Compact Pentaquark

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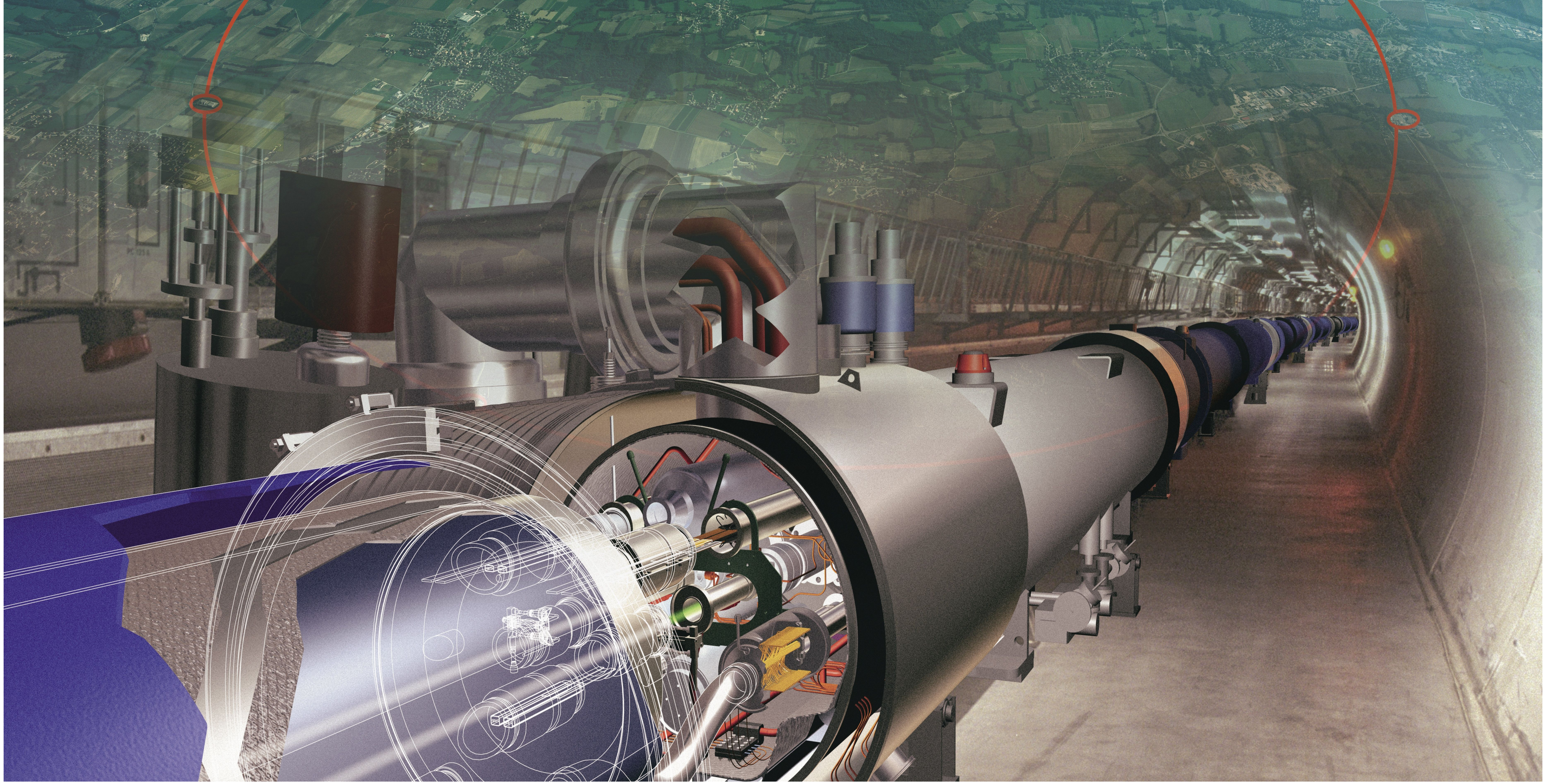
arXive:1606.03769

QCD@WORK 2016



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

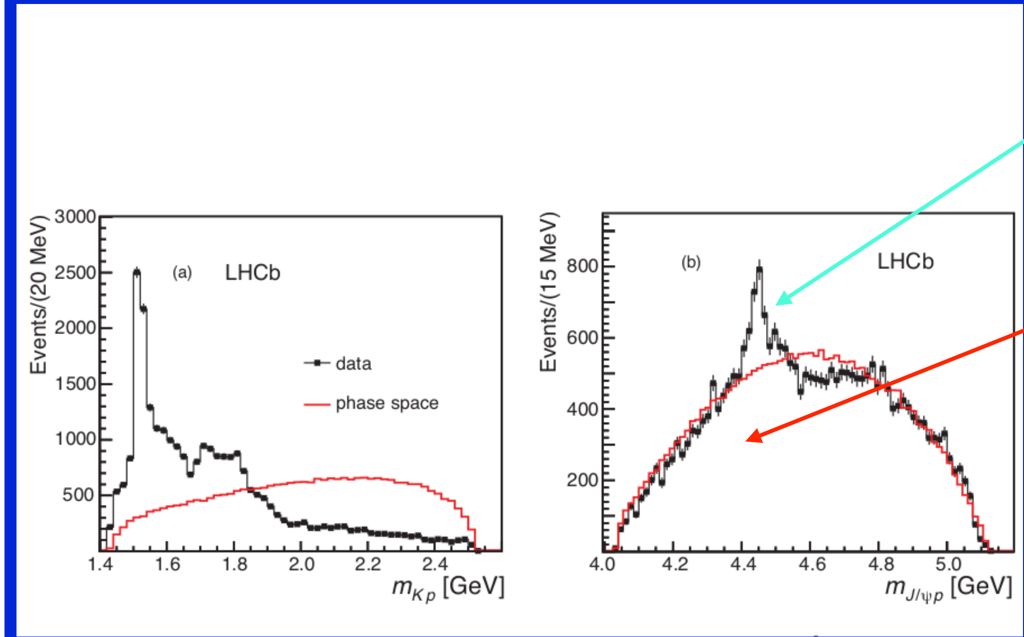
↓

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 experimensts 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



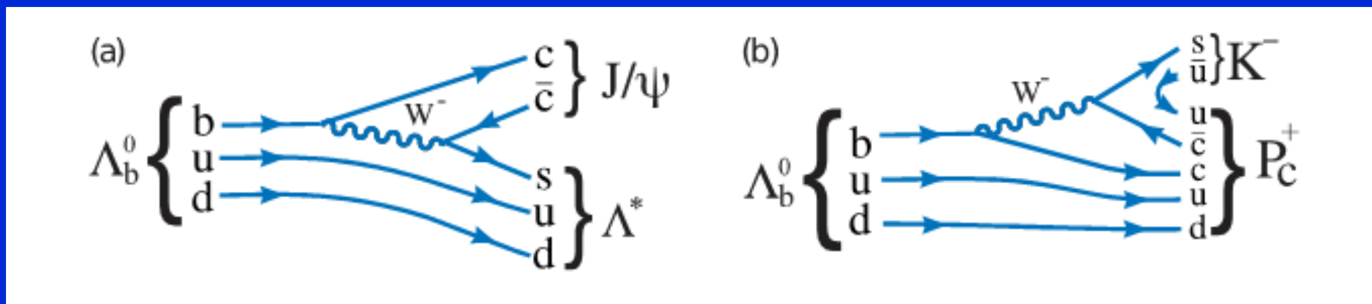
M _P_C^+(4450) = (4449.8 ± 8 ± 29)MeV
Γ = (39 ± 5 ± 19) MeV

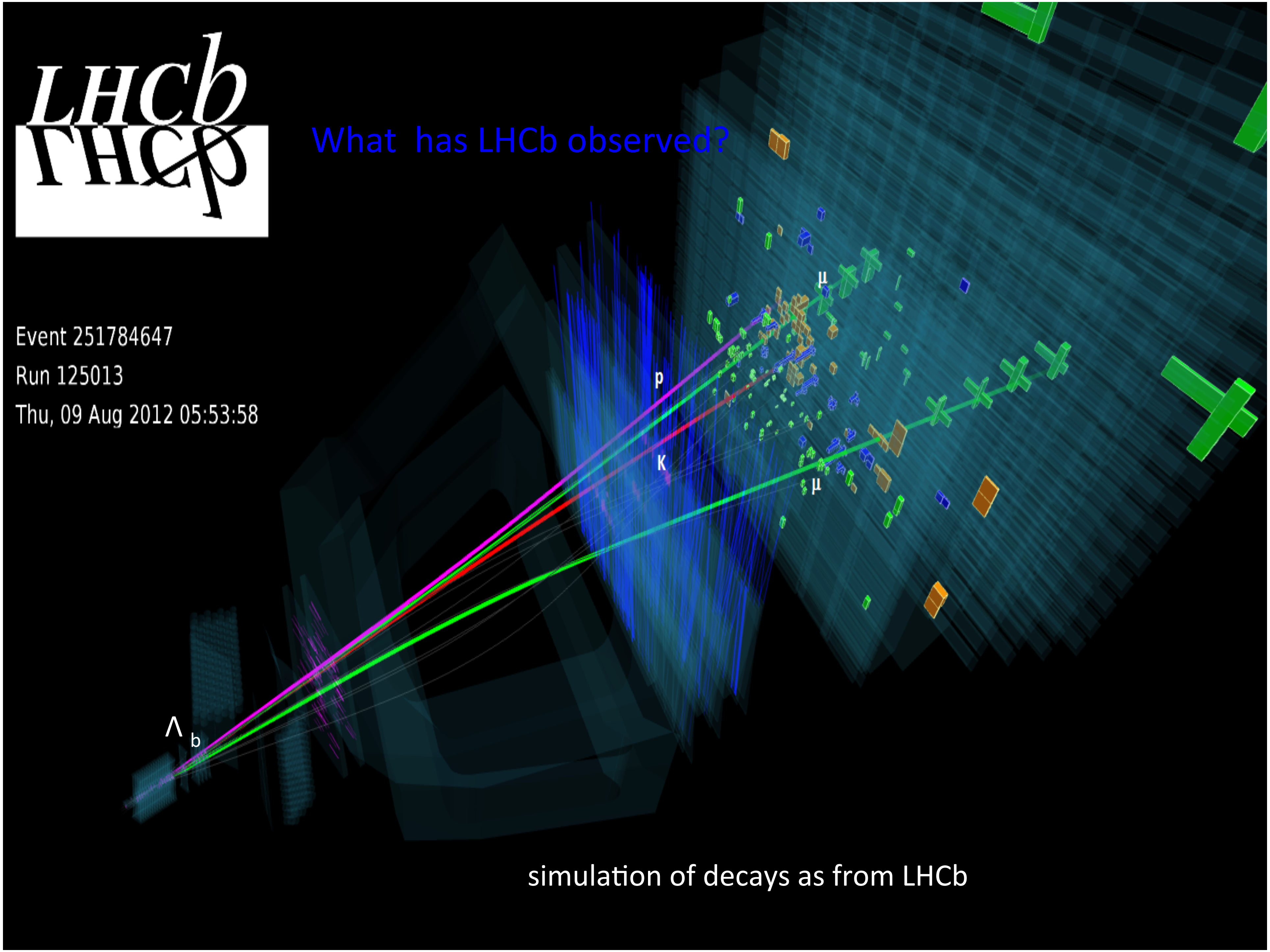
M_P_C^+(4380) = (4380 ± 1.7 ± 2.5)MeV
Γ =(205±18±86)MeV

statistic signifiance 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
Run 125013
Thu, 09 Aug 2012 05:53:58
μ
p
K
μ
Λ b
simulation of decays as from LHCb

santopinto, giachino, hep-ph 1604.03769

- We have used 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 prediction are finally given using a Guersey-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 parameters 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 $\bar{c}$ transforms as $\bar{3}$ so the color representation of the 4 quarks subsystem has to be the [211] state, with permutation symmetry F1

2) in the limit of SU(4) flavour, the total wave function of the 4 quark subsystem should be completely antisymmetric

1) + 2) the two conditions determine the kind of symmetry for the orbital-spin-flavour 4 quark 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 gives the completely antisymmetric state [1111], with symmetry A_2

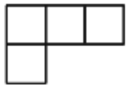
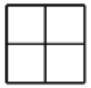
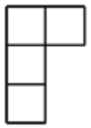
Construction of the states

We know the 4 quark symmetry

↓

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

Four quark 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	–

Pentaquark resonance P_c+(4380)

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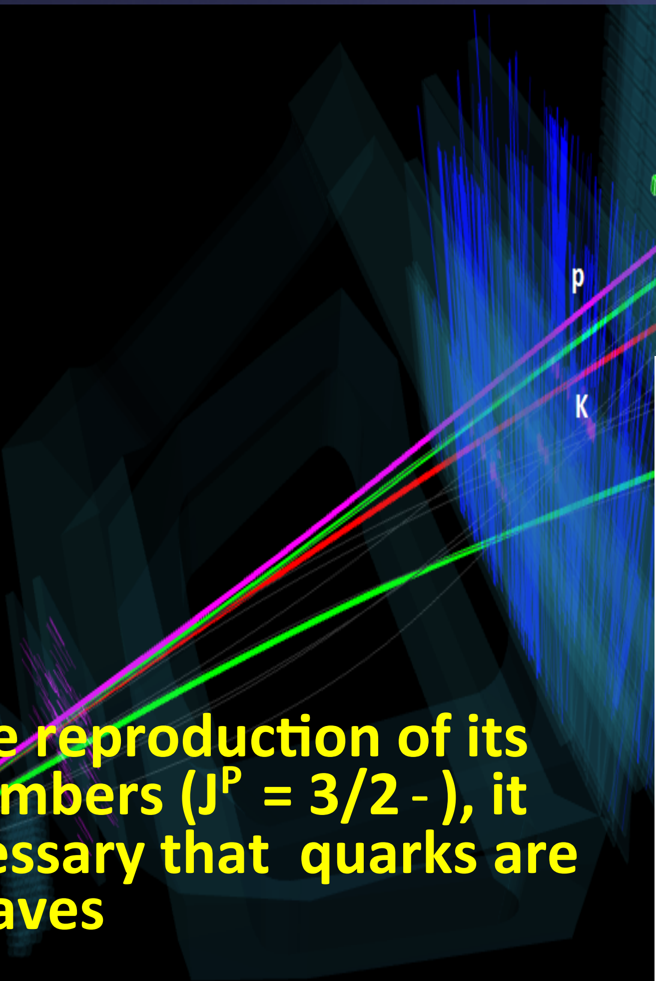

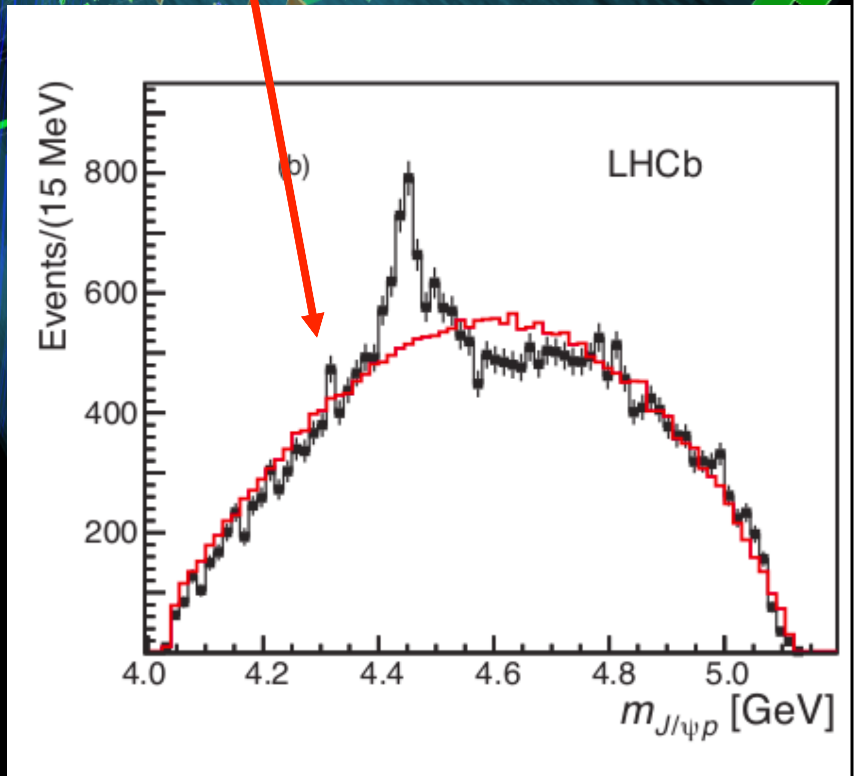

- For the reproduction of its qu. numbers (J^P = 3/2 -), it is necessary that quarks are in S waves

The pentaquark $P_c^+(4450)$ resonance

Event 251784647

Run 125013

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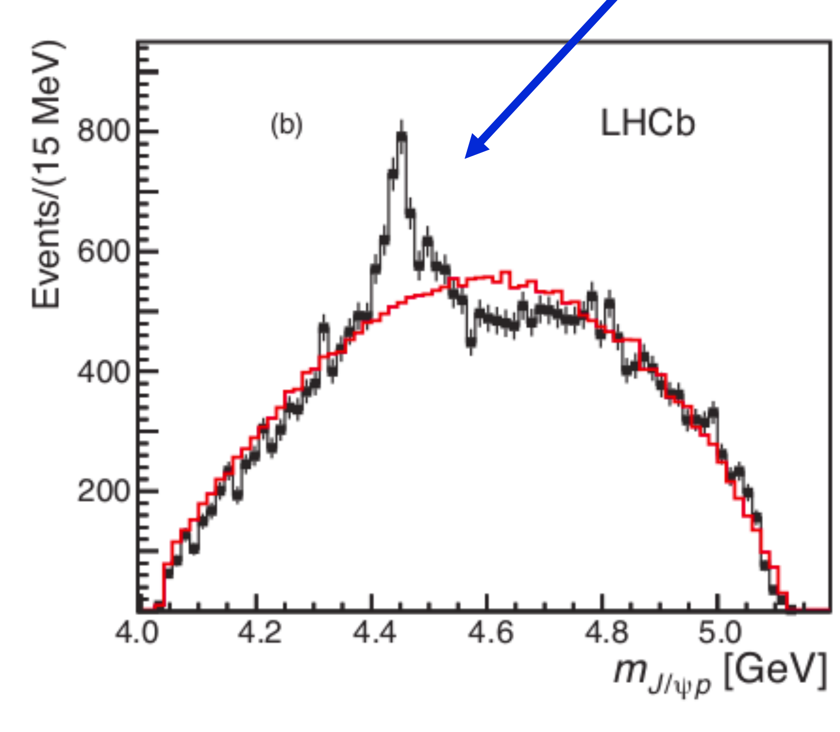


- To reproduce its quantum numbers ($J^P = 5/2+$),and its opposite parity in respect to the lightest pentaquark, one has to think the 4 quark subsystem in P-wave

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 hypothesys that the higher state, $P_c^+(4450)$, is a molecular state is in agreement with Karliner e Rosner's work

IN CONCLUSION:

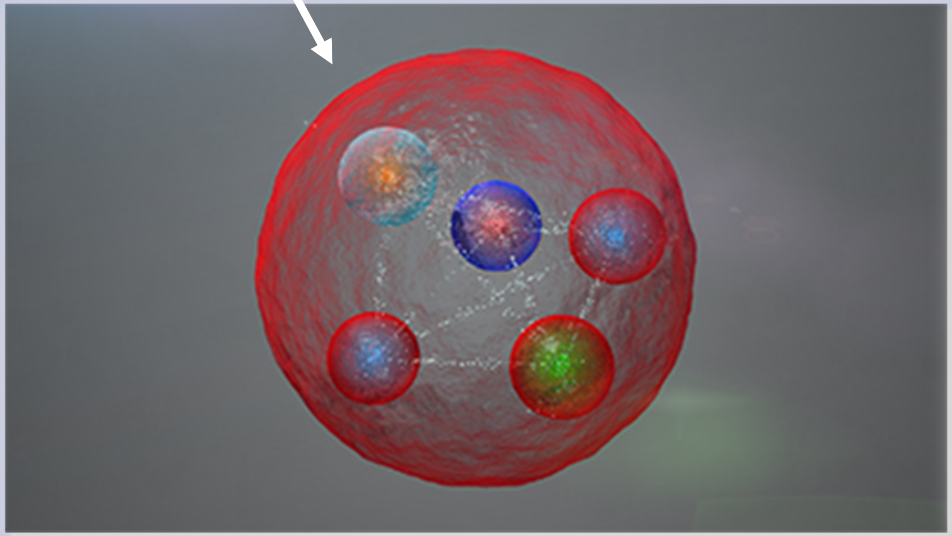
$P_c^+(4380)$

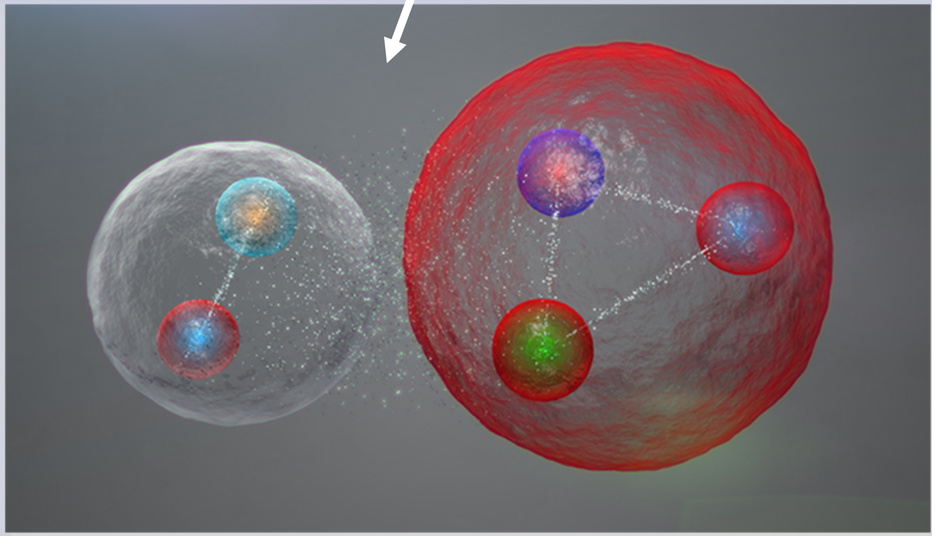
Compact Pentaquark

$P_c^+(4450)$

Molecular state $D^* \Sigma_C$

(Karliner e 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, whyle the haviest 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 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 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 taking into account of c quarks.

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

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;

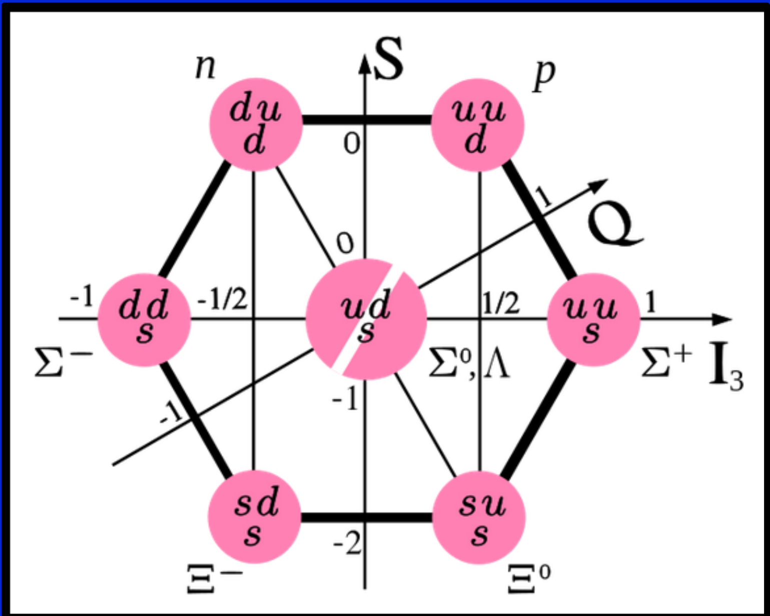
S is the total spin of the baryon.
C_2 $(SU_{Fl}(3))$ are the eigenvalues of the Casimir operator of $SU_{Fl}(3)$;

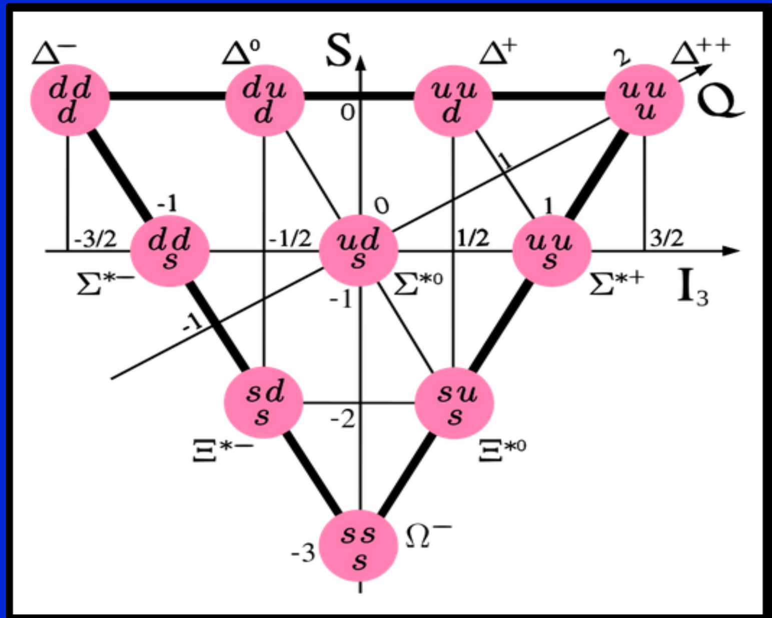
n_c counts the number of c or anti c quarks

OUR EXSTENSION 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 $SU_{SF}(8)$ rapresentation, compatibile with the symmetry principles, into the spin and the flavour parts;

2) Since the lightest resonance has spin S=J=3/2, only the SU(4) representations with spin 3/2 have been selected;

3) Only those representations have been further decomposed into $SU(3) X U_C(1)$, 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 hypercharge Y is defined as:

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

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

⬇

Y=1

⬇

it is necessary to decompose further each SU(3) multiplet into $SU(2)XU_Y(1)$, and next step, select the multiplets with hypercharge 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 octect 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

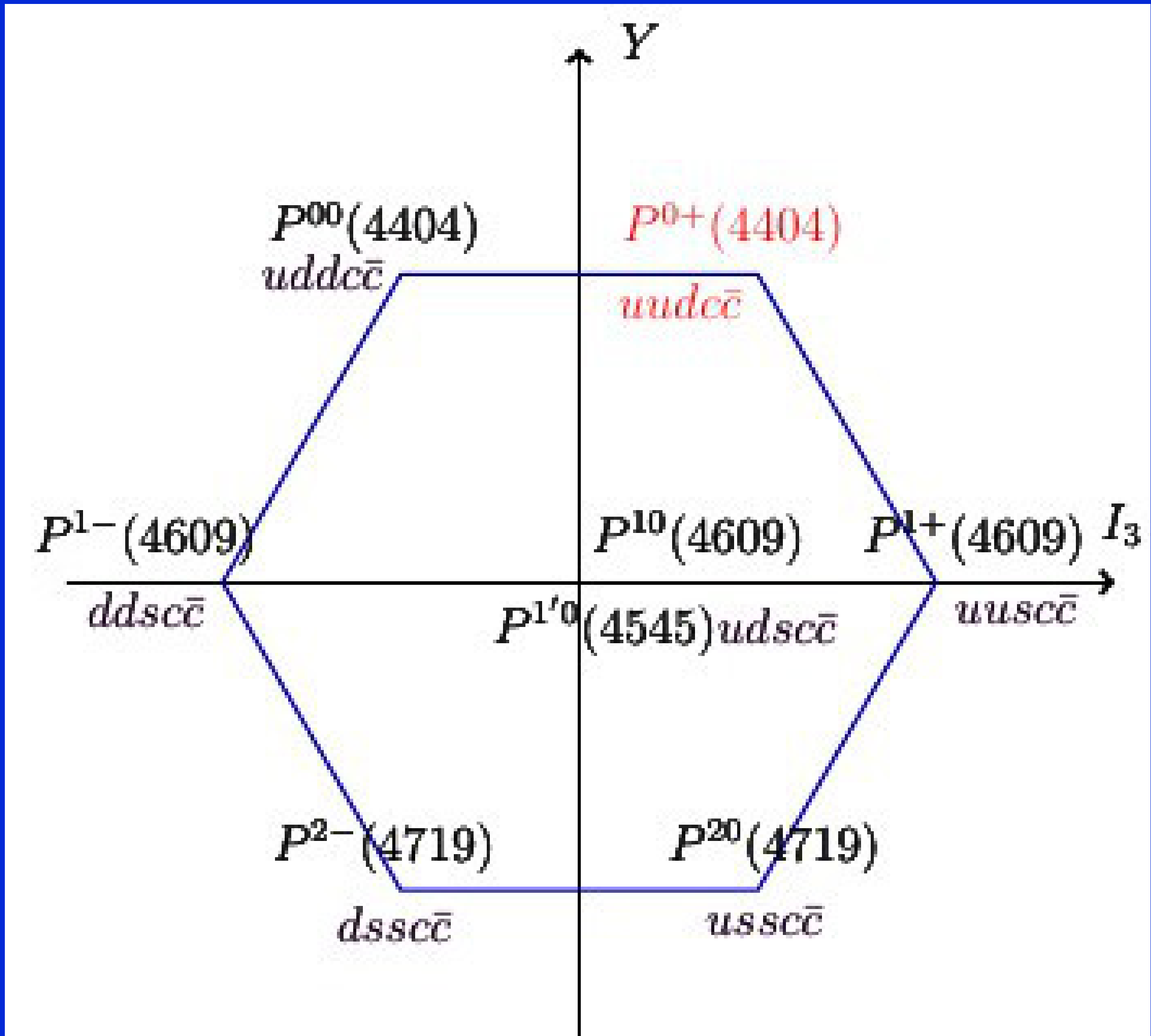
The lightest resonance, the $P_c^+(4380)$, according to LHC_b has a mass M = 4380 ± 8 ± 29 MeV and a width W = 205 ± 18 ± 86 MeV

The predicted theoretical value of the mass is 4404 MeV in agreement with the exper. M = 4380 ± 8 ± 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
$[21]_8 \equiv$ 8	2	$\frac{1}{2}$	1	4404	$P^{00}(4404), P^{0+}(4404)$
	S	0	0	4545	$P^{1'0}(4545)$
	3	1	0	4609	$P^{1+}(4609), P^{10}(4609)$ $P^{1-}(4609)$
	2	$\frac{1}{2}$	-1	4719	$P^{20}(4719), P^{2-}(4719)$

PENTAQUARK OCTECT STATES

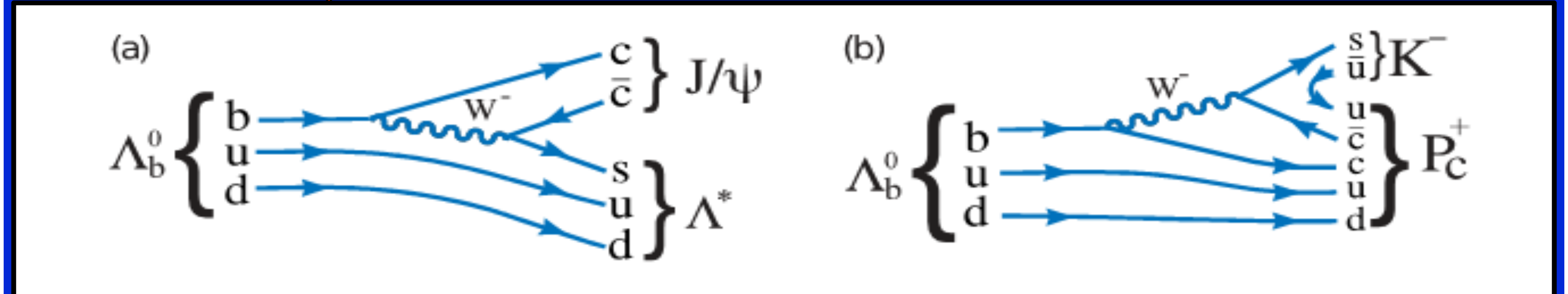


HOW TO OBSERVE OTHER PENTAQUARK STATES?

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 studing the Λ_b decay:

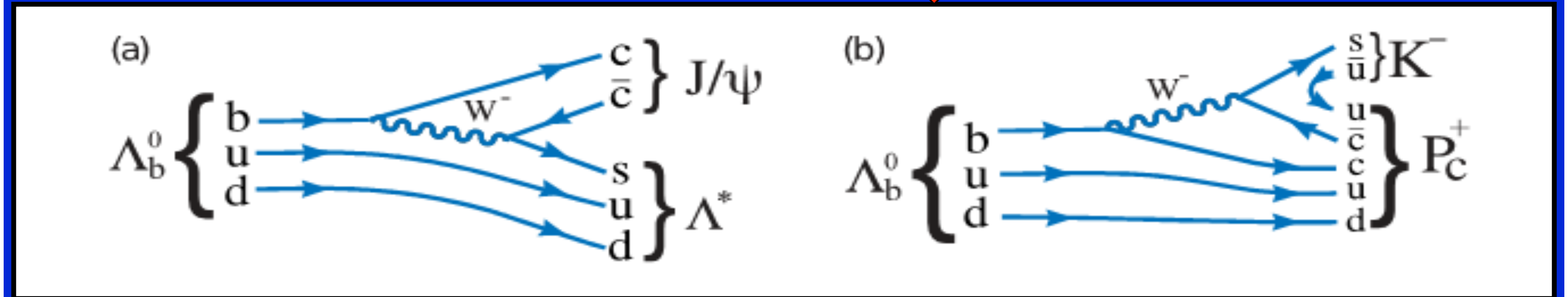
$$\Lambda_b^0 \longrightarrow P^{0+} + K^-, P^{0+} \longrightarrow J/\Psi + p$$



HOW CAN WE OBSERVE PENTAQUARK STATES ?

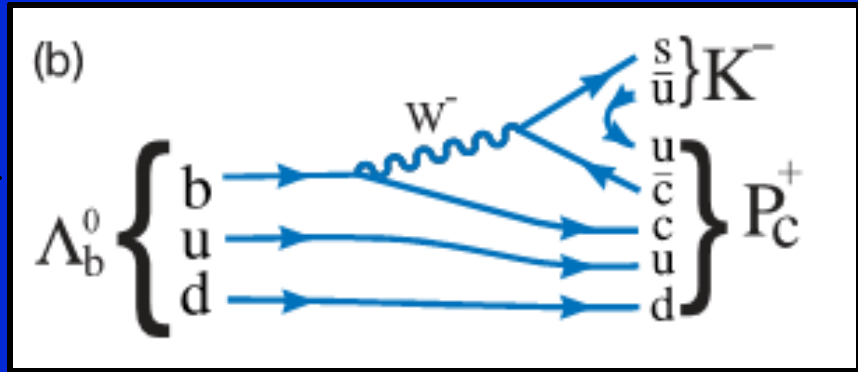
but,as seen, there is also the alternative decay channel that gives origin to the two pentaquark resonances:

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



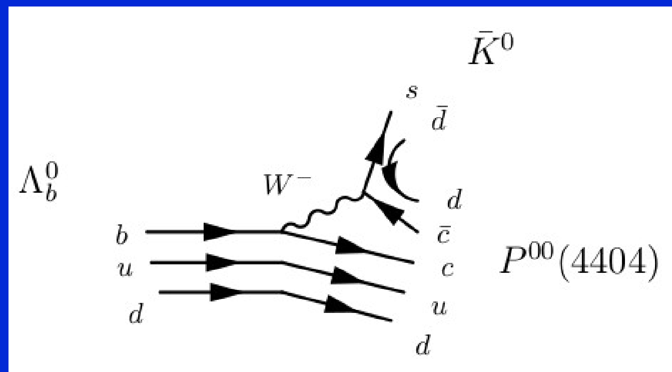
HOW TO OBSERVE OTHER PENTAQUARK STATES?

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



In order to observe the isospin partner P^{00}(4404) of the charged P^{0+} we consider a pair creation of the type d anti d (instead of u anti u)

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



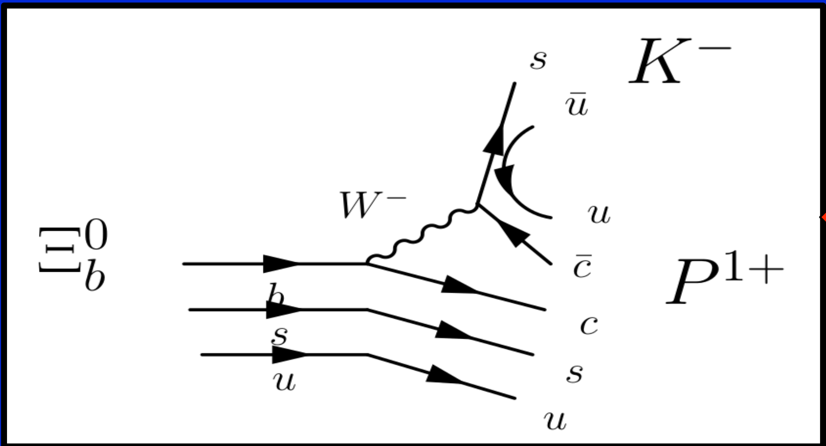
HOW TO OBSERVE OTHER PENTAQUARK STATES?

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

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

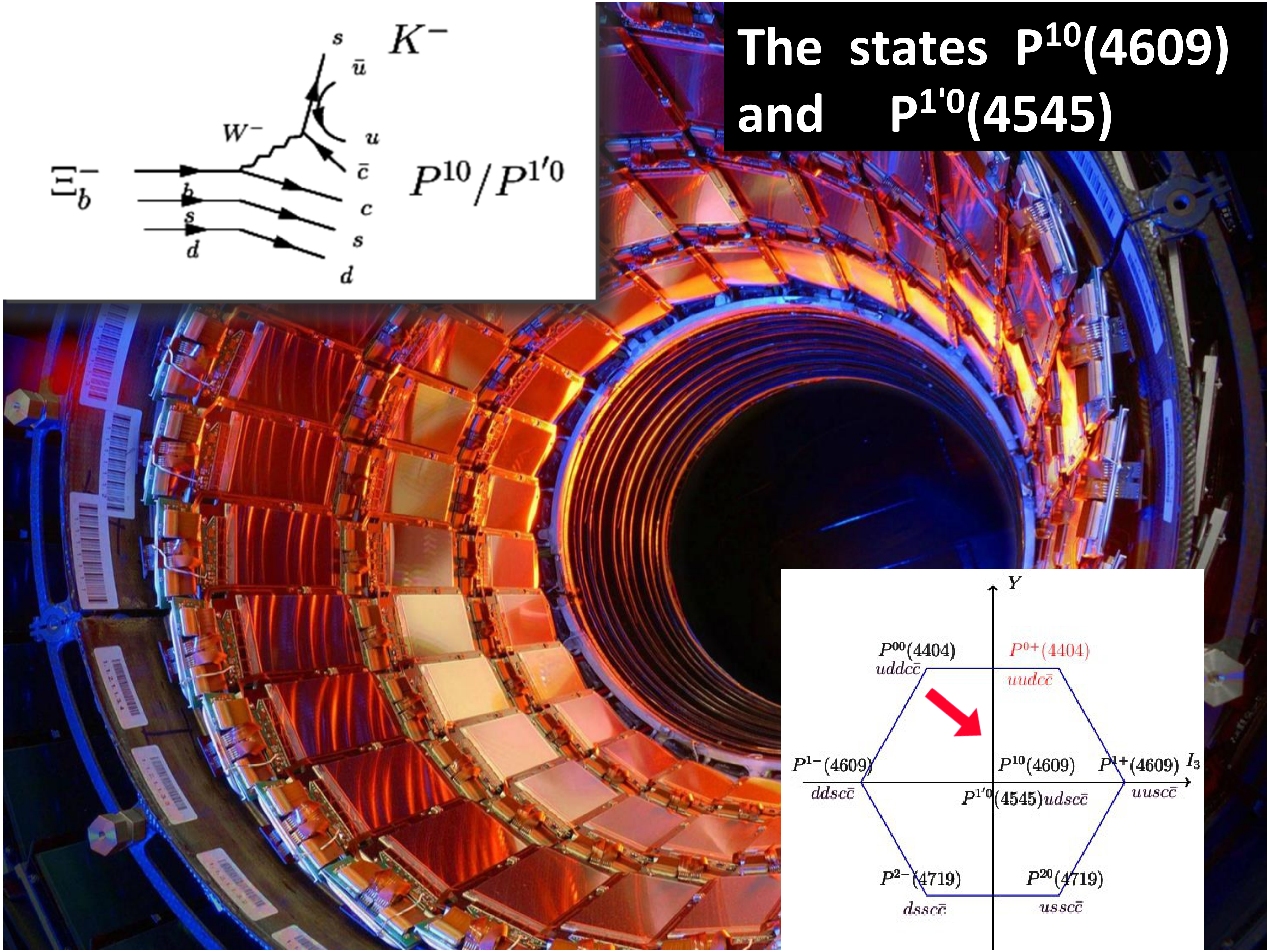
$$\Omega_b^- \longrightarrow J/\psi + \Omega^-$$

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

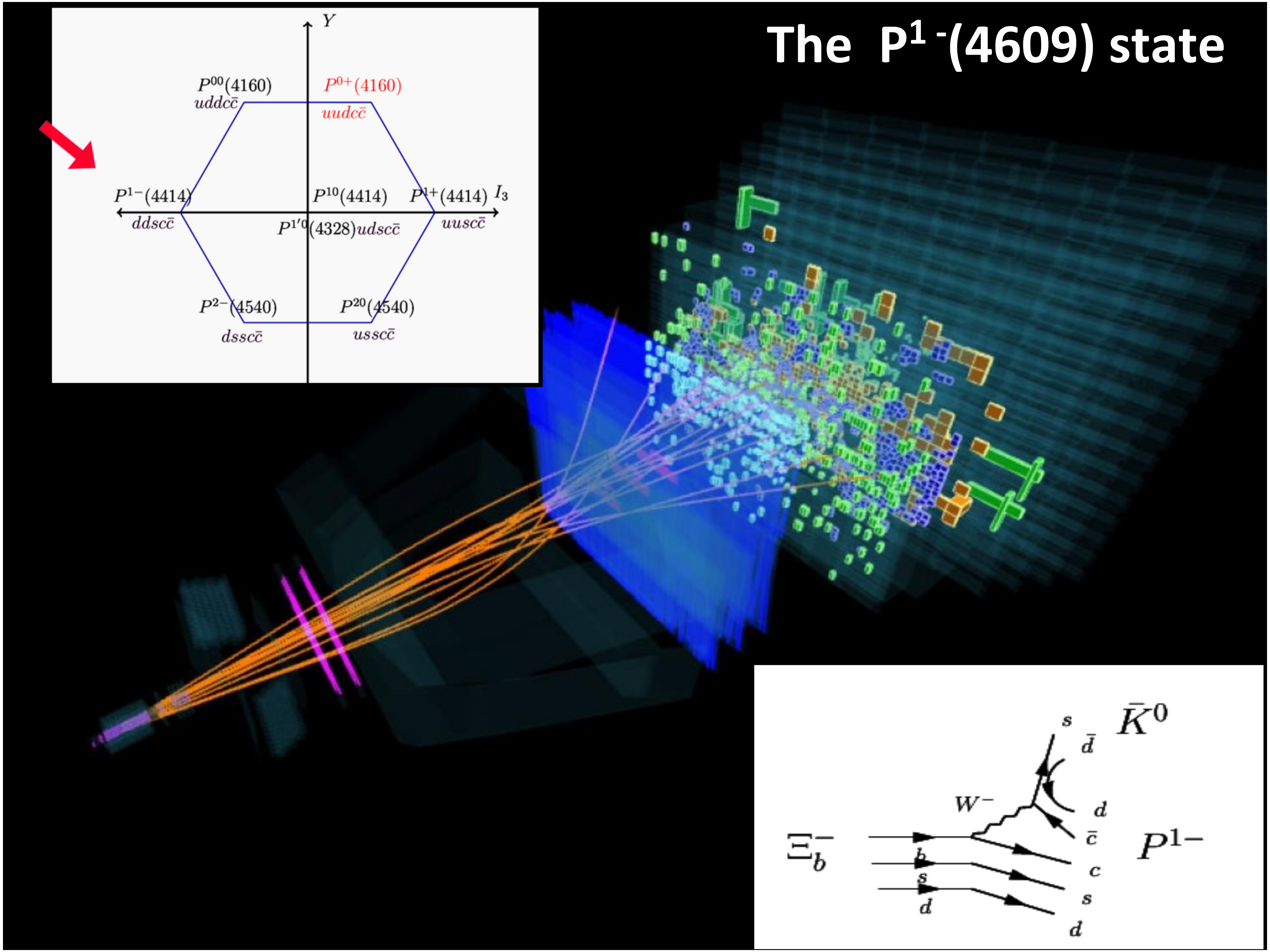


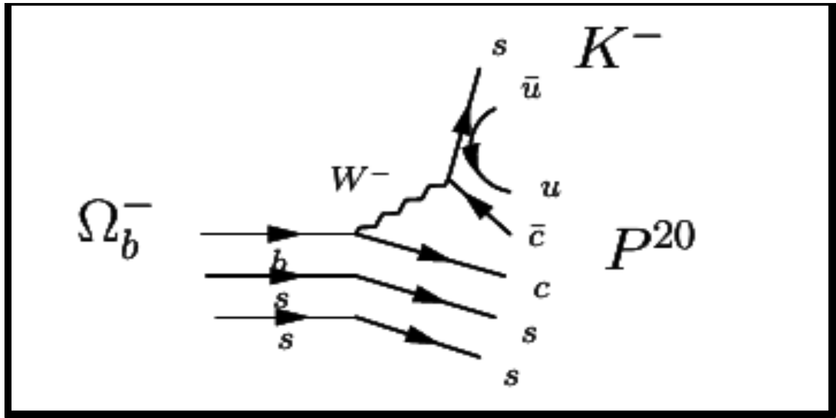
$$\Xi_b^0 \longrightarrow P^{1+} + K^-,\ P^{1+} \longrightarrow J/\Psi + \Sigma^+$$

The states $P^{10}(4609)$ and $P^{1'0}(4545)$

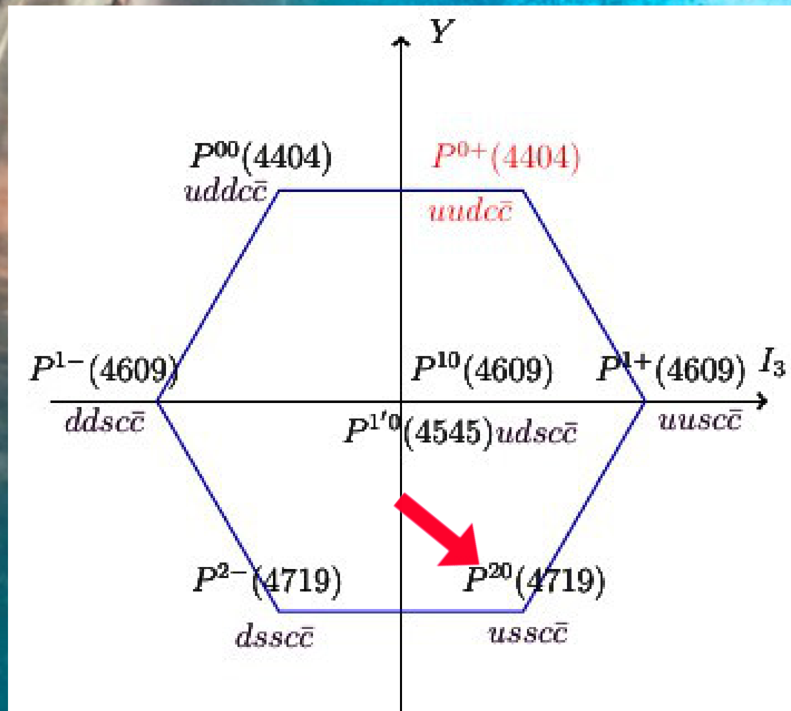


The P^{1-}(4609) state

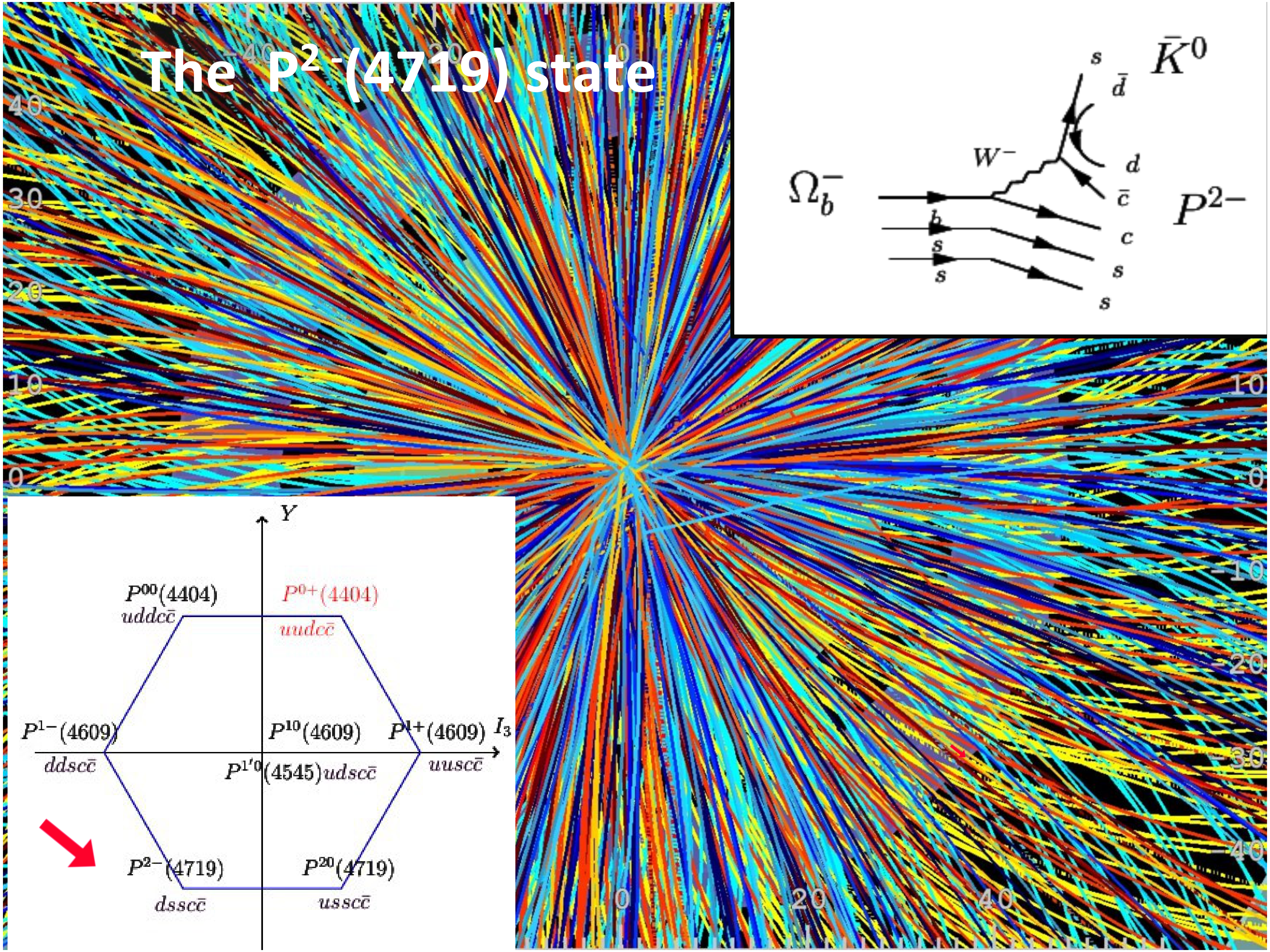




The P^{20}(4719) state

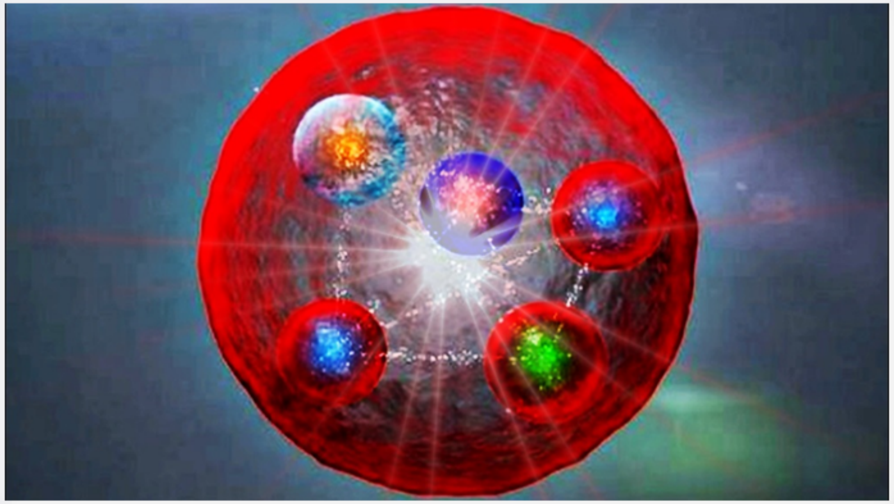


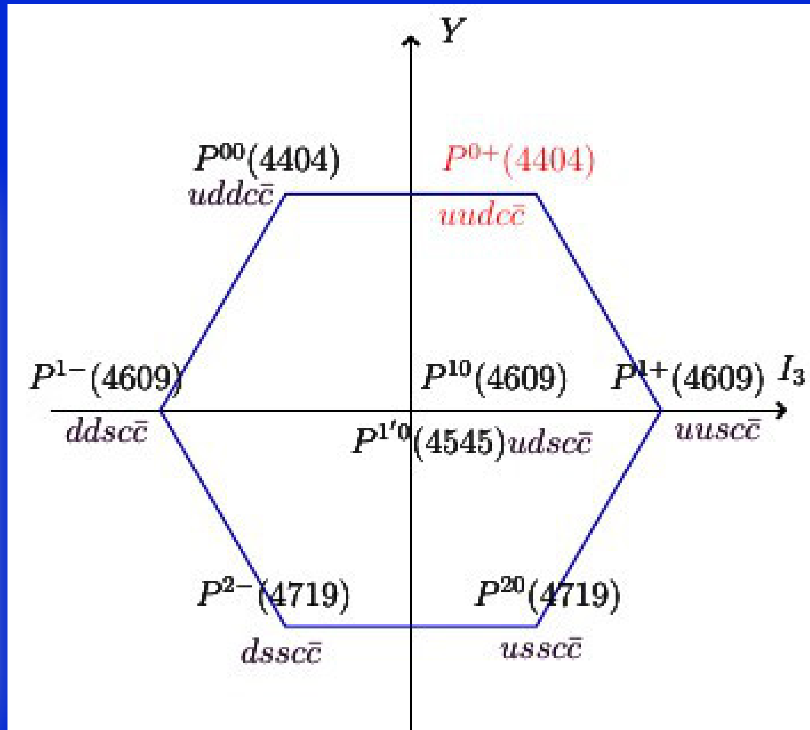
The $P^{2-}(4719)$ state



CONCLUSION

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



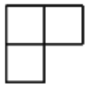


2) Using group theory tecniques and with an extension of the GR mass formula, it has been demonstrated that it belongs to an SU(3) flavour octect

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


LHCb
ATLAS
CERN Meyrin
CERN Prévessin
SPS 7 km
SUISSE
FRANCE
CMS
ALICE
LHC 27 km
Thanks!

Sistema a tre quarks

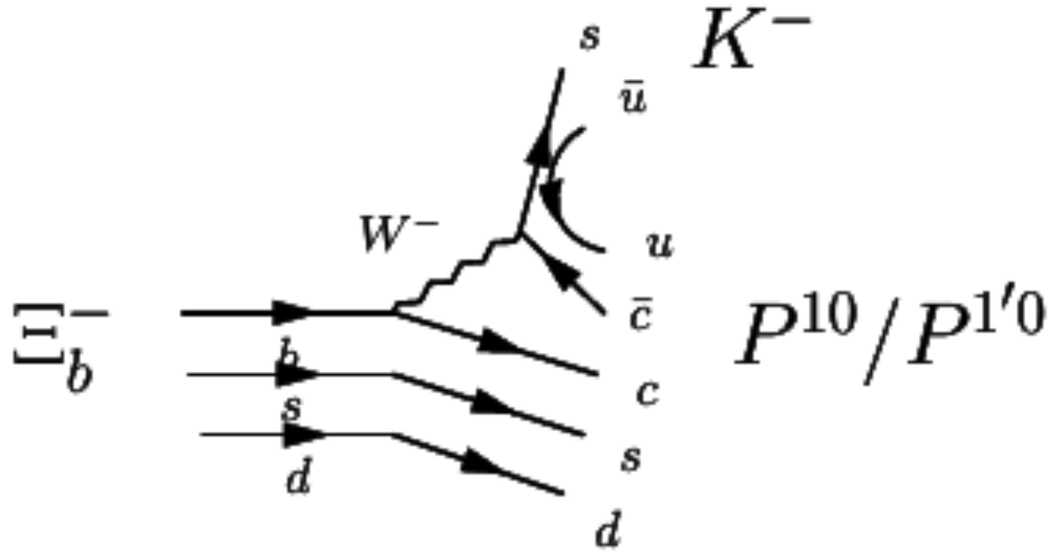
					Dimension		
D_3	$\sim$	S_3	Young tableau	Multiplicity	$SU_{sf}(8)$	$SU_{fl}(4)$	$SU_s(2)$
A_1	$\sim$	[3]		1	120	20	4
E	$\sim$	[21]		2	168	20	2
A_2	$\sim$	[111]		1	56	4	–

orbital symmetry	spin flavour symmetry	$q^4\bar{q}$ configurations
A_1	F_2	$[421^5]_{4752}$ $[21]_{168}$ $[3]_{120}$
F_2	A_1	$[51^6]_{2520}$ $[3]_{120}$
	F_2	$[421^5]_{4752}$ $[21]_{168}$ $[3]_{120}$
	E	$[331^5]_{2520}$ $[21]_{168}$
	F_1	$[3221^4]_{2800}$ $[21]_{168}$ $[111]_{56}$
E	F_2	$[421^5]_{4752}$ $[21]_{168}$ $[3]_{120}$
	F_1	$[3221^4]_{2800}$ $[21]_{168}$ $[111]_{56}$

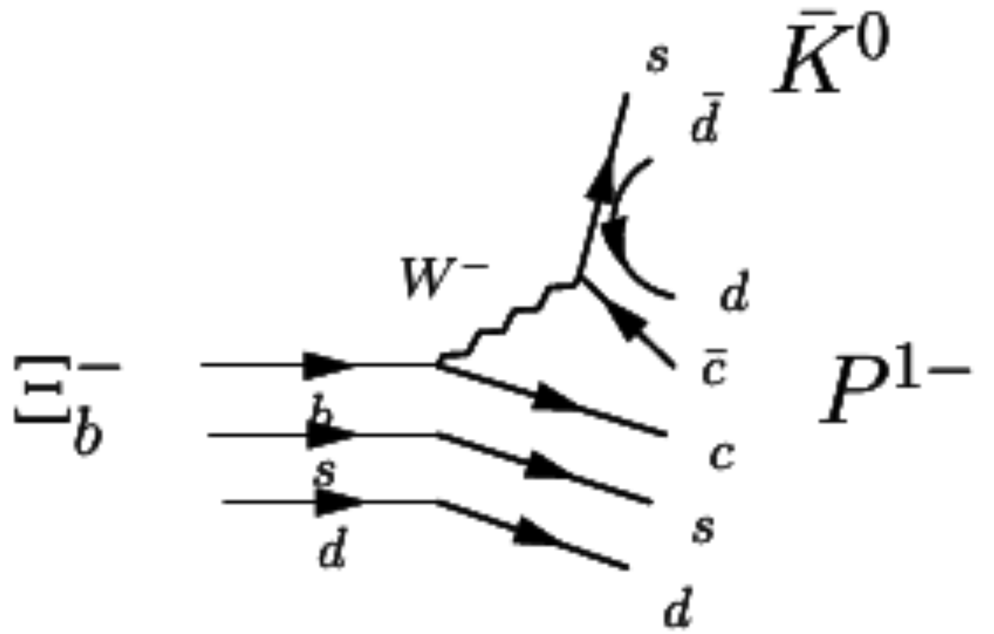
	A_1	F_2	E	F_1	A_2
A_1	A_1	F_2	E	F_1	A_2
F_2	F_2	$A_1 + F_2 + E + F_1$	$F_1 + F_2$	$F_2 + E + F_1 + A_2$	F_1
E	E	$F_1 + F_2$	$A_1 + E + A_2$	$F_1 + F_2$	E
F_1	F_1	$F_2 + E + F_1 + A_2$	$F_1 + F_2$	$A_1 + F_2 + E + F_1$	F_2
A_2	A_2	F_1	E	F_2	A_1

Symmetry	$SU_{sf}(8)$	$\supset$	$SU_{fl}(4)$	$\otimes$	$SU_s(2)$	multiplicity
F_2	$[421^5]_{4752}$		$[421]_{140}$	$\otimes$	$[1]_2$	2
			$[421]_{140}$	$\otimes$	$[3]_4$	2
			$[421]_{140}$	$\otimes$	$[5]_6$	1
			$[511]_{120}$	$\otimes$	$[1]_2$	1
			$[511]_{120}$	$\otimes$	$[3]_4$	1
			$[331]_{60}$	$\otimes$	$[1]_2$	1
			$[331]_{60}$	$\otimes$	$[3]_4$	1
			$[322]_{36}$	$\otimes$	$[1]_2$	2
			$[322]_{36}$	$\otimes$	$[3]_4$	1
			$[3]_{20}$	$\otimes$	$[1]_2$	2
			$[3]_{20}$	$\otimes$	$[3]_4$	2
			$[3]_{20}$	$\otimes$	$[5]_6$	1
			$[21]_{20}$	$\otimes$	$[1]_2$	3
			$[21]_{20}$	$\otimes$	$[3]_4$	3
			$[21]_{20}$	$\otimes$	$[5]_6$	1
			$[111]_4$	$\otimes$	$[1]_2$	1
			$[111]_4$	$\otimes$	$[3]_4$	1

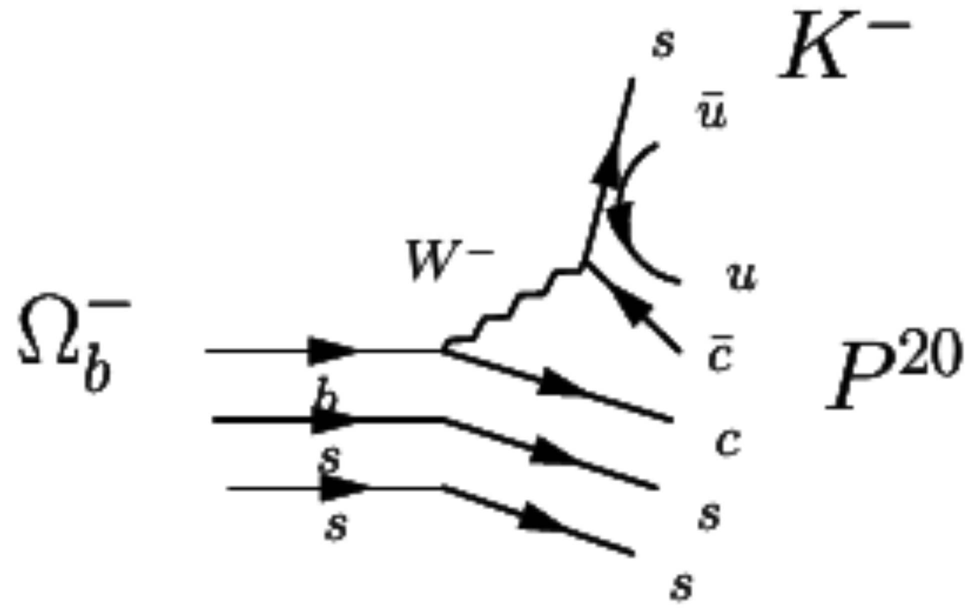
$$\Xi_b^- \longrightarrow P^{10}/P^{1'0} + K^-,\ P^{10}/P^{1'0} \longrightarrow J/\Psi + \Sigma^0/\Lambda$$



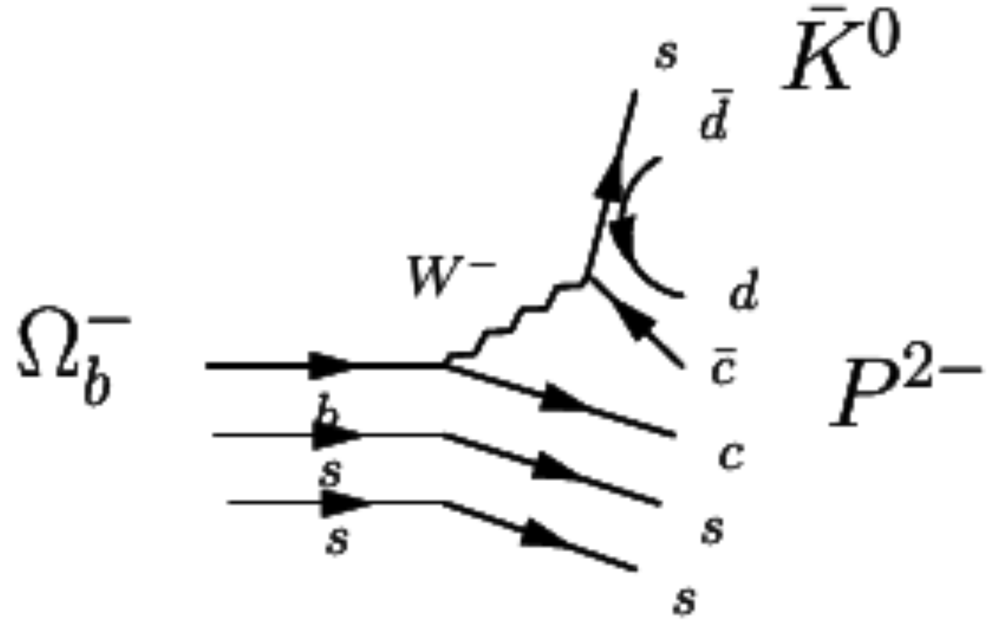
$$\Xi_b^- \longrightarrow P^{1-} + \bar{K}^0,\ P^{1-} \longrightarrow J/\Psi + \Sigma^-$$



$$\Omega_b^- \longrightarrow P^{20} + K^-,\ P^{20} \longrightarrow J/\Psi + \Xi^0$$



$$\Omega_b^- \longrightarrow P^{2-} + \bar{K}^0,\ P^{2-} \longrightarrow J/\Psi + \Xi^-$$



Dal Particle Data Group:

The flavor symmetries shown in Fig. 2 are of course badly broken, but the figure is the simplest way to see what charmed baryons should exist. For example, from Fig. 2(b), we expect to find, in the same $J^P = 1/2^+$ $20'$-plet as the nucleon, a Λ_c, a Σ_c, *two* Ξ_c's, and an Ω_c. Note that this Ω_c has $J^P = 1/2^+$ and is not in the same SU(4) multiplet as the famous $J^P = 3/2^+$ Ω^-.