Towards Meson Spectroscopy Instead of Bump Hunting

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I. What's wrong with bump hunting (only)?

⇒ A) Mesonic resonances may not show up as bumps
B) Bumps may not be resonances

Examples of A:

- $f_0(600)$ (σ) and $K_0^*(800)$ (κ), due to large widths, Adler zero at $\pi\pi$ resp. $K\pi$ threshold, and overlapping resonances ($f_0(980)$ resp. $K_0^*(1430)$); see e.g. EvB, D. V. Bugg, F. Kleefeld, GR, Phys. Lett. B 641 (2006) 265.

Examples of B:

- Several Xs, Ys, and Zs, such as $X(4260)$ ("depletion"; see below), and possibly $Z_b(10610)$, $Z_b(10650)$ (BB^*, B^*B^* threshold cusps; see D. V. Bugg, arXiv:1105.5492).

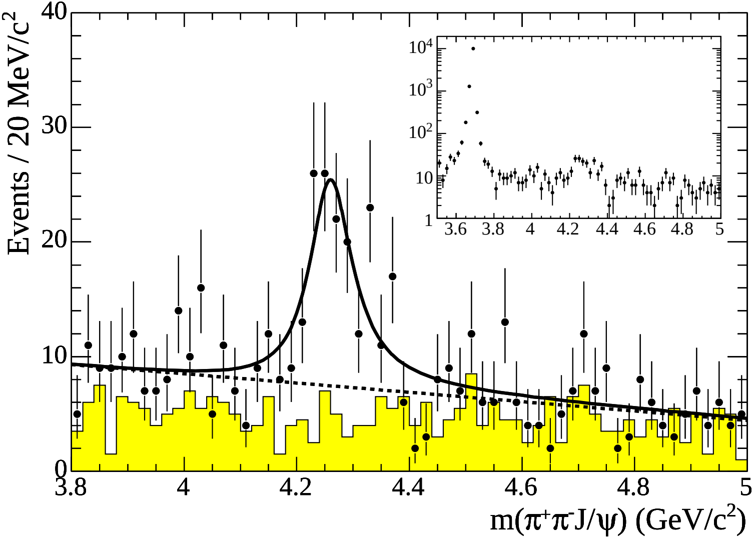
⇒ Further problems for model builders: true resonance bumps may show up considerably shifted, broader, or narrower than expected from the naive quark model, due to "unquenching".

Examples:

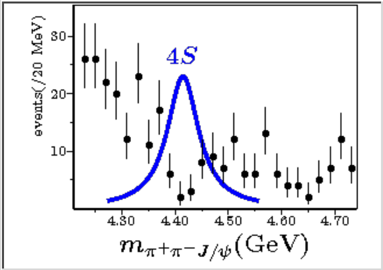
- $X(3872)$; $D_1(2420)$, $D_1(2430)$, $D_{s1}(2536)$, $D_{s1}(2460)$

II. $X(4260)$

⇒ BaBaR Collaboration, Phys. Rev. Lett. 95 (2005) 142001



X(4260)

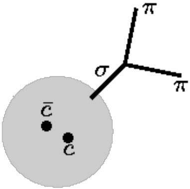
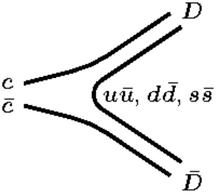


No signal in ππJ/ψ where the ψ(4S) is expected,
Because ψ(4S)→D_s*$\underline{D}_s$* depletes the ππJ/ψ signal.

- **data from BaBar, Phys. Rev. Lett. 95, 142001 (2005)**
- **EvB, GR, Chin. Phys. C 35 (2011) 319**
- **EvB, GR, Phys. Rev. Lett. 105 (2010) 102001**

(http://cft.fis.uc.pt/eef/Frascati2010talk/depletion/4260.htm)

Depletion

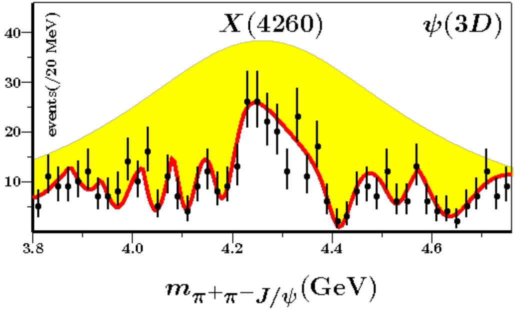
	
Radiation of a system with vacuum quantum numbers (σ). The $c\underline{c}$ system jumps to a lower lying stable state: ψ(1,2S).	Open-charm decay via the creation of a light quark-antiquark pair.

Left: **Slow radiation process.**
Right: **Fast open-charm decay.**

The latter process dominates at resonances and threshold enhancements.
- EvB, GR, arXiv:0904.4351
- EvB, GR, J. Segovia, Phys. Rev. Lett. 105 (2010) 102001

(http://cft.fis.uc.pt/eef/Frascati2010talk/depletion/depletion.htm)

Depletion by open-charm decays of the X(4260) signal in $\pi^+\pi^-$ J/ψ



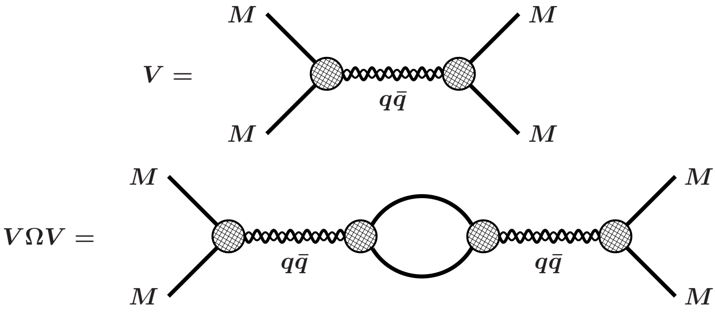
By threshold enhancements:
DD, DD*, D_sD_s, D*D*, D_sD_s*, D_s*D_s*, $\Lambda_c\Lambda_c$.
By c$\underline{c}$ resonances: ψ(3S), ψ(2D), ψ(4S), ψ(3D).

- data from BaBar, Phys. Rev. Lett. 95, 142001 (2005)
- figure from Evb, GR, JS, Phys. Rev. Lett. 105, 102001 (2010)

(http://cft.fis.uc.pt/eef/Frascati2010talk/depletion/octopsi.htm)

III. Resonance-Spectrum Expansion

⇒ Building blocks of RSE are:



- V is the effective two-meson potential;
- Ω is the two-meson loop function;
- the blobs are the $^3P_0$ vertex functions, modelled by a spherical δ shell in coordinate space, i.e., a spherical Bessel function in momentum space;
- the wiggly lines stand for s-channel exchanges of infinite towers of $q\bar{q}$ states, i.e., a kind of Regge propagators.

⇒ For N meson-meson channels and several $q\bar{q}$ channels:

$$\begin{aligned} V_{ij}^{(L_i,L_j)}(p_i,p_j';E) &= \lambda^2 r_0\, j_{L_i}^i(p_i r_0)\, j_{L_j}^j(p_j' r_0) \sum_{\alpha=1}^{N_{q\bar{q}}} \sum_{n=0}^{\infty} \frac{g_i^{(\alpha)}(n) g_j^{(\alpha)}(n)}{E - E_n^{(\alpha)}} \\ &\equiv \mathcal{R}_{ij}(E)\, j_{L_i}^i(p_i r_0)\, j_{L_j}^j(p_j' r_0)\ . \end{aligned}$$

⇒ The closed-form off-energy-shell T-matrix then reads

$$T_{ij}^{(L_i,L_j)}(p_i,p_j';E) =$$

$$-2\lambda^2 r_0 \sqrt{\mu_i p_i \mu_j' p_j'}\, j_{L_i}^i(p_i r_0) \sum_{m=1}^{N} \mathcal{R}_{im}(E) \left\{[\mathbb{1} - \Omega\,\mathcal{R}]^{-1}\right\}_{mj} j_{L_j}^j(p_j' r_0)\ ,$$

$$\Omega \;=\; -2i\lambda^2 r_0\, \mathrm{diag}\left(j_{L_n}^n(k_n r_0) h_{L_n}^{(1)n}(k_n r_0) \right)\ .$$

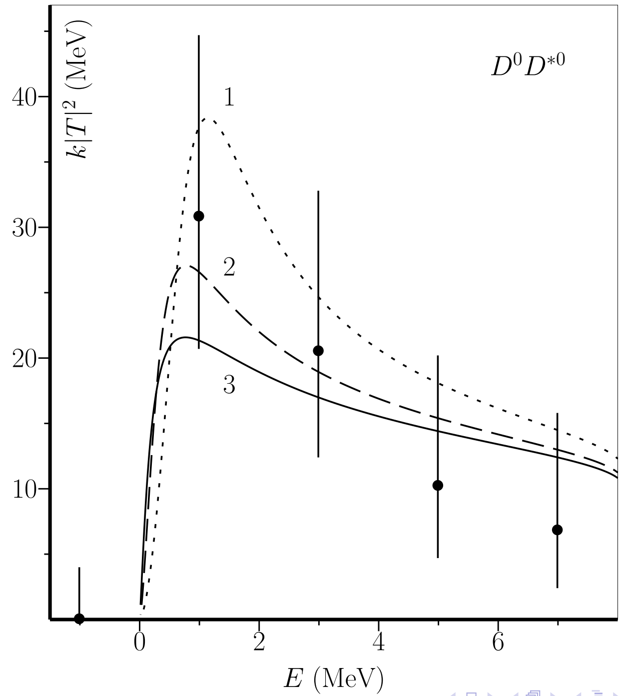
⇒ The corresponding unitary and symmetric S-matrix is given by

$$S_{ij}^{(L_i,L_j)}(k_i,k_j';E) \;=\; \delta_{ij} \;+\; 2iT_{ij}^{(L_i,L_j)}(k_i,k_j';E)\ .$$

IV. $X(3872)$ as a unitarised 1^{++} $c\bar{c}$ state

⇒ SC, GR, EvB, arXiv:1008.5100, to appear in Eur. Phys. J. C

- In RSE, bare $2\,^3P_1$ $c\bar{c}$ state lies at 3979 MeV;
- Couple it to $D^0 D^{*0}$ and other OZI-allowed channels, as well as to $\omega J/\psi$ and $\rho^0 J/\psi$;
- $\omega J/\psi$ and $\rho^0 J/\psi$ channels are smeared out so as to account for the ω and ρ widths, by taking complex ω and ρ masses and reunitarising the S-matrix (see paper in EPJC);
- $D^0 D^{*0}$ and $\rho^0 J/\psi$ data are easily described (see plot on next slide), as well as the $\omega J/\psi / \rho^0 J/\psi$ branching ratio;
- Corresponding $X(3872)$ pole settles at or slightly below the $D^0 D^{*0}$ threshold, with an imaginary part of about 0.1–0.7 MeV;
- Peak in $\rho^0 J/\psi$ at $\approx$3872- MeV and cusp-like structure in $D^0 D^{*0}$ at $\approx$3874 MeV appear naturally, with no need for an additional state.

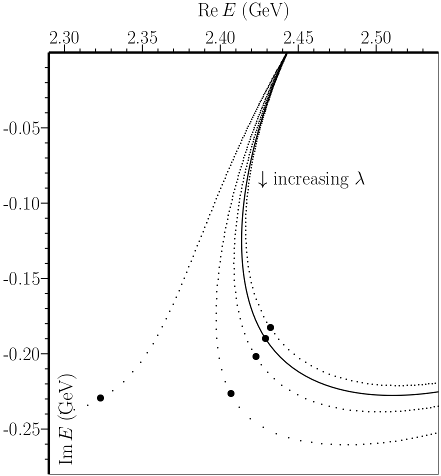


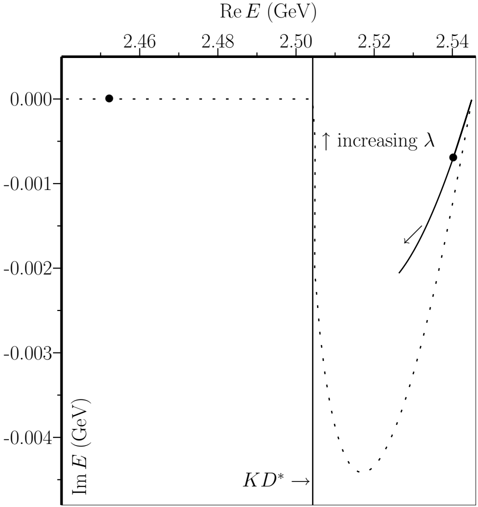
$D^0 D^{*0}$
$k|T|^2$ (MeV)
E (MeV)
1
2
3
40
30
20
10
0
2
4
6

V. $D_1(2420)$, $D_1(2430)$, $D_{s1}(2536)$, $D_{s1}(2460)$

⇒ SC, GR, EvB, arXiv:1106.2760 (expanded version under review)

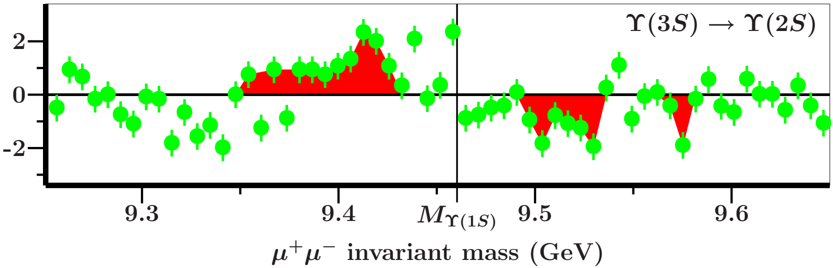
- $D_1(2420)$ and $D_1(2430)$ are almost degenerate in mass, whereas $D_{s1}(2536)$ and $D_{s1}(2460)$ are 76 MeV apart;
- $D_{s1}(2536)$ and $D_{s1}(2460)$ are very narrow (< 2.3 resp. < 3.5 MeV, $D_1(2420)$ is narrow (20–25 MeV), and $D_1(2430)$ is very broad (~ 384 MeV);
- No simple quark model, with spin-orbit splitting, can reproduce this pattern of masses and widths;
- Also chiral Lagrangians for heavy-light systems, with chiral loop corrections, fail dramatically, with the loops even worsening the discrepancies.
- **Our work:** couple bare $^3P_1$ and $^1P_1$ $c\bar{q}$ and $c\bar{s}$ systems to the most important OZI-allowed meson-meson channels, in RSE approach;
- Dynamics of equations generates 2 quasi-bound states in the continuum ($D_1(2420)$ and $D_{s1}(2536)$), as well as 2 strongly shifted states ($D_1(2430)$ and $D_{s1}(2460)$); see next slide;
- 8 observables are quite well reproduced with 2 parameters.


Re E (GeV)
2.30
2.35
2.40
2.45
2.50
-0.05
-0.10
-0.15
-0.20
-0.25
Im E (GeV)
↓ increasing λ


Re E (GeV)
2.46
2.48
2.50
2.52
2.54
0.000
-0.001
-0.002
-0.003
-0.004
Im E (GeV)
↑ increasing λ
$KD^* \rightarrow$

VI. A possible surprise: $E(38)$

$\Rightarrow$ EvB, GR, arXiv:1102.1863



- Data from E. Guido [BaBaR Collaboration], arXiv:0910.0423

VII. Conclusions

- In experiment, usually only the largest bumps are identified as resonances and analysed, whereas smaller structures are often discarded as "background" and/or "statistical fluctuations";
- Moreover, effects from strong thresholds are disregarded or parametrised in a too simple way;
- New mesonic enhancements that do not seem to fit in mainstream models are too easily interpreted as exotic states, instead of checking other possibilities, such as non-resonant threshold or depletion effects, and large shifts due to unquenching;
- The RSE model provides a simple empirical approach to unquenching the quark model, being fully solvable and manifestly non-perturbative;
- A detailed and more quantitative description of production processes in meson spectroscopy will require a better understanding of OZI-allowed and OZI-forbidden decays.