Exotic Mesons

Th. Gutsche

Institut für Theoretische Physik

Universität Tübingen

Overview

- Introductory remarks: quark-antiquark states and exotics

- Scalar glueball:

  - decay properties and J/ψ production modes of the high lying scalars

  - can the $f_0(1500)$ really be the ground state glueball

- Hadron molecules:

  - binding of the X(3872) as a $D\bar{D}^*$ molecule

  - the puzzling radiative decays of X(3872)

Constituent quark model:

- Mesons: quark-antiquark ($Q\bar{Q}$)

- QCD $\overset{soft\ limit}{\Longrightarrow}$ " dressed quasiparticle " : Q = constituent quark

  $$(m_Q \approx 300 \ \text{MeV for u,d})$$

- in low-energy physics, 3 flavors: u,d,s, mesons are grouped in nonets

0^{-+}
pseudoscalar

1^{--}
vector

0^{++}
scalar

$K_0(1430)$

$f_0(1370)$

$f_0(1590)$

$a_0(1450)$
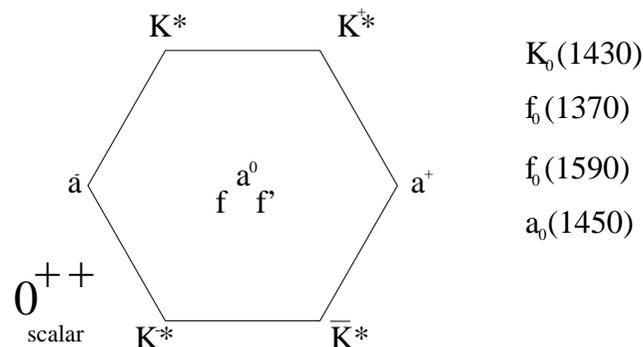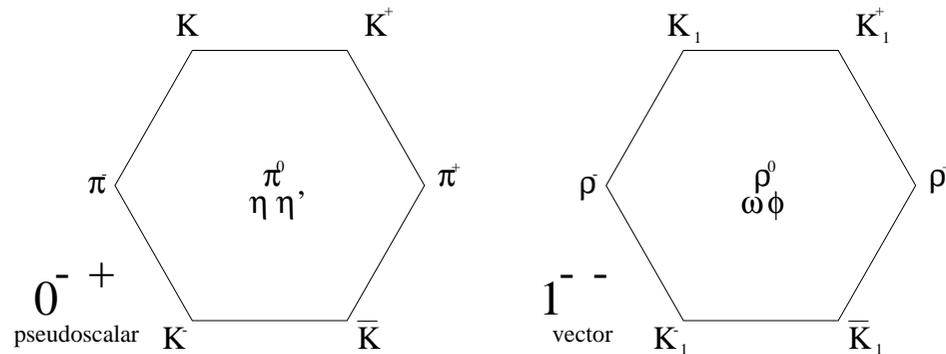
Introduction: Meson Spectroscopy

Assignment of mesons to quark model states

$n^{2S+1}L_J$	J^{PC}	$I = 1$ $u\bar{d}\cdots$	$I = \frac{1}{2}$ $u\bar{s}\cdots$	$I = 0$ f	$I = 0$ f'	θ_q	θ_l
1^1S_0	0^{-+}	π	K	η	η'	$-11.5°$	$-24.6°$
1^3S_1	1^{--}	ρ	K^*	ω	ϕ	$38.7°$	$36.0°$
1^1P_1	1^{+-}	$b_1(1235)$	K_{1B}	$h_1(1170)$	$h_1(1380)$		
1^3P_0	0^{++}	$a_0(1450)$	$K_0^*(1430)$	$f_0(1370)$	$f_0(1710)$		
1^3P_1	1^{++}	$a_1(1260)$	K_{1A}	$f_1(1285)$	$f_1(1420)$		
1^3P_2	2^{++}	$a_2(1320)$	$K_2^*(1430)$	$f_2(1270)$	$f_2'(1525)$	$29.6°$	$28.0°$
1^1D_2	2^{-+}	$\pi_2(1670)$	$K_2(1770)$	$\eta_2(1645)$	$\eta_2(1870)$		
1^3D_1	1^{--}	$\rho(1700)$	$K^*(1680)$	$\omega(1650)$			
1^3D_2	2^{--}		$K_2(1820)$				
1^3D_3	3^{--}	$\rho_3(1690)$	$K_3^*(1780)$	$\omega_3(1670)$	$\phi_3'(1850)$	$32.0°$	$31.0°$
1^1F_4	4^{++}	$a_4(2040)$	$K_4^*(2045)$	$f_4(2050)$			
1^3G_5	5^{--}	$\rho_5(2350)$					
1^3H_6	6^{++}	$a_6(2450)$		$f_6(2510)$			
2^1S_0	0^{-+}	$\pi(1300)$	$K(1460)$	$\eta(1295)$	$\eta(1475)$	$-22.4°$	$-22.6°$
2^3S_1	1^{--}	$\rho(1450)$	$K^*(1410)$	$\omega(1420)$	$\phi(1680)$		

Modified reproduction of table from minireview "Quark Model", RPP (2010)

Introduction: Meson Spectroscopy

" dressed quasiparticle " Q = constituent quark ($m_Q \approx 300\ MeV$)

g=" constituent gluon "(usually $J^{PC} = 0^{++}$) ?

$\Downarrow$ extrapolation, color singlets

- baryonium $Q^2 \bar{Q}^2$, Jaffe (1977)

- hybrids $Q\bar{Q}g$, Chanowitz et al. (1983)

- glueball gg, Barnes et al. (1982)

- ....

however !

- meson-meson molecules, Weinstein and Isgur (1982)

- $N\bar{N}$ bound states, Dover et al. (1992)

- dynamically generated resonances

- ....

Introduction: Non-$Q\bar{Q}$ states = Exotics

- **1st kind (utterly exotic)**

  open exotic values in principal quantum number like charge $|Q| \geq 2$, strangeness $|S| \geq 2$

  no candidates !

- **2nd kind (phano-exotic)**

  exotic sets of J^{PC}

  $Q\bar{Q} : \ P = (-)^{L+1}, C = (-)^{L+S}$

  $$\left.\begin{array}{l} \rightarrow \ S = 1 \rightarrow CP = +1 \\ \rightarrow \ S = 0 \rightarrow CP = -1 \end{array}\right\} \rightarrow J^{PC} = 0^{-+}, 1^{+-}, 2^{-+}, ...$$

  however: $J^{PC} = 0^{+-}, 1^{-+}, 2^{+-}, ... \neq Q\bar{Q}$

  evidence for 1^{-+} states !

- **3rd kind (crypto-exotic)**

  hidden exotics

  no obvious exotic features, anomalous dynamical features

  serious candidates (extra states) !

Introduction: Exp. Evidence for Non-$Q\bar{Q}$ States

selected examples (see PDG or Godfrey and Napolitano, Rev. Mod. 71 (1999)):

$$\pi_1(1400) \quad I^G(J^{PC}) = 1^-(1^{-+})$$

- BNL (E852) (1997): $\pi^- p \longrightarrow p\ X$
  $\searrow \eta\ \pi^-$
  $l=1$
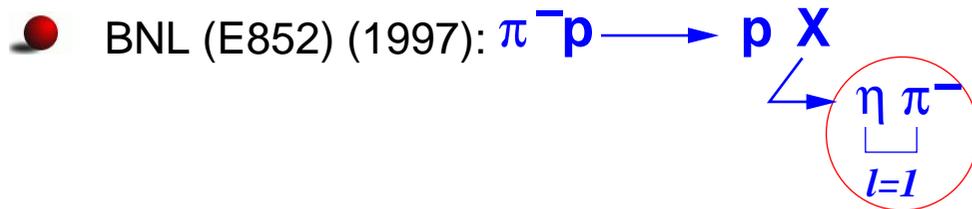
$M_X = 1370 \pm 16 \pm 50$ MeV,
$\Gamma_X = 385 \pm 40^{+65}_{-105}$ MeV

- Crystal Barrel (1998): $\bar{p}\ d \longrightarrow p_{spec} X \pi^0$
  $\searrow \eta\ \pi^-$
  $l=1$

$M_X = 1398 \pm 20$ MeV,
$\Gamma_X = 309 \pm 50$ MeV

$$f_0(1500) \quad I^G(J^{PC}) = 0^+(0^{++})$$

● Crystal Barrel (see compilation in Amsler, Rev. Mod. Phys. 70 (1998))

$\bar{\text{p}}$ p $\longrightarrow$ π^0 + f$_0$(1500)

$$\pi\pi \quad 29.0 \pm 7.5 \text{ \%}$$
$$\eta\eta \quad 4.6 \pm 1.3 \text{ \%}$$
$$\eta\eta' \quad 1.2 \pm 0.3 \text{ \%}$$
$$\text{KK} \quad 3.5 \pm 0.3 \text{ \%}$$
$$4\pi \quad 61.7 \pm 9.6 \text{ \%}$$

$$M_{f_0} = 1505 \pm 9 \text{ MeV}, \quad \Gamma = 111 \pm 12 \text{ MeV}$$

Introduction: "Exotic Heavy Meson States"

State	M (MeV)	Γ (MeV)	J^{PC}	Decay Modes	Production Modes
$X(3872)$	3871.4 ± 0.6	< 2.3	1^{++}	$\pi^+\pi^- J/\psi, \gamma J/\psi$	$B \to KX(3872), p\bar{p}$
$X(3875)$	3875.5 ± 1.5	$3.0^{+2.1}_{-1.7}$	?	$D^0\bar{D}^0\pi^0(\gamma)$	$B \to KX(3875)$
$Z(3940)$	3929 ± 5	29 ± 10	2^{++}	$D\bar{D}$	$\gamma\gamma \to Z(3940)$
$X(3940)$	3942 ± 9	37 ± 17	J^{P+}	$D\bar{D}^*$	$e^+e^- \to J/\psi X(3940)$
$Y(3940)$	3943 ± 17	87 ± 34	J^{P+}	$\omega J/\psi$	$B \to KY(3940)$
$Y(4008)$	4008^{+82}_{-49}	226^{+97}_{-80}	1^{--}	$\pi^+\pi^- J/\psi$	e^+e^- (ISR)
$Y(4140)$	4130 ± 4.1	$11.7^{+12.0}_{-8.7}$	J^{P+}	$J/\psi\phi$	$B^+ \to K^+Y(4140)$
$X(4160)$	4156 ± 29	139^{+113}_{-65}	J^{P+}	$D^*\bar{D}^*$	$e^+e^- \to J/\psi X(4160)$
$Y(4260)$	4264 ± 12	83 ± 22	1^{--}	$\pi^+\pi^- J/\psi$	e^+e^- (ISR)
$Y(4350)$	4361 ± 13	74 ± 18	1^{--}	$\pi^+\pi^- \psi'$	e^+e^- (ISR)
$Z^\pm(4430)$	4433 ± 5	45^{+35}_{-18}	?	$\pi^\pm\psi'$	$B \to KZ^\pm(4430)$
$Y(4660)$	4664 ± 12	48 ± 15	1^{--}	$\pi^+\pi^- \psi'$	e^+e^- (ISR)

strong deviations from $c\bar{c}$ mass predictions, width etc. (see talk by K. Seth)

THE SCALAR GLUEBALL

Glueball Spectrum

scalar ground state:

$$m_{0++}\,[MeV]$$

1550 ± 50	Bali (93)
1600 ± 160	Michael (93)
1648 ± 58	Vaccarino (98)
1630 ± 100	Morningstar (97)
1740 ± 71	Chen (94)
1730 ± 130	Morningstar, Peardon (99)
1710 ± 130	Chen et al (06)

Sexton et al., PRL75 (1995):

$$\Gamma_{0++} \approx O(100) \text{ MeV}$$
$$\neq O(1000) \text{ MeV}$$

$\rightarrow$ observable !!

Hart et al., PRD74 (2006):

unquenching $m_{0++} \rightarrow 1\,GeV$?

SU(3) Glueball Spectrum

C.Morningstar and M.Peardon
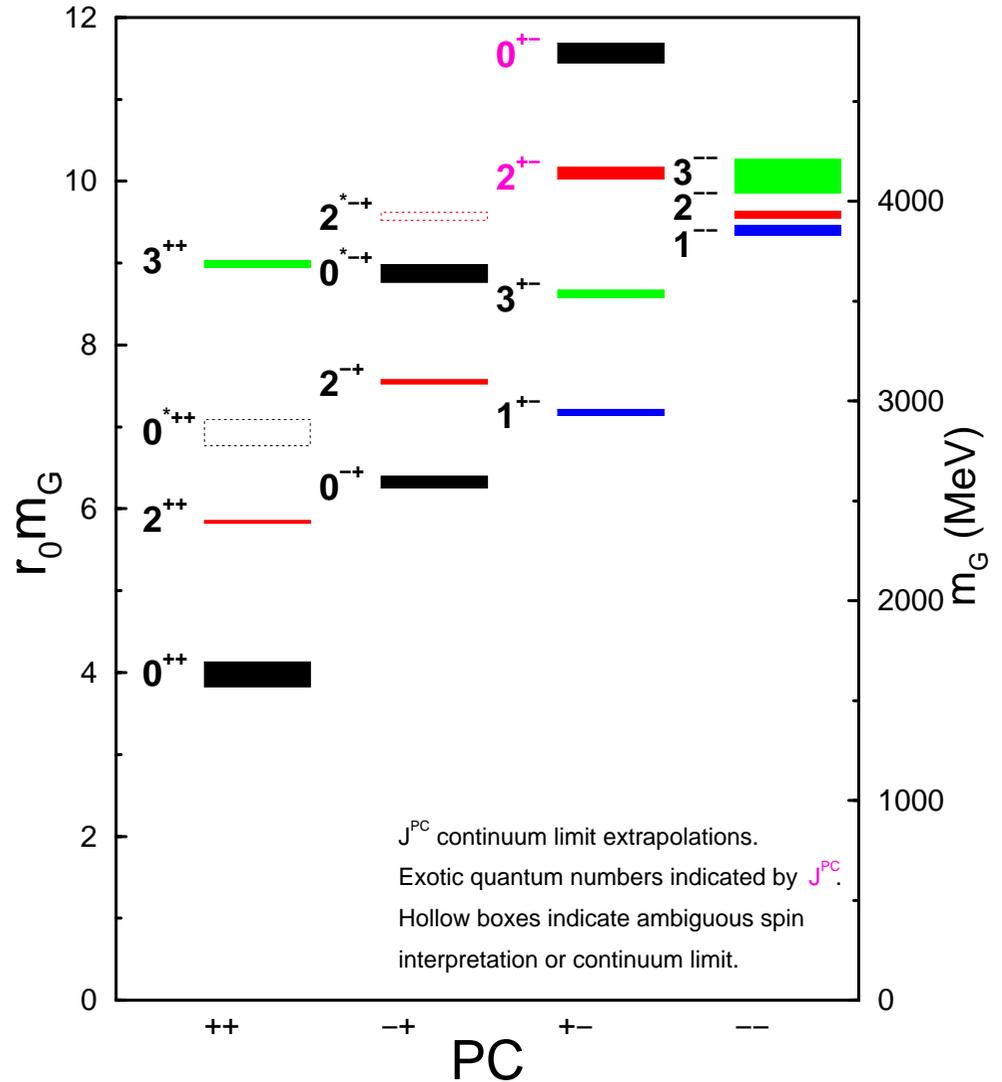
Scalar glueball candidates

$$f_0(1500), \; m = 1505 \pm 6 \text{ MeV}, \; \Gamma = 109 \pm 7 \text{ MeV}$$

gluon rich

$p\bar{p} \rightarrow \pi^0 f_0$ N   π   Crystal Barrel (9

$\bar{n} p \rightarrow \pi^+ f_0$ N̄   f₀   Obelix (98)

$pp \rightarrow pp f_0$ p   p   WA91 (95)

f₀   WA102 (99)

p   p

$J/\Psi \rightarrow \gamma f_0$ c   γ   Bugg (95)

c̄   f₀   Dunwoodie (97

γ

no signal   f₀   WA102 (99)

γ
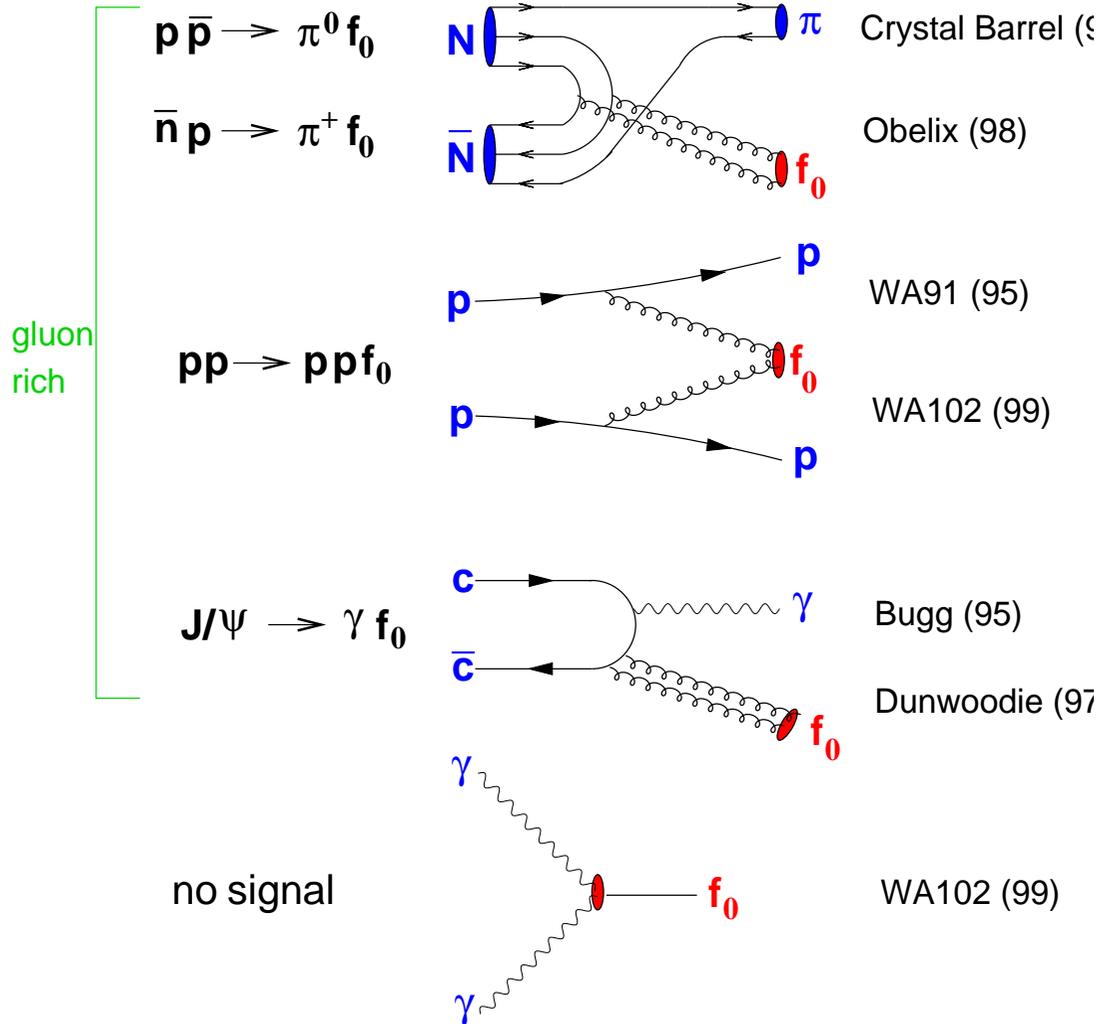
Scalar glueball candidates

$f_0(1710)$, $m = 1720 \pm 6$ MeV, $\Gamma = 135 \pm 8$ MeV

gluon rich

$\mathbf{pp} \longrightarrow \mathbf{pp\,f_0}$
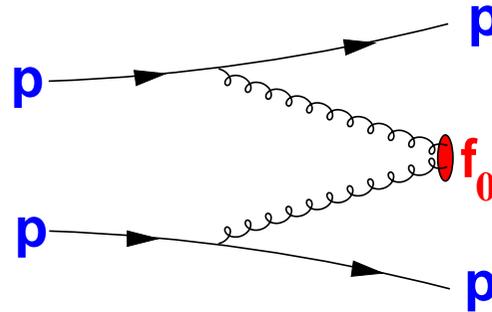
WA102 (99

$\mathbf{J/\Psi} \longrightarrow \gamma\,\mathbf{f_0}$
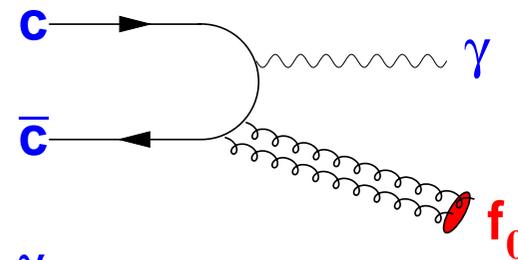
Bai (96)

no signal
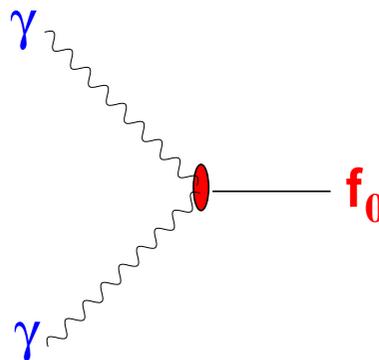
WA102 (99

Scalar Nonet

$$J^{PC} = 0^{++} \text{ with } [L = 1 \times S = 1]_{J=0}$$

I = 1/2	I = 1	I = 0
$K_0^*(800)?$	$a_0(980)$	$f_0(400-1200)$ $f_0(980)$
$K_0^*(1430)$	$a_0(1450)$	$f_0(1370)$ $f_0(1500)$ $f_0(1710)$

$\Downarrow$ $\Downarrow$ $\Downarrow$

$d\bar{s}, u\bar{s}$ $\frac{1}{\sqrt{2}}(u\bar{u} - d\bar{d})$ $\frac{1}{\sqrt{2}}(u\bar{u} + d\bar{d})$ **+**   scalar glueball

$s\bar{d}, s\bar{u}$ $u\bar{d}, d\bar{u}$ $s\bar{s}$

- scalar resonances below 1 GeV possibly four-quark states or mesonic molecules
- scale of scalar nonet set by other $Q\bar{Q}$ nonets, also $a_0(1450)$
- mixing of nearby scalars with scalar glueball, Amsler/Close (1996)

Chiral Resonance Lagrangians

- Resonance saturation of low-energy constants (LEC) (see Ecker, Gasser, Pich and de Rafael, NPB 321 (1989) or Donoghue, Ramirez and Valencia, PRD39 (1989))

- mass splittings and couplings to decay channels can be studied in framework of chiral resonance Lagrangian

- a priori justified for soft Goldstone bosons

- for resonances far above 1 GeV at best phenomenological model

- F. Giacosa, TG, V. E. Lyubovitskij and A. Faessler
  Phys. Lett. B **622** (2005) 277, PRD **72** (2005) 094006, PRD **72** (2005) 114021,
  TG, V. E. Lyubovitskij and M. Tichy
  PRD **79** (2009) 014036, PRD **80** (2009) 014014,
  P.Chatzis, A. Faessler, TG and V. E. Lyubovitskij
  PRD **84** (2011) 034027,

Test case tensor meson nonet $J^{PC} = 2^{++}$

$f_2(1270),\ f_2'(1525),\ a_2(1230)$ and $K_2^*(1430)$

Well-established nonet

Precise data for decay modes:

- $T \to PS\ PS$
- $T \to \gamma\gamma$
- $T \to V\ PS$
- $T \to \gamma\ PS$

T=tensor, PS=pseudoscalar,

V=vector meson

K^{*}　K^{+*}

a_2^- 　 a_2^0 　 a_2^+

$f_2\ f_2'$

K^{-*}　$\overline{K}^{*}$

2^{++}
tensor
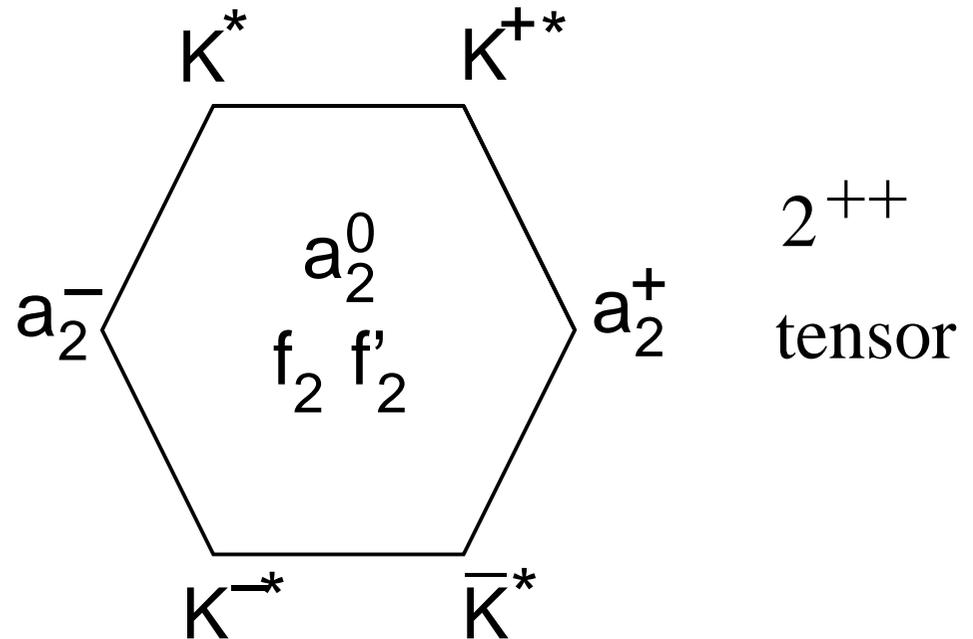
Chiral Lagrangians: Tensor mesons

Effective Lagrangian coupling tensor mesons (T) to vector (V), pseudoscalar mesons (PS) and photons (γ) (see Bellucci, Gasser and Sainio, NPB423 (1994)):

$$
\begin{aligned}
\mathcal{L}_{\text{eff}}^{T} &= \frac{F^2}{4}\left\langle D_\mu U\, D^\mu U^\dagger + \chi_+ \right\rangle - \frac{1}{4}\langle \mathcal{T}_{\mu\nu} D^{\mu\nu;\rho\sigma}\mathcal{T}_{\rho\sigma}\rangle - \\
&\quad - \frac{1}{4}\langle \mathcal{V}_{\mu\nu}\mathcal{V}^{\mu\nu} - 2M_V^2 \mathcal{V}_\mu \mathcal{V}^\mu \rangle + \mathcal{L}_{\text{mix}}^{P} + \mathcal{L}_{\text{mix}}^{T} \\
&\quad + c_{TPP}^{8}\left\langle \mathcal{T}_{\mu\nu}^{octet}\,\Theta_P^{\mu\nu}\right\rangle + \frac{c_{TPP}^{0}}{\sqrt{3}}\,T_{\mu\nu}^{0}\left\langle \Theta_P^{\mu\nu}\right\rangle + c_{T\gamma\gamma}\left\langle \mathcal{T}_{\mu\nu}\Theta_\gamma^{\mu\nu}\right\rangle \\
&\quad + ic_{TPV}\left\langle \mathcal{T}^{[\mu\nu]\alpha}[\widetilde{\mathcal{V}}_{\mu\nu}, \partial_\alpha \mathcal{P}]\right\rangle + ic_{TP\gamma}\left\langle \mathcal{T}^{[\mu\nu]\alpha}[Q\widetilde{F}_{\mu\nu}, \partial_\alpha \mathcal{P}]\right\rangle
\end{aligned}
$$

corresponds to tree level graphs
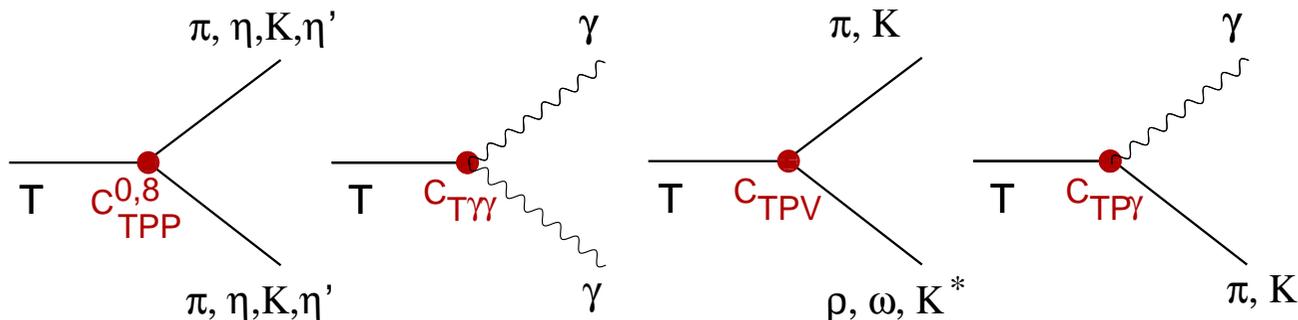
Chiral Lagrangians: Tensor mesons

Results for $T \to PS\,PS$:

fit parameters: $c^8_{TPP} = 0.0353$ GeV, $c^0_{TPP} = 0.0410$ GeV, $\theta_T = 28.78°$

| Mode	Exp. (MeV)	Theo. (MeV)
$\Gamma_{f_2 \to \pi\pi}$	157.0 ± 7.6	153.51
$\Gamma_{f_2 \to \bar{K}K}$	8.5 ± 0.9	9.15
$\Gamma_{f_2 \to \eta\eta}$	0.83 ± 0.20	0.80
$\Gamma_{f'_2 \to \pi\pi}$	0.60 ± 0.16	0.55
$\Gamma_{f'_2 \to \bar{K}K}$	64.8 ± 7.6	41.64
$\Gamma_{f'_2 \to \eta\eta}$	7.5 ± 2.9	6.49
$\Gamma_{a_2 \to \bar{K}K}$	5.2 ± 1.1	6.64
$\Gamma_{a_2 \to \eta\pi}$	15.5 ± 2.0	18.42
$\Gamma_{a_2 \to \eta'\pi}$	0.57 ± 0.12	0.80
$\Gamma_{K^*_2 \to \bar{K}K}$	51.8 ± 3.2	49.08
χ^2_{tot}	-	18.496

and
$$\Gamma_{K^*_2 \to K\eta} / \left(\Gamma_{K^*_2}\right)_{tot} = 3.93 \times 10^{-3} (theor.)$$
$$1.5^{+3.4}_{-1.0} \times 10^{-3} (exp.)$$

Scalar sector: chiral Lagrangian, graphical representation

mixing of the scalar-isoscalar states (also see Amsler/Close(1996))

$$M_S \quad \underline{\qquad}$$

$$M_G \quad \underline{\qquad}$$

$$M_N \quad \underline{\qquad}$$

$f_3 = f_0(1710)$

$f_2 = f_0(1500)$

mixing

$f_1 = f_0(1370)$
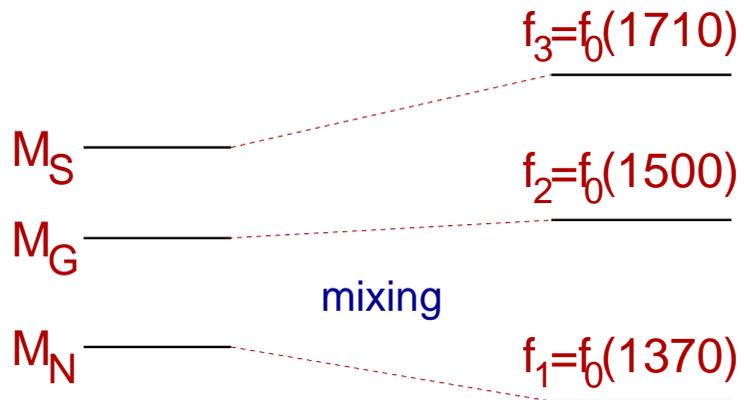
$$N, \; G, \; S \quad \longrightarrow \quad \begin{pmatrix} M_N^2 & \sqrt{2}f & \varepsilon \\ \sqrt{2}f & M_G^2 & f \\ \varepsilon & f & M_S^2 \end{pmatrix}$$

$$\longrightarrow \quad |f_0\rangle = \sum_{j=N,G,S} B_{ij} \; |j\rangle$$

Scalar sector: chiral Lagrangian, graphical representation

corresponds to tree level graphs for direct decay of scalar quarkonia (S) and glueball (G) components
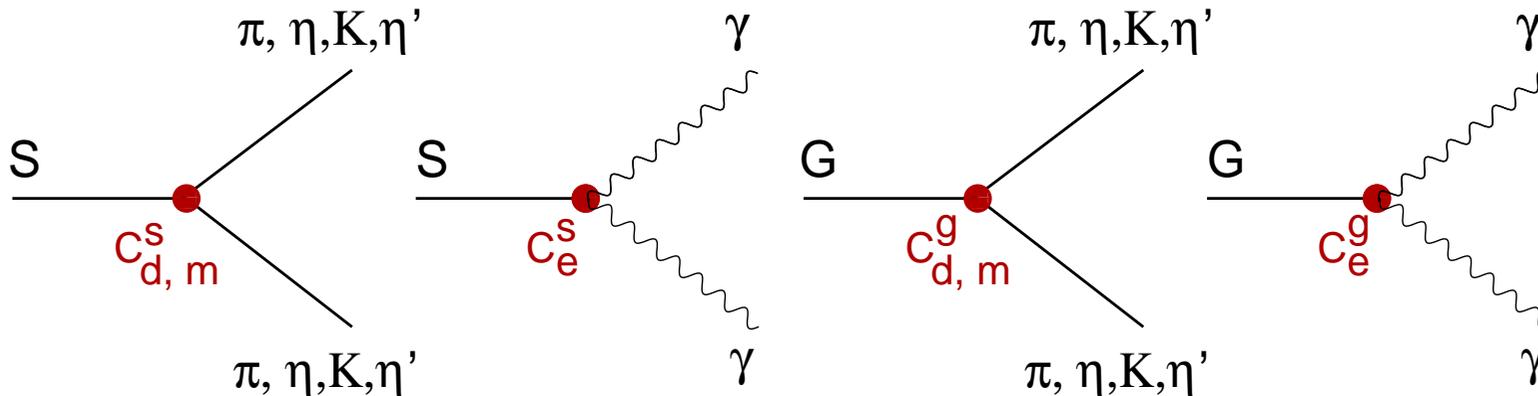
$c_m^{S,g}$ encode SU(3)-flavor violation

- flavor blind decay rates: $\pi\pi : K\bar{K} : \eta\eta : \eta\eta' : \eta'\eta' = 3 : 4 : 1 : 0 : 1$

- Sexton et al. (1996), decay rates scale with meson mass ?!

- Chanowitz (2005), chiral suppression mechanism for scalar glueball, $K\bar{K}$ enhanced

Scalar sector: strong decay scheme

parameters: bare masses $M_N = 1.485$ GeV, $M_G = 1.482$ GeV, $M_S = 1.698$ GeV

mixing parameters $f = 0.068$ GeV^2, $\varepsilon = 0.236$ GeV^2

decay parameters $c_d^s = 8.8$ MeV, $c_m^s = 2.2$ MeV $c_d^s = 1.8$ MeV, $c_m^s = 27.7$ MeV

Quantity	Exp	Theo
M_{f_1} (MeV)	1350 ± 200	1432
M_{f_2} (MeV)	1505 ± 6	1510
M_{f_3} (MeV)	1720 ± 6	1720
$\Gamma_{f_2 \to \eta\eta'}$ (MeV)	2.07 ± 8.87	1.2
$\Gamma_{f_2 \to \eta\eta}$ (MeV)	5.56 ± 0.98	2.8
$\Gamma_{f_2 \to \overline{K}K}$ (MeV)	9.37 ± 1.09	10.4
$\Gamma_{f_2 \to \pi\pi}$ (MeV)	38.04 ± 2.51	37.7
$\Gamma_{f_3 \to \pi\pi}/\Gamma_{f_3 \to \overline{K}K}$	0.41 ± 0.14	0.43
$\Gamma_{f_3 \to \eta\eta}/\Gamma_{f_3 \to \overline{K}K}$	0.48 ± 0.15	0.25
$\Gamma_{f_3 \to 2PS}$ (MeV)	137 ± 8	137
$\Gamma_{a_0 \to \overline{K}K}/\Gamma_{a_0 \to \pi\eta}$	0.88 ± 0.23	0.8
$\Gamma_{a_0 \to \pi\eta'}/\Gamma_{a_0 \to \pi\eta}$	0.35 ± 0.16	0.29
$\Gamma_{K_0^* \to K\pi}$ (MeV)	251 ± 74.4	64.7 !

- $M_N \longrightarrow$
  $M_{a_0} = 1.474 \pm 0.019\,GeV$

- $M_G \longrightarrow$ lattice

- $M_S - M_N \approx$
  $200\,MeV \approx M_{f_2'} - M_{f_2}$

- Glueball-quarkonia mixing strength:
  $f \to z = 22\,MeV \to z = 43 \pm 31\,MeV$
  (Lee,Weingarten (2000))

- $\Gamma_{K_0^* \to K\pi}$ a general problem in theory

Scalar sector: strong decay and mixing scheme

Resulting mixing scheme

$$
\begin{pmatrix} |f_1\rangle \equiv |f_0(1370)\rangle \\ |f_2\rangle \equiv |f_0(1500)\rangle \\ |f_3\rangle \equiv |f_0(1710)\rangle \end{pmatrix} = \begin{pmatrix} 0.75 & 0.6 & 0.26 \\ -0.59 & 0.8 & -0.14 \\ -0.29 & -0.05 & 0.95 \end{pmatrix} \begin{pmatrix} |N\rangle \equiv |\bar{n}n\rangle \\ |G\rangle \equiv |gg\rangle \\ |S\rangle \equiv |\bar{s}s\rangle \end{pmatrix}
$$

Decays of $f_1 = f_0(1370)$

Quantity	Exp	Theo.
$\Gamma_{f_1 \to \overline{K}K}/\Gamma_{f_1 \to \pi\pi}$	0.46 ± 0.19 (WA102)	1.07
	0.91 ± 0.20 (OBLX)	
$\Gamma_{f_1 \to \eta\eta}/\Gamma_{f_1 \to \pi\pi}$	0.16 ± 0.07	0.22

● glueball/flavor singlet dominantly resides in $f_0(1500)$

Scalar sector: J/ψ hadronic decays

$J/\psi \to \phi, \omega + f_0 \to \phi, \omega + K\bar{K}, \pi\pi$ described by tree level graph:
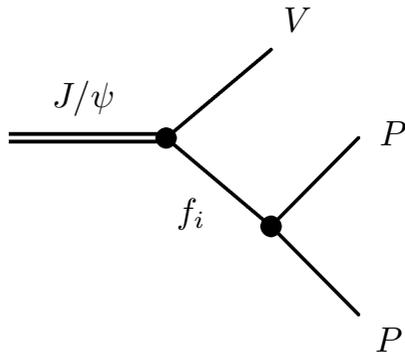
● $J/\psi VS$ and $J/\psi VG$ couplings fitted to $J/\psi \to (\phi, \omega)f_0(1710) \to (\phi, \omega)K\bar{K}$ decay rates.

Branchings of the J/ψ hadronic decays in units 10^{-4}:

Meson	$\phi K\bar{K}$	Data	$\omega K\bar{K}$	Data	$\phi\pi\pi$	Data	$\omega\pi\pi$	Data
f_3	3.6	3.6 ± 0.4	4.8	4.8 ± 1.1	1.7	-	2.2	-
f_2	0.5	0.8 ± 0.5	0.2	-	2.0	1.7 ± 0.8	0.6	-
f_1	4.1	0.3 ± 0.3	1.3	-	4.3	4.3 ± 1.1	1.4	-

PDG averaged data from Mark III, DM2 and BES II (04,05)
further predictions for radiative J/ψ decays Chatzis et al.,PRD84 (2011)

HADRONIC MOLECULE X(3872)

Basics about $X(3872)$ (see talk by K. Seth)

- first seen in $X(3872) \to J/\psi\pi^+\pi^-$ by BELLE (2003),
  also seen by CDF, D0 (2004) and BABAR (2005).

- $\Gamma_X < 2.3$ MeV

- quantum numbers:

  C=+ from $X(3872) \to \gamma J/\psi$, I=0 no signal in $X \to \pi\pi^0 J/\psi$

  $J^{PC} = 1^{++}$ or $J^{PC} = 2^{-+}$ from $X(3872) \to J/\psi\pi^+\pi^-$ helicity amplitude analysis

- $X(3871.57 \pm 0.25)$ close to $D^0\bar{D}^{*0}$ threshold with $m_{thr} = 3871.81 \pm 0.36$ MeV;

- S-wave $D^0\bar{D}^{*0}$ hadron molecule favors $J^{PC} = 1^{++}$

- charmonium interpretation disfavored, $1^{++}(2^3P_1)$ too low in mass compared to $m(2^3P_2) \approx m(Z(3930))$

Binding mechanism for $D\bar{D}^*$

binding by meson exchange mechanism

- **nuclear-like bound states of mesons:** Voloshin + Okun (1976), de Rujula, Georgi + Glashow (1977)

- **binding of $D^0\bar{D}^{*0}$ by π-exchange for $J^{PC} = 1^{++}$,**
  relevance of tensor interaction (S-D mixing), form factors at vertices (Tornqvist (1994)).

- **isospin-breaking effects** in $D^0\bar{D}^{*0}$ relative to $D^-\bar{D}^{*+}$ (Tornqvist (2004)).

- **relevance of thresholds:** $D^0\bar{D}^{*0}$ (3871.2 MeV), $D^-\bar{D}^{*+}$ (3879.3 MeV),
  $\rho J/\psi$ (3867.9 MeV), $\omega J/\psi$ (3879.5 MeV).

- **pion and quark exchange:**
  important admixtures of $\rho J/\psi$ and $\omega J/\psi$ components (Swanson 2004)

- **only moderate binding:** π-exchange, neutral and charged modes, S- and D-waves,
  (Thomas and Close (2008))

- **no binding** when σ exchange is included (Liu et al. (2008)).

- **dynamical generation** of X(3872) resonance (Gamermann/Oset (2007))

Prediction

Early predictions: N. Törnqvist, Z. Phys. C 61 (1994)

Table 8. The predicted heavy deuson states (all with $I=0$) close to the $D\bar{D}^*$ and the $D^*\bar{D}^*$ thresholds and about 50 MeV below the $B\bar{B}^*$ and $B^*\bar{B}^*$ thresholds. As discussed in the text, the mass values are obtained from a rather conservative one-pion exchange contribution only. With additional attraction of shorter range, the masses can decrease considerably. Mixing between the two η_b's (and two η_c's) should decrease the lighter mass somewhat (and increase the heavier mass)

Composite	J^{PC}	Deuson
$D\bar{D}^*$	0^{-+}	$\eta_c\ (\approx 3\,870)$
$D\bar{D}^*$	1^{++}	$\chi_{c1}\ (\approx 3\,870)$
$D^*\bar{D}^*$	0^{++}	$\chi_{c0}\ (\approx 4\,015)$
$D^*\bar{D}^*$	0^{-+}	$\eta_c\ (\approx 4\,015)$
$D^*\bar{D}^*$	1^{+-}	$h_{c0}\ (\approx 4\,015)$
$D^*\bar{D}^*$	2^{++}	$\chi_{c2}\ (\approx 4\,015)$
$B\bar{B}^*$	0^{-+}	$\eta_b\ (\approx 10\,545)$
$B\bar{B}^*$	1^{++}	$\chi_{b1}\ (\approx 10\,562)$
$B^*\bar{B}^*$	0^{++}	$\chi_{b0}\ (\approx 10\,582)$
$B^*\bar{B}^*$	0^{-+}	$\eta_b\ (\approx 10\,590)$
$B^*\bar{B}^*$	1^{+-}	$h_b\ (\approx 10\,608)$
$B^*\bar{B}^*$	2^{++}	$\chi_{b2}\ (\approx 10\,602)$

Binding of $D\bar{D}^*$

- Lee, Faessler, TG, Lyubovitskij, PRD 80, 094005 (2009)

- full meson exchange contributions (π, σ, η, ρ, ω)

- π and ρ exchange dominate

- neutral and charged $D\bar{D}$ components relevant

- binding with $J^{PC} = 1^{++}$ for "reasonable" short-range regularization ($\Lambda_{cutoff} > 1$ GeV)

full wave function for binding energy $E_{bin} = E - M_0 = 2$ MeV ($M_0 = m_{D^0} + m_{\bar{D}^{*0}}$),
solid-$D^0\bar{D}^{*0}$, dashed - D^+D^{*-}
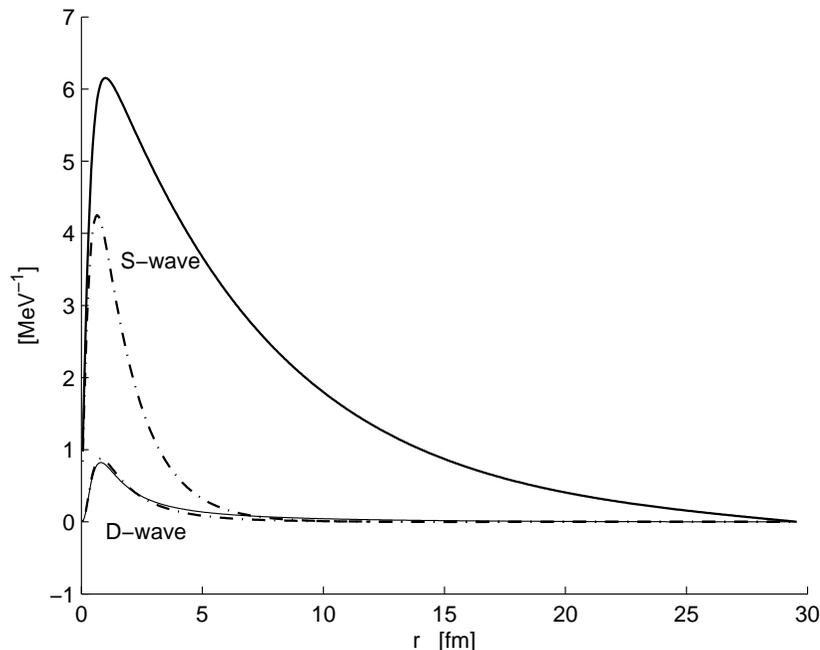
$X(3872)$: observed decay modes

Basics about $X(3872)$ – Decay Modes

- $\mathbf{\Gamma(X \to J/\psi\pi^+\pi^-\pi^0)/\Gamma(X \to J/\psi\pi^+\pi^-) = 1.0 \pm 0.4 \pm 0.3}$
  BELLE (hep-ex/0505037)

  - isospin violating decay modes
  - decays dominated by subthreshold decays of $\omega J/\psi$ and $\rho J/\psi$

- $\mathbf{\Gamma(X \to J/\psi\gamma)/\Gamma(X \to J/\psi\pi^+\pi^-) = 0.14 \pm 0.05}$ (Belle); $\mathbf{0.33 \pm 0.12}$ (BABAR)
  BELLE (hep-ex/0505037), BABAR PRL 102 (2009)

  - large radiative decay mode !!

- $\mathbf{\Gamma(X \to \psi(2S)\gamma)/\Gamma(X \to J/\psi\gamma) = 3.4 \pm 1.4}$ (BABAR); $\mathbf{< 2.1}$ (Belle)
  BABAR, PRL 102, (2009); Belle, PRL 107, (2011)

  - possible evidence for charmonium component ?

$X(3872)$

Aim: results for decay rates of the $X(3872)$

Ansatz: $X(3872)$ is S-wave molecule with $J^{PC} = 1^{++}$

$$
|X(3872)> = \cos\theta \left[\frac{Z^{1/2}_{D^0 D^{*0}}}{\sqrt{2}} (|D^0 \bar{D}^{*0}\rangle + |D^{*0}\bar{D}^0\rangle) + \frac{Z^{1/2}_{D^\pm D^{*\mp}}}{\sqrt{2}} (|D^+ D^{*-}\rangle + |D^- D^{*+}\rangle) + \right.
$$
$$
\left. Z^{1/2}_{J_\psi \omega} |J_\psi \omega\rangle + Z^{1/2}_{J_\psi \rho} |J_\psi \rho\rangle \right] + \sin\theta |c\bar{c}\rangle
$$

$(m_{D^0} = 1864.85$ MeV, $m_{D^{*0}} = 2006.7$ MeV, $m_x = m_{D^0} + m_{D^{*0}} - \epsilon)$

- dominant $|D^0 \bar{D}^{*0}\rangle + |D^{*0}\bar{D}^0\rangle$ component

- quantitatively see Swanson (2004): for $\epsilon = 0.7$ MeV,
  $Z_{D^0 D^{*0}} = 0.82\,, \quad Z_{D^\pm D^{*\mp}} = 0.079\,, \quad Z_{J_\psi \omega} = 0.096\,, \quad Z_{J_\psi \rho} = 0.009$

- admixture of 1^{++} $c\bar{c}$ component: $\propto \sin\theta$

- Compositeness condition: $Z_X = 1 - (\Sigma^M_X(m^2_X))' - (\Sigma^C_X(m^2_X))' = 0$ fixes coupling of X to its components

$X(3872) \to J/\psi, \psi(2S) + \gamma$
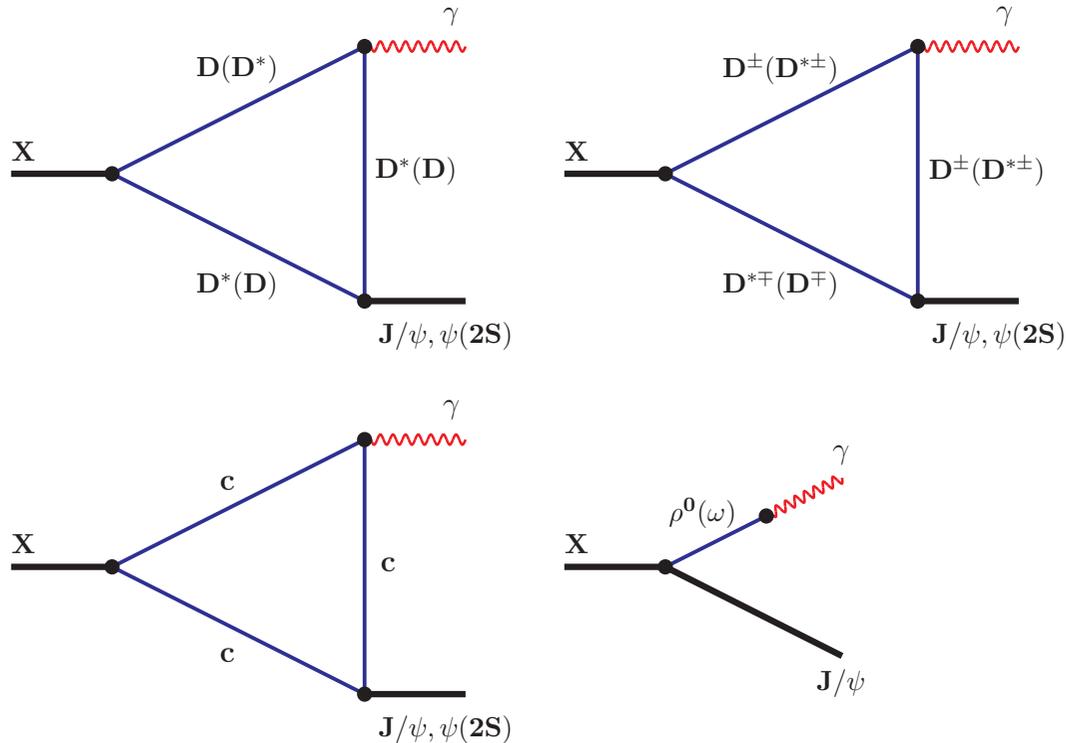
Interaction vertices: $c\bar{c}\,(2^3P_1) \to J/\psi(\psi(2S))\gamma$ fixed by quark model (next page) ,
$D^{(*)}D^{(*)}J/\psi$ fixed by world averaged values: $g_{J_\psi DD} = g_{J_\psi D^*D^*} = 6.5$
$D^{*\,0}D^0\gamma$ fixed by $BR(D^{*0} \to D^0\gamma) = 38.1\%$

Dong, Faessler, TG, Kovalenko, Lyubovitskij, PRD 77 (2008), 79 (2009), JPG38 (2011) 015001

Quark model results for $c\bar{c}(2^3 P_1) \to \gamma J/\psi$ and $\psi(2s)$

<div style="background:yellow">E1 transitions in the quark model for $c\bar{c}(2^3 P_1)$</div>

$$\Gamma_\psi = \Gamma(c\bar{c} \to \gamma\psi(2S)), \, \Gamma_{J_\psi} = \Gamma(c\bar{c} \to \gamma J/\psi),$$

$$\mathbf{R}_\gamma = \frac{\Gamma(X \to \psi(2S) + \gamma)}{\Gamma(X \to J/\psi + \gamma)} = 3.4 \pm 1.4 \text{ (BABAR, 2009)}$$

model I	model II	model III
Barnes, Godfrey (04)	Barnes, Godfrey, Swanson (05)	Li, Chao (09)
$m_{c\bar{c}} = 3872$ MeV	$m_{c\bar{c}} = 3925$ MeV	$m_{c\bar{c}} = 3901$ MeV
$\Gamma_\psi = 64$ keV	$\Gamma_\psi = 183$ keV	$\Gamma_\psi = 60$ keV
$\Gamma_{J_\psi} = 11$ keV	$\Gamma_{J_\psi} = 71$ keV	$\Gamma_{J_\psi} = 45$ keV
$R_\gamma = 5.8$	$R_\gamma = 2.6$	$R_\gamma = 1.3$

- also: de Fazio (2009) HQET, $R_\gamma = 1.64 \pm 0.25$

- enhancement of Γ_ψ in model II – phase space

- Γ_{J_ψ} sensitive to node in form factor

Results for $X(3872) \to \gamma J/\psi$ and $\psi(2s)$

Model	Quantity	$c\bar{c}$	DD^*	$J/\psi V$	$DD^* + J/\psi V$	Total
	Γ_{J_ψ}, keV	11	3.4	3.1	10.6	16.6
I	Γ_ψ, keV	64	0.01	0	0.01	58.2
	R_γ	5.8	3.2×10^{-3}	0	1.0×10^{-3}	3.4 $(\theta = 72.1^0)$
	Γ_{J_ψ}, keV	45	3.4	3.1	10.6	2.0
III	Γ_ψ, keV	60	0.01	0	0.01	7.0
	R_γ	1.3	3.2×10^{-3}	0	1.0×10^{-3}	3.4 $(\theta = -20.4^0)$

- *Results for binding energy $\epsilon = 0.7$ MeV.*

- *"additional" charmonium contribution with $Z_{c\bar{c}} = sin^2\theta \approx 0.05(III) - 0.90(I)$ required*

- *destructive/constructive interference between molecular and $c\bar{c}$ components*

- *ratio R_γ not conclusive*

- *absolute rates necessary*

Results for $X(3872) \to J/\psi + h$ with $h = 2\pi, 3\pi$

Assumption that $X(3872) \to J/\psi + h$ proceeds via $J/\psi\omega$ and $J/\psi\rho$ components
(see also Braaten and Kusunoki PRD 69 (2004)):

Quantity	Nonlocal case
$\Gamma(X \to J/\psi\pi^+\pi^-)$, keV	$1.1 \times 10^3 \, Z_{J_\psi\rho}$ (9.7)
$\Gamma(X \to J/\psi\pi^+\pi^-\pi^0)$, keV	$77 \, Z_{J_\psi\omega}$ (7.4)
$\Gamma(X \to J/\psi\pi^0\gamma)$, keV	$13 \, Z_{J_\psi\omega}$ (1.2)
$\dfrac{\Gamma(X \to J/\psi\pi^+\pi^-\pi^0)}{\Gamma(X \to J/\psi\pi^+\pi^-)} = 1.0 \pm 0.4 \pm 0.3$	0.76
$\dfrac{\Gamma(X \to J/\psi\gamma)}{\Gamma(X \to J/\psi\pi^+\pi^-)} = 0.14 \pm 0.05; 0.33 \pm 0.12$	1.71(I) 0.36(II) 0.27(III)

Explicit numbers for configuration of Swanson (2004) at $\epsilon = 0.7$ MeV.

Subleading $J/\psi\omega$, $J/\psi\rho$ and $c\bar{c}$ components dominate ratios !

Summary

- there is life beyond quark-antiquark states

- Scalar glueball, an old problem:
  - quarkonia-glueball mixing in the high lying scalar sector $f_0(1370)$, $f_0(1500)$ and $f_0(1710)$
  - decay properties and J/ψ production modes
  - a scalar gluball component (or flavor singlet component) dominantly resides in the $f_0(1500)$
  - further tests in radiative J/ψ decays

- Hadron molecules - the case of the X(3872):
  - binding of the X(3872) as a $D\bar{D}^*$ molecule
  - the puzzling radiative decays of X(3872)
  - large BABAR ratio for
    $$\mathbf{\Gamma(X \to \psi(2S)\gamma)/\Gamma(X \to J/\psi\gamma) = 3.4 \pm 1.4}$$ still allows for molecular interpretation
  - absolute rates necessary to pin down $c\bar{c}$ component

EXTRAS

Chiral Lagrangians: Tensor mesons

$$\Gamma_{f_2' \to \gamma\gamma}/\Gamma_{f_2 \to \gamma\gamma} = 0.046 \, (theor) \,, 0.031 \pm 0.010 \, (exp)$$

$$\Gamma_{a_2 \to \gamma\gamma}/\Gamma_{f_2 \to \gamma\gamma} = 0.378 \, (theor) \,, 0.383 \pm 0.057 \, (exp)$$

$T \to V\,PS$:

Quantity	Experiment (MeV)	Theory (MeV)
$\Gamma_{a_2 \to \pi\rho}$	75.0 ± 6.4	75.0 (fixed)
$\Gamma_{K_2^* \to \pi K^*(892)}$	24.5 ± 1.4	28.97
$\Gamma_{K_2^* \to K\rho}$	8.6 ± 1.0	7.40
$\Gamma_{K_2^* \to K\omega}$	2.86 ± 0.87	2.64

$T \to PS\,\gamma$:

$$\frac{\Gamma_{K_2^{*\pm} \to K^{\pm}\gamma}}{\Gamma_{a_2^{\pm} \to \pi^{\pm}\gamma}} = 0.83 \, (theor) \,,\ 0.82 \pm 0.29 \, (exp)$$

Scalar sector: two-photon decays

setting

- $c_e^g = 0$ (suppressed $G \to \gamma\gamma$ transition)

- $c_e^s = 0.0138 \; GeV^{-1}$ (only $Q\bar{Q}$ components active, F. Giacosa, T.G., PRC71 (2005))

$$
\begin{aligned}
\Gamma_{f_1 \to 2\gamma} &= 0.703 \text{ keV} \,, \quad \Gamma_{f_2 \to 2\gamma} = 0.235 \text{ keV} \,, \\
\Gamma_{f_3 \to 2\gamma} &= 0.002 \text{ keV} \,, \quad \Gamma_{a_0^0 \to 2\gamma} = 0.362 \text{ keV} \,.
\end{aligned}
$$

Note: $\Gamma_{N \to 2\gamma} \approx 1 \; keV \approx 10 \cdot \Gamma_{S \to 2\gamma}$, destructive interference of N and S components

Exp. (PDG):

- $\Gamma_{f_0(1370) \to 2\gamma} = 3.8 \pm 1.5 \; keV, \, 5.4 \pm 2.3 \; keV$
  (upper limit, contribution from $f_0(400-1200)$?)

- $\Gamma_{f_0(1500) \to 2\gamma} < 1.4 \; keV$

- $\Gamma_{f_0(1710) \to 2\gamma} < 0.3 \; keV$

$\mathbf{f_0(980) \to \gamma\gamma}$ and $\mathbf{a_0(980) \to \gamma\gamma}$

(*see Branz, TG, Lyubovitskij: EPJA 37 (2008) 303; PRD 78 (2008) 114013*)
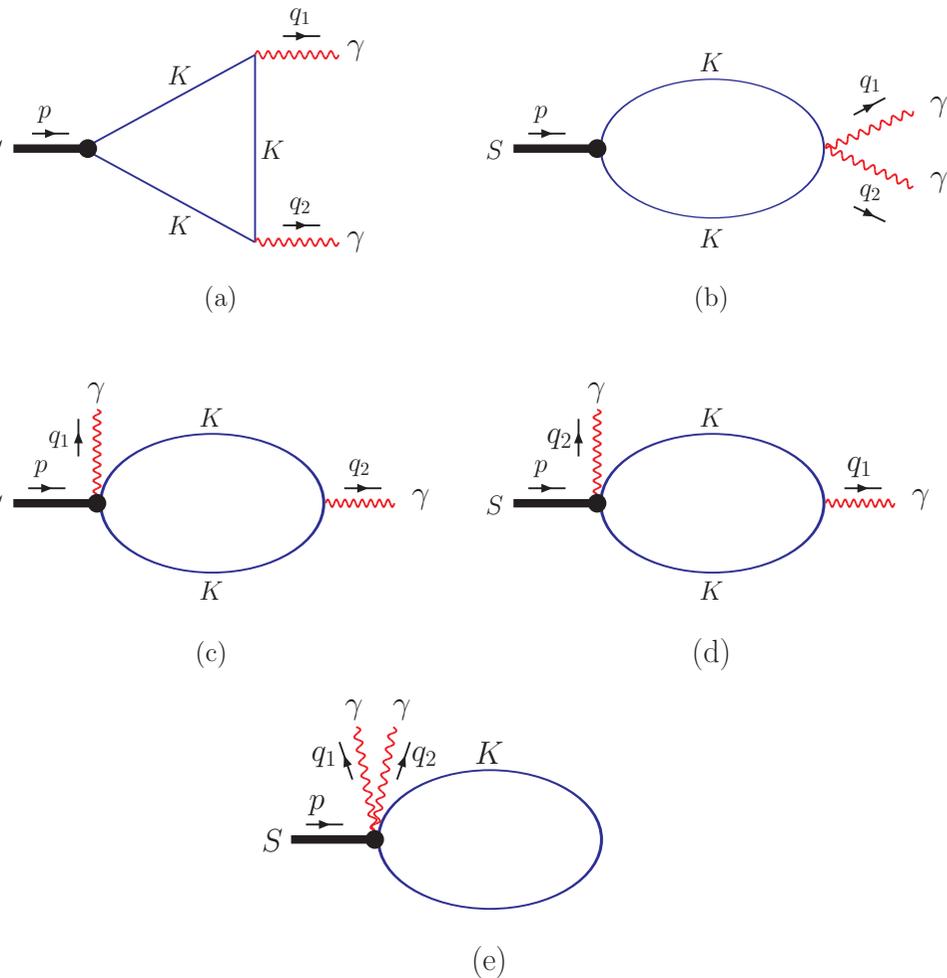
	$\Gamma_{f_0 \to \gamma\gamma}$ [keV]
PDG (2008)	$0.29^{+0.07}_{-0.09}$
Theo. (Λ =1 GeV)	0.25
Theo. (local lim.)	0.29

	$\Gamma_{a_0 \to \gamma\gamma}$ [keV]
Amsler (98)	0.30 ± 0.1
Theo. (Λ =1 GeV)	0.19
Theo. (local lim.)	0.23

Strong decays $f_0 \to \pi\pi$ and $a_0 \to \pi\eta$

(a)   (b)
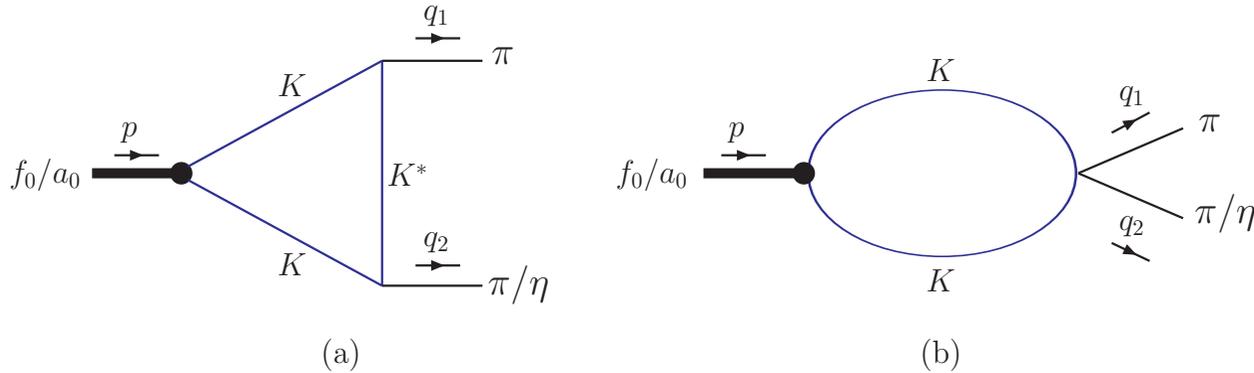
based on:

$$\mathcal{L}_{K^*K\pi} = \frac{g_{K^*K\pi}}{\sqrt{2}} K_\mu^{*\dagger} \vec{\pi}\vec{\tau} \, i\overset{\leftrightarrow}{\partial}^\mu K + h.c \, , \, \mathcal{L}_{K^*K\eta} = \frac{g_{K^*K\eta}}{\sqrt{2}} K_\mu^{*\dagger} \eta \, i\overset{\leftrightarrow}{\partial}^\mu K + h.c.$$

$$\mathcal{L}_U(x) = \frac{F^2}{4} \langle D_\mu U(x) D^\mu U^\dagger(x) + \chi U^\dagger(x) + \chi^\dagger U(x) \rangle$$

$\boxed{\Gamma(f_0 \to \pi\pi) = 45 - 90 \text{ MeV}(\Lambda = 0.8 - 1.2 \text{ GeV})}$ compared to $40 - 100$ MeV (PDG)

$\boxed{\Gamma(a_0 \to \pi\eta) = 48 - 93 \text{ MeV}(\Lambda = 0.8 - 1.2 \text{ GeV})}$ compared to $50 - 100$ MeV (PDG)

$X(3872)$: **Binding mechanism for $D\bar{D}^*$**

couplings taken from HHChPT (Wise (1992),Isola et al. (2003), Liu et al. (2009))
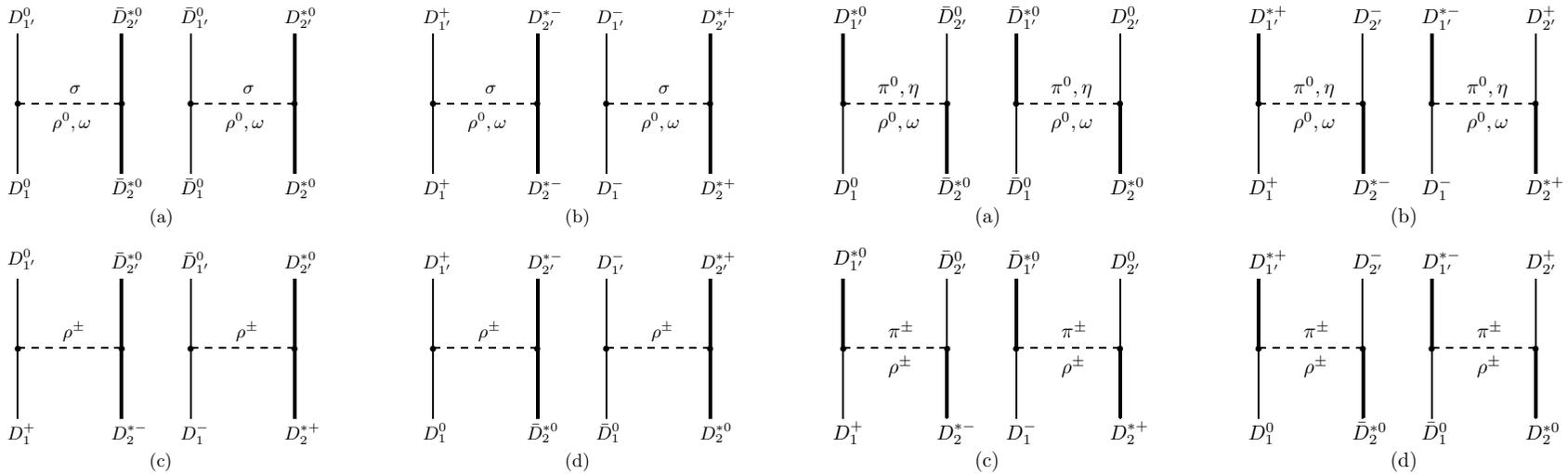
- form factor at each vertex with $\mathbf{F(q^2) = \dfrac{\Lambda^2 - m^2}{\Lambda^2 - q^2}}$ and cutoff $\mathbf{\Lambda \approx 1\ GeV}$.

- configuration $\boxed{|X\rangle = \frac{1}{2}[(|D^0\bar{D}^{*0}\rangle - |D^{*0}\bar{D}^0\rangle) \pm (|D^+D^{*-}\rangle - |D^{*+}D^-\rangle)]}$
  $\pm$ corresponds to isospin I=0,1.

Lee, Faessler, TG, Lyubovitskij, PRD 80, 094005 (2009)

here: $\Lambda = 1.2$ GeV
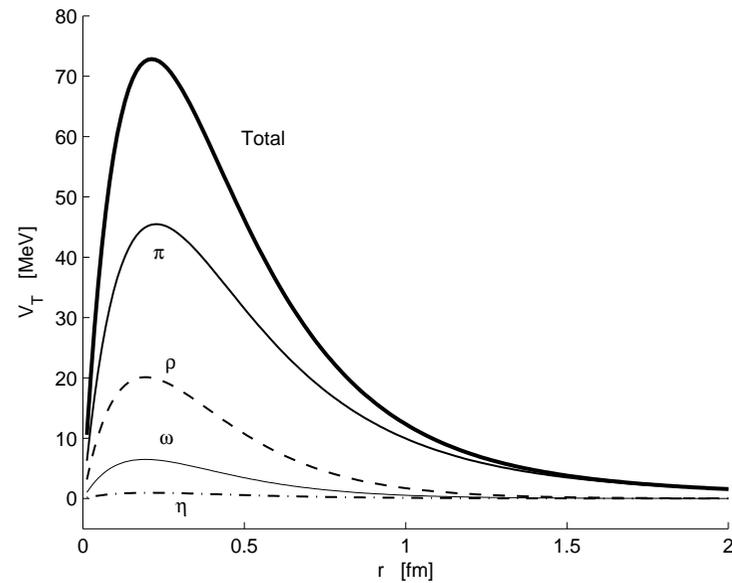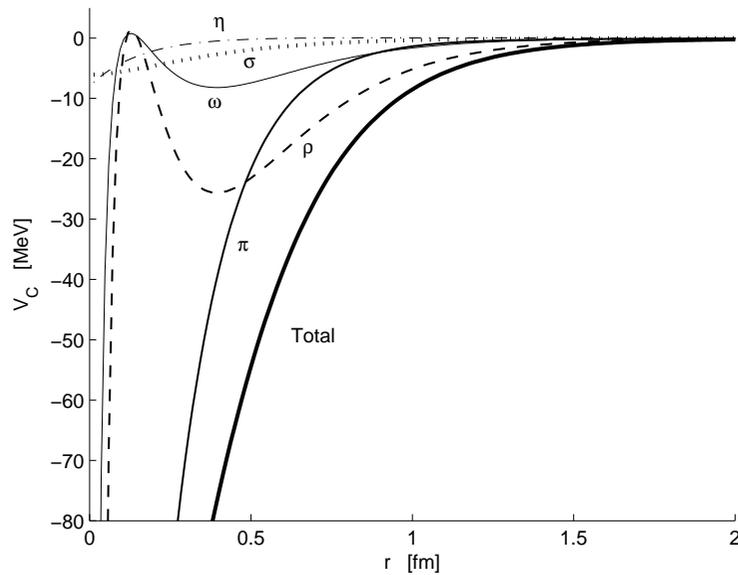
- $\mathbf{V_{total}} = \mathbf{V_C} \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} + \mathbf{V_T} \begin{pmatrix} 0 & -\sqrt{2} \\ -\sqrt{2} & 1 \end{pmatrix}$

- π and ρ exchange dominate

$X(3872)$: Binding mechanism for $D\bar{D}^*$

Results for binding energy $E_{bin} = E - M_0$ $(M_0 = m_{D^0} + m_{\bar{D}^{*0}})$

Λ [MeV]	E_{bin} [MeV]	$P(0_S)\%$	$P(0_D)\%$	$P(\pm_S)\%$	$P(\pm_D)\%$
1100	No bound state	-	-	-	-
1136	-0.10	91.9	0.3	7.5	0.3
1150	-0.40	86.0	0.5	13.0	0.5
1160	-0.71	82.1	0.6	16.7	0.7
1168	-1.02	79.2	0.7	19.3	0.7
1200	-2.65	70.5	1.0	27.5	1.0
1250	-6.32	62.6	1.3	34.9	1.3

- binding for $\Lambda > 1100$ MeV with $J^{PC} = 1^{++}$

- only π exchange, binding for $\Lambda > 1700$ MeV

- neutral $D^0\bar{D}^{*0}$ component and π-exchange only, $\Lambda > 4450$

- I=0 dominates, importance of isospin breaking effects $M_\pm - M_0 \approx 8$ MeV