Hadron Spectroscopy

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Lecture 1:
An Experimental Overview

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Lecture 2:
A Theoretical Overview

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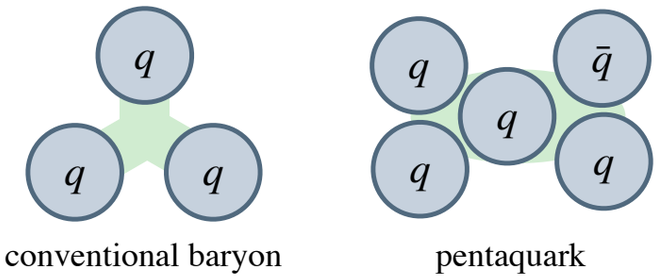
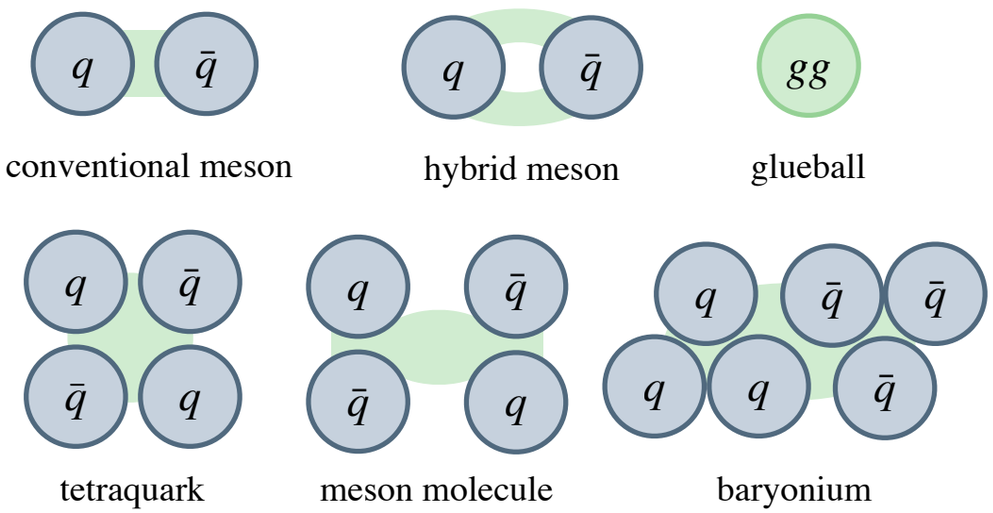
QUARKS

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

BARYONS



MESONS



Hadron Spectroscopy

HADRON SPECTROSCOPY: the study of the spectrum of hadrons

$\Longrightarrow$ *masses, widths, decay patterns, connections to models and theories*

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

$\Longrightarrow$ *strongly interacting particles, held together by the strong force*

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

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

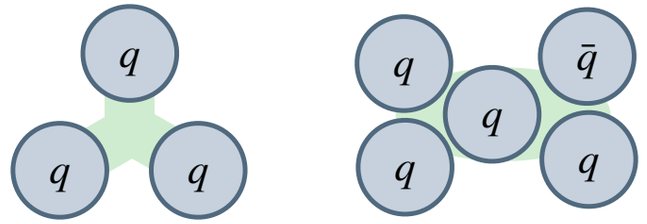
MESONS: hadrons with equal numbers of quarks and antiquarks (*e.g.* $q\bar{q}$)

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

QUARKS

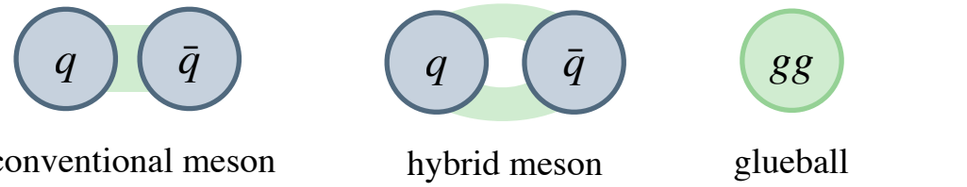
electric charge	I	II	III
		generations	
$+\frac{2}{3}$	u (up)	c (charm)	t (top)
$-\frac{1}{3}$	d (down)	s (strange)	b (bottom)

BARYONS



conventional baryon pentaquark

MESONS



conventional meson hybrid meson glueball

tetraquark meson molecule baryonium

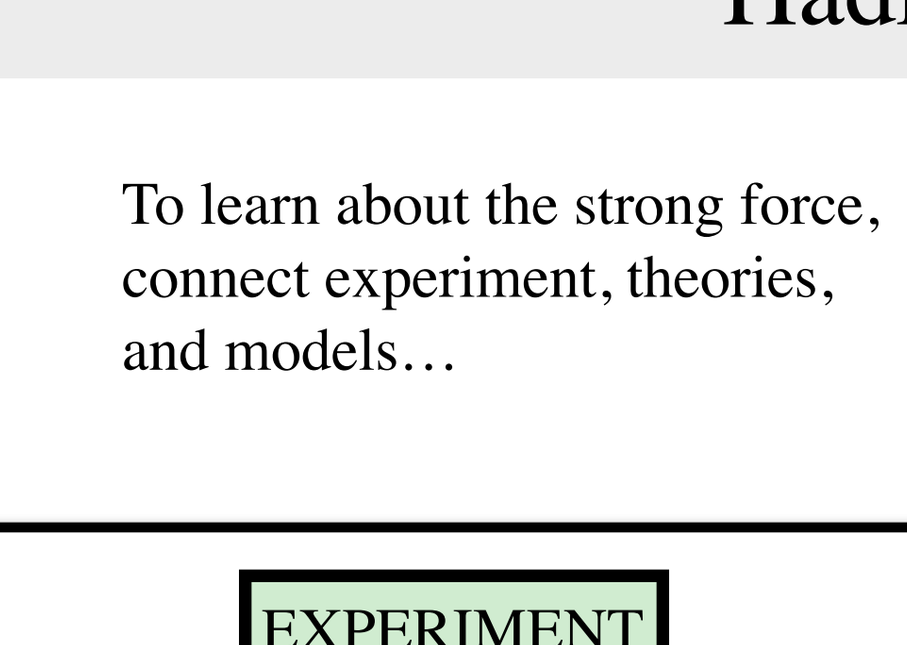
Hadron Spectroscopy

To learn about the strong force, connect experiment, theories, and models…

EXPERIMENT

$\psi(2S) \to \gamma\eta_c(1S); \quad \eta_c(1S) \to 6\pi$

[PRL 108, 222002 (2012)]



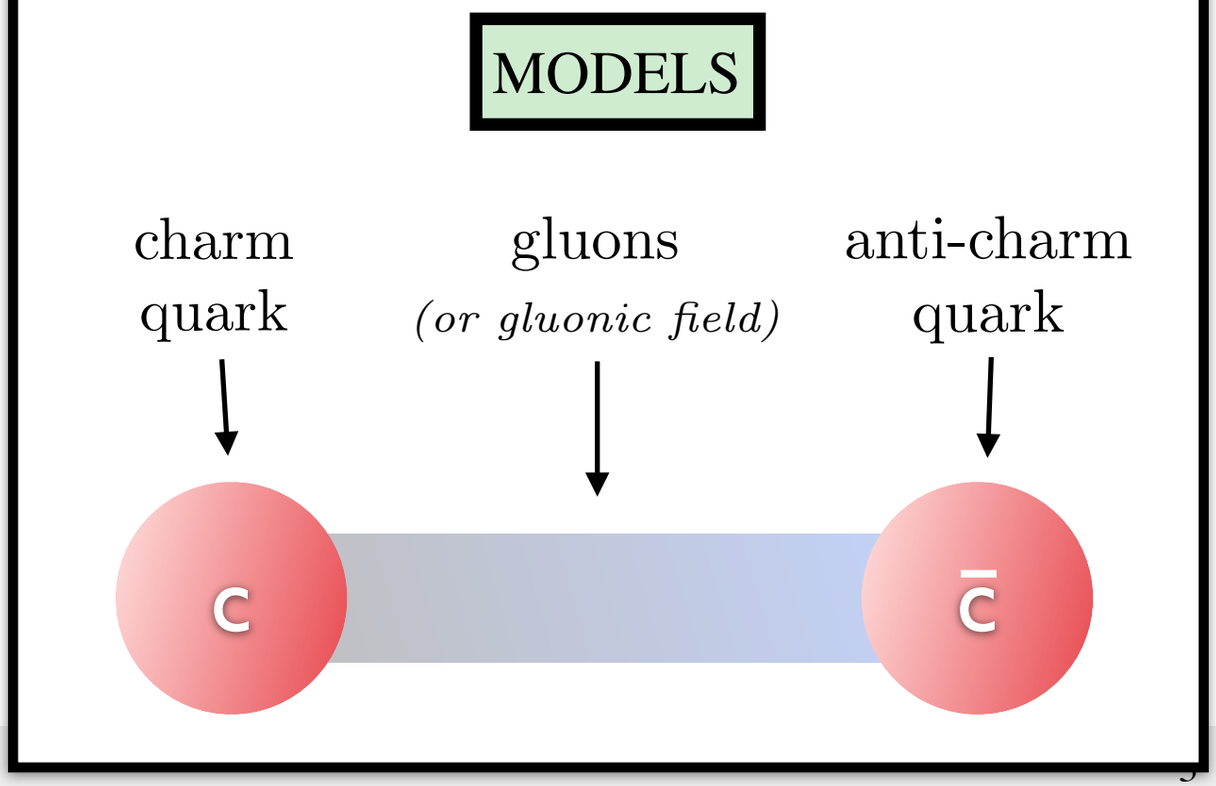
THEORY

$$\mathscr{L}_{\text{QCD}} = \mathscr{L}_0 - g_s \bar{\psi}_{qi} \gamma^\mu T^a_{ij} \psi_{qj} A^a_\mu - \frac{1}{4} G^a_{\mu\nu} G^{\mu\nu}_a$$

$$\mathscr{L}_0 = \bar{\psi}_{qi}(i\gamma^\mu \delta_\mu - m_q)\psi_{qi}$$

$$G^a_{\mu\nu} = \delta_\mu A^a_\nu - \delta_\nu A^a_\mu + g_s f^{abc} A^b_\mu A^c_\nu$$

MODELS



Hadrons in the PDG (2024)

Meson Summary Table

Including non-$q\overline{q}$ states. See also the table of suggested $q\overline{q}$ quark-model assignments in the "Quark Model" review.

• Indicates particles that appear in the preceding Meson Summary Table. We do not regard the other entries as being established.

LIGHT UNFLAVORED ($S = C = B = 0$)

	$I^G(J^{PC})$
• $\pi^\pm$	$1^-(0^{-})$
• π^0	$1^-(0^{-+})$
• η	$0^+(0^{-+})$
• $f_0(500)$	$0^+(0^{++})$
• $\rho(770)$	$1^+(1^{--})$
• $\omega(782)$	$0^-(1^{--})$
• $\eta'(958)$	$0^+(0^{-+})$
• $f_0(980)$	$0^+(0^{++})$
• $a_0(980)$	$1^-(0^{++})$
• $\phi(1020)$	$0^-(1^{--})$
• $h_1(1170)$	$0^-(1^{+-})$
• $b_1(1235)$	$1^+(1^{+-})$
• $a_1(1260)$	$1^-(1^{++})$
• $f_2(1270)$	$0^+(2^{++})$
• $f_1(1285)$	$0^+(1^{++})$
• $\eta(1295)$	$0^+(0^{-+})$
• $\pi(1300)$	$1^-(0^{-+})$
• $a_2(1320)$	$1^-(2^{++})$
• $f_0(1370)$	$0^+(0^{++})$
$\pi_1(1400)$	$1^-(1^{-+})$
• $\eta(1405)$	$0^+(0^{-+})$
• $h_1(1415)$	$0^-(1^{+-})$
• $f_1(1420)$	$0^+(1^{++})$
• $\omega(1420)$	$0^-(1^{--})$
$f_2(1430)$	$0^+(2^{++})$
• $a_0(1450)$	$1^-(0^{++})$
• $\rho(1450)$	$1^+(1^{--})$
• $\eta(1475)$	$0^+(0^{-+})$
• $f_0(1500)$	$0^+(0^{++})$
$f_1(1510)$	$0^+(1^{++})$
• $f_2'(1525)$	$0^+(2^{++})$
• $f_2(1565)$	$0^+(2^{++})$
$\rho(1570)$	$1^+(1^{--})$
$h_1(1595)$	$0^-(1^{+-})$
• $\pi_1(1600)$	$1^-(1^{-+})$
• $a_1(1640)$	$1^-(1^{++})$
$f_2(1640)$	$0^+(2^{++})$
• $\eta_2(1645)$	$0^+(2^{-+})$
• $\omega(1650)$	$0^-(1^{--})$
• $\omega_3(1670)$	$0^-(3^{--})$
• $\pi_2(1670)$	$1^-(2^{-+})$
• $\phi(1680)$	$0^-(1^{--})$
• $\rho_3(1690)$	$1^+(3^{--})$
• $\rho(1700)$	$1^+(1^{--})$
• $a_2(1700)$	$1^-(2^{++})$
$a_0(1710)$	$0^+(0^{++})$
• $f_0(1710)$	$0^+(0^{++})$
$X(1750)$	$?^-(1^{--})$
$\eta(1760)$	$0^+(0^{-+})$
$f_0(1770)$	$0^+(0^{++})$
• $\pi(1800)$	$1^-(0^{-+})$
$f_2(1810)$	$0^+(2^{++})$
$X(1835)$	$0^+(0^{-+})$
• $\phi_3(1850)$	$0^-(3^{--})$
$\eta_1(1855)$	$0^+(1^{-+})$
• $\eta_2(1870)$	$0^+(2^{-+})$
• $\pi_2(1880)$	$1^-(2^{-+})$
$\rho(1900)$	$1^+(1^{--})$
$f_2(1910)$	$0^+(2^{++})$
$a_0(1950)$	$1^-(0^{++})$
• $f_2(1950)$	$0^+(2^{++})$
• $a_4(1970)$	$1^-(4^{++})$
$\rho_3(1990)$	$1^+(3^{--})$
$\pi_2(2005)$	$1^-(2^{-+})$
• $f_2(2010)$	$0^+(2^{++})$
• $f_0(2020)$	$0^+(0^{++})$
• $f_4(2050)$	$0^+(4^{++})$
$\pi_2(2100)$	$1^-(2^{-+})$
$f_0(2100)$	$0^+(0^{++})$
$f_2(2150)$	$0^+(2^{++})$
$\rho(2150)$	$1^+(1^{--})$
• $\phi(2170)$	$0^-(1^{--})$
$f_0(2200)$	$0^+(0^{++})$
$f_J(2220)$	$0^+(2^{++})$ or 4^{++}
$\omega(2220)$	$0^-(1^{--})$
$\eta(2225)$	$0^+(0^{-+})$
$\rho_3(2250)$	$1^+(3^{--})$
• $f_2(2300)$	$0^+(2^{++})$
$f_4(2300)$	$0^+(4^{++})$
$f_0(2330)$	$0^+(0^{++})$
• $f_2(2340)$	$0^+(2^{++})$
$\rho_5(2350)$	$1^+(5^{--})$
$X(2370)$	$?^?(?^{??})$
$f_0(2470)$	$0^+(0^{++})$
$f_6(2510)$	$0^+(6^{++})$

STRANGE ($S = \pm1$, $C = B = 0$)

	$I(J^P)$
• $K^\pm$	$1/2(0^-)$
• K^0	$1/2(0^-)$
• K_S^0	$1/2(0^-)$
• K_L^0	$1/2(0^-)$
• $K_0^*(700)$	$1/2(0^+)$
• $K^*(892)$	$1/2(1^-)$
• $K_1(1270)$	$1/2(1^+)$
• $K_1(1400)$	$1/2(1^+)$
• $K^*(1410)$	$1/2(1^-)$
• $K_0^*(1430)$	$1/2(0^+)$
• $K_2^*(1430)$	$1/2(2^+)$
• $K(1460)$	$1/2(0^-)$
$K_2(1580)$	$1/2(2^-)$
$K(1630)$	$1/2(?^?)$
• $K_1(1650)$	$1/2(1^+)$
• $K^*(1680)$	$1/2(1^-)$
• $K_2(1770)$	$1/2(2^-)$
• $K_3^*(1780)$	$1/2(3^-)$
• $K_2(1820)$	$1/2(2^-)$
$K(1830)$	$1/2(0^-)$
• $K_0^*(1950)$	$1/2(0^+)$
• $K_2^*(1980)$	$1/2(2^+)$
• $K_4^*(2045)$	$1/2(4^+)$
$K_2(2250)$	$1/2(2^-)$
$K_3(2320)$	$1/2(3^+)$
$K_5^*(2380)$	$1/2(5^-)$
$K_4(2500)$	$1/2(4^-)$
$K(3100)$	$?^?(?^{??})$

CHARMED ($C = \pm1$)

	$I(J^P)$
• $D^\pm$	$1/2(0^-)$
• D^0	$1/2(0^-)$
• $D^*(2007)^0$	$1/2(1^-)$
• $D^*(2010)^\pm$	$1/2(1^-)$
• $D_0^*(2300)$	$1/2(0^+)$
• $D_1(2420)$	$1/2(1^+)$
• $D_1(2430)^0$	$1/2(1^+)$
• $D_2^*(2460)$	$1/2(2^+)$
$D_0(2550)^0$	$1/2(0^-)$
$D_1^*(2600)^0$	$1/2(1^-)$
$D^*(2640)^\pm$	$1/2(?^?)$
$D_2(2740)^0$	$1/2(2^-)$
• $D_3^*(2750)$	$1/2(3^-)$
$D_1^*(2760)^0$	$1/2(1^-)$
$D(3000)^0$	$1/2(?^?)$

CHARMED, STRANGE ($C = \pm1$, $S = \pm1$)

	$I(J^P)$
• $D_s^\pm$	$0(0^-)$
• $D_s^{*\pm}$	$0(1^-)$
• $D_{s0}^*(2317)^\pm$	$0(0^+)$
• $D_{s1}(2460)^\pm$	$0(1^+)$
• $D_{s1}(2536)^\pm$	$0(1^+)$
• $D_{s2}^*(2573)$	$0(2^+)$

CHARMED, STRANGE continued

	$I(J^P)$
$D_{s0}(2590)^+$	$0(0^-)$
• $D_{s1}^*(2700)^\pm$	$0(1^-)$
$D_{s1}^*(2860)^\pm$	$0(1^-)$
• $D_{s3}^*(2860)^\pm$	$0(3^-)$
$D_{sJ}(3040)^\pm$	$0(?^?)$

BOTTOM ($B = \pm1$)

	$I(J^P)$
• $B^\pm$	$1/2(0^-)$
• B^0	$1/2(0^-)$
• $B^\pm/B^0$ ADMIXTURE	
• $B^\pm/B^0/B_s^0/b$-baryon ADMIXTURE	
V_{cb} and V_{ub} CKM Matrix Elements	
• B^*	$1/2(1^-)$
• $B_1(5721)$	$1/2(1^+)$
$B_J^*(5732)$	$?(?^?)$
• $B_2^*(5747)$	$1/2(2^+)$
$B_J(5840)$	$1/2(?^?)$
• $B_J(5970)$	$1/2(?^?)$

BOTTOM, STRANGE ($B = \pm1$, $S = \mp1$)

	$I(J^P)$
• B_s^0	$0(0^-)$
• B_s^*	$0(1^-)$
• $B_{s1}(5830)^0$	$0(1^+)$
• $B_{s2}^*(5840)^0$	$0(2^+)$
$B_{sJ}^*(5850)$	$?(?^?)$
$B_{sJ}(6063)^0$	$0(?^?)$
$B_{sJ}(6114)^0$	$0(?^?)$

BOTTOM, CHARMED ($B = C = \pm1$)

	$I(J^P)$
• B_c^+	$0(0^-)$
• $B_c(2S)^\pm$	$0(0^-)$

$c\overline{c}$

	$I^G(J^{PC})$
• $\eta_c(1S)$	$0^+(0^{-+})$
• $J/\psi(1S)$	$0^-(1^{--})$
• $\chi_{c0}(1P)$	$0^+(0^{++})$
• $\chi_{c1}(1P)$	$0^+(1^{++})$
• $h_c(1P)$	$0^-(1^{+-})$
• $\chi_{c2}(1P)$	$0^+(2^{++})$
• $\eta_c(2S)$	$0^+(0^{-+})$
• $\psi(2S)$	$0^-(1^{--})$
• $\psi(3770)$	$0^-(1^{--})$
• $\psi_2(3823)$	$0^-(2^{--})$
• $\psi_3(3842)$	$0^-(3^{--})$
$\chi_{c0}(3860)$	$0^+(0^{++})$
• $\chi_{c1}(3872)$	$0^+(1^{++})$
• $\chi_{c0}(3915)$	$0^+(0^{++})$
• $\chi_{c2}(3930)$	$0^+(2^{++})$
$X(3940)$	$?^?(?^{??})$
• $\psi(4040)$	$0^-(1^{--})$
• $\chi_{c1}(4140)$	$0^+(1^{++})$
• $\psi(4160)$	$0^-(1^{--})$
$X(4160)$	$?^?(?^{??})$

$c\overline{c}$ continued

	$I^G(J^{PC})$
• $\psi(4230)$	$0^-(1^{--})$
• $\chi_{c1}(4274)$	$0^+(1^{++})$
$X(4350)$	$0^+(?^{?+})$
• $\psi(4360)$	$0^-(1^{--})$
• $\psi(4415)$	$0^-(1^{--})$
$\chi_{c0}(4500)$	$0^+(0^{++})$
$X(4630)$	$0^+(?^{?+})$
• $\psi(4660)$	$0^-(1^{--})$
$\chi_{c1}(4685)$	$0^+(1^{++})$
$\chi_{c0}(4700)$	$0^+(0^{++})$

$b\overline{b}$

	$I^G(J^{PC})$
• $\eta_b(1S)$	$0^+(0^{-+})$
• $\Upsilon(1S)$	$0^-(1^{--})$
• $\chi_{b0}(1P)$	$0^+(0^{++})$
• $\chi_{b1}(1P)$	$0^+(1^{++})$
• $h_b(1P)$	$0^-(1^{+-})$
• $\chi_{b2}(1P)$	$0^+(2^{++})$
$\eta_b(2S)$	$0^+(0^{-+})$
• $\Upsilon(2S)$	$0^-(1^{--})$
• $\Upsilon_2(1D)$	$0^-(2^{--})$
• $\chi_{b0}(2P)$	$0^+(0^{++})$
• $\chi_{b1}(2P)$	$0^+(1^{++})$
• $h_b(2P)$	$0^-(1^{+-})$
• $\chi_{b2}(2P)$	$0^+(2^{++})$
• $\Upsilon(3S)$	$0^-(1^{--})$
• $\chi_{b1}(3P)$	$0^+(1^{++})$
• $\chi_{b2}(3P)$	$0^+(2^{++})$
• $\Upsilon(4S)$	$0^-(1^{--})$
$\Upsilon(10753)$	$?^?(1^{--})$
• $\Upsilon(10860)$	$0^-(1^{--})$
• $\Upsilon(11020)$	$0^-(1^{--})$

OTHER

$T_{cs0}^*(2870)^0$	$?(0^+)$
$T_{cs1}^*(2900)^0$	$?(1^-)$
$T_{c\overline{s}0}^*(2900)$	$1(0^+)$
$T_{cc}(3875)^+$	$?(?^?)$
• $T_{c\overline{c}1}(3900)$	$1^+(1^{+-})$
$T_{c\overline{c}s1}(4000)$	$1/2(1^+)$
• $T_{c\overline{c}}(4020)$	$1^+(?^{?-})$
$T_{c\overline{c}}(4050)^+$	$1^-(?^{?+})$
$T_{c\overline{c}}(4055)^+$	$1^+(?^{?-})$
$T_{c\overline{c}}(4100)^+$	$1^-(?^{?+})$
$T_{c\overline{c}1}(4200)^+$	$1^+(1^{+-})$
$T_{c\overline{c}s1}(4220)^+$	$1/2(1^+)$
$T_{c\overline{c}0}(4240)^+$	$1^+(0^{-+})$
$T_{c\overline{c}}(4250)^+$	$1^-(?^{?+})$
• $T_{c\overline{c}1}(4430)^+$	$1^+(1^{+-})$
$T_{bs}(5568)^+$	$1(?^?)$
$T_{cc\overline{c}\overline{c}}(6900)^0$	$0^+(?^{?+})$
• $T_{b\overline{b}1}(10610)$	$1^+(1^{+-})$
• $T_{b\overline{b}1}(10650)^+$	$1^+(1^{+-})$
Further States	

Baryon Summary Table

This short table gives the name, the quantum numbers (where known), and the status of baryons in the Review. Only the baryons with 3- or 4-star status are included in the Baryon Summary Table. Due to insufficient data or uncertain interpretation, the other entries in the table are not established baryons. The names with masses are of baryons that decay strongly. The spin-parity J^P (when known) is given with each particle. For the strongly decaying particles, the J^P values are considered to be part of the names.

p	$1/2^+$	****	$\Delta(1232)$	$3/2^+$	****	Σ^+	$1/2^+$	****	Λ_c^+	$1/2^+$	****	Λ_b^0	$1/2^+$	***
n	$1/2^+$	****	$\Delta(1600)$	$3/2^+$	****	Σ^0	$1/2^+$	****	$\Lambda_c(2595)^+$	$1/2^-$	***	$\Lambda_b(5912)^0$	$1/2^-$	***
$N(1440)$	$1/2^+$	****	$\Delta(1620)$	$1/2^-$	****	Σ^-	$1/2^+$	****	$\Lambda_c(2625)^+$	$3/2^-$	***	$\Lambda_b(5920)^0$	$3/2^-$	***
$N(1520)$	$3/2^-$	****	$\Delta(1700)$	$3/2^-$	****	$\Sigma(1385)$	$3/2^+$	****	$\Lambda_c(2765)^+$		*	$\Lambda_b(6070)^0$	$1/2^+$	***
$N(1535)$	$1/2^-$	****	$\Delta(1750)$	$1/2^+$	*	$\Sigma(1580)$	$3/2^-$	*	$\Lambda_c(2860)^+$	$3/2^+$	***	$\Lambda_b(6146)^0$	$3/2^+$	***
$N(1650)$	$1/2^-$	****	$\Delta(1900)$	$1/2^-$	***	$\Sigma(1620)$	$1/2^-$	*	$\Lambda_c(2880)^+$	$5/2^+$	***	$\Lambda_b(6152)^0$	$5/2^+$	***
$N(1675)$	$5/2^-$	****	$\Delta(1905)$	$5/2^+$	****	$\Sigma(1660)$	$1/2^+$	***	$\Lambda_c(2910)^+$		*	Σ_b	$1/2^+$	***
$N(1680)$	$5/2^+$	****	$\Delta(1910)$	$1/2^+$	****	$\Sigma(1670)$	$3/2^-$	****	$\Lambda_c(2940)^+$	$3/2^-$	***	Σ_b^*	$3/2^+$	***
$N(1700)$	$3/2^-$	***	$\Delta(1920)$	$3/2^+$	***	$\Sigma(1750)$	$1/2^-$	***	$\Sigma_c(2455)$	$1/2^+$	****	$\Sigma_b(6097)^+$		***
$N(1710)$	$1/2^+$	****	$\Delta(1930)$	$5/2^-$	***	$\Sigma(1775)$	$5/2^-$	****	$\Sigma_c(2520)$	$3/2^+$	***	$\Sigma_b(6097)^-$		***
$N(1720)$	$3/2^+$	****	$\Delta(1940)$	$3/2^-$	**	$\Sigma(1780)$	$3/2^+$	*	$\Sigma_c(2800)$		***	Ξ_b^-	$1/2^+$	***
$N(1860)$	$5/2^+$	**	$\Delta(1950)$	$7/2^+$	****	$\Sigma(1880)$	$1/2^+$	**	Ξ_c^+	$1/2^+$	***	Ξ_b^0	$1/2^+$	***
$N(1875)$	$3/2^-$	***	$\Delta(2000)$	$5/2^+$	**	$\Sigma(1900)$	$1/2^-$	**	Ξ_c^0	$1/2^+$	****	$\Xi_b'(5935)^-$	$1/2^+$	***
$N(1880)$	$1/2^+$	***	$\Delta(2150)$	$1/2^-$	*	$\Sigma(1910)$	$3/2^-$	***	$\Xi_c'^+$	$1/2^+$	***	$\Xi_b(5945)^0$	$3/2^+$	***
$N(1895)$	$1/2^-$	****	$\Delta(2200)$	$7/2^-$	***	$\Sigma(1915)$	$5/2^+$	****	$\Xi_c'^0$	$1/2^+$	***	$\Xi_b(5955)^-$	$3/2^+$	***
$N(1900)$	$3/2^+$	****	$\Delta(2300)$	$9/2^+$	**	$\Sigma(1940)$	$3/2^+$	*	$\Xi_c(2645)$	$3/2^+$	***	$\Xi_b(6087)^0$	$3/2^-$	***
$N(1990)$	$7/2^+$	**	$\Delta(2350)$	$5/2^-$	*	$\Sigma(2010)$	$3/2^-$	*	$\Xi_c(2790)$	$1/2^-$	***	$\Xi_b(6095)^0$	$3/2^-$	***
$N(2000)$	$5/2^+$	**	$\Delta(2390)$	$7/2^+$	*	$\Sigma(2030)$	$7/2^+$	****	$\Xi_c(2815)$	$3/2^-$	***	$\Xi_b(6100)^-$	$3/2^-$	***
$N(2040)$	$3/2^+$	*	$\Delta(2400)$	$9/2^-$	**	$\Sigma(2070)$	$5/2^+$	*	$\Xi_c(2882)$		*	$\Xi_b(6227)^-$		***
$N(2060)$	$5/2^-$	***	$\Delta(2420)$	$11/2^+$	****	$\Sigma(2080)$	$3/2^+$	*	$\Xi_c(2923)$		**	$\Xi_b(6227)^0$		***
$N(2100)$	$1/2^+$	***	$\Delta(2750)$	$13/2^-$	**	$\Sigma(2100)$	$7/2^-$	*	$\Xi_c(2930)$		**	$\Xi_b(6327)^0$		***
$N(2120)$	$3/2^-$	***	$\Delta(2950)$	$15/2^+$	**	$\Sigma(2110)$	$1/2^-$	*	$\Xi_c(2970)$	$1/2^+$	***	$\Xi_b(6333)^0$		***
$N(2190)$	$7/2^-$	****				$\Sigma(2230)$	$3/2^+$	*	$\Xi_c(3055)$		***	Ω_b^-	$1/2^+$	***
$N(2220)$	$9/2^+$	****	Λ	$1/2^+$	****	$\Sigma(2250)$		**	$\Xi_c(3080)$		***	$\Omega_b(6316)^-$		***
$N(2250)$	$9/2^-$	****	$\Lambda(1380)$	$1/2^-$	**	$\Sigma(2455)$		*	$\Xi_c(3123)$		*	$\Omega_b(6330)^-$		***
$N(2300)$	$1/2^+$	**	$\Lambda(1405)$	$1/2^-$	****	$\Sigma(2620)$		*	Ω_c^0	$1/2^+$	***	$\Omega_b(6340)^-$		***
$N(2570)$	$5/2^-$	**	$\Lambda(1520)$	$3/2^-$	****	$\Sigma(3000)$		*	$\Omega_c(2770)^0$	$3/2^+$	***	$\Omega_b(6350)^-$		***
$N(2600)$	$11/2^-$	***	$\Lambda(1600)$	$1/2^+$	****	$\Sigma(3170)$		*	$\Omega_c(3000)^0$		***			
$N(2700)$	$13/2^+$	**	$\Lambda(1670)$	$1/2^-$	****				$\Omega_c(3050)^0$		***	$P_{c\overline{c}}(4312)^+$		*
			$\Lambda(1690)$	$3/2^-$	****	Ξ^0	$1/2^+$	****	$\Omega_c(3065)^0$		***	$P_{c\overline{c}s}(4338)^0$	$1/2^-$	*
			$\Lambda(1710)$	$1/2^+$	*	Ξ^-	$1/2^+$	****	$\Omega_c(3090)^0$		***	$P_{c\overline{c}}(4380)^+$		*
			$\Lambda(1800)$	$1/2^-$	***	$\Xi(1530)$	$3/2^+$	****	$\Omega_c(3120)^0$		***	$P_{c\overline{c}}(4440)^+$		*
			$\Lambda(1810)$	$1/2^+$	***	$\Xi(1620)$		**	$\Omega_c(3185)^0$		***	$P_{c\overline{c}}(4457)^+$		*
			$\Lambda(1820)$	$5/2^+$	****	$\Xi(1690)$		***	$\Omega_c(3327)^0$		***	$P_{c\overline{c}s}(4459)^0$		*
			$\Lambda(1830)$	$5/2^-$	****	$\Xi(1820)$	$3/2^-$	***						
			$\Lambda(1890)$	$3/2^+$	****	$\Xi(1950)$		***	Ξ_{cc}^+		*			
			$\Lambda(2000)$	$1/2^-$	*	$\Xi(2030)$	$\geq \frac{5}{2}^?$	***	Ξ_{cc}^{++}		***			
			$\Lambda(2050)$	$3/2^-$	*	$\Xi(2120)$		*						
			$\Lambda(2070)$	$3/2^+$	*	$\Xi(2250)$		**						
			$\Lambda(2080)$	$5/2^-$	*	$\Xi(2370)$		**						
			$\Lambda(2085)$	$7/2^+$	**	$\Xi(2500)$		*						
			$\Lambda(2100)$	$7/2^-$	****									
			$\Lambda(2110)$	$5/2^+$	***	Ω^-	$3/2^+$	****						
			$\Lambda(2325)$	$3/2^-$	*	$\Omega(2012)^-$	$?^-$	***						
			$\Lambda(2350)$	$9/2^+$	***	$\Omega(2250)^-$		***						
			$\Lambda(2585)$		*	$\Omega(2380)^-$		**						
						$\Omega(2470)^-$		**						

**** Existence is certain, and properties are at least fairly well explored.

*** Existence ranges from very likely to certain, but further confirmation is desirable and/or quantum numbers, branching fractions, etc. are not well determined.

** Evidence of existence is only fair.

* Evidence of existence is poor.

Lecture 1:
An Experimental Overview
(or A Field Guide to the Mesons)

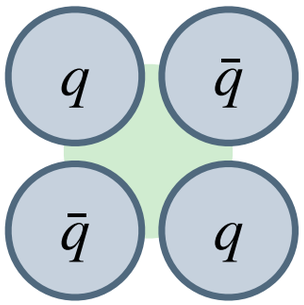
NNPSS, IU, July 24, 2024

Ryan Mitchell
Indiana University
(BESIII, GlueX, PDG)

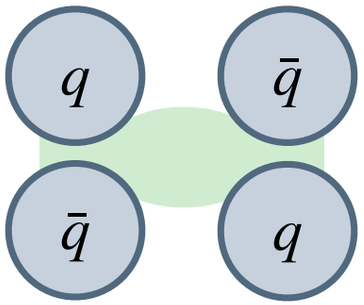
conventional meson

hybrid meson

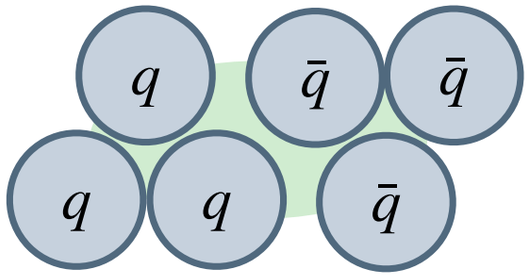
glueball



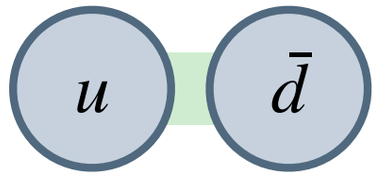
tetraquark



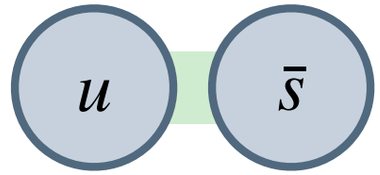
meson molecule



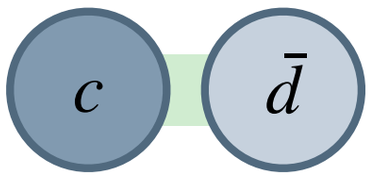
baryonium



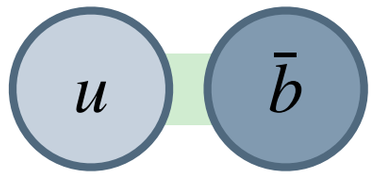
π^+ (pion)
$M \approx 140$ MeV



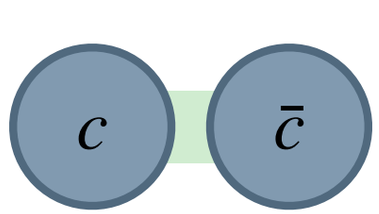
K^+ (kaon)
$M \approx 494$ MeV



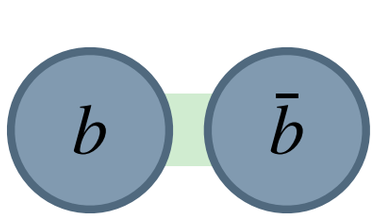
D^+ (D meson)
$M \approx 1870$ MeV



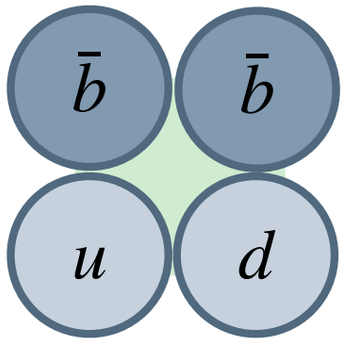
B^+ (B meson)
$M \approx 5279$ MeV



J/ψ (charmonium)
$M \approx 3097$ MeV

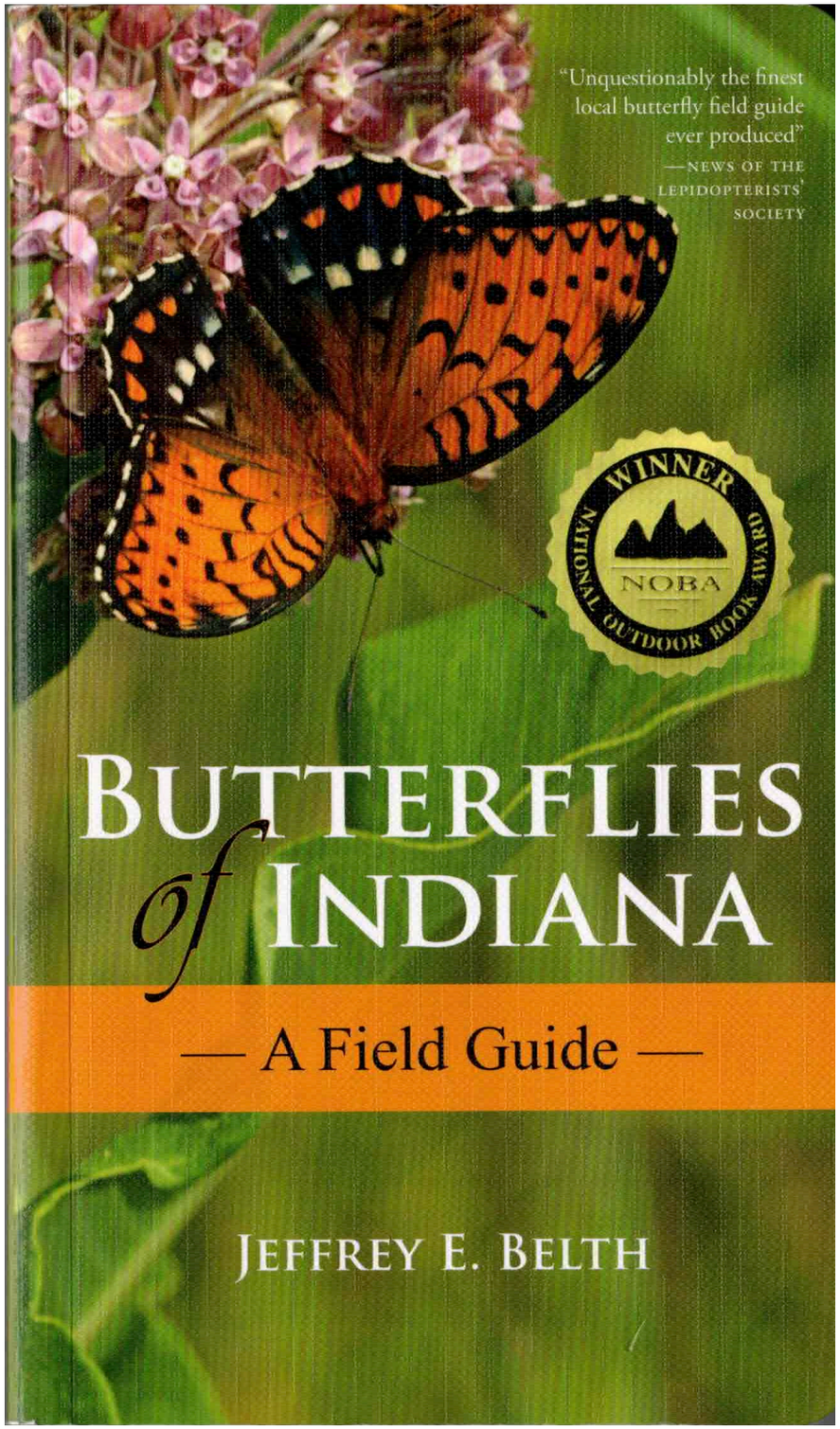


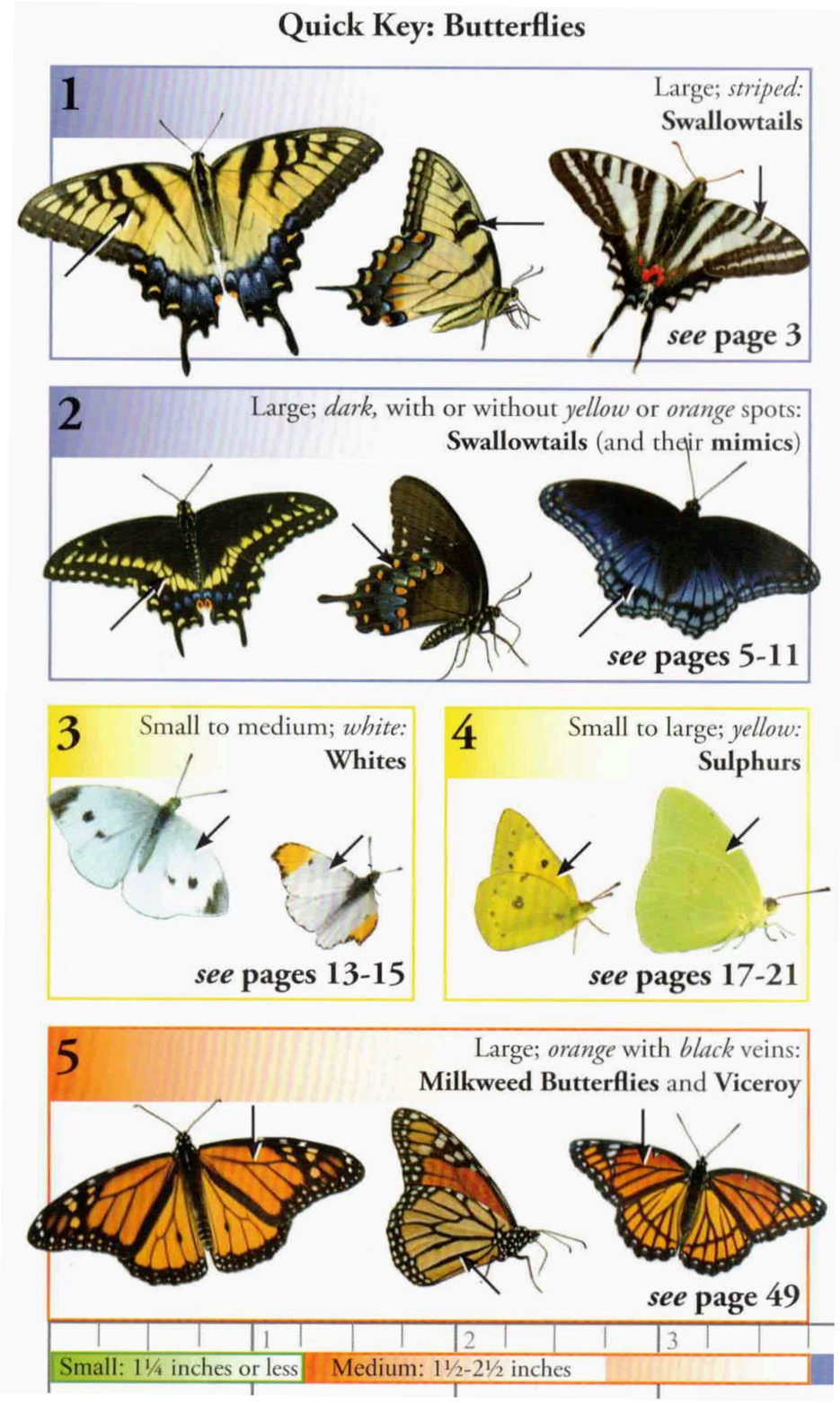
$\Upsilon(1S)$ (bottomonium)
$M \approx 9460$ MeV



double-bottom
tetraquark
$M \approx 10400$ MeV

The Approach of a Field Guide





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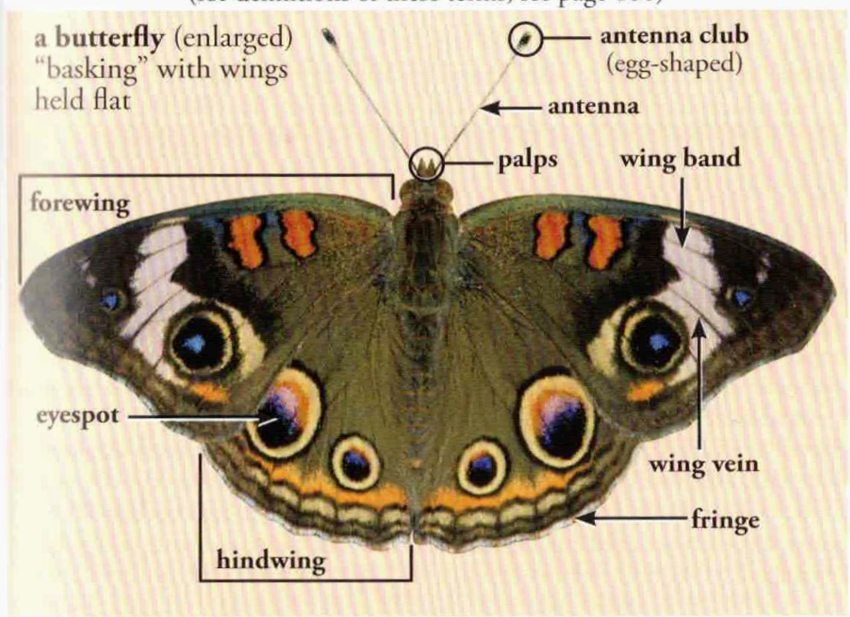
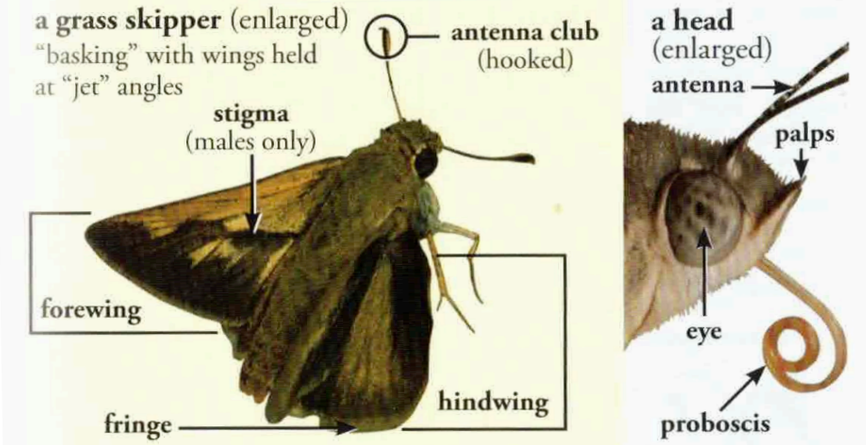
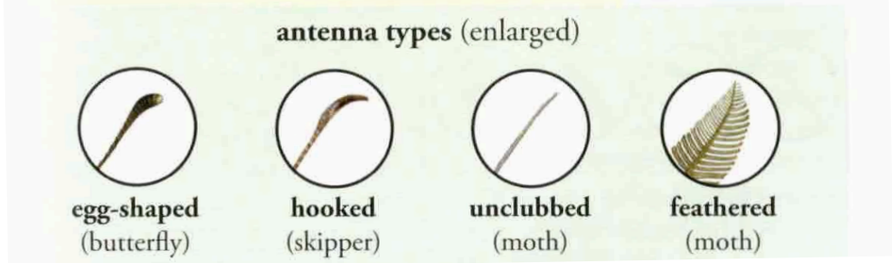
Terms Used When Identifying Butterflies and Skippers
(for definitions of these terms, see page 180)







The Approach of a Field Guide

Contents

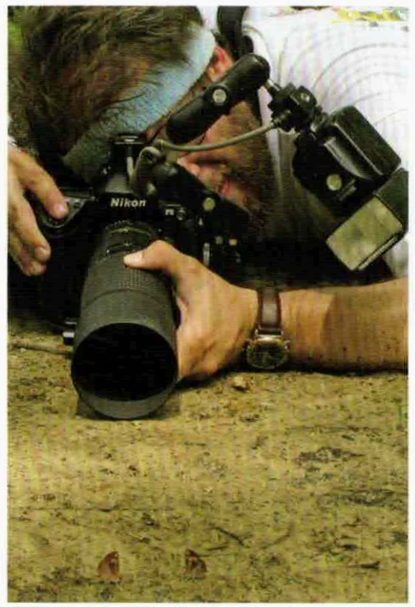
about two-thirds of the images in this book were taken with slide film—either the discontinued Agfa RSXII 50, or more recently, Fuji Astia 100.

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.



getting parallel to two Harvesters

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

The Approach of a Field Guide

Contents

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

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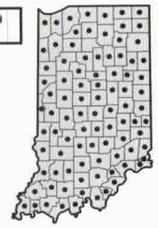
Contents

Cabbage White (*Pieris rapae rapae*)

J F M A M J J A S O N D



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*)

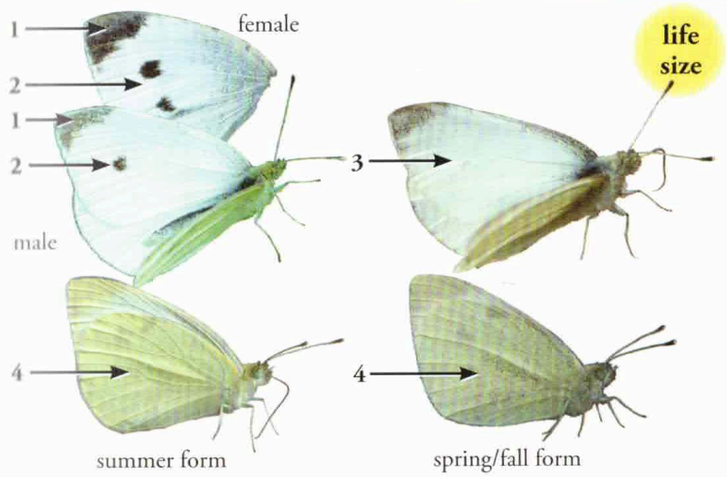
J F M A M J J A S O N D

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.

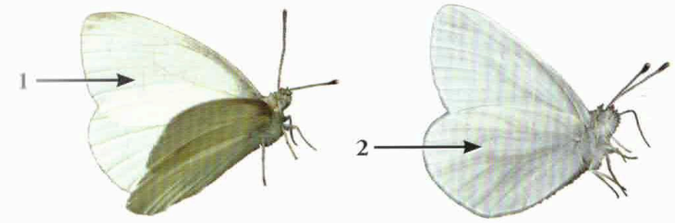
Mustard White (*Pieris oleracea oleracea*)

J F M A M J J A S O N D

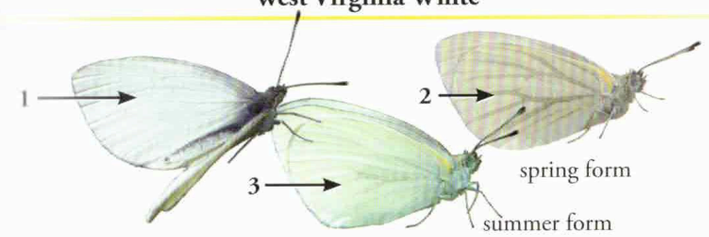
Identification:
1 Both forms *unmarked* above, occasionally with *faint* spots
2 Spring form with distinct *grayish-green* venation
3 Summer form *without* venation (or, if present, *very faint*)
Habitat: Fens and adjacent uplands
Larval host: Watercress (*Nasturtium officinale*) [143]
Notes: State endangered;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



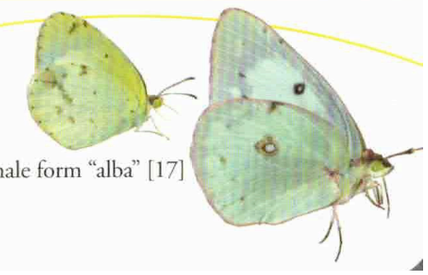
Cabbage White



West Virginia White



Mustard White



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

A Field Guide to the Mesons

Contents

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?

A Field Guide to the Mesons

Contents

This Talk:

I. What are Mesons?

II. Families of Mesons

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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?

HADRON SPECTROSCOPY: the study of the spectrum of hadrons

$\Longrightarrow$ *masses, widths, decay patterns, connections to models and theories*

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

$\Longrightarrow$ *strongly interacting particles, held together by the strong force*

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

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

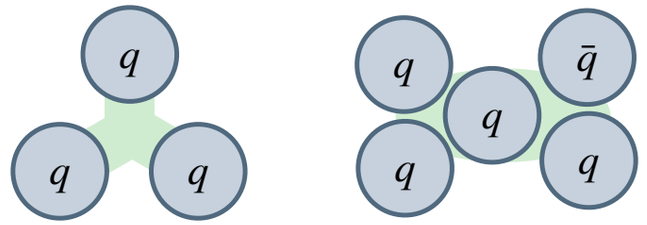
MESONS: hadrons with equal numbers of quarks and antiquarks (*e.g.* $q\bar{q}$)

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

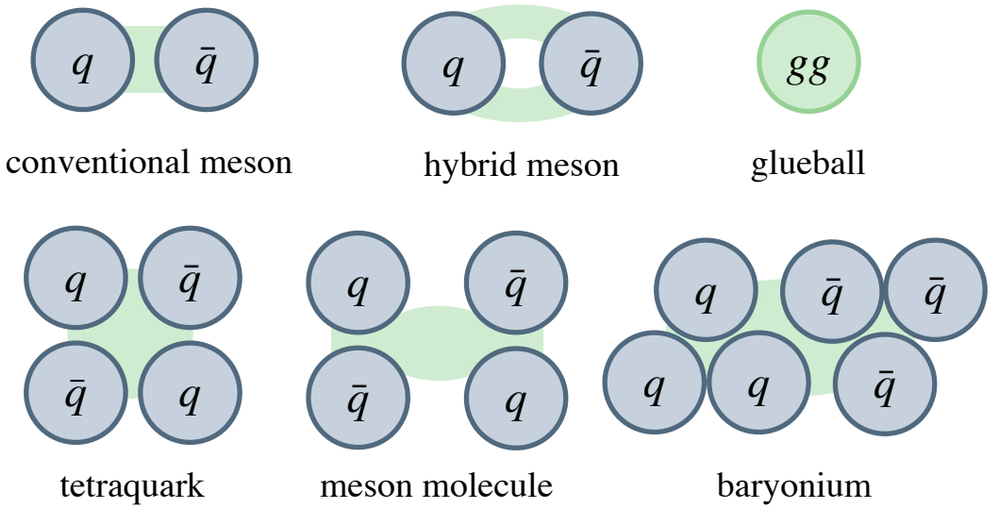
QUARKS

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

BARYONS

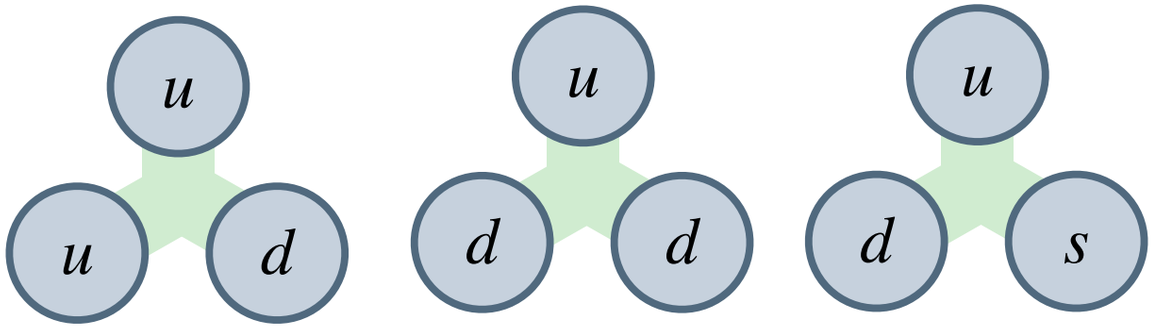


MESONS



I. What are Mesons?

A few famous baryons…



p (proton)
$M \approx 938$ MeV

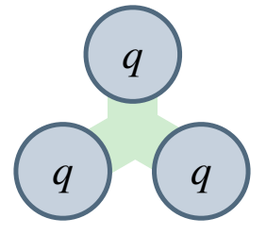
n (neutron)
$M \approx 940$ MeV

Λ (lambda)
$M \approx 1116$ MeV

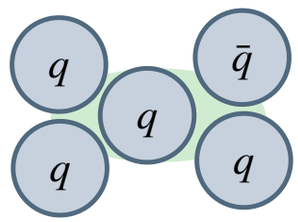
QUARKS

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

BARYONS

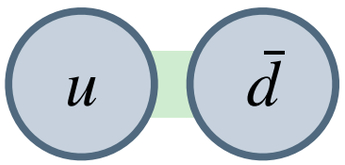


conventional baryon

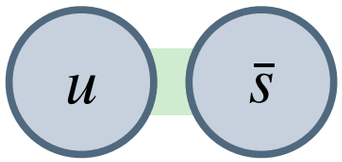


pentaquark

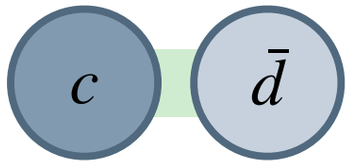
A few famous mesons…



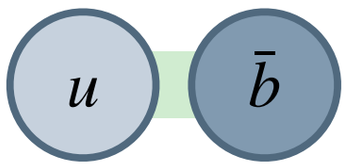
π^+ (pion)
$M \approx 140$ MeV



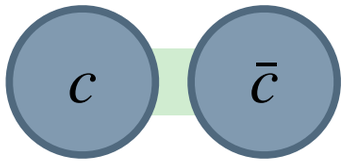
K^+ (kaon)
$M \approx 494$ MeV



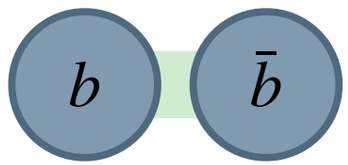
D^+ (D meson)
$M \approx 1870$ MeV



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

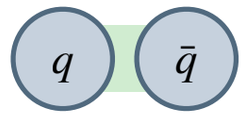


J/ψ (charmonium)
$M \approx 3097$ MeV

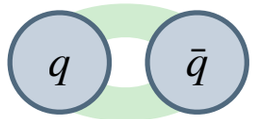


$\Upsilon(1S)$ (bottomonium)
$M \approx 9460$ MeV

MESONS

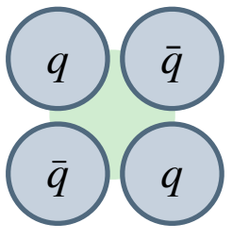


conventional meson

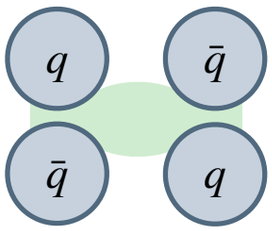


hybrid meson

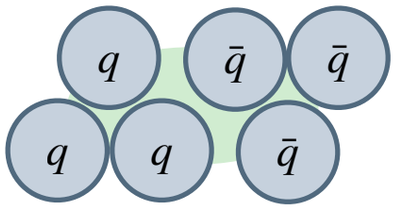
glueball



tetraquark



meson molecule

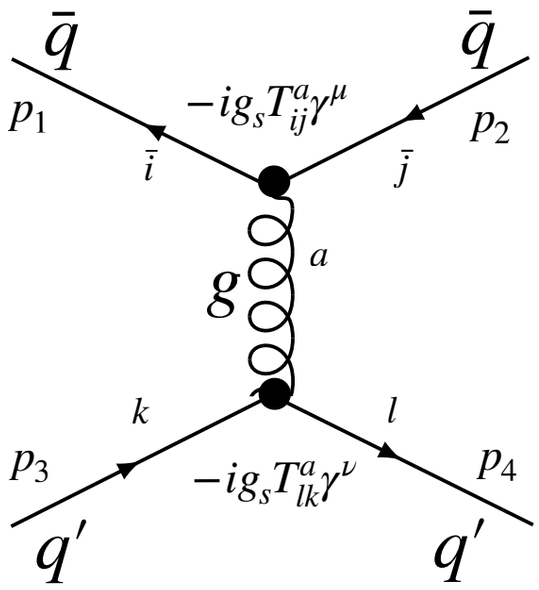


baryonium

I. What are Mesons?

Inside a meson:

Mesons are held together by the strong force, which is fundamentally due to quark-gluon and gluon-gluon interactions…



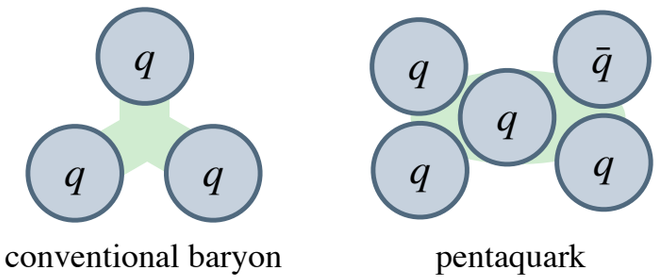
The theory of Quantum Chromodynamics (QCD) describes the strong force.

(It's probably the most complex corner of the Standard Model of particle physics.)

QUARKS

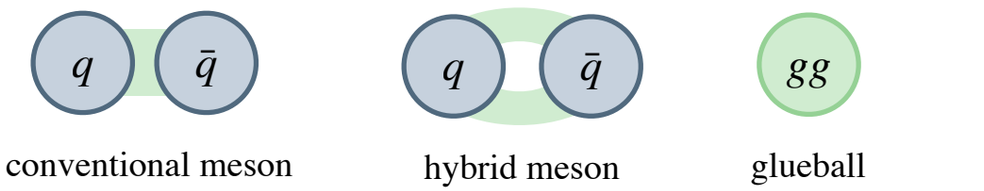
electric charge	generations I	II	III
$+\frac{2}{3}$	u (up)	c (charm)	t (top)
$-\frac{1}{3}$	d (down)	s (strange)	b (bottom)

BARYONS

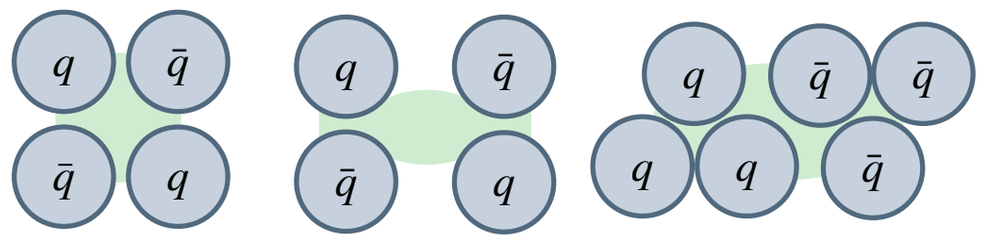


conventional baryon pentaquark

MESONS



conventional meson hybrid meson glueball



tetraquark meson molecule baryonium

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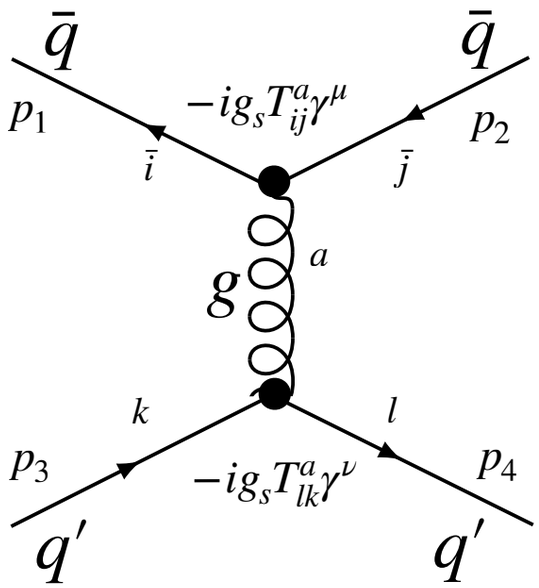

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QUARKS

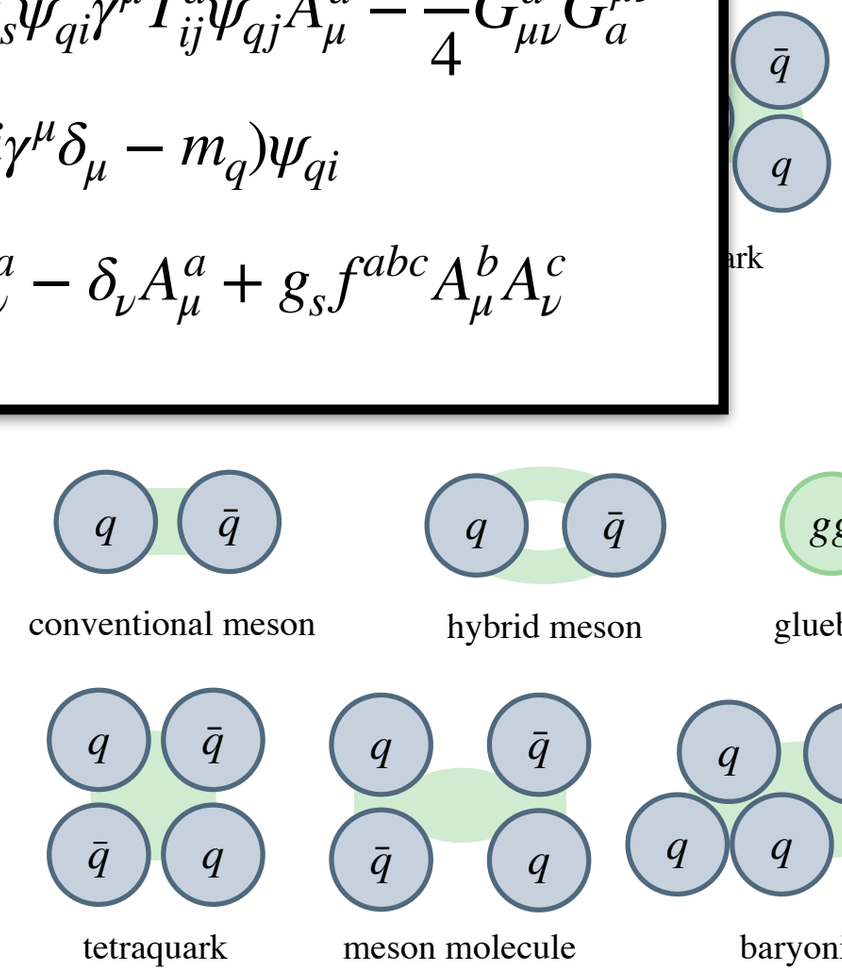
	generations I	II	III
$+\frac{2}{3}$	u (up)	c (charm)	t (top)
1	d	s	b (bottom)

QCD Lagrangian

$$\mathscr{L}_{\text{QCD}} = \mathscr{L}_0 - g_s \bar{\psi}_{qi}\gamma^\mu T^a_{ij}\psi_{qj}A^a_\mu - \frac{1}{4}G^a_{\mu\nu}G^{\mu\nu}_a$$

$$\mathscr{L}_0 = \bar{\psi}_{qi}(i\gamma^\mu\delta_\mu - m_q)\psi_{qi}$$

$$G^a_{\mu\nu} = \delta_\mu A^a_\nu - \delta_\nu A^a_\mu + g_s f^{abc}A^b_\mu A^c_\nu$$



I. What are Mesons?

Why are only certain combinations of quarks and gluons allowed?

Quarks and gluons interact via a "color charge" that follows SU(3) symmetry:

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

qqq: $3 \otimes 3 \otimes 3 = (6 \oplus \bar{3}) \otimes 3$

$= 10 \oplus 8 \oplus 8 \oplus 1$

The strong force is so strong that only "colorless" (color singlet) objects appear in nature.

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

electric charge	generations I	II	III
$+\frac{2}{3}$	u (up)	c (charm)	t (top)
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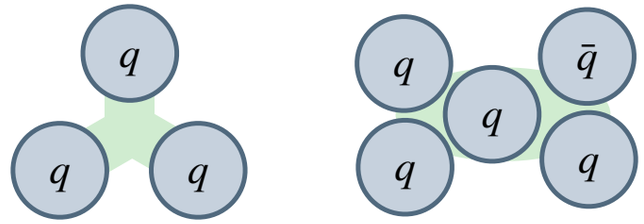
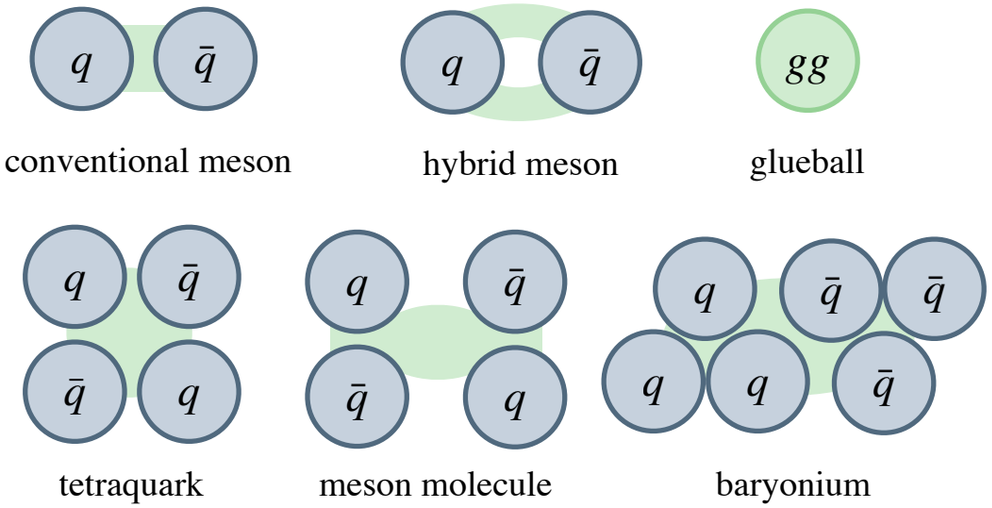
BARYONS



conventional baryon pentaquark

MESONS



conventional meson hybrid meson glueball

tetraquark meson molecule baryonium

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The strong force is so strong that only "colorless" (color singlet) objects appear in nature.

state	color	size
$q\bar{q}$	**1**	$-4/3$
$q\bar{q}$	**8**	$+1/6$
qq	$\bar{\mathbf{3}}$	$-2/3$
qq	**6**	$+1/3$

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

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QUARKS

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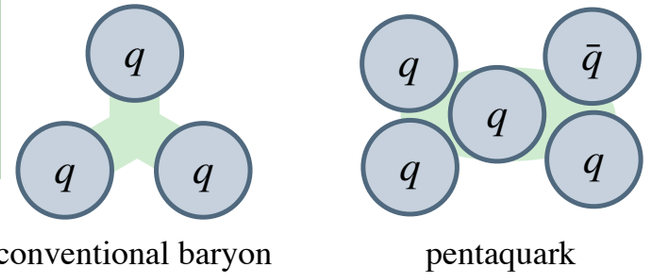
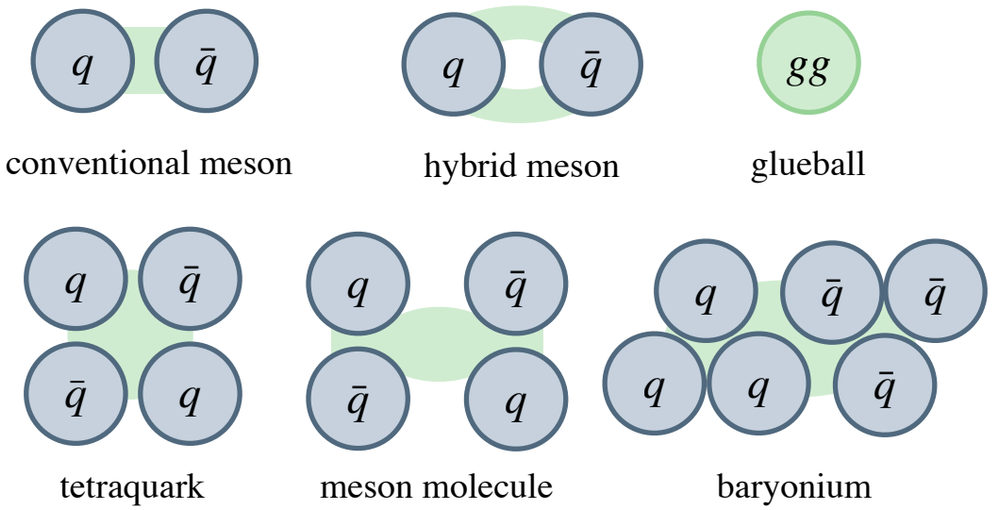


conventional baryon pentaquark

MESONS



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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?

II. Families of Mesons

QUARKS

ANTIQUARKS	d	u	s	c	b
$\bar{d}$					
$\bar{u}$					
$\bar{s}$					
$\bar{c}$					
$\bar{b}$					

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^+	$\eta \mid \eta' \diagup \phi$	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

II. Families of Mesons

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$\bar{b}$	B^0	B^+	B_s^0	B_c^+	Υ

K^+ family
(weak decays, no mixing)

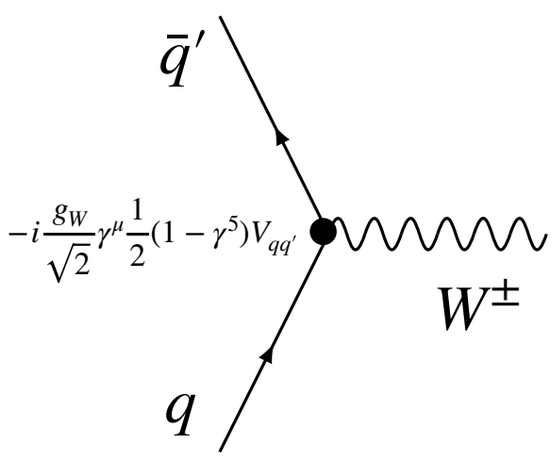
K^0 family
(weak decays, mixing)

π^0 family
(large electromagnetic decays)

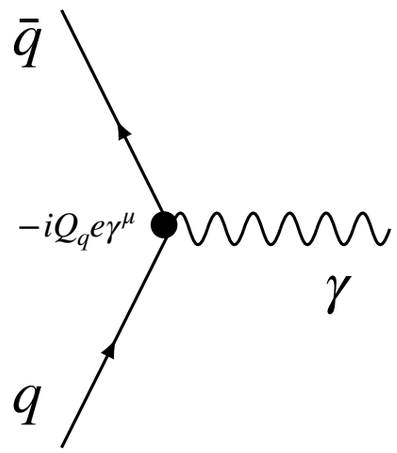
J/ψ family
(strong decays, near or below open flavor threshold)

Meson properties are largely dictated by how they decay.

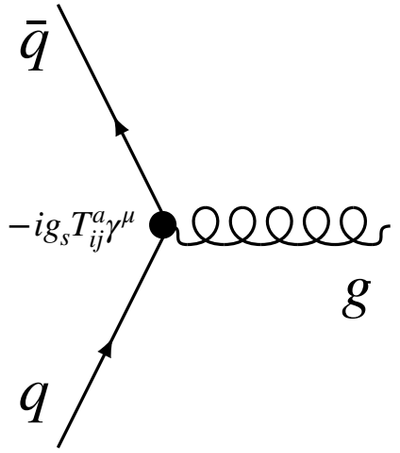
WEAK



ELECTROMAGNETIC



STRONG



II. Families of Mesons

QUARKS

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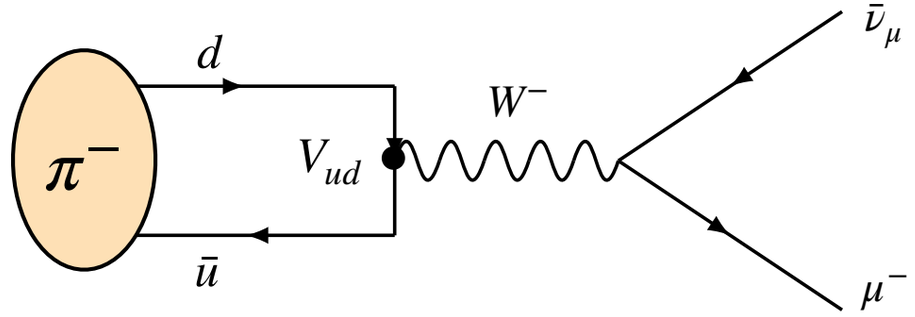
$\bar{b}$	B^0	B^+	B_s^0	B_c^+	Υ

Decays via the weak force are slow:



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

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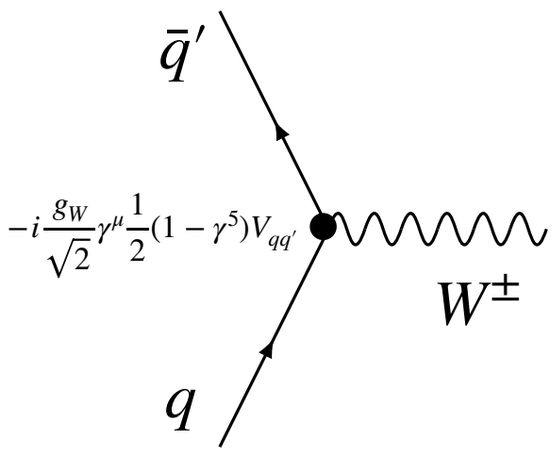

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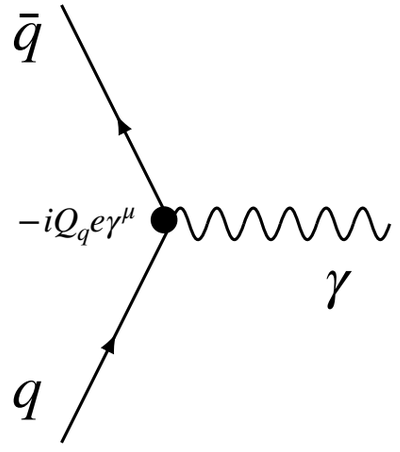

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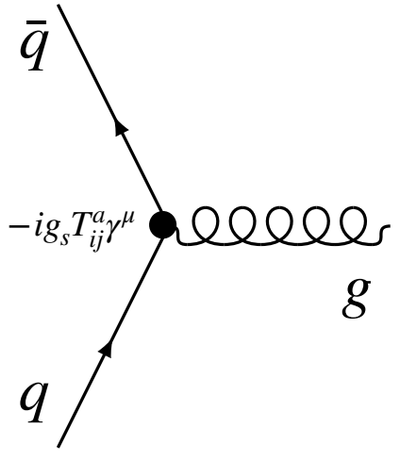

II. Families of Mesons

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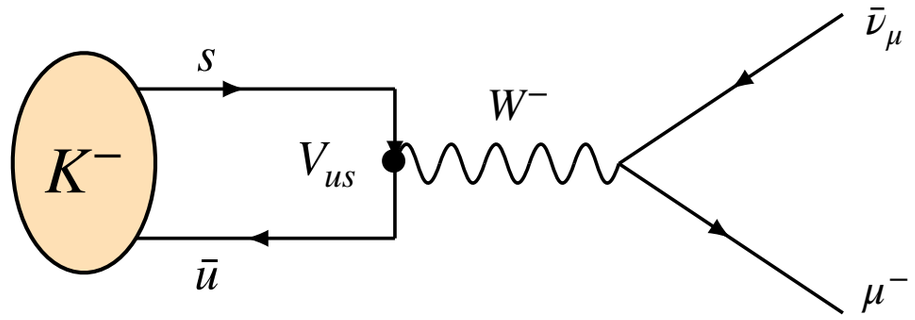

$\tau_K = 1.2 \times 10^{-8}$ s $\qquad c\tau_K = 3.7$ m

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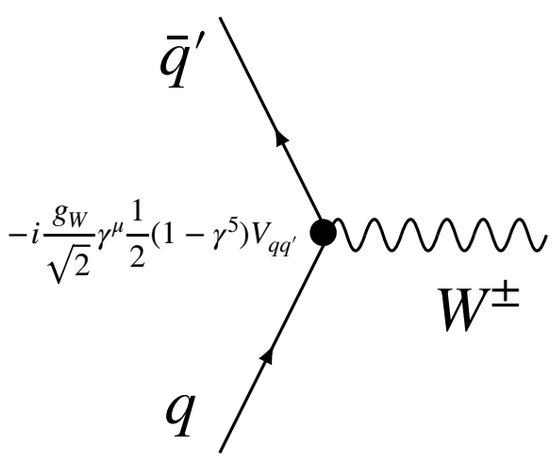
WEAK



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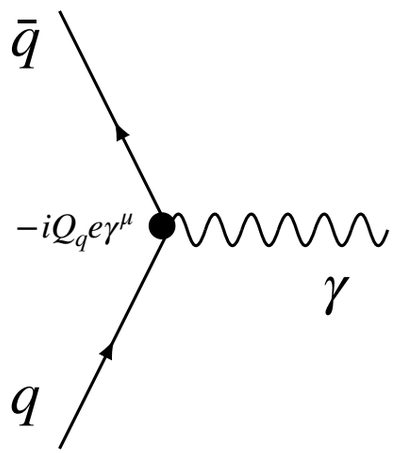

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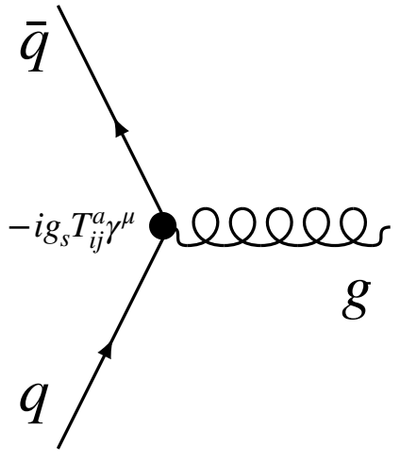


II. Families of Mesons

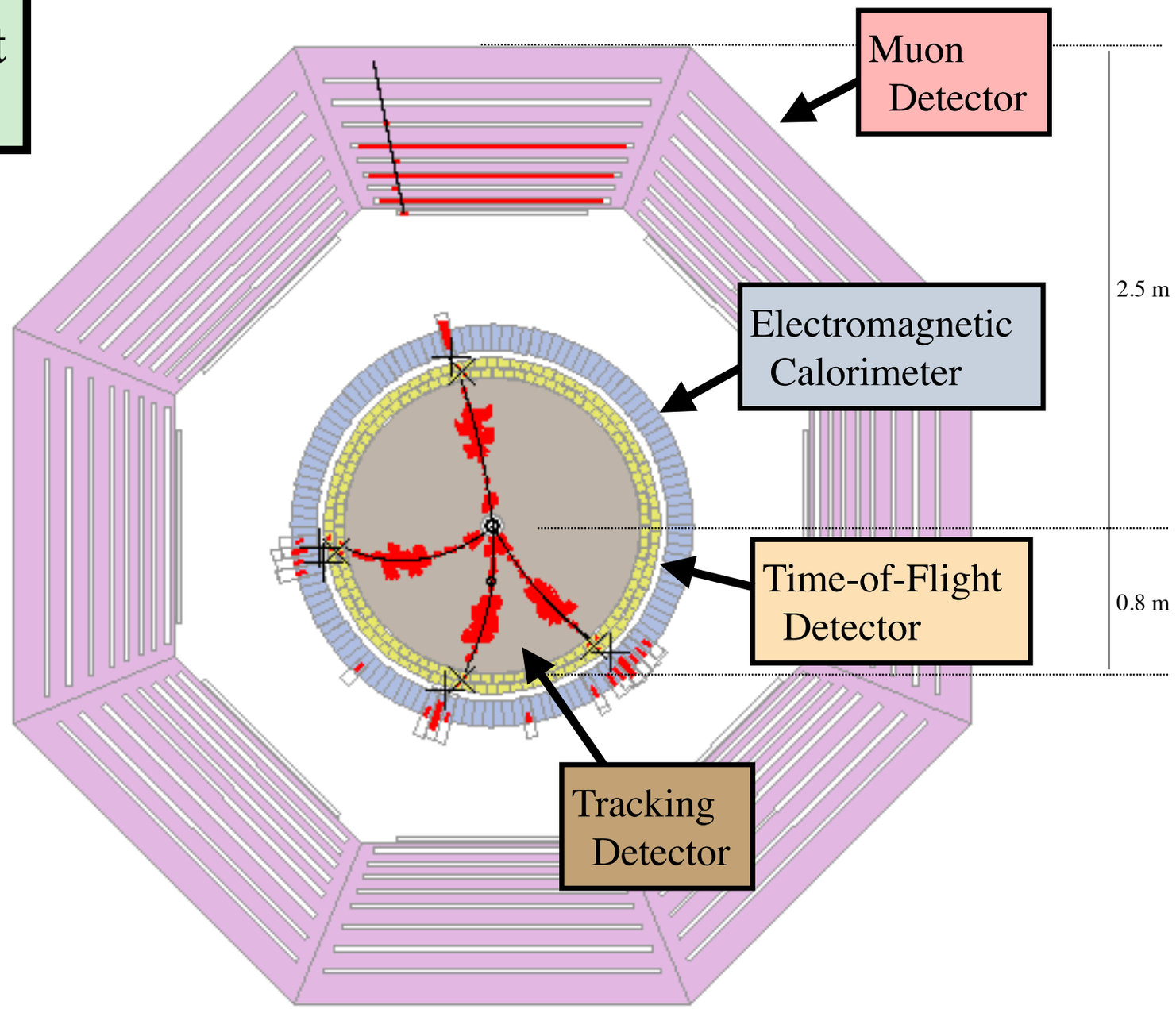
BESIII Experiment

(Beijing, China)

Event display for:

$e^+e^- \to K^+K^-\pi^+\pi^-$

at $E_{CM} \approx 3.7$ GeV



II. Families of Mesons

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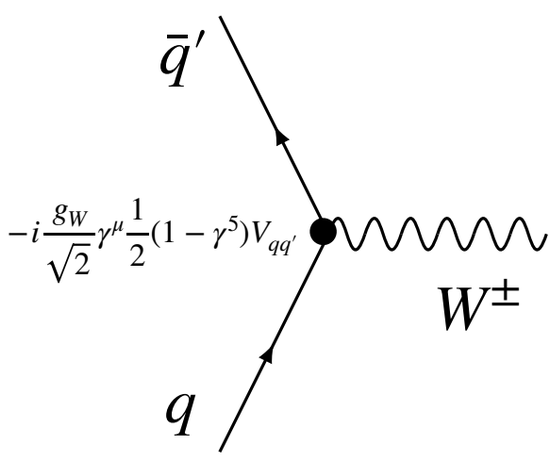
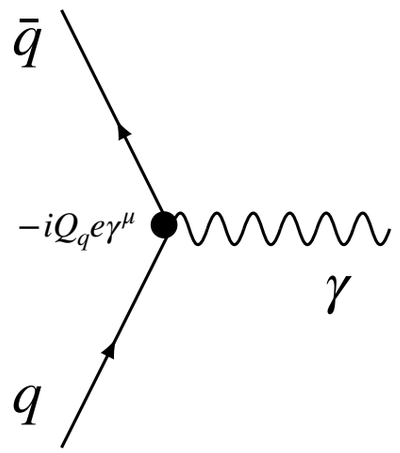


ELECTROMAGNETIC



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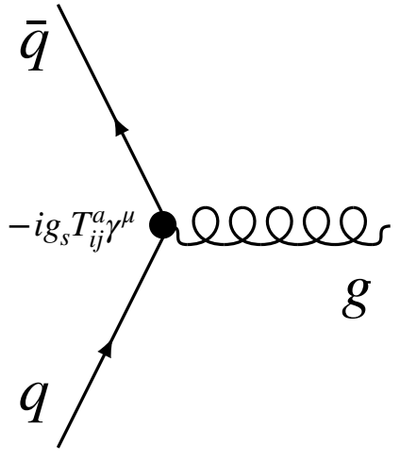

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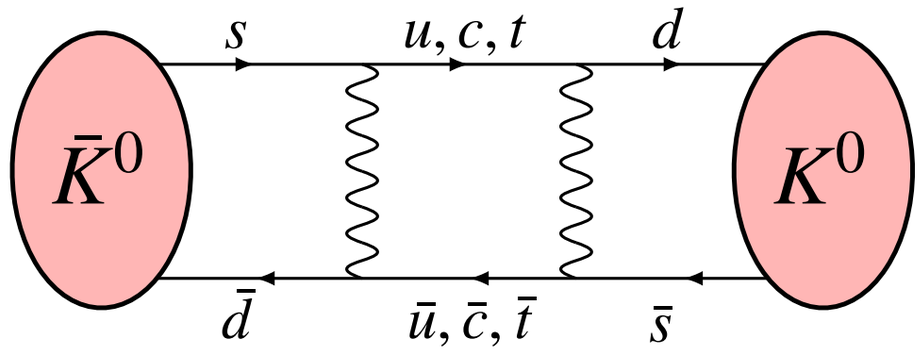
$\bar{b}$	B^0	B^+	B_s^0	B_c^+	Υ

The weak force can cause oscillations:



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

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

Meson properties are largely dictated by how they decay.

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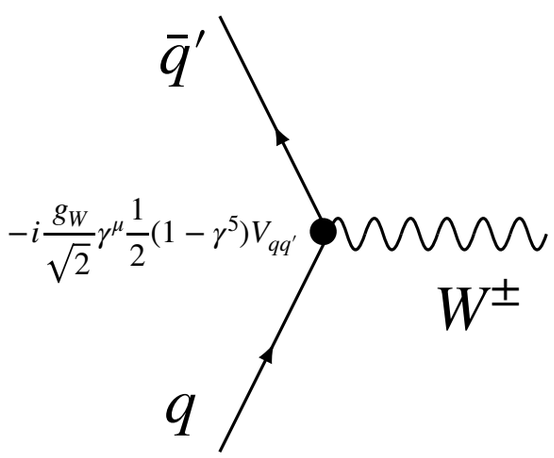

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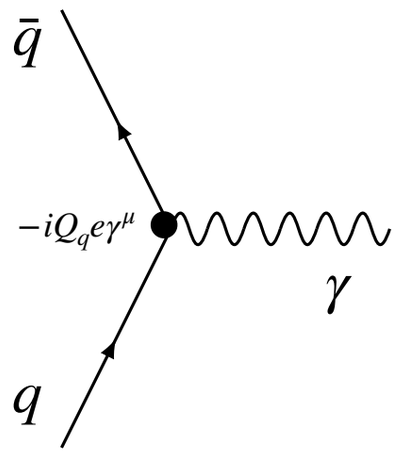

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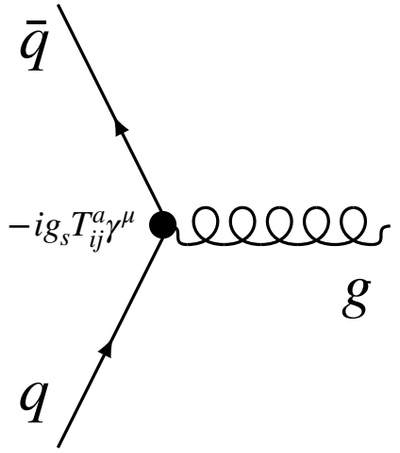

II. Families of Mesons

QUARKS

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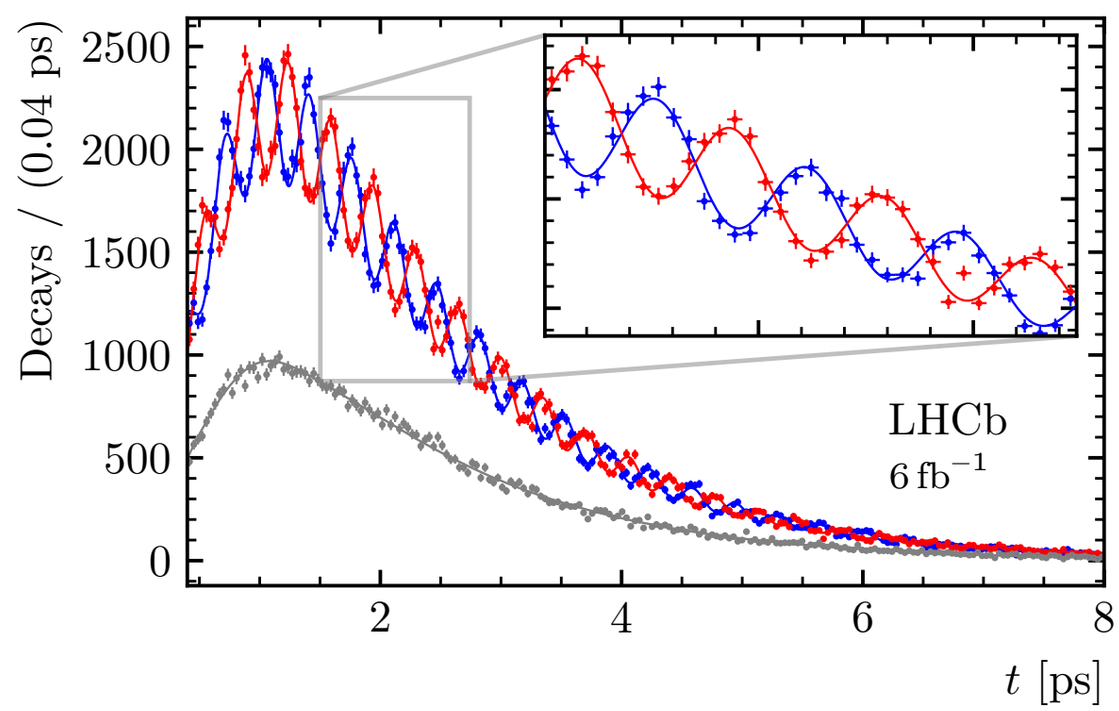
$\bar{d}$	$\pi^0 \mid \eta \mid \eta'$	π^+	$\bar{K}^0$	
$\bar{u}$	π^-	$\pi^0 \mid \eta \mid \eta'$	K^-	
$\bar{s}$	K^0	K^+	$\eta \mid \eta'$ / ϕ	
$\bar{c}$	D^-	$\bar{D}^0$	D_s^-	
$\bar{b}$	B^0	B^+	B_s^0	

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

LHCb, Nature Physics 18, 1 (2022)



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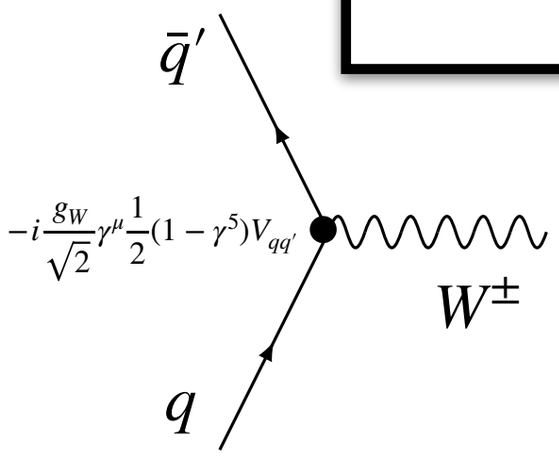
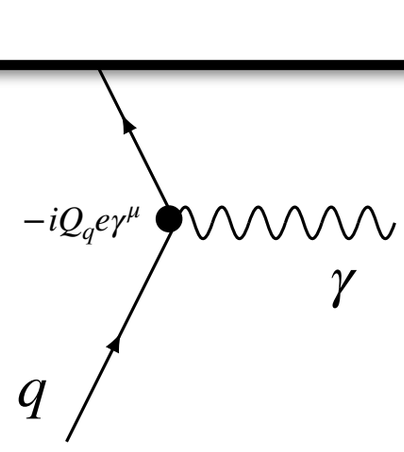
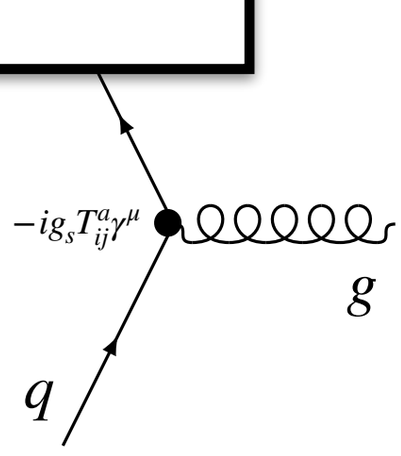
Meson properties are largely dictated by how they decay.







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)

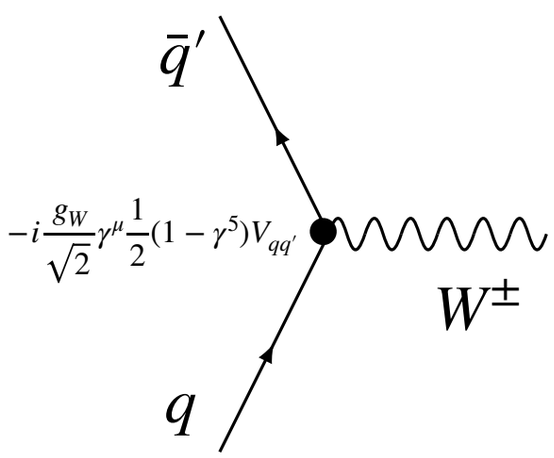
K^0 family
(weak decays, mixing)

π^0 family
(large electromagnetic decays)

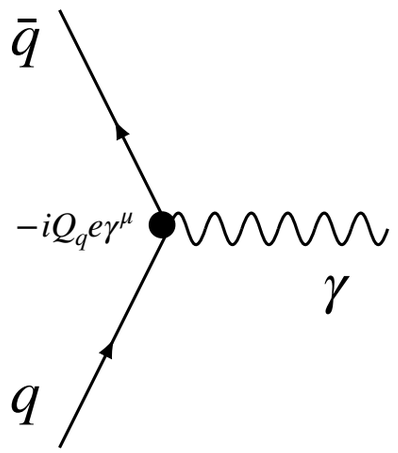
J/ψ family
(strong decays, near or below open flavor threshold)

Meson properties are largely dictated by how they decay.

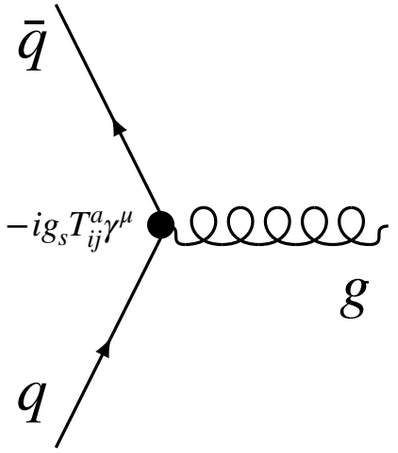
WEAK



ELECTROMAGNETIC



STRONG

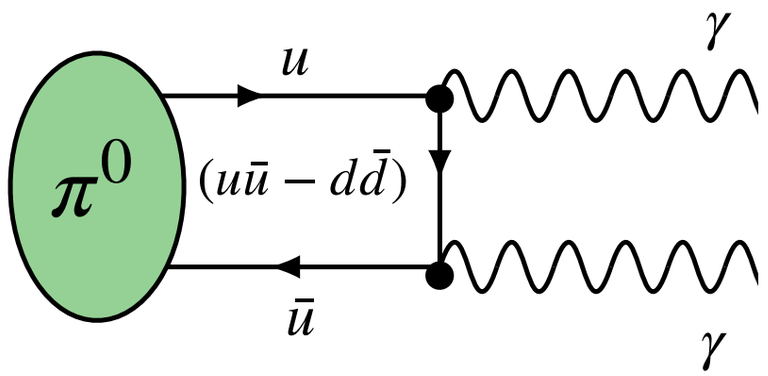


II. Families of Mesons

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^+	$\eta \mid \eta' \;/\; \phi$	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

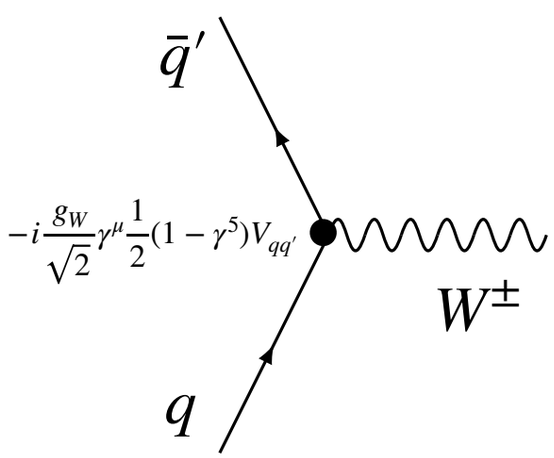
Decays via the electromagnetic force are less slow:



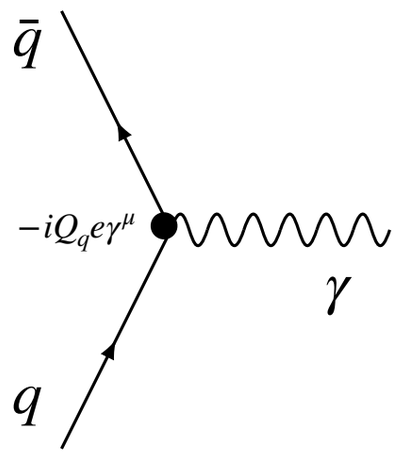
$\tau_{\pi^0} = 8.5 \times 10^{-17}$ s $\qquad c\tau_{\pi^0} = 26$ nm

Meson properties are largely dictated by how they decay.

WEAK



ELECTROMAGNETIC



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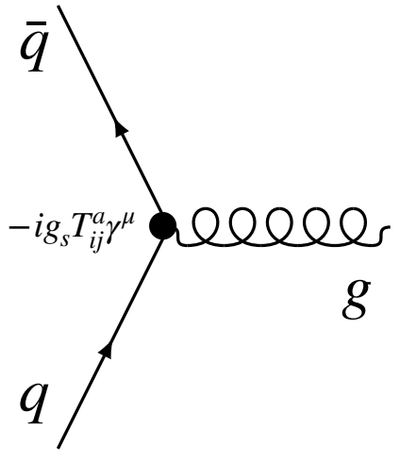


II. Families of Mesons

QUARKS

ANTIQUARKS

BESIII Experiment

(Beijing, China)

Event display for:

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

with:

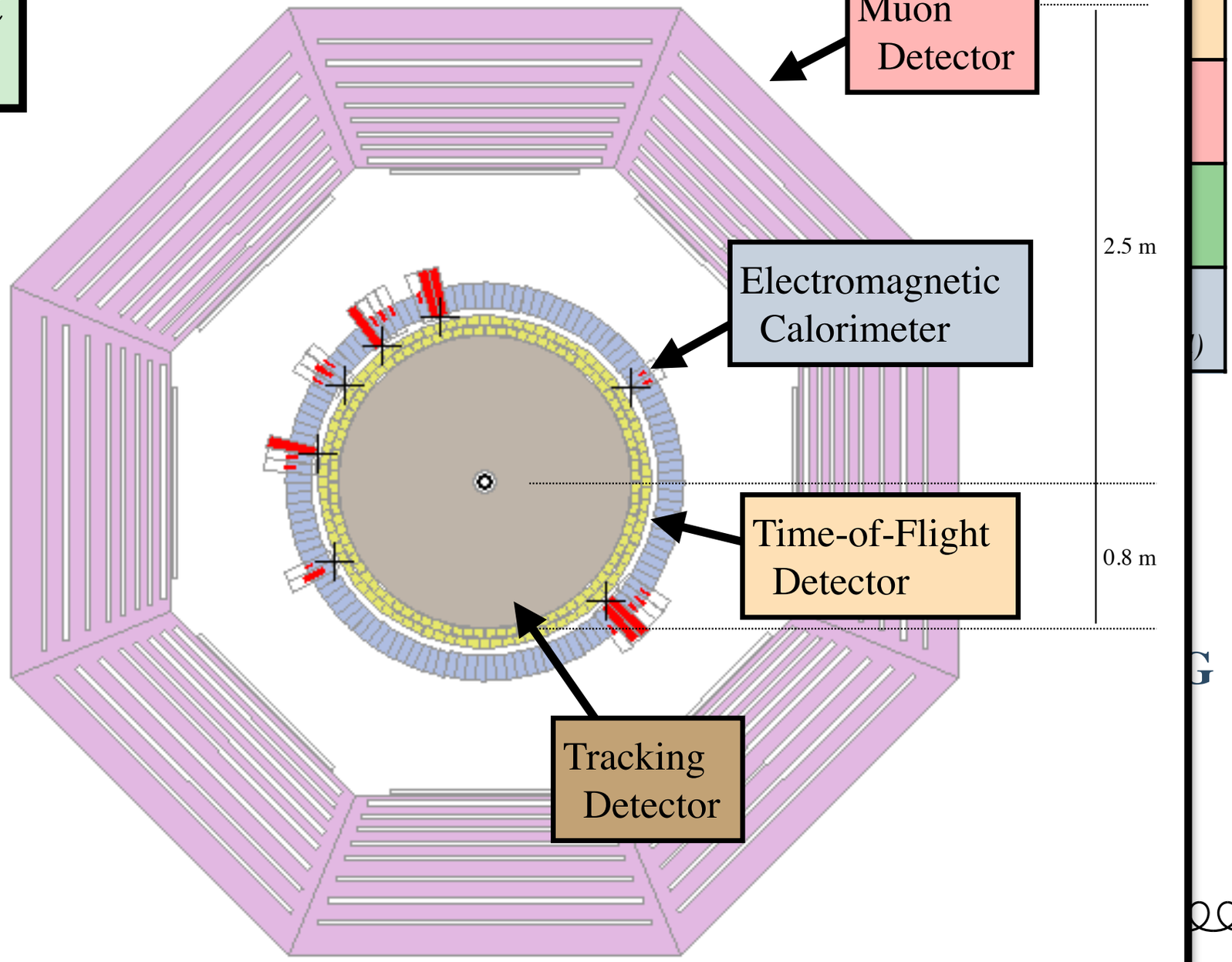
$J/\psi \to \gamma\eta'$

$\eta' \to \eta\pi^0\pi^0$

$\eta \to \gamma\gamma$

$\pi^0 \to \gamma\gamma$

(total of 7γ)



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II. Families of Mesons

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(Beijing, China)

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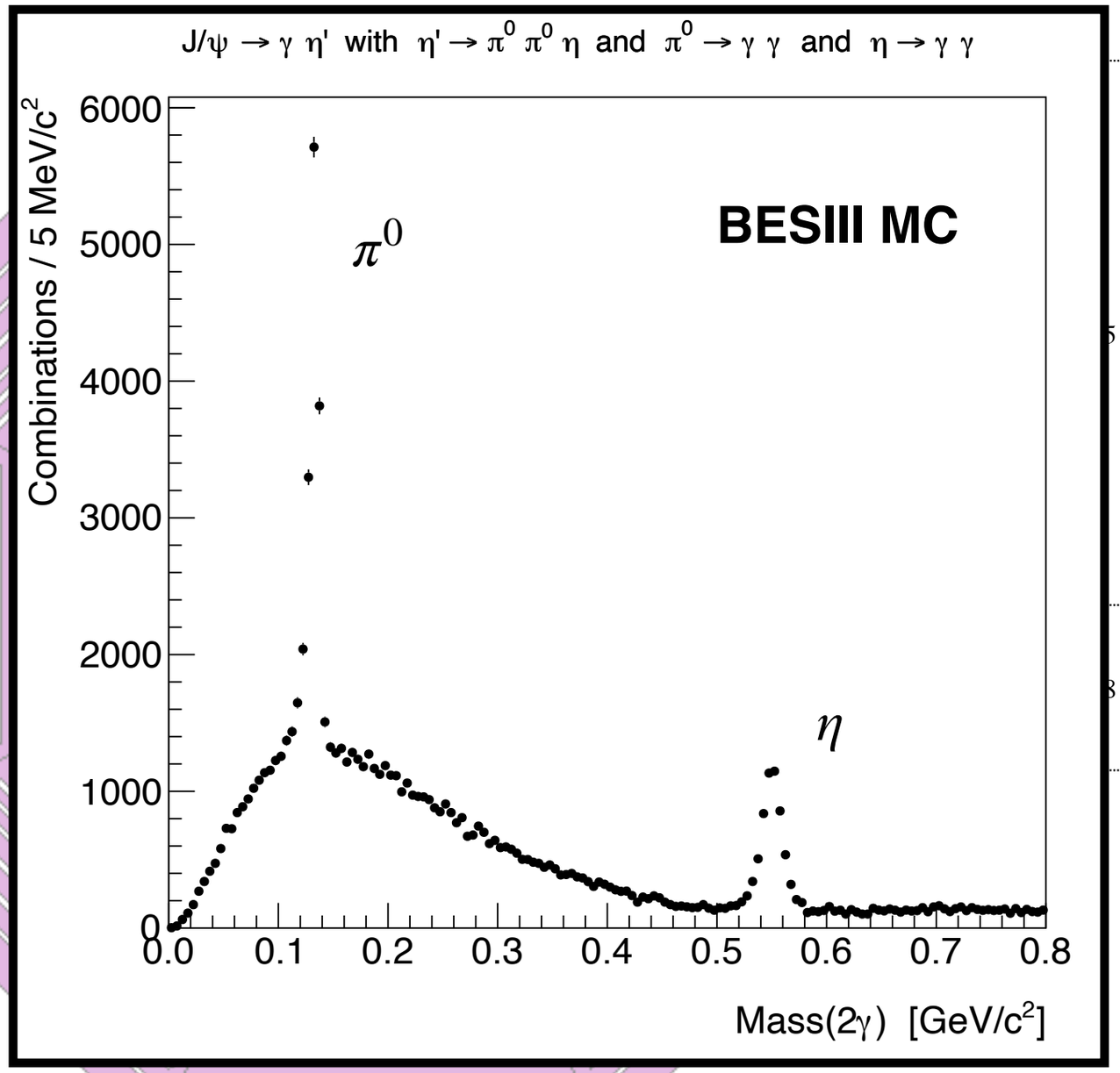
$\eta \to \gamma\gamma$

$\pi^0 \to \gamma\gamma$

(total of 7γ)



II. Families of Mesons

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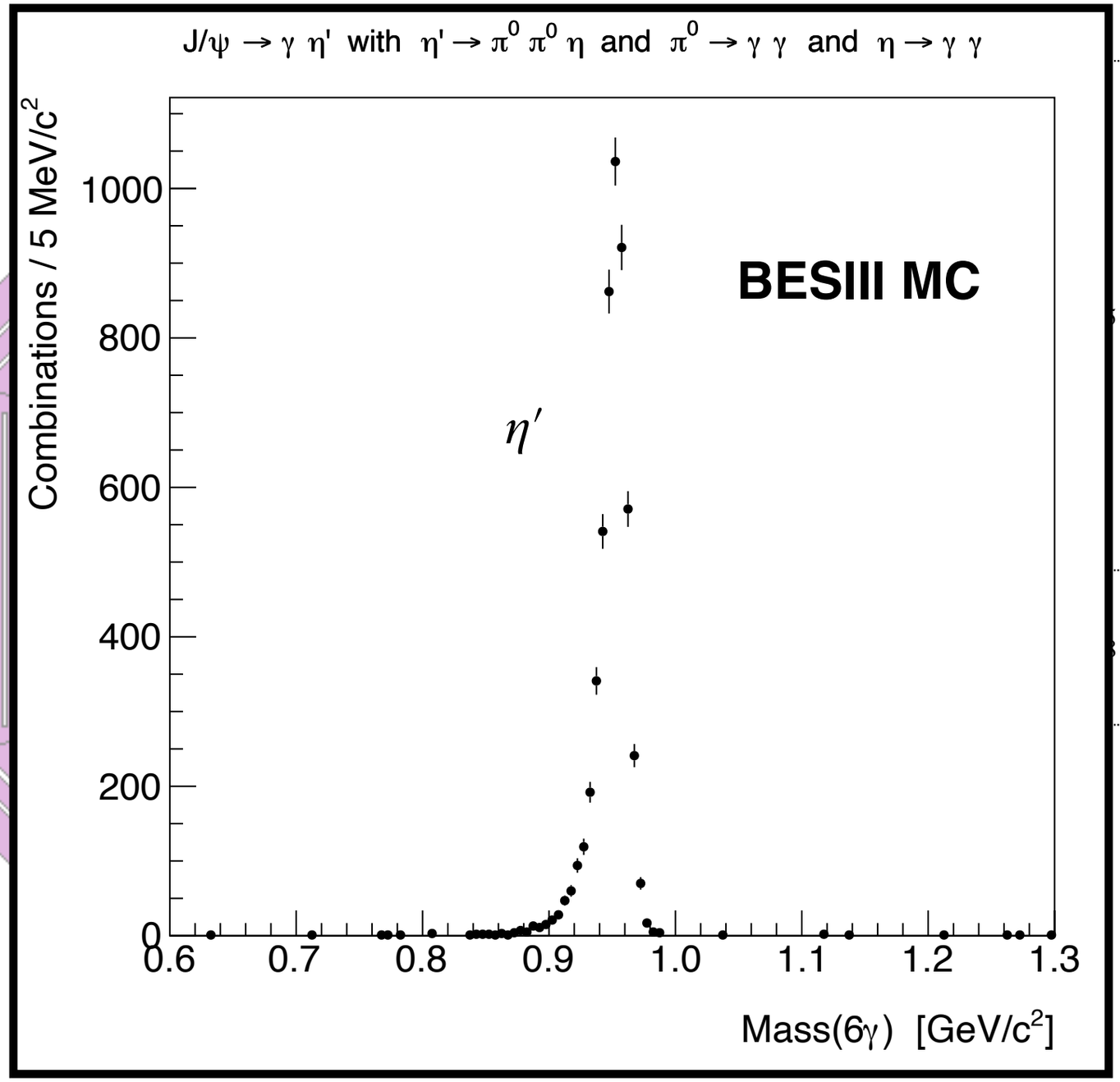
(total of 7γ)



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)

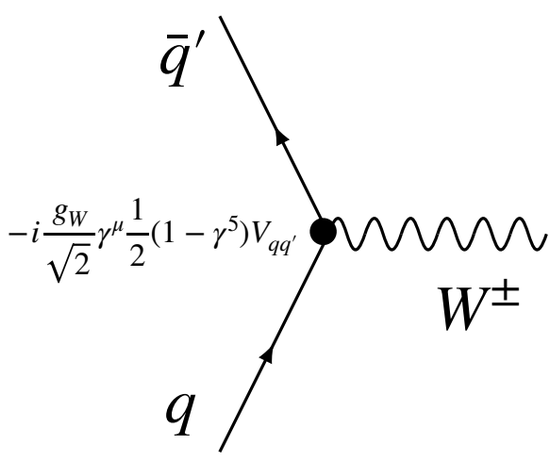
K^0 family
(weak decays, mixing)

π^0 family
(large electromagnetic decays)

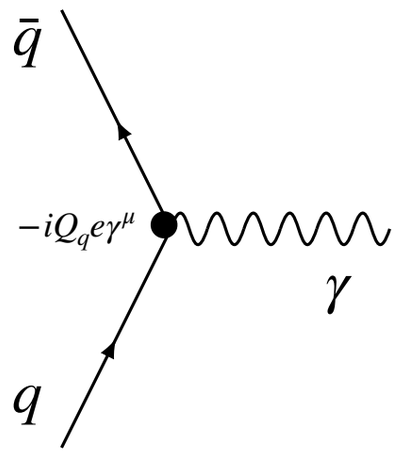
J/ψ family
(strong decays, near or below open flavor threshold)

Meson properties are largely dictated by how they decay.

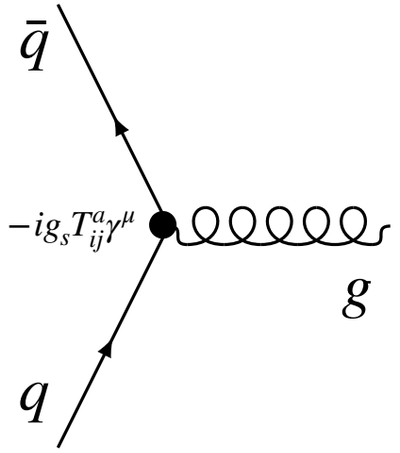
WEAK



ELECTROMAGNETIC



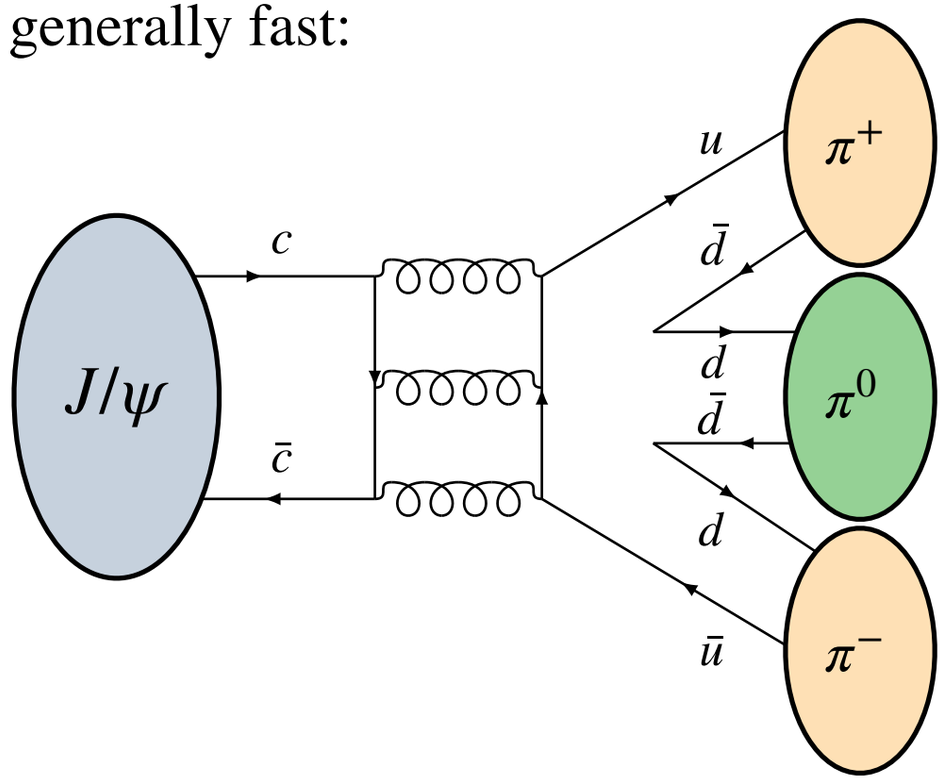
STRONG



II. Families of M

ANTIQUARKS \ QUARKS	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

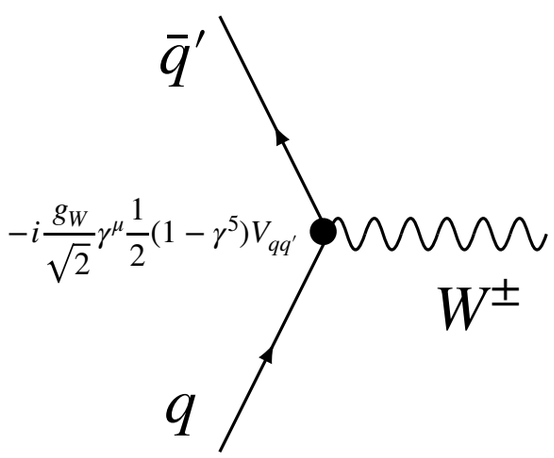
Decays via the strong force are generally fast:



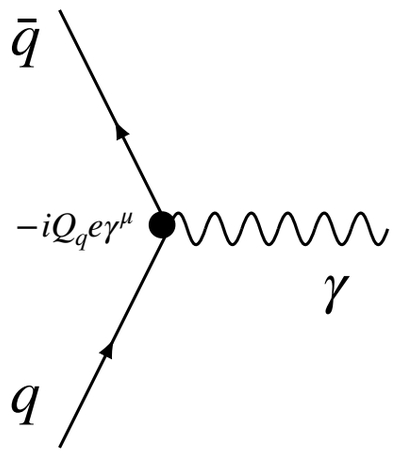
$\tau_{J/\psi} = 7.1 \times 10^{-21}$ s $\quad c\tau_{J/\psi} = 2.1$ pm

Meson properties are largely dictated by how they decay.

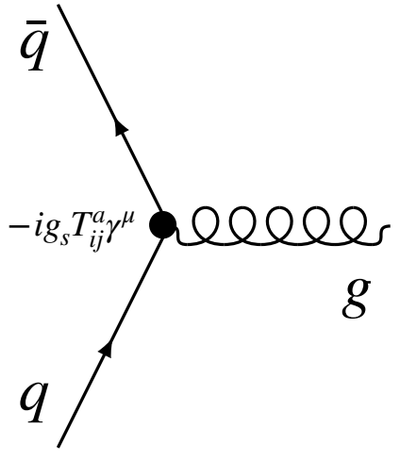
WEAK



ELECTROMAGNETIC



STRONG



II. Families of M

Decays via the strong force are generally fast:

QUARKS

ANTIQUARKS

BESIII Experiment

(Beijing, China)

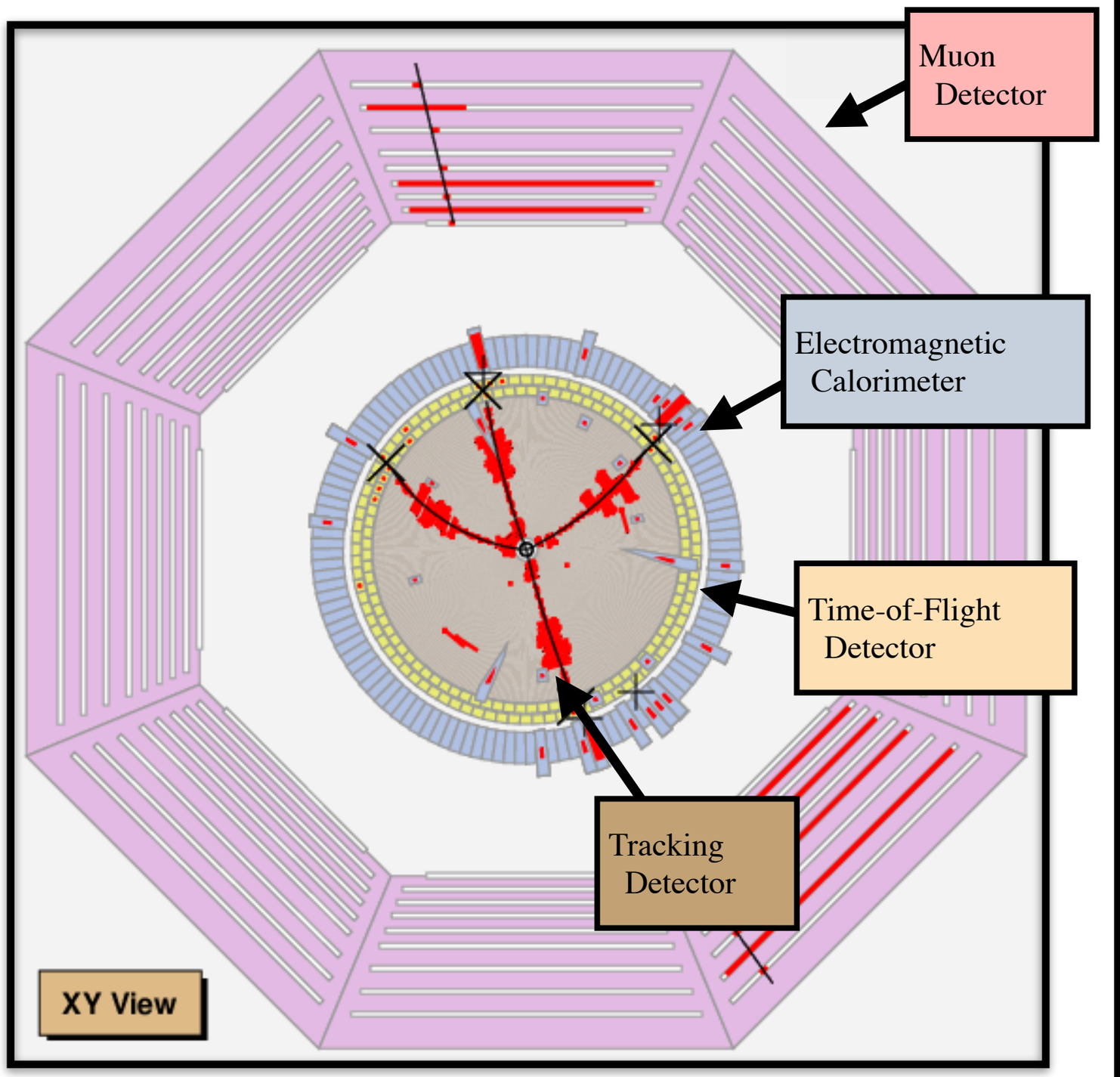
Event display for:

$e^+e^- \to ??$

with:

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

$J/\psi \to \mu^+\mu^-$



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II. Families of M

Decays via the strong force are generally fast:

QUARKS

ANTIQUARKS

BESIII Experiment

(Beijing, China)

Event display for:

$e^+e^- \to ??$

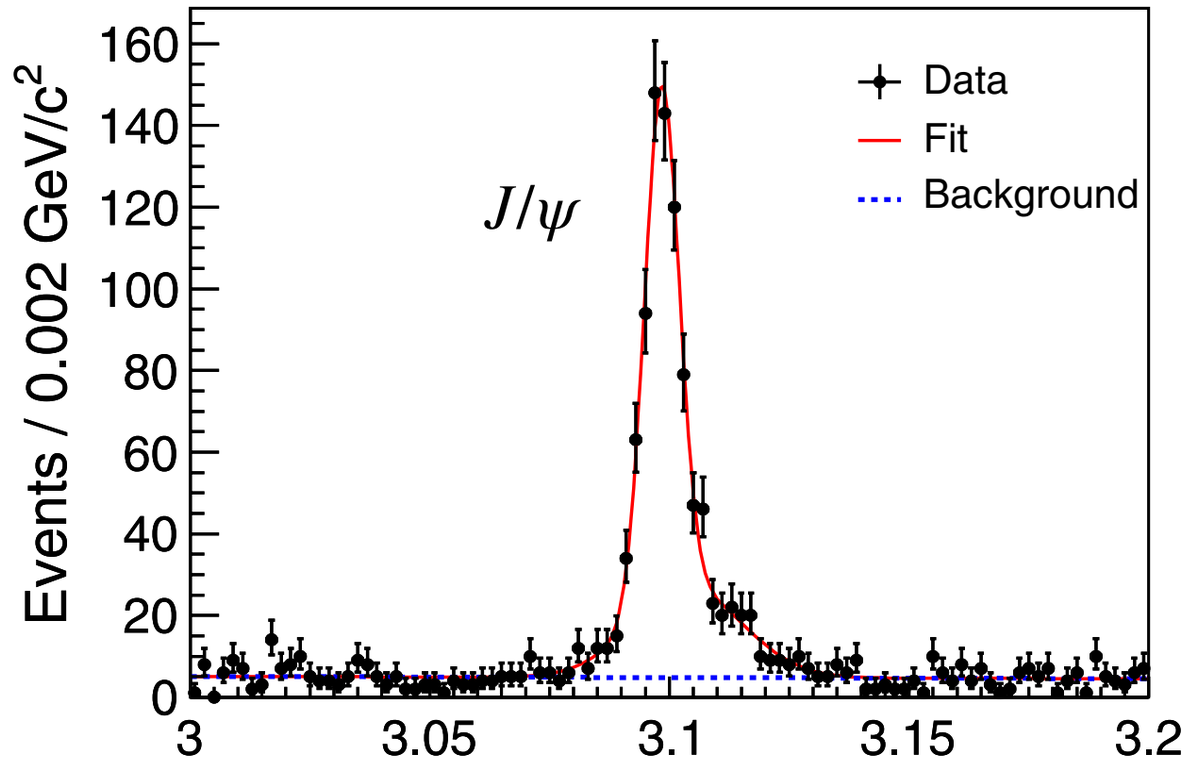
with:

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

$J/\psi \to \mu^+\mu^-$

Muon Detector

BESIII, PRL110, 252001 (2013)



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

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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)

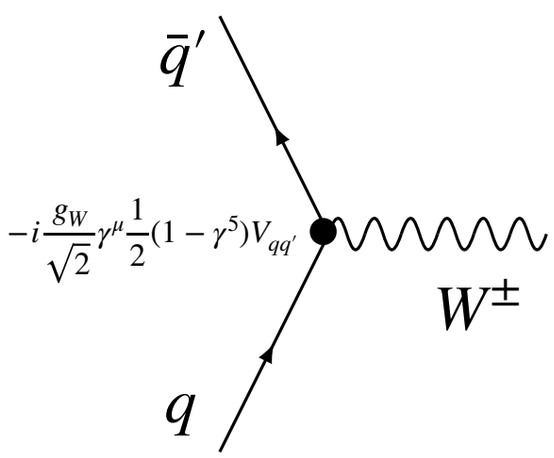
K^0 family
(weak decays, mixing)

π^0 family
(large electromagnetic decays)

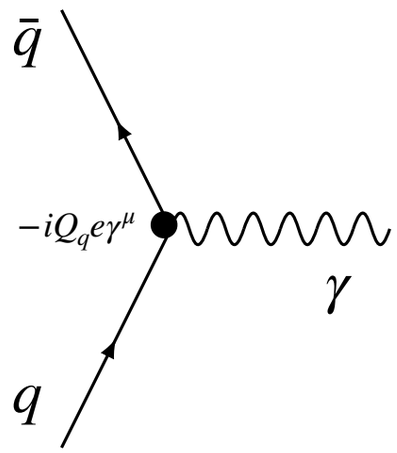
J/ψ family
(strong decays, near or below open flavor threshold)

Meson properties are largely dictated by how they decay.

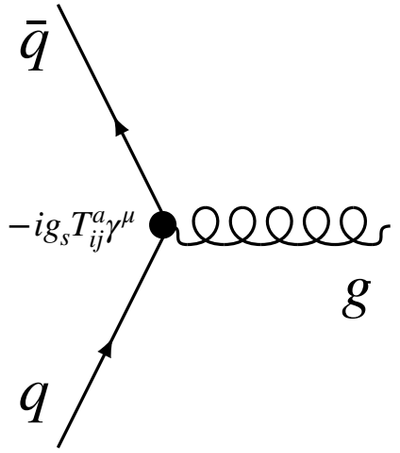
WEAK



ELECTROMAGNETIC



STRONG



II. Families of Mesons

QUARKS

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$\bar{d}$	$\pi^0 \mid \eta \mid \eta'$	π^+	$\bar{K}^0$	D^+	$\bar{B}^0$
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$\bar{s}$	K^0	K^+	$\eta \mid \eta' \mid \phi$	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}
$0^{-(+)}$	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*

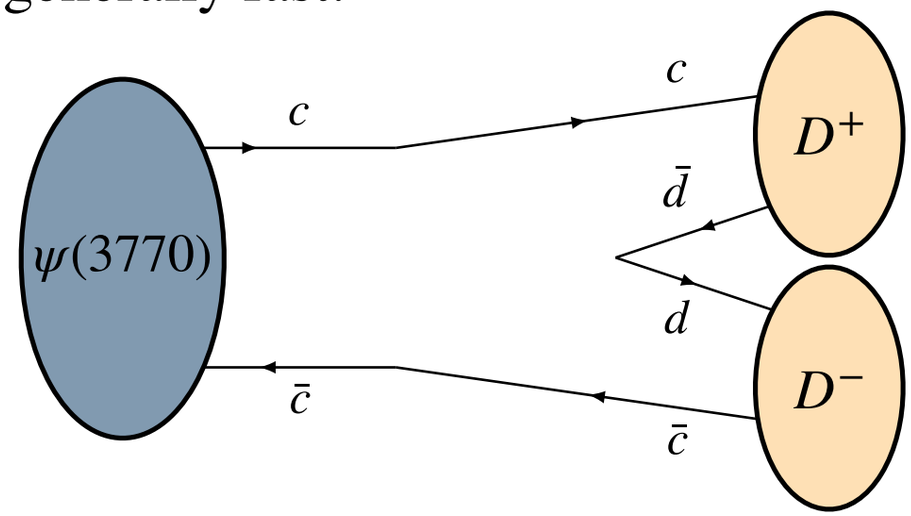
For a $q\bar{q}'$ meson: $\vec{J} = \vec{L} + \vec{S}$ and $P = (-1)^{L+1}$ and $C = (-1)^{L+S}$

II. Families of M

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 strong force are generally fast:



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

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

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

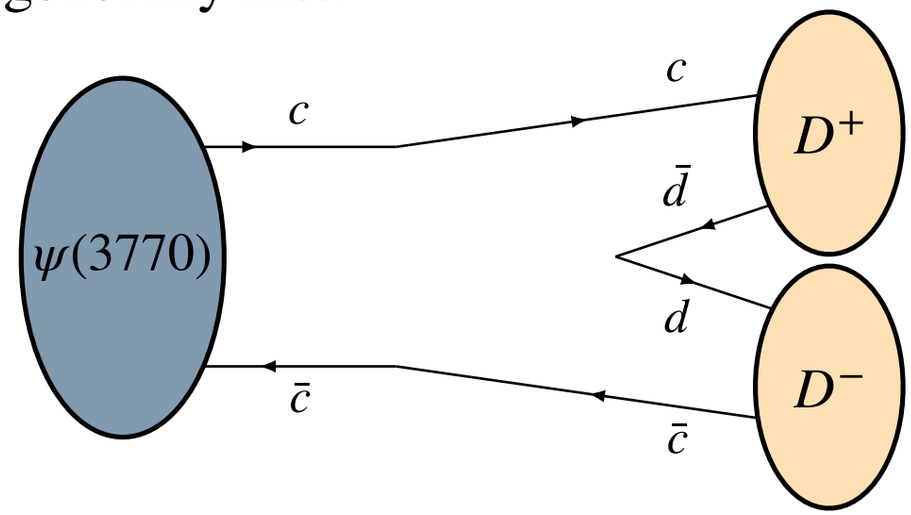
$J^{P(C)}$	$u\bar{d},\ u\bar{u},\ d\bar{d},\ s\bar{s}$			$c\bar{c}$	$b\bar{b}$	$d\bar{s}, u\bar{s}$	$c\bar{u}, c\bar{d}$		$c\bar{s}$	$d\bar{b}, u\bar{b}$	$s\bar{b}$
$1^{-(-)}$	$\rho(1700)$	$\omega(1650)$	$\phi(1680)$	$\psi(3770)$	$\Upsilon(4S)$	$K^*(1680)$			$D_{s1}^*(2700)^+$		
$2^{+(+)}$	$a_2(1320)$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

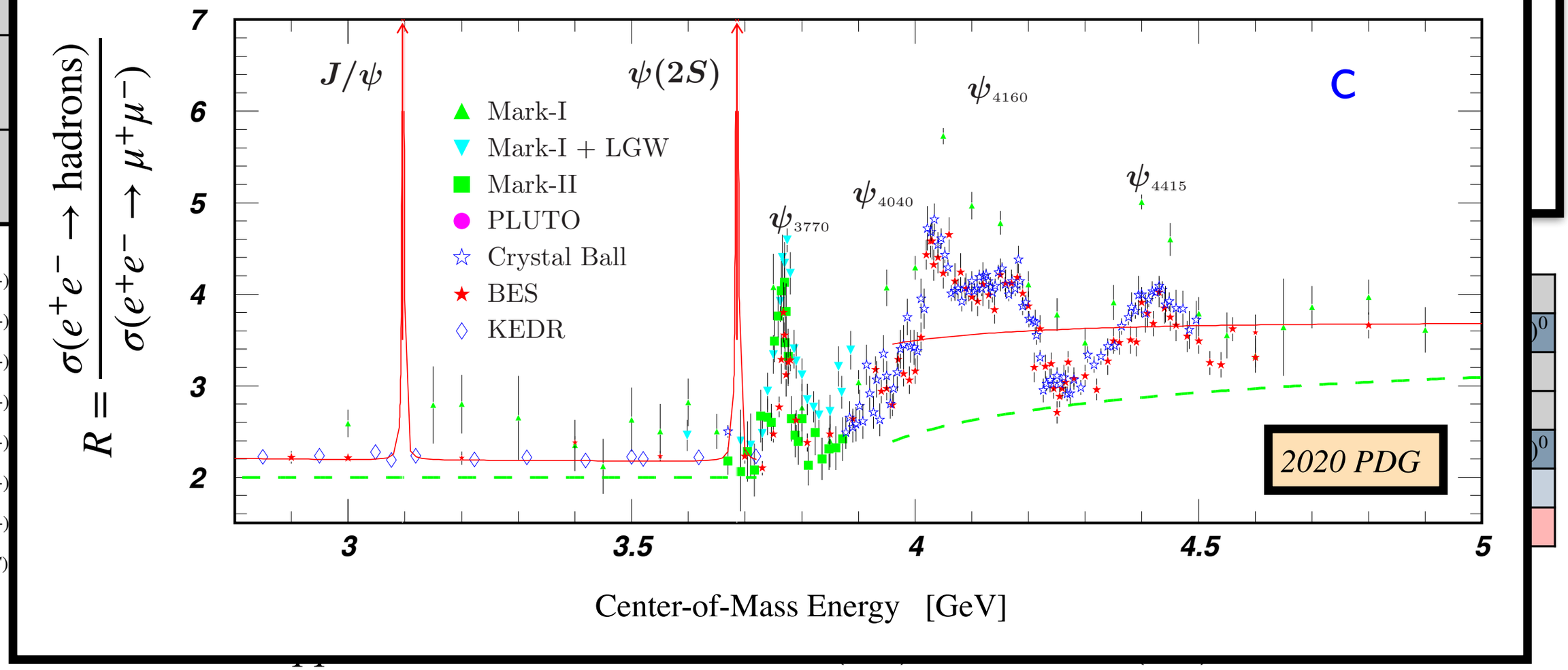
II. Families of M

Decays via the strong force are generally fast:



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^-
			$\eta \mid \eta'$		



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}
$0^{-(+)}$	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

ANTIQUARKS \ QUARKS	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}
$0^{-(+)}$	π^0	π^+	$\eta \mid \eta'$	$\eta_c(1S)$	$\eta_b(1S)$	K^0	K^+	D^0	D^+	D_s^+	B^0	B^+	B_s^0

excited states ↑ *ground state*

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

II. Families of Mesons

QUARKS

ANTIQUARKS

BESIII Experiment

(Beijing, China)

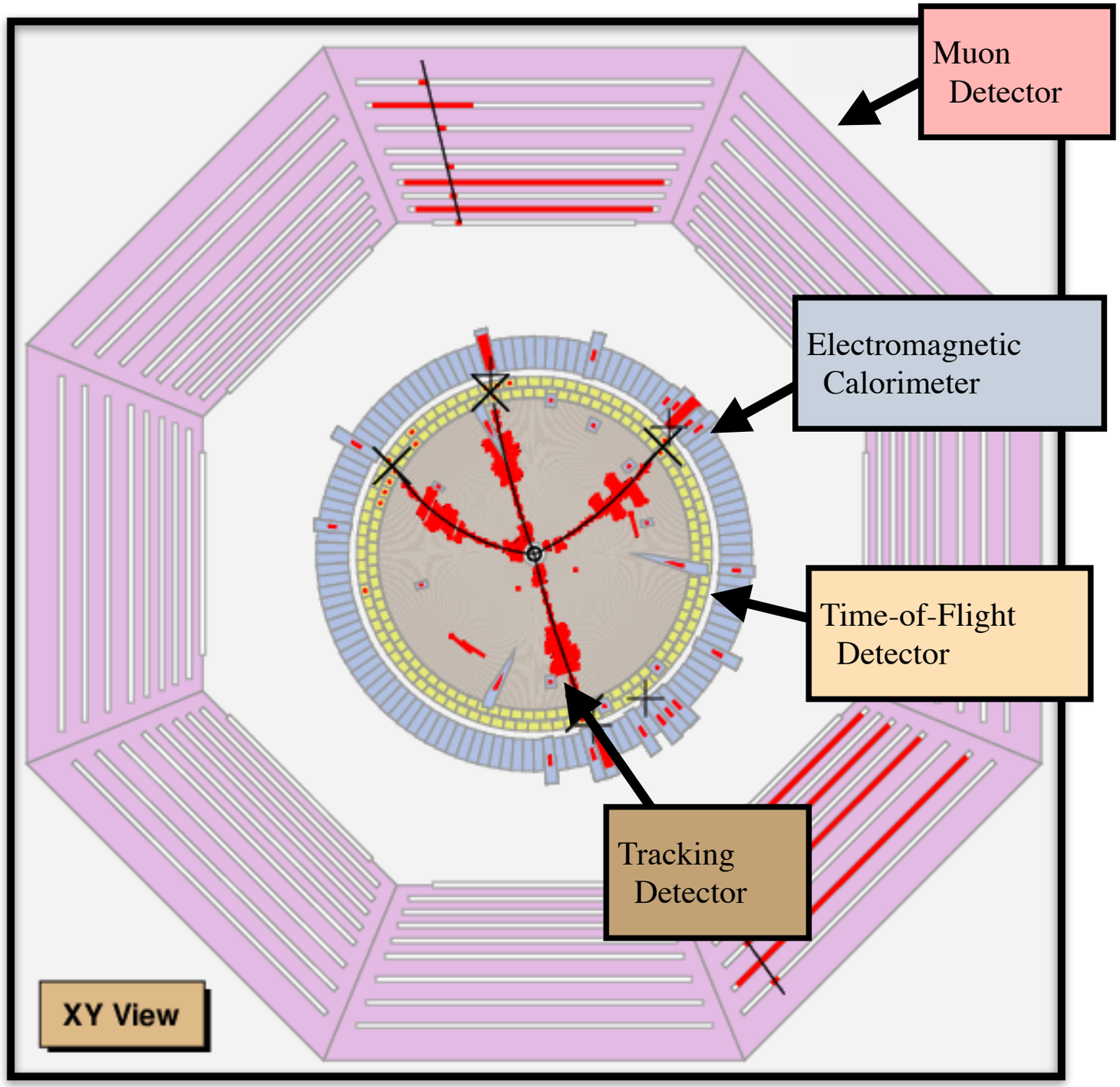
Event display for:

$e^+e^- \to ??$

with:

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

$J/\psi \to \mu^+\mu^-$



excited states

ground state

J^P

sb

$(5840)^0$

$(5830)^0$

B_s^{*0}

B_s^0

$Z_c(3900)^+ \to \pi^+ J/\psi$	$Z_{cs}(4000)^+ \to K^+ J/\psi$	$Z_b(10610)^+ \to \pi^+ h_b, \pi^+ \Upsilon$	$T_{cc\bar{c}\bar{c}}(6900) \to J/\psi J/\psi$

II. Families of Mesons

QUARKS

ANTIQUARKS

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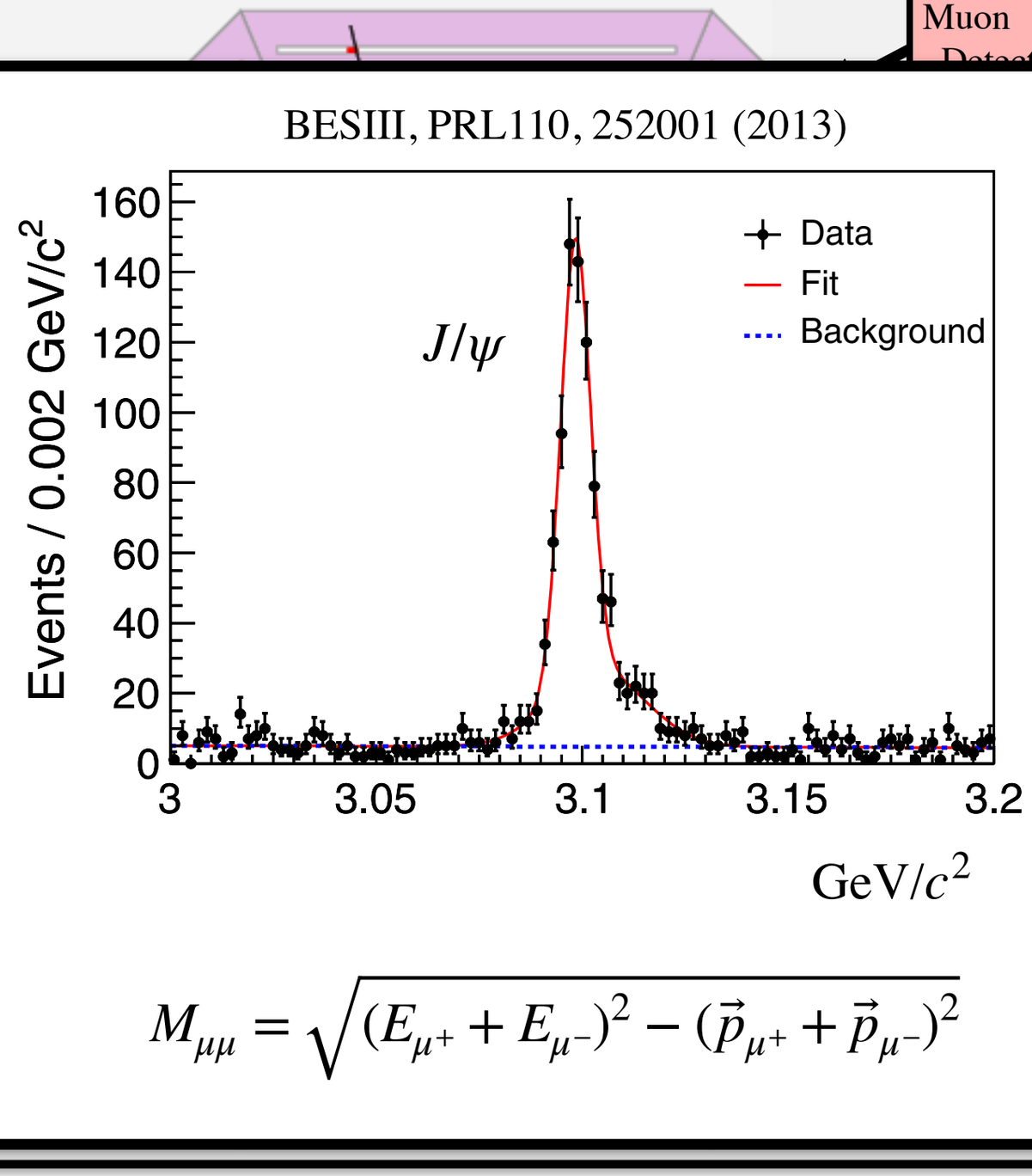
Event display for:

$e^+e^- \to ??$

with:

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

$J/\psi \to \mu^+\mu^-$



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

excited states

ground state

$J^{P(}$

$1^{-(}$ $2^{+(}$ $1^{+(}$ $0^{+(}$ $1^{+(}$ $1^{-(}$ $0^{-(}$

$s\bar{b}$

$(5840)^0$

$(5830)^0$

B_s^{*0}

B_s^0

$Z_c(3900)^+ \to \pi^+ J/\psi$	$Z_{cs}(4000)^+ \to K^+ J/\psi$	$Z_b(10610)^+ \to \pi^+ h_b, \pi^+ \Upsilon$	$T_{cc\bar{c}\bar{c}}(6900) \to J/\psi J/\psi$

II. Families of Mesons

QUARKS

ANTIQUARKS

BESIII Experiment

(Beijing, China)

Event display for:

$e^+e^- \to ??$

with:

$?? \to \pi^\mp Z_c(3900)^\pm$

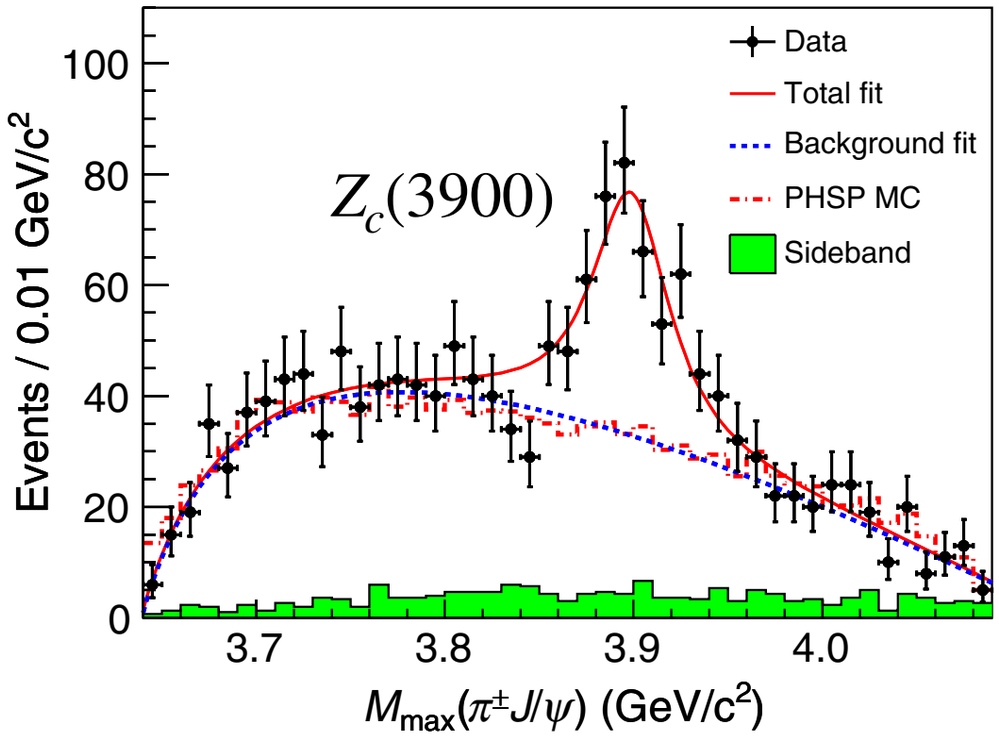
$Z_c(3900)^\pm \to \pi^\pm J/\psi$

$J/\psi \to \mu^+\mu^-$

Muon Detector

XY View

BESIII, PRL110, 252001 (2013)



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

excited states

ground state

J^P

1^- 2^+ 1^+ 0^+ 1^+ 1^- 0^-

sb

$(5840)^0$

$(5830)^0$

B_s^{*0}

B_s^0

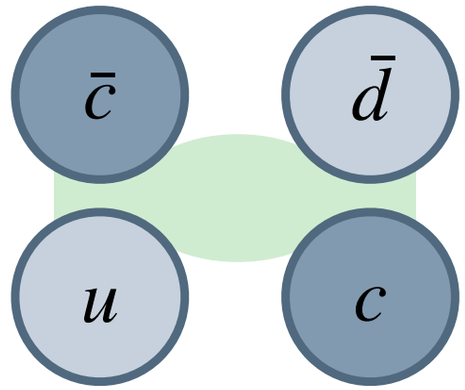
$Z_c(3900)^+ \to \pi^+ J/\psi$	$Z_{cs}(4000)^+ \to K^+ J/\psi$	$Z_b(10610)^+ \to \pi^+ h_b, \pi^+ \Upsilon$	$T_{cc\bar{c}\bar{c}}(6900) \to J/\psi J/\psi$

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

$Z_c(3900)^+$
Tetraquark Candidate



$Z_c(3900)^+ \rightarrow \pi^+ J/\psi$

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

$Z_c(4020)^+ \rightarrow \pi^+ h_c$	$Z_c(4430)^+ \rightarrow \pi^+ \psi(2S)$	$Z_b(10650)^+ \rightarrow \pi^+ h_b, \pi^+ \Upsilon$	$X(2900)^0 \rightarrow D^+ K^-$
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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)*	

$J^{P(C)}$	$u\bar{d},\ u\bar{u},\ d\bar{d},\ s\bar{s}$			$c\bar{c}$	$b\bar{b}$	$d\bar{s}, u\bar{s}$	$c\bar{u}, c\bar{d}$	$c\bar{s}$	$d\bar{b}, u\bar{b}$	$s\bar{b}$
$1^{-(-)}$	$\rho(1700)$	$\omega(1650)$	$\phi(1680)$	$\psi(3770)$	$\Upsilon(4S)$	$K^*(1680)$		$D_{s1}^*(2700)^+$		
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$1^{+(+)}$	$a_1(1260)$	$f_1(1285)$	$f_1(1420)$	$\chi_{c1}(1P)$	$\chi_{b1}(1P)$	$K_1(1400)$	$D_1(2430)$	$D_{s1}(2536)^+$		
$0^{+(+)}$	$a_0(1450)$	$f_0(1370)$	$f_0(1710)$	$\chi_{c0}(1P)$	$\chi_{b0}(1P)$	$K_0^*(1430)$	$D_0^*(2300)$	$D_{s0}^*(2317)^+$		
$1^{+(-)}$	$b_1(1235)$	$h_1(1170)$	$h_1(1415)$	$h_c(1P)$	$h_b(1P)$	$K_1(1270)$	$D_1(2420)$	$D_{s1}(2460)^+$	$B_1(5721)$	$B_{s1}(5830)^0$
$1^{-(-)}$	$\rho(770)$	$\omega(782)$	$\phi(1020)$	$J/\psi(1S)$	$\Upsilon(1S)$	$K^*(892)$	$D^*(2007)^0 \mid D^*(2010)^+$	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

excited states ↑ *ground state*

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

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

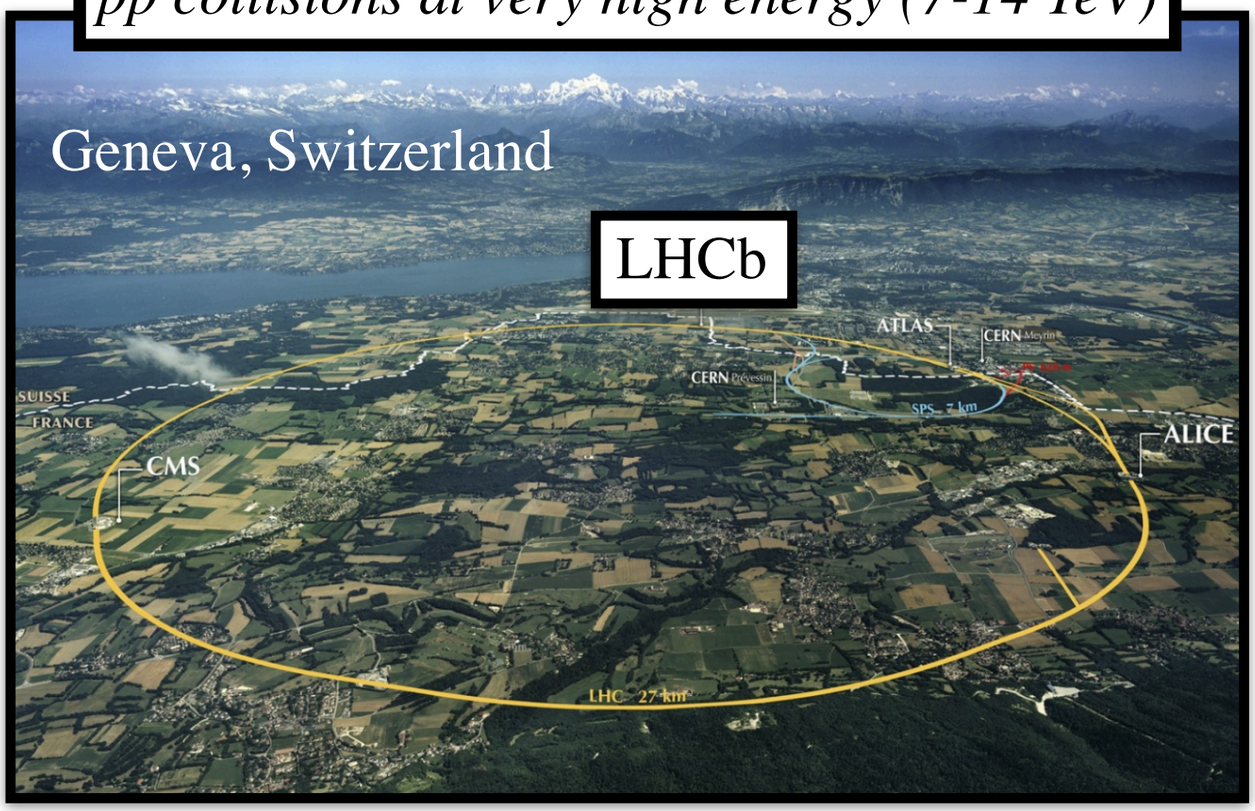
VI. Why Mesons?

III. Looking for Mesons

Step 1: Produce mesons…

…using a sledgehammer:

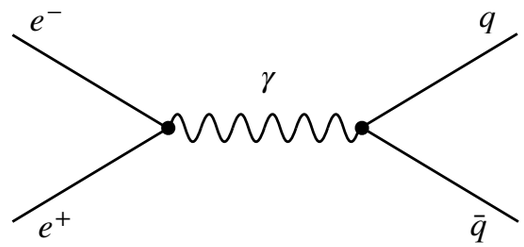
Large Hadron Collider (LHC)
pp collisions at very high energy (7-14 TeV)



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

…using a scalpel:

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



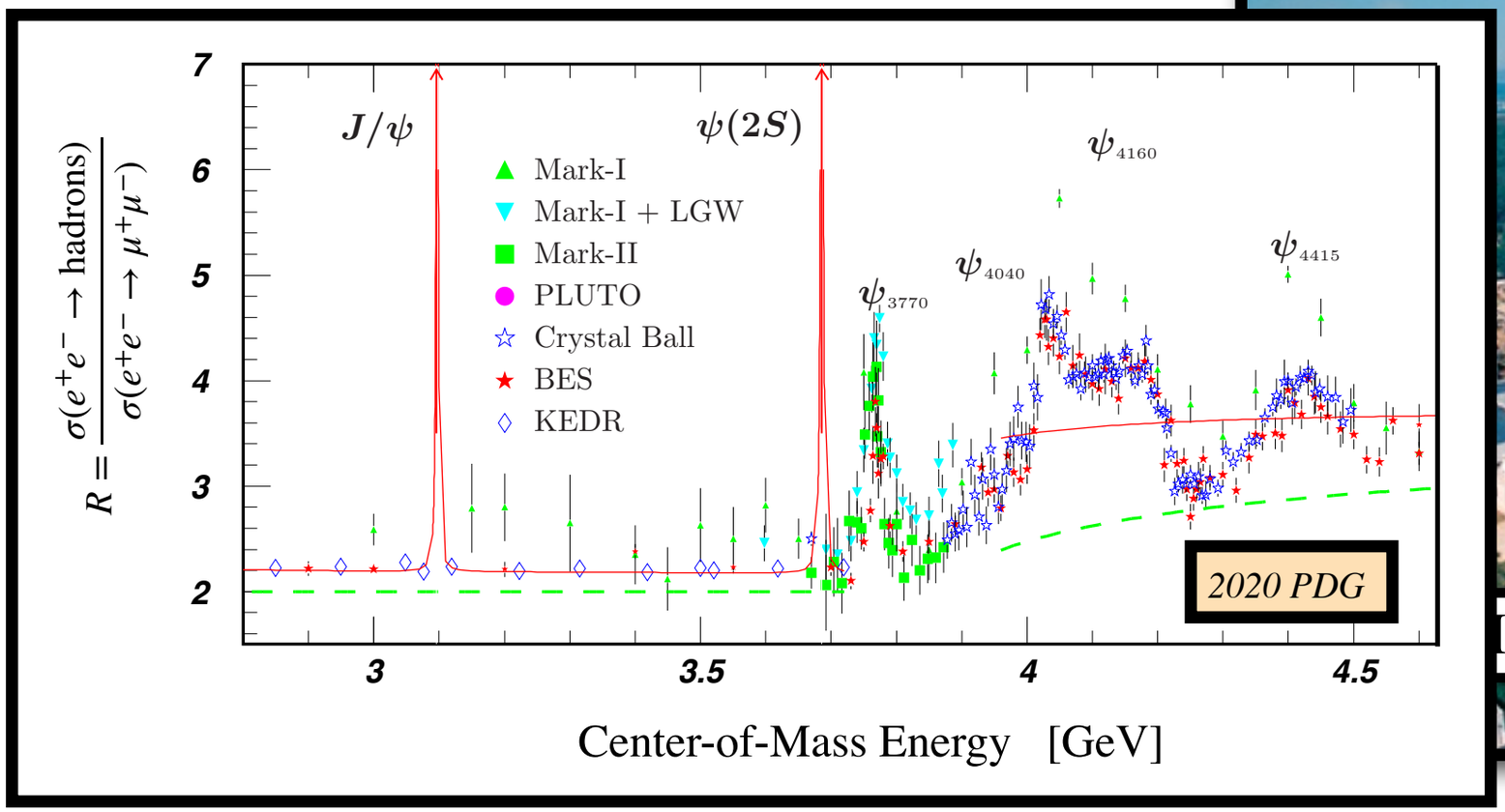
e.g., $e^+e^- \rightarrow \pi^+\pi^- J/\psi \rightarrow \pi^+\pi^-\mu^+\mu^-$

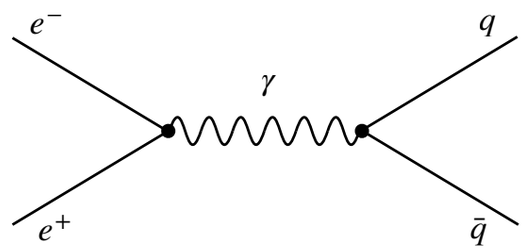
III. Looking for Mesons

Step 1: Produce mesons…

…using a scalpel:

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





e.g., $e^+e^- \to \pi^+\pi^- J/\psi \to \pi^+\pi^-\mu^+\mu^-$

III. Looking for Mesons

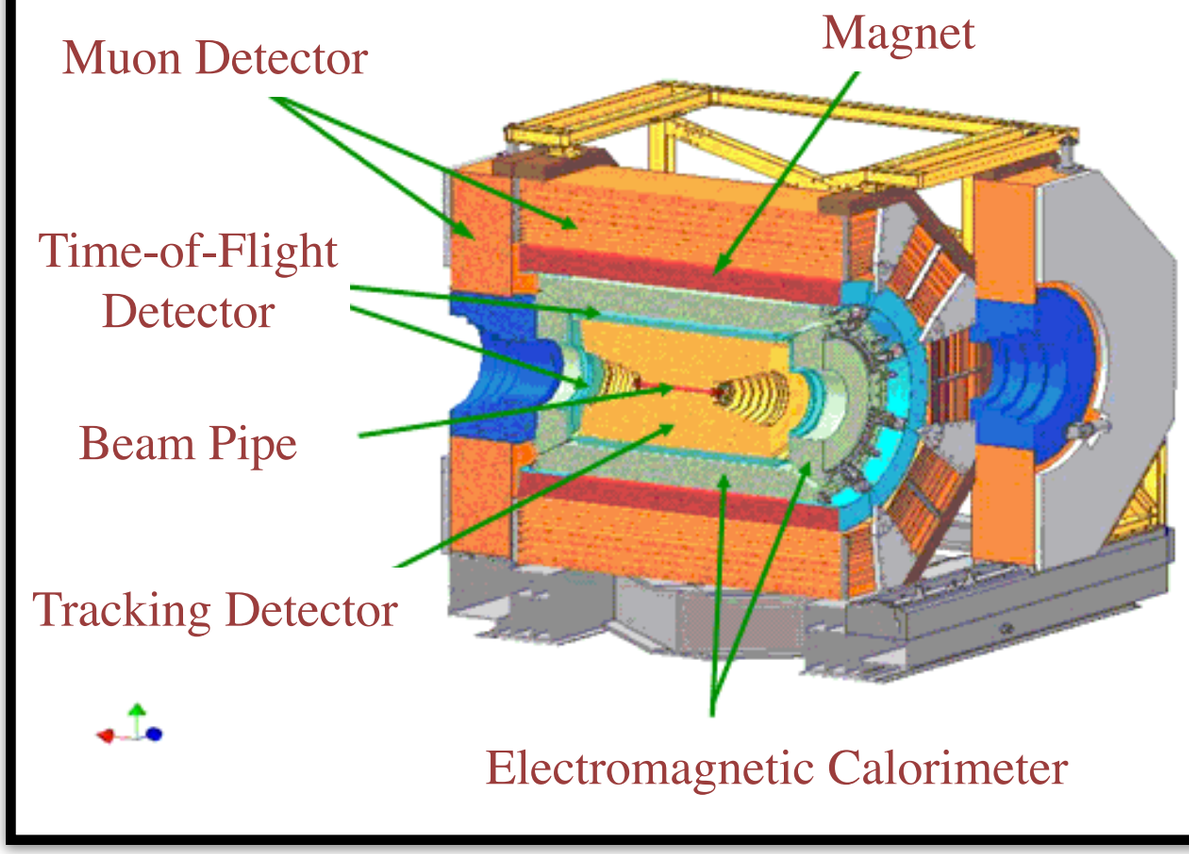
Step 2: Detect mesons.

<u>BESIII Detector</u> *<u>(a standard high-energy physics experiment)</u>*

(1) Tracking detector ⇒ *charged particle momentum*

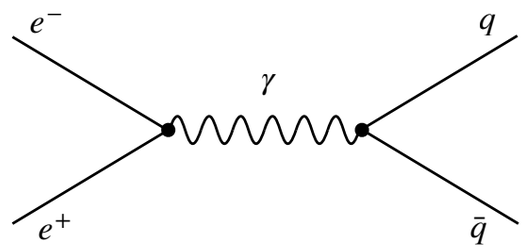
(2) Time-of-Flight (TOF) ⇒ *charged particle mass*

(3) Calorimeter ⇒ *photon energy and direction*



Beijing Electron Positron Collider (BEPCII)

e^+e^- collisions at low energies (2-5 GeV)

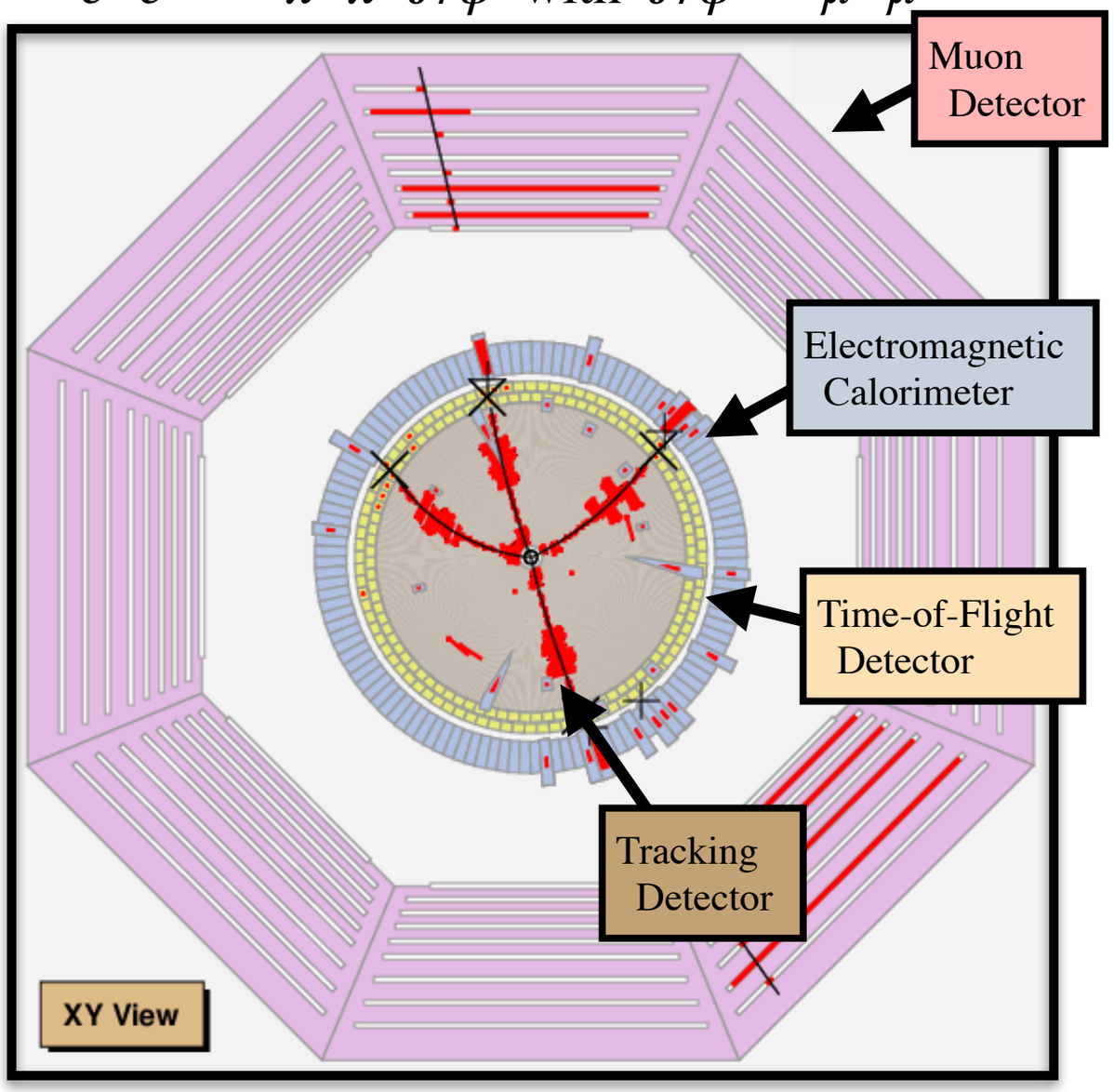


e.g., $e^+e^- \to \pi^+\pi^- J/\psi \to \pi^+\pi^-\mu^+\mu^-$

III. Looking for Mesons

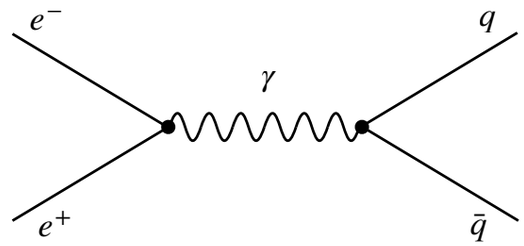
Step 2: Detect mesons.

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



Beijing Electron Positron Collider (BEPCII)

e^+e^- collisions at low energies (2-5 GeV)

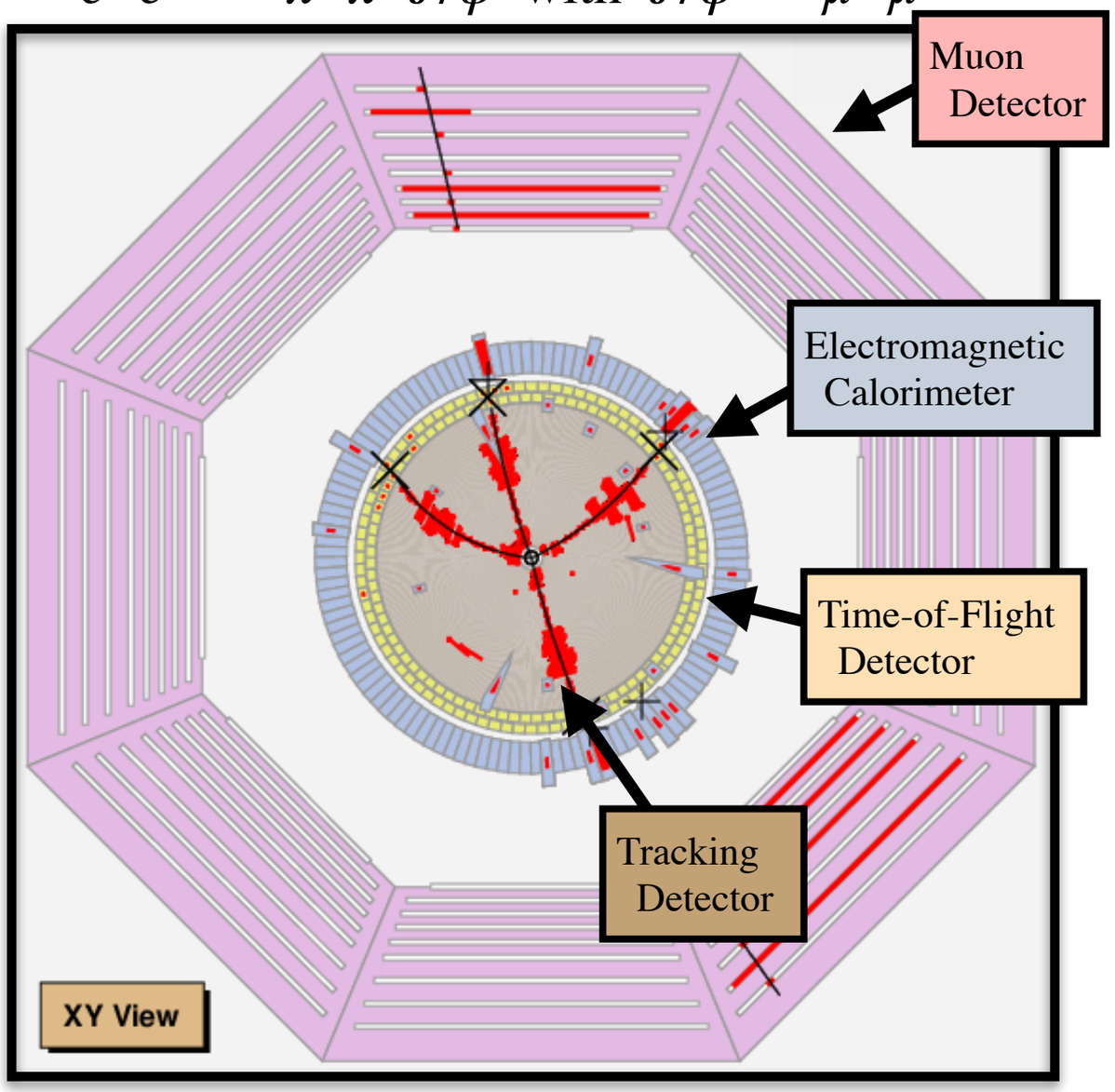


e.g., $e^+e^- \to \pi^+\pi^- J/\psi \to \pi^+\pi^-\mu^+\mu^-$

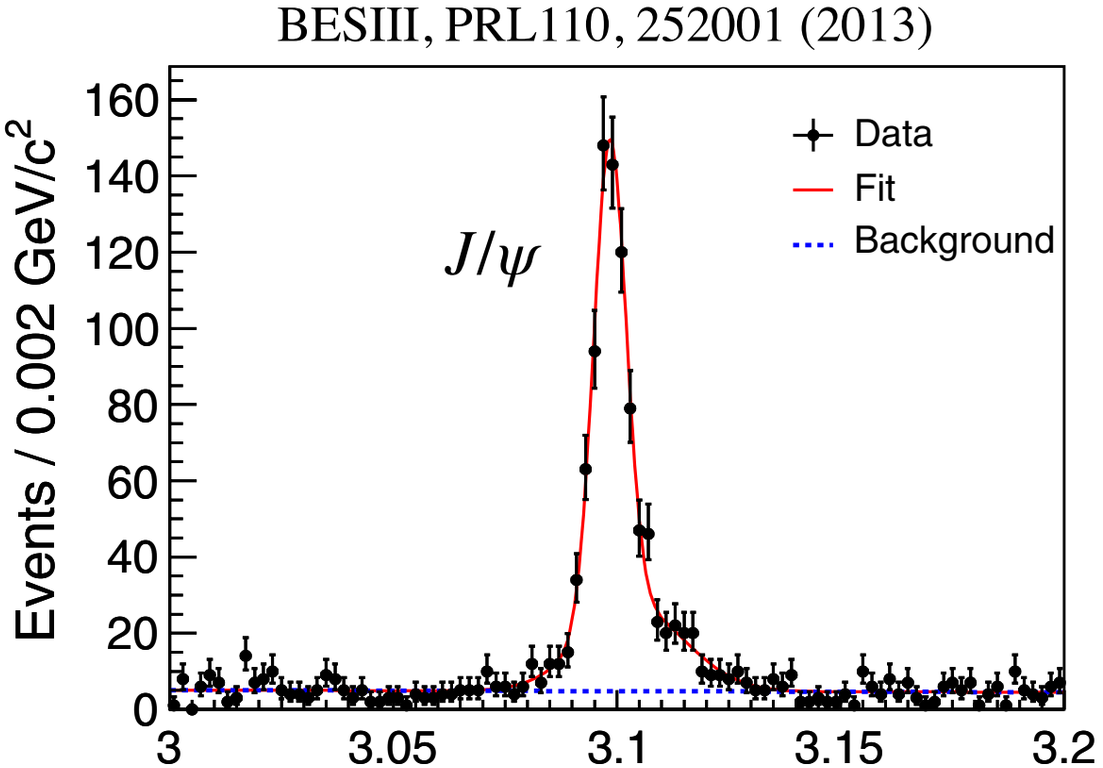
III. Looking for Mesons

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 $J/\psi \to \mu^+\mu^-$

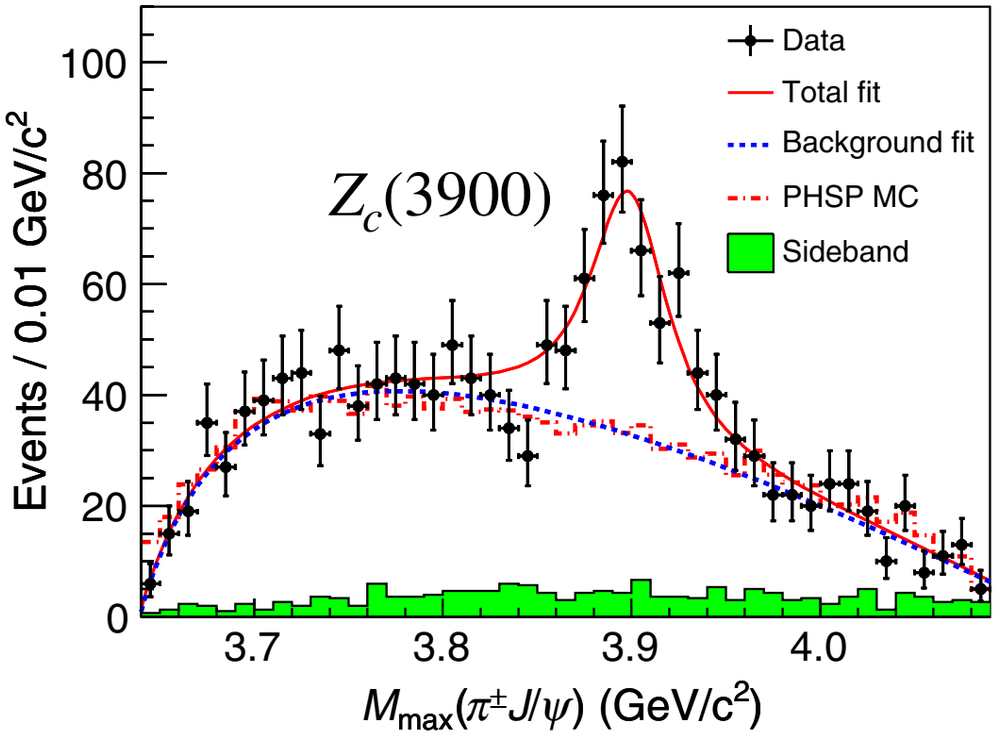


$$M_{\mu\mu} = \sqrt{(E_{\mu^+} + E_{\mu^-})^2 - (\vec{p}_{\mu^+} + \vec{p}_{\mu^-})^2}$$

III. Looking for Mesons

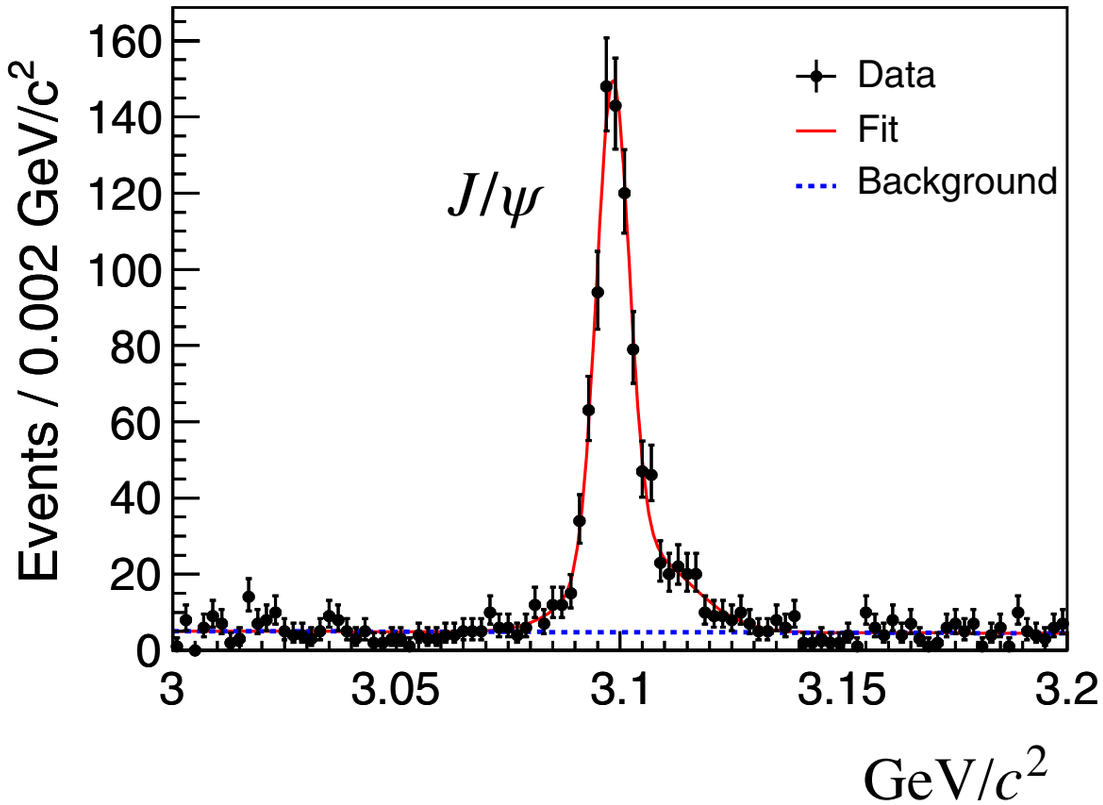
Step 2: Detect mesons.

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



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

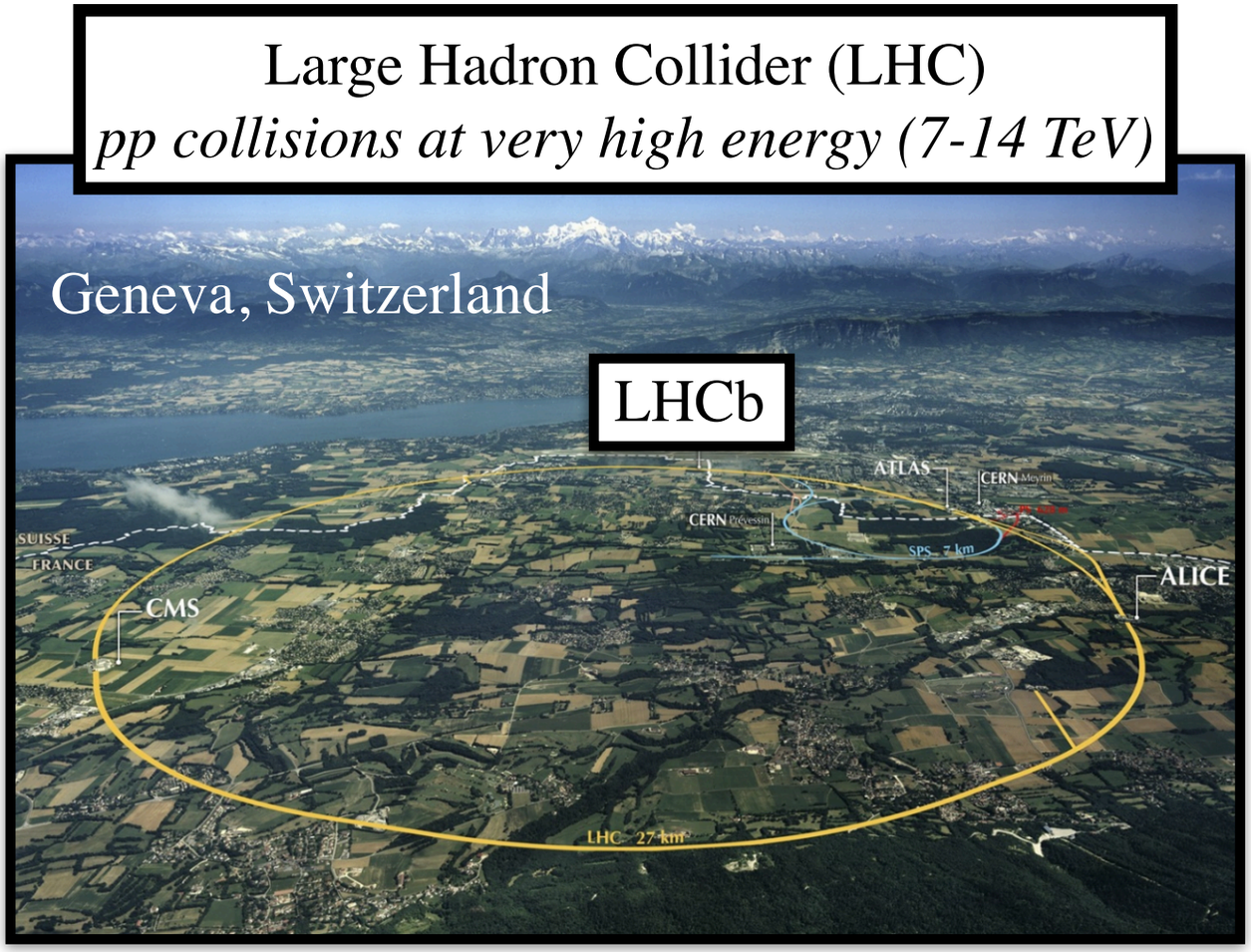
$e^+e^- \to \pi^+\pi^- J/\psi$ with $J/\psi \to \mu^+\mu^-$

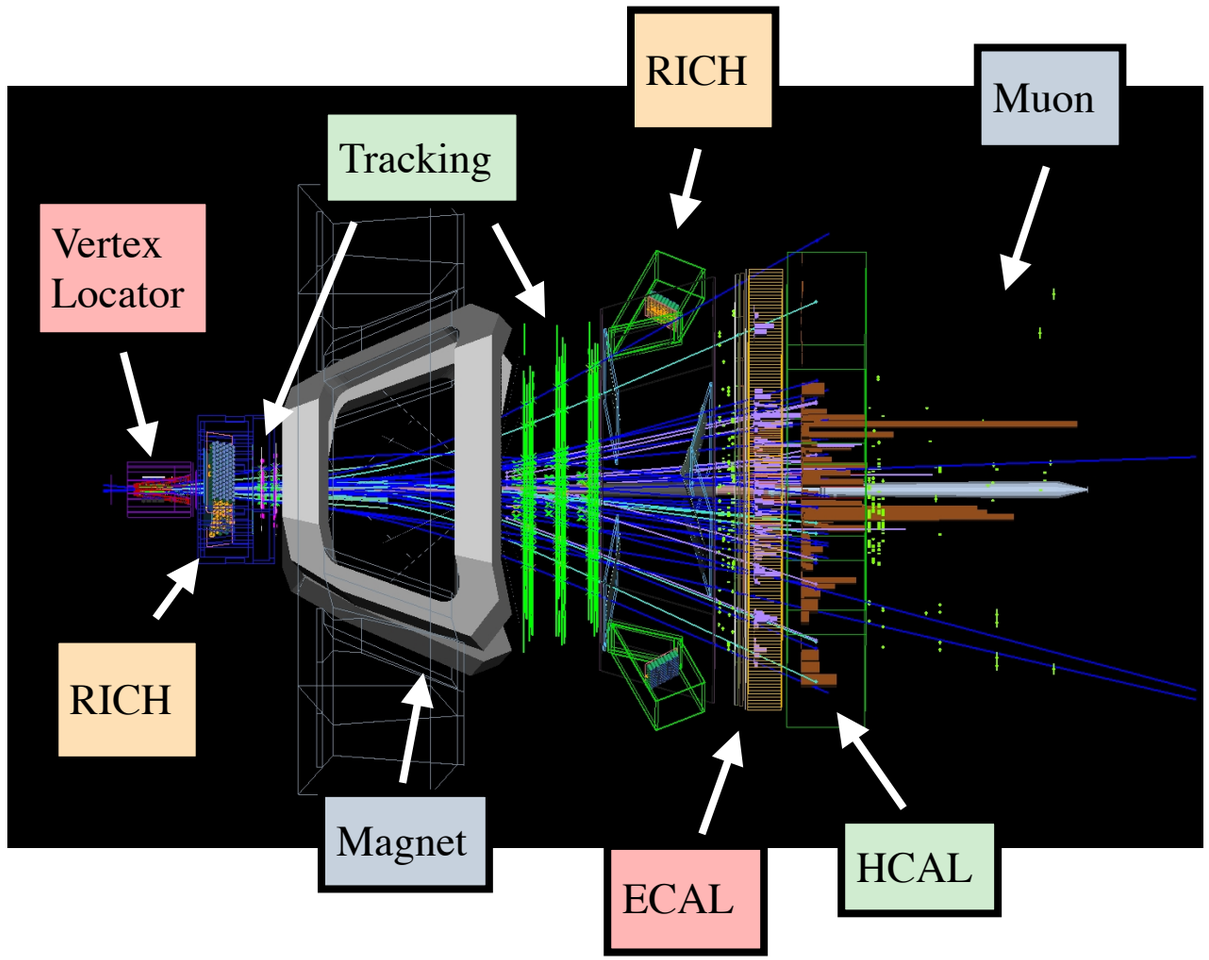


$$M_{\mu\mu} = \sqrt{(E_{\mu^+} + E_{\mu^-})^2 - (\vec{p}_{\mu^+} + \vec{p}_{\mu^-})^2}$$

III. Looking for Mesons

Step 2: Detect mesons.

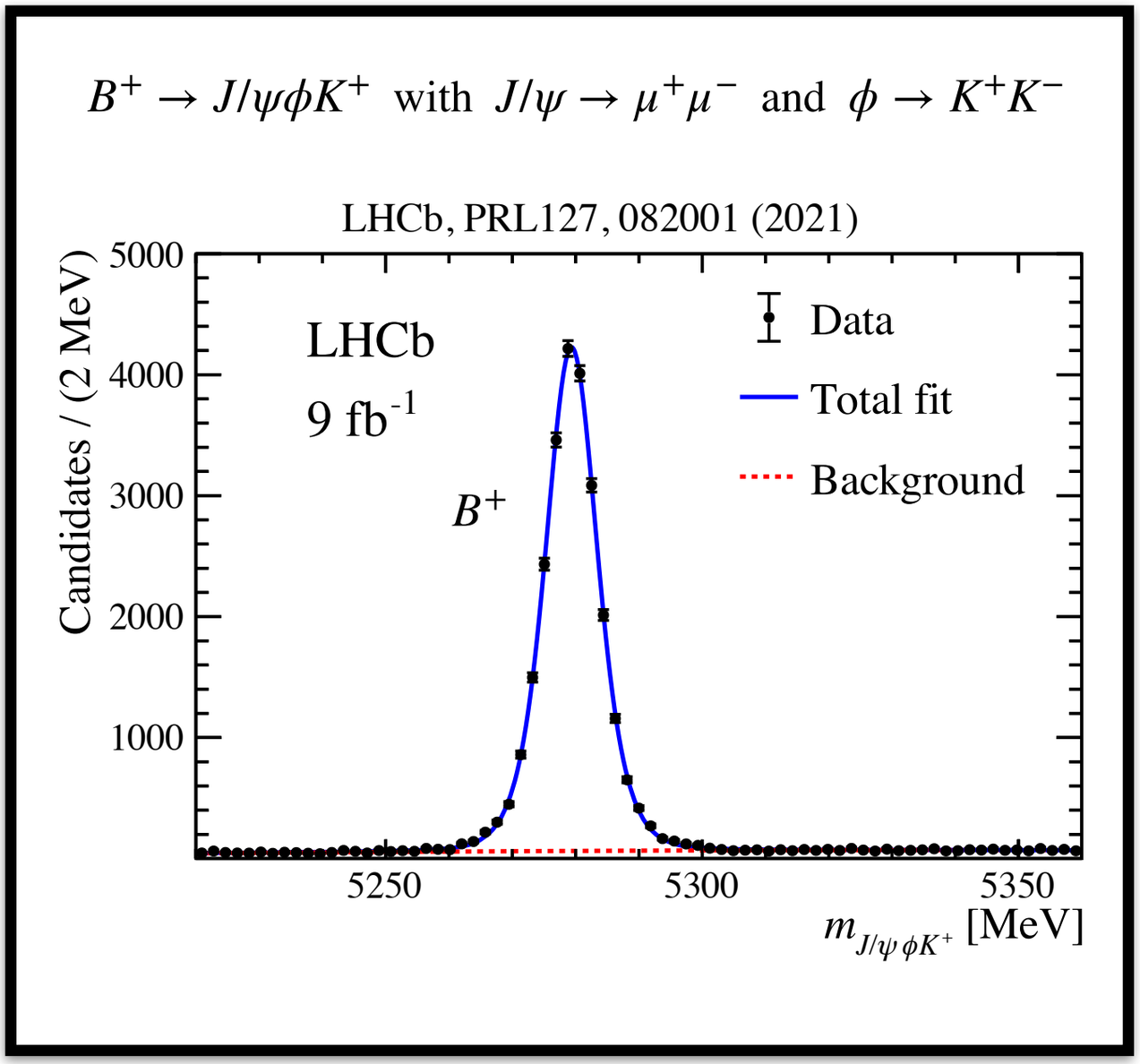


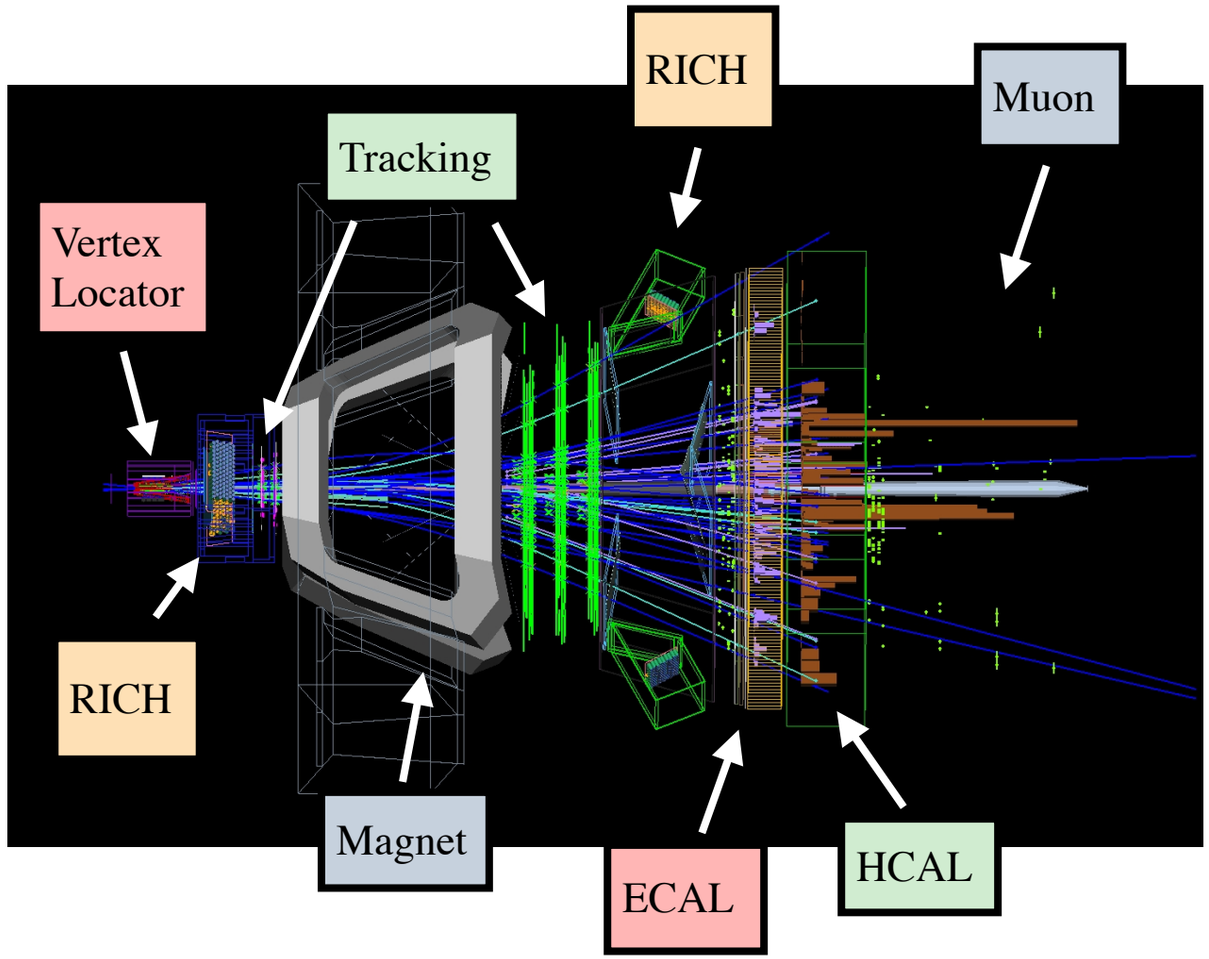


$pp \rightarrow$ many many hadrons (baryons and mesons)

III. Looking for Mesons

Step 2: Detect mesons.

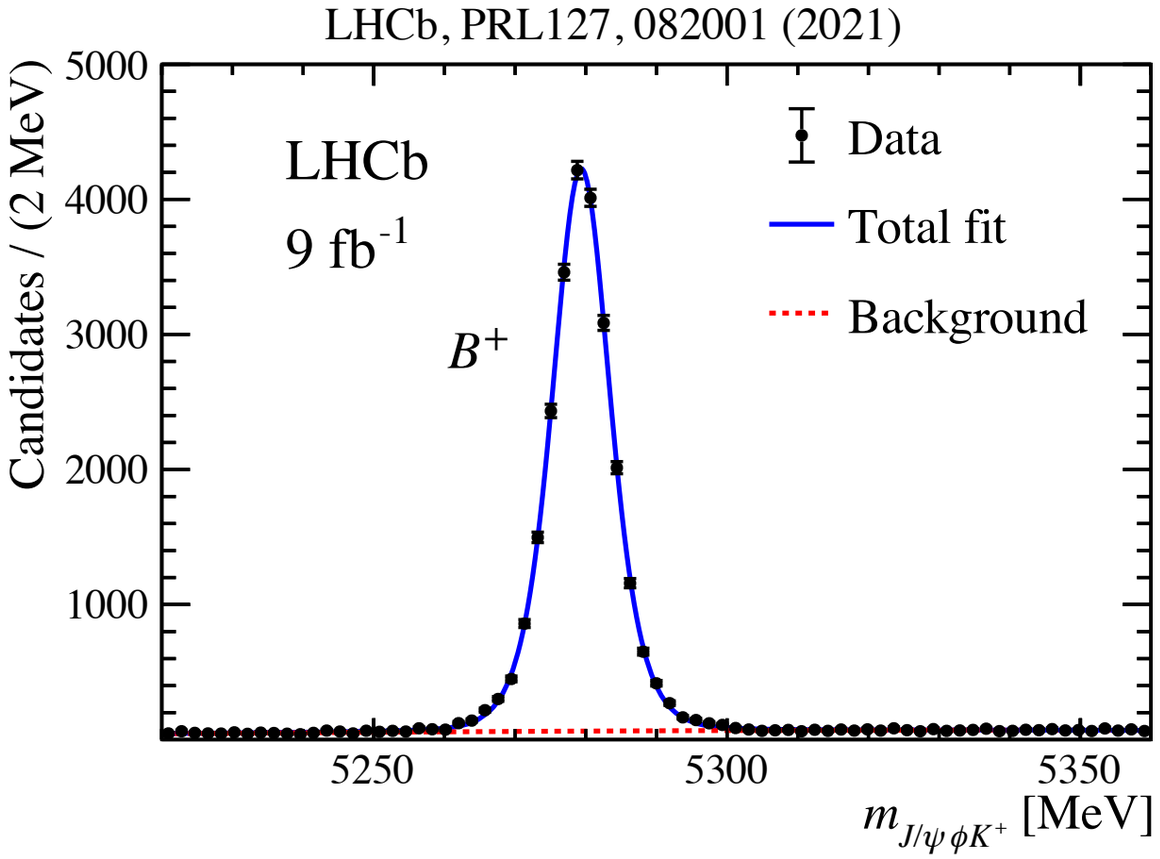




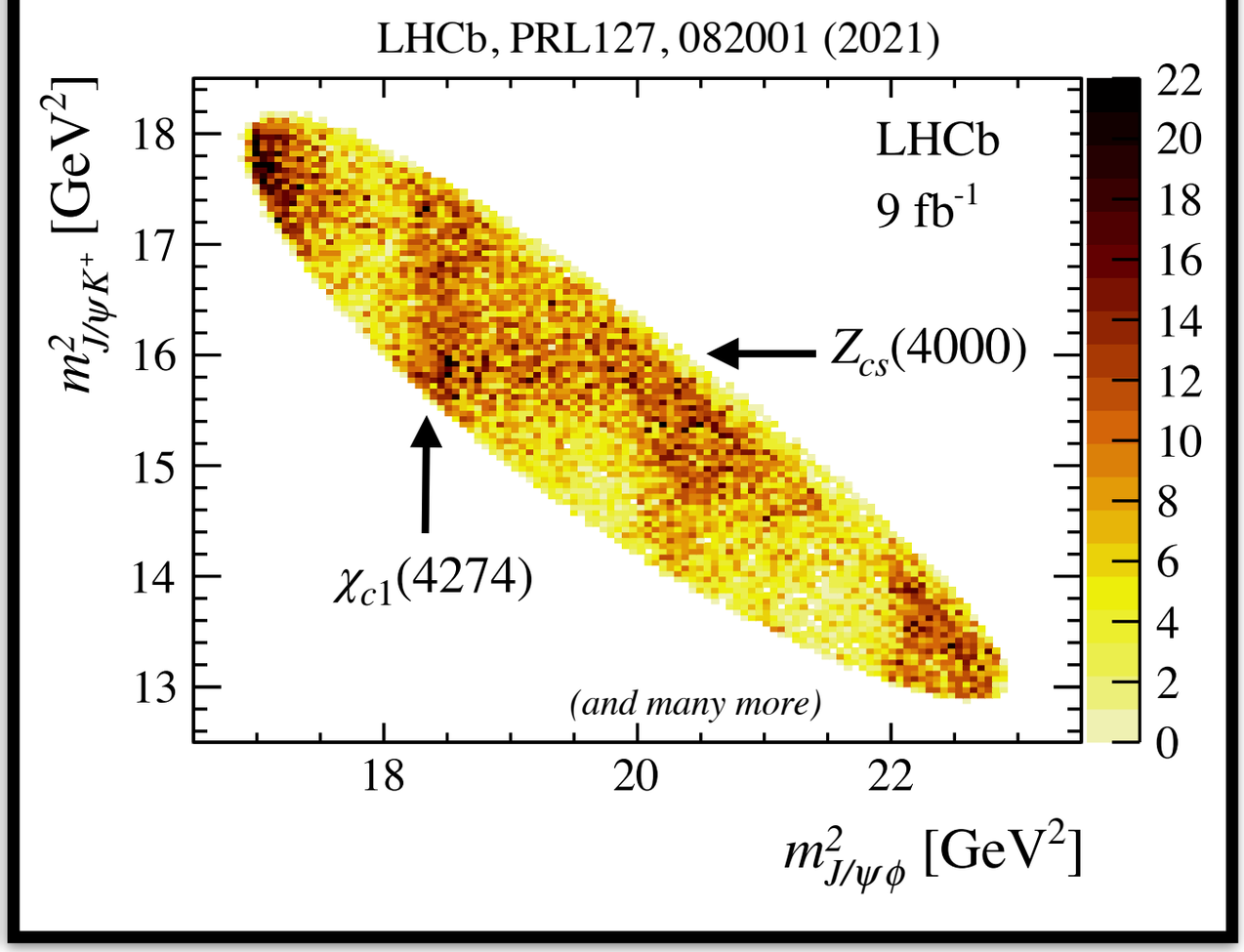
III. Looking for Mesons

Step 2: Detect mesons.

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

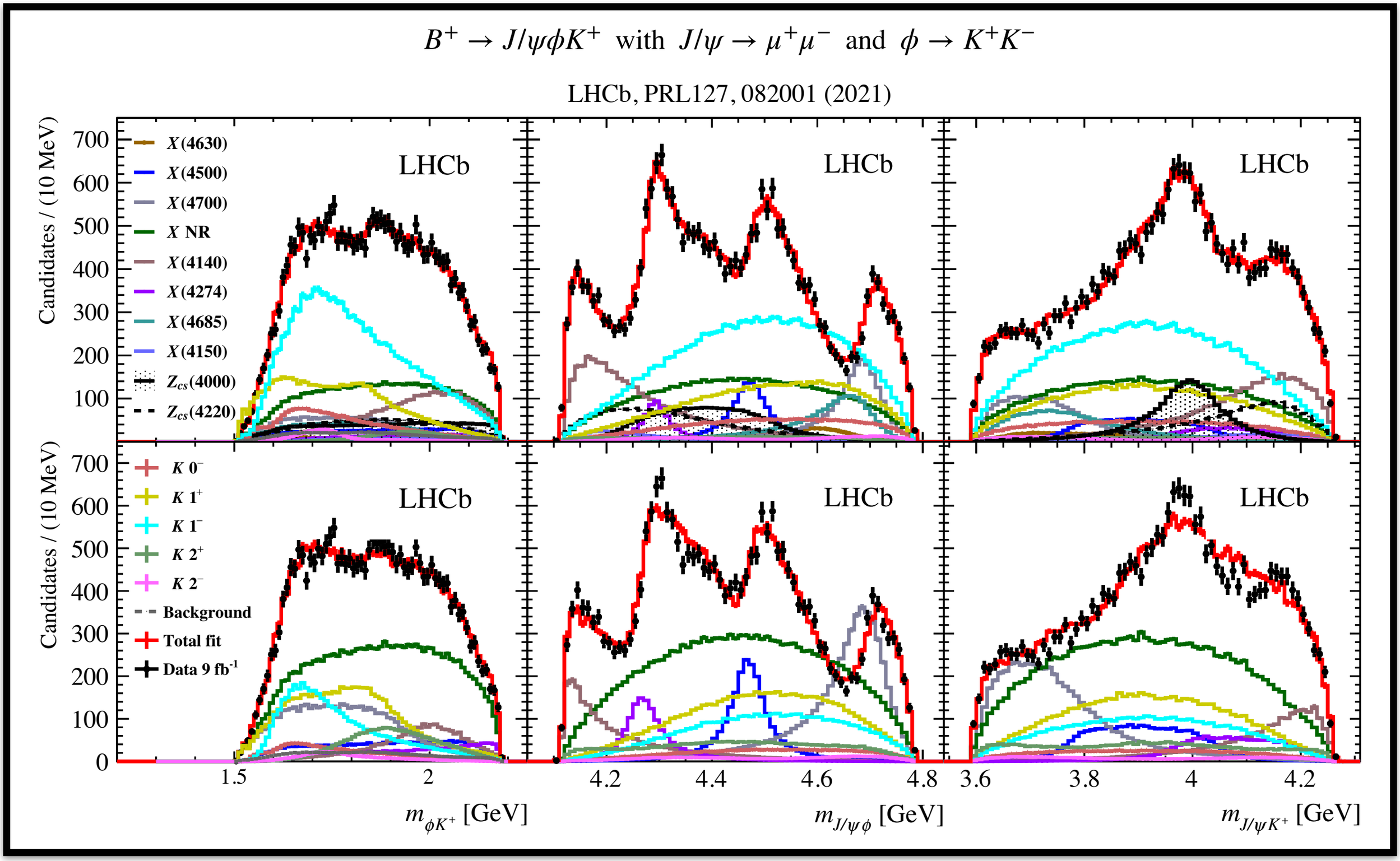


$B^+ \to J/\psi\phi K^+$ with $J/\psi \to \mu^+\mu^-$ and $\phi \to K^+K^-$



III. Looking for Mesons

Step 2: Detect mesons.



A Field Guide to the Mesons

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I. What are Mesons?

II. Families of Mesons

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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

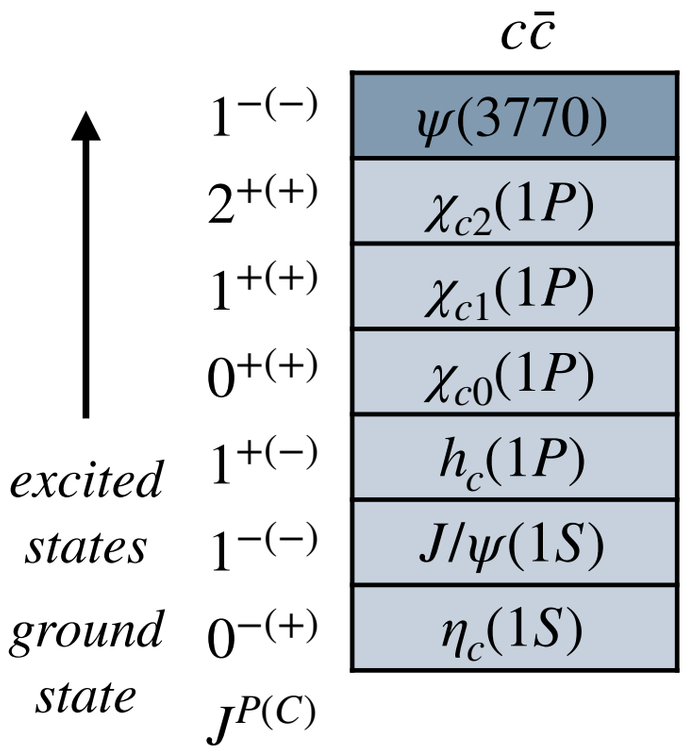
K^+ family	*(weak decays, no mixing)*
K^0 family	*(weak decays, mixing)*
π^0 family	*(large electromagnetic decays)*
J/ψ family	*(strong decays, near or below open flavor threshold)*
ρ family	*(strong decays, above open flavor threshold)*
$Z_c(3900)$ family	*(exotic flavor quantum numbers)*

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

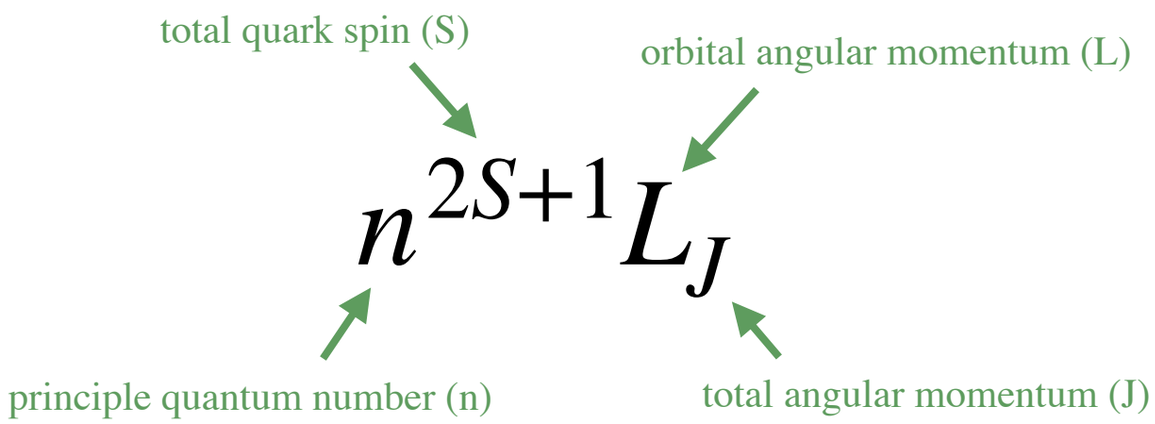
excited states ↑ *ground state*

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

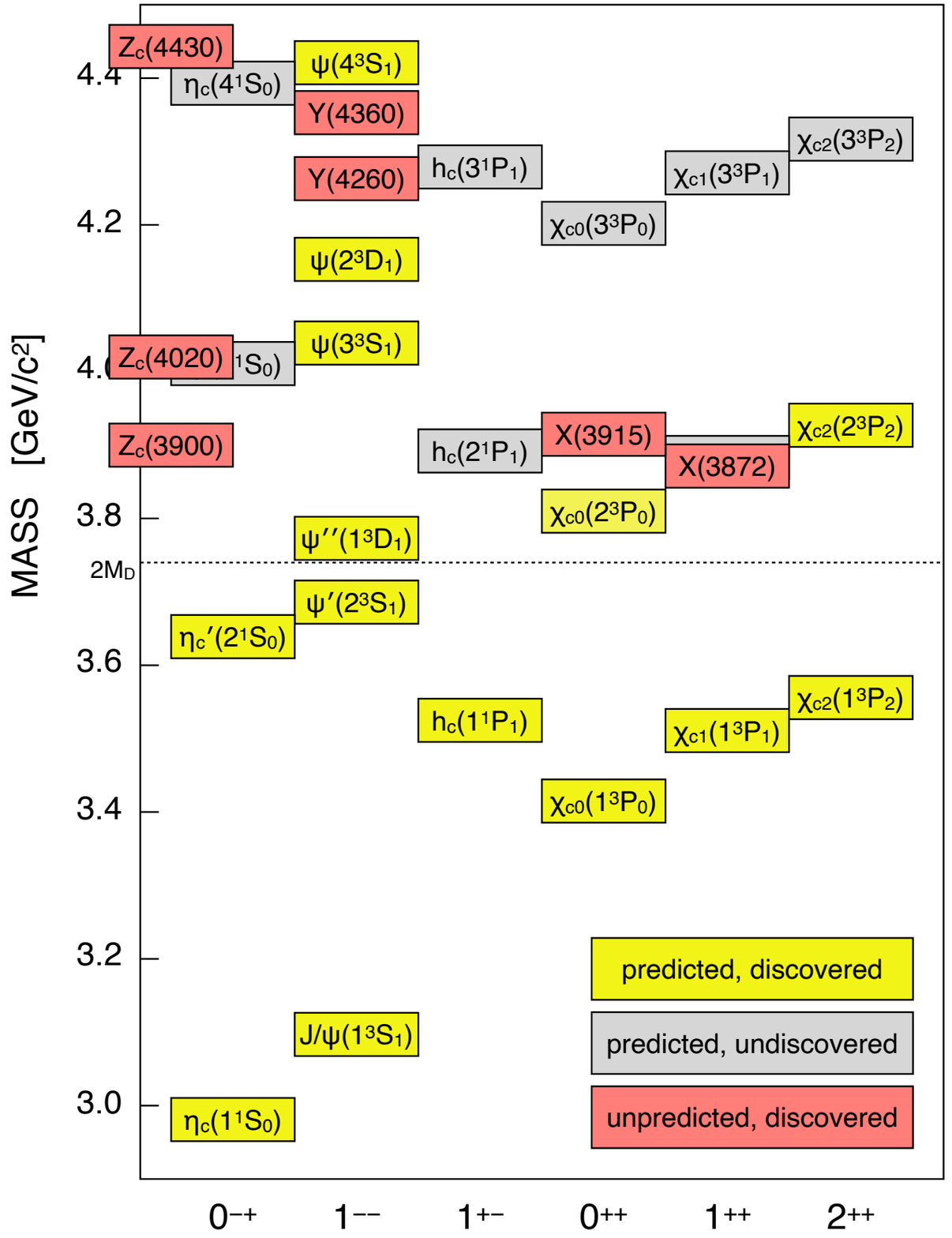
IV. The Plates: $c\bar{c}$ and cc mesons



Spectroscopic notation:



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

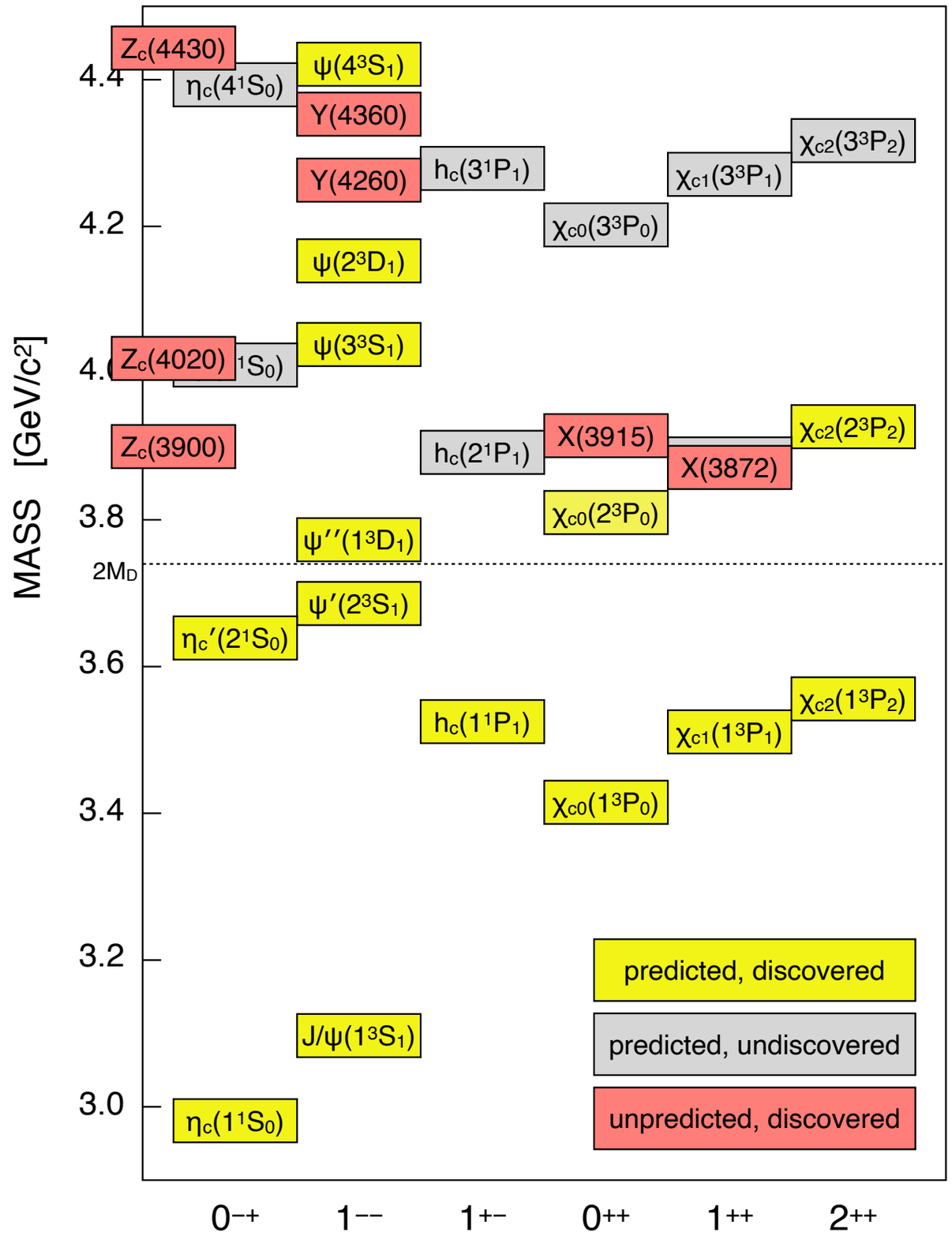
$$\tilde{\delta}_\sigma(r) = (\sigma/\sqrt{\pi})^3 e^{-\sigma^2 r^2}$$

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

spin-orbit (fine) tensor (hyperfine)

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

The charmonium spectrum:

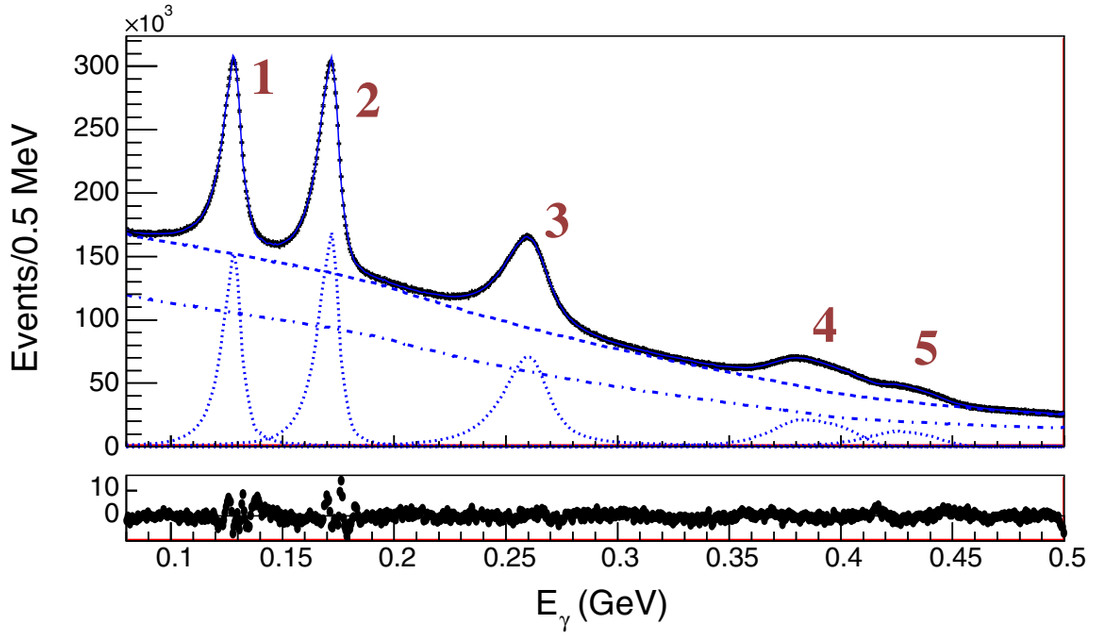


IV. The Plates: $c\bar{c}$ and cc mesons

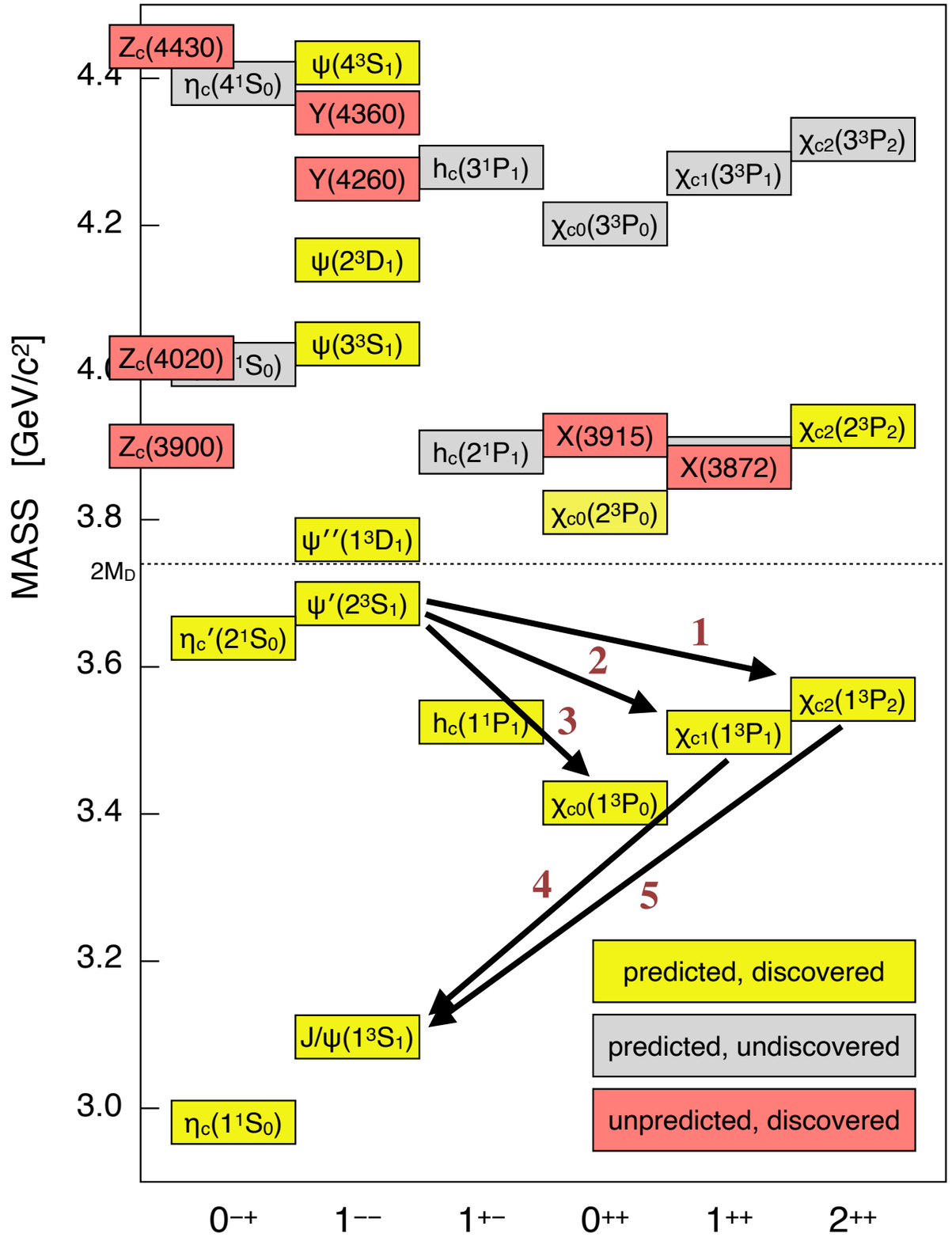
PHYSICAL REVIEW D **96,** 032001 (2017)

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

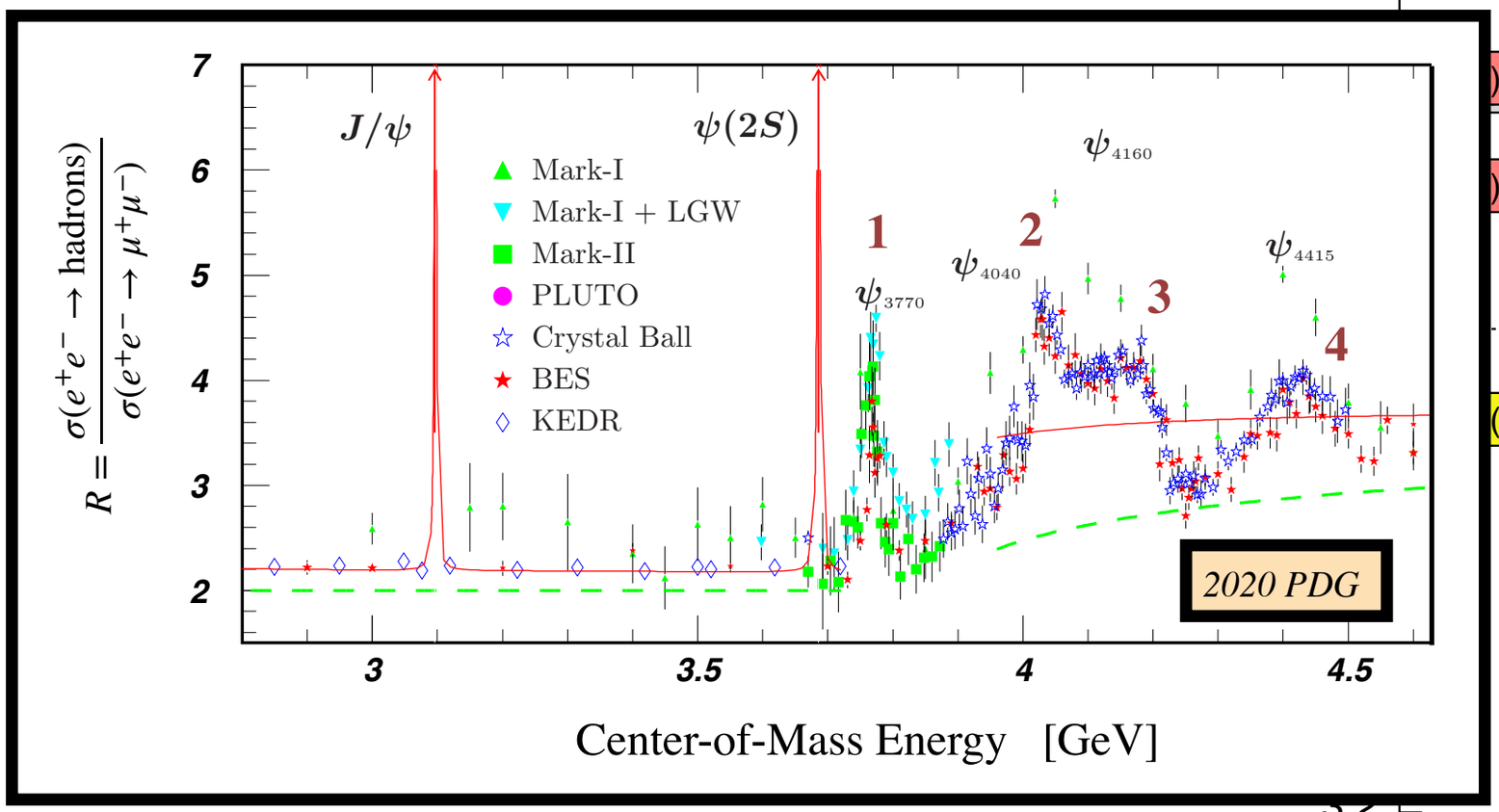
(BESIII Collaboration)



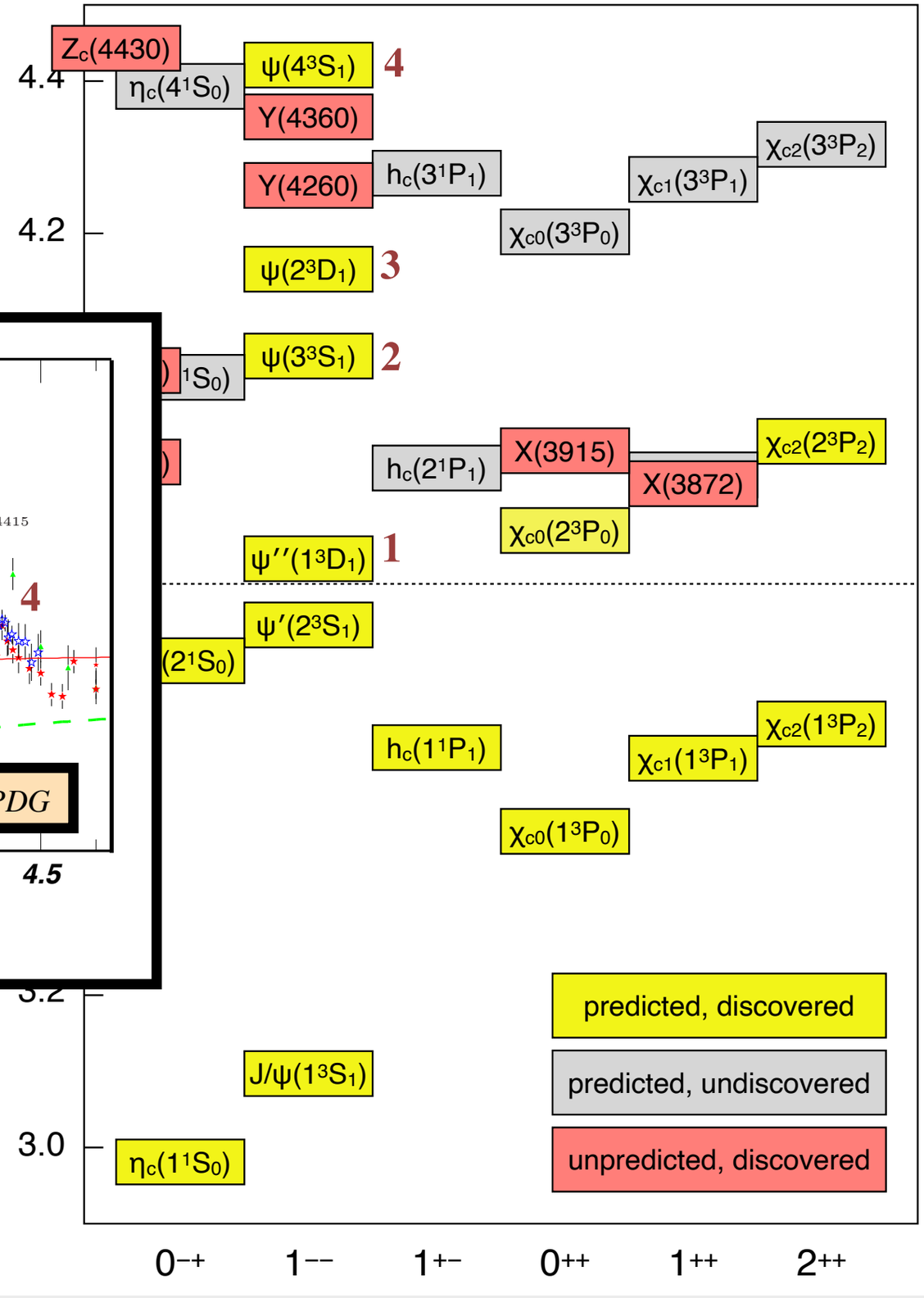
The charmonium spectrum:



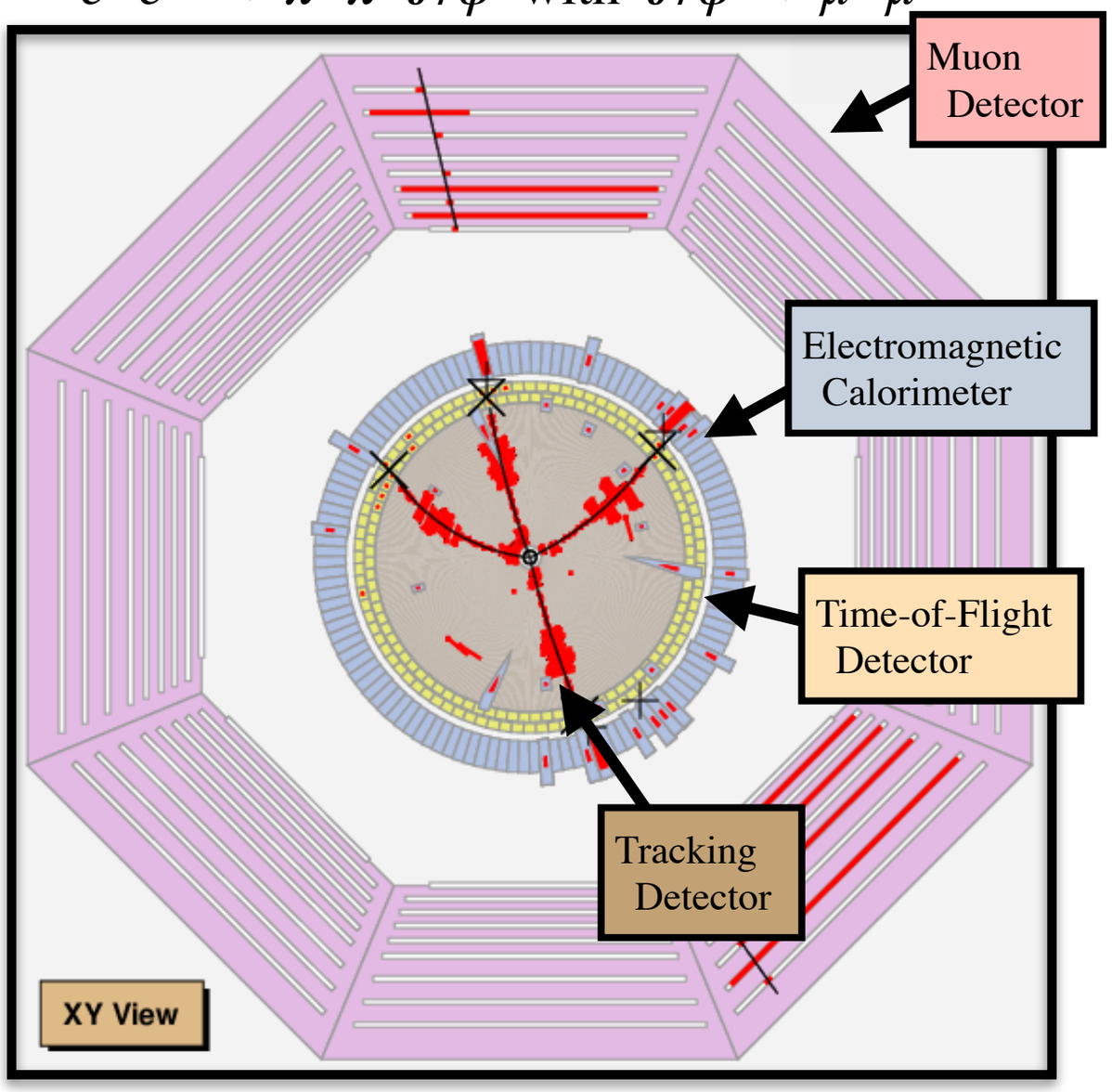
IV. The Plates: $c\bar{c}$ and cc mesons



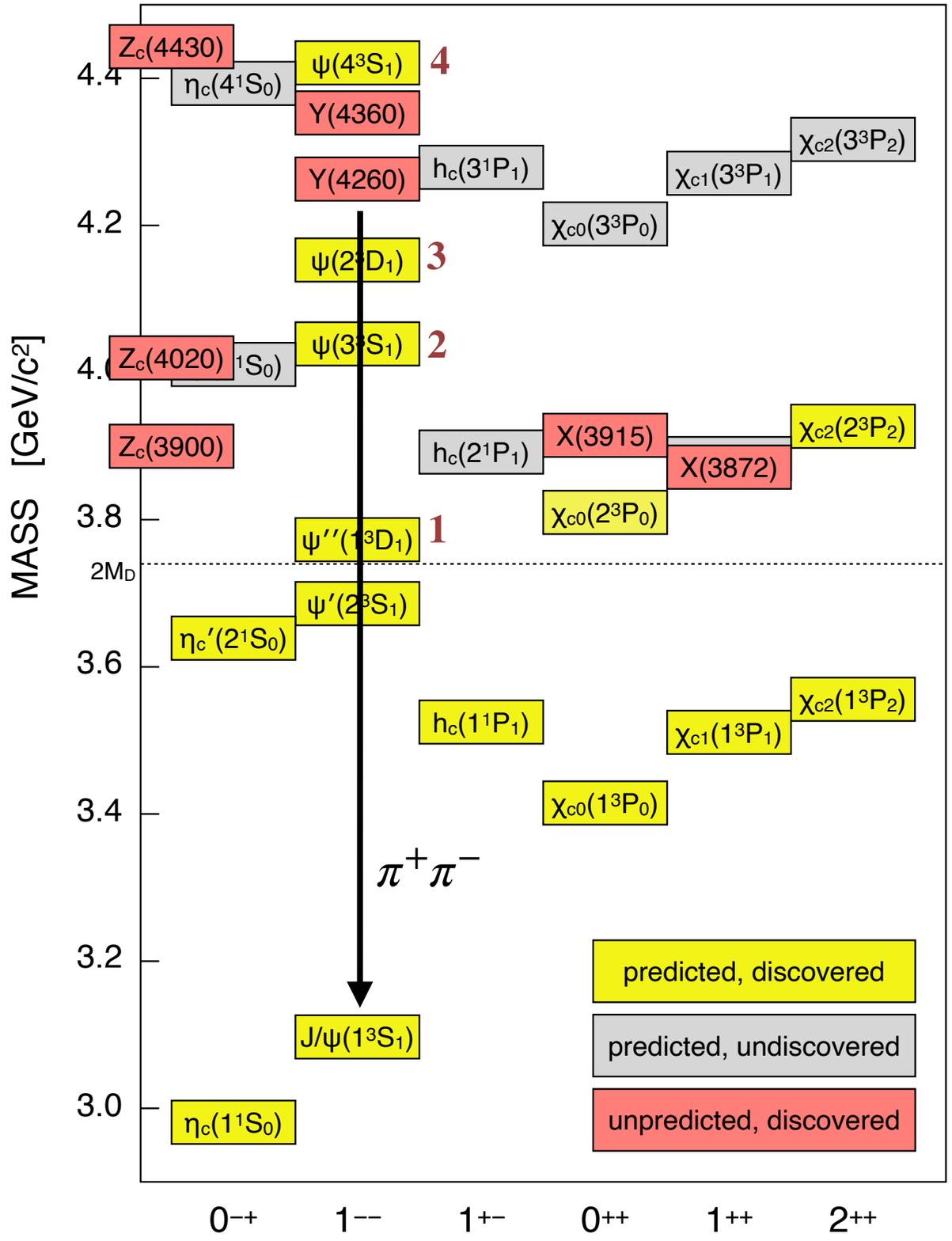
The charmonium spectrum:



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



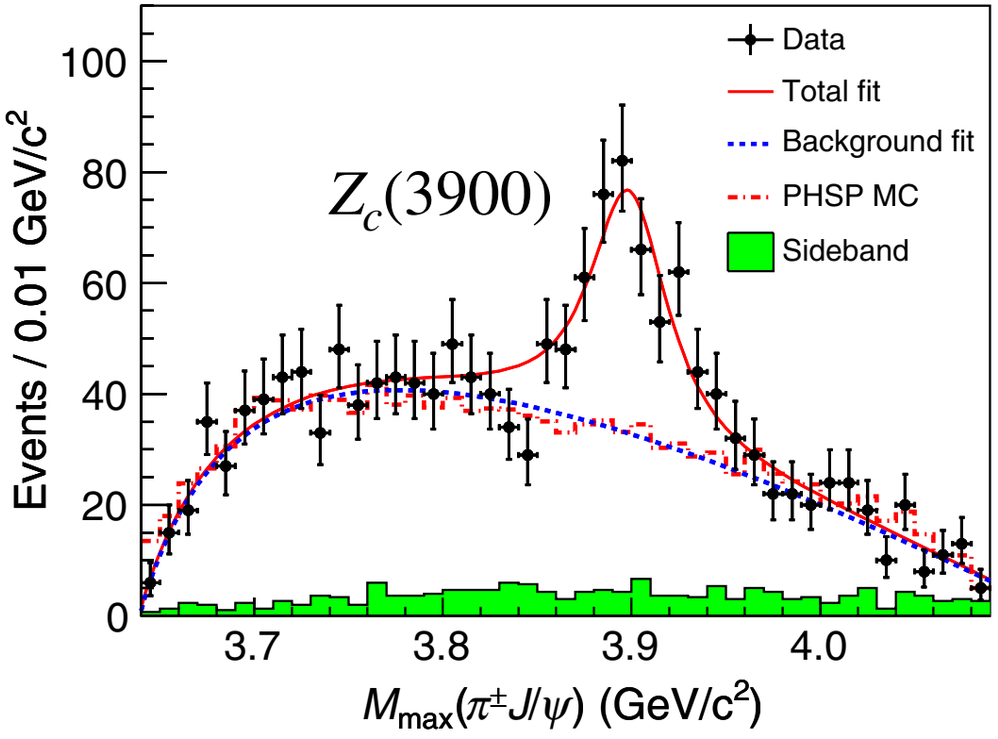
The charmonium spectrum:



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

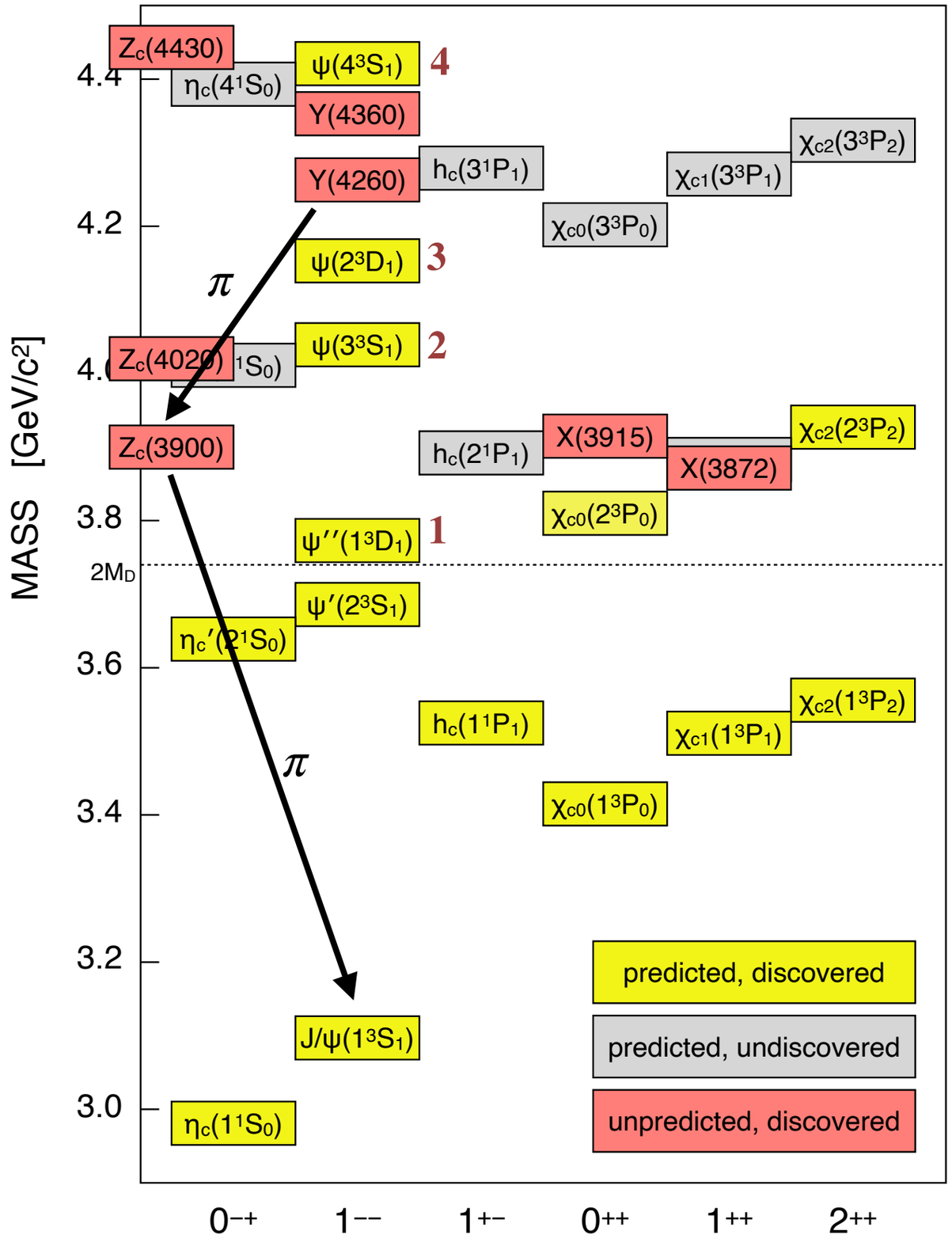
$e^+e^- \to \pi^+\pi^- J/\psi$ with $J/\psi \to l^+l^-$

BESIII, PRL110, 252001 (2013)

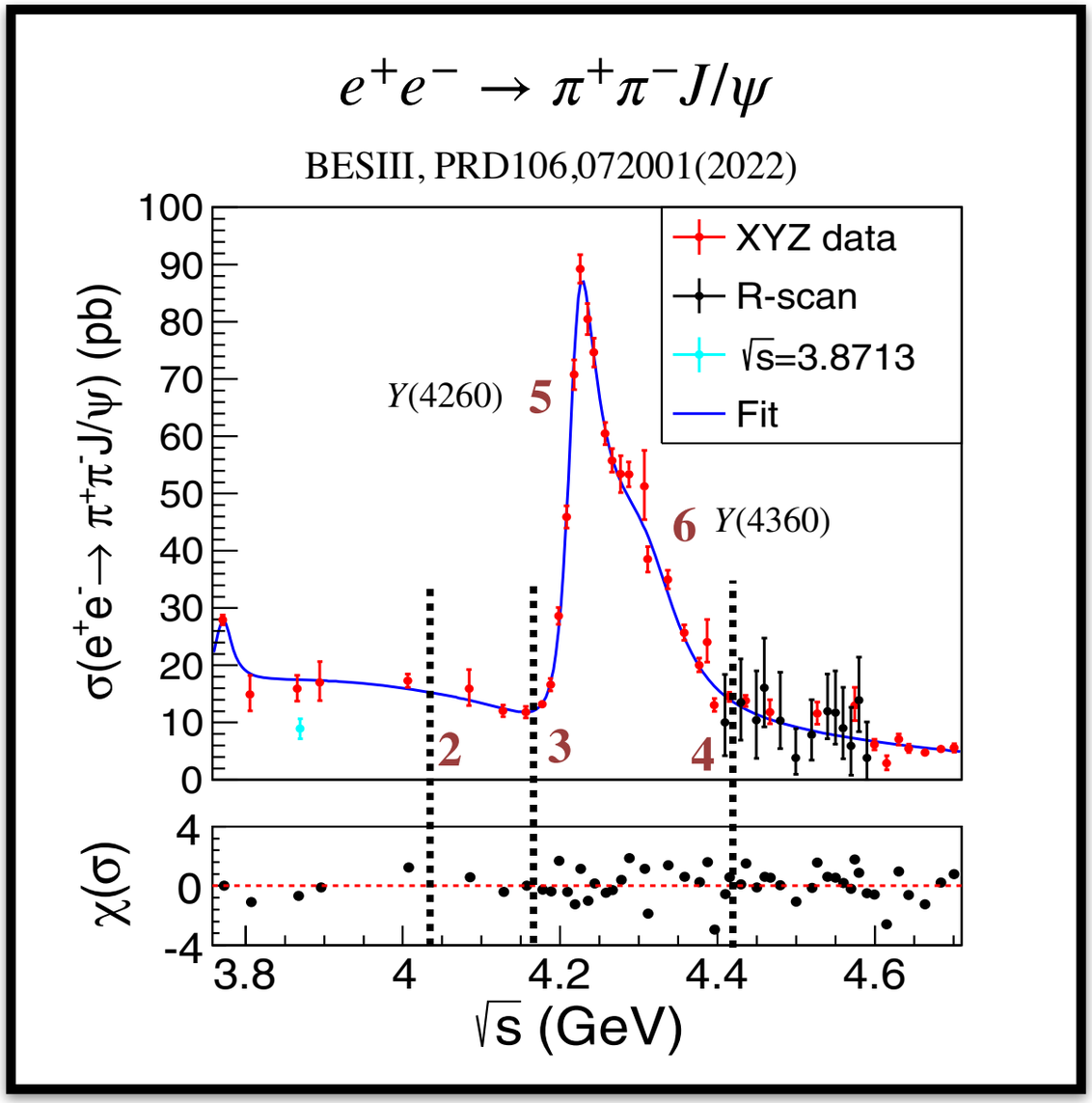


$$M_{\pi J/\psi} = \sqrt{(E_\pi + E_{ll})^2 - (\vec{p}_\pi + \vec{p}_{ll})^2}$$

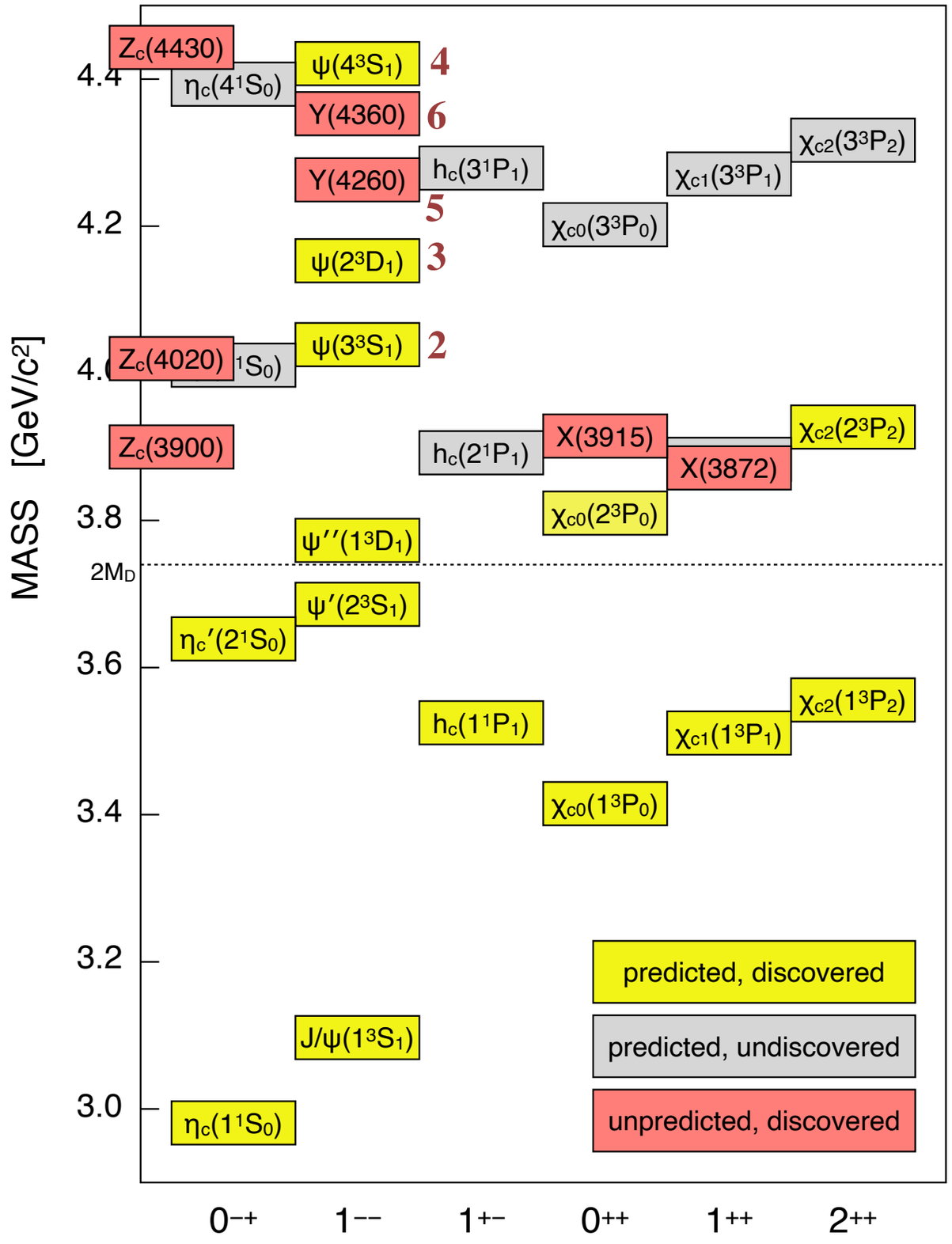
The charmonium spectrum:



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

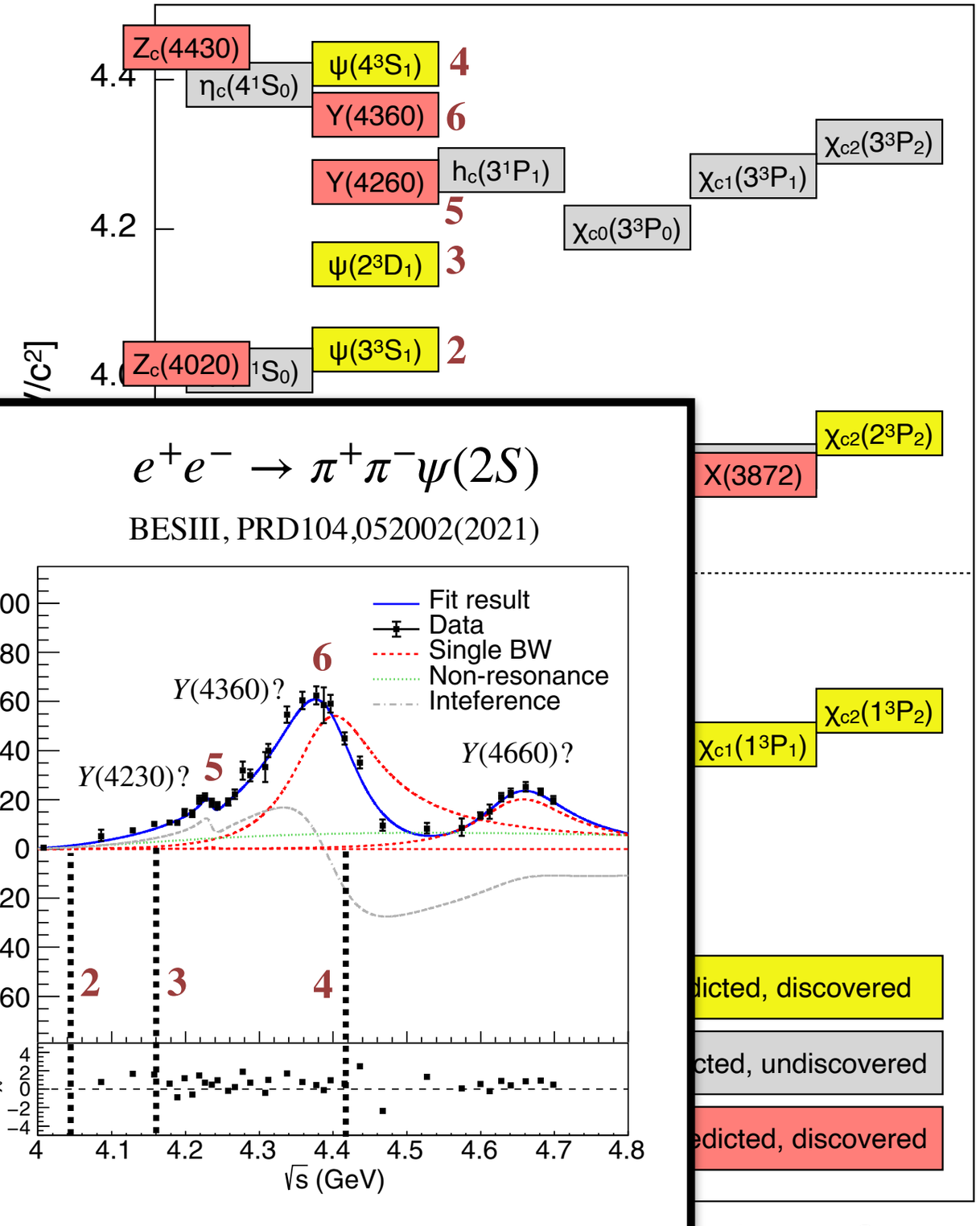


The charmonium spectrum:



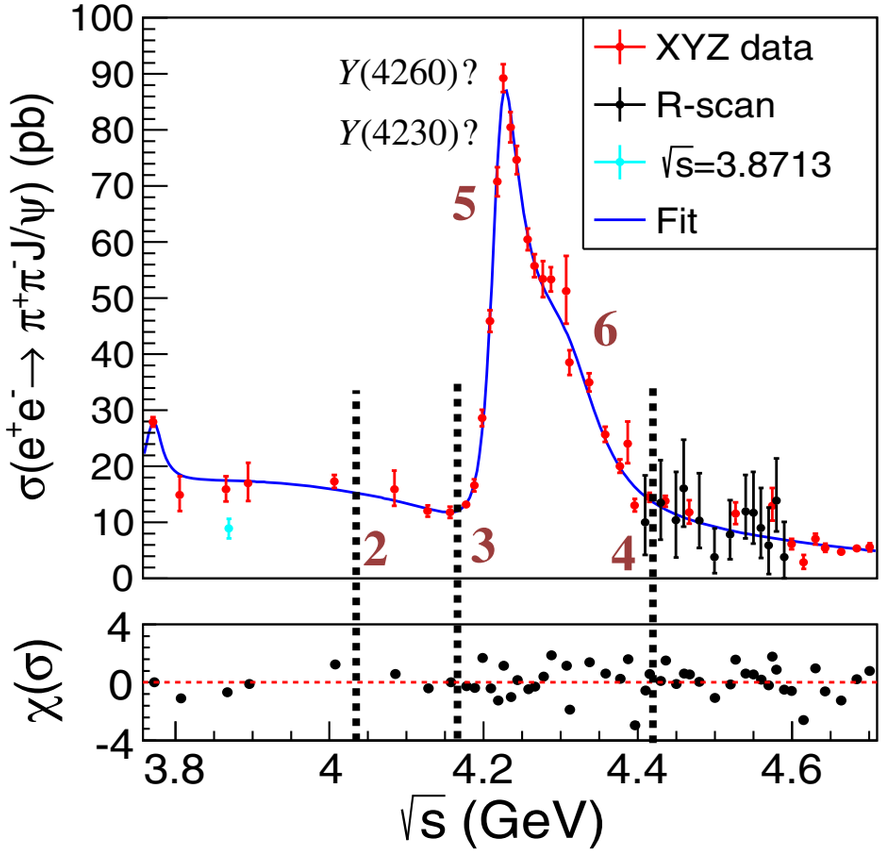
IV. The Plates: $c\bar{c}$ and cc mesons

The charmonium spectrum:



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

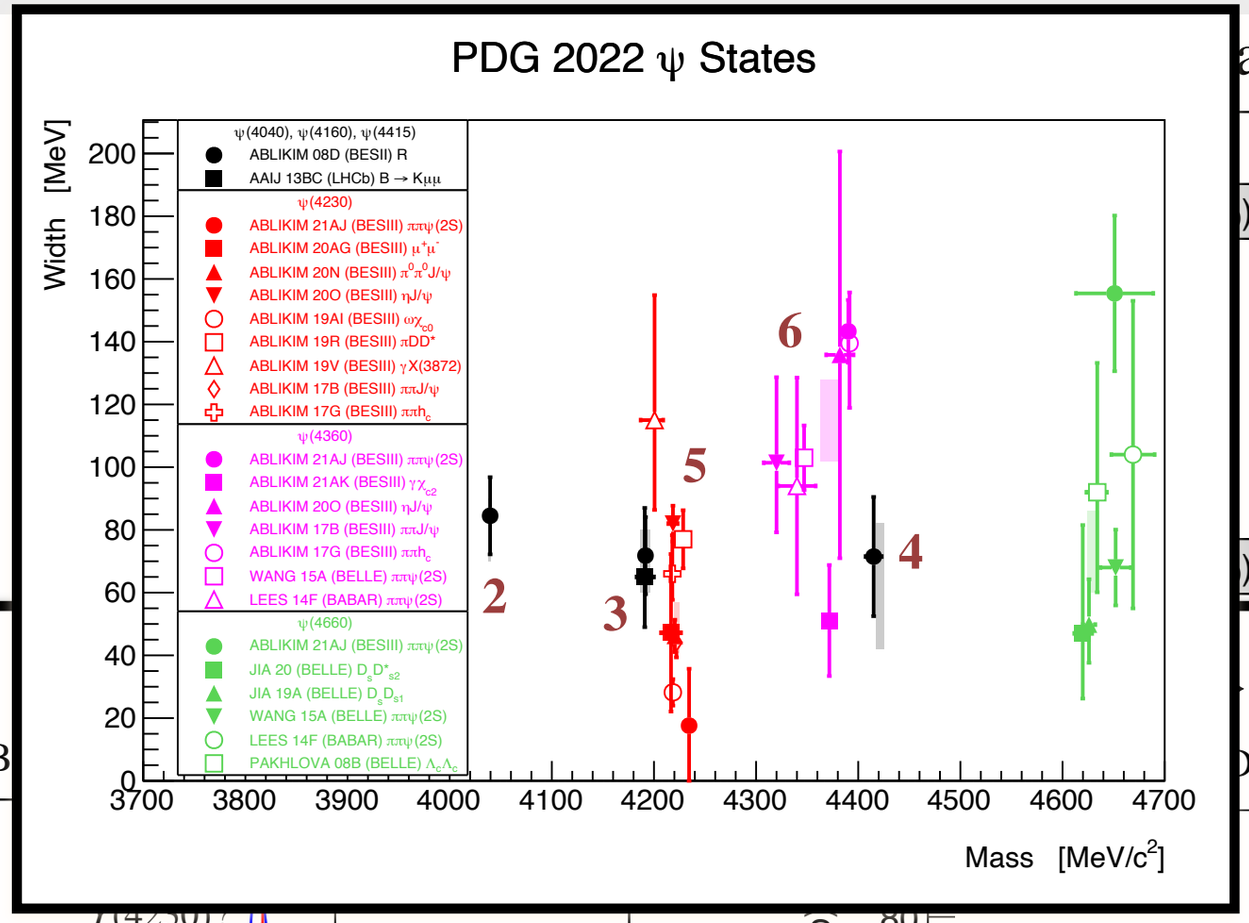
BESIII, PRD106,072001(2022)



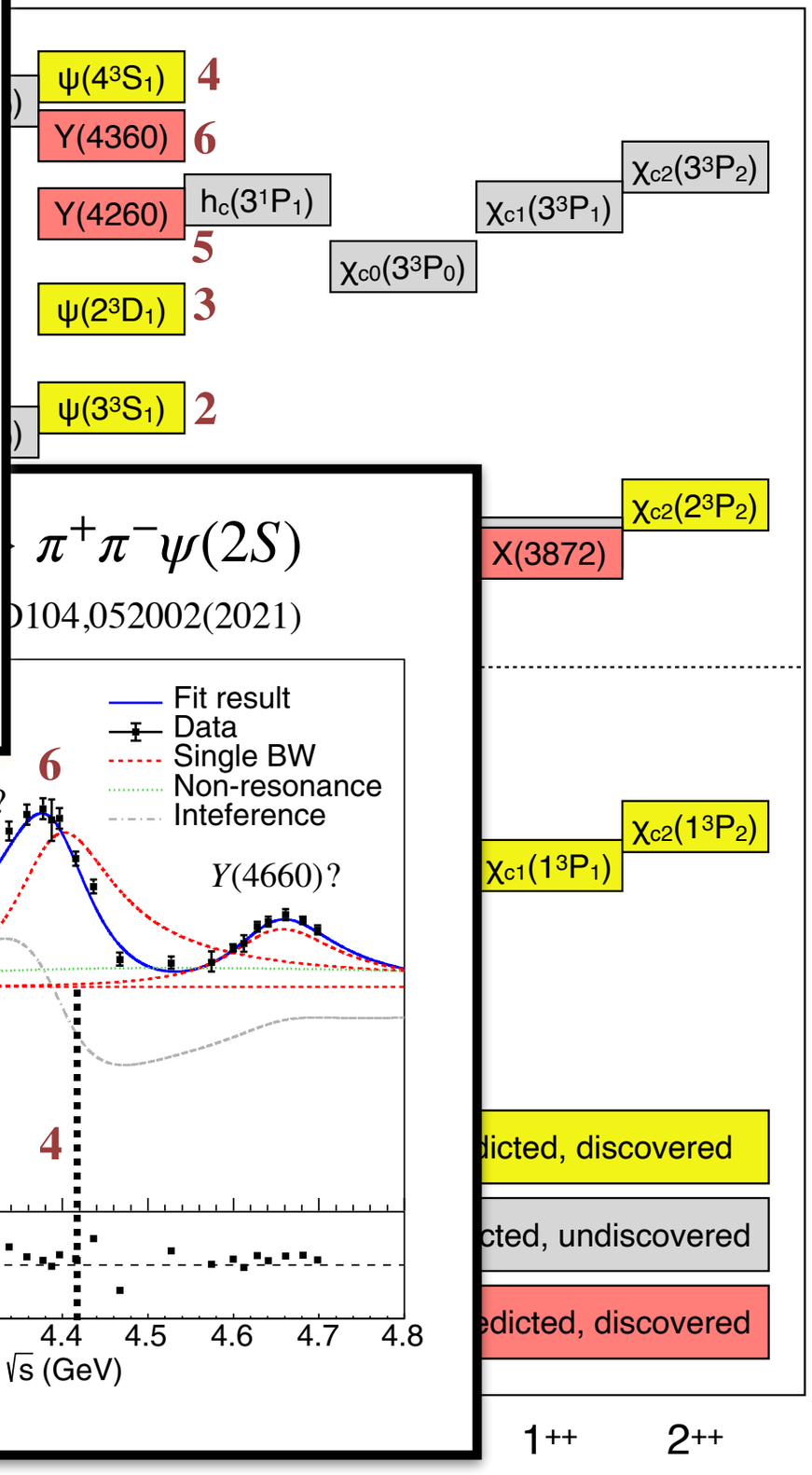
$e^+e^- \to \pi^+\pi^-\psi(2S)$

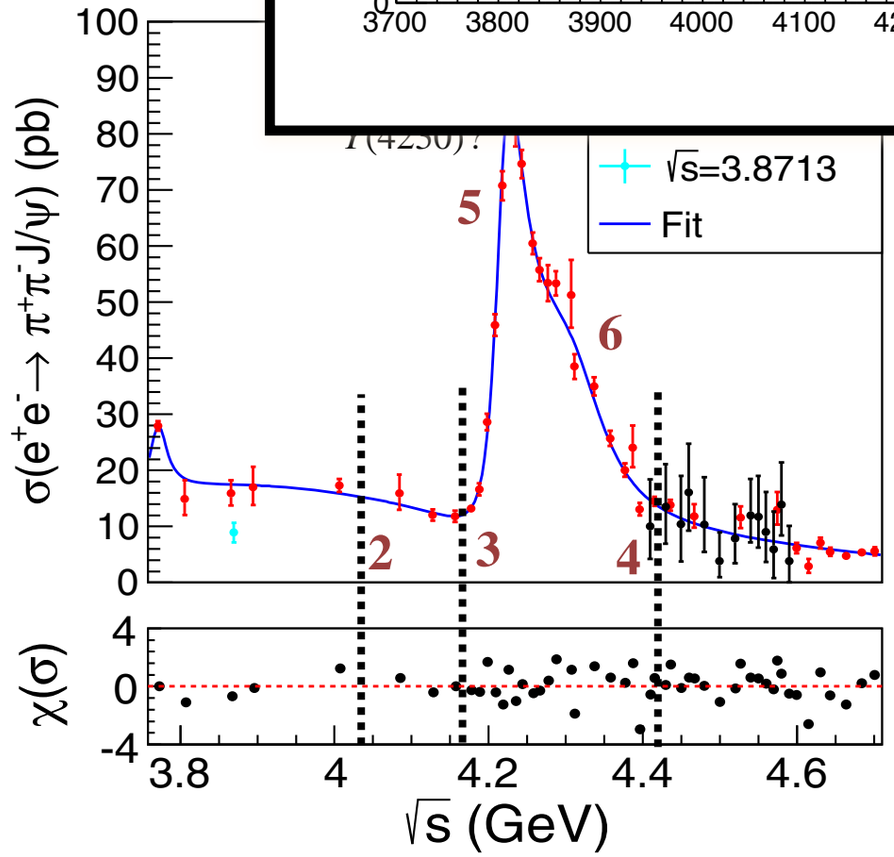
BESIII, PRD104,052002(2021)

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



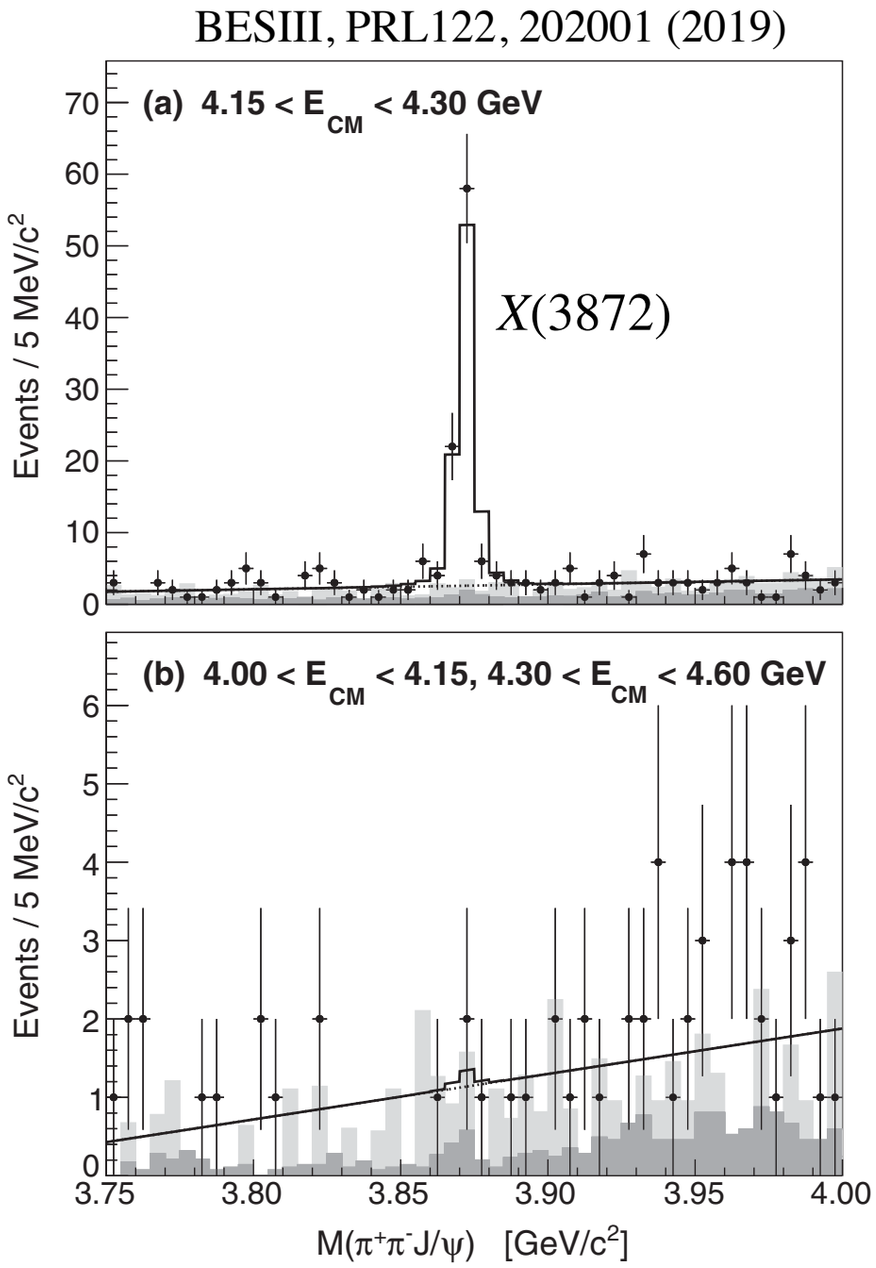
armonium spectrum:



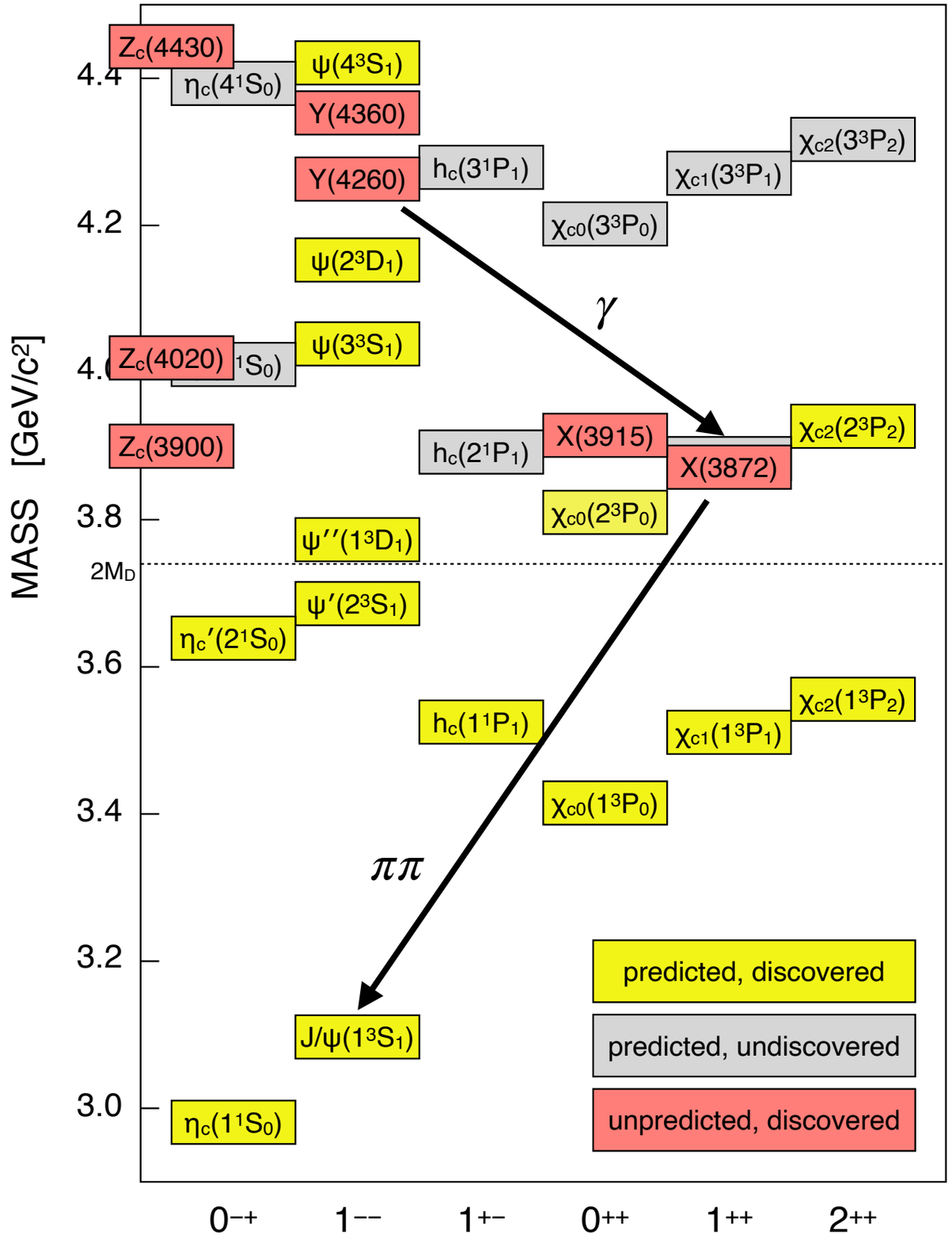


IV. The Plates: $c\bar{c}$ and cc mesons

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



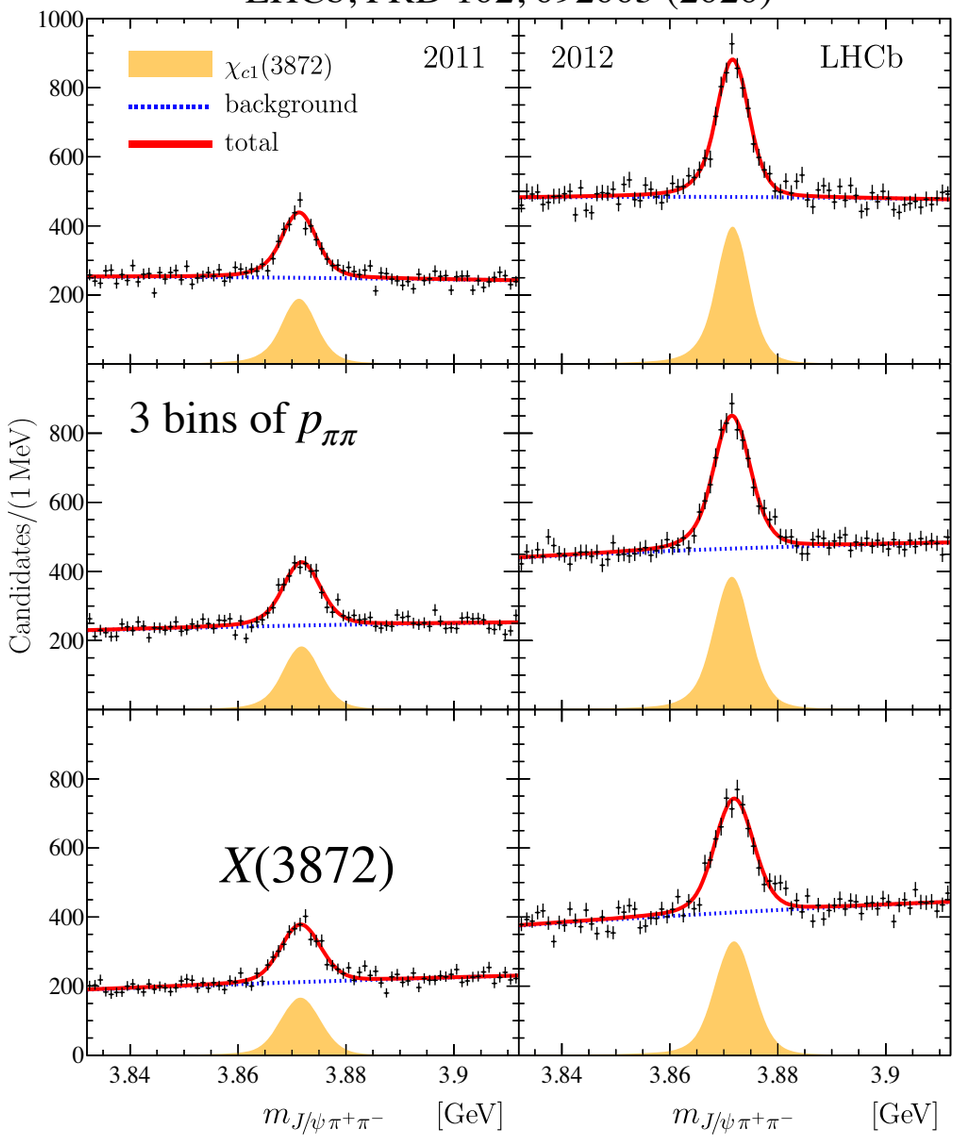
The charmonium spectrum:



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

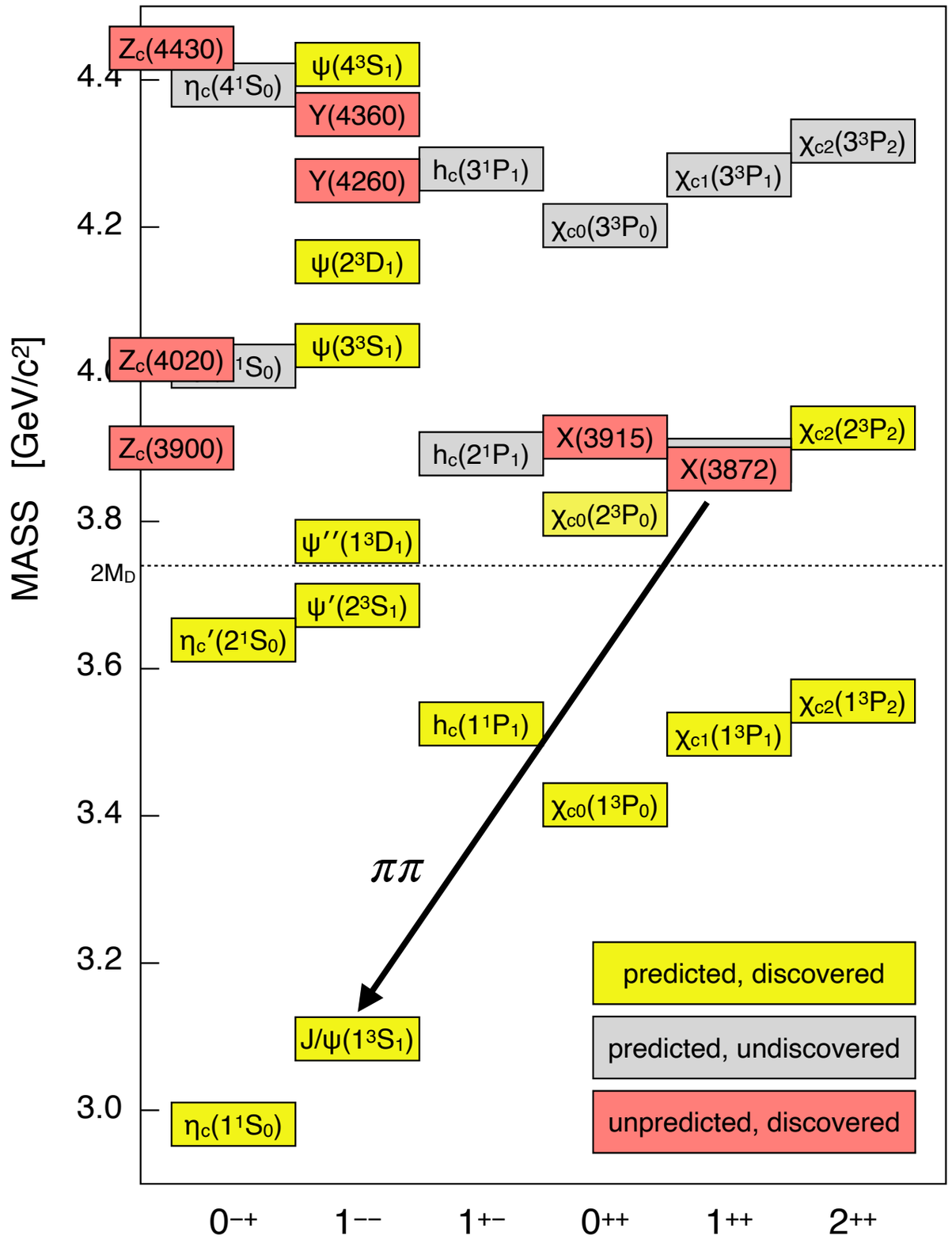
$$pp \to b\bar{b} + \text{hadrons}$$
$$\to X(3872) + \text{hadrons}$$
$$\to (\pi^+\pi^- J/\psi) + \text{hadrons}$$

LHCb, PRD 102, 092005 (2020)



$$M_{\rm BW}(X(3872)) - M(D^{*0}\bar{D}^0) = -0.05 \pm 0.12 \text{ MeV}/c^2$$
$$\Gamma_{\rm BW}(X(3872)) = 1.39 \pm 0.24 \pm 0.10 \text{ MeV}/c^2$$

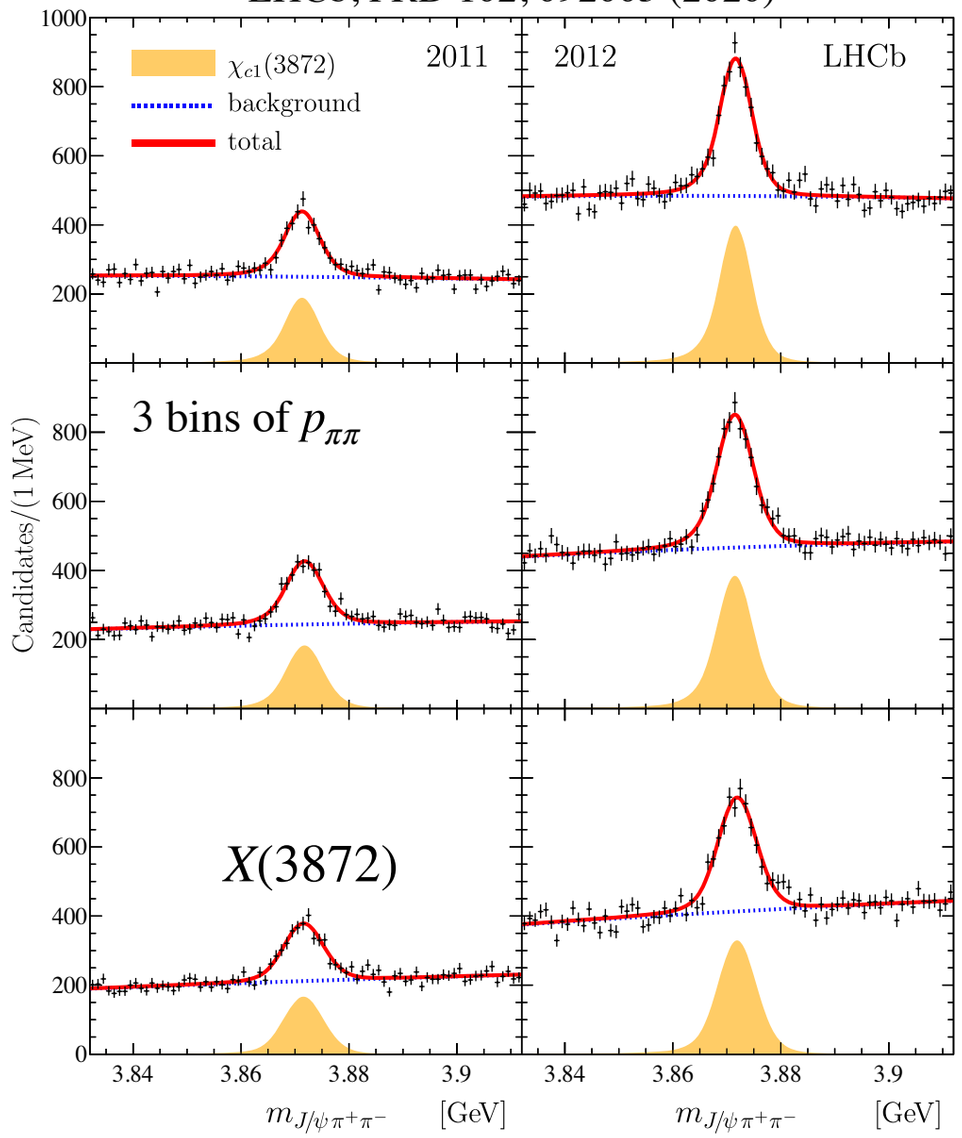
The charmonium spectrum:



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

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

LHCb, PRD 102, 092005 (2020)



$$M_{\rm BW}(X(3872)) - M(D^{*0}\bar{D}^0) = -0.05 \pm 0.12 \text{ MeV}/c^2$$
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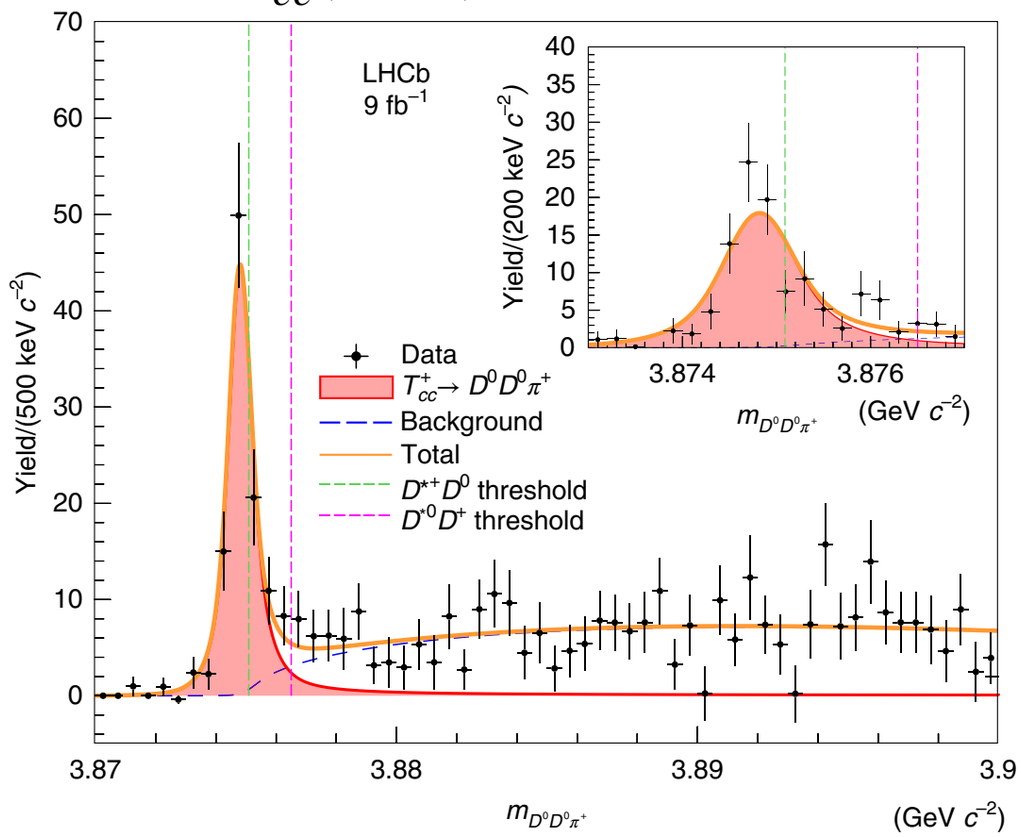
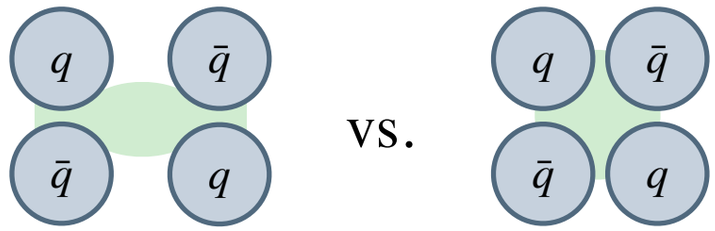
NATURE PHYSICS | VOL 18 | JULY 2022 | 751–754 |

LHCb

Observation of an exotic narrow doubly charmed tetraquark

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





???

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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

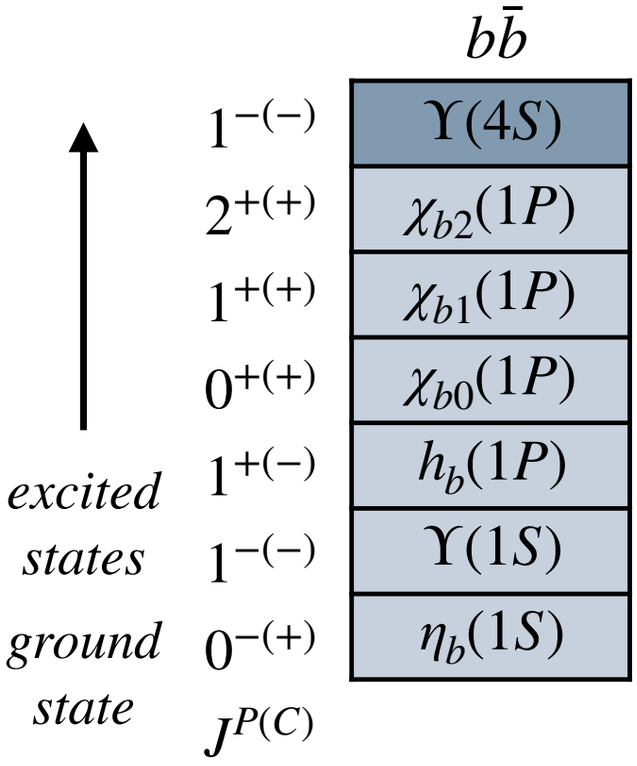
- K^+ family *(weak decays, no mixing)*
- K^0 family *(weak decays, mixing)*
- π^0 family *(large electromagnetic decays)*
- J/ψ family *(strong decays, near or below open flavor threshold)*
- ρ family *(strong decays, above open flavor threshold)*
- $Z_c(3900)$ family *(exotic flavor quantum numbers)*

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

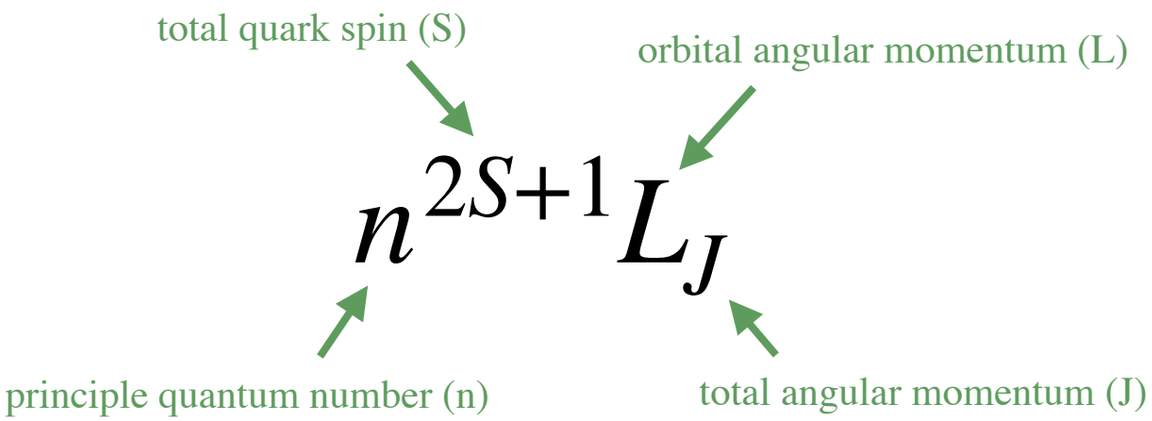
excited states ↑ *ground state*

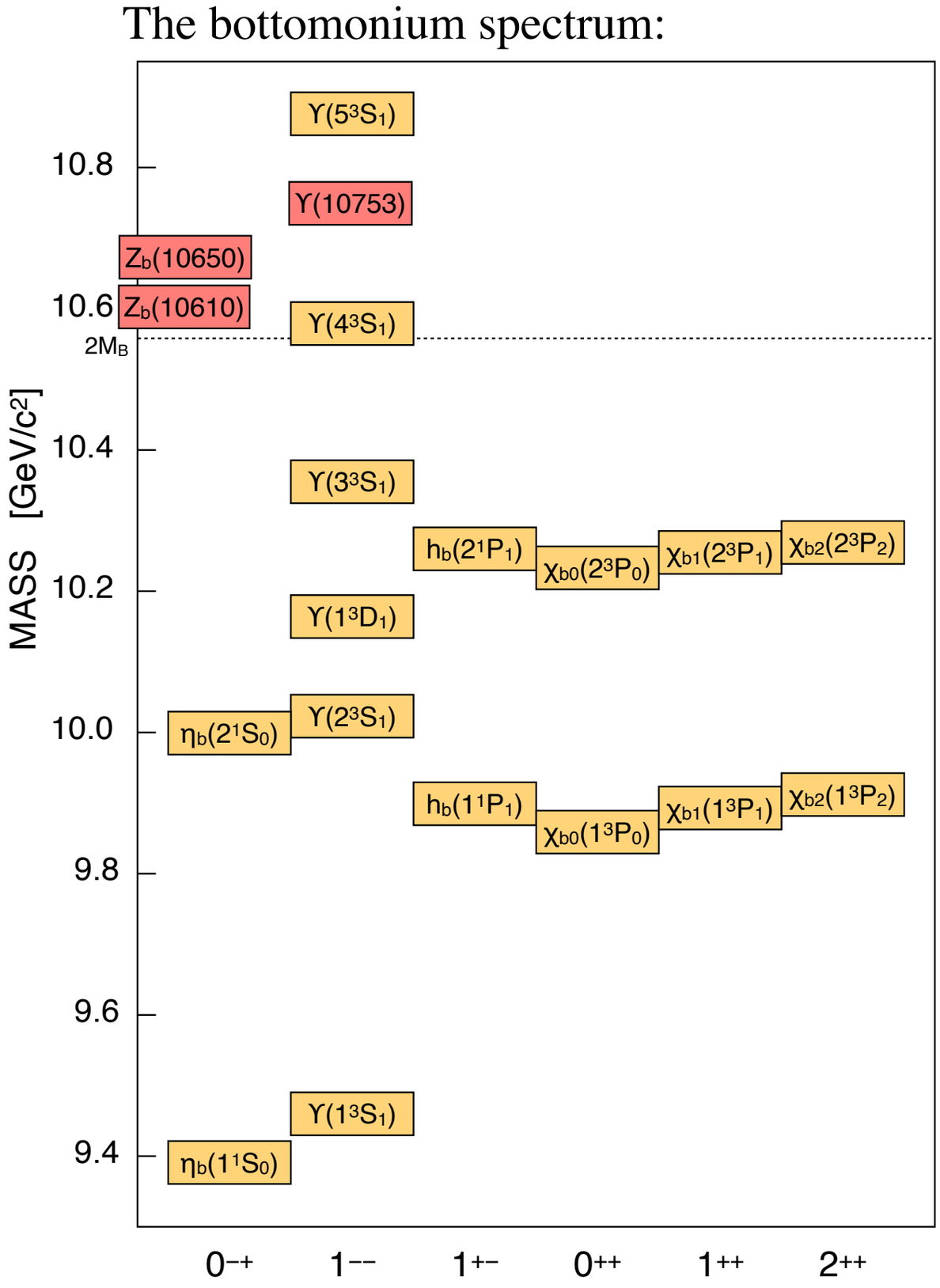
$Z_c(4020)^+ \to \pi^+ h_c$	$Z_c(4430)^+ \to \pi^+ \psi(2S)$	$Z_b(10650)^+ \to \pi^+ h_b, \pi^+ \Upsilon$	$X(2900)^0 \to D^+ K^-$
$Z_c(3900)^+ \to \pi^+ J/\psi$	$Z_{cs}(4000)^+ \to K^+ J/\psi$	$Z_b(10610)^+ \to \pi^+ h_b, \pi^+ \Upsilon$	$T_{cc\bar{c}\bar{c}}(6900) \to J/\psi J/\psi$

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



Spectroscopic notation:



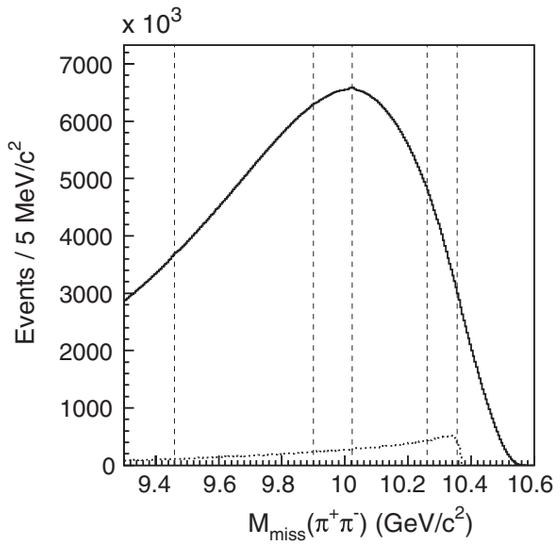


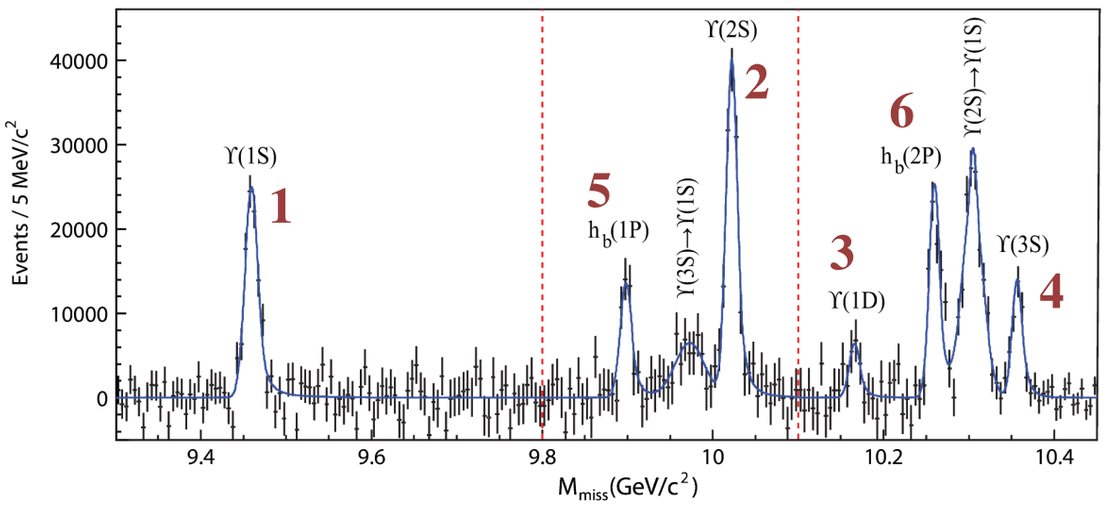
V. The Plates: $b\bar{b}$ and bb mesons

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

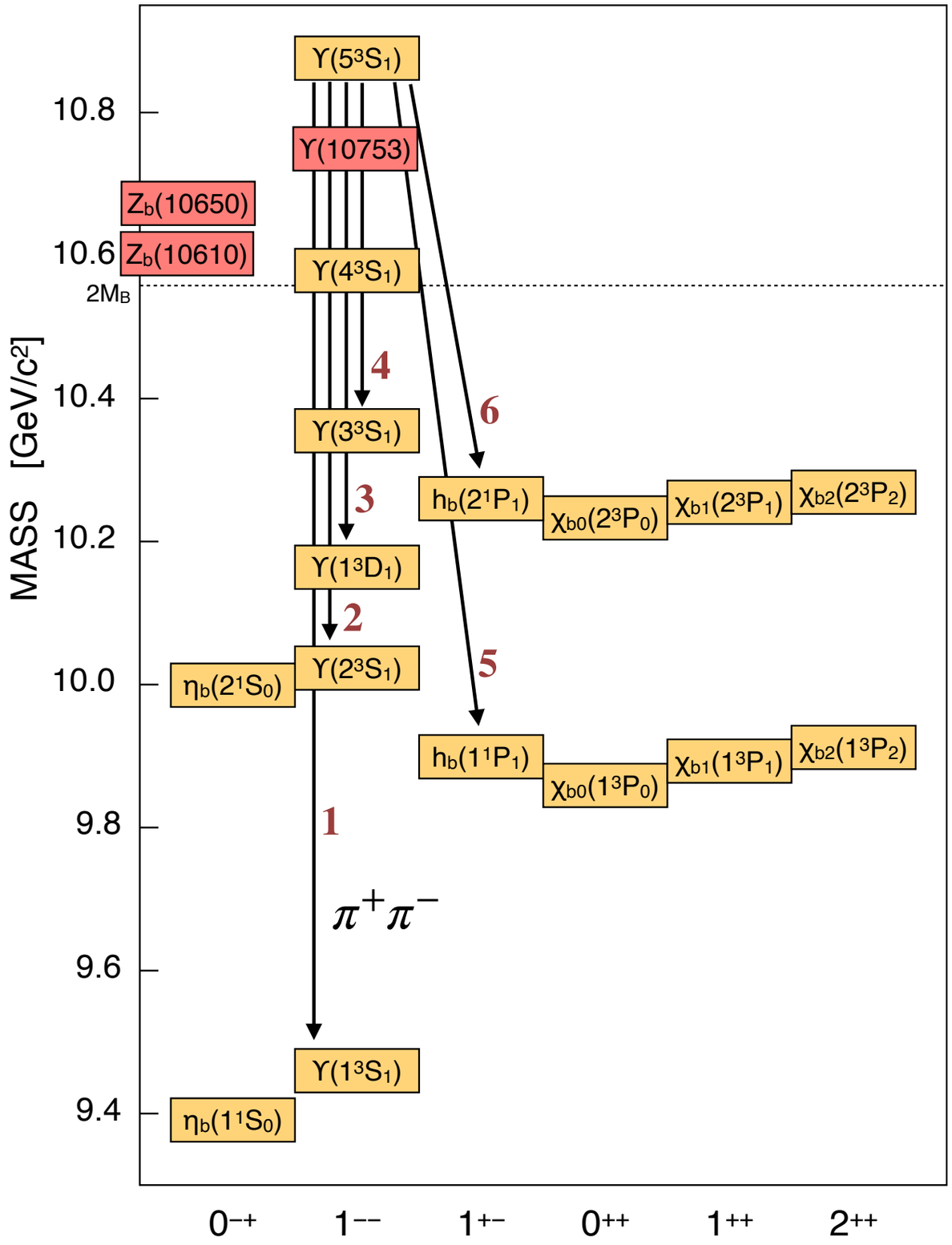
First Observation of the *P*-Wave Spin-Singlet Bottomonium States $h_b(1P)$ and $h_b(2P)$

Belle





The bottomonium spectrum:

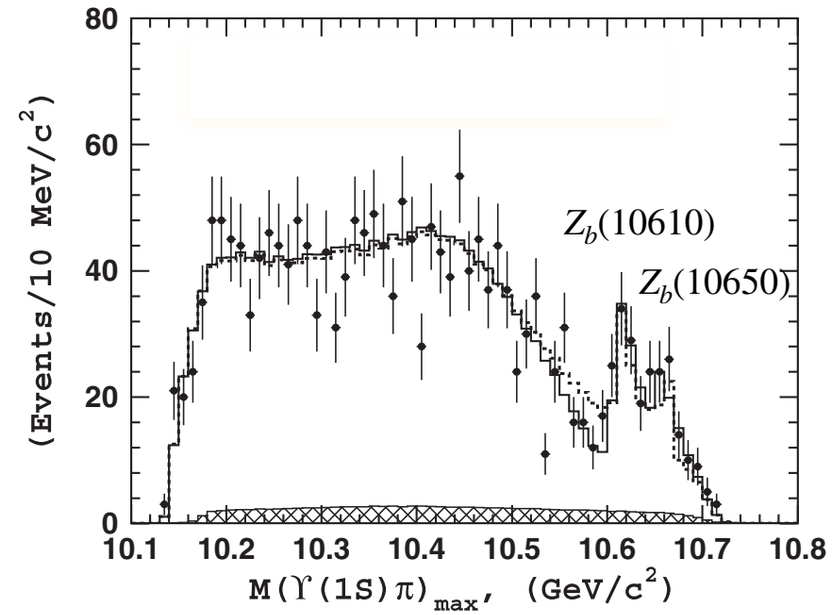


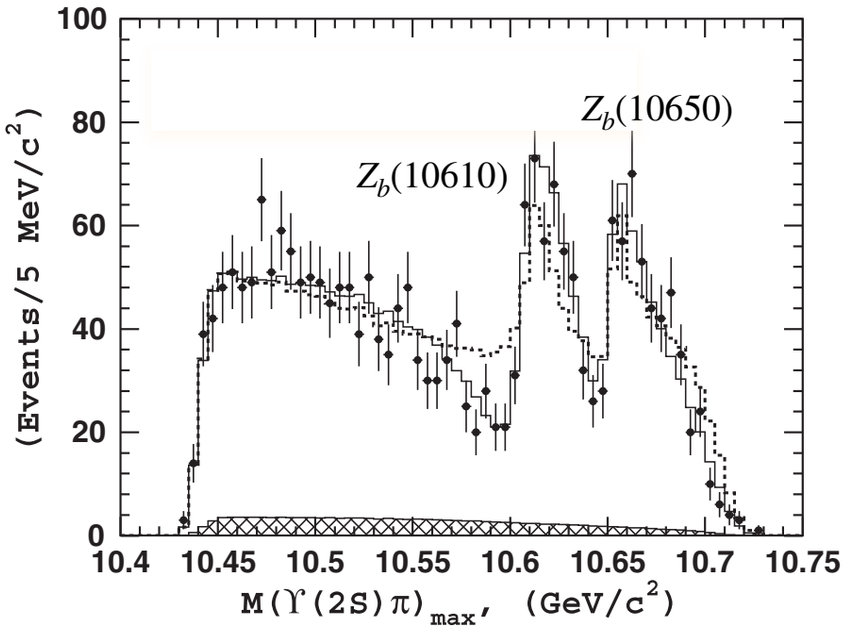
V. The Plates: $b\bar{b}$ and bb mesons

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

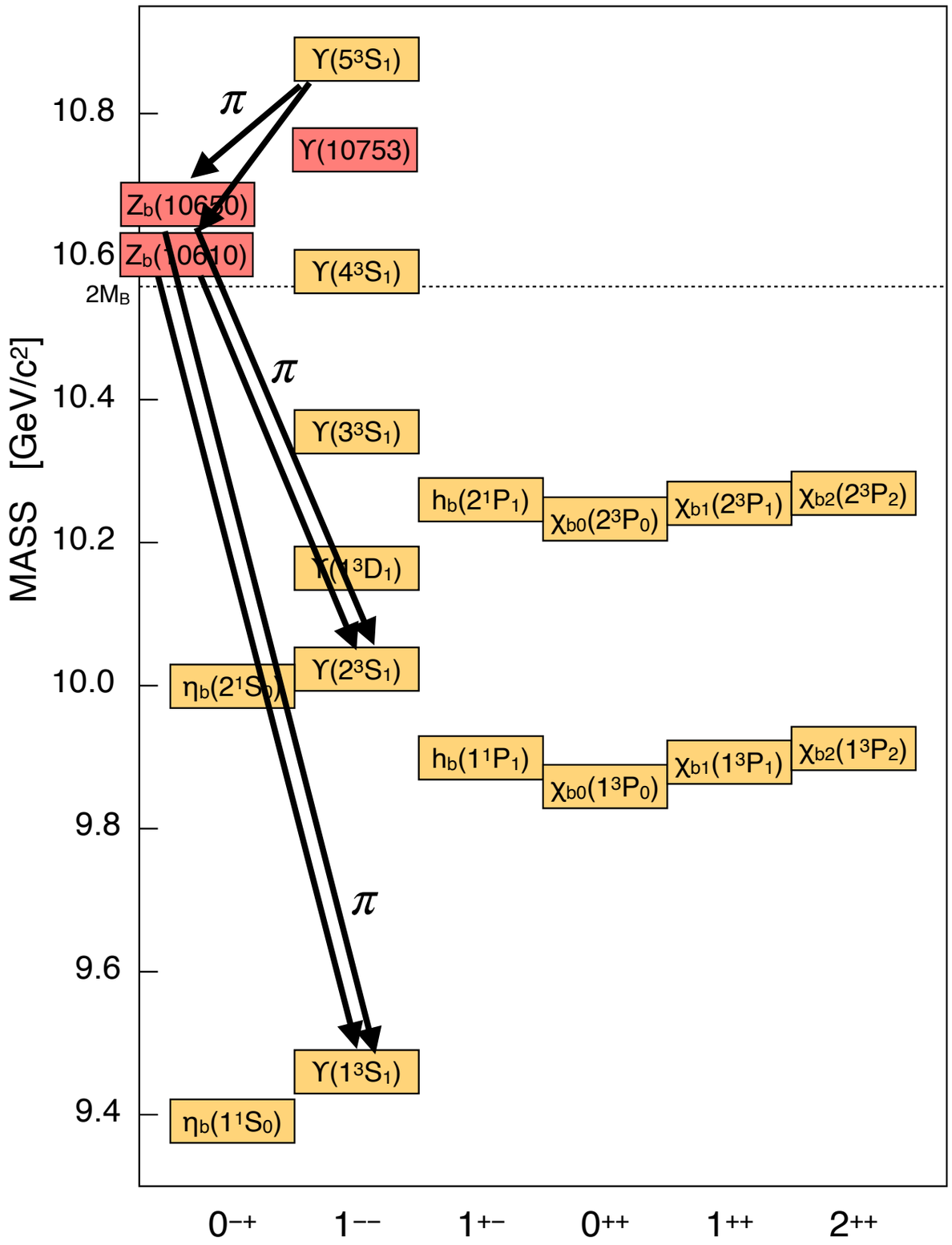
Belle

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





The bottomonium spectrum:

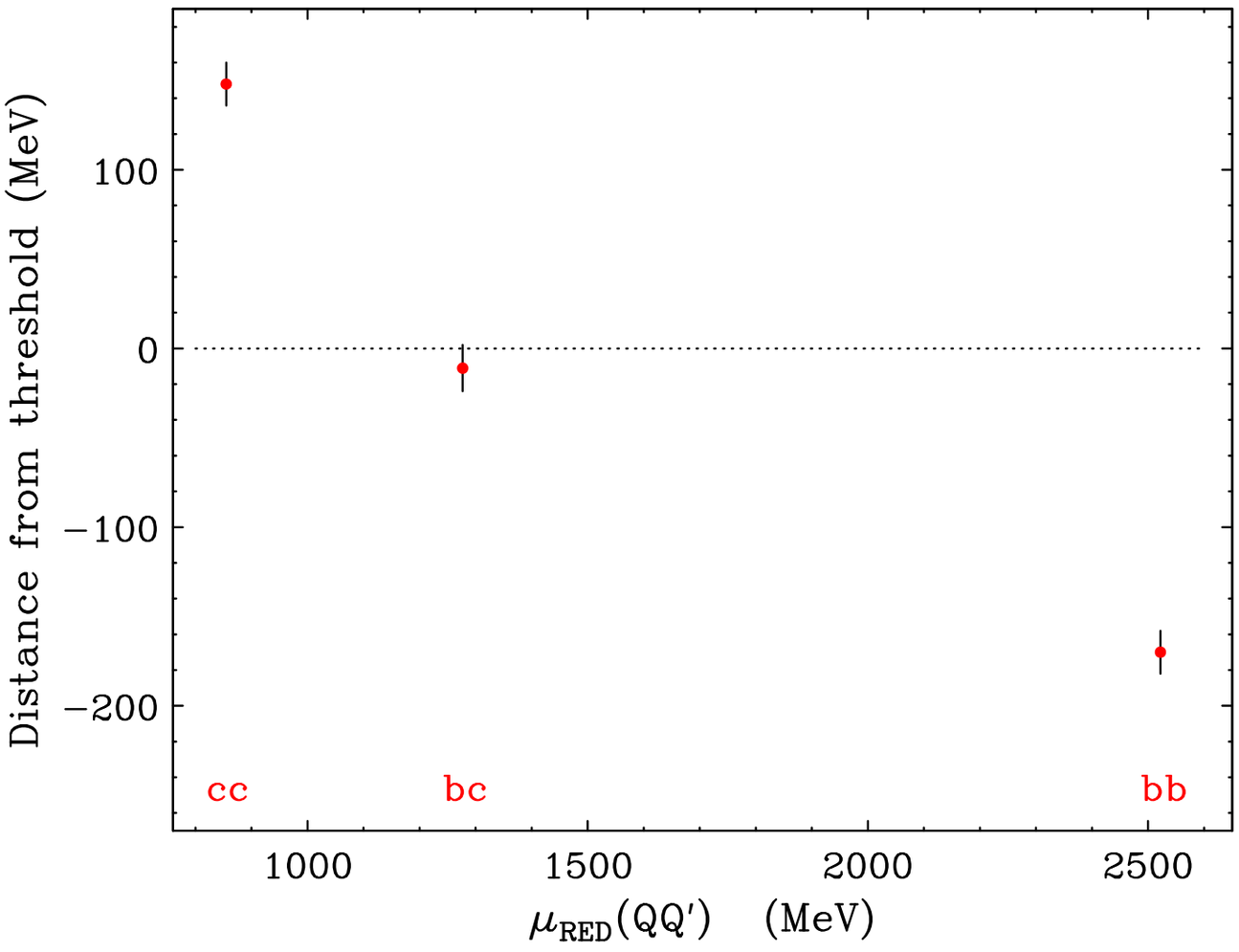


V. The Plates: $b\bar{b}$ and bb mesons

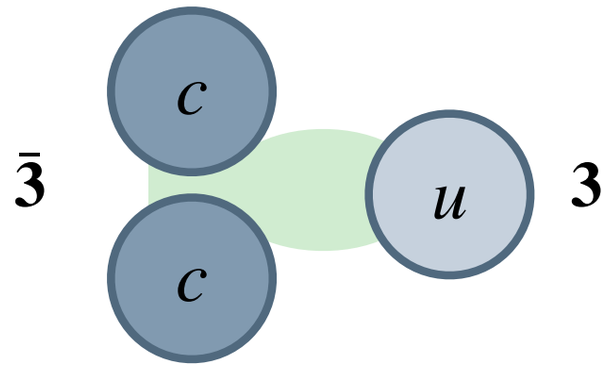
PRL **119,** 202001 (2017) PHYSICAL REVIEW LETTERS week ending 17 NOVEMBER 2017

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

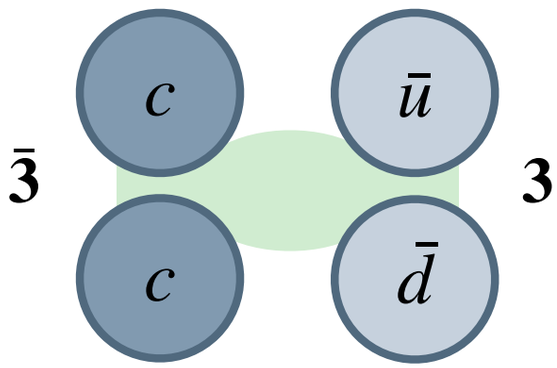
Marek Karliner[1,*] and Jonathan L. Rosner[2,†]



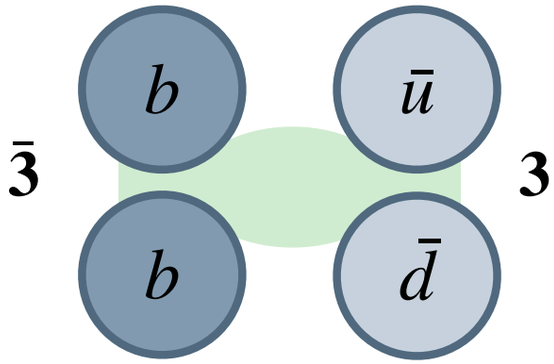
Ξ_{cc}^{++} baryon:



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



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

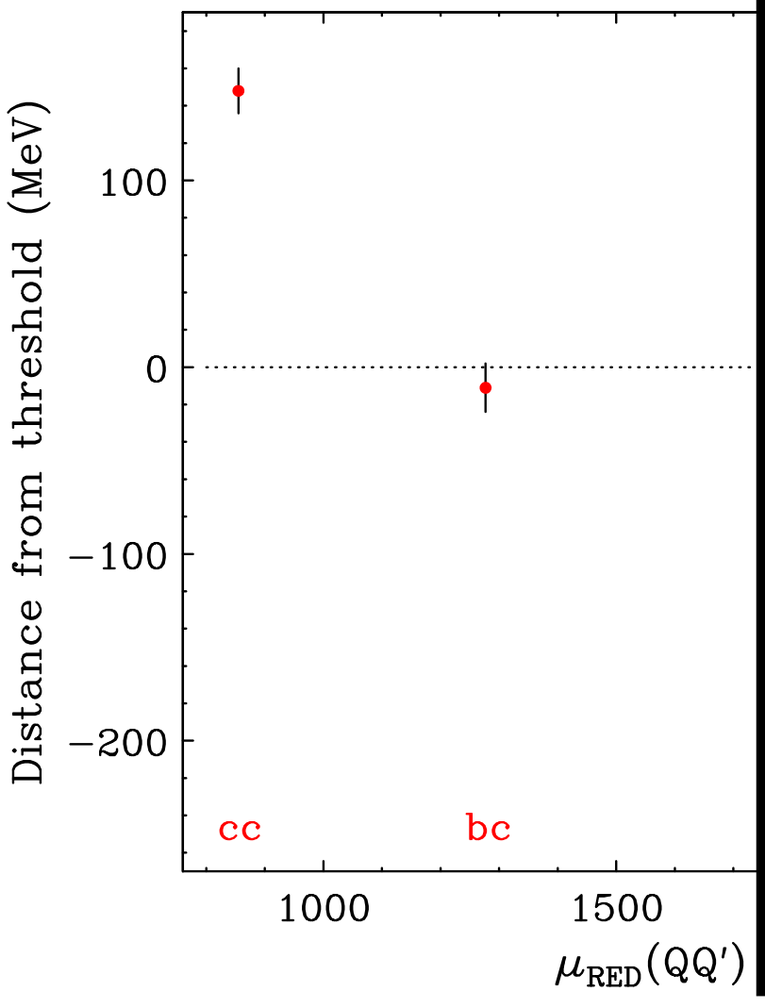


V. The Plates: $b\bar{b}$ and bb mesons

PRL 119, 202001 (2017) PHYSICAL REVI

Discovery of the Doubly Charmed Ξ_{cc} Ba

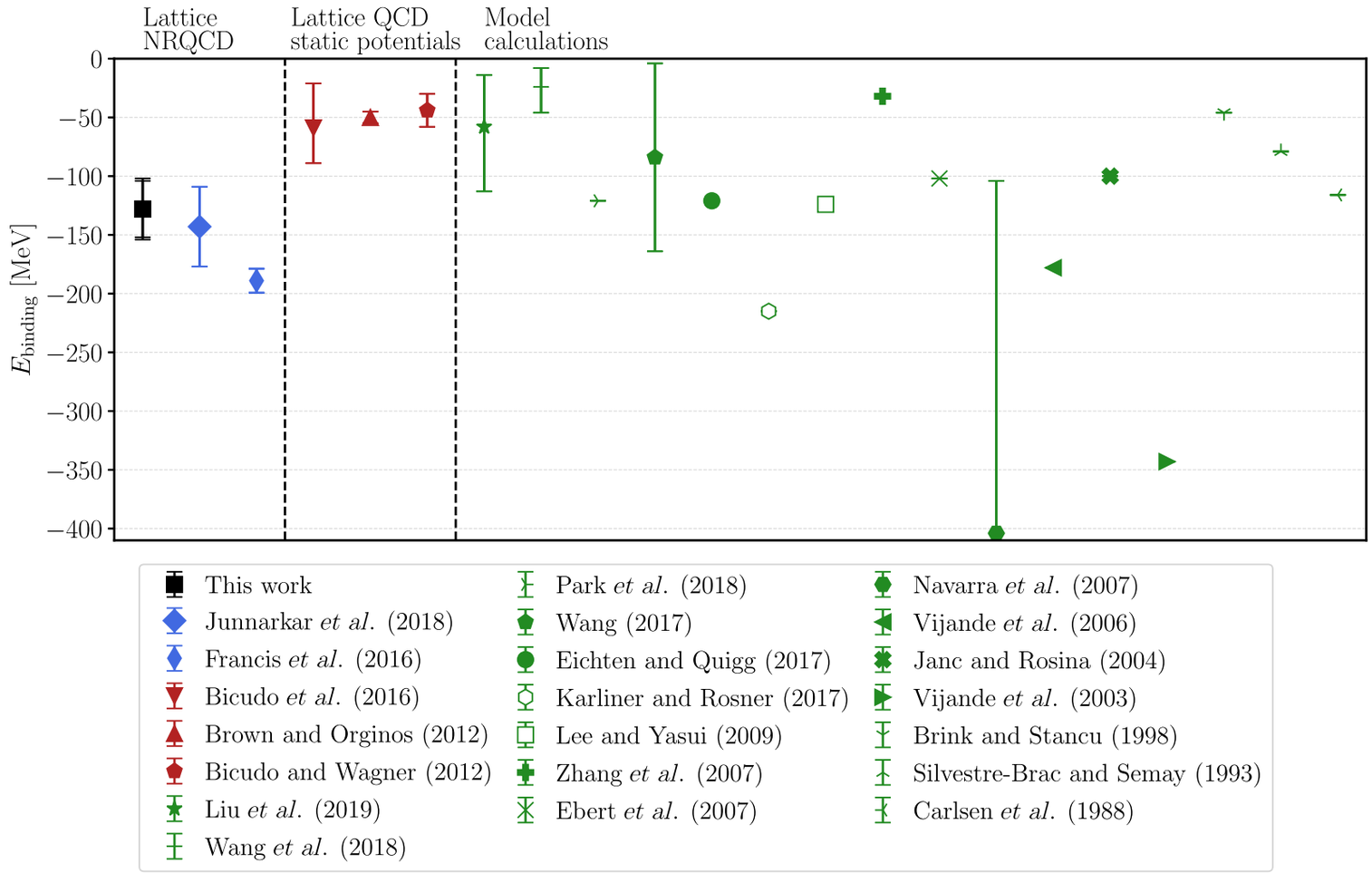
Marek Karliner[1,*] and J



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]



A Field Guide to the Mesons

Contents

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?

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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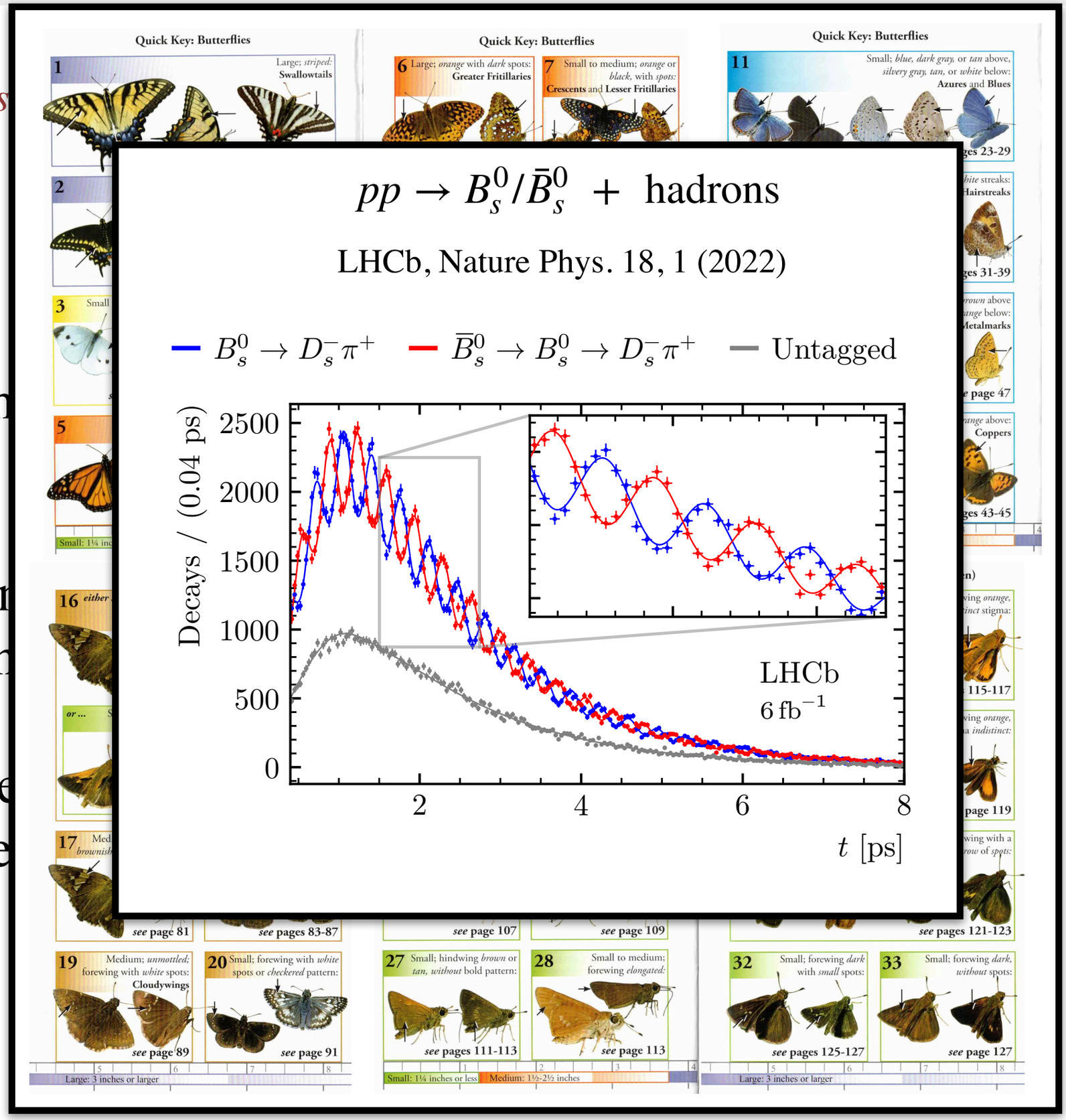

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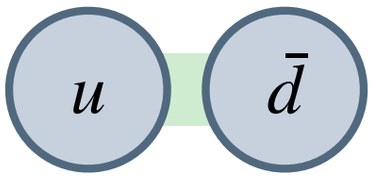
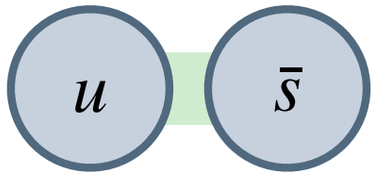
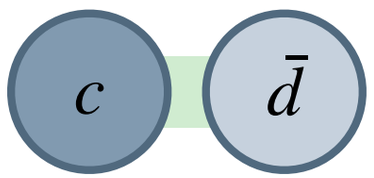
A Field Guide to the Mesons



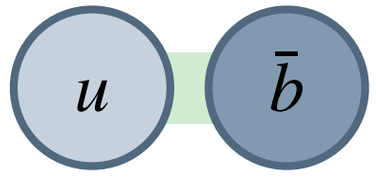
π^+ (pion)
$M \approx 140$ MeV
$J^P = 0^-$



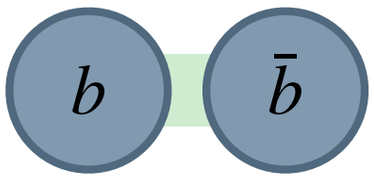
K^+ (kaon)
$M \approx 494$ MeV
$J^P = 0^-$



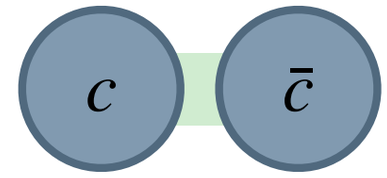
D^+ (D meson)
$M \approx 1870$ MeV
$J^P = 0^-$



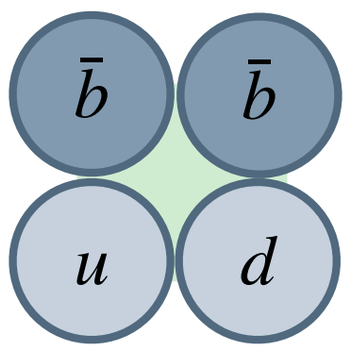
B^+ (B meson)
$M \approx 5279$ MeV
$J^P = 0^-$



$\Upsilon(1S)$ (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
$J^P = 1^+$

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I. What are Mesons?

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The collecting/sorting/analyzing continues!

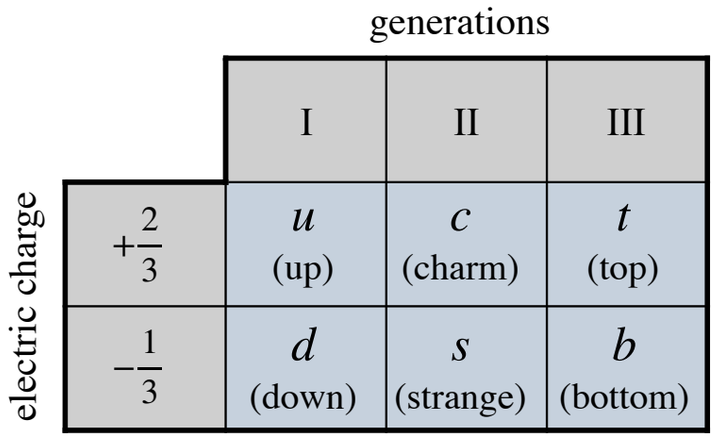
Hadron Spectroscopy

NNPSS, IU, July 24-25, 2024

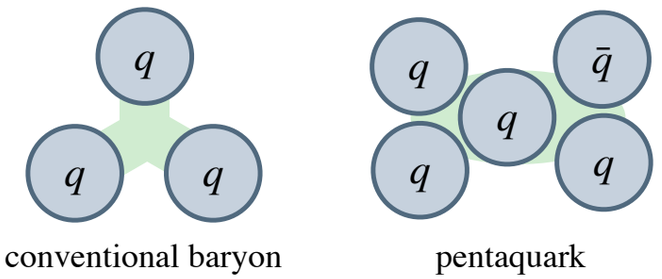
Lecture 1:
An Experimental Overview
Ryan Mitchell
Indiana University
(BESIII, GlueX, PDG)

Lecture 2:
A Theoretical Overview
Adam Szczepaniak
Indiana University
(JPAC)

QUARKS



BARYONS



MESONS