XYZ to ssbar

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Act I
The setting
Topics covered at workshop:

1. Glueballs, hybrids, quarkonia
2. Exotic meson spectroscopy
3. Final state interactions
4. Coupled channels
QCD is theory of strong interactions

Hadrons
  • reflect QCD in the non-perturbative regions
  • Laboratory for precision tests of lattice QCD, effective field theory, chiral dynamics, quark model,…

Use constituent quark model states as benchmark

But also expect
  • Molecules
  • Tetraquarks
  • Hybrids
  • Glueballs

Many newly discovered states have puzzling properties
Conventional Mesons & Potential Models

Meson quantum numbers characterized by given $J^{PC}$:

- $S = S_1 + S_2$
- $J = L + S$
- $P = (-1)^{L+S}$
- $C = (-1)^{L+S}$

For given spin and orbital angular momentum configurations & radial excitations generate the meson spectrum

$V(r) = -\frac{4}{3} \frac{\alpha_s(r)}{r} + br$

Allowed:

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

Not allowed: exotic combinations:

$J^{PC} = 0^{--} 0^{+-} 1^{-+} 2^{+-} \ldots$
Spin-dependent potentials:

- Lorentz vector 1-gluon exchange + scalar confinement
- Spin-dependent interactions are \((v/c)^2\) corrections

Spin-spin interactions:

\[
H_{ij}^{\text{hyp}} \quad = \quad \frac{4\alpha_s(r)}{3m_im_j} \left\{ \frac{8\pi}{3} \mathbf{S}_i \cdot \mathbf{S}_j \delta^3(\mathbf{r}_{ij}) + \frac{1}{r_{ij}^3} \left[ 3\mathbf{S}_i \cdot \mathbf{r}_{ij} \mathbf{S}_j \cdot \mathbf{r}_{ij} - \mathbf{S}_i \cdot \mathbf{S}_j \right] \right\}
\]

Spin-orbit interactions:

\[
H_{ij}^{\text{s.o.}}(cm) = \frac{4\alpha_s(r)}{3r_{ij}^3} \left( \frac{1}{m_i} + \frac{1}{m_j} \right) \left( \frac{\mathbf{S}_i}{m_i} + \frac{\mathbf{S}_j}{m_j} \right) \cdot \mathbf{\vec{L}}
\]

\[
H_{ij}^{\text{s.o.}}(tp) = \frac{-1}{2r_{ij}} \frac{\partial V(r)}{\partial r_{ij}} \left( \frac{\mathbf{S}_i}{m_i^2} + \frac{\mathbf{S}_j}{m_j^2} \right) \cdot \mathbf{\vec{L}}
\]
Decays & Transitions

• Decays and transitions are sensitive to the internal structure

• An important tool in disentangling the observed spectrum

• Need to understand them to disentangle exotics from $q\bar{q}$

Strong Decays:
  • Strong decays modeled by
  • $^3P_0$ Model
  • Flux tube breaking model
  • Give good qualitative agreement with experiment with only 1 free parameter (using QM wavefunctions)
Electromagnetic Transitions & Decays

Electromagnetic Transitions:

- **E1**
  \[ \Gamma = \frac{4}{3} e_Q^2 \alpha C(J_i L_i J_f L_f S) \langle P | r | S \rangle \omega^3 \]

- **M1**
  \[ \Gamma^{3S_1 \rightarrow 1S_0 + \gamma} = \frac{4}{3} \frac{e_Q^2}{m_Q^2} |\langle f | j_0(kr/2) | i \rangle|^2 \omega^3 \]

Decays

\[ \rho \rightarrow e^+ e^- \]

\[ (^{3}S_{1} \rightarrow e^+ e^-) \]

In non-relativistic limit (Van Royen-Weisskopf)

\[ f_V = \sqrt{12M} \psi_S(0) \quad \Gamma = \frac{16\pi \alpha^2 e_Q^2}{M^2} |\psi(0)|^2 \]

2\(\gamma\) couplings

\[ \Gamma_{\gamma \gamma}(f_2) \cdot B(f_2 \rightarrow \pi^0 \pi^0) \]
Annihilation Decays:

Hadronic Transitions:

Put everything together to produce a detailed description of expected meson that can be used to unravel the experimental spectrum
Conventional (Charmonium) States
The photon has significant $S\bar{S}$ content.

Therefore can study strangeonium in detail:
- Fill in missing states
- Resolve puzzles
“Exotic States”

Hybrids
- States with excited gluonic degrees of freedom
- Distinctive decay modes

Multiquark States
- Molecular state
  - loosely bound pair of mesons near threshold
  - Exhibit large isospin violations
- Tetraquarks
  - tightly bound diquark-diantiquark states
  - Expect flavour multiplet of states

Threshold-effects
- Rescattering near threshold due to interactions between two outgoing mesons
- Mass shifts due to thresholds
- Coupled channel effects mixing 2-meson states with resonances
**Hybrid Mesons**

Hybrid mesons are defined as those in which the gluonic component is non-trivial

- Quarks move in adiabatic potentials
- Conventional hadrons correspond to gluon fields in ground states
- Hybrids correspond to excitations of quantum strings
• Lowest mass hybrids corresponds to transverse excitations:

- Transverse phonon modes
- Hybrid mesons
- 1 GeV mass difference
- Normal mesons

Lowest mass hybrids at ~1.9 GeV
Doubly degenerate:

\[ J^{PC} = 0^- 0^- 1^- 1^- 2^- 1^+ 1^- \]

Expect degeneracies to be broken by different excitation energies of flux tube modes, spin dependence, mixings with \( q\bar{q} \)

Lattice results generally consistent with these predictions

\[ M(1^+) \sim 1.9 \text{ GeV} \]
\[ M(0^+) \sim 2.1 \text{ GeV} \]
\[ M(2^+) \sim 2.1 \text{ GeV} \]
Hybrid Decays

Flux Tube Model:

Expect stronger coupling to one s-wave and one p-wave final state meson

A General Selection Rule:
To preserve symmetries of quark and colour fields the hybrid must decay to meson in a P-wave
e.g. cannot transfer angular momentum as relative angular momentum but appears as internal angular momentum
This appears to be a universal selection rule

For $1^-$ exotic expect $\hat{\rho} \rightarrow b_1 \pi, f_1 \pi$ modes to dominate
Low Lying Hybrid Decays

- S-wave decays have large phase space so may be too broad to be seen $\hat{a}_0, f'_0$

- Favoured final state contains broad P-wave meson
  - Eg $\omega^{\pm}_{g_1} \rightarrow [a_1 \pi]_S$ $(\Gamma \approx 100 \text{ MeV})$
  - $\rightarrow [\pi(1300)\pi]_P$ $(\Gamma \approx 100 \text{ MeV})$

- Similarly for $\hat{\phi}_1$

- Best bets (according to flux tube model)
  - $\hat{\rho}_1 \rightarrow [b_1 \pi]_S, [f_1 \pi]_S$ $(\Gamma \approx 100 \text{ & } 30 \text{ MeV})$
  - $\hat{f}_2 \rightarrow [b_1 \pi]_P$ $(\Gamma \approx 350 \text{ MeV})$
  - $\hat{f}'_2 \rightarrow [K^*_2 K]_P$ $(\Gamma \approx 300 \text{ MeV})$
  - $\rightarrow [K_1 \overline{K}]_P$ $(\Gamma \approx 250 \text{ MeV})$

But there is variation in model predictions

Isgur, Kokoski and Paton, PRL, 54, 907
Page Swanson Szczepaniak, PRD59, 034016
• Another important ingredient
  $f_0(980), a_0(980)$ believed to be multiquark states
  $f_1(1430)$ long standing puzzle (E/1 puzzle)
  $f_J(1710)$ also open to interpretation
• Could also have multiquarks with exotic quantum #’s
• Best bets are doubly charged mesons

Much interesting physics:
• Meson-meson potentials in scattering
• Higher Fock space components which shift $\bar{q}q$ masses
Glueballs

Glueballs are hadrons with no valence quark content

• Observation is test of QCD

Mass predictions by Lattice QCD

• Lowest mass glueballs have conventional quantum numbers:
  - \( M_{0^{++}} \sim 1.6 \text{ GeV} \)
  - \( M_{2^{++}} \sim 2.3 \text{ GeV} \)
  - \( M_{0^{-+}} \sim 2.5 \text{ GeV} \)

Lowest lying glueballs with exotic quantum numbers \( 0^{+-}, 2^{+-}, 1^{-+} \) are much higher in mass

• Difficult to produce exotic glueballs
• Difficult to disentangle glueballs with conventional Q#’s from dense background of conventional states
Glueball Properties

Expect glueball decays to have flavour symmetric couplings to final state hadrons:

$$\Gamma(G \rightarrow \pi\pi: KK: \eta\eta: \eta\eta': \eta' \eta')$$

Phase Space

But situation complicated by mixing with $qq$ and $qqqq$

Physical states are linear combinations:

$$\left| f_0 \right> = \alpha \left| n\bar{n} \right> + \beta \left| s\bar{s} \right> + \gamma \left| G \right> + \delta \left| q\bar{q}q\bar{q} \right>$$

Will shift unquenched glueball mass and distort naïve couplings

Act II
The XYZ States
New Charmonium like states “XYZ” states
Large number of charmonium-like states that are not understood

<table>
<thead>
<tr>
<th>state</th>
<th>$M$ (MeV)</th>
<th>$\Gamma$ (MeV)</th>
<th>$J^{PC}$</th>
<th>Seen In</th>
<th>Observed by</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Y_s(2175)$</td>
<td>2175 ± 8</td>
<td>58 ± 26</td>
<td>1--</td>
<td>$(e^+ e^-)_{ISR}, J/\psi \rightarrow Y_s(2175) \rightarrow \phi f_0(980)$</td>
<td>BaBar, BESII, Belle</td>
<td></td>
</tr>
<tr>
<td>$X(3872)$</td>
<td>3871.4 ± 0.6</td>
<td>&lt; 2.3</td>
<td>1++</td>
<td>$B \rightarrow K X(3872) \rightarrow \pi^+ \pi^- J/\psi, \gamma J/\psi, D\bar{D}^*$</td>
<td>Belle, CDF, D0, BaBar</td>
<td>Molecule?</td>
</tr>
<tr>
<td>$Z(3930)$</td>
<td>3929 ± 5</td>
<td>29 ± 10</td>
<td>2++</td>
<td>$\gamma \gamma \rightarrow Z(3940) \rightarrow D\bar{D}$</td>
<td>Belle</td>
<td>$2^3 P_2(c\bar{c})$</td>
</tr>
<tr>
<td>$X(3940)$</td>
<td>3942 ± 9</td>
<td>37 ± 17</td>
<td>0^?+</td>
<td>$e^+ e^- \rightarrow J/\psi X(3940) \rightarrow D\bar{D}^*$ (not $D\bar{D}$ or $\omega J/\psi$)</td>
<td>Belle</td>
<td>$3^1 S_0(c\bar{c})$?</td>
</tr>
<tr>
<td>$Y(3940)$</td>
<td>3943 ± 17</td>
<td>87 ± 34</td>
<td>?^+</td>
<td>$B \rightarrow K Y(3940) \rightarrow \omega J/\psi$ (not $D\bar{D}^*$)</td>
<td>Belle, BaBar</td>
<td>$2^3 P_1(c\bar{c})$?</td>
</tr>
<tr>
<td>$Y(4008)$</td>
<td>4008^{+82}_{-49}</td>
<td>228^{+97}_{-80}</td>
<td>1--</td>
<td>$(e^+ e^-)_{ISR} \rightarrow Y(4008) \rightarrow \pi^+ \pi^- J/\psi$</td>
<td>Belle</td>
<td></td>
</tr>
<tr>
<td>$Y(4140)$</td>
<td>4143 ± 3.1</td>
<td>11.7^{+6.1}_{-6.2}</td>
<td>?</td>
<td>$B \rightarrow K Y(4140) \rightarrow J/\psi\phi$</td>
<td>CDF</td>
<td></td>
</tr>
<tr>
<td>$X(4160)$</td>
<td>4156 ± 29</td>
<td>139^{+113}_{-65}</td>
<td>0^?+</td>
<td>$e^+ e^- \rightarrow J/\psi X(4160) \rightarrow D^* \bar{D}^*$ (not $D\bar{D}$)</td>
<td>Belle</td>
<td></td>
</tr>
<tr>
<td>$Y(4260)$</td>
<td>4264 ± 12</td>
<td>83 ± 22</td>
<td>1--</td>
<td>$(e^+ e^-)_{ISR} \rightarrow Y(4260) \rightarrow \pi^+ \pi^- J/\psi$</td>
<td>BaBar, CLEO, Belle</td>
<td>Hybrid?</td>
</tr>
<tr>
<td>$Y(4350)$</td>
<td>4361 ± 13</td>
<td>74 ± 18</td>
<td>1--</td>
<td>$(e^+ e^-)_{ISR} \rightarrow Y(4350) \rightarrow \pi^+ \pi^- \psi'$</td>
<td>BaBar, Belle</td>
<td></td>
</tr>
<tr>
<td>$Y(4630)$</td>
<td>4634^{+9.4}_{-10.6}</td>
<td>92^{+41}_{-32}</td>
<td>1--</td>
<td>$(e^+ e^-)_{ISR} \rightarrow Y(4630) \rightarrow \Lambda_c^+ \Lambda_c^-$</td>
<td>Belle</td>
<td></td>
</tr>
<tr>
<td>$Y(4660)$</td>
<td>4664 ± 12</td>
<td>48 ± 15</td>
<td>1--</td>
<td>$(e^+ e^-)_{ISR} \rightarrow Y(4660) \rightarrow \pi^+ \pi^- \psi'$</td>
<td>Belle</td>
<td></td>
</tr>
<tr>
<td>$Z_1(4050)$</td>
<td>4051^{+24}_{-23}</td>
<td>82^{+51}_{-29}</td>
<td>?</td>
<td>$B \rightarrow K Z_{1}^+(4050) \rightarrow \pi^+ \chi_c$</td>
<td>Belle</td>
<td></td>
</tr>
<tr>
<td>$Z_2(4250)$</td>
<td>4248^{+185}_{-45}</td>
<td>177^{+320}_{-72}</td>
<td>?</td>
<td>$B \rightarrow K Z_{2}^+(4250) \rightarrow \pi^+ \chi_c$</td>
<td>Belle</td>
<td></td>
</tr>
<tr>
<td>$Z(4430)$</td>
<td>4433 ± 5</td>
<td>45^{+53}_{-18}</td>
<td>?</td>
<td>$B \rightarrow K Z_{2}^+(4430) \rightarrow \pi^+ \psi'$</td>
<td>Belle</td>
<td></td>
</tr>
<tr>
<td>$Y_b(10890)$</td>
<td>10,890 ± 3</td>
<td>55 ± 9</td>
<td>1--</td>
<td>$e^+ e^- \rightarrow Y_b \rightarrow \pi^+ \pi^- \Upsilon(1, 2, 3S)$</td>
<td>Belle</td>
<td></td>
</tr>
</tbody>
</table>
First observed by Belle

Confirmed by:
- CDF PRL 93, 072001 (2004)
- D0 PRL 93, 162002 (2004)
- BABAR PR D71, 071103 (2005)

$M = 3872.0 \pm 0.6 \pm 0.5 \text{ MeV}$

$\Gamma < 2.3 \text{ MeV at 90\% C.L.}$ consistent with detector resolution.

- $X(3872) \to \gamma J/\psi$ implies $C = +$

$\psi'$

Angular distributions favour $J^{PC} = 1^{++}$ Belle [hep-ex/0505038]

Higher statistics by CDF allow $J^{PC} = 1^{++}$ or $2^{-+}$ PRL 98, 132002 (2007)

- $X(3872) \to D^0 \bar{D}^0 \pi^0$ seen [Belle PRL 97, 162002 (2006)]
- $X(3872) \to D^0 \bar{D}^0 \gamma$ seen [BaBar PR D77, 011102R (2008)]

• Implies decays predominantly to $D^0 \bar{D}^* 0$
1. Conventional Charmonium

- $1^1D_2$ or $2^3P_1$ only possible conventional states with correct quantum numbers close enough in mass
- But identification of $Z(3931)$ with $2^3P_2$ implies $2P$ mass $\sim 3940$ MeV
- $X(3872) \rightarrow \gamma J/\psi, \gamma \psi'$ disfavours $1^1D_2$

2. Tetraquark

- Predict more nearly degenerate states including charged states which have not been seen
- High statistics study by CDF of $X(3872)$ mass and width and tested hypothesis of two states and find $\Delta m < 3.6$ (95% C.L.) $M=3871.61 \pm 0.16 \pm 0.19$ MeV/c$^2$
- Mass splitting between $X(3872)$ from charged and neutral $B$ mesons consistent with zero.

Disfavours tetraquark models

Barnes, Godfrey, PR D69, 050400 (2004)
Eichten, Lane, Quigg, PR D69, 094019 (2004)
Barnes, Godfrey, Swanson, PR D 054026 (2005)
Maiani et al PR D71, 014028 (2008)
3. $D^0D^{*0}$ molecule

- Close to $D^0D^{*0}$ threshold so might be $S$-wave $D^0D^{*0}$ bound state "molecule"

$$X(3872) \rightarrow \rho J/\psi \sim X(3872) \rightarrow \omega J/\psi$$

So large isospin violation indicative of molecule

But decays $X(3872) \rightarrow \gamma J/\psi$ & $X(3872) \rightarrow \gamma \psi'$ implies ccbar content

BaBar: PRL 102,132001(2009)

Probably mixing with $\chi'_c$ explains both $X(3872)$ and $Y(3940)$ properties as admixtures of molecule and $2^3P_1$ states

Danilin & Simonov, 0907.1088; SG hep-ph/0605152; Ortega et al, 0907.3997, Matheus et al 0907.2683
$e^+e^- \rightarrow \gamma_{\text{ISR}} Y$

$Y(4260) \rightarrow J/\psi \, \pi^+\pi^-$
BaBar: PRL 95, 142001(2005)

$Y(4008) \rightarrow J/\psi \, \pi^+\pi^-$

$Y(4325) \rightarrow \psi(2S) \, \pi^+\pi^-$

$Y(4360) \rightarrow \psi(2S) \, \pi^+\pi^-$

$Y(4630) \rightarrow \Lambda_c^+ \, \Lambda_c^-$

$Y(4660) \rightarrow \psi(2S) \, \pi^+\pi^-$
Y(4260)

Discovered by Babar as enhancement in $\pi\pi J/\psi$ subsystem in $e^+e^-\rightarrow \gamma_{\text{ISR}} \psi\pi\pi$ PRL 95, 142001(2005)

$M=4259 \pm 8 \pm 4 \text{ MeV}$

$\Gamma = 88 \pm 23 \pm 5 \text{ MeV}$

$\Gamma_{ee}\times\text{BR}(Y \rightarrow \pi^+\pi^-J/\psi)=5.5 \pm 1.0\pm0.8 \text{ eV}$

ISR production tells us $J^{PC}=1^{--}$

Further evidence in $B\rightarrow K(\pi^+\pi^-J/\psi)$ PR D73, 011101(2006)

Confirmed by

CLEO PRL 96, 162003 (2006)

Belle PRL 99, 182004 (2007)
Conventional Charmonium:
• The first unaccounted $1^-$ state is the $\psi(3D)$
• Quark models estimate $M(\psi(3D)) \sim 4500$ MeV much too heavy for the $Y(4260)$
• $Y(4260)$ represents an overpopulation of expected $1^-$ states
• Absence of open charm production also against conventional $cc$ state

Other explanations are:
• $\psi(4S)$ Phys Rev D72, 031503 (2005)
• Tetraquark Phys Rev D72, 031502 (2005)
• $D_1D^*$ Bound state PRL 102, 242003
Y(4260): Hybrid?

• Flux tube model predicts lowest cc hybrid at 4200 MeV
• LGT expects lowest cc hybrid at 4200 MeV [Phys Lett B401, 308 (1997)]

• The dominant decay mode expected to be $D + D_1(2420)$
  $D_1(2420)$ has width $\sim 300$ MeV and decays to $D^*\pi$
  • Suggests search for $Y(4260)$ in $DD^*\pi$

• Evidence of large $DD_1(2420)$ signal would be strong evidence for hybrid

• Search for Partner States: $(fill\ in\ the\ multiplet)$
  • Identify $J^{PC}$ partners of the hybrid candidate nearby in mass.
  • The F-T model expects:
    $0^{--}, 1^{++}, 2^{--}, 0^{--}, 1^{--}, 2^{++}, 1^{++}, 1^{--}$
Dibaryon threshold effect?
  • Dibaryonic peak near threshold

$X(4630) = Y(4660)$?

$5^3S_1$ charmonium state?
  • $M \sim 4670$ MeV
Y states in ISR: What are they?

- Conventional states?
  - Don’t match the peaks in $D^*(*)D^*(*)$ cross-sections
  - No room unless predictions way off

- Are $Y$ states threshold effects?
  - Opening up of channels
  - Coupled-channel effects
  - Recattering of charmed meson pairs could shift masses, cause binding and account for observed spectrum

  Voloshin hep-ph/0602233; Close & Downum, PRL 102, 242003(2009);
  Danilin & Simonov, 0907.1088; van Beveren & Rupp 0904.4351

- Charmonium hybrids
- Multiquark states

Most need to be confirmed

The $Y(4260)$ is the most robust and might be hybrid
New state in $B \to K\pi^\pm \psi(2S)$

$M = 4433 \pm 4 \pm 2$ MeV
$\Gamma = 45^{+18}_{-12} +30^{ -13}$ MeV
$\mathcal{B}(B^0 \to K^\mp Z^\pm) \times \mathcal{B}(Z^\pm \to \pi^\pm \psi')$

$= (4.1 \pm 1.0 \pm 1.4) \times 10^{-5}$

Charged and hidden charm so cannot be conventional charmonium or hybrid

The usual suspects:

- $[cu][\bar{c}\bar{d}]$ Tetraquark
- $D^* \bar{D}_1(2420)$ Threshold effect
- $D^* \bar{D}_1(2420)$ $J^P=0^-, 1^-$ Molecule

Molecule predict:
- decays into $D^*D^*\pi$
- Rescattering into $\psi'\pi$

Maiani et al 0708.3997
Rosner PR D76, 114002 (2007)
Meng, Chao 0708.4222
$B \rightarrow K\pi^{\pm}\psi(2S)$

- Detailed study of $K\pi$ system
- Correct for efficiency
- Includes S, P, and D waves

$\mathcal{B}(B^0 \rightarrow K^+Z^- \rightarrow \psi(2S)\pi^-K^+) < 3.1 \times 10^{-5}$ @ 95% C.L.

No conclusive evidence by BaBar for the $Z^-$ (4430)
Belle confirms the original result on $Z^+(4430)^+$

$M = (4443^{+15}_{-12}^{+17}_{-13})$ MeV/c$^2$,  
$\Gamma = (109^{+86}_{-43}^{+57}_{-52})$ MeV,  

Width is larger than original but uncertainties are large
Two resonance like structures in $\pi^+\chi_{c1}$ mass distributions

$\bar{B}^0 \rightarrow K^-\pi^+\chi_{c1}$

$M_1 = (4051 \pm 14^{+20}_{-41})$ MeV
$\Gamma_1 = (82^{+21+47}_{-17-22})$ MeV
$M_2 = (4248^{+44+180}_{-29-35})$ MeV
$\Gamma_2 = (177^{+54+316}_{-39-61})$ MeV

Evidence for three charged charmonium-like objects
Need experimental confirmation for all three of them
Lessons

• Many unexpected Charmonium-like states
  • This should have been easy.

• Are they all real?
  • If not, how do we kill them off?
  • If yes, how do we figure out what they are?

• What is missing?
  • What physics are we missing?
  • What steps do we need to take to sort this out?
Act III
Strange-onium
• Many unconfirmed states:
  \( f_1(1510), h_1(1380), f_2(1640), \phi(2170), f_4(2300), \ldots \)
• Many unclassified states:
  \( f_2(1950), f_2(2010), f_4(2050), f_2(2300), f_2(2340), \ldots \)
• Many puzzles:
  \( \eta(1405), \eta(1475), f_1(1420), f_0(1500), f_0(1710), f_j(2200), \ldots \)
The photon has significant $\bar{S}S$ content so photoproduction at JLab is a good source of strangeonia.
Photo-production

Qualitative alternative to hadronic peripheral production
• series of preferred excitations is likely to be different
• strong source of ss states

\[ \rho, \omega, \phi \]
\[ q\bar{q} \text{ with } S = 1 \]

Interaction with target can excite flux tube

Quark spins already aligned

• Production of exotic hybrids is favoured: \( J^{PC} = 0^{+-}, 1^{-+}, 2^{--} \)
• Almost no data is available
\[ 2^{--} 1^3 D_2 \]

- Can be diffractively photoproduced
- Not too big width
- Two dominant decay modes: KK*, ηφ
- Latter indicates ssbar content
- Tests calculations

<table>
<thead>
<tr>
<th>Mode</th>
<th>(\Gamma_i(\text{MeV}))</th>
<th>Amps.</th>
</tr>
</thead>
<tbody>
<tr>
<td>KK</td>
<td></td>
<td></td>
</tr>
<tr>
<td>KK*</td>
<td>151</td>
<td>(^3P_2 = +0.14)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(^3F_2 = -0.049)</td>
</tr>
<tr>
<td>K*K**</td>
<td>7</td>
<td>(^5P_2 = +0.073)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(^5F_2 = +0.0072)</td>
</tr>
<tr>
<td>KK(_1)(1273)</td>
<td>2</td>
<td>(^3D_2 = +0.028)</td>
</tr>
<tr>
<td>ηφ</td>
<td>53</td>
<td>(^3P_2 = -0.20)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(^3F_2 = +0.038)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(\Gamma_{\eta\phi} = 214\ \text{MeV})</td>
</tr>
</tbody>
</table>
To distinguish non-exotic hybrids from conventional states need detailed predictions of properties:

Useful references on strong decays:

• *Strong Decays of Strange Quarkonia*

• *Hybrid Meson Decay Phenomenology*
Distinguishing states

To distinguish non-exotic hybrids from conventional states need detailed predictions of properties:

\[ \pi(1800) \]

**TABLE III.** Decay of quark model and hybrid \( \pi(1800) \).

<table>
<thead>
<tr>
<th>State</th>
<th>( \pi\rho )</th>
<th>( \omega\rho )</th>
<th>( \rho(1465)\pi )</th>
<th>( f_0(1300)\pi )</th>
<th>( f_2\pi )</th>
<th>( K^*K )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \pi_{3S}(1800) )</td>
<td>30</td>
<td>74</td>
<td>56</td>
<td>6</td>
<td>29</td>
<td>36</td>
</tr>
<tr>
<td>( \pi_H(1800) )</td>
<td>30</td>
<td>—</td>
<td>30</td>
<td>170</td>
<td>6</td>
<td>5</td>
</tr>
</tbody>
</table>

\( \rho\omega \) can be used as discriminator between possibilities observed in \( \pi f_0(1300) \)

(but Swanson and Szczepaniak [PR D56, 5692] predict small \( \rho\omega \) partial width)
**$f_0(1500)$ and $f_0(1710)$**

**Glueball:**

$B(1/p.s. \ (\pi\pi:KK:\eta\eta:\eta\eta':\eta'\eta') = 3:4:1:0:1.)$

<table>
<thead>
<tr>
<th>Mode</th>
<th>$\Gamma_i$(MeV)</th>
<th>$^1S_0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$KK$</td>
<td>214</td>
<td>$+0.28$</td>
</tr>
<tr>
<td>$KK^*$</td>
<td>66</td>
<td>$-0.33$</td>
</tr>
<tr>
<td>$\eta\eta'$ (no $\pi\pi$)</td>
<td>(\Gamma_{th} = 279) MeV</td>
<td>see text</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>State</th>
<th>Experiment</th>
<th>$\pi\pi$</th>
<th>$KK$</th>
<th>$\eta\eta$</th>
<th>$\eta\eta'$</th>
<th>$4\pi$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_0(1500)$</td>
<td>WA102 1</td>
<td>0.33 ± 0.07</td>
<td>0.18 ± 0.003</td>
<td>0.096 ± 0.026</td>
<td>1.36 ± 0.15</td>
<td></td>
</tr>
<tr>
<td></td>
<td>CBar 1</td>
<td>0.184 ± 0.025</td>
<td>0.08 ± 0.04</td>
<td>0.065 ± 0.008</td>
<td>1.62 ± 0.18</td>
<td></td>
</tr>
<tr>
<td>$f_0(1710)$</td>
<td>WA102 1</td>
<td>5.0 ± 0.7</td>
<td>2.4 ± 0.6</td>
<td>&lt;0.18</td>
<td>&lt;5.4</td>
<td></td>
</tr>
</tbody>
</table>

Implies states are mixtures but other input like radiative transitions and $2\gamma$ decays could help sort this out.
$$2^3 P_1$$

<table>
<thead>
<tr>
<th>Mode</th>
<th>$f_1(1950)$</th>
<th>$\Gamma_i$(MeV)</th>
<th>Amps.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$KK$</td>
<td></td>
<td>68</td>
<td>$^3S_1 = +0.0025$</td>
</tr>
<tr>
<td>$KK^*$</td>
<td></td>
<td>$^3D_1 = +0.092$</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>$^5D_1 = -0.11$</td>
<td></td>
</tr>
<tr>
<td>$K^<em>K^</em>$</td>
<td></td>
<td>29</td>
<td></td>
</tr>
<tr>
<td>$KK_1(1273)$</td>
<td></td>
<td>108</td>
<td>$^3P_1 = -0.16$</td>
</tr>
<tr>
<td>$KK_1(1402)$</td>
<td></td>
<td>1</td>
<td>$^3P_1 = -0.025$</td>
</tr>
<tr>
<td>$KK_0^*(1412)$</td>
<td></td>
<td>1</td>
<td>$^1P_1 = -0.026$</td>
</tr>
<tr>
<td>$KK_1^*(1429)$</td>
<td></td>
<td>8</td>
<td>$^5P_1 = +0.081$</td>
</tr>
<tr>
<td>$KK^*(1414)$</td>
<td></td>
<td>80</td>
<td>$^3S_1 = -0.22$</td>
</tr>
<tr>
<td>$KK(1460)$</td>
<td></td>
<td>80</td>
<td>$^3D_1 = +0.013$</td>
</tr>
<tr>
<td>$\eta\eta$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\eta\eta'$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\eta\eta'$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\eta\eta(1415)$</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**hybrid**

<table>
<thead>
<tr>
<th>$K^*K$</th>
<th>S 9</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_2^*(1430)K$</td>
<td>P 13</td>
</tr>
<tr>
<td>$K_1(1270)K$</td>
<td>P 11</td>
</tr>
<tr>
<td>$K_2^*(1430)K$</td>
<td>P 11</td>
</tr>
<tr>
<td>$K_1(1400)K$</td>
<td>P 16</td>
</tr>
<tr>
<td>$f_2'(1525)\eta$</td>
<td>P 2</td>
</tr>
<tr>
<td>$f_1(1510)\eta$</td>
<td>P 4</td>
</tr>
<tr>
<td>$f_0(1370)\eta$</td>
<td>P 0</td>
</tr>
<tr>
<td>$K^*(1410)K$</td>
<td>S 103</td>
</tr>
<tr>
<td>$\Gamma$ (MeV)</td>
<td>164</td>
</tr>
</tbody>
</table>

$\Gamma_{th0} = 296$ MeV
\[
\begin{array}{cccc}
\text{Mode} & \Gamma_i \quad \text{(MeV)} & \text{Amps.} \\
\hline
KK & 53 & {^3}P_0 = +0.081 \\
KK^* & 67 & {^3}P_0 = -0.17 \\
KK_1(1273) & & \\
KK_1(1402) & & \\
KK^*_1(1412) & 30 & {^1}S_0 = -0.13 \\
KK^*_2(1429) & 0 & {^5}D_0 = -0.016 \\
KK^*(1414) & 25 & {^3}P_0 = +0.12 \\
KK(1460) & & \\
\eta \phi & & \\
\eta' \phi & & \\
\eta h_1(1380) & & \\
\hline
\Gamma_{zh} = 175 \text{ MeV} \\
\end{array}
\]

\[0^- + \quad 3^1 S_0 \quad \text{hybrid} \]

\[
\begin{array}{cccc}
\text{Mode} & \Gamma_i \quad \text{(MeV)} & \text{Amps.} \\
\hline
K^*K & P & 52 \\
K_2^*(1430)K & D & 6 \\
K_0^*(1430)K & S & 117 \\
f_2'(1525)\eta & D & .2 \\
f_0(1370)\eta & S & 105 \\
K^*(1410)K & P & 110 \\
\end{array}
\]
can be produced in diffractive photoproduction

\[ \frac{\phi(2050)}{\Gamma_i (\text{MeV}) \quad \text{Amps.}} \]

<table>
<thead>
<tr>
<th>Mode</th>
<th>( \Gamma_i ) (MeV)</th>
<th>( \phi(2050) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( KK )</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>( KK^* )</td>
<td>20</td>
<td>3 ( P_1 = -0.047 )</td>
</tr>
<tr>
<td>( K^<em>K^</em> )</td>
<td>102</td>
<td>1 ( P_1 = -0.039 ), 2 ( P_1 = +0.17 )</td>
</tr>
<tr>
<td>( KK_1(1273) )</td>
<td>58</td>
<td>3 ( S_i = 0 ), 3 ( D_i = -0.10 )</td>
</tr>
<tr>
<td>( KK_1(1402) )</td>
<td>26</td>
<td>3 ( S_i = +0.083 ), 3 ( D_i = 0 )</td>
</tr>
<tr>
<td>( KK^*_6(1412) )</td>
<td>9</td>
<td>3 ( D_i = +0.053 )</td>
</tr>
<tr>
<td>( KK^*_7(1429) )</td>
<td>93</td>
<td>3 ( P_1 = -0.16 )</td>
</tr>
<tr>
<td>( KK(1460) )</td>
<td>29</td>
<td>1 ( P_1 = -0.10 )</td>
</tr>
<tr>
<td>( \eta \phi )</td>
<td>21</td>
<td>3 ( P_1 = +0.10 )</td>
</tr>
<tr>
<td>( \eta' \phi )</td>
<td>11</td>
<td>3 ( P_1 = -0.11 )</td>
</tr>
<tr>
<td>( \eta h_1(1386) )</td>
<td>8</td>
<td>3 ( S_i = -0.078 ), 3 ( D_i = -0.060 )</td>
</tr>
</tbody>
</table>

**\( K^*K \)**: P 26
**\( \phi \eta \)**: P 19
**\( \phi \eta' \)**: P 2

**\( K^*_2(1430)K \)**: D 2
**\( K_1(1270)K \)**: S 16
**\( K_1(1400)K \)**: S 40
**\( h_1(1380) \eta \)**: S

**\( K^*(1410)K \)**: P 55

**\( \Gamma \) (MeV)**: 155

\( \Gamma_{hyp} = 378 \text{ MeV} \)
Y(2175)

Ding & Yan, Phys Lett B657 (2007)

Observed by BaBar: $Y(2175) \rightarrow \phi f_0(980)$

in ISR process: $e^+ e^- \rightarrow \gamma_{ISR} \rightarrow \phi f_0(980) \rightarrow (K^+ K^-) + (\pi^+ \pi^-)$

Confirmed by Belle arXiv:0808:0006

& by BES in: $J/\psi \rightarrow \phi f_0\eta$ PRL 100, 102003 (2008)

Seen in ISR so $1^-$ and $I=0$, most likely $S\bar{S}$

Use decays to discriminate between possibilities

<table>
<thead>
<tr>
<th>$Y(2175)$ as $2^2 D_{1s\bar{s}}$ quarkonium</th>
<th>$Y(2175)$ as $s\bar{s}g$ hybrid [2]</th>
<th>$Y(2175)$ as $3^2 S_1 s\bar{s}$ quarkonium [6]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Decay modes</td>
<td>$\Gamma_{JJ}$ in $^3 P_0$ model</td>
<td>$\Gamma_{JJ}$ in flux tube model</td>
</tr>
<tr>
<td>$KK$</td>
<td>$\Gamma_{P0} = 9.8$</td>
<td>$\Gamma_{P0} = 23.1$</td>
</tr>
<tr>
<td>$\phi \eta'$</td>
<td>$\Gamma_{P1} = 1.3$</td>
<td>$\Gamma_{P1} = 0$</td>
</tr>
<tr>
<td>$K^* K^*$</td>
<td>$\Gamma_{P0} = 0.76$</td>
<td>$\Gamma_{P0} = 0$</td>
</tr>
<tr>
<td>$K(1460) K$</td>
<td>$\Gamma_{P0} = 58.3$</td>
<td>$\Gamma_{P0} = 50.2$</td>
</tr>
<tr>
<td>$K^*(1410) K$</td>
<td>$\Gamma_{P1} = 31.9$</td>
<td>$\Gamma_{P1} = 26.0$</td>
</tr>
<tr>
<td>$h_1(1380) \eta$</td>
<td>$\Gamma_{S1} = 3.6$</td>
<td>$\Gamma_{S1} = 20.5$</td>
</tr>
<tr>
<td>$K_1(1270) K$</td>
<td>$\Gamma_{S1} = 2.3$</td>
<td>$\Gamma_{S1} = 20.5$</td>
</tr>
<tr>
<td>$K_1(1400) K$</td>
<td>$\Gamma_{D1} = 5.6$</td>
<td>$\Gamma_{D1} = 8.6$</td>
</tr>
<tr>
<td>$K_2(1430) K$</td>
<td>$\Gamma_{D2} = 10.8$</td>
<td>$\Gamma_{D2} = 15.3$</td>
</tr>
<tr>
<td>$\Gamma_{tot}$</td>
<td>167.21</td>
<td>211.9</td>
</tr>
</tbody>
</table>
As the curtain drops
The Message:

- We thought charmonium would be relatively straightforward.
- But above threshold the situation is very confusing and it’s not clear to me what is going on.

- Strangeonium will be far more complicated with overlapping resonances.

- Understanding the charmonium will be an very useful exercise if we have any hope of disentangling the strangeonium spectrum.

- **BUT with high statistics have important tool in PWA**