P_c and P_{cs} pentaquarks as threshold phenomena of two hadrons

Hadrons beyond $\bar{q}q$, qqq

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Collaborations with
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Sachiko Takeuchi (Japan Coll. Social Work)

1. History — Hadrons beyond $\bar{q}q$, qqq
2. Threshold
3. Quasi-stable hadronic molecules
4. Coupled channels of MB and $5q$ — Results
5. Summary

1. Histories

Hadrons beyond $\bar{q}q$, qqq

1. Histories

20th century

A SCHEMATIC MODEL OF BARYONS AND MESONS

Phys. Lett. 8, 214 (1964)

M. GELL-MANN
California Institute of Technology, Pasadena, California

Received 4 January 1964

anti-triplet as anti-quarks $\bar{q}$. Baryons can now be constructed from quarks by using the combinations $(q\,q\,q)$, $(q\,q\,q\,q\,\bar{q})$, etc., while mesons are made out of $(q\,\bar{q})$, $(q\,q\,\bar{q}\,\bar{q})$, etc. It is assuming that the lowest baryon configuration $(q\,q\,q)$ gives just the represen-

Molecular Charmonium: A New Spectroscopy?*

Phys. Lett. 38, 317 (1977)

A. De Rújula, Howard Georgi,† and S. L. Glashow
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02138

(Received 23 November 1976)

Recent data compel us to interpret several peaks in the cross section of e^-e^+ annihilation into hadrons as being due to the production of four-quark molecules, i.e., resonances between two charmed mesons. A rich spectroscopy of such states is predicted and may be studied in e^-e^+ annihilation.

$\bar{K}N$ molecule — $\Lambda(1405)$

POSSIBLE RESONANT STATE IN PION-HYPERON SCATTERING*

R. H. Dalitz and S. F. Tuan
Enrico Fermi Institute for Nuclear Studies and Department of Physics,
University of Chicago, Chicago, Illinois
(Received April 27, 1959)

Phys. Rev. Lett. 2, 425

. . . .

will be pointed out here that this situation makes it quite probable that there should exist a resonant state for pion-hyperon scattering at an energy of about 20 Mev below the $K^- - p$ (c.m.) threshold energy. In the present discussion, charge-

. . . .

This is being confirmed….

Pole position of Λ(1405) measured in d(K−,n)πΣ reactions

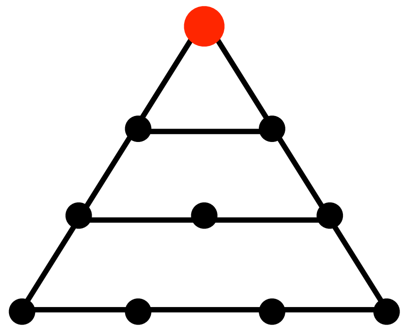
J-PARC E31 Collaboration • S. Aikawa (Tokyo Inst. Tech.) et al. (Sep 17, 2022)

Published in: *Phys.Lett.B* 837 (2023) 137637 • e-Print: 2209.08254 [nucl-ex]

21th century

Pentaquark Θ^+ in 2003

D. Diakonov in Osaka 2012



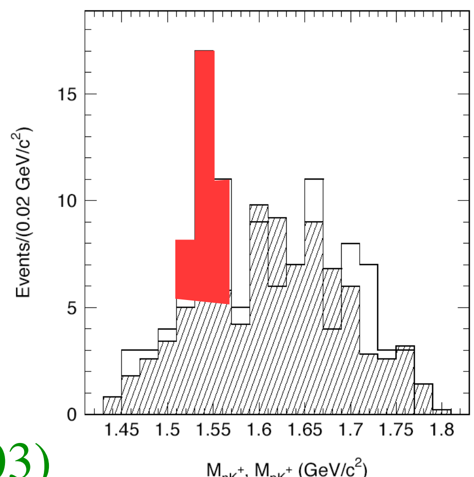
$uudd\bar{s}$

Prediction
by the chiral Solitons

Z.Phys. A359 (1997) 305-314

T. Nakano

PRL91, 012002 (2003)

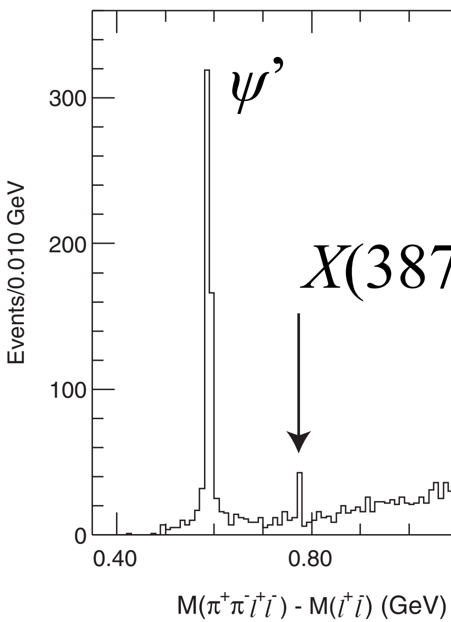


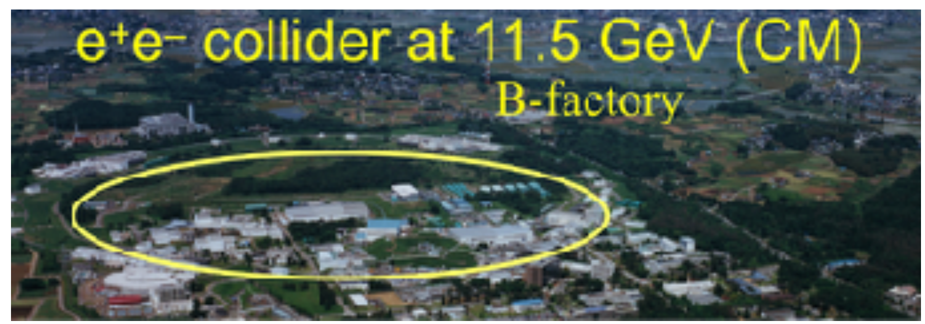
LEPS@SPring-8

Further analysis is going on…

Tetraquark $X(3872)$

Belle@KEK, PRL91, 262001 (2003)
and further confirmed at Fermi Lab, SLAC, LHC, BEP, …





$u\bar{u}c\bar{c}$, $d\bar{d}c\bar{c}$

Heavy and light quarks

Many other findings have are following

Pentaquarks P_c, P_{cs}

- 2015, 2019: LHC reported evidences, $P_c \sim uudc\bar{c}$

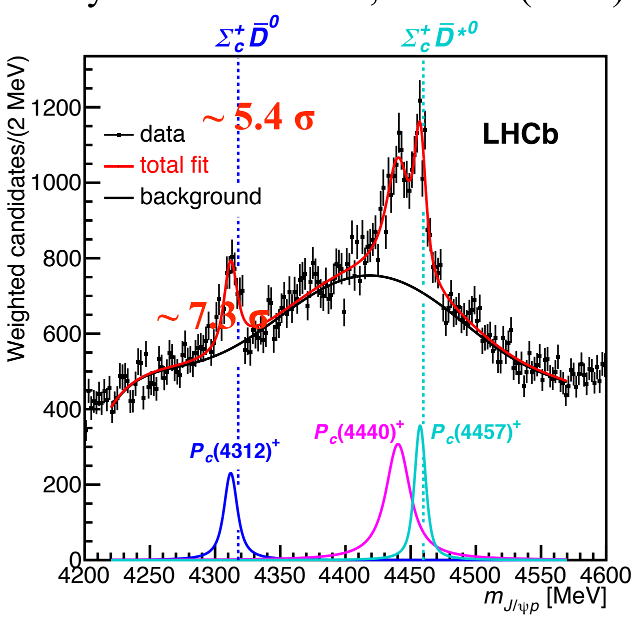
$$\Lambda_b^0 \to P_c^+ K^- \to (J/\psi p) K^-$$

- 2021, 2022: Yet further evidence, $P_{cs} \sim udsc\bar{c}$

$$\Xi_b^- \to P_{cs}(4459) K^- \to (J/\psi \Lambda) K^-$$

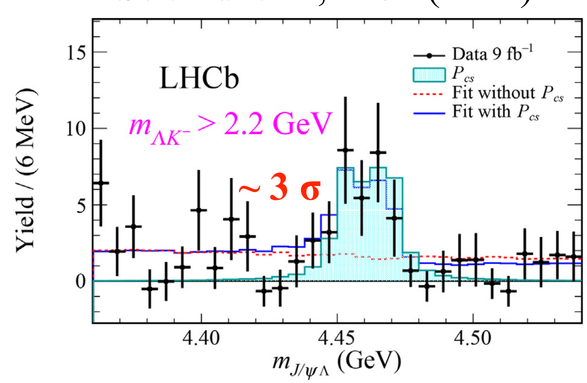
P_c

Phys. Rev. Lett. 122, 222001 (2019)

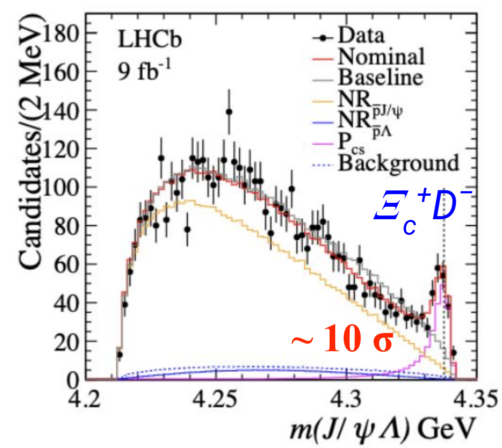


P_{cs}

Sci. Bull. 66, 1278 (2021)

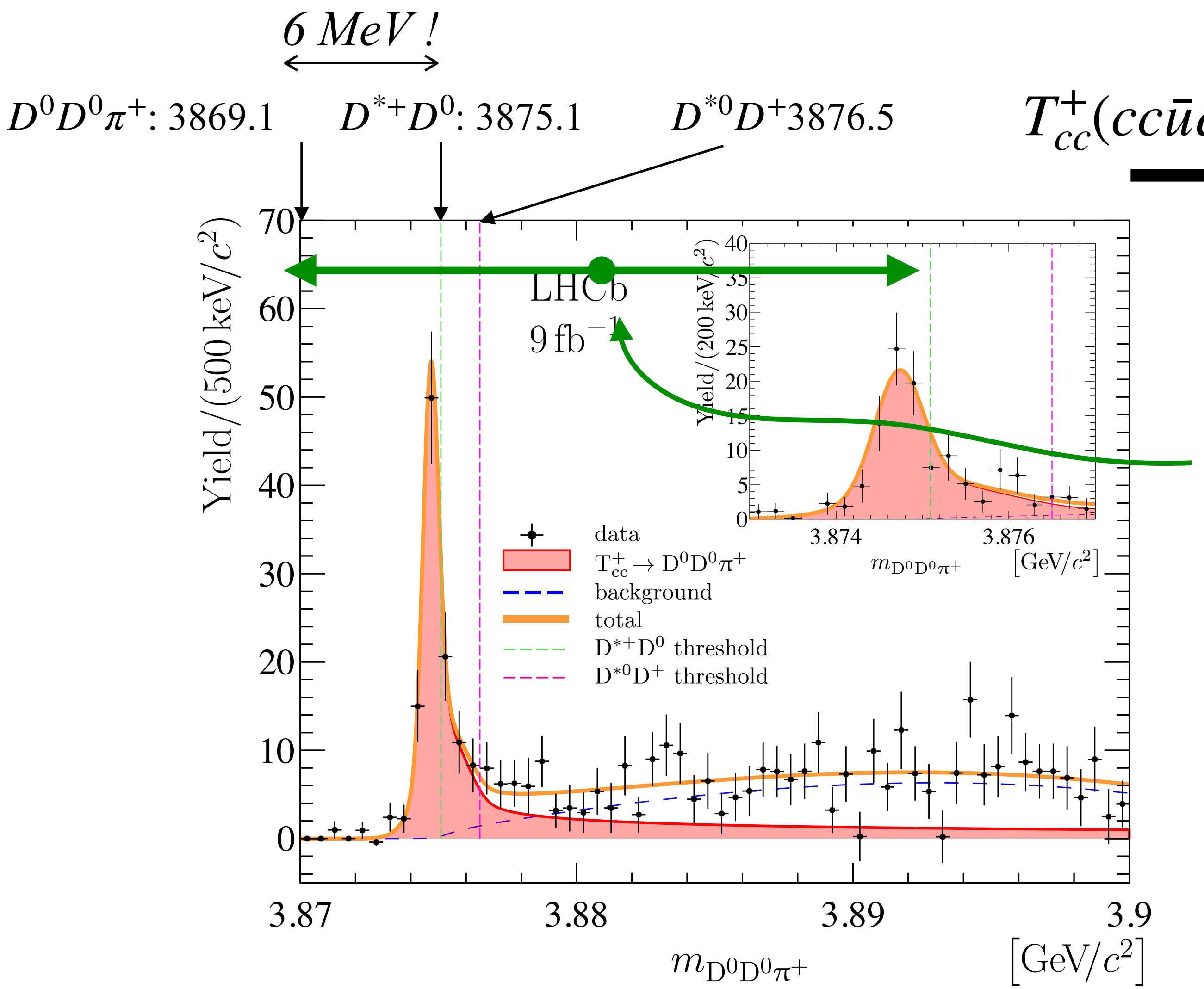


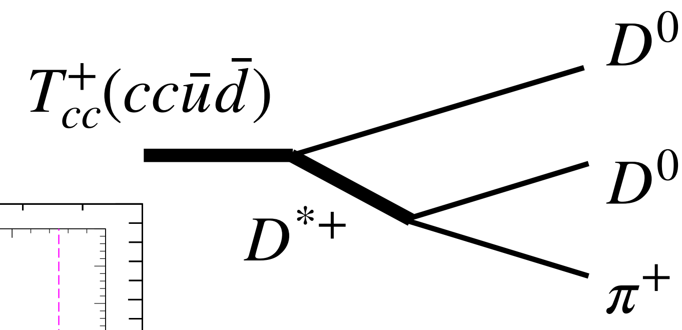
CERN seminar, Jul. 2022
e-Print: 2210.10346 [hep-ex]



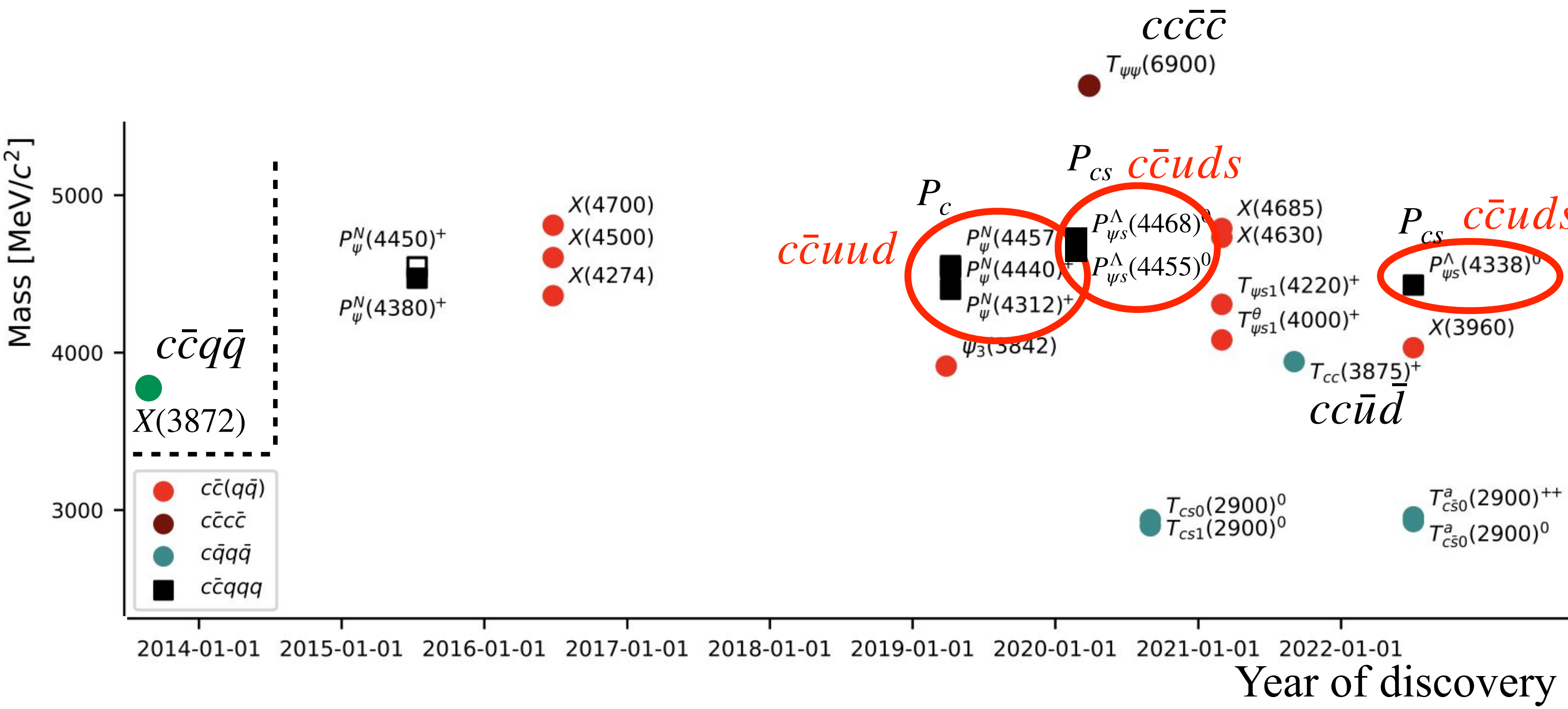
Tetraquark T_{cc}

Nature Commun. 13 (2022) 1, 3351, arXiv: 2109.01056





LHCb summary (2022)



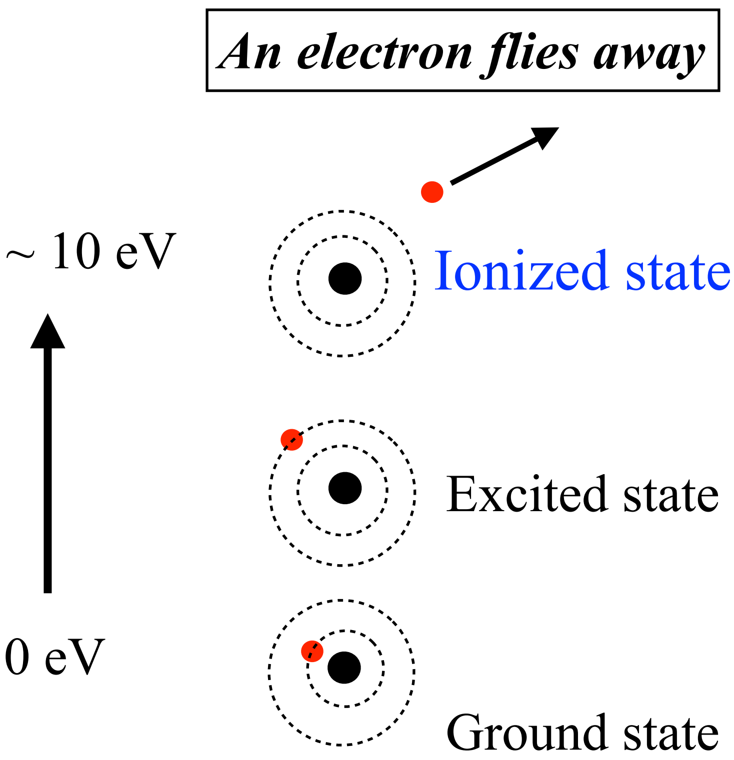
- Hidden charm meson: $c\bar{c}q\bar{q}$, $X(3872), \ldots, T_{\psi\psi}(6900), \ldots$
- Hidden charm baryon: $c\bar{c}qqq$, $P_c, P_{cs}, \ldots$
- Doubly charm meson: $cc\bar{q}\bar{q}$, $T_{cc}(3875), \ldots$

2. Threshold

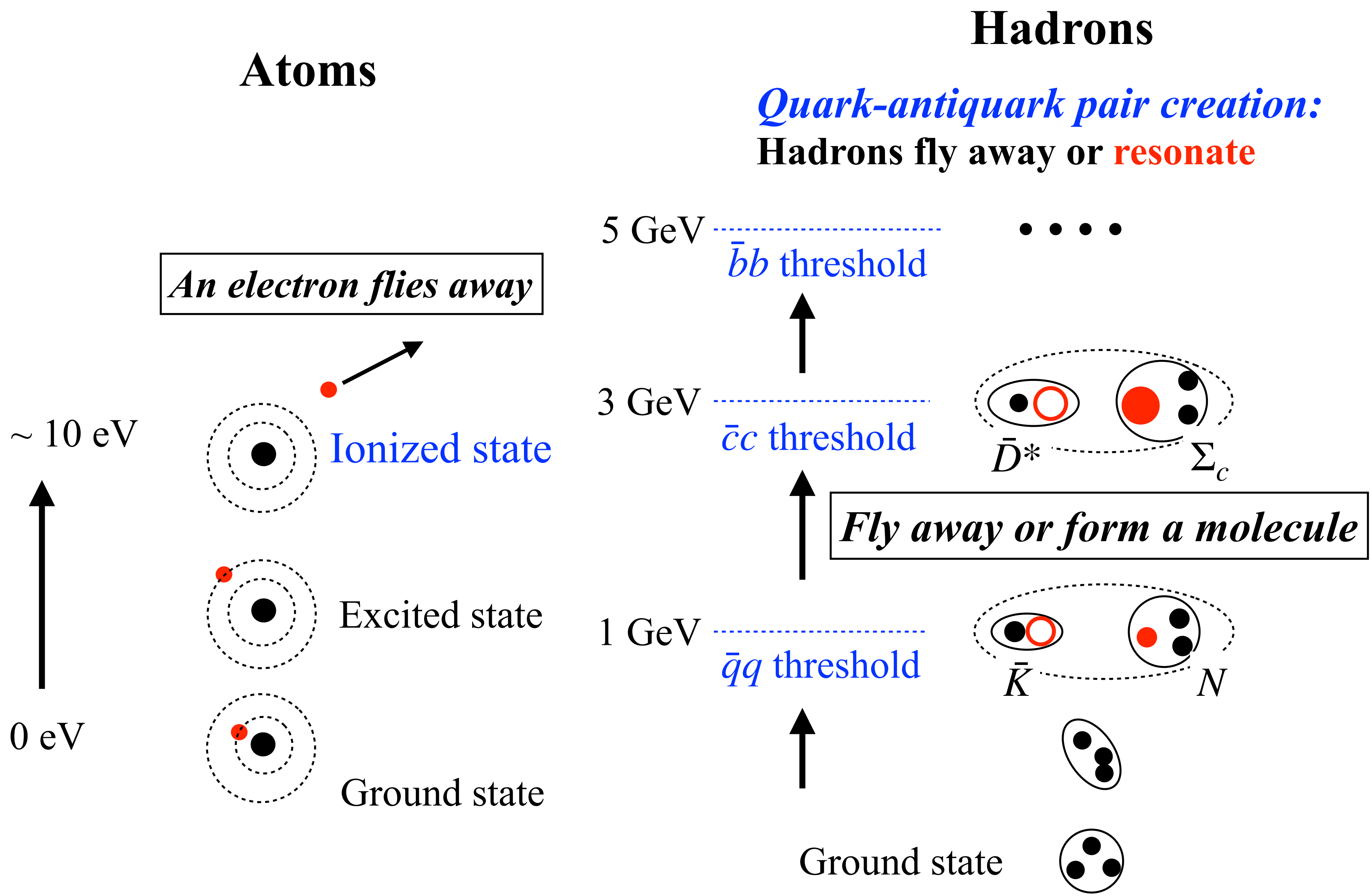
Imagine: *What happens when energy is deposited to a ground state?*

2. Threshold

Atoms



2. Threshold



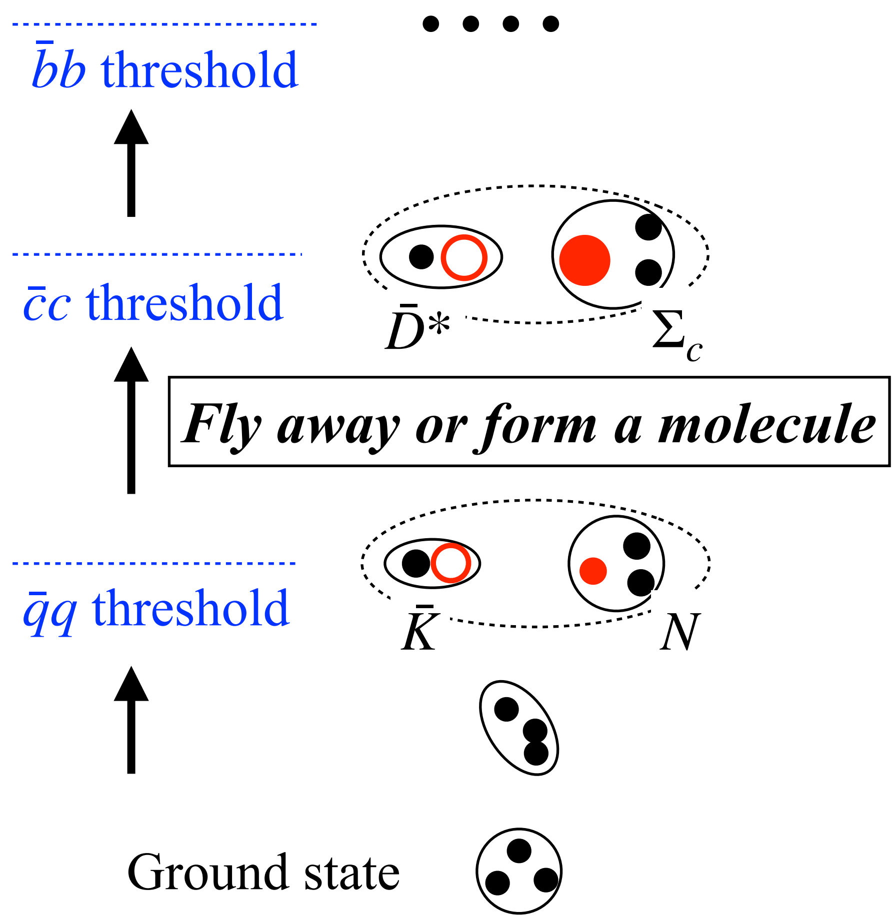
Atoms
Hadrons
Quark-antiquark pair creation:
Hadrons fly away or resonate
An electron flies away
~ 10 eV
0 eV
Ionized state
Excited state
Ground state
5 GeV
$\bar{b}b$ threshold
3 GeV
$\bar{c}c$ threshold
1 GeV
$\bar{q}q$ threshold
$\bar{D}^*$
Σ_c
Fly away or form a molecule
$\bar{K}$
N
Ground state

2. Threshold

Hadrons

Quark-antiquark pair creation:
Hadrons fly away or resonate

- Multiquarks
- Form colorless clusters
  due to strong colored force
  Color neutralization
- Weakly interacting clusters
- Multi-clusters = molecules

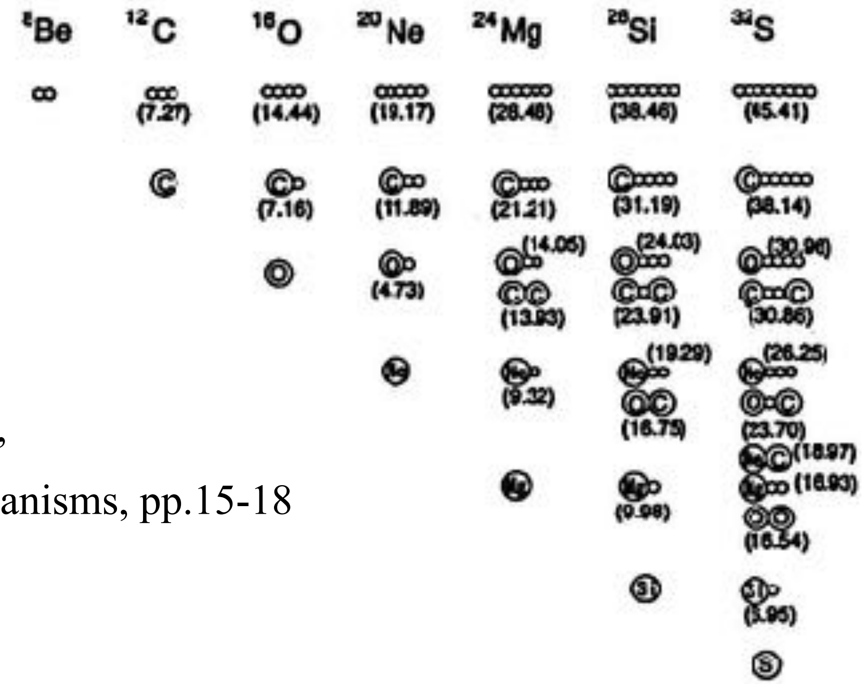


Universality

Alpha clustering in atomic nuclei

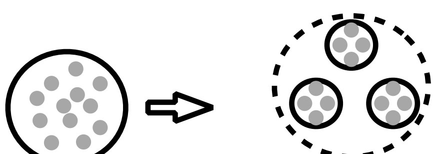
Spin-isopin neutralization

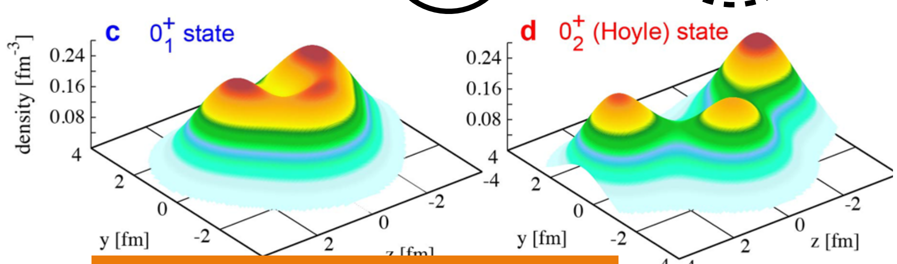
Prog. Theor. Phys. 40, 277 (1968)



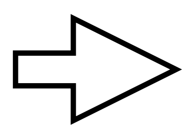
Also see,
Brink, D M (Oxford U., Theor. Phys.)
"Prof. Ikeda's important contributions to nuclear physics"
12th International Conference on Nuclear Reaction Mechanisms, pp.15-18
15 - 19 Jun 2009, Villa Monastero, Varenna, Italy
https://cds.cern.ch/record/1237837/files/p15.pdf

Structure of ^{12}C

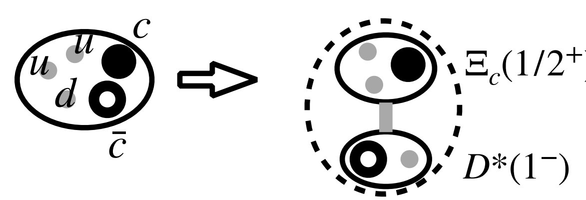




https://doi.org/10.1038/s41467-022-29582-0



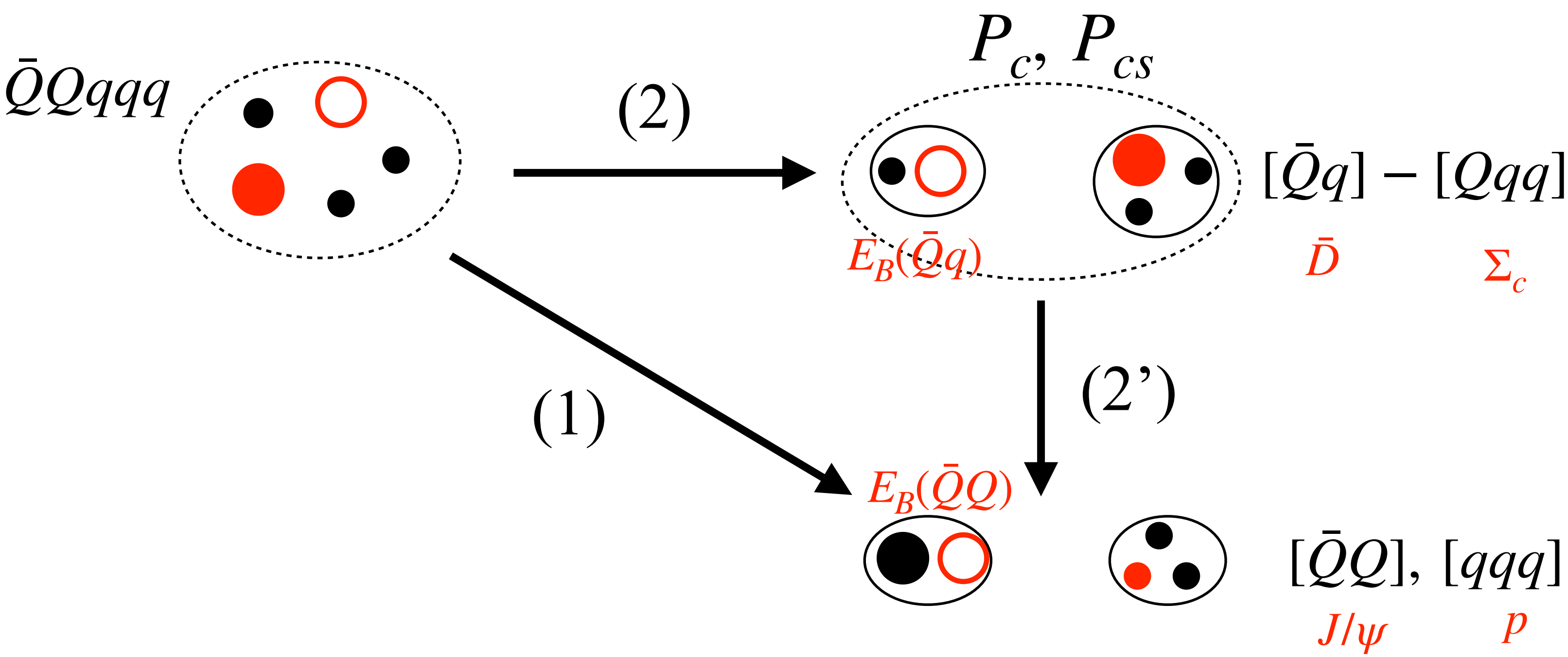
Structure of Pentaquarks



3. Quasi-stable hadronic molecules

Hadronic molecules are not stable but may become quasi-stable due to the balance of ***two scales****: heavy quark and QCD*

3. Quasi-stable hadronic molecules



(1) Direct decay into quarkonium $\bar{Q}Q$ and nucleon qqq

(2) Going through a quasi-stable (resonant) state, P_c, P_{cs}

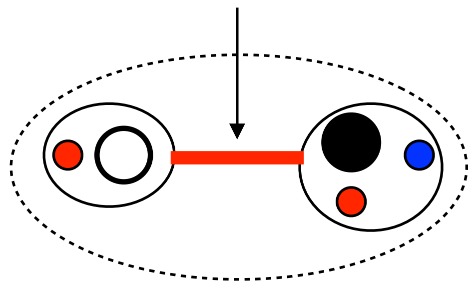
Color electric force ($\sim 1/r$) $\rightarrow E_B(\bar{Q}Q) \gg E_B(\bar{Q}q)$

$$M_{HQ} \gg \Lambda_{QCD}$$

Question

Need to know the ***interaction***

P_c, P_{cs}



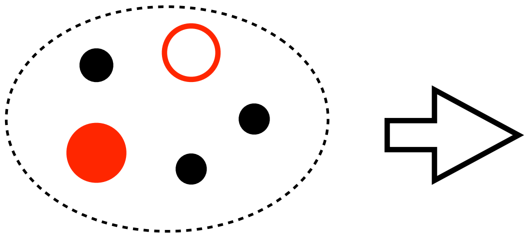
$$[\bar{Q}q] - [Qqq]$$

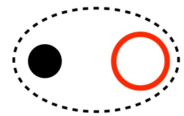
$\bar{D}$ Σ_c

- We construct a model of coupled channels.
- Eventually, derived from lattice QCD.

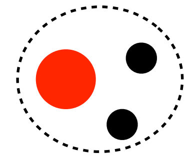
Remark:
If constituent **hadrons** are sufficiently **heavy**, any weak attraction allow a **(quasi-)bound state**

Important configurations





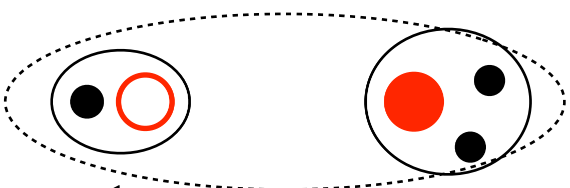
+



$3 \times \bar{3} = 1 + 8 \qquad 3 \times 3 \times 3 = 1 + 8 + 8 + 10$

Making color singlet

MB (Meson-Baryon)

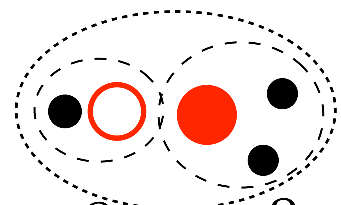


1 1

Extended

+

5q (Confined five-quarks)

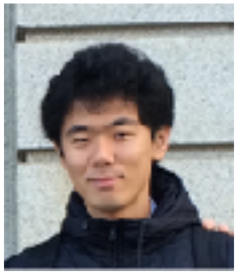


8 8

Compact

Two configurations are implemented in a basis set

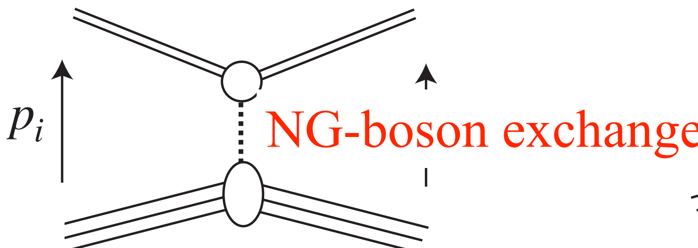
4. Coupled channels of *MB* and 5*q*

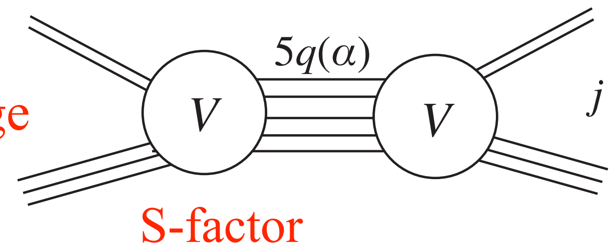


Y. Yamaguchi et al, Phys. Rev. D 96, 114031 (2017): P_c
Y. Yamaguchi et al, Phys. Rev. D 101, 091502 (2020) : P_c
A. Giachino et al, e-Print: 2209.10413 [hep-ph]: P_{cs}

$M \equiv \bar{D}, \bar{D}^*$

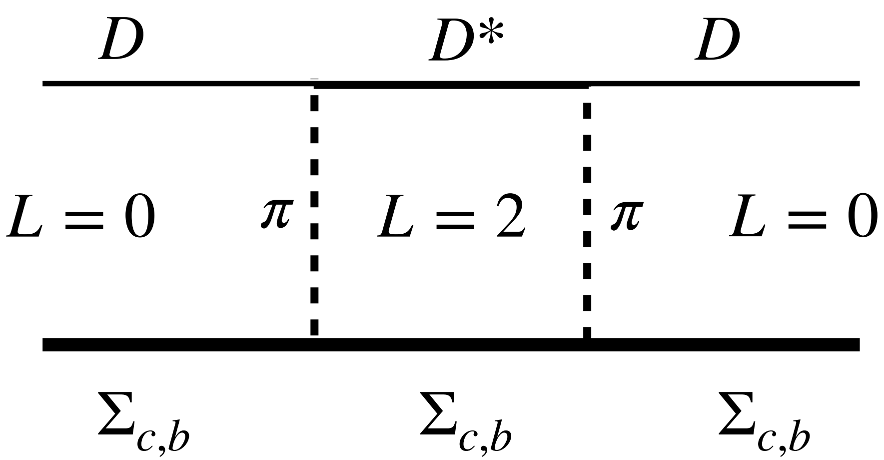
$B \equiv \Sigma_c, \Sigma_c^*, \Lambda_c$





- *MB* channels interacting via NG boson (π, K) exchange
- 5*q* channels have masses larger than *MB*
- *MB* and 5*q* couples vis S-factor (overlap)

NG boson exchange and tensor force



$M_{D^*} - M_D \sim 140$ MeV

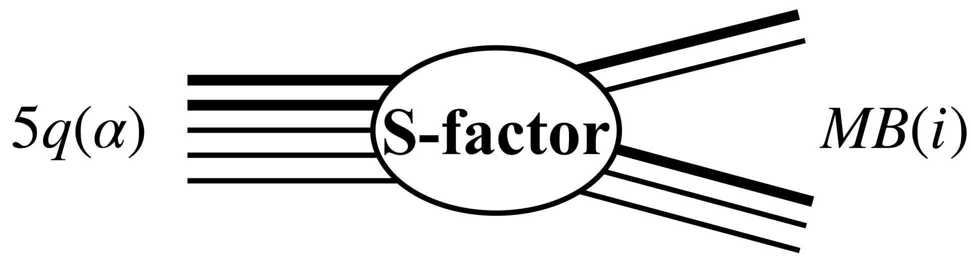
$M_{B^*} - M_B \sim 45$ MeV

- Large attraction due to the 2nd oder process
- Heavy particles are more easily bound
- Deuteron is bound by the tensor force

S-factors couple MB and $5q$ states

The 5q states transit to meson and baryon, when $\bar{Q}q$ and qqq in 5q state take corresponding quantum numbers

$$\langle MB \,|\, V \,|\, 5q \rangle \sim \langle MB(i) \,|\, 5q(\alpha) \rangle \equiv S_i^\alpha$$



$5q(\alpha)$ | $MB(i)$

J	$S_{c\bar{c}}$	S_{3q}	$\bar{D}\Lambda_c$	$\bar{D}^*\Lambda_c$	$\bar{D}\Sigma_c$	$\bar{D}\Sigma_c^*$	$\bar{D}^*\Sigma_c$	$\bar{D}^*\Sigma_c^*$
$\frac{1}{2}$	0	$\frac{1}{2}$	0.35	0.61	−0.35	⋯	0.20	−0.58
	1	$\frac{1}{2}$	0.61	−0.35	0.20	⋯	−0.59	−0.33
	1	$\frac{3}{2}$	0.00	0.00	−0.82	⋯	−0.47	0.33
$\frac{3}{2}$	0	$\frac{3}{2}$	⋯	0.00	⋯	−0.50	0.58	−0.65
	1	$\frac{1}{2}$	⋯	0.71	⋯	0.41	−0.24	−0.53
	1	$\frac{3}{2}$	⋯	0.00	⋯	−0.65	−0.75	−0.17
$\frac{5}{2}$	1	$\frac{3}{2}$	⋯	⋯	⋯	⋯	⋯	−1.00

Solving Schrodinger eq for *MB*'s

$$H = \begin{pmatrix} H^{MB} & V \\ V^\dagger & H^{5q} \end{pmatrix}$$

$$\psi = (\psi^{MB}, \psi^{5q})$$

⇨

Coupled equations

$$H^{MB}\psi^{MB} + V\psi^{5q} = E\psi^{MB} \, ,$$
$$V^\dagger\psi^{MB} + H^{5q}\psi^{5q} = E\psi^{5q} \, .$$

Eliminate ψ^{5q}: Feshbach's method

$$\left(K^{MB} + V^{\pi} + V \frac{1}{E - H^{5q}} V^\dagger \right) \psi^{MB} = E\psi^{MB}$$

$$\sim -f \sum_{\alpha} S_j^{\alpha} e^{-Ar^2} S_i^{\alpha}$$

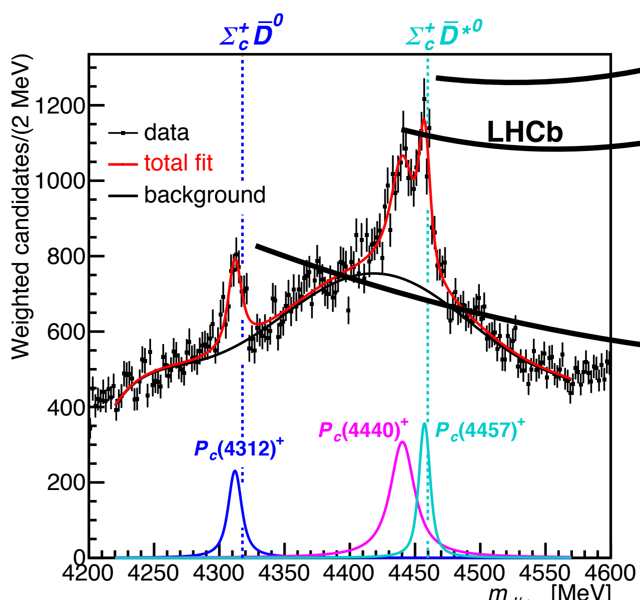
Only one parameter f

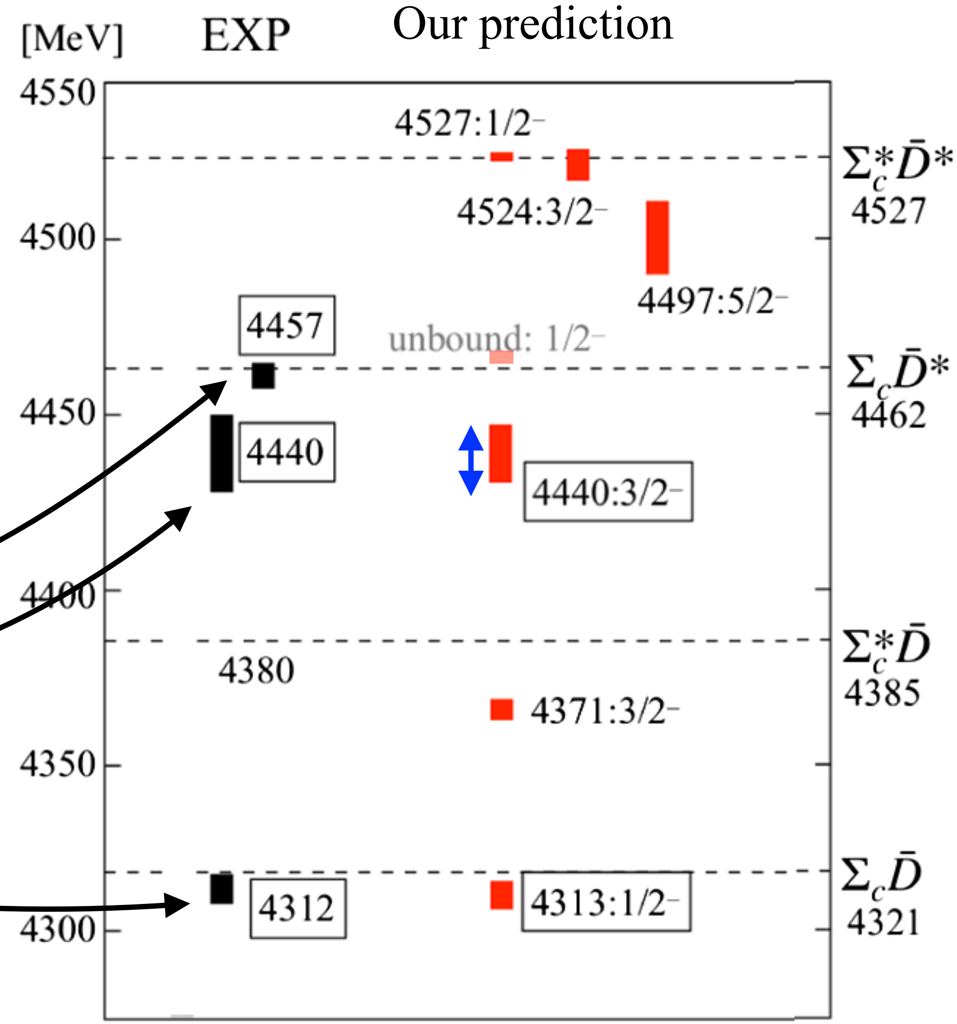
⇨ Solve for the T (scattering) matrix

Results for P_c

Phys. Rev. D 96, 114031 (2017)
Phys. Rev. D 101, 091502 (2020)

- 4312, 4440 and 4457 agree with data
- Their spin and parities are predicted.
- $\Sigma_c^* D$ singlet and $\Sigma_c^* D^*$ triplet are predicted
- OPEP and V^{5q} are both important for binding
- Widths and spin splittings are due to OPEP

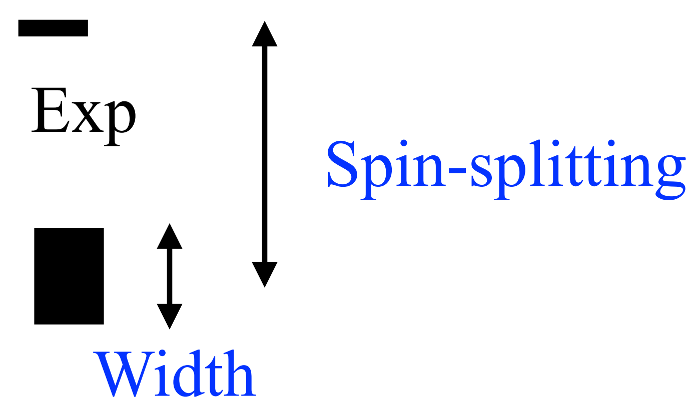




	EXP [1,34]		Our Results for $f/f_0 = 50$		
State	Mass	Width	J^P	Mass	Width
$P_c^+(4312)$	$4311.9 \pm 0.7^{+6.8}_{-0.6}$	$9.8 \pm 2.7^{+3.7}_{-4.5}$	$1/2^-$	4313	9.6
$P_c^+(4380)$	$4380 \pm 8 \pm 29$	$205 \pm 18 \pm 86$	$3/2^-$	4371	5.0
$P_c^+(4440)$	$4440.3 \pm 1.3^{+4.1}_{-4.7}$	$20.6 \pm 4.9^{+8.7}_{-10.1}$	$3/2^-$	4440	16
$P_c^+(4457)$	$4457.3 \pm 0.6^{+4.1}_{-1.7}$	$6.4 \pm 2.0^{+5.7}_{-1.9}$	...	...	...
			$1/2^-$	4527	0.88
			$3/2^-$	4524	7.6
			$5/2^-$	4497	20

Only slightly above the threshold

Role of tensor force



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			$1/2^-$	4527	0.88
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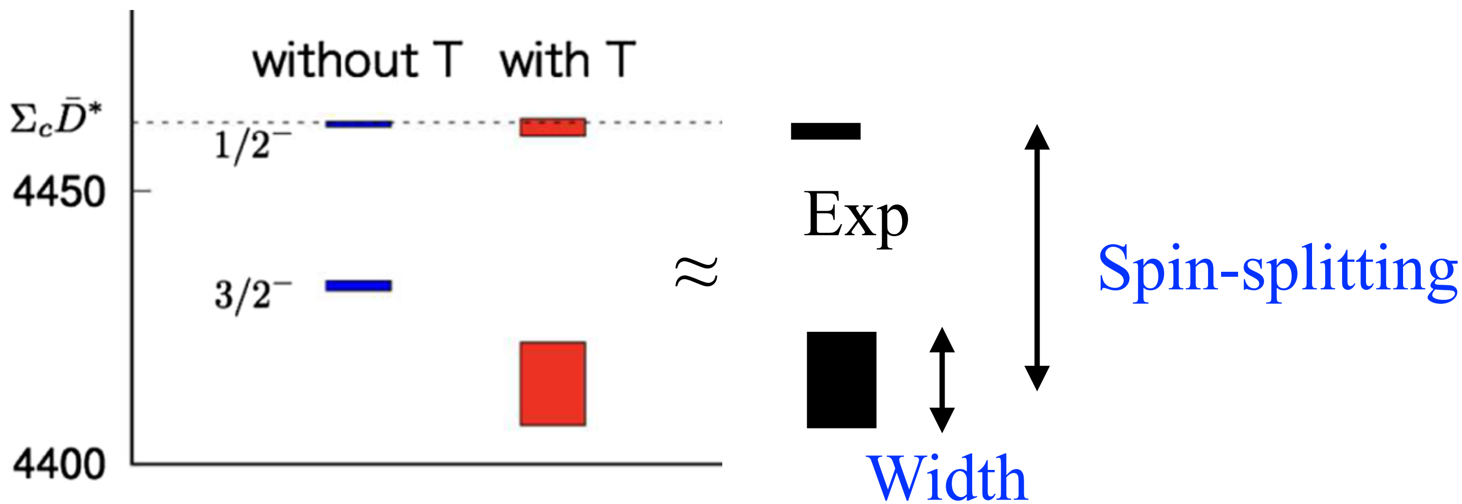
			$5/2^-$	4497	20

Only slightly above the threshold

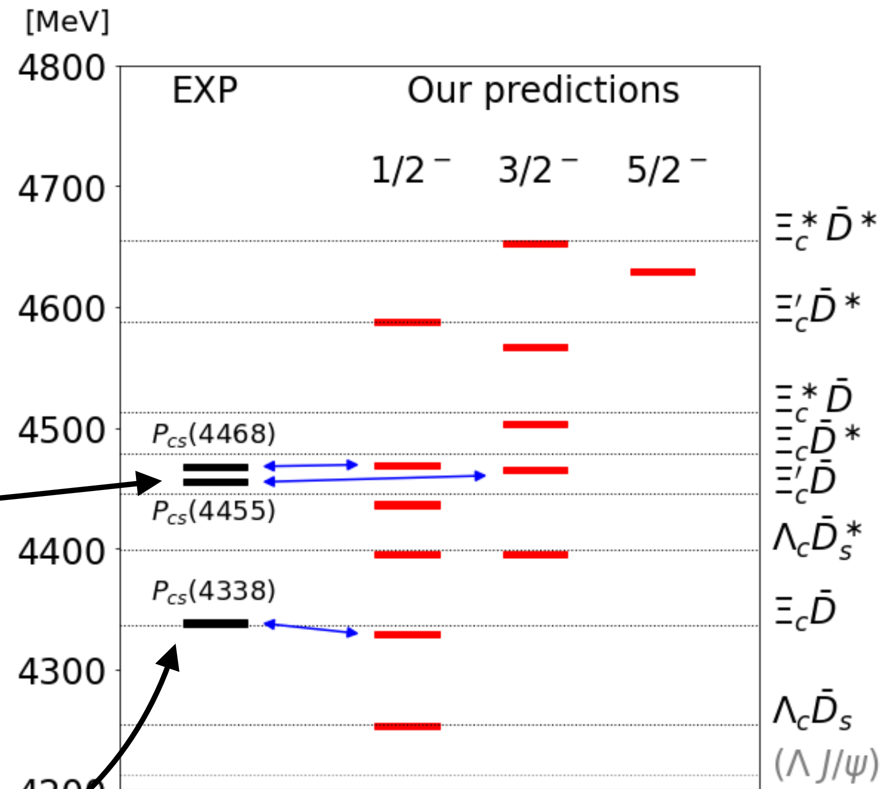
Role of tensor force

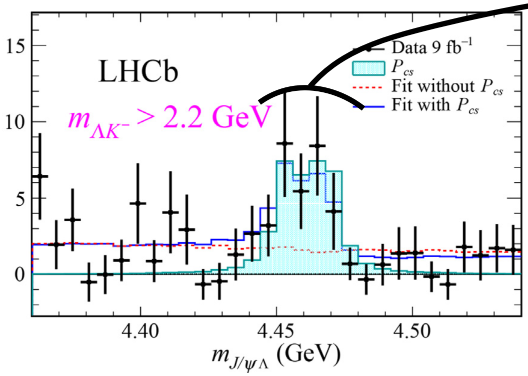


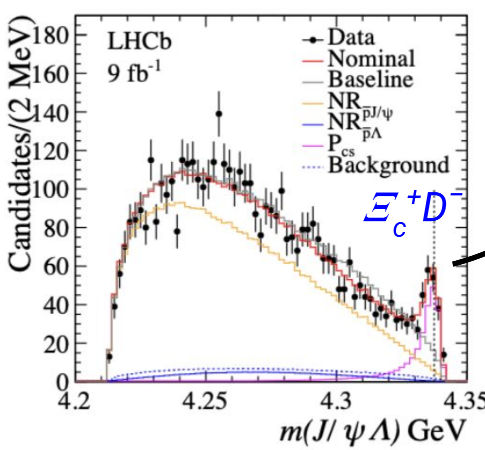
Results for P_{cs}

e-Print: 2209.10413 [hep-ph]

- 4338, 4455 and 4468 agree with data
- Their spin and parities are predicted.
- More states are predicted
- OPEP and V^{5q} are both important for binding
- Widths and spin-splittings are due to OPEP







	EXP [12, 14]		Our results for $f = 98$ MeV		
State	Mass	Width	J^P	Mass	Width
—	—	—	$1/2^-$	4252.65	—
$P_{cs}(4338)$	4338.2	7.0	$1/2^-$	4329.11	1.54
—	—	—	$1/2^-$	4394.97	7.31×10^{-4}
—	—	—	$3/2^-$	4395.76	8.78×10^{-4}
—	—	—	$1/2^-$	4436.24	2.12
$P_{cs}(4455)$	4454.9	7.5	$3/2^-$	4465.24	1.08
$P_{cs}(4468)$	4467.8	5.2	$1/2^-$	4469.24	2.31
—	—	—	$3/2^-$	4502.91	4.09
—	—	—	$3/2^-$	4567.12	9.95
—	—	—	$1/2^-$	4587.53	1.25
—	—	—	$5/2^-$	4629.81	14.7
—	—	—	$3/2^-$	4653.02	5.52

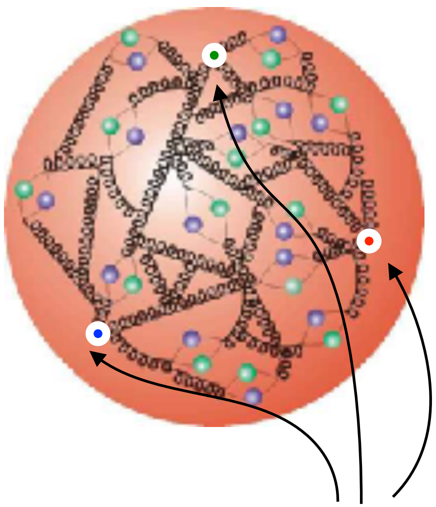
- Fare agreement with data
- Coupling to the decay channels improve (in preparation)

Summary

- P_c, P_{cs} pentaquarks are threshold phenomema
- With suitable interaction of
  long-range (hadron) and short-range (quark) dynamics
- Determination of spin and parity is important
- Search for other threshold states
- Clustering and the cluster interaction
  → hierarchal structure of matter

Remark: "Quarks" here are quasi-particles

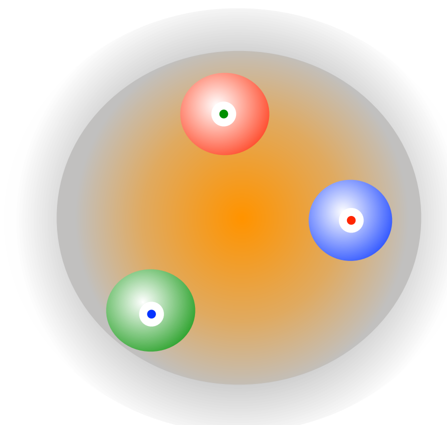
QCD
bare quarks
and gluons



Complicated structure
by ***three quarks***

Fundamental degrees of freedom

Quark model
constituent "***quarks***"



Simple structure
by ***three "quarks"***

Quasi-particles

$\bar{Q}Q$ threshold

$$R(s) = \sigma(e^+e^- \to hadrons, s)/\sigma(e^+e^- \to \mu^+\mu^-, s).$$