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Meson spectroscopy: too much excitement and too few excitations

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I. Introduction

II. Status of mainstream meson spectroscopy

III. Resonance-Spectrum Expansion

IV. Selected Results

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I. Introduction

⇒ Myth to be busted in meson spectroscopy: *“there are too many resonances to be accounted for by normal $q\bar{q}$ states.”* Reasons:

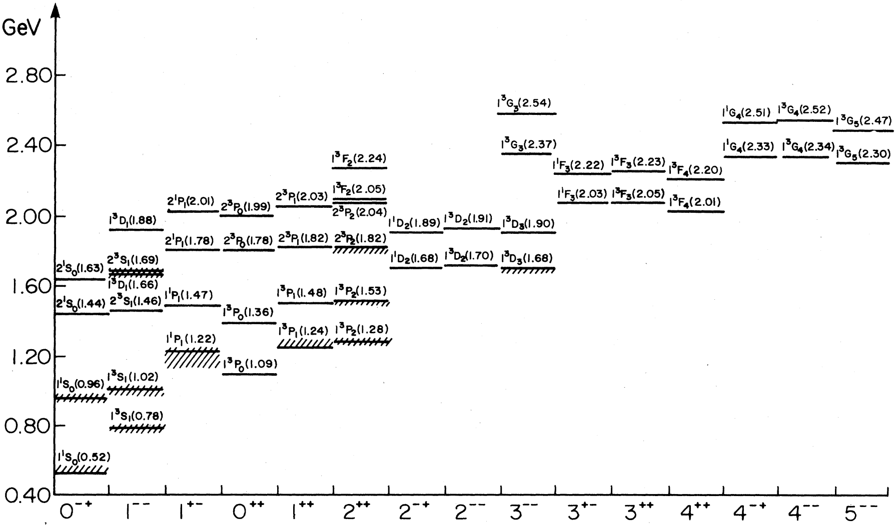
- Quenched quark-model predictions with standard Coulomb-plus-linear confinement are taken for granted, despite serious failures.
- Often biased PDG interpretation and selection of experimental results are usually mistaken for the true status of meson resonances.
- Statistically significant bumps in the data are almost invariably interpreted as resonances, without even considering possible threshold effects or inelasticity phenomena 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”).
- When meson loops are included, their effect is in general strongly underestimated by ignoring the Coulombic part of the potential.
- Dynamical $q\bar{q}$ resonances from unquenching are not considered.

II. Status of mainstream meson spectroscopy

⇒ Reference (quenched) quark model (1716 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:



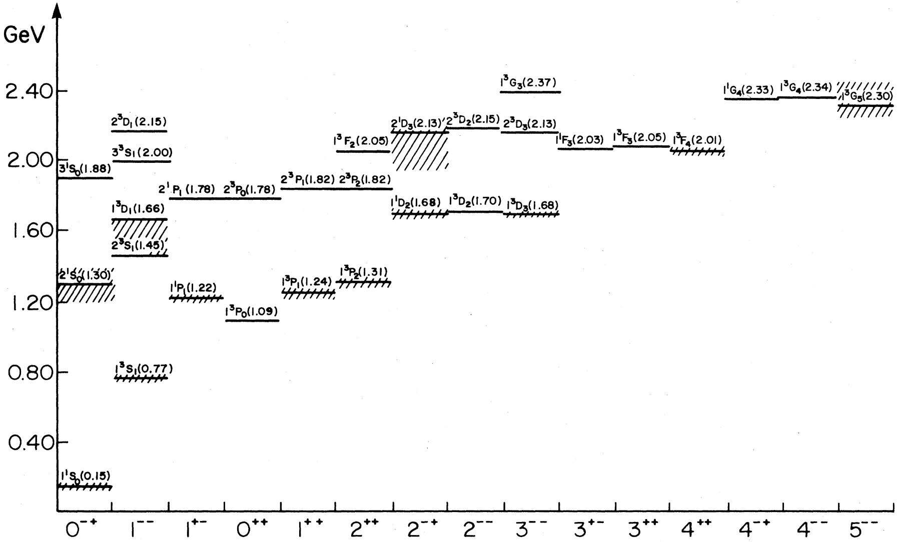
Principal problems:

- $0^{++}/{}^3P_0$: 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 ≈ 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 ≈ 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: $a_1(1260)$, $a_1(1640)$.
  GI: $a_1(1240)$ $(1\,{}^3P_1)$, $a_1(1820)$ $(2\,{}^3P_1)$.
- $2^{++}/{}^3P_2$: PDG: $a_2(1320)$, $a_2(1700)$.
  GI: $a_2(1310)$ $(1\,{}^3P_2)$, $a_2(1820)$ $(2\,{}^3P_2)$.
- $1^{--}/{}^3S_1$-${}^3D_1$: 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

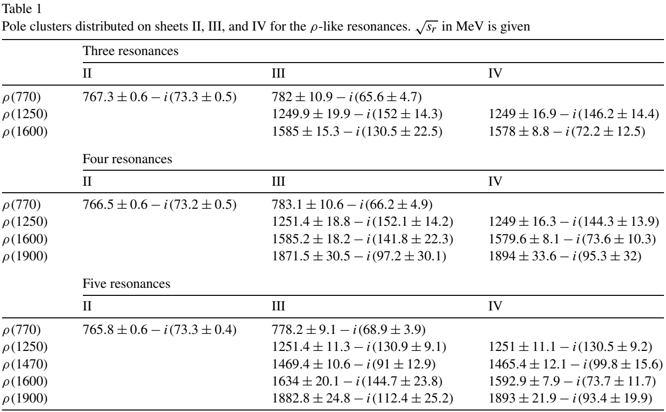


Table 1
Pole clusters distributed on sheets II, III, and IV for the ρ-like resonances. $\sqrt{s_r}$ in MeV is given

	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
$\rho(770)$	$765.8 \pm 0.6 - i(73.3 \pm 0.4)$	$778.2 \pm 9.1 - i(68.9 \pm 3.9)$	
$\rho(1250)$		$1251.4 \pm 11.3 - i(130.9 \pm 9.1)$	$1251 \pm 11.1 - i(130.5 \pm 9.2)$
$\rho(1470)$		$1469.4 \pm 10.6 - i(91 \pm 12.9)$	$1465.4 \pm 12.1 - i(99.8 \pm 15.6)$
$\rho(1600)$		$1634 \pm 20.1 - i(144.7 \pm 23.8)$	$1592.9 \pm 7.9 - i(73.7 \pm 11.7)$
$\rho(1900)$		$1882.8 \pm 24.8 - i(112.4 \pm 25.2)$	$1893 \pm 21.9 - i(93.4 \pm 19.9)$

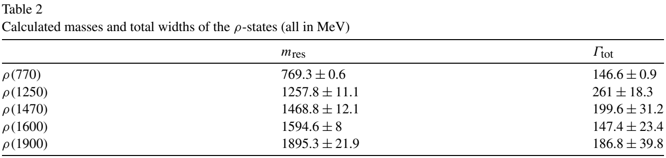
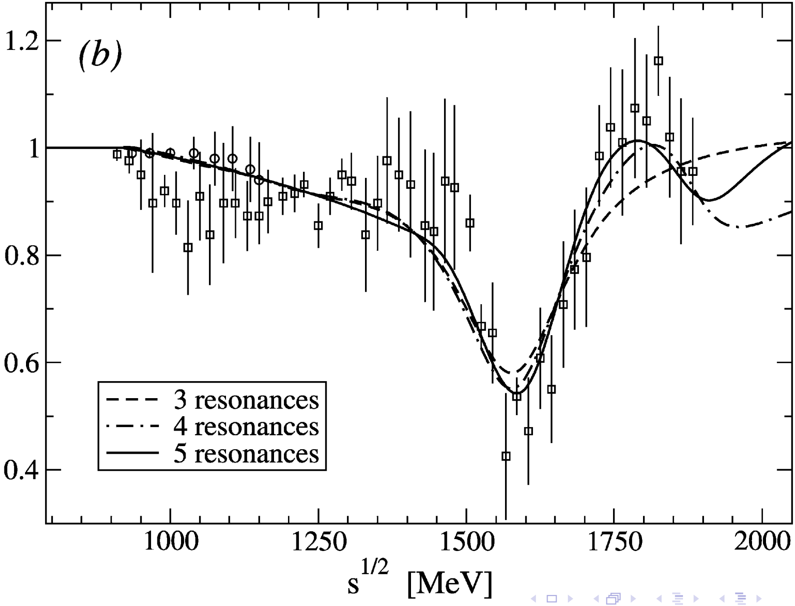


Table 2
Calculated masses and total widths of the ρ-states (all in MeV)

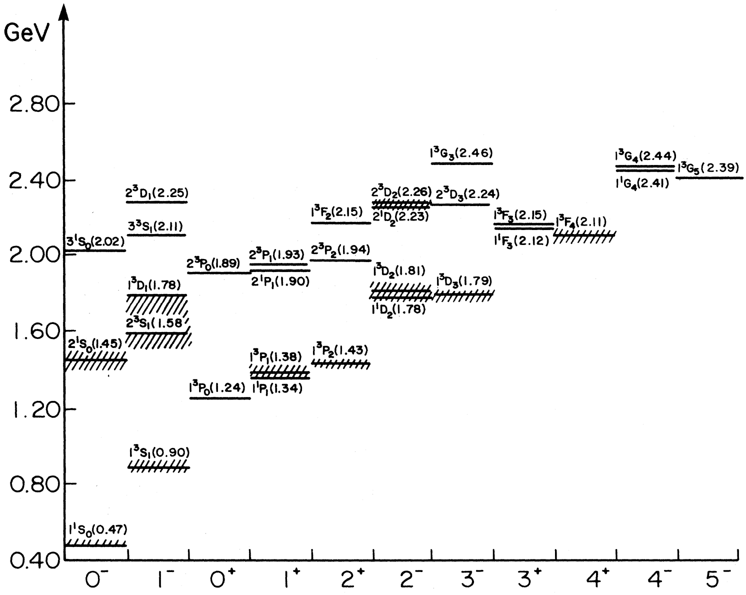
	m_{res}	Γ_{tot}
$\rho(770)$	769.3 ± 0.6	146.6 ± 0.9
$\rho(1250)$	1257.8 ± 11.1	261 ± 18.3
$\rho(1470)$	1468.8 ± 12.1	199.6 ± 31.2
$\rho(1600)$	1594.6 ± 8	147.4 ± 23.4
$\rho(1900)$	1895.3 ± 21.9	186.8 ± 39.8

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

$\pi\pi$-$\omega\pi$ inelasticity η:



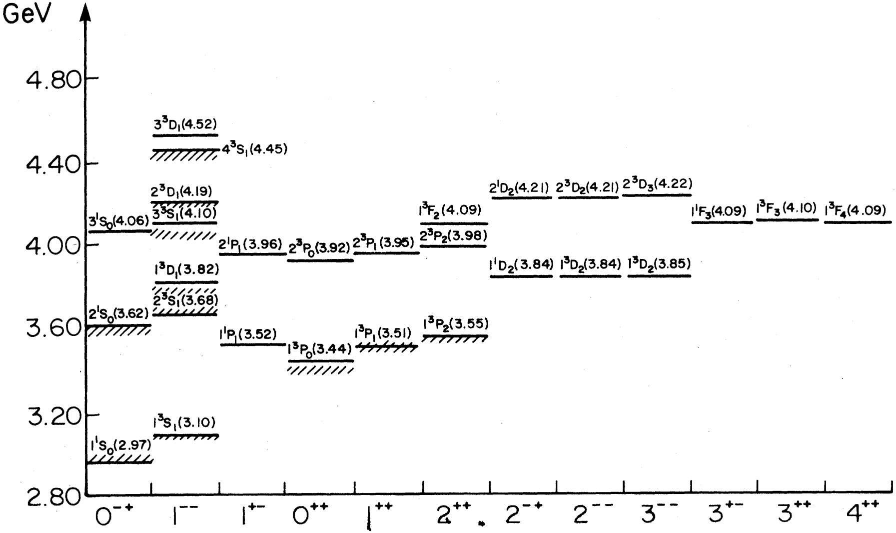
GI model, strange mesons:



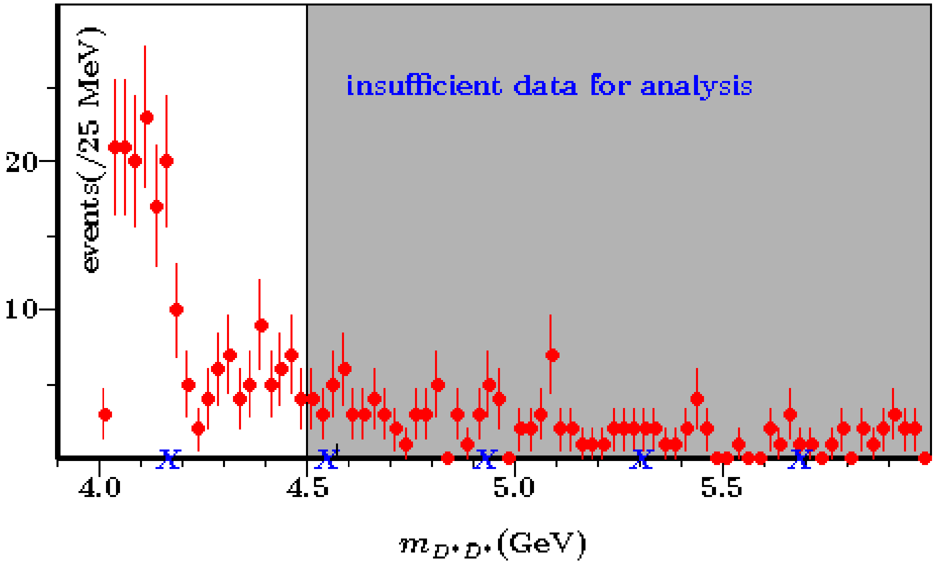
Principal problems:

- $0^-/{}^1S_0$: 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: $K_2(1780)$ $(1\,{}^1D_2)$, $K_2(1810)$ $(1\,{}^3D_2)$, $K_2(2230)$ $(2\,{}^1D_2)$, $K_2(2260)$ $(2\,{}^3D_2)$.

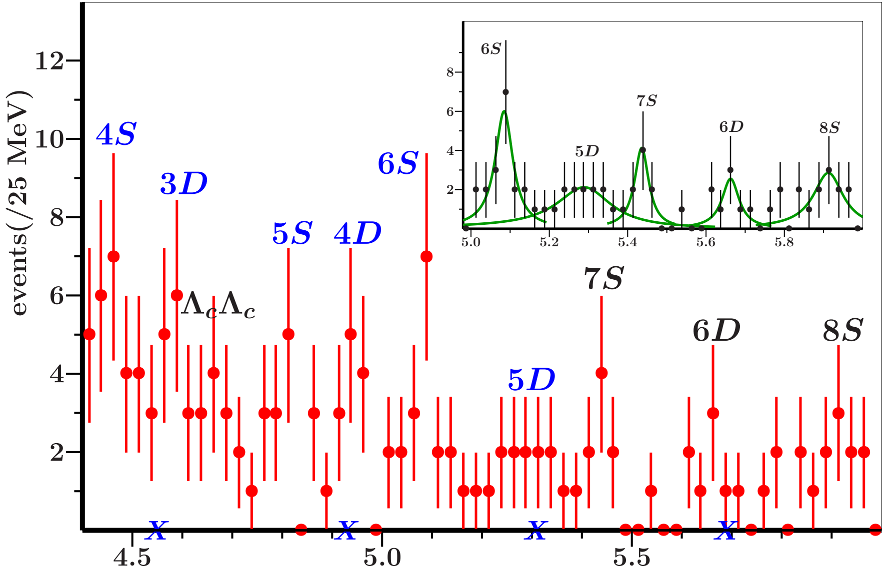
GI model, charmonia:



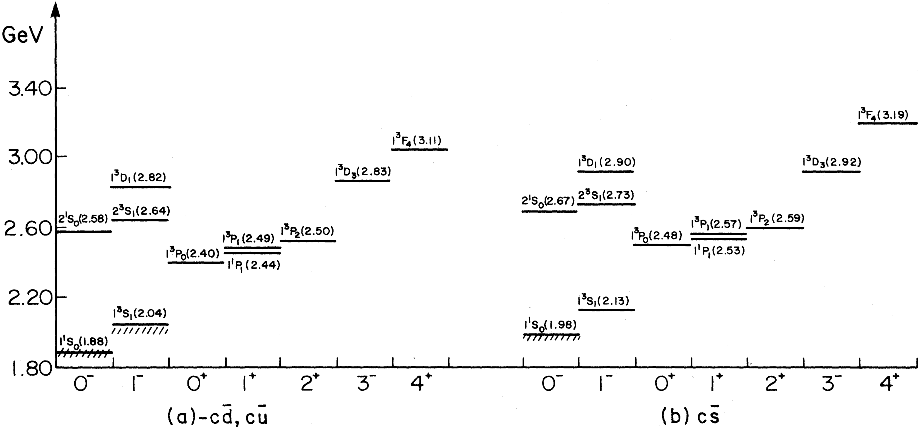
2009 $D^*\bar{D}^*$ BABAR data on vector charmonium:



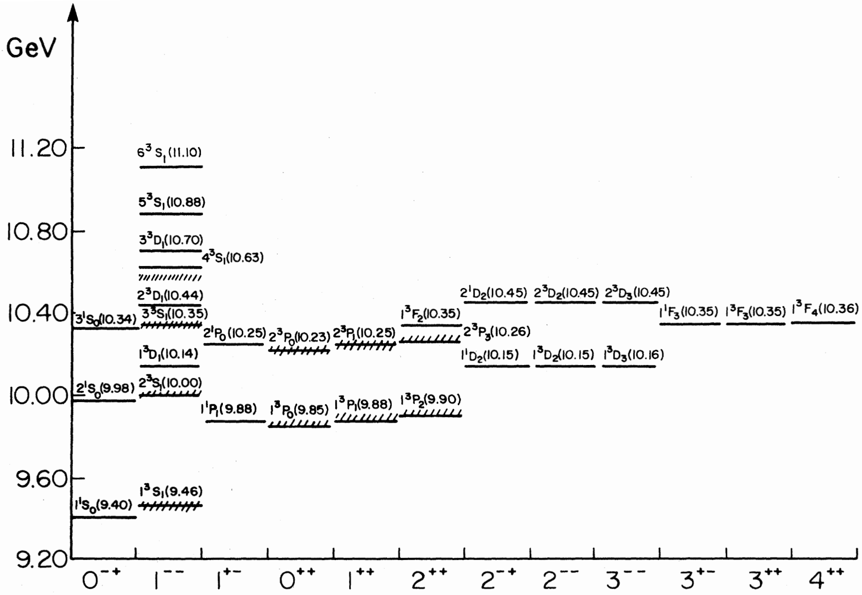
Our interpretation (EvB & GR, Chin. Phys. C **35** (2011) 1):



GI model, charmed mesons:

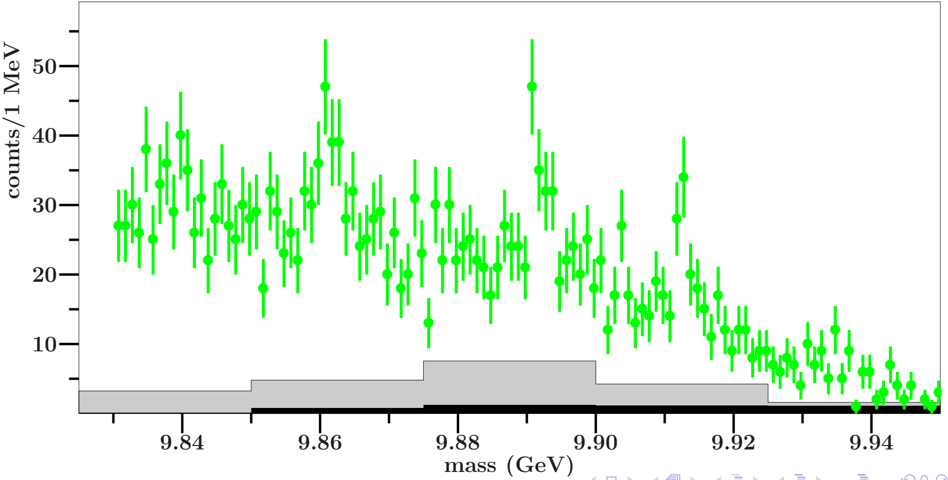


GI model, bottomonia:



“Progress” in $b\bar{b}$ spectroscopy (see EvB, GR, arXiv:1204.1984 [hep-ph]):

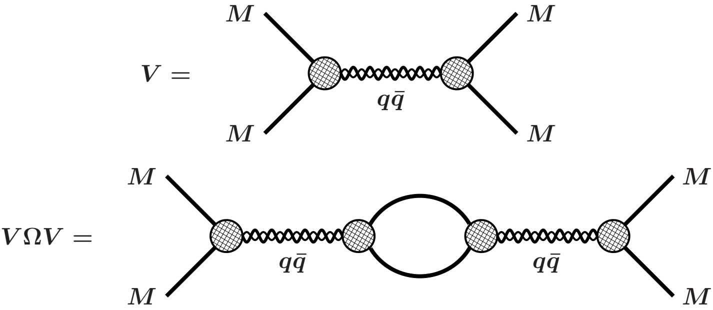
- Green points and error bars: ARGUS data on $\chi_B(1P)$ states (Phys. Lett. B **160** (1985) 331);
- Grey areas: corresponding ATLAS/LHC data (Phys. Rev. Lett. **108** (2012) 152001).



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;
- Ω is the two-meson loop function;
- the blobs are the $^3P_0$ vertex functions, modelled by a spherical δ 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

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

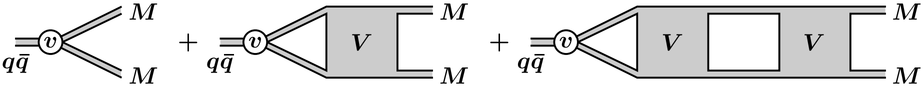
$$-2\lambda^2 r_0 \sqrt{\mu_i p_i \mu'_j p'_j}\, j^i_{L_i}(p_i r_0) \sum_{m=1}^{N} \mathcal{R}_{im}(E)\ \left\{\left[\mathbb{1} - \Omega\,\mathcal{R}\right]^{-1}\right\}_{mj}\ j^j_{L_j}(p'_j r_0)\ ,$$

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

⇒ 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):



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

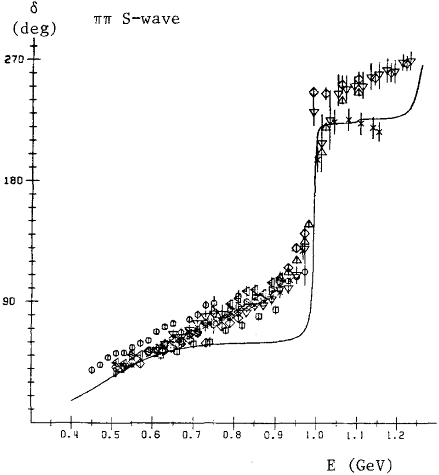
$$\times \left\{ \frac{g_{\alpha i}}{\mathcal{D}^{(\ell)}} + i \sum_{v \neq i} \mu_v p_v h_{\ell}^{(1)}(p_v r_0) \left[g_{\alpha i} \frac{t_{\ell}(v \to v)}{j_{\ell}(p_v r_0)} - g_{\alpha v} \frac{t_{\ell}(i \to v)}{j_{\ell}(p_i r_0)} \right] \right\}$$

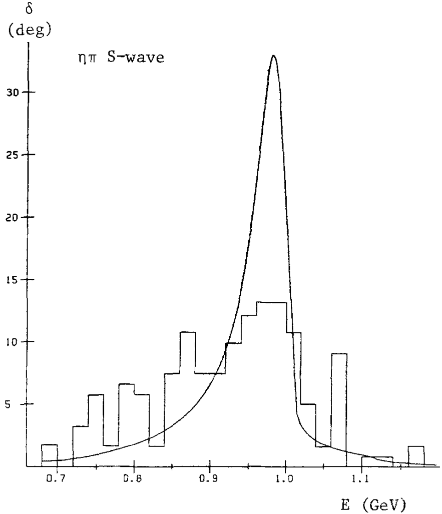
$$\mathcal{D}^{(\ell)}(E) = 1 + 2i\lambda^2 \sum_{v} g_v^2 \left\{ \sum_{n=0}^{\infty} \frac{\left| F_{c\bar{c}}^{(n)}(r_0) \right|^2}{E - E_n} \right\} \mu_v p_v j_{\ell}(p_v r_0) h_{\ell}^{(1)}(p_v r_0)$$

IV. Selected Results

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

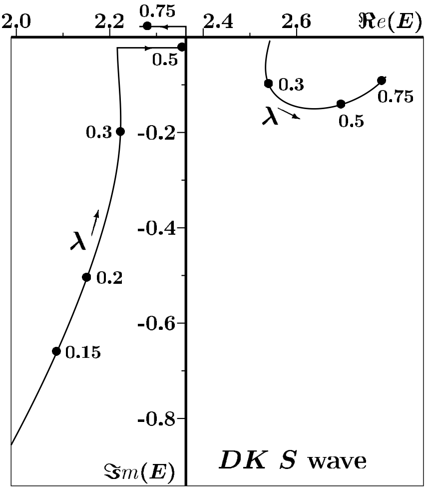
$f_0(470 - i208)$, $K_0^*(727 - i263)$, $a_0(968 - i28)$, $f_0(994 - i20)$

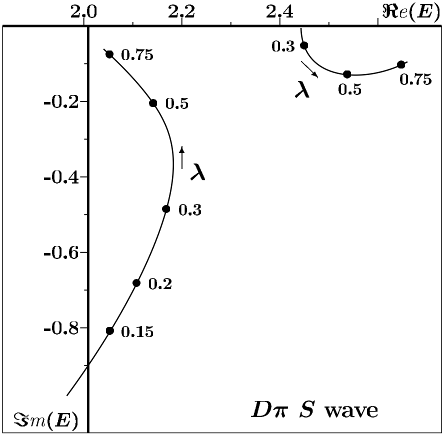




2) Scalar charmed mesons $D_{s0}^*(2317)$, $D_0^*(2300)$

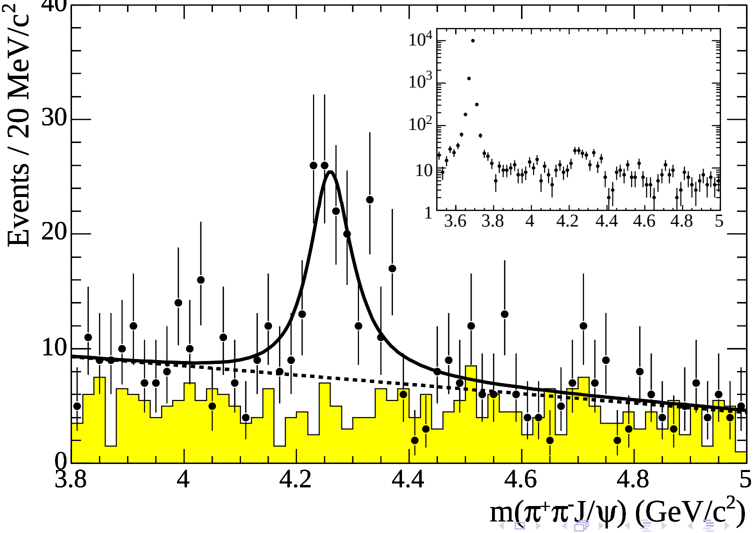
(EvB & GR, Phys. Rev. Lett. **91** (2003) 012003)





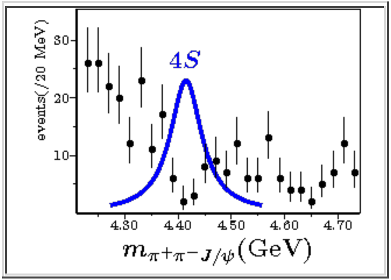
3) $X(4260)$, EvB & GR, Phys. Rev. Lett. **105** (2010) 102001

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



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

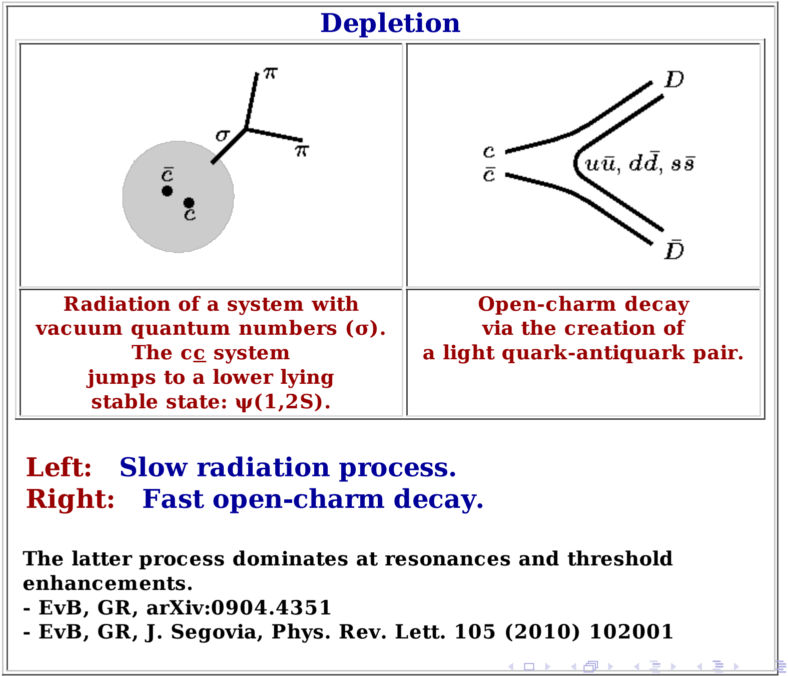
X(4260)



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

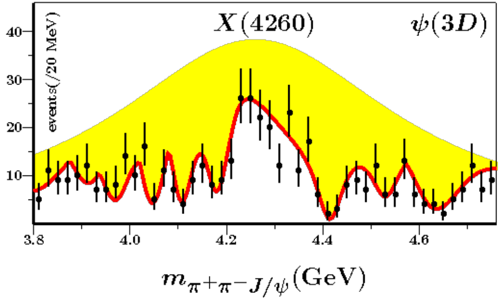
Radiation of a system with vacuum quantum numbers (σ). The $c\underline{c}$ system jumps to a lower lying stable state: $\psi(1,2S)$.	Open-charm decay via the creation of a light quark-antiquark pair.

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



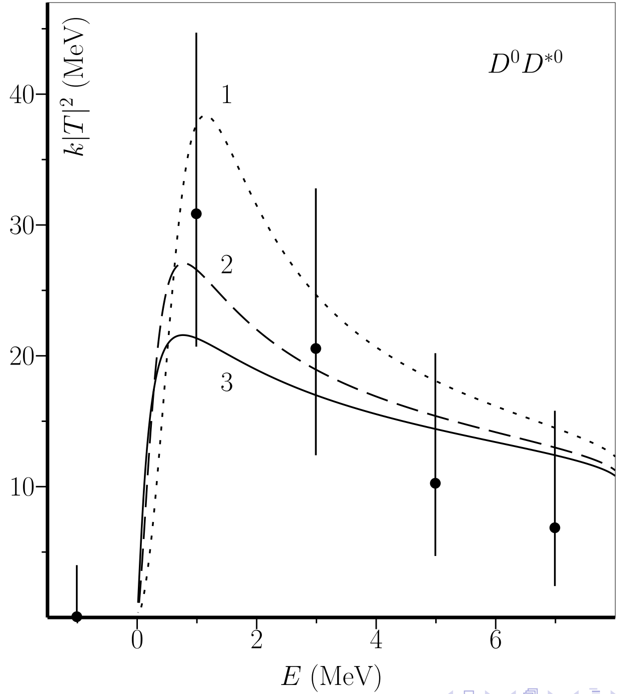
By threshold enhancements:
DD, DD*, D_sD_s, D*D*, D_sD_s*, D_s*D_s*, $\Lambda_c\Lambda_c$.
By c$\underline{c}$ resonances: ψ(3S), ψ(2D), ψ(4S), ψ(3D).

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

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 ω and ρ widths, by taking complex ω and ρ 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 ≈ 3872 MeV and cusp-like structure in D^0D^{*0} at ≈ 3874 MeV appear naturally, with no need for an additional state.


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

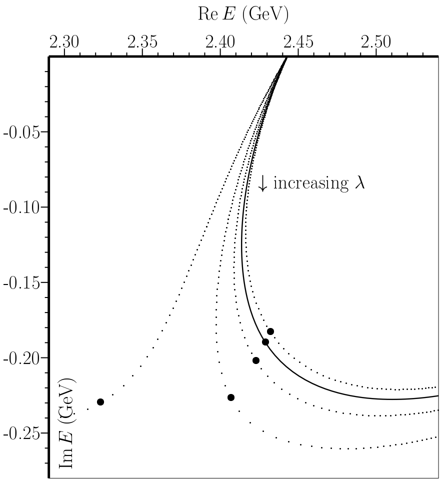
5) $D_1(2420)$, $D_1(2430)$, $D_{s1}(2536)$, $D_{s1}(2460)$

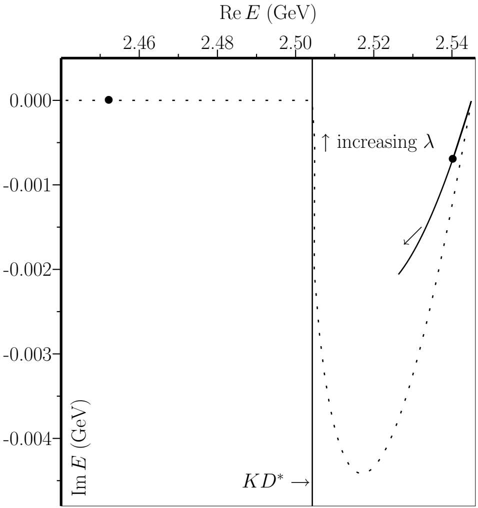
⇒ SC, GR, EvB, Phys. Rev. D **84** (2011) 094020

- $D_1(2420)$ 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 (~ 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 $D_{s1}(2536)$.





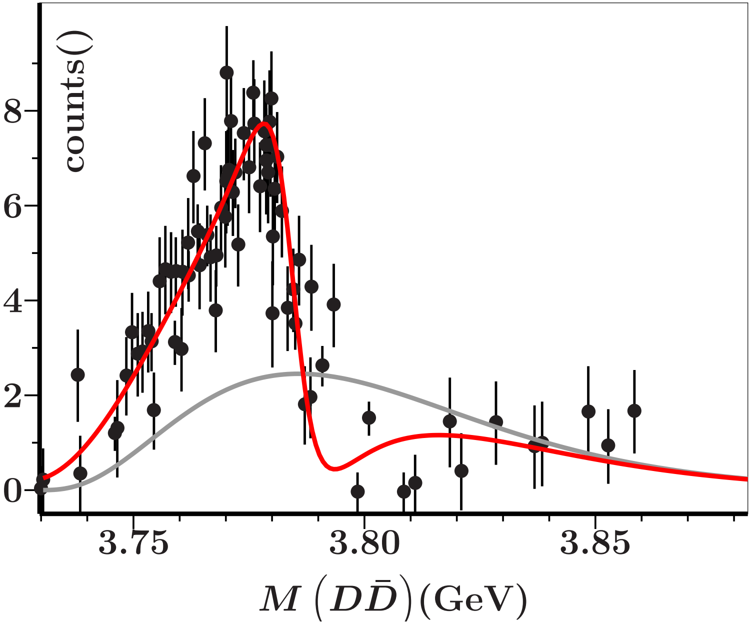
6) $\psi(3770)$

BES reported an “anomalous line shape” of the $\psi(3770)$ resonance in arXiv:0807.0494 [hep-ex]:

> *“The anomalous line-shape may be explained by two possible enhancements of the inclusive hadron production near the center-of-mass energies of 3.764 GeV and 3.779 GeV, indicating that either there is likely a new structure in addition to the* $\psi(3770)$ *resonance around 3.773 GeV, or there are some physics effects reflecting the DD production dynamics.”*

Our explanation in EvB, GR, Phys. Rev. D **80** (2009) 074001:

- Opening of $D\bar{D}$ threshold in e^+e^- produces a broad bump in the production cross section (Bessel function).
- On top of the structure there is a Breit-Wigner resonance, with $M = 3781$ MeV and $\Gamma = 17$ MeV, i.e., narrower and a little bit heavier than in the PDG tables.
- See figure on next slide.


counts()
8
6
4
2
0
3.75
3.80
3.85
$M\left(D\bar{D}\right)$(GeV)

V. Conclusions

⇒ Meson spectroscopy is in a globally bad shape:

- Many $q\bar{q}$ states predicted by the quark model are missing, especially in the charmed, bottom, $c\bar{c}$, and $b\bar{b}$ 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 the vast majority of meson resonances are inelastic, there is little hope that lattice QCD will come to rescue soon. Where Lüscher's method fails, maybe Oset's new approach is a way out.
- Dedicated spectroscopy experiments are needed in all flavour sectors, with reliable partial-wave analyses, and no PDG bias.
- Threshold and inelasticity effects should be included in experimental analyses of meson-production data. This is still in its infancy.
- Spectroscopists must unquench their models in a realistic way, before getting too excited about "exotic" discoveries.
- Modern meson spectroscopy is about poles in S-matrix and production amplitudes, and not bound states in confining potentials.