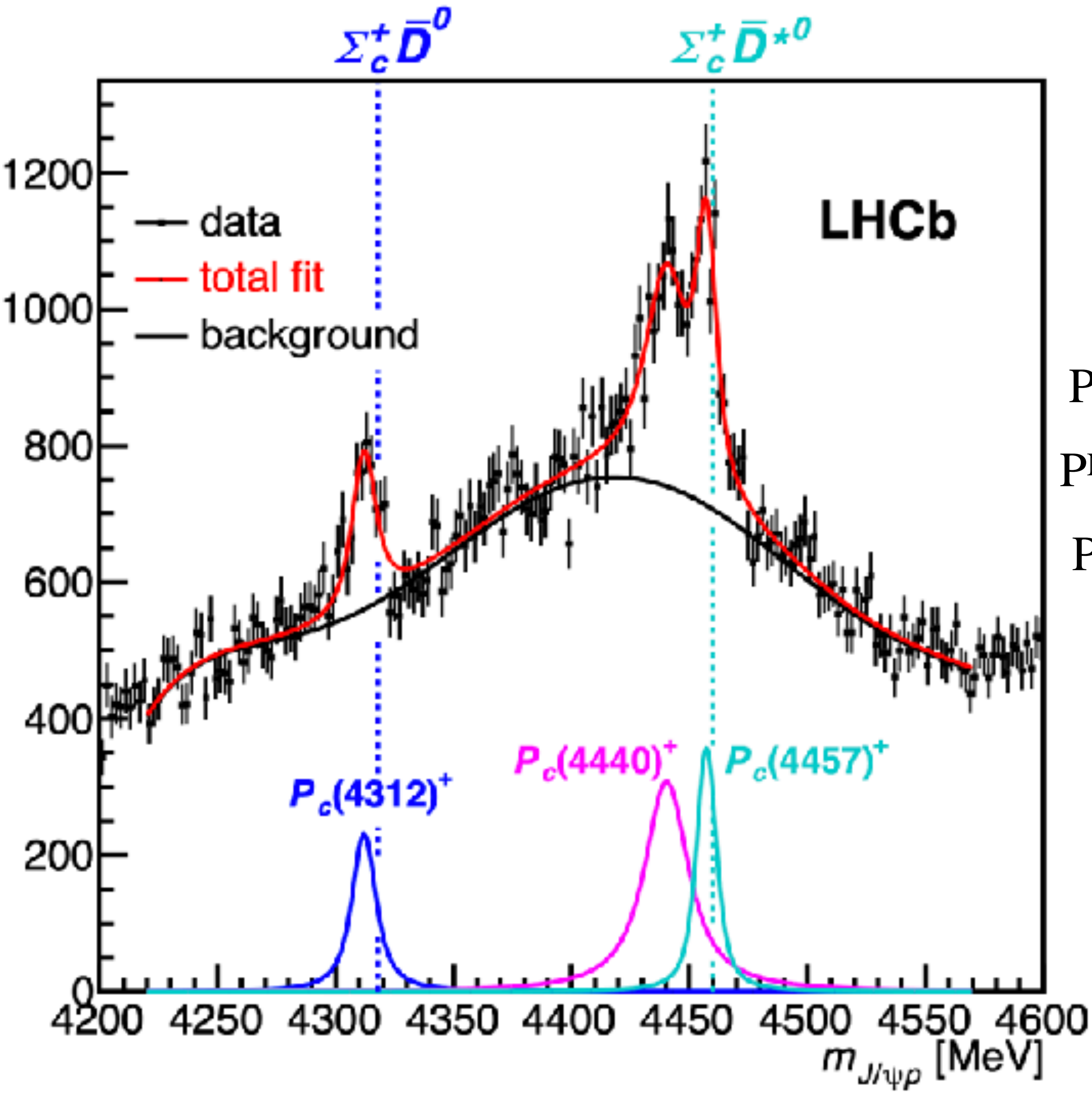
# Pentaquarks

*L.Maiani, CERN, 18/10/2022*




Three non strange pentaquark lines:

$P^N(4312)$: $M = 4311.9 \pm 0.7{+}6.8$, $\Gamma = 9.8 \pm 2.7{+}3.7$

$P^N(4440)$: $M = 4440.3 \pm 1.3{+}4.1$, $\Gamma = 20.6 \pm 4.9{+}8.7$

$P^N(4457)$: $M = 4457.3 \pm 0.6{+}4.1$, $\Gamma = 6.4 \pm 2.0{+}5.7$

$\Lambda_b \to J/\Psi + p + K^-$, R.~Aaij et al. [LHCb], Phys. Rev. Lett. **122** (2019) 222001, arXiv:1904.03947 [hep-ex]

# In addition two (three ?) strange pentaquark lines seen

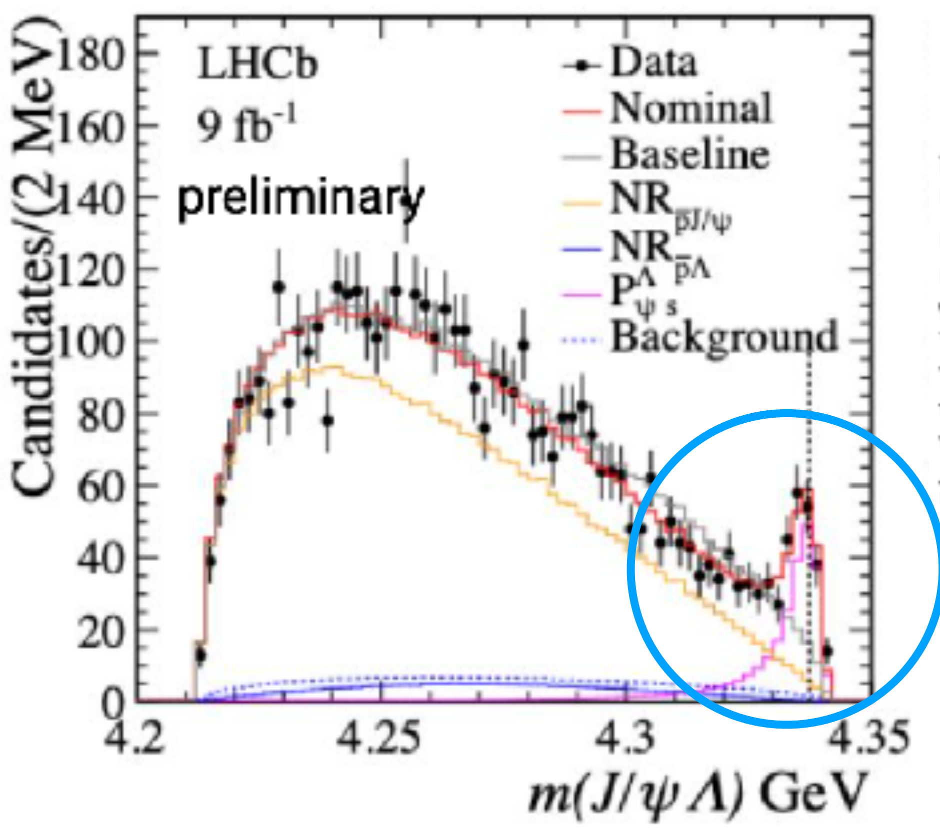
$B^- \to J/\Psi + \Lambda + \bar{p}$, LHCb Paper 2022-031,

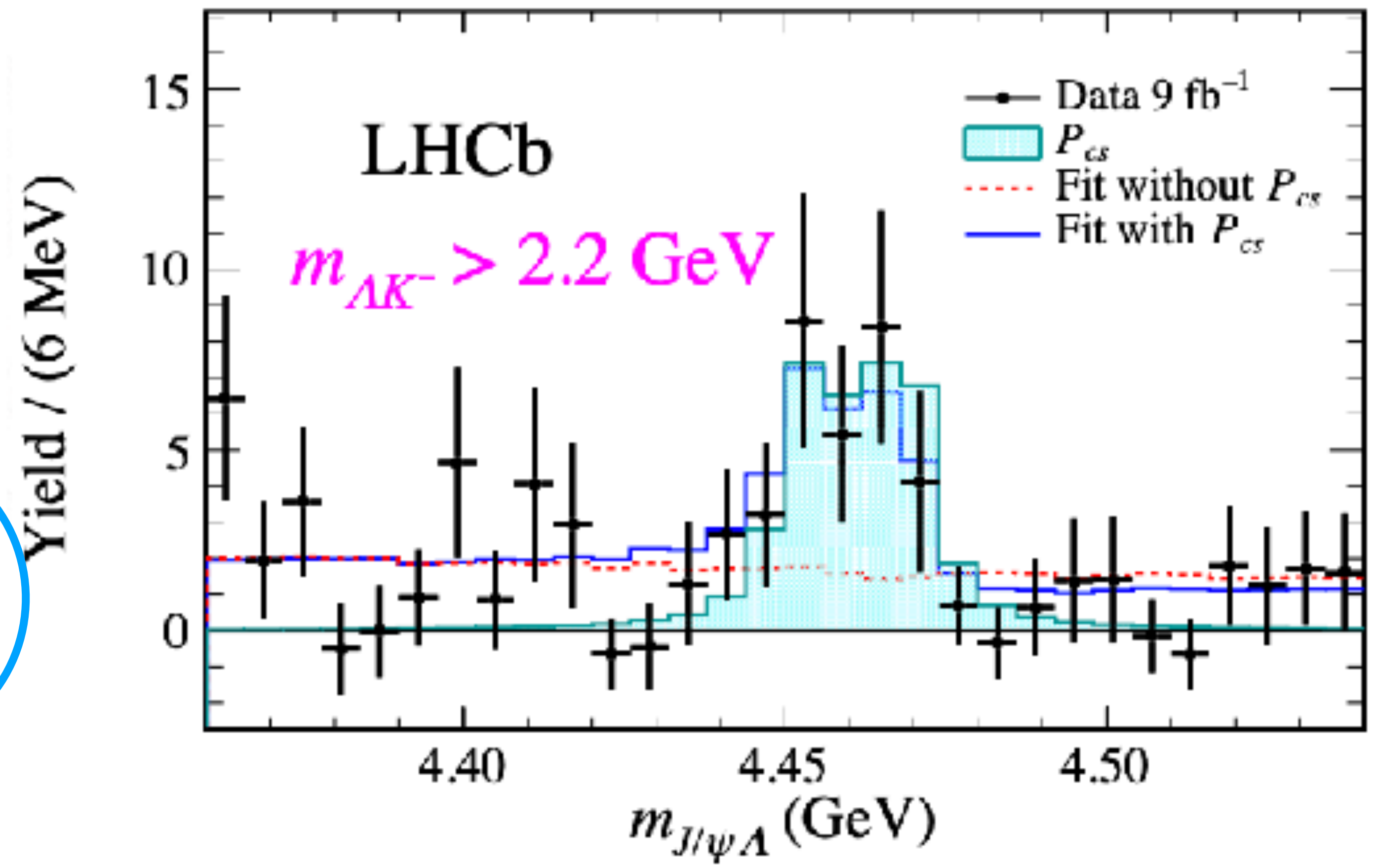
R.Aaij *et al.* [LHCb], Sci. Bull. **66** (2021), 1278; arXiv:2012.10380

$P^\Lambda$ (4338) : M = 4338.2 ± 0.7 MeV, Γ=7.0±1.2MeV

$P^\Lambda$ (4455) : M = 4454.9 ± 2.7 MeV, Γ = 7.5 ± 9.7 MeV

$P^\Lambda$ (4468) : M = 4467.8 ± 3.7 MeV, Γ = 5.2 ± 5.3 MeV



*1. Molecules?*

- ***Non strange Pentaquarks :*** $\Sigma_c - \bar{D}^0$ (spin 1/2), $\Sigma_c - \bar{D}^{*0}$ (spin 1/2, 3/2)
- ***Strange Pentaquarks :*** $\Xi_c - \bar{D}^0$ (spin 1/2), $\Xi_c - \bar{D}^{*0}$ (spin 1/2, 3/2)

Karliner & Rosner arXiv:2207.07581

Binding of strange pentaquarks: 2 pion exchange…

*2. Compact Pentaquarks ?*

L. M., A. D. Polosa and V. Riquer, Phys. Lett. B **749** (2015), 289, [arXiv:1507.04980 [hep-ph]].

- Non strange Pentaquark: $[cu]\ \bar{c}\ [ud]$
- many spin and flavour configurations are possible
- We noted that
  - if the ***ud*** pair is flavour ***antisymmetric*** (therefore spin 0 if in color $\bar{\mathbf{3}}$) it is in flavour $\bar{\mathbf{3}}_f$ and the overall flavour of the three light quarks must be $\bar{\mathbf{3}}_f \otimes \mathbf{3}_f = \mathbf{1}_f + \mathbf{8}_f$
  - if ***ud*** is flavour ***symmetric***, the decuplet appears: three light quarks in $\mathbf{6}_f \otimes \mathbf{3}_f = \mathbf{8}_f + \mathbf{10}_f$
- In the Born-Oppenheimer approximation one starts from $\mathscr{P} = [(\bar{c}\lambda^A c) \times (uud)^A]_{\mathbf{1}},\ A = 1\ldots8$
- Before extending to full flavour $SU(3)_f$ multiplet, we must consider restrictions due to Fermi Statistics to the configurations of the three light quarks in colour octet
- How can be reached full antisymmetry under exchange of: colour, coordinates and flavour x spin, lumped in the $SU(6) \supset SU(3)_f \times SU(2)_{spin}$ symmetry?

# The group $S_3$ and its representations

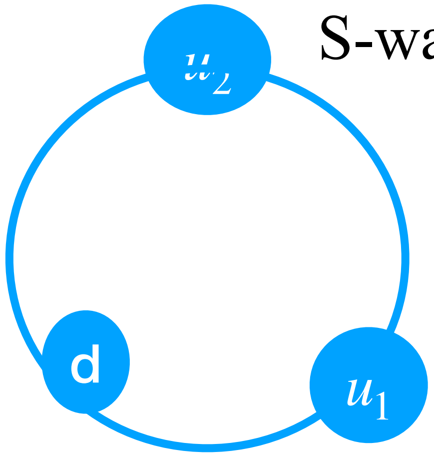
- A state with three light identical quarks must provide a representation of $S_3$, the group of the permutations of three objects.
- We can describe representations of $S_3$ by Young tableux. These are the possible arrays in which we can arrange three elements (each represented by a box) in such a way that boxes in the same row correspond to symmetrized and those in a column to antisymmetrized indices and the number of boxes from one row to the next lower one does not increase.
- With three boxes we can make *three Young tableaux*. Fully antisymmetric (A): 3 boxes in one column; fully symmetric (S): 3 boxes in one row; mixed symmetry (M): 2 boxes in the first row, 1 box in the second. A and S are obviously one-dimensional and the mixed representation, M, is two dimensional.
- Multiplication rules:

$$\frac{1}{\sqrt{2}}(M_1^\rho M_2^\rho + M_1^\lambda M_2^\lambda) = S; \qquad \frac{1}{\sqrt{2}}(M_1^\rho M_2^\lambda - M_1^\lambda M_2^\rho) = A$$

$$\frac{1}{\sqrt{2}}(M_1^\rho M_2^\lambda + M_1^\lambda M_2^\rho) = M^\rho \qquad \frac{1}{\sqrt{2}}(M_1^\rho M_2^\rho - M_1^\lambda M_2^\lambda) = M^\lambda$$

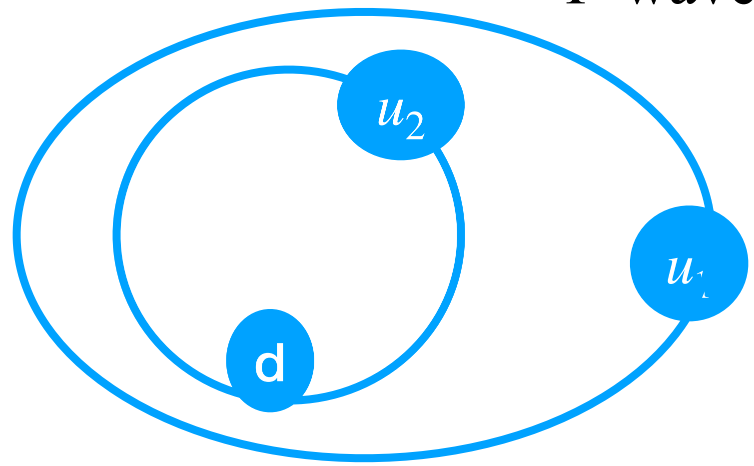
To warm up, consider usual Baryons, ground states and first excited

S-wave




Ground state, 3 quarks in S-wave, positive parity, under coordinate exchange ***fully symmetric: S***

P-wave




1st excited states
2 quarks in S, 1 in P-wave negative parity, under coordinate exchange ***Mixed Symm: M***

***Colour: A*** $\rightarrow \; SU(3)_f \otimes SU(2)_{spin} : \; S$

$i.e.\, SU(6)_f = \mathbf{56} = (\mathbf{8},\ 1/2) + (\mathbf{10},\ 3/2)$

***Colour: A***; $SU(3)_f \otimes SU(2)_{spin} : M \rightarrow SU(6)_f = \mathbf{70} =$

$= (\mathbf{8}, 1/2) + (\mathbf{10}, 1/2) + (\mathbf{8}, 3/2) + (\mathbf{1}, 1/2)$

***Compact Pentaquarks.*** ***C***onsider non strange Pentaquark in the Born-Oppenheimer approximation, with $\bar{c}\ [cu]\ [ud] \rightarrow [(\bar{c}c)_8 \times (uud)_8]_1$

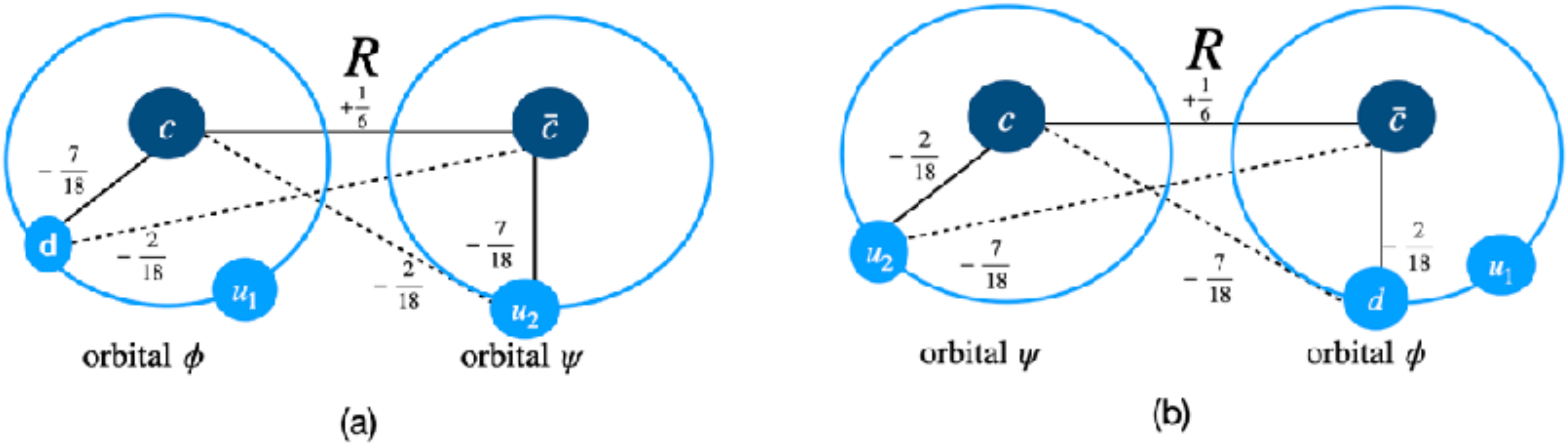
Maiani, Pilloni, Polosa, Riquer, in preparation

| Colour | Coordinates | Notes | $SU(6)$ | $(SU(3)_f,\ \text{spin})$ | BO allowed? |
|---|---|---|---|---|---|
| M | S | Colour & $SU(6)$: A | **70** (M) | $(\mathbf{1}, 1/2),\ (\mathbf{10}, 1/2),\ (\mathbf{8}, 3/2),\ (\mathbf{8}, 1/2)$ | no |
| M | M | Colour & Coord.: A | **56** (S) | $((\mathbf{8}, 1/2)\ (\mathbf{10}, 3/2)$ | yes |
| M | M | Colour & Coord.: S | **20** (A) | $((\mathbf{1}, 3/2)\ (\mathbf{8}, 1/2)$ | yes |
| M | M | Colour & Coord.: M | **70** (M) | same as 1 | no |

- Pentaquark ground state in Born-Oppenheimer approximation, either in **56** or **20**: ***only one*** $\mathbf{8}_{1/2}$
- Since $c\bar{c}$ spin= 0,1, we ***predict three Pentaquarks with spin 1/2(2 states) and 3/2 (1 state).***
- Three lines corresponding to pentaquark decays $\mathscr{P}^N \rightarrow + J/\Psi + p$ and $\mathscr{P}^\Lambda \rightarrow J/\Psi + \Lambda$
- lines corresponding to $\mathscr{P}^\Sigma \rightarrow J/\Psi + \Sigma$ and $\mathscr{P}^\Xi \rightarrow J/\Psi + \Xi$ are also predicted
- the two possibility are discrimonated by presence/absence of $\mathscr{P}^* \rightarrow J/\Psi + \Delta^+$

# Pentaquarks with Born-Oppenheimer in a nutshell

- $c(x_A)$, $\bar{c}(x_B)$ are treated as sources at fixed position (distance R) and fixed color ( $\mathbf{8}_{\mathrm{SU(3)\ colour}}$ )
- find the energy eigestate of the light particles $\epsilon(x_A, x_B)$)
- in molecular physics one assumes light particles in orbitals around the sources
- we do the same in QCD, as in the figure
- **56** can be realised both with (a) and (b), **20** with (b) only.
- Finally: solve the Schroedinger equation for $c(0) - \bar{c}(x)$ with potential $V(x) = V_{c\bar{c}}(x) + \epsilon(0, x)$. The eigenvalue, E, is the energy of the whole system




- (a) mimicks the molecule construction with $B_c \times D/D^*$
- (b) closer to the original ansatz: $[Qq] \times \left(\bar{c}[q'q'']\right)$
- resulting mass spectrum of different case is under study.