Non-perturbative $\bar{q}q$ pair production from gluon field

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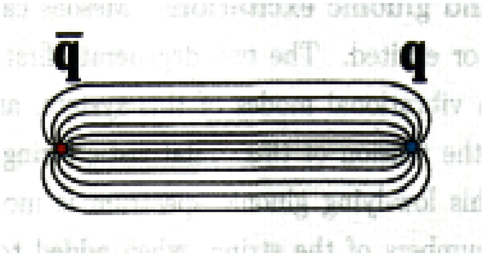
Outline :

1. Introduction
2. Hadron spectroscopy with strangeness
3. Mechanisms for $\bar{q}q$ pair production
4. Conclusions

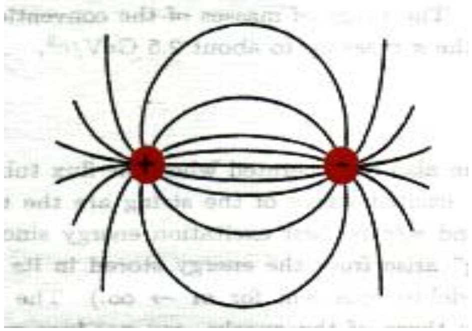
1. Introduction

Key problem in QCD and hadron structure

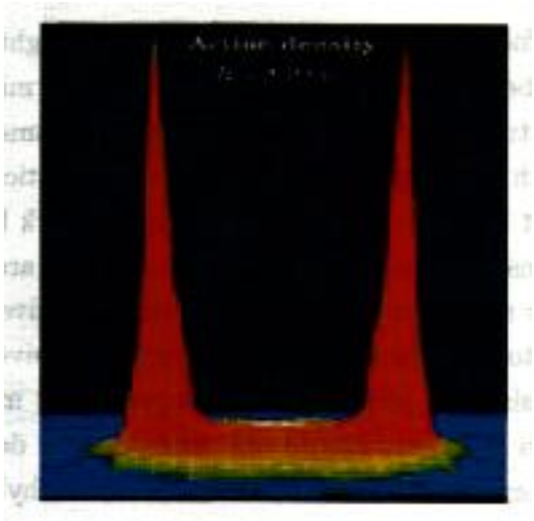
Quark confinement – self-interaction of gluons



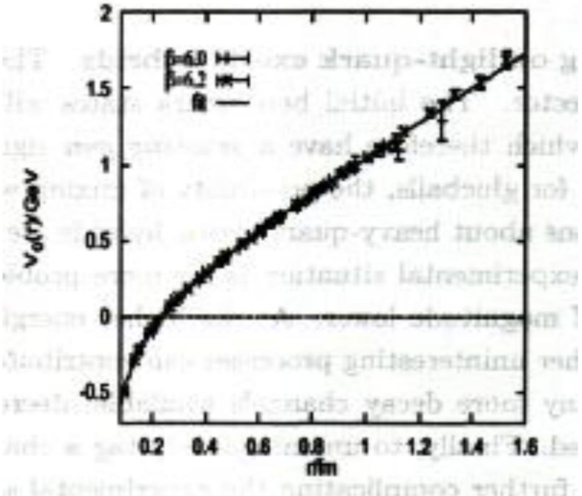
QCD field lines



QED field lines

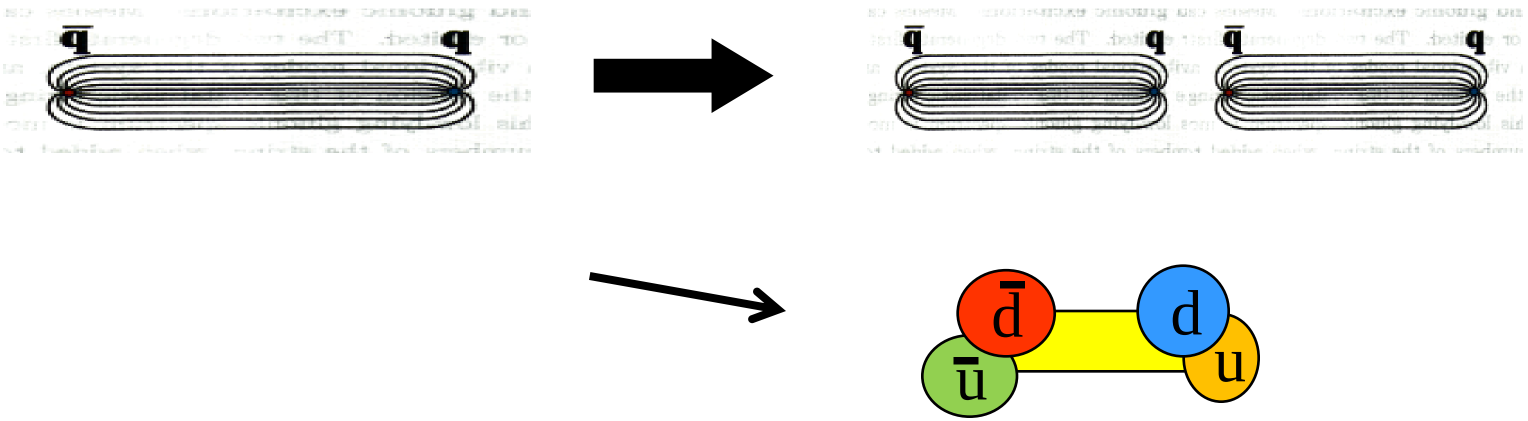


energy density



linear potential

Lattice QCD



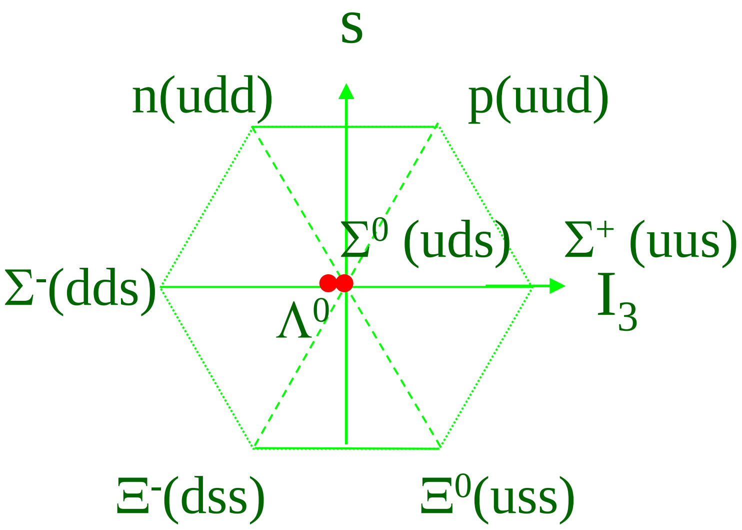
gluons → $\bar{q}q$: crucial for quark confinement
and hadron structure
to be more challenging than
atomic and nuclear structures

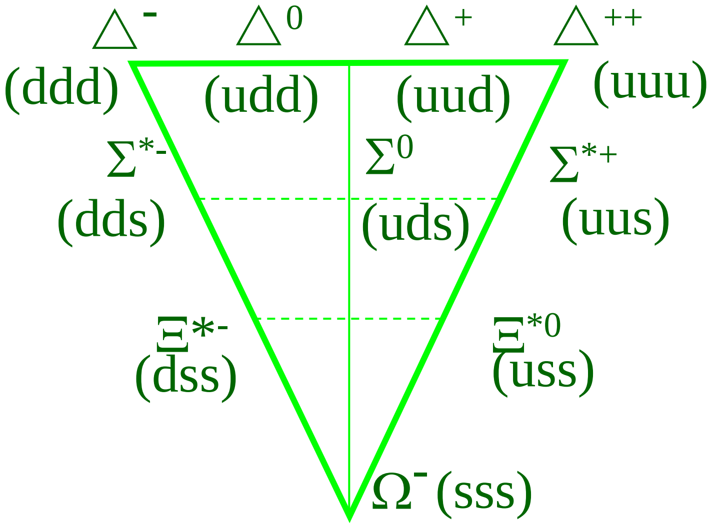
The number of constituents in a hadron is not a constant!

2. Hadron spectroscopy with strangeness

SU(3) 3q-quark model for baryons

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



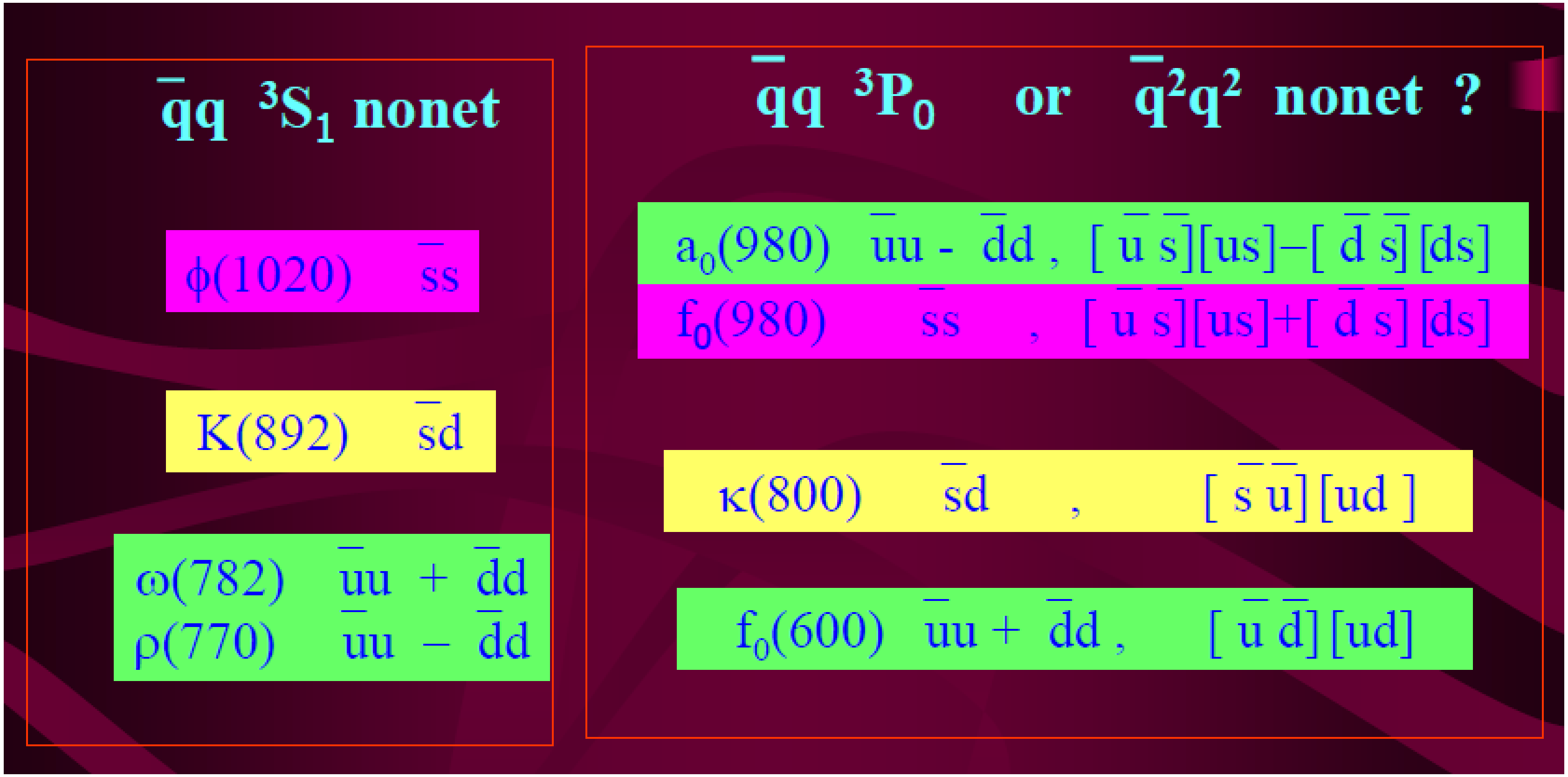


Successful for spatial ground states !

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

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

quenched vs un-quenched for mesons



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

$\phi(1020)$ $\bar{s}s$

$K(892)$ $\bar{s}d$

$\omega(782)$ $\bar{u}u + \bar{d}d$

$\rho(770)$ $\bar{u}u - \bar{d}d$

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

$a_0(980)$ $\bar{u}u - \bar{d}d$, $[\bar{u}\,\bar{s}][us]-[\bar{d}\,\bar{s}][ds]$

$f_0(980)$ $\bar{s}s$, $[\bar{u}\,\bar{s}][us]+[\bar{d}\,\bar{s}][ds]$

$\kappa(800)$ $\bar{s}d$, $[\bar{s}\,\bar{u}][ud]$

$f_0(600)$ $\bar{u}u + \bar{d}d$, $[\bar{u}\,\bar{d}][ud]$

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

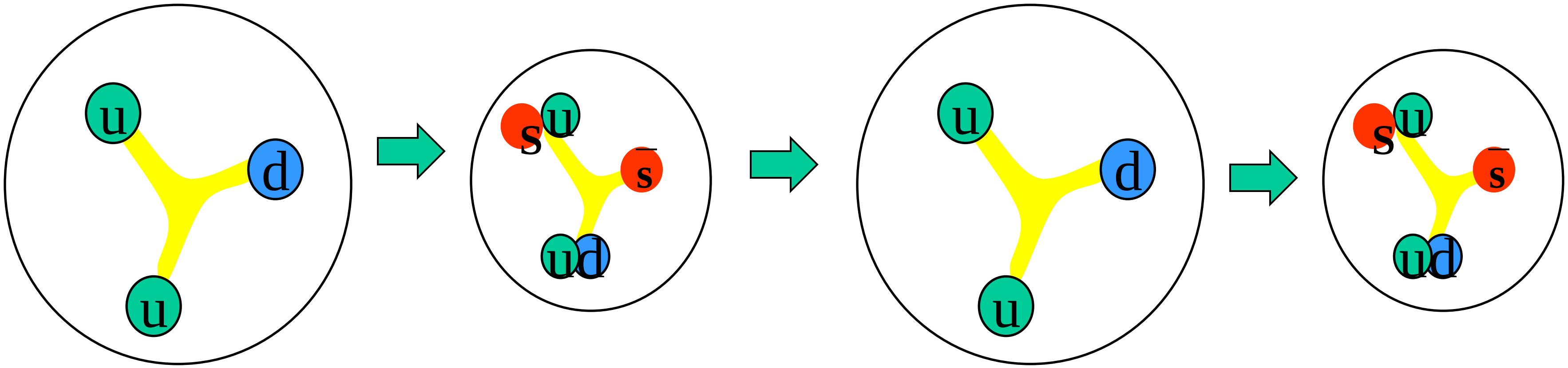
Zou et al, NPA835 (2010) 199 ; CLAS, PRC87(2013)035206

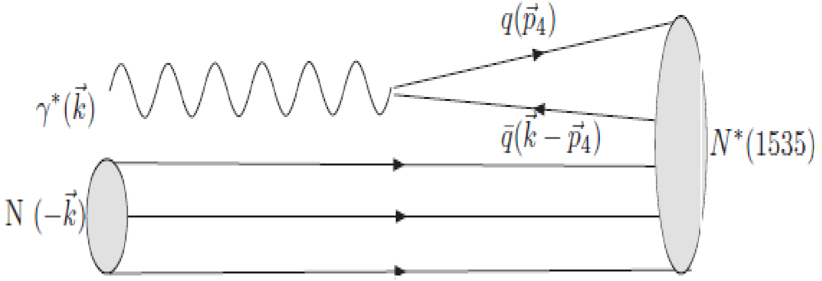
- **Strange decays of N*(1535) and Λ*(1670) :**

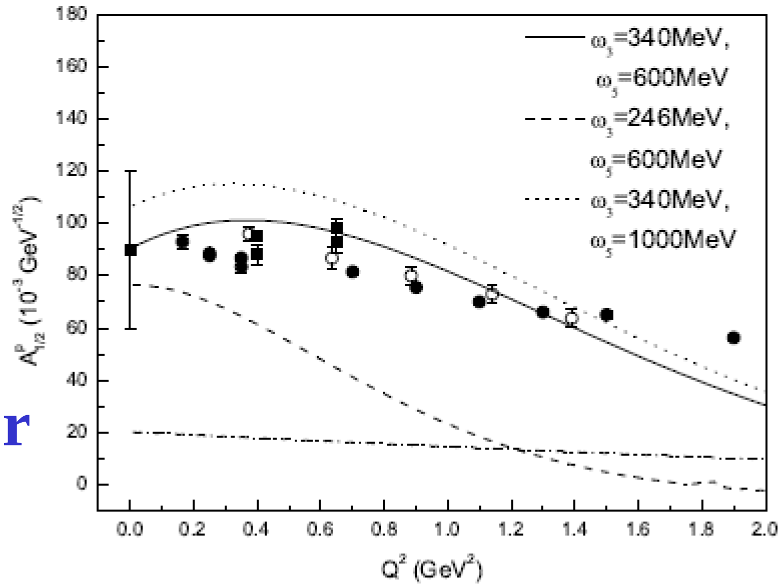
N*(1535) large couplings $g_{N^*N\eta}$, $g_{N^*K\Lambda}$, $g_{N^*N\eta'}$, $g_{N^*N\phi}$

Λ*(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-$\Sigma\pi$	**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 $\sim$ $\bar{q}q^2q^2$ state + …

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

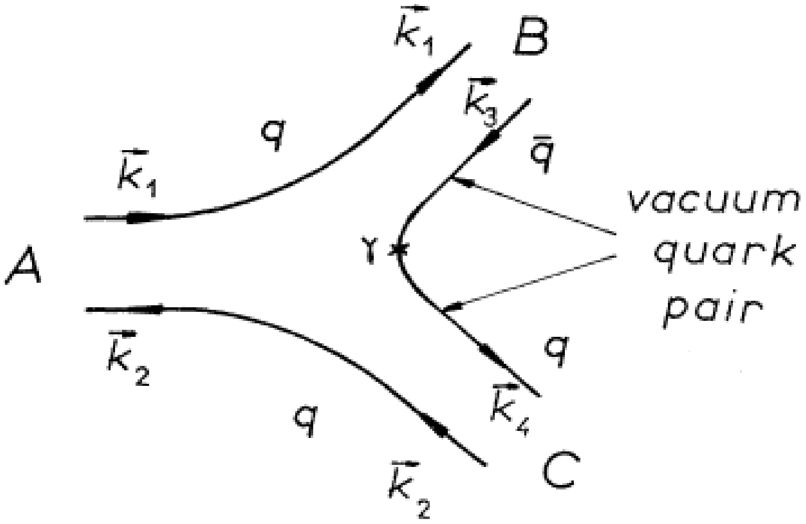
multiquark components are important for hadrons!

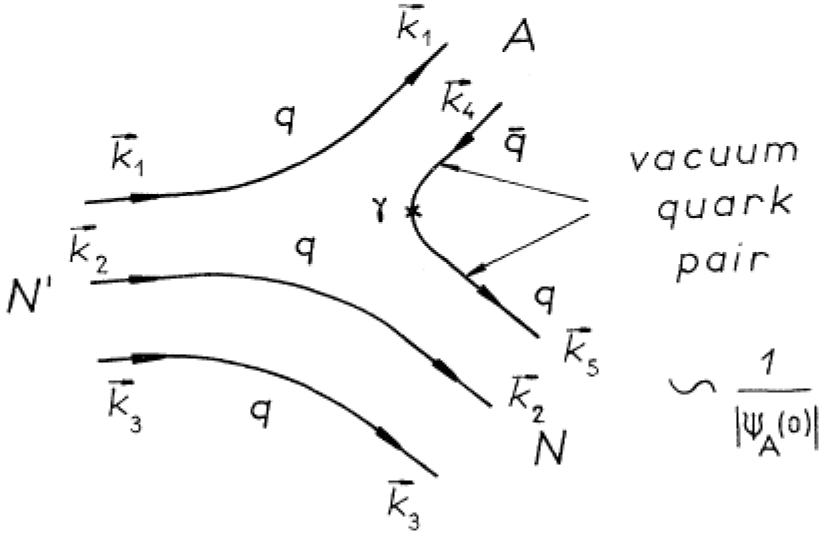
Quark model needs to be unquenched !

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**





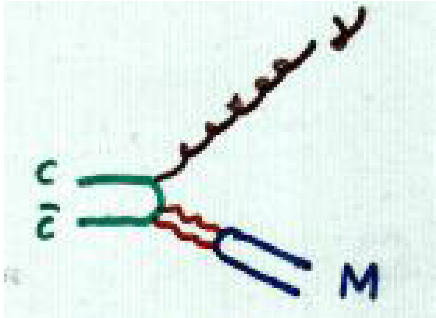
A. Le Yaouanc et al., **Phys.Rev. D8 (1973) 2223**

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

$$\Gamma(Y(4S)\to\eta Y(1S))/\Gamma(Y(4S)\to\pi^+\pi^- Y(1S)) = 2.41 \pm 0.40_{\mathrm{stat}} \pm 0.12_{\mathrm{syst}}$$

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

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

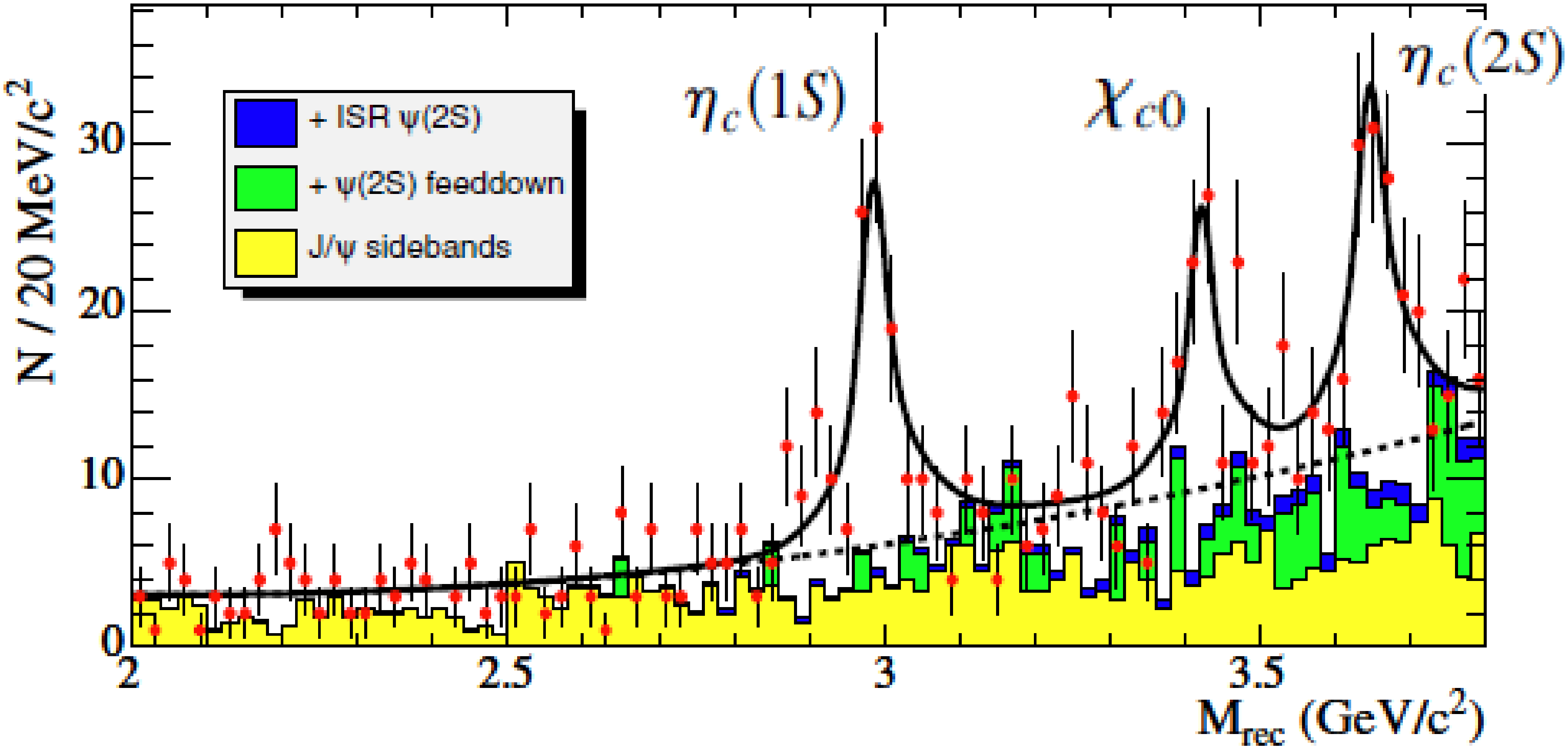


PDG:

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

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

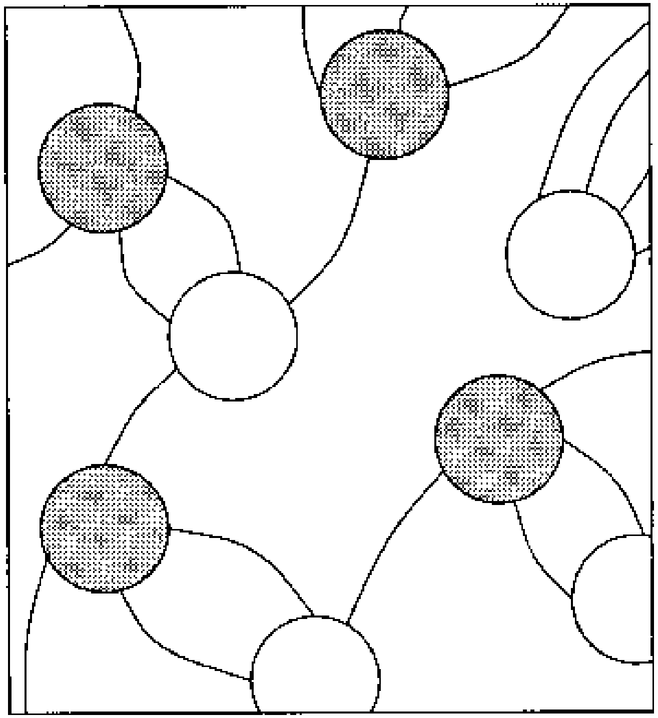
$e^+e^- \rightarrow J/\psi\ c\bar{c}$ **only 0⁻ and 0⁺ $\bar{c}$c observed !**

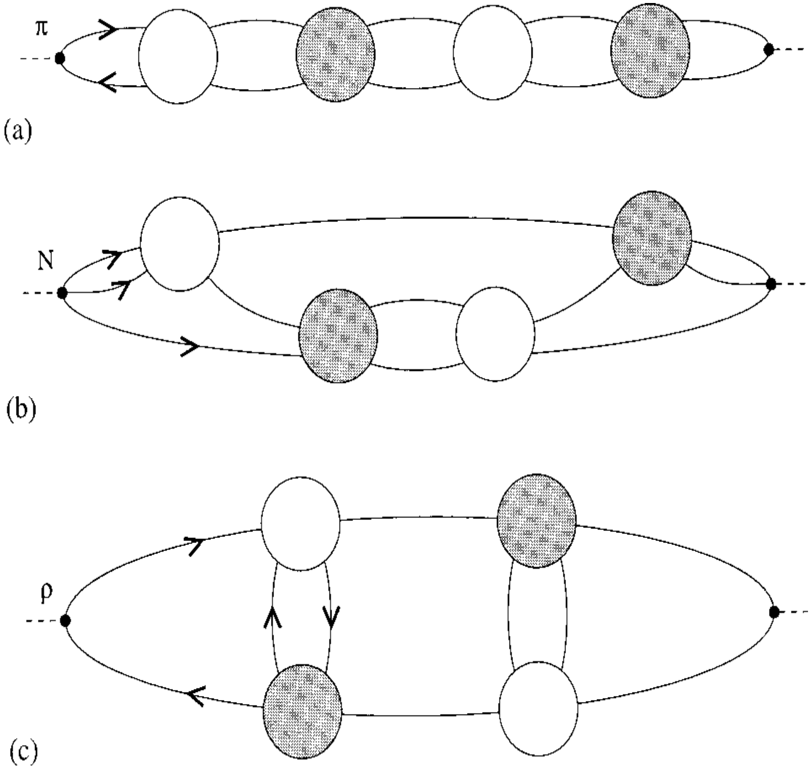


BaBar Collaboration, **Phys.Rev. D72 (2005) 031101**

Phenomenology of instantons in QCD

T. Schafer, E. Shuryak





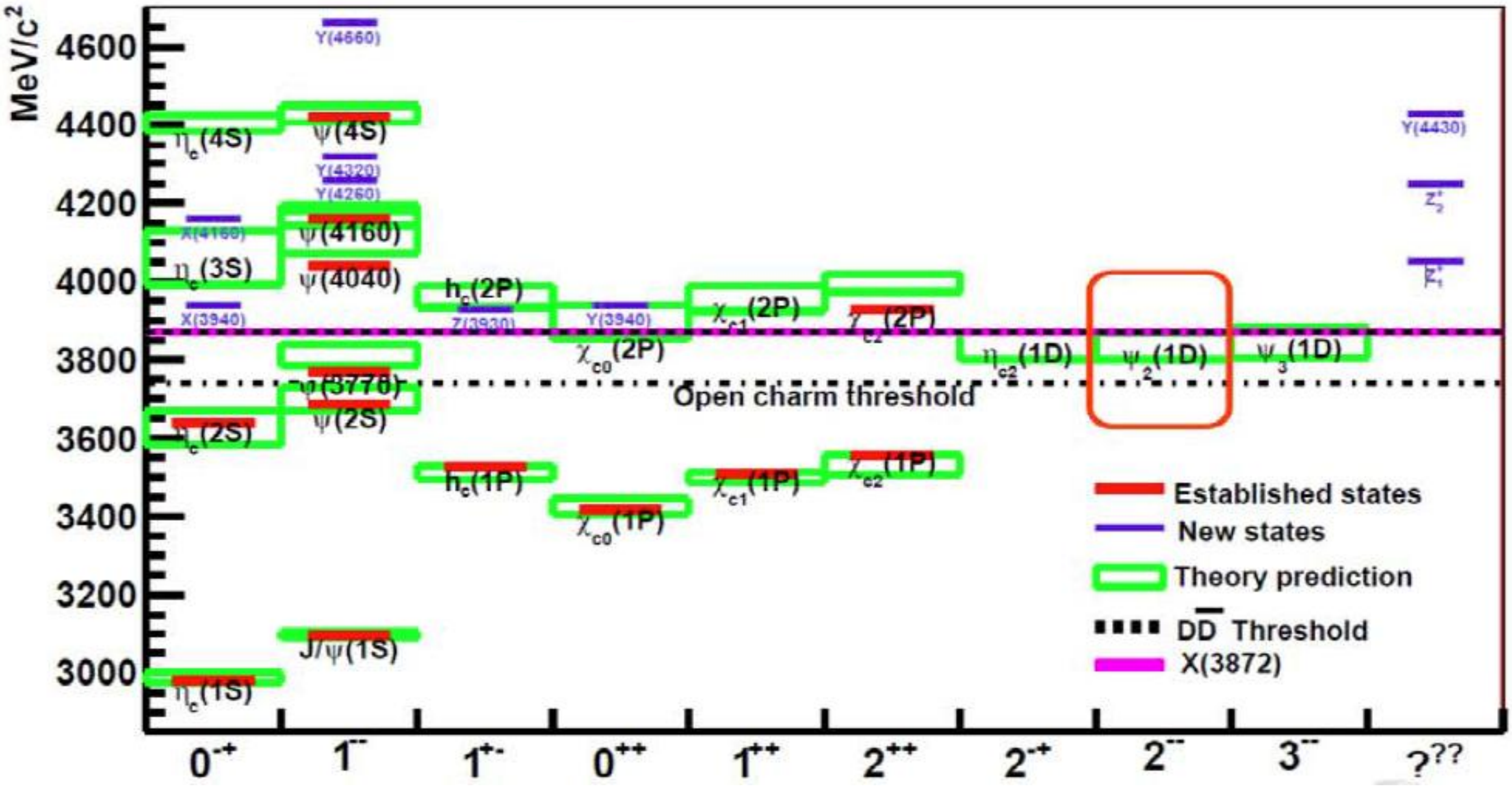
NJL model : **both 0^- & 0^+ important !**

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

Best playgrounds for unquenched quark models:

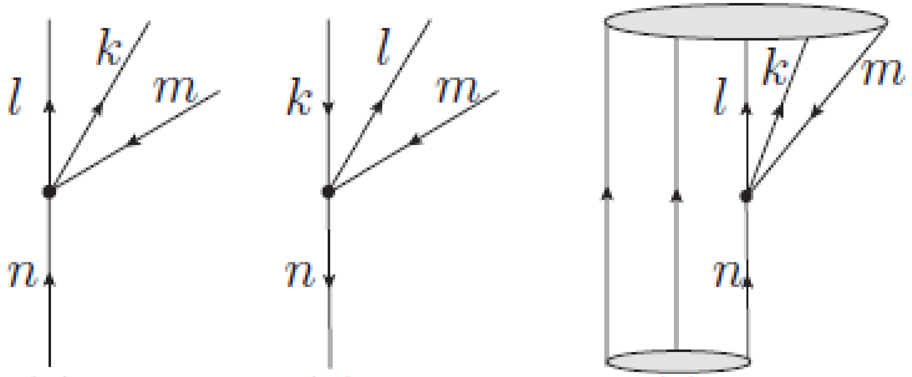
for baryon $sss \rightarrow sss\ \bar{q}q$

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



for baryon sss → sss $\bar{q}q$

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



(a) (b) (c)

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

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

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

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

Predictions for the lowest Ω^* by various models:

$\Omega^*(x/2^-)$ 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, ArXiv:1403.7897

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 = $(5 \pm 2) \times 10^{-5}$

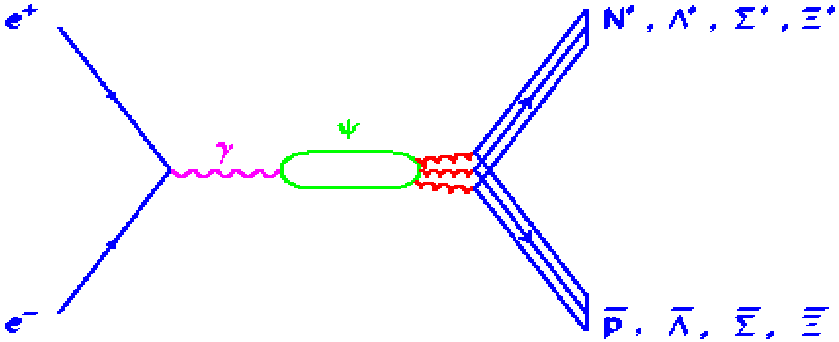
M. Ablikim et al. (BESII Coll.), CPC36(2012)1040

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

→ excitation mechanism for sss states

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

$$\psi \to \bar{B}BM \Rightarrow N^*, \Lambda^*, \Sigma^*, \Xi^*, \Omega^*$$



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

4. Conclusions

- Hadron spectroscopy reveals unquenched quark picture

- Both $^1S_0$ and $^3P_0$ are important for non-perturbtive $\bar{q}q$ pair production from gluon field

- Distinguishable prediction for hyperon spectroscopy is yelling for experimental confirmation :
  Very important to find the lowest Ω^* ($1/2^-$ or $3/2^-$) at BES3 or super τ-charm

Many more interesting channels at super τ-charm :

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

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

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

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

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

Thanks !

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 !!

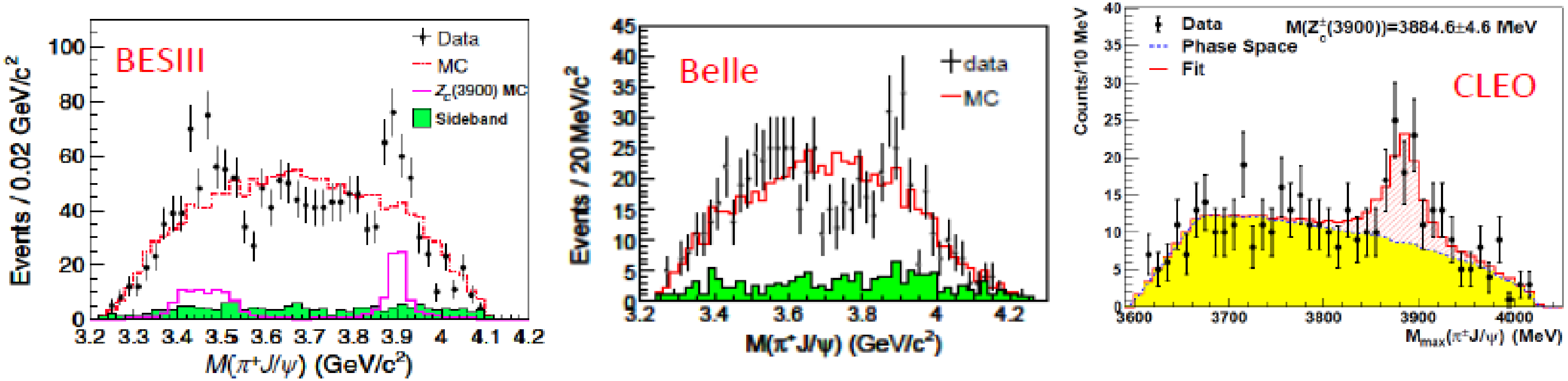
No established $1/2^-$ Σ^* , Ξ^*, Ω^* !

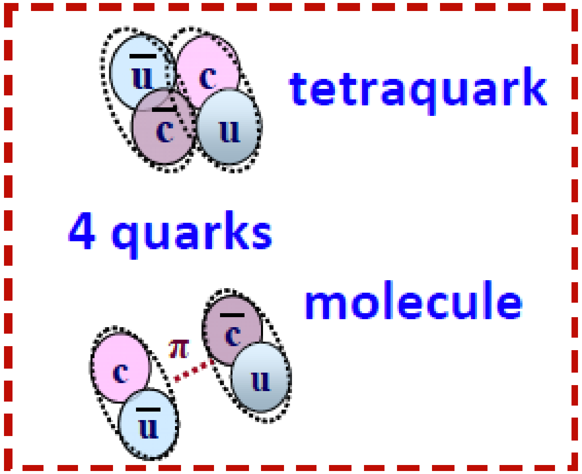
Zc(3900) production from Y(4260) decays

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

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

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



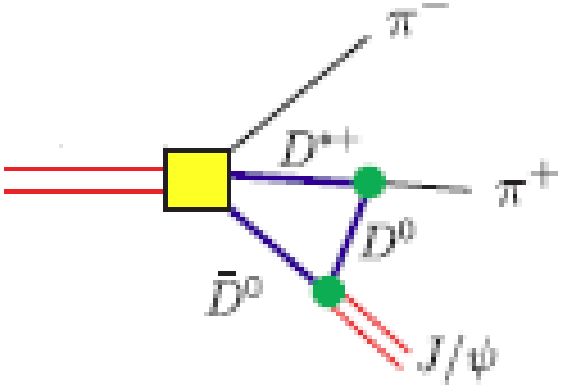


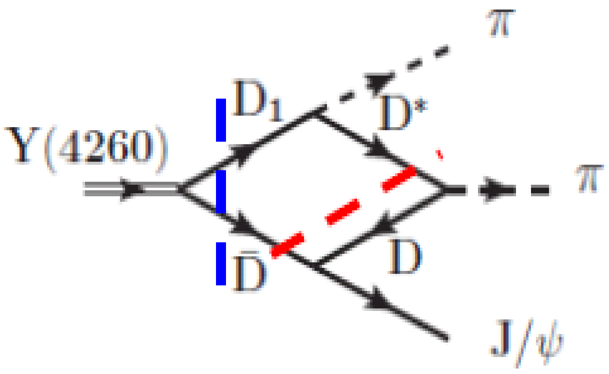
tetraquark

4 quarks

molecule

Exotic!





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

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