Exotic Hadrons

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PART IV of Lecture

Exotic hadrons

Long history of exotic hadrons

1977 Jaffe 4-quark states, di-baryons
    in the MIT bag model

Anything which are not $q\bar{q}$ or qqq are exotic, as far as they are color singlet.

$qq\bar{q}\bar{q}$, $qqq\bar{q}q$ contain extra $q\bar{q}$

$q\bar{q}g$, qqqg, . . contain constituent g

gg, ggg, . . no quark

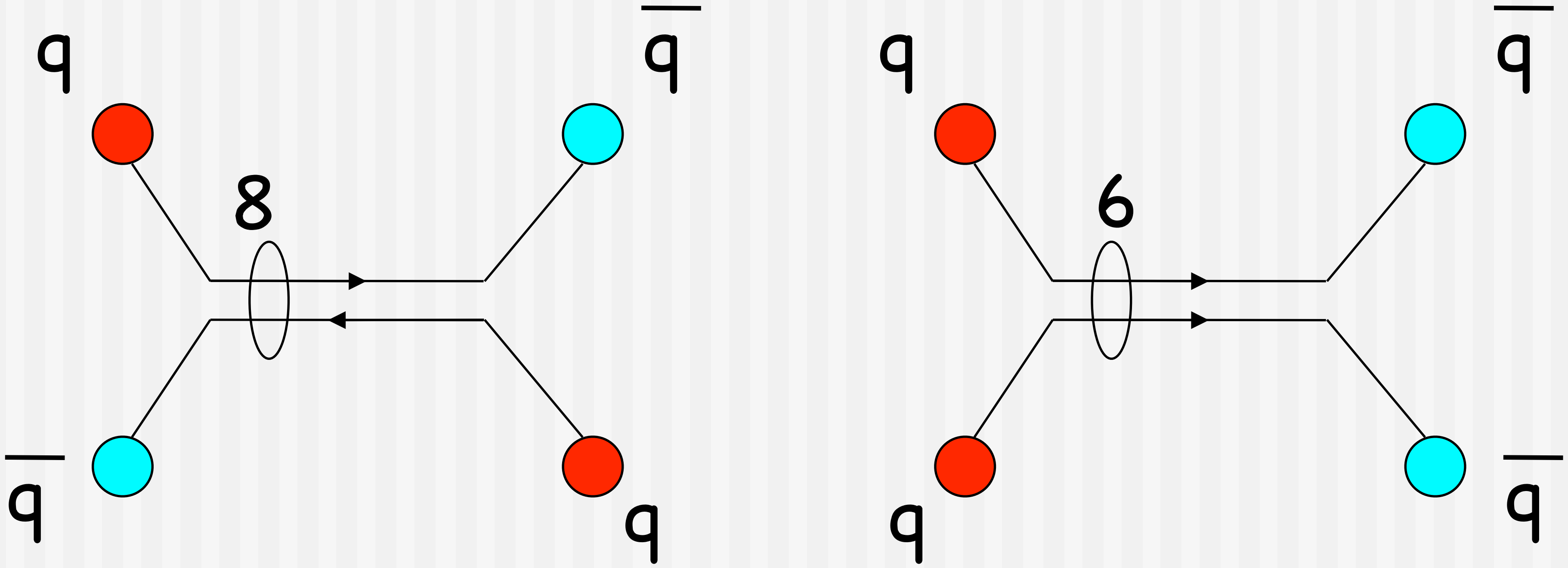
Exotic hadrons

Why are exotics interesting?

★ QCD does not prohibit exotic hadrons!

★ Exotics are more “Colorful” ! (Lipkin)

$(q\bar{q})_8$ or $(qq)_6$ are allowed only in the multi-quarks.



Exotic hadrons

(1) True exotics

minimal $qq\bar{q}\bar{q}$, $qqqq\bar{q}$, . . .

ex. $\Theta^+(S=+1)$, $D_s(I=1)$, $Z_c^+(4430)$,

$Z_b^+(10610)$, $Z_b^+(10650)$

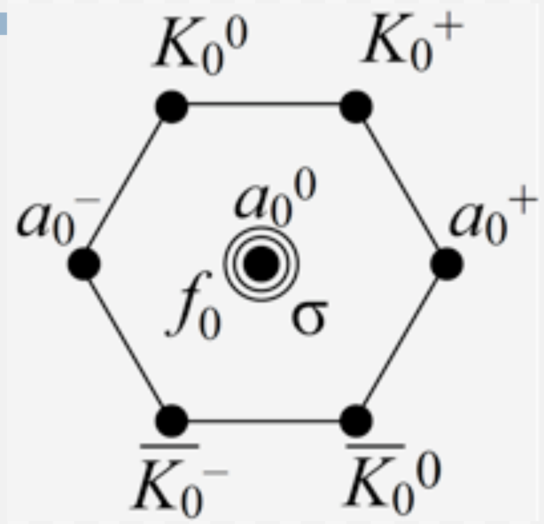
(2) Exotic multi-quark components of “normal" hadrons

meson $q\bar{q} + qq\bar{q}\bar{q}$

baryon $qqq + qqqq\bar{q}$

"Normal" so that no conserved quantum number prohibits the state as $q\bar{q}$ or qqq.

Tetraquarks?



Scalar mesons $J^\pi = 0^+$

light meson sector

$f_0(\sigma) \sim 600$ MeV $f_0' \sim 980$ MeV

$a_0 \sim 985$ MeV $K_0^*(\kappa) \sim 841$ MeV

The mass spectrum does not coincide with the $q\bar{q}$ states with SU(3) breaking (ideal mixing).

$f_0(\sigma) \sim u\bar{u}+d\bar{d}$ $f_0' \sim s\bar{s}$

$a_0 \sim u\bar{u}-d\bar{d}, u\bar{d}, d\bar{u}$ $K_0^* \sim u\bar{s}, d\bar{s}, s\bar{u}, s\bar{d}$

expected spectrum $m(\sigma) \sim m(a_0) < m(f_0)$

observed spectrum $m(\sigma) < m(a_0) \sim m(f_0)$

Tetraquarks?

4-quark states

$$\sigma \sim \bar{S}S = (ud)(\bar{u}\bar{d})$$
$$f_0 \sim \frac{\bar{U}U + \bar{D}D}{\sqrt{2}} = \frac{(ds)(\bar{d}\bar{s}) + (su)(\bar{s}\bar{u})}{\sqrt{2}}$$
$$a_0 \sim \frac{\bar{U}U - \bar{D}D}{\sqrt{2}} = \frac{(ds)(\bar{d}\bar{s}) - (su)(\bar{s}\bar{u})}{\sqrt{2}}$$

composed of diquarks in flavor 3

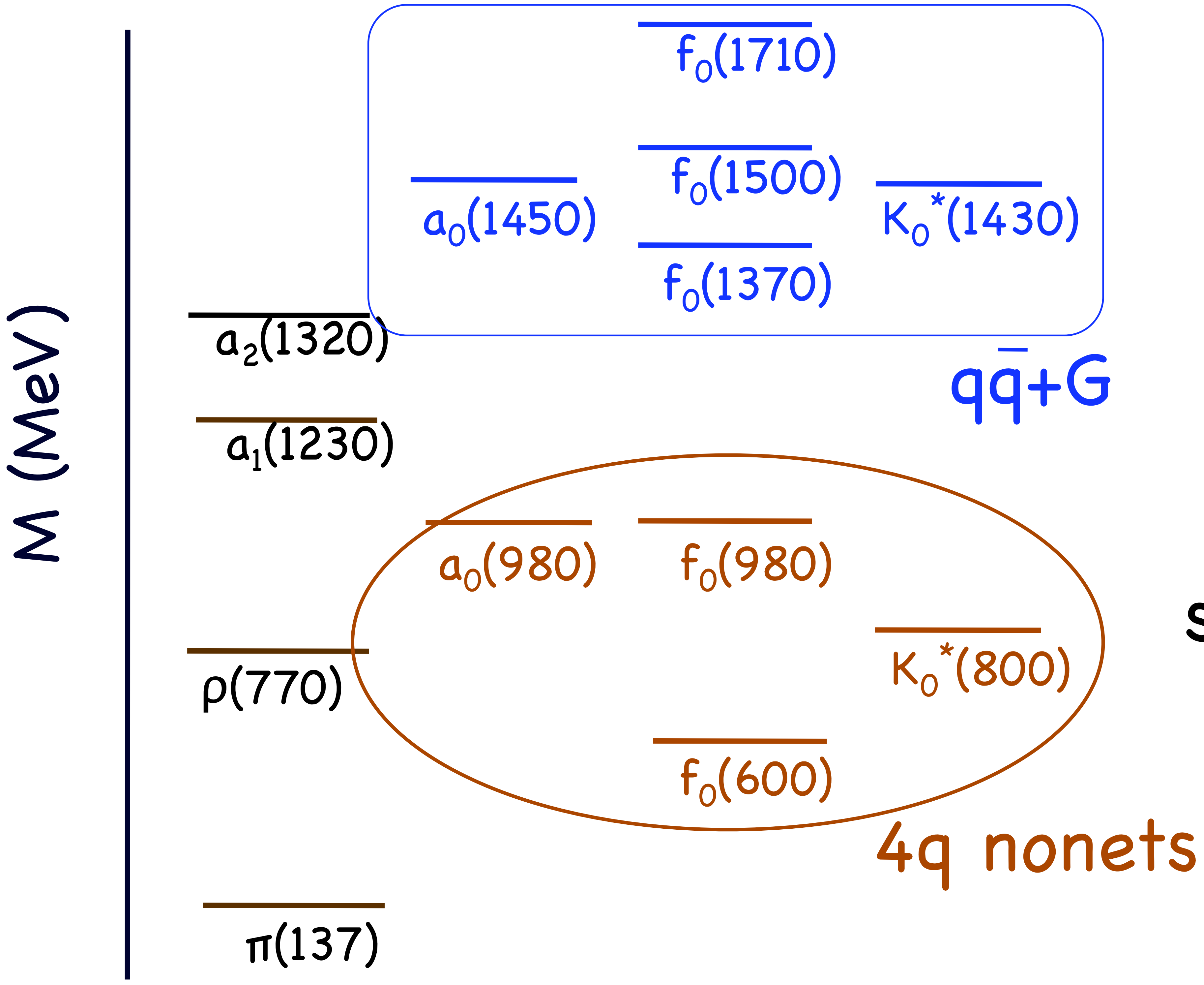
$$U = (\bar{d}\bar{s})_{S=0,C=\bar{3}} \qquad D = (\bar{s}\bar{u})_{S=0,C=\bar{3}} \qquad S = (\bar{u}\bar{d})_{S=0,C=\bar{3}}$$

give the right ordering of the spectrum just by strange quark counting

$$m(\sigma) < m(a_0) \sim m(f_0)$$

Jaffe (1977), Weinstein-Isgur (1982)
Black et al. (2000)

Tetraquarks?



M (MeV)

$f_0(1710)$

$a_0(1450)$

$f_0(1500)$

$K_0^*(1430)$

$f_0(1370)$

$a_2(1320)$

$q\bar{q}+G$

$a_1(1230)$

$a_0(980)$

$f_0(980)$

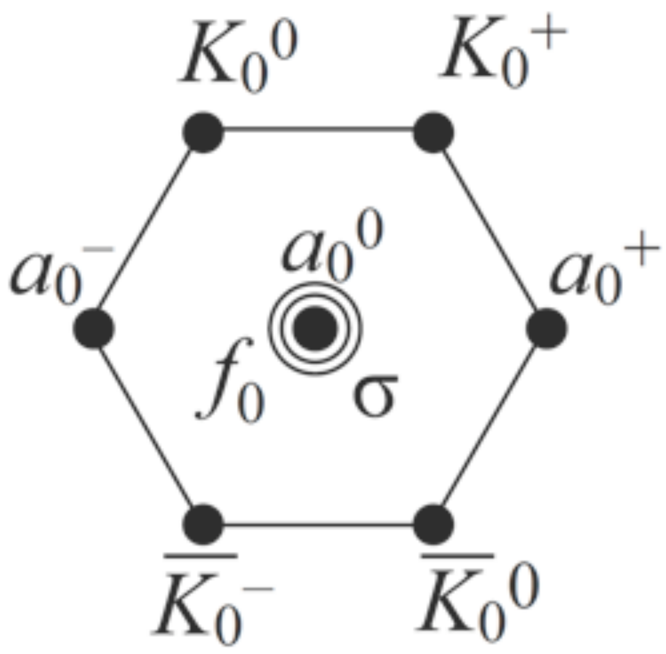
$\rho(770)$

$K_0^*(800)$

$f_0(600)$

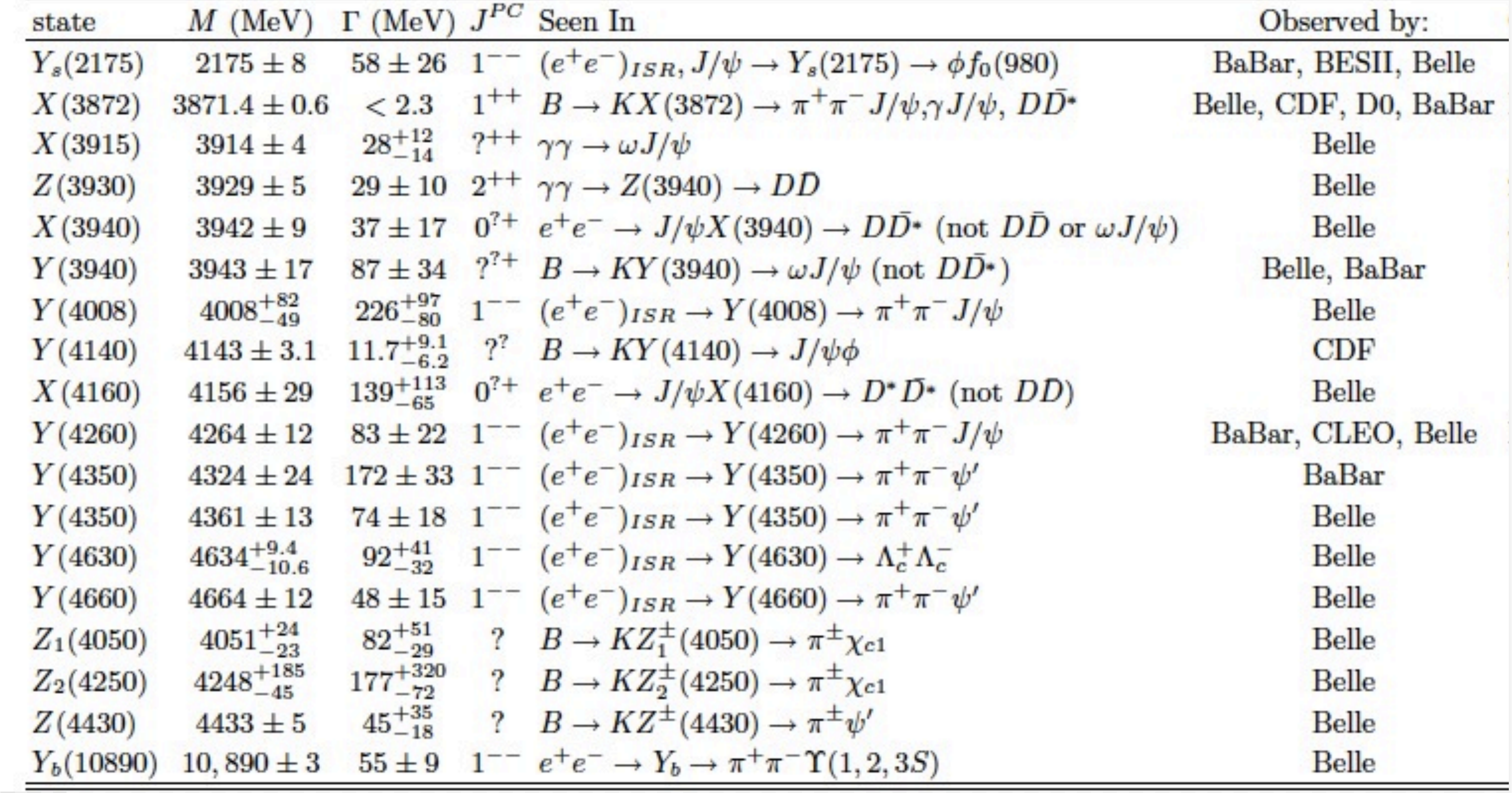
4q nonets

$\pi(137)$



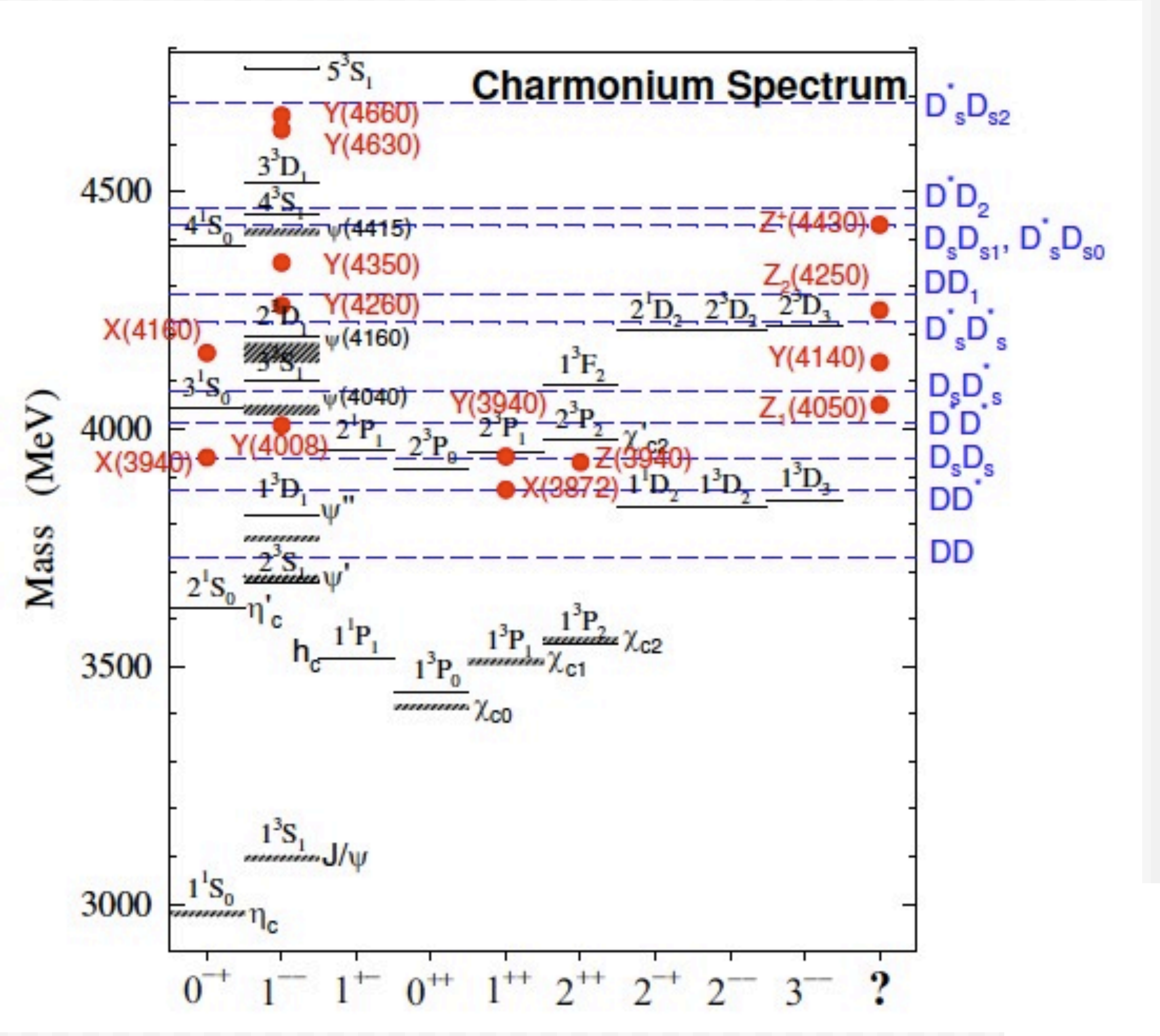
scalar nonets

Heavy Tetraquarks?



state	M (MeV)	Γ (MeV)	J^{PC}	Seen In	Observed by:
$Y_s(2175)$	2175 ± 8	58 ± 26	1^{--}	$(e^+e^-)_{ISR}, J/\psi \to Y_s(2175) \to \phi f_0(980)$	BaBar, BESII, Belle
$X(3872)$	3871.4 ± 0.6	< 2.3	1^{++}	$B \to KX(3872) \to \pi^+\pi^- J/\psi, \gamma J/\psi, D\bar{D}^*$	Belle, CDF, D0, BaBar
$X(3915)$	3914 ± 4	28^{+12}_{-14}	$?^{++}$	$\gamma\gamma \to \omega J/\psi$	Belle
$Z(3930)$	3929 ± 5	29 ± 10	2^{++}	$\gamma\gamma \to Z(3940) \to D\bar{D}$	Belle
$X(3940)$	3942 ± 9	37 ± 17	$0^{?+}$	$e^+e^- \to J/\psi X(3940) \to D\bar{D}^*$ (not $D\bar{D}$ or $\omega J/\psi$)	Belle
$Y(3940)$	3943 ± 17	87 ± 34	$?^{?+}$	$B \to KY(3940) \to \omega J/\psi$ (not $D\bar{D}^*$)	Belle, BaBar
$Y(4008)$	4008^{+82}_{-49}	226^{+97}_{-80}	1^{--}	$(e^+e^-)_{ISR} \to Y(4008) \to \pi^+\pi^- J/\psi$	Belle
$Y(4140)$	4143 ± 3.1	$11.7^{+9.1}_{-6.2}$	$?^?$	$B \to KY(4140) \to J/\psi\phi$	CDF
$X(4160)$	4156 ± 29	139^{+113}_{-65}	$0^{?+}$	$e^+e^- \to J/\psi X(4160) \to D^*\bar{D}^*$ (not $D\bar{D}$)	Belle
$Y(4260)$	4264 ± 12	83 ± 22	1^{--}	$(e^+e^-)_{ISR} \to Y(4260) \to \pi^+\pi^- J/\psi$	BaBar, CLEO, Belle
$Y(4350)$	4324 ± 24	172 ± 33	1^{--}	$(e^+e^-)_{ISR} \to Y(4350) \to \pi^+\pi^- \psi'$	BaBar
$Y(4350)$	4361 ± 13	74 ± 18	1^{--}	$(e^+e^-)_{ISR} \to Y(4350) \to \pi^+\pi^- \psi'$	Belle
$Y(4630)$	$4634^{+9.4}_{-10.6}$	92^{+41}_{-32}	1^{--}	$(e^+e^-)_{ISR} \to Y(4630) \to \Lambda_c^+\Lambda_c^-$	Belle
$Y(4660)$	4664 ± 12	48 ± 15	1^{--}	$(e^+e^-)_{ISR} \to Y(4660) \to \pi^+\pi^- \psi'$	Belle
$Z_1(4050)$	4051^{+24}_{-23}	82^{+51}_{-29}	?	$B \to KZ_1^\pm(4050) \to \pi^\pm \chi_{c1}$	Belle
$Z_2(4250)$	4248^{+185}_{-45}	177^{+320}_{-72}	?	$B \to KZ_2^\pm(4250) \to \pi^\pm \chi_{c1}$	Belle
$Z(4430)$	4433 ± 5	45^{+35}_{-18}	?	$B \to KZ^\pm(4430) \to \pi^\pm \psi'$	Belle
$Y_b(10890)$	$10,890 \pm 3$	55 ± 9	1^{--}	$e^+e^- \to Y_b \to \pi^+\pi^- \Upsilon(1,2,3S)$	Belle

Heavy Tetraquarks?



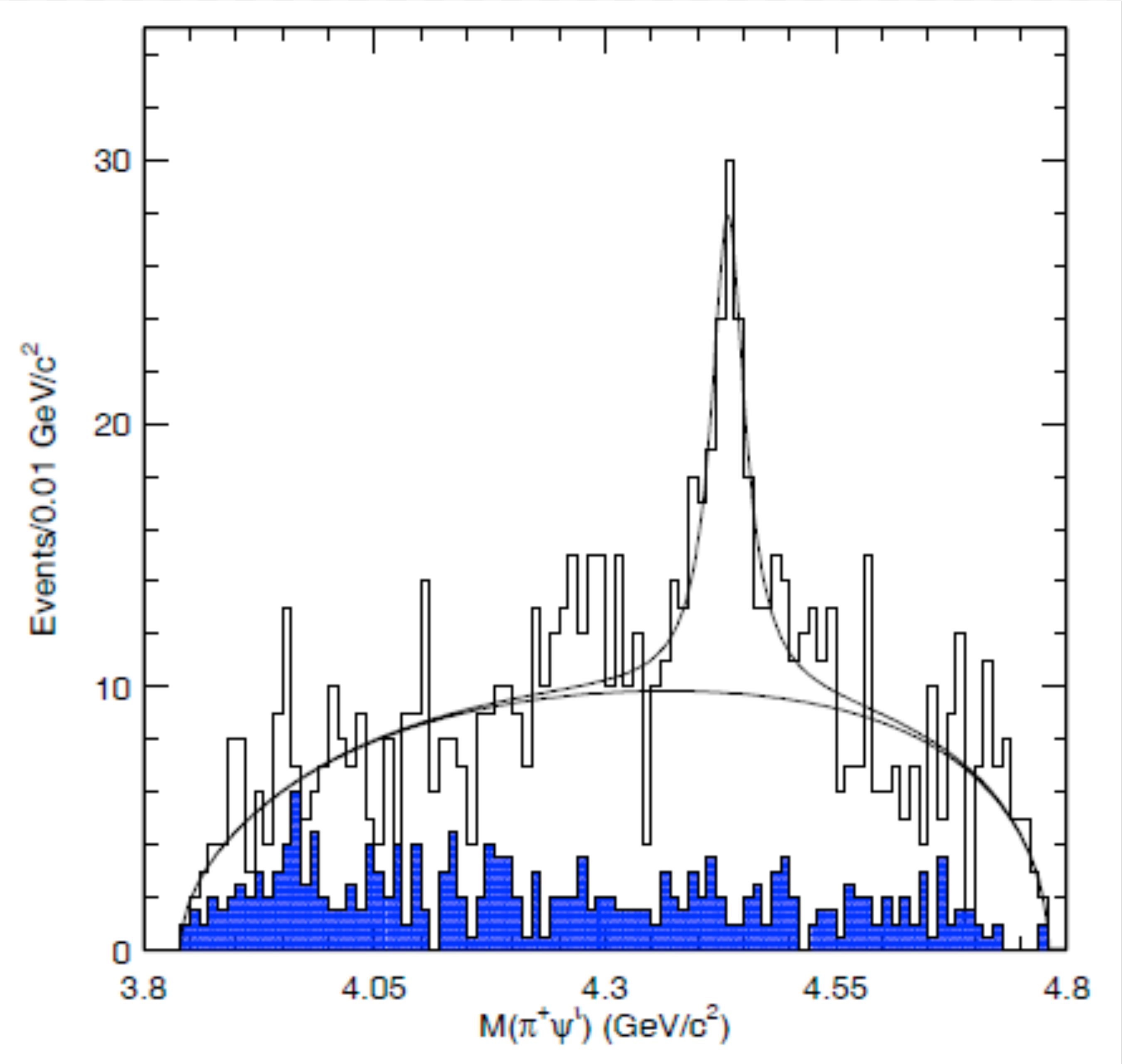
Heavy Tetraquarks?

- charged charmonium-like state $Z^{\pm}(4430)$ observed at the Belle (KEK) from decay of

  $B^0 \rightarrow KZ \rightarrow \pi^{\pm}\psi'$

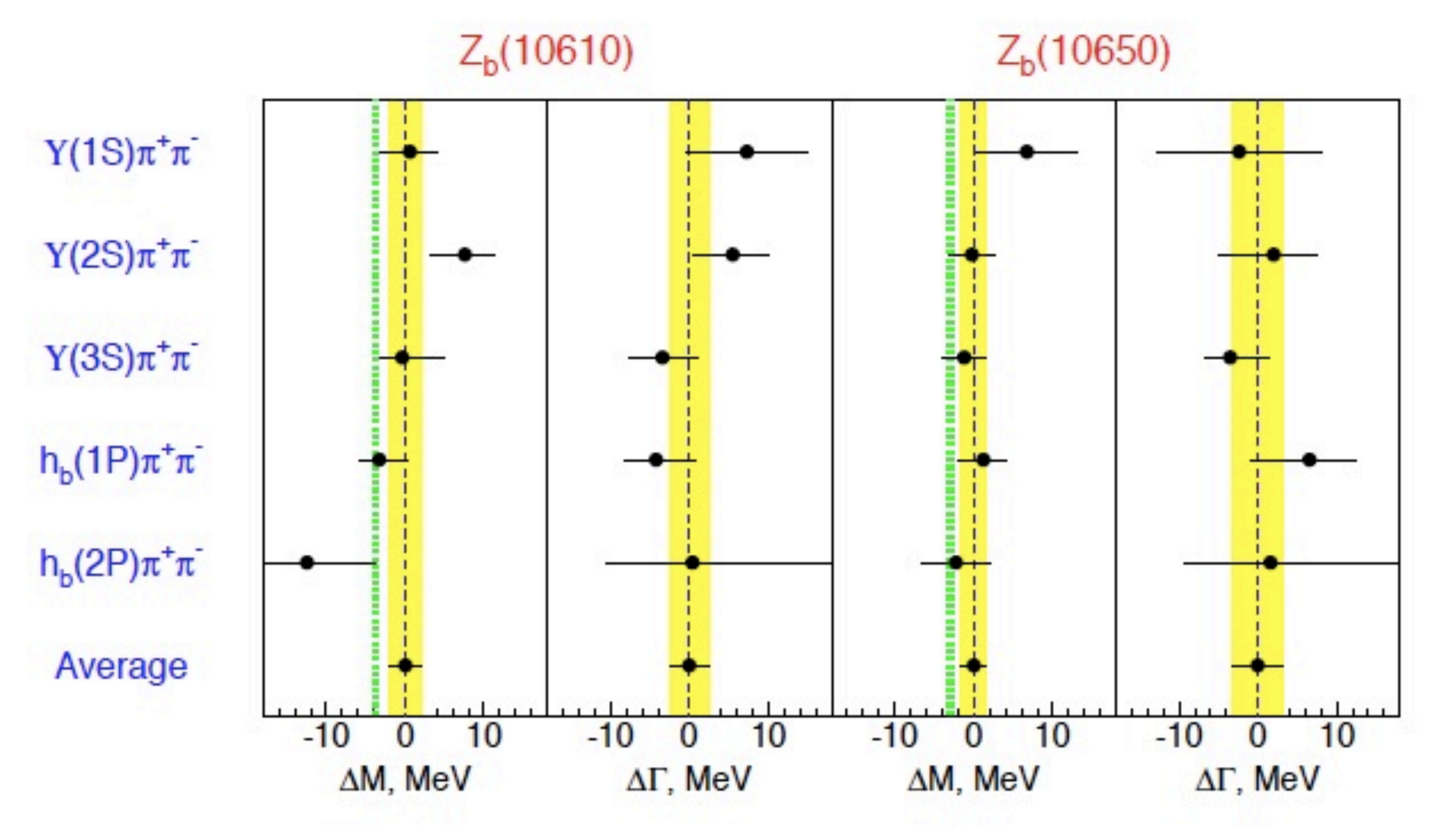
  Width: 45 MeV!

  minimal: $c\bar{c}u\bar{d}$



Heavy Tetraquarks?

- Charged bottomium-like state $Z_b^{\pm}(10610)$, $Z_b^{\pm}(10650)$ observed at the Belle (KEK) from decay of



Heavy Tetraquarks?

$X(3872)$ 4-quark state with spin 1^{++}

$[cq]_{S=1}[\overline{cq}]_{S=0} + [cq]_{S=0}[\overline{cq}]_{S=1}$ tetra-quark?

or $(DD^{*bar} + D^{*}D^{bar})$ molecule?

D_s mesons: $[cq][\overline{sq}]$

Other tetra-quark or molecular candidates include

- Y(4260)
- Y(4360)
- Y(4660)

How shall we determine the number of quarks in hadrons?

Multi-quark components of hadrons

Which hadrons are exotic or do contain exotic multi-quark components?

There are indications that the light scalar mesons, $f_0(600)$, $f_0(980)$, $a_0(980)$, $\kappa(900)$, and/or flavor-singlet negative-parity $\Lambda(1405)$ are multi-quarks.

Multi-quark components of hadrons

Why is $\Lambda(1405)$ likely to be 5q?

$\Lambda(1405)$ $J^{\pi} = 1/2^{-}$, flavor singlet

☆ uds L=1 orbital excited state with spin 1/2

=> $J=1/2^{-}$ and $3/2^{-}$

☆ $udsu\bar{u}$, . . L=0 ground state

$\underline{(ud)}\,\underline{(su)}\,\bar{u}$ . .

s=0 s=0 S=1/2 => J=1/2 isolated

diquarks $\Lambda(1520)$ $3/2^{-}$

The competition between the kinetic energy and the extra quark masses indicates possible mixing of the two Fock components.

Multi-quark components of hadrons

So far, hadrons are regarded as bound states of "valence" quarks defined in the quark model.

What does QCD predict?

In QCD, all hadrons, even N(940), contain extra $q\bar{q}$ as meson clouds and/or sea quarks.

When do we identify the extra flavor-singlet $\bar{q}q$ (or glue) as "valence" components?

We need a "good" definition of multi-quark-ness.

Multi-quark components of hadrons

Natural approach is to take a set of well-defined quantities, which might be useful for the quark model description.

Ex. overlaps of local operators.

$$\langle 0|J_3|\Lambda\rangle = \lambda\cos\theta\, u(x)$$
$$\langle 0|J_5|\Lambda\rangle = \lambda\sin\theta\, u(x)$$

Then one can determine the "mixing angle":

$$\begin{aligned}
\langle J_3(x)\bar{J}_3(0)\rangle \sim \langle 0|J_3(x)|\Lambda\rangle\langle\Lambda|\bar{J}_3(0)|0\rangle &= \lambda^2\cos^2\theta \\
\langle J_5(x)\bar{J}_5(0)\rangle \sim \langle 0|J_5(x)|\Lambda\rangle\langle\Lambda|\bar{J}_5(0)|0\rangle &= \lambda^2\sin^2\theta \\
\langle J_3(x)\bar{J}_5(0)\rangle \sim \langle 0|J_3(x)|\Lambda\rangle\langle\Lambda|\bar{J}_5(0)|0\rangle &= \lambda^2\sin 2\theta/2
\end{aligned}$$

QCD sum rule approach

☆ An approach in QCD sum rule.

a. 4-quark components of flavor non-singlet scalar mesons, a_0(I=1; 0^+), K_0(I=1/2; 0^+)

b. 5-quark components of Λ(singlet; $1/2^-$) baryon

c. 5-quark components of N($1/2^+$), N*($1/2^-$) baryons

T. Nakamura, J. Sugiyama, T. Nishikawa, N. Ishii, M.O.

Phys. Rev. D76 (2007) 114010
Phys. Lett. B662 (2008) 132-138

QCD sum rule approach

A set of interpolating fields (singlet Λ)

$$\begin{aligned}
J_3 &= \epsilon_{abc}\Big[\left(u_a^T C\gamma_5 d_b\right) s_c - \left(u_a^T C d_b\right)\gamma_5 s_c - \left(u_a^T C\gamma_5\gamma^\mu d_b\right)\gamma_\mu s_c\Big] \\
&= 2\epsilon_{abc}\Big[\left(u_a^T C\gamma_5 d_b\right) s_c + \left(d_a^T C\gamma_5 s_b\right) u_c + \left(s_a^T C\gamma_5 u_b\right) d_c\Big] \\
J_5 &= \epsilon_{abc}\epsilon_{def}\epsilon_{cfg}\Big[\left(d_a^T C\gamma_5 s_b\right)\left(s_d^T C\gamma_5 u_e\right)\gamma_5 C\bar{s}_g^T \\
&\qquad + \left(s_a^T C\gamma_5 u_b\right)\left(u_d^T C\gamma_5 d_e\right)\gamma_5 C\bar{u}_g^T \\
&\qquad + \left(u_a^T C\gamma_5 d_b\right)\left(d_d^T C\gamma_5 s_e\right)\gamma_5 C\bar{d}_g^T\Big]
\end{aligned}$$

How are these operators normalized?

Choose a J_5 and define a genuine 5-quark operator J_5' so that J_3 component of J_3 is subtracted.

$$J_5 = J_5' + \underbrace{\left(-\frac{1}{18}(\langle\bar{u}u\rangle + \langle\bar{d}d\rangle + \langle\bar{s}s\rangle)J_3\right)}_{J_3'}$$

QCD sum rule approach

then one may determine the operator which couples most strongly to the physical state,

$$
\begin{aligned}
|\Lambda\rangle &= \cos\theta|\Lambda_{3q}\rangle + \sin\theta|\Lambda_{5q}\rangle \\
|a_0\rangle &= \cos\theta|a_{2q}\rangle + \sin\theta|a_{4q}\rangle
\end{aligned}
$$

This method is "model independent", but it depends on the choice of the operator.

We may prefer having direct connection to the quark model approaches.

Number of quarks in QCD

☆ Is it legitimate to "count" # of quarks?

Not quite, because there exists no conserved current corresponding to the number of quarks: $N(q)+N(\bar{q})$.

It depends on the choice of the quark operator.

Ex. Bogoliubov transformation changes the definition of the # of quarks.

☆ Are there any observables which distinguish valence and sea quarks.

Can be done in the light-cone frame? i.e. partons?

Number of quarks in QCD

Hadronization in heavy ion collisions: Recombination and fragmentation of partons

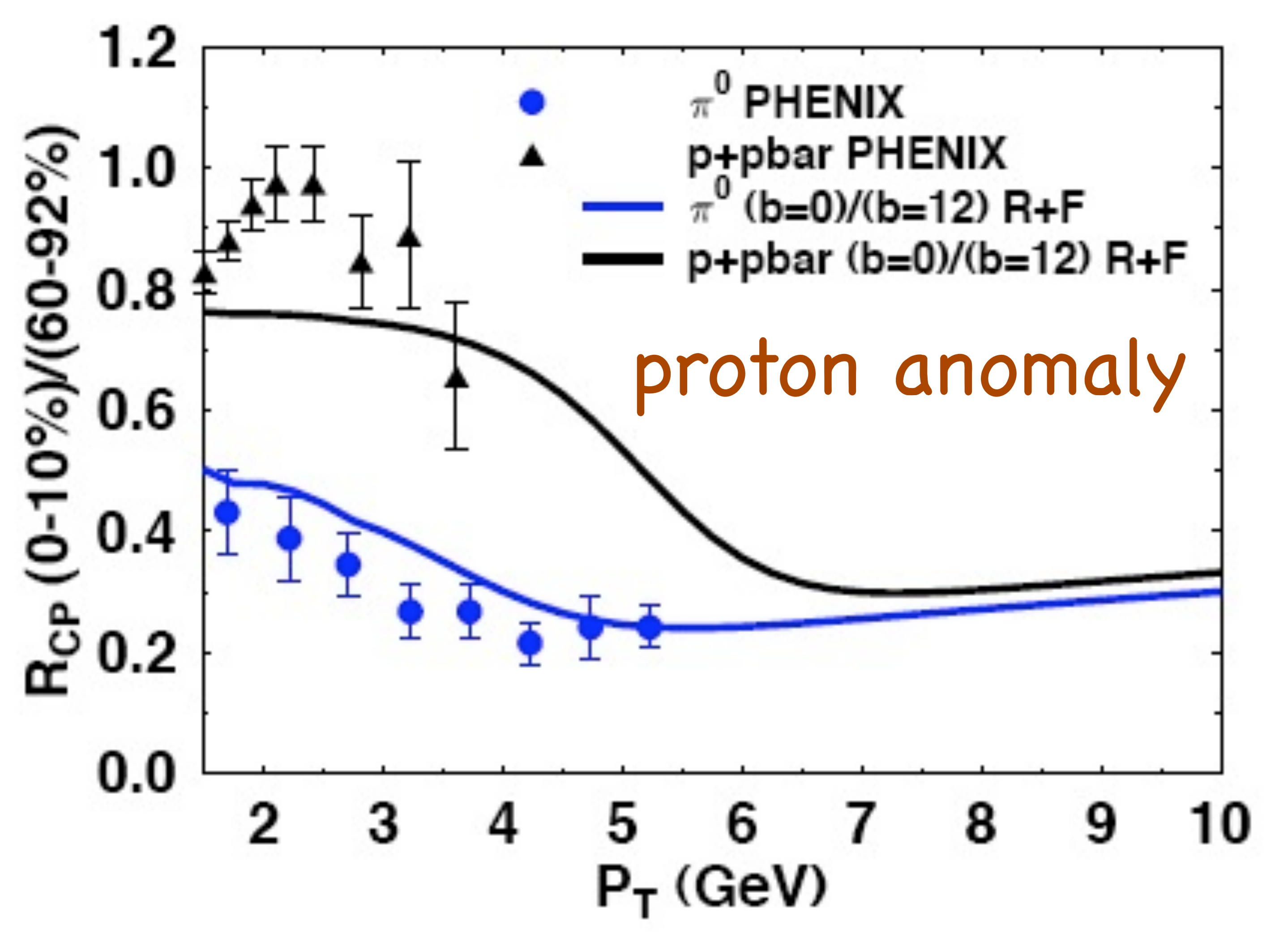
R. J. Fries, S. A. Bass, B. Muller, C. Nonaka, PRL 90 (2003) 202303

meson vs baryon

qq -> 2 $\langle p_T \rangle$

qqq -> 3 $\langle p_T \rangle$

Then 4q ? 5q ?



proton anomaly

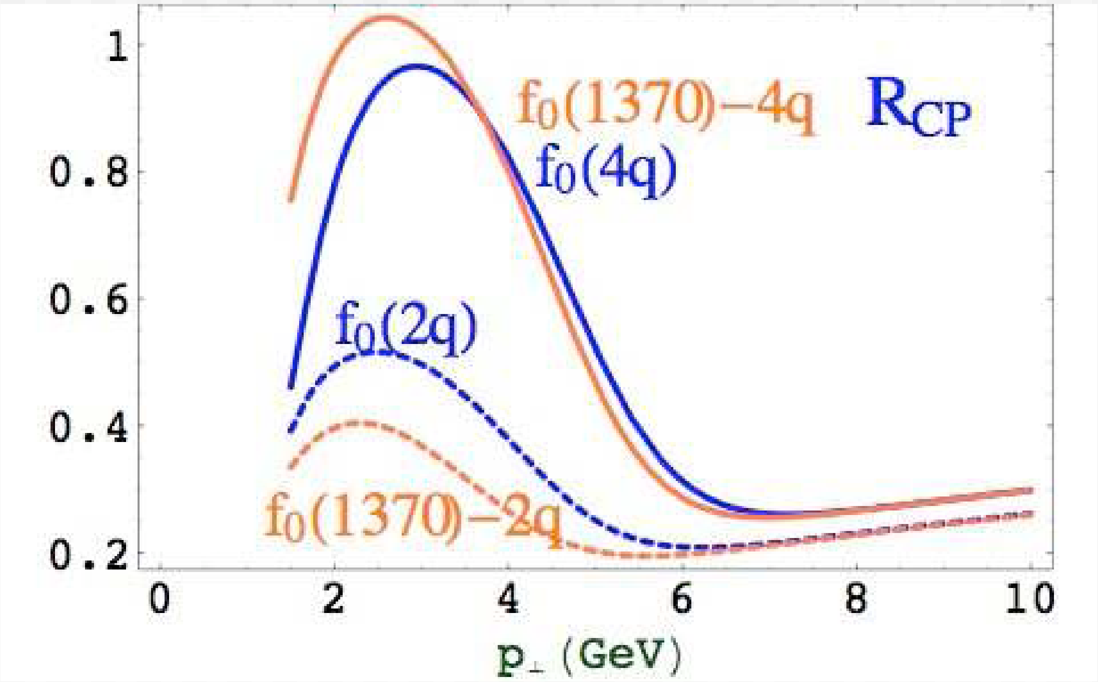
Number of quarks in QCD

Elliptic flow of resonances at RHIC: probing final state interactions and the structure of resonances

C. Nonaka et al. PRC 69 (2004) 031902

Counting valence quarks at RHIC and LHC

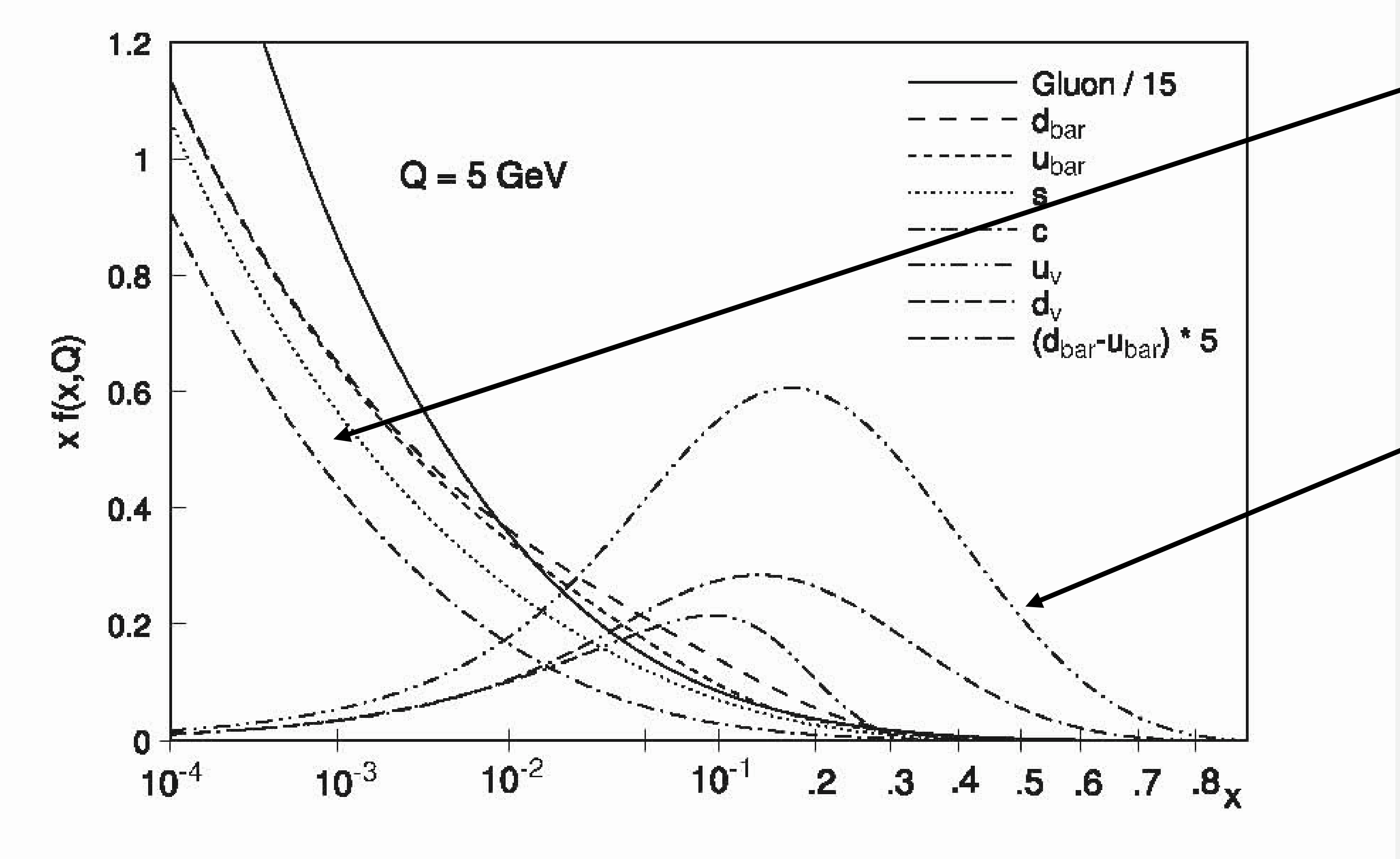
L. Maiani et al. PLB 645 (2007) 138



Number of quarks in QCD

Similarly, in DIS and other high energy processes, one may be able to count "valence" quarks.

Parton distribution = valence + sea



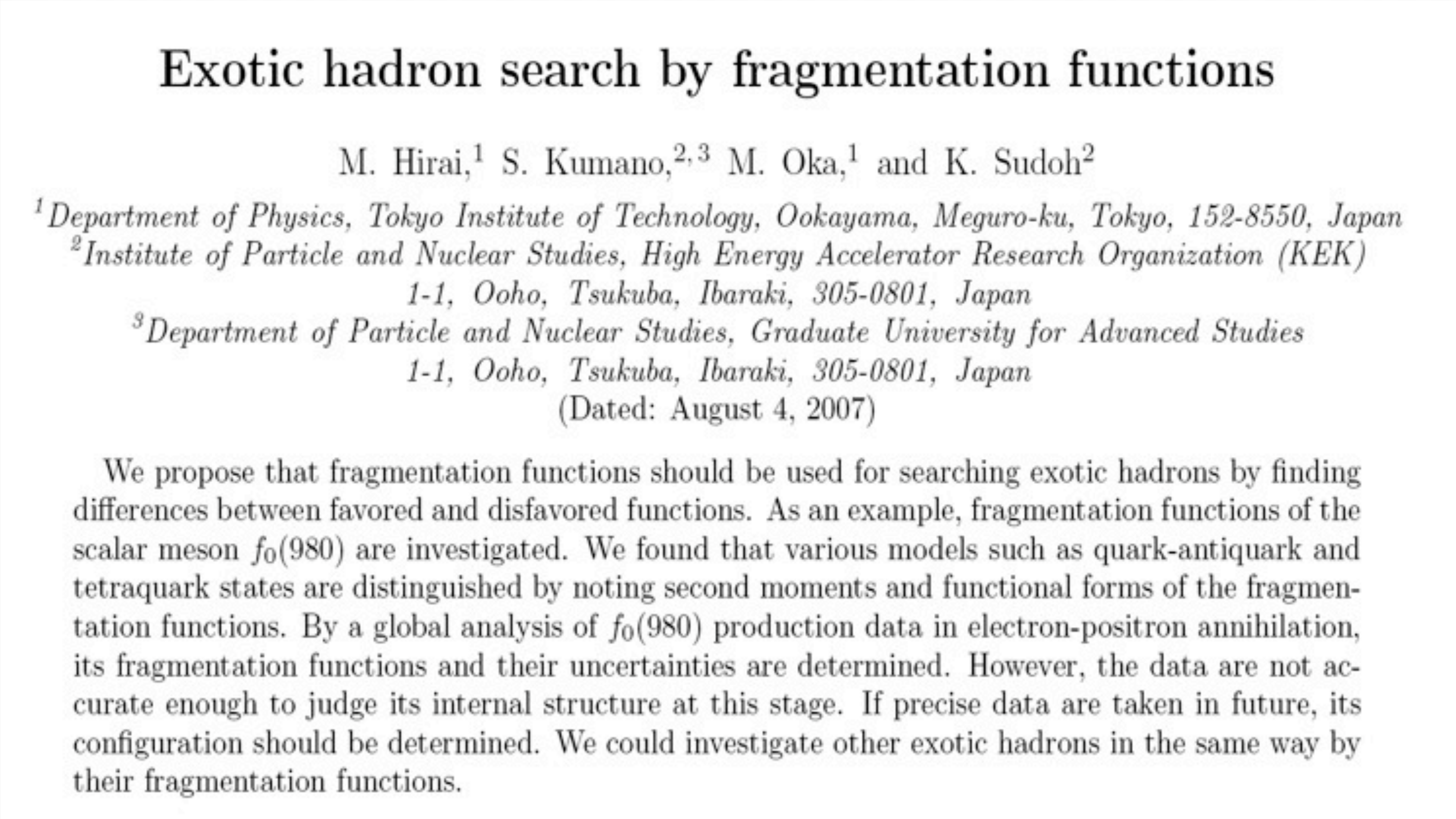
sea quarks

valence quarks

Cannot measure the pdf of resonances: f_0/a_0, Λ etc.

Number of quarks in QCD

New approach with the fragmentation functions



Exotic hadron search by fragmentation functions

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(Dated: August 4, 2007)

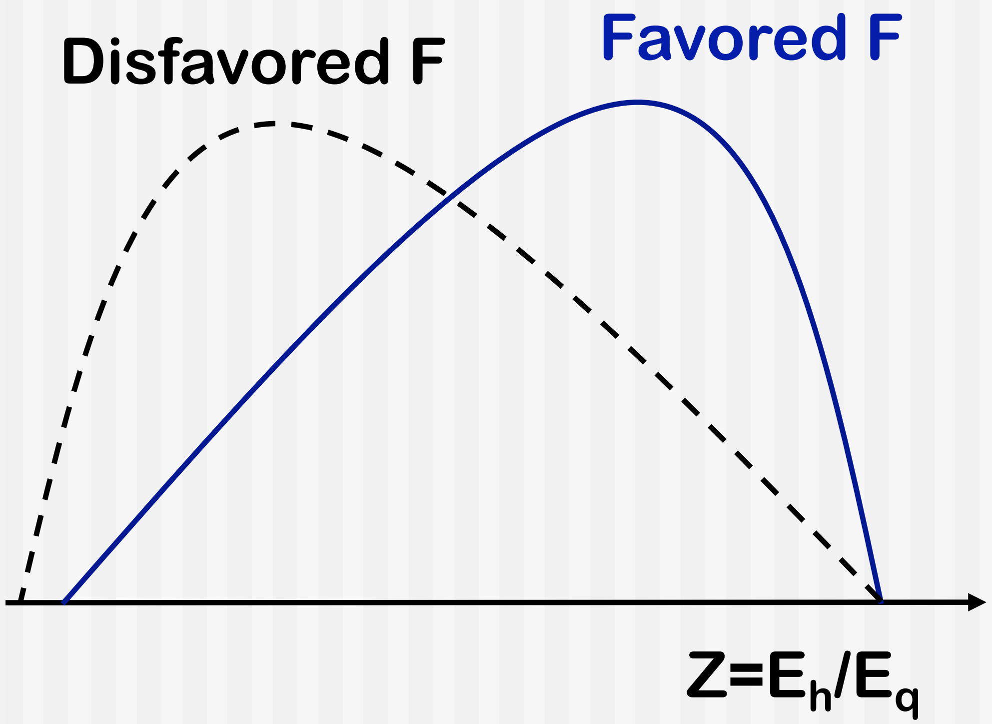
We propose that fragmentation functions should be used for searching exotic hadrons by finding differences between favored and disfavored functions. As an example, fragmentation functions of the scalar meson $f_0(980)$ are investigated. We found that various models such as quark-antiquark and tetraquark states are distinguished by noting second moments and functional forms of the fragmentation functions. By a global analysis of $f_0(980)$ production data in electron-positron annihilation, its fragmentation functions and their uncertainties are determined. However, the data are not accurate enough to judge its internal structure at this stage. If precise data are taken in future, its configuration should be determined. We could investigate other exotic hadrons in the same way by their fragmentation functions.

PRD(2008) ; arXiv:0708.1816v1 [hep-ph]

Number of quarks in QCD

- Fragmentation functions
  - contain non-perturbative information on hadronization
  - determined by a global analysis of $e^+ + e^- \to h + X$ experimental data
- Similar behavior as PDFs
  - Favored FF   valence quarks
    - a constituent of produced hadrons
    - peaked at medium to large z
  - Disfavored FF   sea quarks
    - peaked at small z

K⁺ fragmentations

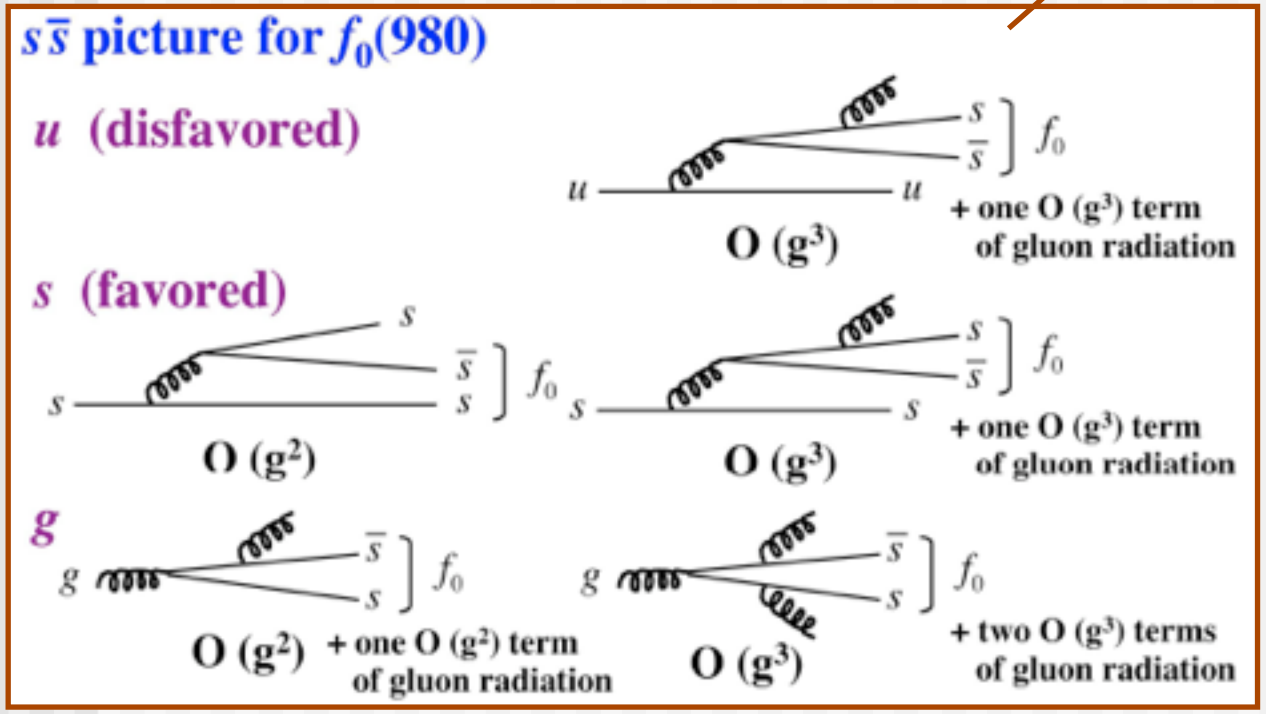


Number of quarks in QCD

Expectations from various possible structure of

Type	Configuration	Second moments	Peak positions
Nonstrange $q\bar{q}$	$(u\bar{u}+d\bar{d})/\sqrt{2}$	$M_s < M_u < M_g$	$z_u^{\max} > z_s^{\max}$
Strange $q\bar{q}$	$s\bar{s}$	$M_u < M_s \lesssim M_g$	$z_u^{\max} < z_s^{\max}$
Tetraquark (or $K\bar{K}$)	$(u\bar{u}s\bar{s}+d\bar{d}s\bar{s})/\sqrt{2}$	$M_u \sim M_s \lesssim M_g$	$z_u^{\max} \sim z_s^{\max}$
Glueball	gg	$M_u \sim M_s < M_g$	$z_u^{\max} \sim z_s^{\max}$

$s\bar{s}$ picture for $f_0(980)$



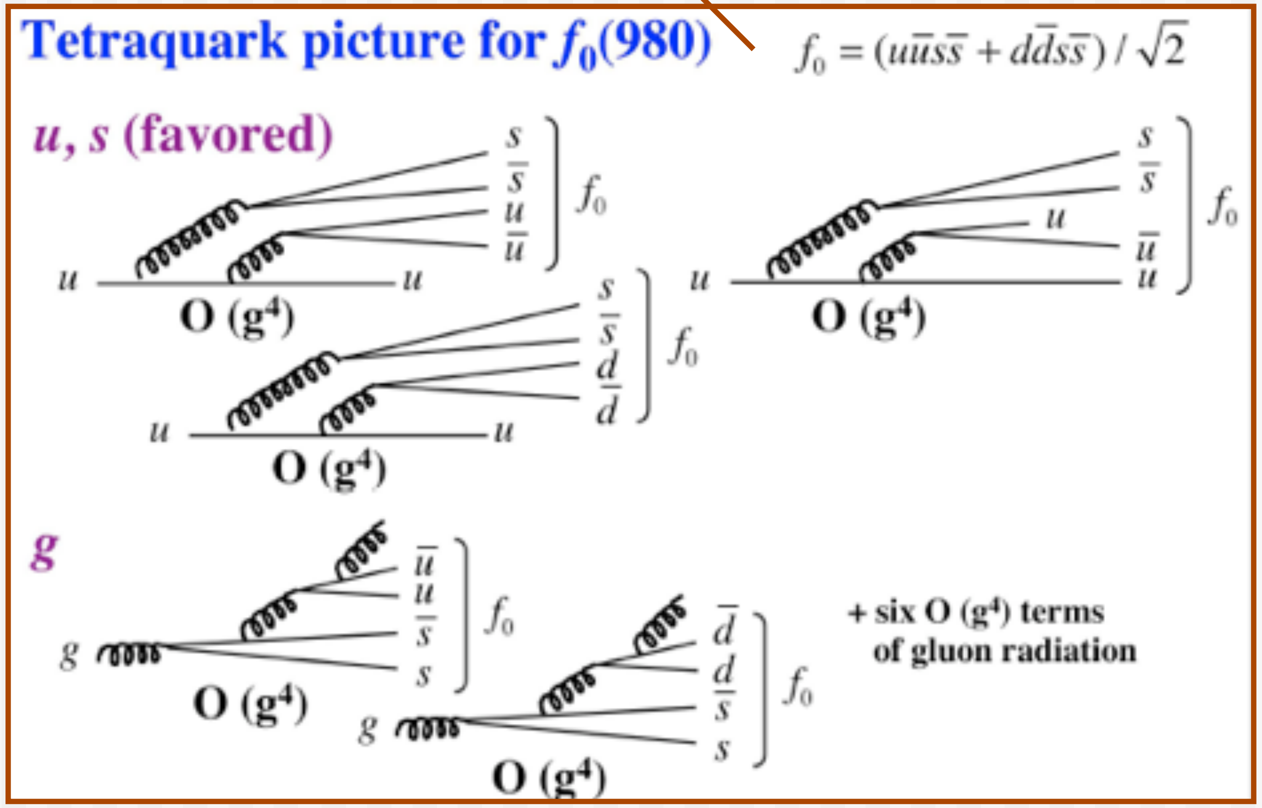
+ one O (g³) term of gluon radiation

+ one O (g³) term of gluon radiation

+ one O (g²) term of gluon radiation

+ two O (g³) terms of gluon radiation

Tetraquark picture for $f_0(980)$ $f_0 = (u\bar{u}s\bar{s}+d\bar{d}s\bar{s})/\sqrt{2}$



+ six O (g⁴) terms of gluon radiation

Number of quarks in QCD

χ^2/d.o.f. = 0.907

- Total Number of data: 23

Tetra-quark configuration

- favored FF: u and s quarks
- Peak at large-z (z~0.85)
- $z_u^{max} \sim z_s^{max}$

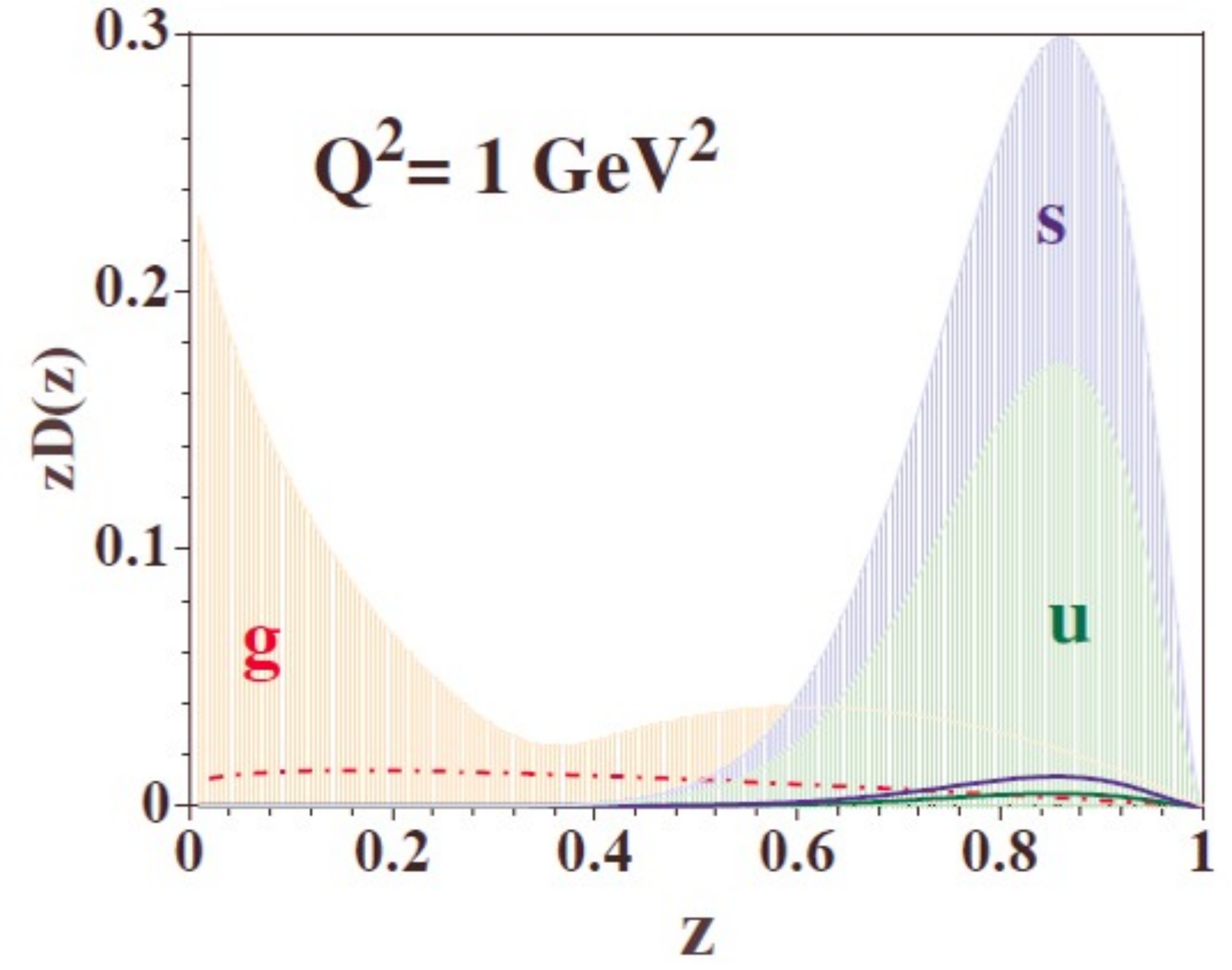
or

$s\bar{s}$ configuration

- $M_u < M_s$
- $(M_u/M_s=0.43 \pm 6.73)$

Large uncertainty

- Need further precise data



2nd moments

- $M_u=0.0012 \pm 0.0107$
- $M_s=0.0027 \pm 0.0183$
- $M_g=0.0090 \pm 0.0046$

Number of quarks in QCD

- We propose a plausible way of searching exotic hadrons using the fragmentation functions in high energy collisions.
- The analysis reveals the quark-gluon structure of excited (exotic) hadrons.
  - The favored & disfavored FFs show similar properties as valence & sea quark distributions: peak position: z^{max}
  - The 2nd moments of FFs are compared with the order counting of perturbative production processes.

  Applied to the global analysis of FFs of the $f_0(980)$ production.

  Indicating tetra-quark and/or $s\bar{s}$ configuration

  Large uncertainty of the current production data does not allow to distinguish them.

Conclusion

- Exotics (including dibaryons) may provide critical information in understanding hadrons from QCD, in particular, on
  - mechanism of confinement
  - perturbative vs non-perturbative dynamics
  - symmetry and broken symmetry

- We need to establish "multiquark-ness" in terms of QCD.
- Fragmentation functions in high energy production processes may be useful in determining number of valence quarks and flavor compositions of hadrons.