Pentaquarks from intrinsic charms in Λ_b decays

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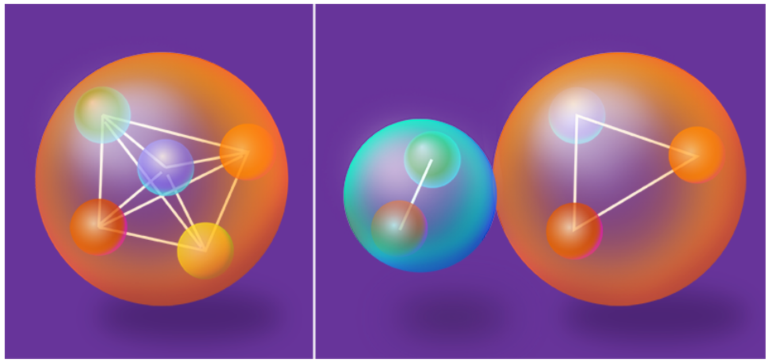
Phys. Lett. B751, 572 (2015)

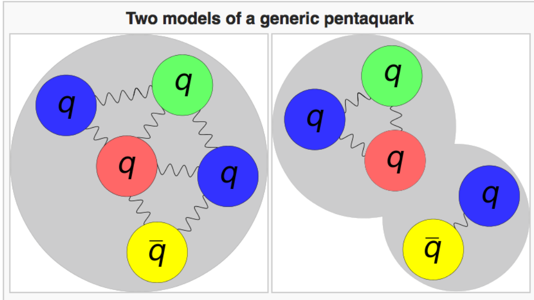
In collaboration with C.Q. Geng

Outline:
1. Introduction
2. Formalism
3. Results
4. Summary



What is Pentaquark?

- Pentaquark, the five-quark bound state



- meson, baryon, tetraquark, pentaqurak, hexaquark.

unicycle (1-wheel), bicycle (2-wheel), ...

- multi-quark bound state besides M, $\mathcal{B}$

proposed by Murray Gell-Mann and George Zweig.

Multiquark states have been discussed since the 1st page of the quark model

A SCHEMATIC MODEL OF BARYONS AND MESONS *

M. GELL-MANN
California Institute of Technology, Pasadena, California

Received 4 January 1964

If we assume that the strong interactions of baryons and mesons are correctly described in terms of the broken "eightfold way" [1-3], we are tempted to look for some fundamental explanation of the situation. A highly promised approach is the purely dynamical "bootstrap" model for all the strongly interacting particles within which one may try to derive isotopic spin and strangeness conservation and broken eightfold symmetry from self-consistency alone [4]. Of course, with only strong interactions, the orientation of the asymmetry in the unitary space cannot be specified; one hopes that in some way the selection of specific components of the F-spin by electromagnetism and the weak interactions determines the choice of isotopic spin and hypercharge directions.

Even if we consider the scattering amplitudes of strongly interacting particles on the mass shell only and treat the matrix elements of the weak, electromagnetic, and gravitational interactions by means ber $n_t - n_{\bar{t}}$ would be zero for all known baryons and mesons. The most interesting example of such a model is one in which the triplet has spin $\frac{1}{2}$ and $z = -1$, so that the four particles d^-, s^-, u^0 and b^0 exhibit a parallel with the leptons.

A simpler and more elegant scheme can be constructed if we allow non-integral values for the charges. We can dispense entirely with the basic baryon b if we assign to the triplet t the following properties: spin $\frac{1}{2}$, $z = -\frac{1}{3}$, and baryon number $\frac{1}{3}$. We then refer to the members $u^{\frac{2}{3}}$, $d^{-\frac{1}{3}}$, and $s^{-\frac{1}{3}}$ of the triplet as "quarks" [6] q and the members of the anti-triplet as anti-quarks $\bar{q}$. Baryons can now be constructed from quarks by using the combinations (qqq), $(qqqq\bar{q})$, etc., while mesons are made out of $(q\bar{q})$, $(qq\bar{q}\bar{q})$, etc. It is assuming that the lowest baryon configuration (qqq) gives just the representations **1**, **8**, and **10** that have been observed, while the lowest meson configuration $(q\bar{q})$ similarly gives just **1** and **8**.

http://cds.cern.ch/record/352337/files/CERN-TH-401.pdf

Multiquark states have been discussed since the quark model was proposed

AN SU_3 MODEL FOR STRONG INTERACTION SYMMETRY AND ITS BREAKING

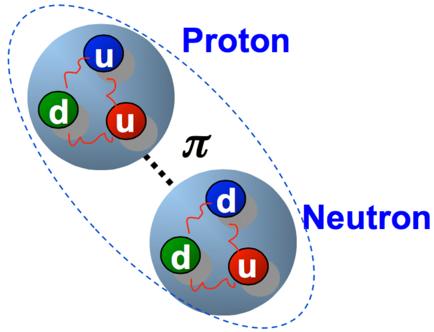
8182/TH.401
17 January 1964

Both mesons and baryons are constructed from a set of three fundamental particles called aces. The aces break up into an isospin doublet and singlet. Each ace carries baryon number $\frac{1}{3}$ and is consequently fractionally charged. SU_3 (but not the Eightfold Way) is adopted as a higher symmetry for the strong interactions. The breaking of this symmetry is assumed to be universal, being due to mass differences among the aces. Extensive space-time and group theoretic structure is then predicted for both mesons and baryons, in agreement with existing experimental information. An experimental search for the aces is suggested.

5) In general, we would expect that baryons are built not only from the product of three aces, AAA, but also from $\bar{A}AAAA$, $\bar{A}\bar{A}AAAAA$, etc., where $\bar{A}$ denotes an anti-ace. Similarly, mesons could be formed from $\bar{A}A$, $\bar{A}\bar{A}AA$ etc. For the low mass mesons and baryons we will assume the simplest possibilities, $\bar{A}A$ and AAA, that is, "deuces and treys".

- hexaquark is real

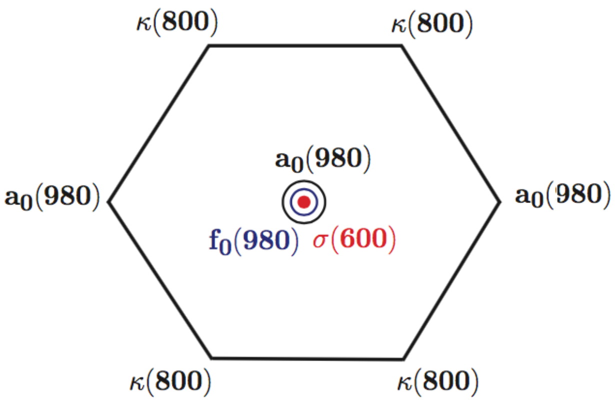
Deuteron: proton-neutron bound state
the nucleus of deuterium or heavy hydrogen



- tetraquark, promising

$f_0(600)$, $ud\bar{u}\bar{d}$; $f_0(980)$, $us\bar{u}\bar{s}$; lighter than 1 GeV

PRL110, 261601 (2013), Steven Weinberg



PRL **110,** 261601 (2013) PHYSICAL REVIEW LETTERS week ending 28 JUNE 2013

Tetraquark Mesons in Large-*N* Quantum Chromodynamics

Steven Weinberg*
Department of Physics, Theory Group, University of Texas Austin, Texas 78712, USA

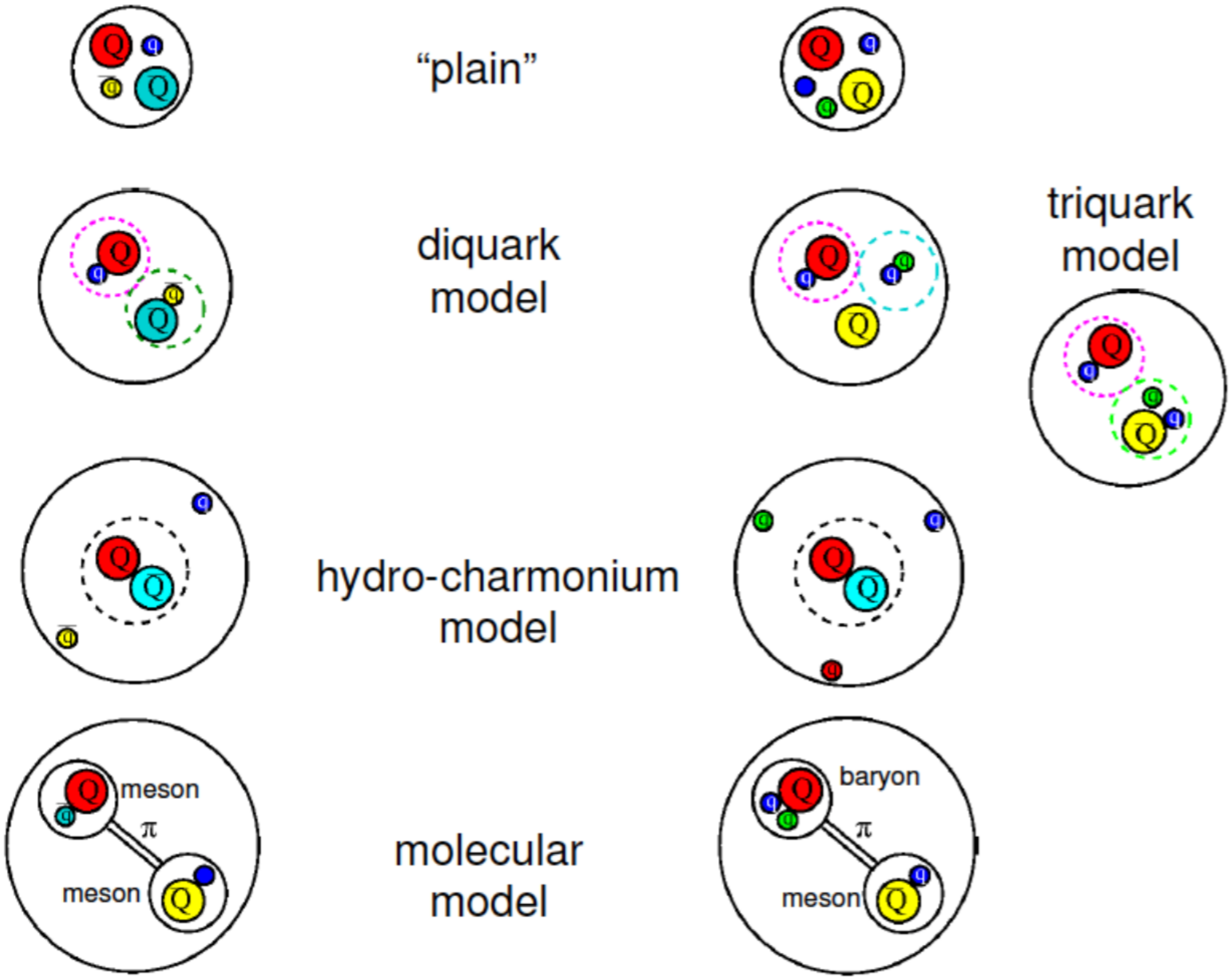
(Received 1 March 2013; published 26 June 2013)

It is argued that exotic mesons consisting of two quarks and two antiquarks are not ruled out in quantum chromodynamics with a large number N of colors, as generally thought. Tetraquarks of one class are typically long-lived, with decay rates proportional to $1/N$.

DOI: 10.1103/PhysRevLett.110.261601 PACS numbers: 11.15.Pg, 12.38.Lg, 14.40.Pq

$X(3872)$, $c\bar{c}u\bar{u}(d\bar{d})$; $Y(4140)$, $c\bar{c}s\bar{s}$; $Z_c(4430)^+$, $c\bar{c}u\bar{d}$

Different types of tetra- or penta-quarks

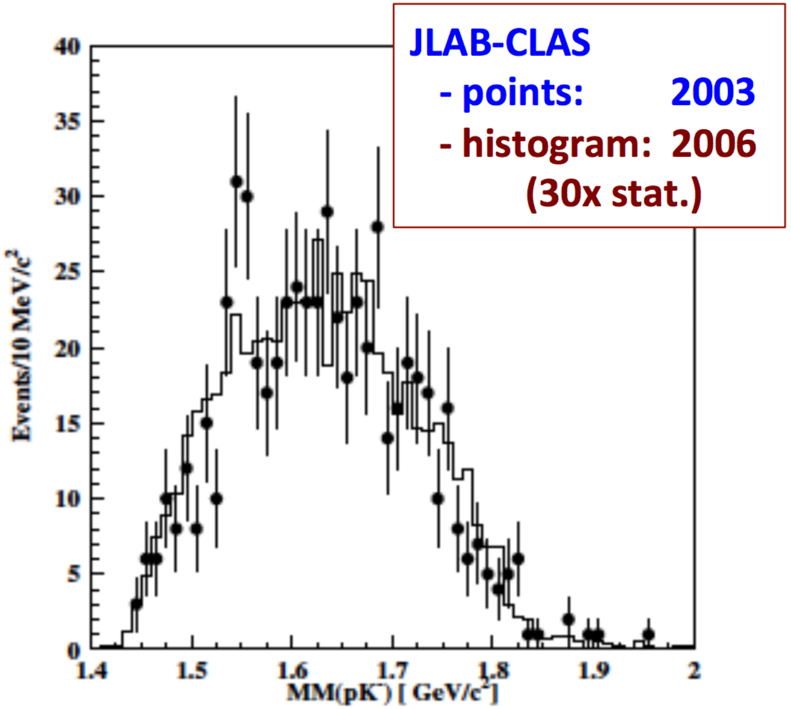


Please consult Karliner's talk.

- pentaqurk, doubtful before 2015

1^{st} observation turned out to be negative result.

LEPS, PRL91, 012002 (2003), cited by 993 records.



The whole story-
the discoveries themselves,
the tidal wave of papers
by theorists and phenomenologists
that followed,
and the eventual undiscovery -
is a curious episode
in the history of science.

PDG review
by C.G. Wohl (LBNL) in 2008

The observations from the $\Lambda_b \to J/\psi p K^-$ decay

LHCb, PRL115, 072001 (2015), arXiv:1507.03414
posted on Jul 13, cited by 111 records.

The first 3 papers posted on Jun 21, Jul 13 and 14, respectivley, published as PRL papers.

15. July 29, G.N. Li, M. He and X.G. He, arXiv:1507.08252;

25. Aug 16, Hsiao and Geng, PLB751, 572 (2015), arXiv:1508.03910;

45. Sep 12, Cheng and Chua, PRD92, 096009 (2015), arXiv:1509.03708.

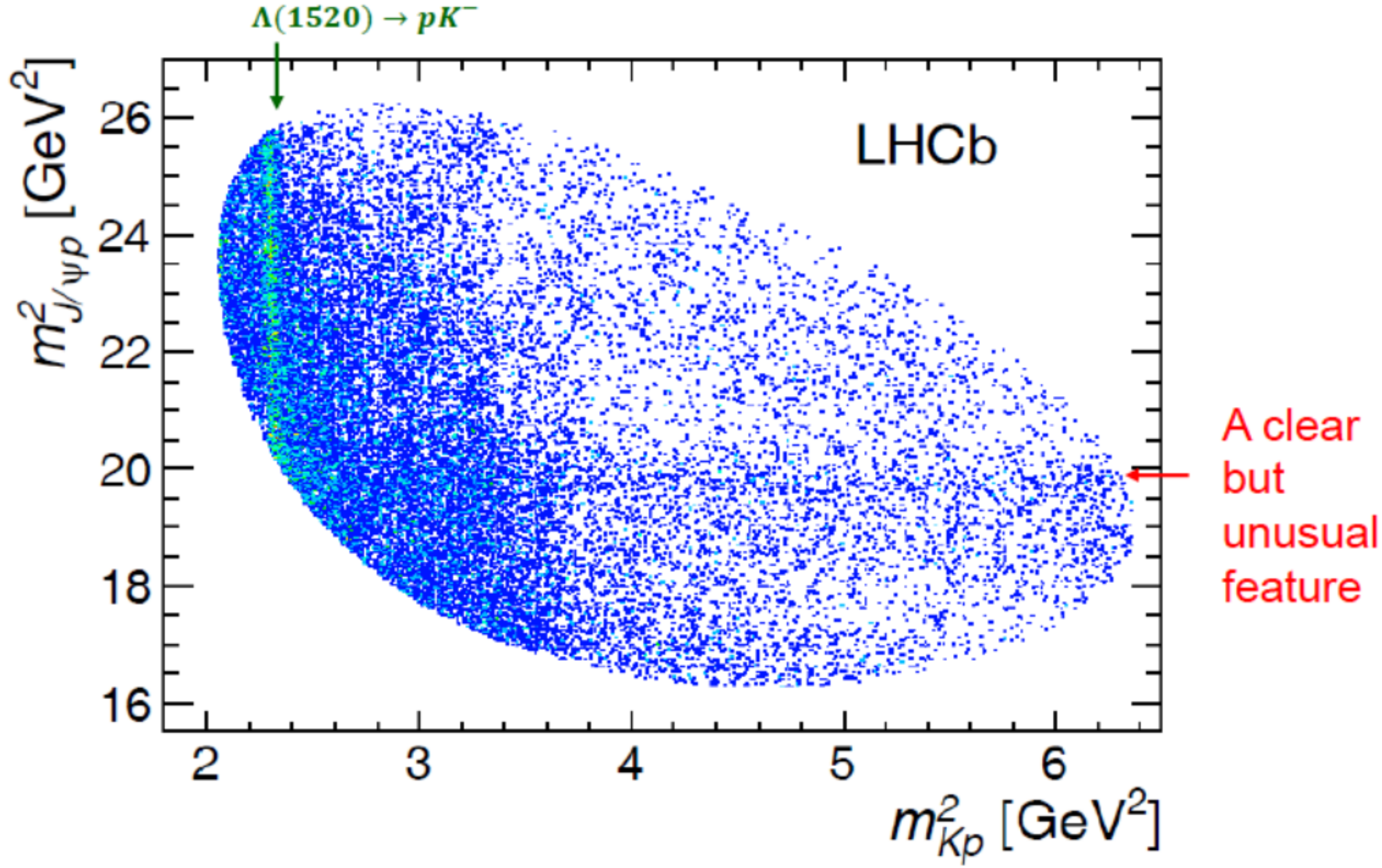
PRL **115,** 122001 (2015) PHYSICAL REVIEW LETTERS week ending 18 SEPTEMBER 2015

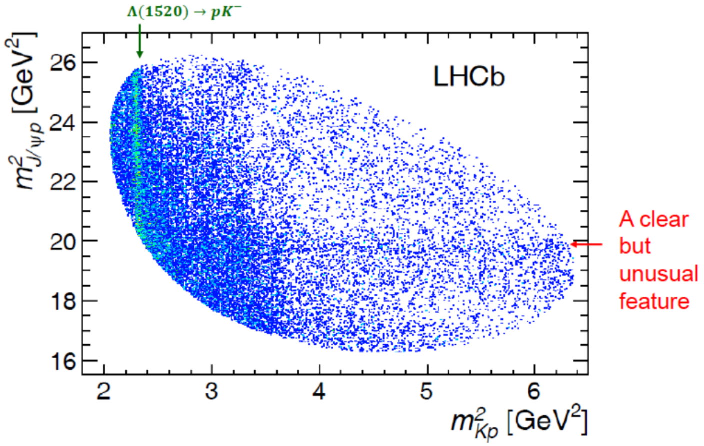
New Exotic Meson and Baryon Resonances from Doubly Heavy Hadronic Molecules

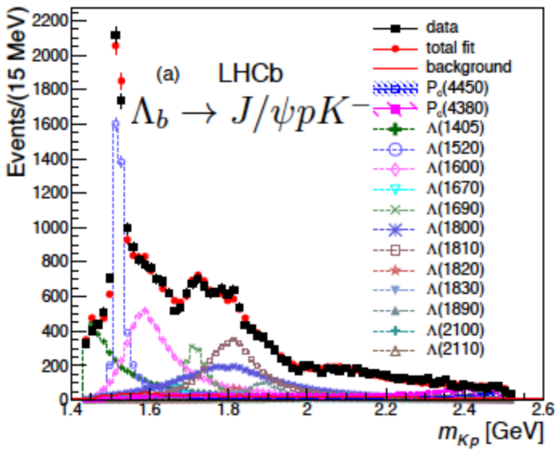
Marek Karliner[1,*] and Jonathan L. Rosner[2,†]

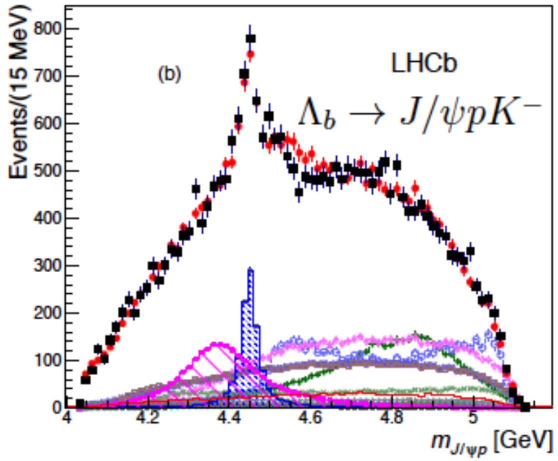
Channel	Minimum isospin	Minimal quark content[a,b]	Threshold (MeV)[c]	S-wave J^P	Example of decay mode
$\Sigma_c \bar{D}^*$	1/2	$c\bar{c}qqq'$	4462.4	$1/2^-, 3/2^-$	$J/\psi p$

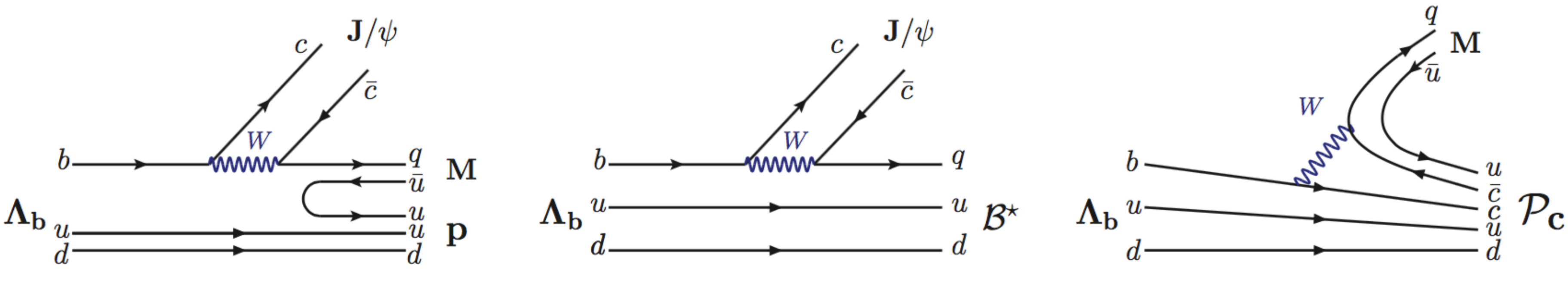
- **LHCb, cautious**











(a) (b) (c)

(a) non-resonant $\Lambda_b \to J/\Psi p M$

(b) resonant $\Lambda_b \to J/\Psi \mathcal{B}^\star, \mathcal{B}^\star \to pM$ $(\Lambda^* \to pK^-,\ N^* \to p\pi^-)$

(c) resonant $\Lambda_b \to M(\mathcal{P}_c \to) J/\psi p$ contributions

Resonance	Mass (MeV)	Width (MeV)	Fit fraction (%)
$P_c(4380)^+$	$4380 \pm 8 \pm 29$	$205 \pm 18 \pm 86$	$8.4 \pm 0.7 \pm 4.2$
$P_c(4450)^+$	$4449.8 \pm 1.7 \pm 2.5$	$39 \pm 5 \pm 19$	$4.1 \pm 0.5 \pm 1.1$
$\Lambda(1405)$			$15 \pm 1 \pm 6$
$\Lambda(1520)$			$19 \pm 1 \pm 4$

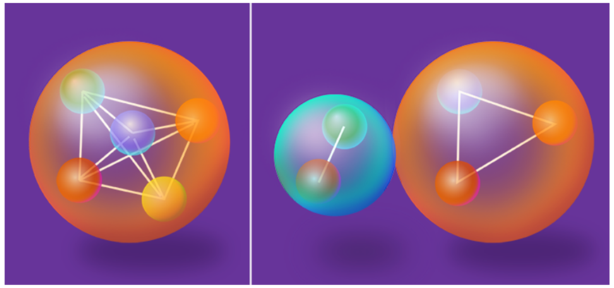
Best fit has $J^P = \left[\frac{3}{2}^- \text{(low)}, \frac{5}{2}^+ \text{(high)}\right]$

$\left[\frac{3}{2}^+ \text{(low)}, \frac{5}{2}^- \text{(high)}\right]$ & $\left[\frac{5}{2}^+ \text{(low)}, \frac{3}{2}^- \text{(high)}\right]$

$\mathcal{P}_{c1} \equiv \mathcal{P}_c(4380)^+$, $\mathcal{P}_{c2} \equiv \mathcal{P}_c(4450)^+$
observed as the resonances
in the $J/\psi p$ invariant mass spectrum
identified to consist of five quarks, $uudc\bar{c}$
consistent with the existence of the pentaquark states.

Physics **8**, 77 (2015)

Viewpoint



Elusive Pentaquark Comes into View

Kenneth Hicks
Department of Physics and Astronomy, Ohio University, Athens, OH 45701, USA

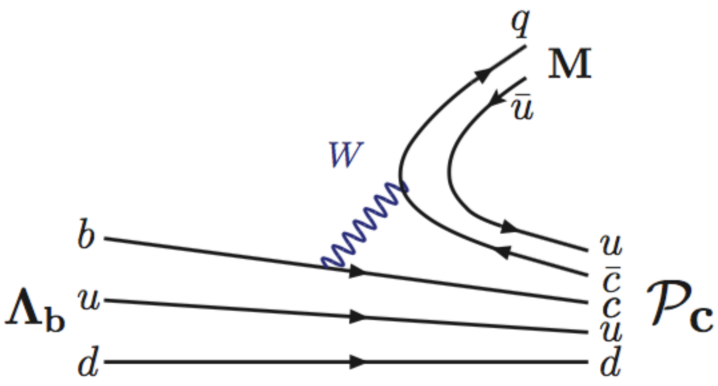
Published August 12, 2015

A new type of particle containing five quarks has been observed by the LHCb experiment.

Subject Areas: **Particles and Fields**

From studying pentaquarks and tetraquarks we will learn more about solutions to the many-body theory of QCD. LHCb's discovery is an important stepping-stone in our understanding of the strong force, the least well known of the four forces in nature.

This research is published in Physical Review Letters.



(c)

non-factorizable
neglected
calculated non-perturbatively

LHCb, PRL115, 072001 (2015), arXiv:1507.03414
LHCb, arXiv:1509.00292

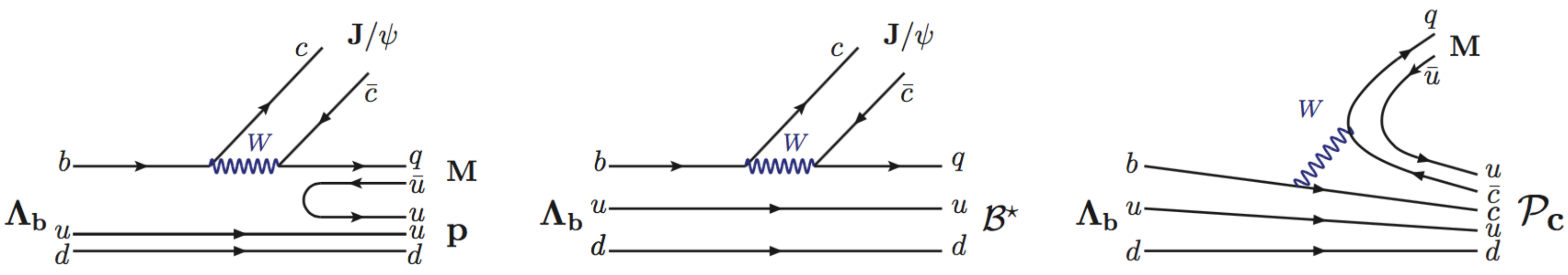
$\mathcal{B}(\Lambda_b \to K^- \mathcal{P}_c, \mathcal{P}_c \to J/\psi p)$
$= (2.56 \pm 0.22 \pm 1.28^{+0.46}_{-0.36}) \times 10^{-5}$ for $P_c(4380)^+$
$= (1.25 \pm 0.15 \pm 0.33^{+0.22}_{-0.18}) \times 10^{-5}$ for $P_c(4450)^+$
10% of $\mathcal{B}(\Lambda_b \to K^- J/\psi p)$
$= (3.04 \pm 0.04 \pm 0.06 \pm 0.33 \pm 0.43) \times 10^{-4}$

Other non-factorizable effects

$\mathcal{B}(B^+ \to \bar{p}pK^+) = (5.9 \pm 0.5) \times 10^{-6}$
$\mathcal{B}(B^+ \to \bar{p}\Theta(1710)^{++}, \Theta(1710)^{++} \to pK^+) < 9.1 \times 10^{-8}$
$60 - 70$ times smaller

$\mathcal{B}(B^0 \to \bar{p}pK^0) = (2.66 \pm 0.32) \times 10^{-6}$
$\mathcal{B}(B^0 \to \bar{p}\Theta(1540)^{+}, \Theta(1540)^{+} \to pK_s^0) < 5 \times 10^{-8}$
50 times smaller

$\mathcal{B}(B^0 \to p\bar{p}\pi^+ D^{(*)-}) = O(10^{-4})$
$\mathcal{B}(B^0 \to \Theta_c\bar{p}\pi^+, \Theta_c \to D^{(*)-}p) < 9 \times 10^{-6}\ (1.4 \times 10^{-5})$
$30 - 40$ times smaller



(a) (b) (c)

LHCb, JHEP 1407, 103 (2014)
LHCb, arXiv:1509.00292

$$\mathcal{R}_{\pi K} \equiv \frac{\mathcal{B}(\Lambda_b \to J/\psi p \pi^-)}{\mathcal{B}(\Lambda_b \to J/\psi p K^-)} = 0.0824 \pm 0.0025 \pm 0.0042$$

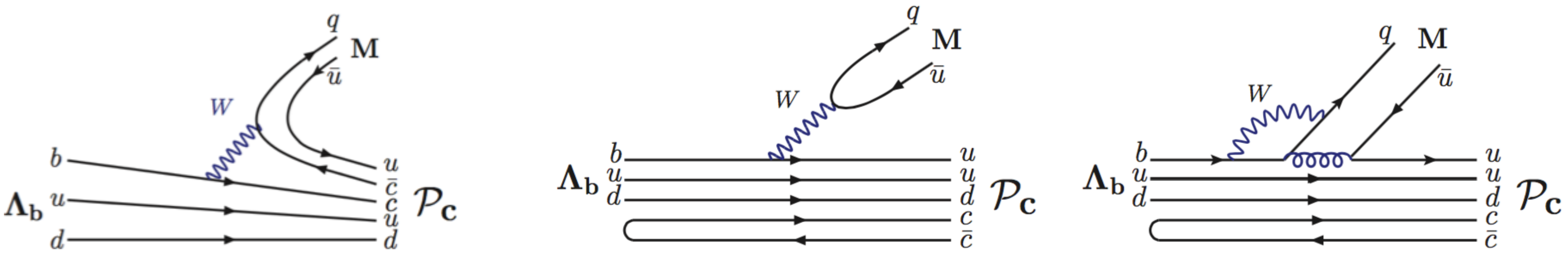
$$\mathcal{B}(\Lambda_b \to J/\psi p \pi^-) = (2.51 \pm 0.08 \pm 0.13^{+0.45}_{-0.35}) \times 10^{-5}$$

$$\Delta\mathcal{A}_{CP} \equiv \mathcal{A}_{CP}(\Lambda_b \to J/\psi p \pi^-) - \mathcal{A}_{CP}(\Lambda_b \to J/\psi p K^-)$$

$$= (5.7 \pm 2.4 \pm 1.2)\%$$

From Figs. (a), (b), (c):

$$\mathcal{R}_{\pi K} \simeq |V_{cd}/V_{cs}|^2 \simeq 0.05, \ \Delta\mathcal{A}_{CP} = 0$$



(c) (a) (b)

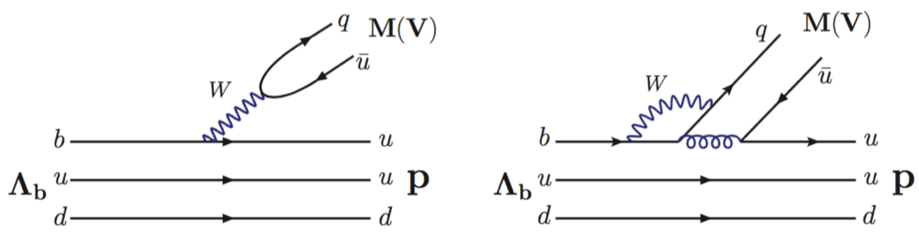
charmless $b \to u\bar{u}q$ transition:

1. $\Lambda_b \to M\mathcal{P}_c, \mathcal{P}_c \to J/\psi p$, factorizable;
2. V_{ub} for the CP phase;
3. $\mathcal{R}_{\pi K}$ raised to be 0.08;
4. The same approach as that for $\Lambda_b \to pK^{(*)-}, \pi^-, \rho^-$.

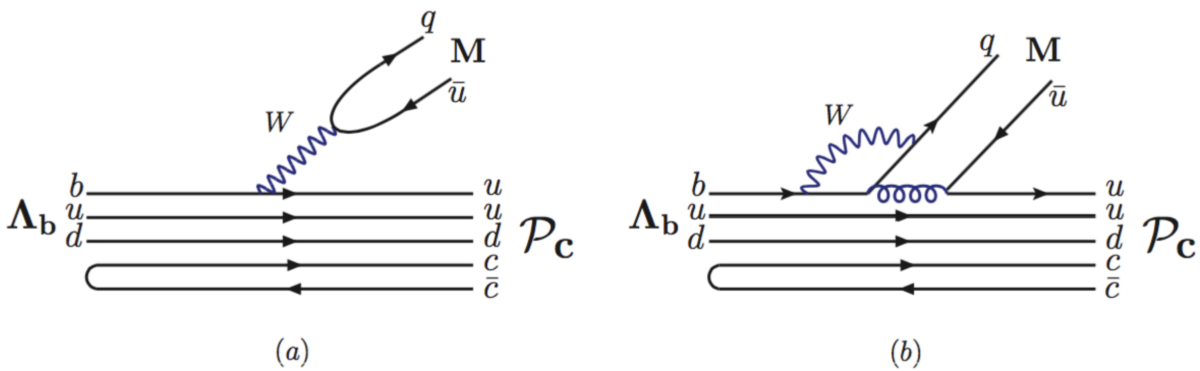
Hsiao and Geng, PRD91, 116007 (2015)

$\mathcal{B}(\Lambda_b \to pK^-, p\pi^-)$, explained.

$\mathcal{A}_{CP}(\Lambda_b \to pK^{*-})$, predicted to be 20%.



(a) (b)



Where to find a $c\bar{c}$ pair in the $b \to u\bar{u}q$ transition?

1. sea quarks

2. intrinsic charms within b-hadron or proton
Brodsky, PLB93, 451 (1980); PRD23, 2745 (1981); PRL78, 4682 (1997) for ρ-π puzzle; PRD65, 054016 (2002) for B and Λ_b.

Fock state decomposition:

$$|\Lambda_b\rangle = \Psi_{bud}|bud\rangle + \Psi_{budc\bar{c}}|budc\bar{c}\rangle + \cdots$$

3. both

- Direct CP violating asymmetry (CPA) in the Λ_b decays

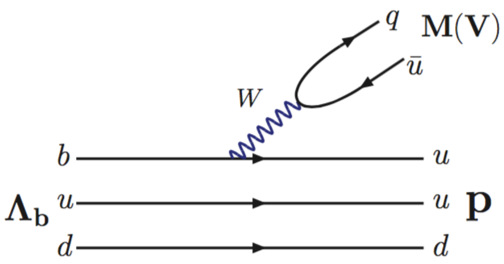
$$\mathcal{A}(\Lambda_b \to f) = a e^{i\delta_w} + b e^{i\delta_s}$$
$$\mathcal{A}(\bar{\Lambda}_b \to \bar{f}) = a e^{-i\delta_w} + b e^{i\delta_s}$$

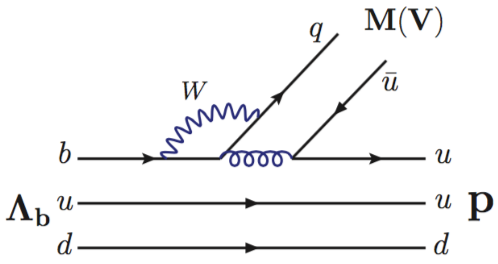
$$\Gamma(\Lambda_b \to f) \neq \Gamma(\bar{\Lambda}_b \to \bar{f})$$
$$\mathcal{A}_{CP}(\Lambda_b \to f) = \frac{\Gamma(\Lambda_b \to f) - \Gamma(\bar{\Lambda}_b \to \bar{f})}{\Gamma(\Lambda_b \to f) + \Gamma(\bar{\Lambda}_b \to \bar{f})} \propto \sin\delta_w \sin\delta_s$$

δ_s: effective Wilson coefficients, final state interactions, ...
on-shell processes give the imaginary parts

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

δ_w: $V_{ub} = A\lambda^3(\rho - i\eta)$





- Amplitude

$$\mathcal{A}(\Lambda_b \to pM) = i\frac{G_F}{\sqrt{2}} m_b f_M \left[\alpha_M \langle p|\bar{u}b|\Lambda_b\rangle + \beta_M \langle p|\bar{u}\gamma_5 b|\Lambda_b\rangle\right]$$

$$\langle M|\bar{q}_1\gamma_\mu\gamma_5 q_2|0\rangle = -if_M q_\mu$$

$$\alpha_M(\beta_M) = V_{ub}V^*_{uq}a_1 - V_{tb}V^*_{tq}(a_4 \pm r_M a_6)$$

$$r_M \equiv 2m_M^2/[m_b(m_q + m_u)]$$

$$a_i \equiv c_i^{eff} + c_{i\pm1}^{eff}/N_c^{(eff)} \text{ for } i = \text{odd (even)}$$

- $\Lambda_b \to p$ transition form factors

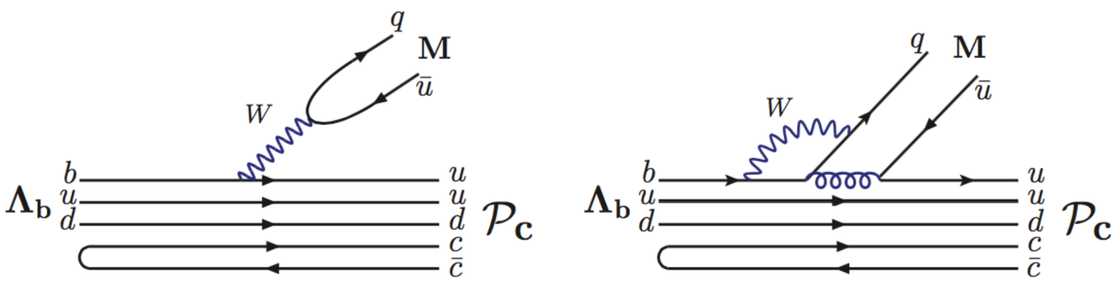
$$\langle \mathcal{B}|\bar{q}\gamma_\mu b|\mathcal{B}_b\rangle = \bar{u}_{\mathcal{B}}[f_1\gamma_\mu + \frac{f_2}{m_{\mathcal{B}_b}} i\sigma_{\mu\nu}q^\nu + \frac{f_3}{m_{\mathcal{B}_b}} q_\mu]u_{\mathcal{B}_b}$$

$$\langle \mathcal{B}|\bar{q}\gamma_\mu\gamma_5 b|\mathcal{B}_b\rangle = \bar{u}_{\mathcal{B}}[g_1\gamma_\mu + \frac{g_2}{m_{\mathcal{B}_b}} i\sigma_{\mu\nu}q^\nu + \frac{g_3}{m_{\mathcal{B}_b}} q_\mu]\gamma_5 u_{\mathcal{B}_b}$$

$$\langle \mathcal{B}|\bar{q}b|\mathcal{B}_b\rangle = f_S\bar{u}_{\mathcal{B}}u_{\mathcal{B}_b},\ \langle \mathcal{B}|\bar{q}\gamma_5 b|\mathcal{B}_b\rangle = f_P\bar{u}_{\mathcal{B}}\gamma_5 u_{\mathcal{B}_b}$$

In equation of motion:

$$f_S = \frac{m_{\mathcal{B}_b} - m_{\mathcal{B}}}{m_b - m_q} f_1,\ f_P = \frac{m_{\mathcal{B}_b} + m_{\mathcal{B}}}{m_b + m_q} g_1.$$



(a) (b)

- Amplitude

$$\mathcal{A}_{\mathcal{P}_c} = i\frac{G_F}{\sqrt{2}} m_b f_M \Big[\alpha_M \langle J/\psi p|\bar{u}b|\Lambda_b\rangle + \beta_M \langle J/\psi p|\bar{u}\gamma_5 b|\Lambda_b\rangle \Big]$$

$$\langle M|\bar{q}_1\gamma_\mu\gamma_5 q_2|0\rangle = -if_M q_\mu$$

$$\alpha_M(\beta_M) = V_{ub}V^*_{uq}a_1 - V_{tb}V^*_{tq}(a_4 \pm r_M a_6)$$

$$r_M \equiv 2m_M^2/[m_b(m_q+m_u)]$$

$$a_i \equiv c_i^{eff} + c_{i\pm1}^{eff}/N_c^{(eff)} \text{ for } i = \text{odd (even)}$$

- $\Lambda_b \to J/\psi p$ transition form factors

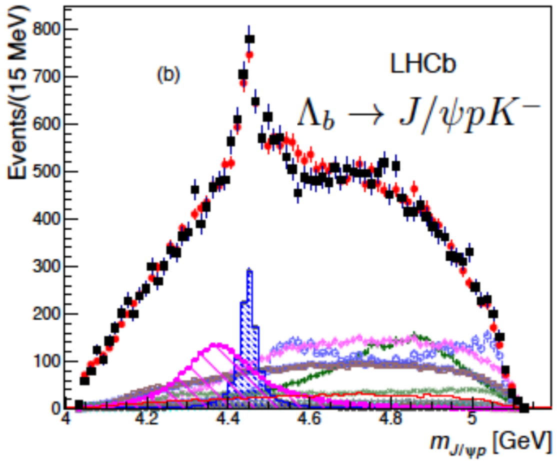
$$\langle J/\psi p|\bar{u}(\gamma_5)b|\Lambda_b\rangle = \langle J/\psi p|\mathcal{P}_c\rangle \mathcal{R}_{\mathcal{P}_c} \langle \mathcal{P}_c|\bar{u}(\gamma_5)b|\Lambda_b\rangle$$

Breit-Wigner factor:

$$\mathcal{R}_{\mathcal{P}_c} = \frac{i}{(t-m_{\mathcal{P}_c}^2)+im_{\mathcal{P}_c}\Gamma_{\mathcal{P}_c}}$$

$$\langle J/\psi p|\bar{u}b|\Lambda_b\rangle = \mathcal{R}_{\mathcal{P}_c}(\varepsilon\cdot q)F_S\bar{u}_p u_{\Lambda_b}$$

$$\langle J/\psi p|\bar{u}\gamma_5 b|\Lambda_b\rangle = \mathcal{R}_{\mathcal{P}_c}(\varepsilon\cdot q)F_P\bar{u}_p\gamma_5 u_{\Lambda_b}$$



$$
\begin{aligned}
&\mathcal{B}(\Lambda_b \to K^-\mathcal{P}_c, \mathcal{P}_c \to J/\psi p) \\
&= (2.56 \pm 0.22 \pm 1.28^{+0.46}_{-0.36}) \times 10^{-5} \text{ for } P_c(4380)^+ \\
&= (1.25 \pm 0.15 \pm 0.33^{+0.22}_{-0.18}) \times 10^{-5} \text{ for } P_c(4450)^+
\end{aligned}
$$

- Reduced amp:

$$\mathcal{A}_{\mathcal{P}_c} \simeq i\frac{G_F}{\sqrt{2}} m_b f_M \mathcal{R}_{\mathcal{P}_c} F_{\mathcal{P}_c} \bar{u}_p(\alpha_M + \beta_M \gamma_5) u_{\Lambda_b}$$

$$\mathcal{A}(\Lambda_b \to M(\mathcal{P}_{c1}, \mathcal{P}_{c2} \to) J/\psi p)$$

$$= \mathcal{A}_{\mathcal{P}_{c1}} + \mathcal{A}_{\mathcal{P}_{c2}} \simeq i\frac{G_F}{\sqrt{2}} m_b f_M F_2 e^{i\delta_2}\, \bar{u}_p(\alpha_M + \beta_M \gamma_5) u_{\Lambda_b}$$

$$F_2 e^{i\delta_2} = \mathcal{R}_{\mathcal{P}_{c1}} F_{\mathcal{P}_{c1}} + \mathcal{R}_{\mathcal{P}_{c2}} F_{\mathcal{P}_{c2}}$$

Numerical results

$$\frac{\mathcal{B}(\Lambda_b \to \pi^- (\mathcal{P}_{c1,c2} \to) J/\psi p)}{\mathcal{B}(\Lambda_b \to K^- (\mathcal{P}_{c1,c2} \to) J/\psi p)} = 0.58 \pm 0.05 \; (b \to u\bar{u}q)$$

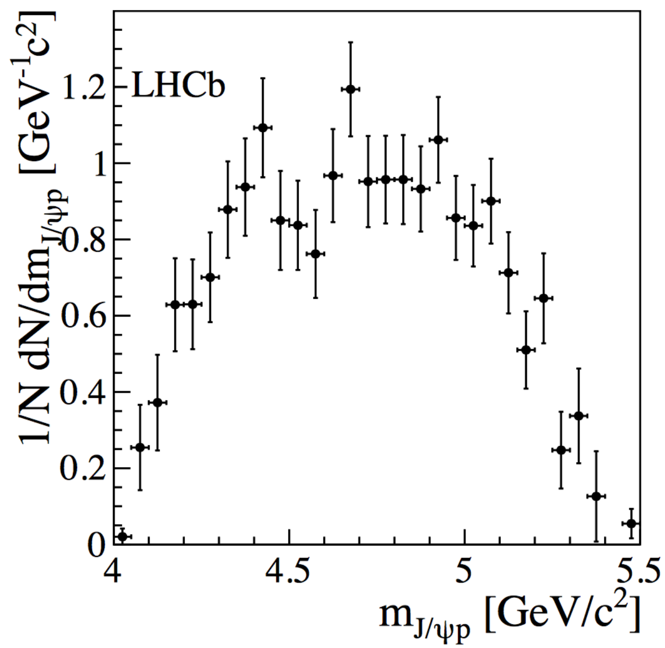
compared to

$$\frac{\mathcal{B}(\Lambda_b \to \pi^- J/\psi p)}{\mathcal{B}(\Lambda_b \to K^- J/\psi p)} = 0.075 \; (b \to c\bar{c}q)$$

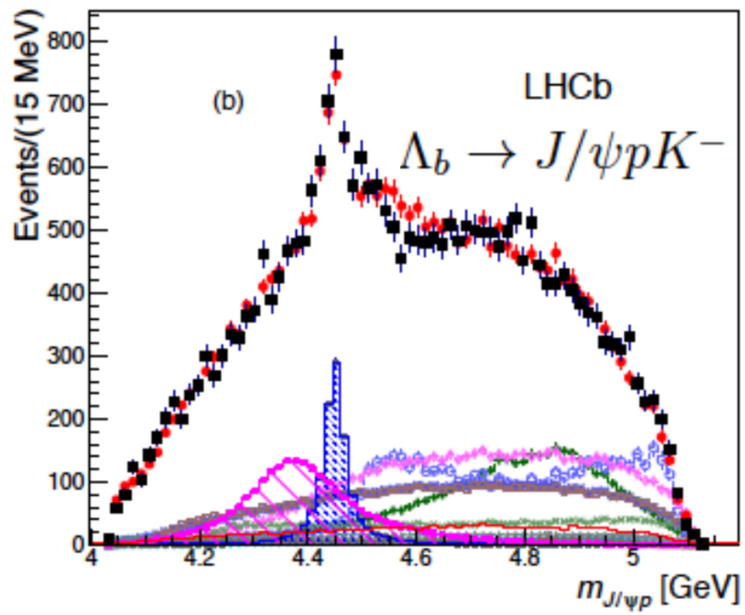
arXiv:1512.01959v1

$$\frac{\mathcal{B}(\Lambda_b \to \pi^- \mathcal{P}_c)}{\mathcal{B}(\Lambda_b \to K^- \mathcal{P}_c)} = 0.07 - 0.08 \; (b \to c\bar{c}q)$$

Cheng and Chua, PRD92, 096009 (2015)



LHCb, JHEP 1407, 103 (2014)

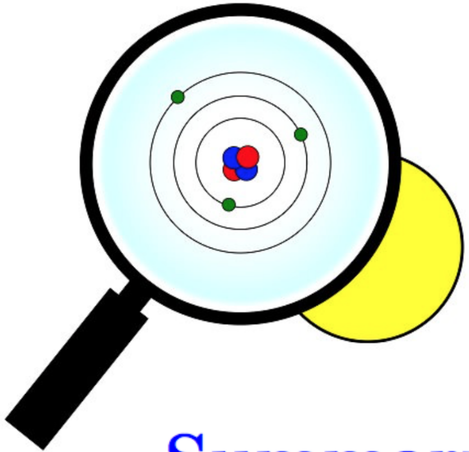


CP violating asymmetries

$$\mathcal{A}_{CP}(\Lambda_b \to \pi^-(\mathcal{P}_{c1,c2} \to)J/\psi p) = (-7.4 \pm 0.9)\%$$

$$\mathcal{A}_{CP}(\Lambda_b \to K^-(\mathcal{P}_{c1,c2} \to)J/\psi p) = (+6.3 \pm 0.2)\%$$

	data	fitting results
$\mathcal{R}_{\pi K}$	$(8.24 \pm 0.49)\%$	$(8.38 \pm 0.77)\%$
$\Delta\mathcal{A}_{CP}$	$(5.7 \pm 2.7)\%$	$(2.9 \pm 1.4)\%$
$10^4\mathcal{B}(\Lambda_b \to K^- J/\psi p)$	3.04 ± 0.55	3.21 ± 0.44
$10^6\mathcal{B}(\Lambda_b \to K^-(\mathcal{P}_{c1} \to)J/\psi p)$	25.6 ± 13.8	10.3 ± 3.9
$10^6\mathcal{B}(\Lambda_b \to K^-(\mathcal{P}_{c2} \to)J/\psi p)$	12.5 ± 4.2	10.9 ± 2.7



Summary

1. New pentaquark contributions are proposed, which provide non-zero CPAs:

$$\mathcal{A}_{CP}(\Lambda_b \to \pi^-(\mathcal{P}_{c1,c2} \to)J/\psi p) = (-7.4 \pm 0.9)\%,$$

$$\mathcal{A}_{CP}(\Lambda_b \to K^-(\mathcal{P}_{c1,c2} \to)J/\psi p) = (+6.3 \pm 0.2)\%.$$

2. $\frac{\mathcal{B}(\Lambda_b \to \pi^-(\mathcal{P}_{c1,c2} \to)J/\psi p)}{\mathcal{B}(\Lambda_b \to K^-(\mathcal{P}_{c1,c2} \to)J/\psi p)} = 0.58 \pm 0.05$

can be compared to the future experiments at LHCb.

Thank You!