Hadron Spectroscopy from Strangeness to charm and beauty

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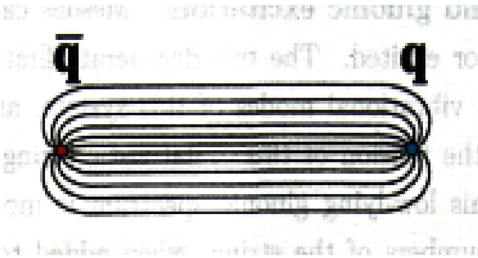
Outline :

1. Introduction
2. Hadron spectroscopy with strangeness
3. From Strangeness to charm & beauty
4. Conclusions

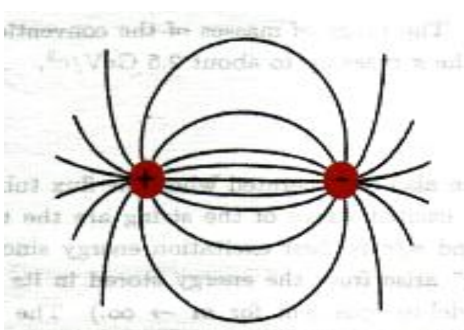
1. Introduction

Key problem in QCD and hadron structure

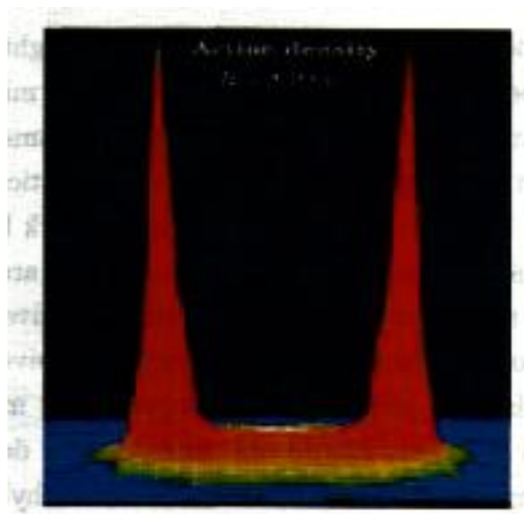
Quark confinement – self-interaction of gluons



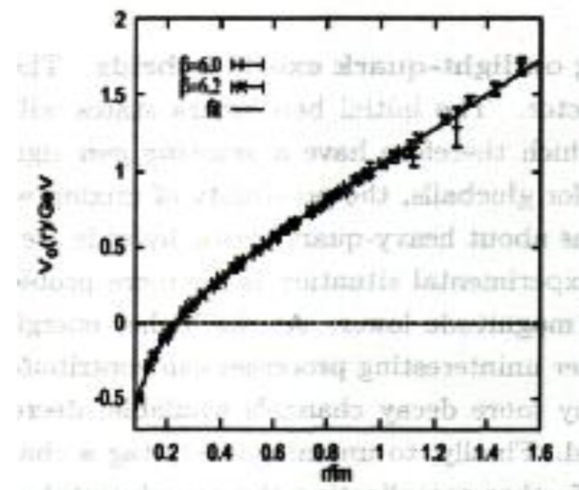
QCD field lines



QED field lines

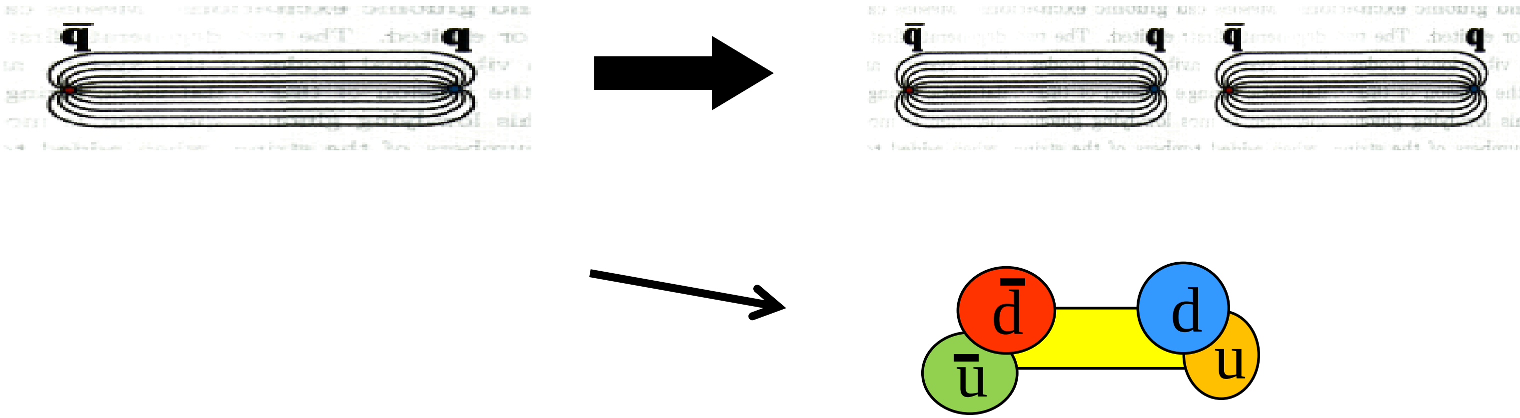


energy density



linear potential

Lattice QCD



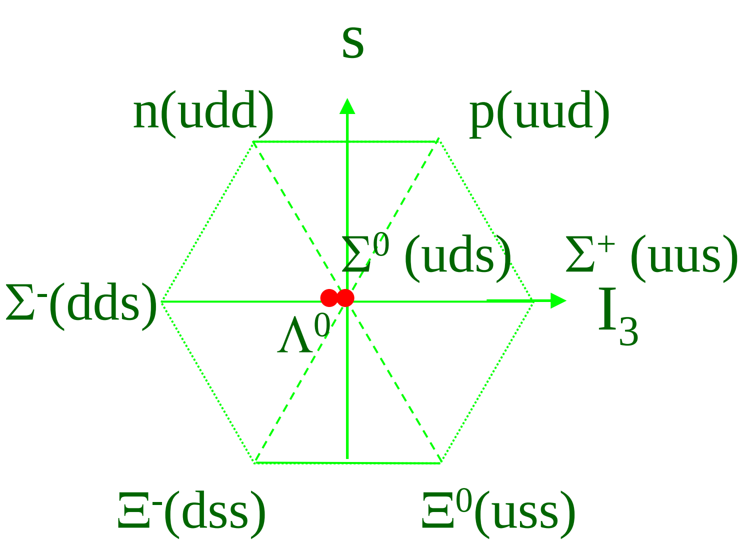
gluons → $\bar{q}q$: crucial for quark confinement
and hadron structure
to be more challenging than
atomic and nuclear structures

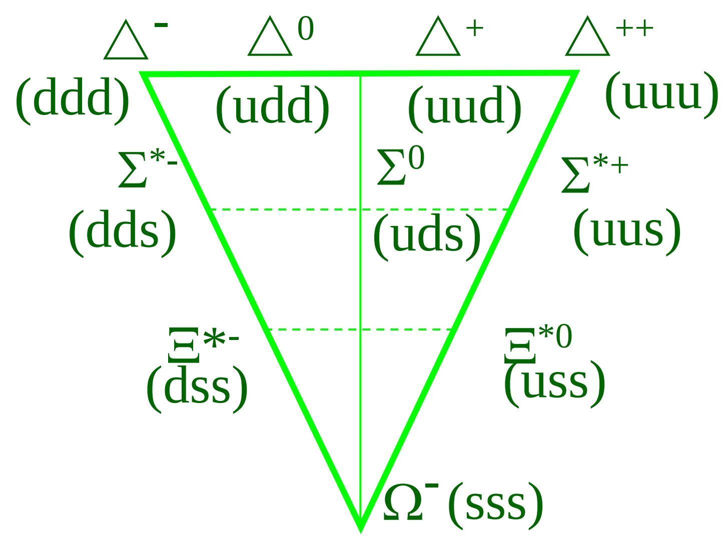
The number of constituents in a hadron is not a constant!

2. Hadron spectroscopy with strangeness

SU(3) 3q-quark model for baryons

1/2 + **spin-parity** **3/2 +**





Successful for spatial ground states !

Prediction $m_{\Omega^-} \cong$ **1670 MeV**

experiment $m_{\Omega^-} \cong$ **1672.45 ±0.29 MeV**

quenched vs un-quenched for mesons

$\bar{q}q$ $^3S_1$ nonet

- $\phi(1020)$ $\quad s\bar{s}$
- $K(892)$ $\quad \bar{s}d$
- $\omega(782)$ $\quad \bar{u}u + \bar{d}d$
- $\rho(770)$ $\quad \bar{u}u - \bar{d}d$

$\bar{q}q$ $^3P_0$ or $\bar{q}^2q^2$ nonet ?

- $a_0(980)$ $\quad \bar{u}u - \bar{d}d$, $[\bar{u}\bar{s}][us]-[\bar{d}\bar{s}][ds]$
- $f_0(980)$ $\quad \bar{s}s$, $[\bar{u}\bar{s}][us]+[\bar{d}\bar{s}][ds]$
- $\kappa(800)$ $\quad \bar{s}d$, $[\bar{s}\bar{u}][ud]$
- $f_0(600)$ $\quad \bar{u}u + \bar{d}d$, $[\bar{u}\bar{d}][ud]$

$1/2^-$ baryon nonet with strangeness

- **Mass pattern : quenched or unquenched ?**

uds (L=1) $1/2^-$ ~ $\Lambda^*(1670)$ ~ [us][ds] $\bar{s}$

uud (L=1) $1/2^-$ ~ N*(1535) ~ [ud][us] $\bar{s}$

uds (L=1) $1/2^-$ ~ $\Lambda^*(1405)$ ~ [ud][su] $\bar{u}$

uus (L=1) $1/2^-$ ~ $\Sigma^*(1390)$ ~ [us][ud] $\bar{d}$

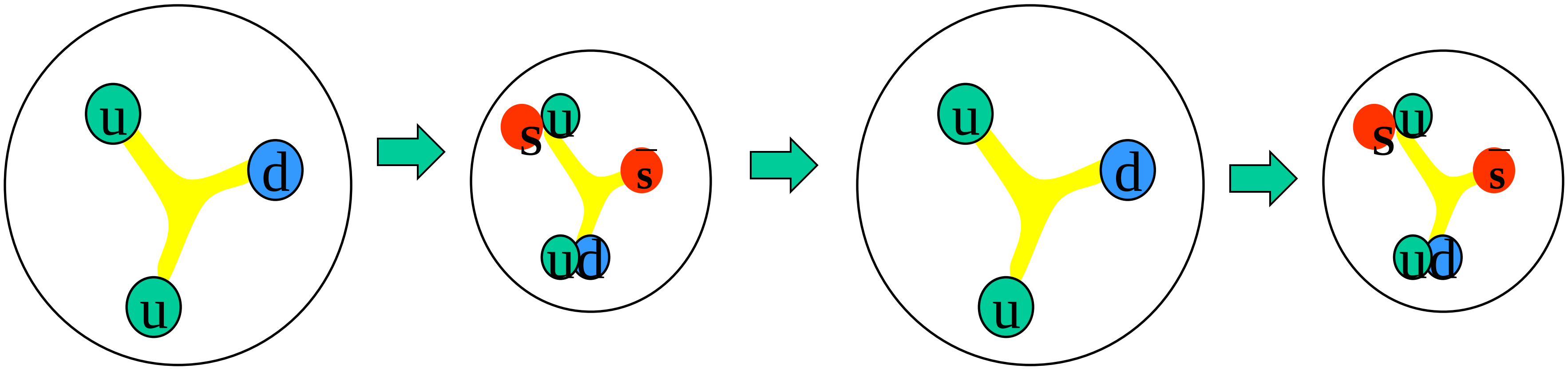
Zou et al, NPA835 (2010) 199 ; CLAS, PRC87(2013)035206

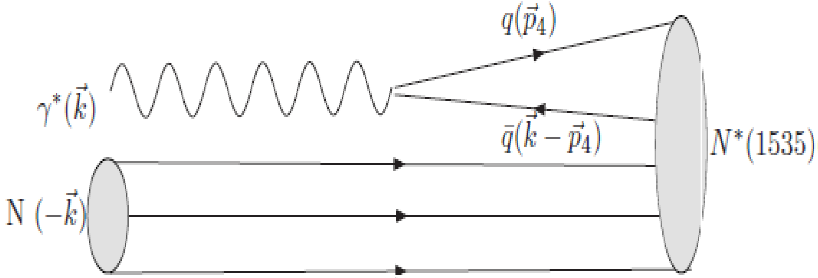
- **Strange decays of N*(1535) and $\Lambda^*(1670)$:**

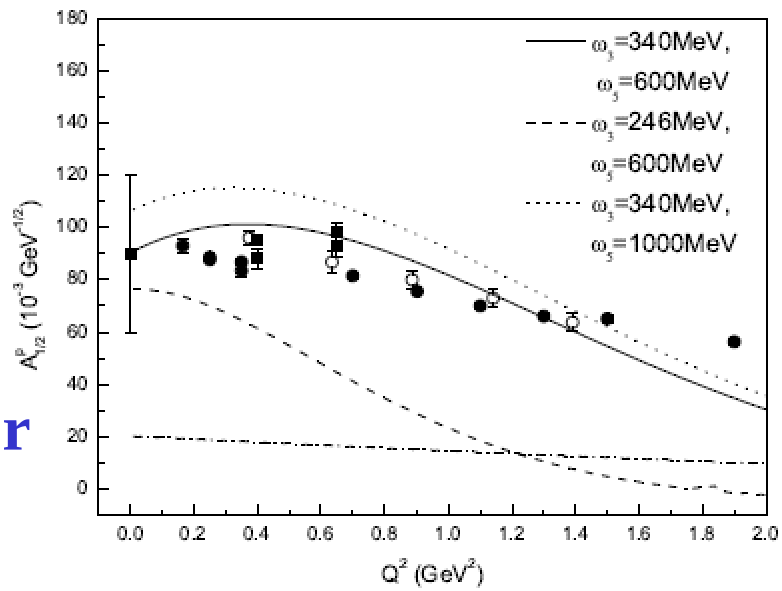
N*(1535) large couplings $g_{N^*N\eta}$, $g_{N^*K\Lambda}$, $g_{N^*N\eta'}$, $g_{N^*N\phi}$

$\Lambda^*(1670)$ large coupling $g_{\Lambda^*\Lambda\eta}$

The breathing mode for the N*(1535)







Important role for N* EM form factor

An & Zou, EPJA39(2009)195

Alternative pictures :

Hadronic molecules	Penta-quark states
N*(1440) ~ Nσ	N*(1440) ~ [ud][ud] $\bar{q}$
N*(1535) ~ KΣ-KΛ	N*(1535) ~ [ud][us] $\bar{s}$
Λ*(1405) ~ KN-Σπ	Λ*(1405) ~ [ud][sq] $\bar{q}$

Kaiser, Weise, Oset, Ramos, Oller, Meissner, Hyodo, Jido, Hosaka, …

Successful extension to $3/2^-$ baryon nonet, 1^+ & 2^+ meson nonets

Oset et al.

Important implications:

- $\bar{q}qqqq$ in S-state more favorable than qqq with L=1 !

  & $\bar{q}qqq$ in S-state more favorable than $\bar{q}q$ with L=1 !

$1/2^-$ baryon nonet ~ $\bar{q}q^2q^2$ state + …

0^+ meson octet ~ $\bar{q}^2q^2$ state + …

multiquark components are important for hadrons!

Quark model needs to be unquenched !

Best playgrounds for unquenched quark models:

for baryon $sss \rightarrow sss\ \bar{q}q$

for meson $\bar{c}c \rightarrow \bar{c}\ c\ \bar{q}\ q$

Totally different predictions for the lowest Ω^* :

$\Omega^*(x/2^-)$ as sss (L=1) : ~ 2020 MeV

Chao, Isgur, Karl, PRD38(1981)155

$\Omega^*(1/2^-)$ as $\bar{K}\Xi$ bound state: ~ 1805 MeV

W.L.Wang, F.Huang, Z.Y.Zhang, F.Liu, JPG35 (2008) 085003

$\Omega^*(x/2^-)$ as $\bar{u}$usss (L=0) : ~ 1820 MeV

Yuan-An-Wei-Zou-Xu, PRC87(2013)025205

$\Omega^*(3/2^-)$ as sss - $\bar{u}$usss mixture : ~ 1780 MeV

by instanton/NJL interaction

An-Metsch-Zou, PRC87(2013) 065207; An-Zou, PRC89(2014)055209

Experiment knowledge on Ω* states still very poor !

Ω* in PDG:

*******   Ω(1672) $3/2^+$,**

***** Ω (2250)**

**** Ω (2380), Ω (2470)**

No $1/2^-$ or $3/2^-$ Ω* observed yet !!

Very important to find the lowest Ω* ($1/2^-$ or $3/2^-$)

$\psi(2S) \rightarrow \bar{\Omega}\Omega$ BR = $(5 \pm 2) \times 10^{-5}$

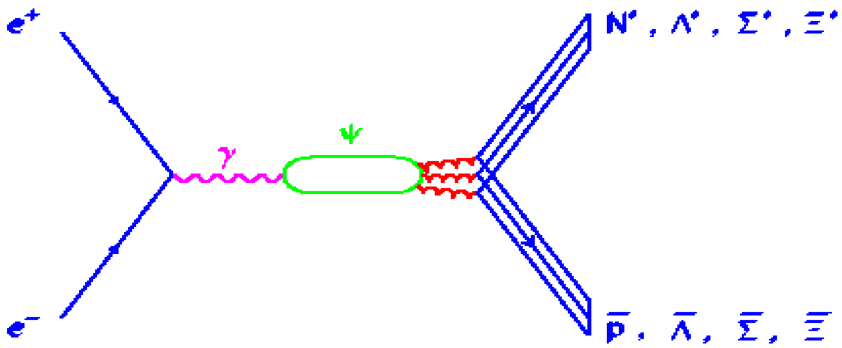
M. Ablikim et al. (BESII Coll.), CPC36(2012)1040

$\psi(2S) \rightarrow \bar{\Omega}\Omega^*$ with $\Omega^* \rightarrow \gamma\,\Omega$

→ excitation mechanism for sss states

$\bar{c}c$ decays -- a important new source for baryons

$$J/\Psi \rightarrow \bar{B}BM \Rightarrow N^*, \Lambda^*, \Sigma^*, \Xi^*$$



an ideal isospin and low spin filter from $\bar{c}c$ annihilation

No contamination from t/u-channel scattering as in πN and γN

high statistics extension to ψ', χ_{cJ}, η_c

3/7 new N* from PDG92 to PDG03 are from BESII & BESIII

Many more interesting channels:

$\bar{\Omega}\ \Xi\ \bar{K}$, $\bar{\Xi}\,\Xi\pi$, $\bar{\Lambda}\Lambda\gamma$, $\bar{\Sigma}\Lambda\gamma$, $\bar{\Sigma}\Sigma\gamma$, $\bar{\Xi}\,\Xi\gamma$, ...

with $\Omega \to \Lambda K$, $\Xi \to \Lambda\pi$

S.Dulat, J.J.Wu, B.S.Zou, PRD83 (2011) 094032
"Proposal and theoretical formalism for studying baryon radiative decays from $J/\psi \to \bar{B}B^* + \bar{B}^*B \to \bar{B}B\gamma$".

JLAB : $N^*, \Delta^* \to \gamma N$

Super τ -c: $\Lambda^* \to \gamma\Lambda, \gamma\Sigma$; $\Sigma^* \to \gamma\Lambda, \gamma\Sigma$; $\Xi^* \to \gamma\Xi$!

3. From strangeness to charm & beauty

Many N* & Λ* are proposed dynamically generated states and multi-quark states

Problem:

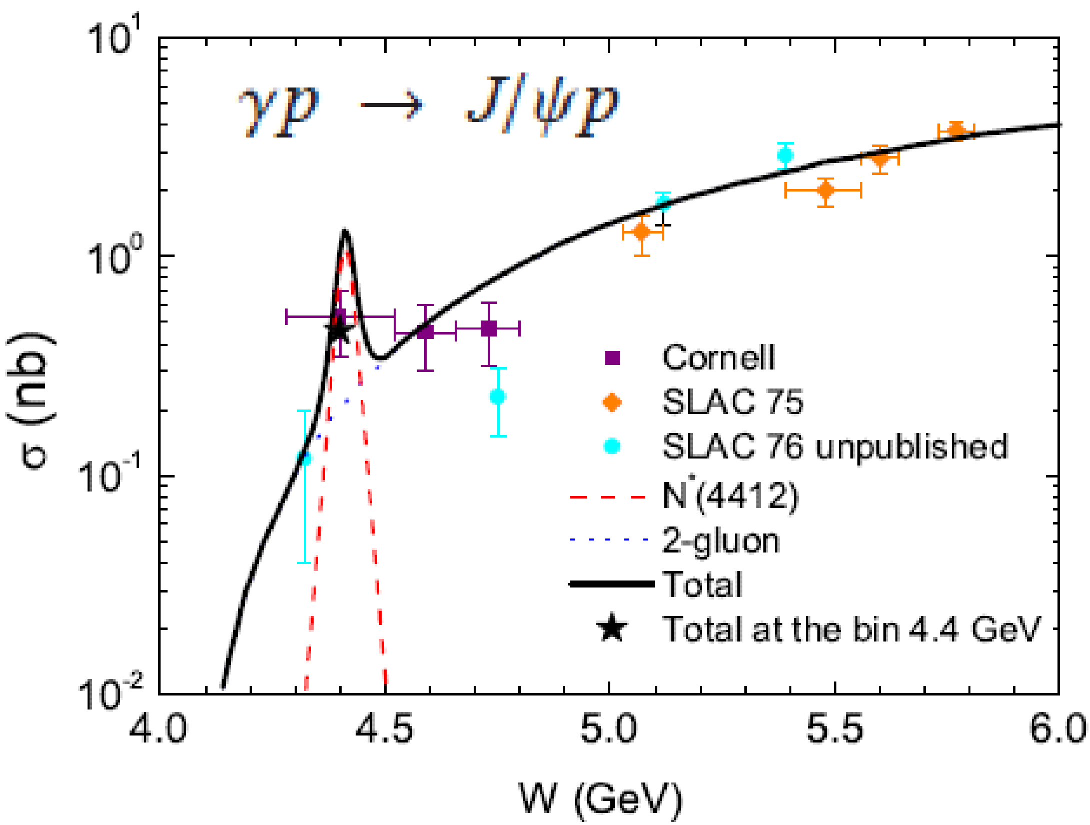
None of them can be clearly distinguished from qqq due to tunable ingredients and possible large mixing of various configurations

Solution: **Extension to hidden charm and beauty for baryons**

N*(1535) $\bar{s}suud$

N*(4260) $\bar{c}cuud$ **J.J.Wu, R.Molina, E.Oset, B.S.Zou. Phys.Rev.Lett. 105 (2010) 232001**

N*(11050) $\bar{b}buud$ **J.J.Wu, L.Zhao, B.S.Zou. PLB709(2012)70**



Y.Huang,J.He,H.F.Zhang,X.R.Chen, ArXiv:1305.4434

$\bar{d}u\bar{b}b$ states ?

RAPID COMMUNICATIONS

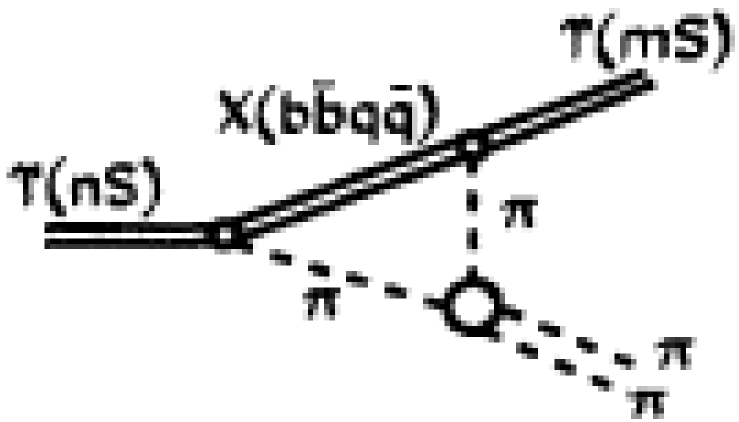
PHYSICAL REVIEW D VOLUME 51, NUMBER 9 1 MAY 1995

$\Upsilon(3S)\rightarrow\Upsilon(1S)\pi\pi$ decay: Is the $\pi\pi$ spectrum puzzle an indication of a $b\bar{b}q\bar{q}$ resonance?

V. V. Anisovich,[1,2] D. V. Bugg,[1] A. V. Sarantsev,[1,2] and B. S. Zou[1]
[1]*Queen Mary and Westfield College, London E1 4NS, United Kingdom*
[2]*Petersburg Nuclear Physics Institute, Gatchina, 188350, Russia*

(Received 22 August 1994; revised manuscript received 2 February 1995)

The $\pi\pi$ mass spectrum in $\Upsilon(3S)\rightarrow\Upsilon(1S)\pi\pi$ has a peculiar double peak structure. This structure and the $\Upsilon(1S)\pi$ spectrum are reproduced by introducing a triangle singularity associated with a $b\bar{b}\pi$ resonance ($J^P=1^+$) in the mass range 10.4–10.8 GeV.



Belle Collaboration, PRL108 (2012) 122001 → $Z_b(10610)$, $Z_b(10650)$

“Observation of Two Charged Bottomoniumlike Resonances in Υ(5S) Decays”

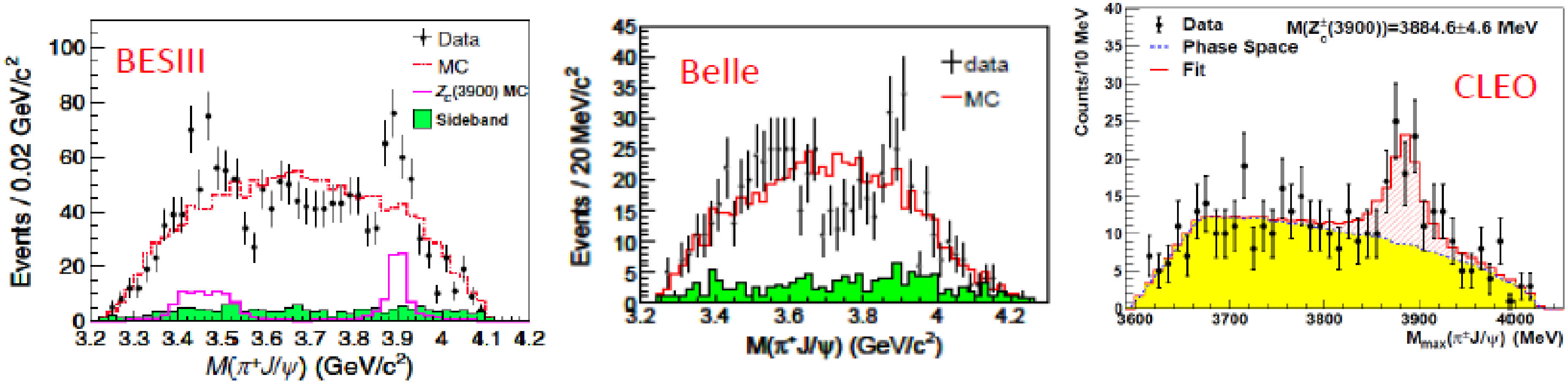
important to confirm them and find their partners

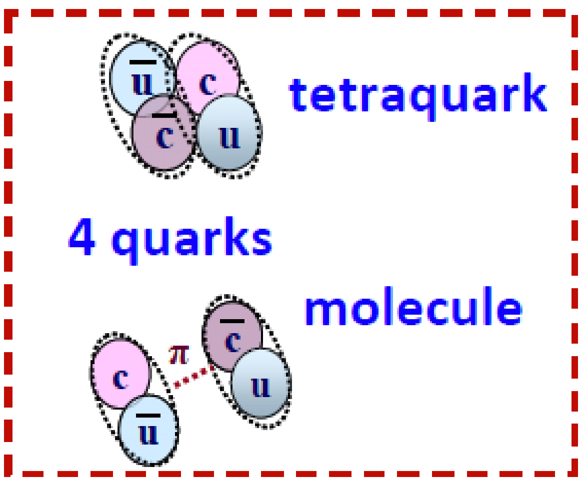
Zc(3900) production from Y(4260) decays

$\bar{d}uc\bar{c}$ states ?

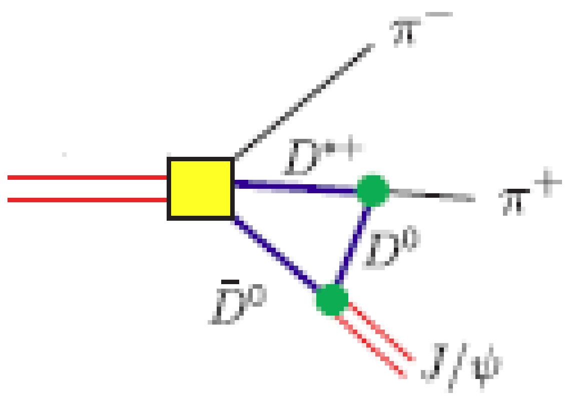
PRL 110, 252001 (2013) PHYSICAL REVIEW LETTERS 21 JUNE 2013

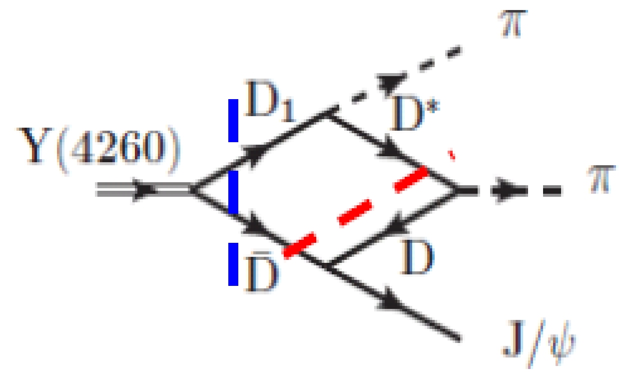
Observation of a Charged Charmoniumlike Structure in $e^+e^- \to \pi^+\pi^- J/\psi$ at $\sqrt{s} = 4.26$ GeV





Exotic!



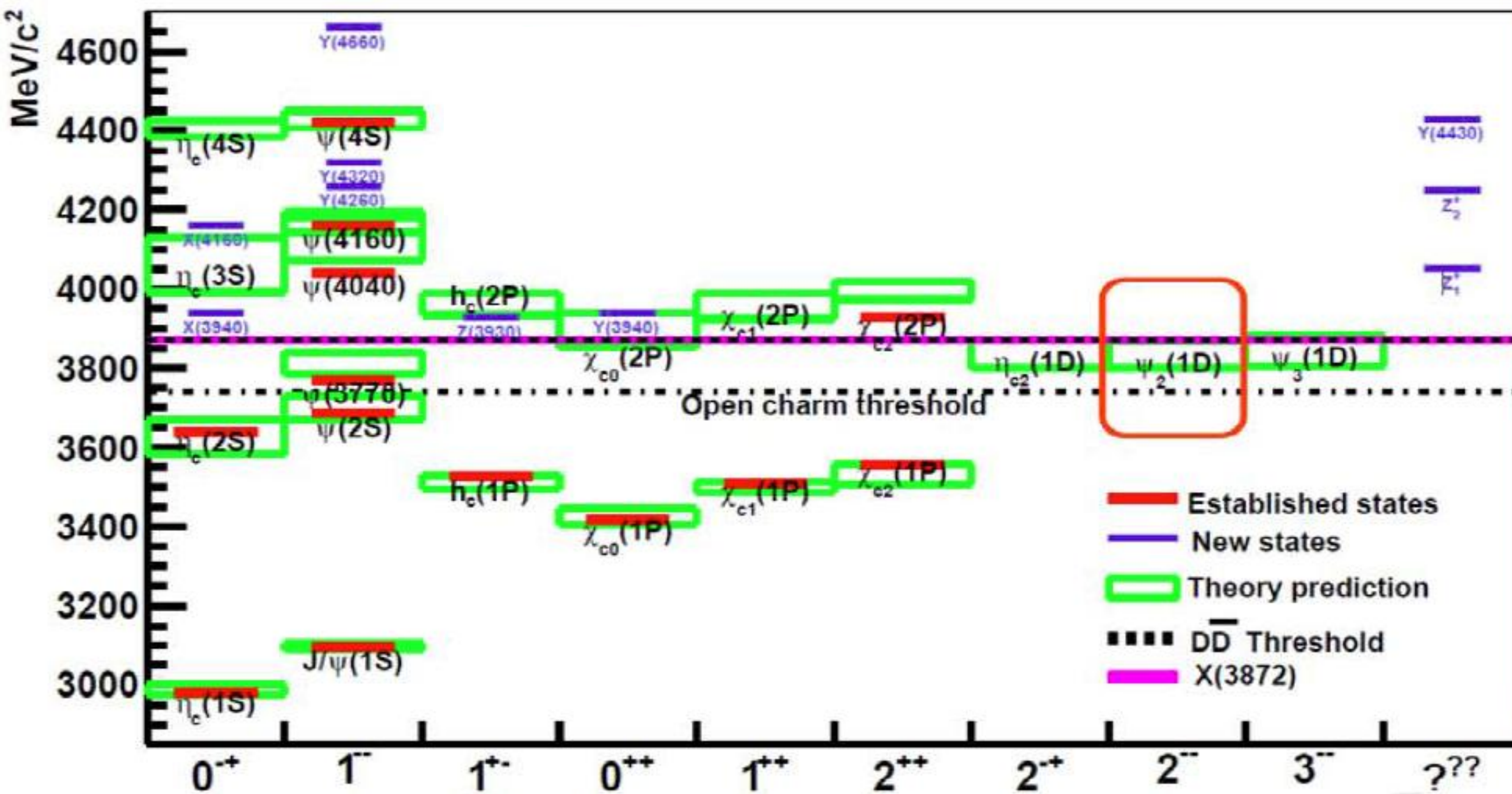


D.Y.Chen, X.Liu, PRD84(2011)034032

Q.Wang,C.Hanhart,Q.Zhao PRL111(2013)132003

Usual hadrons with hidden charm and beauty

$$\bar{c}c \rightarrow \bar{c}\,\bar{q}\,c\,q$$



$c\bar{c}$	$I^G(J^{PC})$
• $\eta_c(1S)$	$0^+(0^{-+})$
• $J/\psi(1S)$	$0^-(1^{--})$
• $\chi_{c0}(1P)$	$0^+(0^{++})$
• $\chi_{c1}(1P)$	$0^+(1^{++})$
• $h_c(1P)$	$?^?(1^{+-})$
• $\chi_{c2}(1P)$	$0^+(2^{++})$
• $\eta_c(2S)$	$0^+(0^{-+})$
• $\psi(2S)$	$0^-(1^{--})$
• $\psi(3770)$	$0^-(1^{--})$
• $X(3872)$	$0^+(1^{++})$
• $\chi_{c0}(2P)$	$0^+(0^{++})$
• $\chi_{c2}(2P)$	$0^+(2^{++})$
$X(3940)$	$?^?(?^{??})$
• $\psi(4040)$	$0^-(1^{--})$
$X(4050)^\pm$	$?(?^?)$
$X(4140)$	$0^+(?^{?+})$
• $\psi(4160)$	$0^-(1^{--})$
$X(4160)$	$?^?(?^{??})$
$X(4250)^\pm$	$?(?^?)$
• $X(4260)$	$?^?(1^{--})$
$X(4350)$	$0^+(?^{?+})$
• $X(4360)$	$?^?(1^{--})$
• $\psi(4415)$	$0^-(1^{--})$
$X(4430)^\pm$	$?(?^?)$
• $X(4660)$	$?^?(1^{--})$

$b\bar{b}$	
$\eta_b(1S)$	$0^+(0^{-+})$
• $\Upsilon(1S)$	$0^-(1^{--})$
• $\chi_{b0}(1P)$	$0^+(0^{++})$
• $\chi_{b1}(1P)$	$0^+(1^{++})$
• $h_b(1P)$	$?^?(1^{+-})$
• $\chi_{b2}(1P)$	$0^+(2^{++})$
$\eta_b(2S)$	$0^+(0^{-+})$
• $\Upsilon(2S)$	$0^-(1^{--})$
• $\Upsilon(1D)$	$0^-(2^{--})$
• $\chi_{b0}(2P)$	$0^+(0^{++})$
• $\chi_{b1}(2P)$	$0^+(1^{++})$
$h_b(2P)$	$?^?(1^{+-})$
• $\chi_{b2}(2P)$	$0^+(2^{++})$
• $\Upsilon(3S)$	$0^-(1^{--})$
• $\chi_b(3P)$	$?^?(?^{?+})$
• $\Upsilon(4S)$	$0^-(1^{--})$
$X(10610)^\pm$	$?^+(1^+)$
$X(10650)^\pm$	$?^+(1^+)$
• $\Upsilon(10860)$	$0^-(1^{--})$
• $\Upsilon(11020)$	$0^-(1^{--})$

Necessary go beyond quenched quark model

hadron molecules, tetra-quark states, mixture, …

cf review by S.L.Zhu et al, arXiv:1311.3763

X(3872) ~ $\bar{c}c$ (L=1) + [$\bar{q}$ $\bar{c}$] [qc] + D*D + …

4. Conclusions

- **Hadron spectroscopy reveals unquenched quark picture**
- **Distinguishable prediction for hyperon spectroscopy is yelling for experimental confirmation**
- **Superheavy narrow N* and Λ* are predicted to exist**

  $\bar{D}\Sigma_c$, $\bar{D}_s\Lambda_c$ → $B\Sigma_b$, $B_s\Lambda_b$ bound states

  ~ 4.2 GeV ~11 GeV

  isovector meson partners $Z_c(3900)$, $Z_b(10610)$, Z_b (10650)

- **Experimental confirmation of them will unambiguously establish multiquark dynamics**

- **They can be looked for at 12GeV@Jlab and PANDA**

  maybe also at JPARC, super-B, RHIC , EIC?

Prospects at Future CCP

- **CCP – Circular Collider of Particles (e$^+$e$^-$, pp, ep, …)**
- **For hadron spectroscopy at CCP, high priority:**

  XYZ mesons with hidden $c\bar{c}$ or $b\bar{b}$ @super c-b

  Ω* baryons @super c

  Superheavy N*&Λ* with hidden $c\bar{c}$ or $b\bar{b}$ @ ep, pp

- **XYZ production from γ*γ*, $\mathfrak{P}\mathfrak{P}$, γ*$\mathfrak{P}$ by (e$^+$e$^-$, pp, ep)**

  → XYZ&$\mathfrak{P}$ structure, $q\bar{q}$ production mechanisms

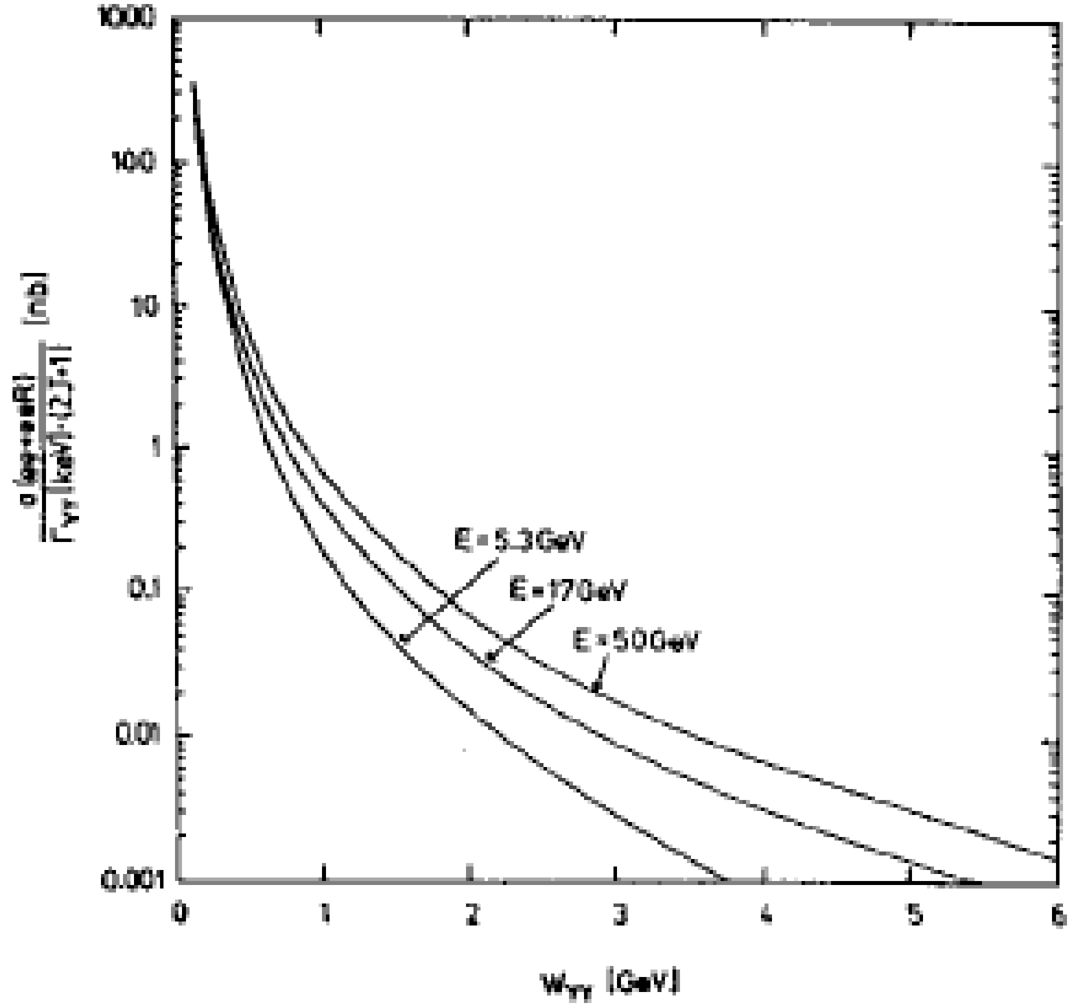
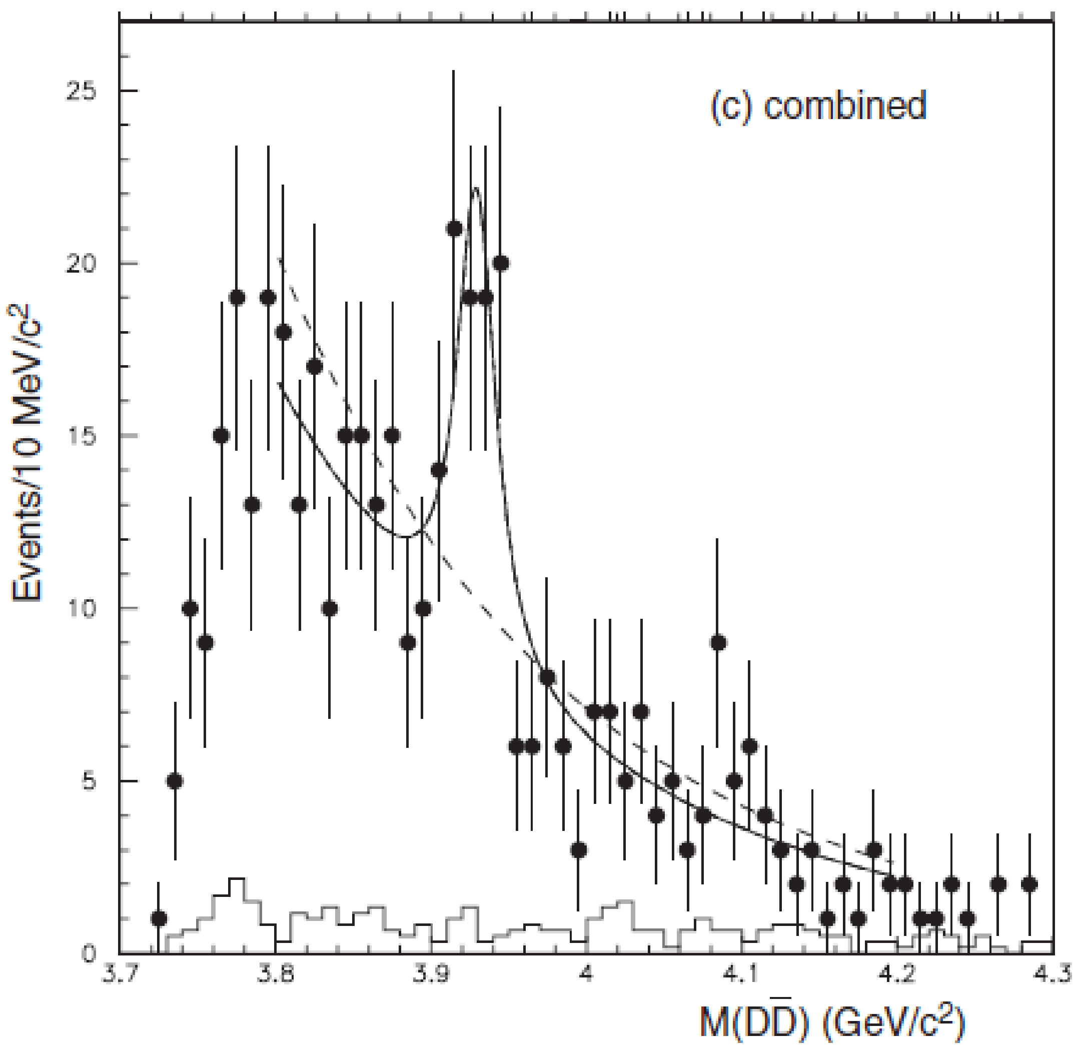


Figure 4: The e^+e^- cross section for the production of a resonance via the two-photon process (normalized to $\Gamma_{\gamma\gamma} = 1\ keV$).

H. Klanoski, P. M. Zerwas, “Two-Photon Physics ” 1987

Observation of a χ'_{c2} Candidate in $\gamma\gamma \to D\bar{D}$ Production at Belle

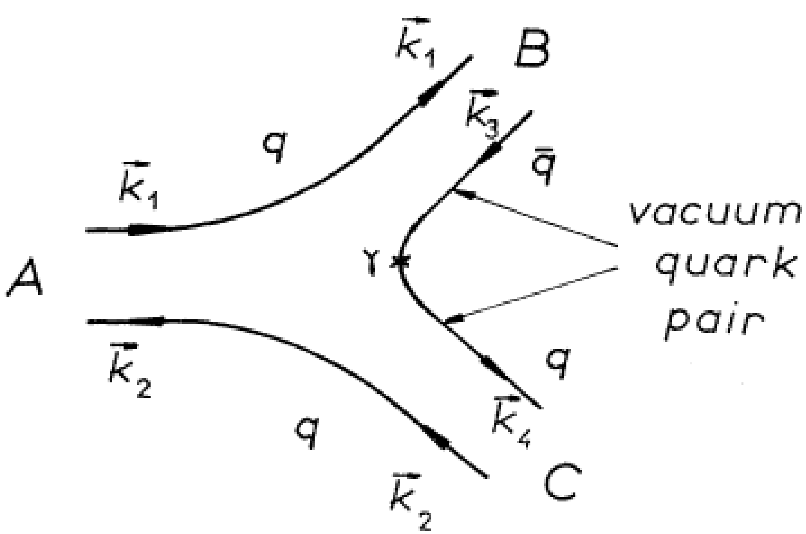


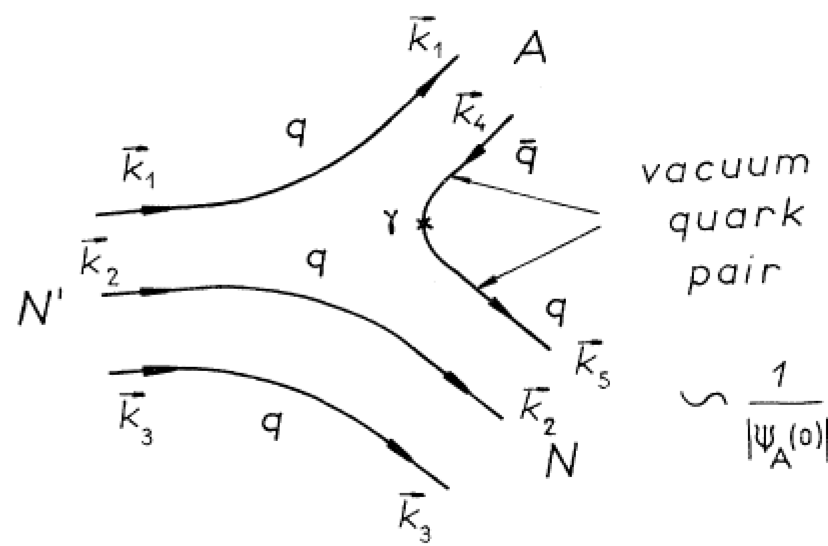
Thanks !

3. Mechanisms for $\bar{q}q$ pair production

1) **Perturbative $^3S_1$** **failed for 1^- and 1^+ decays**

2) **Non-perturbative $^3P_0$** **quite successful & popular**





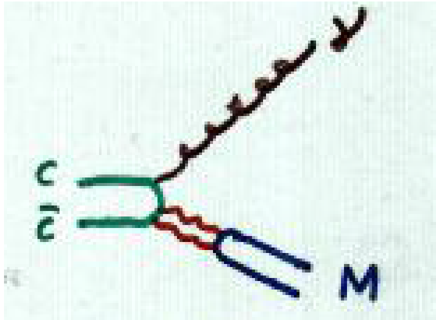
A. Le Yaouanc et al., **Phys.Rev. D8 (1973) 2223**

B. Aubert et al. (BABAR Collaboration), PRD 78 (2008) 112002:

$$\Gamma(\Upsilon(4S)\to\eta\Upsilon(1S))/\Gamma(\Upsilon(4S)\to\pi^+\pi^-\Upsilon(1S)) = 2.41\pm0.40_{\text{stat}}\pm0.12_{\text{syst}}$$

M. Ablikim et al. (BESIII Collaboration), PRD 86 (2012) 071101

$$\Gamma(\psi(4040)\to\eta J/\psi)/\Gamma(\psi(4040)\to\pi^+\pi^- J/\psi) > 2$$



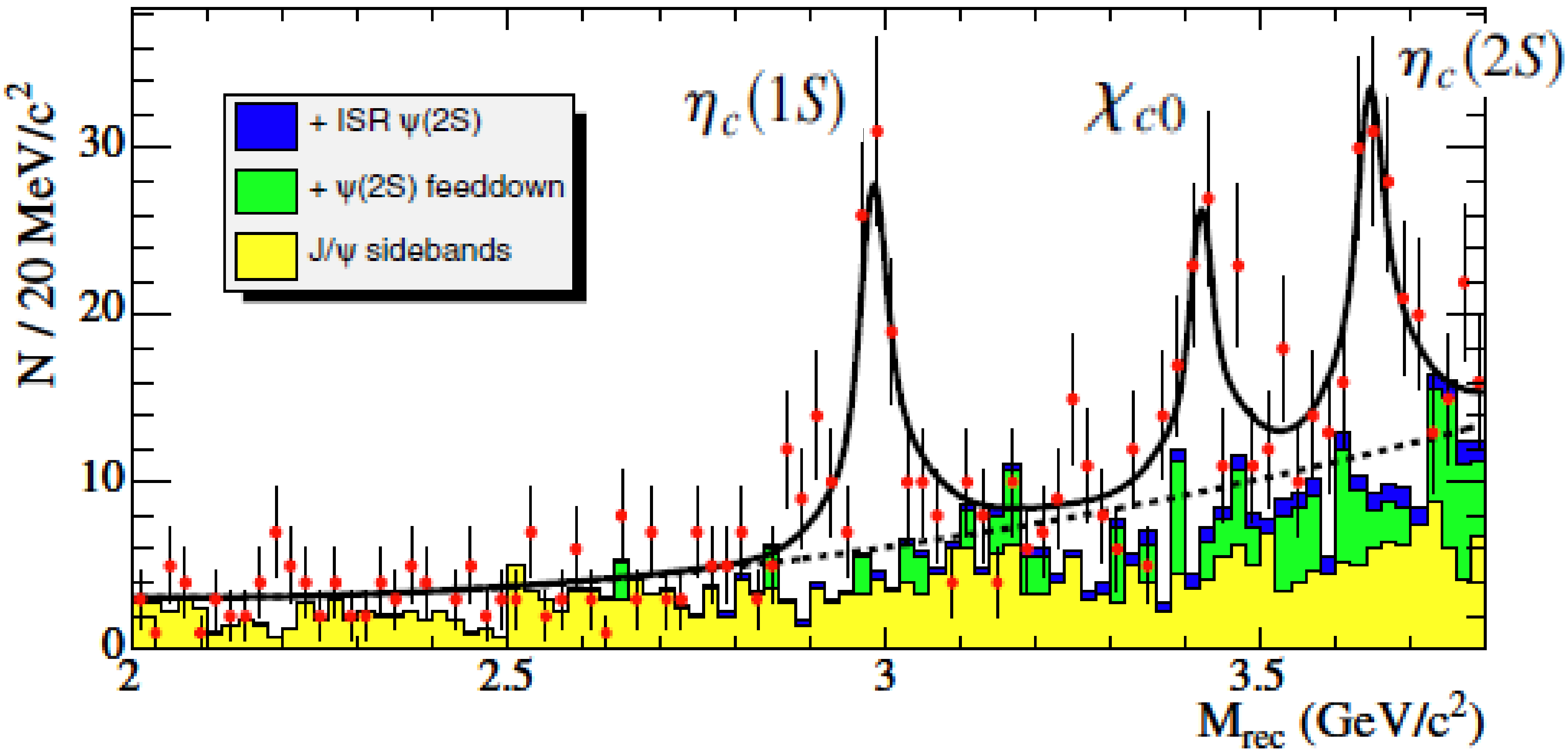
PDG:

$$\Gamma(J/\psi\to\gamma\eta) > \Gamma(J/\psi\to\gamma\sigma)$$

Gluons more favor to produce $\bar{q}q(^1S_0)$ sometimes !

$e^+e^- \to J/\psi\ c\bar{c}$

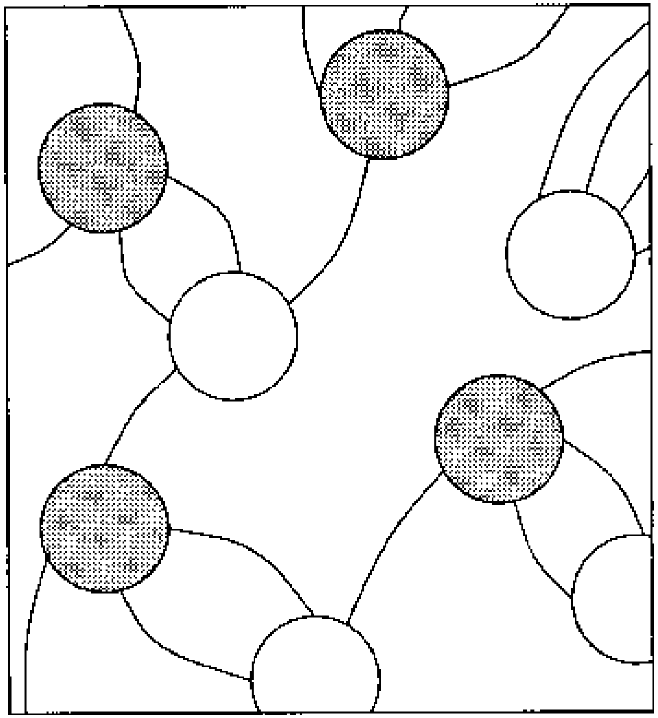
only 0^- and 0^+ $\bar{c}c$ observed !

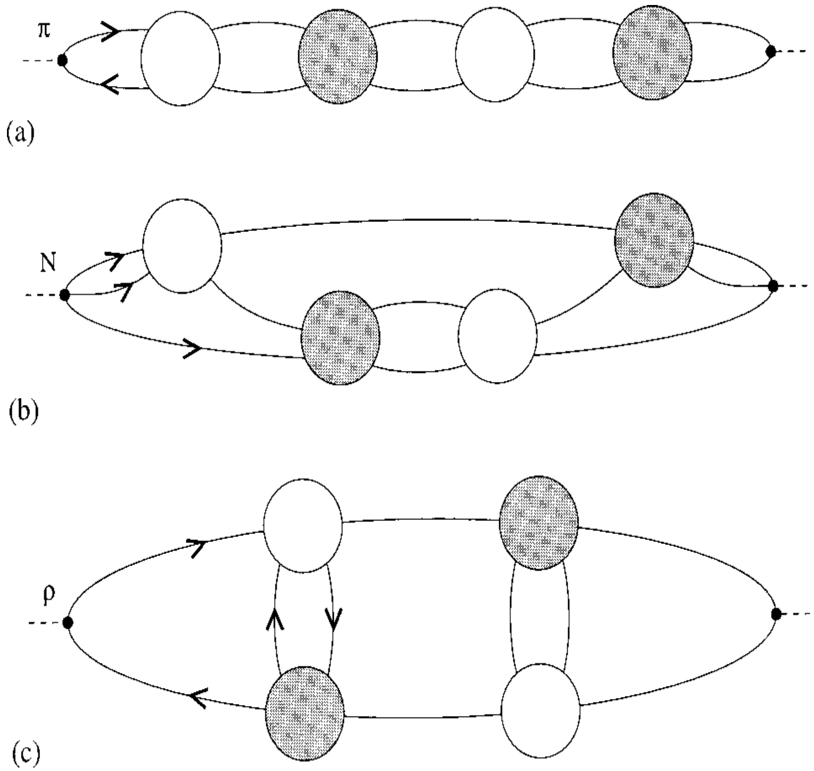


BaBar Collaboration, **Phys.Rev. D72 (2005) 031101**

Phenomenology of instantons in QCD

T. Schafer, E. Shuryak



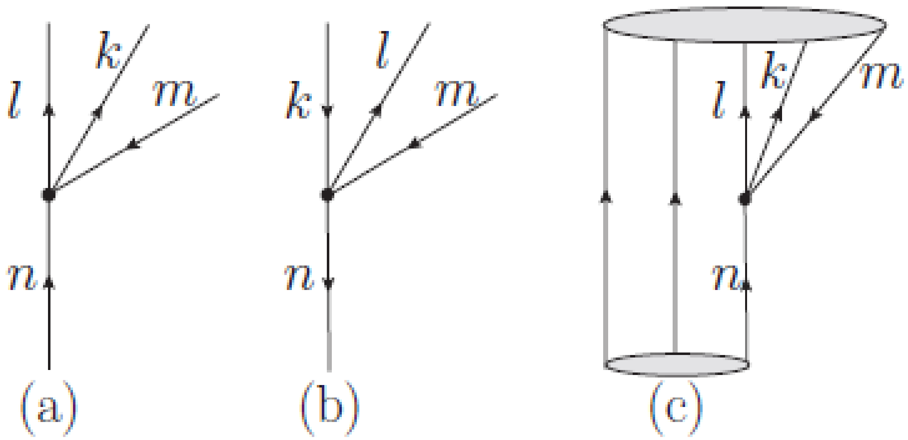


NJL model : **both 0^- & 0^+ important !**

$$\mathcal{L} = i\,\bar\psi\partial\!\!\!/\psi + \frac{\lambda}{4}\left[\left(\bar\psi\psi\right)\left(\bar\psi\psi\right) - \left(\bar\psi\gamma^5\psi\right)\left(\bar\psi\gamma^5\psi\right)\right] = i\,\bar\psi_L\partial\!\!\!/\psi_L + i\,\bar\psi_R\partial\!\!\!/\psi_R + \lambda\left(\bar\psi_L\psi_R\right)\left(\bar\psi_R\psi_L\right).$$

for baryon sss → sss $\bar{q}q$

$$H = \begin{pmatrix} H_3 & V_{\Omega_3 \leftrightarrow \Omega_5} \\ V_{\Omega_3 \leftrightarrow \Omega_5} & H_5 \end{pmatrix}$$



$$H_N = H_o + H_{hyp} + \sum_{i=1}^{N} m_i$$

$$H_o = \sum_{i=1}^{N} \frac{\vec{p}_i^{\,2}}{2m_i} + \sum_{i<j}^{N} V_{conf}(r_{ij})$$

$$H_{qq}^{NJL} = \sum_{i<j}^{N} \sum_{a=0}^{8} \hat{g}_{ij} \lambda_i^a \lambda_j^a [1 + \frac{1}{4m_i m_j} \hat{\sigma}_i \cdot (\vec{p}_i' - \vec{p}_i) \hat{\sigma}_j \cdot (\vec{p}_j' - \vec{p}_j)]$$

from $$\mathcal{L}_{NJL} = \frac{1}{2} g_s \sum_{a=0}^{8} [(\bar{q}\lambda^a q)^2 + (\bar{q} i \lambda^a \gamma_5 q)^2]$$

Totally different predictions for $1/2^-$ hyperons:

unquenched		quenched
Σ^*	$[us][du]\bar{d}$ ~ 1400 MeV	uus (L=1) ~ 1650 MeV
Ξ^*	$[us][ds]\bar{d}$ ~ 1550 MeV	uss (L=1) ~ 1760 MeV
Ω^*	$[us]ss\bar{u}$ ~ 1800 MeV	sss (L=1) ~ 2000 MeV

Meson-Baryon states

	Y.S.Oh	K. P. Khemchandani et al.	
Σ^*	~ 1475 MeV	~ 1426 MeV	
Ξ^*	~ 1616 MeV	~ 1606 MeV	Ramos & Oset
Ω^*	~ 1837 MeV	~ 1810 MeV	Wang & Zhang

Σ^* in PDG

******** $\Sigma(1189)1/2^+$ $\Sigma^*(1385)3/2^+$ $\Sigma^*(1670)3/2^-$
$\Sigma^*(1775)5/2^-$ $\Sigma^*(1915)5/2^+$ $\Sigma^*(2030)7/2^+$

******* $\Sigma^*(1660)1/2^+$ $\Sigma^*(1750)1/2^-$ $\Sigma^*(1940)3/2^-$
$\Sigma^*(2250)$??

****** $\Sigma^*(1690)$?? $\Sigma^*(1880)1/2^+$ $\Sigma^*(2080)3/2^+$
$\Sigma^*(2455)$?? $\Sigma^*(2620)$??

***** $\Sigma^*(1480)$?? $\Sigma^*(1560)$?? $\Sigma^*(1580)3/2^-$
$\Sigma^*(1620)1/2^-$ $\Sigma^*(1770)1/2^+$ $\Sigma^*(1840)3/2^+$
$\Sigma^*(2000)3/2^-$ $\Sigma^*(2070)5/2^+$ $\Sigma^*(2100)7/2^-$
$\Sigma^*(3000)$?? $\Sigma^*(3170)$??

All from old experiments of 1970-1985 !!

No established $1/2^-$ Σ^*, Ξ^*, Ω^* !