XII. INTERNATIONAL CONFERENCE ON HADRON SPECTROSCOPY

8-13
OCTOBER
2007

Laboratori Nazionali di Frascati (Rome)

Open Problems in Hadron Spectroscopy

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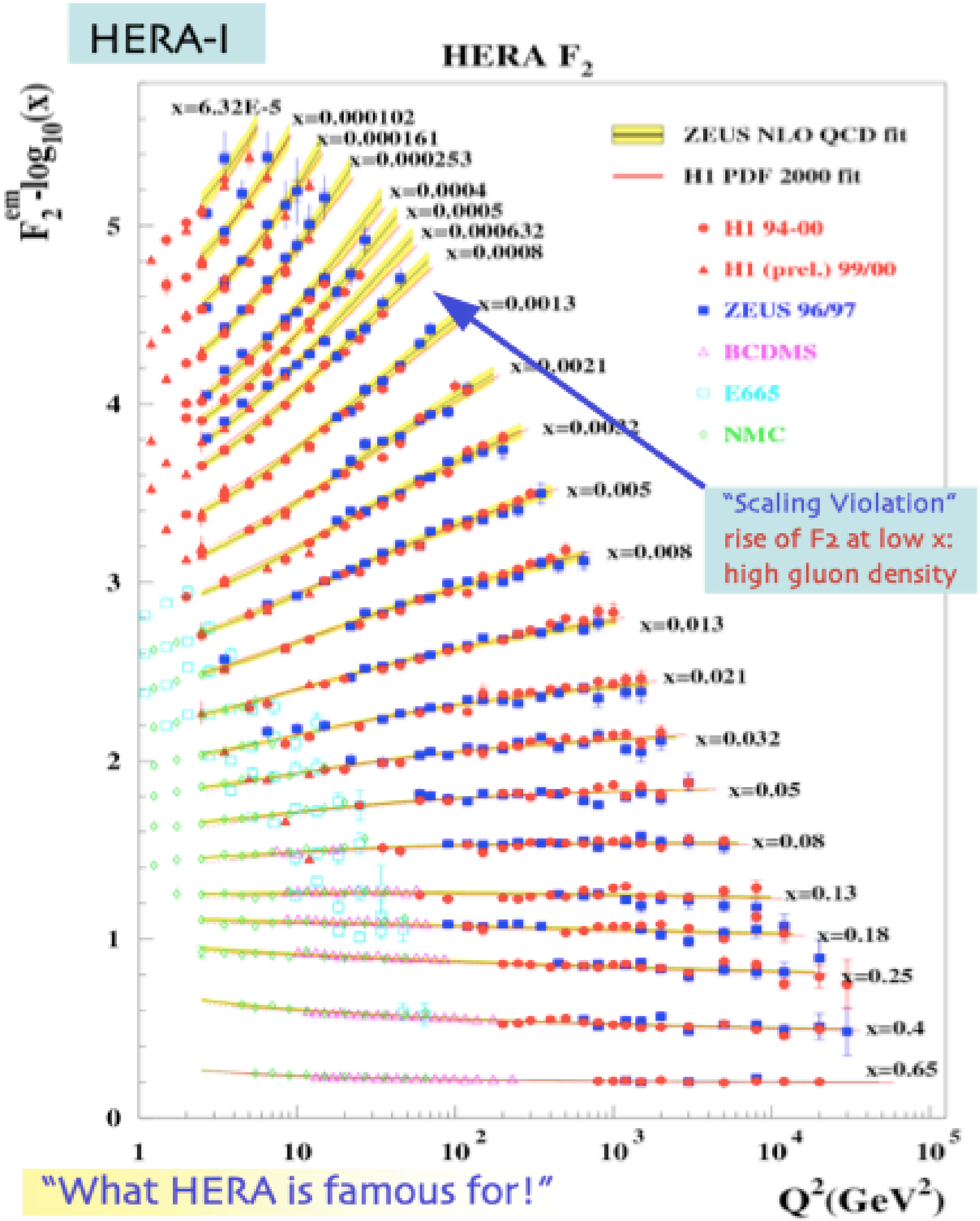
Opening Talk

October 08, 2007

Summary

1. Introduction
2. Light scalar mesons resolved
3. QCD strings
4. New Charmonium states
5. Thresholds, cusps and new states
6. Two X states ?
7. A charged charmonium ?
8. Outlook



1. Introduction

- Thirty years after its discovery, we still do not fully control QCD.
- Only in few cases, we can produce reliable theoretical predictions. Even in these cases we need to rely upon phenomenological parameters. Ab initio calculations (lattice) still have many limitations.
- Scaling violations in DIS, input: the structure function at some Q_0^2

Large quark mass makes it possible to use potential theory. Input: the parameters of the potential. Remarkable accuracy has been achieved

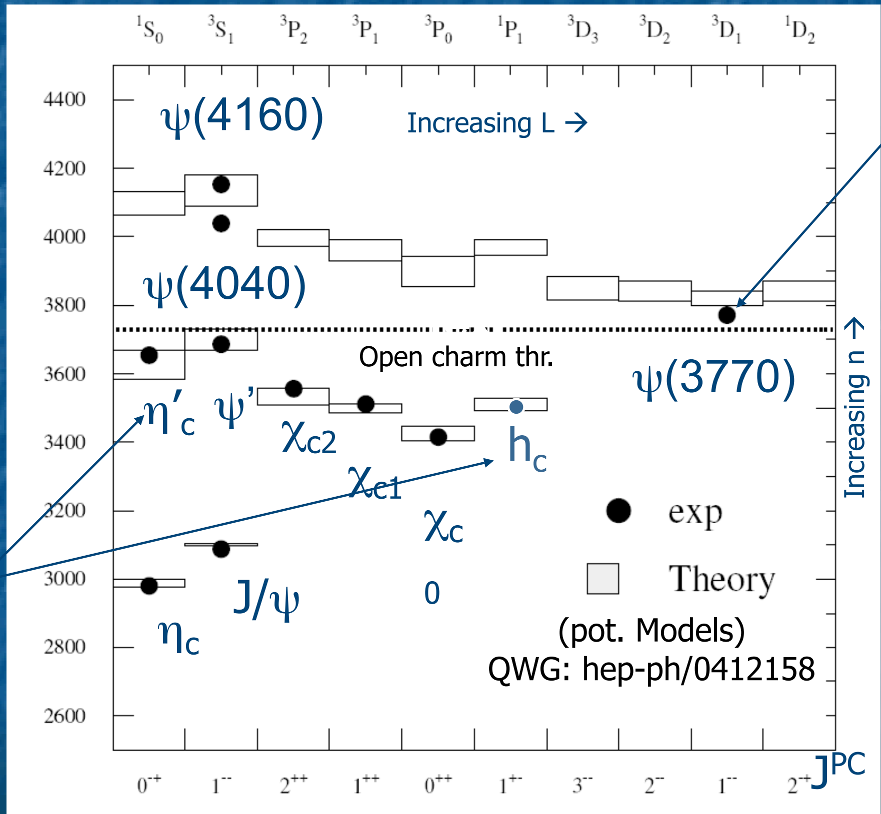
slide from
R. Faccini, LP07

Charmonium: state of the art

same J^{PC} as J/ψ but mostly D wave !

$^{(2S+1)}L_J$

M(MeV)



Recent acquisitions

Basically all states below the open charm threshold are observed and explained

The (unexplained) success of the constituent quark model

- A. Sakharov, Zeldovich
- H. Lipkin
- A. De Rujula, H. Georgi and S. Glashow

- Quark constituent masses and spin-spin interaction:

$$H = \sum_i m_i + \sum_{i<j} \kappa_{ij} \left(\sigma_i \cdot \sigma_j\right) \delta^3(\vec{r}_{ij})$$

$$\kappa_{ij} \simeq \frac{v}{m_i m_j}$$

- Hyperfine interaction explains, among other things, the Λ-Σ^0 mass difference (they have the same flavor composition) as due to the hyperfine interaction
- Baryons with one heavy and two light quarks can be described by a light diquark+the heavy quark

contribution of the hyperfine interaction energies is removed. For the two cases of spin-zero [8] $S = 0$ and spin-one $S = 1$ diquarks,

$$\begin{array}{ccccccc} M(N) - \tilde{M}(\rho) & = & M(\Lambda) - \tilde{M}(K^*) & = & M(\Lambda_c) - \tilde{M}(D^*) & = & M(\Lambda_b) - \tilde{M}(B^*) \\ 323 \text{ MeV} & \approx & 321 \text{ MeV} & \approx & 312 \text{ MeV} & \approx & 310 \text{ MeV} \end{array}$$

- M. Karliner, H. Lipkin, hep-ph/0611306v3

$$\begin{array}{ccccccc} \tilde{M}(\Delta) - \tilde{M}(\rho) & = & \tilde{M}(\Sigma) - \tilde{M}(K^*) & = & \tilde{M}(\Sigma_c) - \tilde{M}(D^*) & = & \tilde{M}(\Sigma_b) - \tilde{M}(B^*) \\ 517.56 \text{ MeV} & \approx & 526.43 \text{ MeV} & \approx & 523.95 \text{ MeV} & \approx & 512.45 \text{ MeV} \end{array}$$

Tilde= spin average= eliminates spin- spin interaction between the diquark and the “valence quark”

2. Light Scalar Mesons Resolved

Mass and width of the lowest resonance in QCD

I. Caprini
National Institute of Physics and Nuclear Engineering, Bucharest, R-077125 Romania

G. Colangelo and H. Leutwyler
Institute for Theoretical Physics, University of Bern, Sidlerstr. 5, CH-3012 Bern, Switzerland

arXiv:hep-ph/0512364v2, 7 Apr 2006

The values of the S-matrix element

$$S_0^0(s) = 1 - 2\sqrt{4\,M_\pi^2/s - 1}\;t_0^0(s) \qquad (6)$$

on the second sheet can be calculated from those on the first sheet: unitarity implies the relation [15]

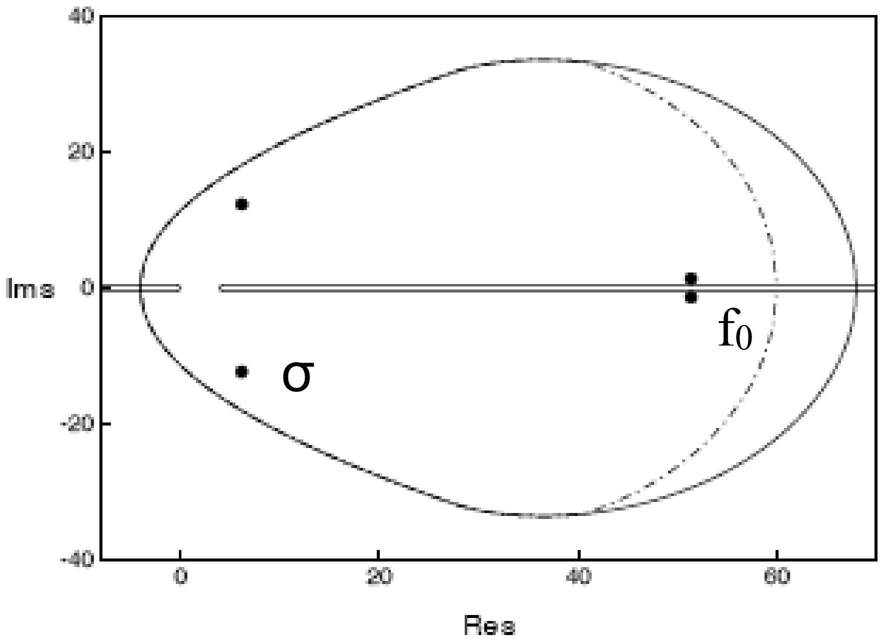
$$S_0^0(s)^{II} = 1/S_0^0(s)^I \ . \qquad (7)$$

The Roy equation thus automatically also specifies the function $S_0^0(s)$ on the second sheet, in the same domain of the s-plane [16]. In particular, the amplitude contains a pole on the second sheet if and only if $S_0^0(s)$ has a zero

Partial-wave S matrix elements are "real analytic" functions : $S^*(s)=S(s^*)$
From unitarity: $S(s)S^*(s)=1$;
one gets: $S(s)=1/S(s^*)$, hence

Dispersion equation analysis of π π scattering in S-wave indicate a broad resonance around 500 MeV, σ, and a narrow one around 980, f_0.

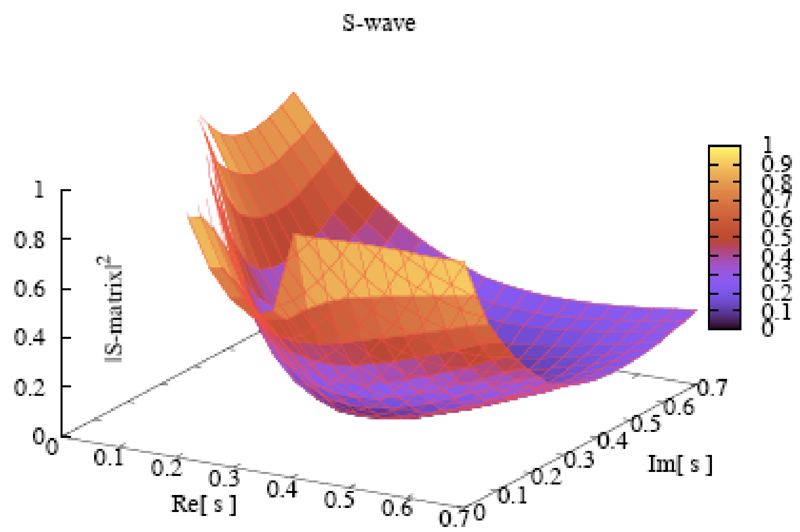
$$m_0 = (441 \pm 4) - i\,(272 \pm 6)\ \mathrm{MeV}$$

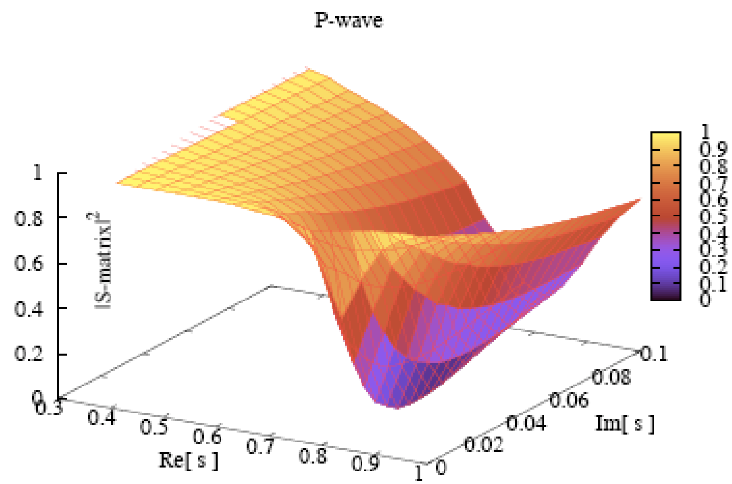


Re s and Im s are in units of m_π^2

FIG. 2: Domain of validity of the Roy equations.

a similar analysis proves the existence of kappa





The $K_0^*(800)$ scalar resonance from Roy-Steiner representations of πK scattering

arXiv:hep-ph/0607133v2 25 Aug 2006

S. Descotes-Genon[a] and B. Moussallam[b]

$$M_\kappa = 658 \pm 13 \text{ MeV}\,, \quad \Gamma_\kappa = 557 \pm 24 \text{ MeV}$$

		M_κ (MeV)	Γ_κ (MeV)
	This work	658 ± 13	557 ± 24
	Zhou, Zheng [16]	694 ± 53	606 ± 89
	Jamin et al. [18]	708	610
E791	Aitala et al. [7]	$721 \pm 19 \pm 43$	$584 \pm 43 \pm 87$
	Pelaez [19]	750 ± 18	452 ± 22
	Bugg [9]	750^{+30}_{-55}	684 ± 120
BES II	Ablikim et al. [20]	$841 \pm 23^{+64}_{-55}$	$618 \pm 52^{+55}_{-87}$
	Ishida et al. [14]	877^{+65}_{-30}	668^{+235}_{-110}

a complete nonet

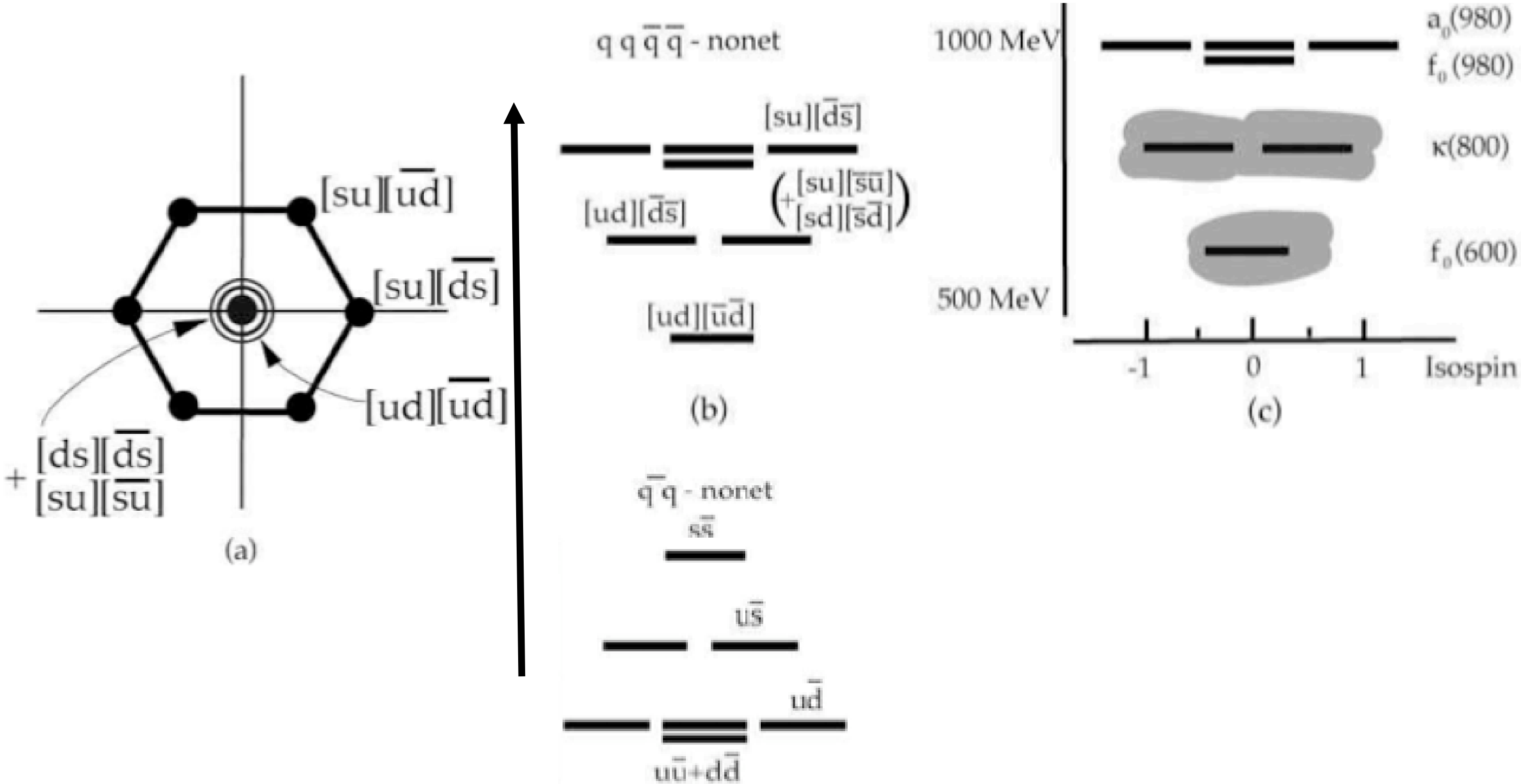
- σ(450, I=0), ϰ(660, I=1/2), f_0(980, I=0) and a_0(980, I=1)) fill neatly an entire nonet, but masses are in reverse order with respect to a q-qbar nonet
- pattern at complete variance with the very successful constituent quark model
- Candidate for a Cryptoexotic multiplet diquarks(antidiquarks) are antisymmetric in:
  - color (diquark = $\bar{\mathbf{3}}_{color}$ antidiquark = $\mathbf{3}_{color}$)
  - spin (diquark and antidiquark have spin = 0)
  - flavor (diquark is $\bar{\mathbf{3}}_{flavor}$ antidiquark is $\mathbf{3}_{flavor}$)
- earlier proposal by R. Jaffe (1977) and by R. Jaffe &F. Wilczeck, more recently reconsidered by our group.

L.Maiani, F. Piccinini, A. Polosa, V. Riquer, PRL **93**(2004) 212002

$$\kappa = [su][\bar{u}\bar{d}],\ [sd][\bar{u}\bar{d}]$$
$$\sigma = [ud][\bar{u}\bar{d}]$$

$$f_0/(a_0)^0 = \frac{[su][\bar{s}\bar{u}] \pm [sd][\bar{s}\bar{d}]}{\sqrt{2}}$$

Quantum numbers and mass spectrum



The reversed mass spectrum reveals the 4-quark composition of the lightest scalar mesons

The fully antisymmetric (anti) diquark structure agrees with the absence of truly exotic states, i.e. I=2, ππ resonances.

Tetraquark structure explains the conspicuous affinity for Kaons displayed by f_0 decays

$$BW_{f_0} = \frac{1}{s - m_0^2 + i m_0 (\Gamma_\pi + \Gamma_K)}$$

$$\Gamma_\pi = g_\pi \sqrt{s/4 - m_\pi^2}$$

$$\Gamma_K = \frac{g_K}{2} \left(\sqrt{s/4 - m_{K^+}^2} + \sqrt{s/4 - m_{K^0}^2} \right)$$

	m_{f_0} [MeV]	$g_{\pi\pi}$	$g_{K\bar{K}}$
WA76 (1991) $\pi\pi$ & KK seen	979±4	0.28±0.04	0.56±0.18
BES (2004) $\psi \to \phi\ \pi\pi,\ \phi$ KK	965±8±6	0.34±0.04	1.4±0.11

$$f_0/(a_0)^0 = \frac{[su][\bar{s}\bar{u}] \pm [sd][\bar{s}\bar{d}]}{\sqrt{2}}$$

- new experimental evidence for light scalar states, to complete the full nonet, has accumulated recently in D non leptonic decays (E791, BES, more recently BeBar)
- other alternative: K-Kbar *molecules* (DeRujula, Georgi, Glashow), see

  N. A. Tornqvist, Z. Phys. C 61, 525 (1994).
  N. A. Tornqvist, "Comment on the narrow charmonium state of Belle at 3871.8 MeV as a deuson", arXiv:hep-ph/0308277.

- the existence of sigma is crucial to tell the difference:
  - tetraquark → complete $SU(3)_{flavor}$ nonet
  - molecule →large $SU(3)_{flavor}$ breaking, maybe only K-Kbar are bound, sigma and kappa may not even exist

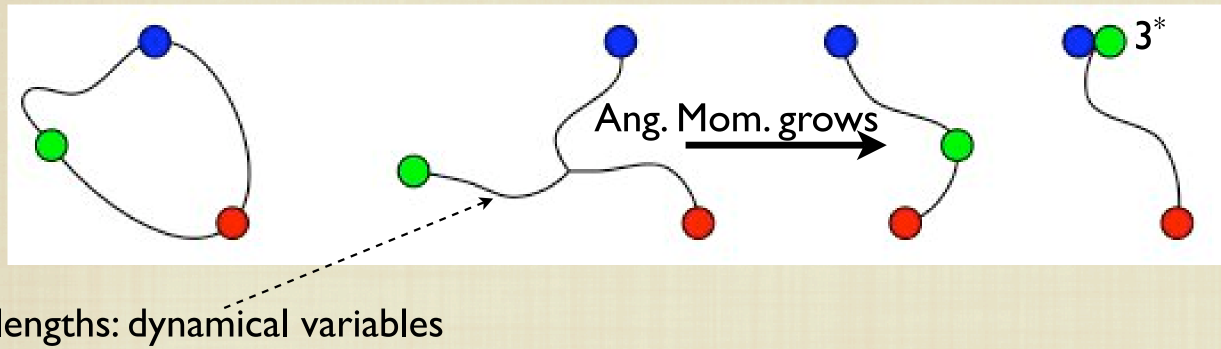
Homework:

Decays of light scalars still not fully understood

Where is it the q-qbar, P-wave, scalar nonet?

3. Strings & hadrons

G. `t Hooft hep-th/0408148

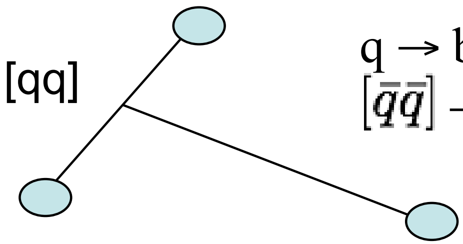


The Regge Trajectories for mesons and baryons
seem to have the same slope.

The classically stable config. has a single open string with two quarks at the end points and one bouncing between them.

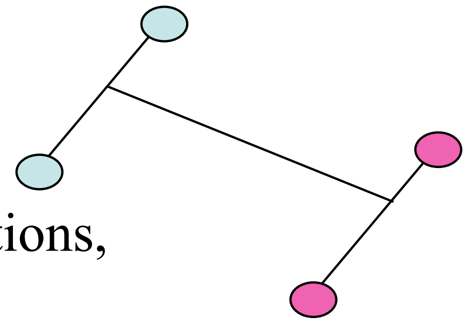
Diquark [qq] in color = 3bar, spin=0, SU3 flavour = 3bar makes a simple unit to form color singlets (Jaffe..more recently Jaffe&Wilcezck, Karliner & Lipkin for penta-quark)

Diquark needs to combine with other colored objects



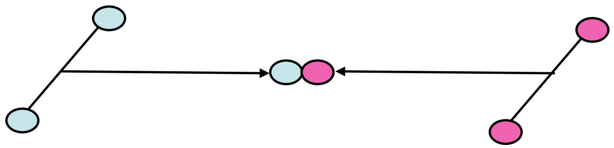
$q \rightarrow$ baryon (e.g. Λ), Y-shape

$[\bar{q}\bar{q}] \rightarrow$ scalar meson, H-shape

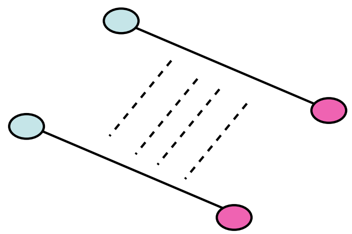


radial and orbital excitations, many states

string topology is related to Baryon-antiBaryon: if you stretch the string, $[qq][\bar{q}\bar{q}] \rightarrow B\bar{B}$



Meson-meson molecules have a different string topology:
- are they bound?
- very few states



Strong Decays of Tetra-quarks

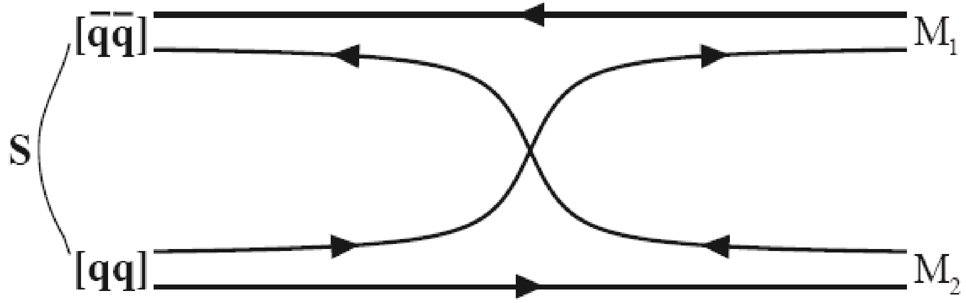


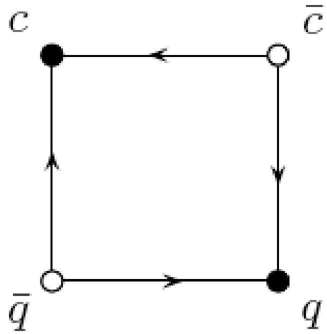
FIG. 1: The decay of a scalar meson S made up of a diquark-antidiquark pair in two mesons M_1M_2 made up of standard $(q\bar{q})$ pairs.

Below the Baryon-Antibaryon threshold

- Tunneling from colored to uncolored pairs, free to move away from each other
- A fully non-perturbative effect
- Amplitude may depend strongly on the quark mass

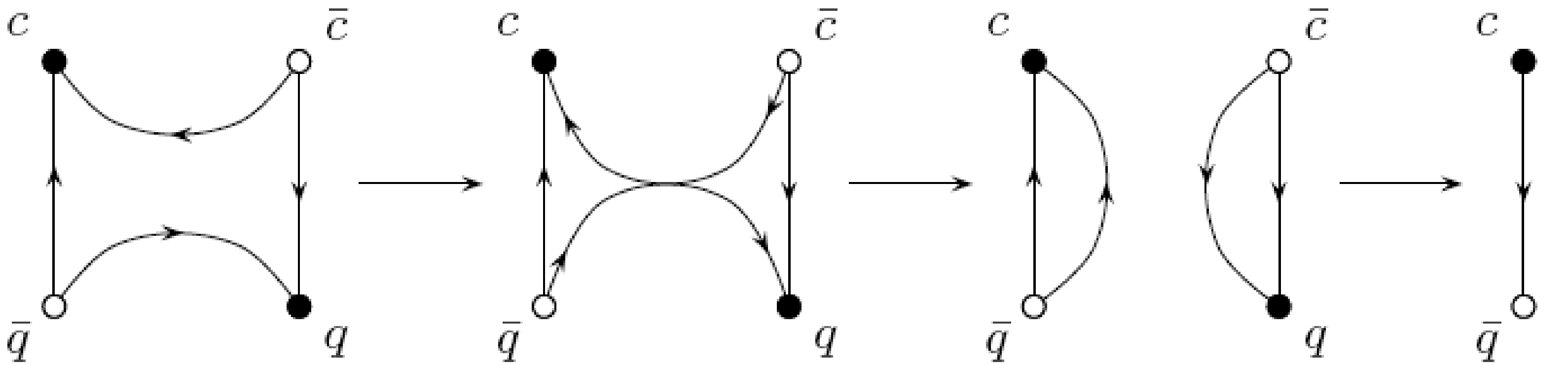
One could expect tunneling to be suppressed with respect to the natural process of string breaking. So states below the baryon-antibaryon threshold tend to be narrow. Is this the reason of the narrow X ??

H-shaped diquarks are not the only possibility: □ tetraquarks proposed (Gershtein, A.K. Likhoded and G.P. Pronko) to explain 4-quark charmonia



- c-cbar are in color octet (favoured in B decay?)
- radial and orbital excitations are possible

Mechanism for strong decay of □- mesons
is very different from that of H mesons



light mesons...

- Poor control of QCD in light hadronic systems will make it very difficult to identify unambiguously the light tetraquark mesons
- Some additional tools:
  - comparison of the f_0 and η e.m. form factor ("γ"→f0 ω vs. "γ"→η ω), S. Pacetti, 2005
  - Measure of the Nuclear Modification Ratios of f_0 in Relativistic Heavy Ion Colllisions (RHIC, LHC) (LM, Riquer, Polosa, Salgado, 2006)
- go to heavy flavored tetraquarks: $[(cq)(\bar{c}\bar{q}')]_{S-wave}$

Extrapolating boldly from the light scalar decays ... one would predict very small widths, of the order of ten MeV.

Narrow states of this kind are seen in the hadronic final states of B non-leptonic decays, by Belle and PEPII.

Some of them are explained by conventional $c - \bar{q}$ bound states, but there may be a wholly new spectroscopy waiting for us there, which we are only now beginning to decode.

DAFNE Workshop, Frascati, 2004

4. New charmonium states: beyond the SM

- Hidden charm mesons are being found by BELLE and BaBar, which do not fit the Charmonium picture
- main processes are:
  - B non leptonic decays:

$$B^{\pm} \to K^{\pm} + X^0; \quad B^0 \to K^0 + X^0$$
$$X^0 \to \psi(nS) + \pi's, \text{ or } D^{(*)}D^{(*)}$$

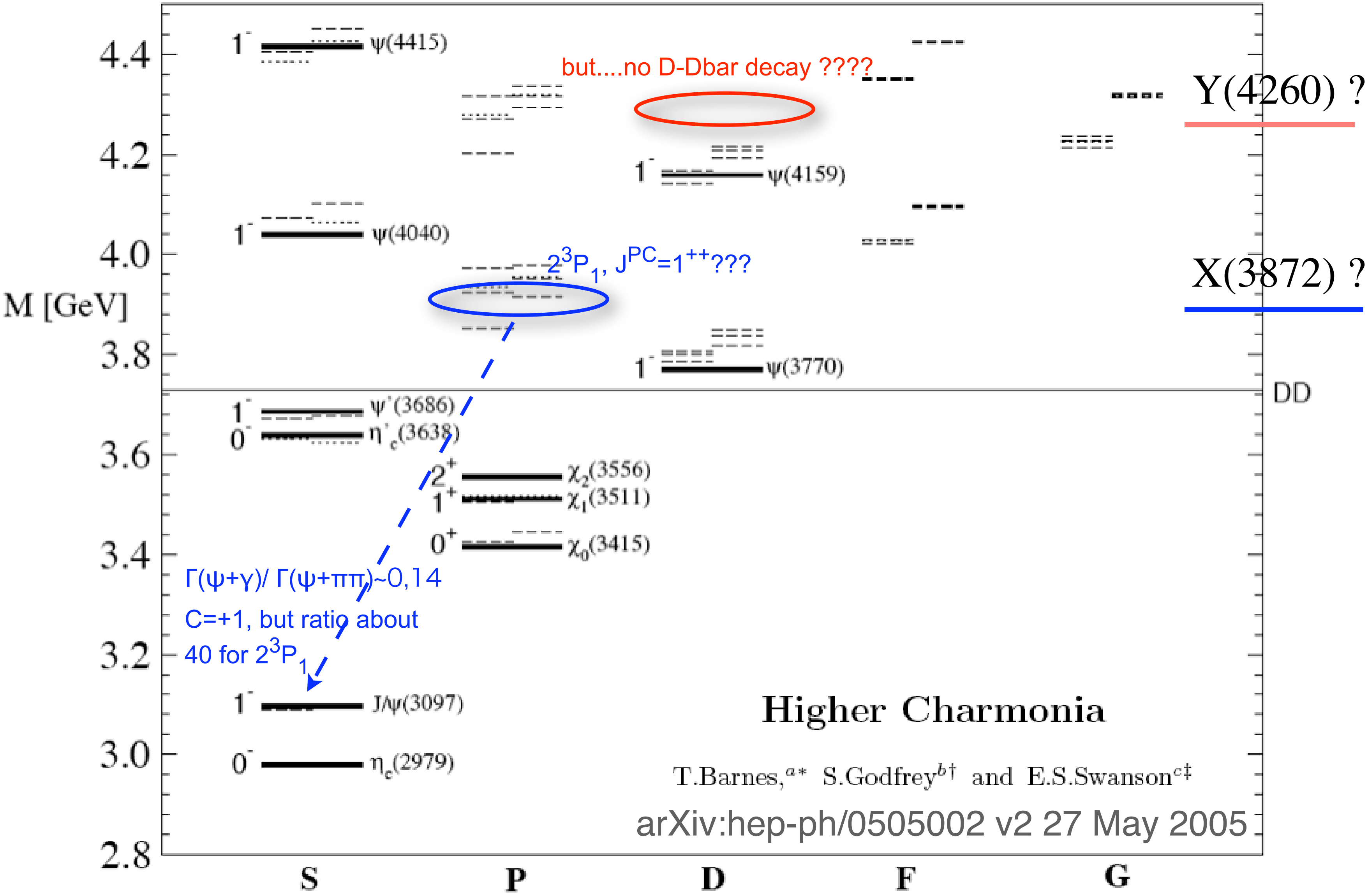
$$B^{\pm} \to K^0 + Z^{\pm}; \quad B^0 \to K^{\pm} + Z^{\mp}$$
$$Z^+ \to \psi(nS) + \pi^+ + \pi^0, \text{ or } D^{(*)}D^{(*)}$$

  - Initial State Radiation:

$$e^+e^- \to \gamma(\text{initial state}) + Y$$
$$Y \to \psi(nS) + \pi's, \text{ or } D^{(*)}D^{(*)}$$

    since Y originates from a virtual photon, it has $J^{PC}=1^{--}$.
  - $e^+e^- \to \psi(1S) + (D^{(*)}D^{(*)})_M$ (only C=+1 are produced)

X(3872) and Y(4260) are not charmonium states



Proposed interpretations

- X(3872) =
  - D-D* molecule: $M(X) - M(D^{*0}\bar{D}^0) = +0.6$ MeV
    - F.E. Close, P.R. Page PL B 578 (2004) 119;
    - N.A. Tornqvist PL B590 (2004) 209;
    - E. Swanson, PL B588 (2004) 189.
  - diquark-antidiquark bound state: $[(cq)\ (\bar{c}\bar{q})]_{S-wave},\ J^{PC} = 1^{++};\ \ (q = u,\ d)$
    - L. Maiani, F. Piccinini, A.D. Polosa and V. Riquer, PR D 71 (2005) 014028

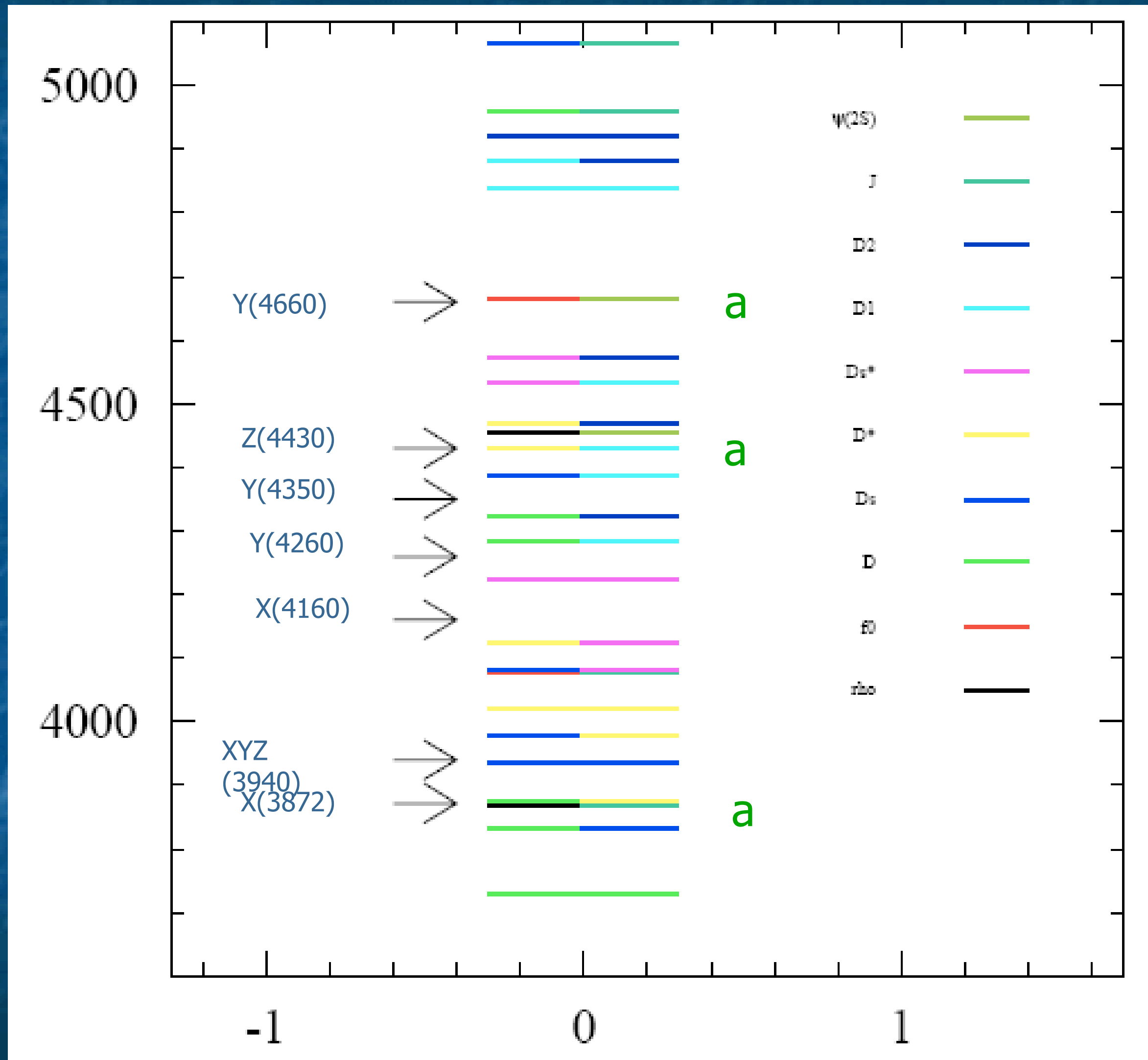
- Y(4260) =
  - Hybrid state: $(c\ \bar{c}\ g)$
    - F.E. Close and P.R. Page, PL B 628 (2005) 215;
    - E. Kou and O. Pene, PL B 631, 164 (2005)
  - diquark-antidiquark bound state: $[(cs)\ (\bar{c}\bar{s})]_{P-wave},\ J^{PC} = 1^{--}.$
    - L. Maiani, V. Riquer, F. Piccinini and A.D. Polosa, PR D 72 (2005) 031502
  - molecular state ($\chi_c + \omega$)
    - C.Z. Yuan, P. Wang and X.H. Mo, PL B 634 (2006) 399
  - baryonium: Λ_c^+-Λ_c^-
    - C.F. Qiao, PL B 639 (2006) 263

- hybrid classification for X(3872) excluded by the large isospin violation seen in ψρ and ψω decays;
- Y(4260) is some 33 MeV above D*-D* threshold; parity calls for P-wave: molecule unfavoured ??

5. Thresholds, cusps and new states

Molecular models and threshold effects require vicinity to threshold

Is this the case?



Cusps effects

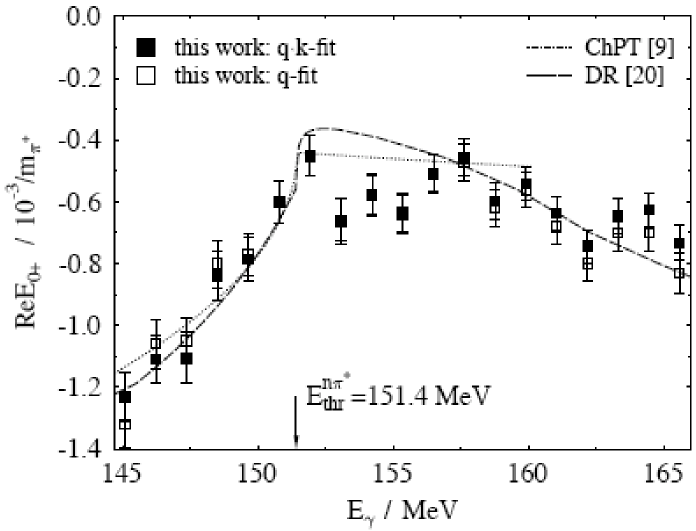
EFFECTS OF S-WAVE THRESHOLDS

Jonathan L. Rosner

Enrico Fermi Institute and Department of Physics, University of Chicago
5640 South Ellis Avenue, Chicago, IL 60637

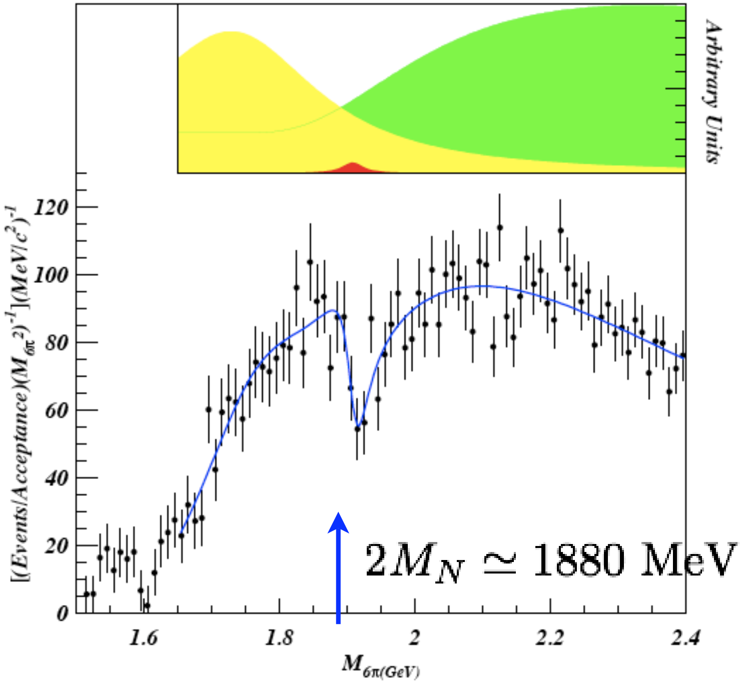
August 2006

- Dips are observed in various reactions as the effect of the opening of an S-wave threshold in another channel

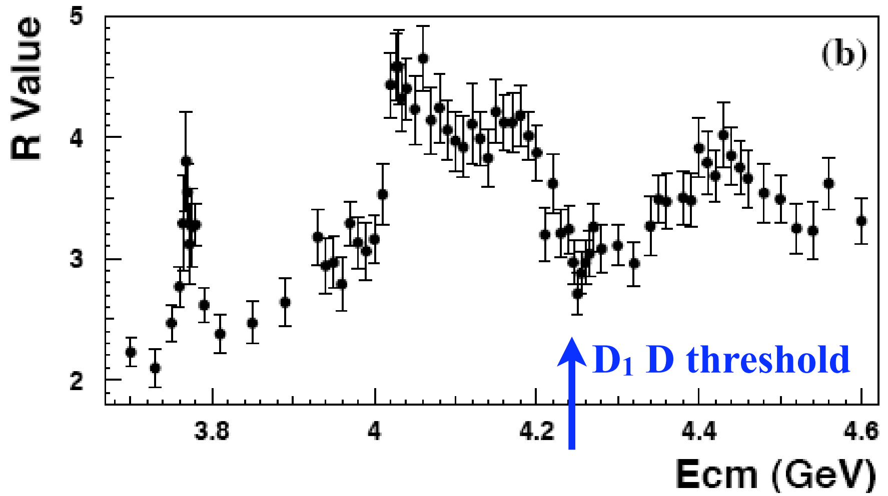


$\gamma p \to p\pi^0$ in the proximity of the $n\pi^+$ threshold
A. Schmidt et al., Phys. Rev. Lett. **87** (2001), 232501

Spectrum of diffractively produced 3π+3π− , together with results of a fit with two resonances and continuum.
The inset shows the relative fraction of each amplitude without interference.

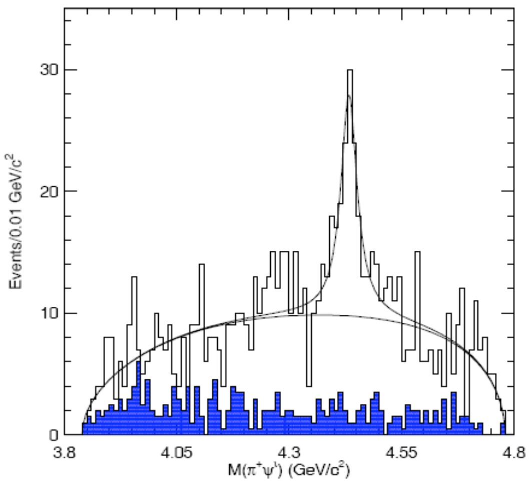


Cusp effects (cont'd)



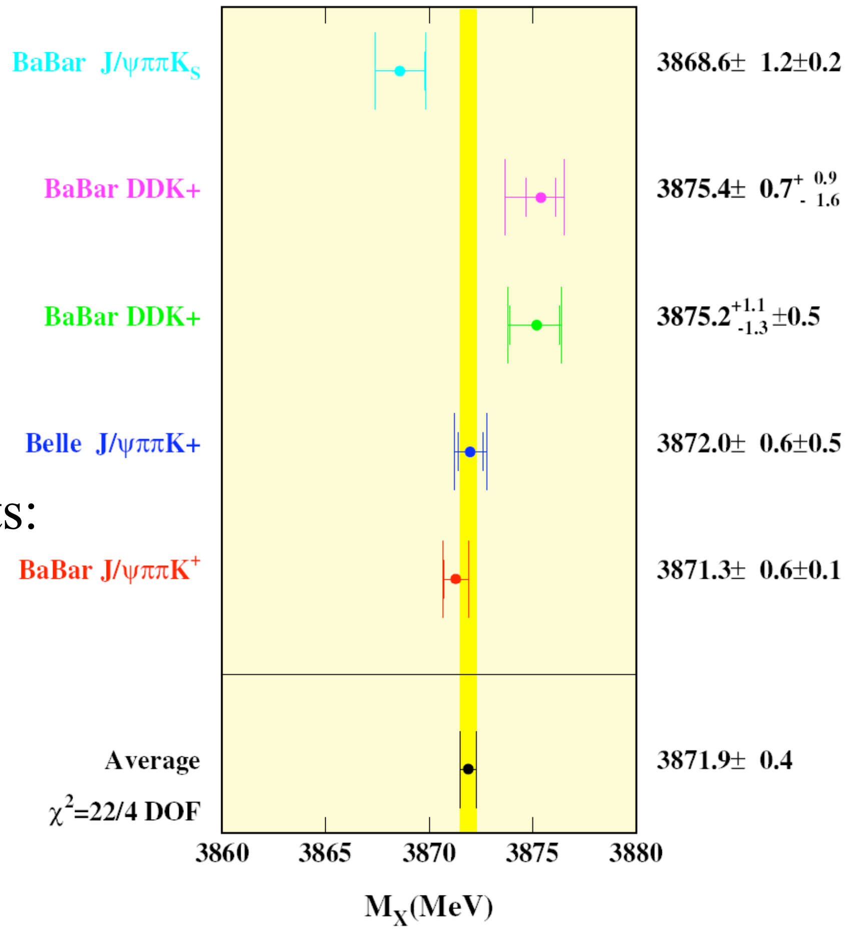
The lightest established candidate for D_1 has a mass of about 2.42 GeV/c^2, corresponding to a threshold of 4.285 GeV. It is this threshold that we associate with the dip in R between 4.19 and 4.25 GeV.

For comparison:
$Z^+(4430) \to \pi^+ \psi(2S)$



5. Two X states?

arXiv:0707.3354 [hep-ph] 23 Jul 2007



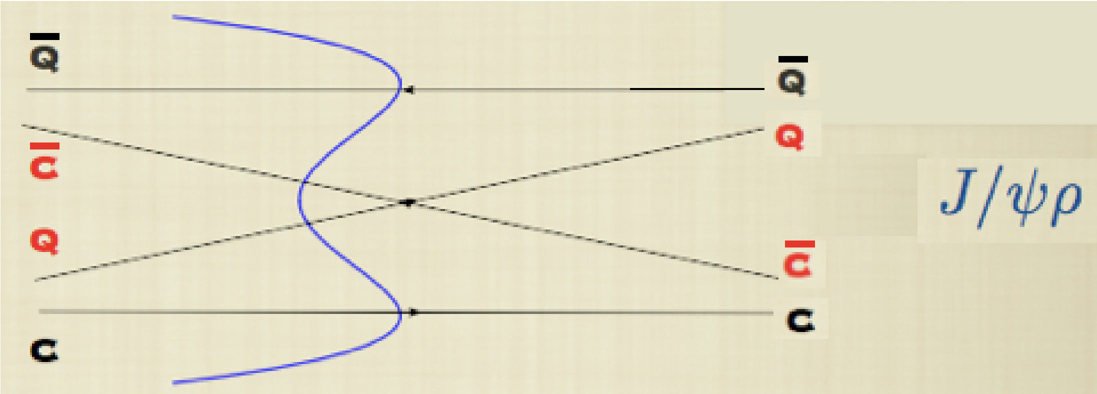
Poor agreement among mass measurements:

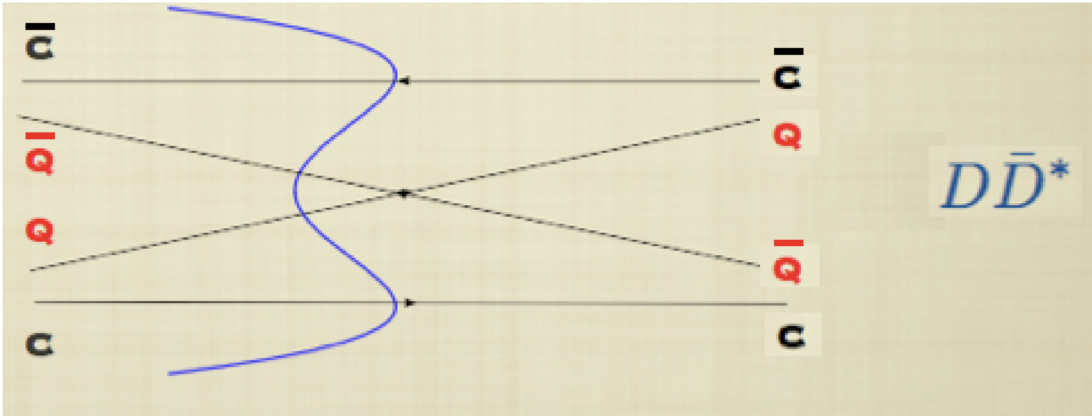
$X \to J/\psi\pi\pi$ and $X \to DD^{(*)}$ differ by ~4σ

Molecule interpretation disfavored by:

- two X states @ 3872 and 3876
- decay rate in $D^0 D^0 \pi^0$ much larger than γψ

are production and decay consistent? J/ψππ must be suppressed w.r.t. D^*D





Tunneling of c quark to flip from one equilibrium position to the other could be much suppressed with respect to the tunneling of the light quark Q:

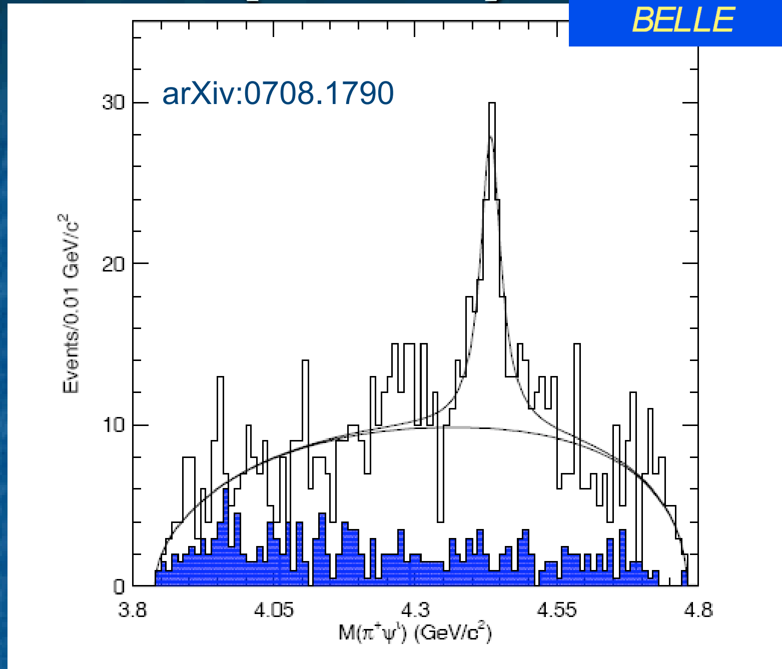
$$\Gamma(X_u \to D^0\bar{D}^0\pi^0) >> \Gamma(X_u \to J/\psi\pi^+\pi^-) \simeq$$
$$\simeq \Gamma(X_d \to J/\psi\pi^+\pi^-) >> \Gamma(X_d \to D^0\bar{D}^0\pi^0)$$

The first charged state: Z(4430)!

BELLE

$B^{\pm} \to Z^{\pm} K_s$ or $B^0 \to Z^{i} K^{\pm}$

$Z^{\pm} \to \psi(2S)\pi^{\pm}$



Total significance: 7.3s

M = (4433±4) MeV

$\Gamma = (44^{+17}_{-13})$ MeV

Too narrow to be a reflection

$BF(B \to KZ) \times BF(Z \to \psi(2S)\pi) = (4.1 \pm 1.0 \pm 1.3)\ 10^{-5}$

Subset	Signal events	Mass (GeV)	Width (GeV)	signif. (σ)	constr. yield ($\Gamma = 0.044$GeV)
$\psi' \to \pi^+\pi^- J/\psi$	52.9 ± 15.1	4.435 ± 0.004	$0.026^{+0.013}_{-0.008}$	5.5	67.3 ± 14.9
$\psi' \to \ell^+\ell^-$	104.8 ± 34.5	4.435 ± 0.010	$0.097^{+0.041}_{-0.031}$	5.6	60.1 ± 13.8
$J/\psi(\psi') \to e^+e^-$	45.4 ± 16.6	4.430 ± 0.010	$0.052^{+0.026}_{-0.020}$	4.1	40.9 ± 11.9
$J/\psi(\psi') \to \mu^+\mu^-$	79.4 ± 24.6	4.434 ± 0.004	$0.039^{+0.022}_{-0.013}$	6.1	84.8 ± 17.0
$K^{\pm}\pi^{\mp}\psi'$	106.5 ± 26.6	4.434 ± 0.005	$0.046^{+0.017}_{-0.013}$	6.6	104.7 ± 18.6
$K_S\pi^{\mp}\psi'$	21.0 ± 8.3	4.430 ± 0.009	0.046-fixed	3.0	20.6 ± 8.2
vary K^* veto	238.1 ± 64.2	4.436 ± 0.005	$0.068^{+0.031}_{-0.019}$	7.9	178.4 ± 26.4

Xcheck: separate in subsamples

BF and mass consistent between $B^{\pm}$ and B0 within large errors [in $B^{\pm}$ decays M= (4430±9) MeV ; BF_+/BF_0=1.0 ±0.4]

Prior search with no evidence: $B \to X^+K$ with $X^+ \to J/\psi\ \pi\pi^0$

PRD 71, 031501 (2005)

R.Faccini, LeptonPhoton Conference 2007

Proposed interpretations (cont'd)

- $Z^+(4433)$, BELLE Collaboration

  arXiv:0708.1790v1 [hep-ex] 14 Aug 2007

  – charged tetraquark in 2S

    • L. Maiani, A.D. Polosa and V. Riquer, hep-ph: 0708.3997;
    • Gershtein, A.K. Likhoded and G.P. Pronko, hep-ph 0709.2058
    • K.m. Cheung, W.Y. Keung and T. C. Yuan,hep-ph:0709.1312 [hep-ph] (propose similar states with b quark)

  – Threshold enhancement in D_1-D^*

    • J.L. Rosner, hep-ph:0708.3496;
    • C. Meng and K.T. Chao, hep-ph:0708.4222;
    • D.V. Bugg, hep=ph :0709.1254;

  – Baryonium: $\Lambda_c^+ \; \bar{\Sigma}_c^0$

    • C.~F.~Qiao, hep-ph :0709.4066

8. Outlook

- A new spectroscopy is being discovered with the new “charmonia”;
- this is made possible by the fact that the Standard Charmonium model is so precise: years of efforts to compute precisely the c-cbar spectroscopy take now their reward;
- The observation of two X states and of the charged charmonium, Z, has given more credibility to the tetraquark interpretation;
- In this case, there must exist neutral states close to Z as well as the Z(1S) around 3890 MeV, with $Z(1S) \to \pi + \psi(1S)$.
- X and Z states should fall in complete nonets, with masses calculable within the constituent quark model, that works so well for S-wave hadrons;
- alternative schemes still exist and more data are (badly) needed.

Outlook (cont'd)

- Hadron spectroscopy below 1 GeV seems established. But decays are still problematics: what is the source of $f_0 \rightarrow \pi\pi$ decay
- But where is it the q-qbar scalar nonet?
- $\eta\pi$, $J=0^{++}$ resonances "counts" scalar nonets, but a systematic study above 1 GeV is still lacking: is there more than the $a_0(1450)$?
- The new spectroscopy is still in its infancy, theory needs guidance from experiments, as last years have shown!

A new generation of machines and detectors are called for Super-B factory ideal. Meanwhile, can FAIR take the challenge? Can Lattice QCD calculations play a role ?