



Exotic spectroscopy

Compact Pentaquark structures

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arXiv:1604.03769

Gell-Mann and Zweig 60ties
suggested also the existence of penta and tetra quarks

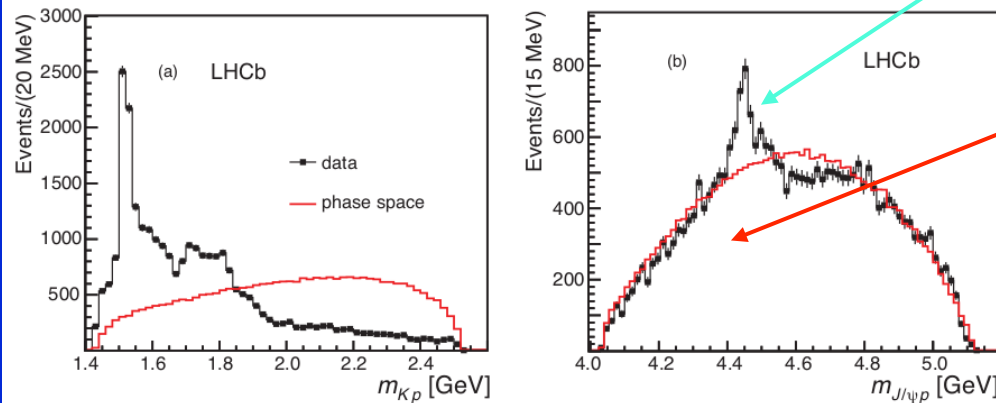


M. Gell-Mann, Phys. Lett. **8** (1964) 214. doi:10.1016/S0031-9163(64)92001-3

G. Zweig, CERN-TH-401.

LHCb, one of the great experiments at the
Large Hadron Collider LHC,
has observed in the study of the decays of
the heavy baryon Λ_b ,
a new class of exotic particles

LHCb



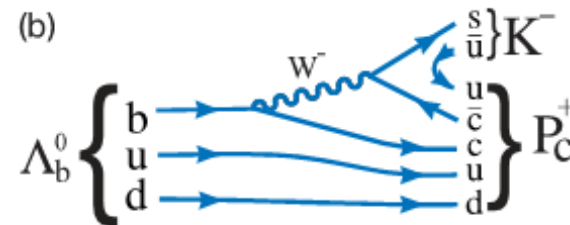
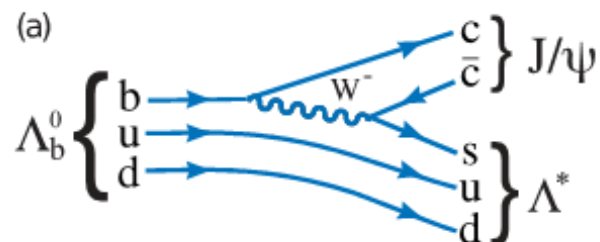
$$P_c^+(4450) = (4449.8 \pm 39) \text{ MeV}$$

$$P_c^+(4380) = (4380 \pm 205) \text{ MeV}$$

statistic significance greater
then 9 sigma !

$$\Lambda_b^0 \longrightarrow J/\psi + \Lambda^*, \Lambda^* \longrightarrow K^- + p$$

$$\Lambda_b^0 \longrightarrow P^{0+} + K^-, P^{0+} \longrightarrow J/\psi + p$$



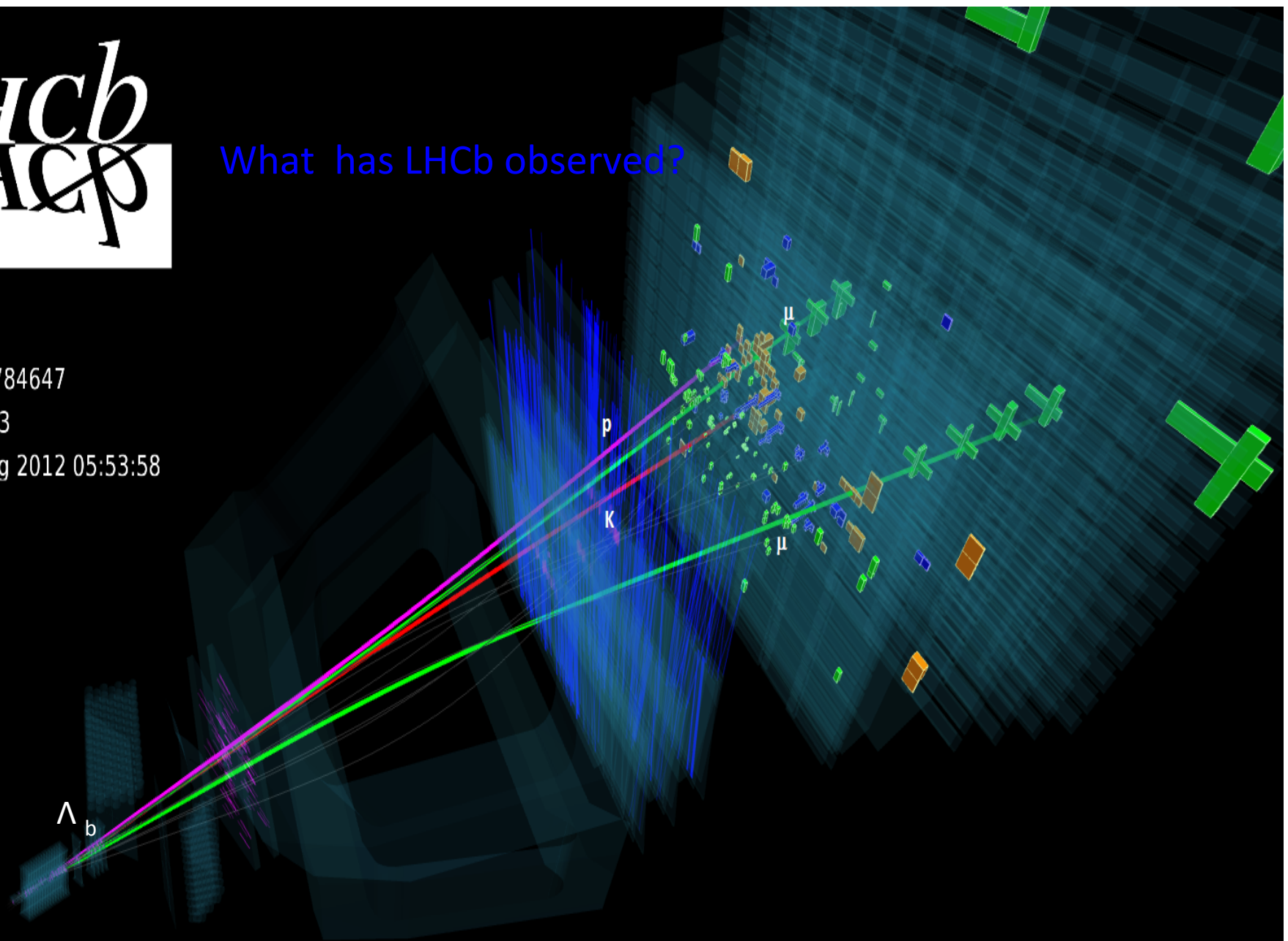


What has LHCb observed?

Event 251784647

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simulation of decays as from LHCb

santopinto, giachino, hep-ph 1604.03769

- We use very general arguments dictated by symmetry considerations, in order to describe pentaquark states within a group theory approach. A complete classification of all possible states and quantum numbers, that can be useful both to the experimentalists, for new finding, or to theoretical model builders are given, without the introduction of any particular dynamical model.
- Some predictions are finally given using a Guersy-Radicati inspired mass formula. We reproduce the mass and the quantum numbers of the lightest pentaquark state reported by LHCb ($J^P = 3/2^-$), with a parameter free mass formula fixed on known well established baryons.
- We predicted the other pentaquark resonances (giving their masses, and suggesting possible decay channels) which belong to the same multiplet of the discovered one.

Construction of the states

1) a pentaquark state should be a color singlet $SU_c(3)$




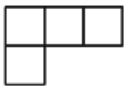



the antiquark c^- transforms as $\bar{3}$ so the color representation of the 4 quarks subsystem has to be the $[211]$ state (with permutation symmetry F_1)

2) be antisymmetric under any permutation of the four quarks (Pauli principle)

→ 1) + 2) the two conditions determine the kind of symmetry for the orbital-spin-flavour 4 quarks subsystem

By the second condition, the orbital-spin-flavour part of the w.f., ψ , is necessarily a $[31]$ state with F_2 symmetry, which is obtained from the colour state $[211]$, by inter-changing rows and columns. In fact, the $[211]$ and the $[31]$ state are one the conjugate to the other, and so their product give the completely antisymmetric state $[1111]$, with symmetry A_2

Four quarks subsystem

\mathcal{T}_d	\sim	S_4	Young tableau	Multiplicity	Dimension		
					$SU_{sf}(8)$	$SU_{fl}(4)$	$SU_s(2)$
A_1	\sim	[4]		1	330	35	5
F_2	\sim	[31]		3	630	45	3
E	\sim	[22]		2	336	20	1
F_1	\sim	[211]		3	378	3	—
A_2	\sim	[1111]		1	70	1	—

Construction of the states

We know the 4 quark symmetry



We obtain the $SU(8)$ spin-flavour representations compatible with symmetry principles



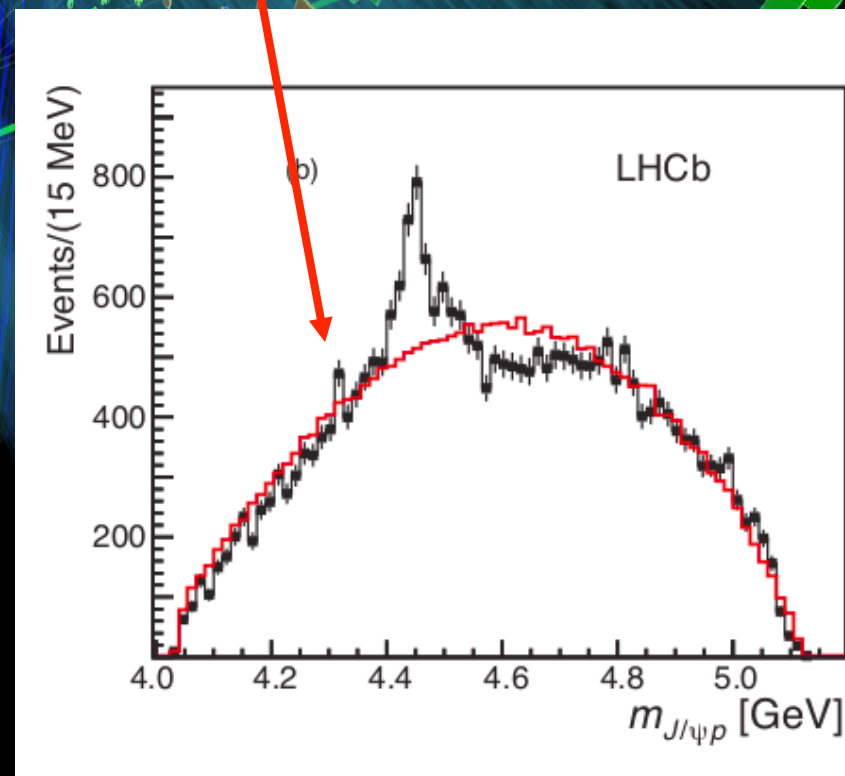
Pentaquark resonance $P_c^+(4380)$

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- For the reproduction of its qu. numbers ($J^P = 3/2^-$), it is necessary that quarks are in S waves



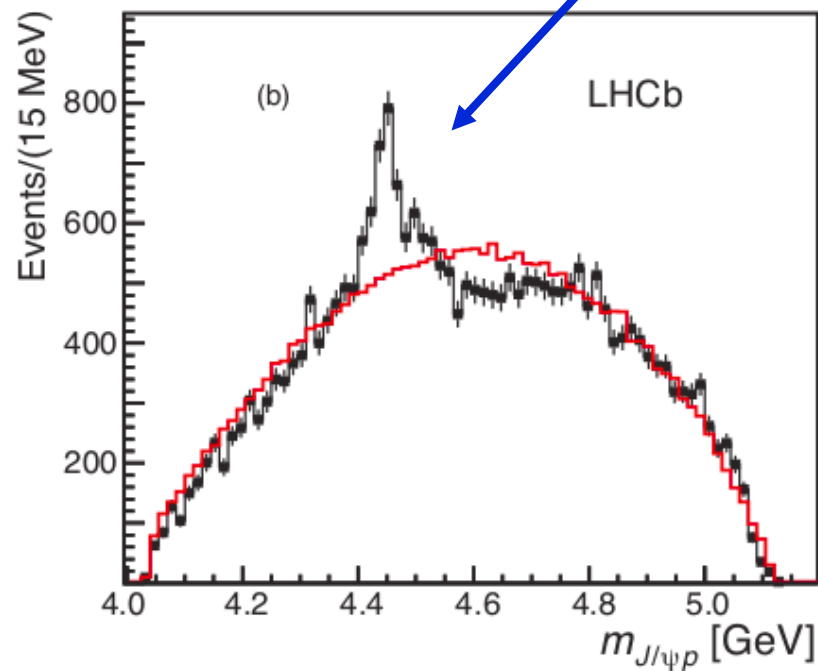


The pentaquark $P_c^+(4450)$ resonance

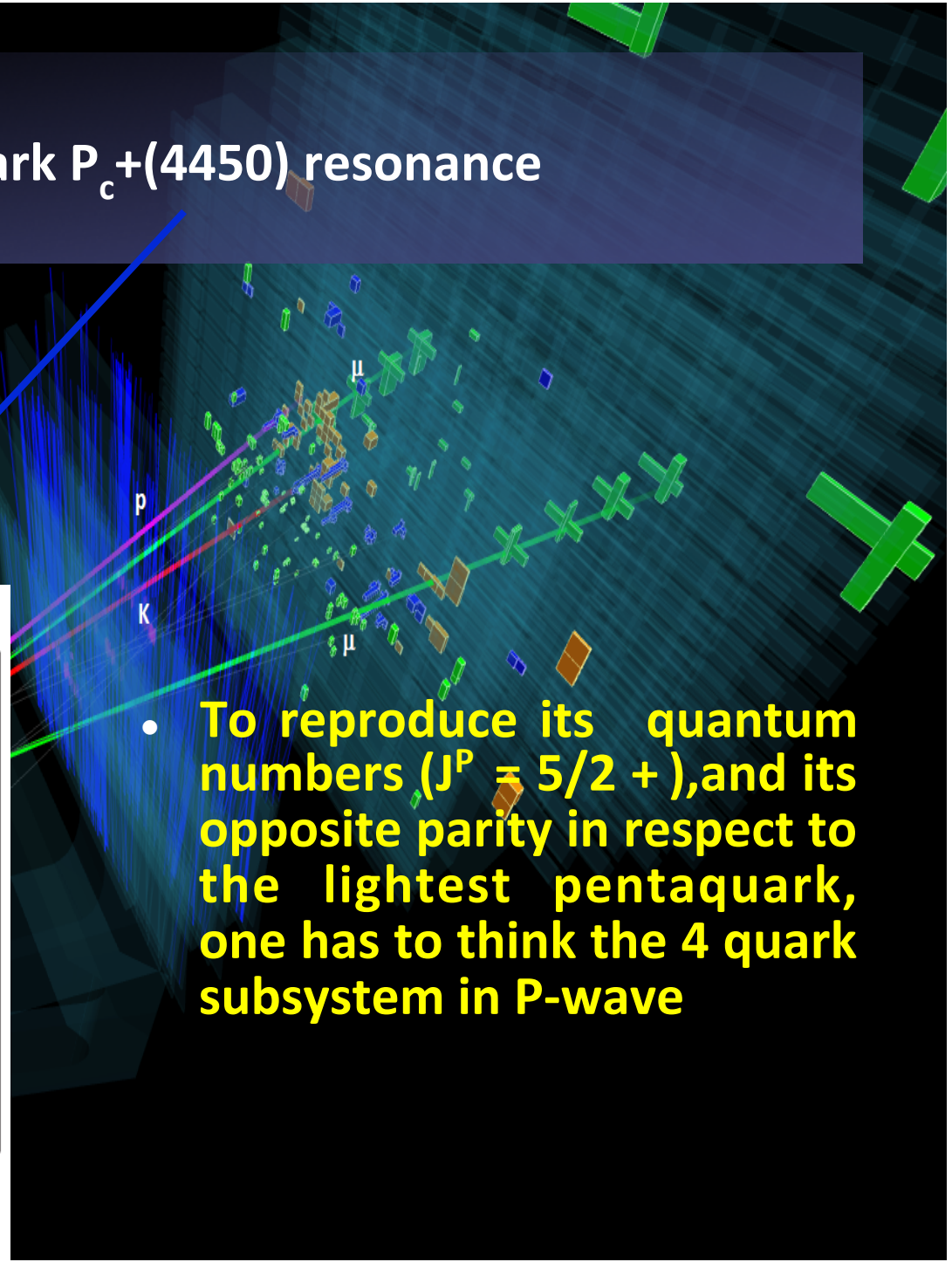
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- To reproduce its quantum numbers ($J^P = 5/2^+$), and its opposite parity in respect to the lightest pentaquark, one has to think the 4 quark subsystem in P-wave



Compact pentaquark or molecular states?

The heaviest resonance , $P_c^+(4450)$,
has a mass close to the threshold of $\Sigma_c D^*$ (4462.4 MeV)



This suggest that this state can not be explained as compact pentaquark, but in first approximation as a molecular state

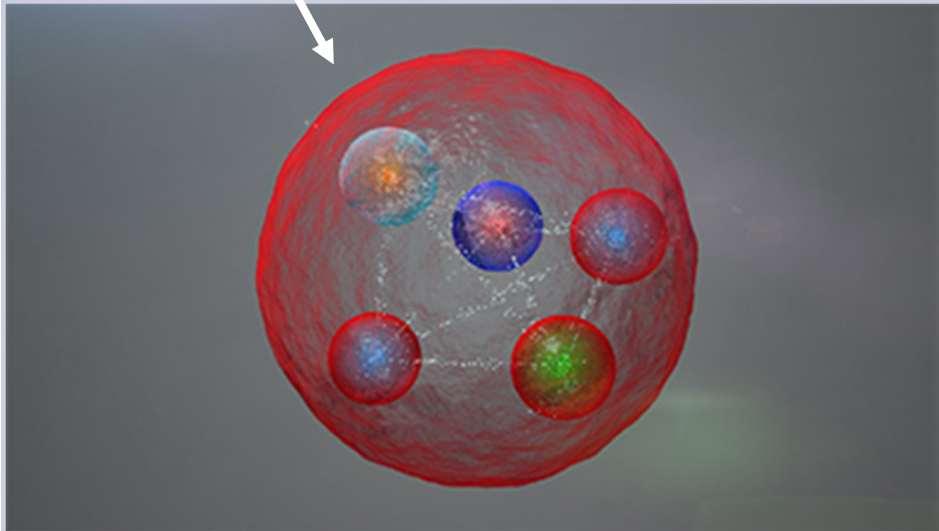
Karliner & Rosner interpretation

The hypothesis that the higher state, $P_c^+(4450)$, is a molecular state is in accordance with Karliner & Rosner's work

IN CONCLUSION:

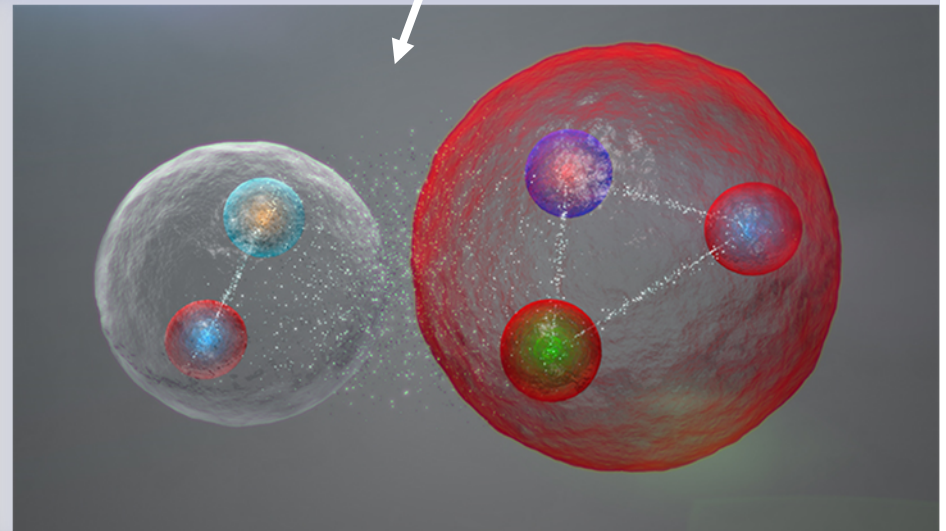
$P_c^+(4380)$

Compact Pentaquark



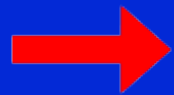
$P_c^+(4450)$

Molecular state $D^* \Sigma_c$
(Karliner & Rosner)



EXTENSION OF THE GÜRSEY-RADICATI MASS FORMULA

We have just seen as only the $P_c^+(4380)$ resonance can be interpreted as a compact pentaquark, while the heaviest one is a molecular state



We will concentrate only on the $P_c^+(4380)$ resonance

In order to determine the SU(3) flavour multiplet to whom belongs to the $P_c^+(4380)$ resonance, it has been necessary an extension of the GÜRSEY-RADICATI



THE GELL-MANN and OKUBO MASS FORMULA

The Gell-Mann and Okubo mass formula, takes into account the SU(3) breaking as due to the different masses of the quarks

According to that the mass M_{GMO} of a baryon belonging to a given SU(3) multiplet can be written as

$$M_{GMO} = M_0 + DY + E[I(I + 1) - \frac{1}{2}Y^2]$$

M_0 is the average value of the SU(3) multiplet ;

Y is the baryon hypercharge

I is the total isospin

THE GÜRSEY-RADICATI MASS FORMULA

The Gürsey e Radicati mass formula is an extension of the Gell-Mann and Okubo's one, since it takes into account of the differences in the mass values as due to as due to different spin of the baryons

$$M_{GR} = M_0 + AS(S + 1) + DY + E[I(I + 1) - \frac{1}{2}Y^2]$$

M_0 is the average value of the masses of a given baryon SU(3) multiplet;

Y is the baryon hypercharge;

I is the total isospin;

S is the total spin of the baryon.

OUR EXTENSION OF THE GÜRSEY-RADICATI MASS FORMULA

La più semplice estensione della formula di massa, che tenga conto del contributo dei quarks c , \bar{c} che discrimini i diversi multipletti di SU(3):

$$M_{GR}^{extended} = M_0 + AS(S+1) + DY + E[I(I+1) - \frac{1}{2}Y^2] + GC_2(SU_{fl}(3)) + Fn_c$$

M_0 is the average value of the masses of a given baryon SU(3) multiplet;

Y is the baryon hypercharge;

I is the total isospin;

S is the total spin of the baryon.

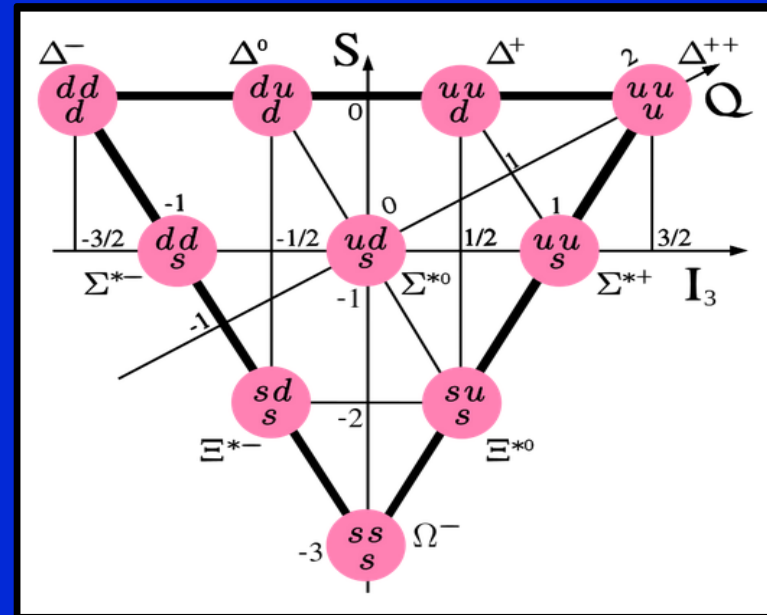
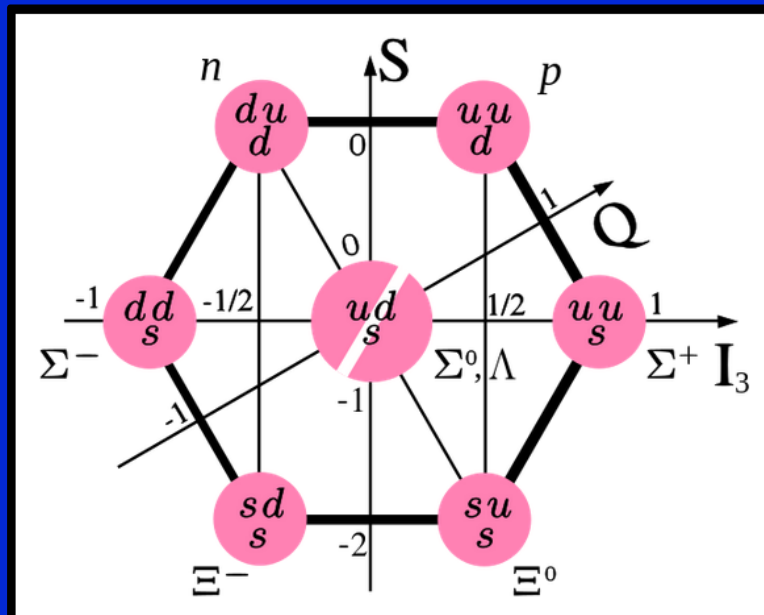
$C_2(SU_{fl}(3))$ are the eigenvalues of the Casimir operator of $SU_{fl}(3)$;

n_c counts the number of c or anti c quarks

OUR EXTENSION of THE GÜRSEY-RADICATI MASS FORMULA

$$M_{GR}^{extended} = M_0 + AS(S+1) + DY + E[I(I+1) - \frac{1}{2}Y^2] + GC_2(SU_{fl}(3)) + Fn_c$$

The A, D, E, G and M_0 coefficients have been fixed using well known strange and non strange baryons



the F coefficient has been derived from charmed baryons

The decomposition procedure of the states

- 1) Decomposition of the $SU_{SF}(8)$ representation, compatible with the symmetry principle, into the spin and the flavour parts;
- 2) Since the lightest resonance has spin $S=J=3/2$, only the $SU(4)$ representation with spin $3/2$ have been selected;
- 3) Only those representations have been further decomposed into $SU(3) \times U_c(1)$, in such a way to select at the end only the $SU(3)$ multiplet with charm quantum number C equal to zero;

Decomposition procedure of the states

4) In the most general case the ipercharge Y is defined as:

$$Y = B + S - \frac{C - B + T}{3}$$

since, for the lightest pentaquark state is $T=B=C=S=0$, and $B=1$



$$Y=1$$

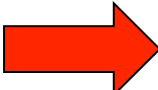


it is necessary to decompose further each $SU(3)$ multiplet into $SU(2) \times U_Y(1)$, and next step, select the multiplets with ipercharge $Y=1$

Decomposition procedure of the states

- 5) The mass of each multiplets has been calculated by means of an extension of the Gürsey e Radicati mass formula as already discussed
**The multiplet with minimum energy is the octet of SU(3) ,
 that is the [21] multiplet**

$SU_{fl}(3)$ multiplet $\supset SU_I(2) \otimes U_{Y=1}(1)$ submultiplets mass (MeV)



[51] ₃₅	[5] ₆	5296
	[3] ₄	5081
[42] ₂₇	[3] ₄	4729
	[1] ₂	4600
[3] ₁₀	[3] ₄	4553
[33] ₁₀	[1] ₂	4424
 [21] ₈	[1] ₂	4160

The lightest resonance, the $P_c^+(4380)$,
 according to LHC_b
 has a mass $M = 4380 \pm 8 \pm 29$ MeV
 and a width $\Gamma = 205 \pm 18 \pm 86$ MeV

The predicted theoretical value of the mass is 4404 MeV in
 agreement with the exper. $M = 4380 \pm 8 \pm 29$ MeV

Notation:
 $P^{IJ}(M)$ where
 I is the number of
 s quarks;
 J the electric
 charge;
 M predicted mass

$SU_{fl}(3)$ multiplet	$SU_I(2)$ submultiplet	I	Y	mass (MeV)	isospin states
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 $[21]_8 \equiv$ 
8


2

$\frac{1}{2}$

1

4160

$P^{00}(4160), P^{0+}(4160)$

S

0

0

4328

$P^{1'0}(4328)$


3

1

0

4414

$P^{1+}(4414), P^{10}(4414)$
 $P^{1-}(4414)$


2

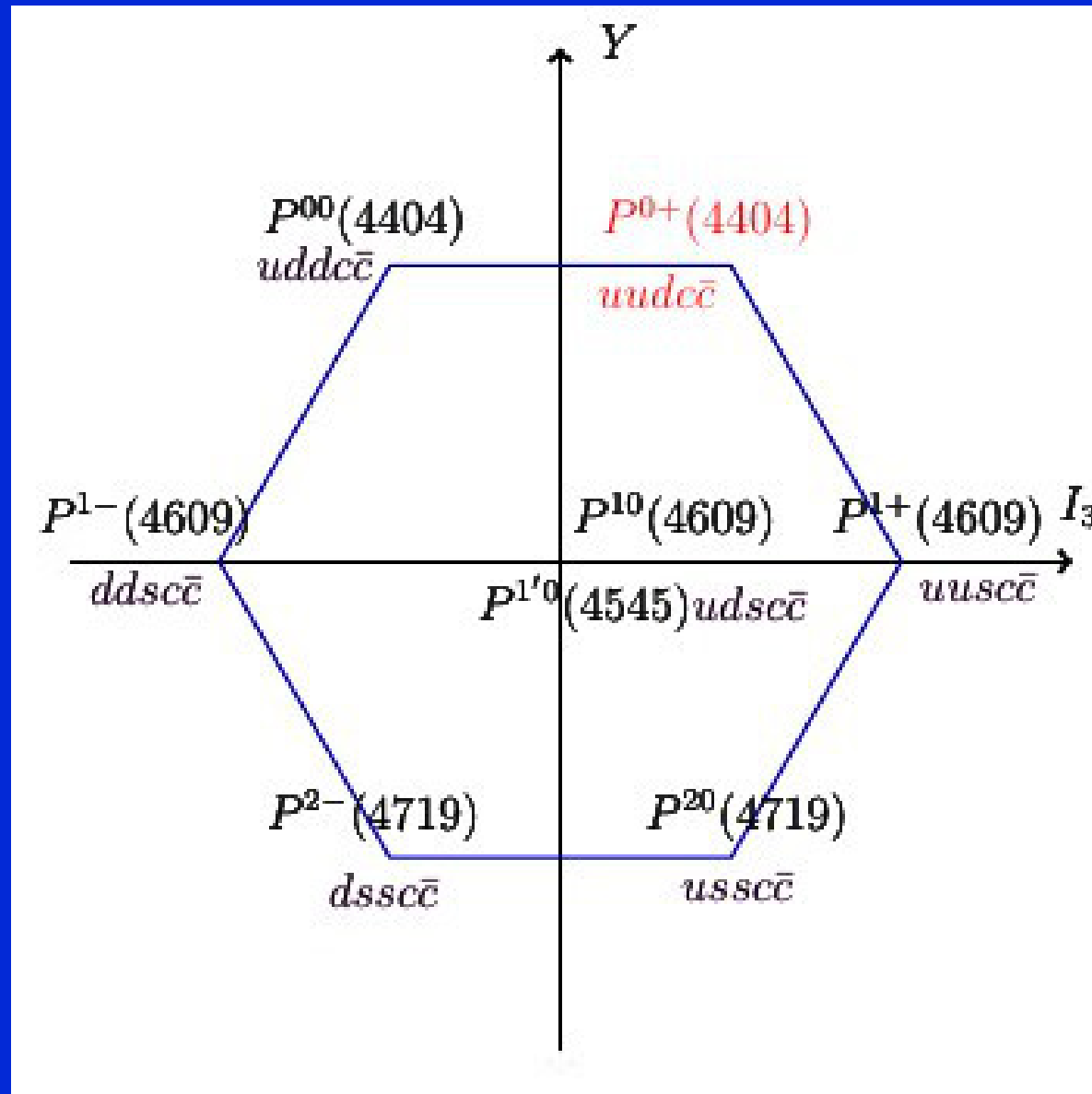
$\frac{1}{2}$

-1

4540

$P^{20}(4540), P^{2-}(4540)$

PENTAQUARK OCTET STATES

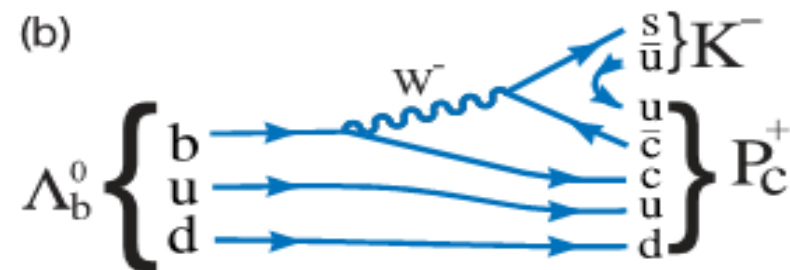
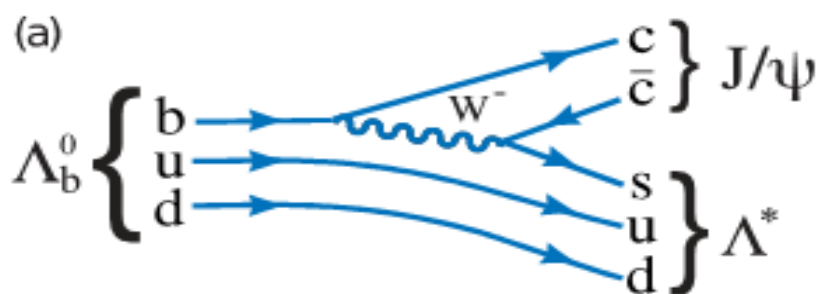


HOW TO OBSERVE OTHER PENTAQUARK STATES?

in order to give an answer to this question, we go back to study the decay channel in which the two pentaquark resonances have been observed

$P_c^+(4380)$ is part of an isospin doublet and it has been observed studying the Λ_b decay:

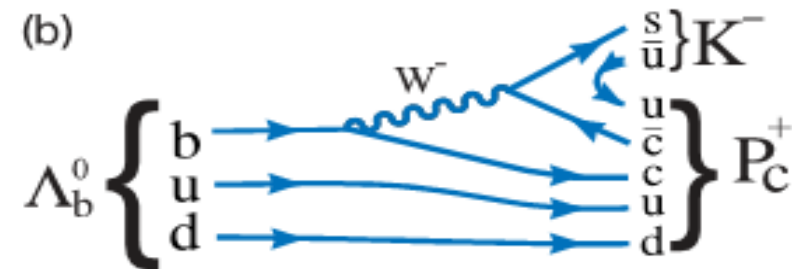
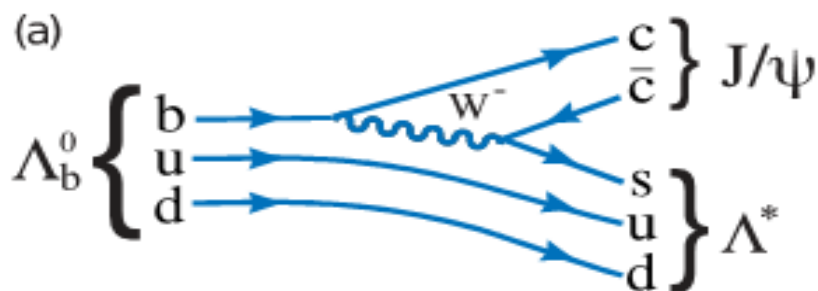
$$\Lambda_b^0 \longrightarrow P^{0+} + K^-, P^{0+} \longrightarrow J/\Psi + p$$



HOW CAN WE OBSERVE PENTAQUARK STATES ?

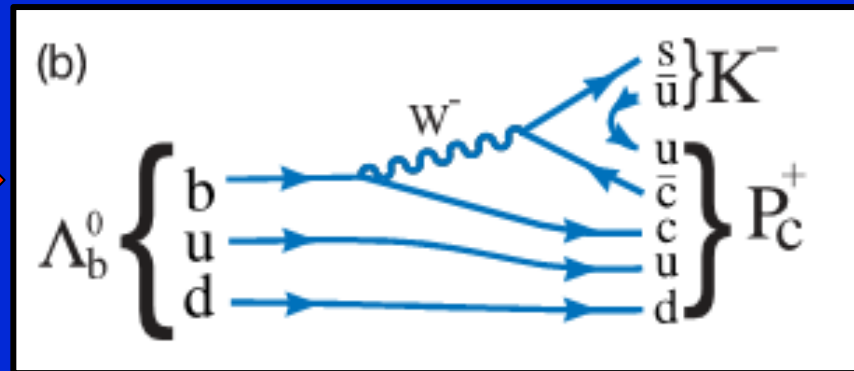
but, as seen, there is also the alternative decay channel that gives origin to the two pentaquark resonances:

$$\Lambda_b^0 \longrightarrow P^{0+} + K^-, P^{0+} \longrightarrow J/\Psi + p$$



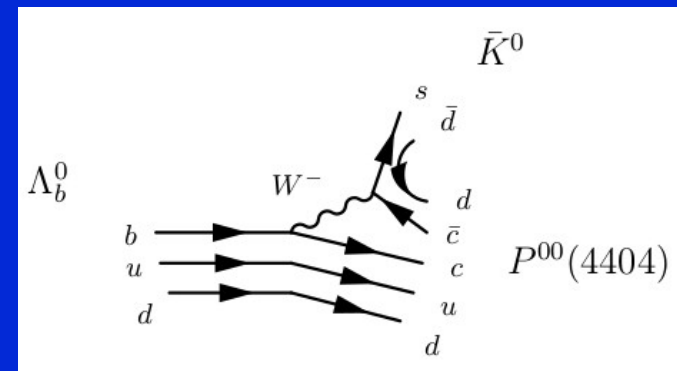
HOW TO OBSERVE OTHER PENTAQUARK STATES?

$$\Lambda_b^0 \longrightarrow P^{0+} + K^-, P^{0+} \longrightarrow J/\Psi + p$$



In order to observe the isospin partner $P^{00}(4160)$ of the charged P^{0+} we consider a pair creation of the type d anti d (instead of u anti u)

$$\Lambda_b^0 \longrightarrow P^{00} + \bar{K}^0, P^{00} \longrightarrow J/\Psi + n$$



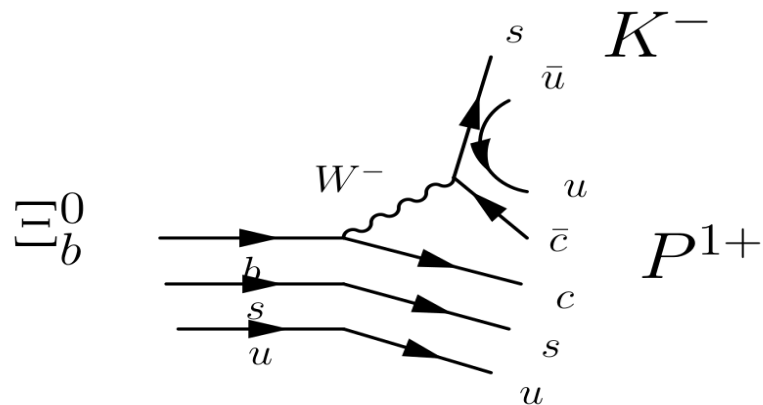
HOW TO OBSERVE OTHER PENTAQUARK STATES?

Regarding other pentaquark states with strangeness, we can consider bottomed baryon decays

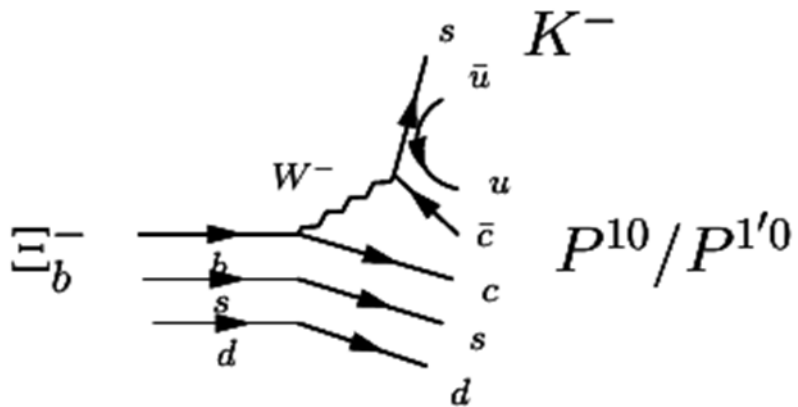
$$\Xi_b^- \longrightarrow J/\psi + \Xi^-$$

$$\Omega_b^- \longrightarrow J/\psi + \Omega^-$$

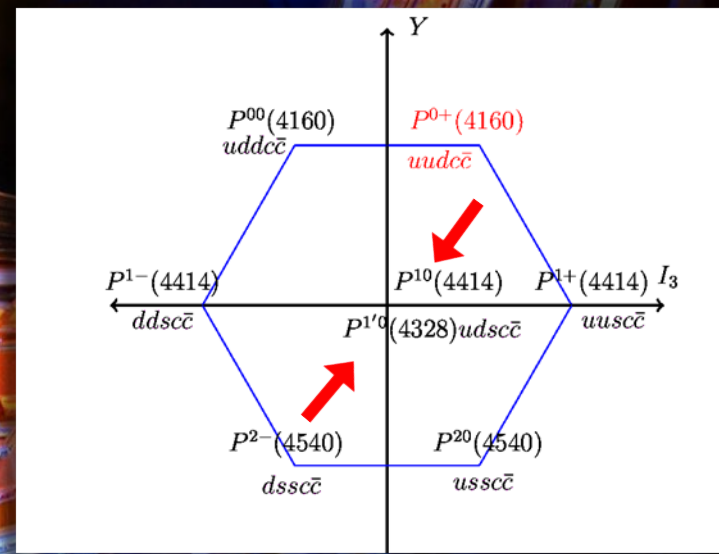
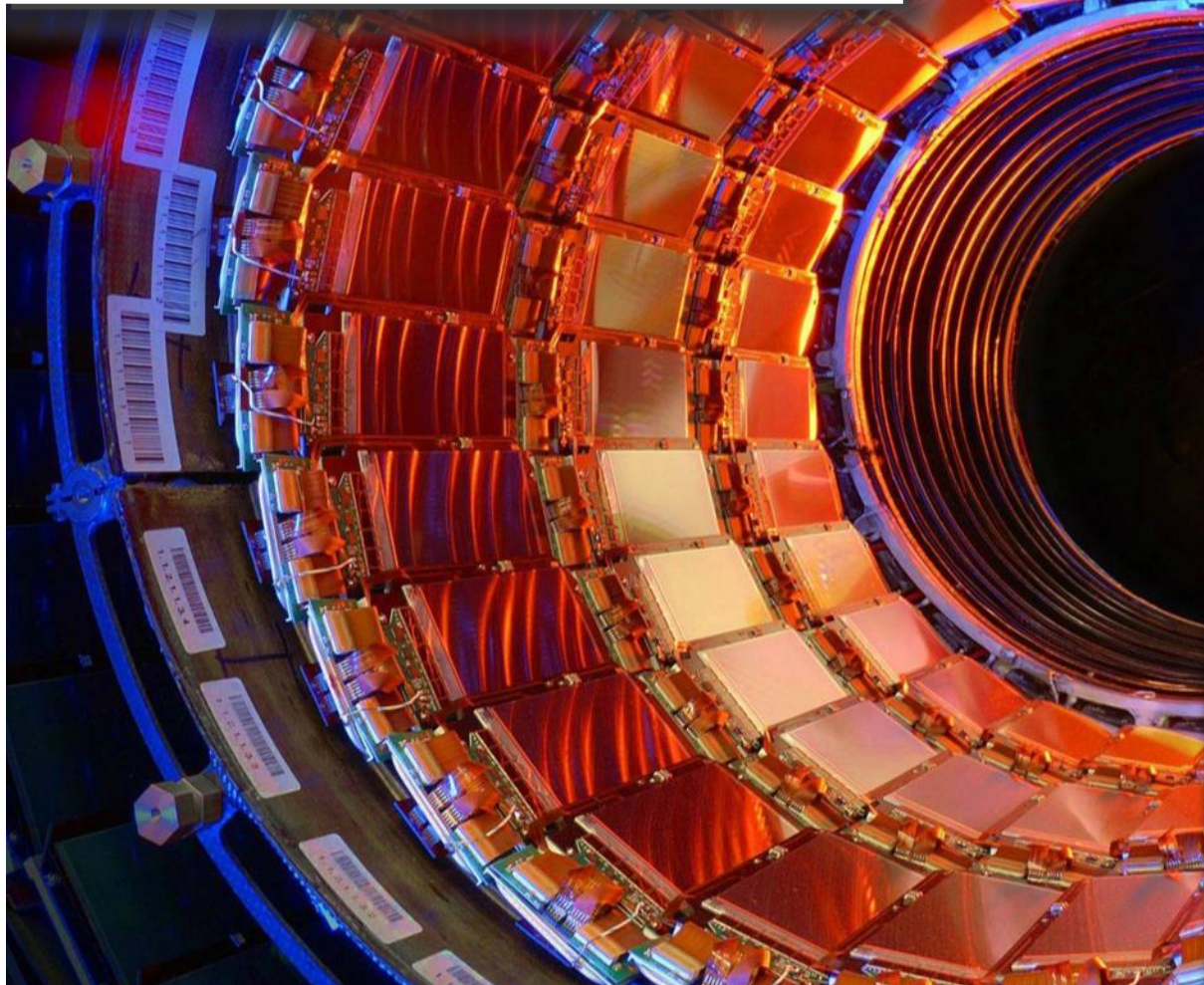
The charged $P^{1+}(4414)$ state is the most interesting from the experimental point of view, since all the final state particles are charged particles, so easier to be detected :



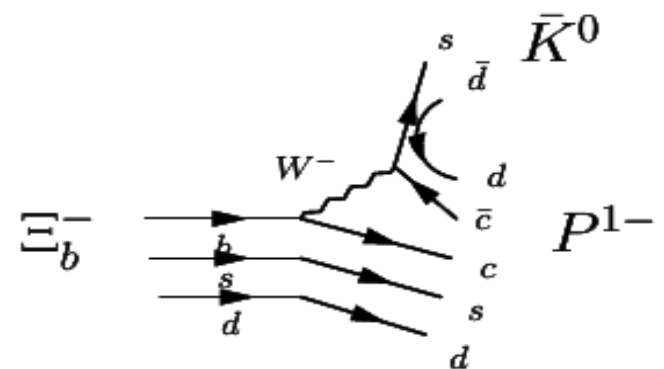
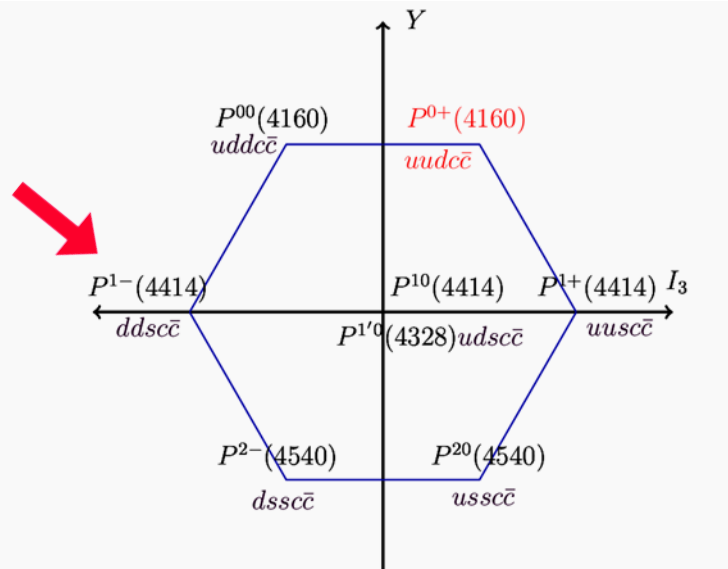
$$\Xi_b^0 \longrightarrow P^{1+} + K^-, P^{1+} \longrightarrow J/\Psi + \Sigma^+$$

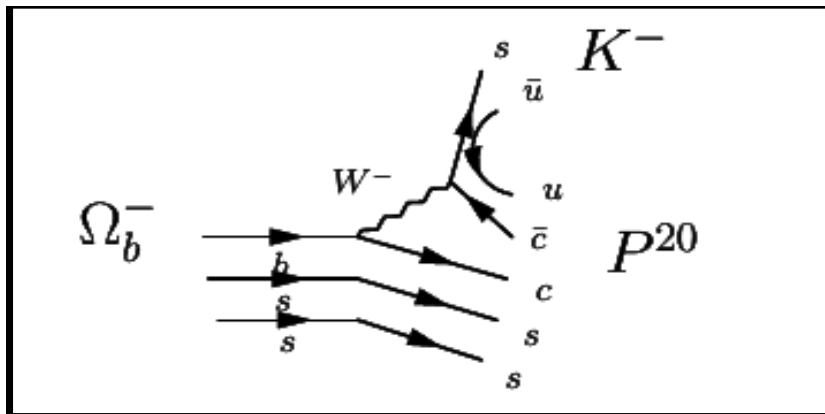


The states $P^{10}(4540)$
and $P^{1'0}(4328)$

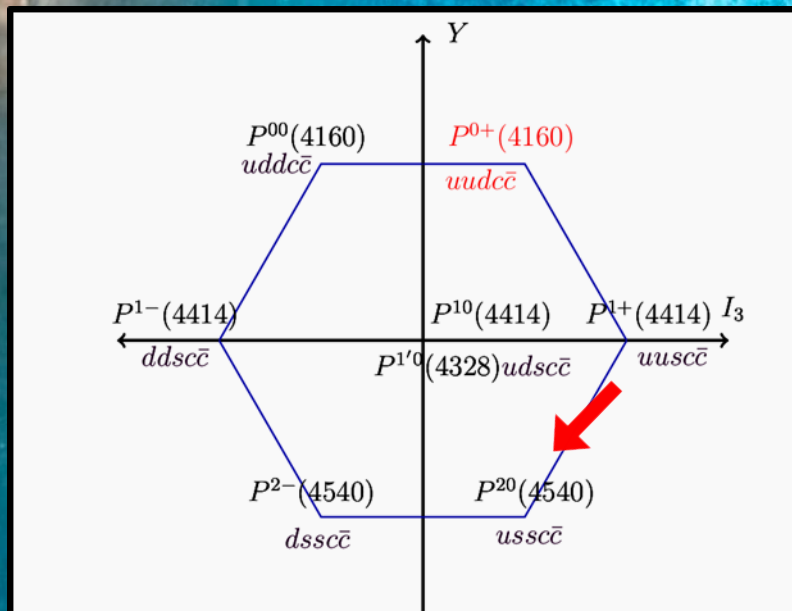
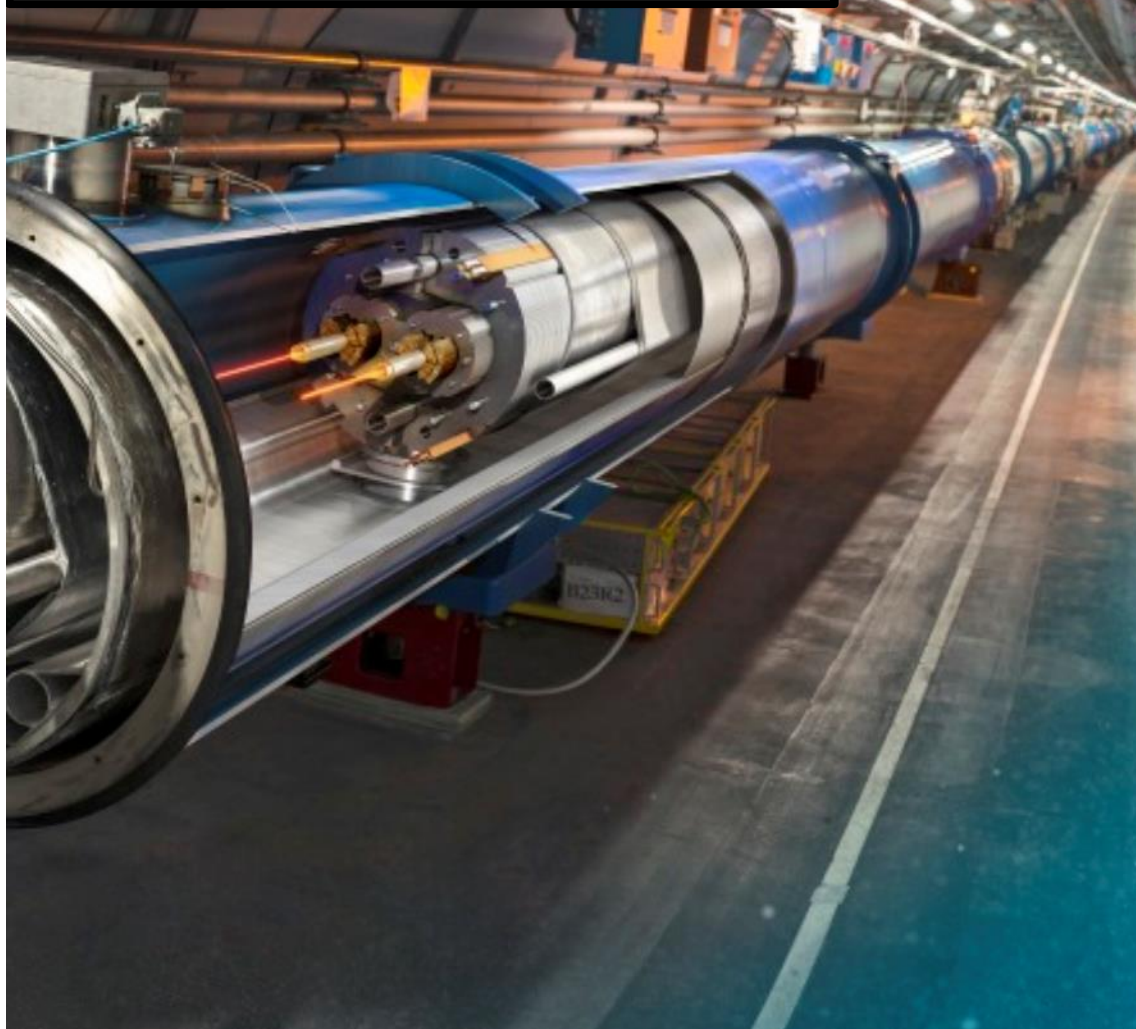


The $P^{1-}(4414)$ state

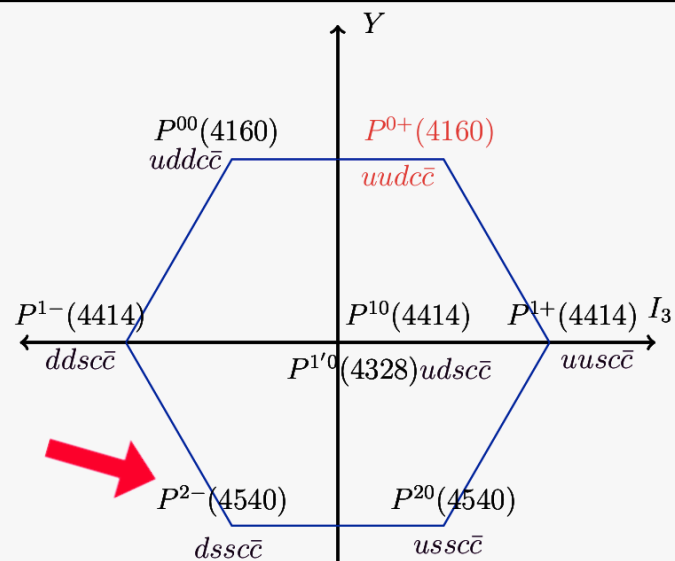
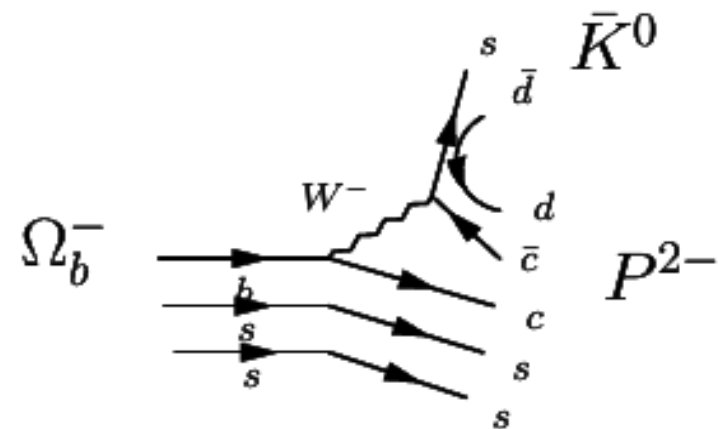




The $P^{20}(4540)$ state

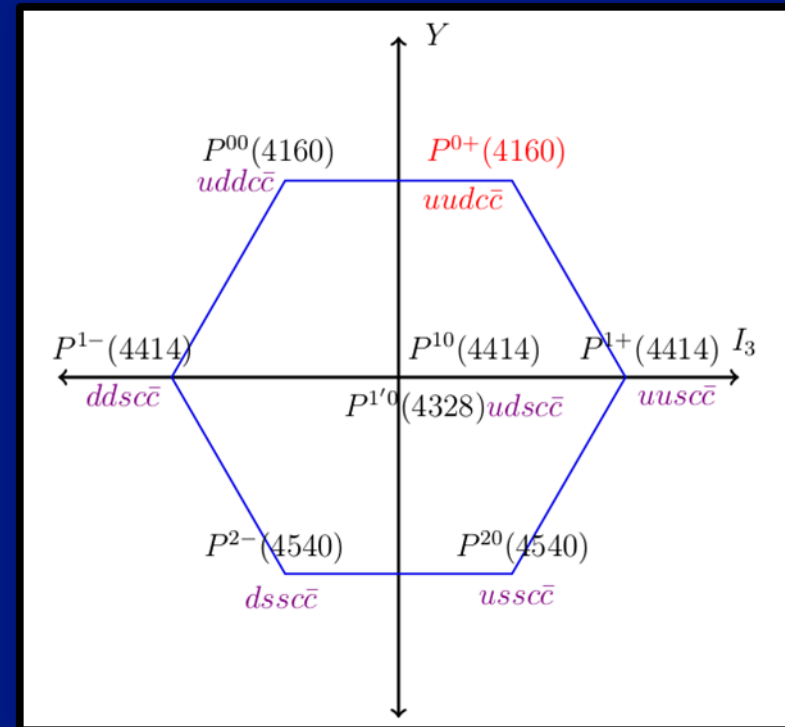
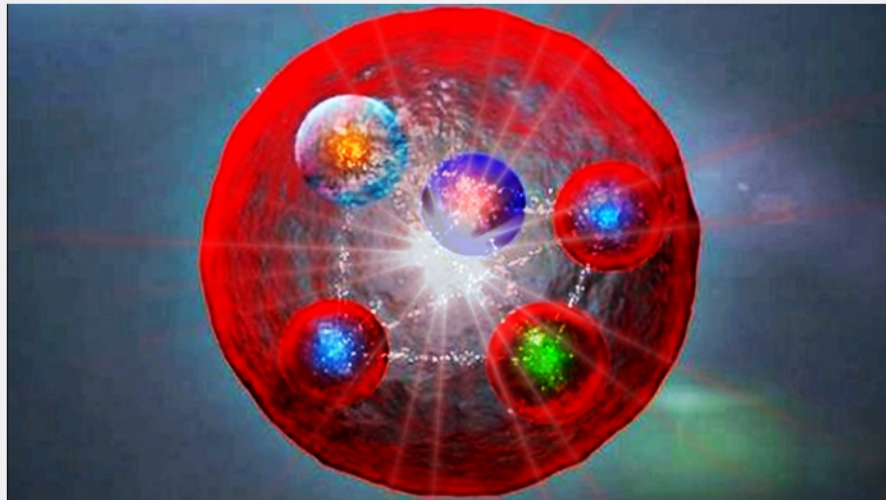


The $P^{2-}(4540)$ state



CONCLUSION

- 1) The $P_c^+(4380)$ state is well described by means of a compact pentaquark approach



- 2) Using group theory techniques and with an extension of the GR mass formula, it has been demonstrated that it belongs to an $SU(3)$ flavour octet

- 3) the compact pentaquark approach brings the existence also of other states, of which we have predicted the masses, and also suggested possible decay channels where the experimentalists can try to look for them

