A Simple Model for Pentaquarks

Davide Germani

Based on:

D. Germani, A. D. Polosa, F. Niliani, **A Simple Model of Pentaquarks (arXiv:2403.04068 [hep-ph])**

Istituto Nazionale di Fisica Nucleare
LABORATORI NAZIONALI DI FRASCATI

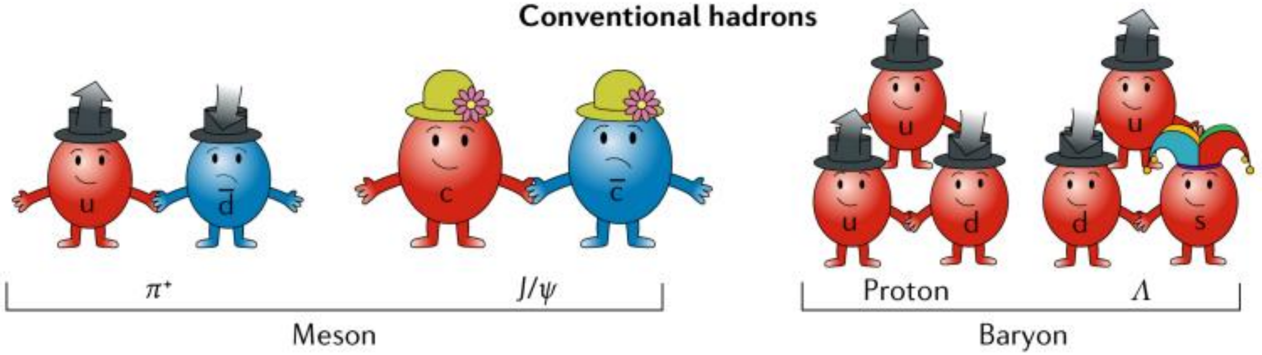
SAPIENZA
UNIVERSITÀ DI ROMA

Outline

- Exotic hadrons spectroscopy
    - What is an exotic hadron?
    - Why study exotic hadron spectroscopy
- A simple model for pentaquarks
    - Overview of the current situation
    - Our ‘Hadro-Charmonia’ model: the role of the exchange interaction
    - Spin assignment and Mass prediction
    - Conclusions

Exotic hadrons

- **Conventional hadrons: Mesons and Baryons;**



- **Exotic hadrons:**

Exotic hadrons are subatomic particles composed of quarks and gluons, but which consist of more than three valence quarks or have an explicit valence gluon content.

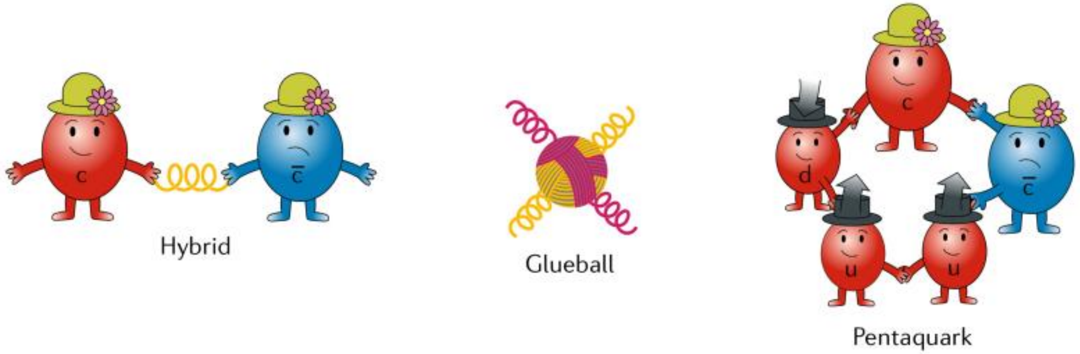


Figure from Nat Rev Phys 1, 480-494 (2019)

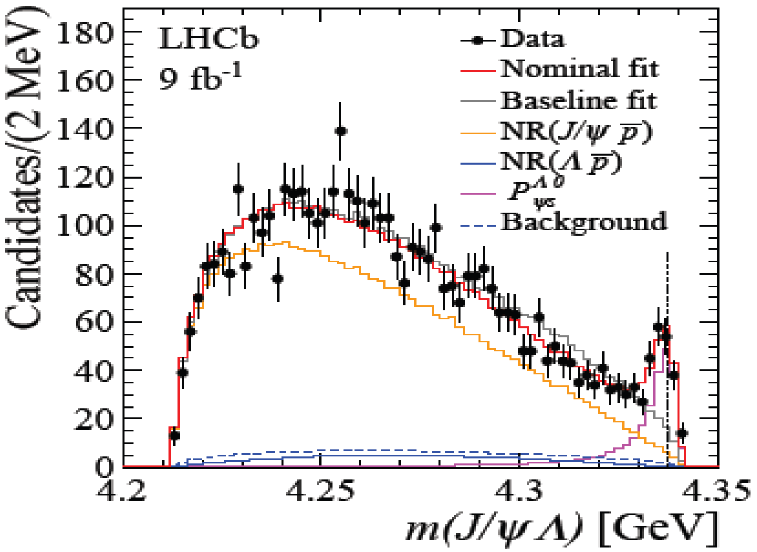
Why study exotic hadron spectroscopy?

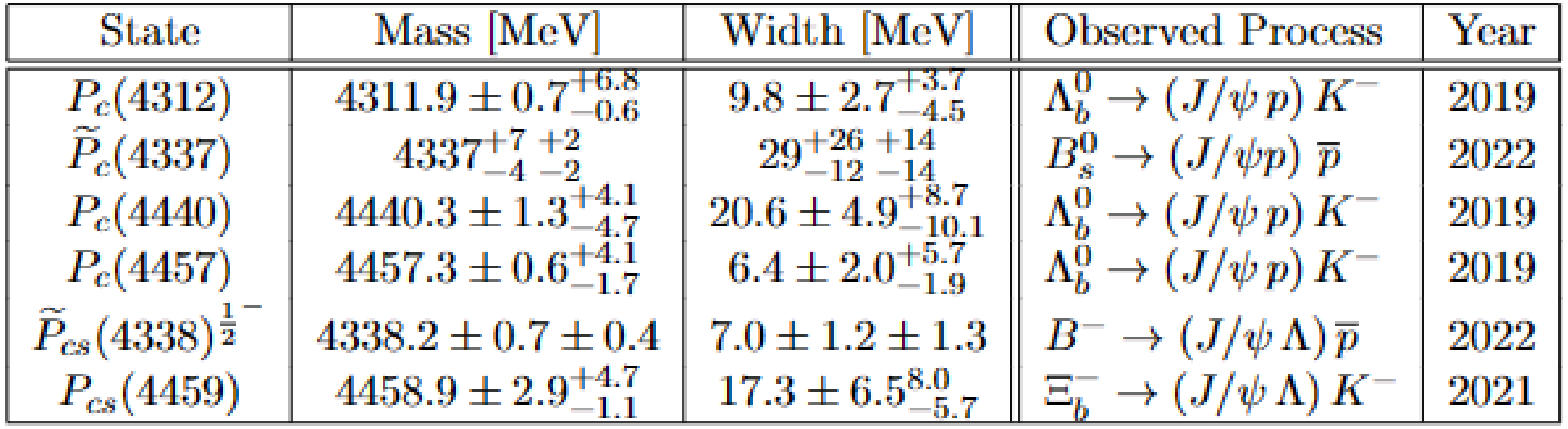
Research into physics beyond the Standard Model requires increasingly precise measurements and the comparison of these results with the most sophisticated theoretical calculations. QCD stands out as one of the main sources of theoretical uncertainty (many analyses are limited by PDFs, α_s, and QCD modeling). If we aim to broaden our horizons, we must enhance our understanding of non-perturbative phenomena in QCD.

- **Testing QCD:** Exotic hadrons challenge our theoretical understanding of QCD. Traditional hadrons, like mesons and baryons, fit neatly into QCD's framework, but exotic hadrons with unusual combinations of quarks and gluons present theoretical puzzles. Investigating these particles helps refine and test QCD in particular how quarks and gluons interact at the smallest scales.

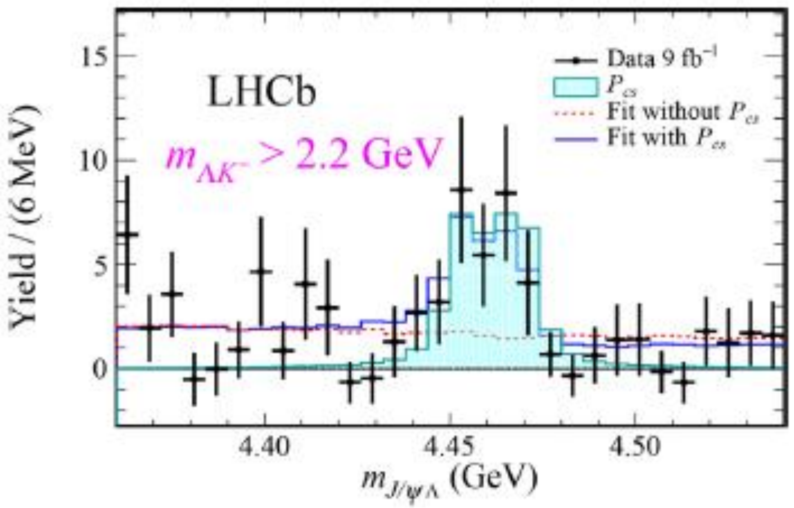
- **Constraining Uncertainties**: Uncertainties in Monte Carlo simulations can arise from various sources, such as the choice of **parton distribution functions** and the modeling of **hadronization processes**. Studies of exotic hadrons can help constrain these uncertainties by providing precise measurements of their properties, which can then be incorporated into Monte Carlo simulations to reduce systematic errors.

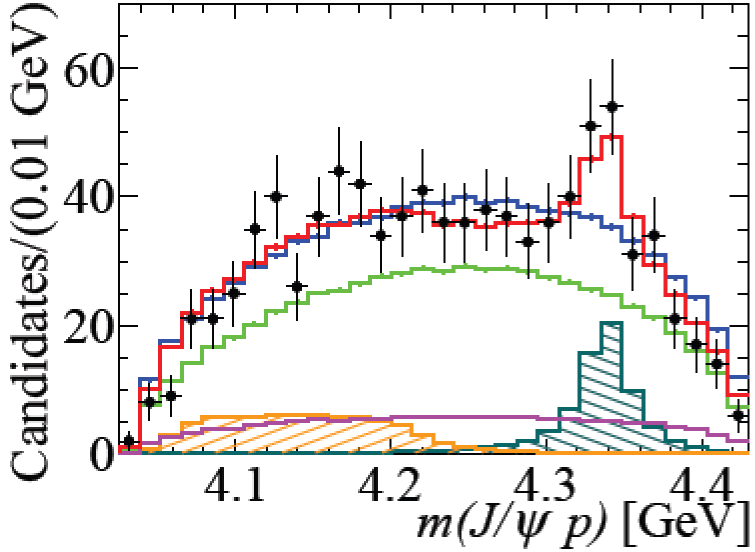
Current situation

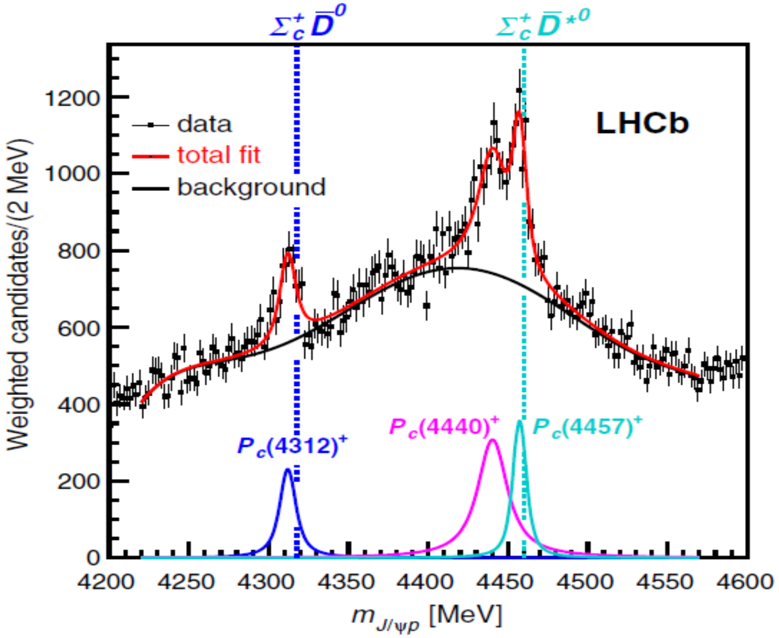




State	Mass [MeV]	Width [MeV]	Observed Process	Year
$P_c(4312)$	$4311.9 \pm 0.7^{+6.8}_{-0.6}$	$9.8 \pm 2.7^{+3.7}_{-4.5}$	$\Lambda_b^0 \to (J/\psi\, p)\, K^-$	2019
$\widetilde{P}_c(4337)$	$4337^{+7}_{-4}{}^{+2}_{-2}$	$29^{+26}_{-12}{}^{+14}_{-14}$	$B_s^0 \to (J/\psi p)\, \overline{p}$	2022
$P_c(4440)$	$4440.3 \pm 1.3^{+4.1}_{-4.7}$	$20.6 \pm 4.9^{+8.7}_{-10.1}$	$\Lambda_b^0 \to (J/\psi\, p)\, K^-$	2019
$P_c(4457)$	$4457.3 \pm 0.6^{+4.1}_{-1.7}$	$6.4 \pm 2.0^{+5.7}_{-1.9}$	$\Lambda_b^0 \to (J/\psi\, p)\, K^-$	2019
$\widetilde{P}_{cs}(4338)^{\frac{1}{2}^-}$	$4338.2 \pm 0.7 \pm 0.4$	$7.0 \pm 1.2 \pm 1.3$	$B^- \to (J/\psi\, \Lambda)\, \overline{p}$	2022
$P_{cs}(4459)$	$4458.9 \pm 2.9^{+4.7}_{-1.1}$	$17.3 \pm 6.5^{8.0}_{-5.7}$	$\Xi_b^- \to (J/\psi\, \Lambda)\, K^-$	2021







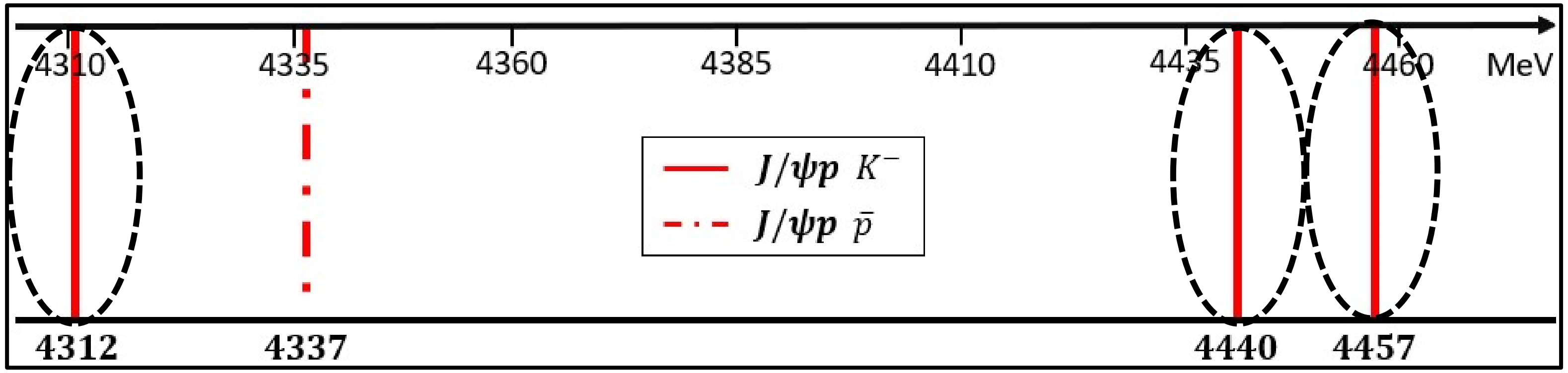
R. Aaij et al. arXiv:1904.03947 [hep-ex] (2019), R. Aaij et al. arXiv:2012.10380v2 [hep-ex] (2021), R. Aaij et al. arXiv:2210.10346 [hep-ex] (2021), R. Aaij et al. arXiv:2108.04720 [hep-ex] (2022)

A different point of view

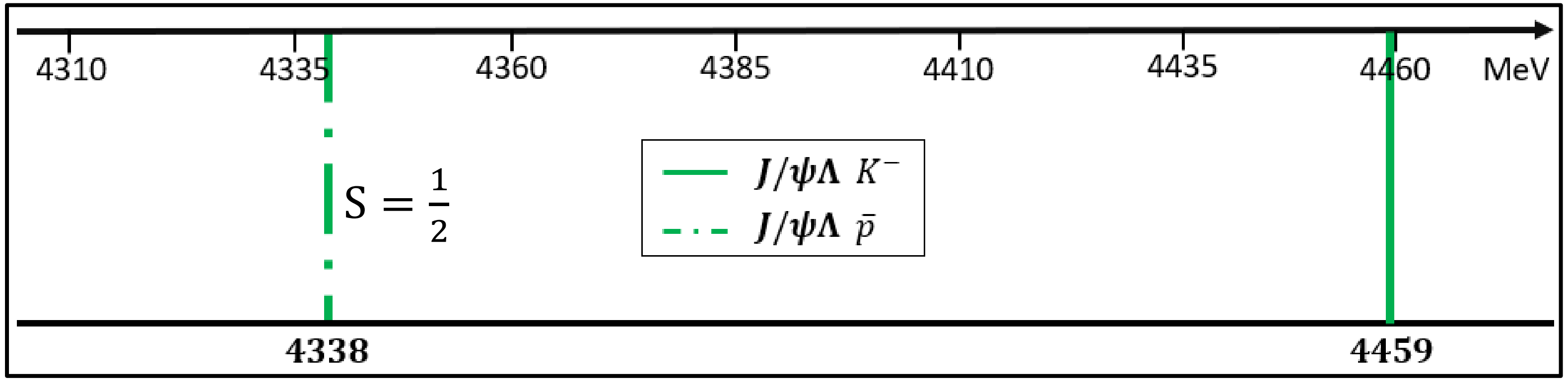
- We divide the spectrum according to strangeness content.
- Data suggests two different type of production: in association with a K^- or with an $\bar{p}$.
- Pentaquark seems to appear in triplet

Can we build a model to account for these properties?

$P_c^+\ [c\bar{c}uud]$

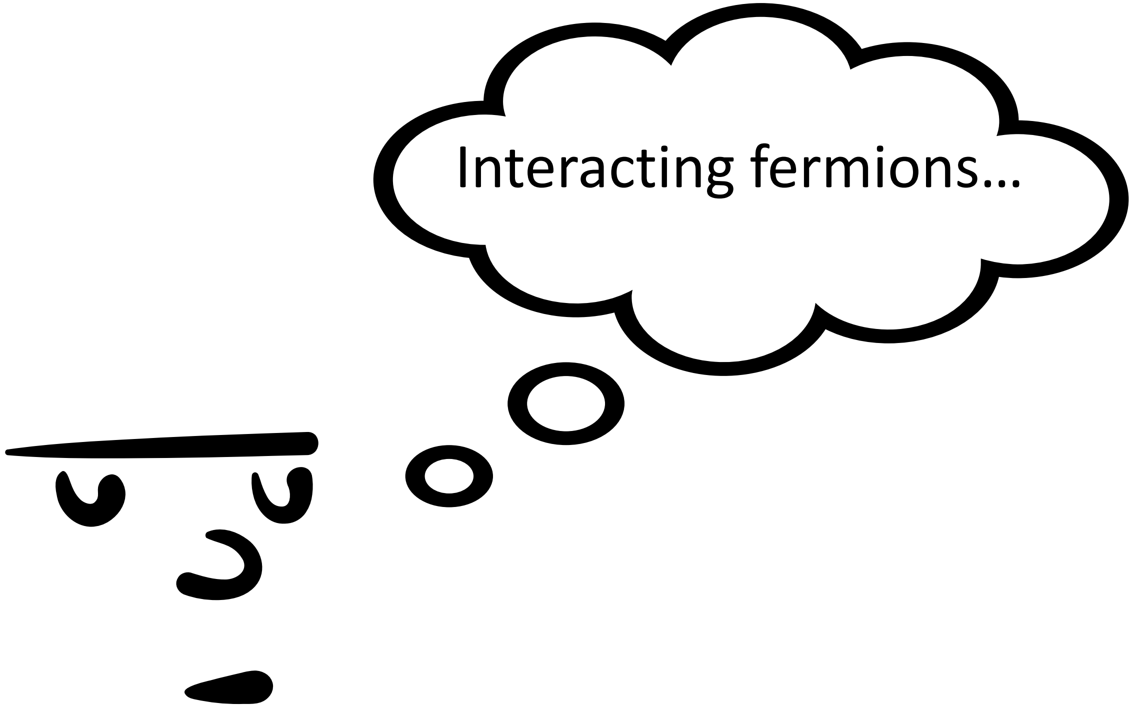


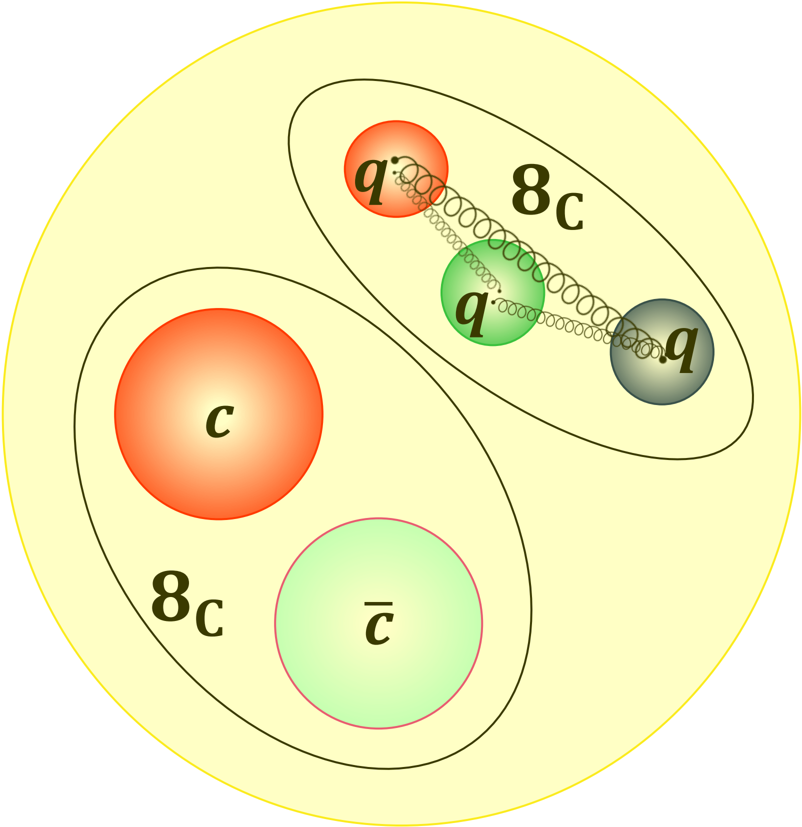
$P_{cs}^0\ [c\bar{c}uds]$



An ‘Hadro-Charmonia’ Model

- The starting point is more or less the same of the Born-Oppenheimer approach. We consider the $c\bar{c}$ system in a color octet as well as the three light quarks sysyem;
- **Fermi statistics for ligth quarks;**





Exchange Interaction! Three Fermions Case

$$\boxed{V = -\sum_{\text{pairs}} J_{ab}\left(\frac{1}{2} + 2\mathbf{S}_a \cdot \mathbf{S}_b\right)}$$

Generalization of the well known two fermions case

$$J_{ab} \equiv \int \left[\phi_a(\mathbf{r}_1)\phi_b(\mathbf{r}_2)\right]^* U(\mathbf{r}_1 - \mathbf{r}_2)\ \left[\phi_b(\mathbf{r}_1)\phi_a(\mathbf{r}_2)\right]\, d^3\mathbf{r}_1\, d^3\mathbf{r}_2$$

The potential has **three** distinct eigenvalues

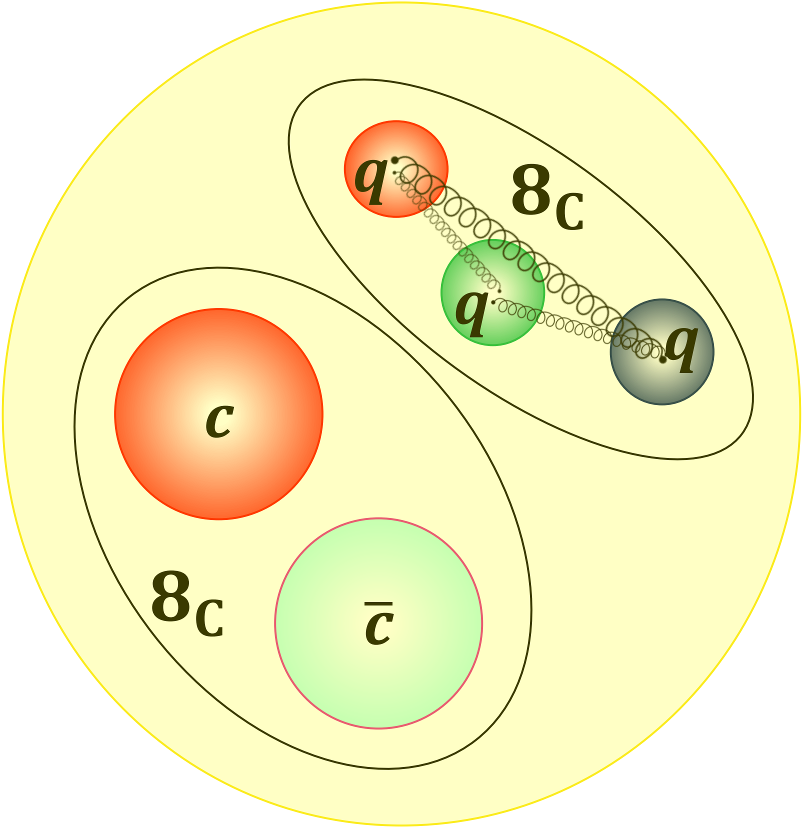
$$\Delta E_{1/2} = \pm\sqrt{J_{12}^2 + J_{13}^2 + J_{23}^2 - J_{12}J_{13} - J_{12}J_{23} - J_{13}J_{23}}$$

$$\Delta E_{3/2} = -J_{12} - J_{13} - J_{23}$$

An ‘Hadro-Charmonia’ Model

- The starting point is more or less the same of the Born-Oppenheimer approach. We consider the $c\bar{c}$ system in a color octet as well as the three light quarks sysyem;
- Fermi statistics for ligth quarks;
- **Exchange Interaction**. But to use to use the exchange interaction, we need to have a precise symmetry on the spin-orbital part which means a complete symmetry in the **color-flavor** sector

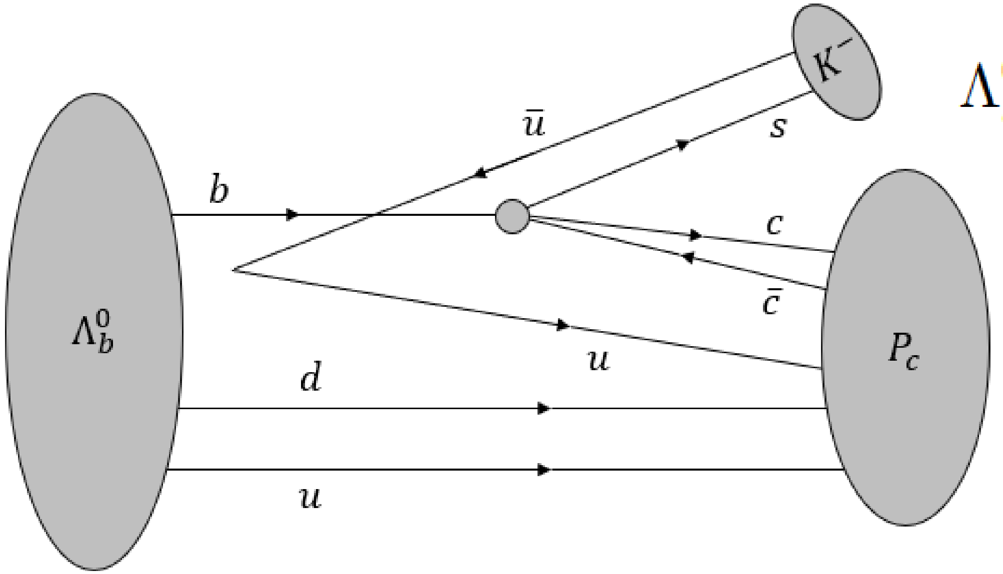
$$\mathbf{3} \otimes \mathbf{3} \otimes \mathbf{3} = \mathbf{1} \oplus \boxed{\mathbf{8} \oplus \mathbf{8}'} \oplus \mathbf{10} \quad \text{(flavor)}$$



Symmetric and Antisymmetric Combination

1. $$\boxed{\mathbf{S}^{abc}_{ijk} = 6\left(\eta^{[a}_{i}\eta^{b]}_{j}\eta^{c}_{k} - \eta^{[a}_{j}\eta^{b]}_{k}\eta^{c}_{i}\right) = 6\left(\eta^{a}_{[i}\eta^{b}_{j]}\eta^{c}_{k} - \eta^{a}_{[j}\eta^{b}_{k]}\eta^{c}_{i}\right)}$$ P $$\eta^{a,i}\eta^{b,j} = \eta^{b,j}\eta^{a,i}$$

2. $$\boxed{\mathbf{A}^{abc}_{ijk} = 6\left(\psi^{[a}_{i}\psi^{b]}_{j}\psi^{c}_{k} - \psi^{[a}_{j}\psi^{b]}_{k}\psi^{c}_{i}\right) = 6\left(\psi^{a}_{(i}\psi^{b}_{j)}\psi^{c}_{k} - \psi^{a}_{(j}\psi^{b}_{k)}\psi^{c}_{i}\right)}$$ $\tilde{P}$ $$\psi^{a,i}\psi^{b,j} = -\psi^{b,j}\psi^{a,i}$$



$$\Lambda_b^0 \to (J/\psi\, p)\, K^-$$

The diquark ud has initially $[ud]^{\bar{3}_c}_{\bar{3}_F\, 0_S}$ (good diquark) so it means that is in a symmetric configuration wrt color-flavor. We assume that the color-flavor symmetry is preserved in the process so we choose the S tensor for the pentaquarks produced in association with K^-.

Our ‘Hadro-Charmonia’ model

- **Fermi statistics for ligth quarks**

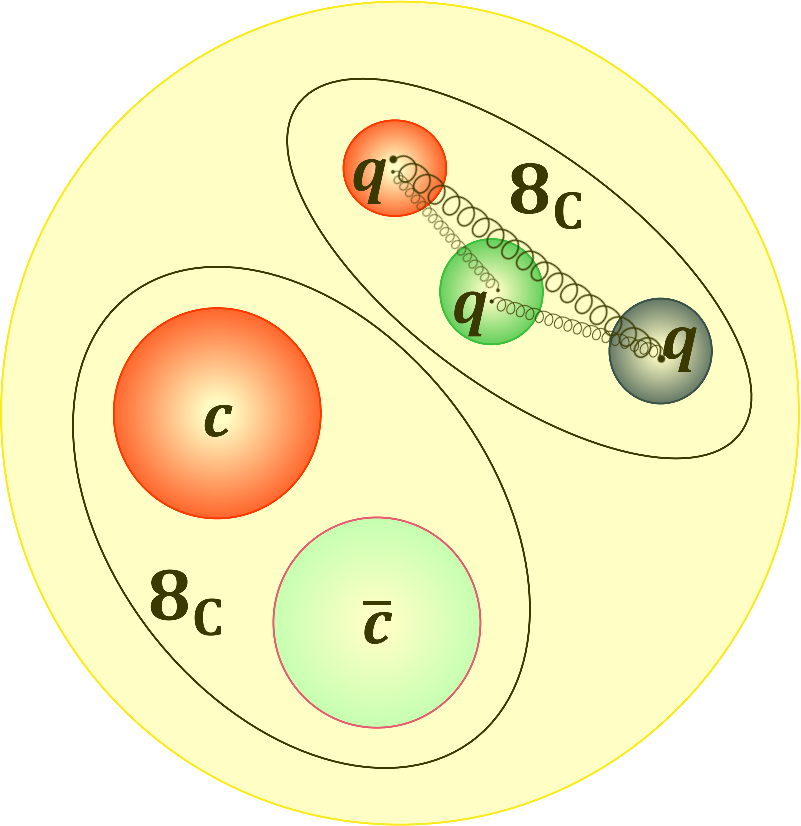
$$\frac{\begin{array}{ccc}\textbf{Color-Flavour} & + & \textbf{Spin-Orbital}\\ S & & A\end{array}}{\begin{array}{ccc} A & \qquad\qquad & S\end{array}}$$

- **Exchange Interaction**

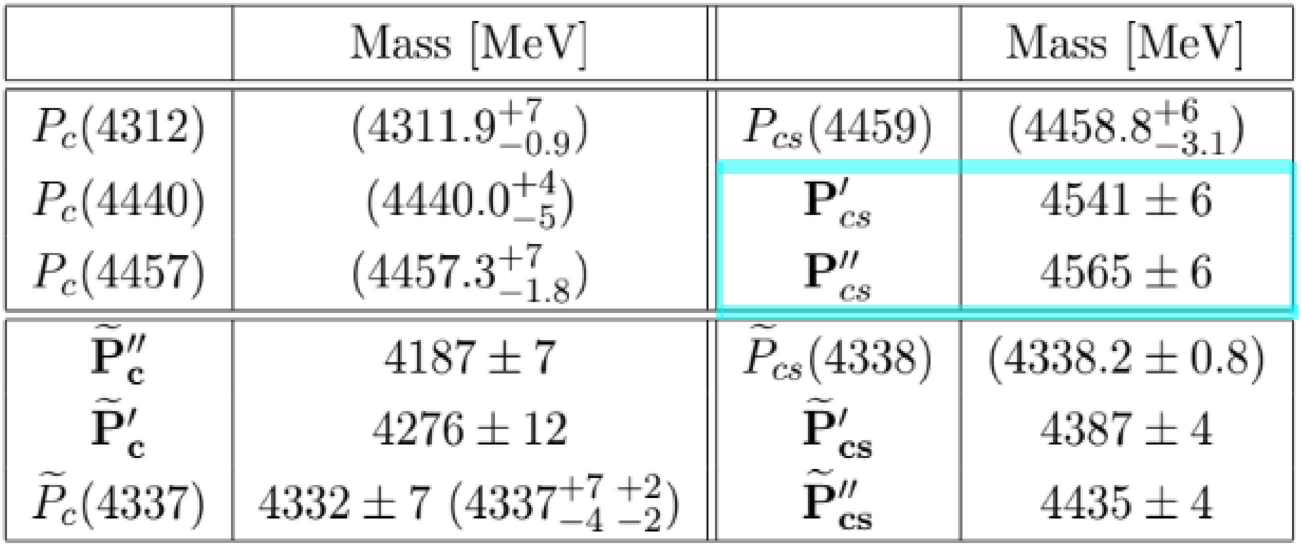
$$V = -\sum_{\text{pairs}} J_{ab}\left(\frac{1}{2} + 2\mathbf{S}_a \cdot \mathbf{S}_b\right)$$

- **J couplings:**

Experimental Data + qq interactions in one gluon exchange approximation + Spin assignment

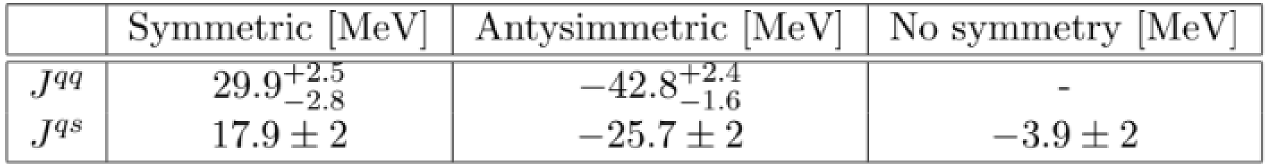


Spin assignment and Mass predictions



	Mass [MeV]		Mass [MeV]
$P_c(4312)$	$(4311.9^{+7}_{-0.9})$	$P_{cs}(4459)$	$(4458.8^{+6}_{-3.1})$
$P_c(4440)$	(4440.0^{+4}_{-5})	$\mathbf{P'_{cs}}$	4541 ± 6
$P_c(4457)$	$(4457.3^{+7}_{-1.8})$	$\mathbf{P''_{cs}}$	4565 ± 6
$\widetilde{\mathbf{P}}''_{\mathbf{c}}$	4187 ± 7	$\widetilde{P}_{cs}(4338)$	(4338.2 ± 0.8)
$\widetilde{\mathbf{P}}'_{\mathbf{c}}$	4276 ± 12	$\widetilde{\mathbf{P}}'_{\mathbf{cs}}$	4387 ± 4
$\widetilde{P}_c(4337)$	$4332 \pm 7\ (4337^{+7}_{-4}{}^{+2}_{-2})$	$\widetilde{\mathbf{P}}''_{\mathbf{cs}}$	4435 ± 4

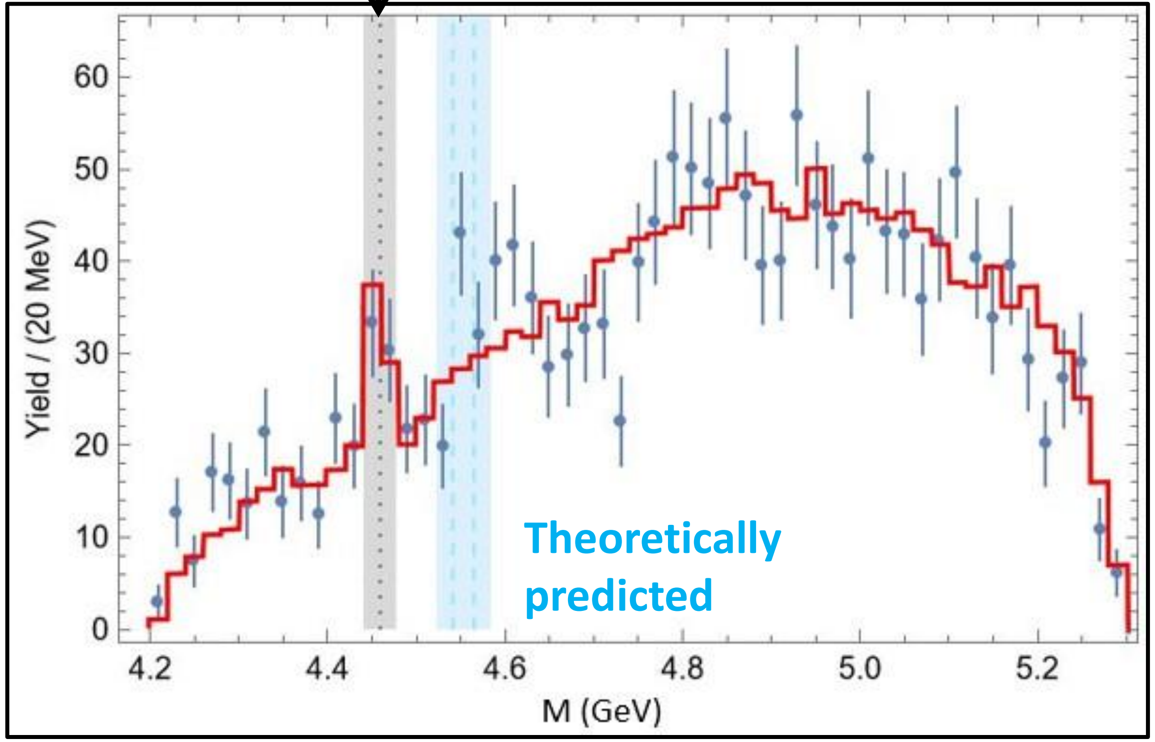
We have the spin prediction for these particles. Each triplet is ordered from top to bottom with $S = 1/2, 3/2, 1/2$.



	Symmetric [MeV]	Antysimmetric [MeV]	No symmetry [MeV]
J^{qq}	$29.9^{+2.5}_{-2.8}$	$-42.8^{+2.4}_{-1.6}$	-
J^{qs}	17.9 ± 2	-25.7 ± 2	-3.9 ± 2

R. Aaij et al. arXiv:2012.10380v2 [hep−ex]

$\boldsymbol{P^0_{cs}(4459)}$ $\Xi_b^- \to (J/\psi\Lambda)K^-$



Theoretically predicted

Conclusions

- By exploiting Fermi statistics and exchange interaction, we are able to provide a prediction for the spin of the observed pentaquarks and make predictions for the masses of the remaining pentaquarks to complete the triplets;
- The data suggests two different types of production for pentaquarks. Our model, based on the existence of two tensors in color-flavor space, could provide a way to account for this experimental fact.
- There are still various aspects to study, such as decays into open-charm channels and the predicted decay widths of pentaquarks.


THANK
YOU!