# What does true meson spectroscopy encompass?

*George Rupp*

CFIF, Instituto Superior Técnico, Lisbon

Collaborator: Eef van Beveren PhD Student: Susana Coito

I. Introduction

II. Problems with “Standard Model” for meson spectroscopy

III. Resonance-Spectrum Expansion

IV. Selected Results

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# I. Introduction

⇒ Meson spectroscopy is in an impasse, despite many newly announced resonances:

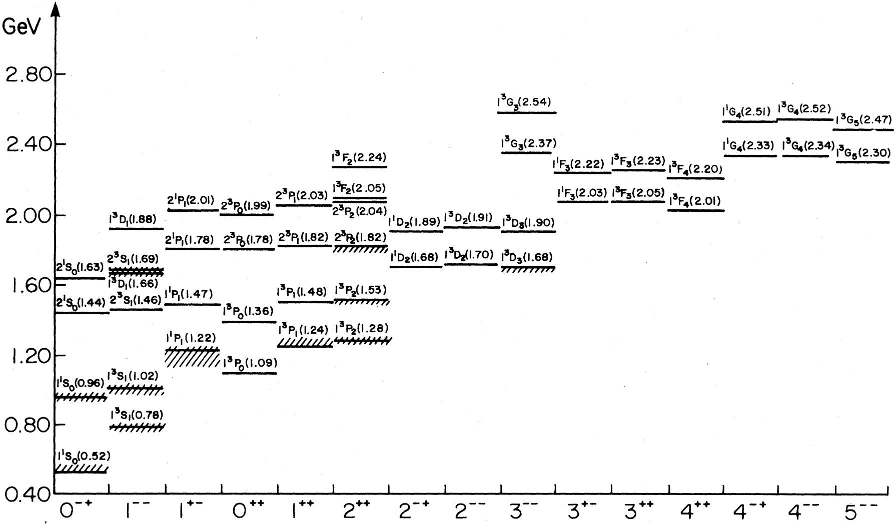
- No systematic search for quark-model states is carried out in energy regions or for quantum numbers where states are missing.
- Usually only the biggest bumps in the data are considered relevant, often ignoring other interesting structures.
- Such bumps are invariably interpreted as resonances, without even considering possible threshold effects or phenomena related to inelasticities due to competing channels.
- When a new "resonance" does not seem to fit in mainstream spectroscopy, it becomes right away an exotic candidate, ignoring possible mass shifts due to meson loops ("unquenching").
- The PDG seems often biased by mainstream (quenched) quark models in cataloguing mesonic resonances.
- Such models present a number of very serious problems.

# II. Problems with “Standard Model” for meson spectroscopy

⇒ Reference (quenched) quark model (1681 citations in *INSPIRE*): Stephen Godfrey and Nathan Isgur, Phys. Rev. D **32** (1985) 189:

- Typical Coulomb-plus-linear (“funnel”) confing potential, with a phenomenological running strong coupling $\alpha_s(r)$.
- One-gluon exchange gives rise the Coulombic part, as well as the usual spin-spin and spin-orbit interactions.
- The model uses relativistic kinematics, fixed constituent quark masses, and phenomenological smearing functions as regulators.
- The model was applied to a very large variety of light, heavy-light, and heavy $q\bar{q}$ states, thus almost covering the whole PDG meson spectrum.
- Most other constituent quark model predict masses that are generally in reasonable agreement with those of the Godfrey-Isgur (GI) model, but no other model has been applied so widely.
- Despite the enormous merits of the GI model, several shortcomings have become evident over the years.

# GI model, light-quark isoscalar mesons:



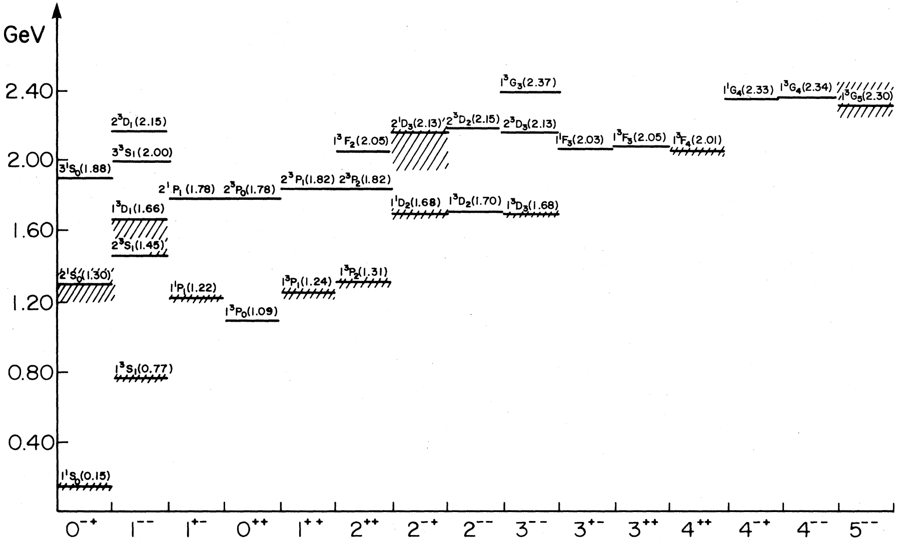
Principal problems:

- $0^{++}/{}^3P_0$: Lowest GI scalar $\sim$500 MeV heavier than $f_0(600)$.
- $0^{++}/{}^3P_0$: GI $s\bar{s}$ scalar almost 400 MeV heavier than $f_0(980)$.
- $2^{++}/{}^3P_2$-${}^3F_2$: PDG listings report 6 likely $n\bar{n}$ ($n = u, d$) states up to $\approx 2.15$ GeV, viz. $f_2(1270)$, $f_2(1565)$, $f_2(1640)$, $f_2(1810)$, $f_2(1910)$, $f_2(2150)$, whereas GI only predict 3.

  In probably dominant $s\bar{s}$ sector, PDG also lists 6 states up to $\approx 2.35$ GeV: $f_2(1430)$, $f_2'(1525)$, $f_2(1950)$, $f_2(2010)$, $f_2(2300)$, $f_2(2340)$, and GI again only predicts 3.

  Note: some PDG $f_2$ states may not be resonances (see D. V. Bugg, Phys. Rept. **397** (2004) 257), but $f_2(1565)$ looks reliable. Then, PDG: $m(2\,{}^3P_2) - m(1\,{}^3P_2) \approx 300$ MeV; GI: $m(2\,{}^3P_2) - m(1\,{}^3P_2) = 540$ MeV.
  For unknown reasons, PDG omits $f_2(1565)$ from Summary Table.
- $1^{+-}/{}^1P_1$: PDG $n\bar{n}$ states: $h_1(1170)$, $h_1(1595)$.
  GI predicts: $h_1(1220)$ $(1\,{}^1P_1)$, $h_1(1780)$ $(2\,{}^1P_1)$.

# GI model, light-quark isovector mesons:



# Principal problems:

- $0^{++}/{}^3P_0$: PDG: $a_0(980)$, $a_0(1450)$.
  GI: $a_0(1090)$ $(1\,{}^3P_0)$, $a_0(1780)$ $(2\,{}^3P_0)$.
- $1^{++}/{}^3P_1$: PDG: $a_1(1260)$, $a_0(1640)$.
  GI: $a_1(1240$ $(1\,{}^3P_1)$, $a_1(1820)$ $(2\,{}^3P_1)$.
- $2^{++}/{}^3P_2$: PDG: $a_2(1320)$, $a_2(1700)$.
  GI: $a_2(1310$ $(1\,{}^3P_2)$, $a_2(1820)$ $(2\,{}^3P_2)$.
- $1^{--}/{}^3S_1\text{-}{}^3D_1$: PDG: $\rho(1450)$, $\rho(1570)$, $\rho(1700)$, $\rho(1900)$.
  GI: $\rho(1450$ $(2\,{}^3S_1)$, $\rho(1660)$ $(1\,{}^3D_1)$, $\rho(2000)$ $(3\,{}^3S_1)$, $\rho(2150)$ $(2\,{}^3D_1)$.
  Note: a recent analytic $S$-matrix analysis by S. Surovtsev and P. Bydzovsky, Nucl. Phys. A **807** (2008) 145, arrived at assignments quite different from both PDG and GI (see Table): $\rho(1250)$, $\rho(1470)$, $\rho(1600)$, $\rho(1900)$. Also, they conclude that only $\rho(1250)$ and $\rho(1600)$ are crucial to describe the phase shifts, whereas $\rho(1900)$ and, to a lesser extent, $\rho(1470)$ improve the inelasticity (see plot). PDG hides $\rho(1250)$ under the $\rho(1450)$ entry!!

# S. Surovtsev, P. Bydzovsky, Nucl. Phys. A **807** (2008) 145

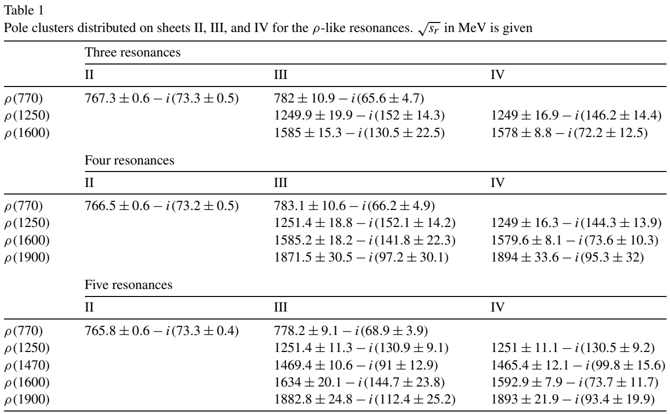


Table 1

Pole clusters distributed on sheets II, III, and IV for the $\rho$-like resonances. $\sqrt{s_r}$ in MeV is given

| | Three resonances | | |
|---|---|---|---|
| | II | III | IV |
| $\rho(770)$ | $767.3 \pm 0.6 - i(73.3 \pm 0.5)$ | $782 \pm 10.9 - i(65.6 \pm 4.7)$ | |
| $\rho(1250)$ | | $1249.9 \pm 19.9 - i(152 \pm 14.3)$ | $1249 \pm 16.9 - i(146.2 \pm 14.4)$ |
| $\rho(1600)$ | | $1585 \pm 15.3 - i(130.5 \pm 22.5)$ | $1578 \pm 8.8 - i(72.2 \pm 12.5)$ |
| | Four resonances | | |
| | II | III | IV |
| $\rho(770)$ | $766.5 \pm 0.6 - i(73.2 \pm 0.5)$ | $783.1 \pm 10.6 - i(66.2 \pm 4.9)$ | |
| $\rho(1250)$ | | $1251.4 \pm 18.8 - i(152.1 \pm 14.2)$ | $1249 \pm 16.3 - i(144.3 \pm 13.9)$ |
| $\rho(1600)$ | | $1585.2 \pm 18.2 - i(141.8 \pm 22.3)$ | $1579.6 \pm 8.1 - i(73.6 \pm 10.3)$ |
| $\rho(1900)$ | | $1871.5 \pm 30.5 - i(97.2 \pm 30.1)$ | $1894 \pm 33.6 - i(95.3 \pm 32)$ |
| | Five resonances | | |
| | II | III | IV |
| $\rho(770)$ | $765.8 \pm 0.6 - i(73.3 \pm 0.4)$ | $778.2 \pm 9.1 - i(68.9 \pm 3.9)$ | |
| $\rho(1250)$ | | $1251.4 \pm 11.3 - i(130.9 \pm 9.1)$ | $1251 \pm 11.1 - i(130.5 \pm 9.2)$ |
| $\rho(1470)$ | | $1469.4 \pm 10.6 - i(91 \pm 12.9)$ | $1465.4 \pm 12.1 - i(99.8 \pm 15.6)$ |
| $\rho(1600)$ | | $1634 \pm 20.1 - i(144.7 \pm 23.8)$ | $1592.9 \pm 7.9 - i(73.7 \pm 11.7)$ |
| $\rho(1900)$ | | $1882.8 \pm 24.8 - i(112.4 \pm 25.2)$ | $1893 \pm 21.9 - i(93.4 \pm 19.9)$ |

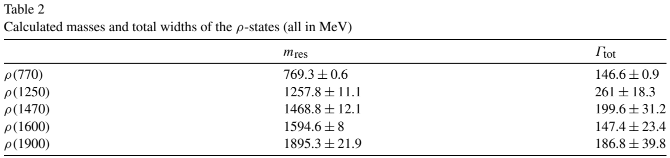


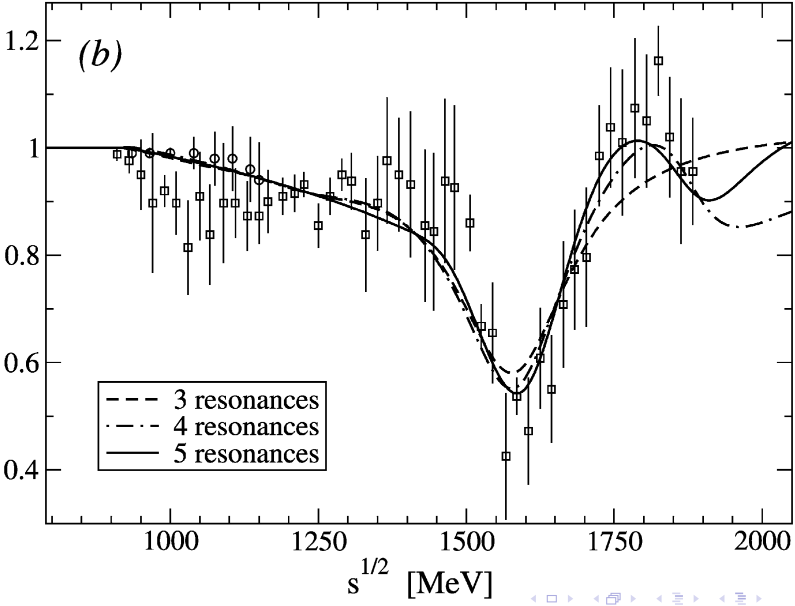
Table 2

Calculated masses and total widths of the $\rho$-states (all in MeV)

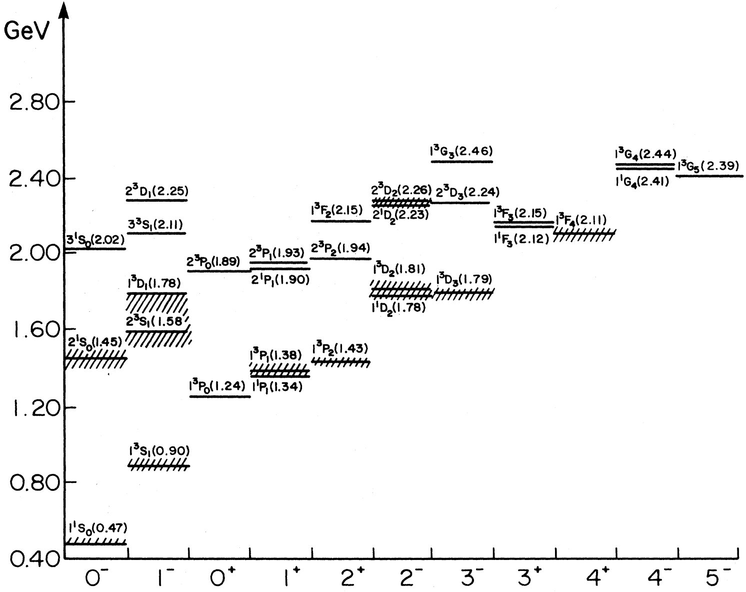
| | $m_{\text{res}}$ | $\Gamma_{\text{tot}}$ |
|---|---|---|
| $\rho(770)$ | $769.3 \pm 0.6$ | $146.6 \pm 0.9$ |
| $\rho(1250)$ | $1257.8 \pm 11.1$ | $261 \pm 18.3$ |
| $\rho(1470)$ | $1468.8 \pm 12.1$ | $199.6 \pm 31.2$ |
| $\rho(1600)$ | $1594.6 \pm 8$ | $147.4 \pm 23.4$ |
| $\rho(1900)$ | $1895.3 \pm 21.9$ | $186.8 \pm 39.8$ |

S. Surovtsev, P. Bydzovsky, Nucl. Phys. A **807** (2008) 145

$\pi\pi$-$\omega\pi$ inelasticity $\eta$:



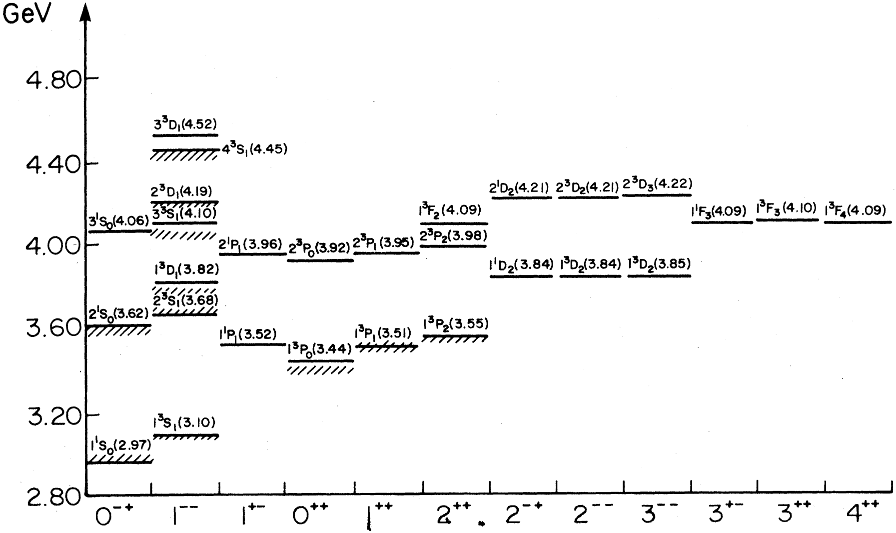
# GI model, strange mesons:



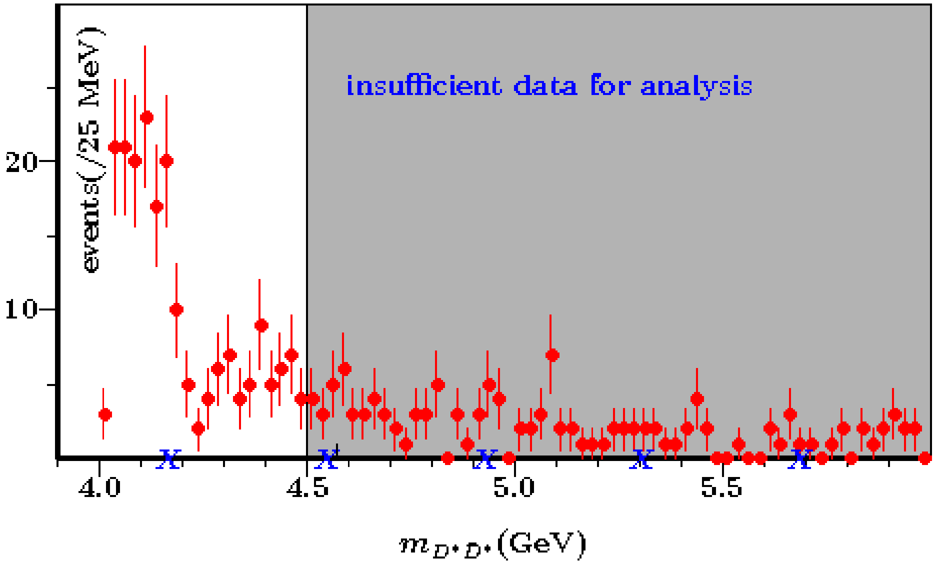
## Principal problems:

- $0^-/{}^1S_0$: PDG: $K(1460)$, $K(1830)$.
  GI: $K(1450)$ $(2\,{}^1S_0)$, $K(2020$ $(3\,{}^1S_0)$.
- $0^+/{}^3P_0$: PDG: $K_0^*(800)$, $K_0^*(1430)$, $K_0^*(1950)$. .
  GI: $K_0^*(1240)$ $(1\,{}^3P_1)$, $K_0^*(1890)$ $(2\,{}^3P_1)$
- $1^-/{}^3S_1$-${}^3D_1$: PDG: $K^*(1410)$, $K^*(1680)$.
  GI: $K^*(1580)$ $(2\,{}^3S_1)$, $K^*(1780)$ $(1\,{}^3D_1)$.
- $1^+/{}^3P_1$-${}^1P_1$: PDG: $K_1(1270)$, $K_1(1400)$, $K_1(1650)$.
  GI: $K_1(1340)$ $(1\,{}^1P_1)$, $K_1(1380)$ $(1\,{}^3P_1)$, $K_1(1900)$ $(2\,{}^1P_1)$, $K_1(1930)$ $(2\,{}^3P_1)$.
- $2^-/{}^1D_2$-${}^3D_2$: PDG: $K_2(1580)$, $K_2(1770)$, $K_2(1820)$, $K_2(2250)$.
  GI: $K_2(1780)$ $(1\,{}^1D_2)$, $K_2(1810)$ $(1\,{}^3D_2)$, $K_2(2230)$ $(2\,{}^1D_2)$, $K_2(2260)$ $(2\,{}^3D_2)$.

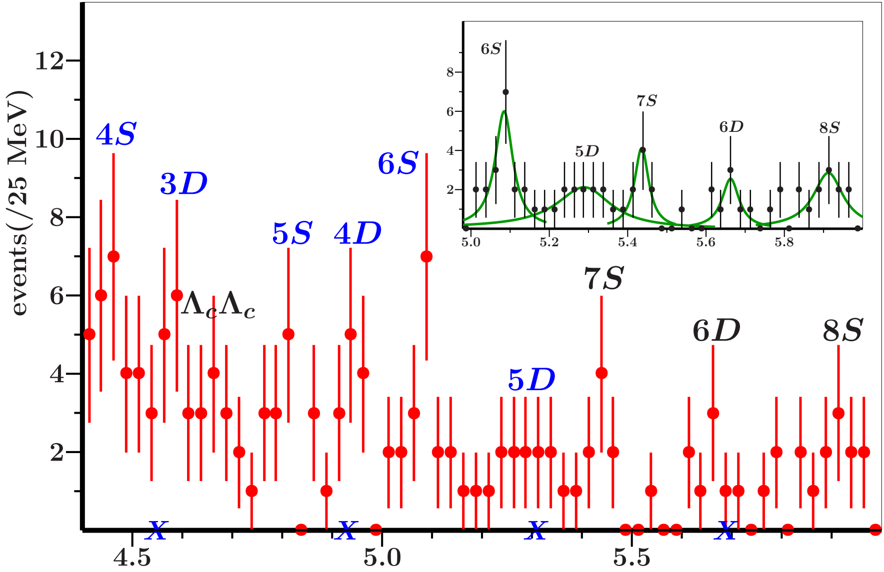
# GI model, charmonia:



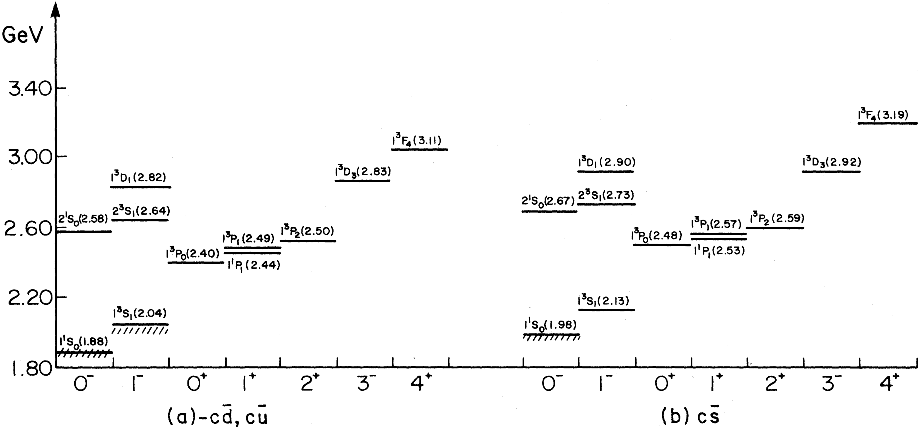
# 2009 $D^*\bar{D}^*$ BABAR data on vector charmonium:



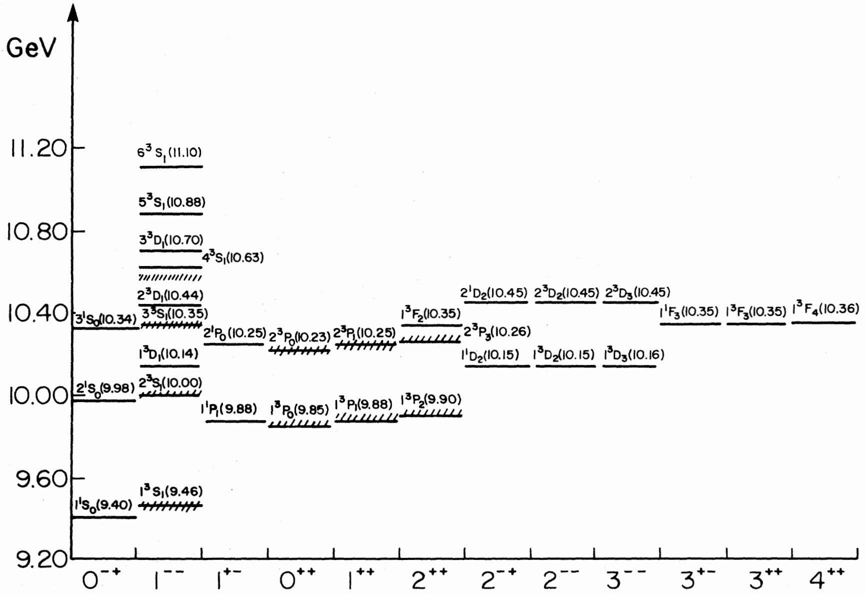
Our interpretation (EvB & GR, Chin. Phys. C **35** (2011) 1):



# GI model, charmed mesons:



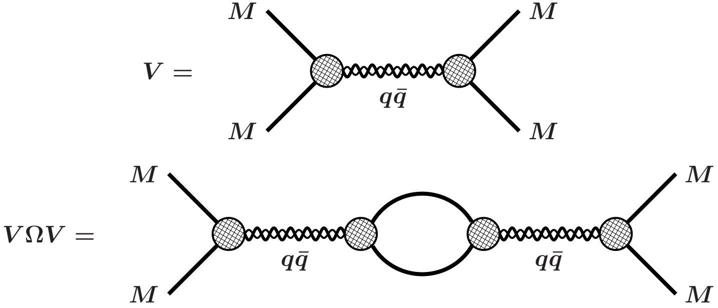
# GI model, bottomonia:



# III. Resonance-Spectrum Expansion

(EvB & GR, Annals Phys. **324** (2009) 1620)

⇒ Building blocks of (non-exotic) RSE are:



- $V$ is the effective two-meson potential;
- $\Omega$ is the two-meson loop function;
- the blobs are the ${}^3P_0$ vertex functions, modelled by a spherical $\delta$ shell in $r$ space, i.e., a spherical Bessel function in $p$ 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:

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

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

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

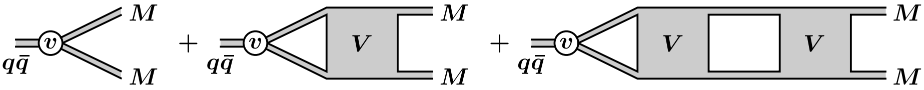
$$-2\lambda^2 r_0 \sqrt{\mu_i p_i \mu'_j p'_j}\, j^i_{L_i}(p_i r_0) \sum_{m=1}^{N} \mathcal{R}_{im}(E) \left\{[\mathbb{1} - \Omega\,\mathcal{R}]^{-1}\right\}_{mj} j^j_{L_j}(p'_j r_0)\ ,$$

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

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

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

# Production amplitudes (EvB & GR, Annals Phys. **323** (2008) 1215):



$$a(\alpha \to i) = \frac{\lambda}{\sqrt{\pi}} \sum_{\ell,m} (-i)^{\ell} j_{\ell}(p_i r_0) Y_m^{(\ell)}(\hat{p}_i) Q_{\ell_{q\bar{q}}}^{(\alpha)}(E)$$

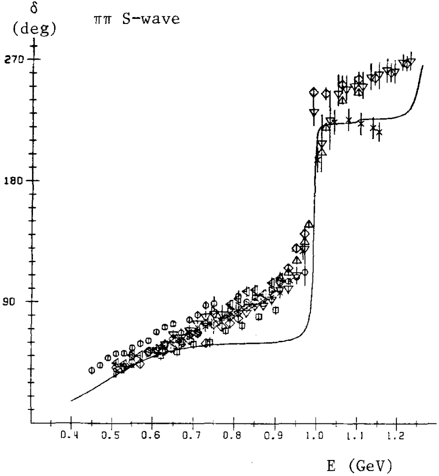
$$\times \left\{ \frac{g_{\alpha i}}{\mathcal{D}^{(\ell)}} + i \sum_{\nu \neq i} \mu_\nu p_\nu h_\ell^{(1)}(p_\nu r_0) \left[ g_{\alpha i} \frac{t_\ell(\nu \to \nu)}{j_\ell(p_\nu r_0)} - g_{\alpha \nu} \frac{t_\ell(i \to \nu)}{j_\ell(p_i r_0)} \right] \right\}$$

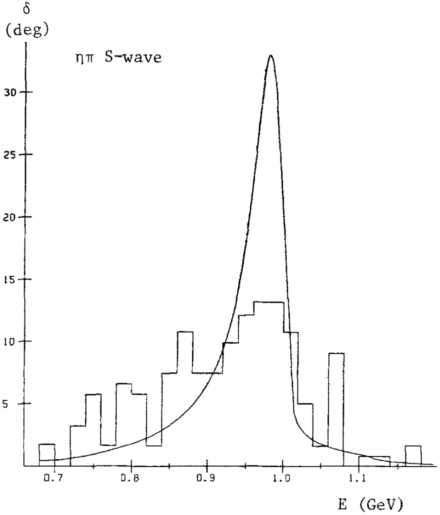
$$\mathcal{D}^{(\ell)}(E) = 1 + 2i\lambda^2 \sum_{\nu} g_\nu^2 \left\{ \sum_{n=0}^{\infty} \frac{\left| F_{c\bar{c}}^{(n)}(r_0) \right|^2}{E - E_n} \right\} \mu_\nu p_\nu j_\ell(p_\nu r_0) h_\ell^{(1)}(p_\nu r_0)$$

## IV. Selected Results

### 1) Light scalar mesons (EvB, GR, *et al.*, Z. Phys. C **30** (1986) 615)

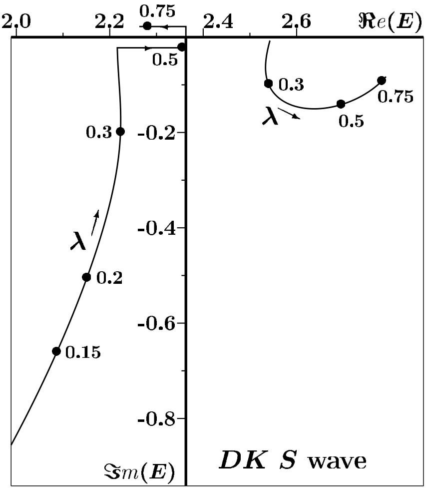
$f_0(470 - i208)$, $K_0^*(727 - i263)$, $a_0(968 - i28)$, $f_0(994 - i20)$

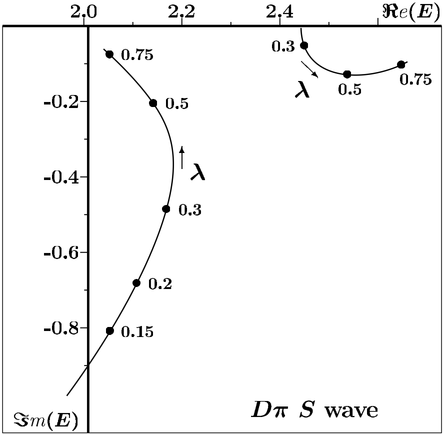




## 2) Scalar charmed mesons $D_{s0}^*(2317)$ , $D_0^*(2300)$

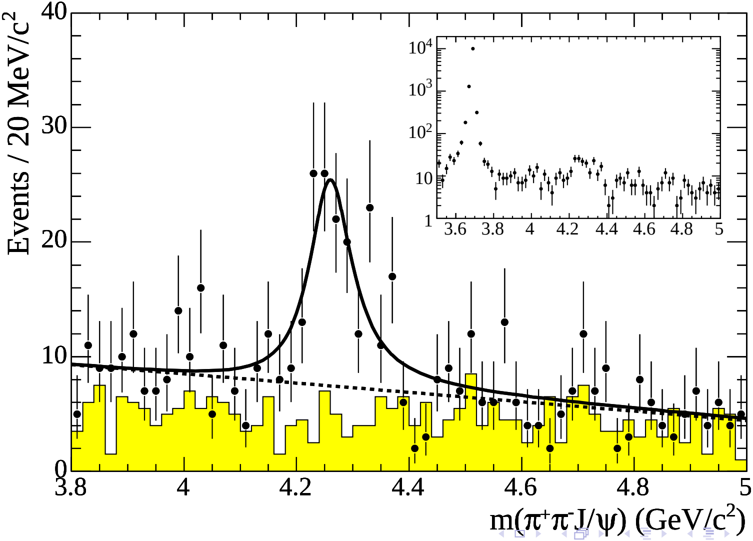
(EvB & GR, Phys. Rev. Lett. **91** (2003) 012003)





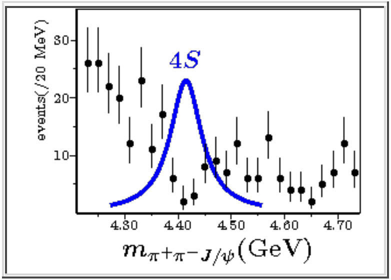
## 3) *X*(4260), EvB & GR, Phys. Rev. Lett. **105** (2010) 102001

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



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

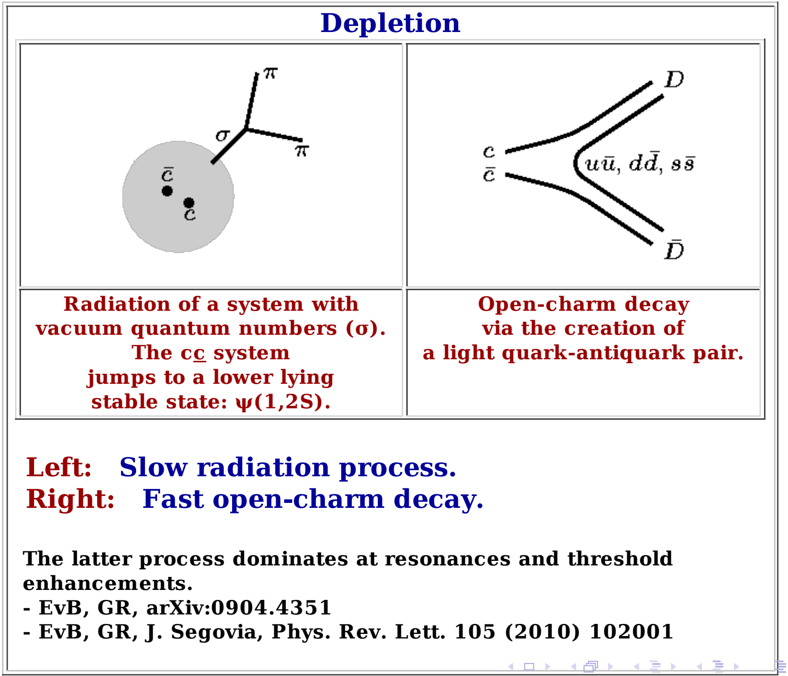
# X(4260)



**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/depletion.htm



## Depletion

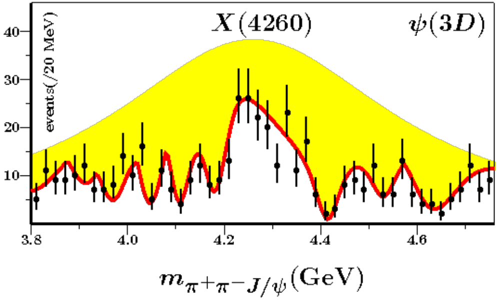
| | |
|---|---|
| **Radiation of a system with vacuum quantum numbers (σ). The c$\underline{c}$ system jumps to a lower lying stable state: ψ(1,2S).** | **Open-charm decay via the creation of a light quark-antiquark pair.** |

**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/octopsi.htm

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



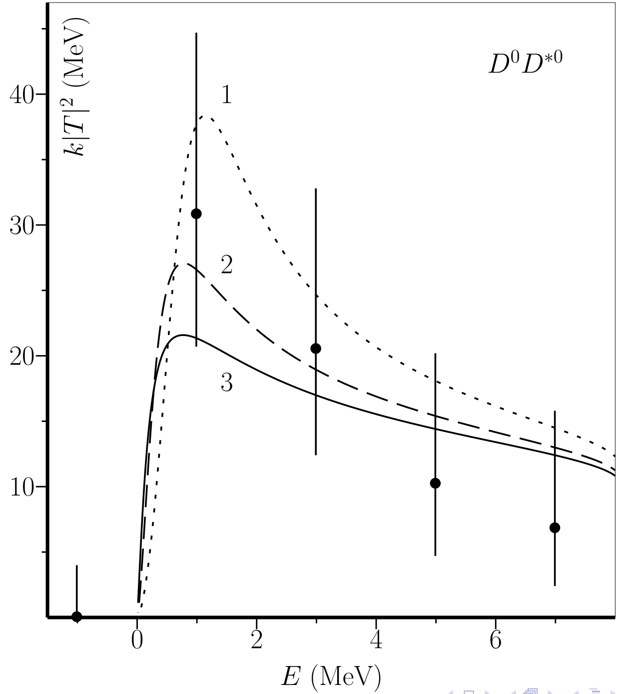
**By threshold enhancements:**
**DD, DD*, $D_sD_s$, D*D*, $D_sD_s$*, $D_s$*$D_s$*, $\Lambda_c\Lambda_c$.**
**By $c\bar{c}$ resonances: ψ(3S), ψ(2D), ψ(4S), ψ(3D).**

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

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

⇒ SC, GR, EvB, Eur. Phys. J. C **71** (2011) 1762

- In RSE, bare $2\,^3P_1$ $c\bar{c}$ state lies at 3979 MeV;
- Couple it to $D^0D^{*0}$ 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 $\omega$ and $\rho$ widths, by taking complex $\omega$ and $\rho$ masses and reunitarising the $S$-matrix (see paper in EPJC);
- $D^0D^{*0}$ 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 $D^0D^{*0}$ 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 $D^0D^{*0}$ at $\approx 3874$ MeV appear naturally, with no need for an additional state.



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

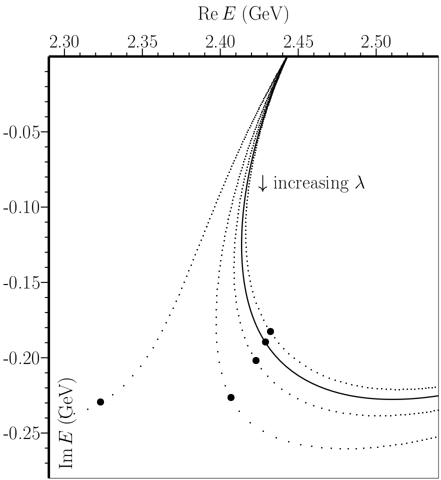
## 5) $D_1(2420)$, $D_1(2430)$, $D_{s1}(2536)$, $D_{s1}(2460)$

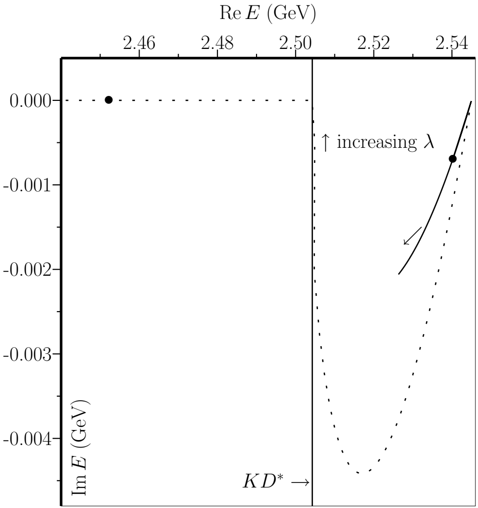
$\Rightarrow$ SC, GR, EvB, Phys. Rev. D **84** (2011) 094020

- $D_1(2420)$ 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 ($\sim 384$ 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.

Left: *D*$_1$(2430) pole trajectories. Right: *D*$_{s1}$(2460) and *D*$_{s1}$(2536).

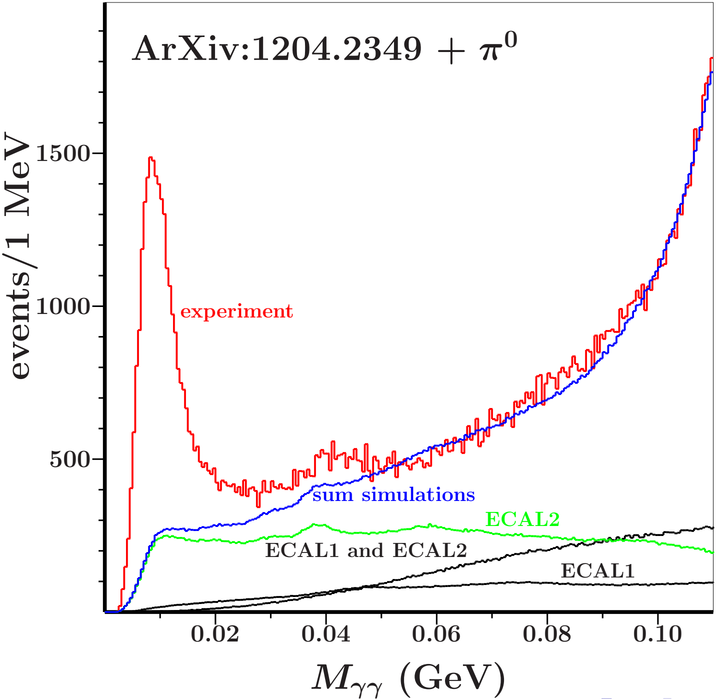




## V. Conclusions

⇒ Meson spectroscopy is in a globally bad shape:

- Many states predicted by the quark model are missing, especially in the charmed, bottom, charmonium, and bottomonium sectors.
- In the light-quark sector, there are very serious discrepancies between several excited states and the Godfrey-Isgur model.
- Other funnel-type models will hardly do much better there.
- As nearly all resonances below 2 GeV are inelastic, there is little hope that lattice QCD will come to rescue in the near future.
- A model with harmonic confinement and flavour-independent spacings of $\approx 380$ *MeV* appears to be favoured below 2 GeV.
- When unquenched, such a model also works for charmonium, bottomonium, and charmed mesons, besides automatically generating the light scalar mesons.
- Dedicated spectroscopy experiments are needed in the 1–2 GeV region, with reliable partial-wave analyses, and no PDG bias. COMPASS might play a significant role here.


ArXiv:1204.2349 + $\pi^0$
events/1 MeV
1500
1000
500
experiment
sum simulations
ECAL2
ECAL1 and ECAL2
ECAL1
0.02
0.04
0.06
0.08
0.10
$M_{\gamma\gamma}$ (GeV)