

# Compact Pentaquark

Elena Santopinto and Alessandro Giachino

INFN and Genova University

arXiv:1606.03769

MENU2016,

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

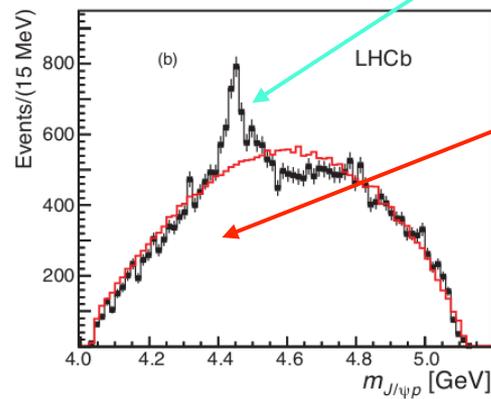
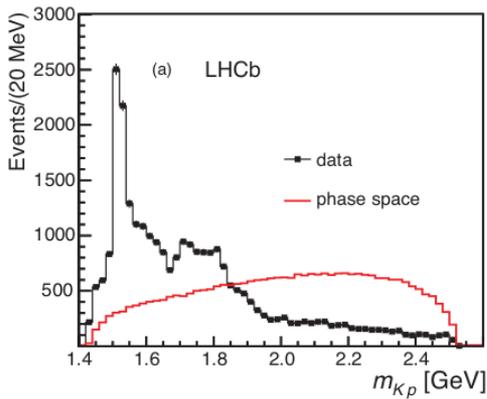


M. Gell-Mann, Phys. Lett. **8** (1964) 214. doi:10.1016/S0031-9163(64)92001-3

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  $\Lambda_b$ ,  
**a new class of exotic particles**

# LHCb



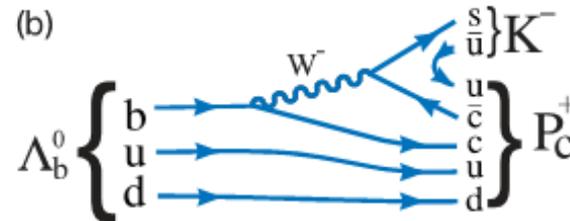
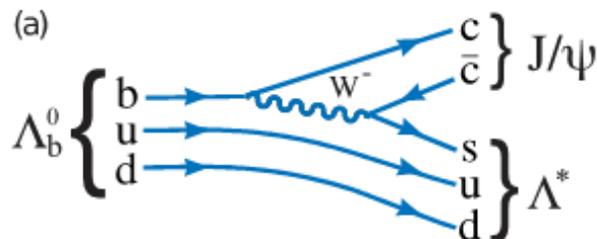
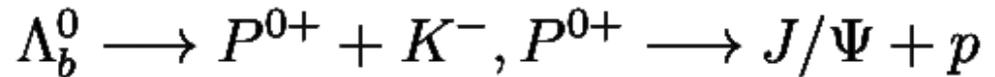
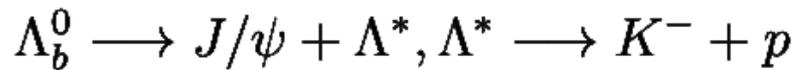
$$M_{P_c^+}(4450) = (4449.8 \pm 8 \pm 29) \text{ MeV}$$

$$\Gamma = (39 \pm 5 \pm 19) \text{ MeV}$$

$$M_{P_c^+}(4380) = (4380 \pm 1.7 \pm 2.5) \text{ MeV}$$

$$\Gamma = (205 \pm 18 \pm 86) \text{ MeV}$$

statistic significance greater  
then 9 sigma !



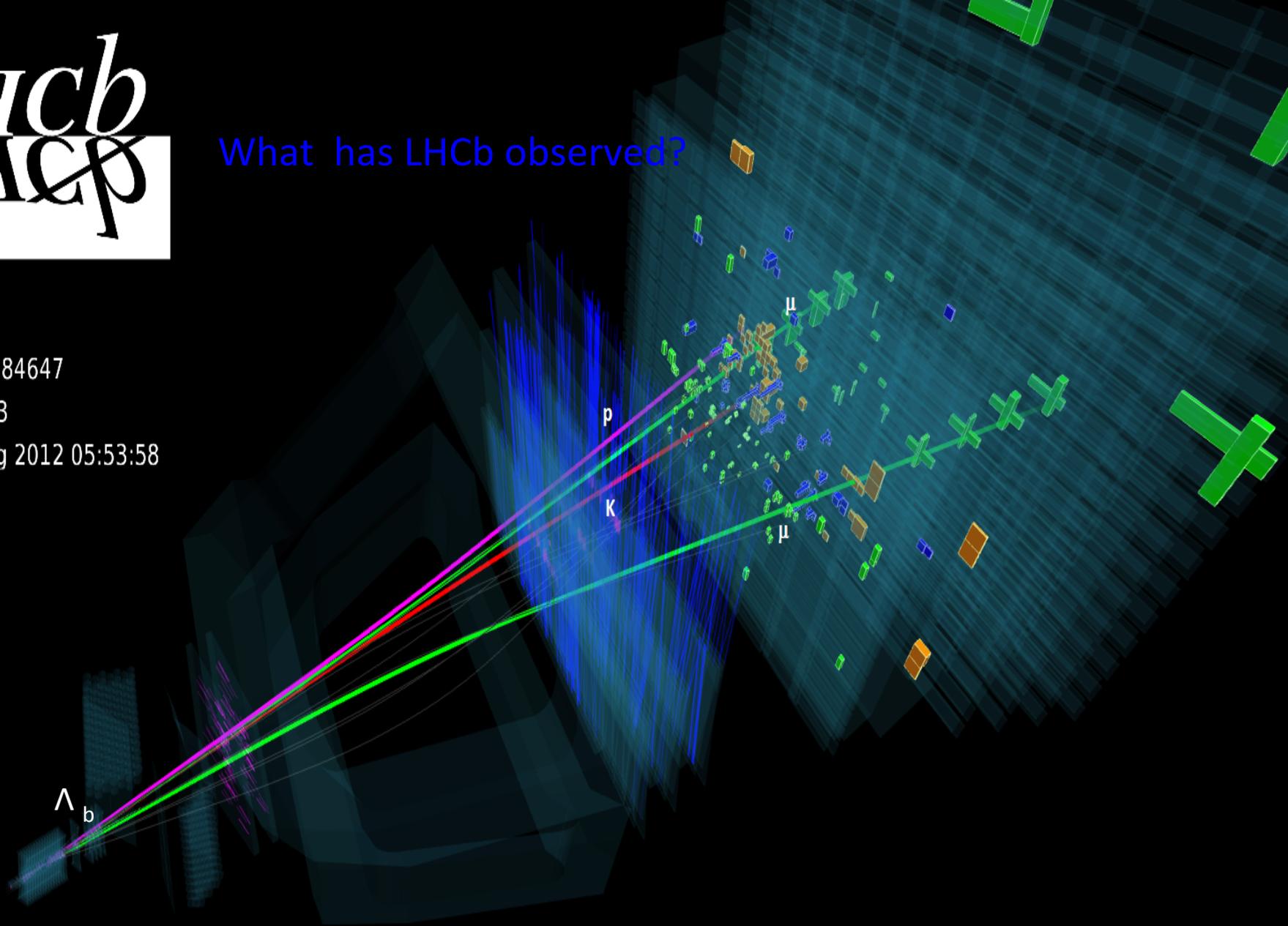


What has LHCb observed?

Event 251784647

Run 125013

Thu, 09 Aug 2012 05:53:58



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  $c^-$  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) 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.,  $\psi$ , 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  $A_2$

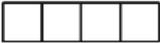
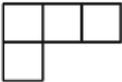
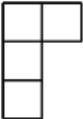
## Construction of the states

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	—

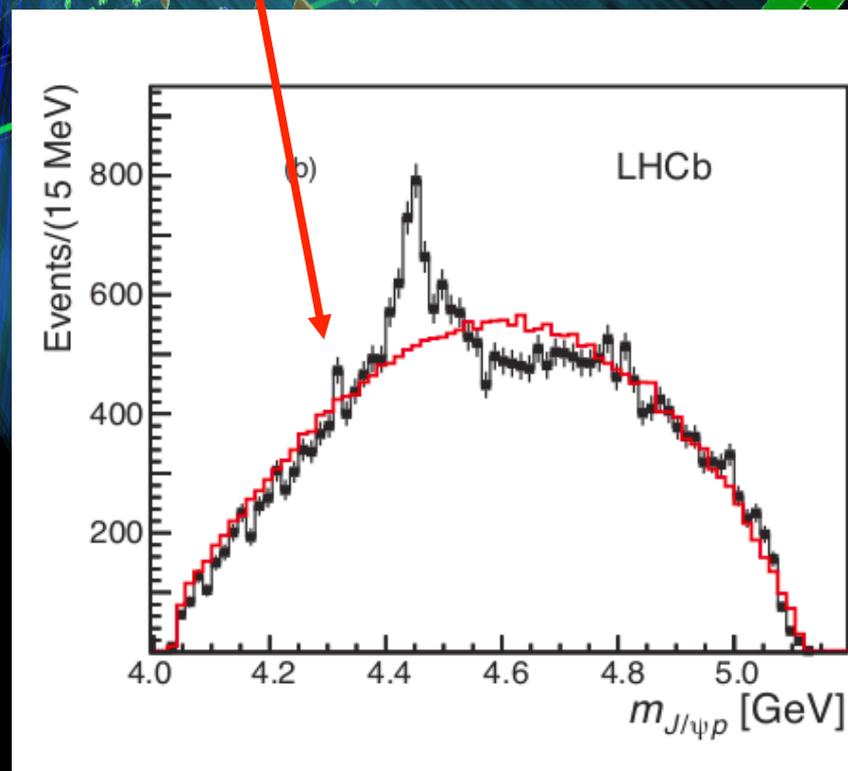
## Pentaquark resonance $P_c^+(4380)$

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

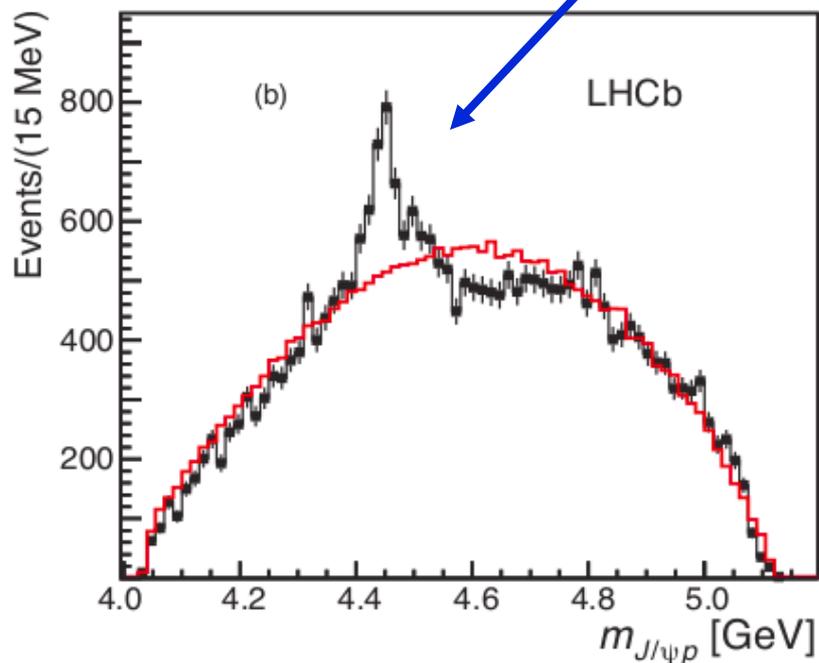


## The pentaquark $P_c^+(4450)$ resonance

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Run 125013

Thu, 09 Aug 2012 05:53:58



- 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**

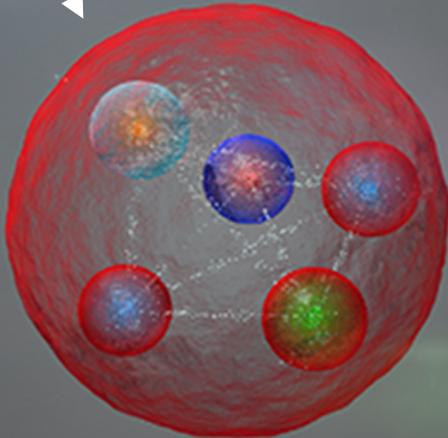
## Karliner & Rosner interpretation

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

IN CONCLUSION:

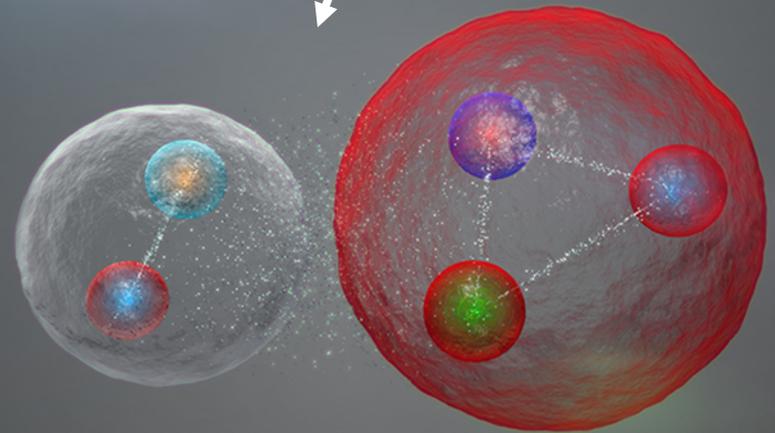
$P_c^+(4380)$

Compact Pentaquark



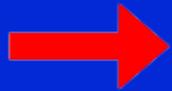
$P_c^+(4450)$

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 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.

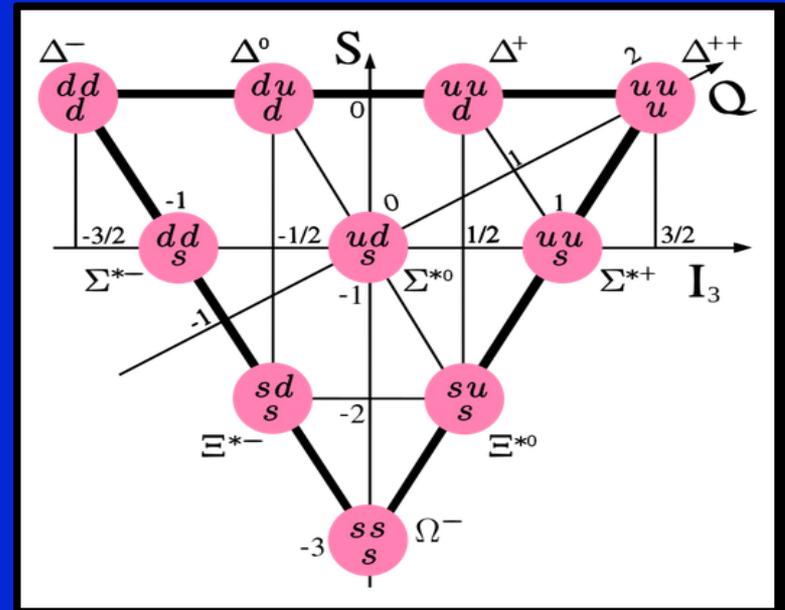
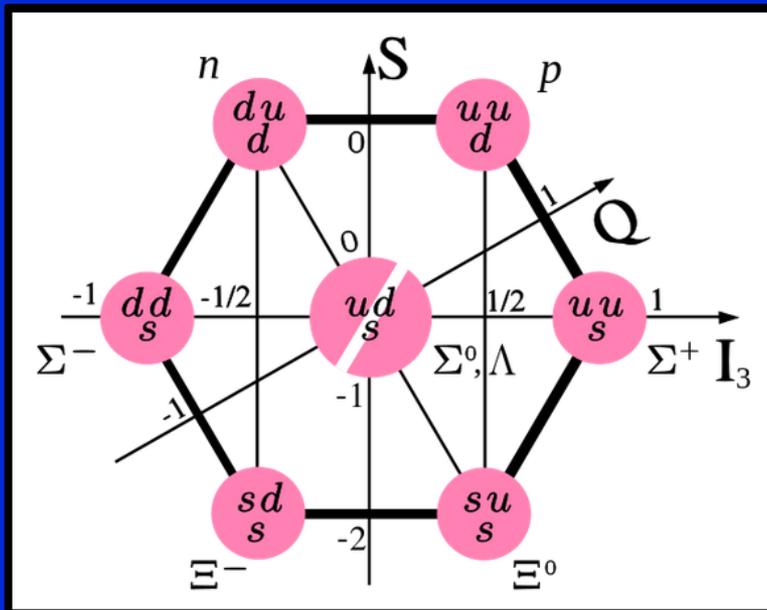
$C_2(SU_{Fl}(3))$  are the eigenvalues of the Casimir operator of  $SU_{Fl}(3)$ ;

$n_c$  counts the number of c or anti c quarks

# OUR 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 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  $SU(3)XU_c(1)$ , 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 lightest pentaquark state is  $T=B=C=S=0$ , and  $B=1$



$$Y=1$$

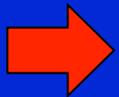


it is necessary to decompose further each  $SU(3)$  multiplet into  $SU(2) \times U_Y(1)$ , and next step, select the multiplets with hypercharge  $Y=1$ ;

# 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 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] <sub>35</sub>	[5] <sub>6</sub>	5133
	[3] <sub>4</sub>	4973
[42] <sub>27</sub>	[3] <sub>4</sub>	4763
	[1] <sub>2</sub>	4667
[3] <sub>10</sub>	[3] <sub>4</sub>	4658
[33] <sub>10</sub>	[1] <sub>2</sub>	4562
[21] <sub>8</sub>	[1] <sub>2</sub>	4404



The lightest resonance, the  $P_c^+(4380)$ ,  
 according to LHC<sub>b</sub>  
 has a mass  $M = 4380 \pm 8 \pm 29$  MeV  
 and a width  $W = 205 \pm 18 \pm 86$  MeV

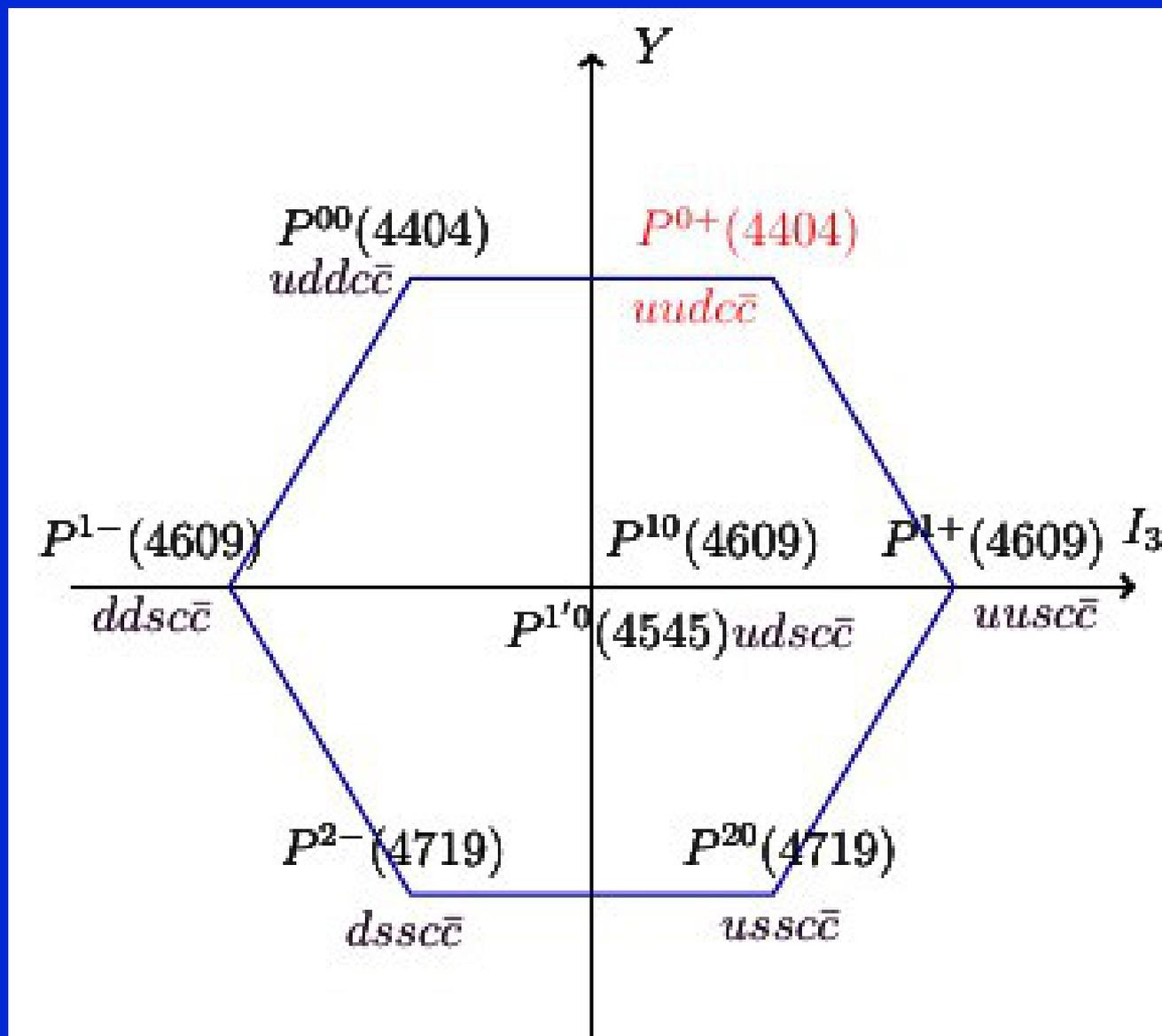
The predicted theoretical value of the mass is 4404 MeV in  
 agreement with the exper.  $M = 4380 \pm 8 \pm 29$  MeV

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

 $[21]_8 \equiv$ 		$\frac{1}{2}$	1	4404	$P^{00}(4404), P^{0+}(4404)$
	8				
	$\square_2$	0	0	4545	$P^{1'0}(4545)$
	S				
		1	0	4609	$P^{1+}(4609), P^{10}(4609)$ $P^{1-}(4609)$
	3				
		$\frac{1}{2}$	-1	4719	$P^{20}(4719), P^{2-}(4719)$
	2				

# PENTAQUARK OCTET STATES

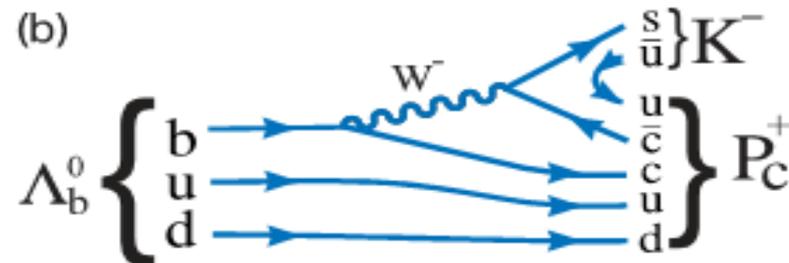
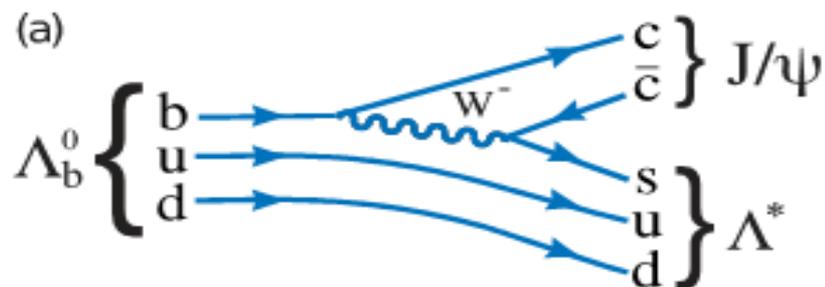


# HOW TO OBSERVE OTHER PENTAQUARK STATES?

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  $\Lambda_b$  decay:

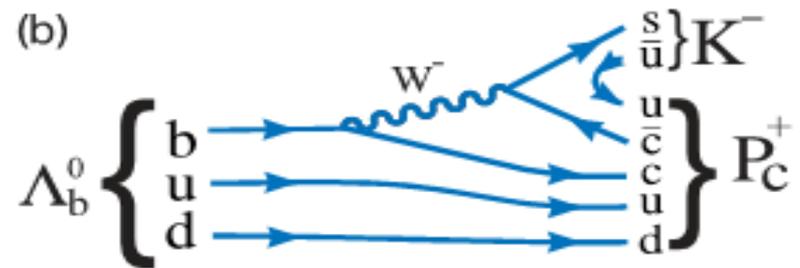
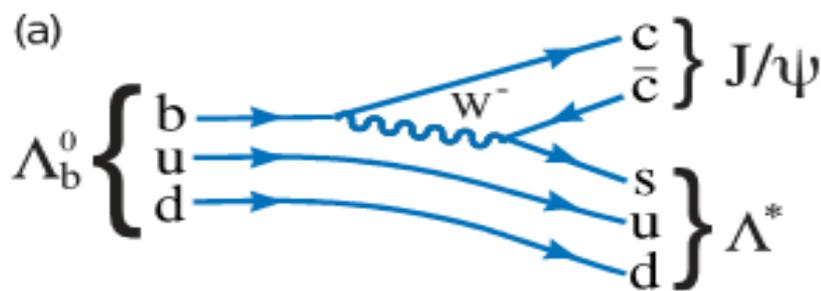
$$\Lambda_b^0 \longrightarrow P^{0+} + K^-, P^{0+} \longrightarrow J/\Psi + p$$



# HOW CAN WE OBSERVE PENTAQUARK STATES ?

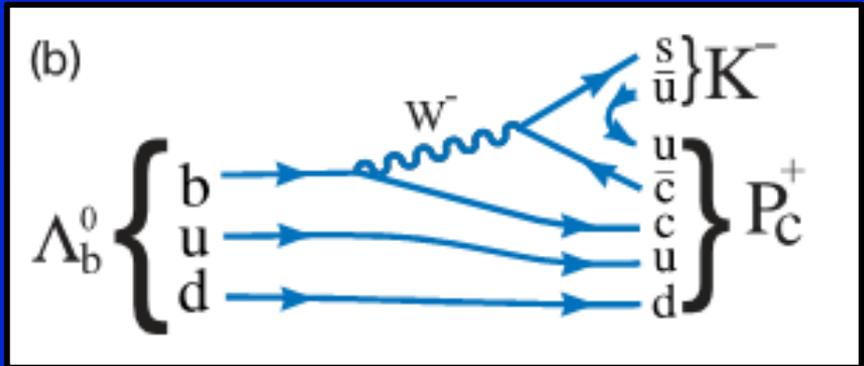
but, as seen, there is also the alternative decay channel that gives origin to the two pentaquark resonances:

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



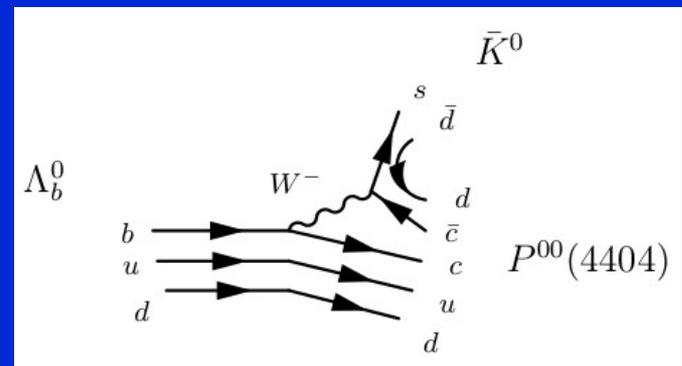
# HOW TO OBSERVE OTHER PENTAQUARK STATES?

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



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)

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



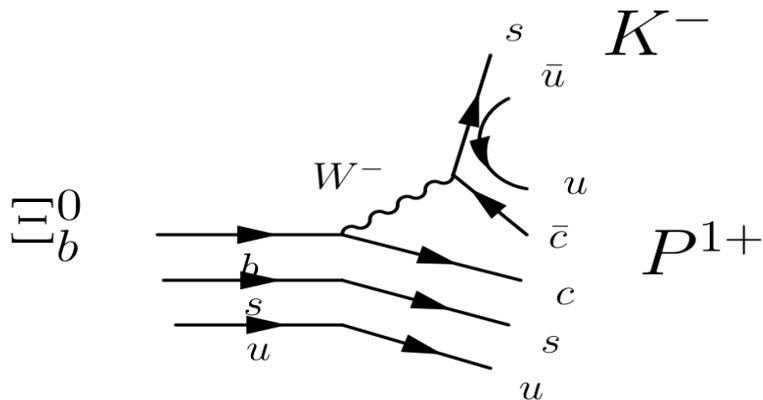
## HOW TO OBSERVE OTHER PENTAQUARK STATES?

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

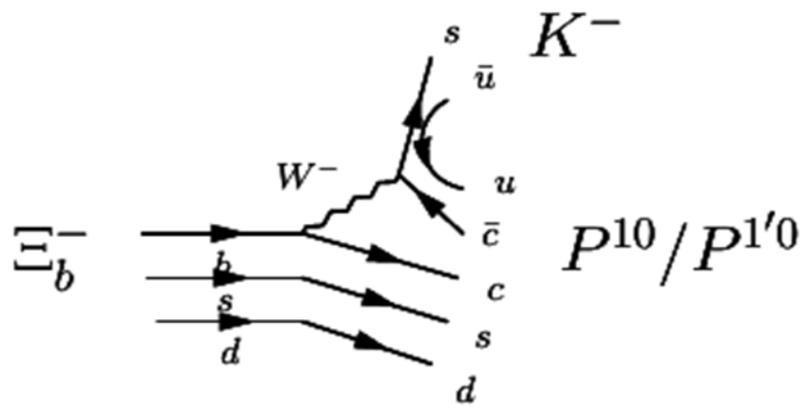
$$\Xi_b^- \longrightarrow J/\psi + \Xi^-$$

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

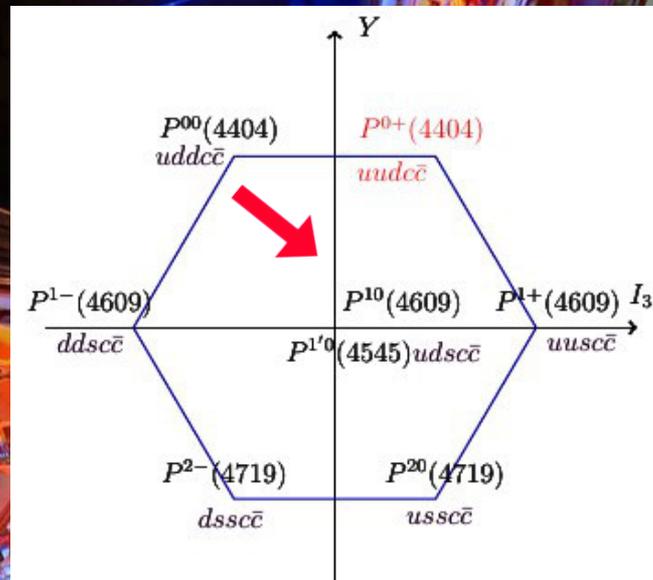
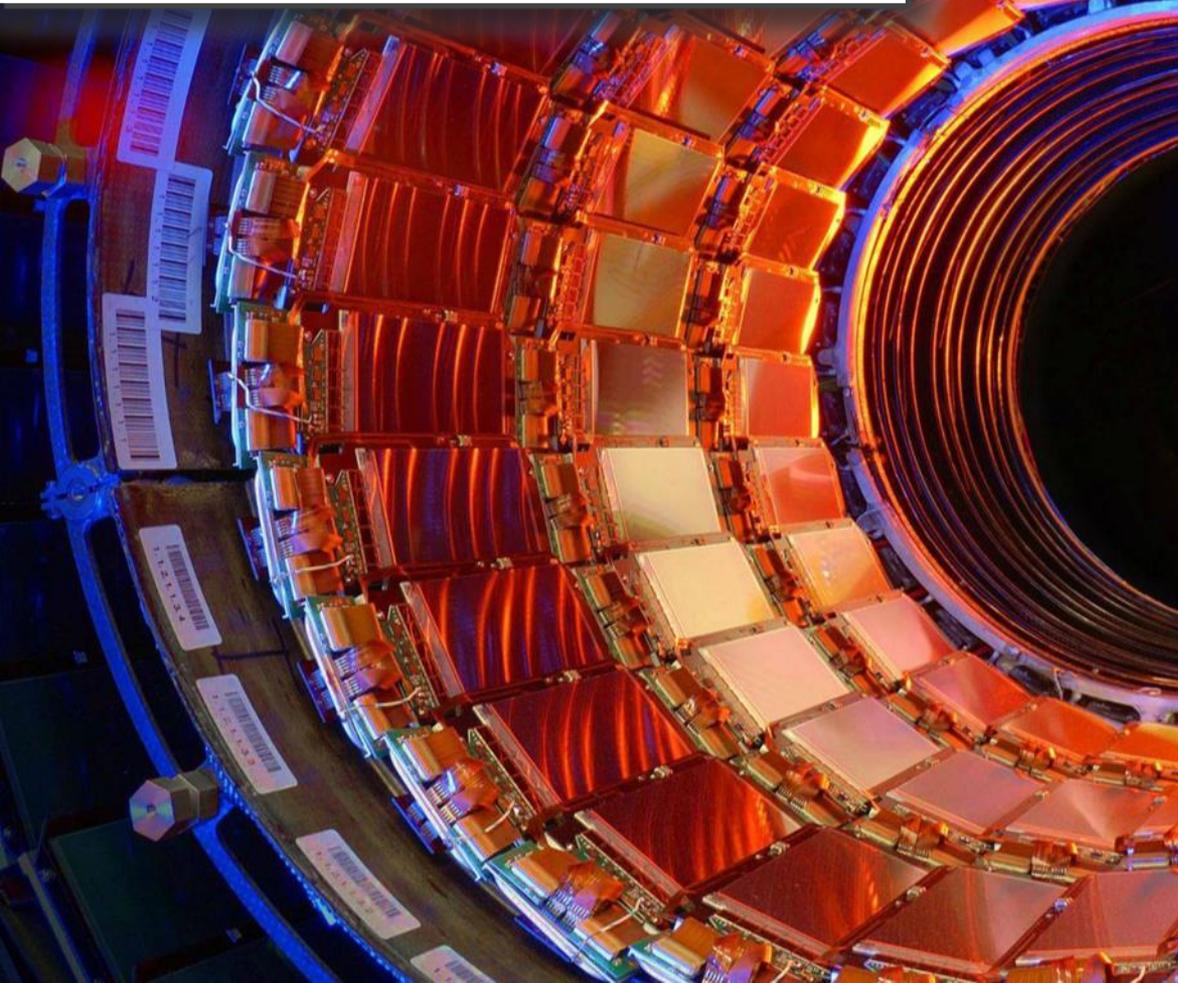
The charged  $P^{1+}(4414)$  state is the most interesting from the experimental point of view, since all the final state particles are charged particles, so easier to be detected :



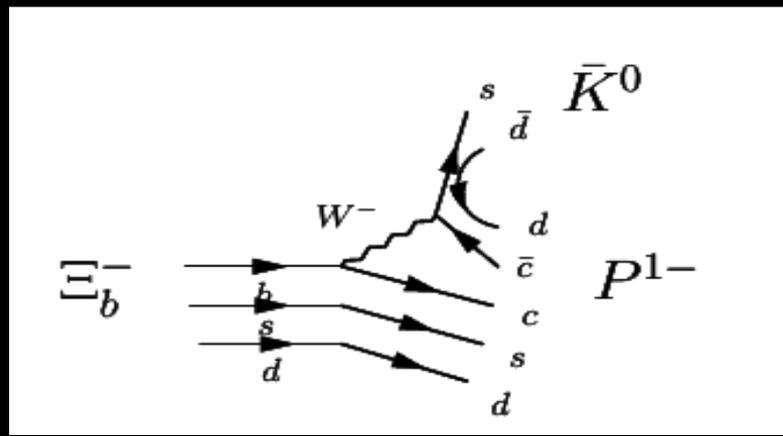
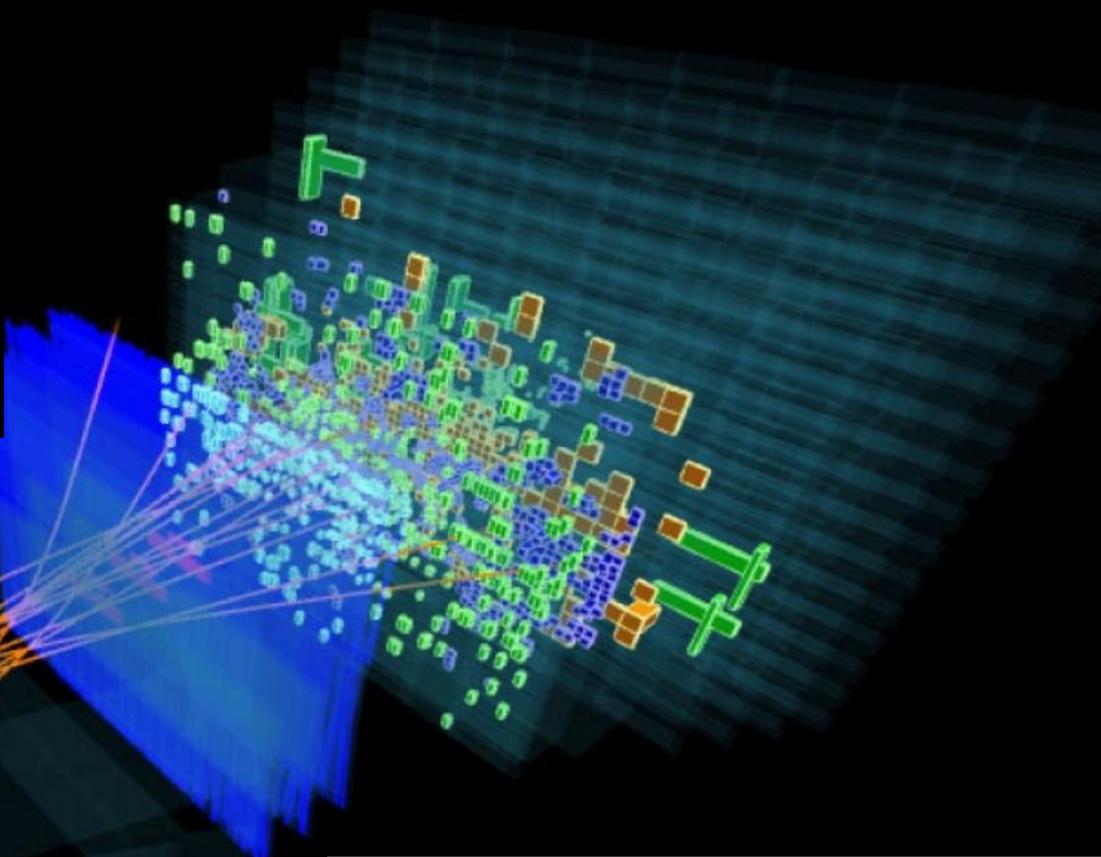
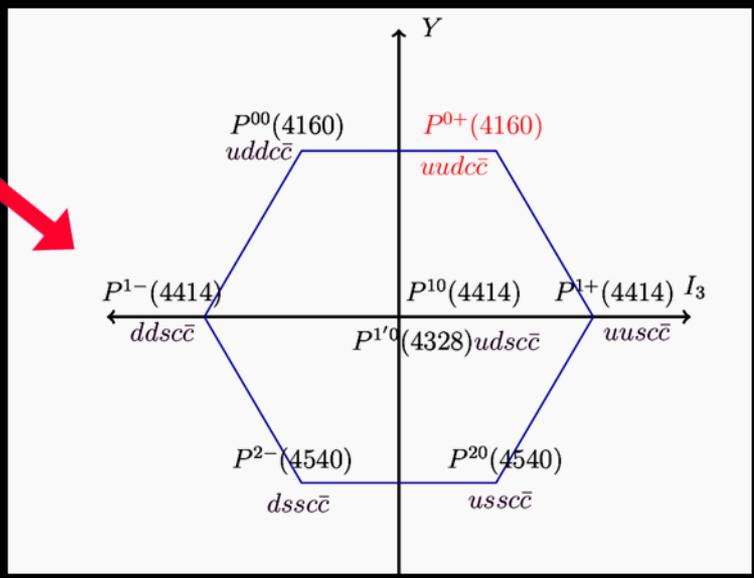
$$\Xi_b^0 \longrightarrow P^{1+} + K^-, P^{1+} \longrightarrow J/\Psi + \Sigma^+$$

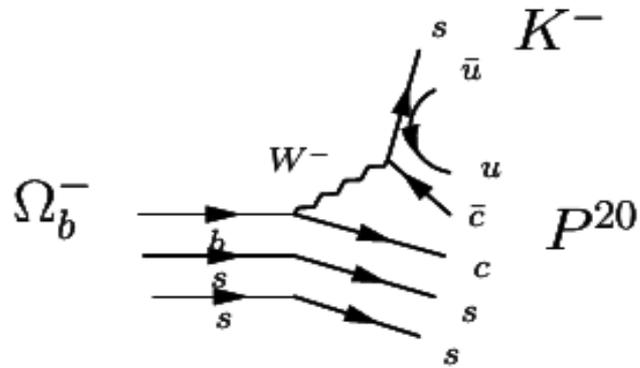


# The states $P^{10}(4609)$ and $P^{1'0}(4545)$

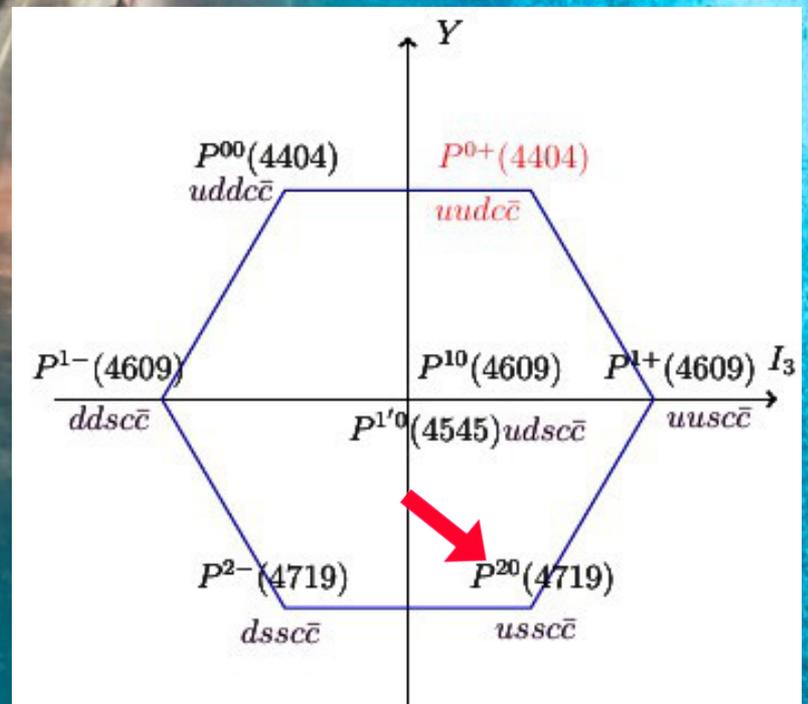


# The $P^1-(4609)$ state

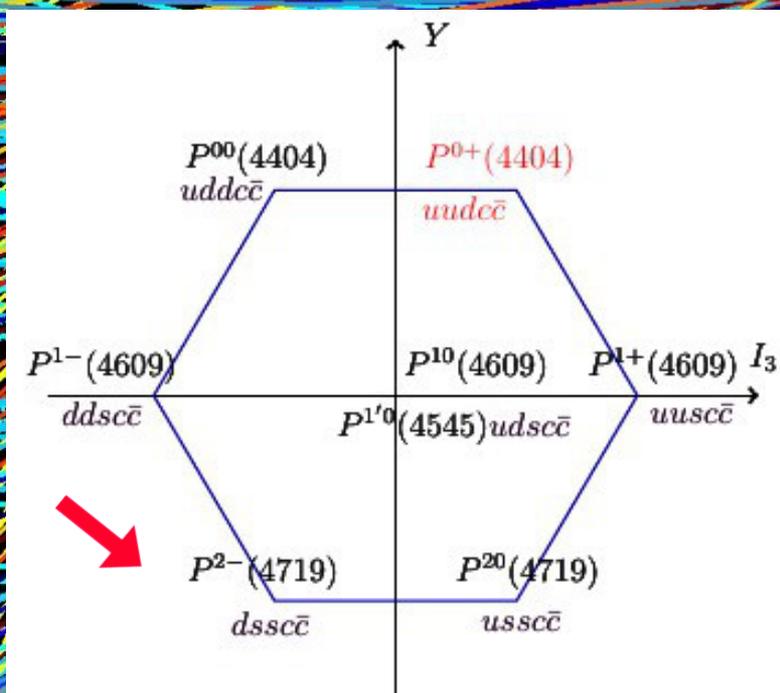
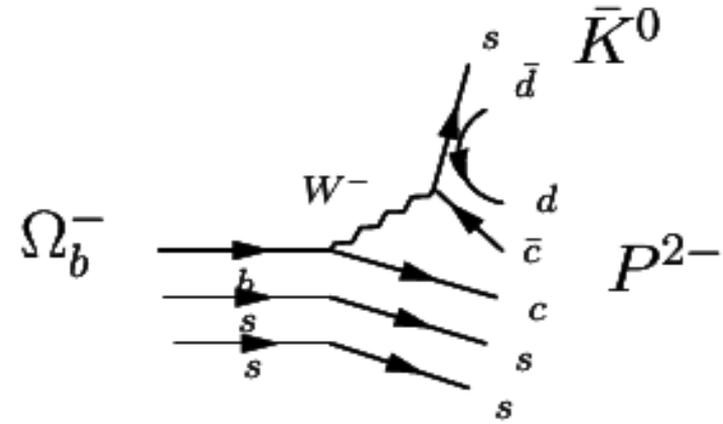




# The $P^{20}(4719)$ state

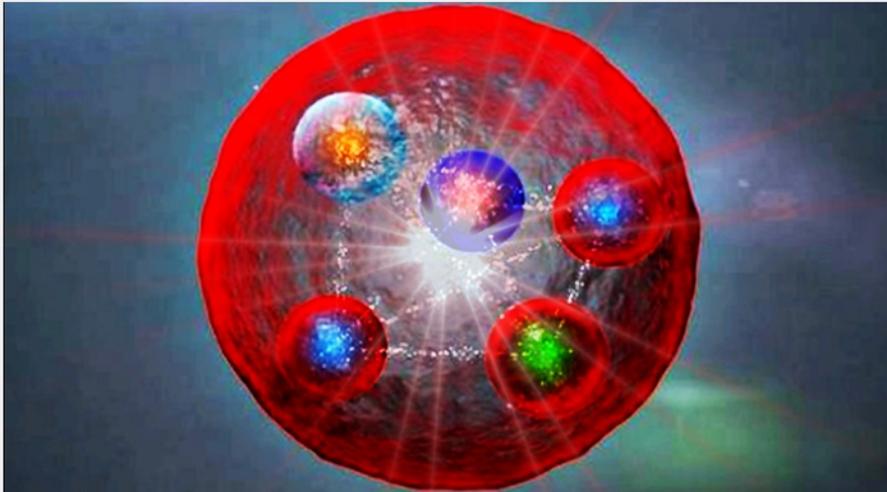


# The $P^2-$ (4719) state

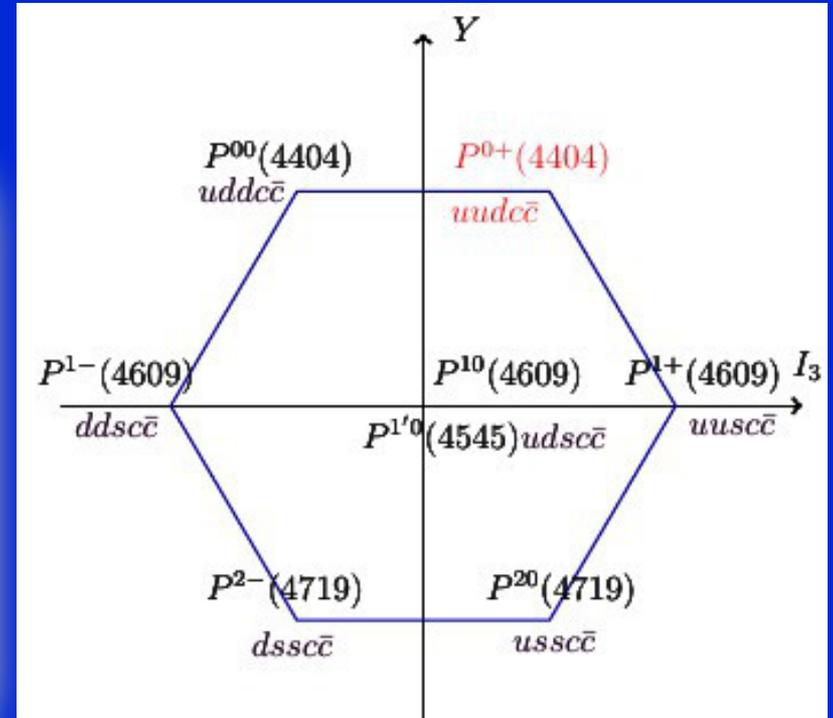


# CONCLUSION

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



- 2) Using group theory 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

TABLE IV: Energies (in unit of MeV) the  $udscc$  and  $uudcc$  systems in the spatial ground state under three kinds of hyperfine interactions (*i.e.*, with configuration mixing considered ).

$J^P$	CM		FS		<i>Inst.</i>	
	$udscc$	$uudcc$	$udscc$	$uudcc$	$udscc$	$uudcc$
$\frac{1}{2}^-$	4273	4267	4084	3933	4209	4114
$\frac{1}{2}^-$	4377	4363	4154	4013	4216	4131
$\frac{1}{2}^-$	4453	4377	4160	4119	4277	4204
$\frac{1}{2}^-$	4469	4471	4171	4136	4295	4207
$\frac{1}{2}^-$	4494	4541	4253	4156	4360	4272
$\frac{1}{2}^-$	4576		4263		4362	
$\frac{1}{2}^-$	4649		4278		4416	
$\frac{3}{2}^-$	4431	4389	4184	4013	4216	4131
$\frac{3}{2}^-$	4503	4445	4171	4119	4295	4204
$\frac{3}{2}^-$	4549	4476	4263	4136	4362	4272
$\frac{3}{2}^-$	4577	4526	4278	4236	4416	4322
$\frac{3}{2}^-$	4629		4362		4461	
$\frac{5}{2}^-$	4719	4616	4362	4236	4461	4322



SUISSE  
FRANCE

CMS

LHCb

CERN Prévessin

ATLAS

CERN Meyrin

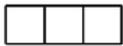
SPS 7 km

ALICE

LHC 27 km

Thanks!

## Sistema a tre quarks

$D_3$	$\sim$	$S_3$	Young tableau	Multiplicity	Dimension		
					$SU_{sf}(8)$	$SU_{fl}(4)$	$SU_s(2)$
$A_1$	$\sim$	[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
$A_1$	$F_2$	$[421^5]_{4752}$ $[21]_{168}$ $[3]_{120}$
$F_2$	$A_1$	$[51^6]_{2520}$ $[3]_{120}$
	$F_2$	$[421^5]_{4752}$ $[21]_{168}$ $[3]_{120}$
	$E$	$[331^5]_{2520}$ $[21]_{168}$
	$F_1$	$[3221^4]_{2800}$ $[21]_{168}$ $[111]_{56}$
$E$	$F_2$	$[421^5]_{4752}$ $[21]_{168}$ $[3]_{120}$
	$F_1$	$[3221^4]_{2800}$ $[21]_{168}$ $[111]_{56}$

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	$A_1$	$F_2$	$E$	$F_1$	$A_2$
--	-------	-------	-----	-------	-------

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

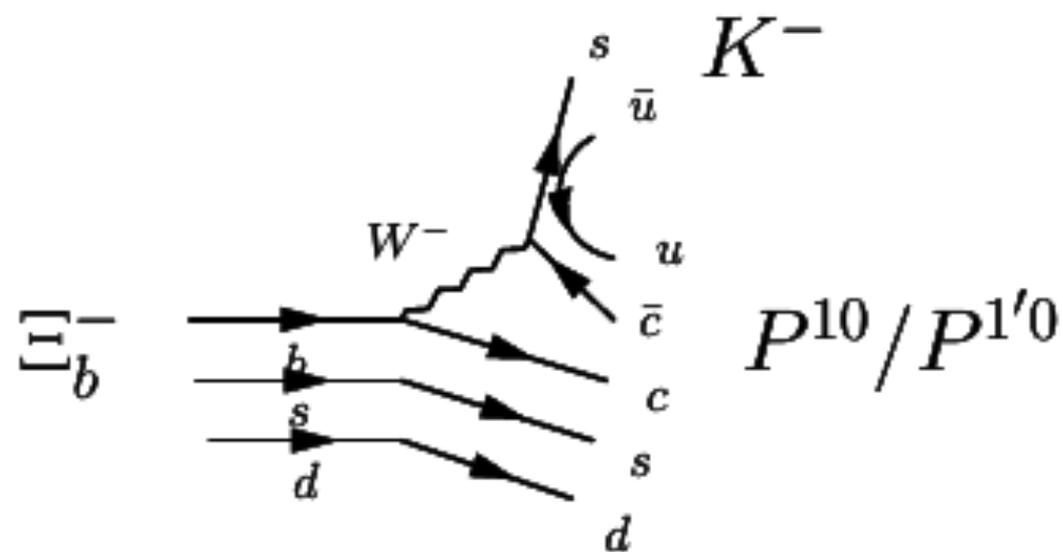
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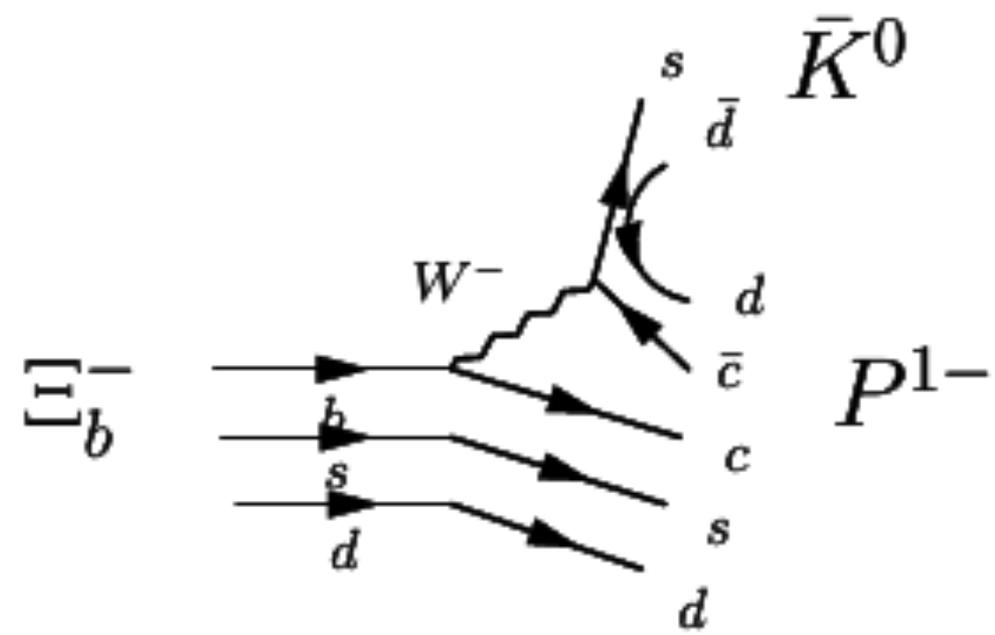
Symmetry	$SU_{sf}(8)$	$\supset$	$SU_{fl}(4)$	$\otimes$	$SU_s(2)$	multiplicity
$F_2$	$[421^5]_{4752}$		$[421]_{140}$	$\otimes$	$[1]_2$	2
		$[421]_{140}$	$\otimes$	$[3]_4$	2	
		$[421]_{140}$	$\otimes$	$[5]_6$	1	
		$[511]_{120}$	$\otimes$	$[1]_2$	1	
		$[511]_{120}$	$\otimes$	$[3]_4$	1	
		$[331]_{60}$	$\otimes$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

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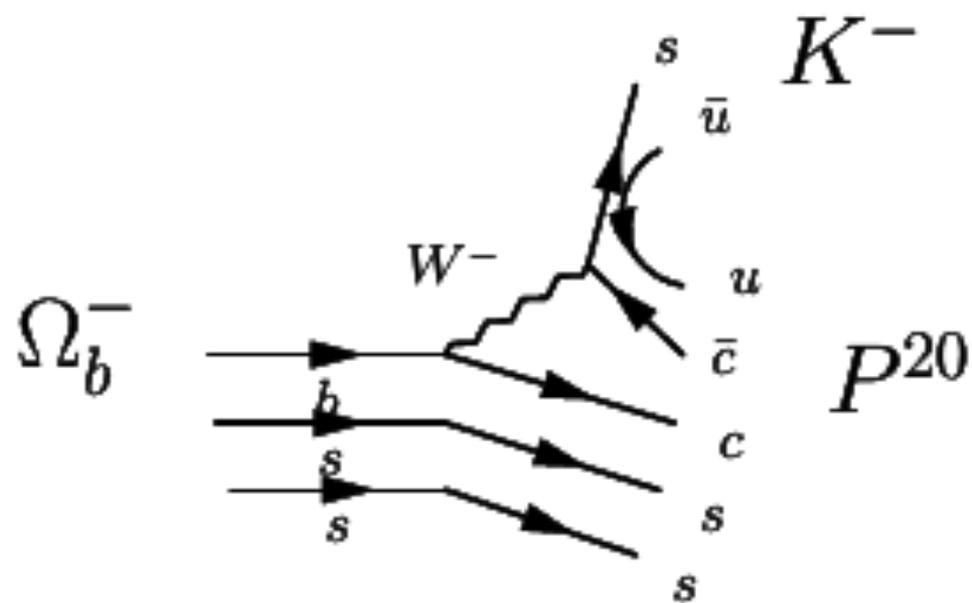
$$\Xi_b^- \longrightarrow P^{10}/P^{1'0} + K^-, \quad P^{10}/P^{1'0} \longrightarrow J/\Psi + \Sigma^0/\Lambda$$



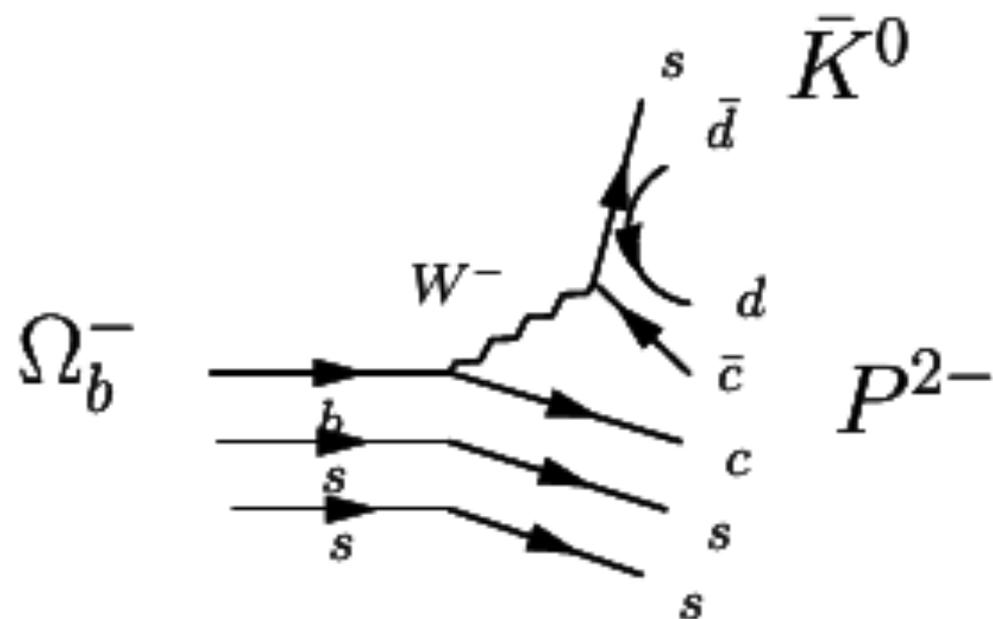
$$\Xi_b^- \longrightarrow P^{1-} + \bar{K}^0, \quad P^{1-} \longrightarrow J/\Psi + \Sigma^-$$



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



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



to find, in the same  $J^P = 1/2^+$   $20'$ -plet as the nucleon, a  $\Lambda_c$ , a  $\Sigma_c$ , two  $\Xi_c$ 's, and an  $\Omega_c$ . Note that this  $\Omega_c$  has  $J^P = 1/2^+$  and is not in the same SU(4) multiplet as the famous  $J^P = 3/2^+$   $\Omega^-$ .

