Newly discovered exotic heavy hadrons

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Outline

New heavy hadrons since 2002

Renaissance in heavy hadron spectroscopy

- **Ordinary** $Q\bar{q}$, $Q\bar{Q}$
- **Ordinary** qqQ, qQQ **(**$q = u, d, s$ **and** $Q = c, b$**)**
- **Exotics, not** $Q\bar{q}$ **or** $Q\bar{Q}$

ORDINARY HADRONS, expected

- (2^1S_0) $\eta_c'(3638)$ $(c\bar{c})$ **CLEO 2004**
- (1^1P_1) $h_c(3524)$ $(c\bar{c})$ **CLEO 2005**
- $B_c(6287)$ $(c\bar{b})$ **CDF 2005**
- $\Xi_{cc}^{+}(3520)$ (ccd) **SELEX 2002,2005**
- $\Xi_b(5793)$, $\Sigma_b^{\pm}(5811)$, $\Sigma_b^{*\pm}(5833)$ (qqb) **CDF 2007**

EXOTIC RESONANCES

- **Open charm:** $D_s(2317)$, $D_s(2460)$, $D_s(2690)$, $D_s(2860)$
- **Hidden charm:** $X(3872)$, $X(3940)$, $Y(3940)$, $Z(3930)$, $X(4160)$, $Y(4260)$, $Z^{\pm}(4433)$, $Y(4660)$

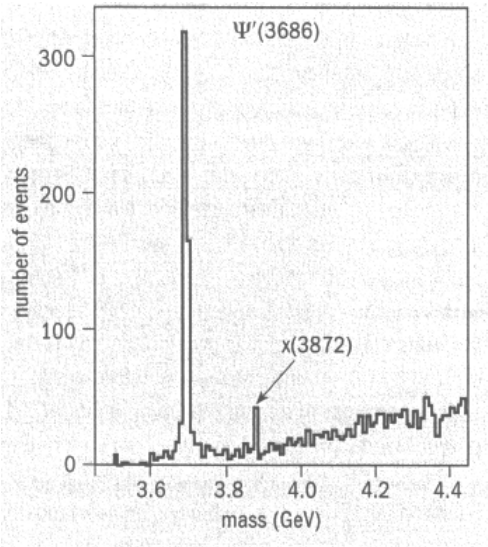
N.B. X Y Z have different dominant decay channels

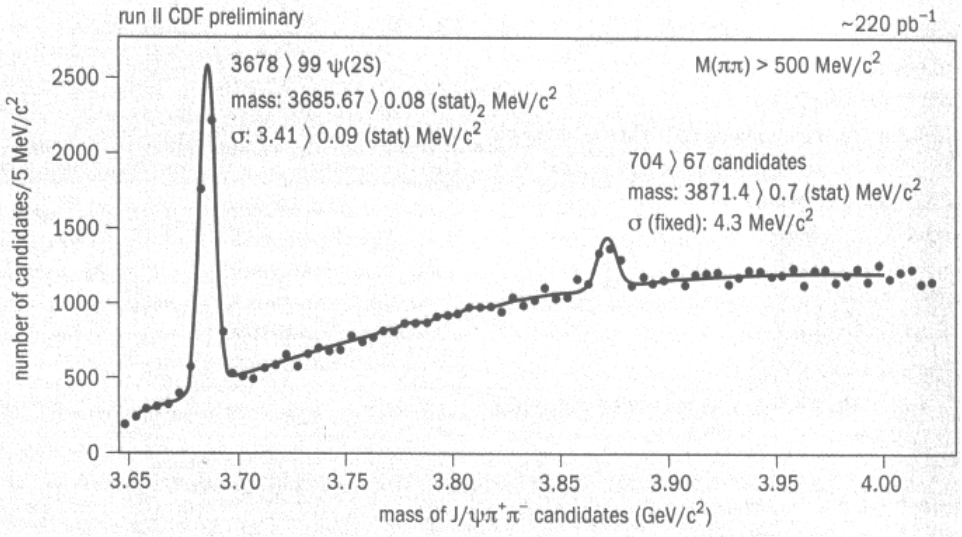
$X(3940) \to D\ \overline{D*}$, C=+ , 0^{-+} ???, $\eta_c(3S)$ expected above 4 GeV

$Z(3930) \to D\ \overline{D}$ $\quad 2^3P_2(\chi'_{c2})$???

$Y(3940) \to \omega$ J/Ψ status not clear, BaBar observes M = 3914 MeV, different from Belle, $\quad 2^3P_1(\chi'_{c1})$???

EXPERIMENTAL RESULTS for X(3872)





Belle **CDF**

EXPERIMENTAL STATUS of X(3872)

Observed by Belle (2003), confirmed by CDF II, DO, BaBar Belle

$$e^+ - e^- \to B^\pm \to K^\pm + X \to K^\pm + J/\Psi + \pi^+ + \pi^-$$

Mass = 3872.0 $\pm$ 0.6 $\pm$ 0.5 MeV
Width $\Gamma < 2.3$ **MeV (95 % C.L.),** $J^{PC} = 1^{++}$

Close to threshold $D^0 + \overline{D}^{*0}$ **= 3871.2 MeV**

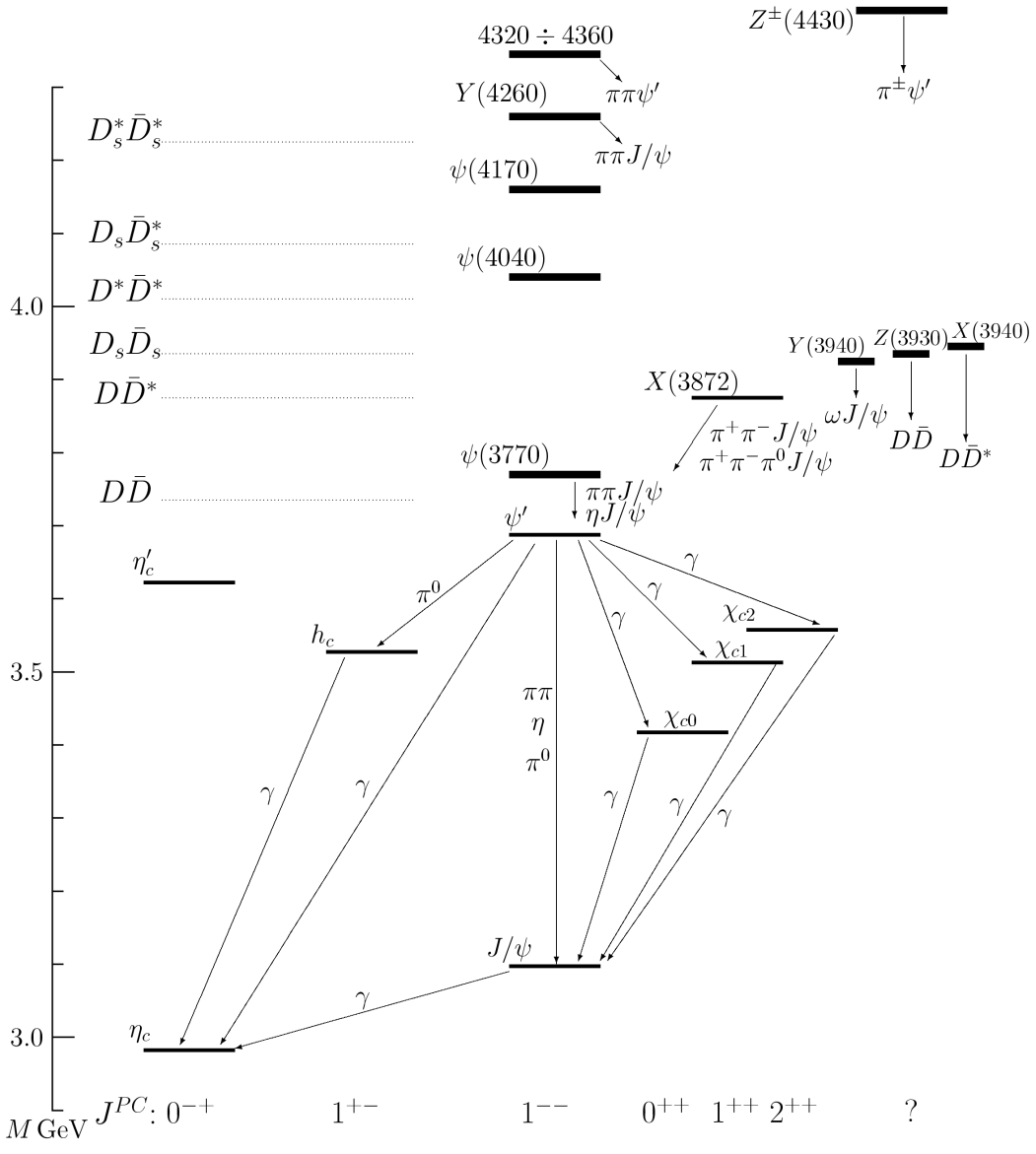
Parameters

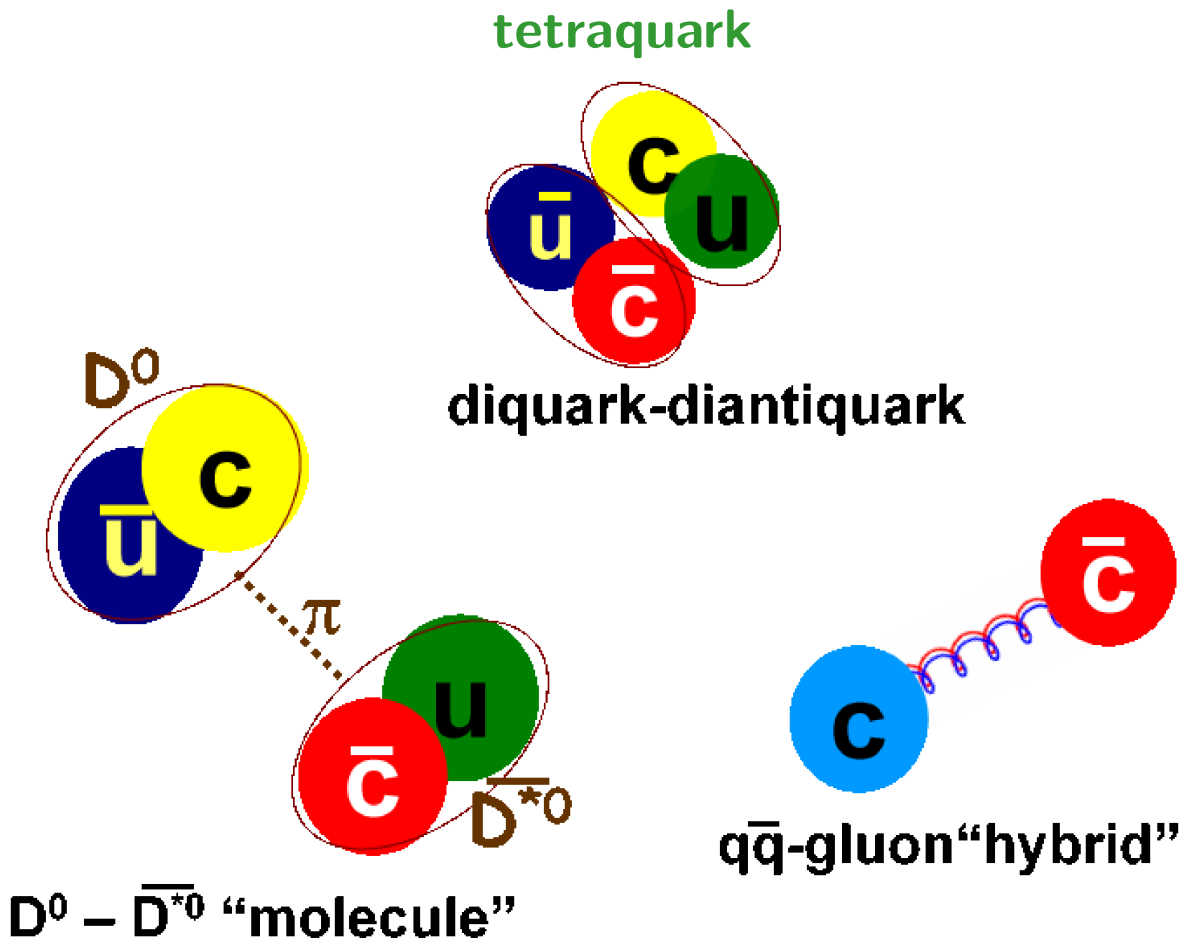
Resonance	Mass (MeV)	Width (MeV)	J^{PC}	Decay modes
X(3872)	3872 ± 0.6	< 2.3	1^{++}	$\pi^+\pi^- J/\Psi, \gamma J/\Psi$
X(3940)	3942 ± 9	37 ± 17	J^{P+}	$D\bar{D}^*$
Y(3940)	3943 ± 17	$87 \pm 22 \pm 26$	J^{P+}	$\omega J/\Psi$
Z(3930)	3929 ± 5	$29 \pm 10 \pm 2$	2^{++}	$D\bar{D}$
X(4160)	4156 ± 29	139^{+113}_{-65}	J^{P+}	$D^*\bar{D}^*$
Y(4260)	4264 ± 12	83 ± 22	1^{--}	$\pi^+\pi^- J/\Psi$
$Z^{\pm}(4430)$	4433 ± 5	45^{+35}_{-18}	?	$\pi^{\pm}\Psi'$
Y(4660)	4664 ± 12	48 ± 15	1^{--}	$\pi^+\pi^-\Psi'$

Selected theoretical approaches for exotics

Options

- **Constituent quark model** $c\bar{c}$
- $D\overline{D}^*$ **molecule** $(c\bar{q}) - (\bar{c}q)$
- **Tetraquarks** $(c\bar{c})(q\bar{q})$
- **Hybrid, excitation of the flux tube**


4320 ÷ 4360
$Z^{\pm}(4430)$
$Y(4260)$
$\pi\pi\psi'$
$\pi^{\pm}\psi'$
$\pi\pi J/\psi$
$\psi(4170)$
$\psi(4040)$
$D_s^*\bar{D}_s^*$
$D_s\bar{D}_s^*$
$D^*\bar{D}^*$
$D_s\bar{D}_s$
$D\bar{D}^*$
$D\bar{D}$
$Y(3940)$
$Z(3930)$
$X(3940)$
$X(3872)$
$\omega J/\psi$
$\pi^+\pi^- J/\psi$
$\pi^+\pi^-\pi^0 J/\psi$
$D\bar{D}$
$D\bar{D}^*$
$\psi(3770)$
$\pi\pi J/\psi$
$\eta J/\psi$
ψ'
η_c'
π^0
γ
h_c
χ_{c2}
χ_{c1}
χ_{c0}
$\pi\pi$
η
π^0
J/ψ
η_c
4.0
3.5
3.0
M GeV
J^{PC}: 0^{-+} 1^{+-} 1^{--} 0^{++} 1^{++} 2^{++} ?


tetraquark
c
ū
u
c̄
diquark-diantiquark
D⁰
c
ū
π
u
c̄
D̄*⁰
D⁰ – D̄*⁰ “molecule”
c̄
c
qq̄-gluon“hybrid”

Molecular picture

- **de Rujula,Georgi,Glashow (1977)** $\Psi(4040)$ **as** $D^*\overline{D}^*$ **molecule**

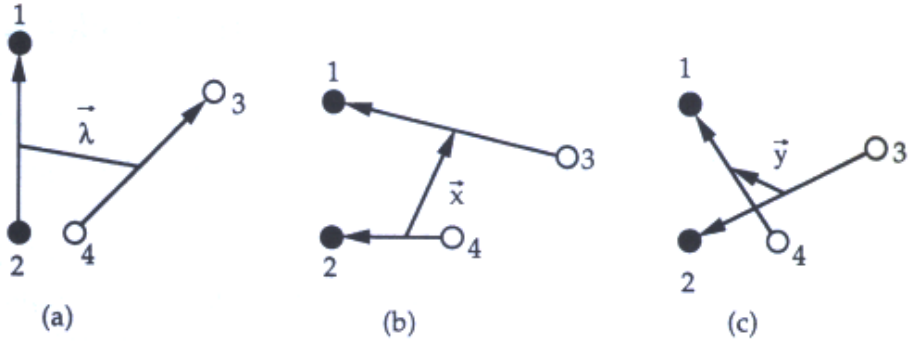
- **Tornqvist (1991) deuteron-like two mesons,** $D\overline{D}^*$, $D^*\overline{D}^*$, **interacting by** π **exchange (Yukawa)**

- **Y.-R. Liu et al, hep-ph/0801.3540,** π **and** σ **exchange** $\rightarrow$ **no bound state except for** $B\overline{B}^*$

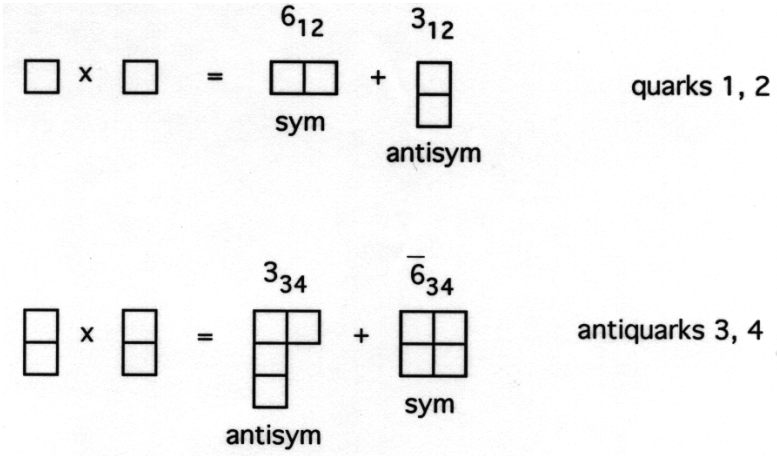
Tetraquarks

- Initiated in 1977 by Jaffe, tetraquarks, MIT bag model
- Potential models, Isgur, Weinstein 1983, light scalar mesons
- Role of heavy quarks, Zouzou et al. 1986
- Role of hidden colour states, DMB & FS, PRD49:4665 (1994)
- Stability due to heavy flavours, DMB & FS, PRD57:6778 (1998)
- Role of confinement, J. Vijande et al. PRD76:114013 (2007)

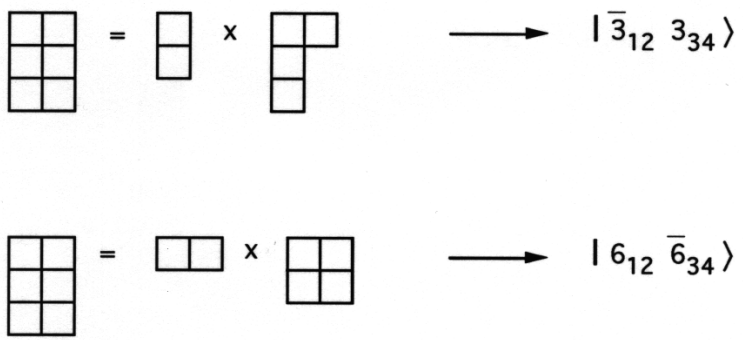
The coordinates



The diquark picure

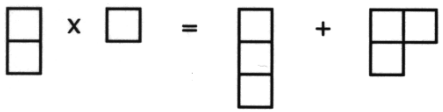


2q - 2$\bar{q}$ system



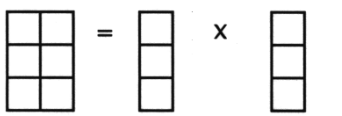
The meson-meson channel

Asymptotic channels $(q\bar{q})\,(q\bar{q})$

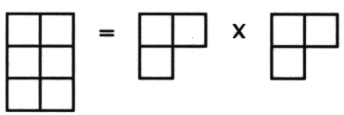


1_{13} 8_{13} } direct channel
1_{24} 8_{24} }

1_{14} 8_{14} } exchange channel
1_{23} 8_{23} }



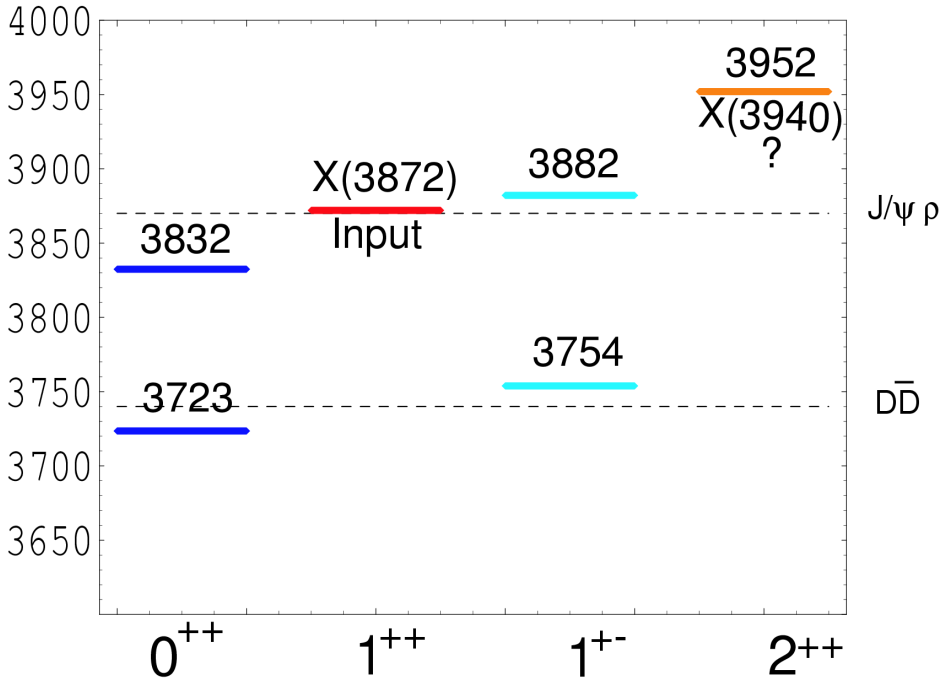
$|1_{13}\,1_{24}\rangle$ or $|1_{14}\,1_{23}\rangle$



$|8_{13}\,8_{24}\rangle$ or $|8_{14}\,8_{23}\rangle$

Hidden colour states

The resonance X(3872)
L.Maiani et al. PRD71,014028 (2005)



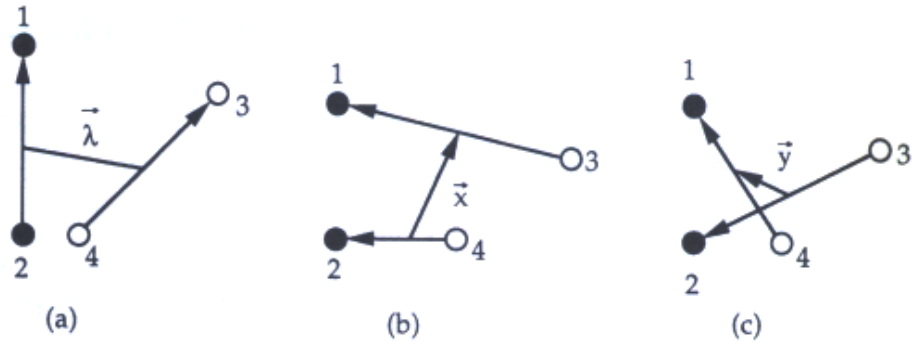
-diquark picture $(cq)(\bar{c}\bar{q})$
-only $\bar{3}_{12}3_{34}$ basis vector $\longrightarrow$ twice less states in the spectrum
-X(3872) is fitted

A simplified OGE model

H. Hogaasen, J.-M. Richard, P.Sorba, PRD73,054013 (2006)

$$\mathcal{M} = \sum_i m_i + \langle H_{cm} \rangle$$

$$H_{cm} = -\sum_{i,j} C_{ij}\, \tilde{\lambda}_i \cdot \tilde{\lambda}_j\, \boldsymbol{\sigma}_i . \boldsymbol{\sigma}_j$$



PARAMETERS

N.B. $c_{12} = c_{34}$, $c_{14} = c_{23}$

m_q= 450 MeV, m_c = 1550 MeV

$c_{12} = c_{qc}$ = 5.0 MeV

$c_{23} = c_{q\bar{c}}$ = 6.5 MeV

$c_{13} = c_{c\bar{c}}$ = 4.0 MeV

$c_{24} = c_{q\bar{q}}$ =20.0 MeV

molecular limit $c_{12} = c_{14} = 0$

$$\langle H_{cm} \rangle \text{ for } J^{PC} = 1^{++}$$

$$Basis \quad |\mathbf{1}\rangle = |\mathbf{1_{13}1_{24}(V_{13}V_{24})_1}\rangle; \quad |\mathbf{2}\rangle = |\mathbf{8_{13}8_{24}(V_{13}V_{24})_1}\rangle$$

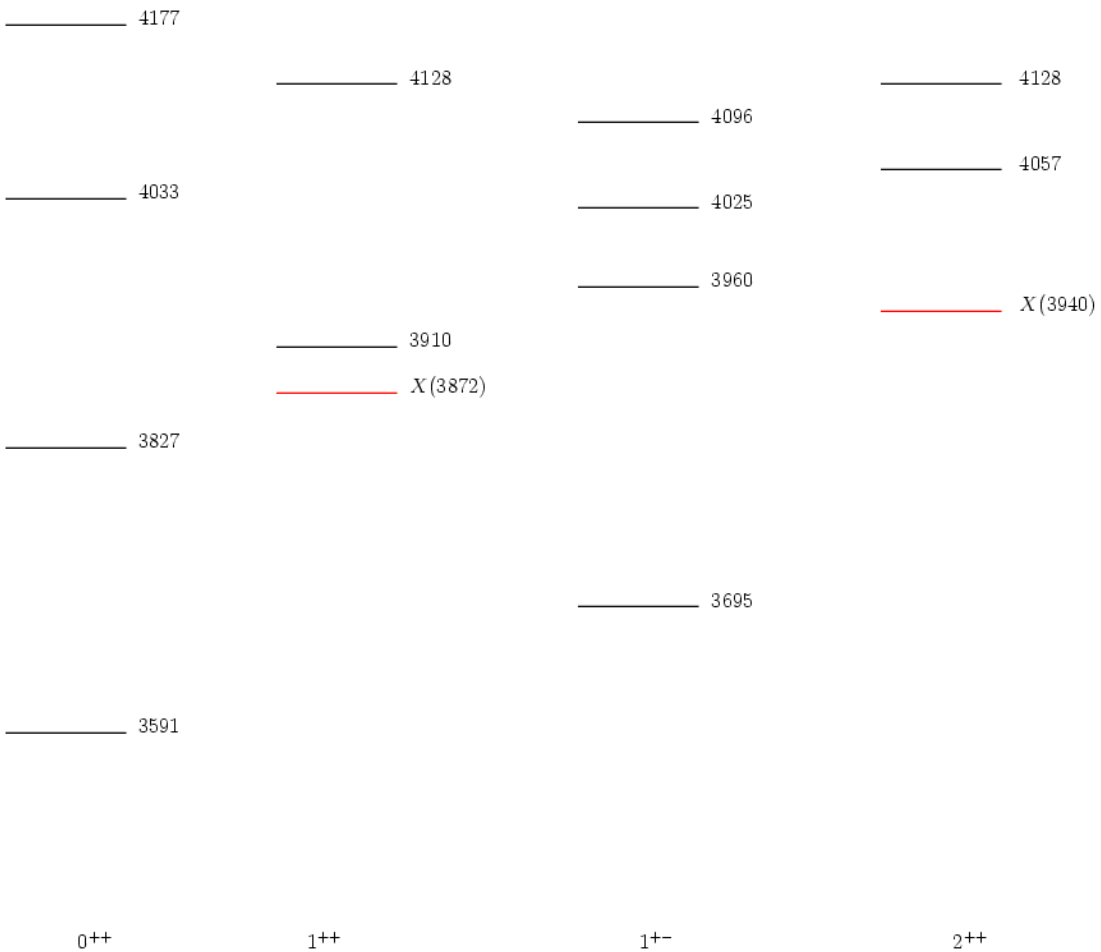
$$\begin{bmatrix} \frac{16}{3}(C_{13}+C_{24}) & \frac{8\sqrt{2}}{3}(C_{12}-C_{23}) \\ \frac{8\sqrt{2}}{3}(C_{12}-C_{23}) & -\frac{2}{3}(4C_{12}+14C_{23}+C_{13}+C_{24}) \end{bmatrix}$$

lowest state components (0.0259, 0.9996)

$\rightarrow$ very small J/Ψ + vector meson component

SPECTRUM of $c\bar{c}q\bar{q}$

$$\mathcal{M} = \sum_i m_i - \langle \sum_{i,j} C_{ij}\, \tilde{\lambda}_i \cdot \tilde{\lambda}_j\, \boldsymbol{\sigma}_i . \boldsymbol{\sigma}_j \rangle$$



More refinements, Maiani et al. PRL99:182003(2007)

$$X_u = [cu][\bar{c}\bar{u}],\ X_d = [cd][\bar{c}\bar{d}], \quad \text{neutral}$$
$$X^+ = [cu][\bar{c}\bar{d}],\ X^- = [cd][\bar{c}\bar{u}], \quad \text{charged}$$

X_d = X(3872) decays into $J/\Psi\pi^+\pi^-$

X_u = X(3876) decays into $D^0\overline{D}^0\pi^0$

Branching ratios with Belle data + weak decay

$$\mathrm{B}(X_d \to J/\Psi\pi^+\pi^-) \approx \tfrac{1}{20}\mathrm{B}(X_u \to D^0\bar{D}^0\pi^0)$$

	$X(3872)$
Mass (MeV)	$3872.0 \pm 0.6 \pm 0.5$ (Belle-2003) $3871.3 \pm 0.7 \pm 0.4$ (CDF-2004) $3871.8 \pm 3.1 \pm 3.0$ (D0-2003) 3873.4 ± 1.4 (Babar-2005) $3875.4 \pm 0.7^{+1.2}_{-2.0}$ (Belle-2006) $3875.6 \pm 0.7^{+1.4}_{-1.5}$ (Babar-2007)
Width	< 2.3 MeV (Belle-2003)
J^{PC}	$1^{++}/2^{-+}$ (angular,angular-CDF)
Branching fractions	$\frac{BR[X(3872)\to\gamma J/\psi]}{BR[X(3872)\to\pi^+\pi^- J/\psi]} = 0.14 \pm 0.05$ (Belle-2005) $\frac{BR[X(3872)\to\gamma J/\psi]}{BR[X(3872)\to\pi^+\pi^- J/\psi]} = 0.25$ (Babar-2006) $\frac{BR[X(3875)\to D^0\bar{D}^0\pi^0]}{BR[X(3875)\to\pi^+\pi^- J/\psi]} = 9.4^{+3.6}_{-4.3}$ (Belle 2006) ???

The resonance $Z^+(4430)$, $I = 1$
Exotique: non-zero electric charge $\rightarrow$ not $c\bar{c}$ or $c\bar{c}g$
observed in $\Psi(2S)\pi^+$ channel.

Options
- $D^*(2010)\ \overline{D}_1(2420)$ molecule (S.L.Zhu et al.,2007)
- diquark-antidiquark $[cu][\bar{c}\bar{u}]$(Maiani et al.,2007)
- tetraquark (Liu, Zhao, Close, hep-ph/0802.2648)
- S-wave threshold effect (Rosner, 2007)

Molecular option: Relative S-wave gives $J^P = 0^-$ (lowest state)
Decay channel: $D^* D^*\ \pi$

Tetraquark option $cu\bar{c}\bar{d}$: Mass estimate

Relative S-wave $\rightarrow \ell = 0 \rightarrow$ **Parity = + 1**

Decay to $\Psi(2S)\pi^+ \rightarrow S = 1 \rightarrow$ **Charge conjugation for neutral partner** $C = (-)^{\ell+S}$ **= + 1**$\rightarrow$ **J**^{P} **= 1**$^{+-}$ **(lowest state)**
Decay channels of neutral partner $D\overline{D}^*$**,**$J/\Psi\pi$**,etc.**

Radial excitation: $M(\Psi'(3685)) - M(J/\Psi(3097)) \approx 600$ **MeV**
The OGE model for J^{PC} **= 1**$^{+-}$ **was 3695 MeV.**
The total: ≈ 4300 **Mev is plausible**

Microscopic calculations are required

Summary

SUMMARY

- **X(3872), Z^+(4430) good candidates for exotics**
- **Richer data needed, quantum numbers, charged X, etc.**
- **More sophisticated calculations needed**
- **Intensive back-and-forth between theory and experiment**
- **New charmonium states to be discovered, also $b\bar{b}$ and $b\bar{c}$**