HUGS 2021 Lectures on:
Experimental Meson Spectroscopy

Prologue: Definitions and Philosophy

I. A Field Guide to Meson Families

II. Meson Quantum Numbers

III. The Quark Model

IV. Exotic Mesons

V. Current and Future Experiments

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I'm a member of the:
BESIII Experiment
GlueX Experiment
Particle Data Group
(which will color these lectures)

HUGS 2021 Lectures on:
Experimental Meson Spectroscopy

Jianwei covered some of this material very clearly *(the zoom transcript was less clear)*:

with three full meals, like for example omega minus three.

13:47:34

Australia calls. If they also need the grace day, then they they like to be known as the grandstand they like to be symmetric but we know for the familiar you like to have the overall waveforms to be anti symmetric.

13:47:45

So then if you put those two Republicans together, you have a potential to violate all the politics principle. That means you need another quantum number to help you to distinguish those states.

13:47:55

So that. Exactly.

Ryan Mitchell

strong track your physics, I was taught my lectures, with the discovery of all the headphones, a venture from hadron to the pothole, the potholes to hydro, that's the plan.

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Prologue: Definitions and Philosophy

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

$\Longrightarrow$ *strongly interacting particles*

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

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

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

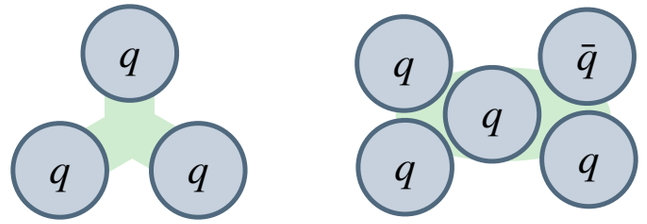
$\Longrightarrow$ *strongly interacting particles, bosons, baryon number = 0*

Spectroscopy: use the diverse spectrum of hadrons/baryons/mesons to explore the strong force (QCD)

QUARKS

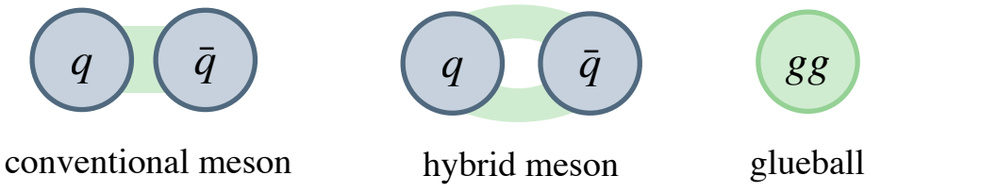
electric charge \ generations	I	II	III
$+\frac{2}{3}$	u (up)	c (charm)	t (top)
$-\frac{1}{3}$	d (down)	s (strange)	b (bottom)

BARYONS



conventional baryon pentaquark

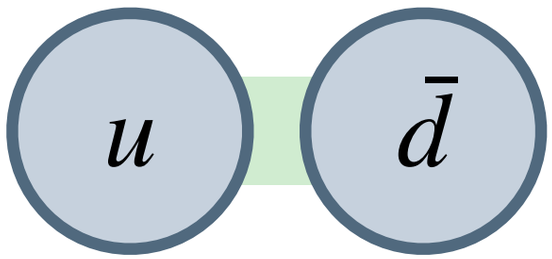
MESONS



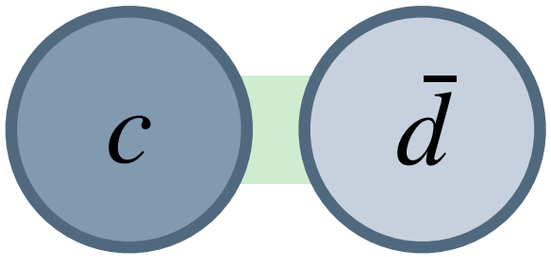
conventional meson hybrid meson glueball

tetraquark meson molecule baryonium

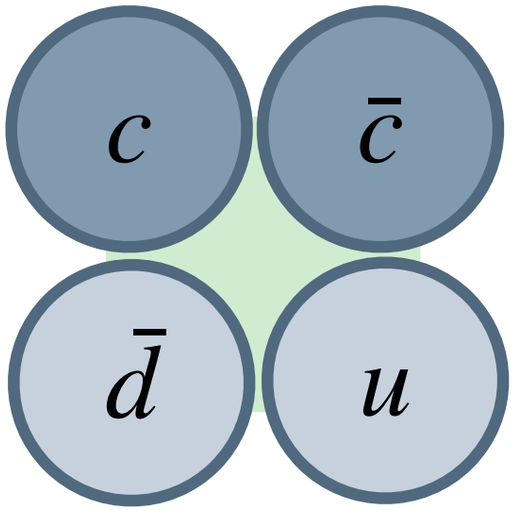
Prologue: Definitions and Philosophy



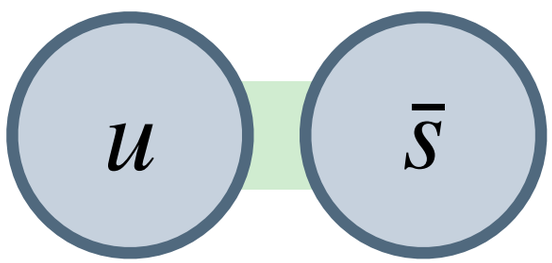
π^+ (pion)
$M \approx 140$ MeV
$J^P = 0^-$



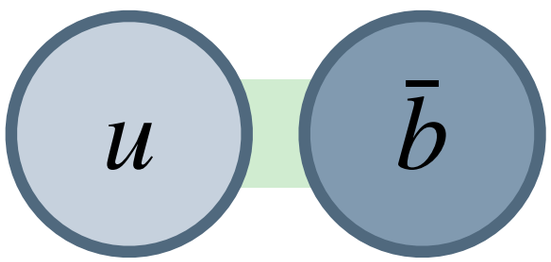
D^+ (D meson)
$M \approx 1870$ MeV
$J^P = 0^-$



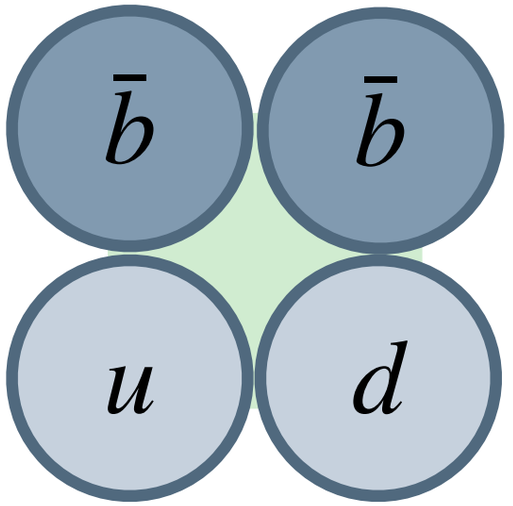
$Z_c(3900)^+$
$M \approx 3900$ MeV
$J^P = 1^+$



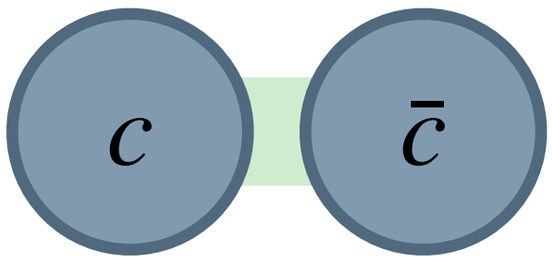
K^+ (kaon)
$M \approx 494$ MeV
$J^P = 0^-$



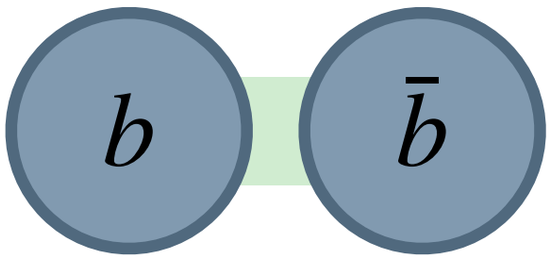
B^+ (B meson)
$M \approx 5279$ MeV
$J^P = 0^-$



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



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



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

Prologue: Definitions and Philosophy

PHYSICAL REVIEW D **100,** 054503 (2019)

Hybrid static potential flux tubes from SU(2) and SU(3) lattice gauge theory

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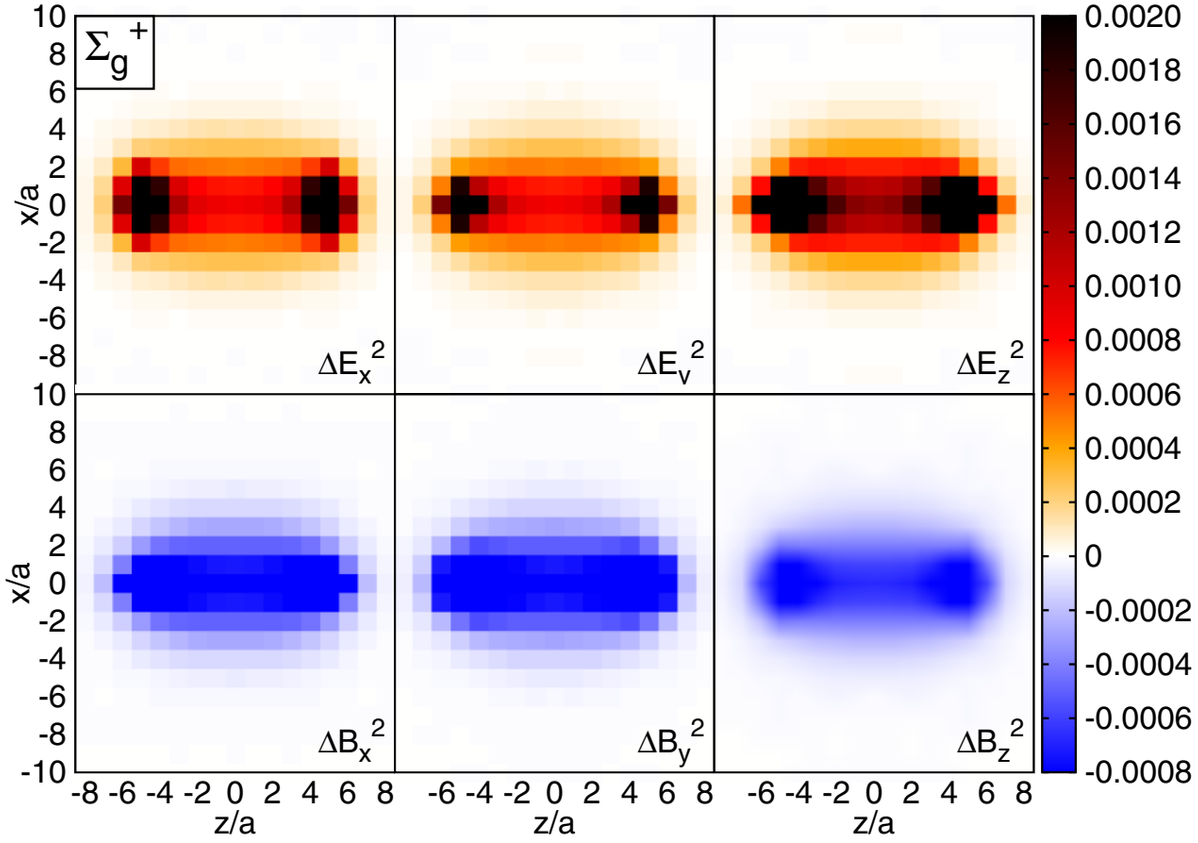
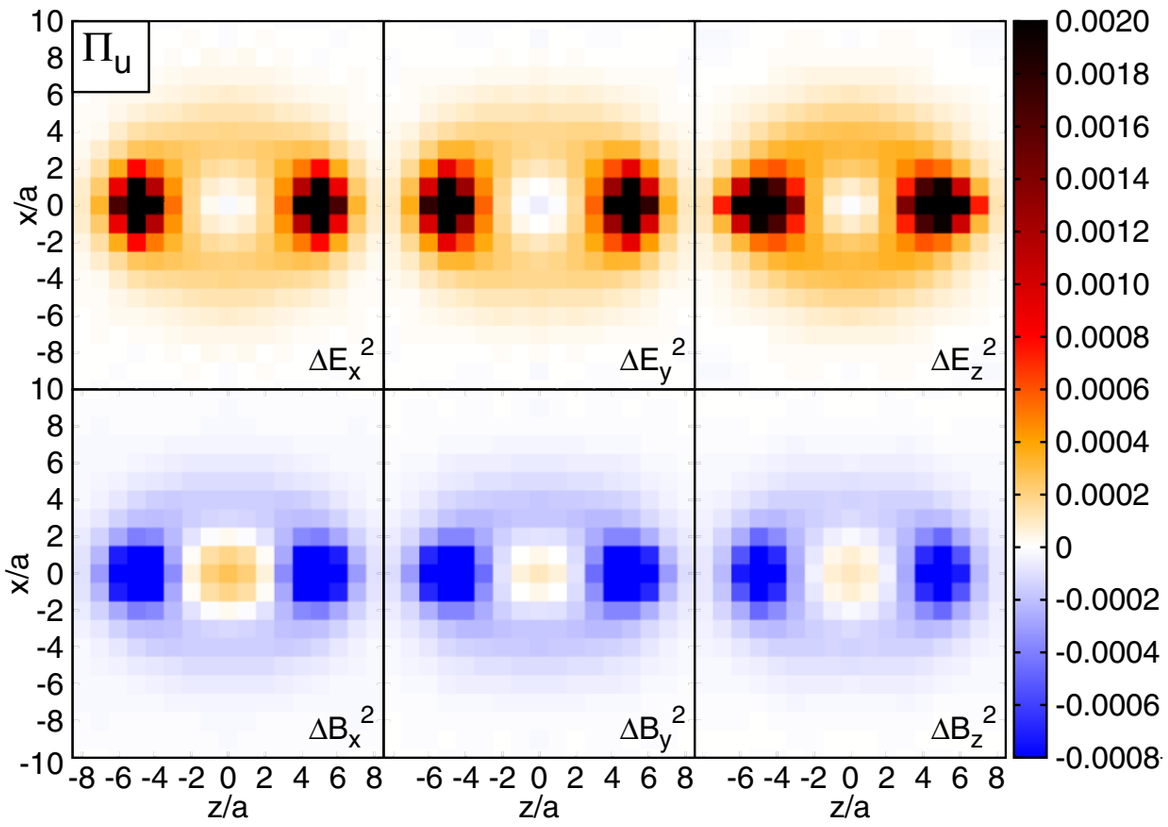
(Received 15 July 2019; published 16 September 2019)

We compute chromoelectric and chromomagnetic flux densities for hybrid static potentials in SU(2) and SU(3) lattice gauge theory. In addition to the ordinary static potential with quantum numbers $\Lambda_\eta^\epsilon = \Sigma_g^+$, we present numerical results for seven hybrid static potentials corresponding to $\Lambda_\eta^{(\epsilon)} = \Sigma_u^+, \Sigma_g^-, \Sigma_u^-, \Pi_g, \Pi_u, \Delta_g, \Delta_u$, where the flux densities of five of them are studied for the first time in this work. We observe hybrid static potential flux tubes, which are significantly different from that of the ordinary static potential. They are reminiscent of vibrating strings, with localized peaks in the flux densities that can be interpreted as valence gluons.





Prologue: Definitions and Philosophy

Meson Summary Table

See also the table of suggested $q\bar{q}$ quark-model assignments in the Quark Model section.

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

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

OTHER LIGHT
Further States

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

CHARMED, STRANGE ($C = S = \pm1$)	$I(J^P)$
• $D_s^\pm$	$0(0^-)$
• $D_s^{*\pm}$	$0(?^?)$
• $D_{s0}^*(2317)^\pm$	$0(0^+)$
• $D_{s1}(2460)^\pm$	$0(1^+)$
• $D_{s1}(2536)^\pm$	$0(1^+)$
• $D_{s2}^*(2573)$	$0(2^+)$
• $D_{s1}^*(2700)^\pm$	$0(1^-)$
$D_{s1}^*(2860)^\pm$	$0(1^-)$
$D_{s3}^*(2860)^\pm$	$0(3^-)$
$D_{sJ}(3040)^\pm$	$0(?^?)$

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^*	$1/2(1^-)$
• $B_1(5721)^+$	$1/2(1^+)$
• $B_1(5721)^0$	$1/2(1^+)$
$B_J^*(5732)$	$?(?^?)$
• $B_2^*(5747)^+$	$1/2(2^+)$
• $B_2^*(5747)^0$	$1/2(2^+)$
$B_J(5840)^+$	$1/2(?^?)$
$B_J(5840)^0$	$1/2(?^?)$
• $B_J(5970)^+$	$1/2(?^?)$
• $B_J(5970)^0$	$1/2(?^?)$

BOTTOM, STRANGE ($B = \pm1$, $S = \mp1$)	$I(J^P)$
• B_s^0	$0(0^-)$
• B_s^*	$0(1^-)$
$X(5568)^\pm$	$?(?^?)$
• $B_{s1}(5830)^0$	$0(1^+)$
• $B_{s2}^*(5840)^0$	$0(2^+)$
$B_{s,J}^*(5850)$	$?(?^?)$

BOTTOM, CHARMED ($B = C = \pm1$)	$I(J^P)$
• B_c^+	$0(0^-)$
$B_c(2S)^\pm$	$0(0^-)$

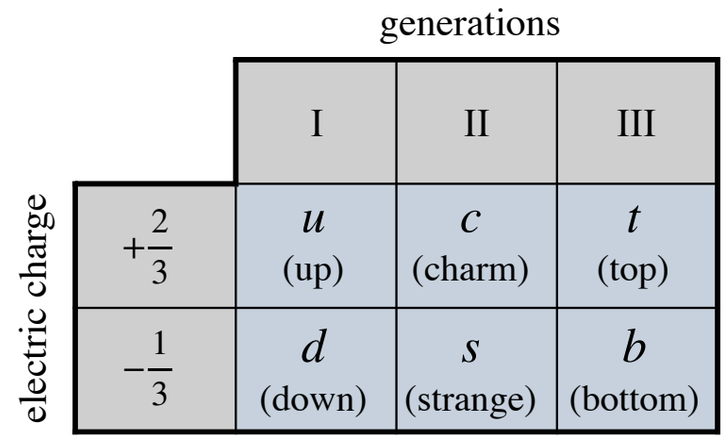
$c\bar{c}$ (+ possibly non-$q\bar{q}$ states)	$I^G(J^{PC})$
• $\eta_c(1S)$	$0^+(0^{-+})$
• $J/\psi(1S)$	$0^-(1^{--})$
• $\chi_{c0}(1P)$	$0^+(0^{++})$
• $\chi_{c1}(1P)$	$0^+(1^{++})$
• $h_c(1P)$	$0^-(1^{+-})$
• $\chi_{c2}(1P)$	$0^+(2^{++})$
• $\eta_c(2S)$	$0^+(0^{-+})$
• $\psi(2S)$	$0^-(1^{--})$

$c\bar{c}$ continued	$I^G(J^{PC})$
• $\psi(3770)$	$0^-(1^{--})$
• $\psi_2(3823)$	$0^-(2^{--})$
• $\psi_3(3842)$	$0^-(3^{--})$
$\chi_{c0}(3860)$	$0^+(0^{++})$
• $\chi_{c1}(3872)$	$0^+(1^{++})$
• $Z_c(3900)$	$1^+(1^{+-})$
• $X(3915)$	$0^+(0/2^{++})$
• $\chi_{c2}(3930)$	$0^+(2^{++})$
$X(3940)$	$?^?(?^{??})$
• $X(4020)^\pm$	$1^+(?^{?-})$
• $\psi(4040)$	$0^-(1^{--})$
$X(4050)^\pm$	$1^-(?^{?+})$
$X(4055)^\pm$	$1^+(?^{?-})$
$X(4100)^\pm$	$1^-(?^{??})$
• $\chi_{c1}(4140)$	$0^+(1^{++})$
• $\psi(4160)$	$0^-(1^{--})$
$X(4160)$	$?^?(?^{??})$
$Z_c(4200)$	$1^+(1^{+-})$
• $\psi(4230)$	$0^-(1^{--})$
$R_{c0}(4240)$	$1^+(0^{--})$
$X(4250)^\pm$	$1^-(?^{?+})$
$\psi(4260)$	$0^-(1^{--})$
• $\chi_{c1}(4274)$	$0^+(1^{++})$
$X(4350)$	$0^+(?^{?+})$
• $\psi(4360)$	$0^-(1^{--})$
$\psi(4390)$	$0^-(1^{--})$
• $\psi(4415)$	$0^-(1^{--})$
• $Z_c(4430)$	$1^+(1^{+-})$
$\chi_{c0}(4500)$	$0^+(0^{++})$
• $\psi(4660)$	$0^-(1^{--})$
$\chi_{c0}(4700)$	$0^+(0^{++})$

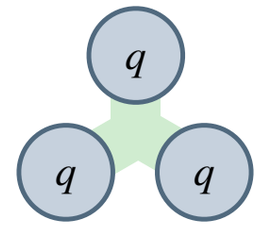
$b\bar{b}$ (+ possibly non-$q\bar{q}$ states)	$I^G(J^{PC})$
• $\eta_b(1S)$	$0^+(0^{-+})$
• $\Upsilon(1S)$	$0^-(1^{--})$
• $\chi_{b0}(1P)$	$0^+(0^{++})$
• $\chi_{b1}(1P)$	$0^+(1^{++})$
• $h_b(1P)$	$0^-(1^{+-})$
• $\chi_{b2}(1P)$	$0^+(2^{++})$
$\eta_b(2S)$	$0^+(0^{-+})$
• $\Upsilon(2S)$	$0^-(1^{--})$
• $\Upsilon_2(1D)$	$0^-(2^{--})$
• $\chi_{b0}(2P)$	$0^+(0^{++})$
• $\chi_{b1}(2P)$	$0^+(1^{++})$
$h_b(2P)$	$0^-(1^{+-})$
• $\chi_{b2}(2P)$	$0^+(2^{++})$
• $\Upsilon(3S)$	$0^-(1^{--})$
• $\chi_{b1}(3P)$	$0^+(1^{++})$
• $\chi_{b2}(3P)$	$0^+(2^{++})$
• $\Upsilon(4S)$	$0^-(1^{--})$
• $Z_b(10610)$	$1^+(1^{+-})$
• $Z_b(10650)$	$1^+(1^{+-})$
$\Upsilon(10753)$	$?^?(1^{--})$
• $\Upsilon(10860)$	$0^-(1^{--})$
• $\Upsilon(11020)$	$0^-(1^{--})$

Particle Data Group (PDG) Meson Summary Table

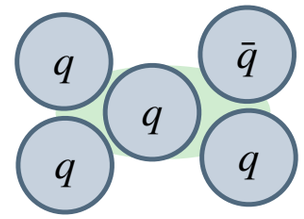
QUARKS



BARYONS

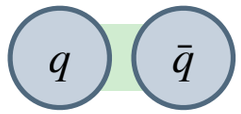


conventional baryon

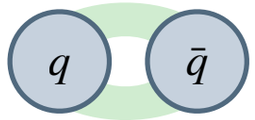


pentaquark

MESONS

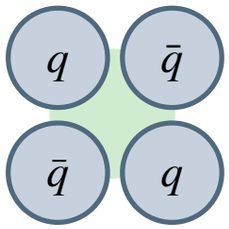


conventional meson

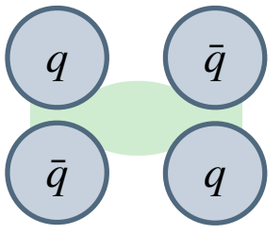


hybrid meson

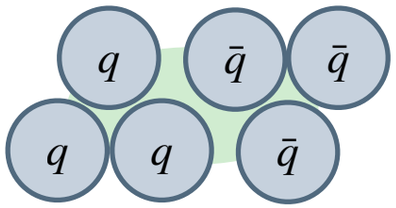
glueball



tetraquark



meson molecule



baryonium

Prologue: Definitions and Philosophy

Meson Summary Table

See also the table of suggested $q\bar{q}$ quark-model assignments in the Quark Model section.

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

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

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

OTHER LIGHT

Further States

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

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

$I(J^P)$	
• $D_s^\pm$	$0(0^-)$
• $D_s^{*\pm}$	$0(?^?)$
• $D_{s0}^*(2317)^\pm$	$0(0^+)$
• $D_{s1}(2460)^\pm$	$0(1^+)$
• $D_{s1}(2536)^\pm$	$0(1^+)$
• $D_{s2}^*(2573)$	$0(2^+)$
• $D_{s1}^*(2700)^\pm$	$0(1^-)$
$D_{s1}^*(2860)^\pm$	$0(1^-)$
$D_{s3}^*(2860)^\pm$	$0(3^-)$
$D_{sJ}(3040)^\pm$	$0(?^?)$

BOTTOM ($B = \pm1$)

• $B^\pm$	$1/2(0^-)$
• 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^*	$1/2(1^-)$
• $B_1(5721)^+$	$1/2(1^+)$
• $B_1(5721)^0$	$1/2(1^+)$
$B_J^*(5732)$	$?(?^?)$
• $B_2^*(5747)^+$	$1/2(2^+)$
• $B_2^*(5747)^0$	$1/2(2^+)$
$B_J(5840)^+$	$1/2(?^?)$
$B_J(5840)^0$	$1/2(?^?)$
• $B_J(5970)^+$	$1/2(?^?)$
• $B_J(5970)^0$	$1/2(?^?)$

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

• B_s^0	$0(0^-)$
• B_s^*	$0(1^-)$
$X(5568)^\pm$	$?(?^?)$
• $B_{s1}(5830)^0$	$0(1^+)$
• $B_{s2}^*(5840)^0$	$0(2^+)$
$B_{sJ}^*(5850)$	$?(?^?)$

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

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

$c\bar{c}$ (+ possibly non-$q\bar{q}$ states)

• $\eta_c(1S)$	$0^+(0^{-+})$
• $J/\psi(1S)$	$0^-(1^{--})$
• $\chi_{c0}(1P)$	$0^+(0^{++})$
• $\chi_{c1}(1P)$	$0^+(1^{++})$
• $h_c(1P)$	$0^-(1^{+-})$
• $\chi_{c2}(1P)$	$0^+(2^{++})$
• $\eta_c(2S)$	$0^+(0^{-+})$
• $\psi(2S)$	$0^-(1^{--})$

$c\bar{c}$ continued

$I^G(J^{PC})$	
• $\psi(3770)$	$0^-(1^{--})$
• $\psi_2(3823)$	$0^-(2^{--})$
• $\psi_3(3842)$	$0^-(3^{--})$
$\chi_{c0}(3860)$	$0^+(0^{++})$
• $\chi_{c1}(3872)$	$0^+(1^{++})$
• $Z_c(3900)$	$1^+(1^{+-})$
• $X(3915)$	$0^+(0/2^{++})$
• $\chi_{c2}(3930)$	$0^+(2^{++})$
$X(3940)$	$?^?(?^{??})$
• $X(4020)^\pm$	$1^+(?^{?-})$
• $\psi(4040)$	$0^-(1^{--})$
$X(4050)^\pm$	$1^-(?^{?+})$
$X(4055)^\pm$	$1^+(?^{?-})$
$X(4100)^\pm$	$1^-(?^{??})$
• $\chi_{c1}(4140)$	$0^+(1^{++})$
• $\psi(4160)$	$0^-(1^{--})$
$X(4160)$	$?^?(?^{??})$
$Z_c(4200)$	$1^+(1^{+-})$
• $\psi(4230)$	$0^-(1^{--})$
$R_{c0}(4240)$	$1^+(0^{--})$
$X(4250)^\pm$	$1^-(?^{?+})$
$\psi(4260)$	$0^-(1^{--})$
• $\chi_{c1}(4274)$	$0^+(1^{++})$
$X(4350)$	$0^+(?^{?+})$
• $\psi(4360)$	$0^-(1^{--})$
$\psi(4390)$	$0^-(1^{--})$
• $\psi(4415)$	$0^-(1^{--})$
• $Z_c(4430)$	$1^+(1^{+-})$
$\chi_{c0}(4500)$	$0^+(0^{++})$
• $\psi(4660)$	$0^-(1^{--})$
$\chi_{c0}(4700)$	$0^+(0^{++})$

$b\bar{b}$ (+ possibly non-$q\bar{q}$ states)

• $\eta_b(1S)$	$0^+(0^{-+})$
• $\Upsilon(1S)$	$0^-(1^{--})$
• $\chi_{b0}(1P)$	$0^+(0^{++})$
• $\chi_{b1}(1P)$	$0^+(1^{++})$
• $h_b(1P)$	$0^-(1^{+-})$
• $\chi_{b2}(1P)$	$0^+(2^{++})$
$\eta_b(2S)$	$0^+(0^{-+})$
• $\Upsilon(2S)$	$0^-(1^{--})$
• $\Upsilon_2(1D)$	$0^-(2^{--})$
• $\chi_{b0}(2P)$	$0^+(0^{++})$
• $\chi_{b1}(2P)$	$0^+(1^{++})$
$h_b(2P)$	$0^-(1^{+-})$
• $\chi_{b2}(2P)$	$0^+(2^{++})$
• $\Upsilon(3S)$	$0^-(1^{--})$
• $\chi_{b1}(3P)$	$0^+(1^{++})$
• $\chi_{b2}(3P)$	$0^+(2^{++})$
• $\Upsilon(4S)$	$0^-(1^{--})$
• $Z_b(10610)$	$1^+(1^{+-})$
• $Z_b(10650)$	$1^+(1^{+-})$
$\Upsilon(10753)$	$?^?(1^{--})$
• $\Upsilon(10860)$	$0^-(1^{--})$
• $\Upsilon(11020)$	$0^-(1^{--})$

Particle Data Group (PDG)
Meson Summary Table

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^+	$1/2^+$	****	Ξ^0	$1/2^+$	****	Ξ_{cc}^{++}		***
n	$1/2^+$	****	$\Delta(1600)$	$3/2^+$	****	Σ^0	$1/2^+$	****	Ξ^-	$1/2^+$	****			
$N(1440)$	$1/2^+$	****	$\Delta(1620)$	$1/2^-$	****	Σ^-	$1/2^+$	****	$\Xi(1530)$	$3/2^+$	****	Λ_b^0	$1/2^+$	***
$N(1520)$	$3/2^-$	****	$\Delta(1700)$	$3/2^-$	****	$\Sigma(1385)$	$3/2^+$	****	$\Xi(1620)$		*	$\Lambda_b(5912)^0$	$1/2^-$	***
$N(1535)$	$1/2^-$	****	$\Delta(1750)$	$1/2^+$	*	$\Sigma(1580)$	$3/2^-$	*	$\Xi(1690)$		***	$\Lambda_b(5920)^0$	$3/2^-$	***
$N(1650)$	$1/2^-$	****	$\Delta(1900)$	$1/2^-$	***	$\Sigma(1620)$	$1/2^-$	*	$\Xi(1820)$	$3/2^-$	***	$\Lambda_b(6146)^0$	$3/2^+$	***
$N(1675)$	$5/2^-$	****	$\Delta(1905)$	$5/2^+$	****	$\Sigma(1660)$	$1/2^+$	***	$\Xi(1950)$		***	$\Lambda_b(6152)^0$	$5/2^+$	***
$N(1680)$	$5/2^+$	****	$\Delta(1910)$	$1/2^+$	****	$\Sigma(1670)$	$3/2^-$	****	$\Xi(2030)$	$\geq \frac{5}{2}^?$	***	Σ_b	$1/2^+$	***
$N(1700)$	$3/2^-$	***	$\Delta(1920)$	$3/2^+$	***	$\Sigma(1750)$	$1/2^-$	***	$\Xi(2120)$		*	Σ_b^*	$3/2^+$	***
$N(1710)$	$1/2^+$	****	$\Delta(1930)$	$5/2^-$	***	$\Sigma(1775)$	$5/2^-$	****	$\Xi(2250)$		**	$\Sigma_b(6097)^+$		***
$N(1720)$	$3/2^+$	****	$\Delta(1940)$	$3/2^-$	**	$\Sigma(1780)$	$3/2^+$	*	$\Xi(2370)$		**	$\Sigma_b(6097)^-$		***
$N(1860)$	$5/2^+$	**	$\Delta(1950)$	$7/2^+$	****	$\Sigma(1880)$	$1/2^+$	**	$\Xi(2500)$		*	Ξ_b^0, Ξ_b^-	$1/2^+$	***
$N(1875)$	$3/2^-$	***	$\Delta(2000)$	$5/2^+$	**	$\Sigma(1900)$	$1/2^-$	**				$\Xi_b'(5935)^-$	$1/2^+$	***
$N(1880)$	$1/2^+$	***	$\Delta(2150)$	$1/2^-$	*	$\Sigma(1910)$	$3/2^-$	***	Ω^-	$3/2^+$	****	$\Xi_b(5945)^0$	$3/2^+$	***
$N(1895)$	$1/2^-$	****	$\Delta(2200)$	$7/2^-$	***	$\Sigma(1915)$	$5/2^+$	****	$\Omega(2012)^-$	$?^-$	***	$\Xi_b(5955)^-$	$3/2^+$	***
$N(1900)$	$3/2^+$	****	$\Delta(2300)$	$9/2^+$	**	$\Sigma(1940)$	$3/2^+$	*	$\Omega(2250)^-$		***	$\Xi_b(6227)$		***
$N(1990)$	$7/2^+$	**	$\Delta(2350)$	$5/2^-$	*	$\Sigma(2010)$	$3/2^-$	*	$\Omega(2380)^-$		**	Ω_b^-	$1/2^+$	***
$N(2000)$	$5/2^+$	**	$\Delta(2390)$	$7/2^+$	*	$\Sigma(2030)$	$7/2^+$	****	$\Omega(2470)^-$		**			
$N(2040)$	$3/2^+$	*	$\Delta(2400)$	$9/2^-$	**	$\Sigma(2070)$	$5/2^+$	*				$P_c(4312)^+$		*
$N(2060)$	$5/2^-$	***	$\Delta(2420)$	$11/2^+$	****	$\Sigma(2080)$	$3/2^+$	*	Λ_c^+	$1/2^+$	****	$P_c(4380)^+$		*
$N(2100)$	$1/2^+$	***	$\Delta(2750)$	$13/2^-$	**	$\Sigma(2100)$	$7/2^-$	*	$\Lambda_c(2595)^+$	$1/2^-$	***	$P_c(4440)^+$		*
$N(2120)$	$3/2^-$	***	$\Delta(2950)$	$15/2^+$	**	$\Sigma(2160)$	$1/2^-$	*	$\Lambda_c(2625)^+$	$3/2^-$	***	$P_c(4457)^+$		*
$N(2190)$	$7/2^-$	****				$\Sigma(2230)$	$3/2^+$	*	$\Lambda_c(2765)^+$		*			
$N(2220)$	$9/2^+$	****	Λ	$1/2^+$	****	$\Sigma(2250)$		***	$\Lambda_c(2860)^+$	$3/2^+$	***			
$N(2250)$	$9/2^-$	****	Λ	$1/2^-$	**	$\Sigma(2455)$		**	$\Lambda_c(2880)^+$	$5/2^+$	***			
$N(2300)$	$1/2^+$	**	$\Lambda(1405)$	$1/2^-$	****	$\Sigma(2620)$		**	$\Lambda_c(2940)^+$	$3/2^-$	***			
$N(2570)$	$5/2^-$	**	$\Lambda(1520)$	$3/2^-$	****	$\Sigma(3000)$		*	$\Sigma_c(2455)$	$1/2^+$	****			
$N(2600)$	$11/2^-$	***	$\Lambda(1600)$	$1/2^+$	****	$\Sigma(3170)$		*	$\Sigma_c(2520)$	$3/2^+$	***			
$N(2700)$	$13/2^+$	**	$\Lambda(1670)$	$1/2^-$	****				$\Sigma_c(2800)$		***			
			$\Lambda(1690)$	$3/2^-$	****				Ξ_c^+	$1/2^+$	***			
			$\Lambda(1710)$	$1/2^+$	*				Ξ_c^0	$1/2^+$	****			
			$\Lambda(1800)$	$1/2^-$	***				$\Xi_c'^+$	$1/2^+$	***			
			$\Lambda(1810)$	$1/2^+$	***				$\Xi_c'^0$	$1/2^+$	***			
			$\Lambda(1820)$	$5/2^+$	****				$\Xi_c(2645)$	$3/2^+$	***			
			$\Lambda(1830)$	$5/2^-$	****				$\Xi_c(2790)$	$1/2^-$	***			
			$\Lambda(1890)$	$3/2^+$	****				$\Xi_c(2815)$	$3/2^-$	***			
			$\Lambda(2000)$	$1/2^-$	*				$\Xi_c(2930)$		**			
			$\Lambda(2050)$	$3/2^-$	*				$\Xi_c(2970)$		***			
			$\Lambda(2070)$	$3/2^+$	*				$\Xi_c(3055)$		***			
			$\Lambda(2080)$	$5/2^-$	*				$\Xi_c(3080)$		***			
			$\Lambda(2085)$	$7/2^+$	**				$\Xi_c(3123)$		*			
			$\Lambda(2100)$	$7/2^-$	****				Ω_c^0	$1/2^+$	***			
			$\Lambda(2110)$	$5/2^+$	***				$\Omega_c(2770)^0$	$3/2^+$	***			
			$\Lambda(2325)$	$3/2^-$	*				$\Omega_c(3000)^0$		***			
			$\Lambda(2350)$	$9/2^+$	***				$\Omega_c(3050)^0$		***			
			$\Lambda(2585)$		**				$\Omega_c(3065)^0$		***			
									$\Omega_c(3090)^0$		***			
									$\Omega_c(3120)^0$		***			

**** 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.

Particle Data Group (PDG)
Baryon Summary Table

Prologue: Definitions and Philosophy

"All science is either physics or stamp collecting."

— *Ernest Rutherford (apocryphal)*

But:

(1) diversity is interesting

(2) hadrons provide a toolkit to address particular questions

(3) general principles can be inferred from patterns

$\Longrightarrow$ spectroscopy is stamp collecting

(which is a good thing)

Prologue: Definitions and Philosophy

Hadron contributions to fundamental physics

Patterns of hadron multiplets

$\Longrightarrow$ the existence of quarks with flavors and colors

Non-observation of hadrons with color (including quarks)

$\Longrightarrow$ color confinement

Patterns of excited hadrons

$\Longrightarrow$ shape of the $q\bar{q}$ and qq potentials, including spin effects

Searches for exotic hadrons

$\Longrightarrow$ tests of our ability to understand and use QCD

Patterns of hadron weak decays

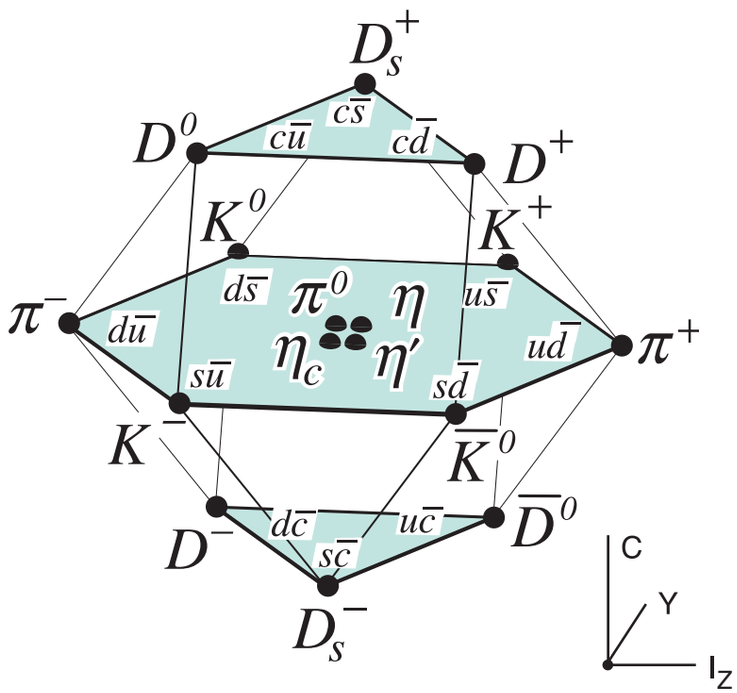
$\Longrightarrow$ parity violation, CP violation, structure of the CKM matrix

Diverse collection of hadrons

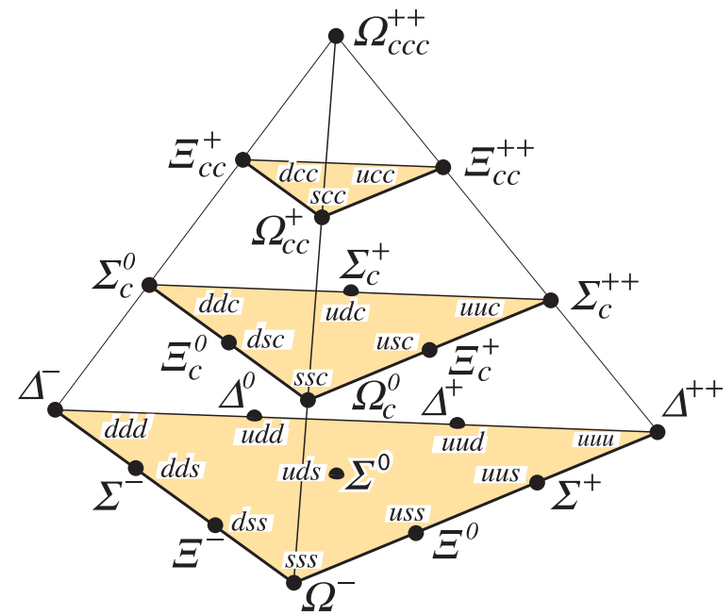
$\Longrightarrow$ opportunities to search for new physics

($e.g.\ B^+ \to K^+\mu^+\mu^-$ and $B^+ \to K^+e^+e^-$)

spin-0 mesons



spin-$\frac{3}{2}$ baryons



[PDG quark model review]

HUGS 2021 Lectures on:
Experimental Meson Spectroscopy

Prologue: Definitions and Philosophy

I. A Field Guide to Meson Families

II. Meson Quantum Numbers

III. The Quark Model

IV. Exotic Mesons

V. Current and Future Experiments

LECTURE I. A Field Guide to Meson Families

IA. Introduction to Meson Families

IB. A Few Basic Principles Determining Meson Behavior

IC. A Tour of Meson Families

* the K^+ family
* the K^0 family
* the π^0 family
* the J/ψ family
* the ρ family
* the $Z_c(3900)$ family

IA. Introduction to Meson Families

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

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)*

IA. Introduction to Meson Families

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

IA. Introduction to Meson Families

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)

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

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

IB. Basic Principles Determining Meson Behavior

Four basic principles determining meson behavior:

1. For a particle A at rest decaying to particles 1, 2, 3, …,

$$m_A = E_A = \sum_i E_i = \sum_i \sqrt{m_i^2 + p_i^2} \geq \sum_i m_i$$

2. Flavor quantum numbers are conserved by the strong and electromagnetic forces, but not by the weak force.

3. When allowed,
   strong decays dominate electromagnetic decays,
   and electromagnetic decays dominate weak decays.

4. Strong decays without $q\bar{q}$ annihilation are usually preferred over decays with $q\bar{q}$ annihilation (OZI suppression).

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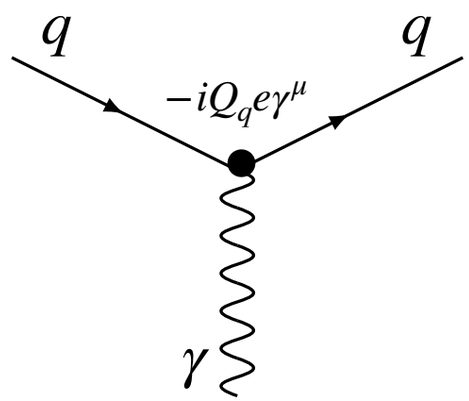
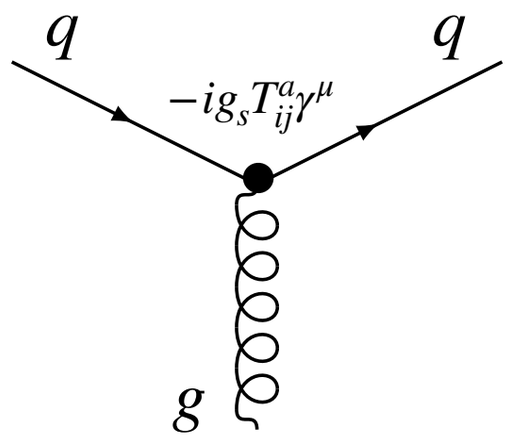
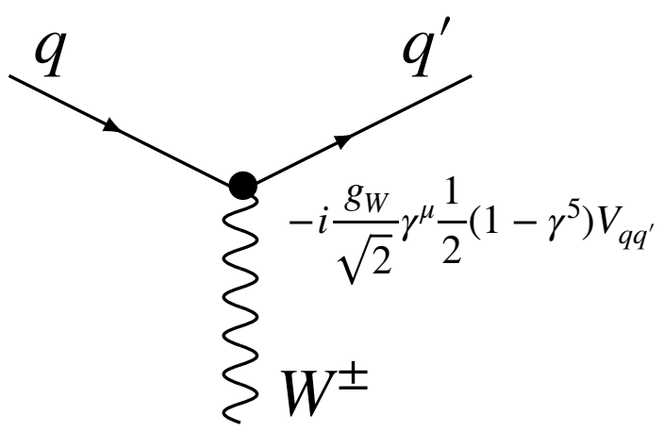
ELECTROMAGNETIC



STRONG



WEAK



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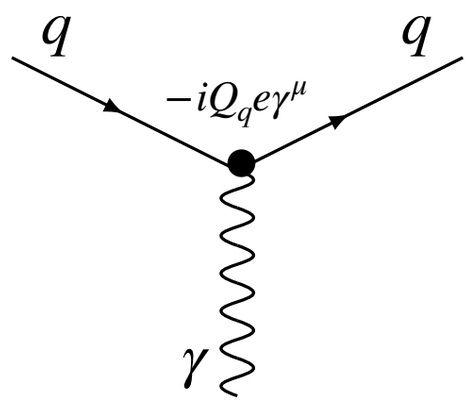
$\Longrightarrow$ all SM interactions conserve baryon number:

$$B = \frac{1}{3} \sum_f (N_{q_f} - N_{\bar{q}_f})$$

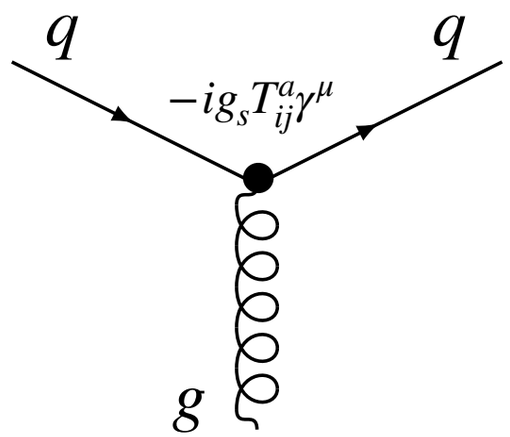
$\Longrightarrow$ electromagnetic and strong interactions conserve quark flavors *(e.g. strangeness, charm, bottomness)*:

$$F = \pm (N_{q_f} - N_{\bar{q}_f})$$

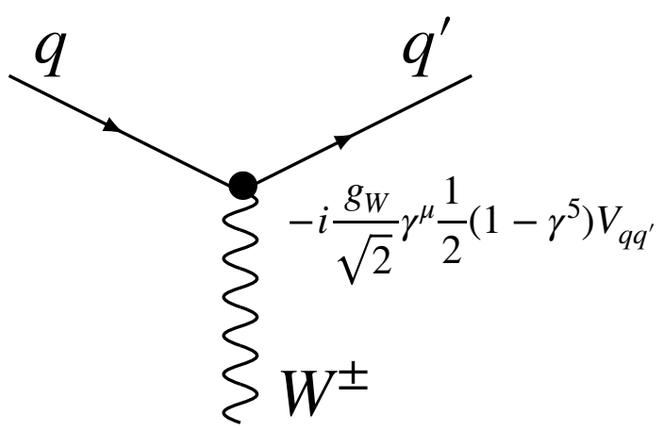
ELECTROMAGNETIC



STRONG



WEAK



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π^+ (decays weakly):

$$\tau_{\pi^+} = 2.6 \times 10^{-8} \text{ s}$$

$$c\tau_{\pi^+} = 7.8 \text{ m}$$

π^0 (decays electromagnetically):

$$\tau_{\pi^0} = 8.5 \times 10^{-17} \text{ s}$$

$$c\tau_{\pi^0} = 26 \text{ nm}$$

$\rho(770)$ (decays strongly):

$$\tau_\rho = \frac{1}{\Gamma} = \frac{1}{150 \text{ MeV}} = 4.4 \times 10^{-24} \text{ s}$$

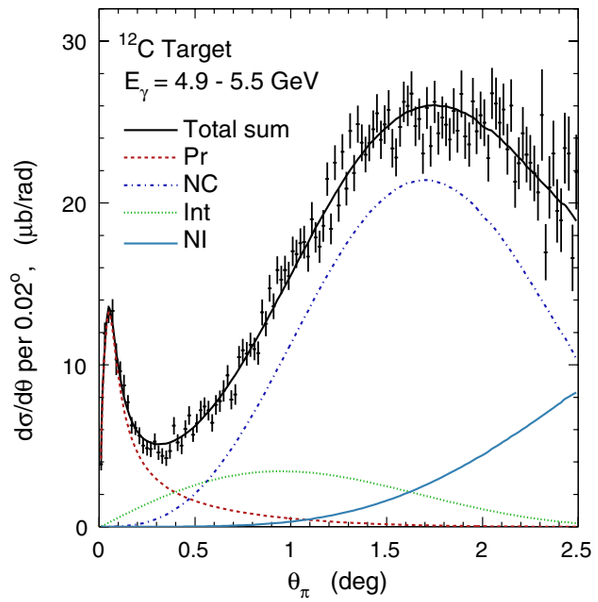
$$c\tau_\rho = 1.3 \text{ fm}$$

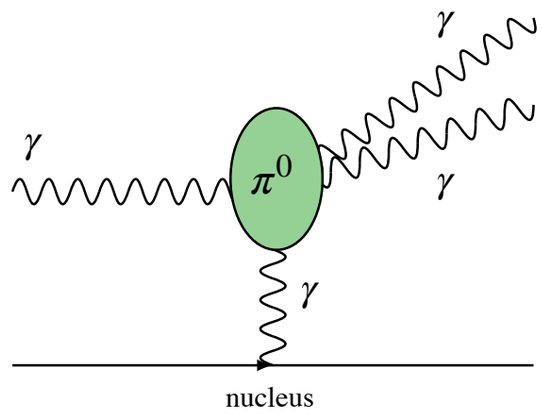
IB. Basic Principles Determining Meson Behavior

PRL **106,** 162303 (2011) PHYSICAL REVIEW LETTERS week ending 22 APRIL 2011

New Measurement of the π^0 Radiative Decay Width

(PrimEx Collaboration)





$$\frac{d\sigma_{\mathrm{Pr}}}{d\Omega} = \Gamma(\pi^0 \to \gamma\gamma)\frac{8\alpha Z^2}{m^3}\frac{\beta^3 E^4}{Q^4}|F_{\mathrm{EM}}(Q)|^2 \sin^2\theta_\pi$$

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IB. Basic Principles Determining Meson Behavior

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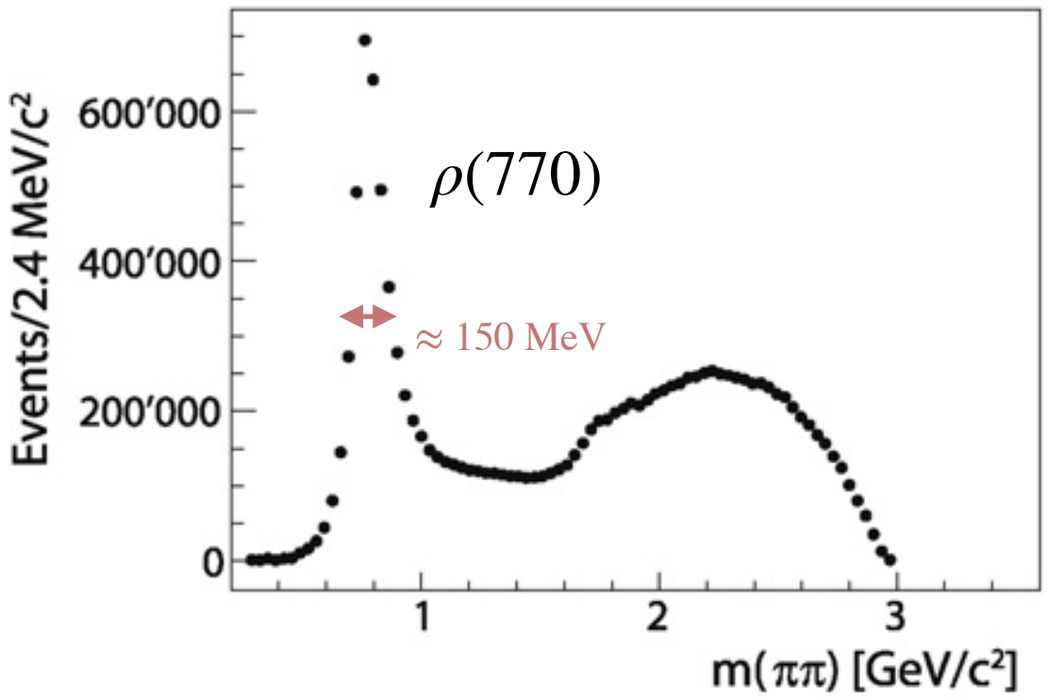
BESIII Collaboration / Physics Letters B 710 (2012) 594–599

$J/\psi \to \pi^+\pi^-\pi^0$



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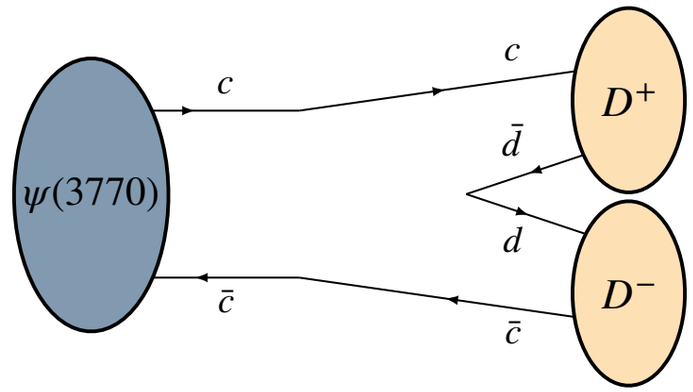

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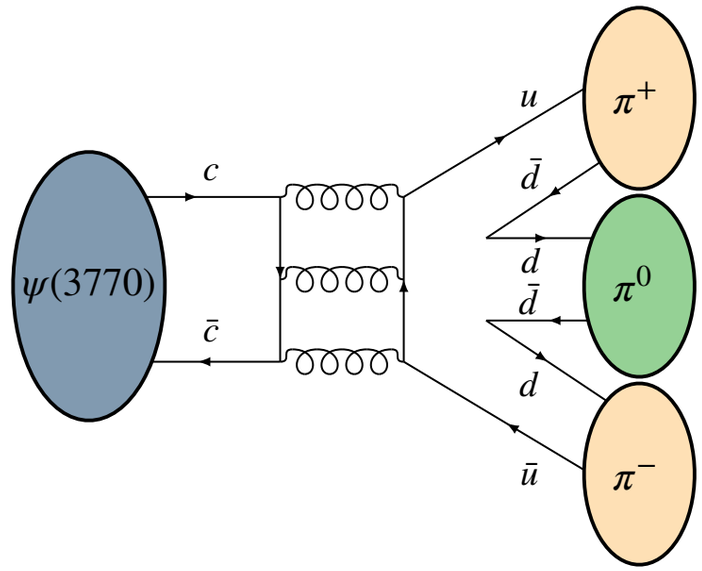

IC. A Tour of Meson Families: the K^+ family

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

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- J/ψ family *(strong decays, near or below open flavor threshold)*
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$J^{P(C)}$	$u\bar{d},\ u\bar{u},\ d\bar{d},\ s\bar{s}$			$c\bar{c}$	$b\bar{b}$	$d\bar{s}, u\bar{s}$	$c\bar{u}, c\bar{d}$	$c\bar{s}$	$d\bar{b}, u\bar{b}$	$s\bar{b}$
$1^{-(-)}$	$\rho(1700)$	$\omega(1650)$	$\phi(1680)$	$\psi(3770)$	$\Upsilon(4S)$	$K^*(1680)$		$D_{s1}^*(2700)^+$		
$2^{+(+)}$	$a_2(1320)$	$f_2(1270)$	$f_2'(1525)$	$\chi_{c2}(1P)$	$\chi_{b2}(1P)$	$K_2^*(1430)$	$D_2^*(2460)$	$D_{s2}^*(2573)^+$	$B_2^*(5747)$	$B_{s2}^*(5840)^0$
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$1^{+(-)}$	$b_1(1235)$	$h_1(1170)$	$h_1(1415)$	$h_c(1P)$	$h_b(1P)$	$K_1(1270)$	$D_1(2420)$	$D_{s1}(2460)^+$	$B_1(5721)$	$B_{s1}(5830)^0$
$1^{-(-)}$	$\rho(770)$	$\omega(782)$	$\phi(1020)$	$J/\psi(1S)$	$\Upsilon(1S)$	$K^*(892)$	$D^*(2007)^0 \mid D^*(2010)^+$	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*

$Z_c(4020)^+ \to \pi^+ h_c$	$Z_c(4430)^+ \to \pi^+ \psi(2S)$	$Z_b(10650)^+ \to \pi^+ h_b, \pi^+ \Upsilon$	$X(2900)^0 \to D^+ K^-$
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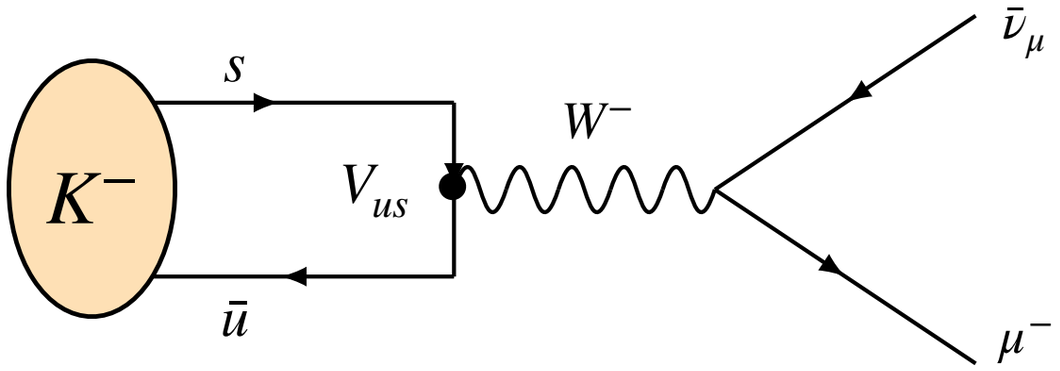
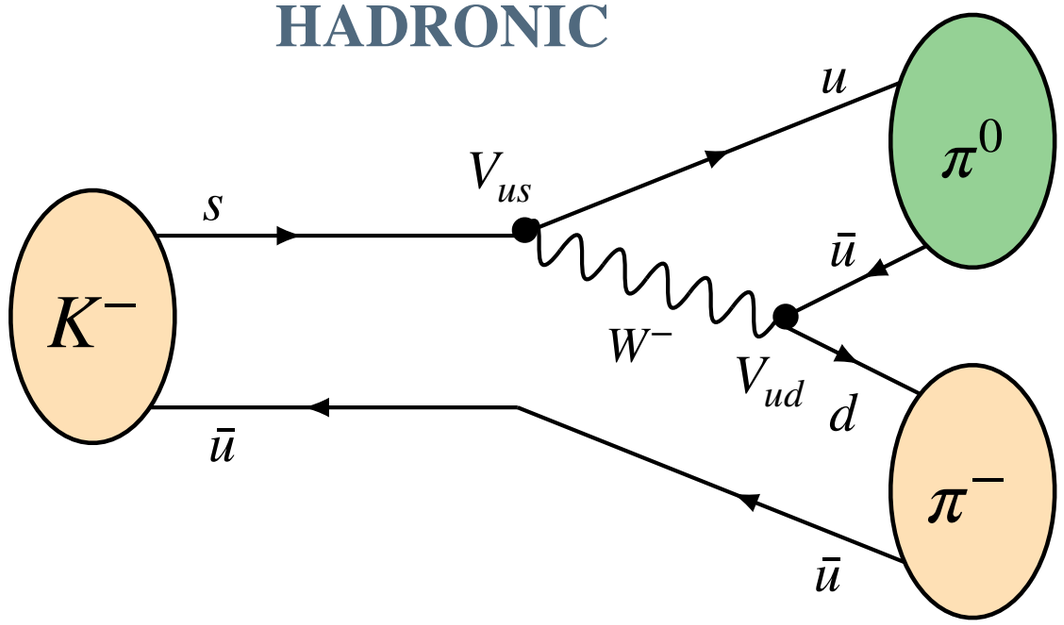
IC. A Tour of Meson Families: the K^+ family

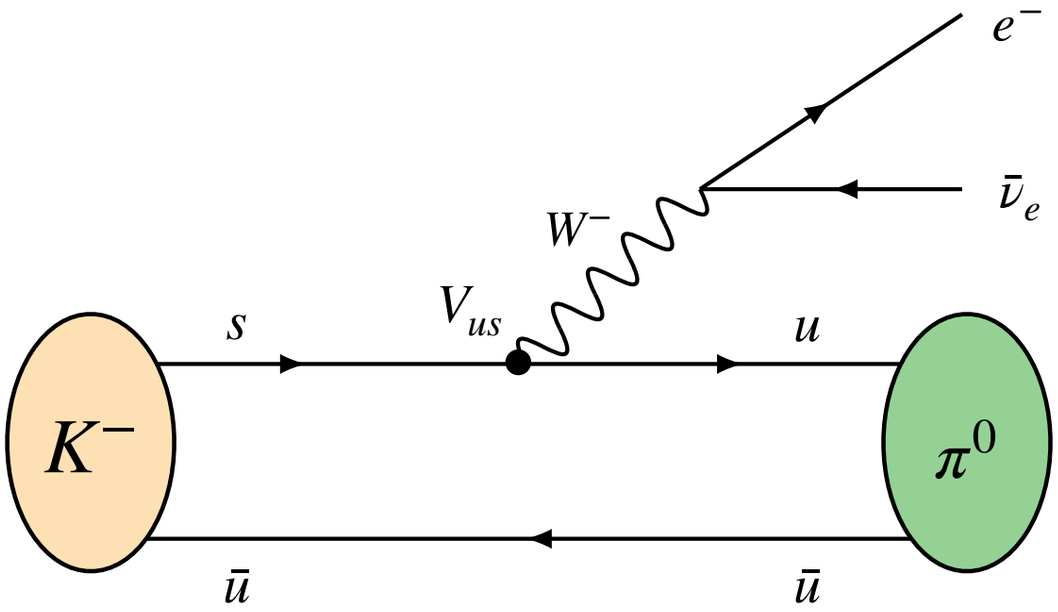
LEPTONIC



HADRONIC



SEMI-LEPTONIC



Similar diagrams exist for:

π^- (only leptonic), D^+, D_s^+, B^-, B_c^-

$\Longrightarrow$ *important access to CKM matrix elements and decay constants*

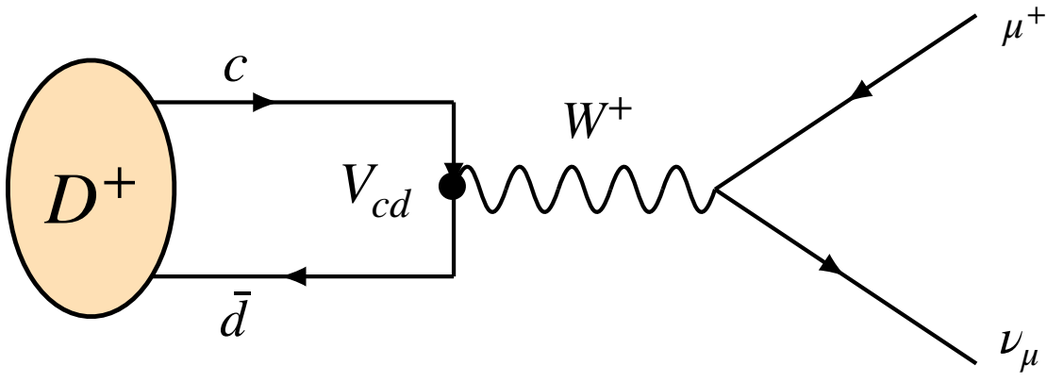
Lifetimes:

$c\tau_\pi = 7.8$ m	$c\tau_{D_s} = 151\ \mu$m
$c\tau_K = 3.7$ m	$c\tau_B = 491\ \mu$m
$c\tau_D = 312\ \mu$m	$c\tau_{B_c} = 150\ \mu$m

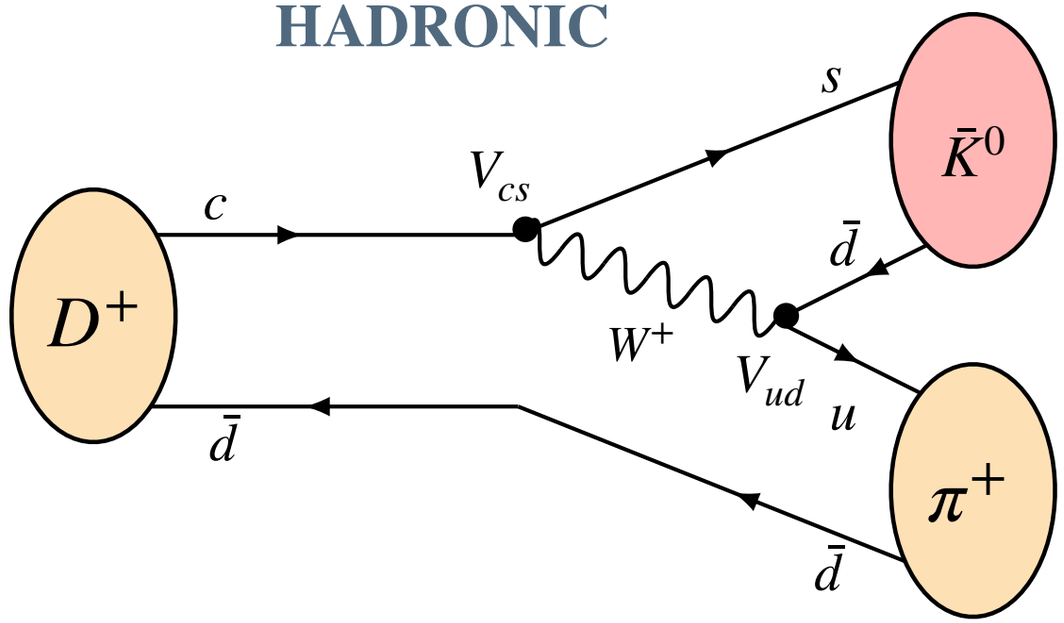
$\Longrightarrow$ *π and K leave tracks in detectors*

IC. A Tour of Meson Families: the K^+ family

LEPTONIC



HADRONIC



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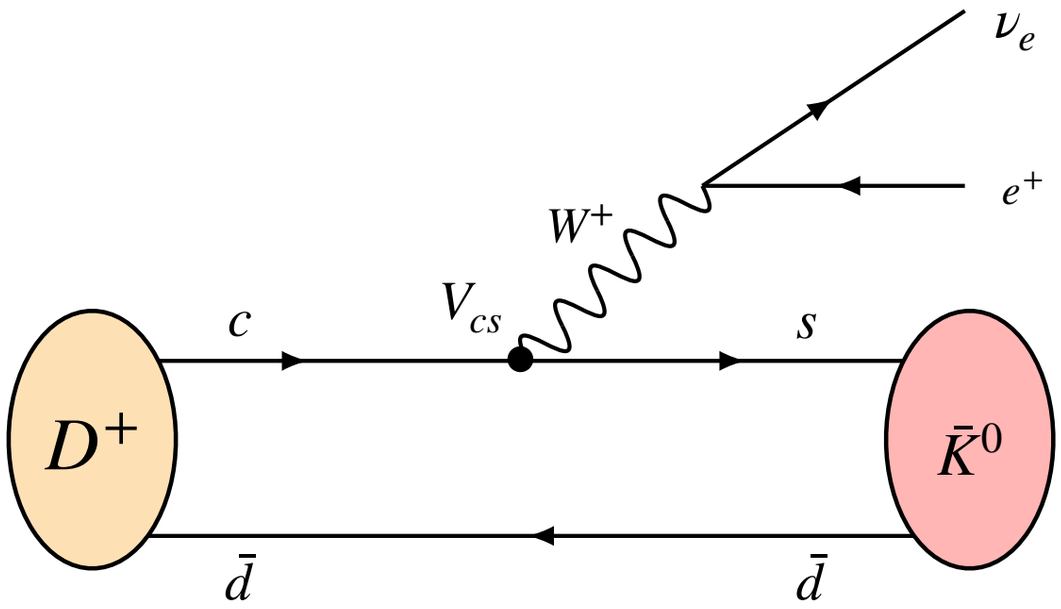

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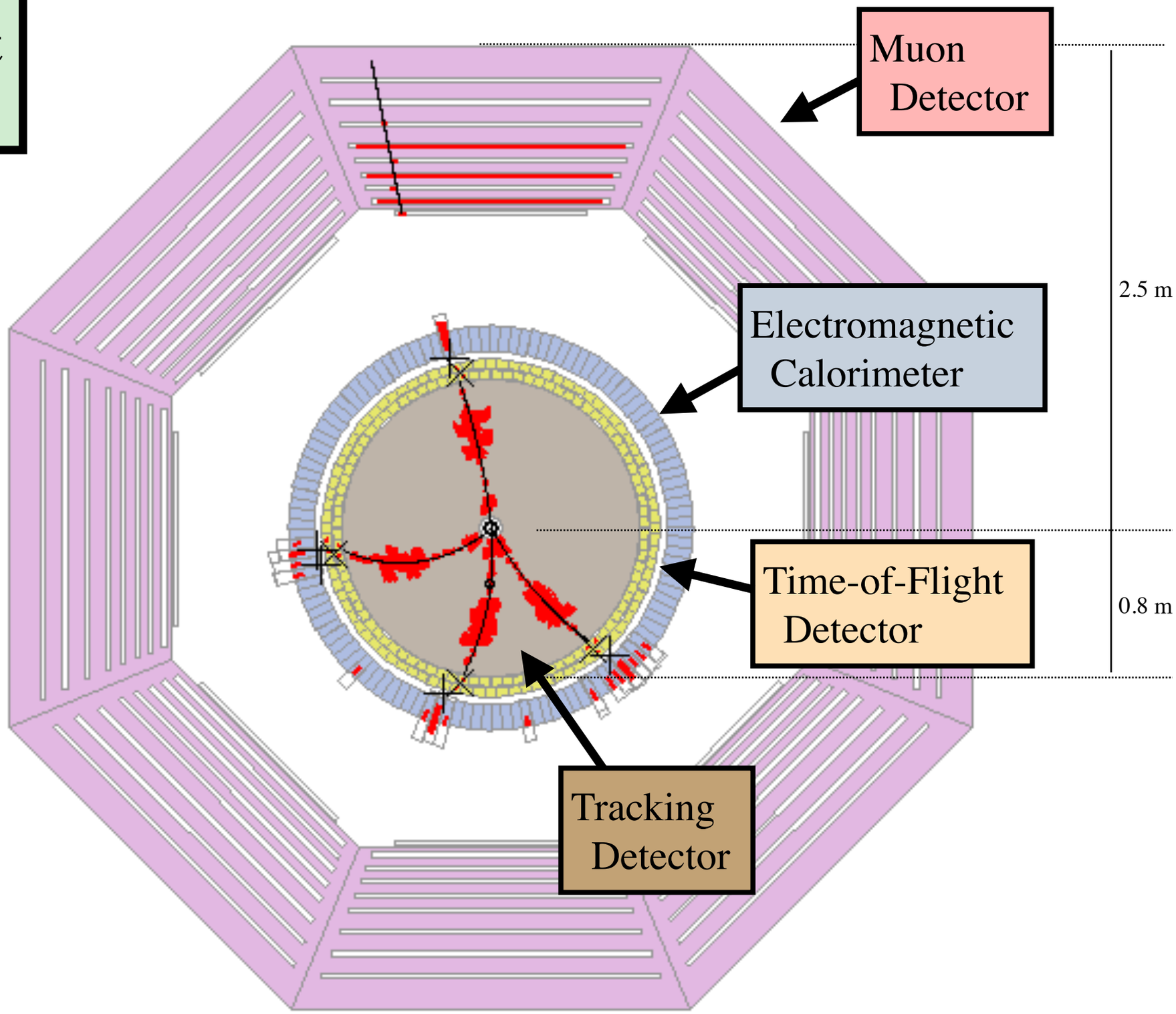
BESIII Experiment

(Beijing, China)

Event display for:

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

at $E_{\rm CM} \approx 3.7$ GeV



IC. A Tour of Meson Families: the K^0 family

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)*

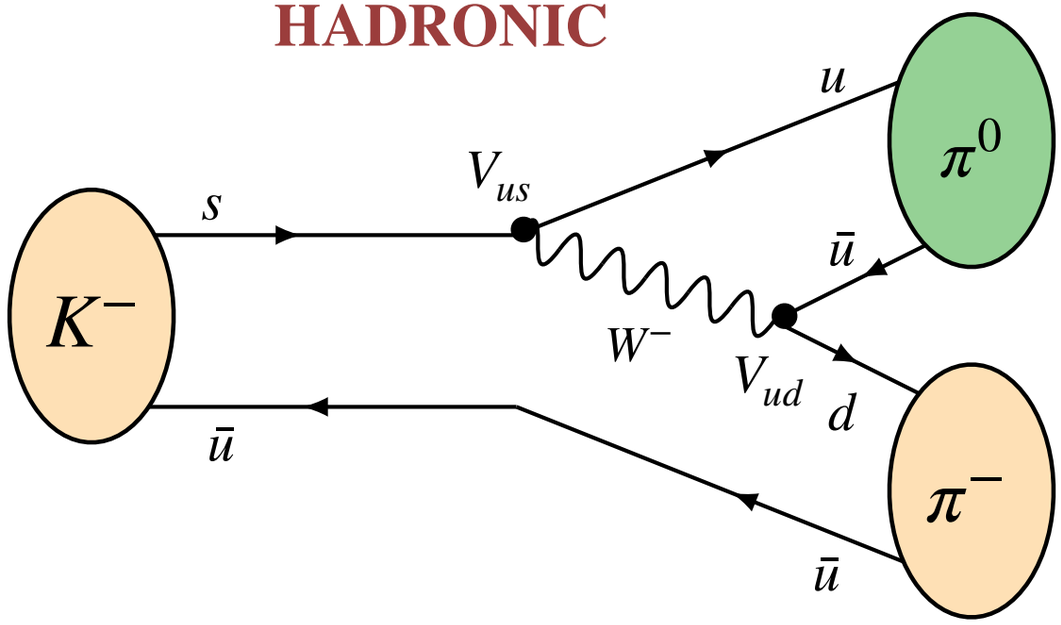
$J^{P(C)}$	$u\bar{d},\ u\bar{u},\ d\bar{d},\ s\bar{s}$			$c\bar{c}$	$b\bar{b}$	$d\bar{s}, u\bar{s}$	$c\bar{u}, c\bar{d}$		$c\bar{s}$	$d\bar{b}, u\bar{b}$	$s\bar{b}$
$1^{-(-)}$	$\rho(1700)$	$\omega(1650)$	$\phi(1680)$	$\psi(3770)$	$\Upsilon(4S)$	$K^*(1680)$			$D_{s1}^*(2700)^+$		
$2^{+(+)}$	$a_2(1320)$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

excited states ↑ *ground state*

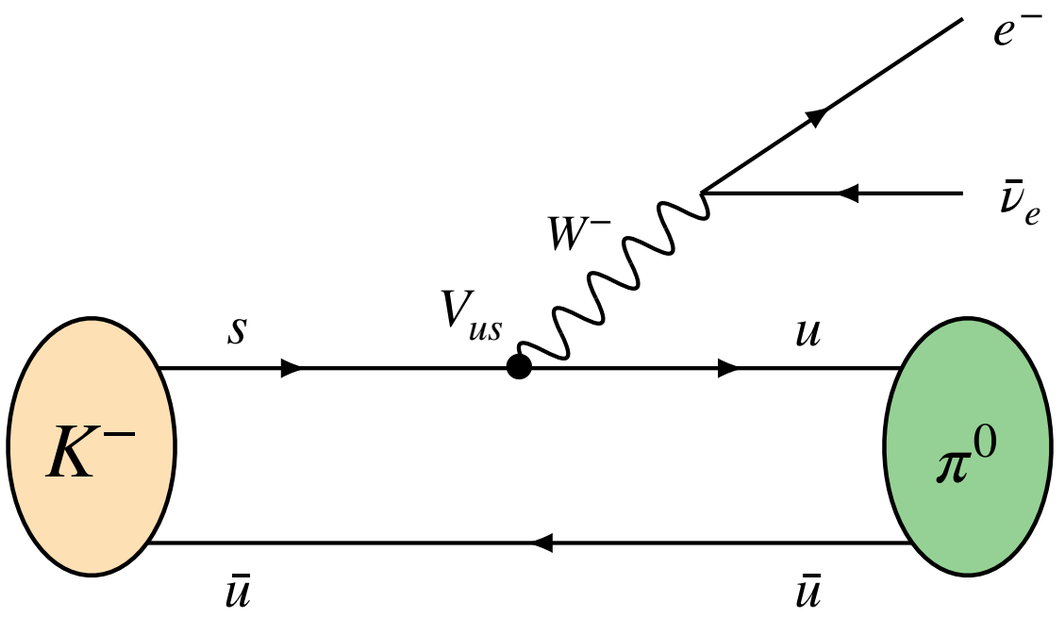
$Z_c(4020)^+ \to \pi^+ h_c$	$Z_c(4430)^+ \to \pi^+ \psi(2S)$	$Z_b(10650)^+ \to \pi^+ h_b, \pi^+ \Upsilon$	$X(2900)^0 \to D^+ K^-$
$Z_c(3900)^+ \to \pi^+ J/\psi$	$Z_{cs}(4000)^+ \to K^+ J/\psi$	$Z_b(10610)^+ \to \pi^+ h_b, \pi^+ \Upsilon$	$T_{cc\bar{c}\bar{c}}(6900) \to J/\psi J/\psi$

IC. A Tour of Meson Families: the K^0 family

HADRONIC



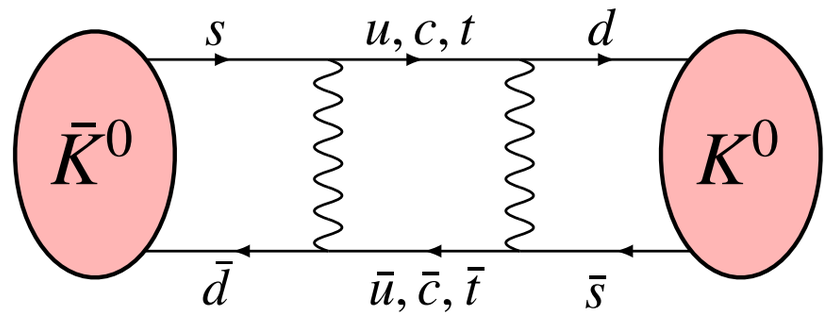
SEMI-LEPTONIC



The K^0 family is similar to the K^+ family (e.g. similar weak decays), except:

(1) members are electrically neutral, so don't leave tracks in detectors

(2) members can mix through the weak force:



$\Longrightarrow$ *K^0 and $\bar{K}^0$ are not mass eigenstates (and similarly for D^0, B^0, and B_s^0)*

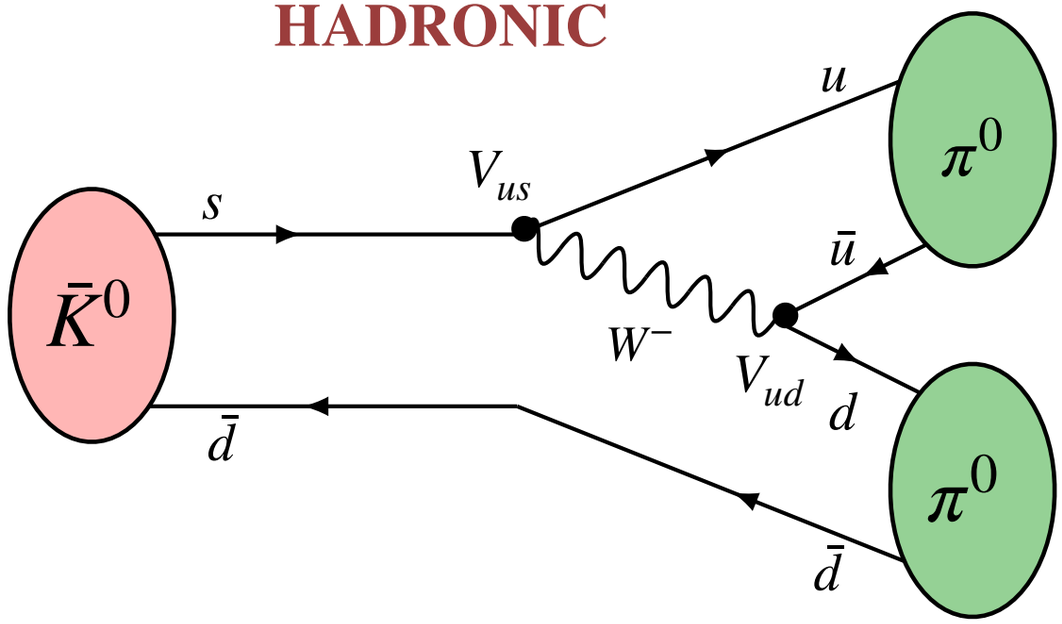
The mass eigenstates are linear combinations:

$$|K_S^0> \approx \frac{1}{\sqrt{2}}\left[|K^0> + |\bar{K}^0>\right]$$

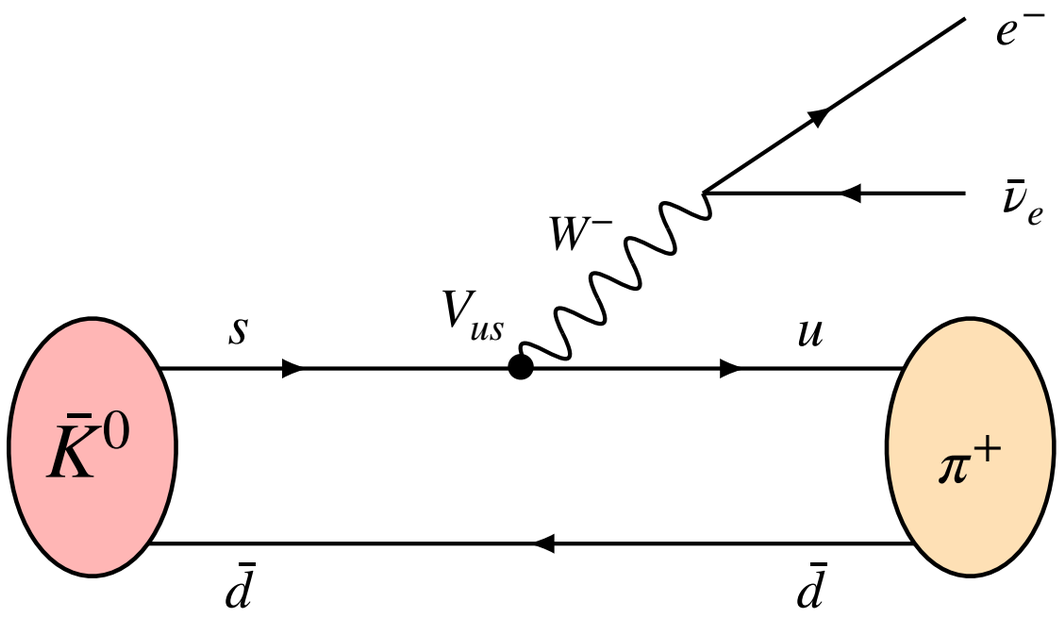
$$|K_L^0> \approx \frac{1}{\sqrt{2}}\left[|K^0> - |\bar{K}^0>\right]$$

IC. A Tour of Meson Families: the K^0 family

HADRONIC



SEMI-LEPTONIC



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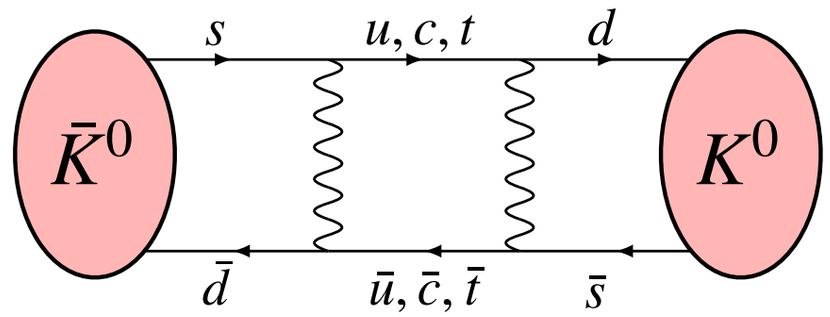

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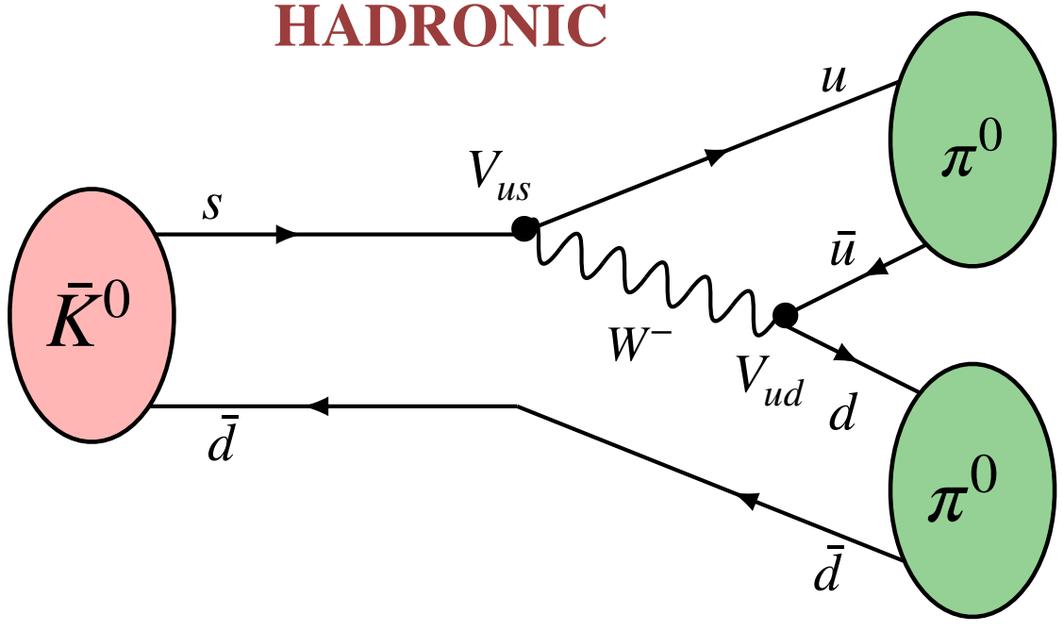
IC. A Tour of Meson Families: the K^0 family



Since CP is almost conserved:

$$\mathscr{B}(K_S^0 \to 2\pi) \gg \mathscr{B}(K_S^0 \to 3\pi)$$
$$\mathscr{B}(K_L^0 \to 3\pi) \gg \mathscr{B}(K_L^0 \to 2\pi)$$

$\Longrightarrow$ *K_S^0 and K_L^0 have very different lifetimes (unique to the K^0 system)*

$$c\tau_{K_S} = 2.7 \text{ cm}$$
$$c\tau_{K_L} = 15.3 \text{ m}$$

The K^0 family is similar to the K^+ family (e.g. similar weak decays), except:

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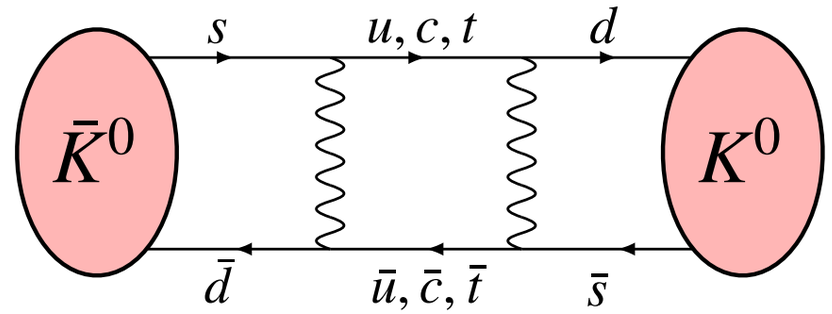

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IC. A Tour of Meson Families: the K^0 family

Mixing also means the K_S^0 and K_L^0 can have slightly different masses, which controls the rate of $K^0 - \bar{K}^0$ oscillations (*and similarly for D^0, B^0, and B_s^0*).

Start with a K^0 at $t = 0$.
The K_S^0 and K_L^0 components evolve differently:

$$|K(t)> = e^{-iHt}|K^0>$$

$$= e^{-iHt}\frac{1}{\sqrt{2}}\left[|K_S^0> + |K_L^0>\right]$$

$$= \frac{1}{\sqrt{2}}\left[e^{-im_S t-\frac{1}{2}\Gamma_S t}|K_S^0> + e^{-im_L t-\frac{1}{2}\Gamma_L t}|K_L^0>\right]$$

So that the probability of finding a K^0 at time t oscillates:

$$< K^0|K(t)> = \frac{1}{2}\left[e^{-im_S t-\frac{1}{2}\Gamma_S t} + e^{-im_L t-\frac{1}{2}\Gamma_L t}\right]$$

$$P_{K^0}(t) = \frac{1}{4}\left[e^{-\Gamma_S t} + e^{-\Gamma_L t} + 2e^{-\frac{1}{2}(\Gamma_S+\Gamma_L)t}\cos((m_L - m_S)t)\right]$$

The K^0 family is similar to the K^+ family (e.g. similar weak decays), except:

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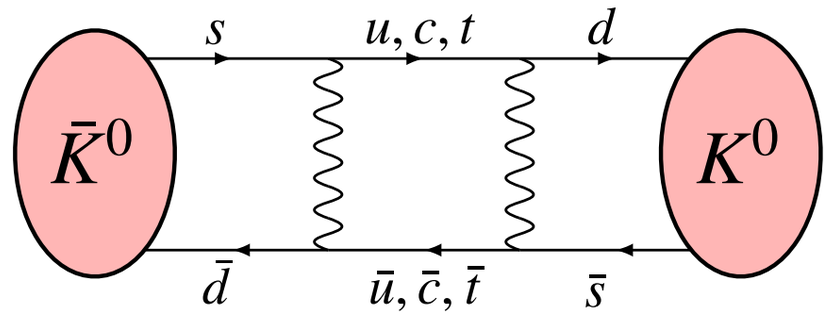

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IC. A Tour of Meson Families: the K^0 family

Mixing also means the K_S^0 and K_L^0 can have slightly different masses, which controls the rate of $K^0 - \bar{K}^0$ oscillations (and similarly for D^0, B^0, and B_s^0).

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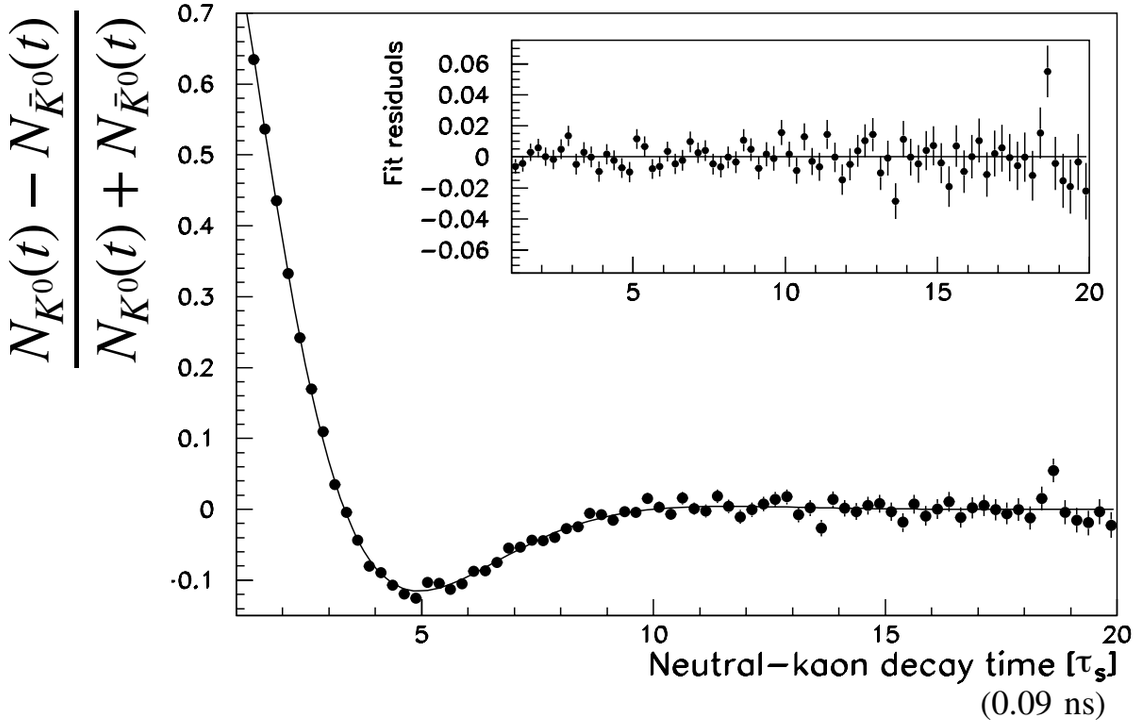
Experimentally, K^0 and $\bar{K}^0$ can be distinguished using semi-leptonic decays, since $K^0 \to \pi^- e^+ \nu_e$ and $\bar{K}^0 \to \pi^+ e^- \bar{\nu}_e$.

Eur. Phys. J. C 22, 55–79 (2001)
Digital Object Identifier (DOI) 10.1007/s100520100793

THE EUROPEAN PHYSICAL JOURNAL C

$\mathcal{T}$-violation and $\mathcal{CPT}$-invariance measurements in the CPLEAR experiment: a detailed description of the analysis of neutral-kaon decays to $e\pi\nu$

The CPLEAR Collaboration



$$m_L - m_S = 3.5 \times 10^{-12}\ \text{MeV} = 5.3\ \text{ns}^{-1}$$

IC. A Tour of Meson Families: the K^0 family

Mixing also means the K_S^0 and K_L^0 can have slightly different masses, which controls the rate of $K^0 - \bar{K}^0$ oscillations (and similarly for D^0, B^0, and B_s^0).

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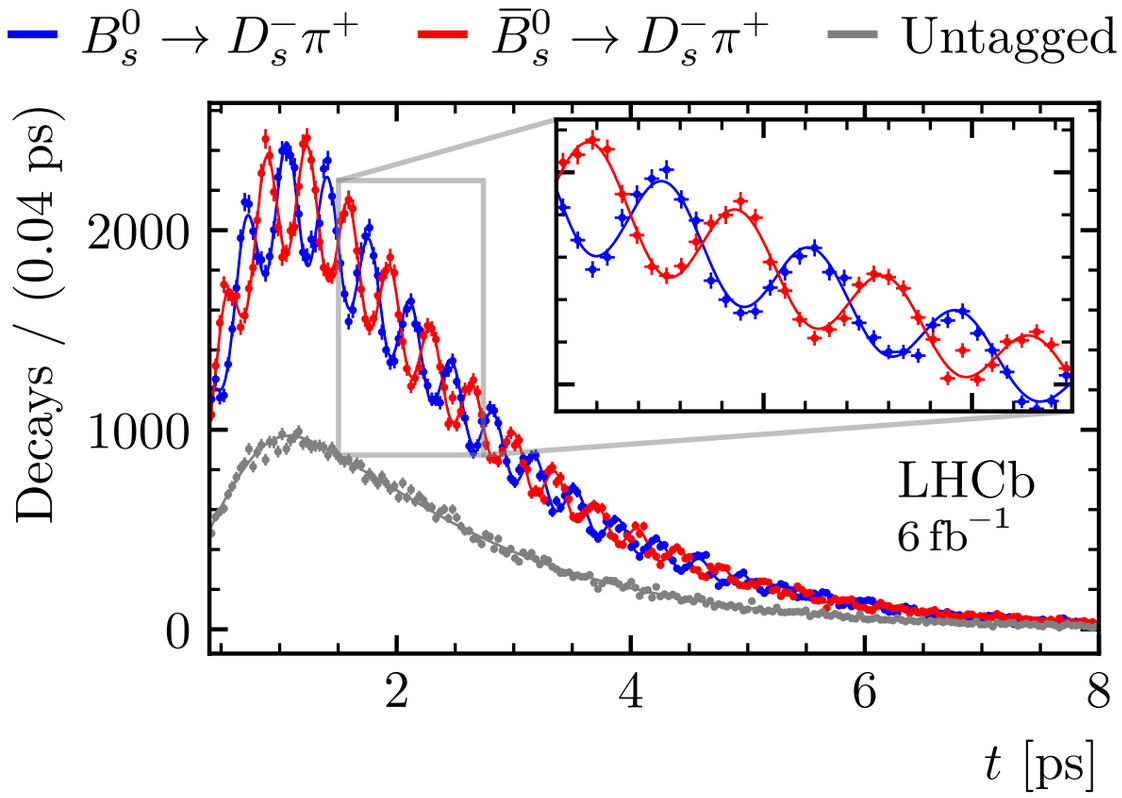
$$P_{K^0}(t) = \frac{1}{4}\left[e^{-\Gamma_S t} + e^{-\Gamma_L t} + 2e^{-\frac{1}{2}(\Gamma_S+\Gamma_L)t}\cos((m_L - m_S)t)\right]$$

There are similar phenomena for the D^0, B^0, and B_s^0, with different lifetimes and mass differences.

Precise determination of the B_s^0–$\overline{B}_s^0$ oscillation frequency

arXiv:2104.04421v1 [hep-ex] 9 Apr 2021

LHCb collaboration†



$$m_H - m_L = 1.17 \times 10^{-8}\ \text{MeV} = 17.8\ \text{ps}^{-1}$$

IC. A Tour of Meson Families: the π^0 family

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*

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

IC. A Tour of Meson Families: the π^0 family

Properties of the π^0, η, and η':

* mixtures of u, d, and s quarks:

$$|\pi^0> = \frac{1}{\sqrt{2}}\left[|u\bar{u}> - |d\bar{d}>\right]$$

$$|\eta> \approx \frac{1}{\sqrt{6}}\left[|u\bar{u}> + |d\bar{d}> - 2|s\bar{s}>\right]$$

$$|\eta'> \approx \frac{1}{\sqrt{3}}\left[|u\bar{u}> + |d\bar{d}> + |s\bar{s}>\right]$$

* the π^0 decays only electromagnetically ($\pi^0 \to \gamma\gamma$ dominant) with a lifetime of 8.5×10^{-17} s ($c\tau = 26$ nm) corresponding to $\Gamma_{\pi^0} = 7.7$ eV.

* the η and η' are also narrow (but not as narrow as the π^0):
$\Gamma_\eta = 1.3$ keV and $\Gamma_{\eta'} = 190$ keV

* important for chiral symmetry breaking, fundamental QCD calculations, searches for new physics, etc.

* also important as decay products from other particles

IC. A Tour of Meson Families: the π^0 family

BESIII Experiment

(Beijing, China)

Event display for:

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

with:

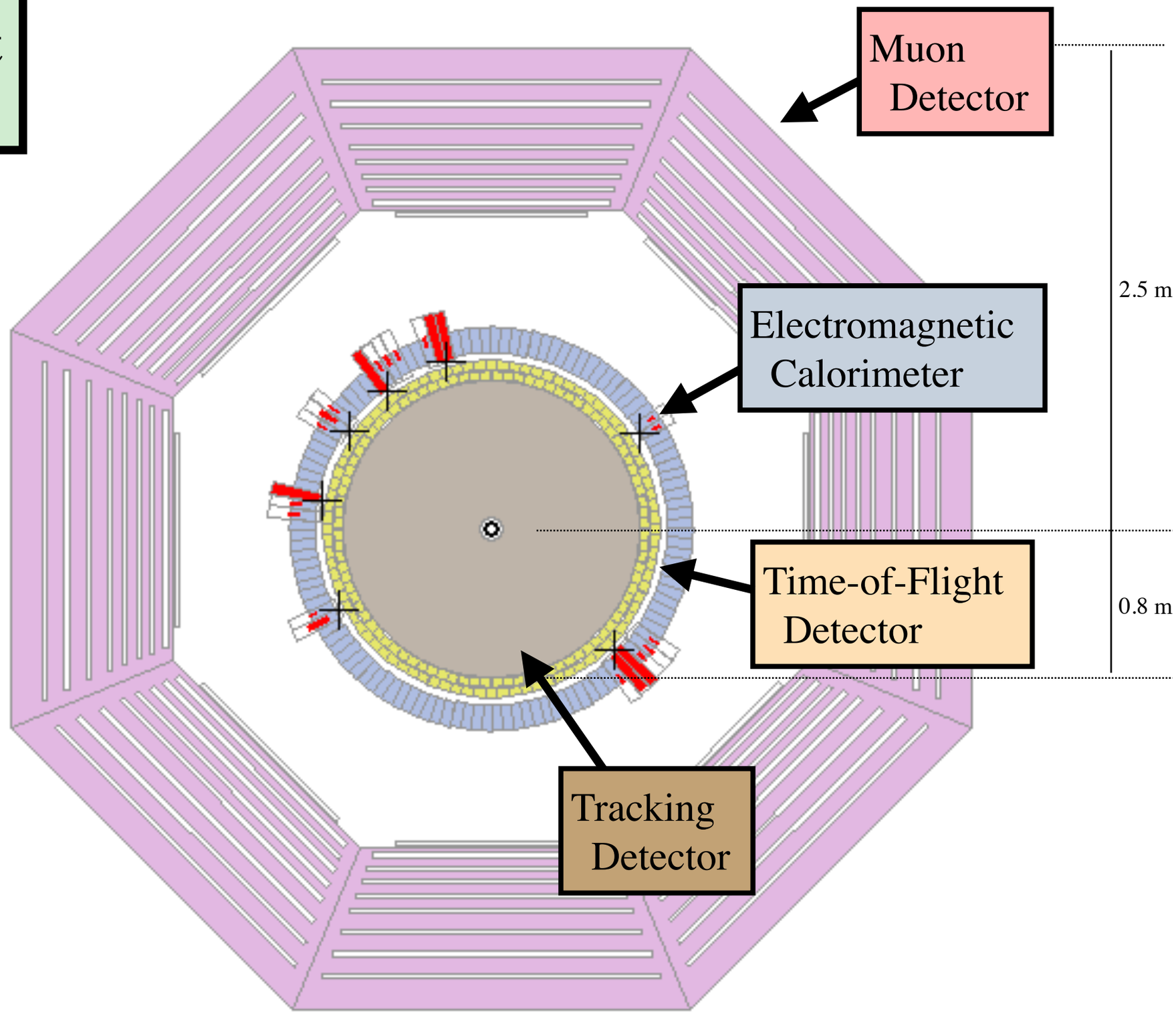
$J/\psi \to \gamma\eta'$

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

$\eta \to \gamma\gamma$

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

(total of 7γ)



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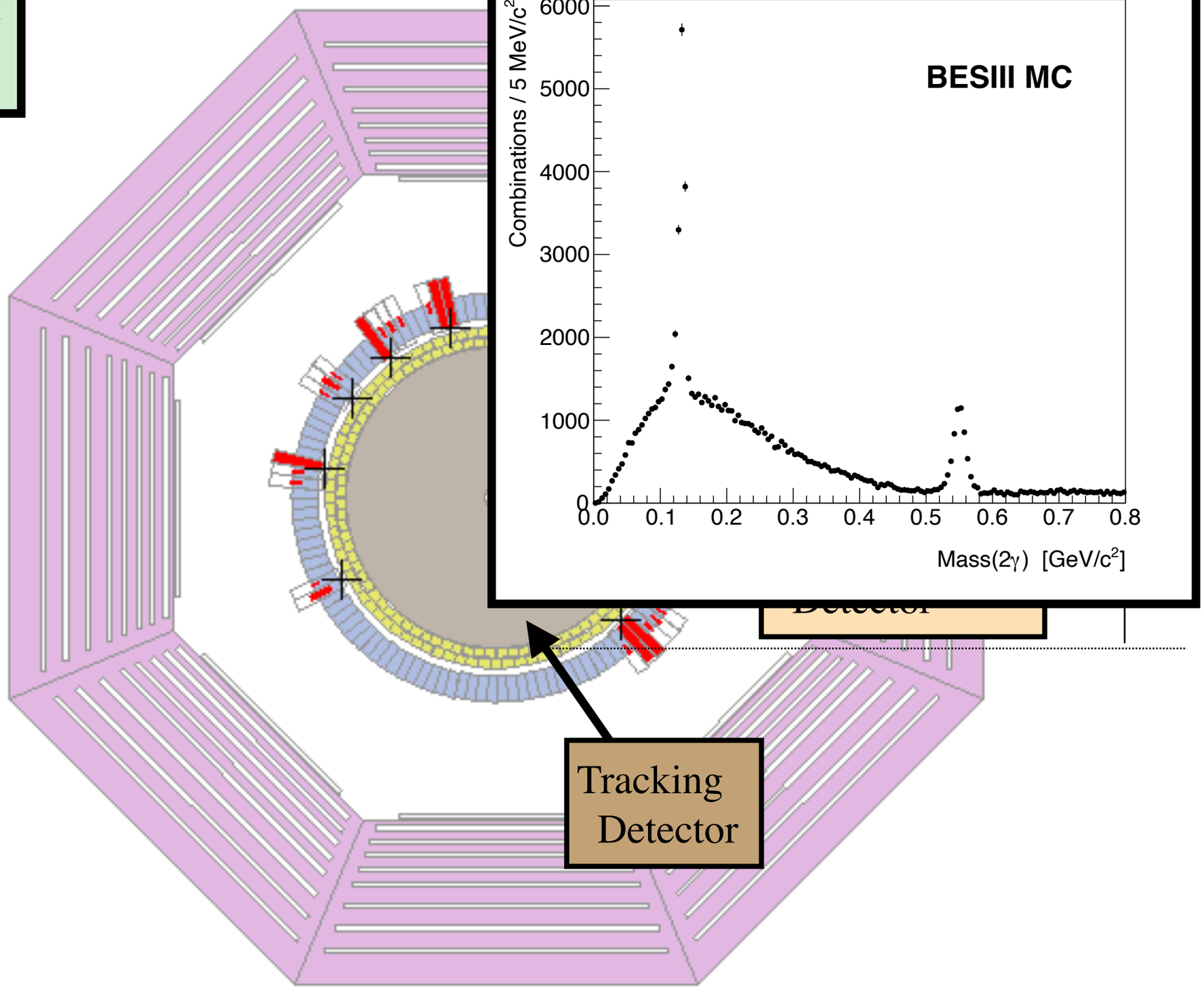
$$\eta \to \gamma\gamma$$

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

(total of 7γ)



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with:

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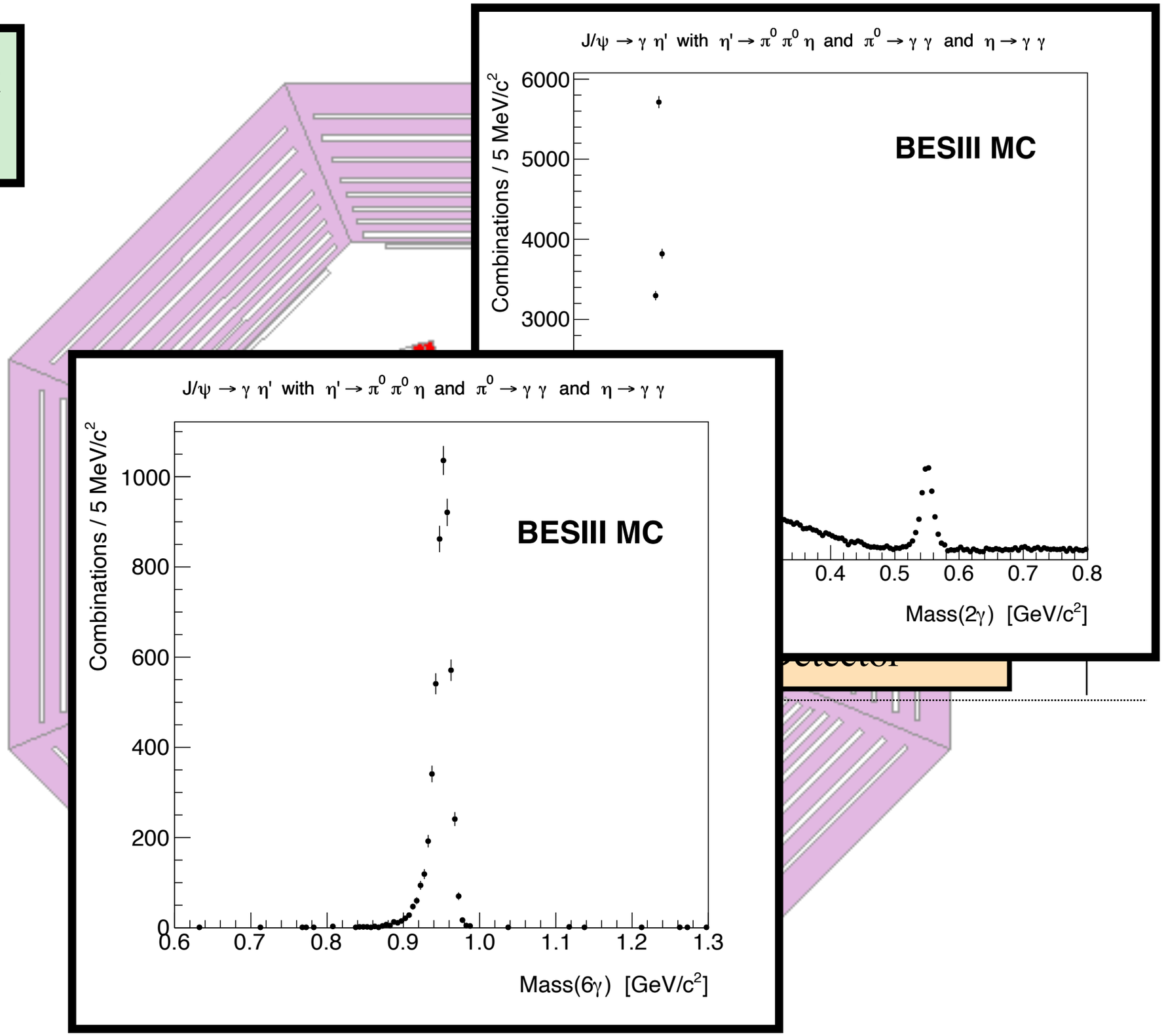
$$\eta \to \gamma\gamma$$

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

(total of 7γ)



IC. A Tour of Meson Families: the J/ψ family

QUARKS

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$\bar{d}$	$\pi^0 \mid \eta \mid \eta'$	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

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

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

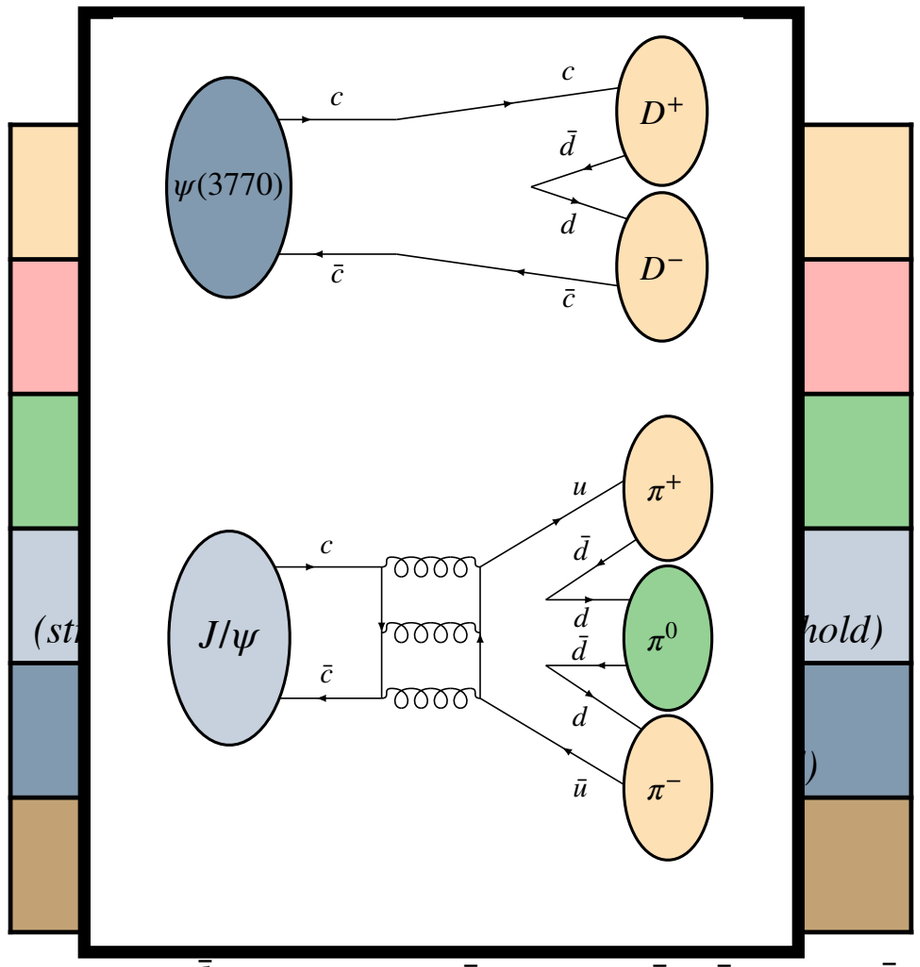
excited states ↑ *ground state*

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

IC. A Tour of Meson Families: the J/ψ family

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



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

excited states

ground state

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

IC. A Tour of Meson Families: the J/ψ family

Excited meson states below open-flavor thresholds:

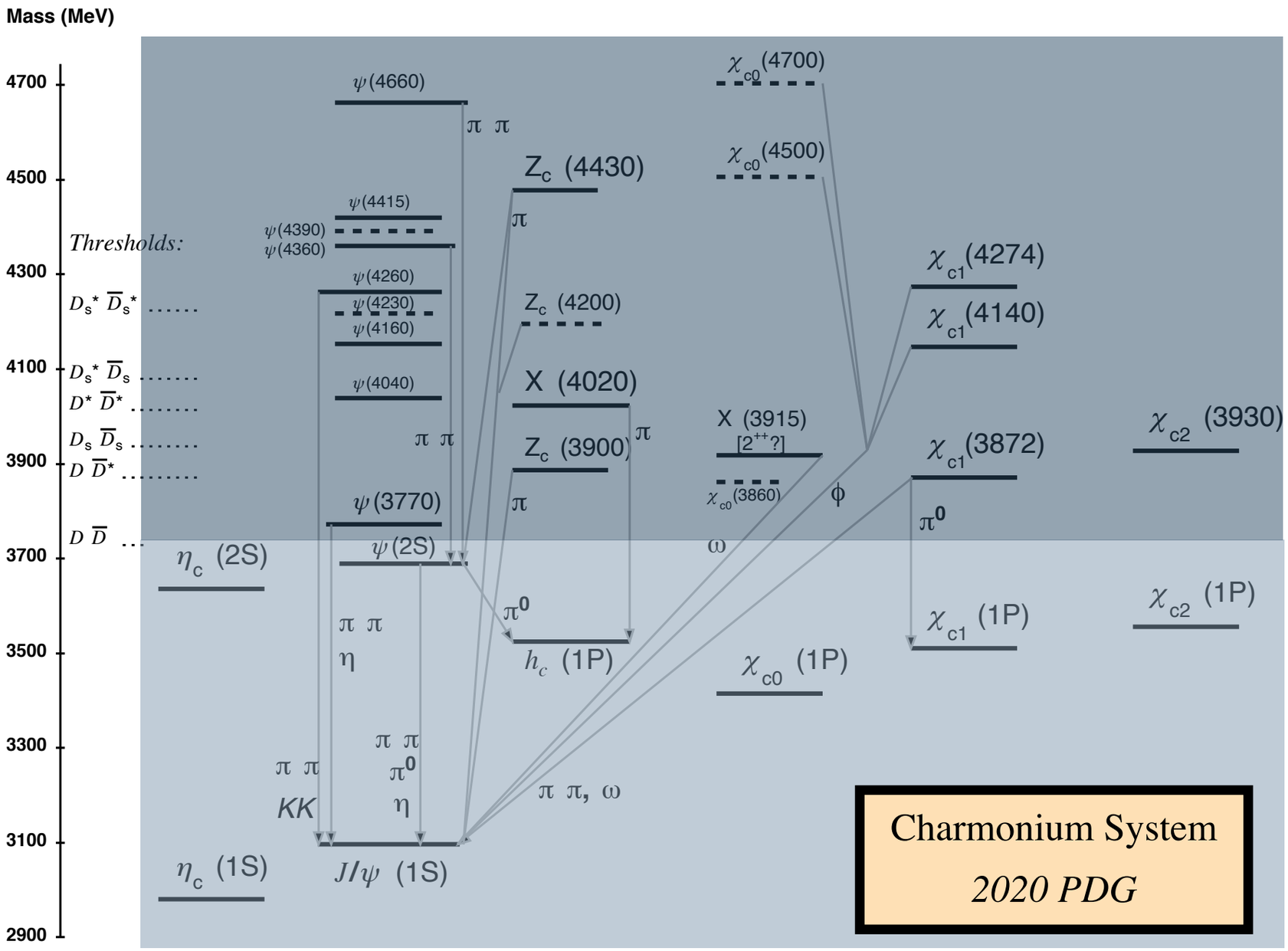
* have suppressed strong decays

  $\Longrightarrow$ *they are relatively narrow*

  $\Longrightarrow$ *electromagnetic transitions are accessible*

* can be considered the positronium of the strong force

* potential models work well



$J^{PC} =$ 0^{-+} 1^{--} 1^{+-} 0^{++} 1^{++} 2^{++}

IC. A Tour of Meson Families: **the J/ψ family**

Excited meson states below open-flavor thresholds:

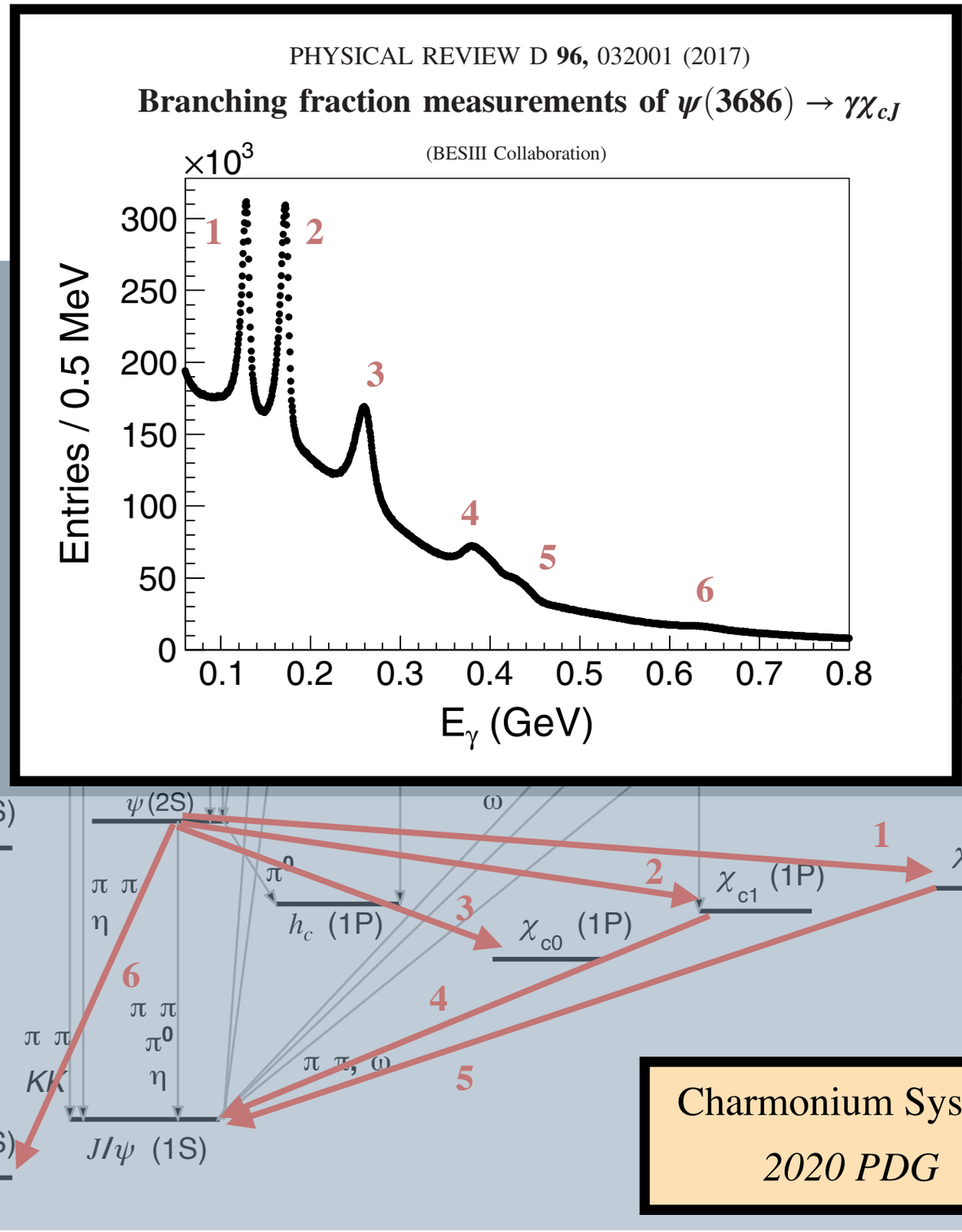
* have suppressed strong decays

  $\Longrightarrow$ *they are relatively narrow*

  $\Longrightarrow$ *electromagnetic transitions are accessible*

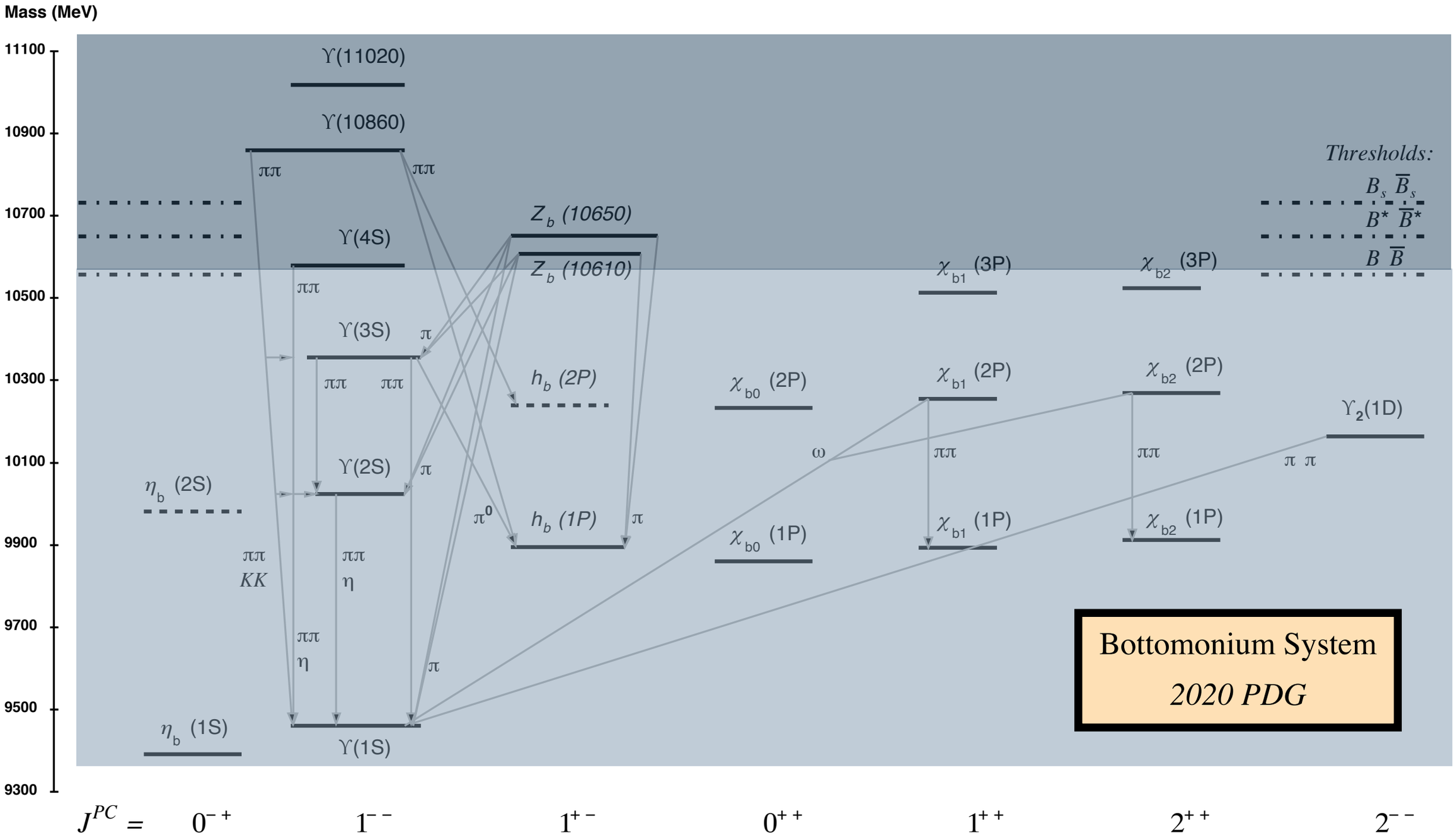
* can be considered the positronium of the strong force

* potential models work well



$J^{PC} =$ 0^{-+} 1^{--} 1^{+-} 0^{++} 1^{++} 2^{++}

IC. A Tour of Meson Families: the J/ψ family

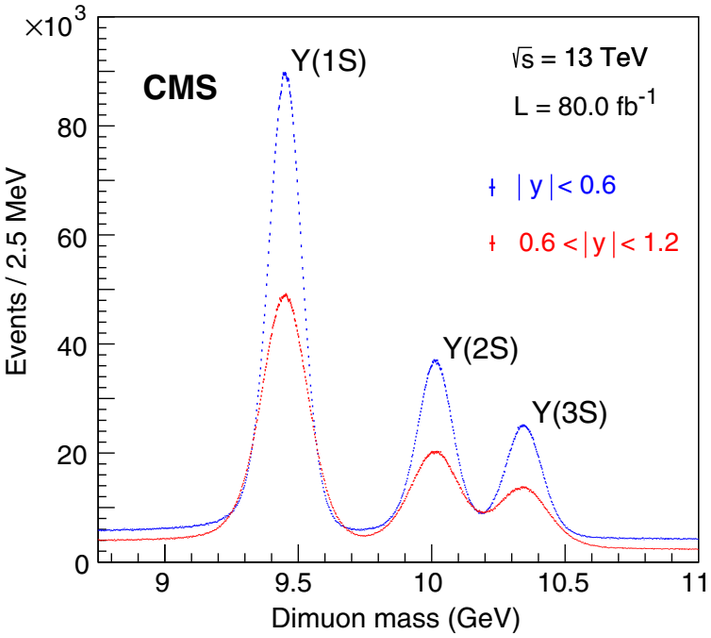


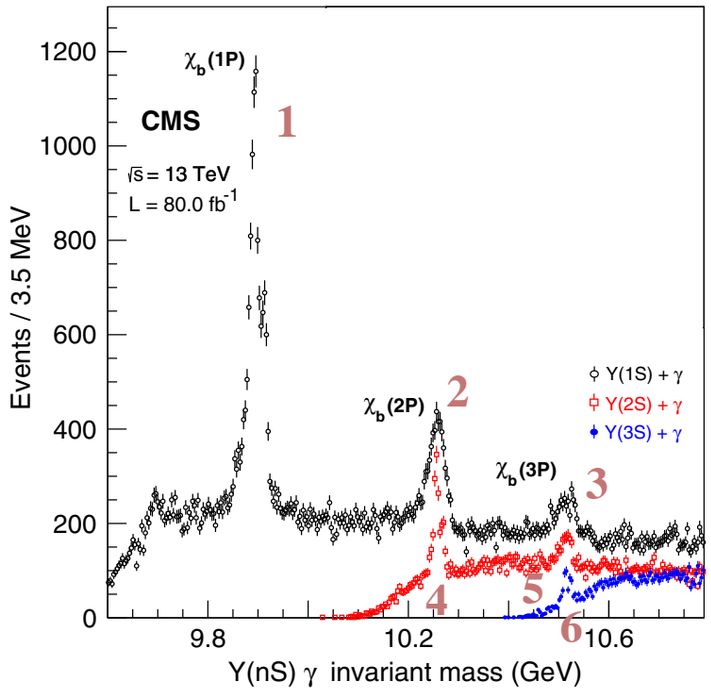
IC. A Tour of Meson Families: the J/ψ family

PHYSICAL REVIEW LETTERS **121,** 092002 (2018)

Observation of the $\chi_{b1}(3P)$ and $\chi_{b2}(3P)$ and Measurement of their Masses

(CMS Collaboration)





IC. A Tour of Meson Families: the ρ family

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)

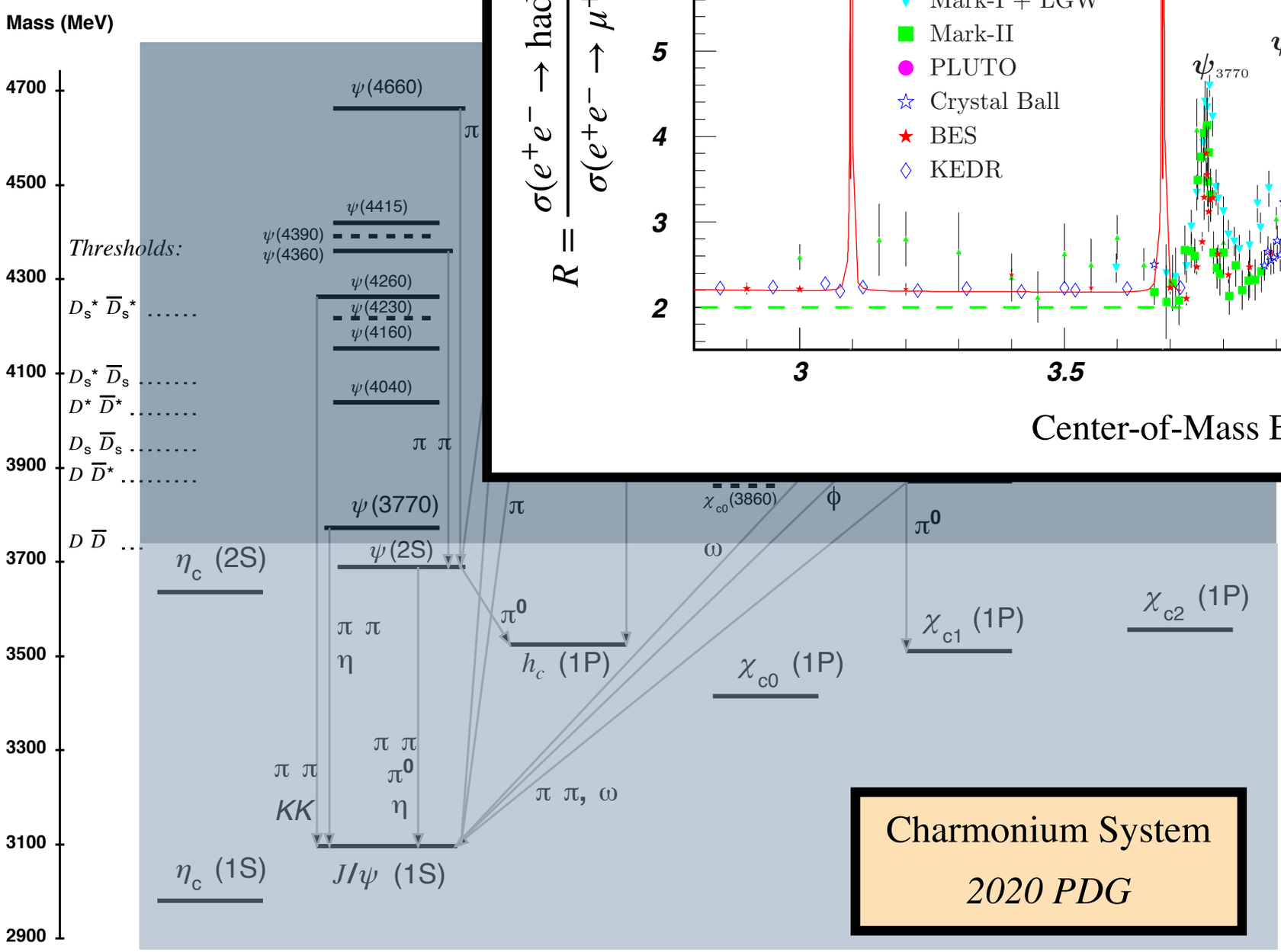
$Z_c(3900)$ family
(exotic flavor quantum numbers)

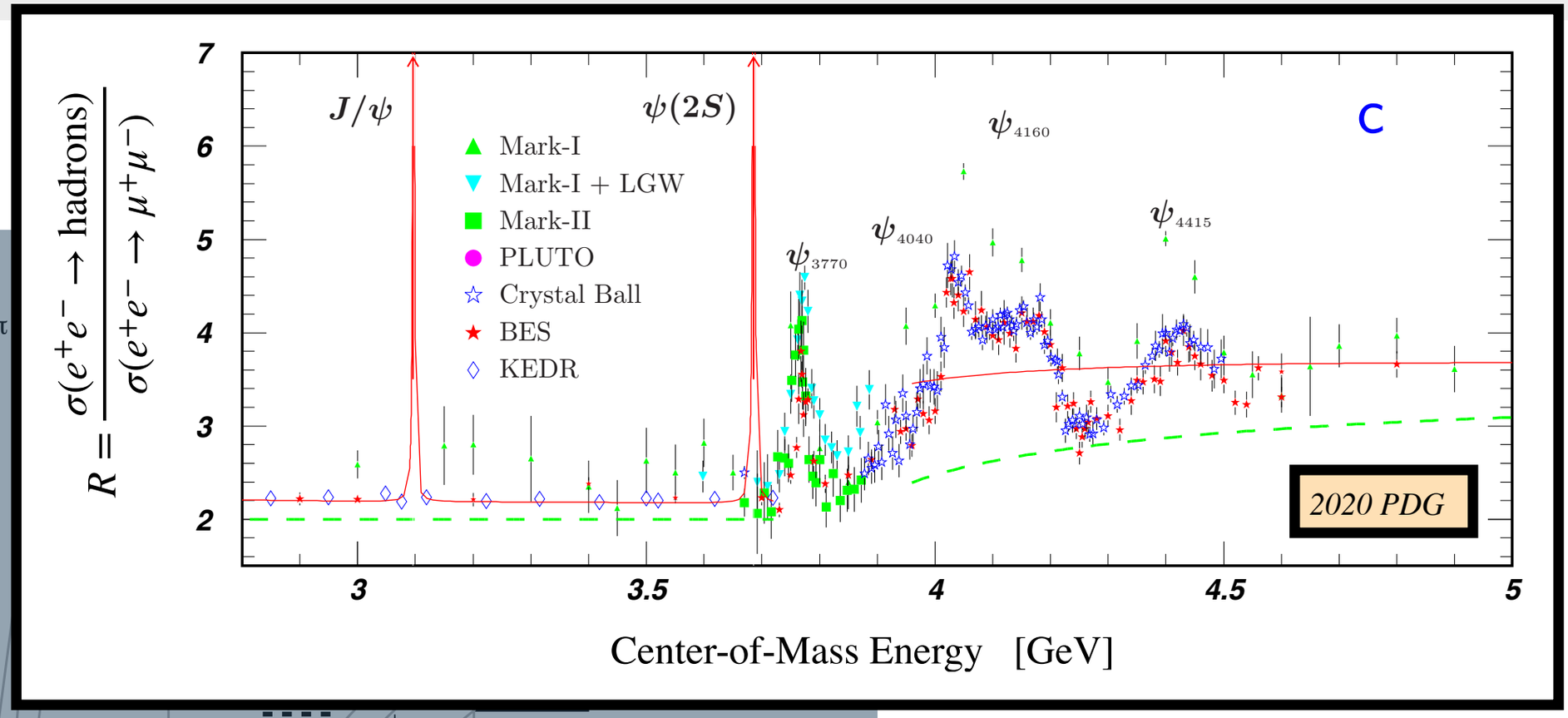
$J^{P(C)}$	$u\bar{d}$, $u\bar{u}$, $d\bar{d}$, $s\bar{s}$			$c\bar{c}$	$b\bar{b}$	$d\bar{s}$, $u\bar{s}$	$c\bar{u}$, $c\bar{d}$	$c\bar{s}$	$d\bar{b}$, $u\bar{b}$	$s\bar{b}$
$1^{-(-)}$	$\rho(1700)$	$\omega(1650)$	$\phi(1680)$	$\psi(3770)$	$\Upsilon(4S)$	$K^*(1680)$		$D_{s1}^*(2700)^+$		
$2^{+(+)}$	$a_2(1320)$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

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

IC. A Tour of Meson Families: the ρ family

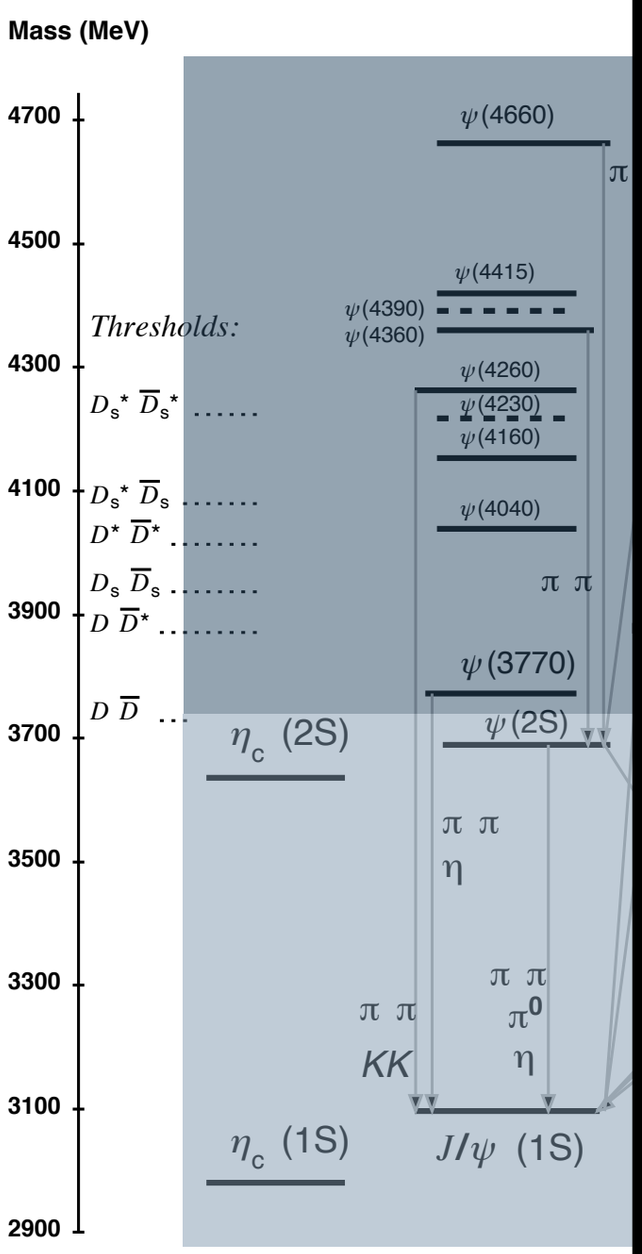


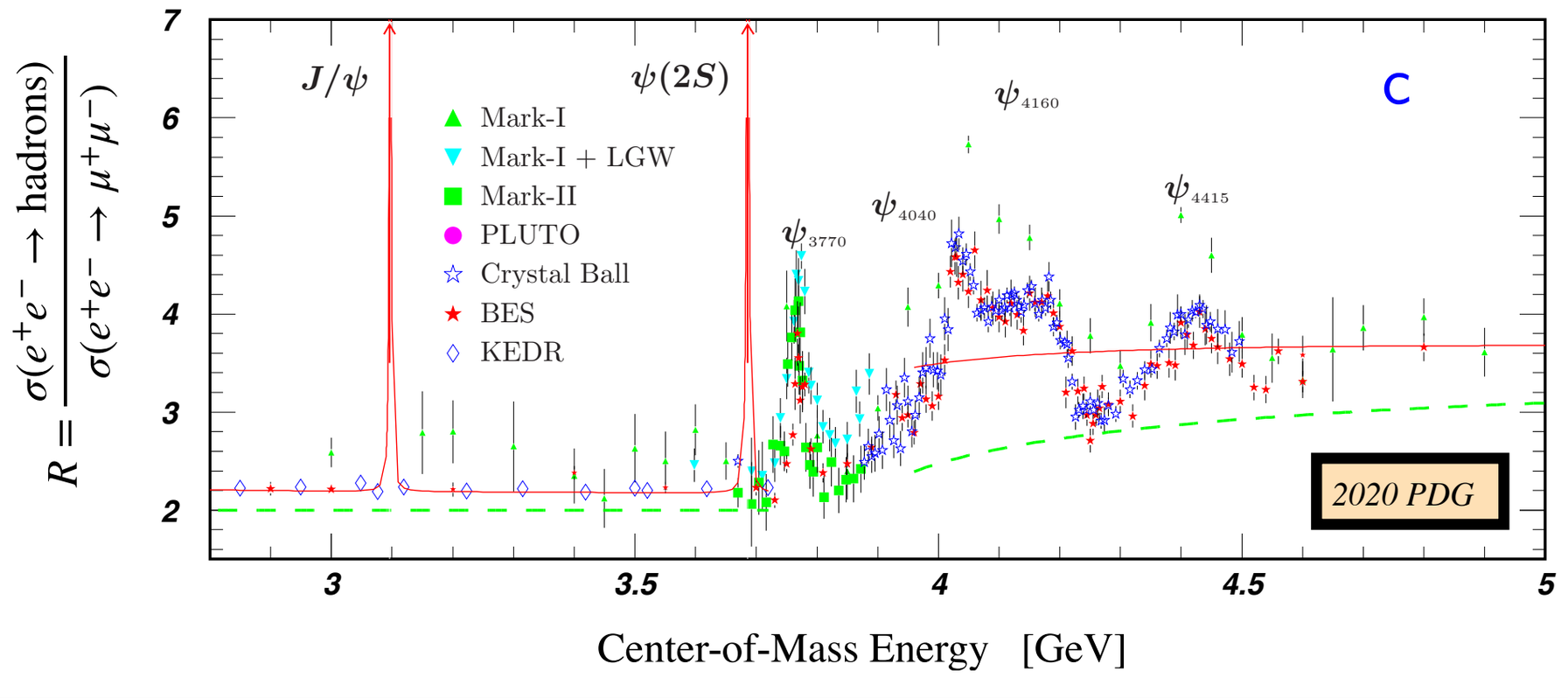


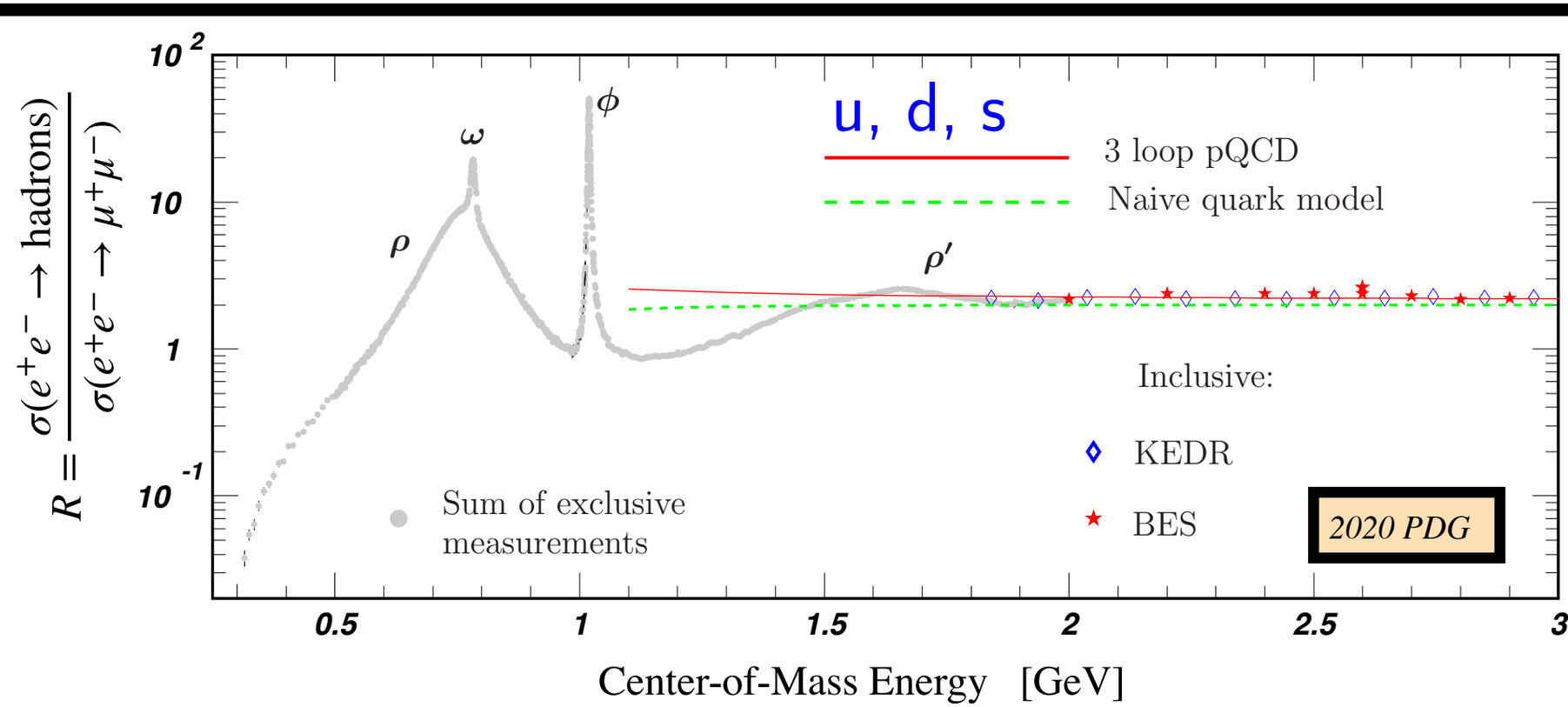
Charmonium System
2020 PDG

$J^{PC} =$ 0^{-+} 1^{--} 1^{+-} 0^{++} 1^{++} 2^{++}

IC. A Tour of Meson Families: the ρ family



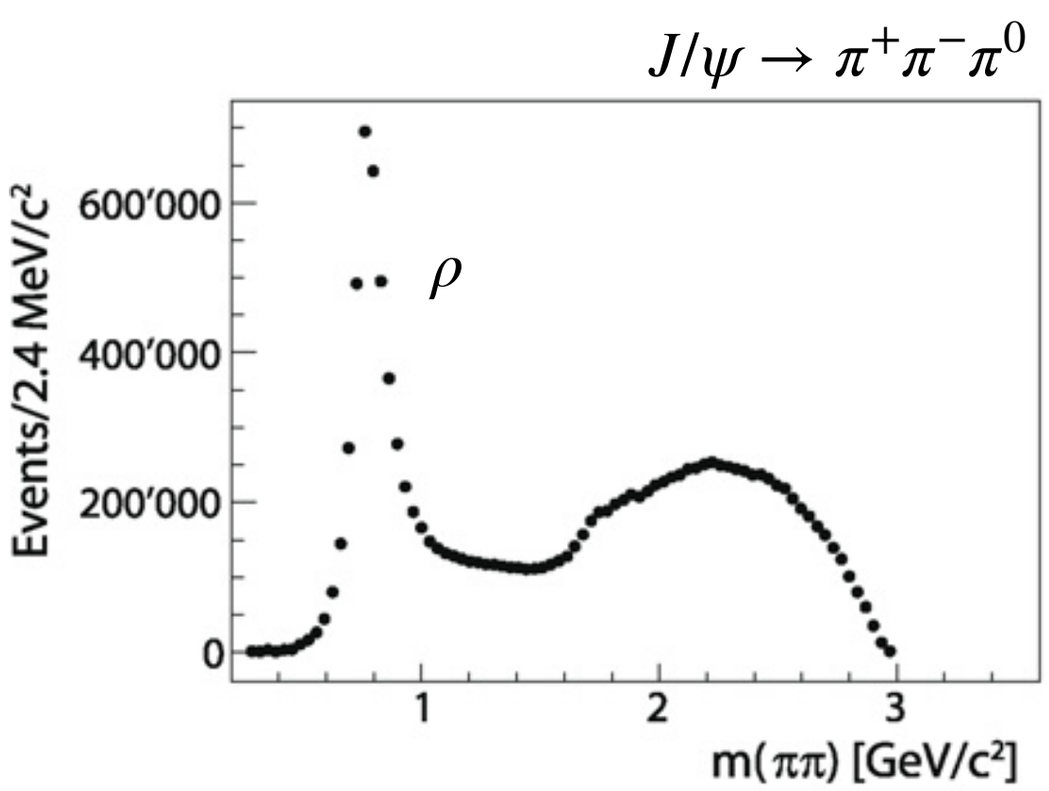


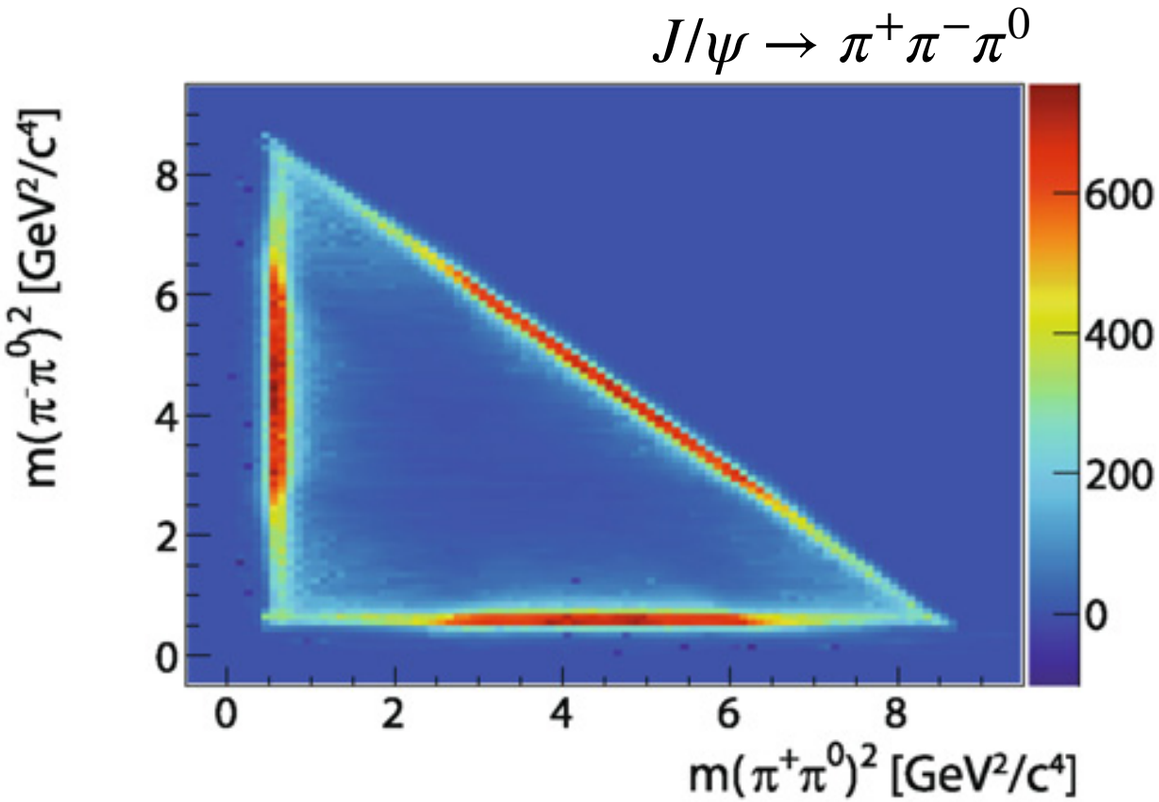


IC. A Tour of Meson Families: the ρ family

Precision measurement of the branching fractions of $J/\psi \to \pi^+\pi^-\pi^0$ and $\psi' \to \pi^+\pi^-\pi^0$

BESIII Collaboration / Physics Letters B 710 (2012) 594–599

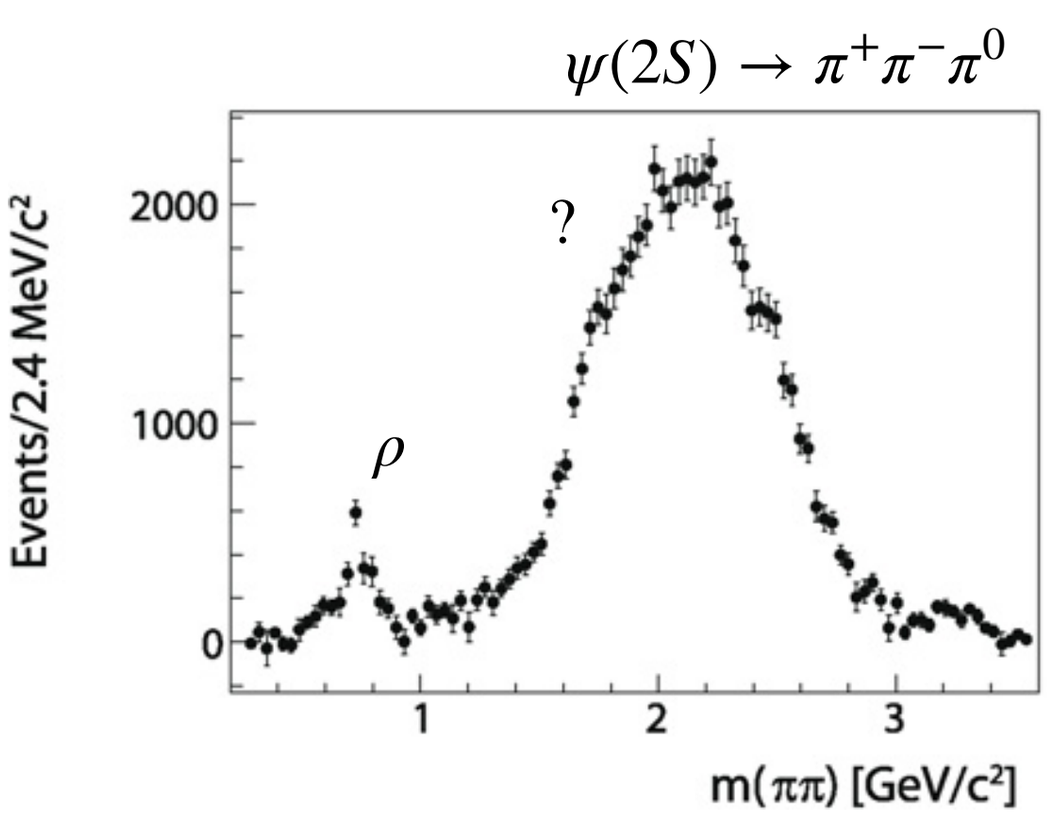


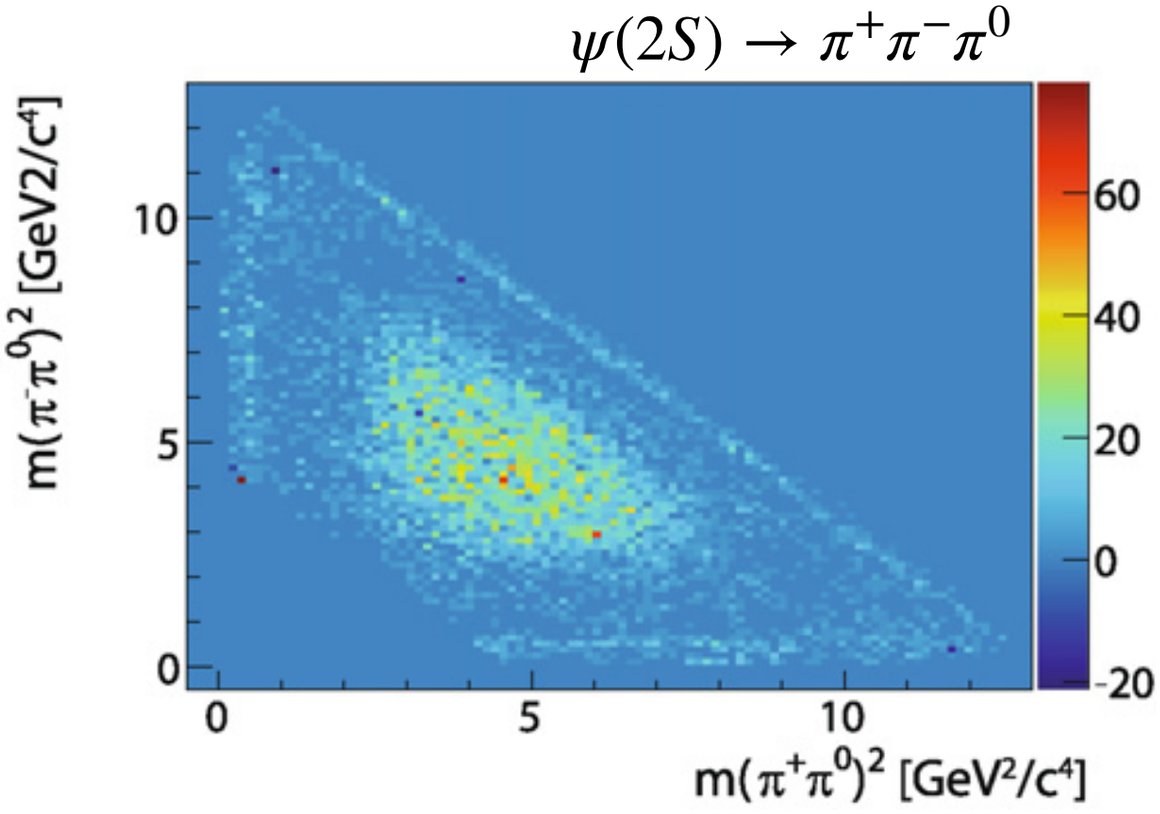


IC. A Tour of Meson Families: **the ρ family**

Precision measurement of the branching fractions of $J/\psi \to \pi^+\pi^-\pi^0$ and $\psi' \to \pi^+\pi^-\pi^0$

BESIII Collaboration / Physics Letters B 710 (2012) 594–599





IC. A Tour of Meson Families: the $Z_c(3900)$ family

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^+	$\eta \mid \eta' \mid \phi$	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)*
- $Z_c(3900)$ 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*

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

IC. A Tour of Meson Families: the $Z_c(3900)$ family

BESIII Experiment

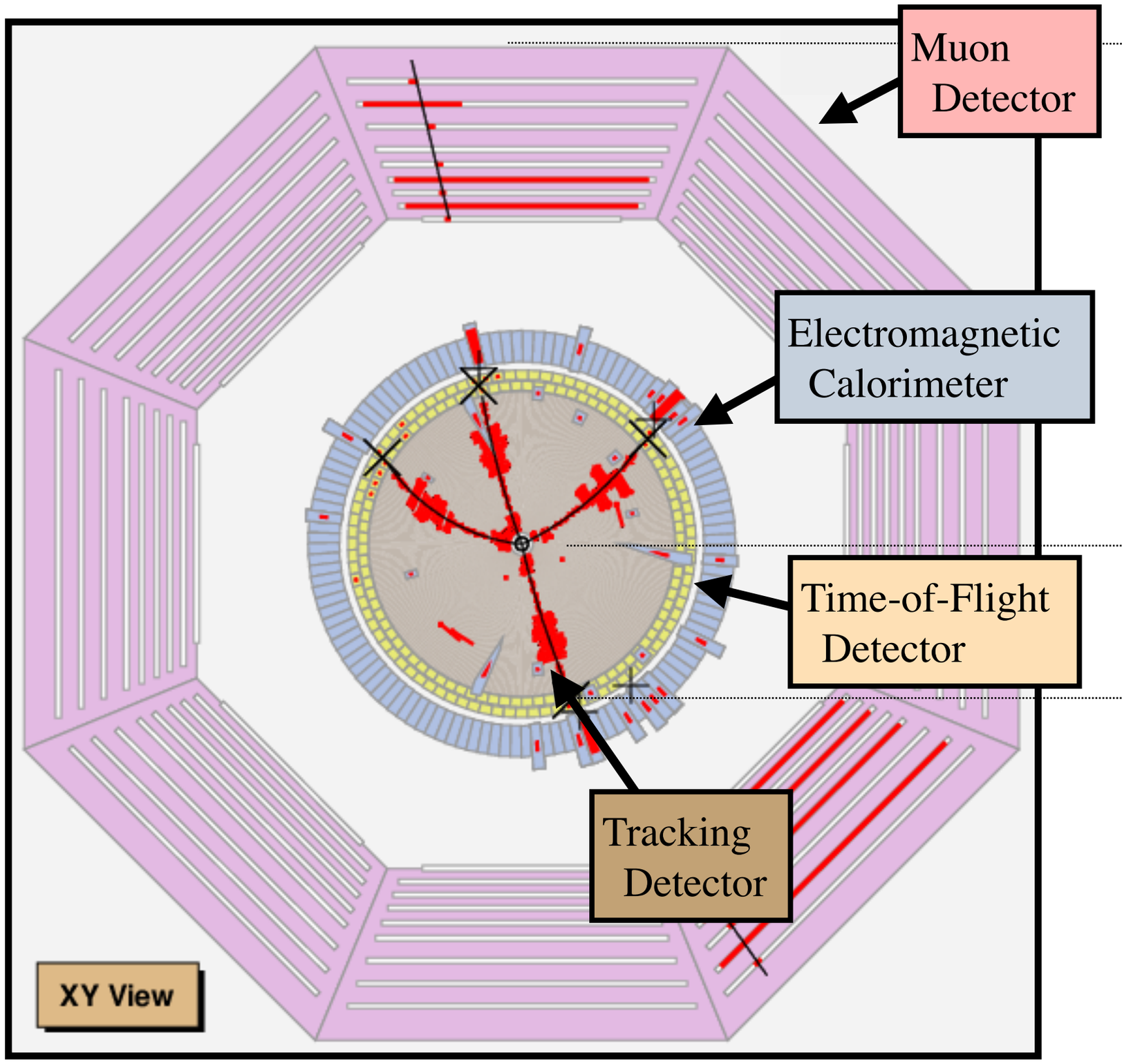
(Beijing, China)

Event display for:

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

with:

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

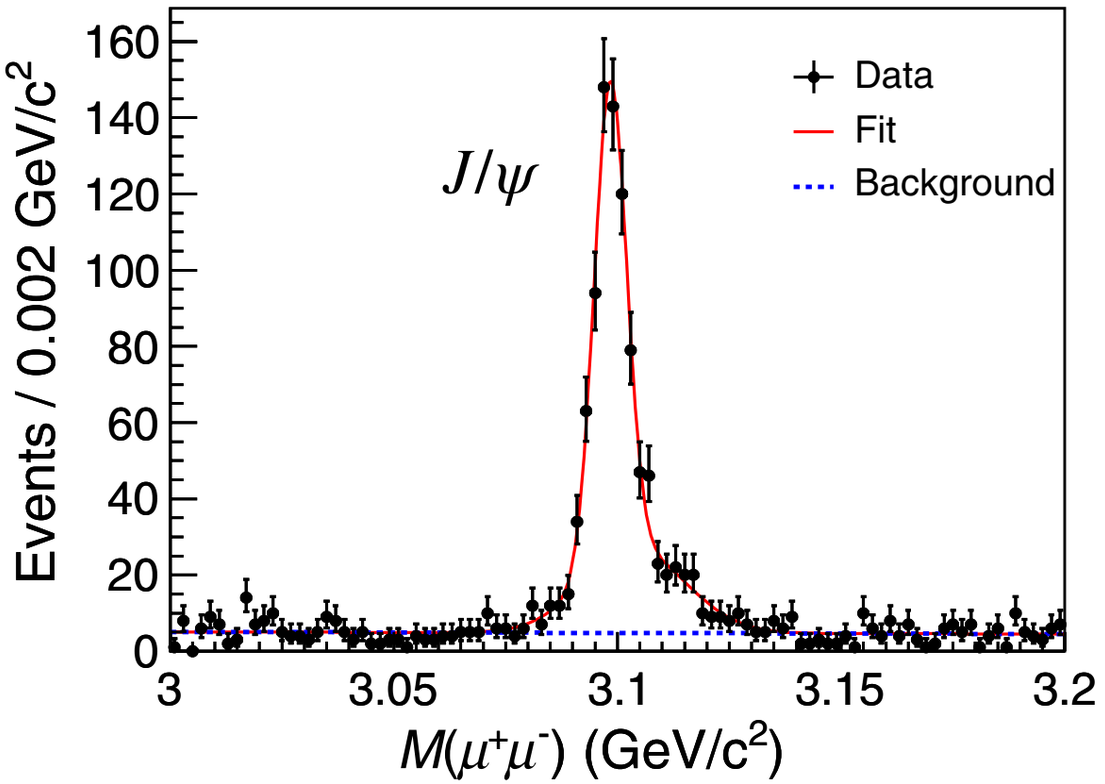


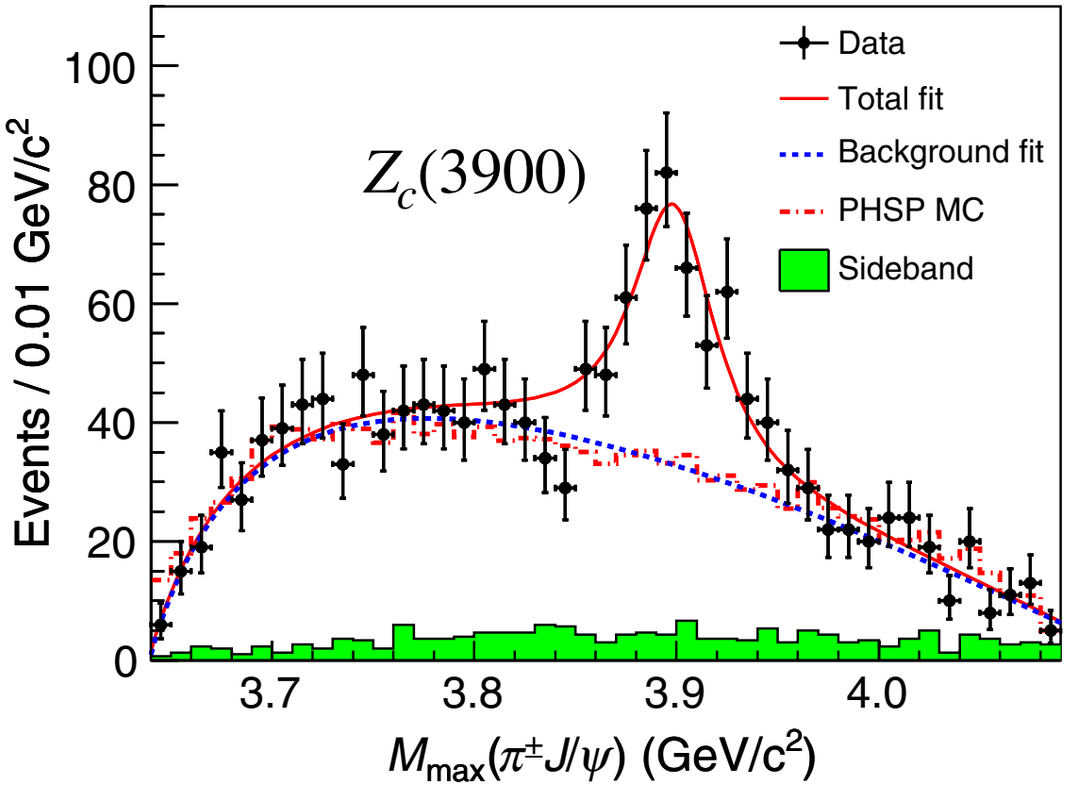
IC. A Tour of Meson Families: the $Z_c(3900)$ family

PRL **110,** 252001 (2013) Selected for a Viewpoint in *Physics* PHYSICAL REVIEW LETTERS week ending 21 JUNE 2013

Observation of a Charged Charmoniumlike Structure in $e^+e^- \to \pi^+\pi^- J/\psi$ at $\sqrt{s} = 4.26$ GeV

(BESIII Collaboration)





$Z_c(3900)^+ \to \pi^+ J/\psi \implies$ *minimal quark content is* $c\bar{c}u\bar{d}$

HUGS 2021 Lectures on:
Experimental Meson Spectroscopy

Prologue: Definitions and Philosophy

I. A Field Guide to Meson Families

II. Meson Quantum Numbers

III. The Quark Model

IV. Exotic Mesons

V. Current and Future Experiments

LECTURE I. A Field Guide to Meson Families

IA. Introduction to Meson Families

IB. A Few Basic Principles Determining Meson Behavior

IC. A Tour of Meson Families

* the K^+ family
* the K^0 family
* the π^0 family
* the J/ψ family
* the ρ family
* the $Z_c(3900)$ family

HUGS 2021 Lectures on:
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Prologue: Definitions and Philosophy

I. A Field Guide to Meson Families

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V. Current and Future Experiments

LECTURE I. A Field Guide to Meson Families

Mesons are hadrons made from equal numbers of quarks and antiquarks.

The gross behavior of a meson is determined by whether it decays weakly *(e.g. the K^+ and K^0)*, electromagnetically *(e.g. the π^0)*, or strongly *(e.g. the J/ψ and ρ):*

* and if weakly, whether it can mix with its antiparticle *(e.g. the K^0)* or not *(e.g. the K^+)*.

* and if strongly, if it's above open-flavor threshold *(e.g. the ρ)* or not *(e.g. the J/ψ)*.

There are also meson candidates with exotic flavors that are hard to classify *(e.g. the $Z_c(3900)$)*.