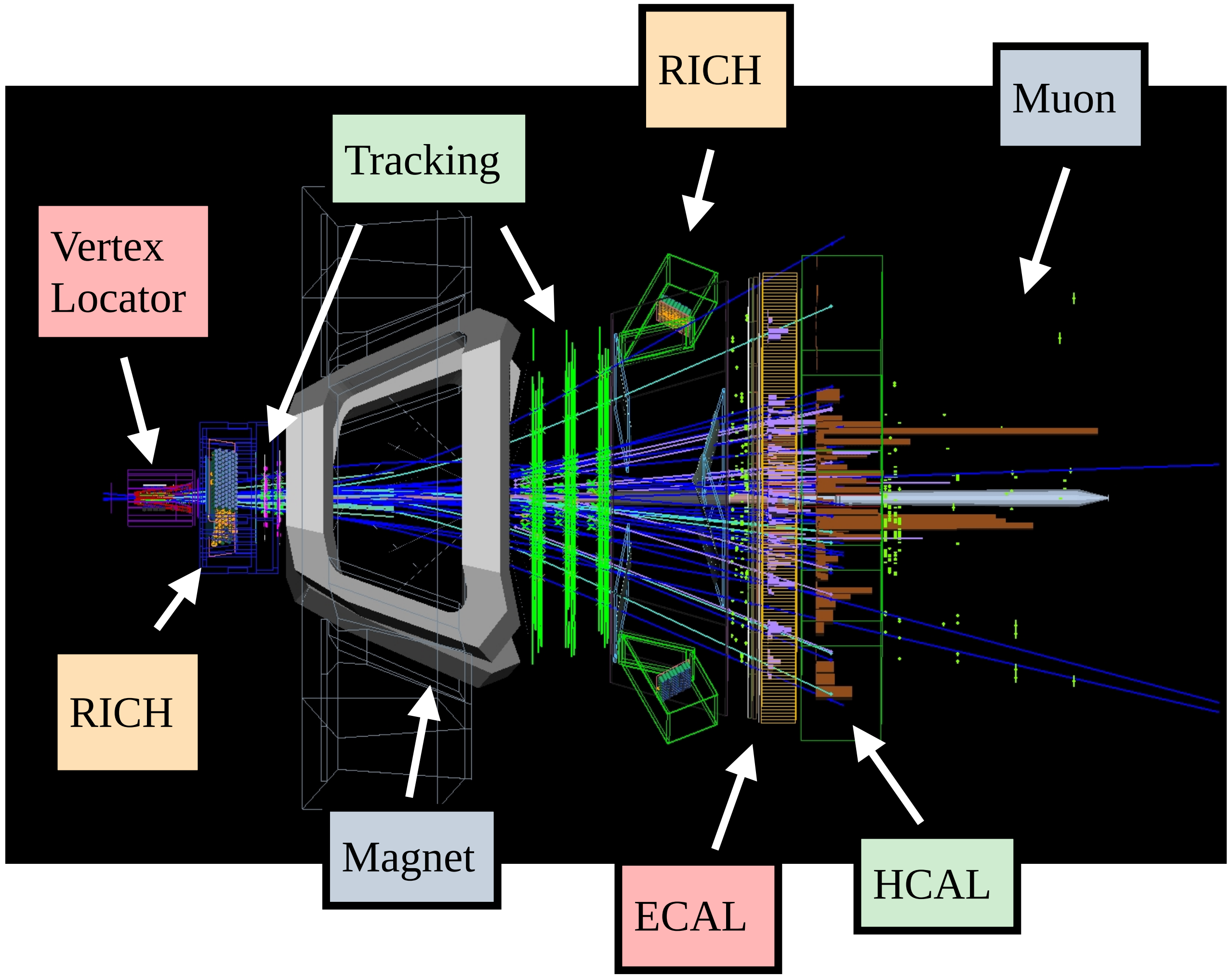
III. Looking for Mesons

Step 2: Detect mesons.

$B^+ \to J/\psi \phi K^+$ with $J/\psi \to \mu^+\mu^-$ and $\phi \to K^+K^-$



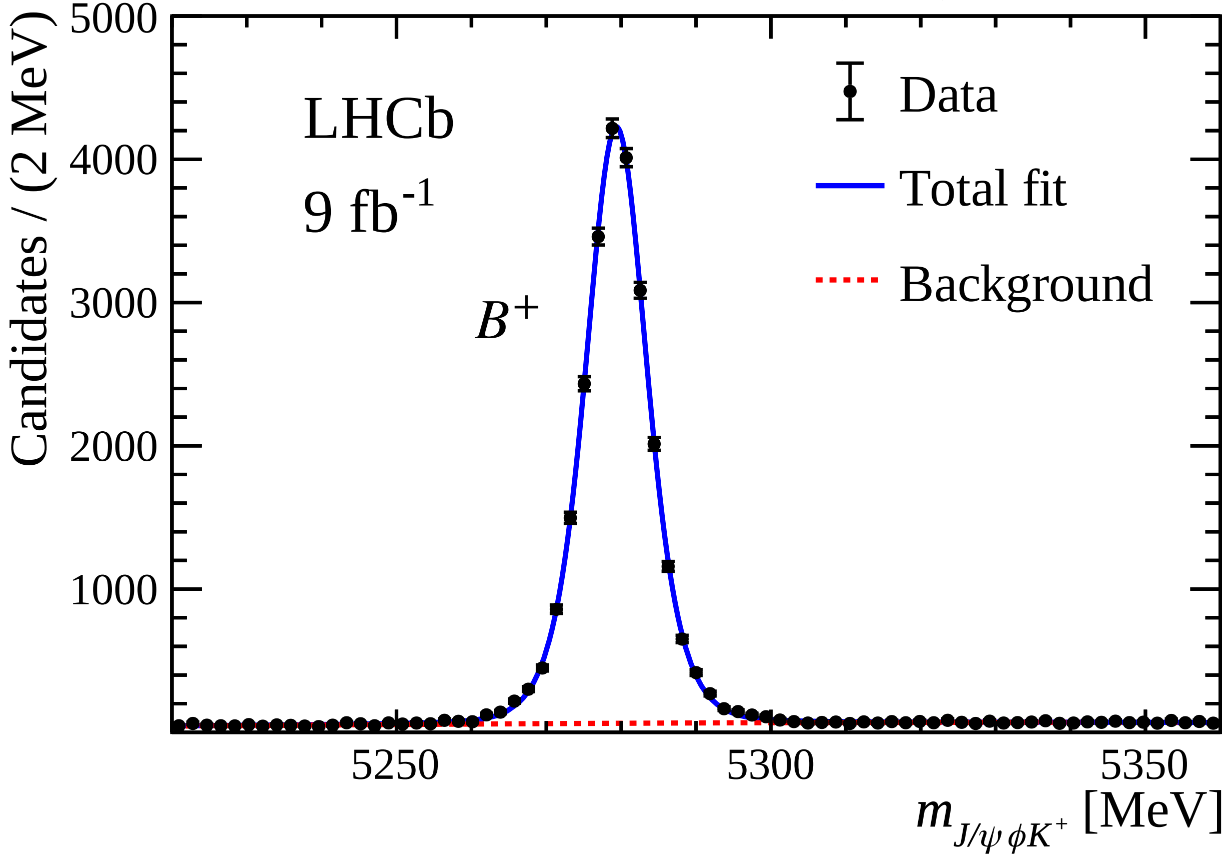
LHCb, PRL127, 082001 (2021)



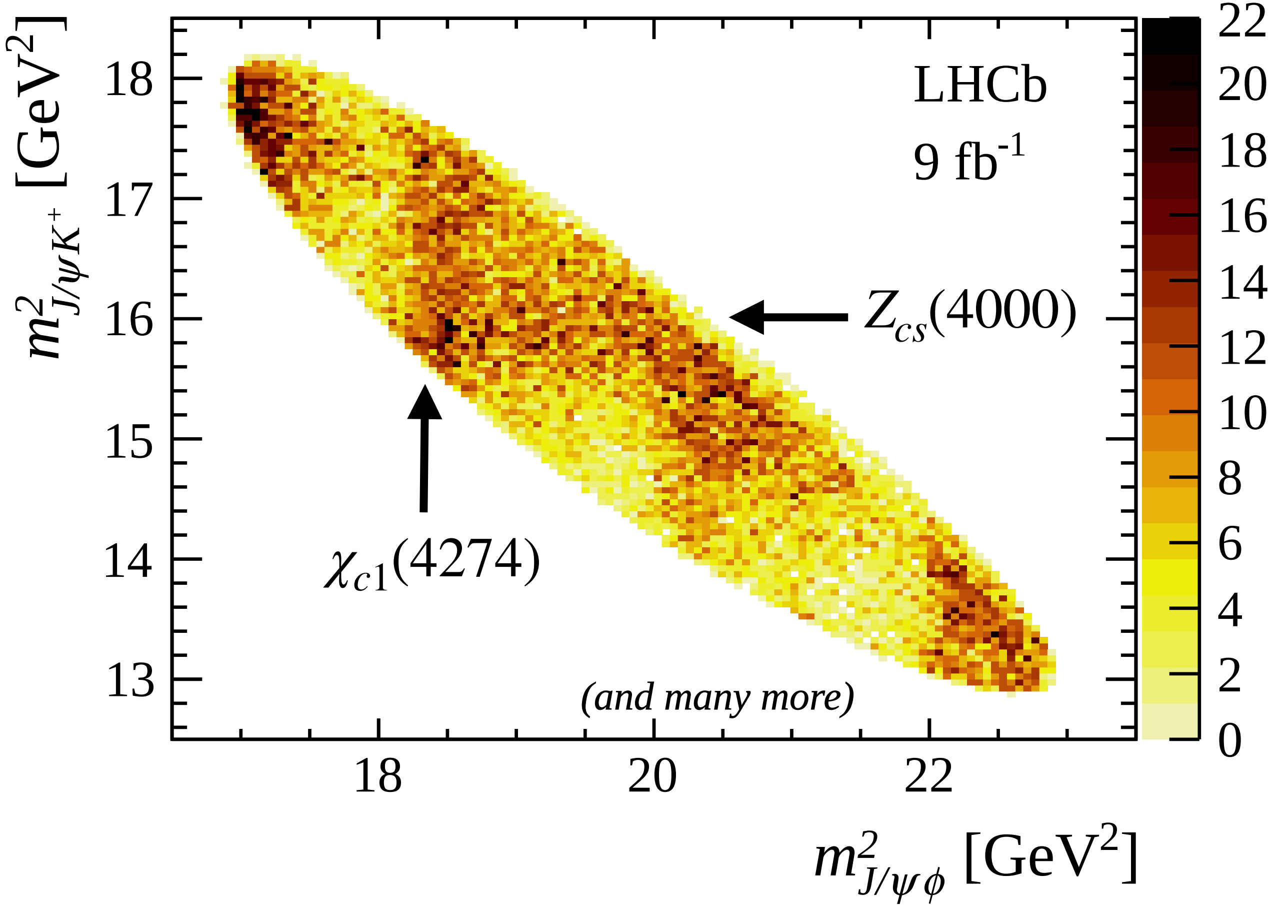
III. Looking for Mesons

Step 2: Detect mesons.

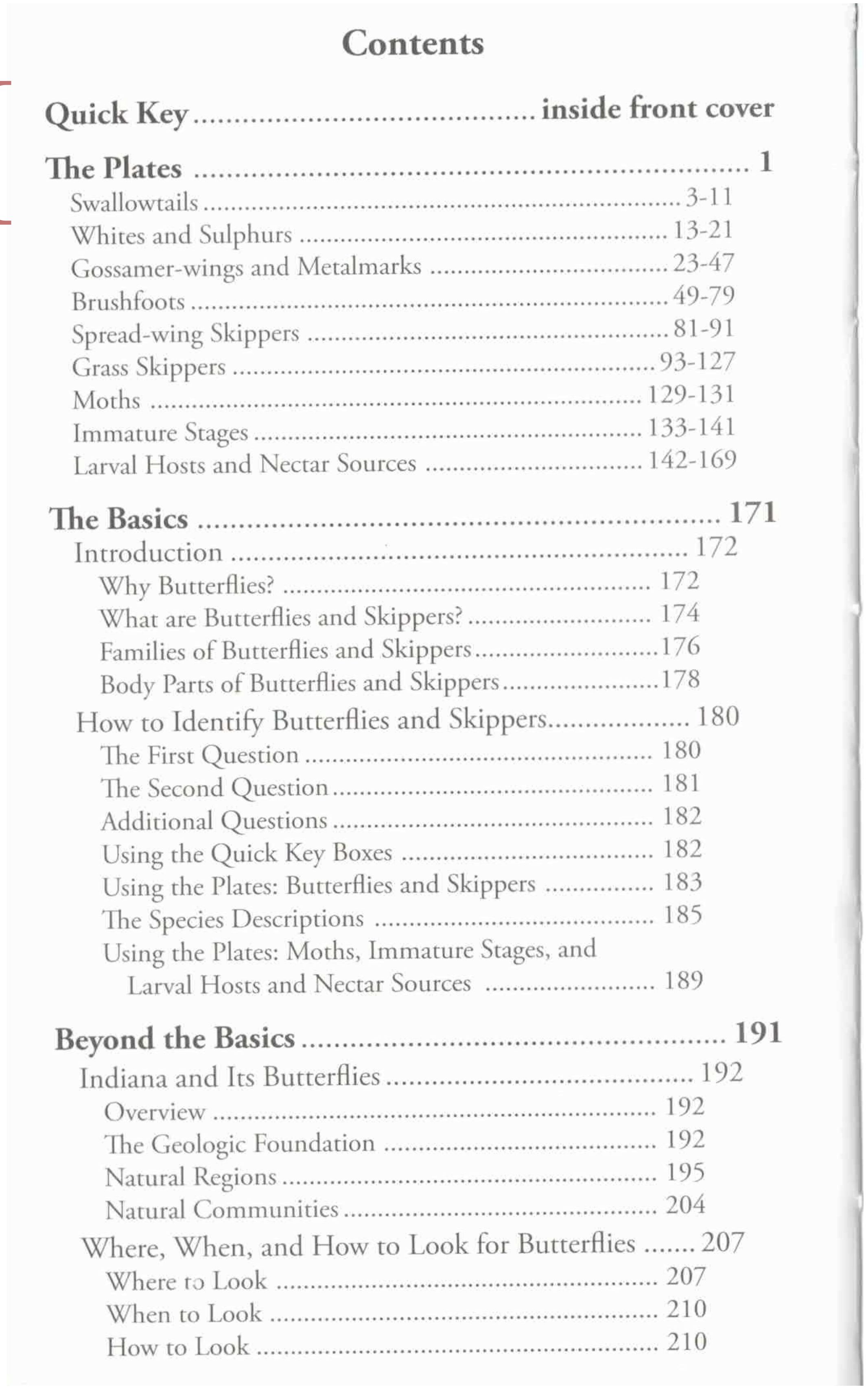
$B^+ \to J/\psi\phi K^+$ with $J/\psi \to \mu^+\mu^-$ and $\phi \to K^+K^-$


LHCb, PRL127, 082001 (2021)

$B^+ \to J/\psi\phi K^+$ with $J/\psi \to \mu^+\mu^-$ and $\phi \to K^+K^-$


LHCb, PRL127, 082001 (2021)

A Field Guide to the Mesons



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II. Families of Mesons

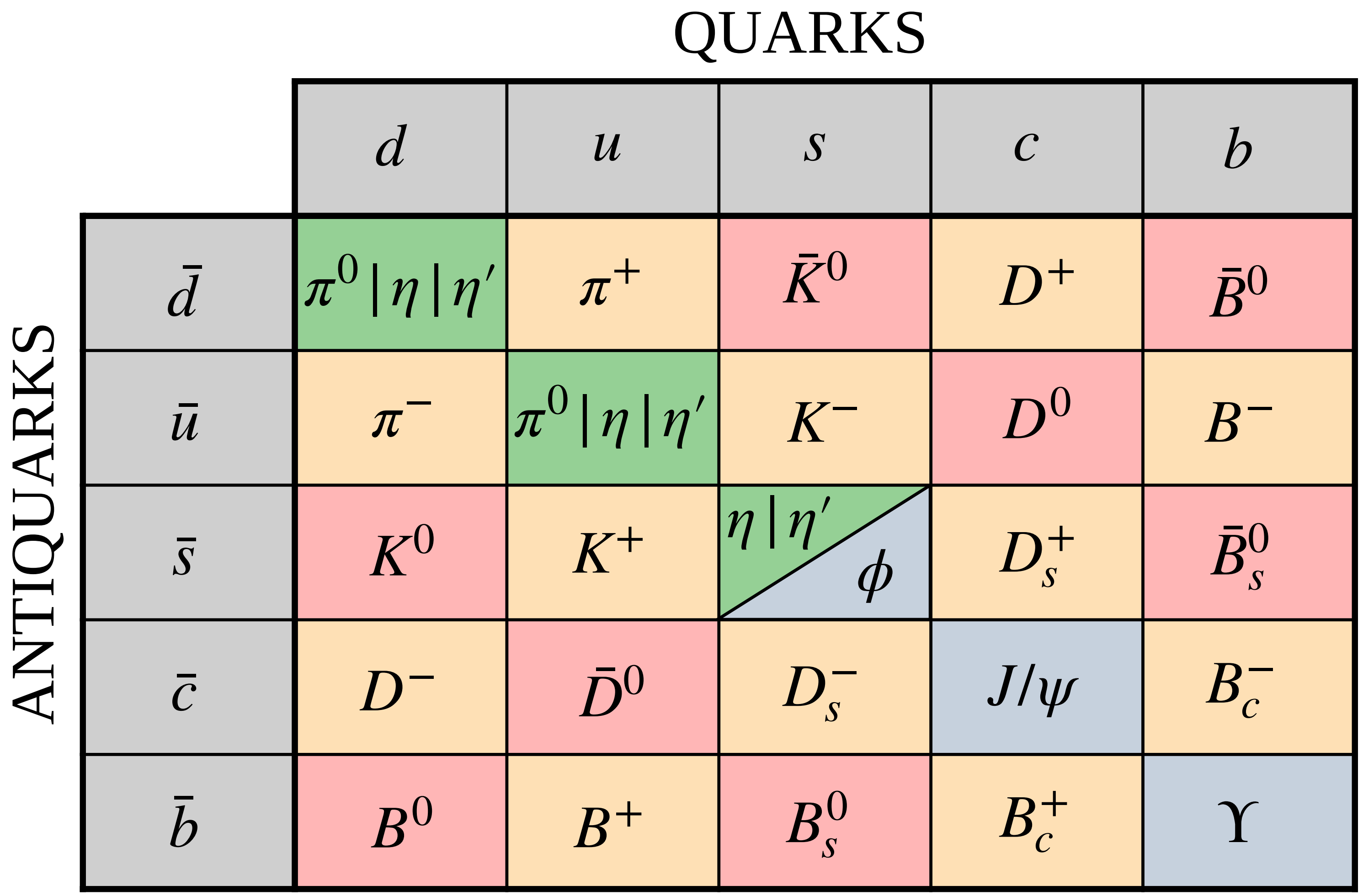
III. Looking for Mesons

IV. The Plates: $c\bar{c}$ and cc mesons

V. The Plates: $b\bar{b}$ and bb mesons

VI. Why Mesons?

IV. The Plates: $c\bar{c}$ and cc mesons



QUARKS

ANTIQUARKS

	d	u	s	c	b
$\bar{d}$	$\pi^0 \mid \eta \mid \eta'$	π^+	$\bar{K}^0$	D^+	$\bar{B}^0$
$\bar{u}$	π^-	$\pi^0 \mid \eta \mid \eta'$	K^-	D^0	B^-
$\bar{s}$	K^0	K^+	$\eta \mid \eta'$ ϕ	D_s^+	$\bar{B}_s^0$
$\bar{c}$	D^-	$\bar{D}^0$	D_s^-	J/ψ	B_c^-
$\bar{b}$	B^0	B^+	B_s^0	B_c^+	Υ

K^+ family
(weak decays, no mixing)

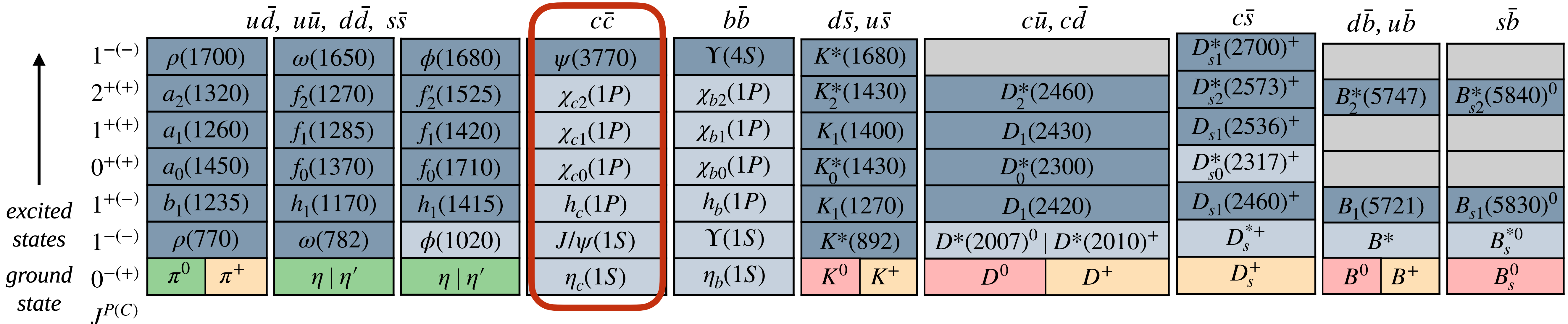
K^0 family
(weak decays, mixing)

π^0 family
(large electromagnetic decays)

J/ψ family
(strong decays, near or below open flavor threshold)

ρ family
(strong decays, above open flavor threshold)

$Z_c(3900)$ family
(exotic flavor quantum numbers)



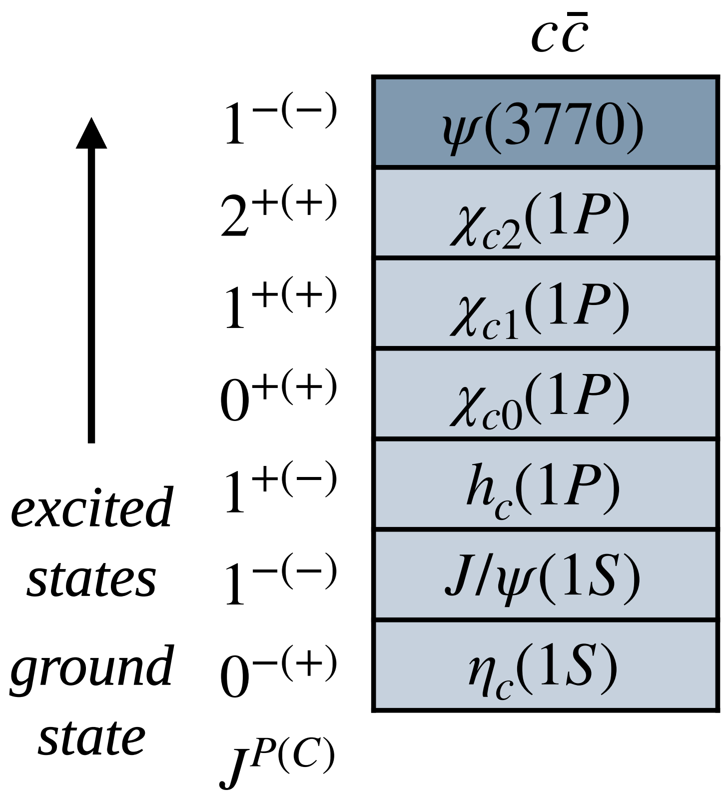
$J^{P(C)}$	$u\bar{d},\ u\bar{u},\ d\bar{d},\ s\bar{s}$			$c\bar{c}$	$b\bar{b}$	$d\bar{s},\ u\bar{s}$	$c\bar{u},\ c\bar{d}$	$c\bar{s}$	$d\bar{b},\ u\bar{b}$	$s\bar{b}$
$1^{-(-)}$	$\rho(1700)$	$\omega(1650)$	$\phi(1680)$	$\psi(3770)$	$\Upsilon(4S)$	$K^*(1680)$		$D_{s1}^*(2700)^+$		
$2^{+(+)}$	$a_2(1320)$	$f_2(1270)$	$f_2'(1525)$	$\chi_{c2}(1P)$	$\chi_{b2}(1P)$	$K_2^*(1430)$	$D_2^*(2460)$	$D_{s2}^*(2573)^+$	$B_2^*(5747)$	$B_{s2}^*(5840)^0$
$1^{+(+)}$	$a_1(1260)$	$f_1(1285)$	$f_1(1420)$	$\chi_{c1}(1P)$	$\chi_{b1}(1P)$	$K_1(1400)$	$D_1(2430)$	$D_{s1}(2536)^+$		
$0^{+(+)}$	$a_0(1450)$	$f_0(1370)$	$f_0(1710)$	$\chi_{c0}(1P)$	$\chi_{b0}(1P)$	$K_0^*(1430)$	$D_0^*(2300)$	$D_{s0}^*(2317)^+$		
$1^{+(-)}$	$b_1(1235)$	$h_1(1170)$	$h_1(1415)$	$h_c(1P)$	$h_b(1P)$	$K_1(1270)$	$D_1(2420)$	$D_{s1}(2460)^+$	$B_1(5721)$	$B_{s1}(5830)^0$
$1^{-(-)}$	$\rho(770)$	$\omega(782)$	$\phi(1020)$	$J/\psi(1S)$	$\Upsilon(1S)$	$K^*(892)$	$D^*(2007)^0 \mid D^*(2010)^+$	D_s^{*+}	B^*	B_s^{*0}
$0^{-(+)}$	$\pi^0 \mid \pi^+$	$\eta \mid \eta'$	$\eta \mid \eta'$	$\eta_c(1S)$	$\eta_b(1S)$	$K^0 \mid K^+$	$D^0 \mid D^+$	D_s^+	$B^0 \mid B^+$	B_s^0

excited states

ground state

$Z_c(4020)^+ \to \pi^+ h_c$	$Z_c(4430)^+ \to \pi^+ \psi(2S)$	$Z_b(10650)^+ \to \pi^+ h_b, \pi^+ \Upsilon$	$X(2900)^0 \to D^+ K^-$
$Z_c(3900)^+ \to \pi^+ J/\psi$	$Z_{cs}(4000)^+ \to K^+ J/\psi$	$Z_b(10610)^+ \to \pi^+ h_b, \pi^+ \Upsilon$	$T_{cc\bar{c}\bar{c}}(6900) \to J/\psi J/\psi$

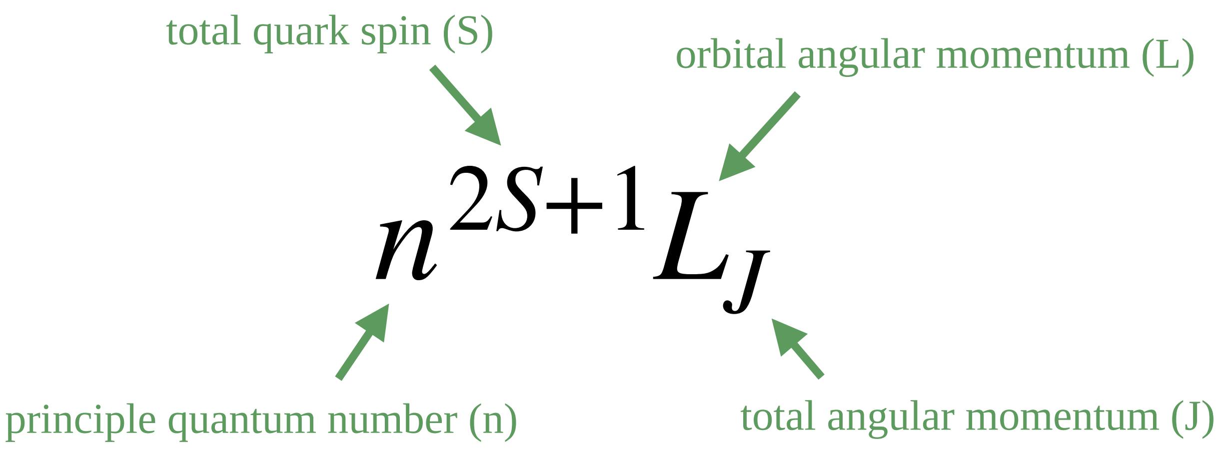
IV. The Plates: $c\bar{c}$ and cc mesons



$c\bar{c}$

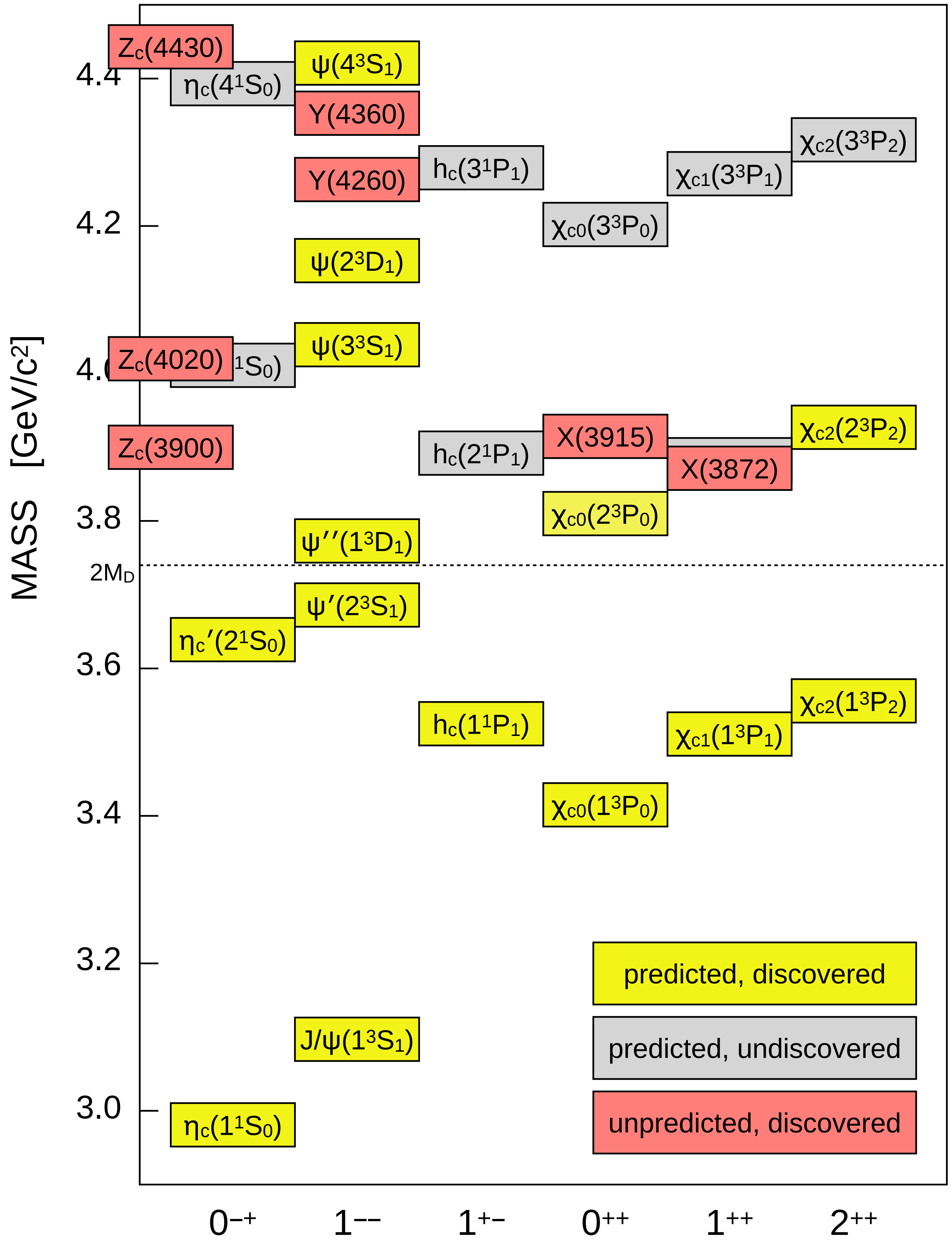
	$1^{-(-)}$	$\psi(3770)$
	$2^{+(+)}$	$\chi_{c2}(1P)$
	$1^{+(+)}$	$\chi_{c1}(1P)$
	$0^{+(+)}$	$\chi_{c0}(1P)$
excited states	$1^{+(-)}$	$h_c(1P)$
	$1^{-(-)}$	$J/\psi(1S)$
ground state	$0^{-(+)}$	$\eta_c(1S)$
	$J^{P(C)}$	

Spectroscopic notation:



$$n^{2S+1}L_J$$

The charmonium spectrum:



IV. The Plates: $c\bar{c}$ and cc mesons

One example of a potential model:

PHYSICAL REVIEW D **72,** 054026 (2005)

Higher charmonia

T. Barnes,[1,*] S. Godfrey,[2,†] and E. S. Swanson[3,‡]

spin-spin (hyperfine)

$$V_0^{(c\bar{c})}(r) = -\frac{4}{3}\frac{\alpha_s}{r} + br + \frac{32\pi\alpha_s}{9m_c^2}\tilde{\delta}_\sigma(r)\vec{S}_c\cdot\vec{S}_{\bar{c}}$$

"Coulomb" confinement

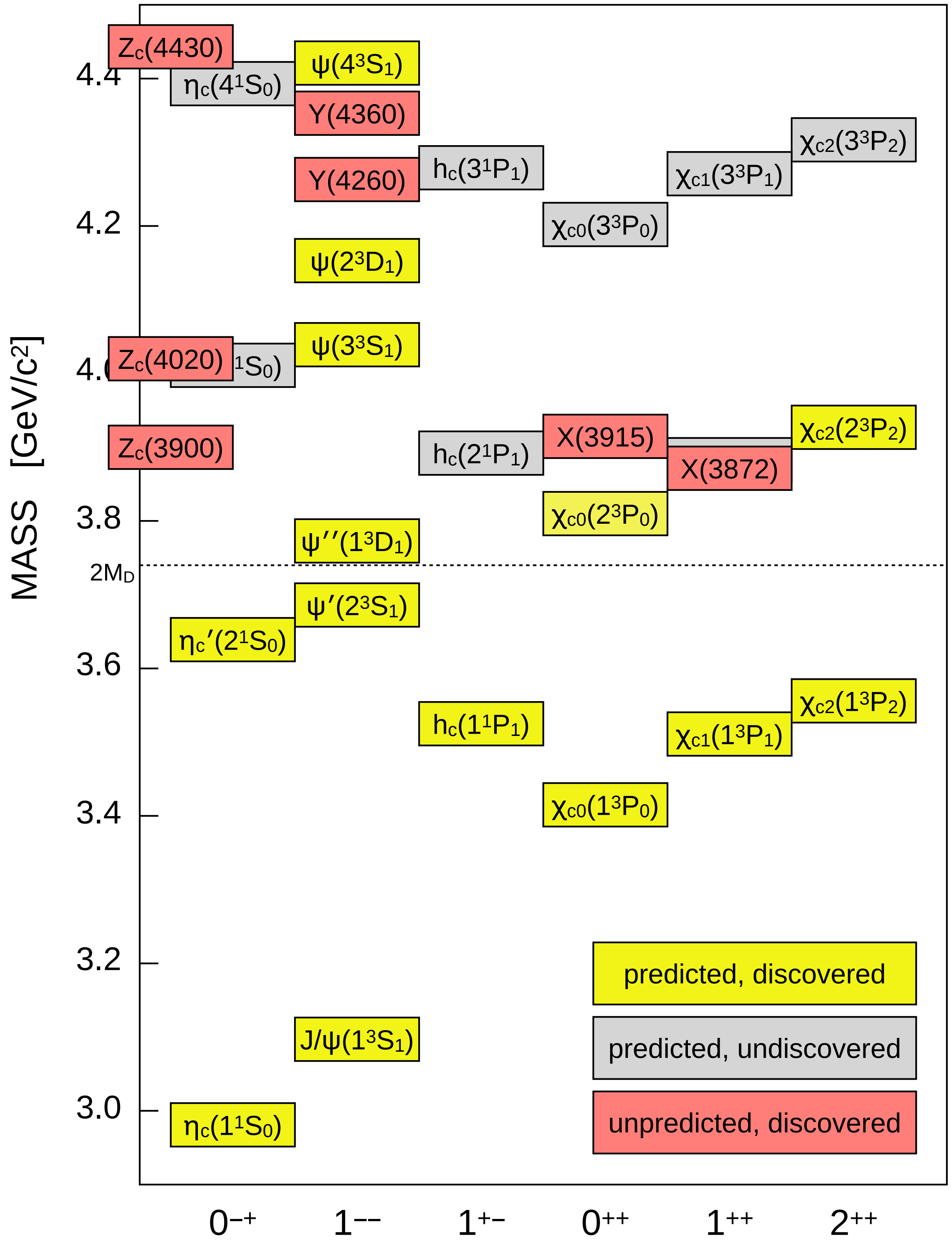
$$\tilde{\delta}_\sigma(r) = (\sigma/\sqrt{\pi})^3 e^{-\sigma^2 r^2}$$

$$V_{\text{spin-dep}} = \frac{1}{m_c^2}\left[\left(\frac{2\alpha_s}{r^3} - \frac{b}{2r}\right)\vec{L}\cdot\vec{S} + \frac{4\alpha_s}{r^3}\mathrm{T}\right]$$

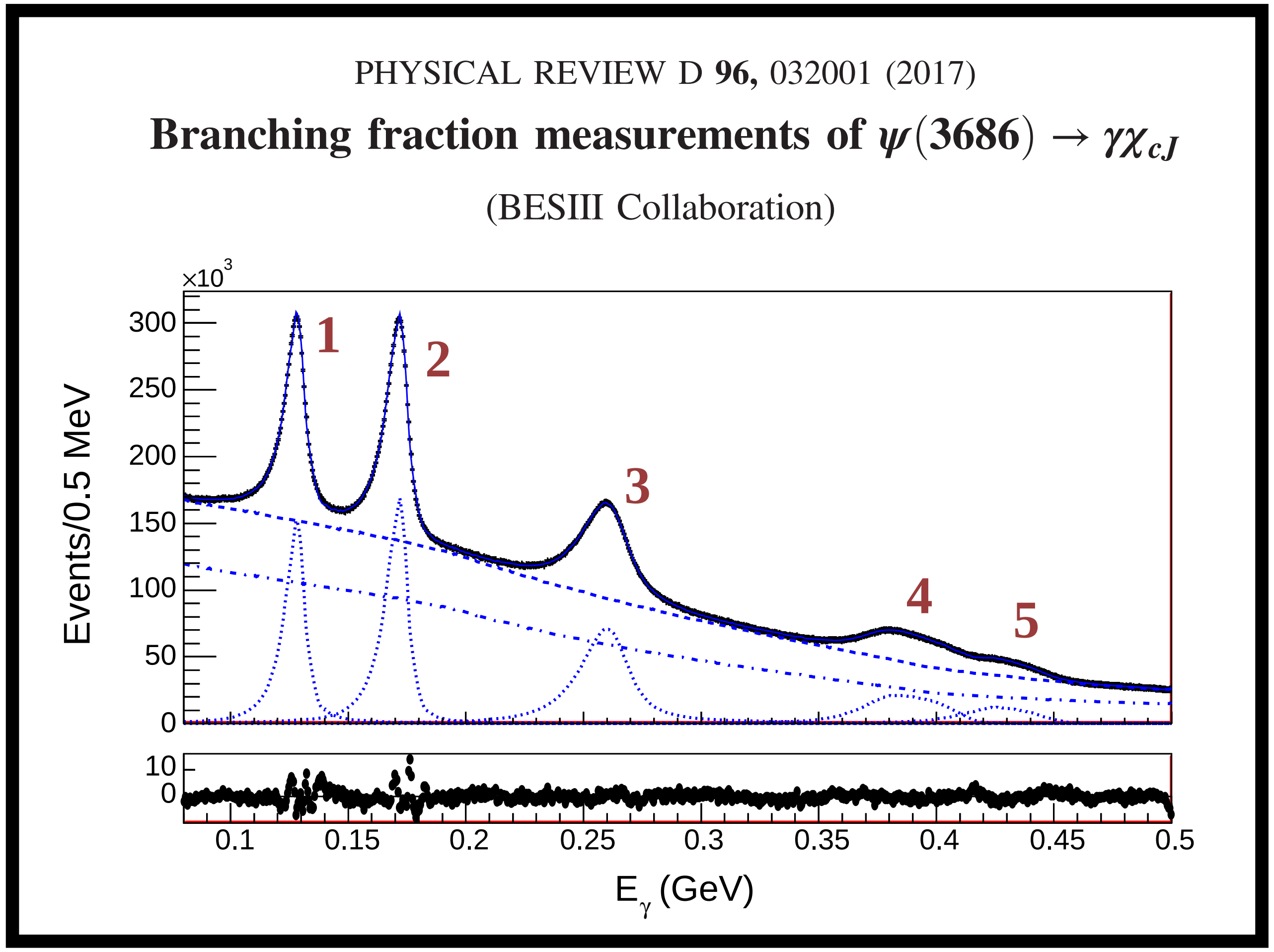
spin-orbit (fine) tensor (hyperfine)

$$\langle {}^3\mathrm{L_J}|\mathrm{T}|{}^3\mathrm{L_J}\rangle = \begin{cases} -\frac{\mathrm{L}}{6(2\mathrm{L}+3)}, & \mathrm{J = L+1} \\ +\frac{1}{6}, & \mathrm{J = L} \\ -\frac{(\mathrm{L}+1)}{6(2\mathrm{L}-1)}, & \mathrm{J = L-1} \end{cases}$$

The charmonium spectrum:



IV. The Plates: $c\bar{c}$ and cc mesons

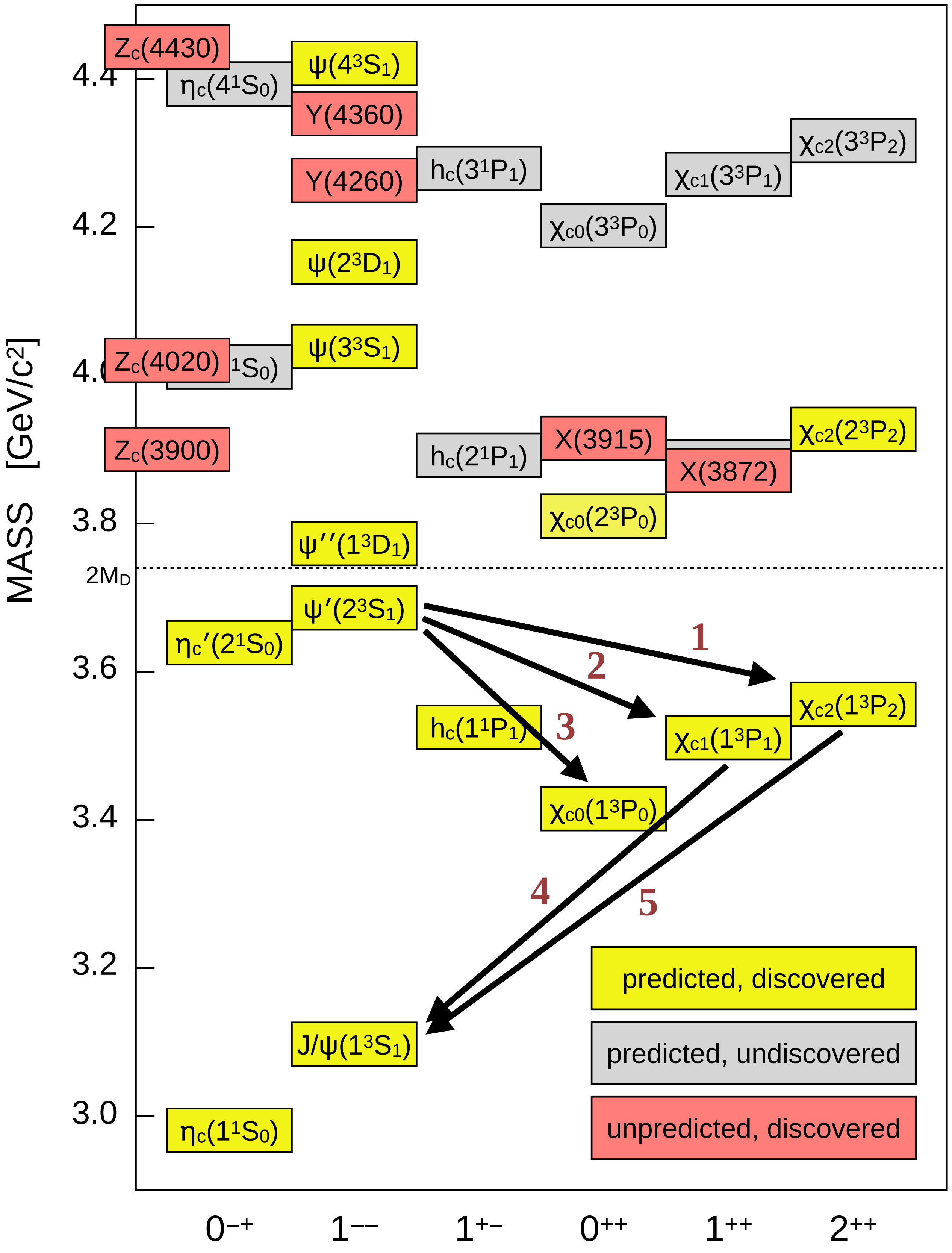


PHYSICAL REVIEW D **96,** 032001 (2017)

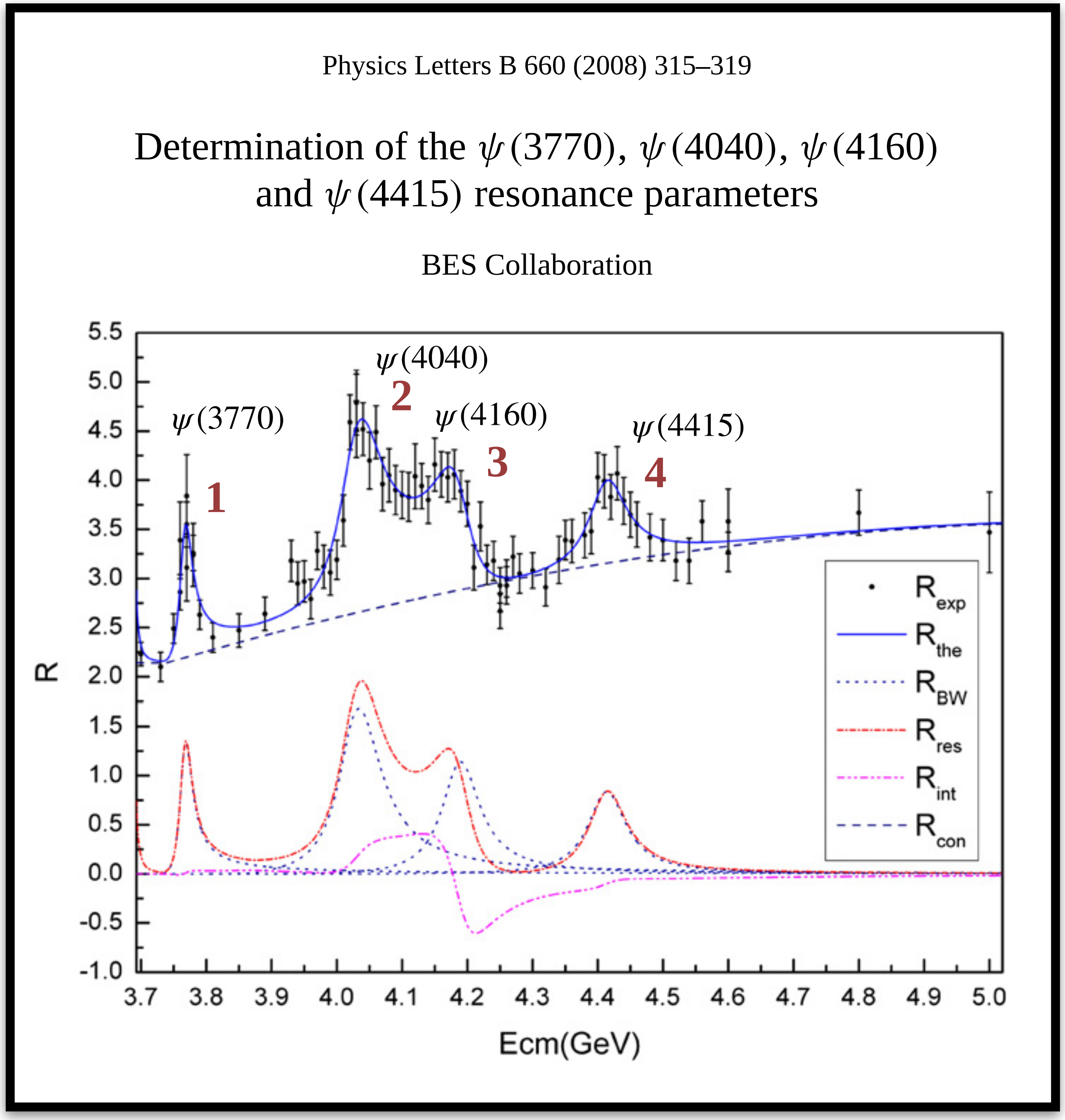
Branching fraction measurements of $\psi(3686) \to \gamma\chi_{cJ}$

(BESIII Collaboration)

The charmonium spectrum:



IV. The Plates: $c\bar{c}$ and cc mesons

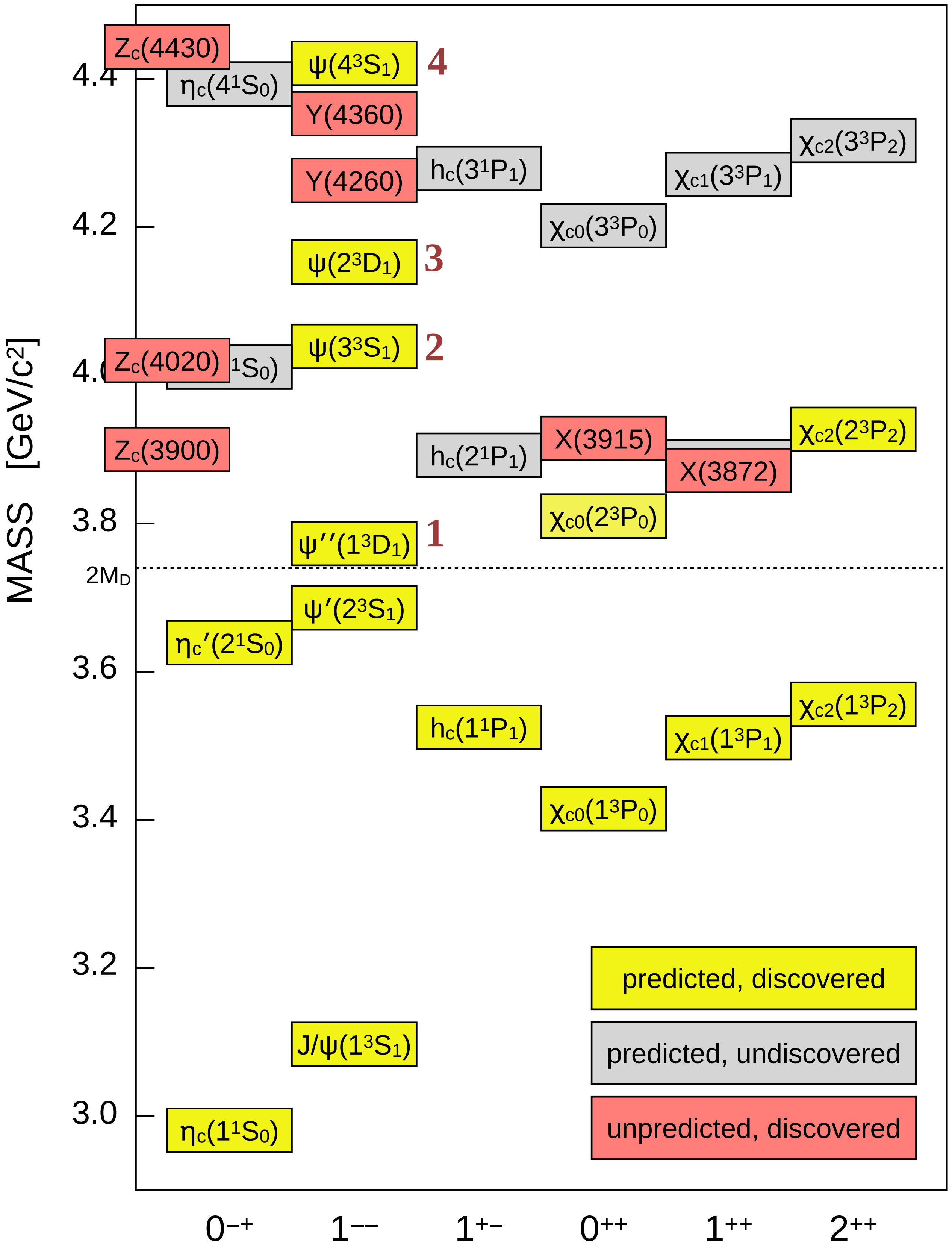


Physics Letters B 660 (2008) 315–319

Determination of the $\psi(3770)$, $\psi(4040)$, $\psi(4160)$ and $\psi(4415)$ resonance parameters

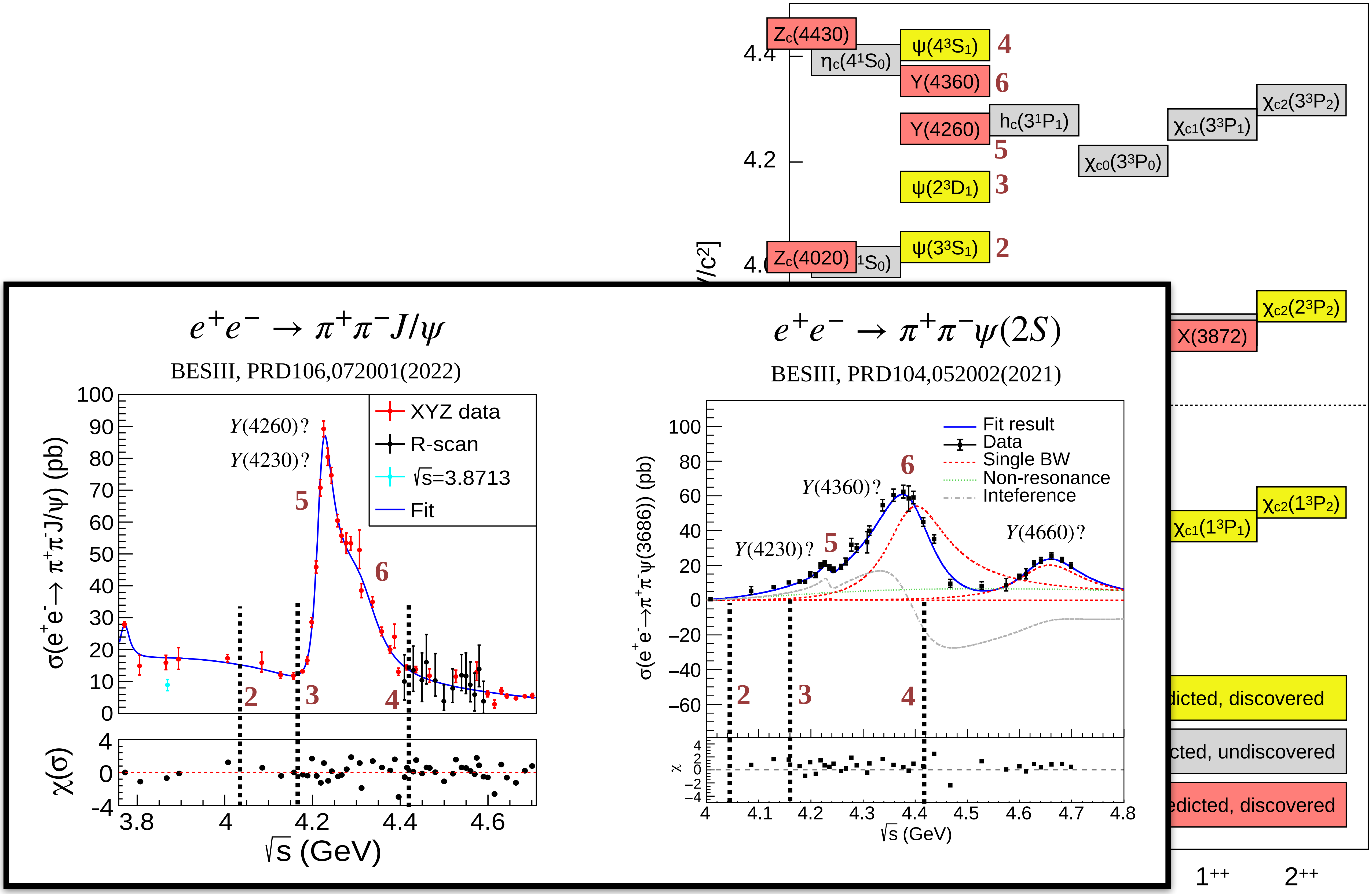
BES Collaboration

The charmonium spectrum:



IV. The Plates: $c\bar{c}$ and cc mesons

The charmonium spectrum:



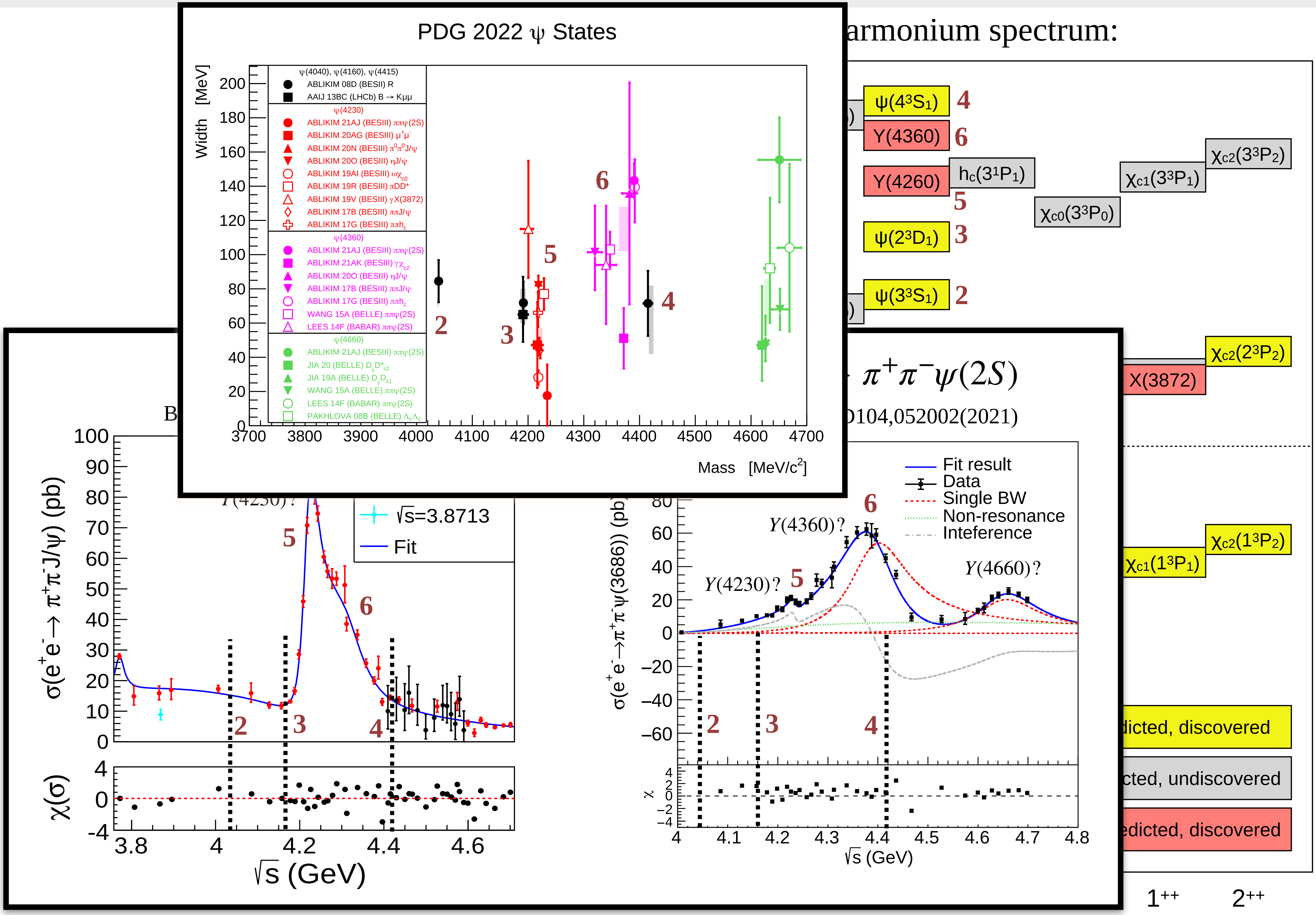
$e^+e^- \to \pi^+\pi^- J/\psi$

BESIII, PRD106,072001(2022)

$e^+e^- \to \pi^+\pi^- \psi(2S)$

BESIII, PRD104,052002(2021)

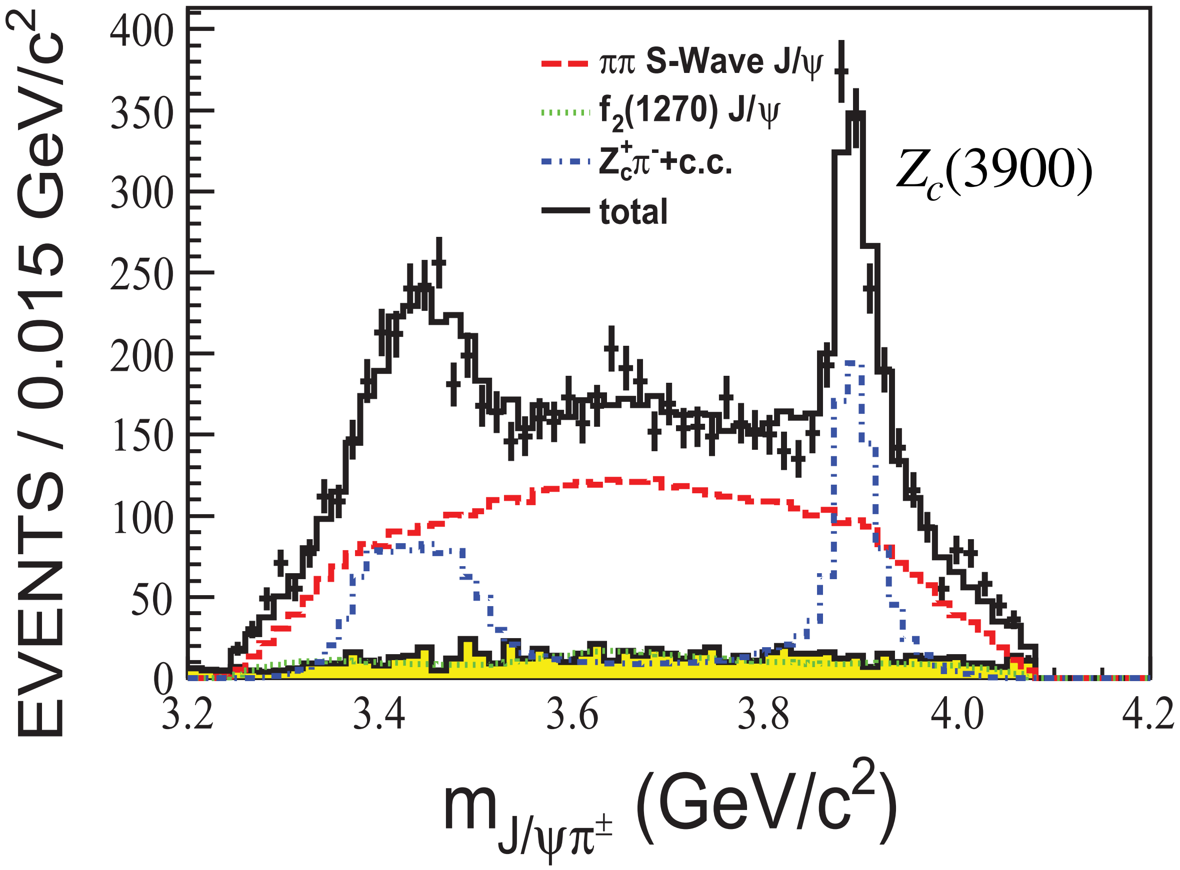
IV. The Plates: $c\bar{c}$ and cc mesons



IV. The Plates: $c\bar{c}$ and cc mesons

$$e^+e^- \to \pi^\mp Z_c(3900)^\pm \to \pi^\mp(\pi^\pm J/\psi)$$

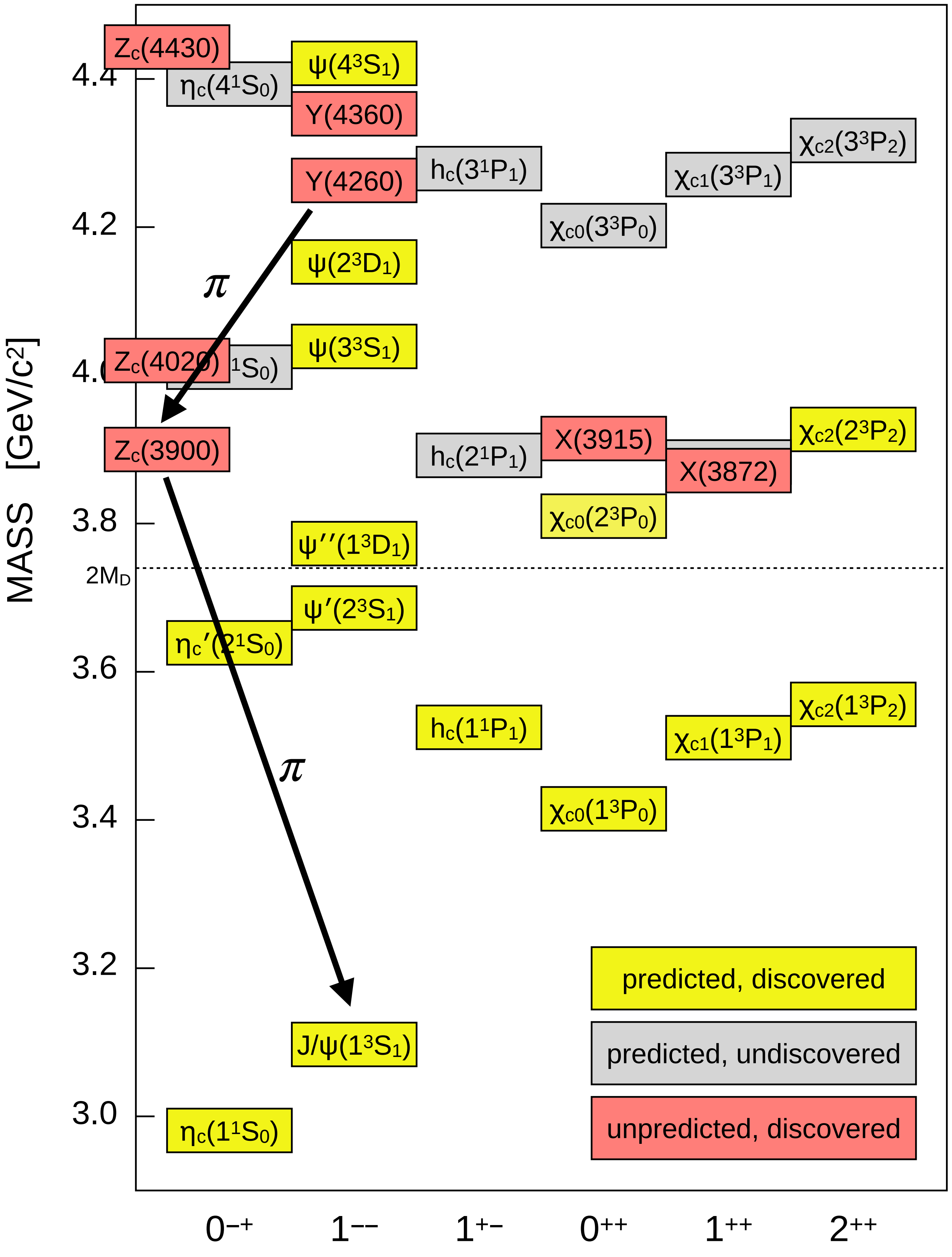
BESIII, PRL 119, 072001 (2017)



(1) $Z_c(3900)^\pm \to \pi^\pm J/\psi$ implies $Z_c(3900)$ is not a $c\bar{c}$ charmonium state.

(2) Its proximity to $D^*\bar{D}$ threshold hints at a meson molecule interpretation.

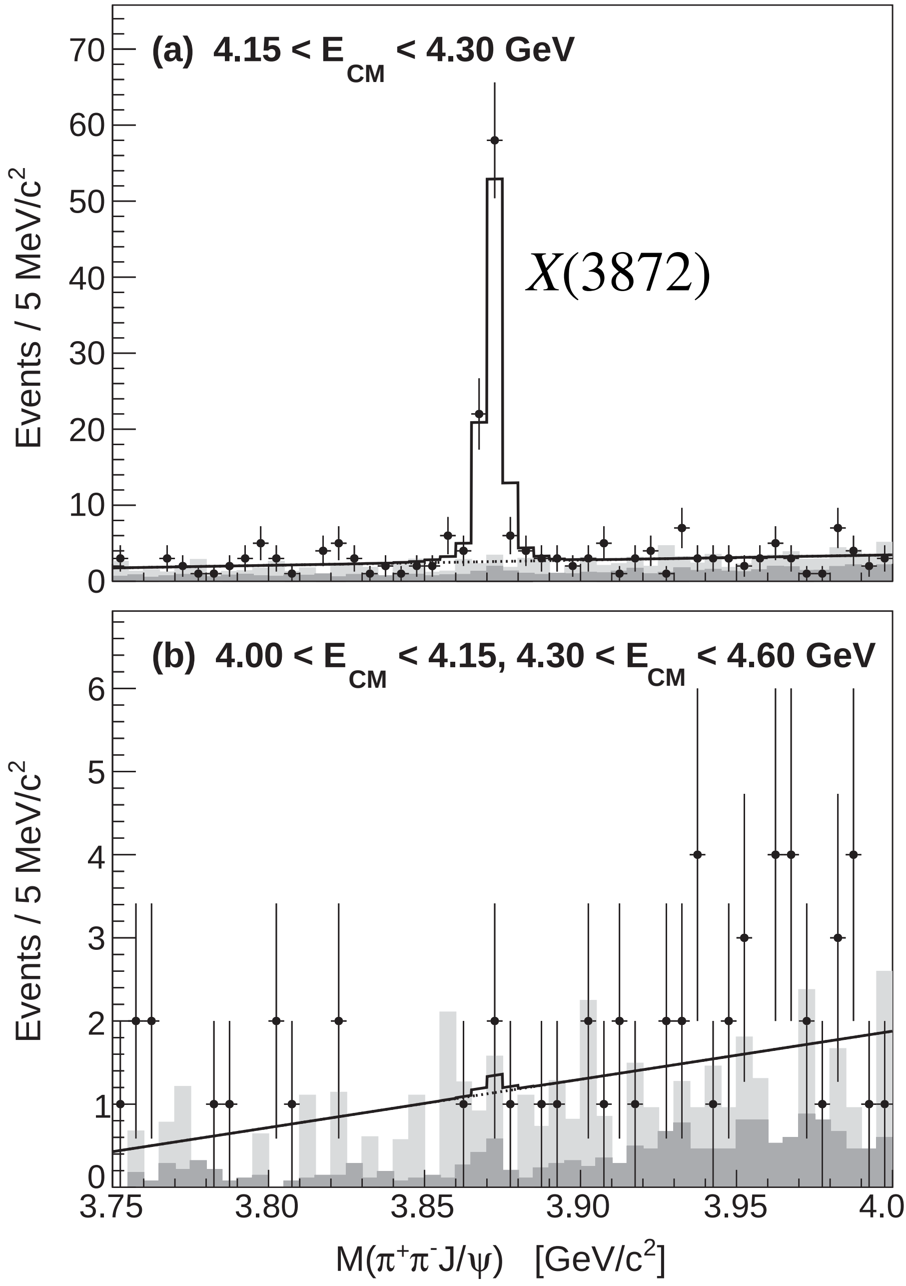
The charmonium spectrum:



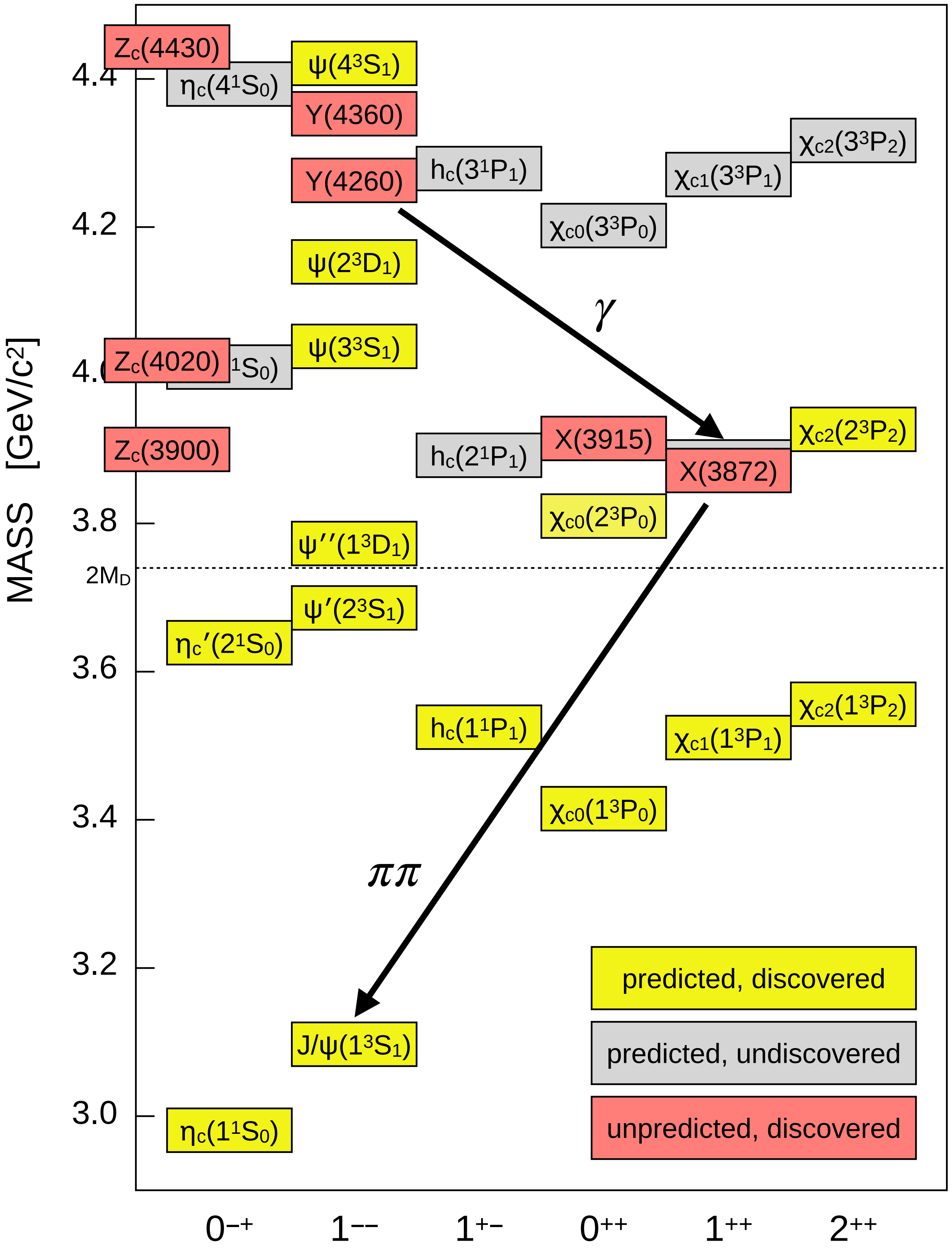
IV. The Plates: $c\bar{c}$ and cc mesons

$$e^+e^- \to \gamma X(3872) \to \gamma(\pi^+\pi^- J/\psi)$$

BESIII, PRL122, 202001 (2019)



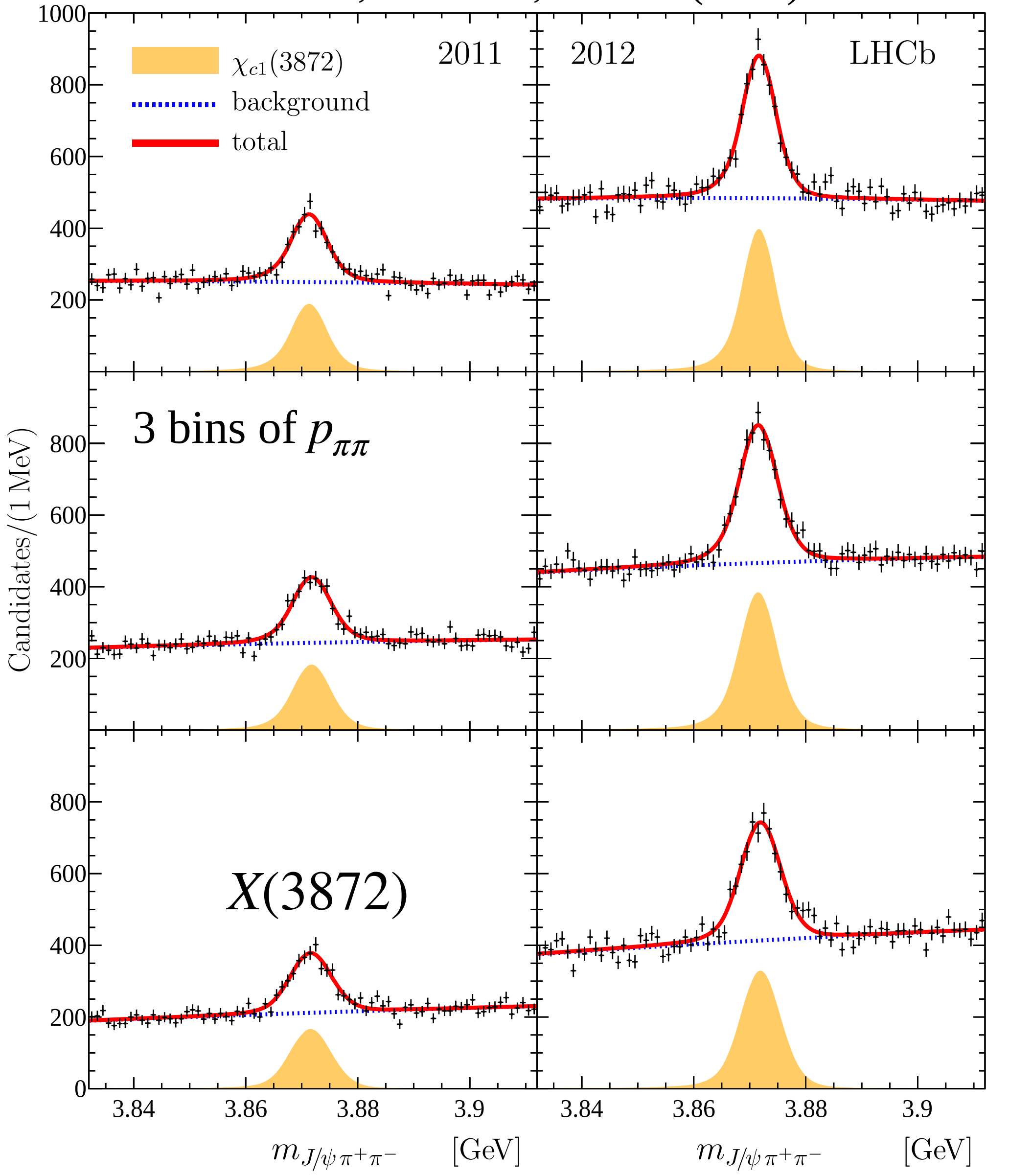
The charmonium spectrum:



IV. The Plates: $c\bar{c}$ and cc mesons

$$\begin{aligned} pp &\to b\bar{b} + \text{hadrons} \\ &\to X(3872) + \text{hadrons} \\ &\to (\pi^+\pi^- J/\psi) + \text{hadrons} \end{aligned}$$

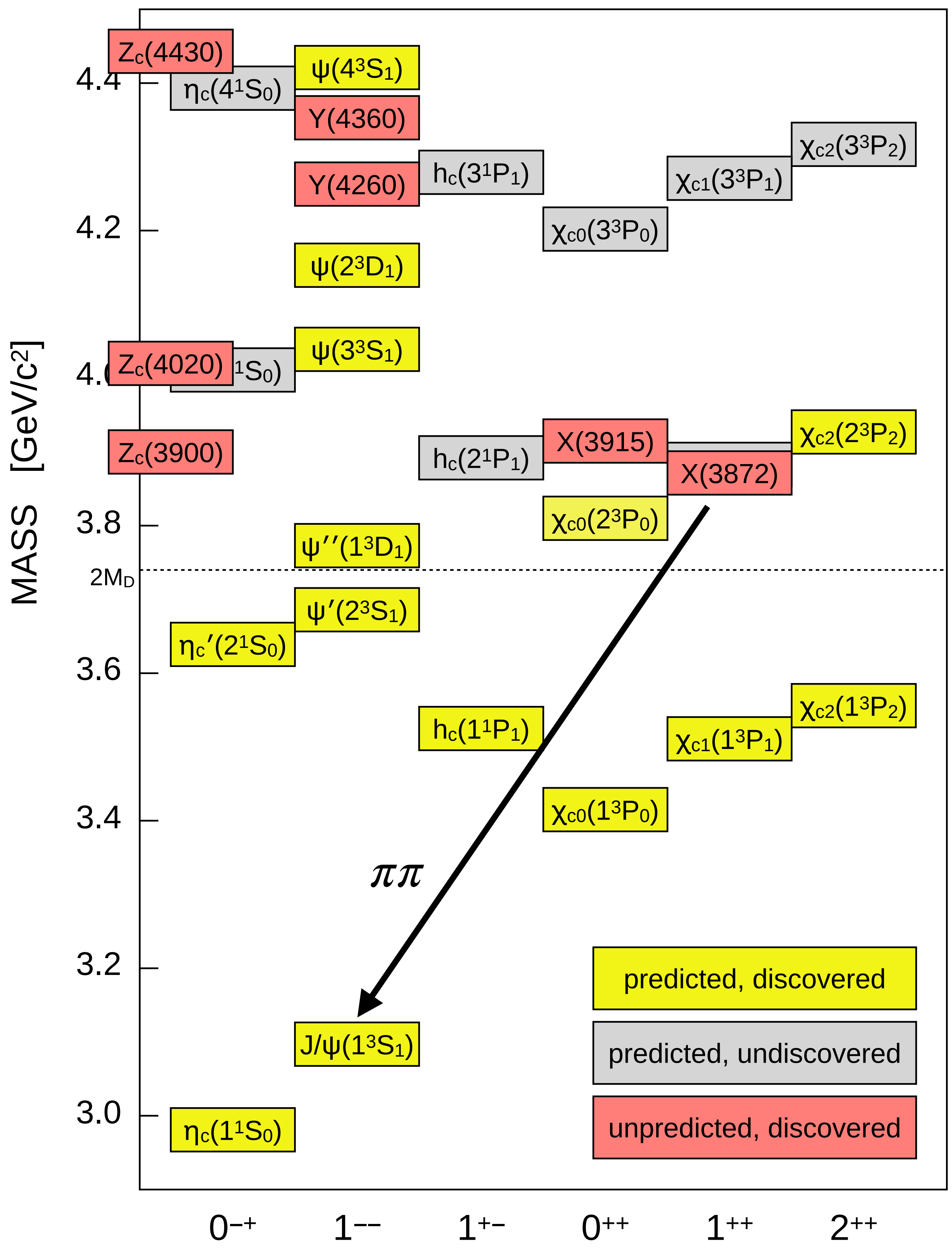
LHCb, PRD 102, 092005 (2020)



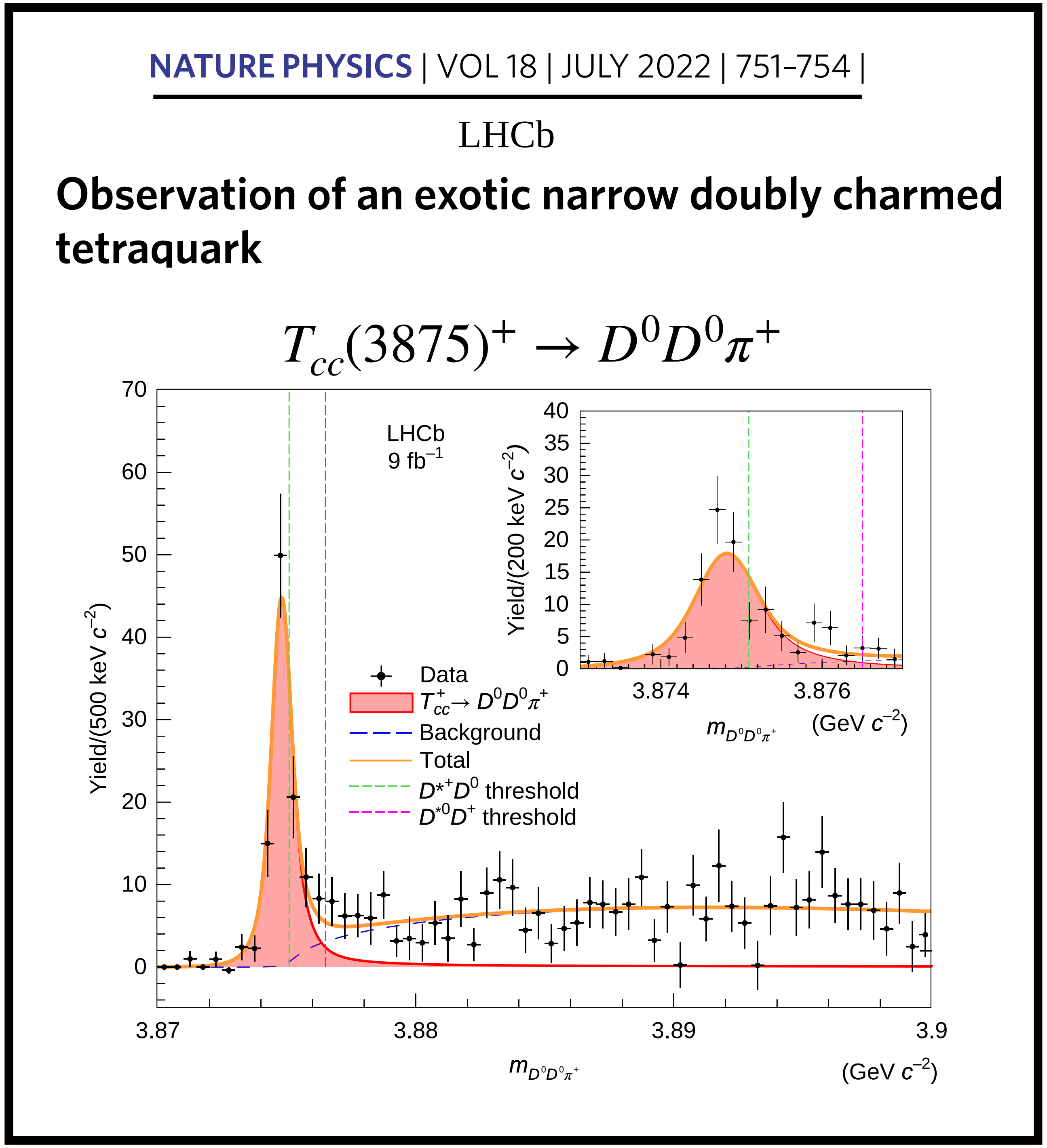
$$M_{\rm BW}(X(3872)) - M(D^{*0}\bar{D}^0) = -0.05 \pm 0.12\ \text{MeV}/c^2$$

$$\Gamma_{\rm BW}(X(3872)) = 1.39 \pm 0.24 \pm 0.10\ \text{MeV}/c^2$$

The charmonium spectrum:



IV. The Plates: $c\bar{c}$ and cc mesons



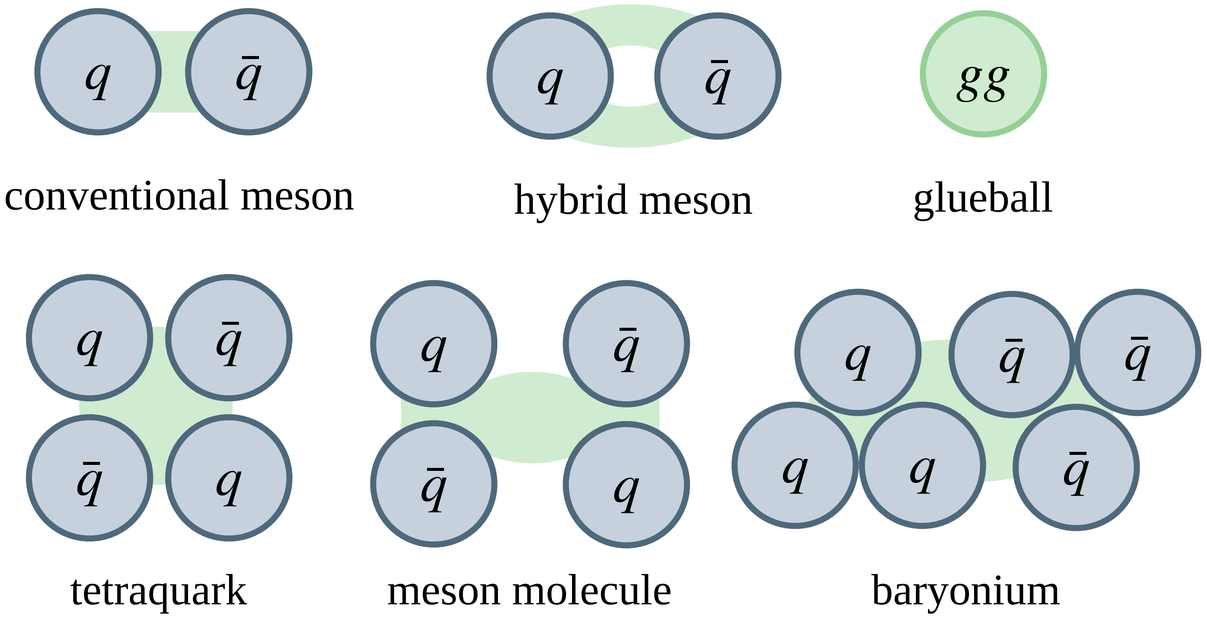
NATURE PHYSICS | VOL 18 | JULY 2022 | 751-754 |

LHCb

Observation of an exotic narrow doubly charmed tetraquark

$T_{cc}(3875)^+ \to D^0D^0\pi^+$

The $Z_c(3900)$, $X(3872)$, and $T_{cc}(3875)$, among others, have clearly taken us beyond conventional mesons.



conventional meson

hybrid meson

glueball

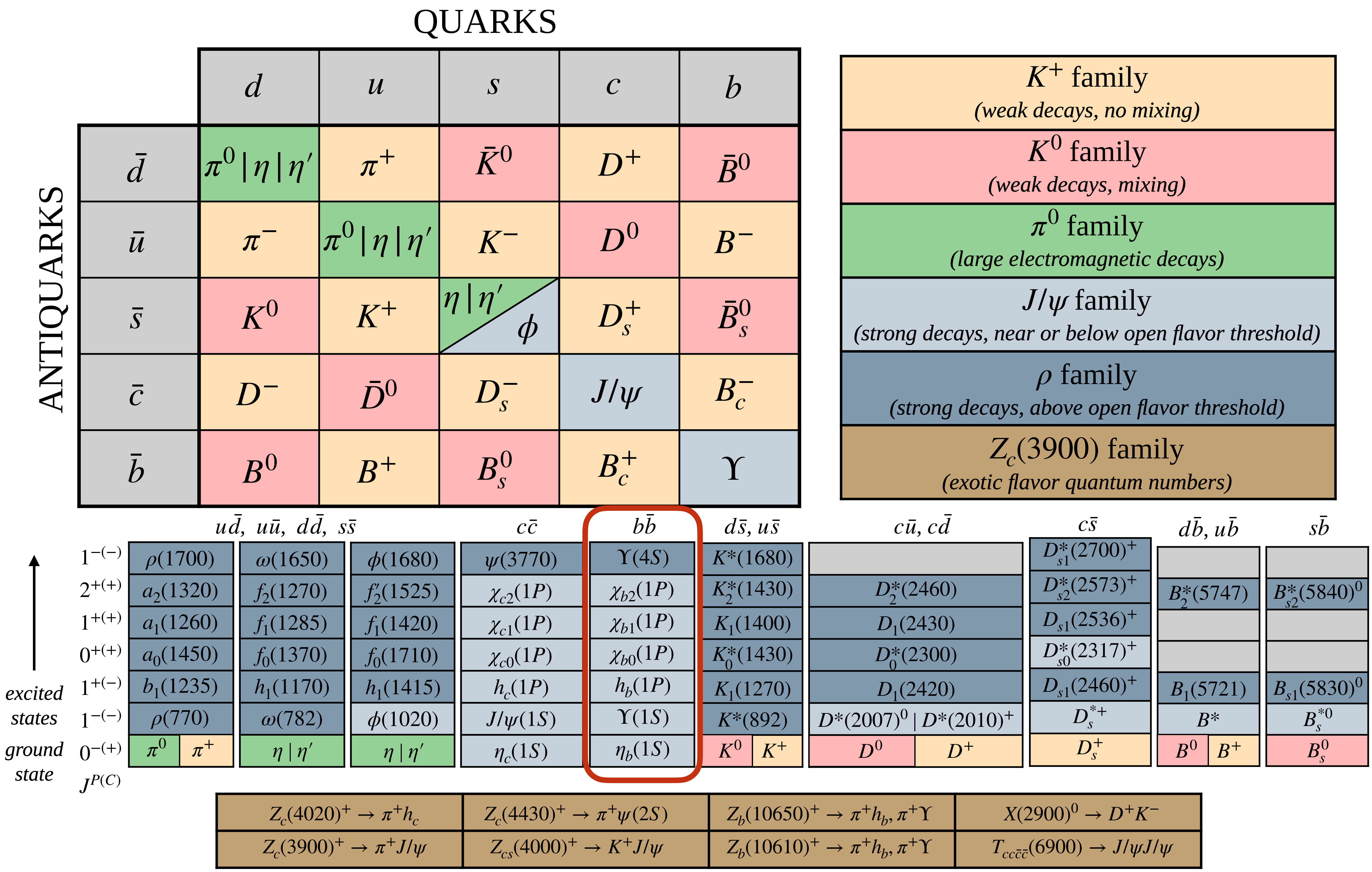
tetraquark

meson molecule

baryonium

Productive conversations about their internal structure continue!

V. The Plates: $b\bar{b}$ and bb mesons



QUARKS

ANTIQUARKS

	d	u	s	c	b
$\bar{d}$	$\pi^0 \mid \eta \mid \eta'$	π^+	$\bar{K}^0$	D^+	$\bar{B}^0$
$\bar{u}$	π^-	$\pi^0 \mid \eta \mid \eta'$	K^-	D^0	B^-
$\bar{s}$	K^0	K^+	$\eta \mid \eta'$ ϕ	D_s^+	$\bar{B}_s^0$
$\bar{c}$	D^-	$\bar{D}^0$	D_s^-	J/ψ	B_c^-
$\bar{b}$	B^0	B^+	B_s^0	B_c^+	Υ

K^+ family
(weak decays, no mixing)

K^0 family
(weak decays, mixing)

π^0 family
(large electromagnetic decays)

J/ψ family
(strong decays, near or below open flavor threshold)

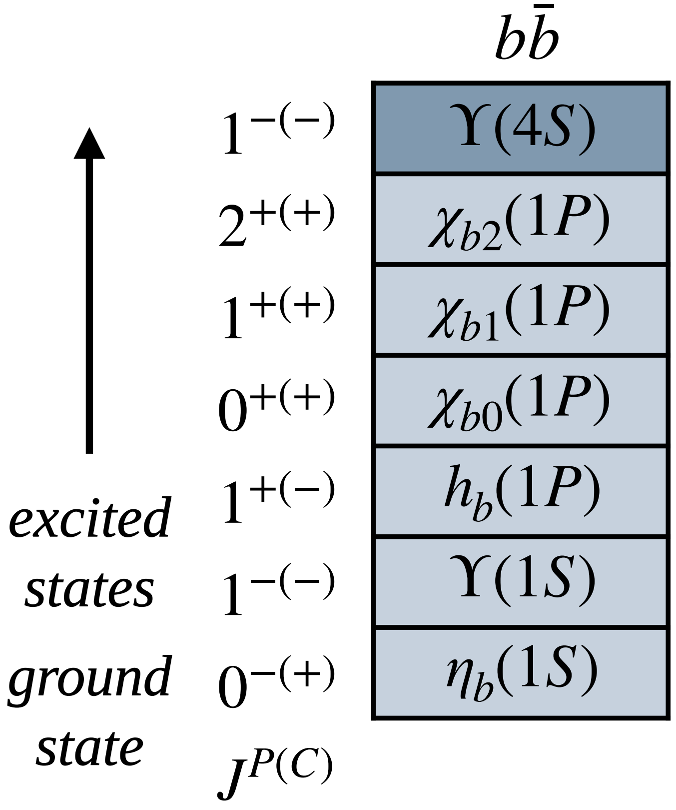
ρ family
(strong decays, above open flavor threshold)

$Z_c(3900)$ family
(exotic flavor quantum numbers)

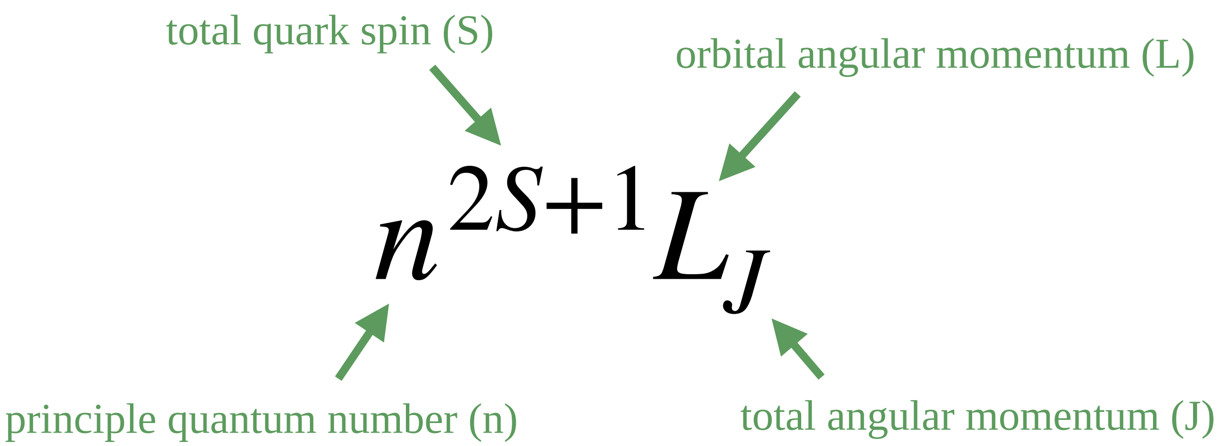
		$u\bar{d},\ u\bar{u},\ d\bar{d},\ s\bar{s}$			$c\bar{c}$	$b\bar{b}$	$d\bar{s},\ u\bar{s}$	$c\bar{u},\ c\bar{d}$	$c\bar{s}$	$d\bar{b},\ u\bar{b}$	$s\bar{b}$
	$1^{-(-)}$	$\rho(1700)$	$\omega(1650)$	$\phi(1680)$	$\psi(3770)$	$\Upsilon(4S)$	$K^*(1680)$		$D_{s1}^*(2700)^+$		
	$2^{+(+)}$	$a_2(1320)$	$f_2(1270)$	$f_2'(1525)$	$\chi_{c2}(1P)$	$\chi_{b2}(1P)$	$K_2^*(1430)$	$D_2^*(2460)$	$D_{s2}^*(2573)^+$	$B_2^*(5747)$	$B_{s2}^*(5840)^0$
	$1^{+(+)}$	$a_1(1260)$	$f_1(1285)$	$f_1(1420)$	$\chi_{c1}(1P)$	$\chi_{b1}(1P)$	$K_1(1400)$	$D_1(2430)$	$D_{s1}(2536)^+$		
	$0^{+(+)}$	$a_0(1450)$	$f_0(1370)$	$f_0(1710)$	$\chi_{c0}(1P)$	$\chi_{b0}(1P)$	$K_0^*(1430)$	$D_0^*(2300)$	$D_{s0}^*(2317)^+$		
excited states	$1^{+(-)}$	$b_1(1235)$	$h_1(1170)$	$h_1(1415)$	$h_c(1P)$	$h_b(1P)$	$K_1(1270)$	$D_1(2420)$	$D_{s1}(2460)^+$	$B_1(5721)$	$B_{s1}(5830)^0$
	$1^{-(-)}$	$\rho(770)$	$\omega(782)$	$\phi(1020)$	$J/\psi(1S)$	$\Upsilon(1S)$	$K^*(892)$	$D^*(2007)^0 \mid D^*(2010)^+$	D_s^{*+}	B^*	B_s^{*0}
ground state	$0^{-(+)}$	π^0 π^+	$\eta \mid \eta'$	$\eta \mid \eta'$	$\eta_c(1S)$	$\eta_b(1S)$	K^0 K^+	D^0 D^+	D_s^+	B^0 B^+	B_s^0
	$J^{P(C)}$										

$Z_c(4020)^+ \to \pi^+ h_c$	$Z_c(4430)^+ \to \pi^+ \psi(2S)$	$Z_b(10650)^+ \to \pi^+ h_b, \pi^+ \Upsilon$	$X(2900)^0 \to D^+ K^-$
$Z_c(3900)^+ \to \pi^+ J/\psi$	$Z_{cs}(4000)^+ \to K^+ J/\psi$	$Z_b(10610)^+ \to \pi^+ h_b, \pi^+ \Upsilon$	$T_{cc\bar{c}\bar{c}}(6900) \to J/\psi J/\psi$

V. The Plates: $b\bar{b}$ and bb mesons

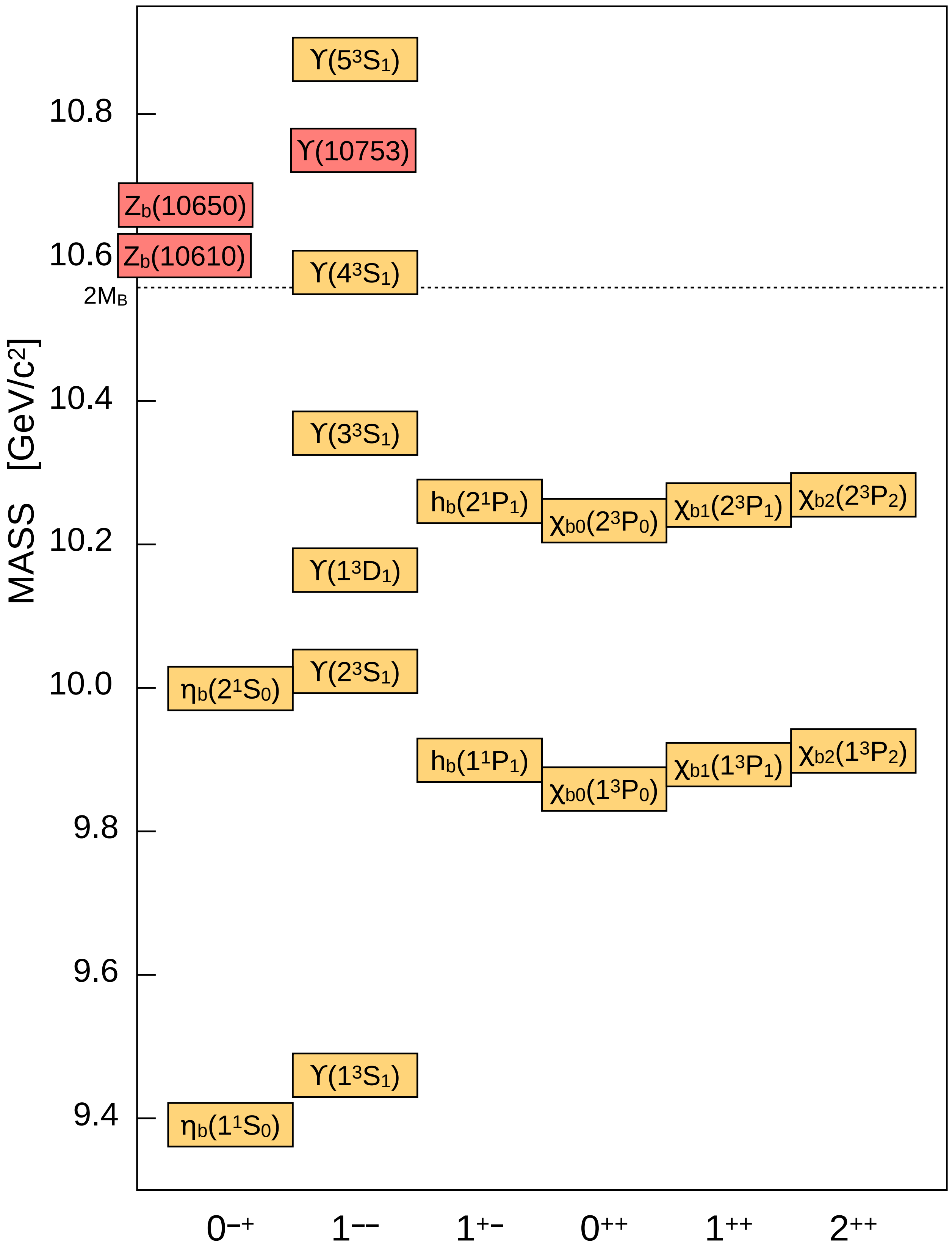


Spectroscopic notation:

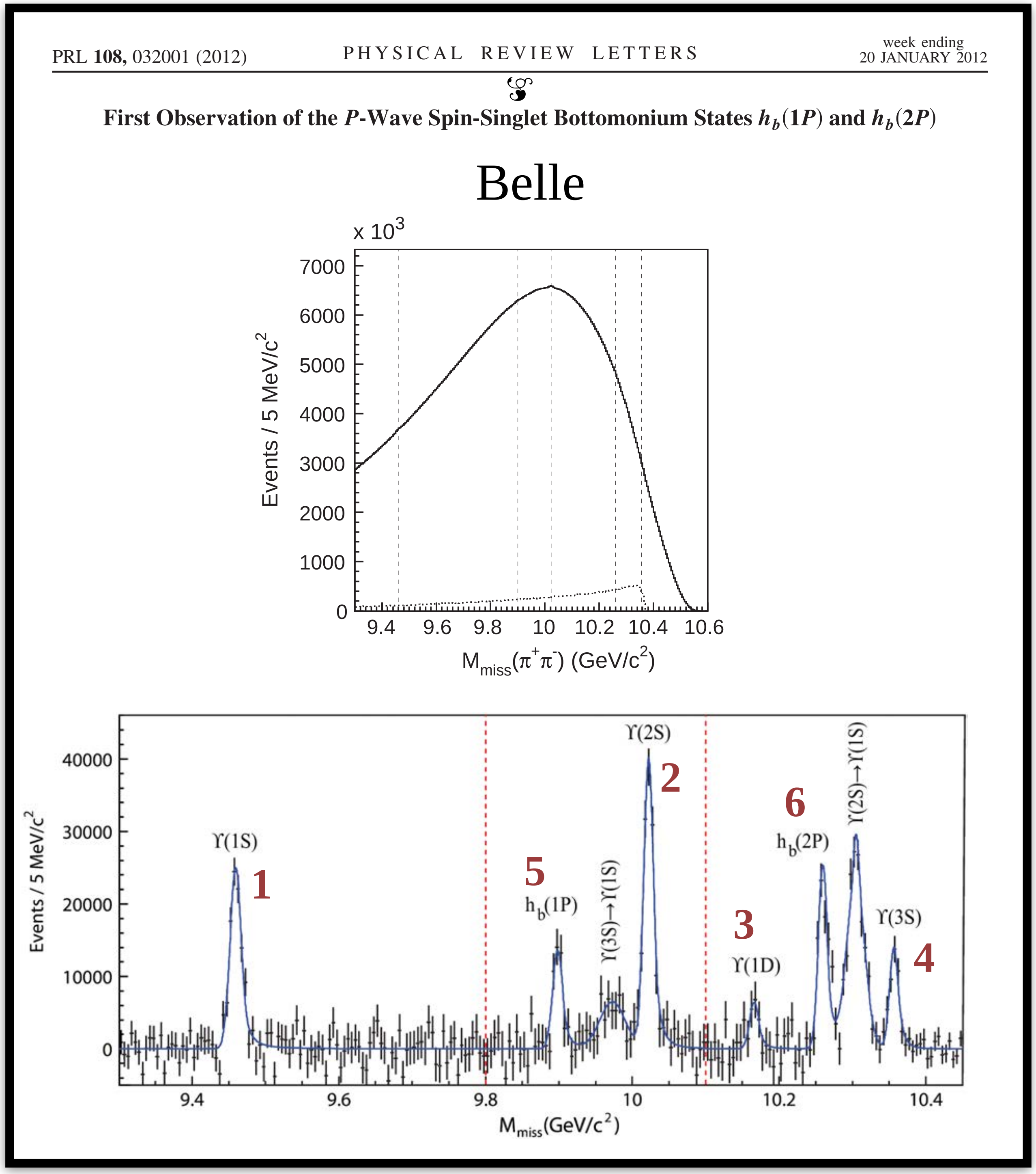


$$n^{2S+1}L_J$$

The bottomonium spectrum:



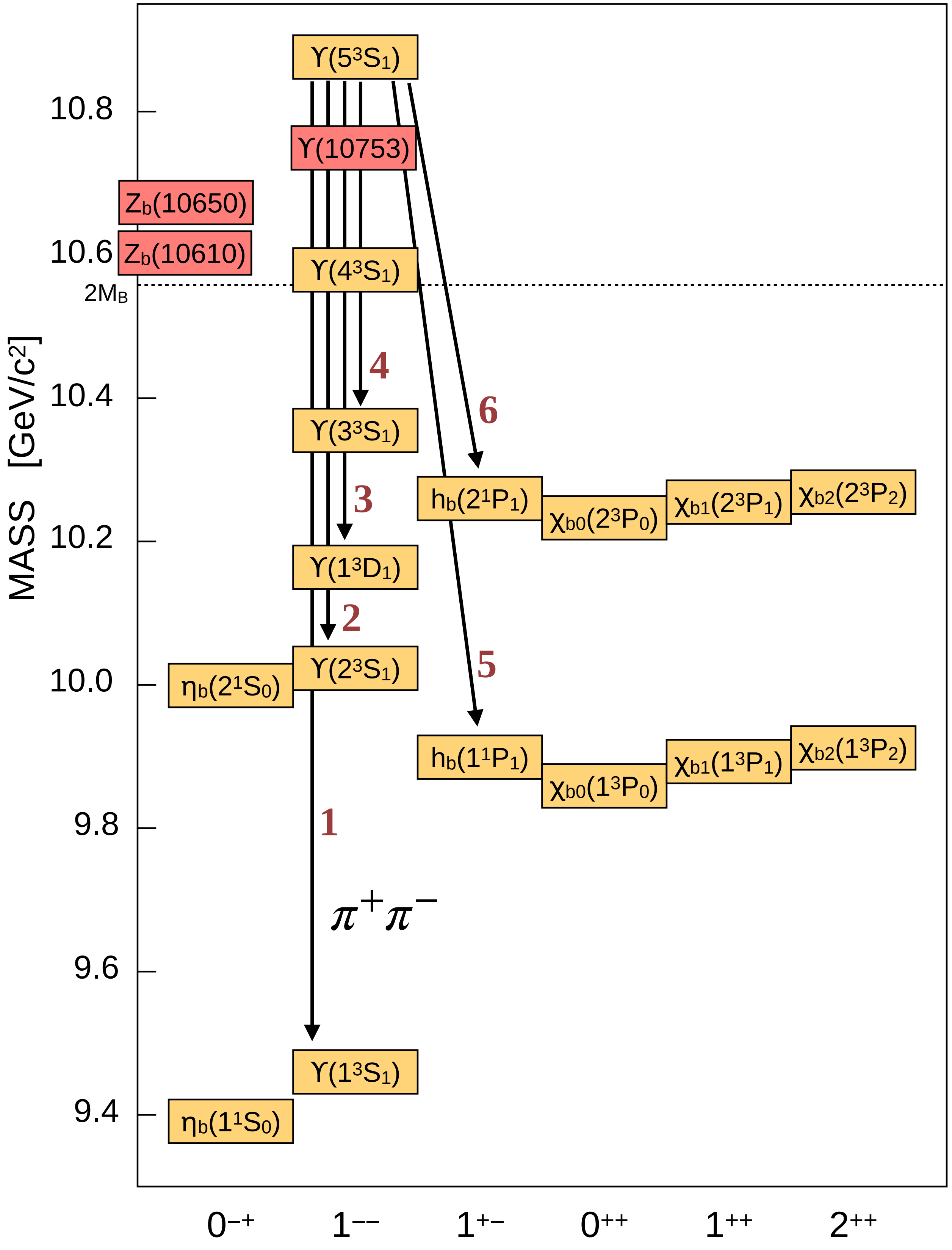
V. The Plates: $b\bar{b}$ and bb mesons



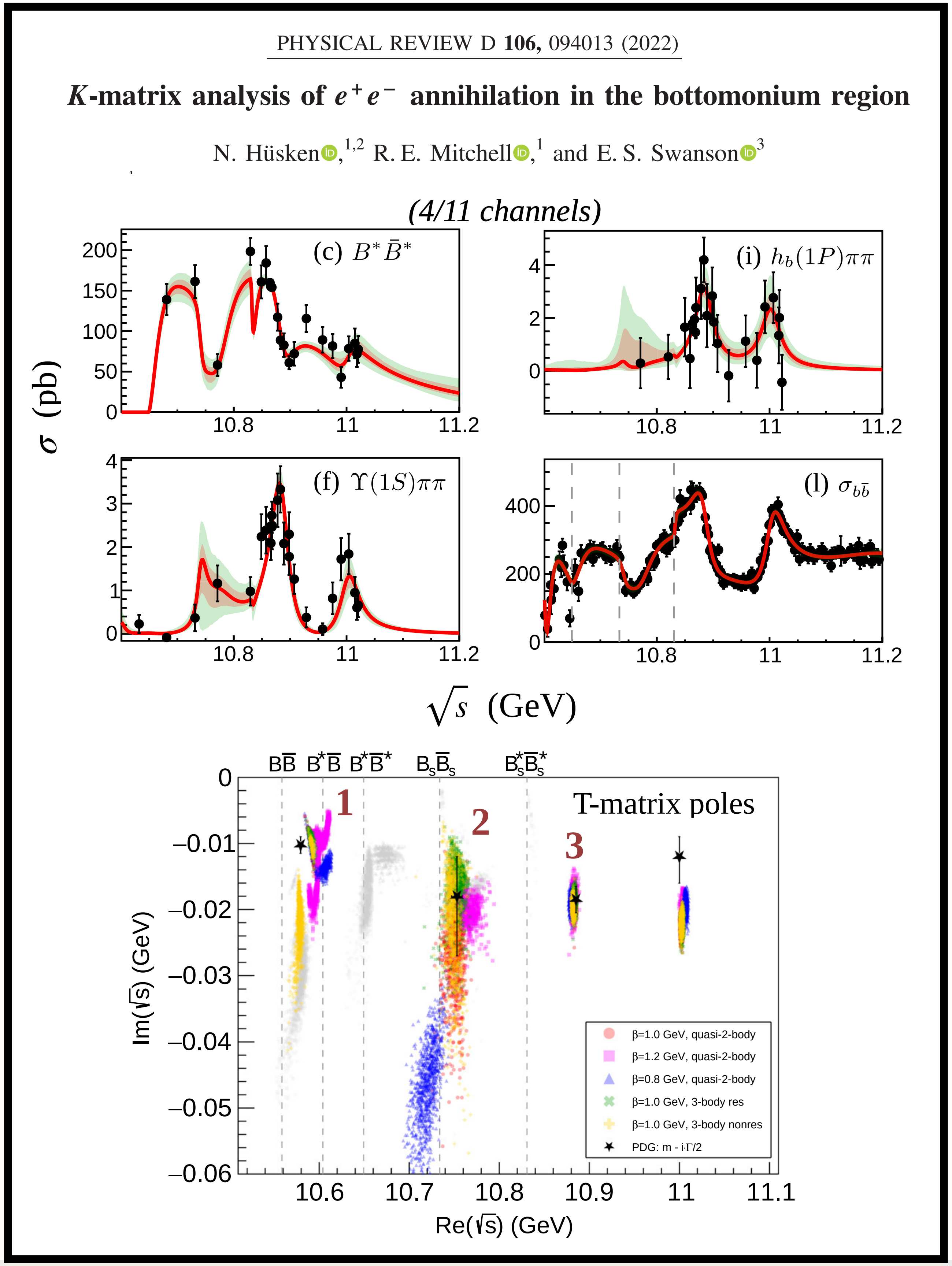
PRL **108,** 032001 (2012) PHYSICAL REVIEW LETTERS week ending 20 JANUARY 2012

First Observation of the *P*-Wave Spin-Singlet Bottomonium States $h_b(1P)$ and $h_b(2P)$

The bottomonium spectrum:



V. The Plates: $b\bar{b}$ and bb mesons



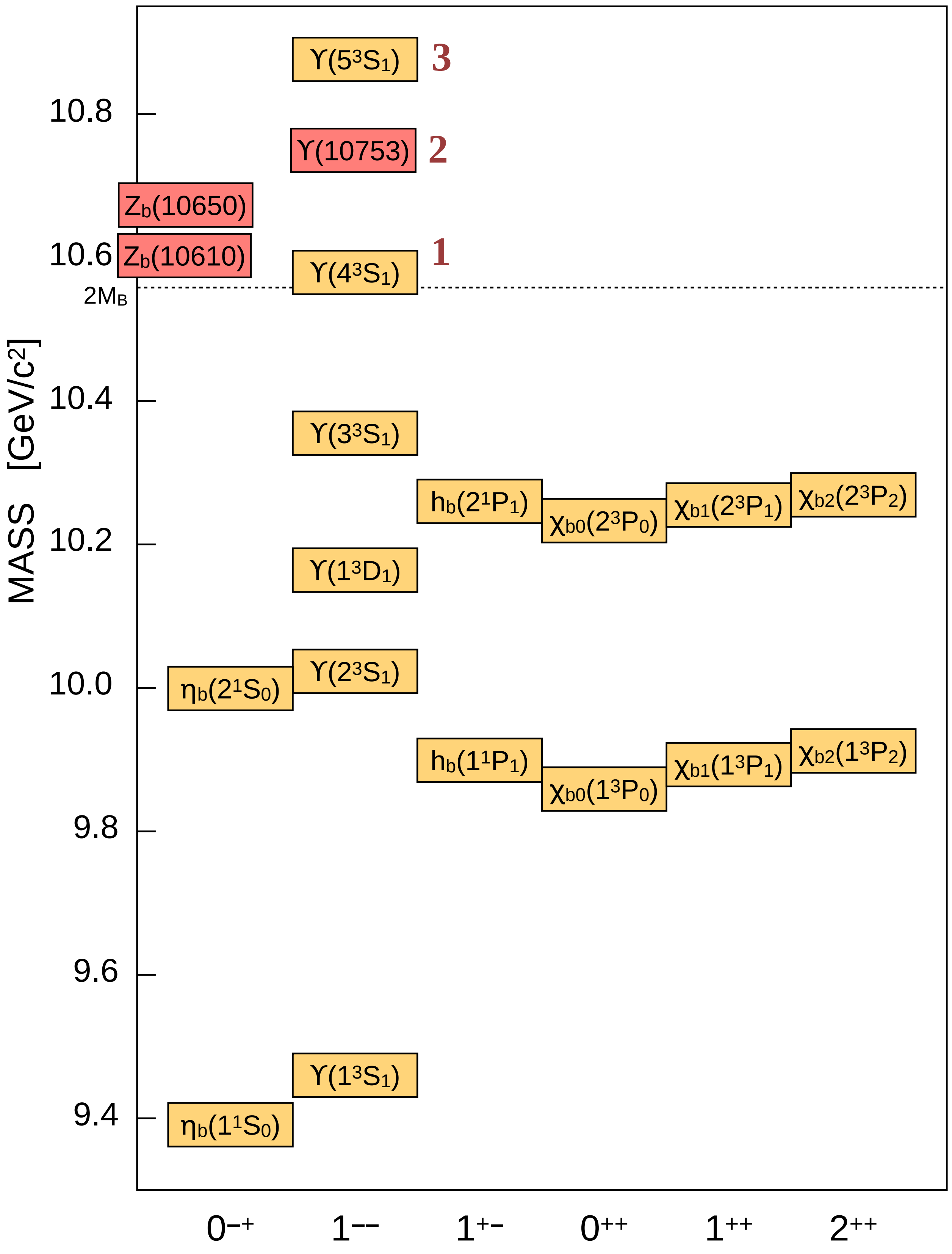
PHYSICAL REVIEW D **106,** 094013 (2022)

K-matrix analysis of e^+e^- annihilation in the bottomonium region

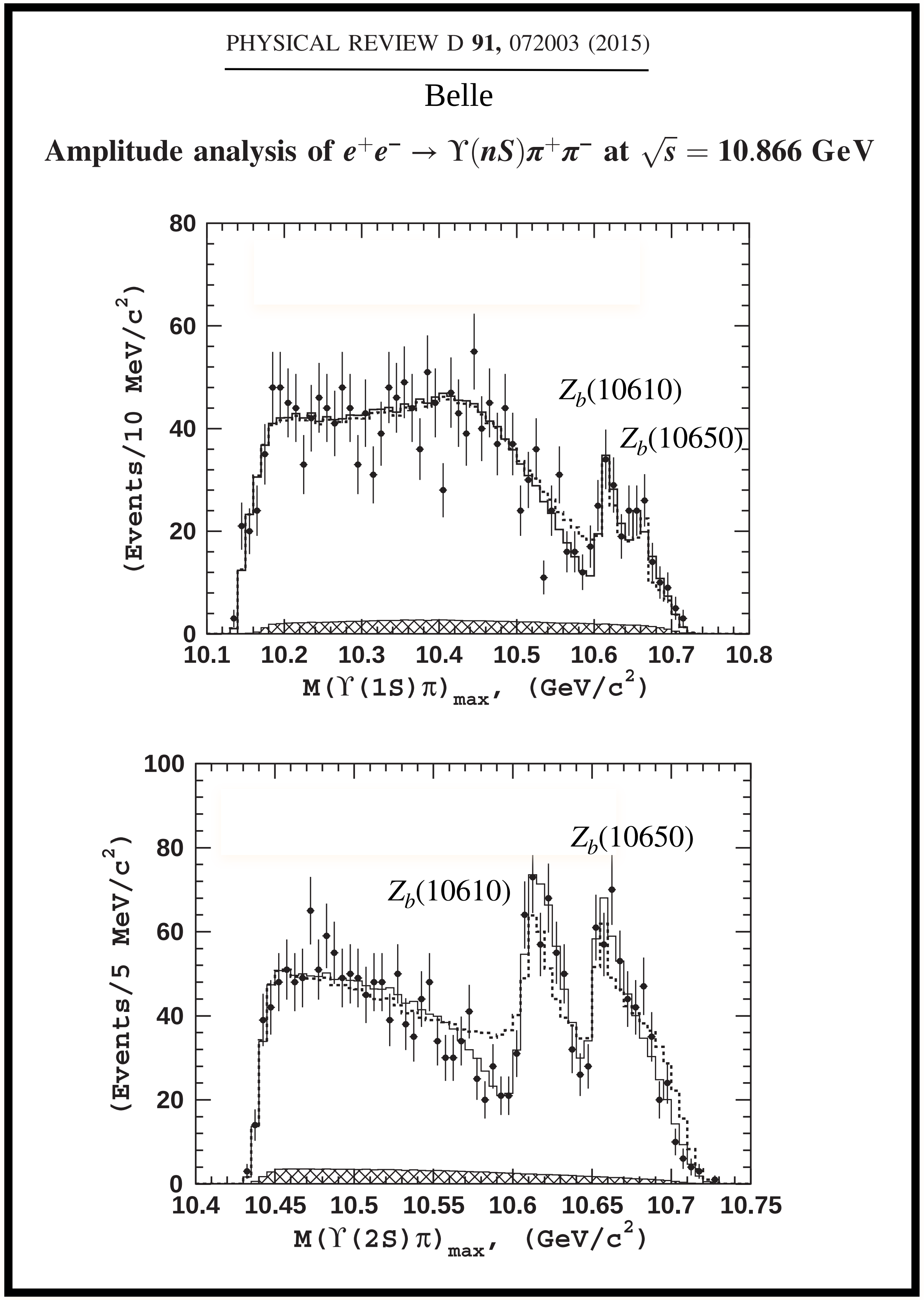
N. Hüsken,[1,2] R. E. Mitchell,[1] and E. S. Swanson[3]

(4/11 channels)

The bottomonium spectrum:



V. The Plates: $b\bar{b}$ and bb mesons

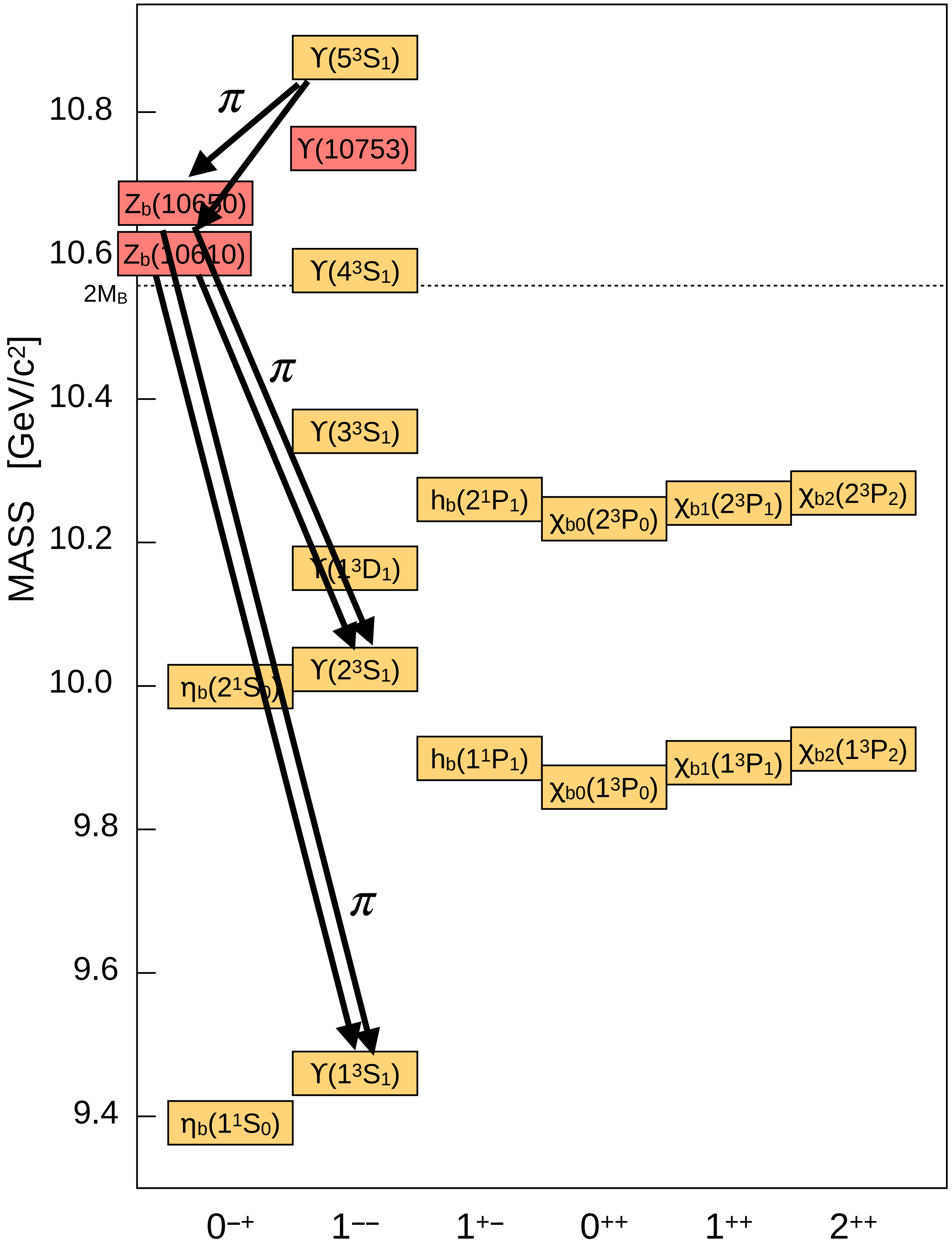


PHYSICAL REVIEW D **91,** 072003 (2015)

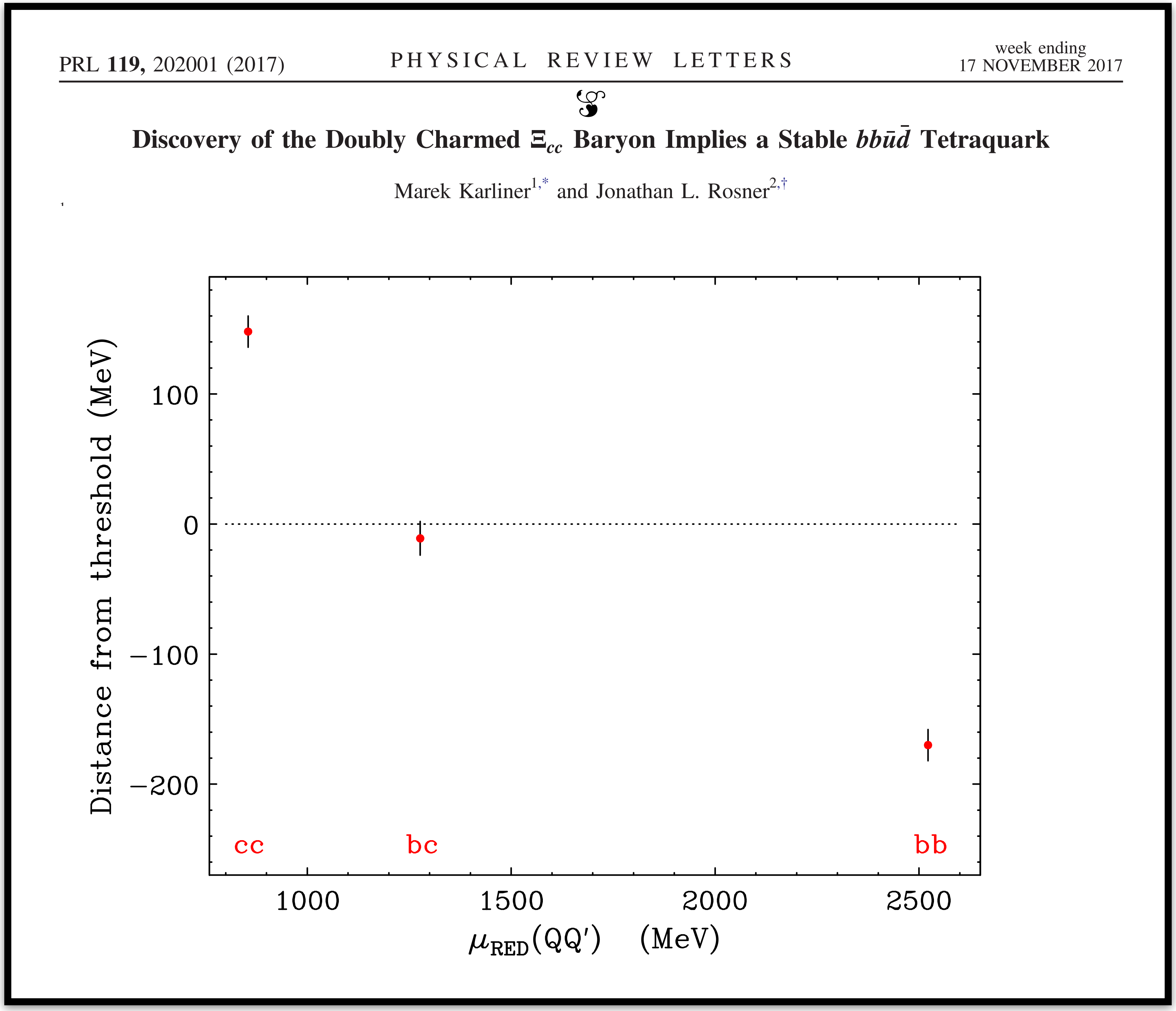
Belle

Amplitude analysis of $e^+e^- \to \Upsilon(nS)\pi^+\pi^-$ at $\sqrt{s} = 10.866$ GeV

The bottomonium spectrum:



V. The Plates: $b\bar{b}$ and bb mesons

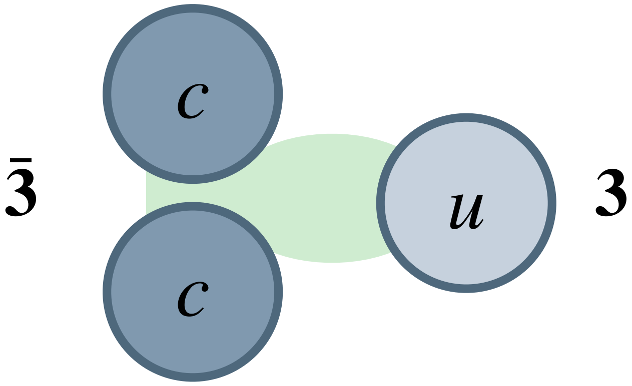


PRL **119,** 202001 (2017) PHYSICAL REVIEW LETTERS week ending 17 NOVEMBER 2017

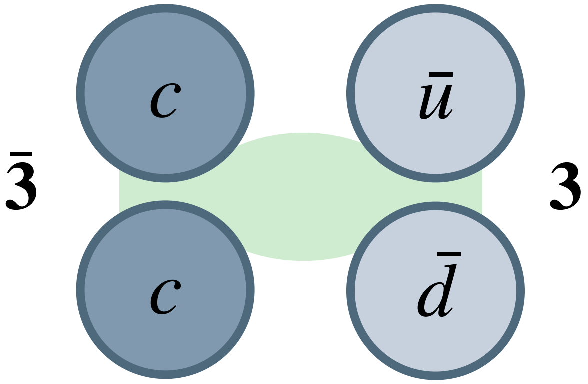
Discovery of the Doubly Charmed Ξ_{cc} Baryon Implies a Stable $bb\bar{u}\bar{d}$ Tetraquark

Marek Karliner[1,*] and Jonathan L. Rosner[2,†]

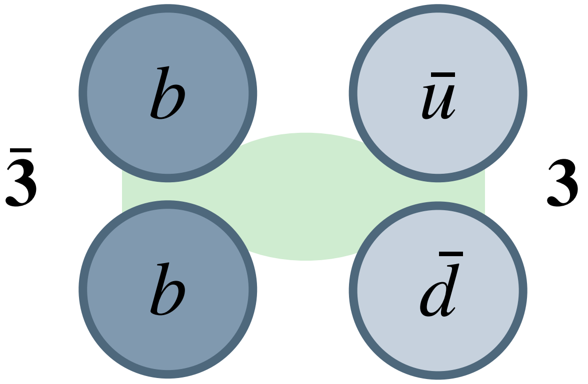
Ξ_{cc}^{++} baryon:



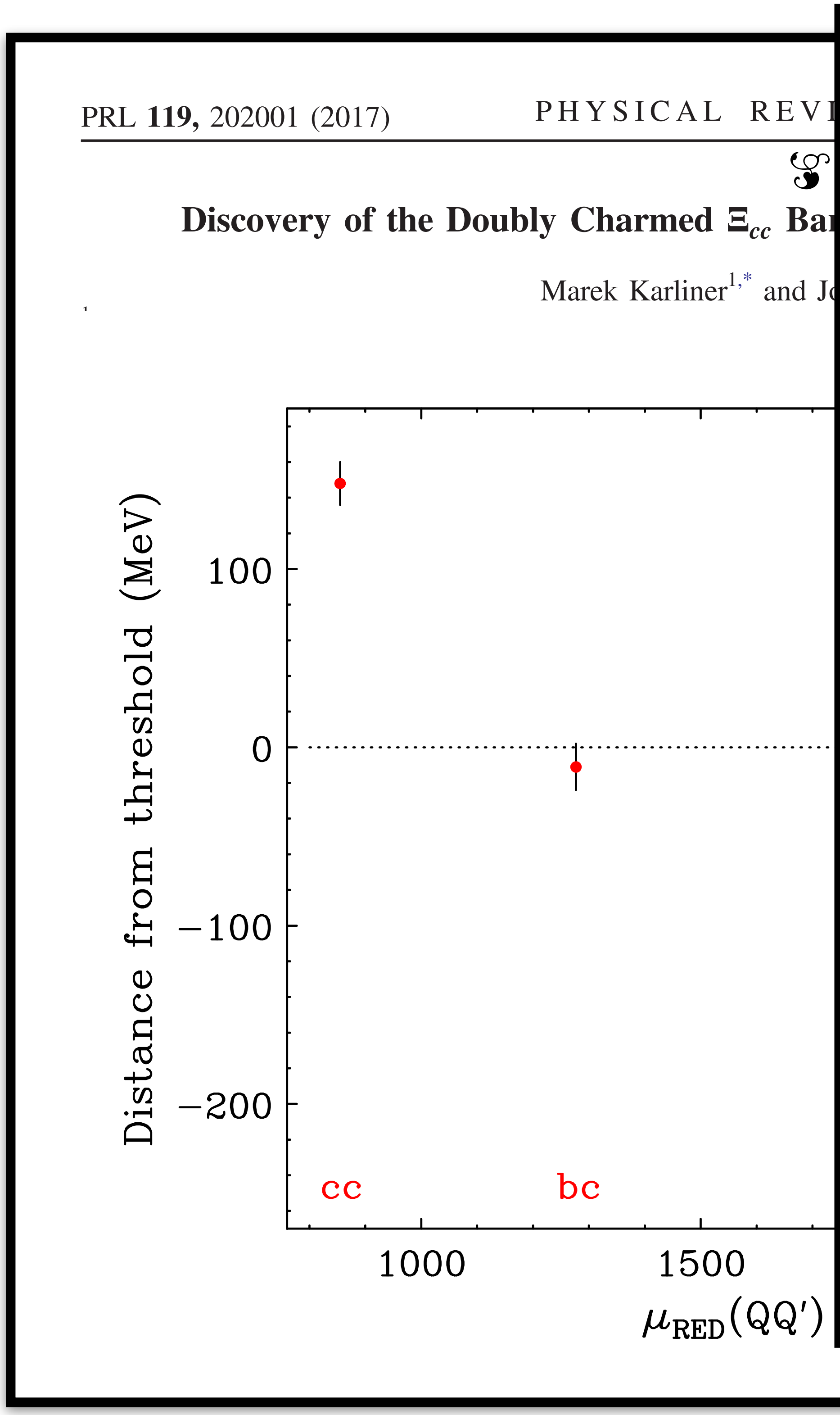
T_{cc}^{+} tetraquark (meson):



T_{bb}^{-} tetraquark (meson):



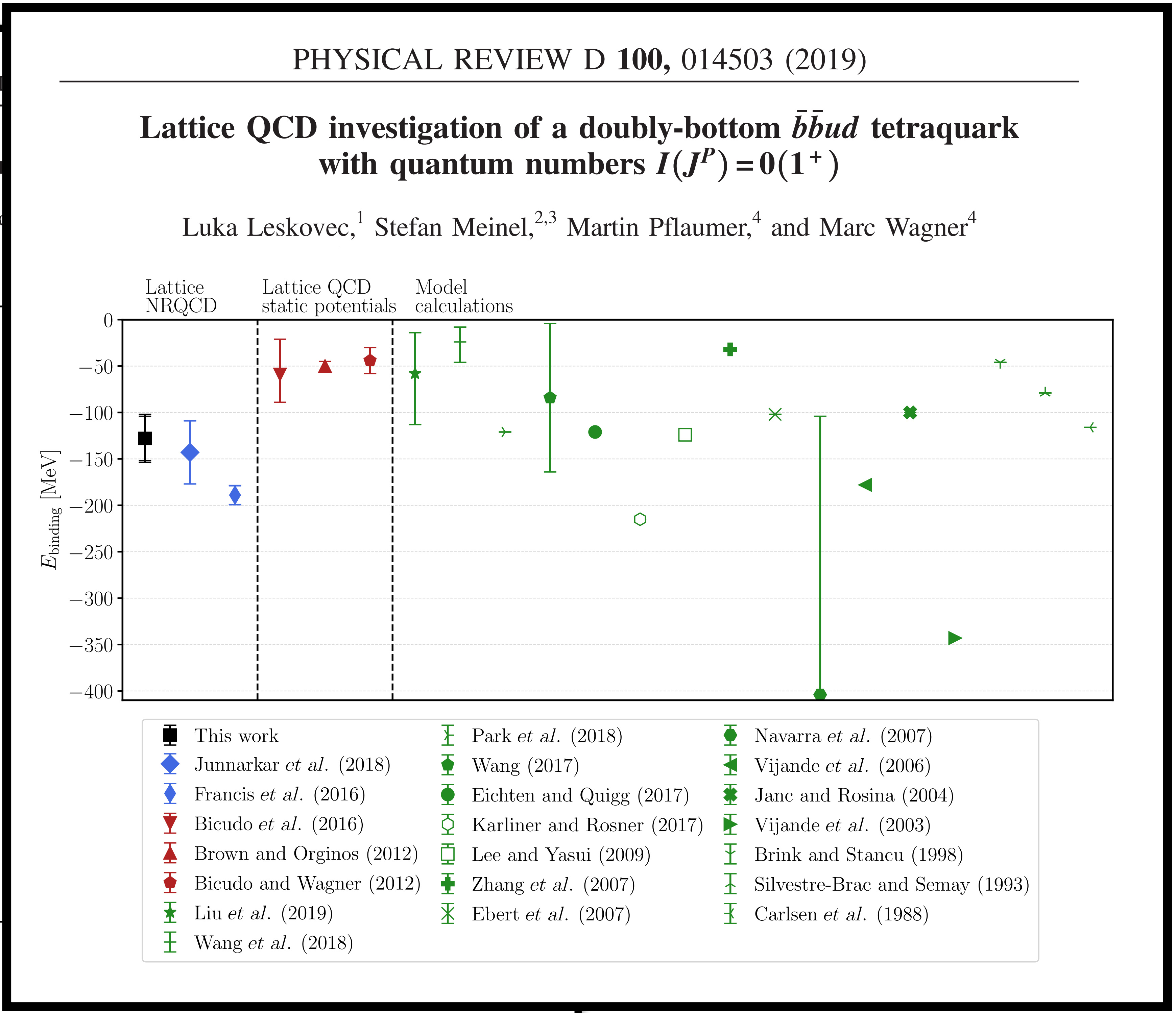
V. The Plates: $b\bar{b}$ and bb mesons



PRL **119,** 202001 (2017) PHYSICAL REVI

Discovery of the Doubly Charmed Ξ_{cc} Bar

Marek Karliner[1,*] and J



PHYSICAL REVIEW D **100,** 014503 (2019)

Lattice QCD investigation of a doubly-bottom $\bar{b}\bar{b}ud$ tetraquark with quantum numbers $I(J^P) = 0(1^+)$

Luka Leskovec,[1] Stefan Meinel,[2,3] Martin Pflaumer,[4] and Marc Wagner[4]

VI. Why Mesons?

"All science is either physics or stamp collecting." — Ernest Rutherford (apocryphal)

Despite Rutherford's quote:

(1) The diversity of mesons is beautiful and can be appreciated in its own right.

(2) The collection of mesons provides countless opportunities to hone in on specific fundamental questions.

(3) The patterns of mesons inform our understanding of how quarks and gluons interact within hadrons.

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(3) The patterns of me
quarks and gluons inte

Quick Key: Butterflies

1 Large; *striped:* **Swallowtails** — ***see*** **page 3**

2 Large; *dark,* with or without *yellow* or *orange* spots: **Swallowtails** (and their **mimics**) — ***see*** **pages 5-11**

3 Small to medium; *white:* **Whites** — ***see*** **pages 13-15**

4 Small to large; *yellow:* **Sulphurs** — ***see*** **pages 17-21**

5 Large; *orange* with *black* veins: **Milkweed Butterflies** and **Viceroy** — ***see*** **page 49**

Small: 1¼ inches or less | Medium: 1½-2½ inches

Quick Key: Butterflies

6 Large; *orange* with *dark* spots: **Greater Fritillaries** — ***see*** **pages 51-55**

7 Small to medium; *orange* or *black,* with *spots:* **Crescents** and **Lesser Fritillaries** — ***see*** **pages 57-61**

8 Medium to Large; with *irregular* wing edges: **Anglewings** and **Tortoiseshells** — ***see*** **pages 63-67**

9 Medium; forewing with *white* or *orange spots* or *bands:* **Ladies, Emperors, Buckeyes,** and **Snouts** — ***see*** **pages 69-71**

10 Small to large; *tan, gray,* or *brown,* with *eyespots:* **Satyrs** — ***see*** **pages 73-79**

Large: 3 inches or larger

Quick Key: Butterflies

11 Small; *blue, dark gray,* or *tan* above, *silvery gray, tan,* or *white* below: **Azures** and **Blues** — ***see*** **pages 23-29**

12 Small; *gray, tan,* or *brown* below, with *white* streaks: **Elfins, Harvester,** and **Hairstreaks** — ***see*** **pages 31-39**

13 Small; underside *green* or *black* below, with tails: **Hairstreaks** — ***see*** **page 41**

14 Small; wings *brown* above and *orange* below: **Metalmarks** — ***see*** **page 47**

15 Small; *gray* and *orange* below with *spots; dark* with *orange* above: **Coppers** — ***see*** **pages 43-45**

Small: 1¼ inches or less | Medium: 1½-2½ inches

Quick Key: Skippers

16 *either ...* Small to Medium; wings held *flat* or at the *same angle* while basking: **Spread-wing Skippers** — ***see*** **Quick Key Boxes 17-20 below**

or ... Small; wings held at *different “jet” angles* while basking: **Grass Skippers** — ***see*** **Quick Key Boxes 21-33 next page**

17 Medium; forewing with *brownish gold* or *gold* bands: — ***see*** **page 81**

18 Small to medium; *mottled brown; with* or *without white* spots: **Duskywings** — ***see*** **pages 83-87**

19 Medium; *unmottled;* forewing with *white* spots: **Cloudywings** — ***see*** **page 89**

20 Small; forewing with *white* spots or *checkered* pattern: — ***see*** **page 91**

Large: 3 inches or larger

Quick Key: Grass Skippers (wings closed)

21 Small; hindwing with *bold* or *chevron-shaped* pattern: — ***see*** **pages 93-97**

22 Small; hindwing *dark,* with *violet* or *gray* border: — ***see*** **page 99**

23 Small; hindwing with *checkered* fringe: — ***see*** **page 101**

24 Small; hindwing with *pale stripes* or *highlighted* veins: — ***see*** **pages 103-105**

25 Small; hindwing *yellow* or *orange, without* bold pattern: — ***see*** **page 107**

26 Small; hindwing *dark brown* or *light gray, without* bold pattern: — ***see*** **page 109**

27 Small; hindwing *brown* or *tan, without* bold pattern: — ***see*** **pages 111-113**

28 Small to medium; forewing *elongated:* — ***see*** **page 113**

Small: 1¼ inches or less | Medium: 1½-2½ inches

Quick Key: Grass Skippers (wings open)

29 Small; forewing *orange,* with *distinct* stigma: — ***see*** **pages 115-117**

30 Small; forewing *orange, without* stigma; or stigma *indistinct:* — ***see*** **page 119**

31 Small to medium; forewing with a *diagonal row* of *spots:* — ***see*** **pages 121-123**

32 Small; forewing *dark* with *small* spots: — ***see*** **pages 125-127**

33 Small; forewing *dark, without* spots: — ***see*** **page 127**

Large: 3 inches or larger

VI. Why Mesons?

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(2) The collection of r
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(3) The patterns of me
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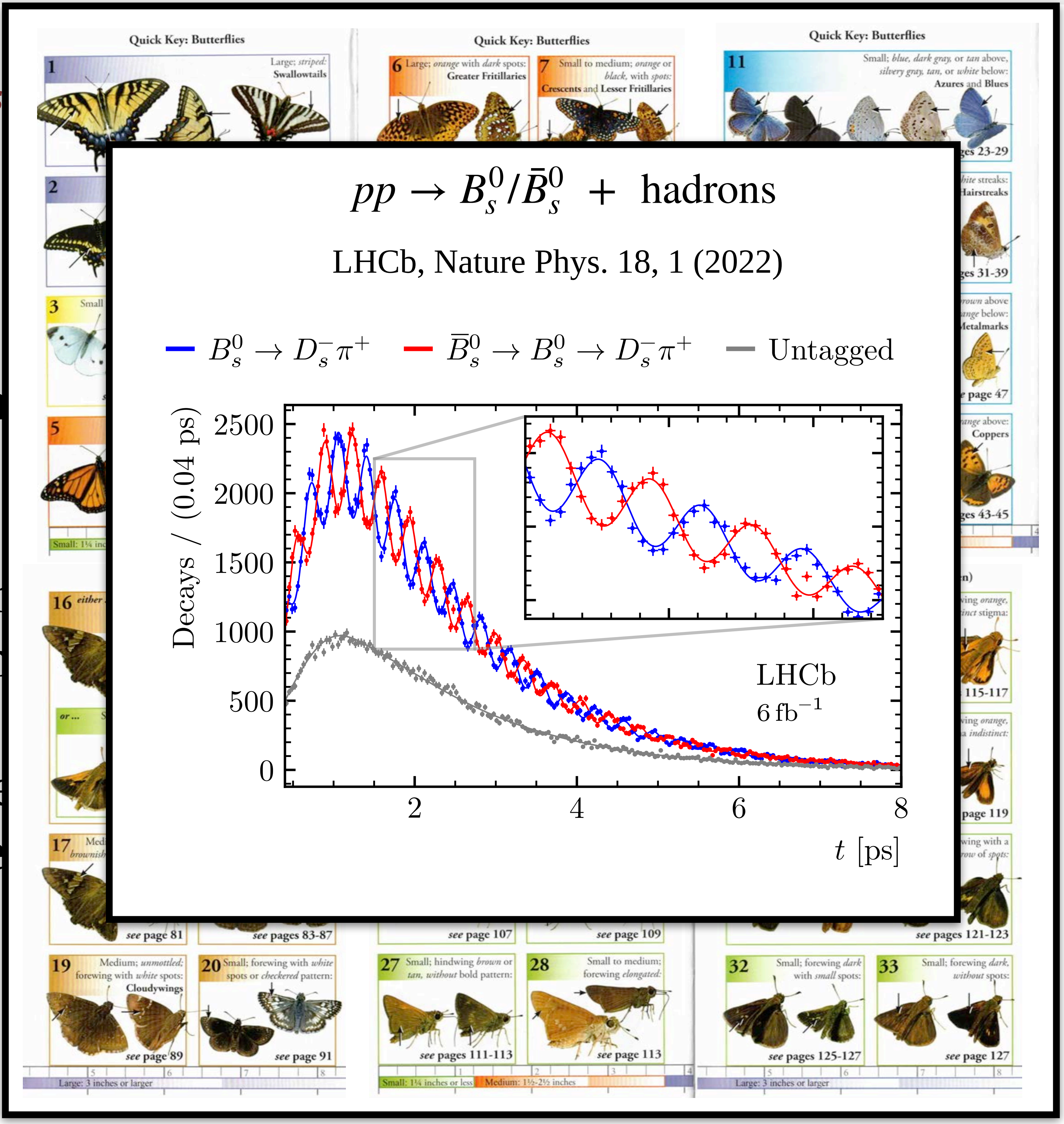

$pp \to B_s^0/\bar{B}_s^0$ + hadrons

LHCb, Nature Phys. 18, 1 (2022)

VI. Why Mesons?

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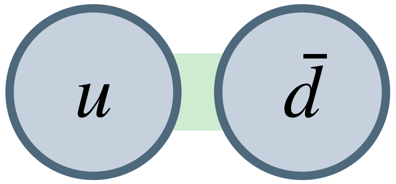
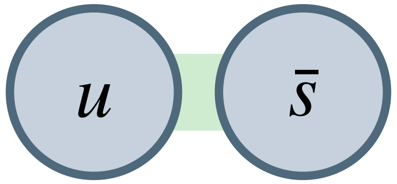
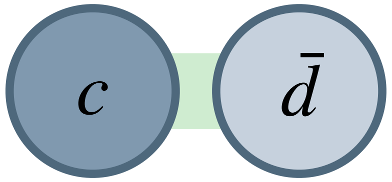
A Field Guide to the Mesons



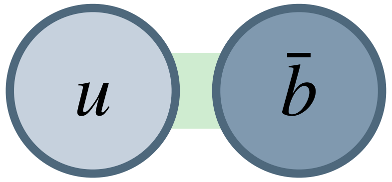
π^+ (pion)
$M \approx 140$ MeV
$J^P = 0^-$



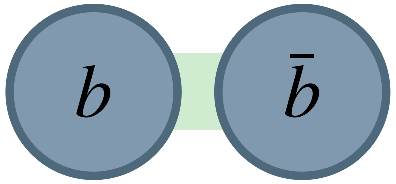
K^+ (kaon)
$M \approx 494$ MeV
$J^P = 0^-$



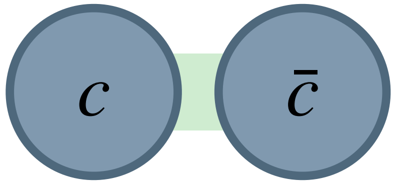
D^+ (D meson)
$M \approx 1870$ MeV
$J^P = 0^-$



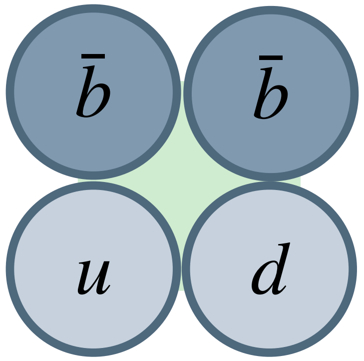
B^+ (B meson)
$M \approx 5279$ MeV
$J^P = 0^-$



$\Upsilon(1S)$ (bottomonium)
$M \approx 9460$ MeV
$J^{PC} = 1^{--}$



J/ψ (charmonium)
$M \approx 3097$ MeV
$J^{PC} = 1^{--}$



double-bottom
tetraquark
$M \approx 10400$ MeV
$J^P = 1^+$

This Talk:

I. What are Mesons?

II. Families of Mesons

III. Looking for Mesons

IV. The Plates: $c\bar{c}$ and cc mesons

V. The Plates: $b\bar{b}$ and bb mesons

VI. Why Mesons?

The discussion continues! *Thanks!*