チャーム・ボトムの
エキゾチックハドロン物理の最近の発展

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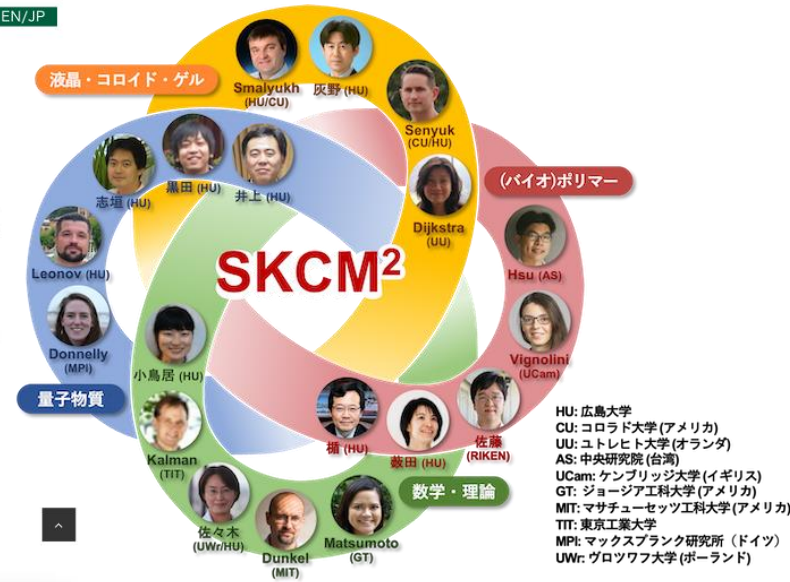
瀬戸内サマーインスティチュートSSI2023@広島大学, 20-22 Sep. 2023

International Institute for Sustainability with Knotted Chiral Meta Matter/**SKCM²**

World Premier International Research Center Initiative/WPI at Hiroshima University



✔ Cross-pollinates mathematical knot theory and chirality knowledge across disciplines and scales

✔ Creation of designable artificial knot-like particles that exhibit highly unusual and technologically useful properties

<u>Hadron & nuclear physics group</u>

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coPI: Muneto NITTA (HU, Keio Uni.)

Keywords

Tetraquark

Exotic

Spectroscopy

Heavy quark symmetry

Charm

XYZ

Heavy hadron effective theory

Bottom

Pentaquark

Spin

この講義の目標

1. ハドロン物理学の基本的知識を理解して用語を説明できること

2. ハドロン現象論の基本的なモデルの特徴を理解しうて説明できること

3. エキゾチックハドロンの性質について実験データあるいは理論に基づいて説明できること

https://www.jps.or.jp/books/gakkaishi/files/71-09_70fushigi.pdf

内容

内容

物質とは？

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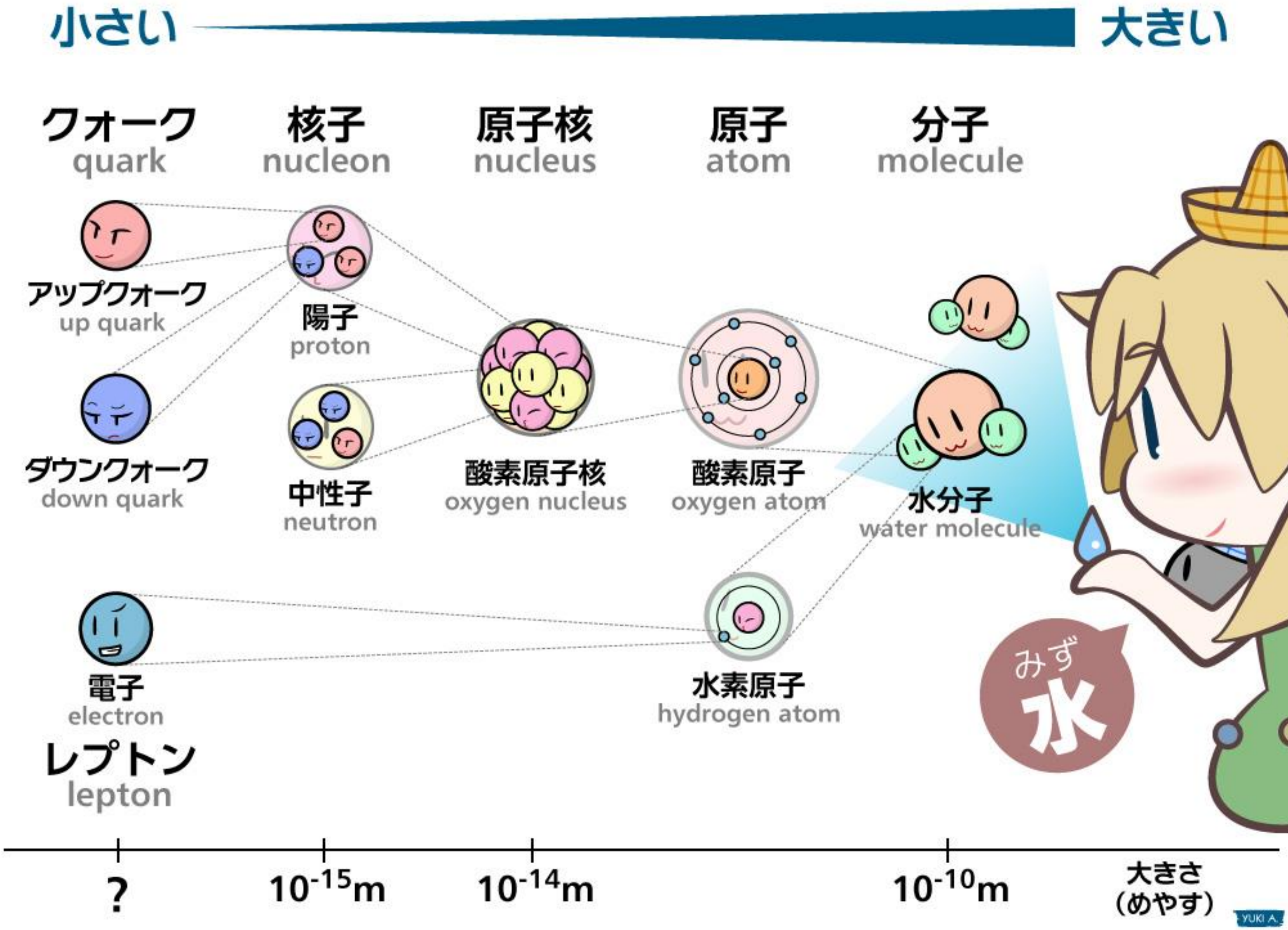
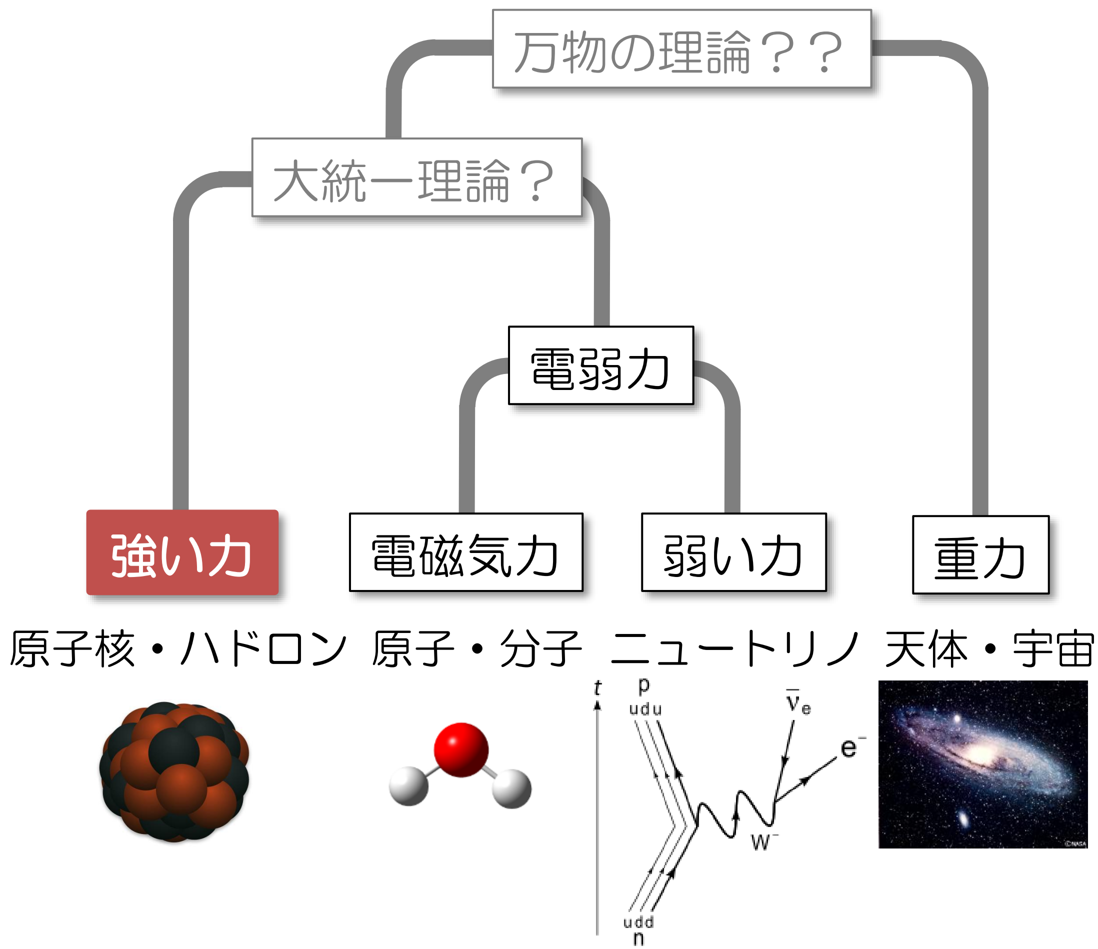


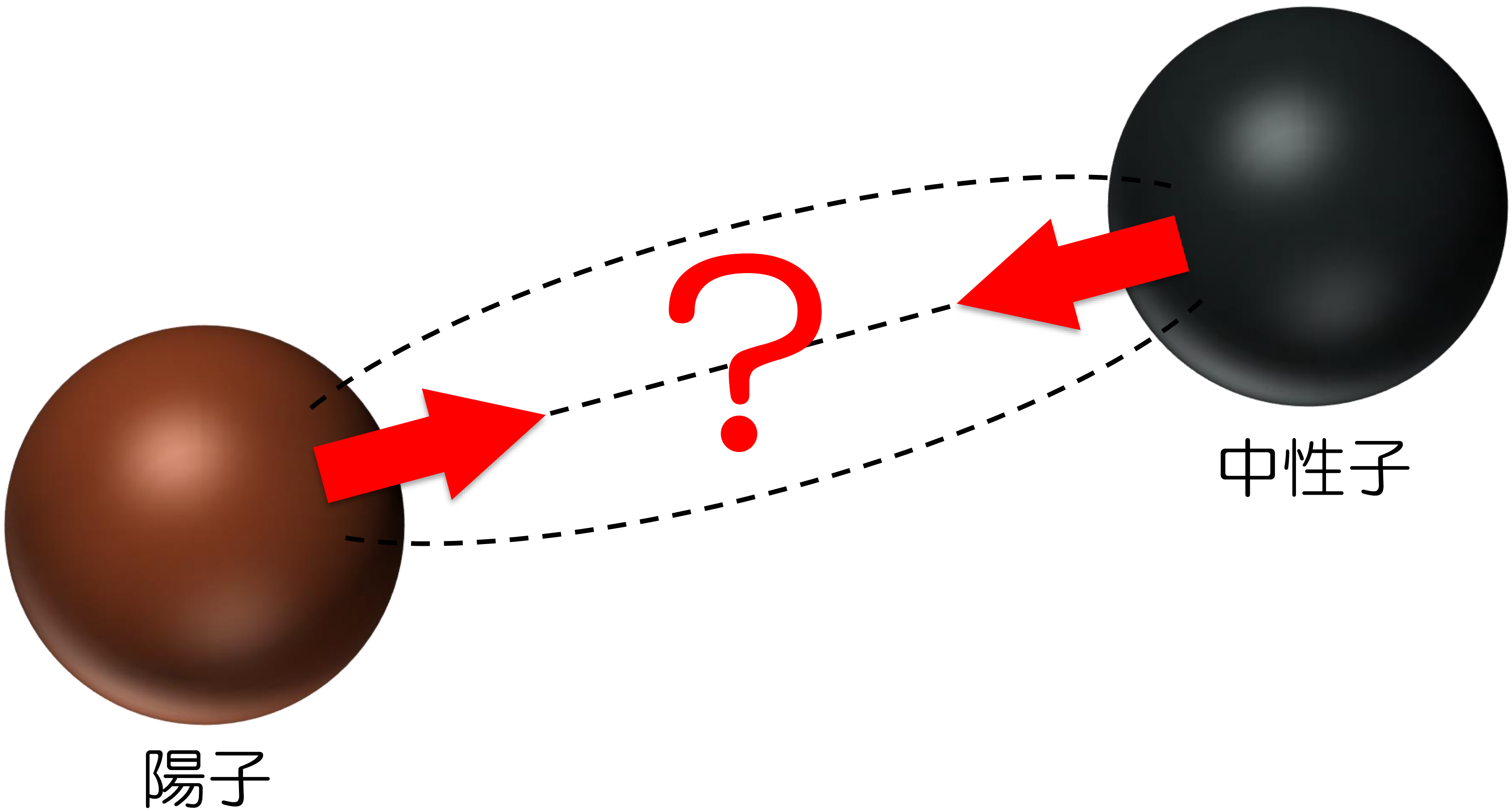
力とは？


万物の理論？？
大統一理論？
電弱力
強い力
電磁気力
弱い力
重力
原子核・ハドロン
原子・分子
ニュートリノ
天体・宇宙
t
p
udu
$\bar{\nu}_e$
e^-
W^-
udd
n

1. Introduction

基本問題

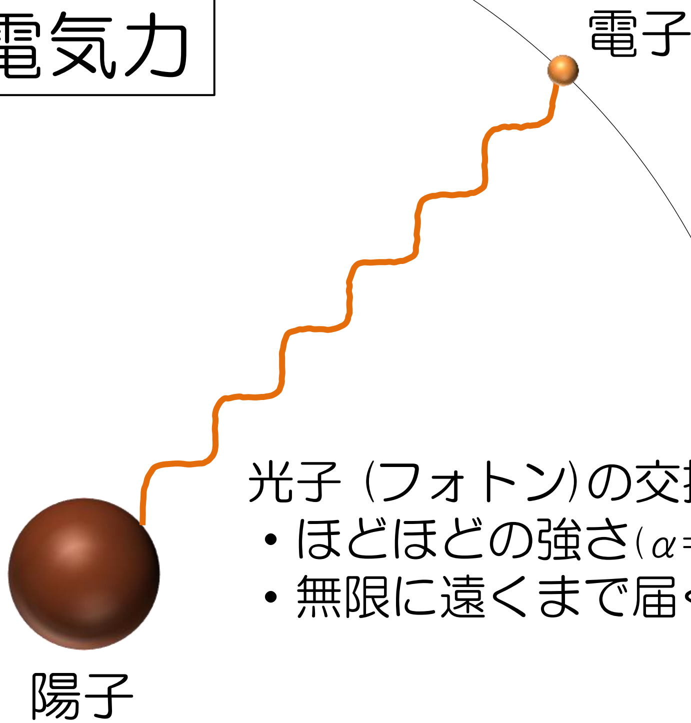
核子間に働く力(核力)とは？



1. Introduction

電気力と核力の性質の違い

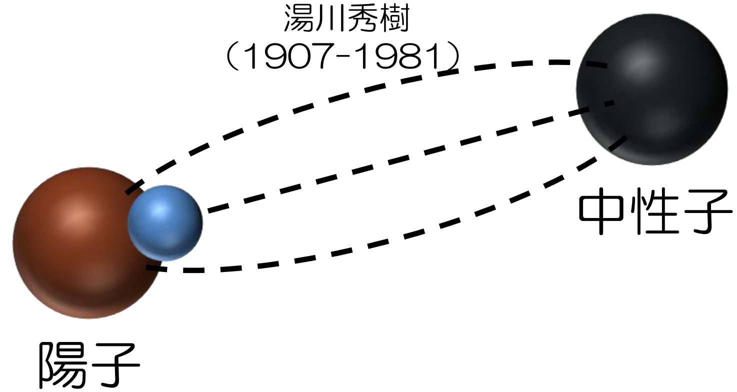
電気力



光子 (フォトン)の交換
- ほどほどの強さ(α=/137)
- 無限に遠くまで届く

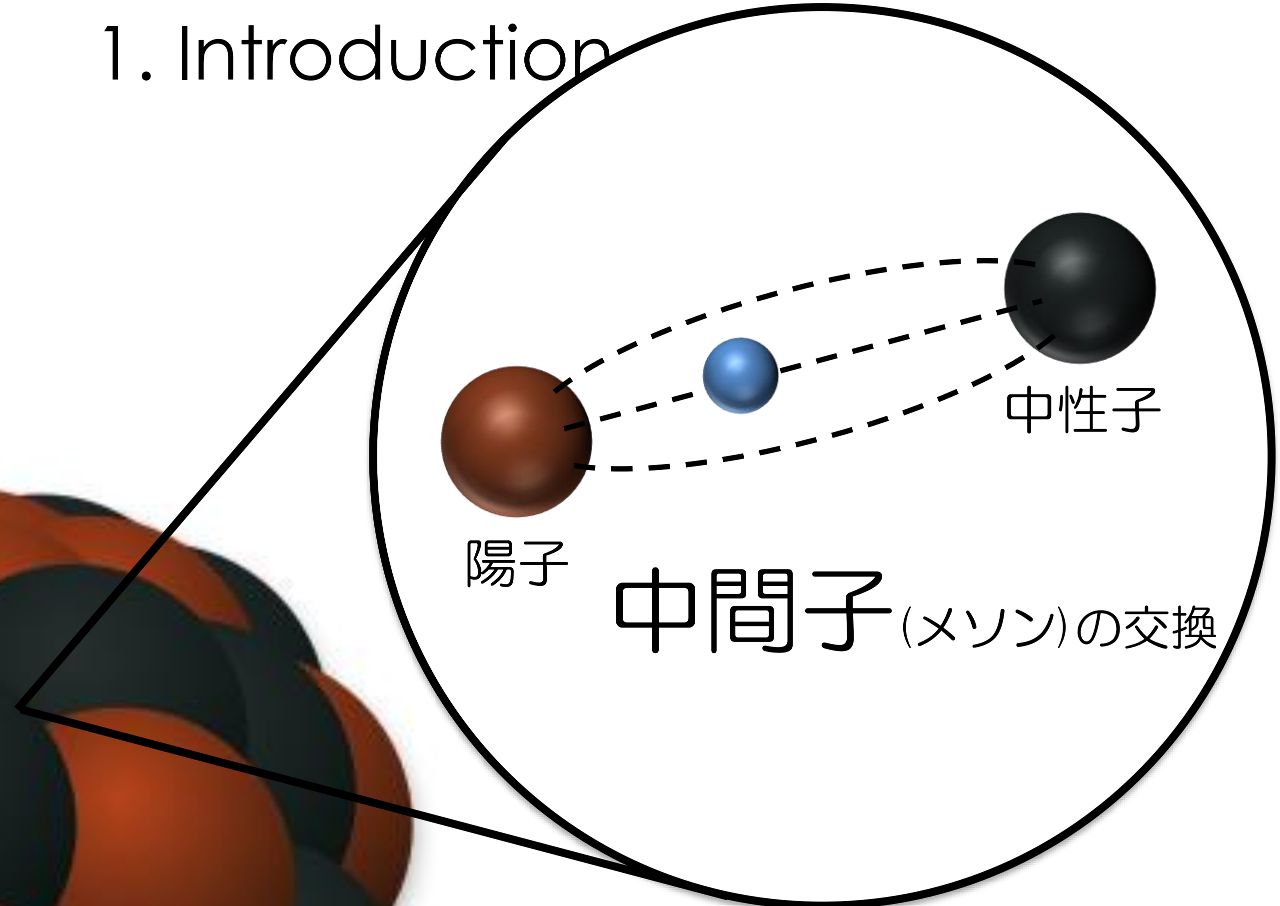
核力

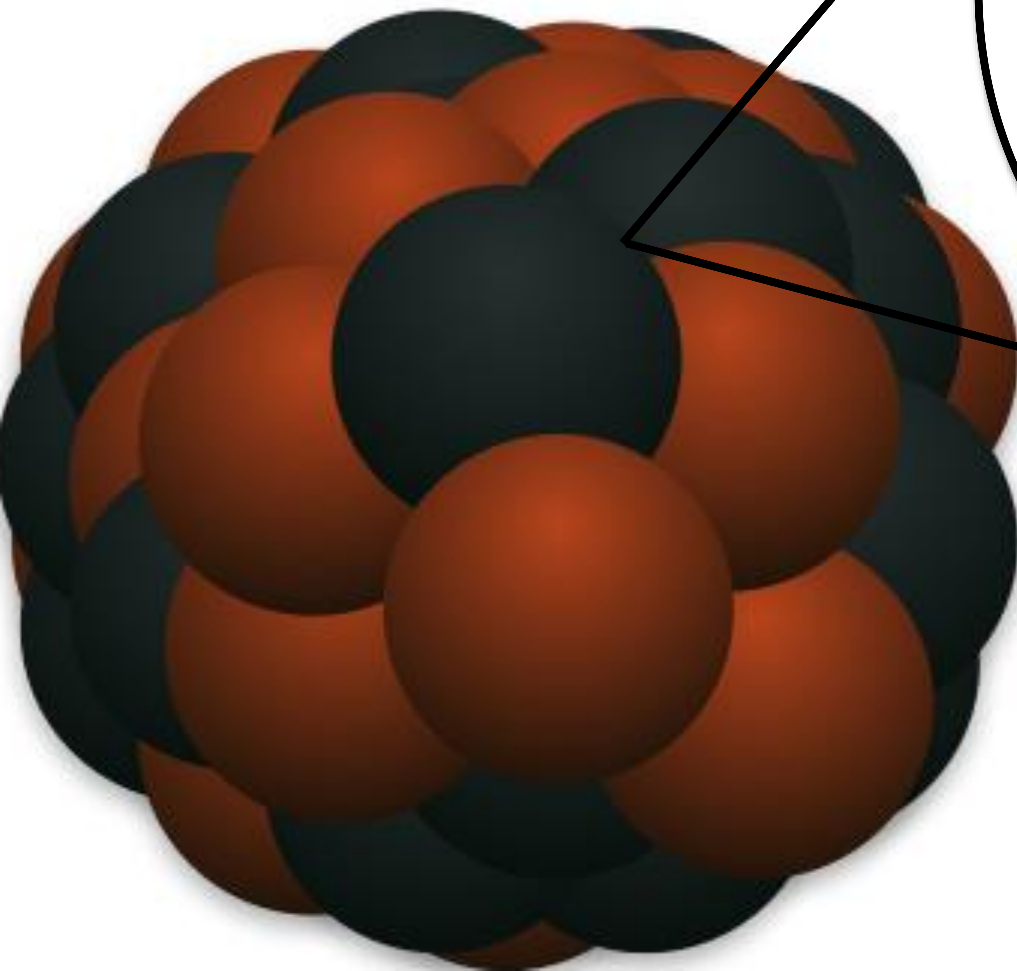
湯川秀樹
(1907-1981)



中間子(メソン)の交換
- かなり強い(電気力の100倍以上)
- 短い距離しか届かない (数fm以下)

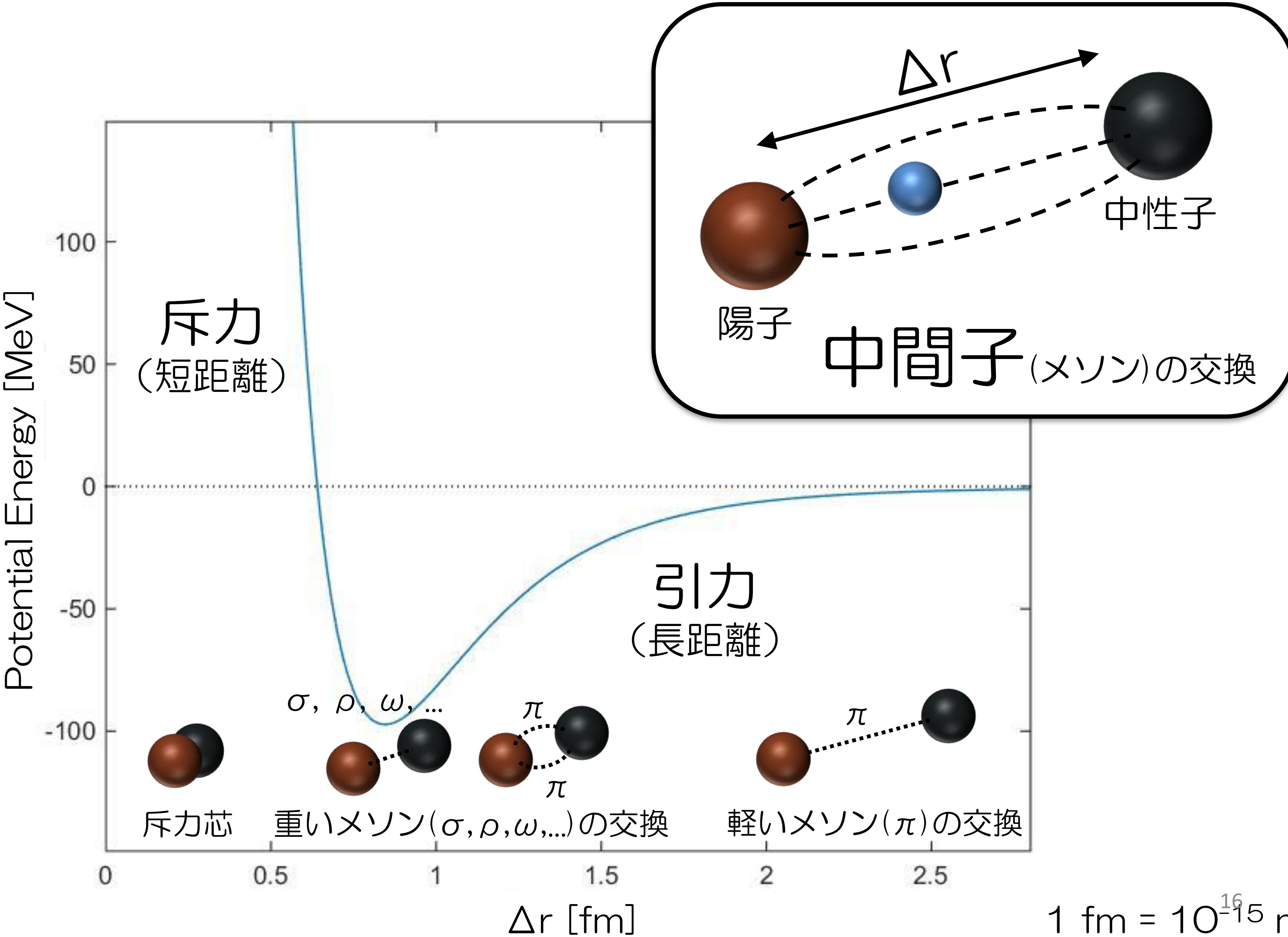
1. Introduction





原子核はメソン交換による力(核力)で核子(陽子・中性子)が集まってできた物質である。

1. Introduction



1 fm = 10^{-15} m

1. Introduction

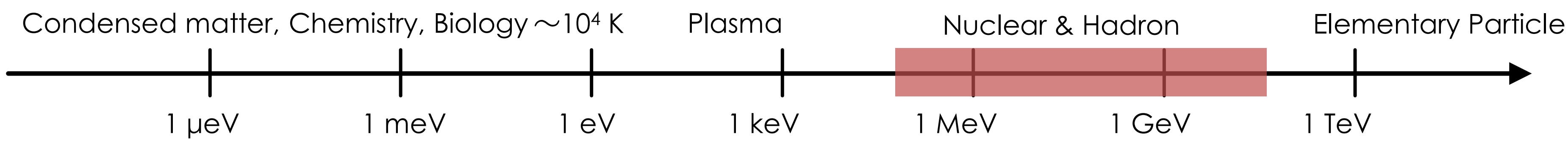
π, σ, ρ, ω, …って何？

(パイ)　(シグマ)　(ロー)　(オメガ)

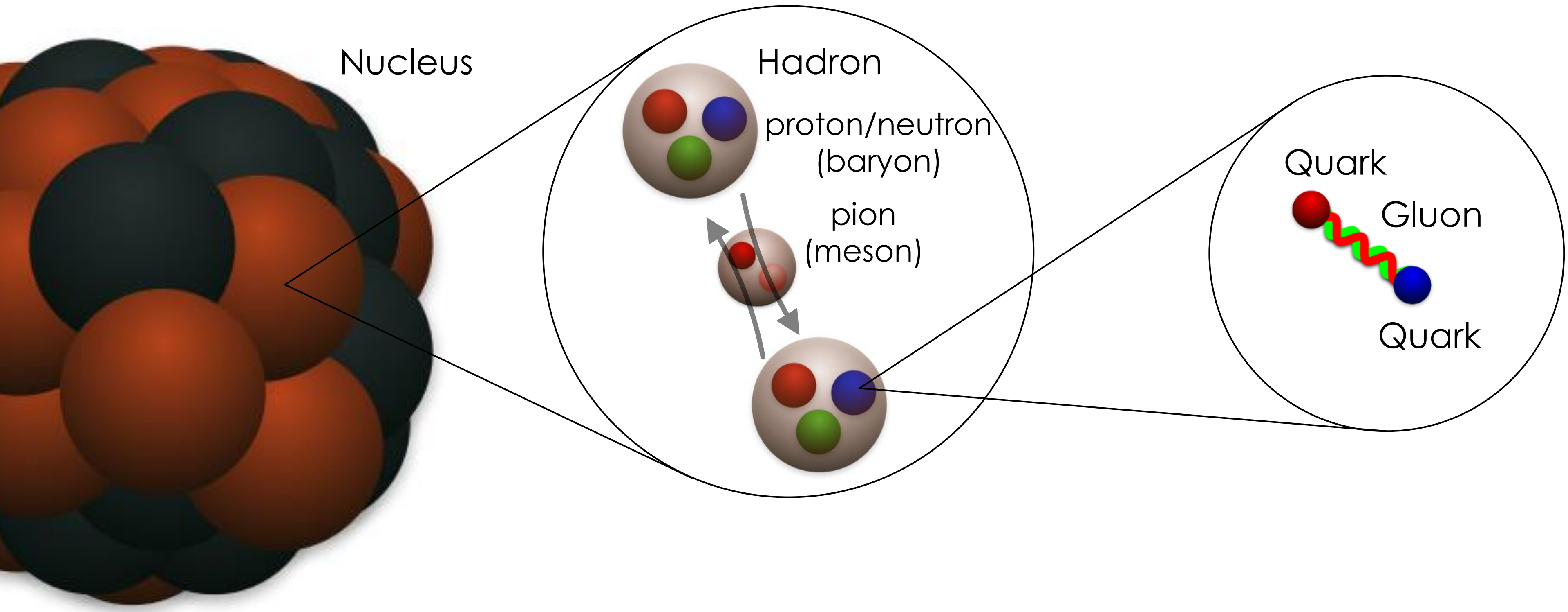
クォークqと反クォーク$\bar{q}$の束縛状態

From nucleus to quark

1 MeV = 10^6 eV
1 GeV = 10^9 eV



∼ 100 keV surface vibration/rotation ∼ 100 MeV excited hadron ∼ 100 GeV quark



From nucleus to quark

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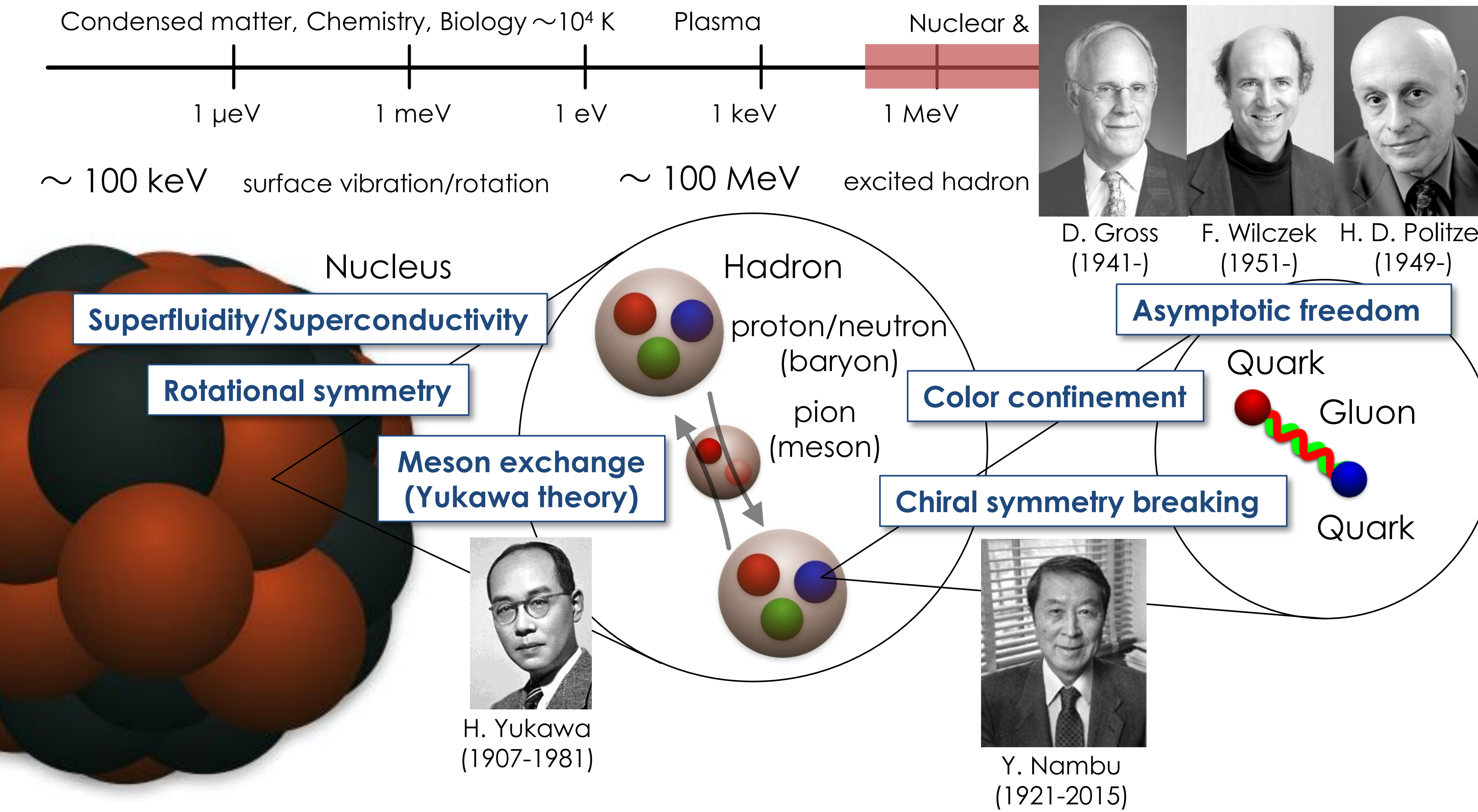
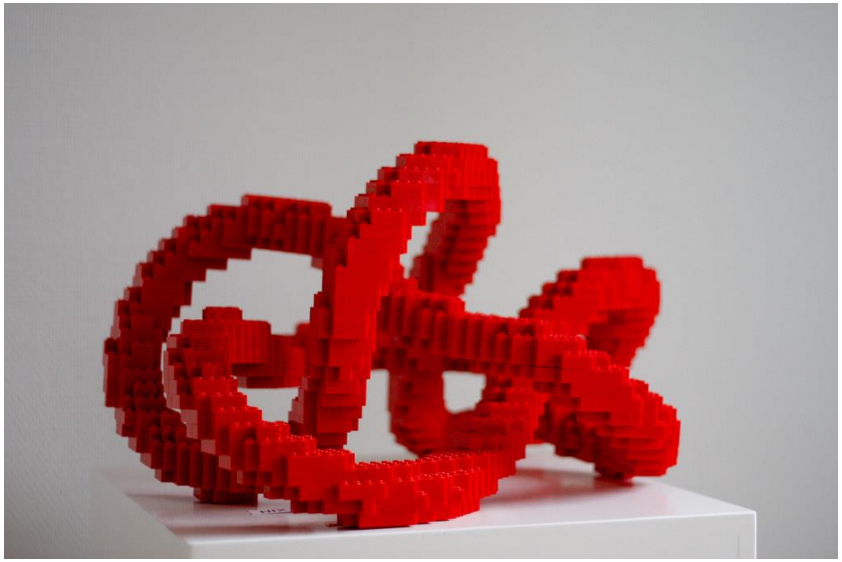


Can we understand nucleus/hadron by quarks and gluons?

Questions

- How do quarks compose hadrons?

quarks



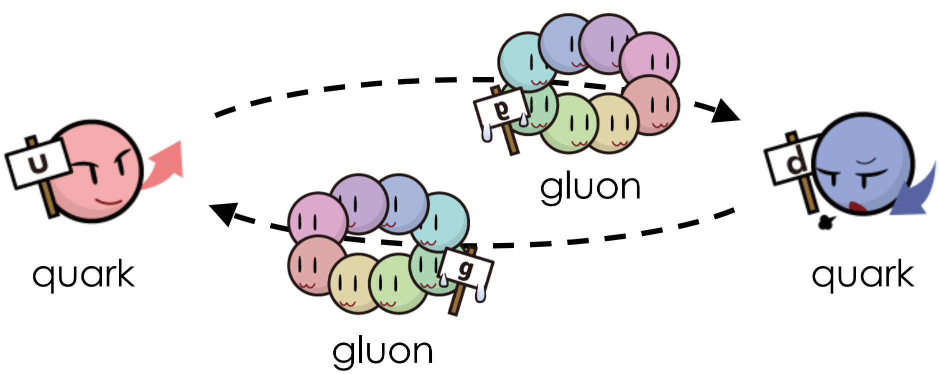
hadrons

1. Introduction

How do quarks move?

$ma = F$

Gluon



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1. Introduction

"Law of motion" of quarks and gluons

Quantum Chromodynamics
(QCD)

$$\mathcal{L}_{\mathrm{QCD}}[\bar{\psi}, \psi, A] = \sum_f \bar{\psi}_f (i\partial\!\!\!/ - g_s A\!\!\!/ - m_f)\psi_f - \frac{1}{4}F_{a\mu\nu}F^{a\mu\nu}$$

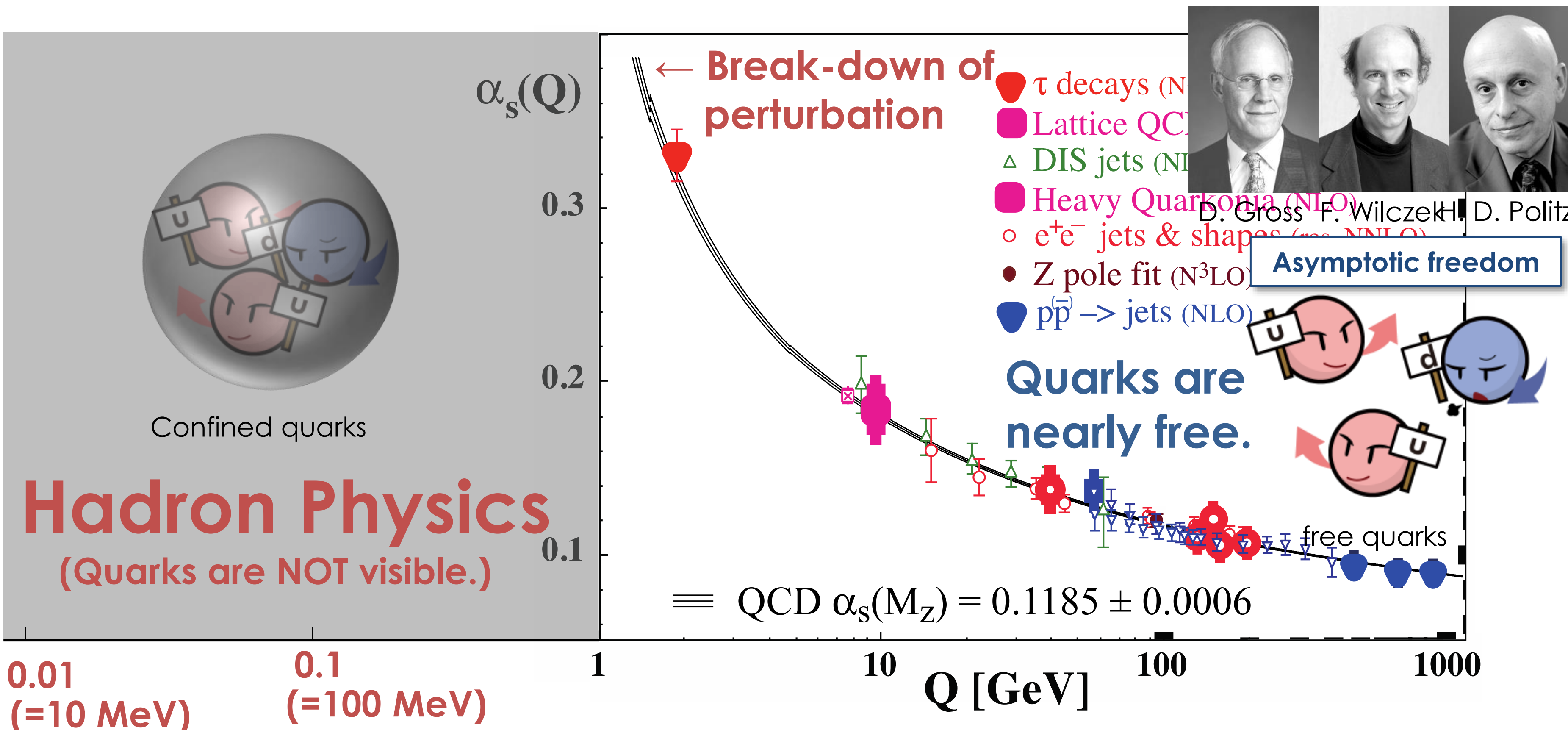
ψ_f: quark field (flavor f)

A_μ, $F_{\mu\nu}$: gluon field

g_s: coupling between quarks and gluons

Why is hadron physics difficult?

Answer: *strong* coupling in low energy

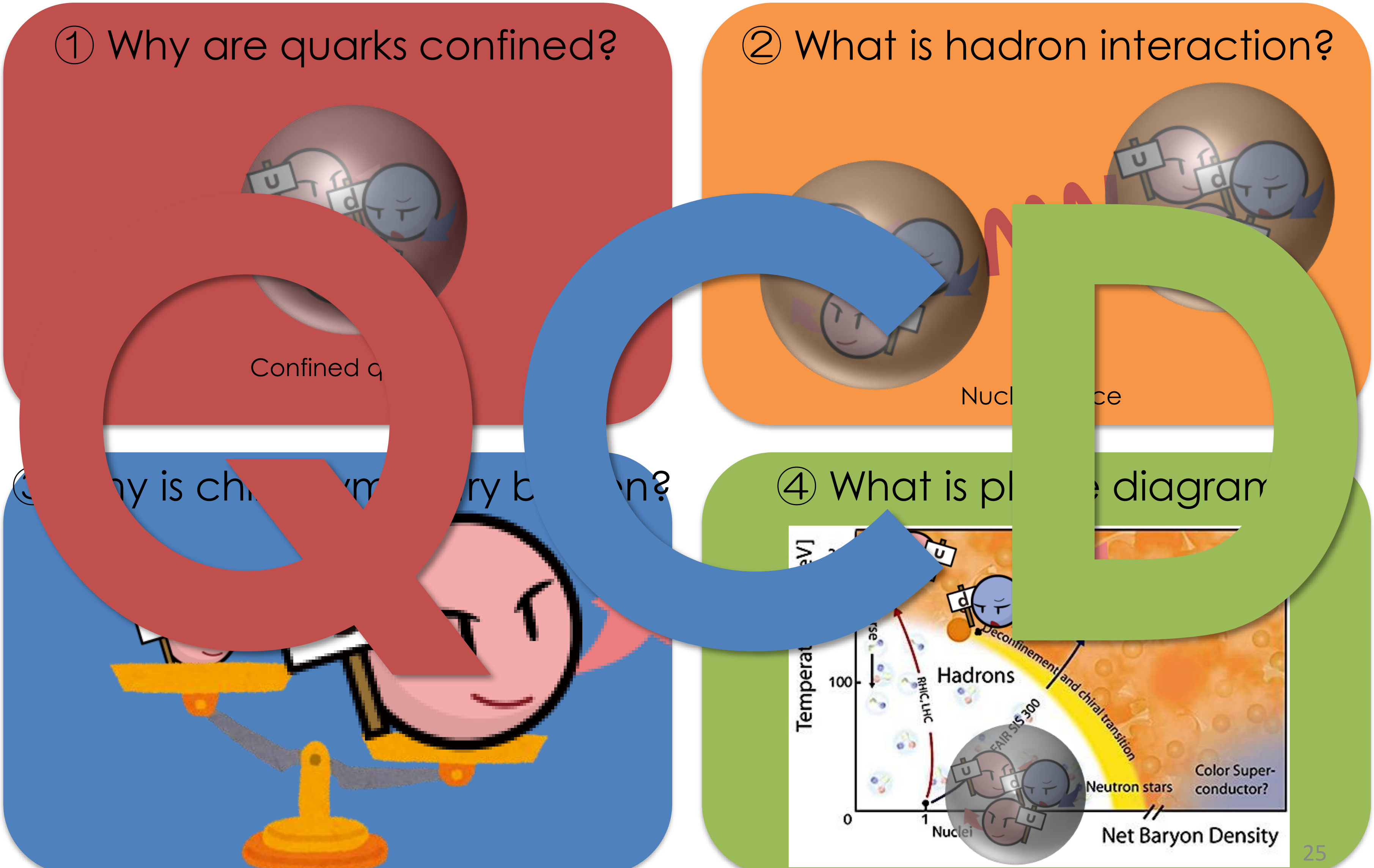


Non-perturative effects in low energy

Origin of a variety of matter states?

1. Introduction

Fundamental 4 Questions in Hadron Physics



Properties of QCD

① Color charge (red, blue, green)

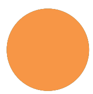
1. Introduction

Color charge (review)

QED

U(1) symmetry

electron e^-



-e

positron e^+

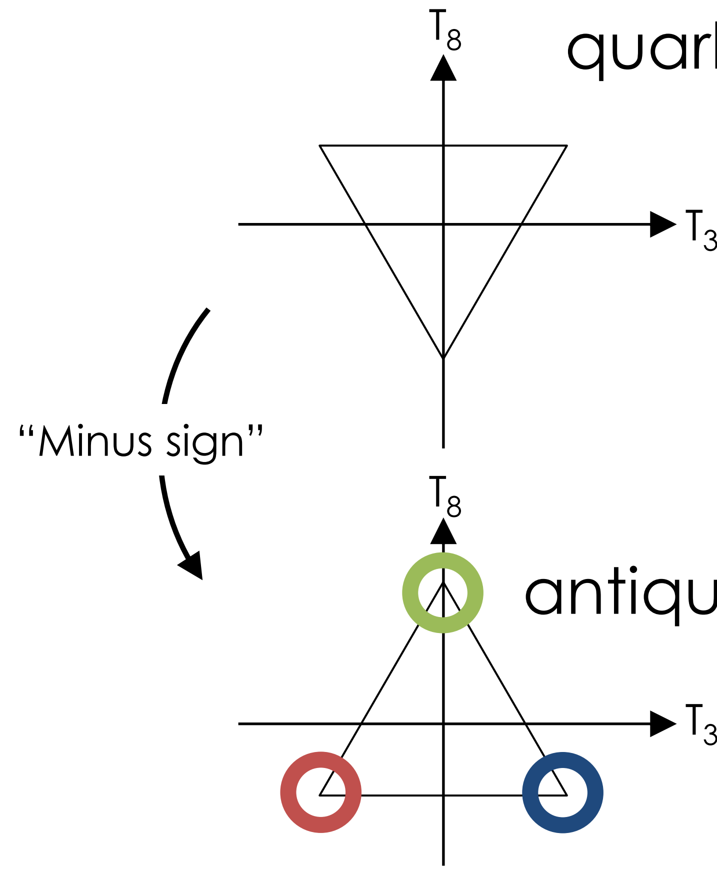
+e

QCD

SU(3) symmetry

quark q

antiquark $\bar{q}$



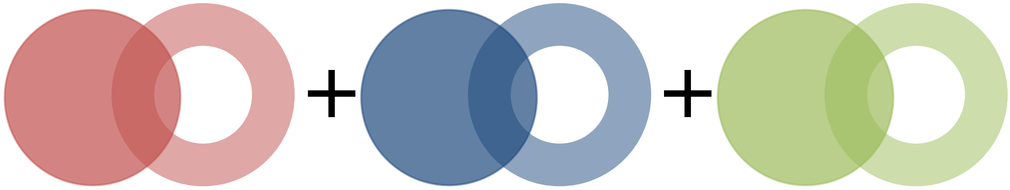
1. Introduction

Color charge (review)

Hadrons are colorless (white: T_3=T_8=0)

meson ($q\bar{q}$)

baryon (qqq)



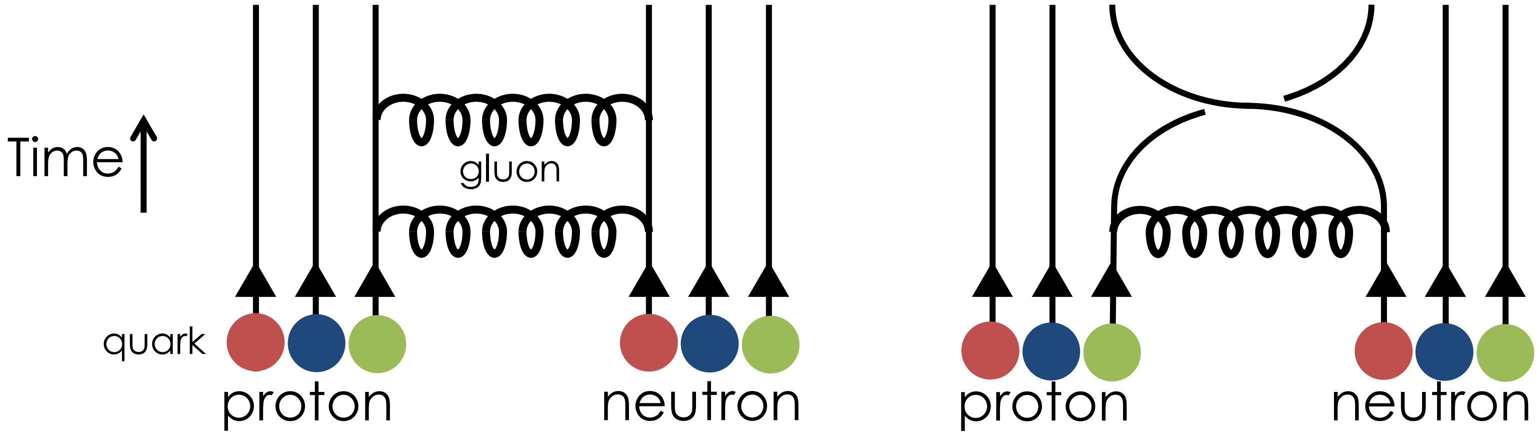
$$q_r\bar{q}_r + q_g\bar{q}_g + q_b\bar{q}_b$$

$$\epsilon_{ijk}q_iq_jq_k$$

Properties of QCD

① Color charge (red, blue, green) ● ● ●

② Gluon exchange in inter-quark



Properties of QCD

① Color charge (red, blue, green)

② Gluon exchange in inter-quark

③ Asymptotic freedom (small coupling at high energy)

④ "Structure" of QCD vacuum

- quarks are confined
- chiral symmetry is broken

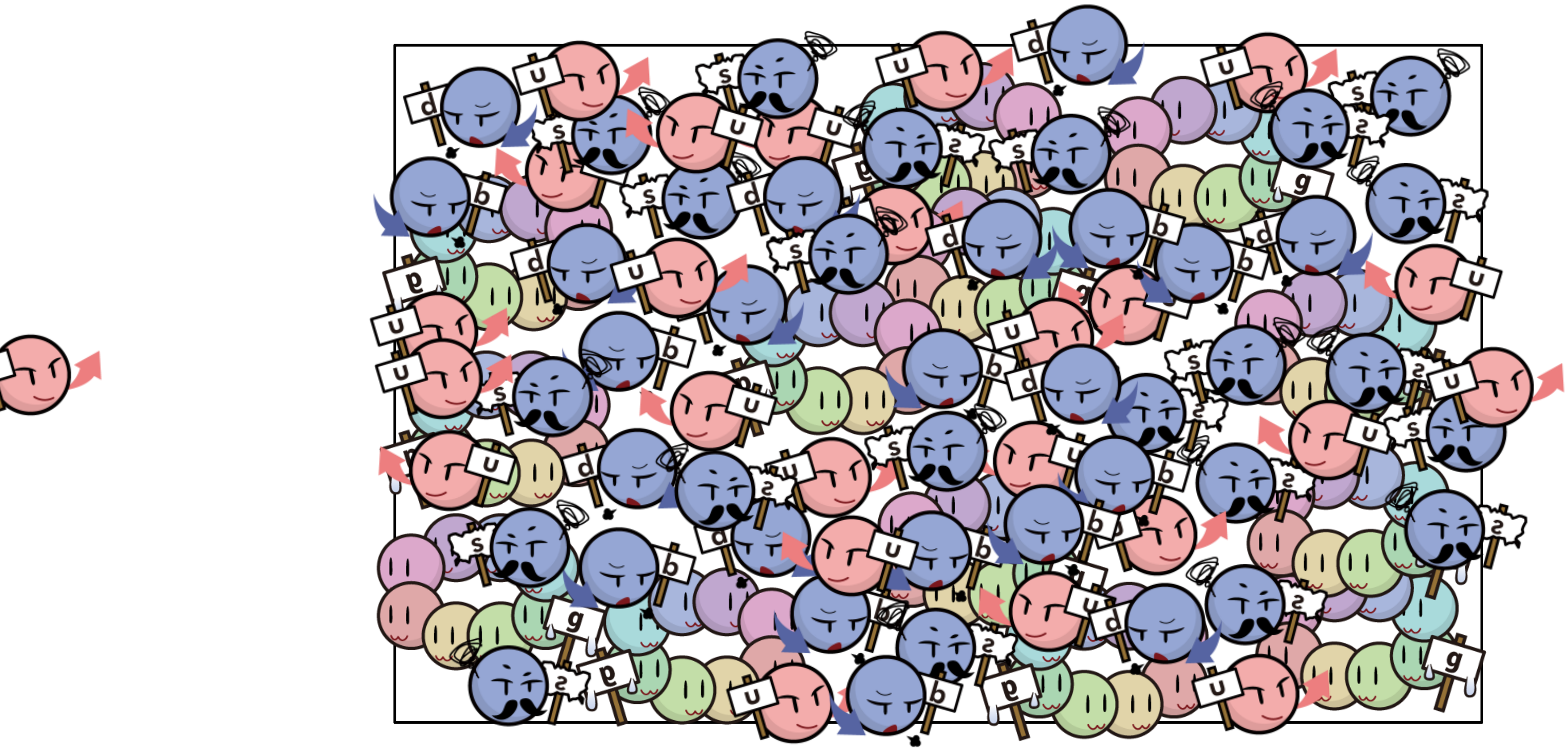
"Big problem" in strong interaction!!

“Structure” of QCD vacuum?

Nothing？

"Structure" of QCD vacuum?

Many particles in QCD vacuum!



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"Non-perturbative vacuum"

(Condensate by interaction is realized by stability of energy.)

“Structure” of QCD vacuum?

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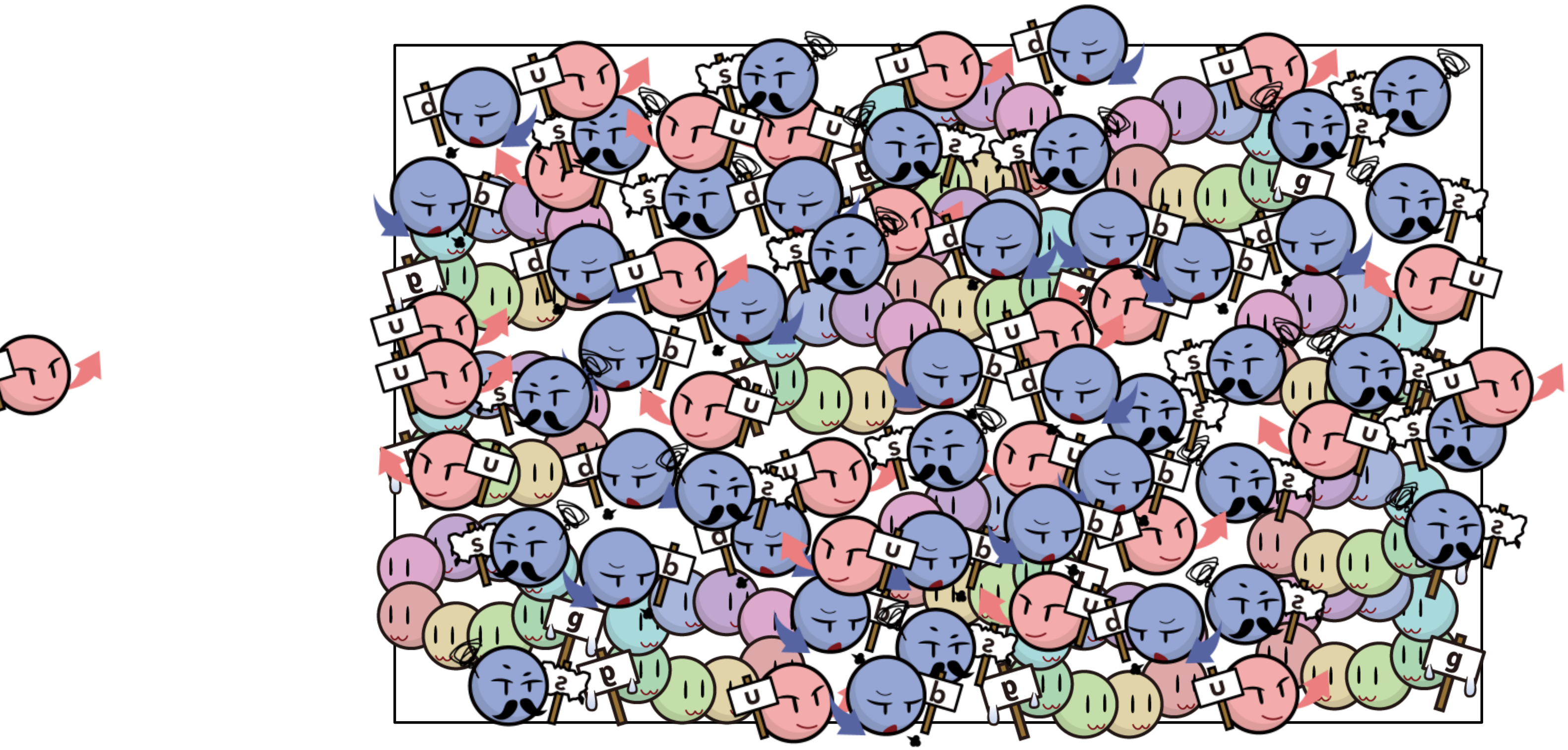

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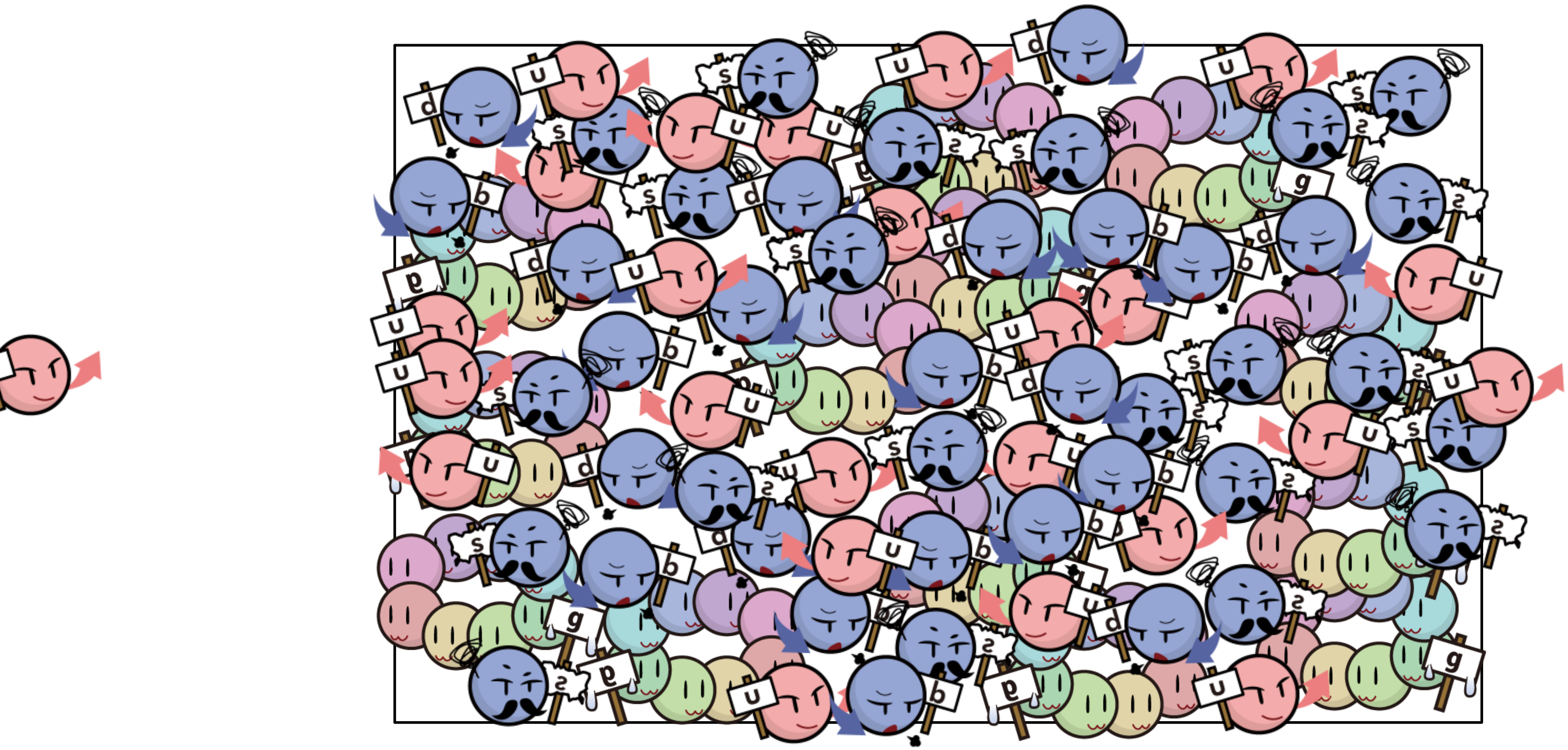

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"Non-perturbative vacuum"

(Condensate by interaction is realized by stability of energy.)

1. Introduction

“Structure” of QCD vacuum?

Many particles in QCD vacuum!

“Vacuum” ≠ Nothing

in field theory

"Structure" of QCD vacuum?

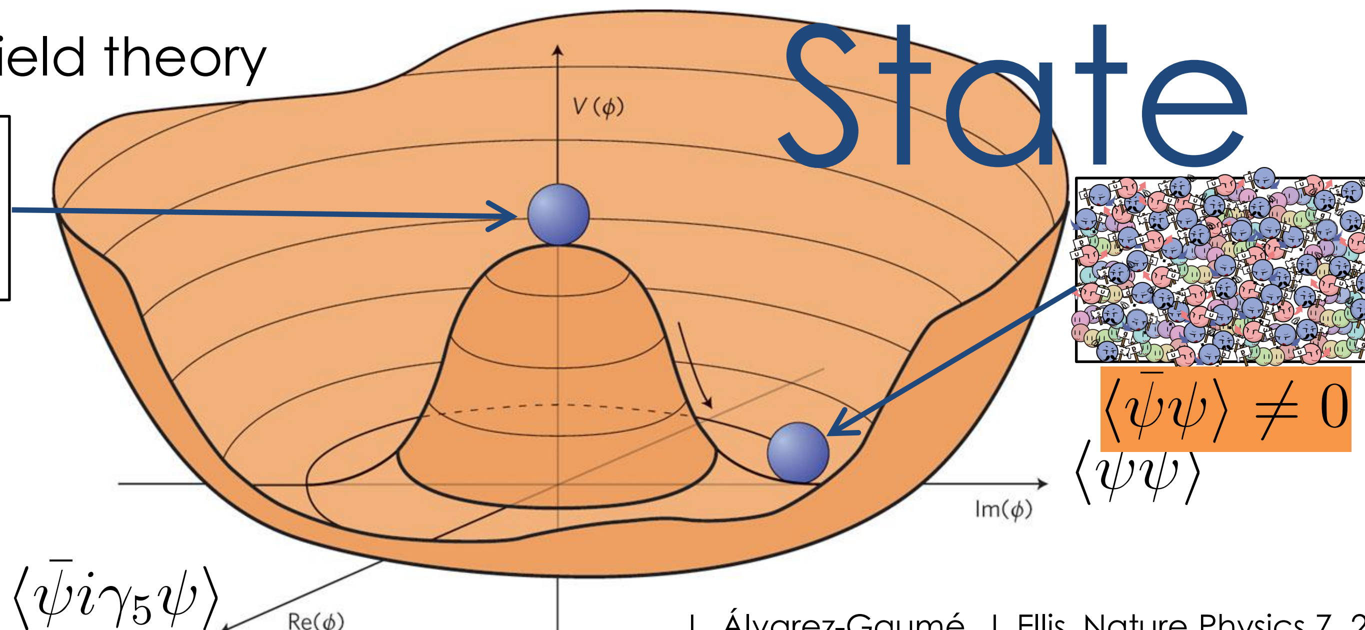
Many particles in QCD vacuum!

"Vacuum" = Most Stable State

in field theory

Nothing

$\langle \bar{\psi}\psi \rangle = 0$



$\langle \bar{\psi}\psi \rangle \neq 0$

$\langle \psi\psi \rangle$

$\langle \bar{\psi} i\gamma_5 \psi \rangle$

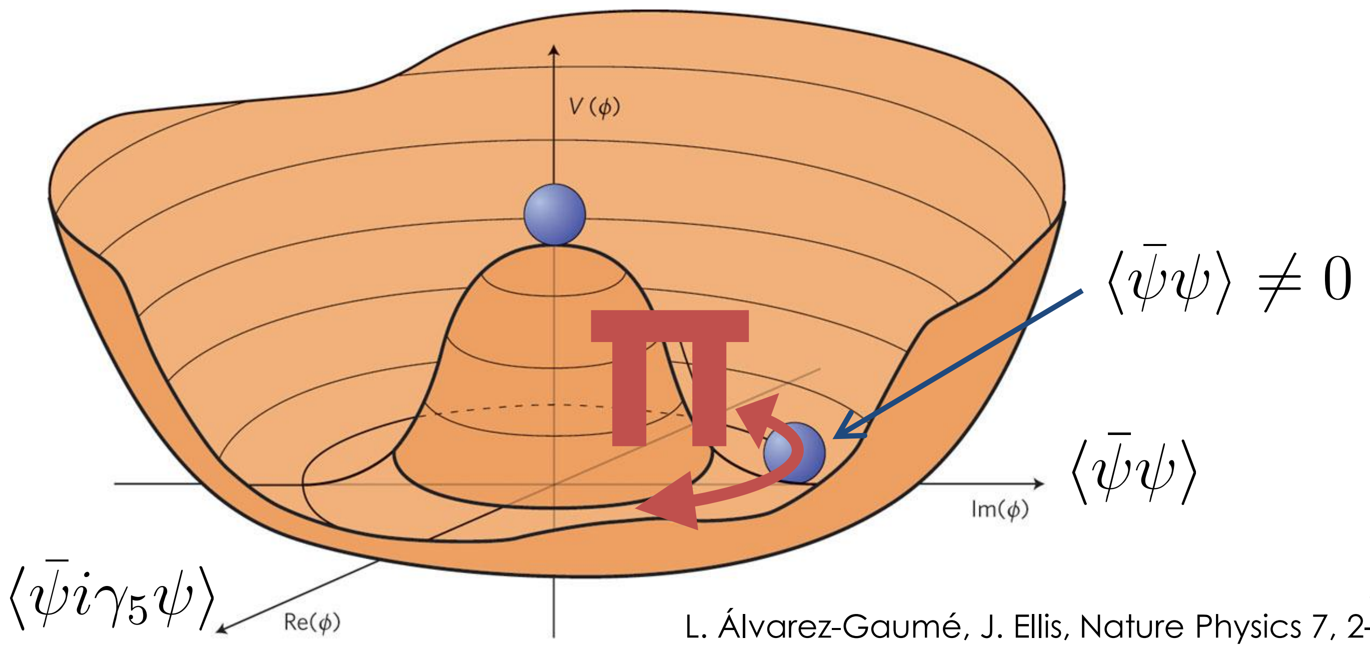
L. Álvarez-Gaumé, J. Ellis, Nature Physics 7, 2–3 (2011)

"Structure" of QCD vacuum?

What happens in QCD vacuum?

Dynamical symmetry breaking induces zero-mass boson
(Nambu-Goldstone (NG) boson)

Origin of light mass of pion
(m_π=140 MeV << m_N=940 MeV)



L. Álvarez-Gaumé, J. Ellis, Nature Physics 7, 2–3 (2011)

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What happens in QCD vacuum?

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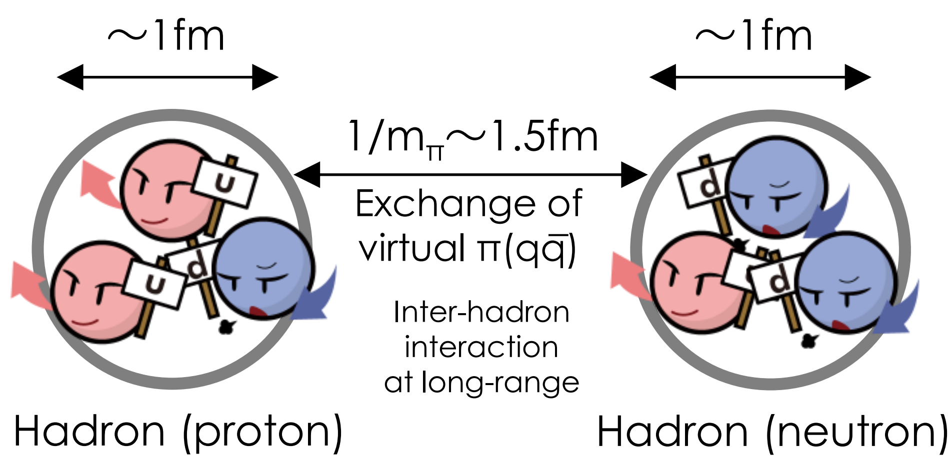
Origin of light mass of pion

(m_{π}=140 MeV << m_N=940 MeV)

Chiral symmetry breaking



Y. Nambu
(1921-2015)

π exchange interaction is dominant *at long distance*.

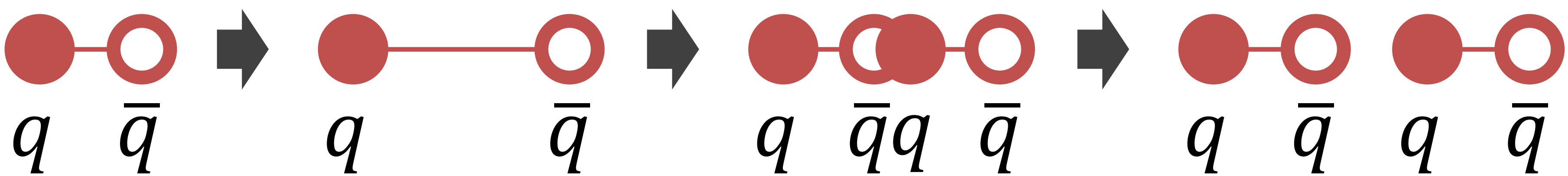
1. Introduction

“Structure” of QCD vacuum?

What happens in QCD vacuum?

color confinement

Can we separate two quarks？



meson

potential increases linearly

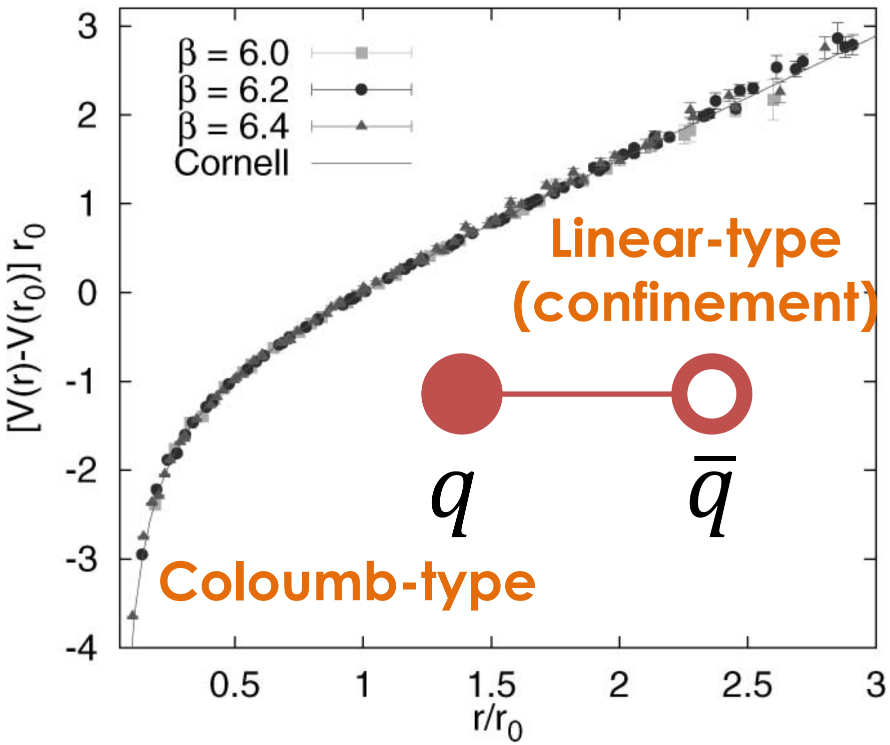
$q\bar{q}$ pair is created from vacuum

two mesons

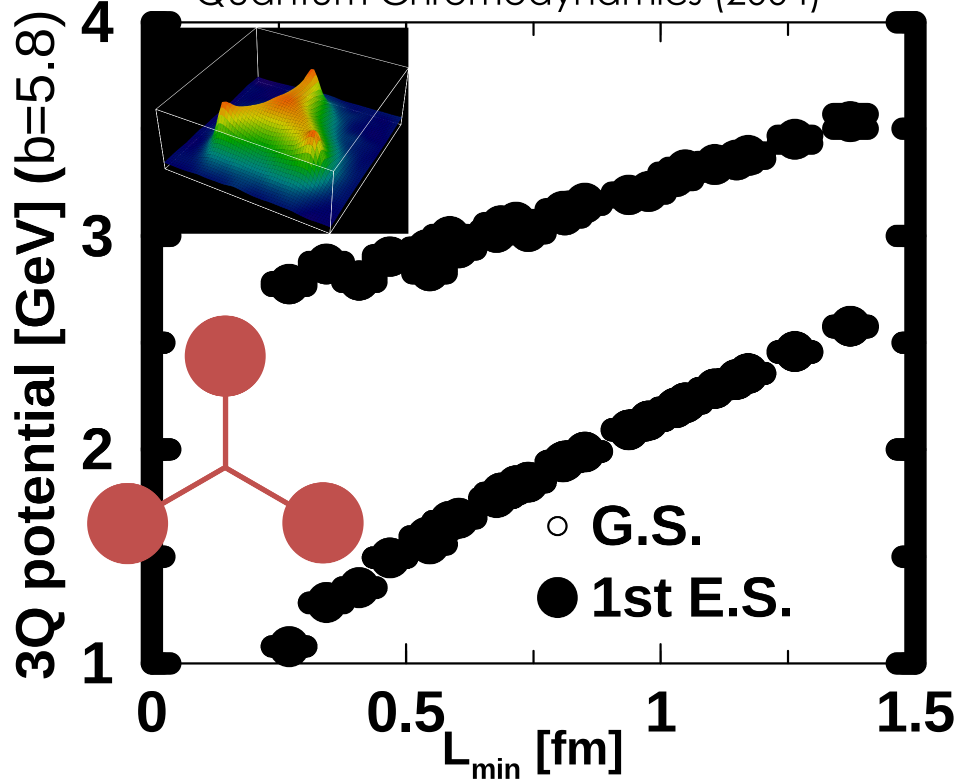
"Structure" of QCD vacuum?

What happens in QCD vacuum?

G.S. Bali, Phys. Rep. 343 (2001) 1



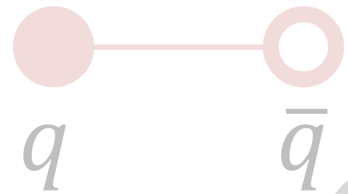
H. Suganuma, H. Ichie, T.T. Takahashi, Color Confinement and Hadrons in Quantum Chromodynamics (2004)



Quarks are always confined inside hadrons.

1. Introduction

color confinement



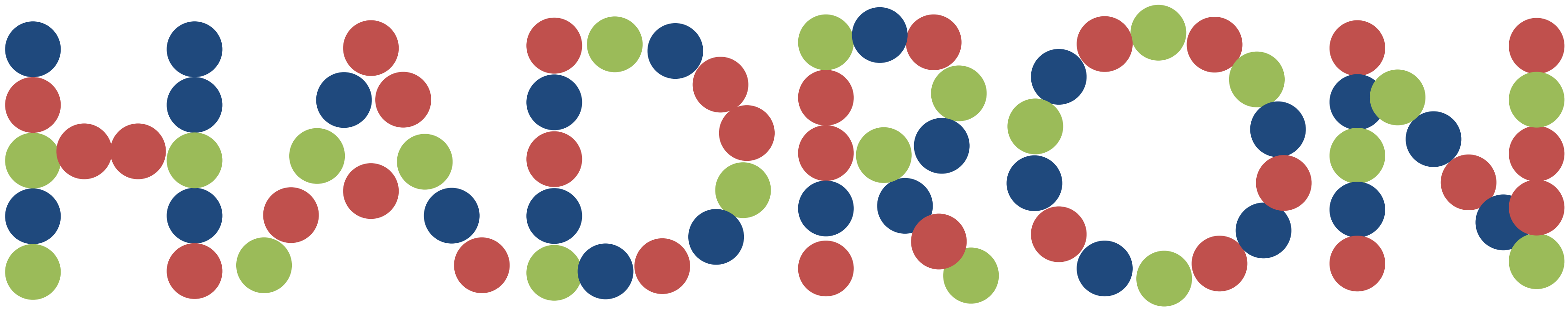
White

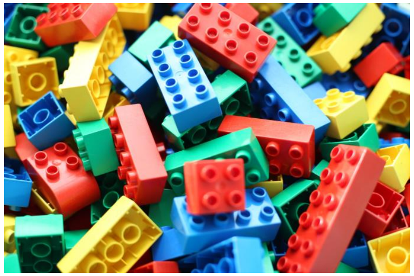
Quarks have to make white (colorless) objects.

1. Introduction

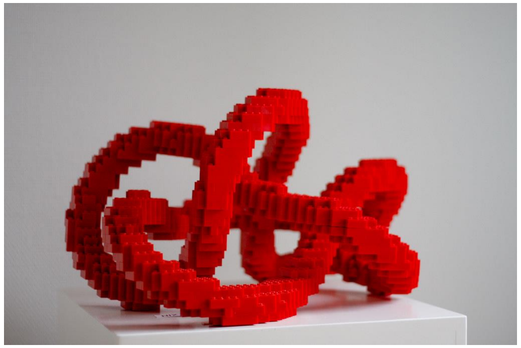
Main subject in this lecture:

Formation mechanism of hadrons by quarks





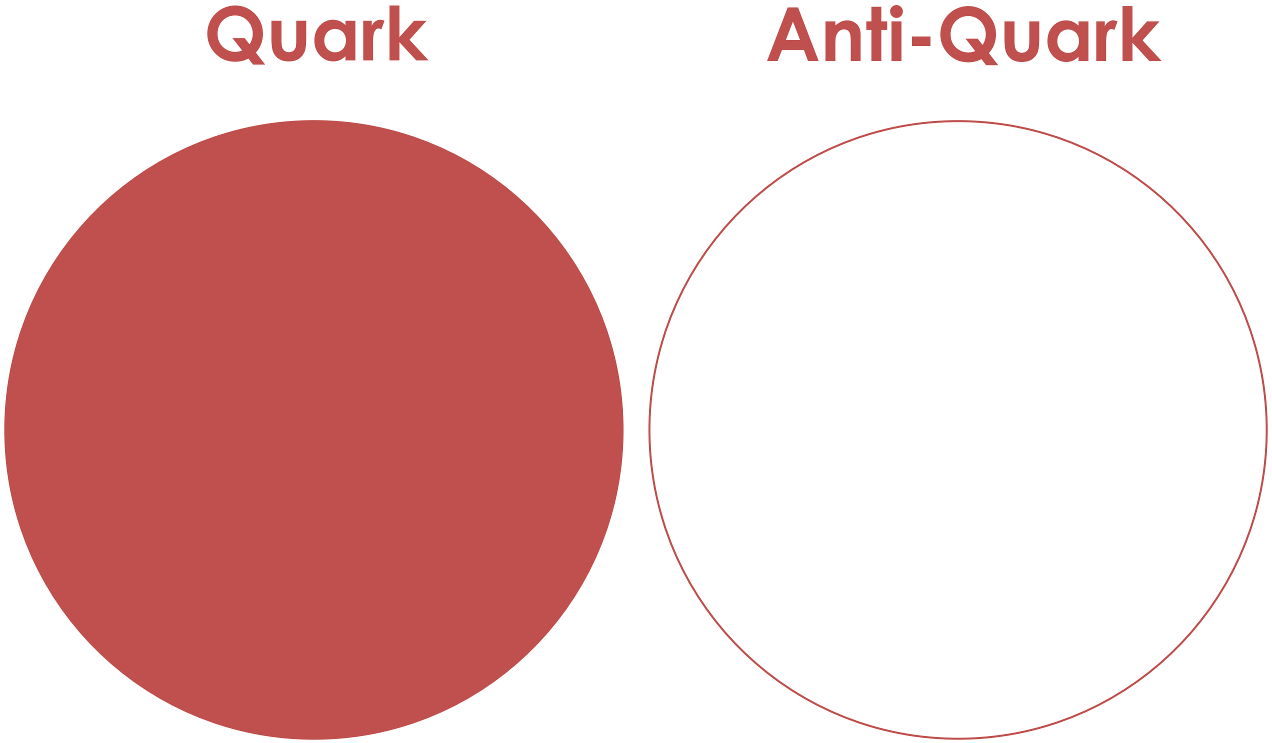
quarks



hadrons

- ✔ **Mass**
- ✔ **Interaction**
- ✔ **Many-body problem**

1. Introduction



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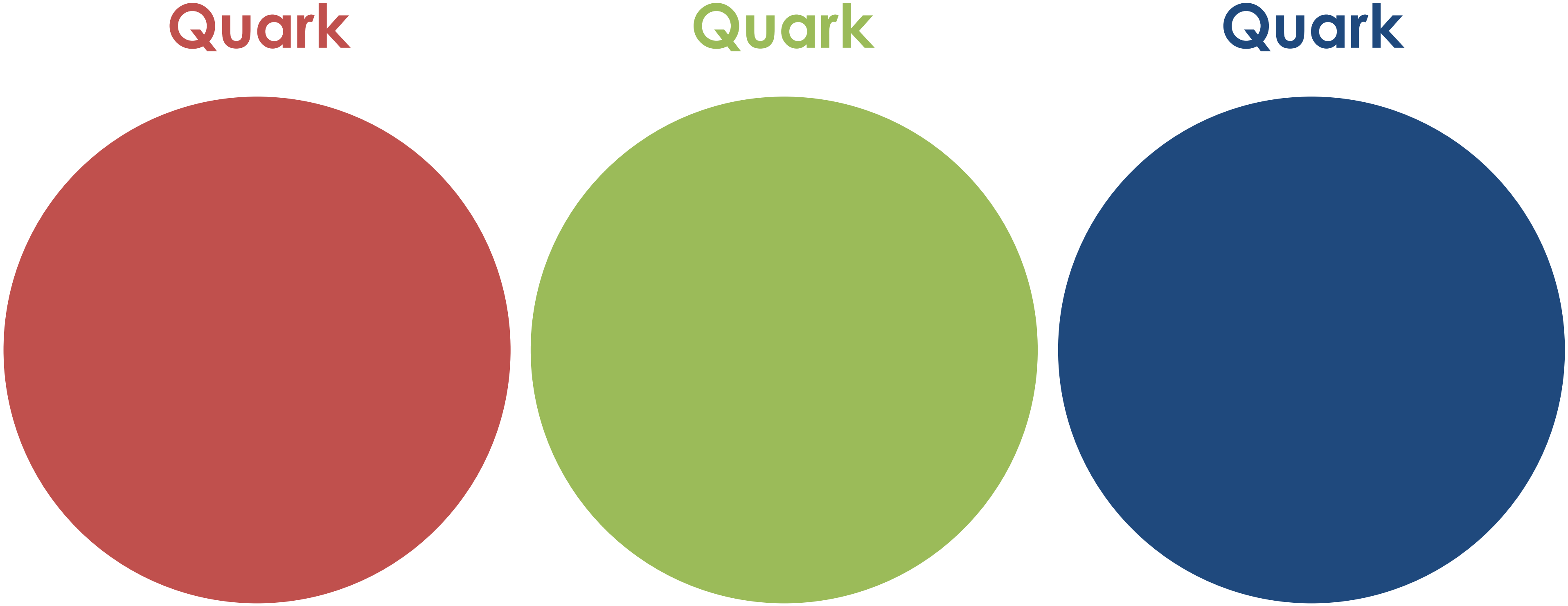
1. Introduction



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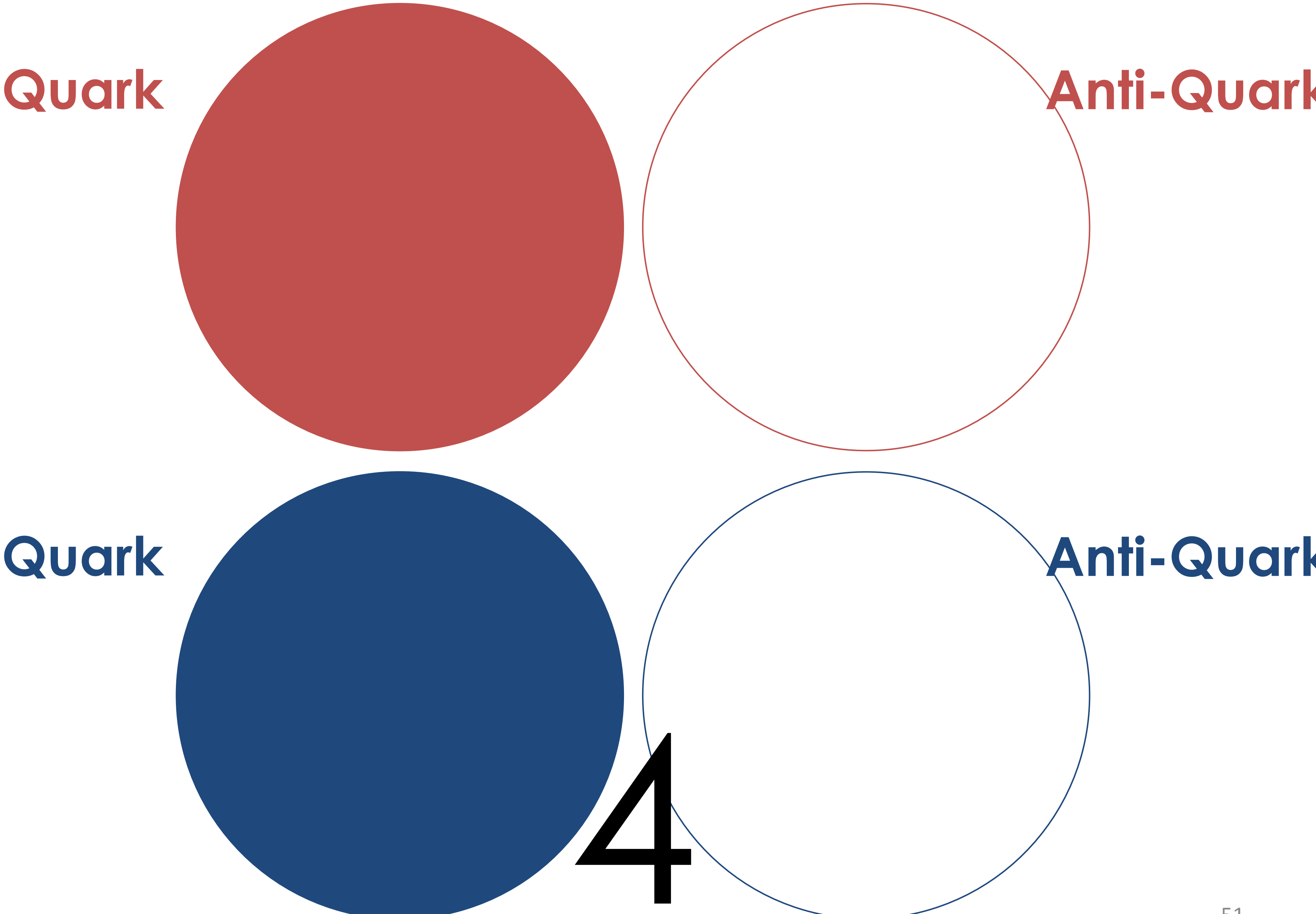
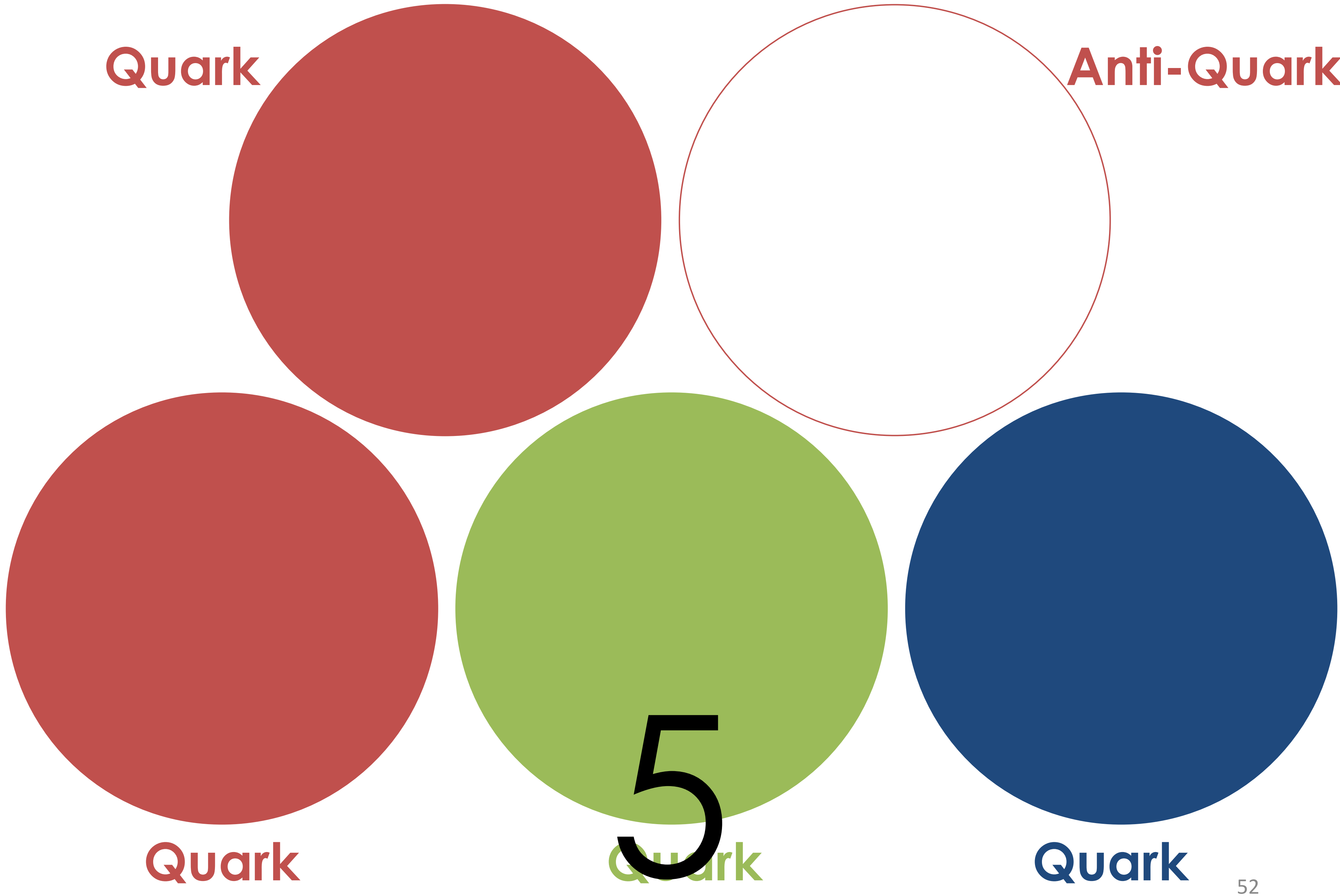
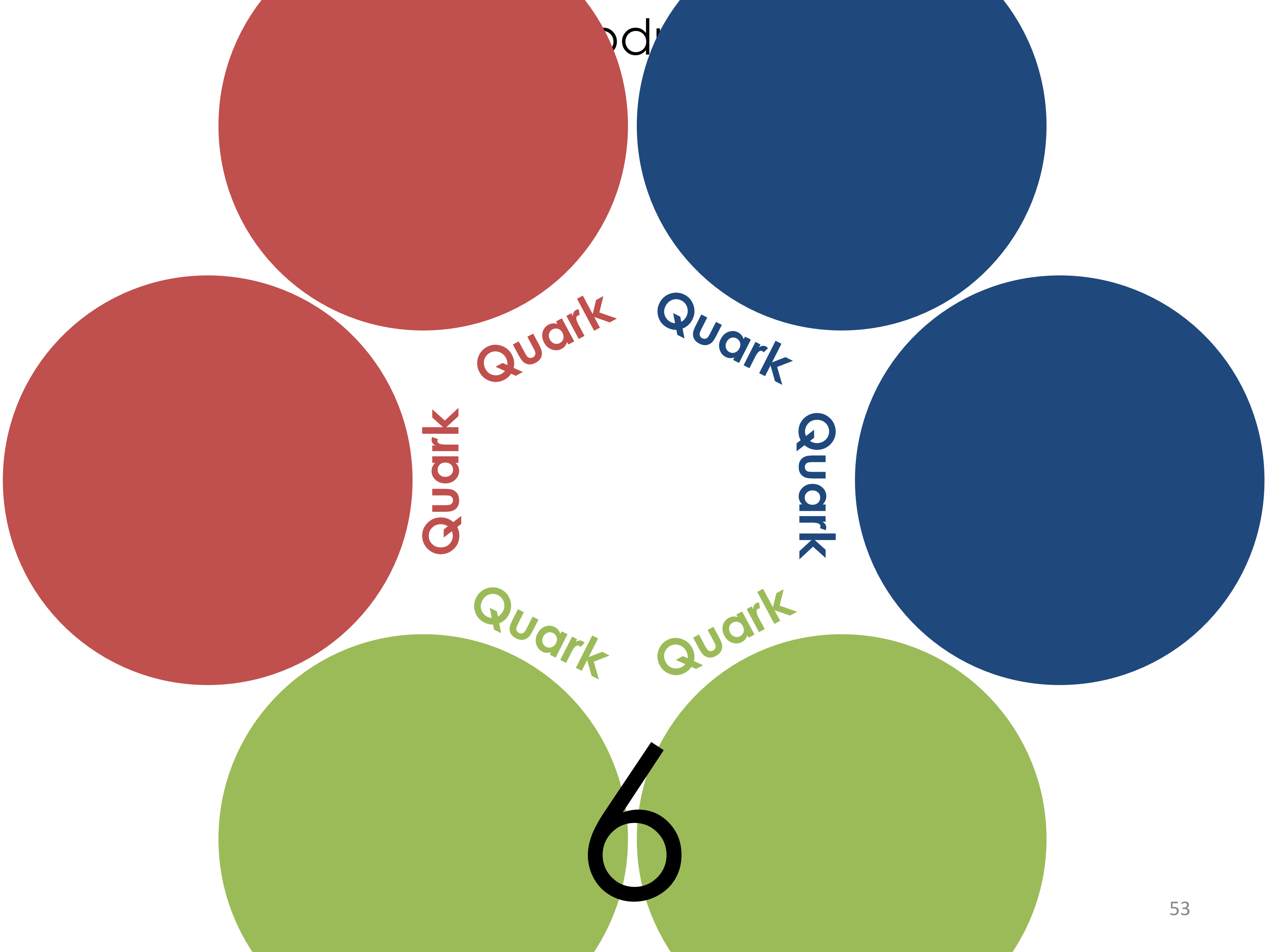


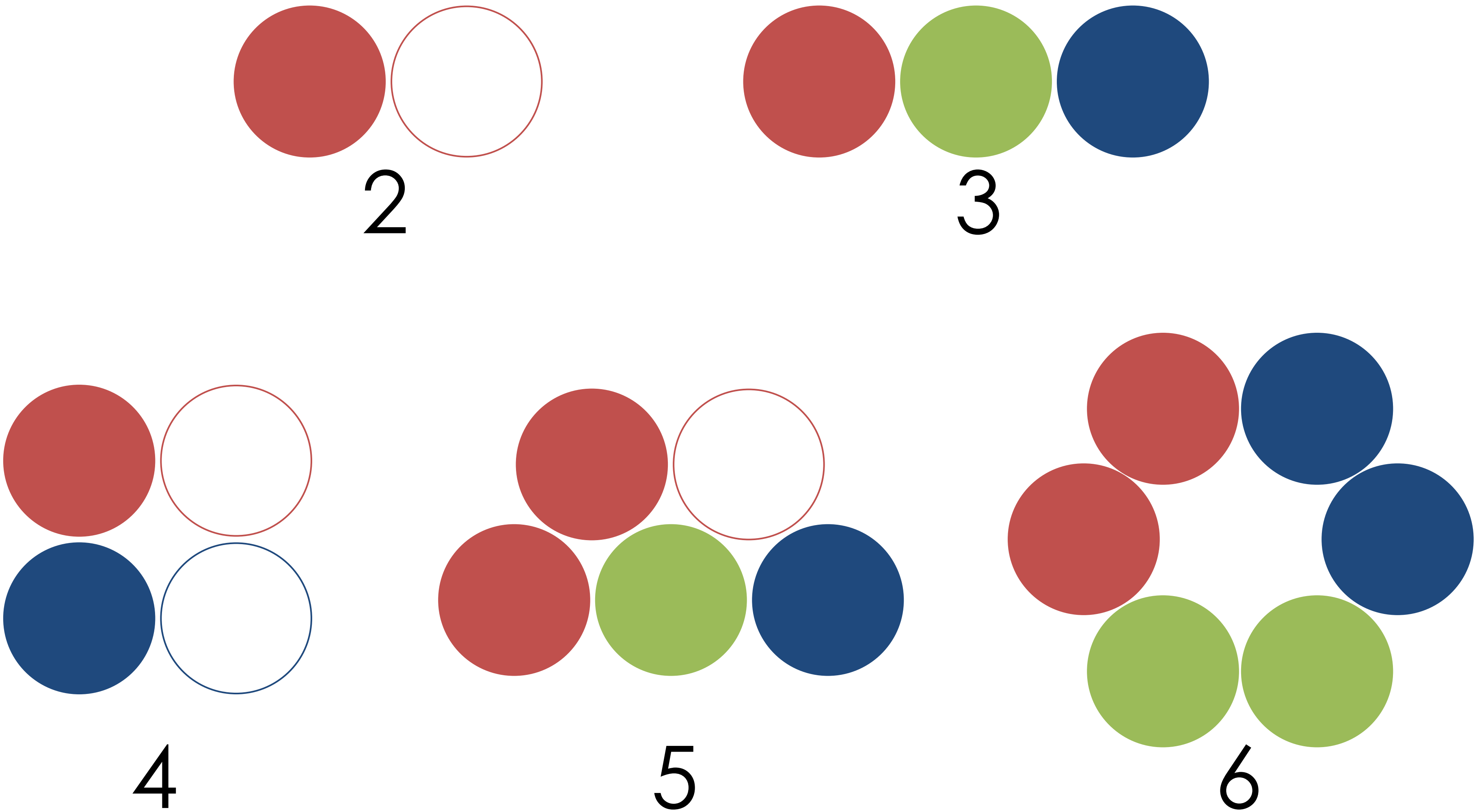
1. Introduction



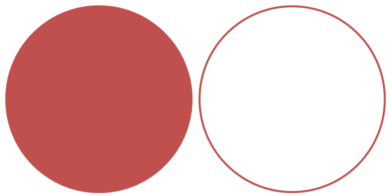

Quark
Quark
Quark
Quark
Quark
Quark
6

To be continued……………

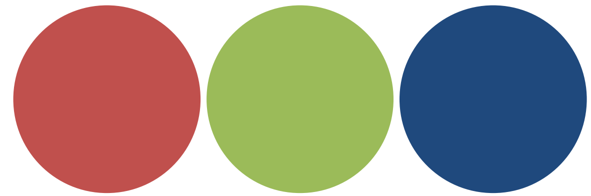
Variety of Hadrons



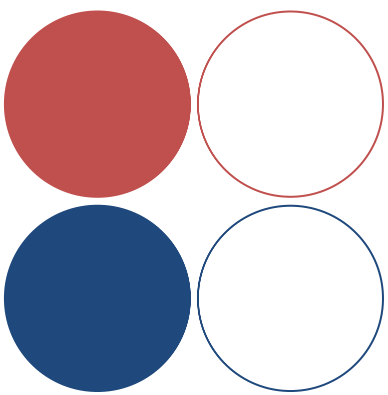
Variety of Hadrons



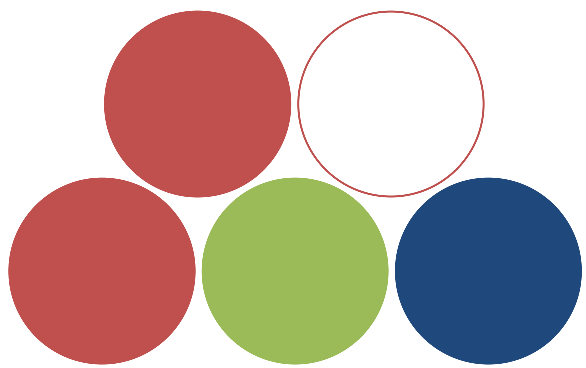
meson



baryon



*tetra*quark



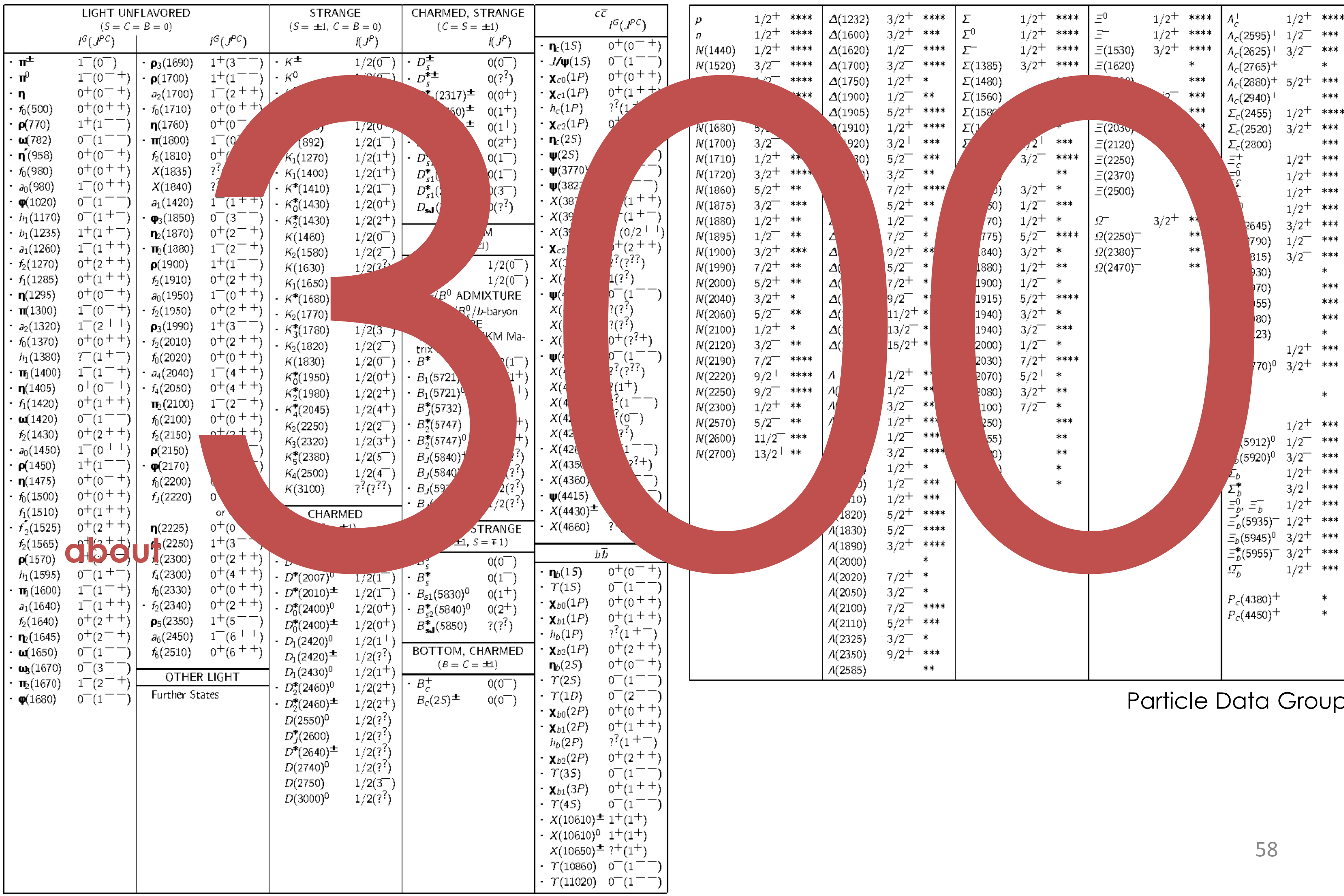
*penta*quark

*hexa*quark

1. Introduction

How many hadrons were discovered?

1. Introduction



Particle Data Group

1. Introduction

Quarks have flavors

1. Introduction

Quarks have flavors

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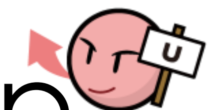
Flavors

electric charge	1st	2nd	3rd
Q=+2/3	up 	charm 	top 
	2 MeV	1300 MeV	173000 MeV
Q=-1/3	down 	strange 	bottom 
	5 MeV	100 MeV	4200 MeV

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weak interaction:
different flavors are interchanged by W and Z bosons (very slow process).

Flavors

electric charge	1st	2nd	3rd
Q=+2/3	**up** 	charm 	top 
	2 MeV	1300 MeV	173000 MeV
Q=-1/3	**down** 	**strange** 	bottom 
	5 MeV	**100 MeV**	4200 MeV

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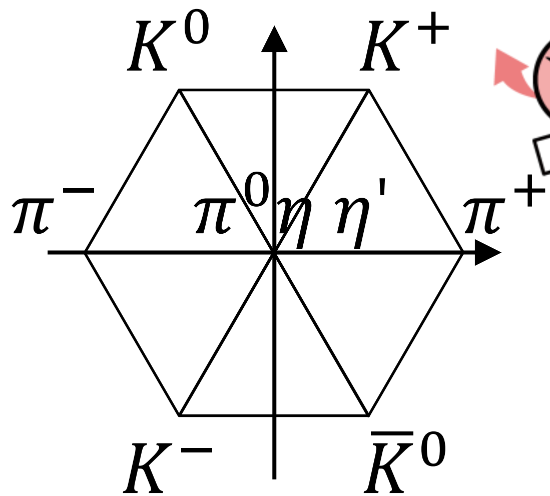
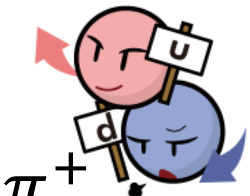
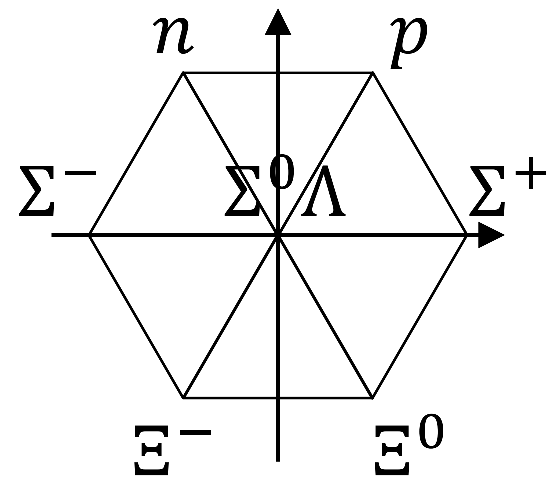
weak interaction:
different flavors are interchanged by W and Z bosons (very slow process).

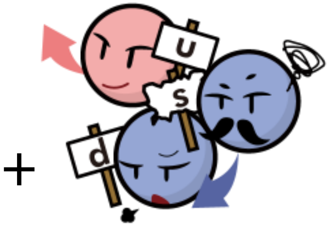
1. Introduction

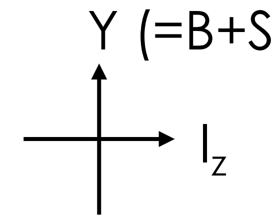
Hadrons made of up, down, strange quarks

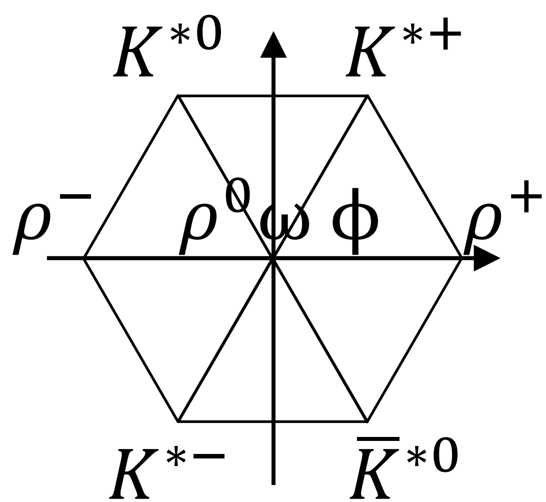


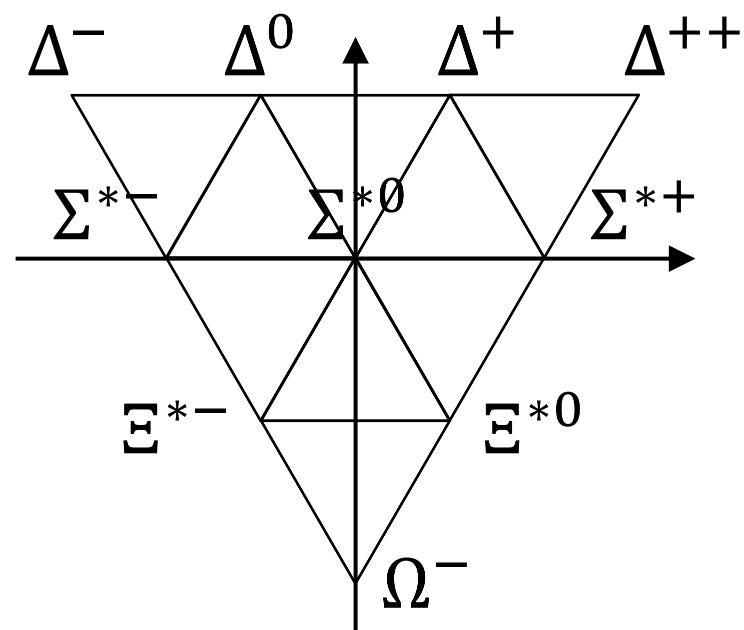












Flavors

electric charge	1st	2nd	3rd
Q=+2/3	up  2 MeV	charm  1300 MeV	top  173000 MeV
Q=-1/3	down  5 MeV	strange  100 MeV	bottom  4200 MeV

HiggsTan.com

weak interaction:
different flavors are interchanged by W and Z bosons (very slow process).

Flavors

electric charge	1st	2nd	3rd
Q=+2/3	up 2 MeV	**charm** **1300 MeV**	top 173000 MeV
Q=-1/3	down 5 MeV	strange 100 MeV	**bottom** **4200 MeV**

HiggsTan.com

weak interaction:
different flavors are interchanged by W and Z bosons (very slow process).

1. Introduction

Charm/bottom quarks

Heavy

$m_c/m_{u,d}$ = 200-400

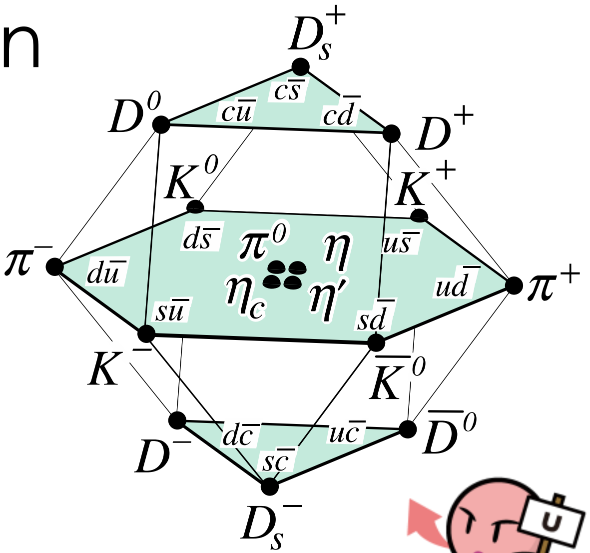
$m_b/m_{u,d}$ = 900-1400

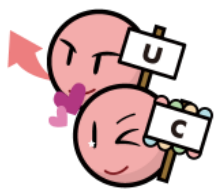
1. Introduction

Hadrons made of up, down, strange, **charm** quarks

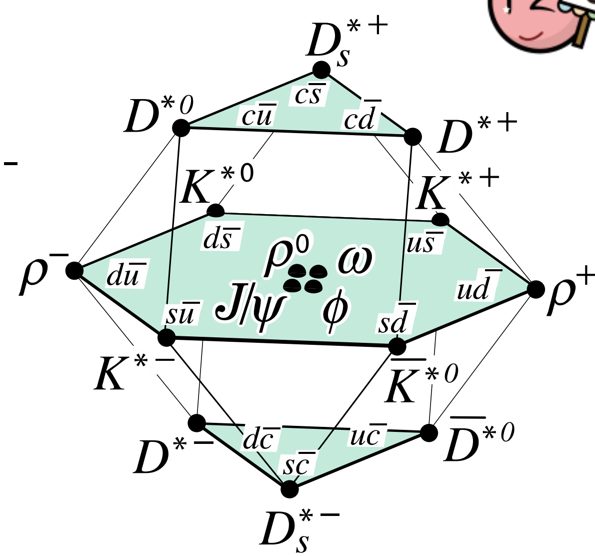
meson

$J^P=0^-$

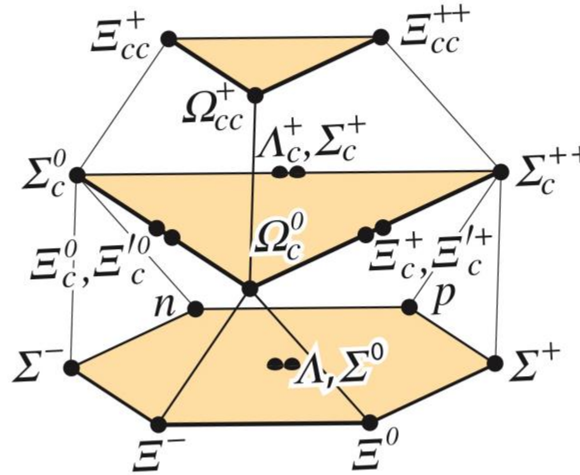


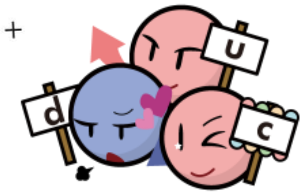


$J^P=1^-$

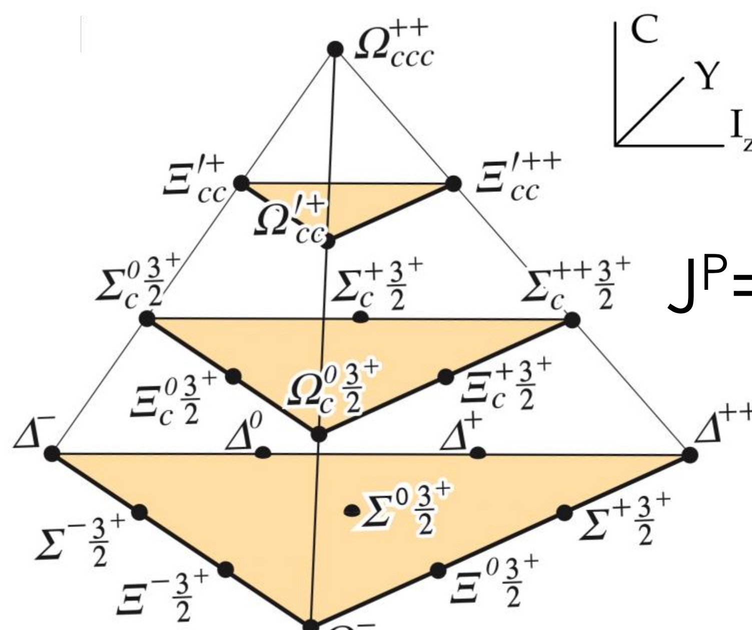


baryon





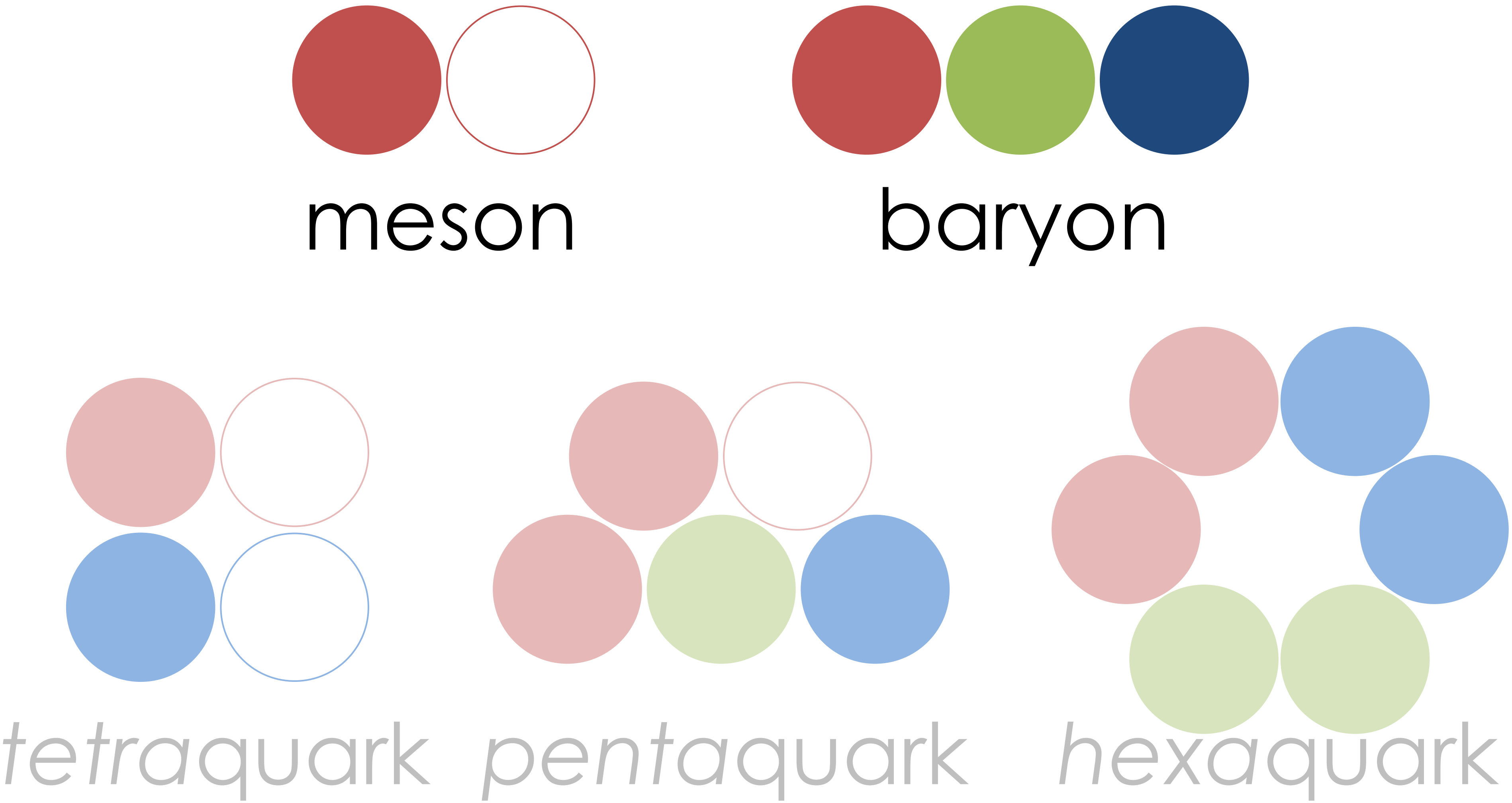
$J^P=1/2^+$



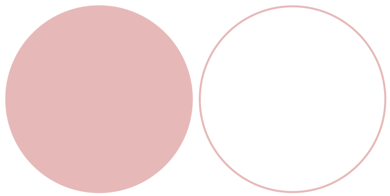
$J^P=3/2^+$

1. Introduction

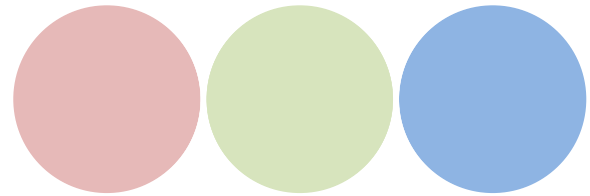
Variety of Hadrons



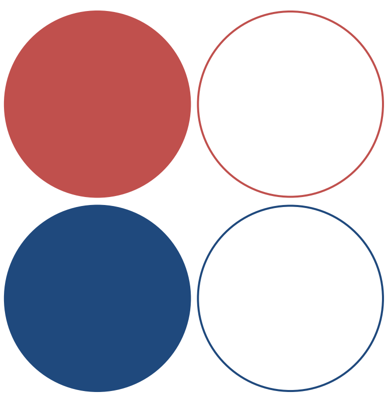
Variety of Hadrons



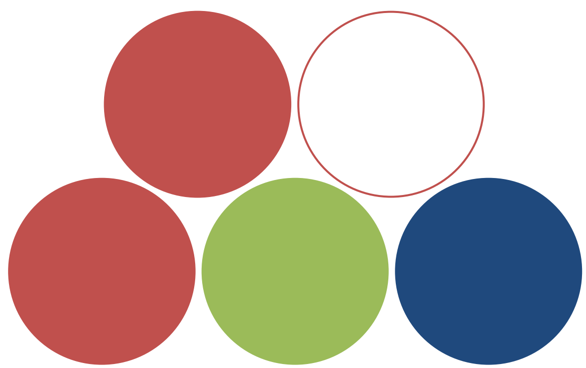
meson



baryon



*tetra*quark



*penta*quark

*hexa*quark

1. Introduction

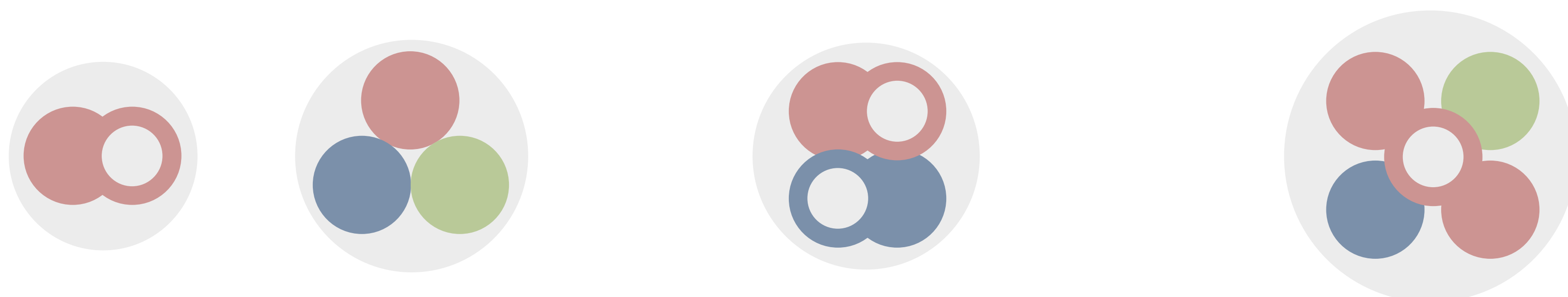
What is "exotic"?

1. Introduction

What is "exotic"?

1. Difference from (conventional) quark model

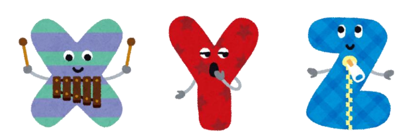
meson baryon tetraquark pentaquark



normal hadron

"simple"
(q$\bar{q}$, qqq)

Exotic hadron



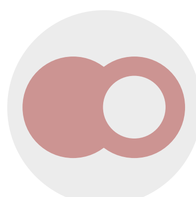
not so simple

1. Introduction

What is "exotic"?

2. Quantum numbers (charge, J^{PC})

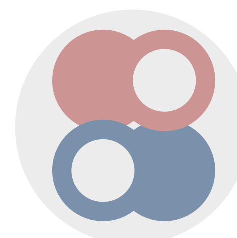
meson



cc^{bar}

or

tetraquark



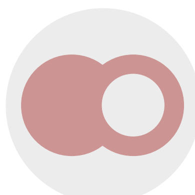
$cc^{bar}qq^{bar}$

1. Introduction

What is “exotic”?

2. Quantum numbers (charge, J^{PC})

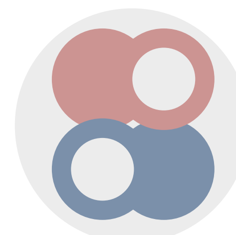
meson



$c c^{bar}$

or

tetraquark



$c c^{bar} \mathbf{u d^{bar}}$

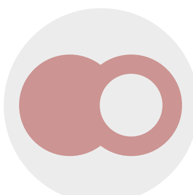
	meson	tetraquark
Electric charge	0	**+1**

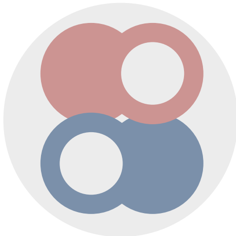
1. Introduction

What is "exotic"?

2. Quantum numbers (charge, J^{PC})

meson or tetraquark





$c c^{bar}$ **prohibited**

$c c^{bar} q q^{bar}$ **allowed**

Exotic J^{PC}
E^{+-}, O^{-+}

E=0, 2, 4, ...
O=1, 3, 5, ...

1. Introduction

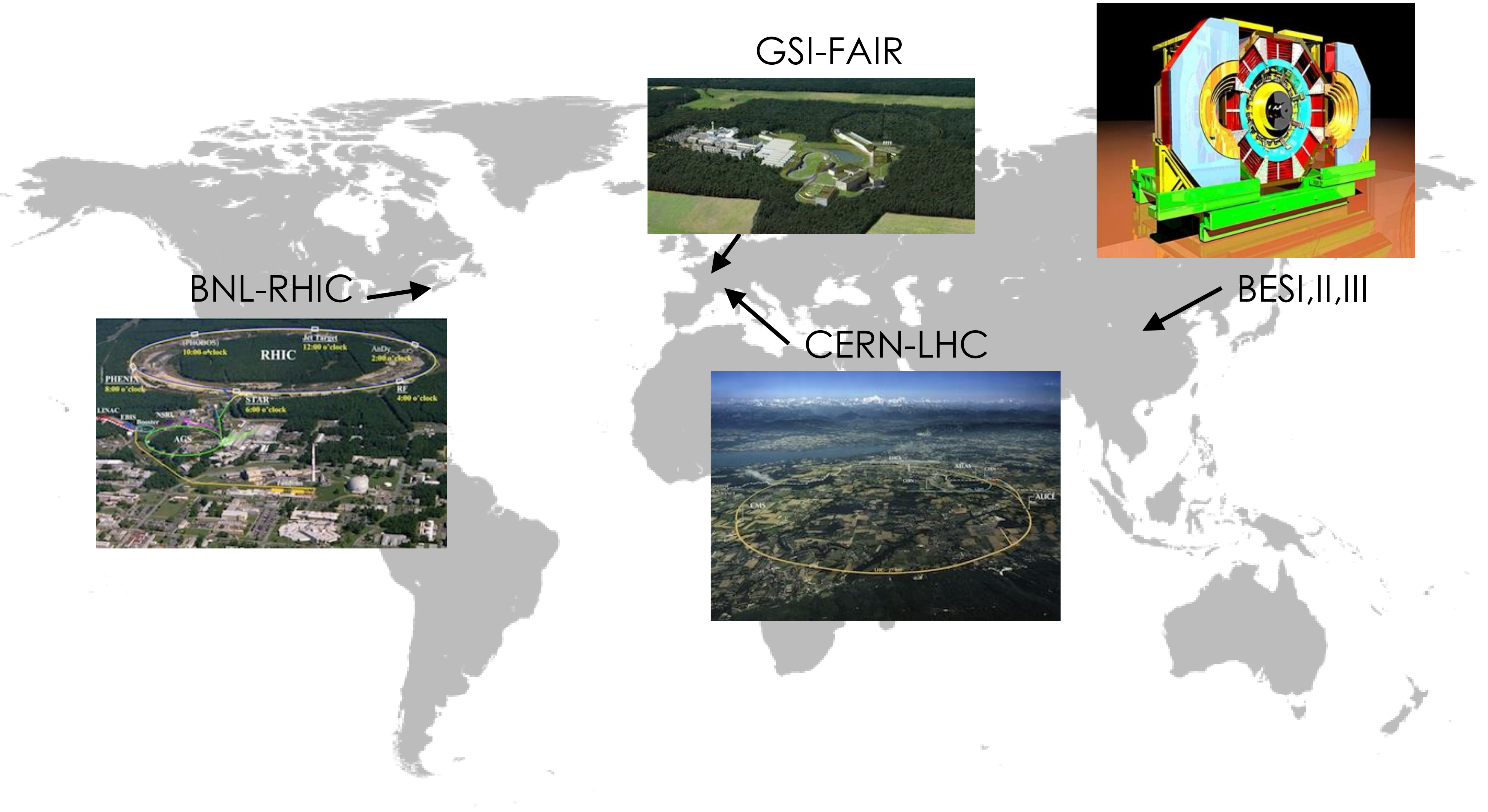
How many X, Y, Z are discovered so far?

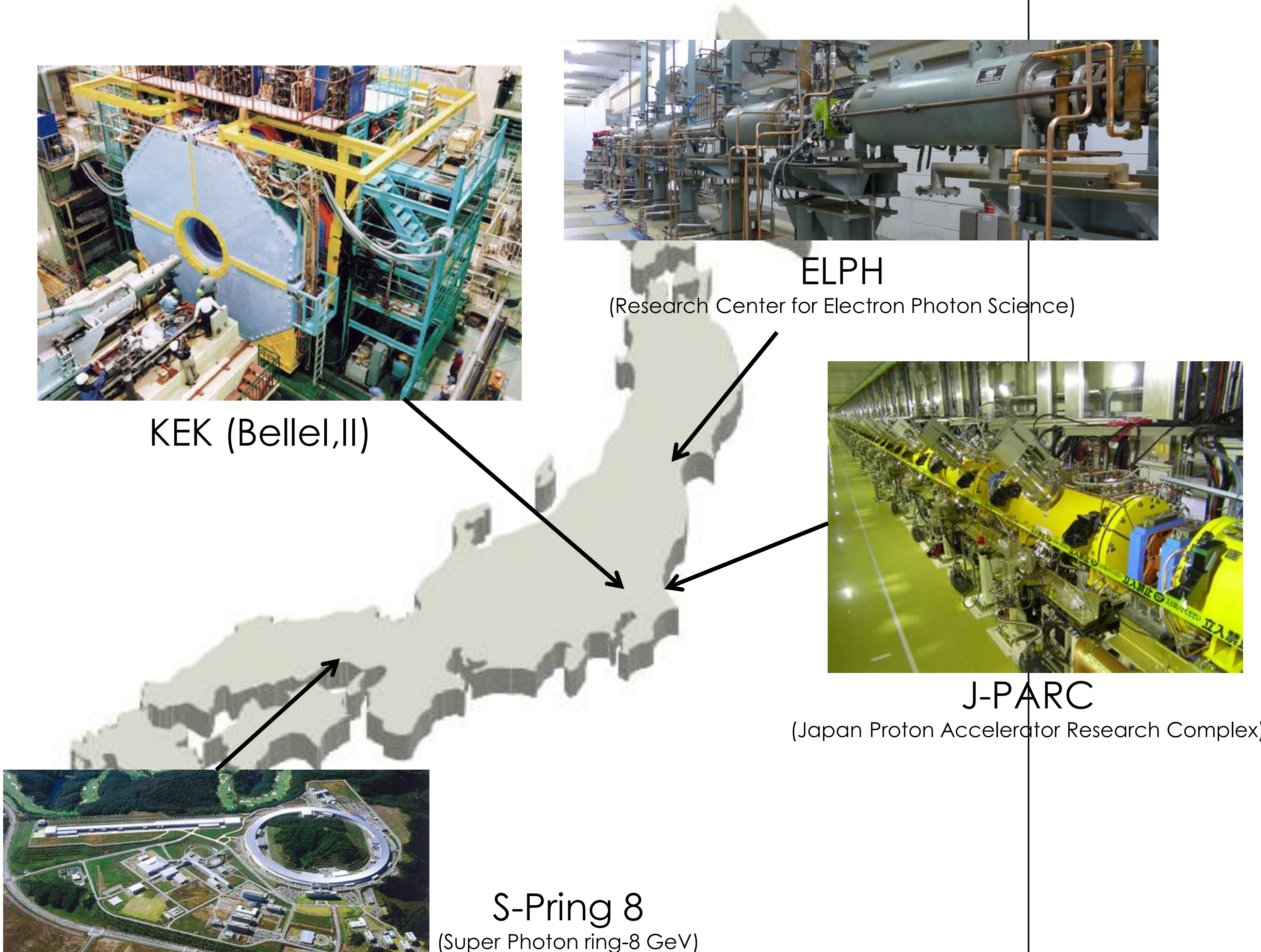
Normal hadron
about **300**

about 30

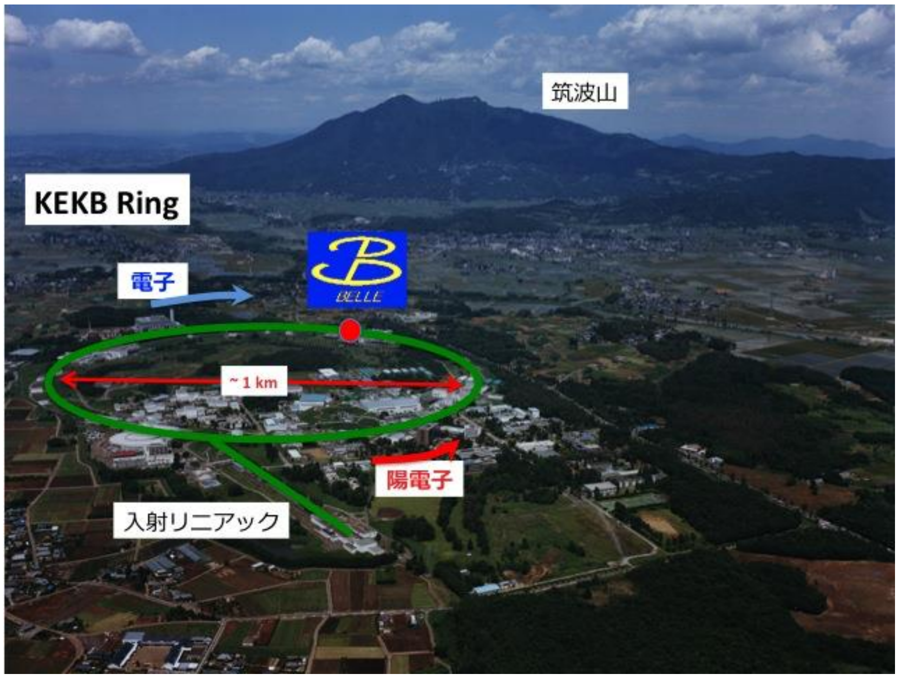
1. Introduction

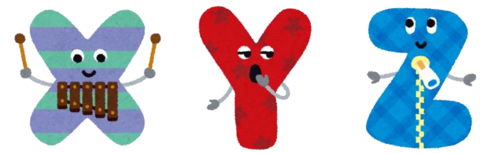
How can we research exotic hadrons？

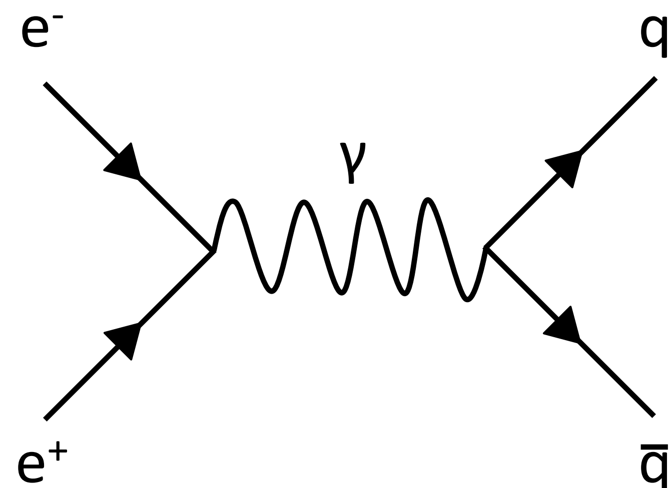

GSI-FAIR
BNL-RHIC
BESI,II,III
CERN-LHC
RHIC
PHENIX
8:00 o'clock
STAR
6:00 o'clock
Jet Target
12:00 o'clock
AnDy
2:00 o'clock
RF
4:00 o'clock
LINAC
AGS
ALICE
CMS


KEK (BelleI,II)
ELPH
(Research Center for Electron Photon Science)
J-PARC
(Japan Proton Accelerator Research Complex)
S-Pring 8
(Super Photon ring-8 GeV)

1. Introduction
Productions of exotic hadrons in Belle@KEK

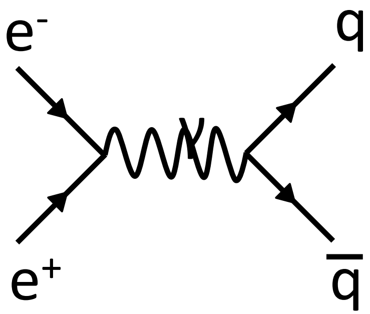






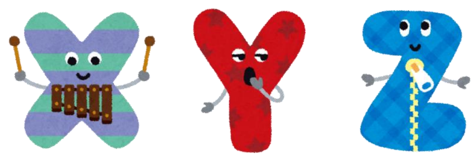
Quark-antiquark pairs are created through electron-positron collisions.

q = charm, bottom

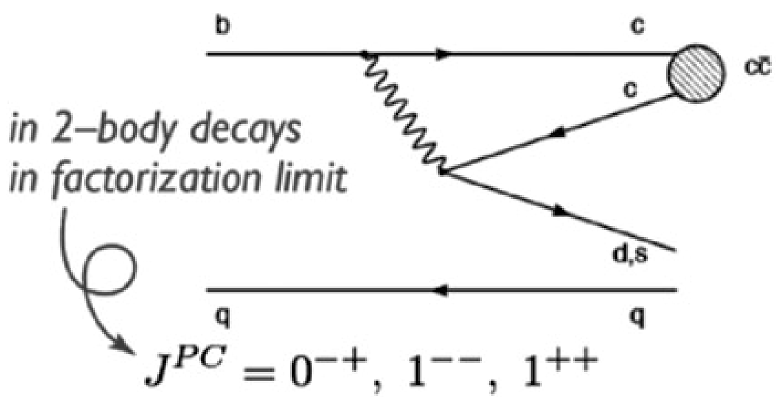


1. Introduction

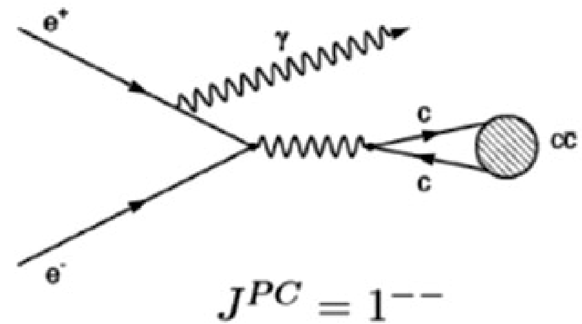
Variety of reactions at KEK



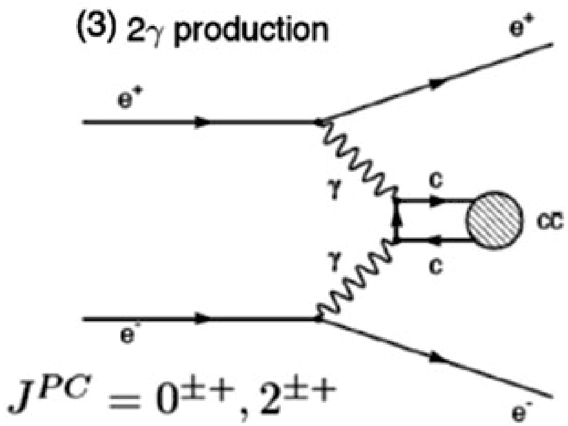
(1) B decay



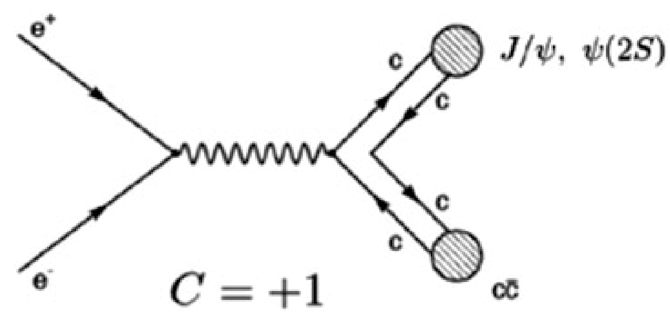
(2) Initial State Radiation (ISR)



(3) 2γ production



(4) Double charmonium production



1. Introduction

S. L. Olsen, T. Skwarnicki, D. Ziemninska, Rev. Mod. Phys. 90, 015003 (2018)

Tables of X, Y, Z discovered so far

State	M (MeV)	Γ (MeV)	J^{PC}	Process (decay mode)	Experiment
$X(3872)$	3871.69 ± 0.17	< 1.2	1^{++}	$B \to K(J/\psi\pi^+\pi^-)$	Belle (Choi *et al.*, 2003, 2011), *BABAR* (Aubert *et al.*, 2005c), LHCb (Aaij *et al.*, 2013a, 2015d)
				$p\bar{p} \to (J/\psi\pi^+\pi^-) + \cdots$	CDF (Acosta *et al.*, 2004; Abulencia *et al.*, 2006; Aaltonen *et al.*, 2009b), D0 (Abazov *et al.*, 2004)
				$B \to K(J/\psi\pi^+\pi^-\pi^0)$	Belle (Abe *et al.*, 2005), *BABAR* (del Amo Sanchez *et al.*, 2010a)
				$B \to K(D^0\bar{D}^0\pi^0)$	Belle (Gokhroo *et al.*, 2006; Aushev *et al.*, 2010b), *BABAR* (Aubert *et al.*, 2008c)
				$B \to K(J/\psi\gamma)$	*BABAR* (del Amo Sanchez *et al.*, 2010a), Belle (Bhardwaj *et al.*, 2011), LHCb (Aaij *et al.*, 2012a)
				$B \to K(\psi'\gamma)$	*BABAR* (Aubert *et al.*, 2009b), Belle (Bhardwaj *et al.*, 2011), LHCb (Aaij *et al.*, 2014a)
				$pp \to (J/\psi\pi^+\pi^-) + \cdots$	LHCb (Aaij *et al.*, 2012a), CMS (Chatrchyan *et al.*, 2013a), ATLAS (Aaboud *et al.*, 2017)
				$e^+e^- \to \gamma(J/\psi\pi^+\pi^-)$	BESIII (Ablikim *et al.*, 2014d)
$X(3915)$	3918.4 ± 1.9	20 ± 5	0^{++}	$B \to K(J/\psi\omega)$	Belle (Choi *et al.*, 2005), *BABAR* (Aubert *et al.*, 2008b; del Amo Sanchez *et al.*, 2010a)
				$e^+e^- \to e^+e^-(J/\psi\omega)$	Belle (Uehara *et al.*, 2010), *BABAR* (Lees *et al.*, 2012c)
$X(3940)$	3942^{+9}_{-8}	37^{+27}_{-17}	$0^{-+}(?)$	$e^+e^- \to J/\psi(D^*\bar{D})$	Belle (Pakhlov *et al.*, 2008)
				$e^+e^- \to J/\psi(\cdots)$	Belle (Abe *et al.*, 2007)
$X(4140)$	$4146.5^{+6.4}_{-5.3}$	83^{+27}_{-25}	1^{++}	$B \to K(J/\psi\phi)$	CDF (Aaltonen *et al.*, 2009a), CMS (Chatrchyan *et al.*, 2014), D0 (Abazov *et al.*, 2014), LHCb (Aaij *et al.*, 2017a, 2017d)
				$p\bar{p} \to (J/\psi\phi) + \cdots$	D0 (Abazov *et al.*, 2015)
$X(4160)$	4156^{+29}_{-25}	139^{+113}_{-65}	$0^{-+}(?)$	$e^+e^- \to J/\psi(D^*\bar{D}^*)$	Belle (Pakhlov *et al.*, 2008)
$Y(4260)$	See $Y(4220)$ entry		1^{--}	$e^+e^- \to \gamma(J/\psi\pi^+\pi^-)$	*BABAR* (Aubert *et al.*, 2005a; Lees *et al.*, 2012b), CLEO (He

$Y(4220)$	4222 ± 3	48 ± 7	1^{--}	$e^+e^- \to (J/\psi\pi^+\pi^-)$	BESIII (Ablikim *et al.*, 2017c)
				$e^+e^- \to (h_c\pi^+\pi^-)$	BESIII (Ablikim *et al.*, 2017a)
				$e^+e^- \to (\chi_{c0}\omega)$	BESIII (Ablikim *et al.*, 2015g)
				$e^+e^- \to (J/\psi\eta)$	BESIII (Ablikim *et al.*, 2015c)
				$e^+e^- \to (\gamma X(3872))$	BESIII (Ablikim *et al.*, 2014d)
				$e^+e^- \to (\pi^- Z_c^+(3900))$	BESIII (Ablikim *et al.*, 2013a), Belle (Liu *et al.*, 2013)
				$e^+e^- \to (\pi^- Z_c^+(4020))$	BESIII (Ablikim *et al.*, 2013b)
$X(4274)$	4273^{+19}_{-9}	56^{+14}_{-16}	1^{++}	$B \to K(J/\psi\phi)$	CDF (Aaltonen *et al.*, 2017), CMS (Chatrchyan *et al.*, 2014), LHCb (Aaij *et al.*, 2017a, 2017d)
$X(4350)$	$4350.6^{+4.6}_{-5.1}$	$13.3^{+18.4}_{-10.0}$	$(0/2)^{++}$	$e^+e^- \to e^+e^-(J/\psi\phi)$	Belle (Shen *et al.*, 2010)
$Y(4360)$	4341 ± 8	102 ± 9	1^{--}	$e^+e^- \to \gamma(\psi'\pi^+\pi^-)$	*BABAR* (Aubert *et al.*, 2007; Lees *et al.*, 2014), Belle (Wang *et al.*, 2007, 2015)
				$e^+e^- \to (J/\psi\pi^+\pi^-)$	BESIII (Ablikim *et al.*, 2017c)
$Y(4390)$	4392 ± 6	140 ± 16	1^{--}	$e^+e^- \to (h_c\pi^+\pi^-)$	BESIII (Ablikim *et al.*, 2017a)
$X(4500)$	4506^{+16}_{-19}	92^{+30}_{-21}	0^{++}	$B \to K(J/\psi\phi)$	LHCb (Aaij *et al.*, 2017a, 2017d)
$X(4700)$	4704^{+17}_{-26}	120^{+52}_{-45}	0^{++}	$B \to K(J/\psi\phi)$	LHCb (Aaij *et al.*, 2017a, 2017d)
$Y(4660)$	4643 ± 9	72 ± 11	1^{--}	$e^+e^- \to \gamma(\psi'\pi^+\pi^-)$	Belle (Wang *et al.*, 2007, 2015), *BABAR* (Aubert *et al.*, 2007; Lees *et al.*, 2014)
				$e^+e^- \to \gamma(\Lambda_c^+\Lambda_c^-)$	Belle (Pakhlova *et al.*, 2008)

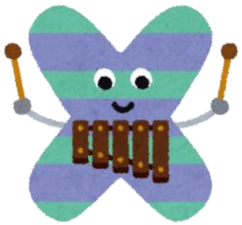
State	M (MeV)	Γ (MeV)	J^{PC}	Process (decay mode)	Experiment
$Z_c^{+,0}(3900)$	3886.6 ± 2.4	28.1 ± 2.6	1^{+-}	$e^+e^- \to \pi^{-,0}(J/\psi\pi^{+,0})$	BESIII (Ablikim *et al.*, 2013a, 2015f), Belle (Liu *et al.*, 2013)
				$e^+e^- \to \pi^{-,0}(D\bar{D}^*)^{+,0}$	BESIII (Ablikim *et al.*, 2014b, 2015e)
$Z_c^{+,0}(4020)$	4024.1 ± 1.9	13 ± 5	$1^{+-}(?)$	$e^+e- \to \pi^{-,0}(h_c\pi^{+,0})$	BESIII (Ablikim *et al.*, 2013b, 2014c)
				$e^+e^- \to \pi^{-,0}(D^*\bar{D}^*)^{+,0}$	BESIII (Ablikim *et al.*, 2014a, 2015d)
$Z^+(4050)$	4051^{+24}_{-43}	82^{+51}_{-55}	$?^{?+}$	$B \to K(\chi_{c1}\pi^+)$	Belle (Mizuk *et al.*, 2008), *BABAR* (Lees *et al.*, 2012a)
$Z^+(4200)$	4196^{+35}_{-32}	370^{+99}_{-149}	1^+	$B \to K(J/\psi\pi^+)$	Belle (Chilikin *et al.*, 2014)
				$B \to K(\psi'\pi^+)$	LHCb (Aaij *et al.*, 2014b)
$Z^+(4250)$	4248^{+185}_{-45}	177^{+321}_{-72}	$?^{?+}$	$B \to K(\chi_{c1}\pi^+)$	Belle (Mizuk *et al.*, 2008), *BABAR* (Lees *et al.*, 2012a)

$Z^+(4430)$	4477 ± 20	181 ± 31	1^+	$B \to K(\psi'\pi^+)$	Belle (Choi *et al.*, 2008; Mizuk *et al.*, 2009), Belle (Chilikin *et al.*, 2013), LHCb (Aaij *et al.*, 2014b, 2015b)
				$B \to K(J\psi\pi^+)$	Belle (Chilikin *et al.*, 2014)
$P_c^+(4380)$	4380 ± 30	205 ± 88	$(\frac{3}{2}/\frac{5}{2})^{\mp}$	$\Lambda_b^0 \to K(J/\psi p)$	LHCb (Aaij *et al.*, 2015c)
$P_c^+(4450)$	4450 ± 3	39 ± 20	$(\frac{5}{2}/\frac{3}{2})^{\pm}$	$\Lambda_b^0 \to K(J/\psi p)$	LHCb (Aaij *et al.*, 2015c)
$Y_b(10860)$	$10891.1^{+3.4}_{-3.8}$	$53.7^{+7.2}_{-7.8}$	1^{--}	$e^+e^- \to (\Upsilon(nS)\pi^+\pi^-)$	Belle (Chen *et al.*, 2008; Santel *et al.*, 2016)
$Z_b^{+,0}(10610)$	10607.2 ± 2.0	18.4 ± 2.4	1^{+-}	$Y_b(10860) \to \pi^{-,0}(\Upsilon(nS)\pi^{+,0})$	Belle (Bondar *et al.*, 2012; Garmash *et al.*, 2015), Belle (Krokovny *et al.*, 2013)
				$Y_b(10860) \to \pi^-(h_b(nP)\pi^+)$	Belle (Bondar *et al.*, 2012)
				$Y_b(10860) \to \pi^-(B\bar{B}^*)^+$	Belle (Garmash *et al.*, 2016)
$Z_b^+(10650)$	10652.2 ± 1.5	11.5 ± 2.2	1^{+-}	$Y_b(10860) \to \pi^-(\Upsilon(nS)\pi^+)$	Belle (Bondar *et al.*, 2012; Garmash *et al.*, 2015)
				$Y_b(10860) \to \pi^-(h_b(nP)\pi^+)$	Belle (Bondar *et al.*, 2012)
				$Y_b(10860) \to \pi^-(B^*\bar{B}^*)^+$	Belle (Garmash *et al.*, 2016)

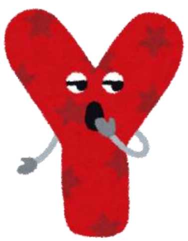
and more!

1. Introduction

Conventional rule of naming



Hadrons whose properties are different from quark model.

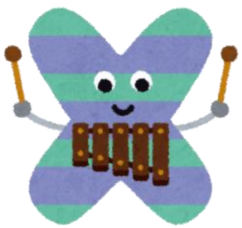


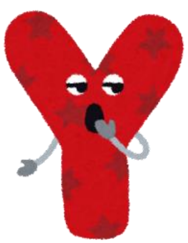
$J^{PC}=1^{--}$

Electrically charged (±)

1. Introduction

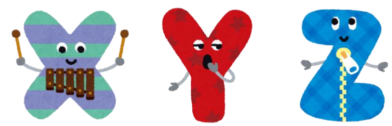
Conventional rule of naming



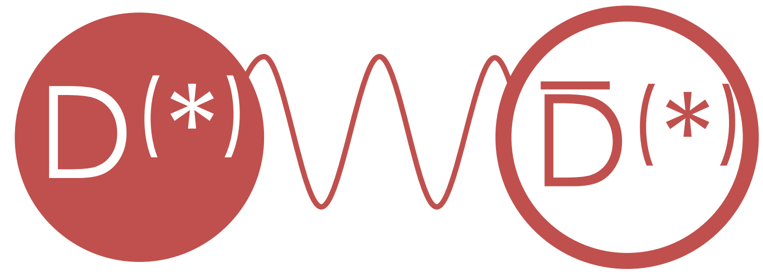


However, all XYZ are “X” in Particle Data Group.

1. Introduction

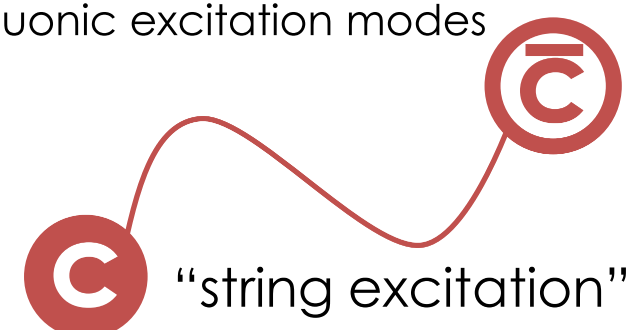
What are structures of  ?

Compact multiquark



Hadronic molecule

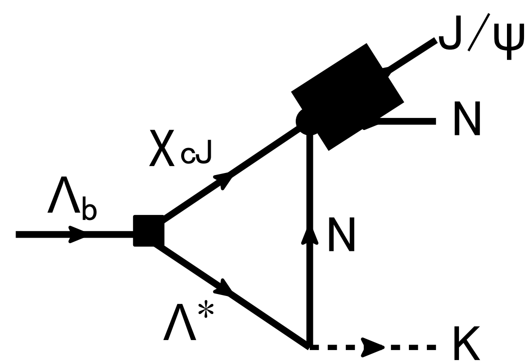
gluonic excitation modes



“string excitation”

Σ, Π, Δ, Φ, ...

(S, P, D, F, ...)



Kinematic effect

1. Introduction

Brief review of early studies on exotic hadron: lessons from “ancient” researches

Confucius (孔子)
(551BC-479BC)

子曰、温故而知新、可以為師矣

If we can keep the old traditions alive and acquire new knowledge, we will be able to become teachers.

1. Introduction

Classical Papers of Exotic Hadrons

and **8**, while from (b t t $\bar{t}$ $\bar{t}$) we get **1**, **8**, **10**, $\overline{\mathbf{10}}$, and **27**. In a similar way, meson singlets and octets can

an isotopic doublet (u, d) with respectively. The anti-triplet $\bar{t}$ ie opposite signs of the charges. ry among the members of the xact eightfold way, while a mass

and b^o discussed above, we would take the weak current to be $i(\bar{b}^o \cos\theta + \bar{u}^o \sin\theta)\, \gamma_\alpha(1+\gamma_5)\, s^-$ + $i(\bar{u}^o \cos\theta - \bar{b}^o \sin\theta)\, \gamma_\alpha(1+\gamma_5)\, d^-$. The part with

namely $i\, \bar{p}\, \gamma_\alpha(1+\gamma_5)(n \cos\theta + \Lambda$ s

in the quark scheme the expressio

$i\, \bar{u}\, \gamma_\alpha(1+\gamma_5)(d \cos\theta + s$

quark model

ber $n_t - n_{\bar{t}}$ would be zero for all known baryons and mesons. The most interesting example of such a model is one in which the triplet has spin $\frac{1}{2}$ and $z = -1$, so that the four particles d^-, s^-, u^o and b^o exhibit a parallel with the leptons.

A simpler and more elegant scheme can be constructed if we allow non-integral values for the charges. We can dispense entirely with the basic baryon b if we assign to the triplet t the following properties: spin $\frac{1}{2}$, $z = -\frac{1}{3}$, and baryon number $\frac{1}{3}$. We then refer to the members $u^{\frac{2}{3}}$, $d^{-\frac{1}{3}}$, and $s^{-\frac{1}{3}}$ of the triplet as "quarks" 6) q and the members of the anti-triplet as anti-quarks $\bar{q}$. Baryons can now be

1. Introduction

Classical Papers of Exotic Hadrons

CERN-TH-401 (1964)

AN SU_3 MODEL FOR STRONG INTERACTION SYMMETRY AND ITS BREAKING

quark model

G. Zweig *)

CERN - Geneva

In general, we would expect that baryons are built not only from the product of three aces, AAA, but also from $\bar{A}AAAA$, $\bar{A}\bar{A}AAAAA$, etc., where $\bar{A}$ denotes an anti-ace. Similarly, mesons could be formed from $\bar{A}A$, $\bar{A}\bar{A}AA$ etc. For the low mass mesons and baryons we will assume the simplest possibilities, $\bar{A}A$ and AAA, that is, "deuces and treys".

1. Introduction

Classical Papers of Exotic Hadrons

VOLUME 38, NUMBER 5 PHYSICAL REVIEW LETTERS 31 JANUARY 1977

Λ(uds)Λ(uds) >> H(uuddss) hexaquark

Perhaps a Stable Dihyperon*

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(Received 1 November 1976)

In the quark bag model, the same gluon-exchange forces which make the proton lighter than the Δ(1236) bind six quarks to form a stable, flavor-singlet (with strangeness of −2) $J^P = 0^+$ dihyperon (*H*) at 2150 MeV. Another isosinglet dihyperon (*H**) with $J^P = 1^+$ at 2335 MeV should appear as a bump in ΛΛ invariant-mass plots. Production and decay systematics of the *H* are discussed.

e of the most interesting candidates for a bound
is the H dibaryon, a bound state of two Λ's.
ugh Jaffe's original calculation [2] and sub-
nt work [3] indicate a gain in hyperfine inter-
ı energy by recoupling color and spins in the
ıark system over the two-Λ system, a lattice
calculation [4] indicates that the H is unbound
well above the ΛΛ threshold. Furthermore,
ıgh hyperfine binding calculations [3] indicate
ivity of the hyperfine energy to flavor-SU(3)
ıetry breaking, the lattice results are insensitive
strange quark mass and SU(3) breaking [4].
difference in the effects of SU(3) breaking

has no possibility of a quark exchange force in the lowest decay channel FN [6]. If this five-quark system breaks up into an F and a nucleon, there is no possible quark exchange between the two hadrons without flavor exchange, and therefore no diagonal matrix element of the one-gluon-exchange interaction that could give rise to a short range repulsion.

Anticharmed baryons were suggested as good candidates for possible bound exotics at the 1980 baryon conference [7]. However, the nonstrange anticharmed baryon was not bound by the hyperfine interaction and the strange anticharmed baryon was very remote from experiment and not pursued seri

Pcs (uudsc)

Note: recently discovered Pcs is different from "Pcs" by Lipkin.

1. Introduction

Classical Papers of Exotic Hadrons

quarks, Gell-Mann comments that "It is amusing that the lowest baryon configuration (QQQ) gives just the representations $\underline{1}$, $\underline{8}$, and $\underline{10}$ that have been observed, while the lowest meson configuration ($Q\overline{Q}$) similarly gives just $\underline{1}$ and $\underline{8}$." In recent years attention has focused on developing a quark dynamics consistent with the absence of free quarks or other states of nonzero triality. The apparent spectroscopic absence of multiquark hadrons ($Q^2\overline{Q}^2$ mesons, $Q^4\overline{Q}$ baryons, etc.) has remained essentially where Gell-Mann left it.[4] Indeed, it seems foolish to attempt an explanation of the absence of exotics without at least some

Surprisingly, we find that it is possible to accommodate $Q^2\overline{Q}^2$ mesons relatively comfortably within the restrictions imposed by experimental meson spectroscopy. We do *not* claim to resolve the problem by elevating unwanted multiquark states to very high masses. On the contrary, we will attempt to identify the lowest $Q^2\overline{Q}^2$ multiplet, a $J^P = 0^+$ nonet, with some of the known 0^+ mesons [$\epsilon(700), S^*(993), \delta(976), \kappa(?)$]. The masses and decay systematics of the observed 0^+ mesons support the $Q^2\overline{Q}^2$ assignment. Other exotics (mesons *not* classifiable as flavor octets or singlets) and cryptoexotics (flavor singlets or octets neverthe-

PHYSICAL REVIEW D VOLUME 25, NUMBER 9 1 MAY 1982

Do narrow heavy multiquark states exist?

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(Received 11 August 1981)

We discuss the existence of states made of four heavy quarks in the context of potential models already used in the study of heavy mesons and baryons. We first consider the situation where the quarks have the same mass and interact through a two-body potential due to color-octet exchange. In this case, we show that for any reasonable confining potential there is no state below the threshold corresponding to the spontaneous dissociation into two mesons. We investigate in detail different possibilities of modifying this negative result. This concerns the effect of hyperfine corrections, the case of orbitally excited states, the case of unequal quark masses, and the use of the static potential derived from the bag model treated in the adiabatic approximation.

1. Introduction

Classical Papers of Exotic Hadrons

For very heavy quarks, the quark pair QQ can form a small color antitriplet object of size $(\alpha_s(m_Q)m_Q)^{-1}$ with a binding energy of order $\alpha_s^2(m_Q)m_Q$. The two heavy quarks act as an almost point-like heavy color antitriplet source with a mass of

Exotic $QQ\bar{q}\bar{q}$ states in QCD

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Received 11 December 1992

Accepted for publication 4 January 1993

QCD contains stable four-quark $QQ\bar{q}\bar{q}$ hadronic states in the limit where the heavy quark mass goes to infinity. (Here Q denotes a heavy quark, $\bar{q}$ a light antiquark and the stability refers

bound states. Thus, although one cannot conclude with certainty it to be the case, this fact does favour the picture that the η (1440) and the f_1 (1420) are mainly $K\bar{K}^*$ composites and the f_0(1710) mainly a $K^*\bar{K}^*$ bound state, while the

only in passing within general phenomenological models for meson-meson bound states [4–14], where pion exchange is not given special attention. Recently, after my first letter [2] Ericson and Karl [15] has also studied the

change alone is strong enough to form at least deuteronlike $B\bar{B}^*$ and $B^*\bar{B}^*$ composites bound by approximately 50 MeV. Composites of $D\bar{D}^*$ and $D^*\bar{D}^*$ states bound by pion exchange alone are expected near the thresholds, while in the light meson sector one generally needs some additional short range attraction to form bound states. The quantum numbers of these states are $I=0$, and $J^{PC}=0^{-+}, 1^{++}$ for the $P\bar{V}$ states and $I=0$,

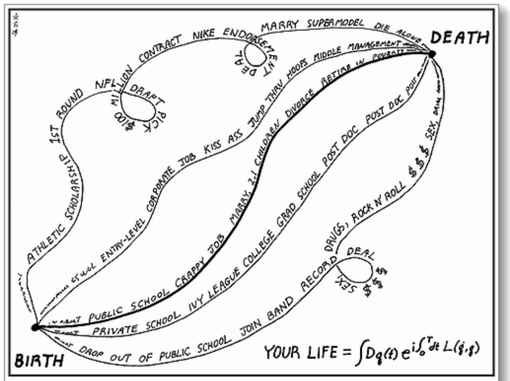
gluonium or "molecular multiquark" can be divided into two kinds, either models or models for bound states o rons. In a recent paper [2] I suggeste the latter, or *"deuteronlike meson-m* pion exchange plays a dominant rôle, important, and may explain the seen c states I suggested the acronym *deus*

1. Introduction

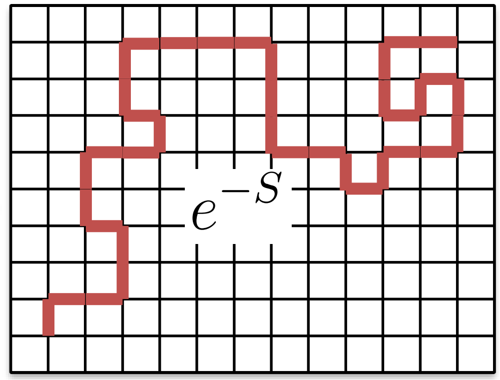
Analysis method based on QCD

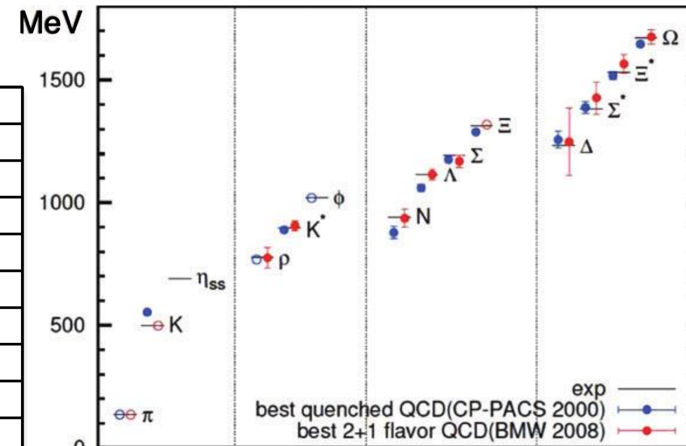
Lattice QCD

$$Z = \int \mathcal{D}\bar{\psi}\mathcal{D}\psi\mathcal{D}\mathcal{A}\, e^{i\int \mathcal{L}_{\rm QCD}[\bar{\psi},\psi,A]{\rm d}^4x}$$



The Path Integral Formulation of Your Life





S. Aoki et al., Phys. Rev. Lett. 84, 238 (2000)
S. Durr et al., Science 322, 1224 (2008)

QCD sum rules

M.A. Shifman, A.I. Vainshtein, V.I. Zakharov, Nucl. Phys. B147, 385 (1979), ibid. 448 (1979)
L. J. Reinders, H. Reubinstein, S. Yazaki, Phys. Rep. 127, 1 (1985)

Correlation function

$$\Pi(p) = \int d^4x\, e^{ipx}\, \langle 0|\, T\big(A(x)\bar{B}(0)\big)\, |0\rangle$$

$$-\frac{i}{(2\pi)^4}\int d^4k\,[D(k^2)-D(k^2)_{\rm pert}]k^2 .$$

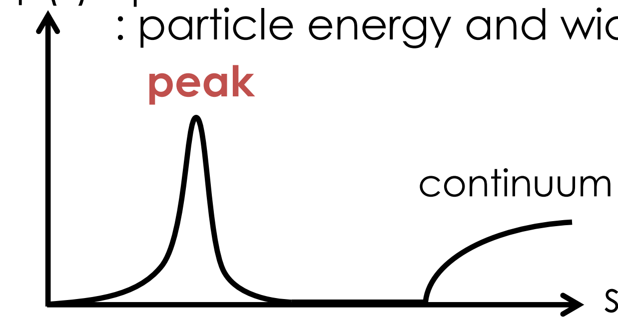
this definition of the gluon condensate we get for (2.18)

$$\Pi(q^2) = \Pi(q^2)_{\rm pert} + g^2\langle 0|G^a_{\mu\nu}G^a_{\mu\nu}|0\rangle \tfrac{1}{16}\partial_{k\alpha}\partial^{\alpha}_{k}C(q,k)|_{k=0} + \cdots ,$$

he expression for the diagrams in front of $G^a_{\mu\nu}G^a_{\mu\nu}$ is given by $\partial_{k\alpha}\partial^{\alpha}_{k}C(q$
r systems containing light quarks the quark propagator will also be mo
m fluctuations and quark condensate contributions have to be tak
lation of the vacuum polarization functions. Of course Q^2 cannot be

$$\Pi(p) = \int_0^\infty ds\, \frac{\rho(s)}{s - p^2 - i\epsilon}$$

ρ(s) spectral function
: particle energy and width



1. Introduction

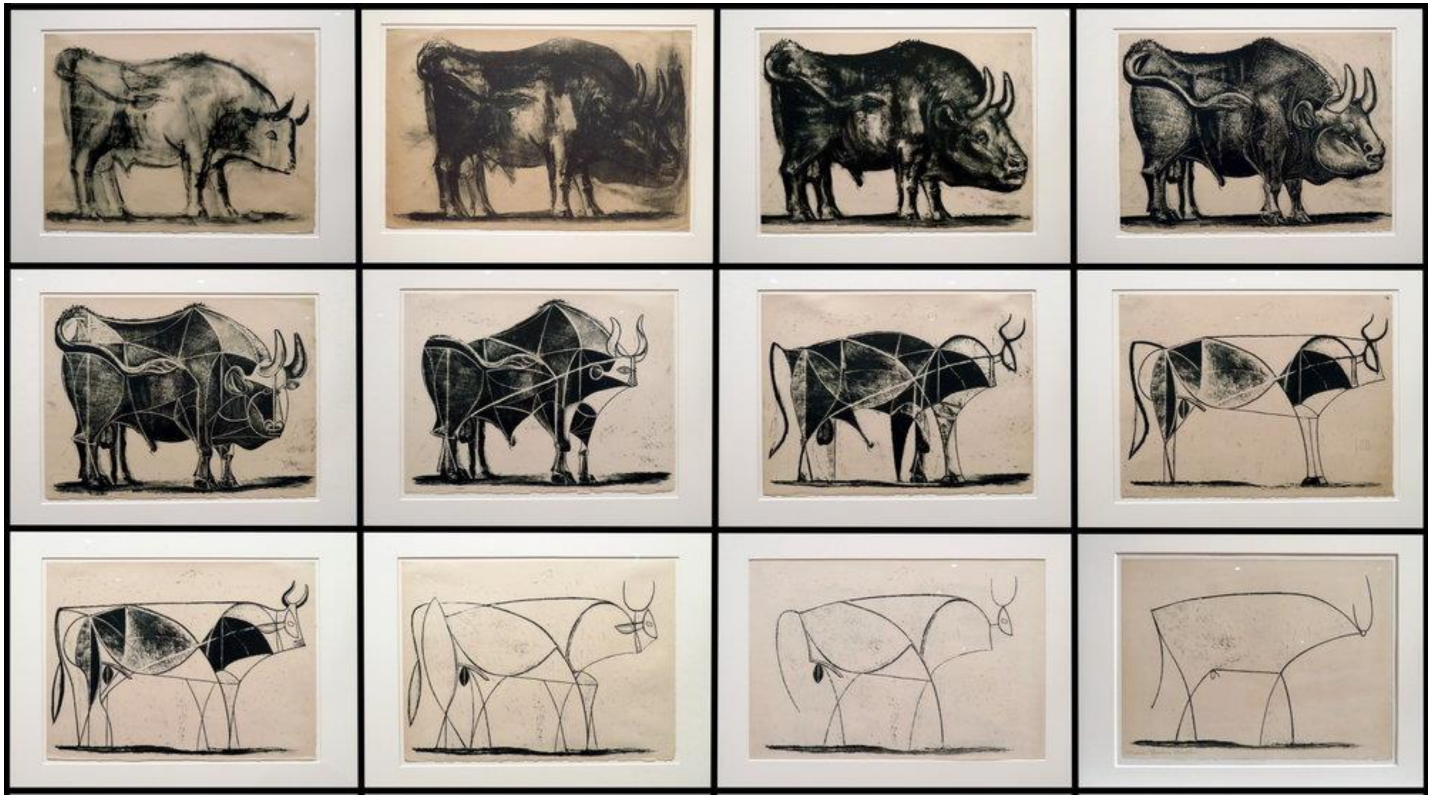
Hadron models ... since early days

What is the essential picture ?

A variety of hadron models have been used up to now. They are very useful to calculate some physical quantities and to provide concrete pictures of hadron dynamics.

Pablo Ruiz Picasso (1881-1973)

complex (realism)



simple (abstract)

1. Introduction

Hadron models ... since early days

Hadron molecule model

Hadrons are fundamental degrees of freedom

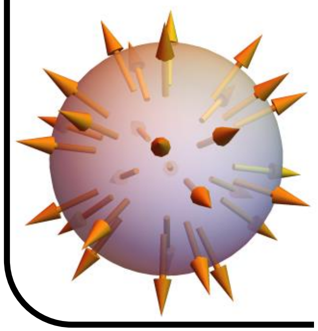
deuteron: N N   σ meson: π π

Λ(1405): $\bar{K}$ N + π Σ   N(1535): η N

R. H. Dalitz, S. F. Tuan, Phys. Rev. Lett. 2, 425 (1959)

Skyrme model

T. H. R. Skyrme, Nuclear Physics 31, 556, (1962)



Describing fermion in terms of boson
(nucleon) (π)

Topological quantity: $\mathbf{R}^3(S^3) \rightarrow SU(2)(S^3)$
= baryon number

Soliton solution: dynamically stable

G. S. Adkins, C. R. Nappi, E. Witten, Nucl. Phys. B228, 552 (1983)

Diquark model

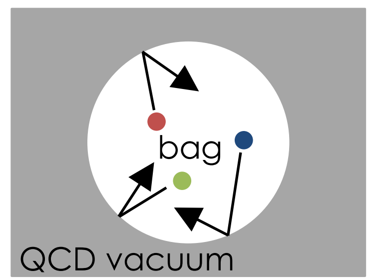
M. Ida, R. Kobayashi, Prog. Thor. Phys. 36, 846 (1966)

A pair of quarks = diquark

Baryon = quark+diquark   H-dibaryon = diquark × 3 (?)

Bag model

A. Chodos, et al., Phys. Rev. D9, 3471 (1974)



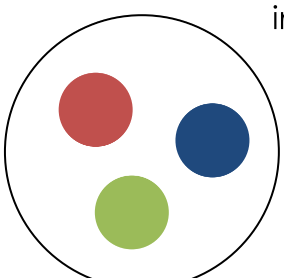
Massless quark (no chiral symmetry breaking inside bag)

Bag pressure B (energy density outside bag)

Confinement of quark by boundary condition

Quark model

A. De. Rujula, H. Georgi, S. L. Gkashow, Phys. Rev. D12, 147 (1975)



inter-quark potential:

$$V(r) = -\frac{4}{3}\frac{\alpha_s}{r} + \frac{32\pi\alpha_s}{9m_1m_2}\delta(r)\vec{S}_1\cdot\vec{S}_2 + \cdots + \sigma r$$

m: dynamical quark mass
(300-400 MeV)

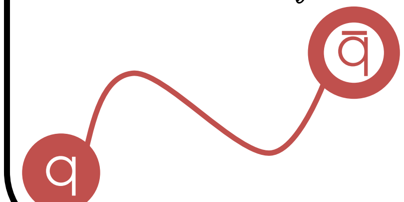
Color Coulomb potential

Confinement (linear) potential

String model

R. Giles, S.-H H. Tye, Phys. Rev. Lett. 37, 1175 (1976)

$$S = \int d^2u\,(-\det(g))^{1/2}\,\bar{\psi} i\gamma_\mu \tau^\mu_\alpha \partial^\alpha \psi + \cdots$$



Excitation of "gluon"
- Flux tube model
- Constituent gluon model
- ...

→ Later example

1. Introduction

Hadron models ... since early days

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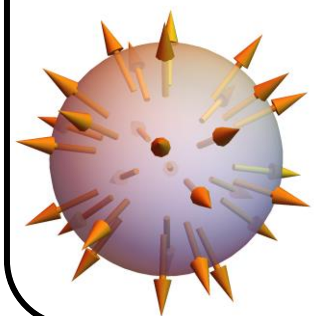

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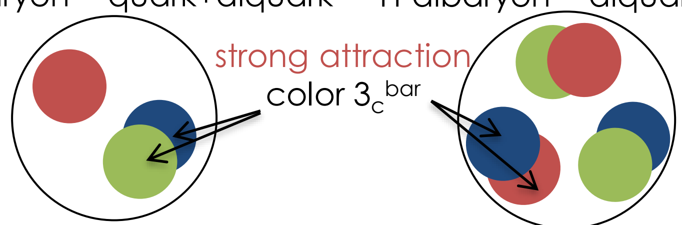

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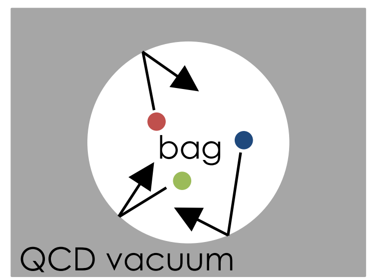

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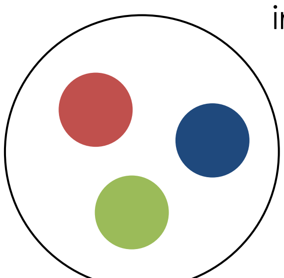

inter-quark potential:

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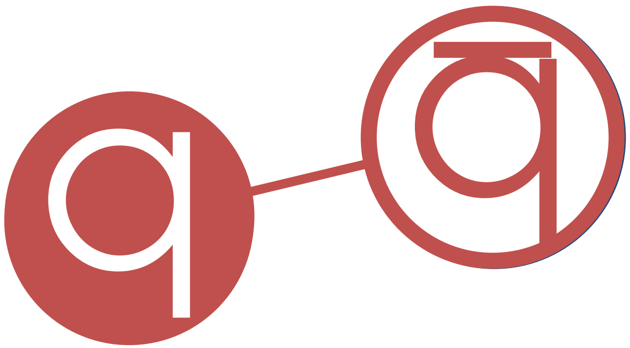
Excitation of "gluon"

Flux tube model
Constituent gluon model
...

→ Later example

1. Introduction
Diquark

Meson



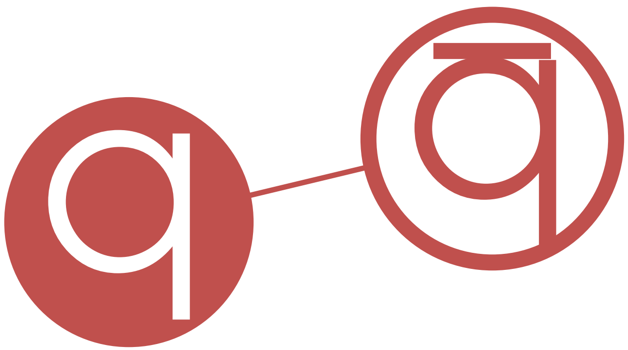
color singlet

Diquark

color anti-triplet/sextet

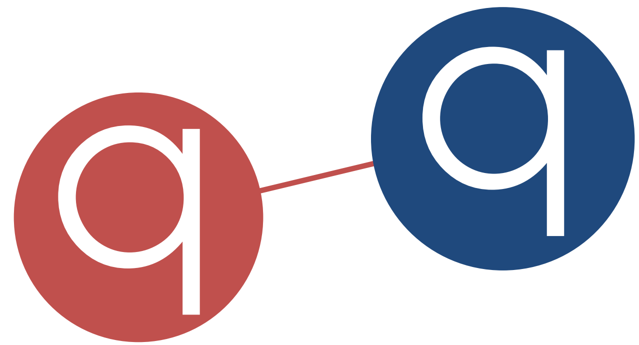
1. Introduction
Diquark

Meson



color singlet

Diquark



color anti-triplet/sextet

NO asymptotic state: **not “visible”**

1. Introduction

Diquark

$$V(r) = \frac{\alpha_s}{r}\frac{\vec{\lambda}_1\cdot\vec{\lambda}_2}{4} + \frac{8\pi\alpha_s}{3m_1m_2}\delta(r)\frac{\vec{\lambda}_1\cdot\vec{\lambda}_2}{4}\vec{S}_1\cdot\vec{S}_2 + \cdots + \sigma r$$

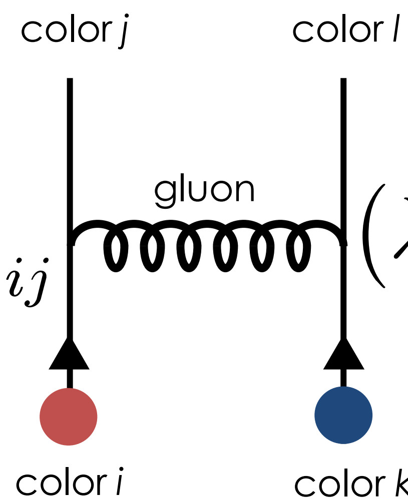
color electric

Light-light diquark

color magnetic (color-spin)

$$\vec{S}_1\cdot\vec{S}_2 = \begin{cases} -\frac{3}{4} & (S=0) \\ \frac{1}{4} & (S=1) \end{cases}$$

$$\sum_{a=1}^{N_c^2-1} \left(\lambda^a\right)_{ij} \left(\lambda^a\right)_{kl}$$



i, j, k, l = 1, 2, 3

r distance between two quarks

1. Introduction

Diquark

$$V(r) = \frac{\alpha_s}{r}\frac{\vec{\lambda}_1 \cdot \vec{\lambda}_2}{4} - \frac{8\pi\alpha_s}{3m_1m_2}\delta(r)\frac{\vec{\lambda}_1 \cdot \vec{\lambda}_2}{4}\vec{S}_1 \cdot \vec{S}_2 + \cdots + \sigma r$$

Light-light diquark
color-spin

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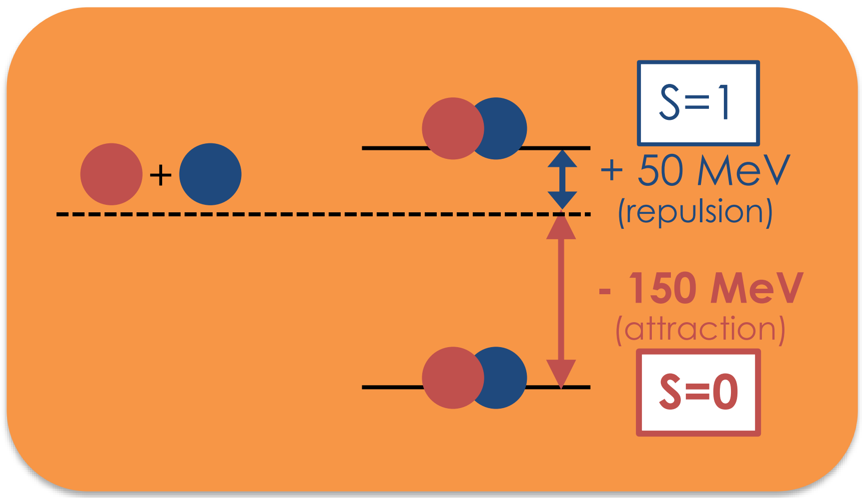

"bad" diquark
spin 1, isospin 1

"good" diquark
spin 0, isospin 0

→ Is "good" diquark favored inside hadrons ?

1. Introduction

Diquark

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Light-light diquark

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The hadrons where we may see diquarks...

① Scalar meson $J^P=0^+$

② Charm/bottom baryon (C, B=1)

③ Exotic hadrons: mass spectrum of colorful state

④ Double charm baryon (C=2)

1. Introduction

Diquark

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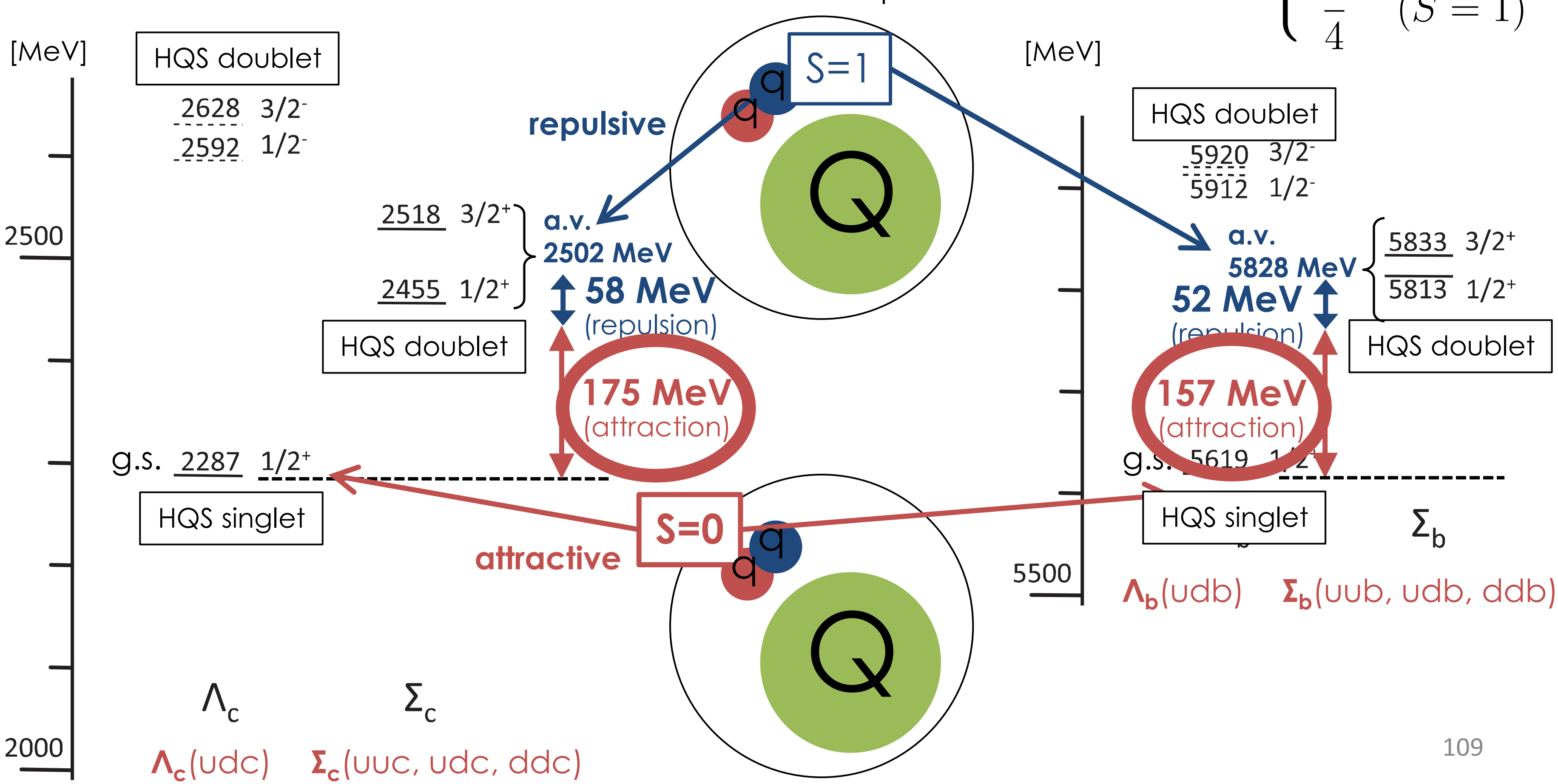
② Charm/botttom baryon (C, B=1)



1. Introduction
Diquarks in lattice QCD

Progress in Particle and Nuclear Physics 116 (2021) 103835

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journal homepage: www.elsevier.com/locate/ppnp

Review

Diquark correlations in hadron physics: Origin, impact and evidence

M.Yu. Barabanov [1], M.A. Bedolla [2], W.K. Brooks [3], G.D. Cates [4], C. Chen [5], Y. Chen [6,7], E. Cisbani [8], M. Ding [9], G. Eichmann [10,11], R. Ent [12], J. Ferretti [13], R.W. Gothe [14], T. Horn [15,12], S. Liuti [4], C. Mezrag [16], A. Pilloni [9], A.J.R. Puckett [17], C.D. Roberts [18,19,*], P. Rossi [12,20], G. Salmé [21], E. Santopinto [22], J. Segovia [23,19], S.N. Syritsyn [24,25], M. Takizawa [26,27,28], E. Tomasi-Gustafsson [16], P. Wein [29], B.B. Wojtsekhowski [12]

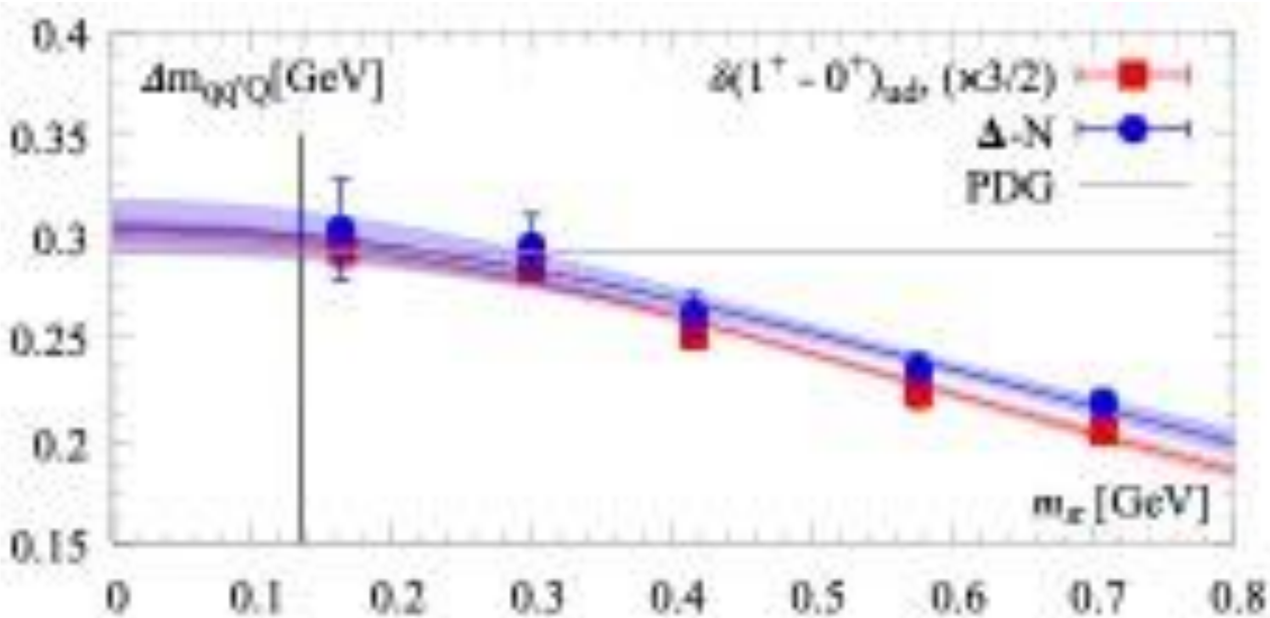
See, e.g., this recent review paper to know more on diquarks.

1. Introduction
“Diquark” in lattice QCD

A. Francis, P. de Forcrand, R. Lewis, K. Mlatman, JHEP05 (2022) 062

“bad”-“good” diquarks mass difference

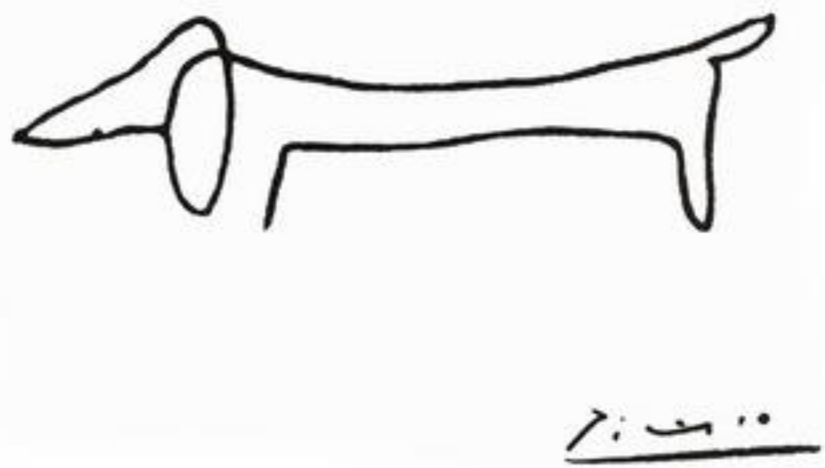
All in [GeV]	$\delta E(m_\pi^{\rm phys})$	A	B
$\delta(1^+ - 0^+)_{ud}$	0.198(4)	0.202(4)	1.00(5)
$\delta(1^+ - 0^+)_{\ell s}$	0.145(5)	0.151(7)	3.7(15)
$\delta(1^+ - 0^+)_{ss'}$	0.118(2)	0.118(2)	



1. Introduction

So far we have briefly reviewed how to understand hadrons by means of simple models.

Pablo Ruiz Picasso (1881-1973)



1. Introduction

more about

Heavy Hadrons

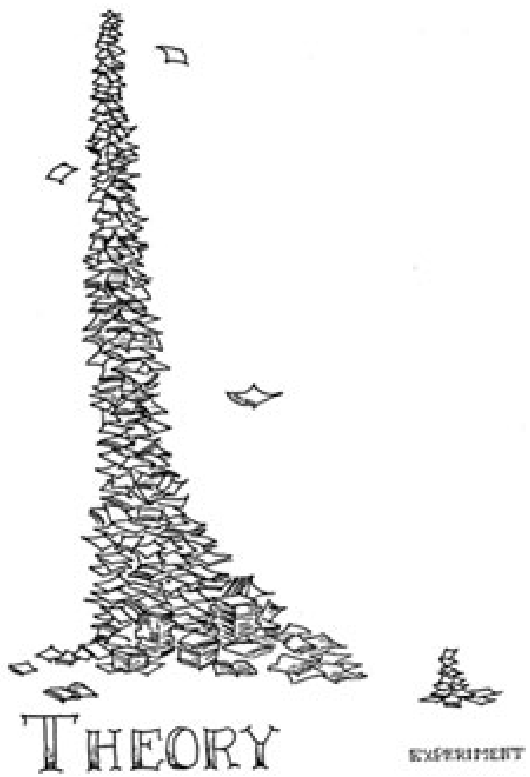
more about

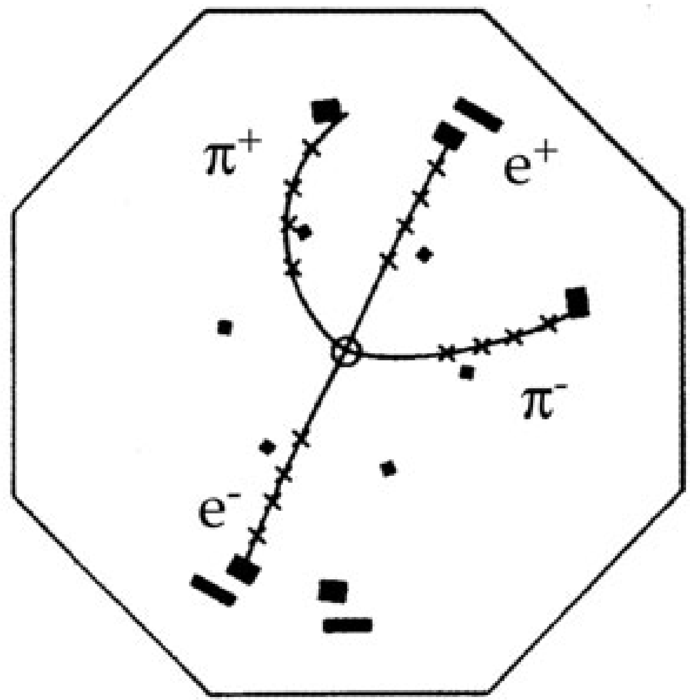
Heavy Hadrons

Charmonium

$c\bar{c}$

1. Introduction
Charmonium
$c\bar{c}$





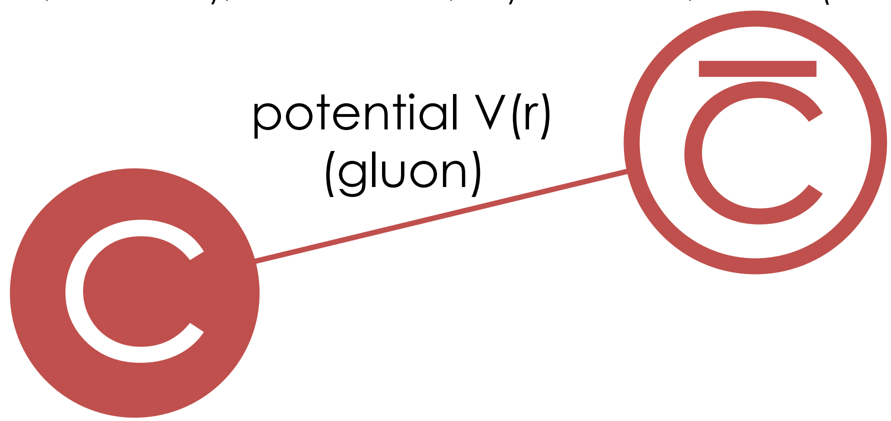
CERN courier, April 1975 (Amsler's textbook)

SLAC MARK I detector 1974

1. Introduction
Charmonium Mass Spectrum

$$c\bar{c}$$

Quark model A. De. Rujula, H. Georgi, S. L. Gkashow, Phys. Rev. D12, 147 (1975)
Cf. T. Barnes, S. Godfrey, E. S. Swanson, Phys. Rev. D72, 054026 (2005)



$$V_0^{(c\bar{c})}(r) = \boxed{-\frac{4}{3}\frac{\alpha_s}{r}} + \boxed{br} + \boxed{\frac{32\pi\alpha_s}{9m_c^2}\tilde{\delta}_\sigma(r)\vec{\mathrm{S}}_c\cdot\vec{\mathrm{S}}_{\bar{c}}} + \frac{1}{m_c^2}\left[\boxed{\left(\frac{2\alpha_s}{r^3}-\frac{b}{2r}\right)\vec{\mathrm{L}}\cdot\vec{\mathrm{S}}} + \boxed{\frac{4\alpha_s}{r^3}\mathrm{T}}\right]$$

Coulomb pot. Confinement pot. Spin-spin pot. L-S pot. Tensor pot.

δ function (smearing)

$$\tilde{\delta}_\sigma(r) = (\sigma/\sqrt{\pi})^3 e^{-\sigma^2 r^2}$$

Tensor operator

$$\langle {}^3\mathrm{L_J}|\mathrm{T}|{}^3\mathrm{L_J}\rangle = \begin{cases} -\frac{\mathrm{L}}{6(2\mathrm{L}+3)}, & \mathrm{J}=\mathrm{L}+1 \\ +\frac{1}{6}, & \mathrm{J}=\mathrm{L} \\ -\frac{(\mathrm{L}+1)}{6(2\mathrm{L}-1)}, & \mathrm{J}=\mathrm{L}-1 \end{cases}$$

1. Introduction
Charmonium

$c\bar{c}$

η_c
0^{-+}
mass: 2983 MeV
width: 32 MeV

J/ψ
1^{--}
mass: 3097 MeV
width: 93 keV

h_c
1^{+-}
mass: 3525MeV
width: 0.7 MeV

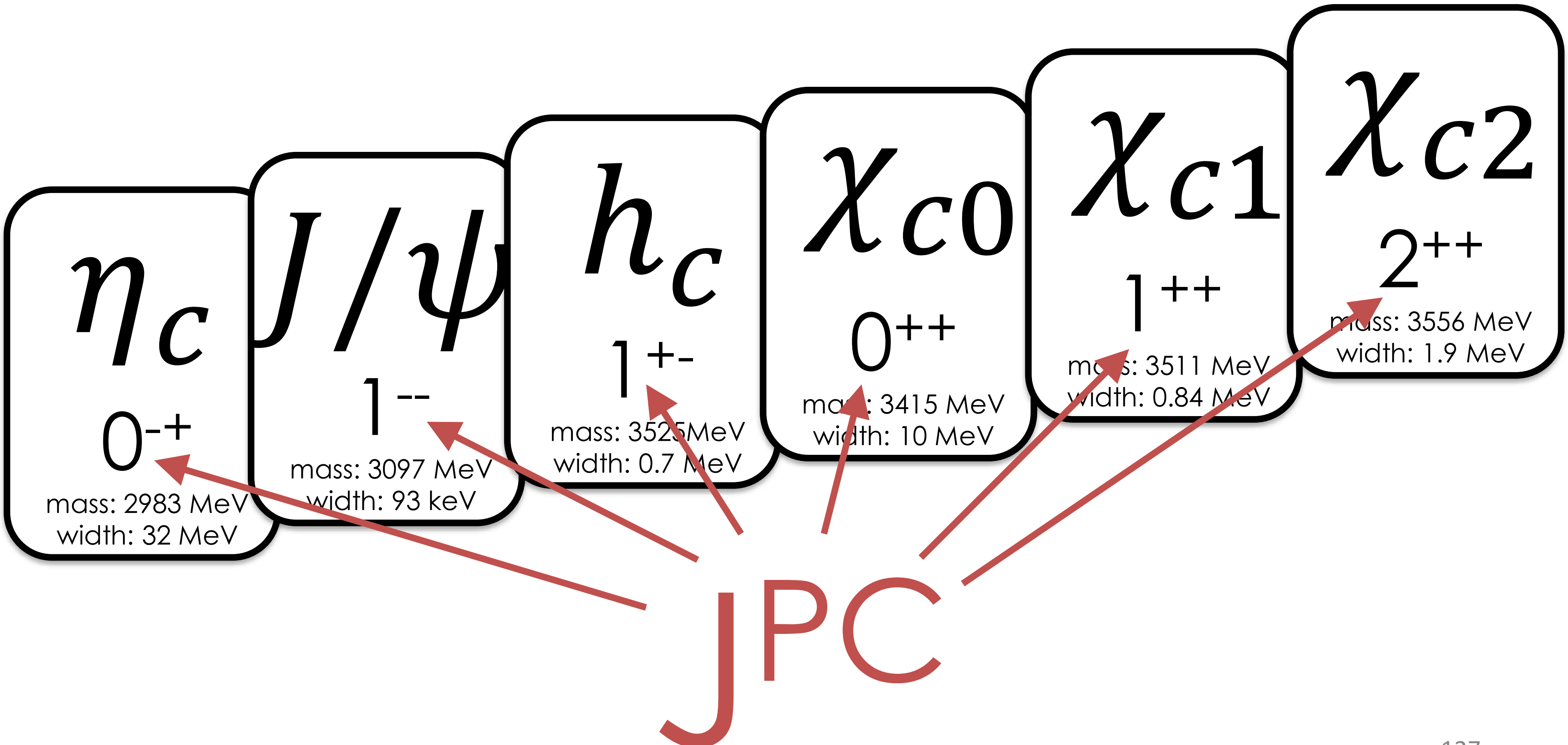
χ_{c0}
0^{++}
mass: 3415 MeV
width: 10 MeV

χ_{c1}
1^{++}
mass: 3511 MeV
width: 0.84 MeV

χ_{c2}
2^{++}
mass: 3556 MeV
width: 1.9 MeV

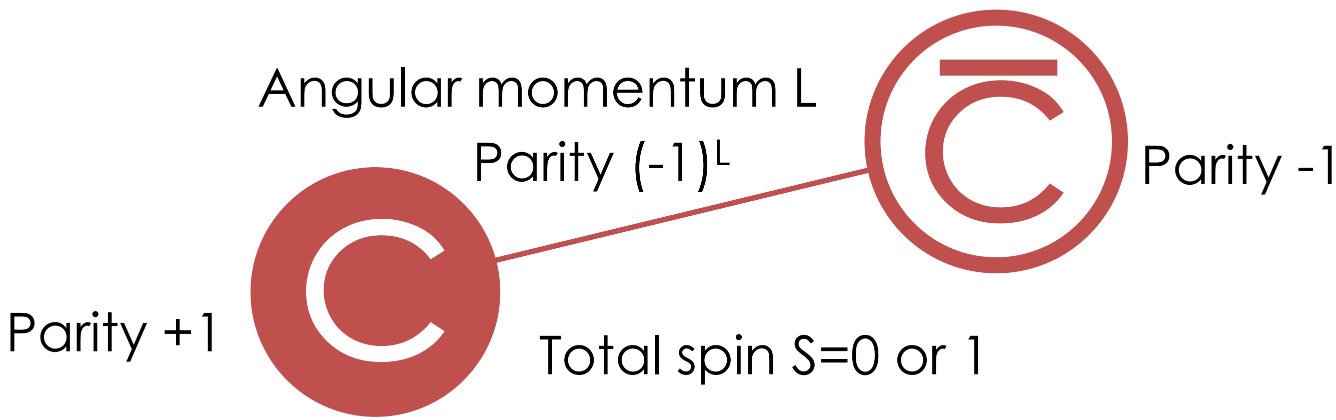
1. Introduction
Charmonium

$c\bar{c}$



1. Introduction
Charmonium

$c\bar{c}$



J^{PC}

- ☑ Total angular momentum J=L, L ±1
- ☑ Total parity $P=(+1)(-1)(-1)^L=(-1)^{L+1}$
- ☑ C parity (charge conjugate): $C=(-1)^{L+S}$

Proof: $\mathcal{C}|f\bar{f}\rangle = (-1)^L(-1)^{S+1}(-1)|f\bar{f}\rangle = (-1)^{L+S}|f\bar{f}\rangle$

J^{PC}

J ... total momentum spin (0, 1/2, 1, 3/2, ...)

P ... parity (±)

C ... charge conjugate (±)

J^{PC}

$Q\bar{Q}$ (quark and antiquark) case ...

J ... total momentum spin (0, 1, ...) ← **L±S**

P ... parity (±) ← **$(-1)^{L+1}$**

C ... charge conjugate (±) ← **$(-1)^{L+S}$**

J^{PC}

$Q\bar{Q}$ (quark and antiquark) case ...

L	0		2n (n≥1)		2n-1 (n≥1)	
S	0	1	0	1	0	1
J	0	1	2n	2n, 2n±1	2n-1	2n-2, 2n-1, 2n
P	-1		-1		+1	
C	+1	-1	+1	-1	-1	+1
J^{PC}	0^{-+}	1^{--}	E^{-+}	E^{--}, O^{--}	O^{+-}	O^{++}, E^{++}

Note: E^{+-} and O^{-+} are _impossible_ for QQ^{bar}.

1. Introduction
Charmonium

$$c\bar{c}$$

η_c	J/ψ	h_c	χ_{c0}	χ_{c1}	χ_{c2}
0^{-+}	1^{--}	1^{+-}	0^{++}	1^{++}	2^{++}
mass: 2983 MeV	mass: 3097 MeV	mass: 3525MeV	mass: 3415 MeV	mass: 3511 MeV	mass: 3556 MeV
width: 32 MeV	width: 93 keV	width: 0.7 MeV	width: 10 MeV	width: 0.84 MeV	width: 1.9 MeV

1. Introduction
Charmonium

$c\bar{c}$

L=0

η_c	J/ψ	h_c	χ_{c0}	χ_{c1}	χ_{c2}
0^{-+}	1^{--}	1^{+-}	0^{++}	1^{++}	2^{++}
mass: 2983 MeV	mass: 3097 MeV	mass: 3525MeV	mass: 3415 MeV	mass: 3511 MeV	mass: 3556 MeV
width: 32 MeV	width: 93 keV	width: 0.7 MeV	width: 10 MeV	width: 0.84 MeV	width: 1.9 MeV

S=0

$J=\mathbf{0}$, $P=\mathbf{-1}$, $C=(-1)^{L+S}=\mathbf{+1}$

1. Introduction
Charmonium

$c\bar{c}$

L=0

η_c

0^{-+}

mass: 2983 MeV
width: 32 MeV

J/ψ

1^{--}

mass: 3097 MeV
width: 93 keV

S=1

h_c

1^{+-}

mass: 3525MeV
width: 0.7 MeV

χ_{c0}

0^{++}

mass: 3415 MeV
width: 10 MeV

χ_{c1}

1^{++}

mass: 3511 MeV
width: 0.84 MeV

χ_{c2}

2^{++}

mass: 3556 MeV
width: 1.9 MeV

$J=\mathbf{1},\ P=\mathbf{-1},\ C=(-1)^{L+S}=\mathbf{-1}$

1. Introduction
Charmonium

$c\bar{c}$

L=1

η_c	J/ψ	h_c	χ_{c0}	χ_{c1}	χ_{c2}
0^{-+}	1^{--}	1^{+-}	0^{++}	1^{++}	2^{++}
mass: 2983 MeV	mass: 3097 MeV	mass: 3525MeV	mass: 3415 MeV	mass: 3511 MeV	mass: 3556 MeV
width: 32 MeV	width: 93 keV	width: 0.7 MeV	width: 10 MeV	width: 0.84 MeV	width: 1.9 MeV

S=0

J=1, P=+1, C=$(-1)^{L+S}$=-1

1. Introduction
Charmonium

$c\bar{c}$

L=1

η_c	J/ψ	h_c	χ_{c0}	χ_{c1}	χ_{c2}
0^{-+}	1^{--}	1^{+-}	0^{++}	1^{++}	2^{++}
mass: 2983 MeV	mass: 3097 MeV	mass: 3525MeV	mass: 3415 MeV	mass: 3511 MeV	mass: 3556 MeV
width: 32 MeV	width: 93 keV	width: 0.7 MeV	width: 10 MeV	width: 0.84 MeV	width: 1.9 MeV
			S=1	S=1	S=1

$J=\mathbf{0},\mathbf{1},\mathbf{2}, P=\mathbf{+1}, C=(-1)^{L+S}=\mathbf{+1}$

1. Introduction
Charmonium

$c\bar{c}$

State	J^{PC}	Mass	Width
η_c	0^{-+}	mass: 2983 MeV	width: 32 MeV
J/ψ	1^{--}	mass: 3097 MeV	width: 93 keV
h_c	1^{+-}	mass: 3525MeV	width: 0.7 MeV
χ_{c0}	0^{++}	mass: 3415 MeV	width: 10 MeV
χ_{c1}	1^{++}	mass: 3511 MeV	width: 0.84 MeV
χ_{c2}	2^{++}	mass: 3556 MeV	width: 1.9 MeV

1. Introduction
Charmonium

$c\bar{c}$

η_c

0^{-+}

mass: 2983 MeV
width: 32 MeV

η

mass: 550 MeV
width: 1.3 keV

J/ψ

1^{--}

mass: 3097 MeV
width: 93 keV

ϕ

mass: 1020 MeV
width: 4.3 MeV

h_c

1^{+-}

mass: 3525MeV
width: 0.7 MeV

h_1

mass: 1170 MeV
width: 375 MeV

χ_{c0}

0^{++}

mass: 3415 MeV
width: 10 MeV

f_0

mass: 980 MeV
width: 100 MeV

χ_{c1}

1^{++}

mass: 3511 MeV
width: 0.84 MeV

f_1

mass: 1280 MeV
width: 23 MeV

χ_{c2}

2^{++}

mass: 3556 MeV
width: 1.9 MeV

f_2

mass: 1275 MeV
width: 187 MeV

1. Introduction
Charmonium

Quiz: what is J^{PC} ?

$$\eta_c$$

mass: 2983 MeV
width: 32 MeV

1. Introduction
Charmonium

Quiz: what is J^{PC} ?

η_c

0^{-+}

mass: 2983 MeV
width: 32 MeV

1. Introduction
Charmonium

Quiz: what is J^{PC} ?

$$J/\psi$$

mass: 3097 MeV
width: 93 keV

1. Introduction
Charmonium

Quiz: what is J^{PC} ?

J/ψ

1^{--}

mass: 3097 MeV
width: 93 keV

1. Introduction
Charmonium

Quiz: what is J^{PC} ?

h_c

mass: 3525 MeV
width: 0.7 MeV

1. Introduction
Charmonium

Quiz: what is J^{PC} ?

h_c

1^{+-}

mass: 3525 MeV
width: 0.7 MeV

1. Introduction
Charmonium

Quiz: what is J^{PC}?

$$\chi_{c0}$$

mass: 3415 MeV
width: 10 MeV

1. Introduction
Charmonium

Quiz: what is J^{PC}?

χ_{c0}

0^{++}

mass: 3415 MeV
width: 10 MeV

1. Introduction
Charmonium

Quiz: what is J^{PC} ?

$$\chi_{c1}$$

mass: 3511 MeV
width: 0.84 MeV

1. Introduction
Charmonium

Quiz: what is J^{PC} ?

χ_{c1}

1^{++}

mass: 3511 MeV
width: 0.84 MeV

1. Introduction
Charmonium

Quiz: what is J^{PC} ?

χ_{c2}

mass: 3556 MeV
width: 1.9 MeV

1. Introduction
Charmonium

Quiz: what is J^{PC} ?

χ_{c2}

2^{++}

mass: 3556 MeV
width: 1.9 MeV

1. Introduction
Bottomonium

$b\bar{b}$

η_b
0^{-+}
mass: 9399 MeV
width: 10 MeV

Υ
1^{--}
mass: 9460 MeV
width: 54 keV

h_b
1^{+-}
mass: 9899 MeV
width: ???

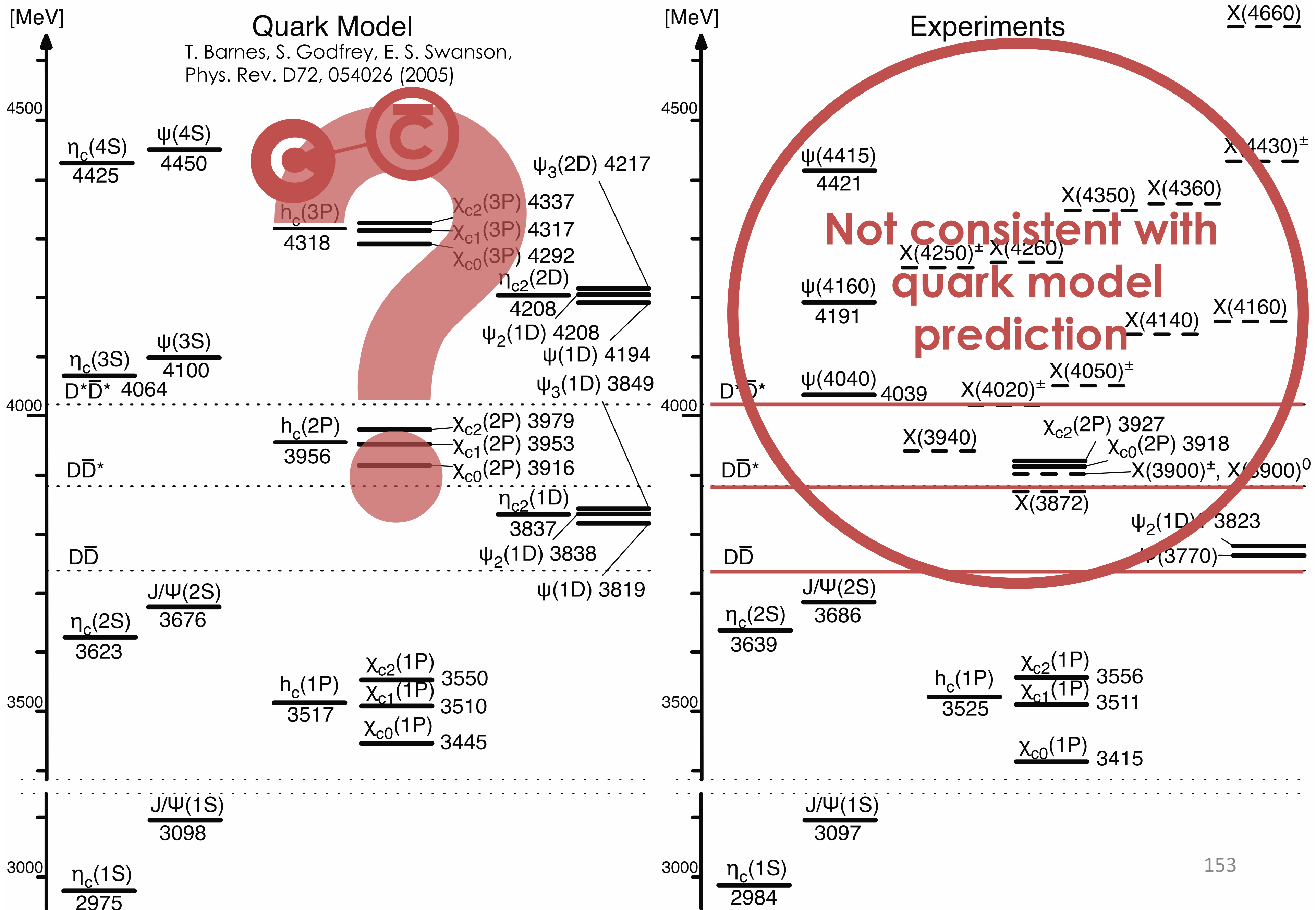
χ_{b0}
0^{++}
mass: 9859 MeV
width: ???

χ_{b1}
1^{++}
mass: 9893 MeV
width: ???

χ_{b2}
2^{++}
mass: 9912 MeV
width: ???

1. Introduction

1. Introduction



1. Introduction
Quarkonium Mass Spectrum

We need to understand heavy-light mesons.

1. Introduction

Names of heavy-light mesons

D meson

Charm
pseudoscalar

$\bar{D}$ meson

D^0 $c\bar{u}$

+2/3 -2/3

$\bar{D}^0$ $\bar{c}u$

-2/3 +2/3

D^+ $c\bar{d}$

+2/3 +1/3

D^- $\bar{c}d$

-2/3 -1/3

1. Introduction

Names of heavy-light mesons

D^* meson

Charm vector

$\bar{D}^*$ meson

D^{*0} $c\bar{u}$ (+2/3, -2/3)

$\bar{D}^{*0}$ $\bar{c}u$ (-2/3, +2/3)

D^{*+} $c\bar{d}$ (+2/3, +1/3)

D^{*-} $\bar{c}d$ (-2/3, -1/3)

1. Introduction

Names of heavy-light mesons

$\bar{B}$ meson

Bottom pseudoscalar

B meson

B^- $b\bar{u}$

-1/3 -2/3

B^+ $\bar{b}u$

+1/3 +2/3

$\bar{B}^0$ $b\bar{d}$

-1/3 +1/3

B^0 $\bar{b}d$

+1/3 -1/3

1. Introduction

Names of heavy-light mesons

$\bar{B}^*$ meson

Bottom vector

B^* meson

B^{*-} $b\bar{u}$ (-1/3, -2/3)

B^{*+} $\bar{b}u$ (+1/3, +2/3)

$\bar{B}^{*0}$ $b\bar{d}$ (-1/3, +1/3)

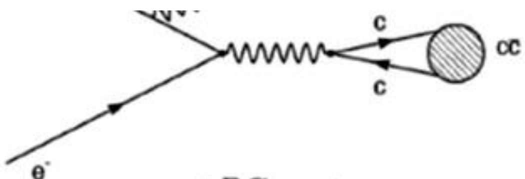
B^{*0} $\bar{b}d$ (+1/3, -1/3)

1. Introduction

Experiment ⇄ Theory

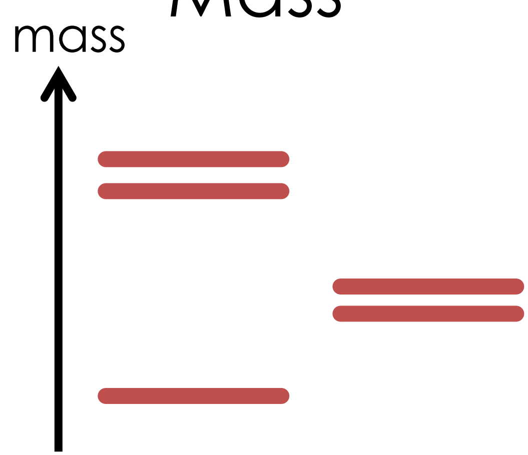
Hadron Spectroscopy

Production

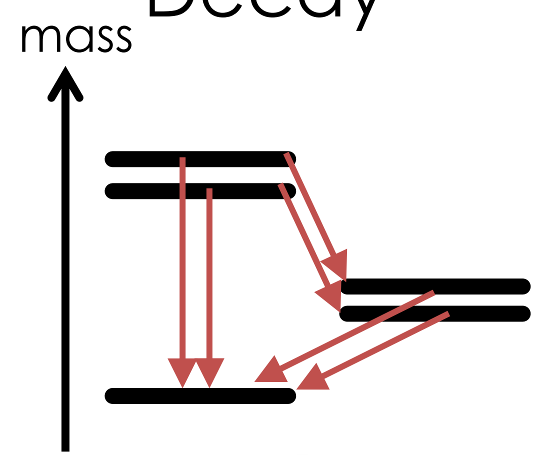


$J^{PC} = 1^{--}$

Mass



Decay



List of related review papers

Exotic heavy hadrons

- **The new heavy mesons: A status report:**
  E. S. Swanson, Phys. Rep. 429, 243 (2006)
- **Charmonium:**
  M. B. Voloshin, Prog. Part. Nucl. Phys. 61, 455 (2008)
- **Heavy quarkonium: progress, puzzles, and opportunities:**
  N. Brambilla et al., Eur. Phys. J. C71, 1534 (2011)
- **QCD and strongly coupled gauge theories: challenges and future perspectives:**
  N. Brambilla et al., Eur. Phys. J. C74, 2981 (2014)
- **The hidden charm pentaquark and tetraquark states:**
  H.-X Chen, W. Chen, X. Liu, S.-L. Zhu, Phys. Rep. 639, 1 (2016)
- **Exotic hadrons with heavy flavors: X, Y, Z, and related states:**
  A. Hosaka, T. Iijima, K. Miyabayashi, Y. Sakai, S. Yasui, PTEP 2016, 062C01 (2016)
- **Heavy-Quark QCD Exotica:**
  R. F. Lebed, R. E. Mitchel, E. S. Swanson, Prog. Part. Nucl. Phys. 93, 143 (2017)
- **Multiquark resonances:**
  A. Esposito, A. Pilloni, A. D. Plolsa, Phys. Rep. 668, 1 (2017)
- **Exotics: Heavy pentaquarks and tetraquarks:**
  A. Ali, J. S. Lange, S. Stone, Prog. Part. Nucl. Phys. 97, 123 (2017)
- **Nonstandard heavy mesons and baryons: Experimental evidence:**
  S.L. Olsen, T. Skwamick, D. Zieminska, Rev. Mod. Phys. 90, 015003 (2018)
- **Hadronic molecules:**
  F.-G. Guo, C. Hanhart, U.-G. Meissner, Q. Qang, Q. Zhao, B.-S. Zou, Rev. Mod. Phys. 90, 015004 (2018)
- **Pentaquark and Tetraquark States:**
  Y.-R. Liu, H.-Z. Chen, W. Chen, Prog. Part. Nucl. Phys. 107, 237 (2019)
- **The XYZ states: experimental and theoretical status and perspectives:**
  N. Brambilla, et al., Phys. Rep. 873 (2020) 1
- **Heavy hadronic molecules with pion exchange and quark core couplings: a guide for practitioners:**
  Y. Yamaguchi, et al., J. Phys. G: Nucl. Part. Phys. 47 (2020) 053001

List of related review papers

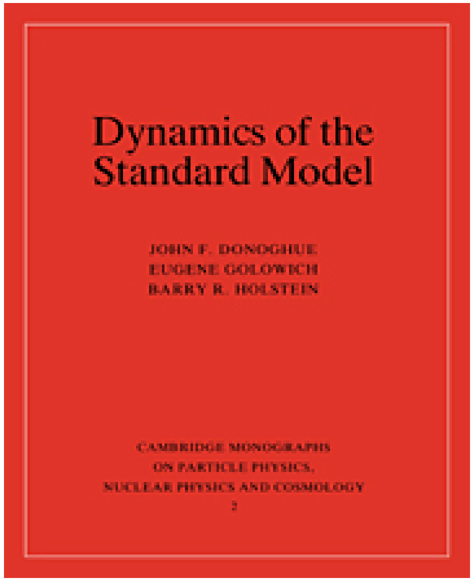
Exotic hadrons from heavy ion collisions

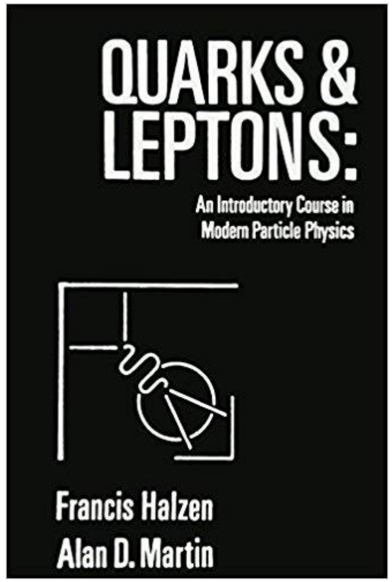
- **Exotic hadrons from heavy ion collisions:**
  S. Cho et al. [ExHIC collaboration], Prog. Part. Nucl. Phys. 95, 279 (2017)

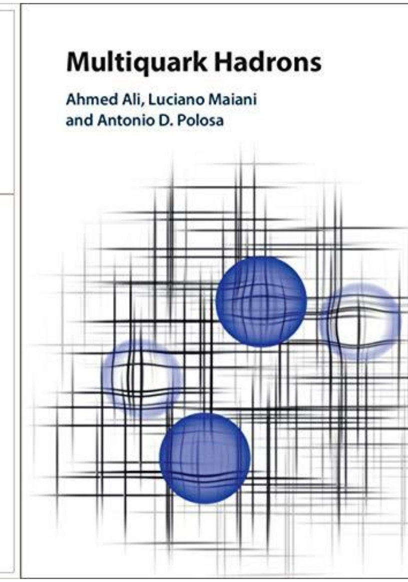
Heavy hadrons in nuclear matter

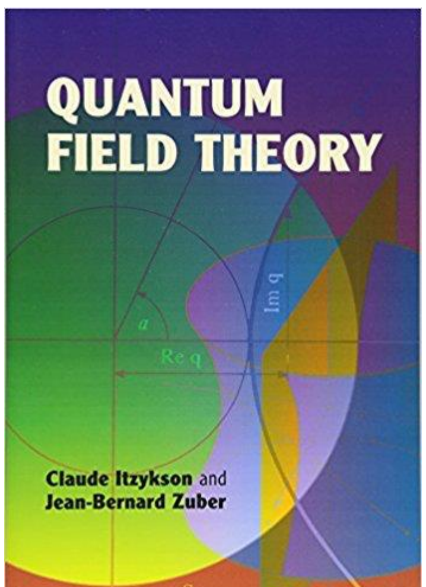
- **Heavy hadrons in nuclear matter:**
  A. Hosaka, T. Hyodo, K. Sudoh, Y. Yamaguchi, S. Yasui, Prog. Part. Nucl. Phys. 96, 88 (2017)
- **Nuclear-bound quarkonia and heavy-flavor hadrons:**
  G. Krein, A.W. Thomas, K. Tushima,, Prog. Part. Nucl. Phys. 100, 161 (2018)

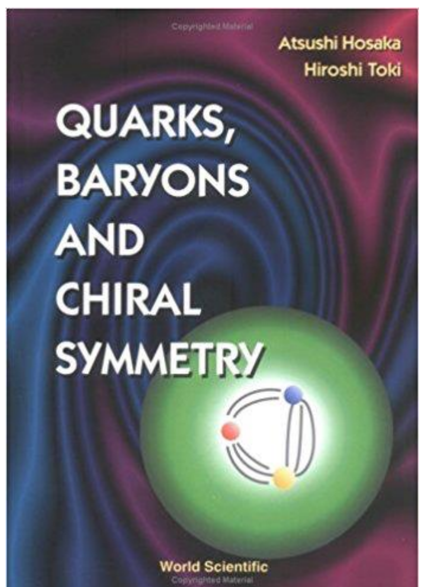
Recommended text books (hadron phenomenology)

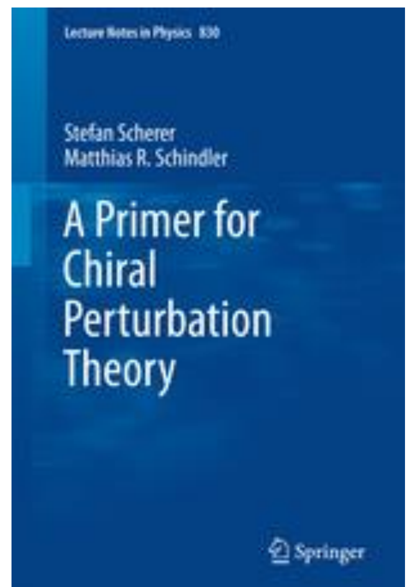


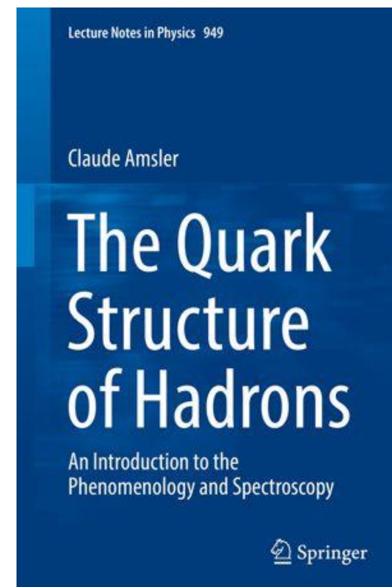












Do you have questions?