Predictions for pentaquark states of hidden charm molecular nature and comparison with experiment.

E. Oset, L. Roca, J. Nieves, E. Wang, J. J Xie, W. H. Liang, L.S. Geng, H.X Chen, J.X. Lu, D. M. Li, A. Feijoo, V. K. Magas and A. Ramos

The Λ_b -> $J/\Psi\ K^-\ p$ reaction

The LHCb experiment claiming two pentaquark states

Theoretical analysis of the experimental data

The Λ_b -> $J/\Psi\ \pi^-\ p$ reaction

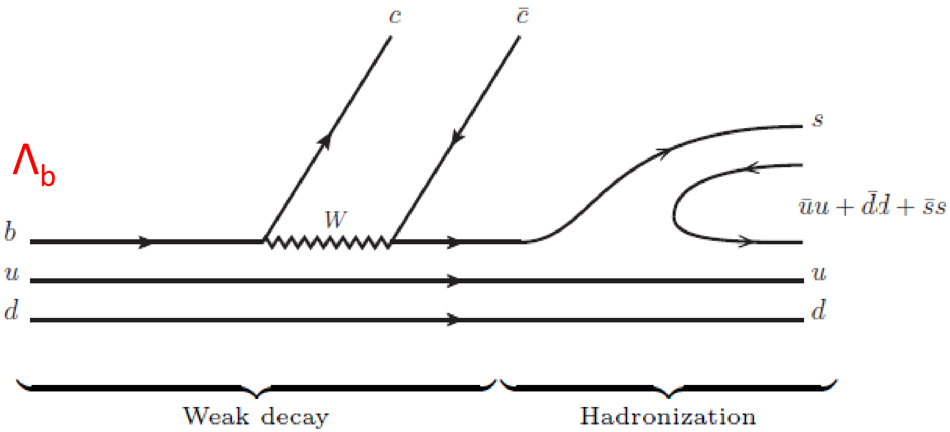
Ξ_b^- -> $J/\Psi\ K^-\ \Lambda$ and a hidden charm strange pentaquark

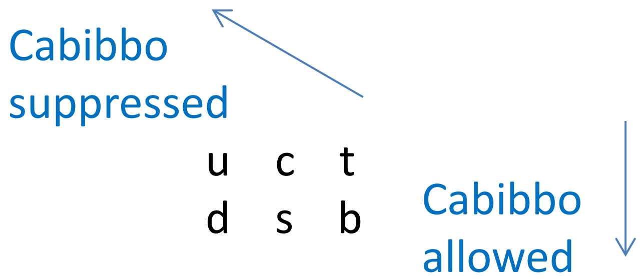
Λ_b -> $J/\Psi\ \eta\ \Lambda$

Λ_b -> $J/\Psi\ K^0\ \Lambda$

Predictions for the $\Lambda_b \to J/\psi\ \Lambda(1405)$ decay

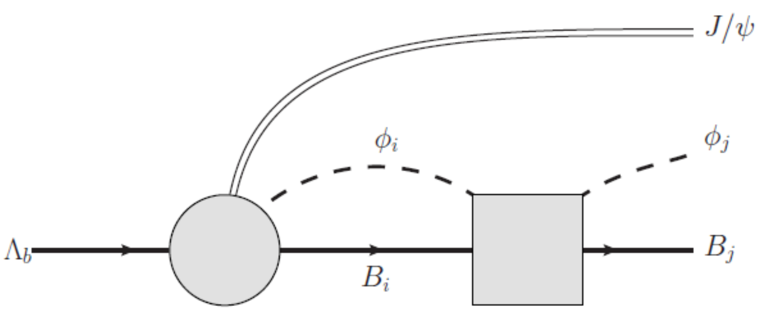
L. Roca, M. Mai, E.Oset and U.G. Meissner, EPJC 2015





$$|H\rangle = |K^- p\rangle + |\bar{K}^0 n\rangle - \frac{\sqrt{2}}{3}|\eta\Lambda\rangle + \frac{2}{3}|\eta'\Lambda\rangle$$

u d quarks in I=0 u d quarks in I=0 (spectators) an s quark -> total I=0



$$\mathcal{M}_j(M_{\rm inv}) = V_p \left(h_j + \sum_i h_i G_i(M_{\rm inv})\, t_{ij}(M_{\rm inv}) \right)$$

$$h_{\pi^0\Sigma^0} = h_{\pi^+\Sigma^-} = h_{\pi^-\Sigma^+} = 0\,,\ \ h_{\eta\Lambda} = -\frac{\sqrt{2}}{3}$$

$$h_{K^-p} = h_{\bar{K}^0 n} = 1\,,\ \ h_{K^+\Xi^-} = h_{K^0\Xi^0} = 0\,,$$

$$|\Lambda_b\rangle = \frac{1}{\sqrt{2}}|b(ud - du)\rangle$$

turning after the weak process into

$$\frac{1}{\sqrt{2}}|s(ud - du)\rangle$$

$$|H\rangle \equiv \frac{1}{\sqrt{2}}|s\,(\bar{u}u + \bar{d}d + \bar{s}s)\,(ud - du)\rangle$$
$$= \frac{1}{\sqrt{2}}\sum_{i=1}^{3}|P_{3i}q_i(ud - du)\rangle\,,$$

$$q \equiv \begin{pmatrix} u \\ d \\ s \end{pmatrix} \quad \text{and} \quad P \equiv q\bar{q}^{\tau} = \begin{pmatrix} u\bar{u} & u\bar{d} & u\bar{s} \\ d\bar{u} & d\bar{d} & d\bar{s} \\ s\bar{u} & s\bar{d} & s\bar{s} \end{pmatrix}$$

$$P = \begin{pmatrix} \frac{\pi^0}{\sqrt{2}} + \frac{\eta}{\sqrt{3}} + \frac{\eta'}{\sqrt{6}} & \pi^+ & K^+ \\ \pi^- & -\frac{1}{\sqrt{2}}\pi^0 + \frac{\eta}{\sqrt{3}} + \frac{\eta'}{\sqrt{6}} & K^0 \\ K^- & \bar{K}^0 & -\frac{\eta}{\sqrt{3}} + \frac{2\eta'}{\sqrt{6}} \end{pmatrix}$$

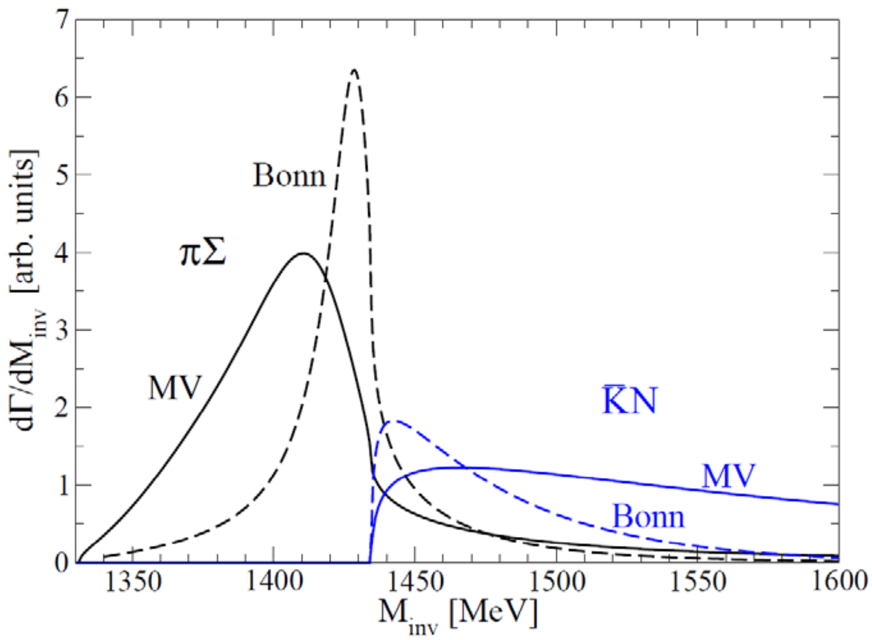
$$|H\rangle = \frac{1}{\sqrt{2}}\Big(K^- u(ud - du) + \bar{K}^0 d(ud - du) + \frac{1}{\sqrt{3}}\left(-\eta + \sqrt{2}\eta'\right) s(ud - du)\Big)$$

$$|p\rangle = \frac{1}{\sqrt{2}}|u(ud - du)\rangle\,,$$
$$|n\rangle = \frac{1}{\sqrt{2}}|d(ud - du)\rangle\,,$$
$$|\Lambda\rangle = \frac{1}{\sqrt{12}}|(usd - dsu) + (dus - uds) + 2(sud - sdu)\rangle$$

$$|H\rangle = |K^- p\rangle + |\bar{K}^0 n\rangle - \frac{\sqrt{2}}{3}|\eta\Lambda\rangle + \frac{2}{3}|\eta'\Lambda\rangle$$

Predictions for the K^- p and $\pi\Sigma$ mass distributions

We need the meson-baryon transition amplitudes in coupled channels.
We take them from the chiral unitary approach.



We have there J/ψ K^- p , the final state in the LHCb pentaquark experiment

One sees a clear peak for the Λ(1405) production in the πΣ invariant mass distribution

Observation of $J/\psi\, p$ resonances consistent with pentaquark states in $\Lambda_b^0 \to J/\psi K^- p$ decays

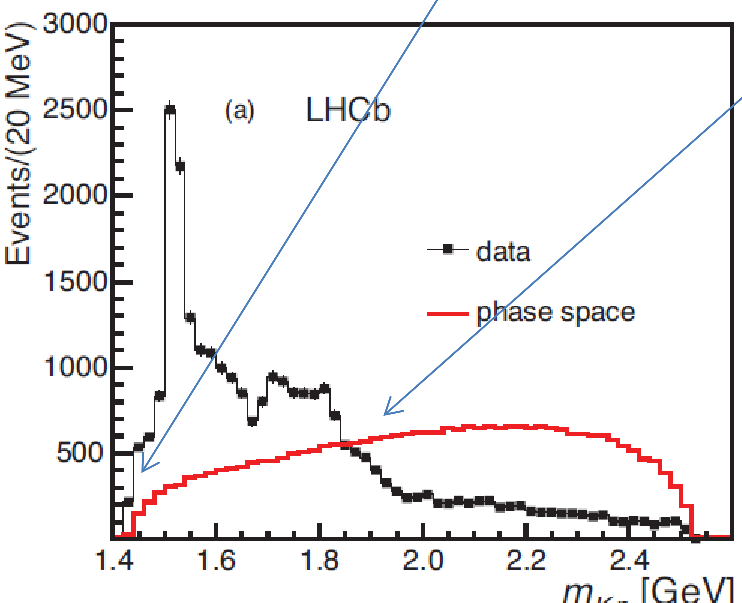
LHCb Collaboration

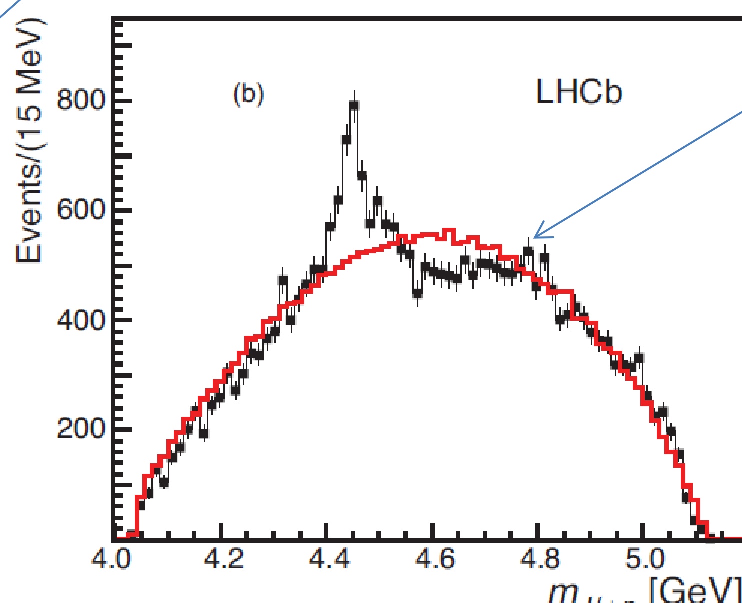
Phys.Rev.Lett. 115 (2015) 072001

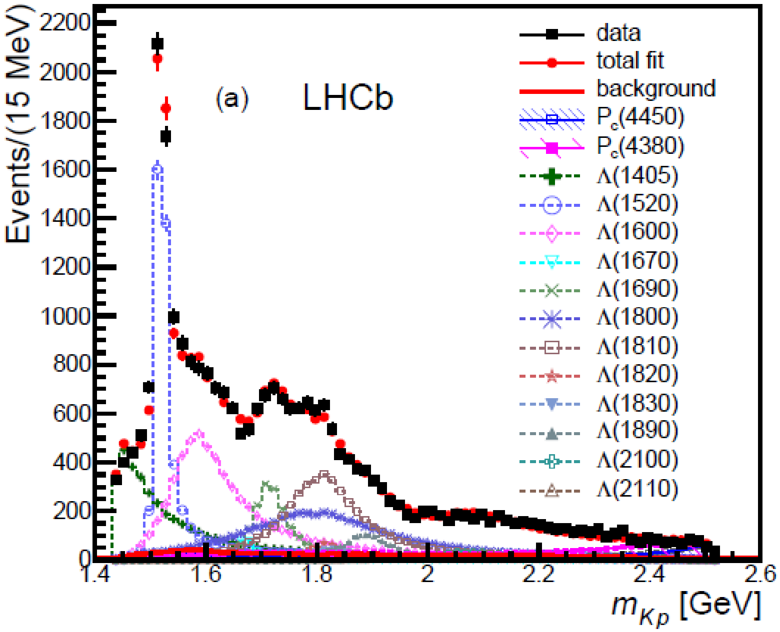
Note the large deviation from phase space for K^- p

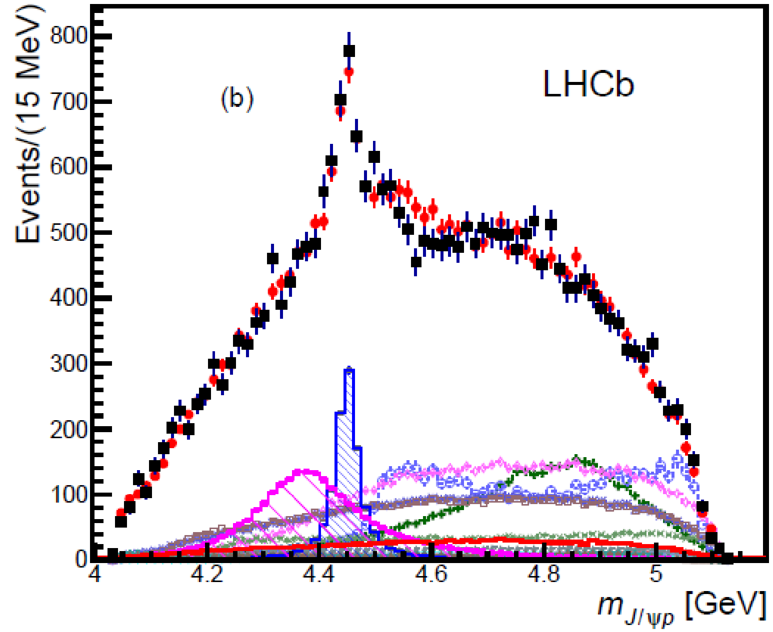
While for J/ψ p one has essentially phase space except for the peak

Large concentration of strength around threshold





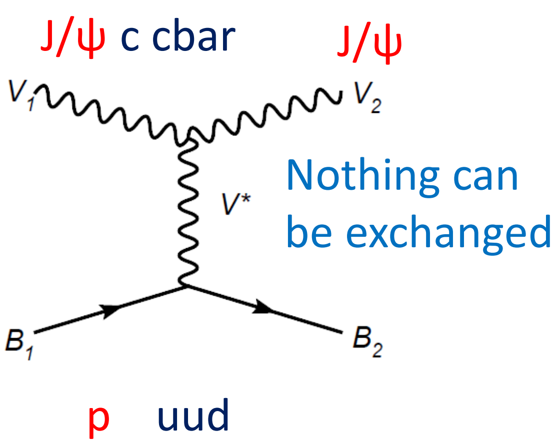


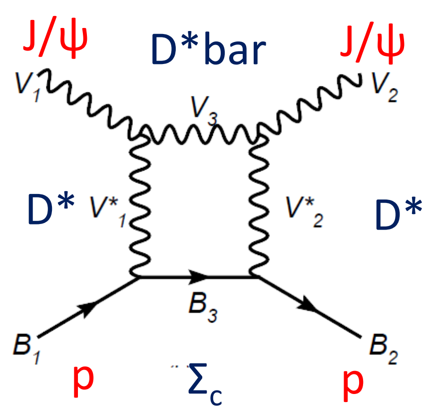


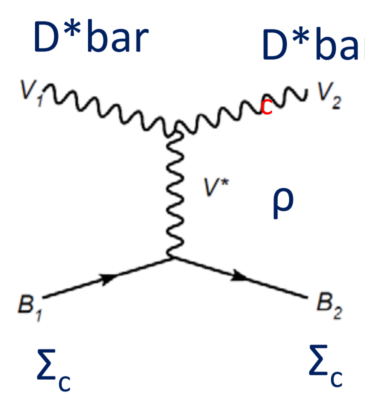
Two states claimed: Pc(4380), Γ=205 MeV ; Pc(4450), Γ=40 MeV

Assignements: $3/2^-$, $5/2^+$; $3/2^+$, $5/2^-$; $5/2^+$, $3/2^-$ .... Other less likeky

How can the peak in J/ψ appear? The J/ψ N interaction is very weak !!







Predictions for hidden charm Baryon states

J J Wu, R Molina, E. O, B S Zou, PRL (2010)

(I,S)	z_R	g_a		
$(1/2,0)$		$\bar{D}^*\Sigma_c$	$\bar{D}^*\Lambda_c^+$	$J/\psi N$
	$4415-9.5i$	$2.83-0.19i$	$-0.07+0.05i$	$-0.85+0.02i$
		2.83	0.08	0.85

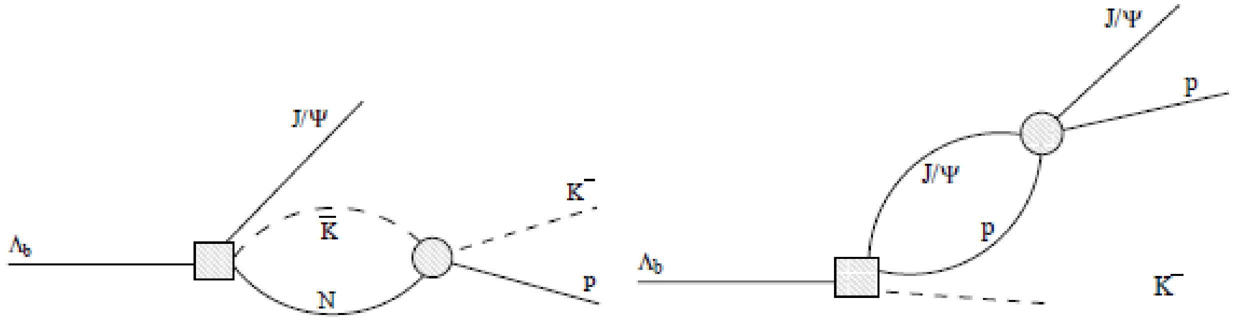
In s-wave: $3/2^-$

C W Xiao, J Nieves , E. O, PRD 2013 : D*bar Σ_c* channel included

$4417.04+i4.11$	$J/\psi N$	$\bar{D}^*\Lambda_c$	$\bar{D}^*\Sigma_c$	$\bar{D}\Sigma_c^*$	$\bar{D}^*\Sigma_c^*$
g_i	$0.53-i0.07$	$0.08-i0.07$	$2.81-i0.07$	$0.12-i0.10$	$0.11-i0.51$
$\lvert g_i\rvert$	0.53	0.11	2.81	0.16	0.52

$4481.04+i17.38$	$J/\psi N$	$\bar{D}^*\Lambda_c$	$\bar{D}^*\Sigma_c$	$\bar{D}\Sigma_c^*$	$\bar{D}^*\Sigma_c^*$
g_i	$1.05+i0.10$	$0.18-i0.09$	$0.12-i0.10$	$0.22-i0.05$	$2.84-i0.34$
$\lvert g_i\rvert$	1.05	0.20	0.16	0.22	2.86

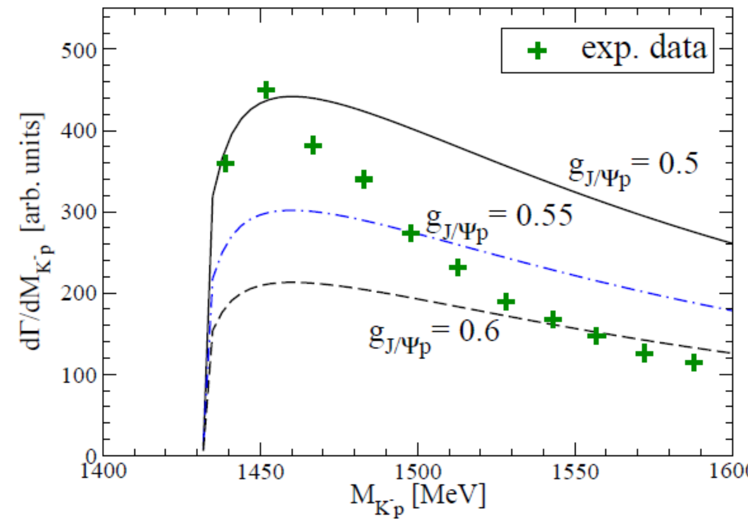
L. Roca, J. Nieves, E. O
PRD 92, 094003 (2015)



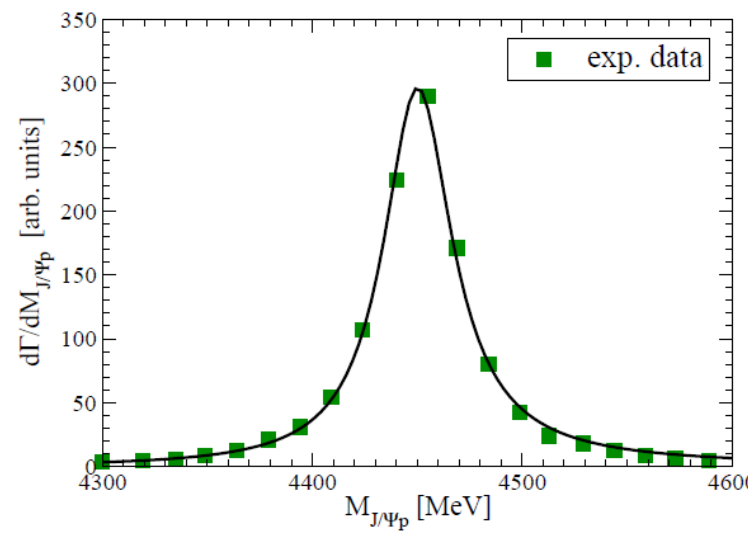
(b) (c)

$$T^{(J/\psi\, p)}(M_{J/\psi\, p}) = V_p\, h_{K^- p} G_{J/\psi\, p}(M_{J/\psi\, p}) \times t_{J/\psi\, p \to J/\psi\, p}(M_{J/\psi\, p}) ,$$

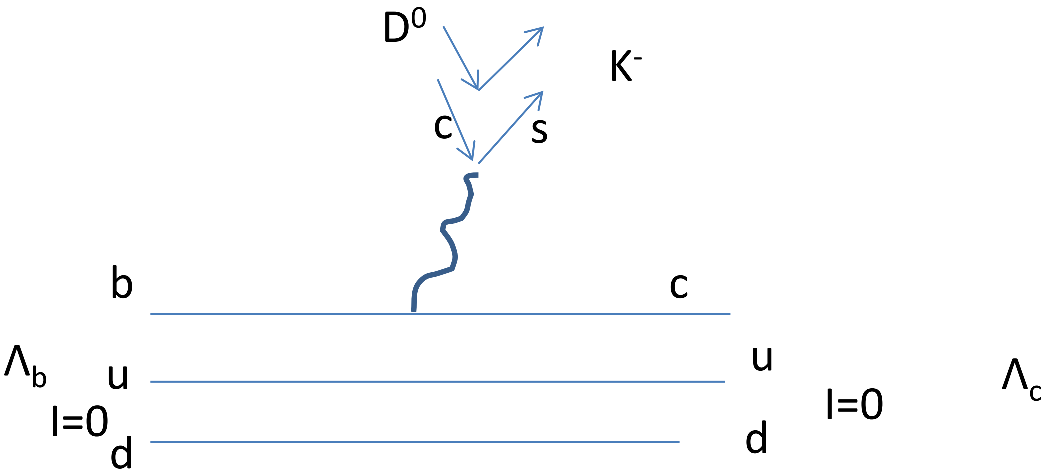
$$t_{J/\psi\, p \to J/\psi\, p} = \frac{g^2_{J/\psi\, p}}{M^2_{J/\psi\, p} - M_R^2 + i M_R \Gamma_R} \quad 2M_R$$



(a)



It is not trivial that the K^- p and J/ψ p distributions can be related like that



Since D*bar Σ_c is the main channel one should start from this production and then make transition to J/ψ p, but this configuration is now allowed

D*bar Λ_c is allowed

but it is has a very small strength in the wave function

This leaves only J/ψ p to initiate the interaction to produce the resonance

The D*bar Σ_c or D*bar Σ^*_c picture endures all tests of experiment: mass and width, spin parity $3/2^-$ acceptable, coupling of resonance to J/ψ acceptable, nontrivial relation of J/ψ p and K^- p distributions established.

Reanalysis including more resonances

L. Roca and E. O, 1602. 06791

The former work assumes the two pentaquark states to be in S-wave in J/Ψ p

If Pc is 3/2- , the K^- is 0^- and we need p-wave in the kaon to match 1/2 of Λ_b

$$\frac{d^2\Gamma_{\Lambda_b\to J/\psi K^- p}(M_{K^-p}, M_{J/\psi p})}{dM_{K^-p}dM_{J/\psi p}} = \frac{1}{16\pi^3}\frac{m_p}{m^2_{\Lambda_b}} \times$$
$$\times M_{Kp}M_{J/\psi p}\left|T(M_{Kp}, M_{J/\psi p})\right|^2 ,$$

$$P_{\frac{3}{2}^-} = \langle m_p \mid k_j\,\epsilon_j + \frac{i}{2}\,\epsilon_{ijl}\,\sigma_l\,k_i\epsilon_j \mid m_{\Lambda_b}\rangle$$

$$P_{\frac{1}{2}^-} = \langle m_p \mid k_j\,\epsilon_j - i\,\epsilon_{ijl}\,\sigma_l\,k_i\epsilon_j \mid m_{\Lambda_b}\rangle$$

$$S_{\frac{1}{2}^-} = \vec{\sigma}\cdot\vec{\epsilon}$$

$$D_{\frac{3}{2}^-} = \langle m_p \mid (k_ik_j - \frac{1}{3}\vec{k}^2\delta_{ij})\sigma_i\epsilon_j \mid m_{\Lambda_b}\rangle$$

$$D_{\frac{5}{2}^+} = \langle m_p \mid i(\vec{\sigma}\times\vec{\epsilon})_i p_j (k_ik_j - \frac{1}{3}\vec{k}^2\delta_{ij}) \mid m_{\Lambda_b}\rangle$$

$\Lambda(1405)$ $(1/2^-)$

$\Lambda(1520)$ $(3/2^-)$

$\Lambda(1600)$ $(1/2^+)$

$\Lambda(1690)$ $(3/2^-)$

$\Lambda(1800)$ $(1/2^-)$

$\Lambda(1810)$ $(1/2^+)$

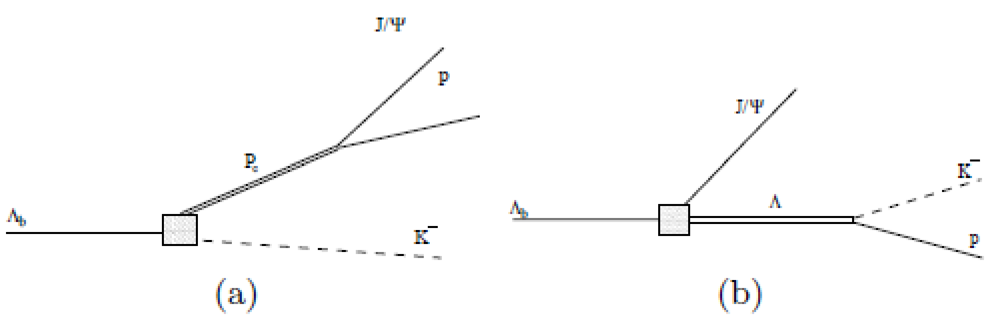
The production of the Λ resonances, and Pc can be put in terms of these operators

$$T = aS_{\frac{1}{2}^-} + bP_{\frac{3}{2}^-} + cP_{\frac{1}{2}^-} + eD_{\frac{3}{2}^-} + fD_{\frac{5}{2}^+}$$

The coefficient a , b, c ,e , f contain parameters associated to the production of the Λ resonances or pentaquarks

The pentaquarks with $1/2^-$ and $3/2^-$ are generated from the J/Ψ p interaction.

Pc with other quantum numbers are introduced explicitly



A fit is done to the experimental mass distributions to determine the parameters

$$
\begin{aligned}
a =&\alpha_1 \left(1 + G_{K^-p}(M_{K^-p})\, t^{I=0}_{\bar{K}N,\bar{K}N}(M_{K^-p})\right) \\
&+\delta_{J^P_B,\frac{1}{2}^-}\alpha_2\, G_{J/\psi p} \frac{g^2_{J/\psi\, p}}{M_{J/\psi\, p} - m_{P_c(4450)} + i\frac{\Gamma_{P_c(4450)}}{2}} \\
&+\delta_{J^P_A,\frac{1}{2}^-}\alpha_3\, G_{J/\psi p} \frac{g^2_{J/\psi\, p}}{M_{J/\psi\, p} - m_{P_c(4380)} + i\frac{\Gamma_{P_c(4380)}}{2}} \\
&+\alpha_4 \frac{1}{M_{K^-p} - m_{\Lambda(1800)} + i\frac{\Gamma_{\Lambda(1800)}}{2}},
\end{aligned}
$$

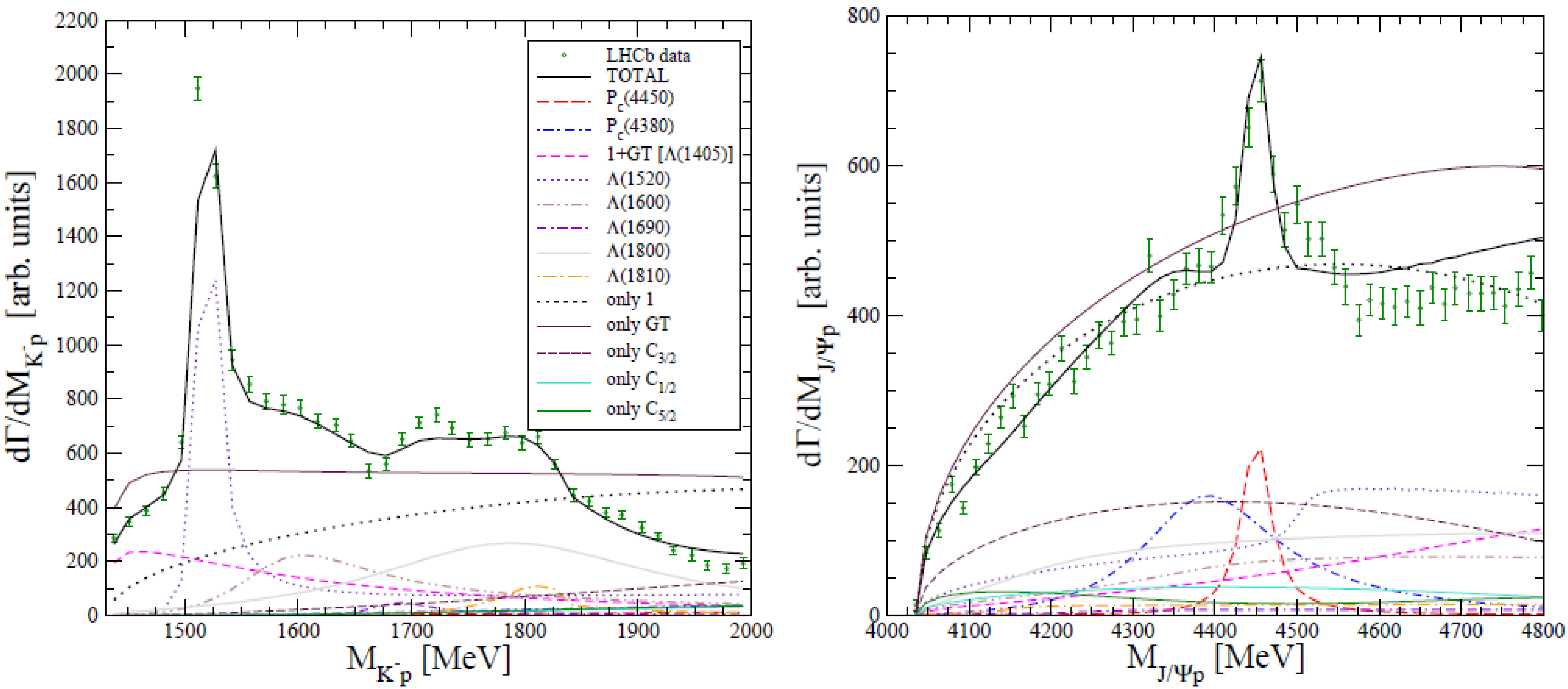
$$
\begin{aligned}
c =& -\frac{1}{3}\alpha_5 \frac{1}{M_{K^-p} - m_{\Lambda(1600)} + i\frac{\Gamma_{\Lambda(1600)}}{2}} \\
&-\frac{1}{3}\alpha_6 \frac{1}{M_{K^-p} - m_{\Lambda(1810)} + i\frac{\Gamma_{\Lambda(1810)}}{2}} \\
&+ C_{1/2}\Big[1+ \\
&+ \delta_{J^P_B,\frac{1}{2}^-}\alpha_2\, G_{J/\psi p} \frac{g^2_{J/\psi\, p}}{M_{J/\psi\, p} - m_{P_c(4450)} + i\frac{\Gamma_{P_c(4450)}}{2}} \\
&+ \delta_{J^P_A,\frac{1}{2}^-}\alpha_3\, G_{J/\psi p} \frac{g^2_{J/\psi\, p}}{M_{J/\psi\, p} - m_{P_c(4380)} + i\frac{\Gamma_{P_c(4380)}}{2}}\Big]
\end{aligned}
\tag{24}
$$

$$
\begin{aligned}
b =& \frac{4}{3}\alpha_5 \frac{1}{M_{K^-p} - m_{\Lambda(1600)} + i\frac{\Gamma_{\Lambda(1600)}}{2}} \\
&+ \frac{4}{3}\alpha_6 \frac{1}{M_{K^-p} - m_{\Lambda(1810)} + i\frac{\Gamma_{\Lambda(1810)}}{2}} \\
&+ C_{3/2}\Big[1+ \\
&+ \delta_{J^P_B,\frac{3}{2}^-}\alpha_2\, G_{J/\psi p} \frac{g^2_{J/\psi\, p}}{M_{J/\psi\, p} - m_{P_c(4450)} + i\frac{\Gamma_{P_c(4450)}}{2}} \\
&+ \delta_{J^P_A,\frac{3}{2}^-}\alpha_3\, G_{J/\psi p} \frac{g^2_{J/\psi\, p}}{M_{J/\psi\, p} - m_{P_c(4380)} + i\frac{\Gamma_{P_c(4380)}}{2}}
\end{aligned}
$$

$$
\begin{aligned}
e =&\alpha_7 \frac{1}{M_{K^-p} - m_{\Lambda(1520)} + i\frac{\Gamma_{\Lambda(1520)}}{2}} \\
&+\alpha_8 \frac{1}{M_{K^-p} - m_{\Lambda(1690)} + i\frac{\Gamma_{\Lambda(1690)}}{2}}
\end{aligned}
\tag{25}
$$

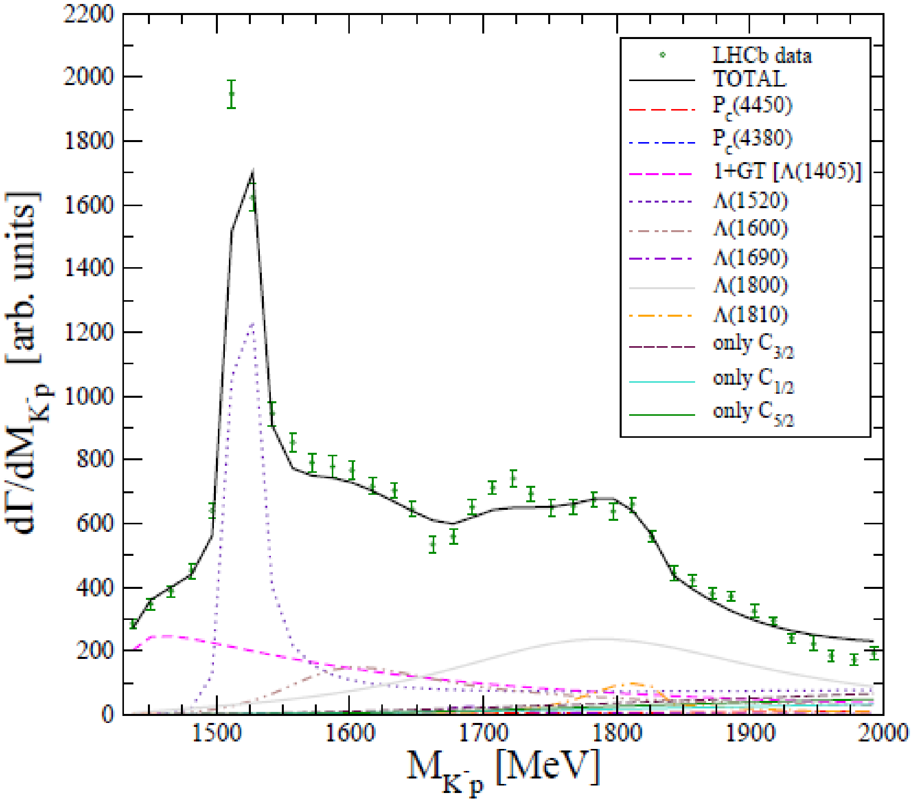
$$
\begin{aligned}
f =&C_{5/2}\Big[1+ \\
&+ \delta_{J^P_B,\frac{5}{2}^+}\alpha_9 \frac{1}{M_{J/\psi\, p} - m_{P_c(4450)} + i\frac{\Gamma_{P_c(4450)}}{2}} \\
&+ \delta_{J^P_A,\frac{5}{2}^+}\alpha_{10} \frac{1}{M_{J/\psi\, p} - m_{P_c(4380)} + i\frac{\Gamma_{P_c(4380)}}{2}}\Big].
\end{aligned}
$$

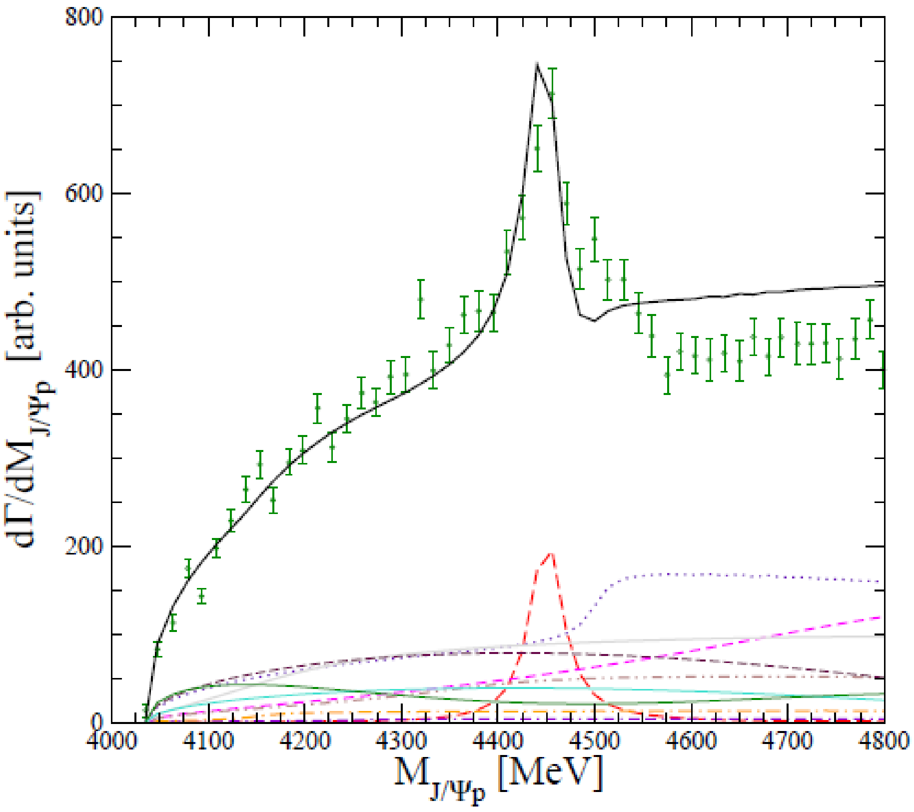
3/2 -, 3/2-



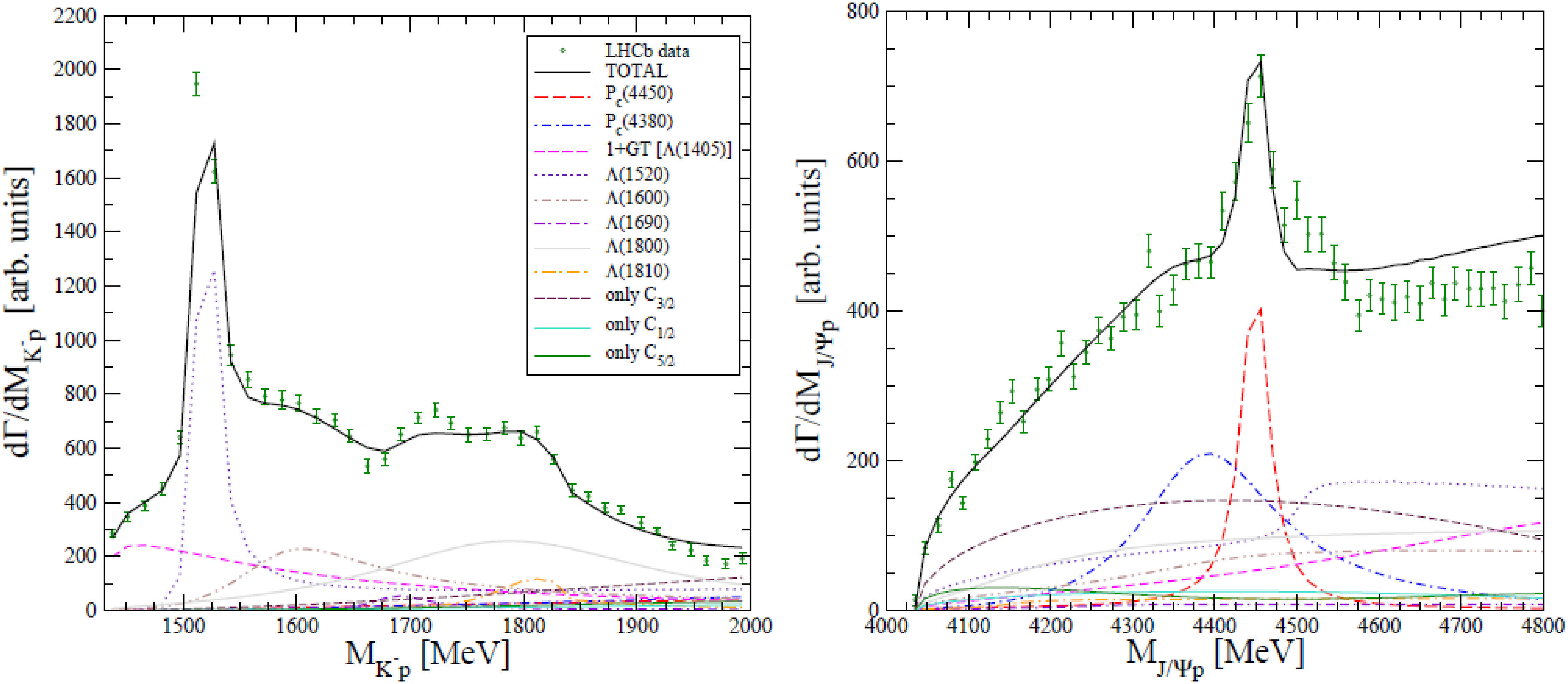
LHCb data
TOTAL
P_c(4450)
P_c(4380)
1+GT [Λ(1405)]
Λ(1520)
Λ(1600)
Λ(1690)
Λ(1800)
Λ(1810)
only 1
only GT
only C_3/2
only C_1/2
only C_5/2
dΓ/dM_K⁻p [arb. units]
M_K⁻p [MeV]
dΓ/dM_J/Ψp [arb. units]
M_J/Ψp [MeV]

Same removing the wide Pc state





3/2 - , 5/2 +



LHCb data
TOTAL
Pc(4450)
Pc(4380)
1+GT [Λ(1405)]
Λ(1520)
Λ(1600)
Λ(1690)
Λ(1800)
Λ(1810)
only C3/2
only C1/2
only C5/2
dΓ/dMK-p [arb. units]
MK-p [MeV]
dΓ/dMJ/Ψp [arb. units]
MJ/Ψp [MeV]

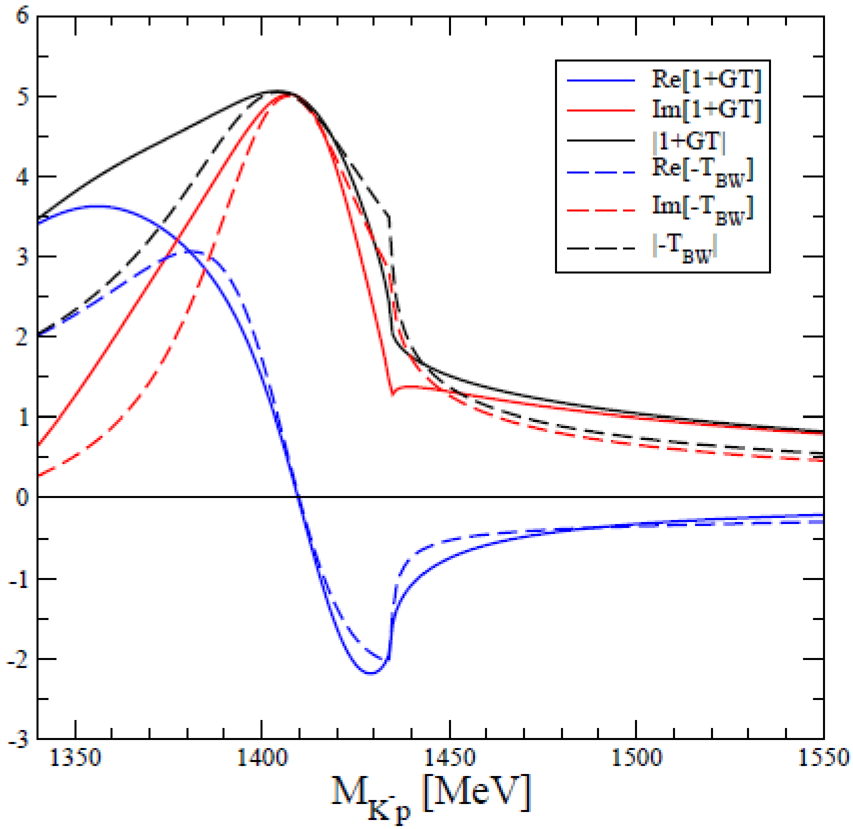
(a) (b)

Lucky experimental analysis

$$1 + GT = V^{-1}T,$$

$$(1 + GT)_{11} = (V^{-1}T)_{11} = \frac{T_{11}V_{22} - T_{12}V_{12}}{V_{11}V_{22} - V_{12}^2}$$

If V_{12} is small $(1 + GT)_{11} \simeq \frac{T_{11}}{V_{11}} \propto -T_{11}$



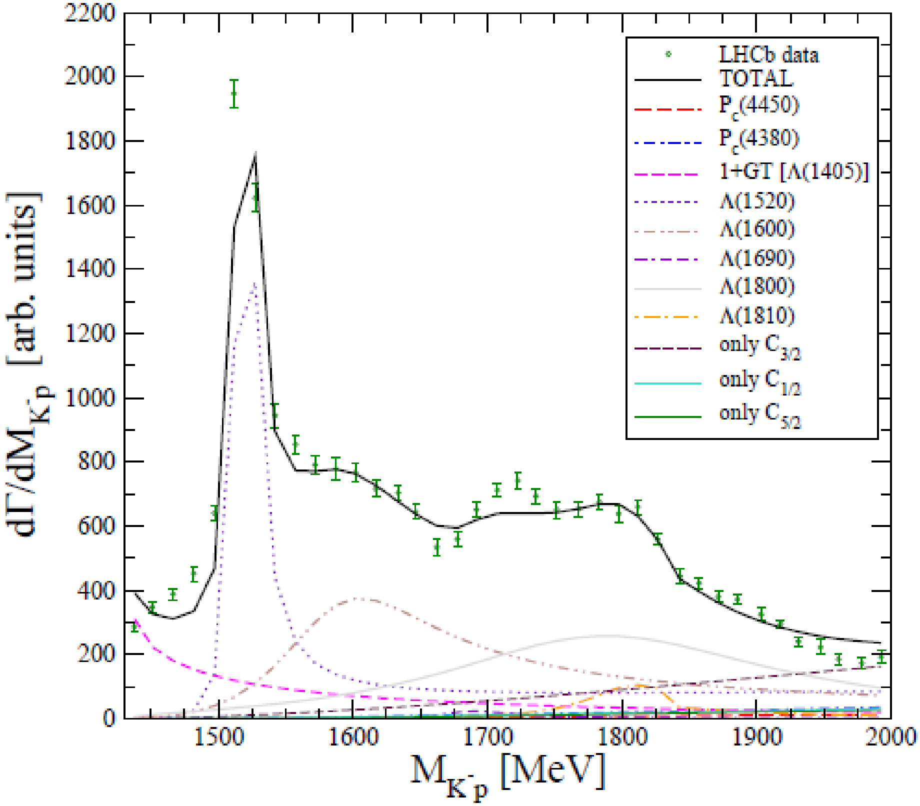
$$T_{11} \simeq \frac{g_1^A g_1^A}{\sqrt{s} - \sqrt{s_0^A}} + \frac{g_1^B g_1^B}{\sqrt{s} - \sqrt{s_0^B}}$$

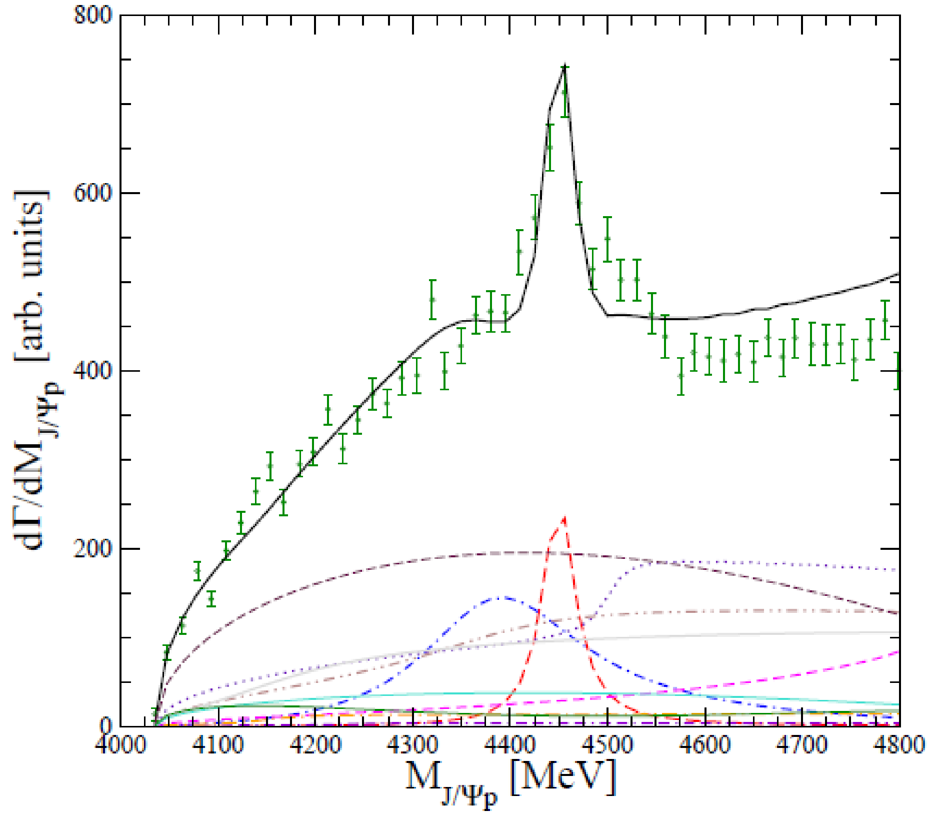
$$T_{12} \simeq \frac{g_1^A g_2^A}{\sqrt{s} - \sqrt{s_0^A}} + \frac{g_1^B g_2^B}{\sqrt{s} - \sqrt{s_0^B}}$$

T_{11} and T_{12} are not proportional because Λ(1405) has two poles

11: Kbar N -> Kbar N
12: Kbar N -> πΣ

Fit substituting 1+GT by the BW form with a Flattee.





Conclusion from fits:

Only from invariant mass distributions there is no preference for certain quantum numbers

There is no need for the wide Pc state

Of course, the LHCb experiment has more information

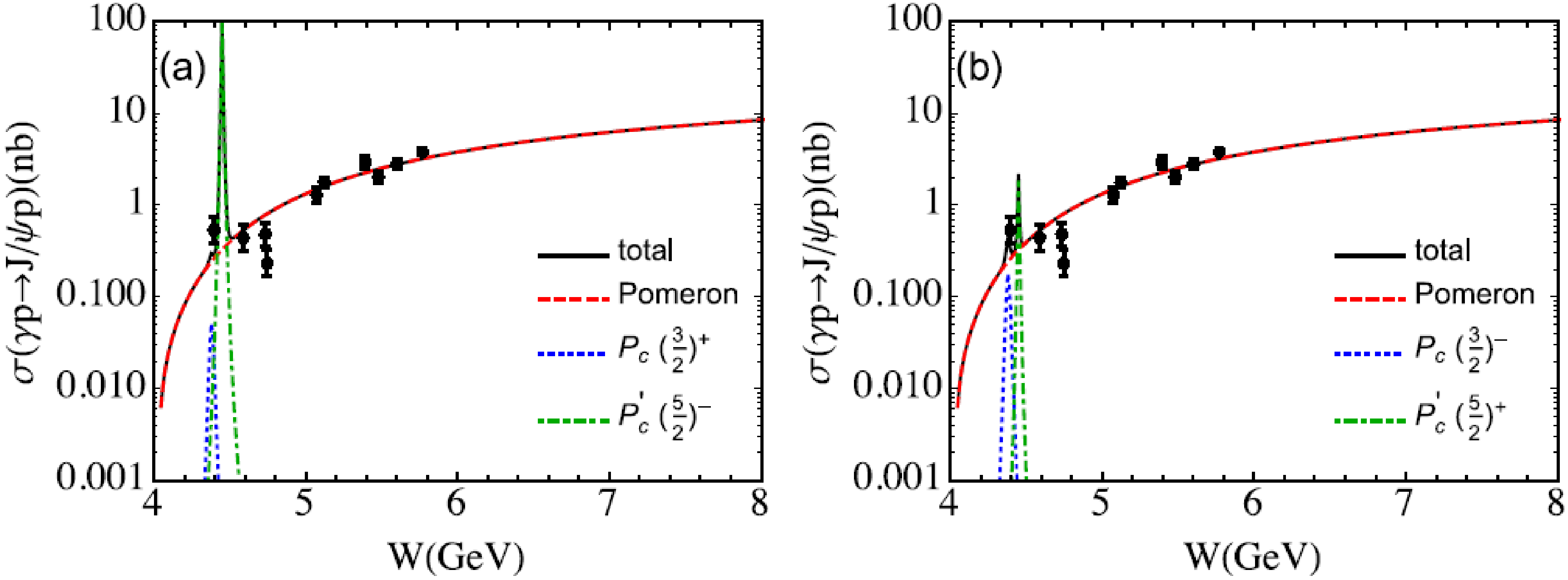
In view of that it is interesting that they pin down the particular observables that give evidence for both

We have shown that the wide Pc can be removed introducing contact tree level contributions, in particular one of the structure $D_{5/2}$. NOTE THAT THE FIT OF LHCB PRODUCES NO BACKGROUND

Wang, Li , Q Zhao, arXiv 1508.00339

Photoproduction of J/psi

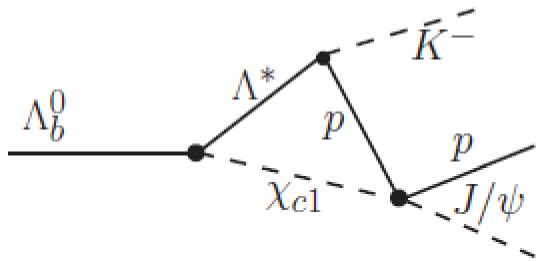
Theory assuming that only 5% of the width goes into J/psi N



How to reveal the exotic nature of the $P_c(4450)$

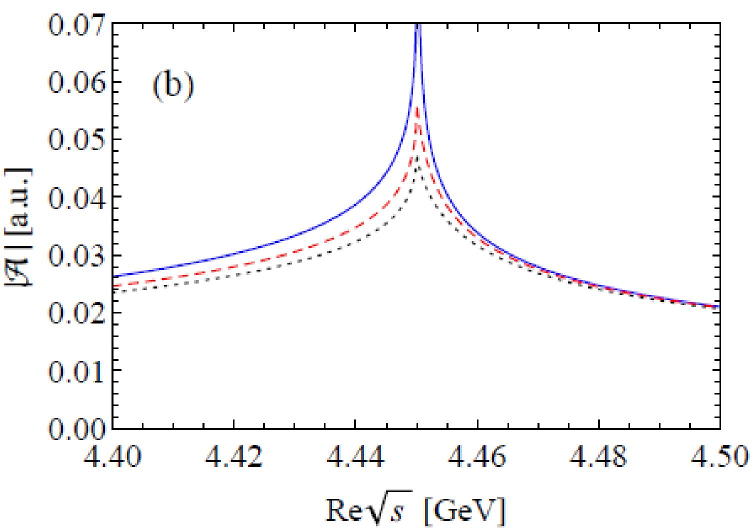
Feng-Kun Guo[1,2,*] Ulf-G. Meißner[2,3,†] Wei Wang[4,1,‡] and Zhi Yang[2,§]

PRD 2015



(b)

assume the $\Lambda(1890)$ with a mass of 1.89 GeV is exchanged in the triangle diagram

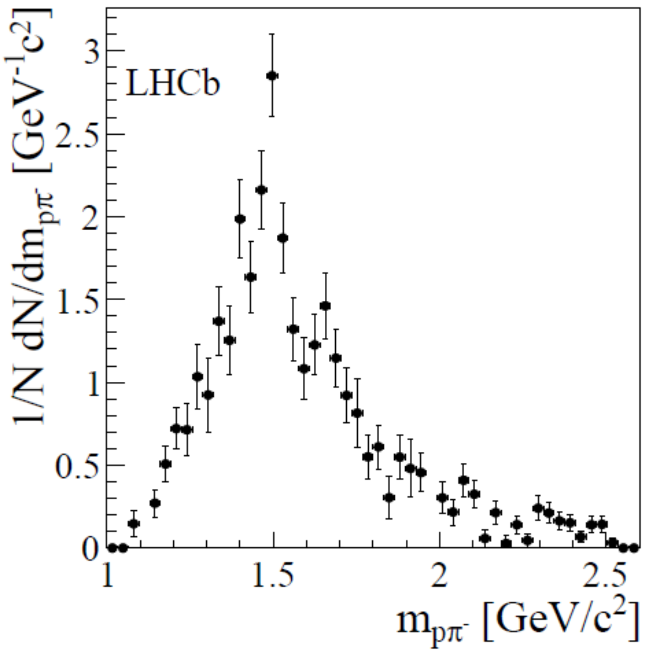


Lower curve is for Γ=100 MeV (exp value)

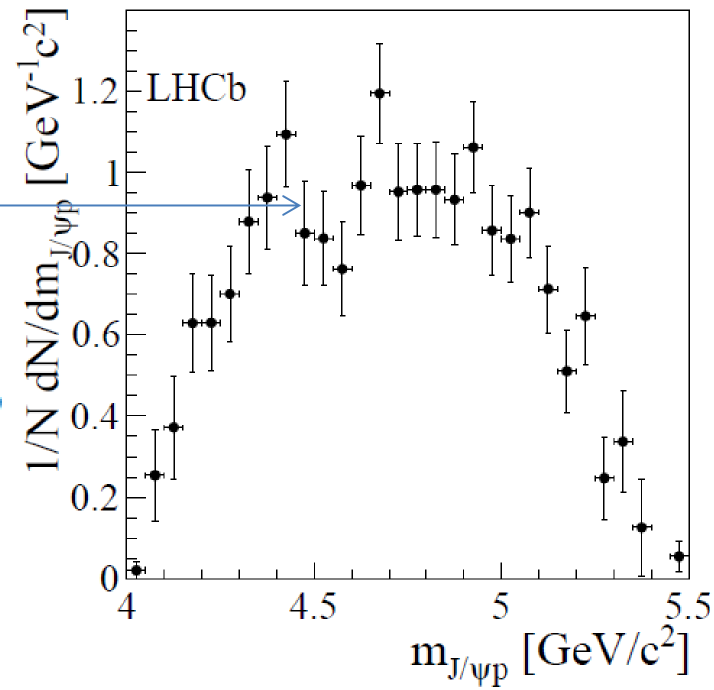
Recent reanalysis by Bayar, Aceti, F.K. Guo and E.O
For 3/2- and 5/2 + for the Pc, one needs p-wave
In xic1 p –> J/psi p, we exclude this mechanism as an explanation. For other Quantum numbers, not excluded, but one can not assert the contribution.

Observation of the $\Lambda_b^0 \to J/\psi\, p\pi^-$ decay

[LHCb Collaboration], JHEP 1407, 103 (2014)

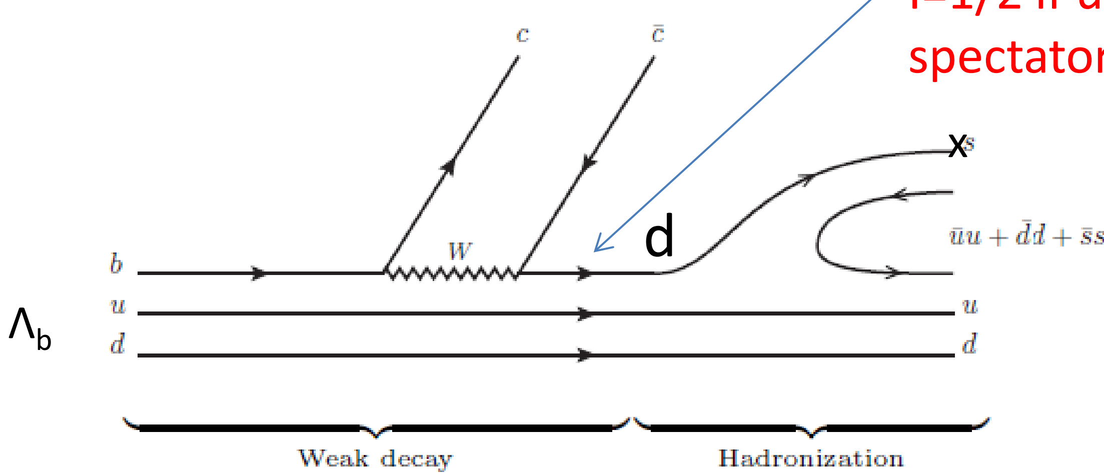


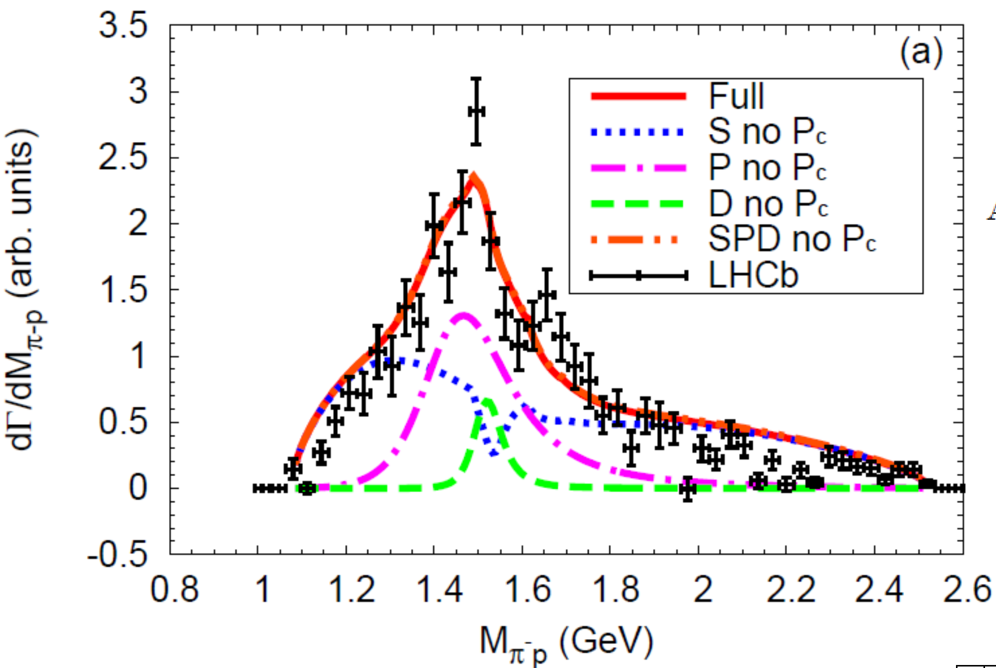
Peak at the same energy as in $\Lambda_b \to J/\psi\ K^- p$



Note: No Δ(1232) !!

I=1/2 if u,d quarks are in I=0 and are spectators

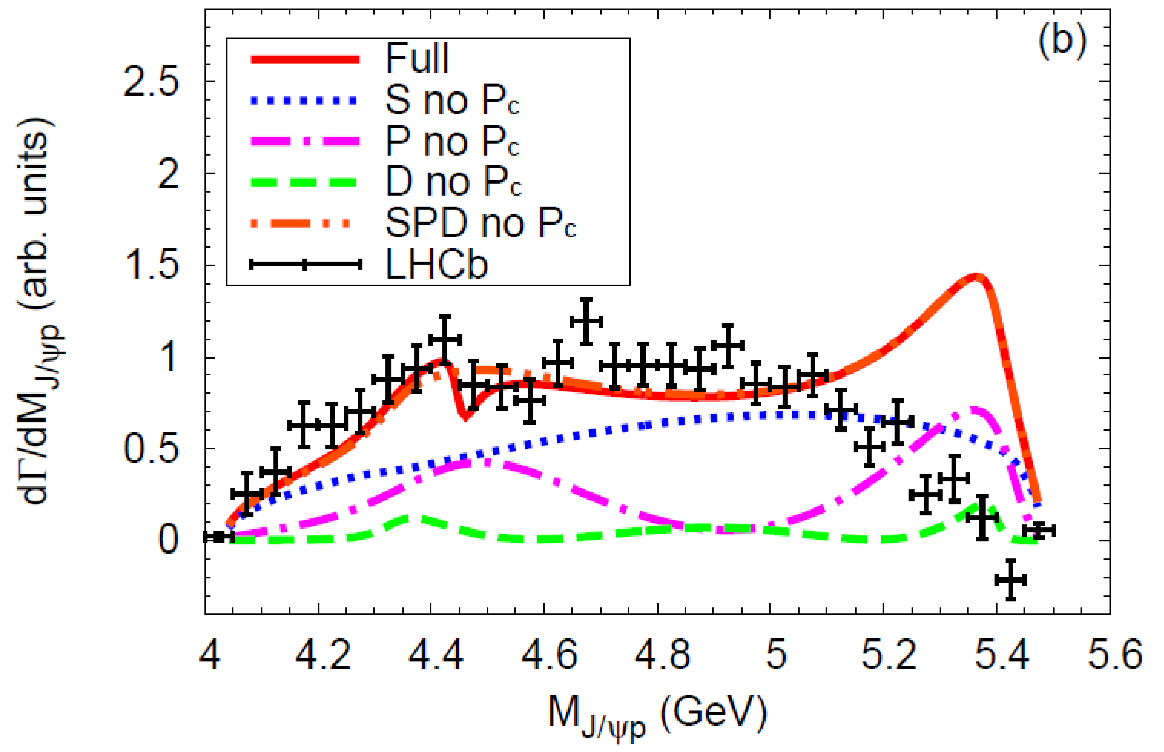




A hidden-charm pentaquark state in $\Lambda_b^0 \to J/\psi p \pi^-$ decay

Wang, Chen, Geng, Li, E. O.

PRD 2016,094001



More pentaquarks?

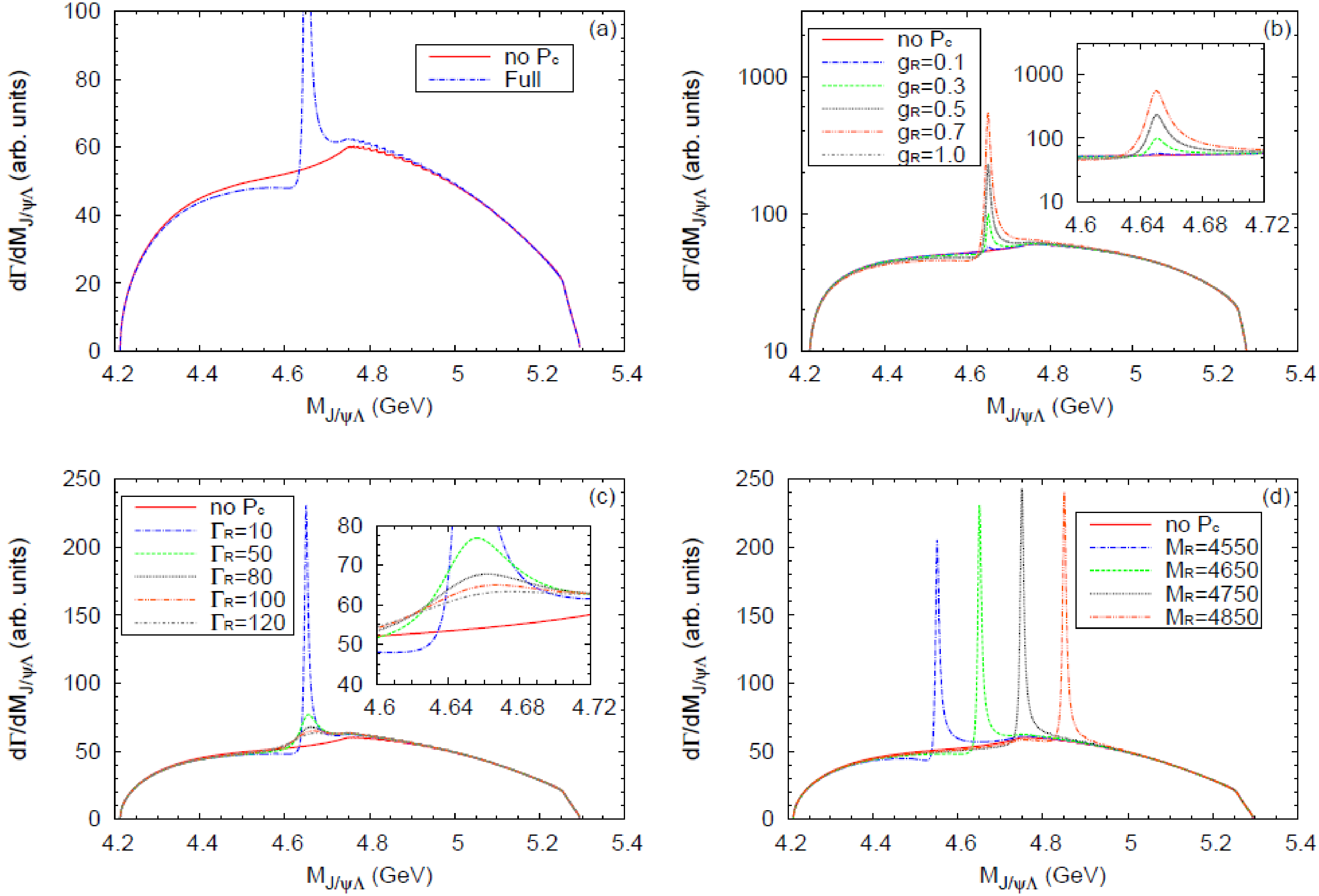
Dynamically generated N^* and Λ^* resonances in the hidden charm sector around 4.3 GeV

Wu, Molina, E.O. and Zou, PRC 84 (2011)

(I,S)	z_R	g_a			
$(1/2,0)$		$\bar{D}^*\Sigma_c$	$\bar{D}^*\Lambda_c^+$	$J/\psi N$	
	$4415-9.5i$	$2.83-0.19i$	$-0.07+0.05i$	$-0.85+0.02i$	
		2.83	0.08	0.85	
$(0,-1)$		$\bar{D}_s^*\Lambda_c^+$	$\bar{D}^*\Xi_c$	$\bar{D}^*\Xi'_c$	$J/\psi\Lambda$
	$4368-2.8i$	$1.27-0.04i$	$3.16-0.02i$	$-0.10+0.13i$	$0.47+0.04i$
		1.27	3.16	0.16	0.47
	$4547-6.4i$	$0.01+0.004i$	$0.05-0.02i$	$2.61-0.13i$	$-0.61-0.06i$
		0.01	0.05	2.61	0.61

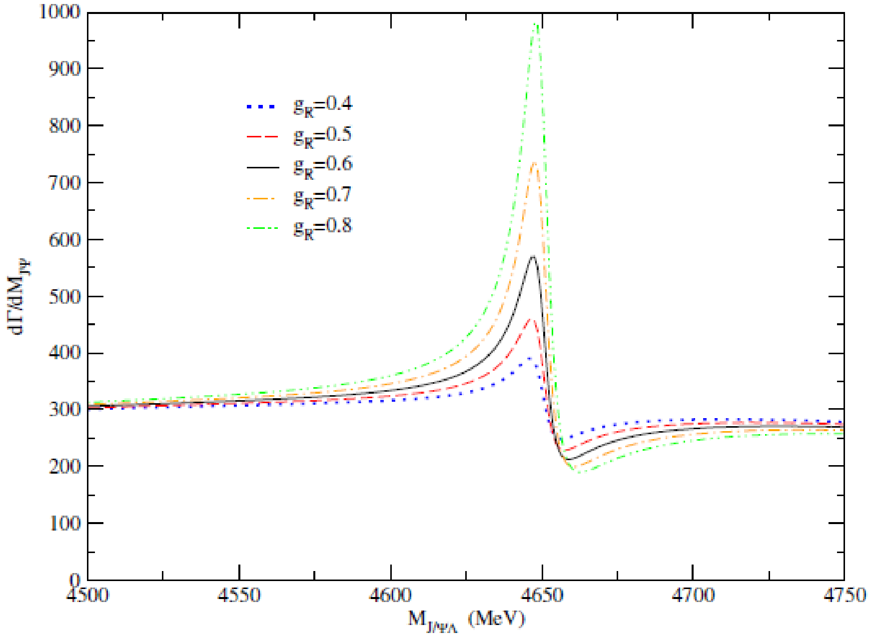
Looking for a hidden-charm pentaquark state with strangeness $S=-1$ from Ξ_b^- decay into $J/\psi K^-\Lambda$

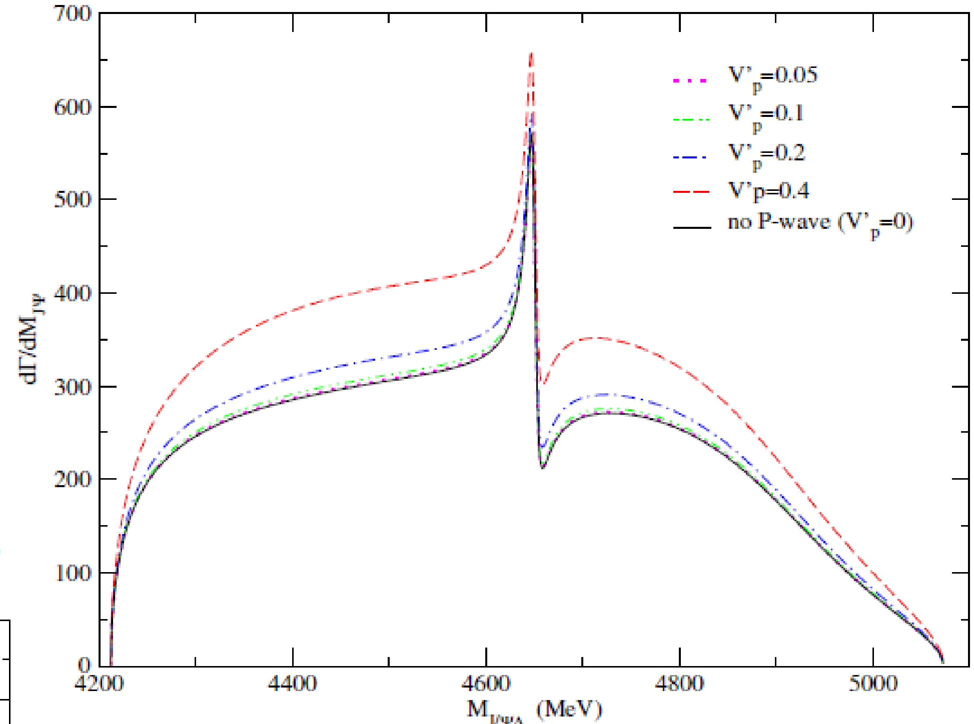
Chen, Geng, Liang, E.O. Wang, Xie, 1510. 01803, PRC 2016

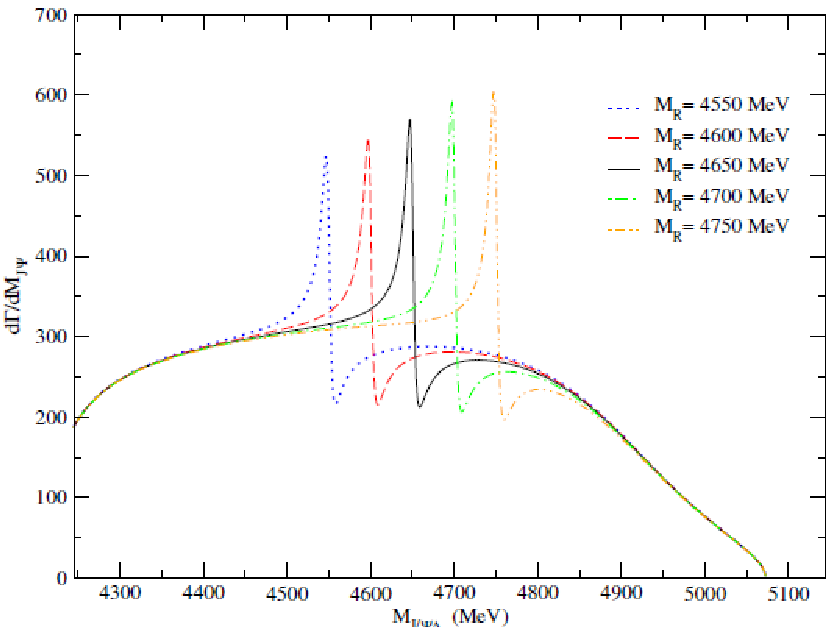


A hidden-charm $S = -1$ pentaquark from the decay of Λ_b into $J/\psi\eta\Lambda$ states

Feijoo, Magas, Ramos, E. O. , 1512.08152

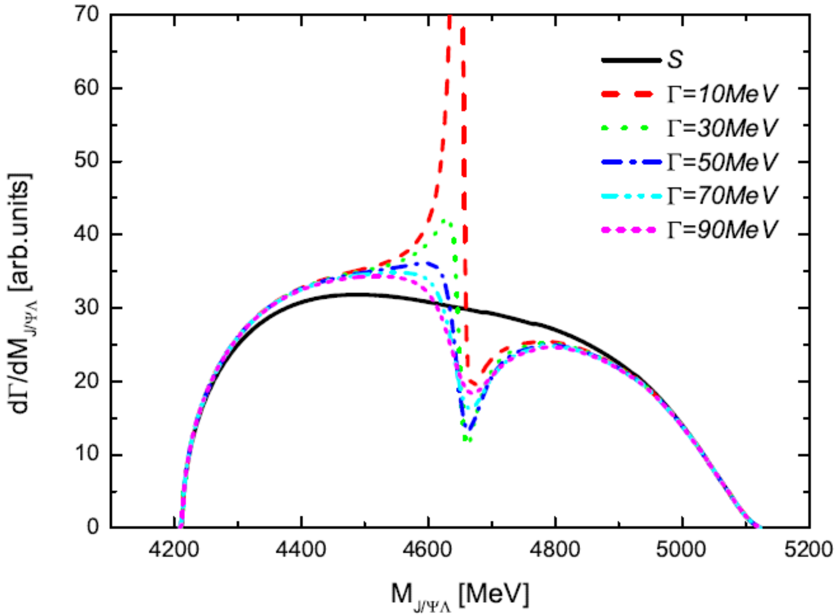


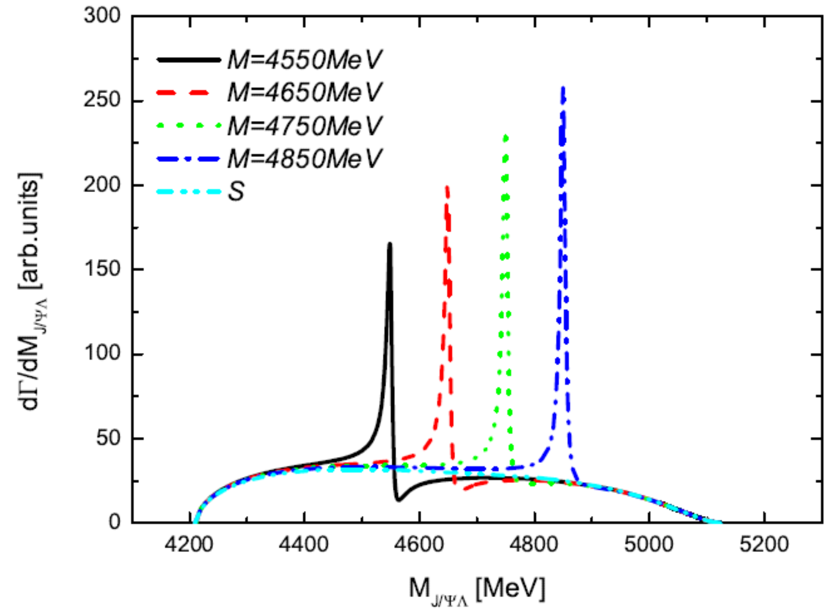


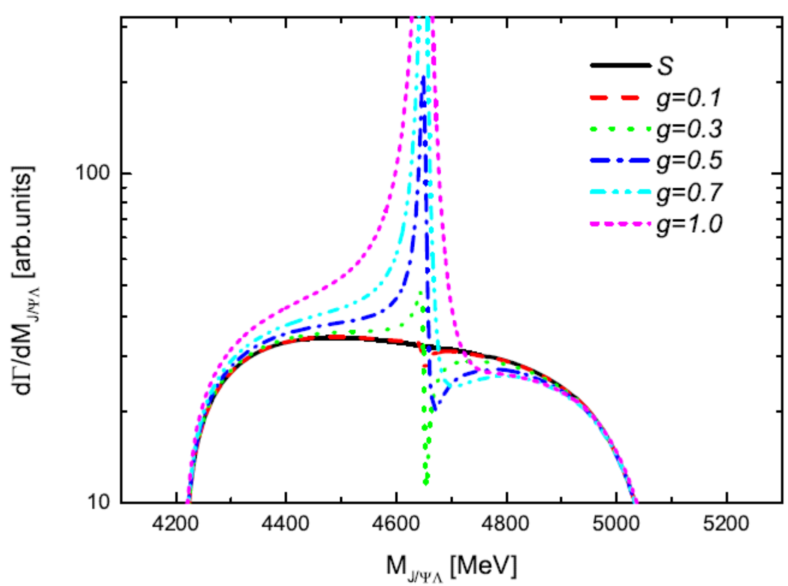


The $\Lambda_b \to J/\psi K^0 \Lambda$ reaction and a hidden-charm pentaquark state with strangeness

Lu, Wang, Xie, Geng, E. O. ,
1601.00075, PRD 2016







Conclusions:

Predictions for Λ_b -> J/ψ Λ(1405) made prior to LHCb experiment
Preditions for D*bar Σ_c and D*bar Σ^*_c bound states also made before.
The combination of both matches recent findings of experiment

A recent theoretical analysis based on only mass distributions shows no preference for any quantum numbers and does not require the wide Pc

The Λ_b -> J/ψ π^- p decay shows the same peak as the Λ_b -> J/ψ K^- p .

Preditions are made for different reactions producing J/Ψ Λ mass in the final state. The mass distribution of this pair exhibits clear signals of new pentaquark states with hidden charm and strangeness.

LHCb is conducting search in some of these reactions. Let us hope that the recent findings are only the beginning of a rich crop.