

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 $\Lambda_b \rightarrow J/\psi K^- p$ reaction

The LHCb experiment claiming two pentaquark states

Theoretical analysis of the experimental data

The $\Lambda_b \rightarrow J/\psi \pi^- p$ reaction

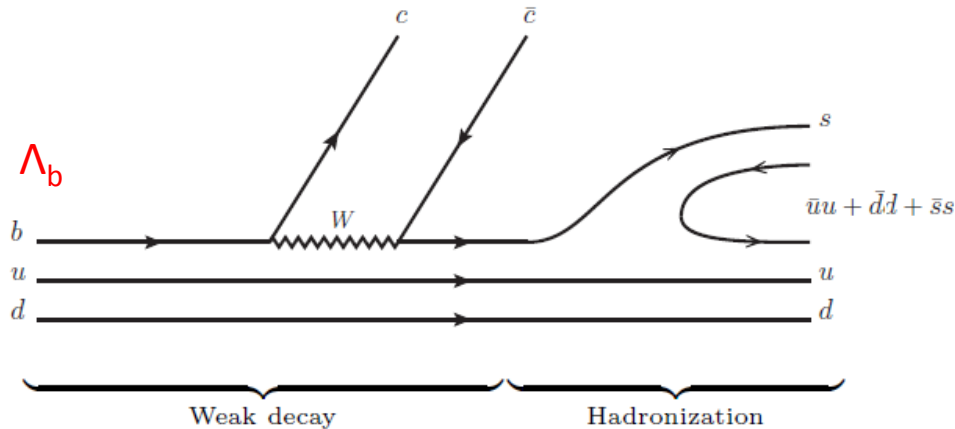
$\Xi_b^- \rightarrow J/\psi K^- \Lambda$ and a hidden charm strange pentaquark

$\Lambda_b \rightarrow J/\psi \eta \Lambda$

$\Lambda_b \rightarrow J/\psi K^0 \Lambda$

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

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



Cabibbo
suppressed

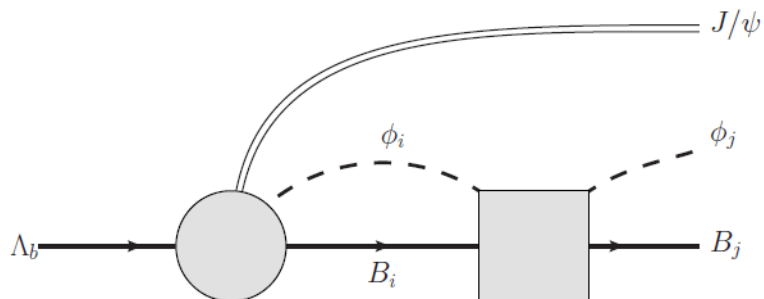
u c t
d s b

Cabibbo
allowed

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

u d quarks in $I=0$

u d quarks in $I=0$ (spectators) and s quark $\rightarrow$ total $I=0$



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

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

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

$$|\Lambda_b\rangle = \frac{1}{\sqrt{2}}|b(ud - du)\rangle \quad \text{turning after the weak process into} \quad \frac{1}{\sqrt{2}}|s(ud - du)\rangle$$

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

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

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

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

$$|p\rangle = \frac{1}{\sqrt{2}}|u(ud - du)\rangle,$$

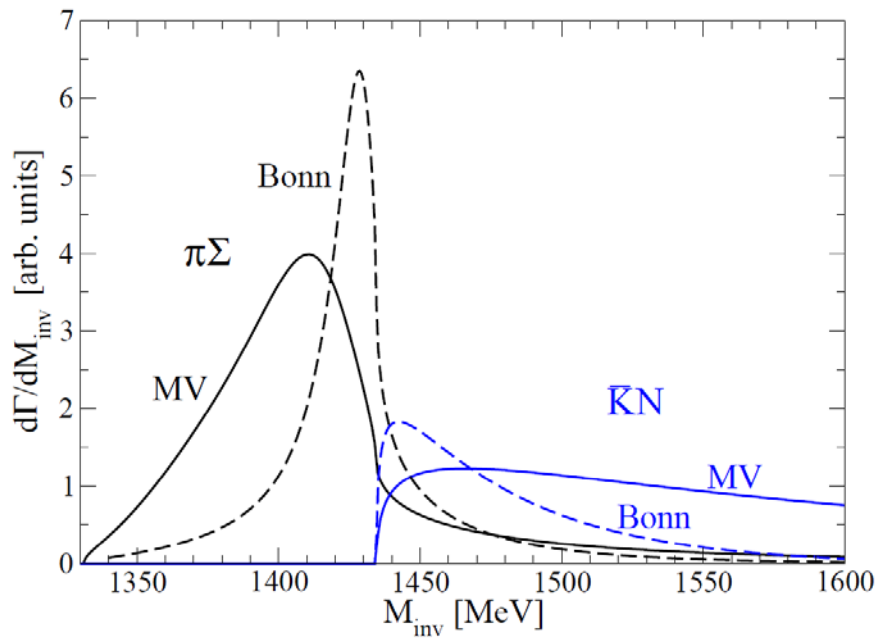
$$|n\rangle = \frac{1}{\sqrt{2}}|d(ud - du)\rangle,$$

$$|\Lambda\rangle = \frac{1}{\sqrt{12}}|(usd - dsu) + (dus - uds) + 2(sud - sdu)\rangle$$

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

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 $J/\psi K^- p$, the final state in the LHCb pentaquark experiment

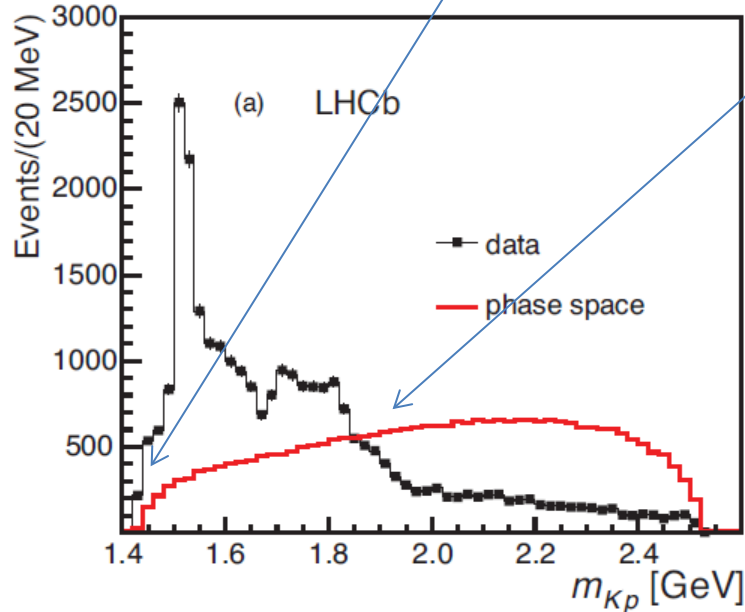
One sees a clear peak for the $\Lambda(1405)$ production in the $\pi\Sigma$ invariant mass distribution

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

LHCb Collaboration

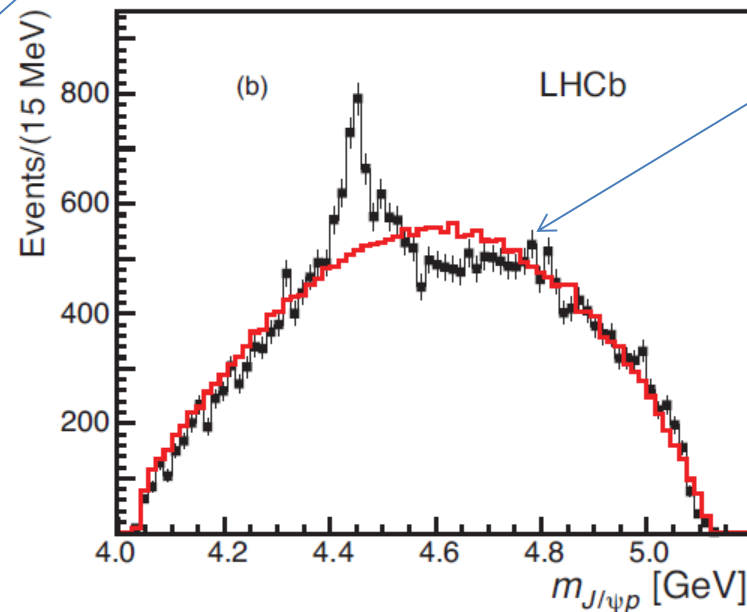
Phys.Rev.Lett. 115 (2015) 072001

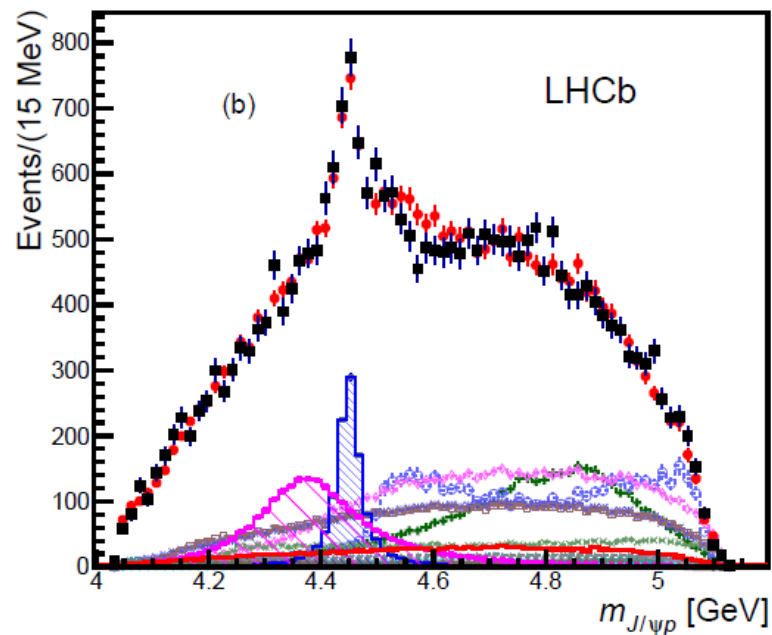
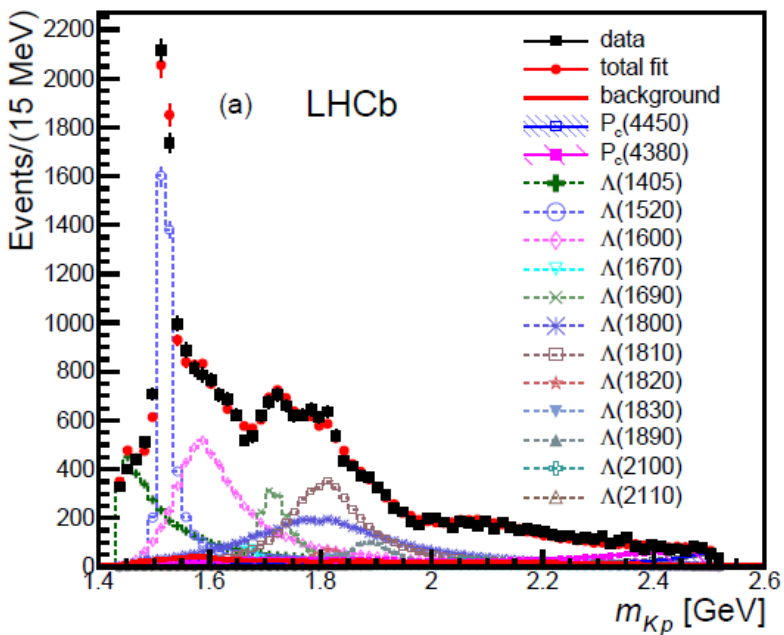
Large concentration of strength around
threshold



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

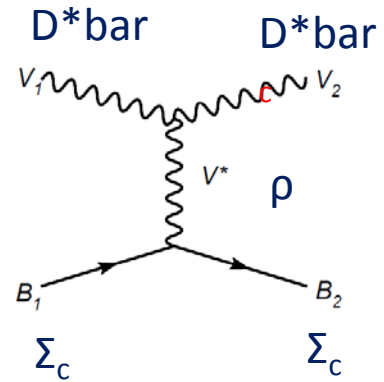
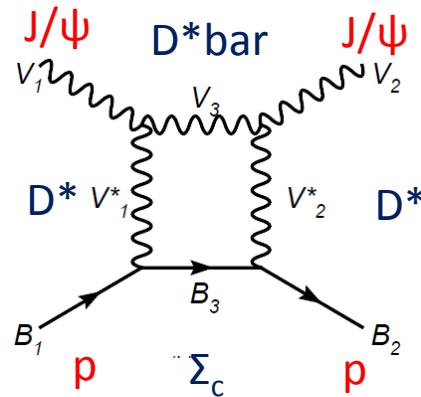
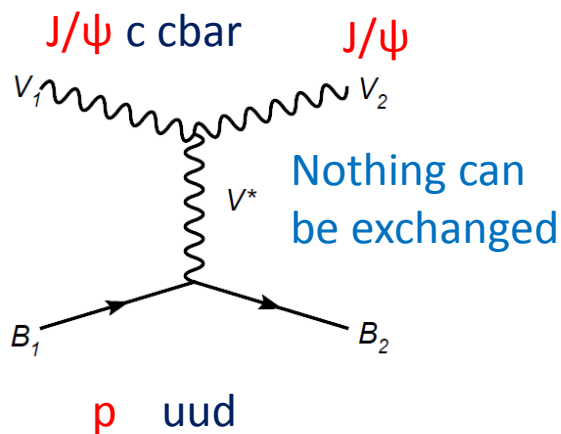
While for $J/\psi p$ one has essentially
phase space except for the peak





Two states claimed: $P_c(4380)$, $\Gamma=205$ MeV ; $P_c(4450)$, $\Gamma=40$ MeV
 Assignments: $3/2^-$, $5/2^+$; $3/2^+$, $5/2^-$; $5/2^+$, $3/2^-$ Other less likely

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



Predictions for hidden charm Baryon states

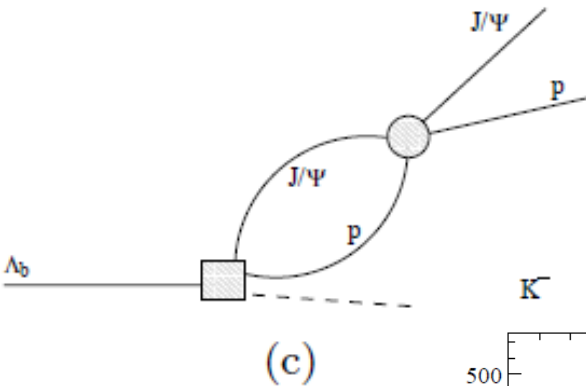
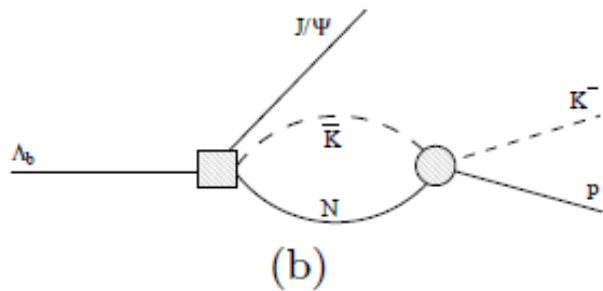
J J Wu, R Molina, E. O, B S Zou, PRL (2010)

(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: $3/2^-$

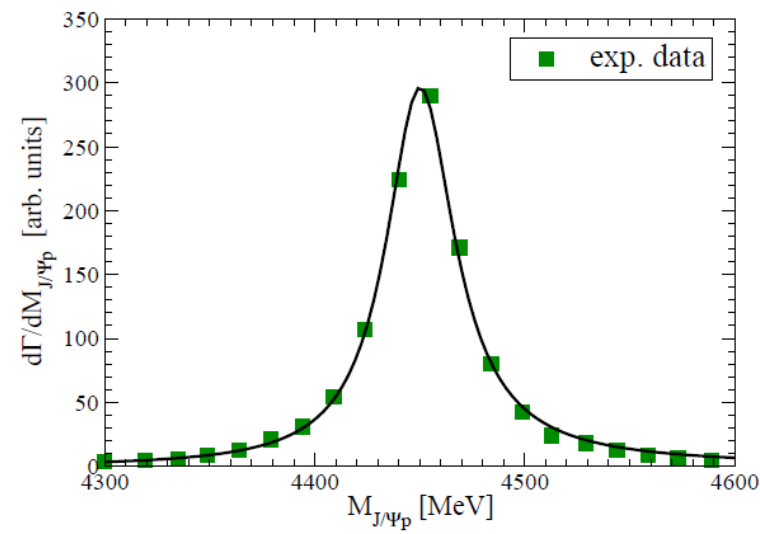
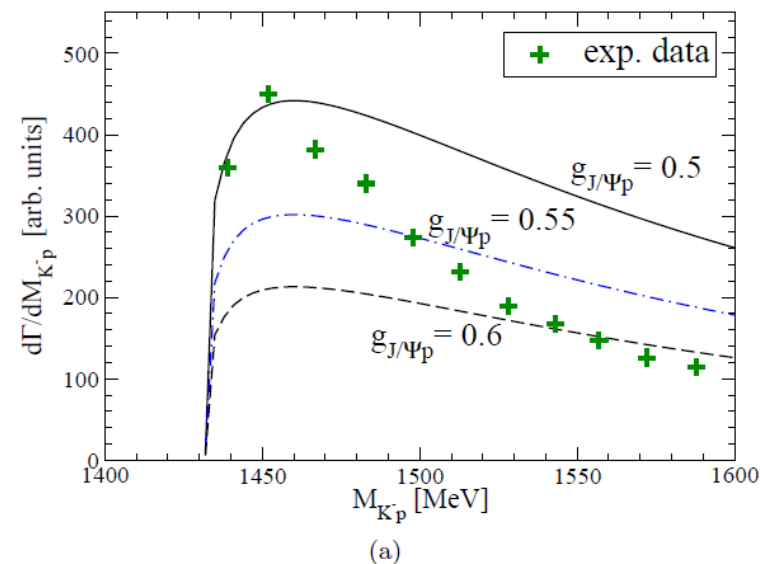
C W Xiao, J Nieves , E. O, PRD 2013 : $\bar{D}^*\Sigma_c^*$ channel included

$4417.04 + i4.11$	$J/\psi N$	$\bar{D}^*\Lambda_c$	$\bar{D}^*\Sigma_c$	$\bar{D}\Sigma_c^*$	$\bar{D}^*\Sigma_c^*$
g_i	$0.53 - i0.07$	$0.08 - i0.07$	$2.81 - i0.07$	$0.12 - i0.10$	$0.11 - i0.51$
$ g_i $	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	$1.05 + i0.10$	$0.18 - i0.09$	$0.12 - i0.10$	$0.22 - i0.05$	$2.84 - i0.34$
$ g_i $	1.05	0.20	0.16	0.22	2.86



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

$$t_{J/\psi p \rightarrow J/\psi p} = \frac{g_{J/\psi p}^2}{M_{J/\psi p}^2 - M_R^2 + iM_R\Gamma_R} 2M_R$$



Reanalysis including more resonances

This assumes the two pentaquark states to be in S-wave in $J/\psi p$

L. Roca and E. O, 1602.06791

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

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

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

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

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

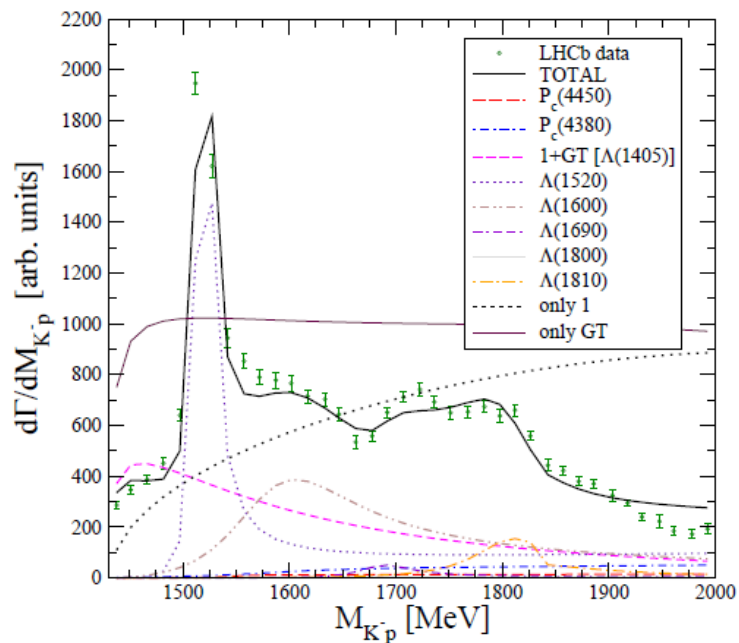
$\Lambda(1800) \quad (1/2^-)$

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

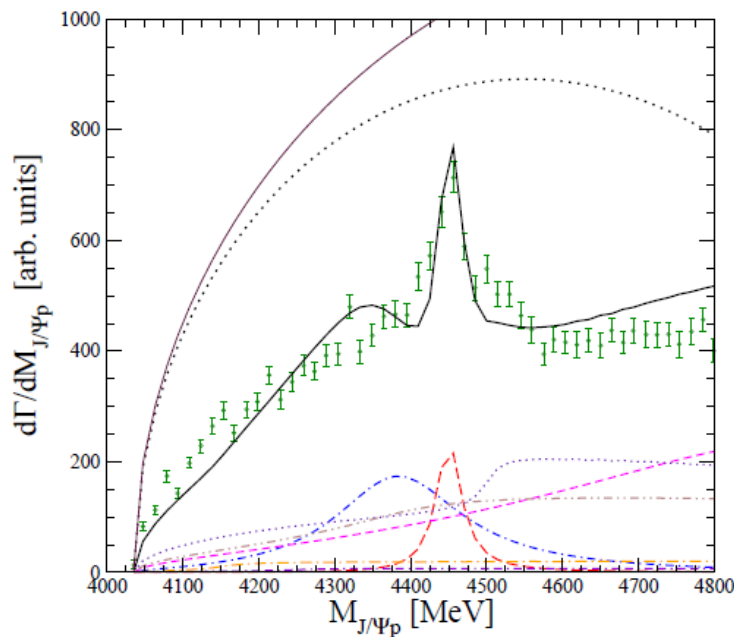
$$|T(M_{Kp}, M_{J/\psi p})|^2 = \\ \left| \alpha_1 \left(1 + G_{K^- p}(M_{K^- p}) t_{\bar{K}N, \bar{K}N}^{I=0}(M_{K^- p}) \right) \right. \\ \left. + \alpha_2 G_{J/\psi p} \frac{g_{J/\psi p}^2}{M_{J/\psi p} - m_{P_c(4450)} + i \frac{\Gamma_{P_c(4450)}}{2}} \right. \\ \left. + \alpha_3 G_{J/\psi p} \frac{g_{J/\psi p}^2}{M_{J/\psi p} - m_{P_c(4380)} + i \frac{\Gamma_{P_c(4380)}}{2}} \right|^2 \\ + \left| \alpha_4 \frac{1}{M_{Kp} - m_{\Lambda(1800)} + i \frac{\Gamma_{\Lambda(1800)}}{2}} \right|^2 \\ + \left| \alpha_5 \frac{q/m_{\Lambda(1600)}}{M_{Kp} - m_{\Lambda(1600)} + i \frac{\Gamma_{\Lambda(1600)}}{2}} \right|^2 \\ + \left| \alpha_6 \frac{q/m_{\Lambda(1810)}}{M_{Kp} - m_{\Lambda(1810)} + i \frac{\Gamma_{\Lambda(1810)}}{2}} \right|^2 \\ + \left| \alpha_7 \frac{(q/m_{\Lambda(1520)})^2}{M_{Kp} - m_{\Lambda(1520)} + i \frac{\Gamma_{\Lambda(1520)}}{2}} \right|^2 \\ + \left| \alpha_8 \frac{(q/m_{\Lambda(1690)})^2}{M_{Kp} - m_{\Lambda(1690)} + i \frac{\Gamma_{\Lambda(1690)}}{2}} \right|^2,$$

Fit with two
Pentaquarks

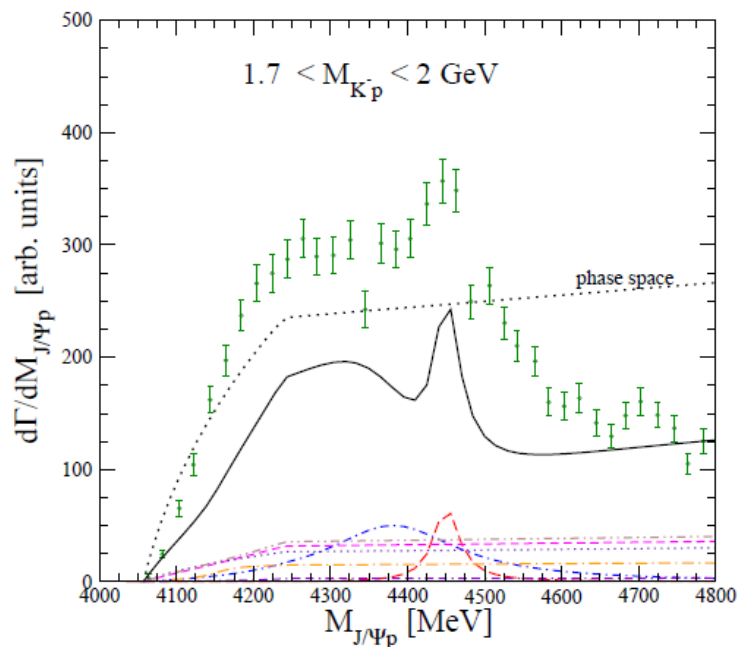
Both in s-wave
in J/ψ ,
for instance
 $3/2^-, 3/2^-$



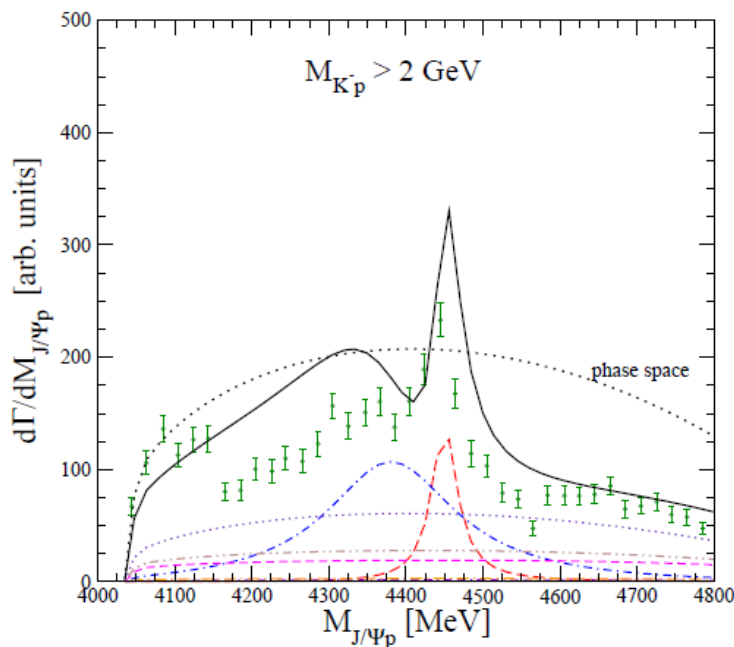
(a)



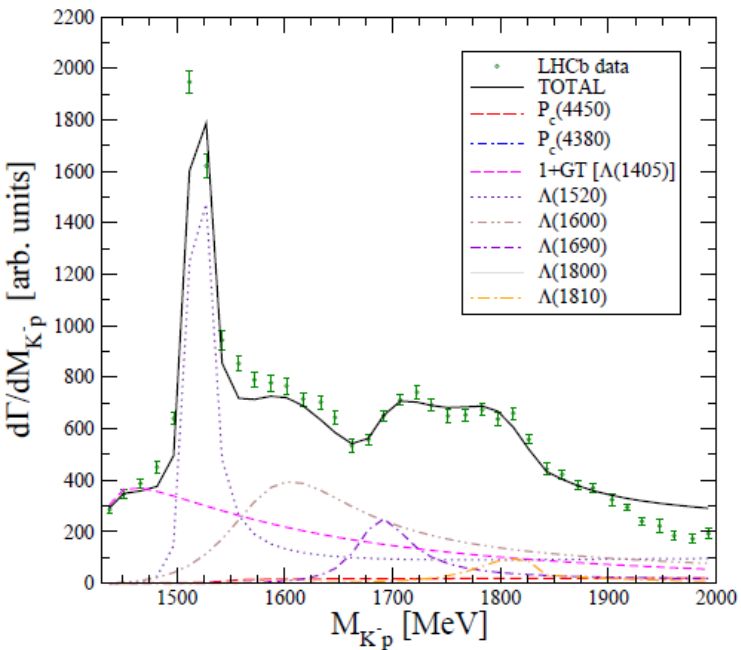
(b)



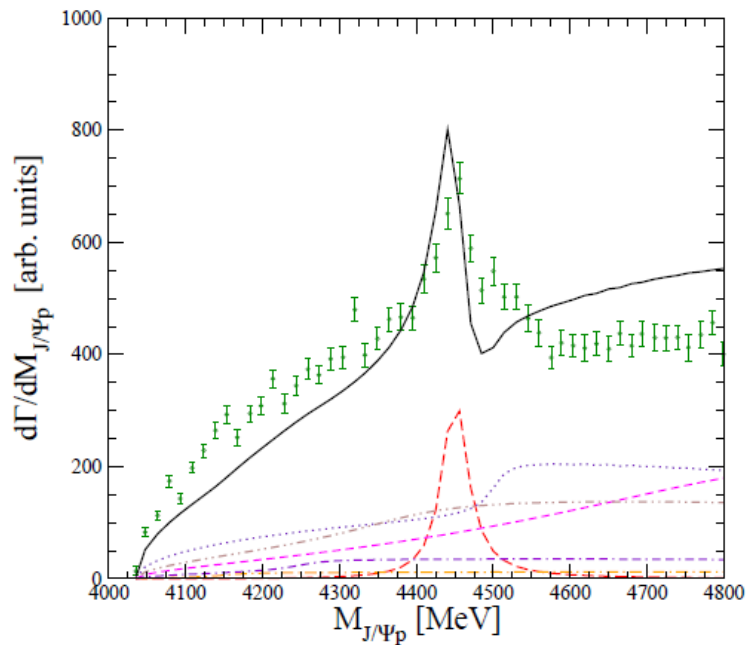
(c)



(d)

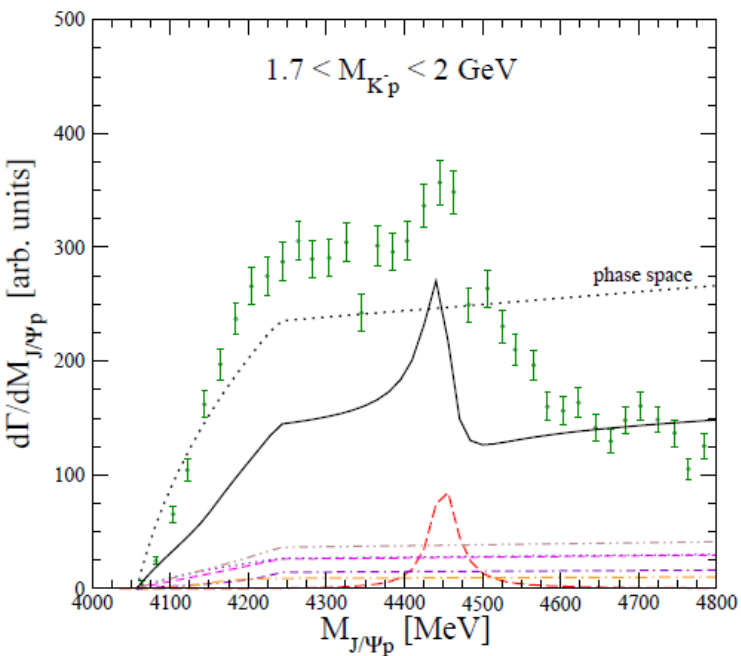


(a)

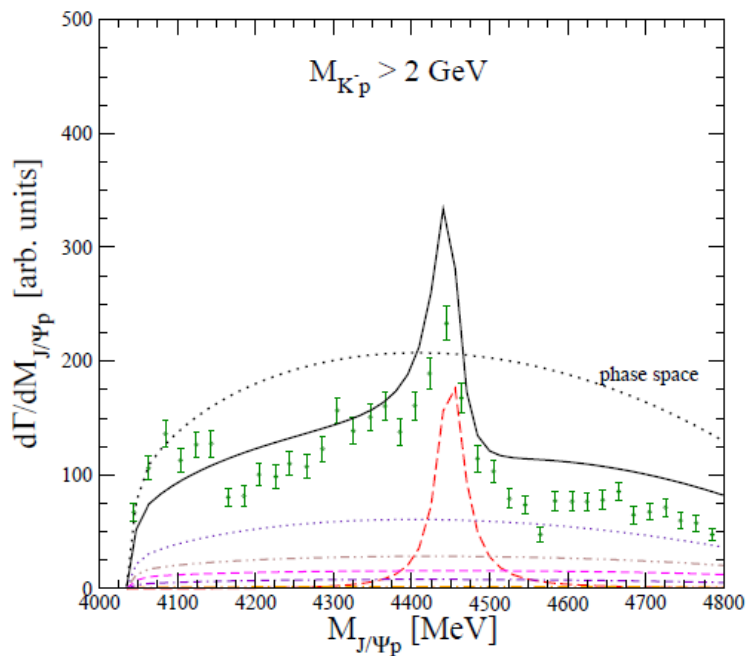


(b)

Fit removing the
 $P_c(4380)$



(c)



(d)

This could be $3/2^-$, $5/2^+$

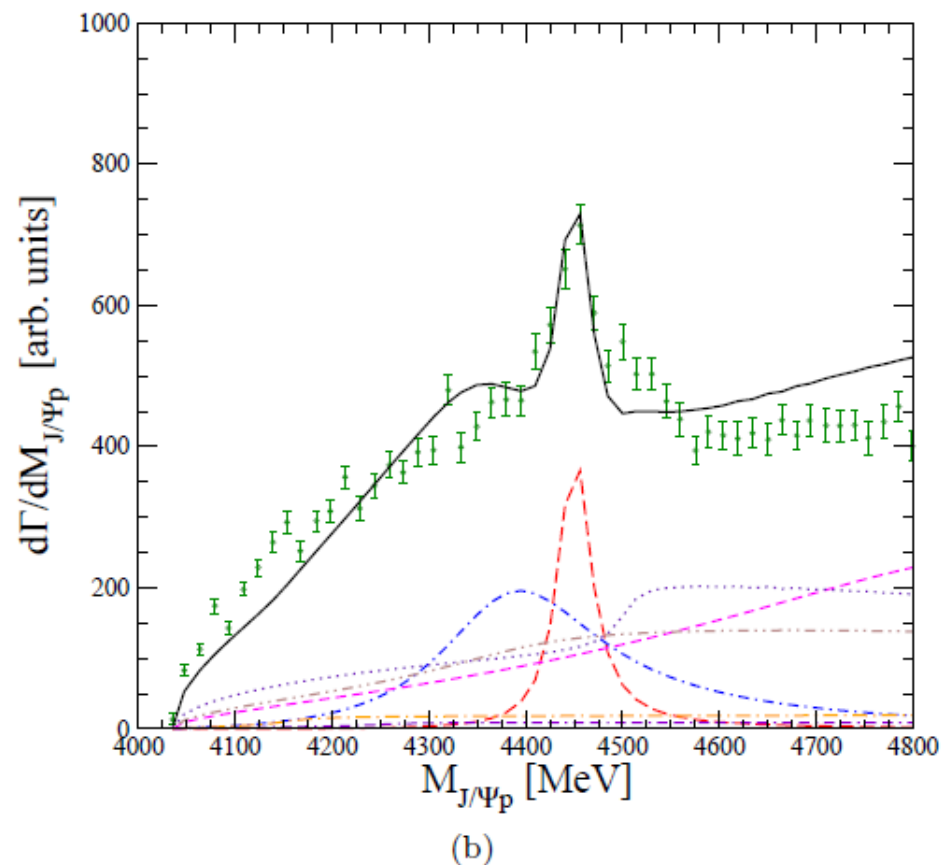
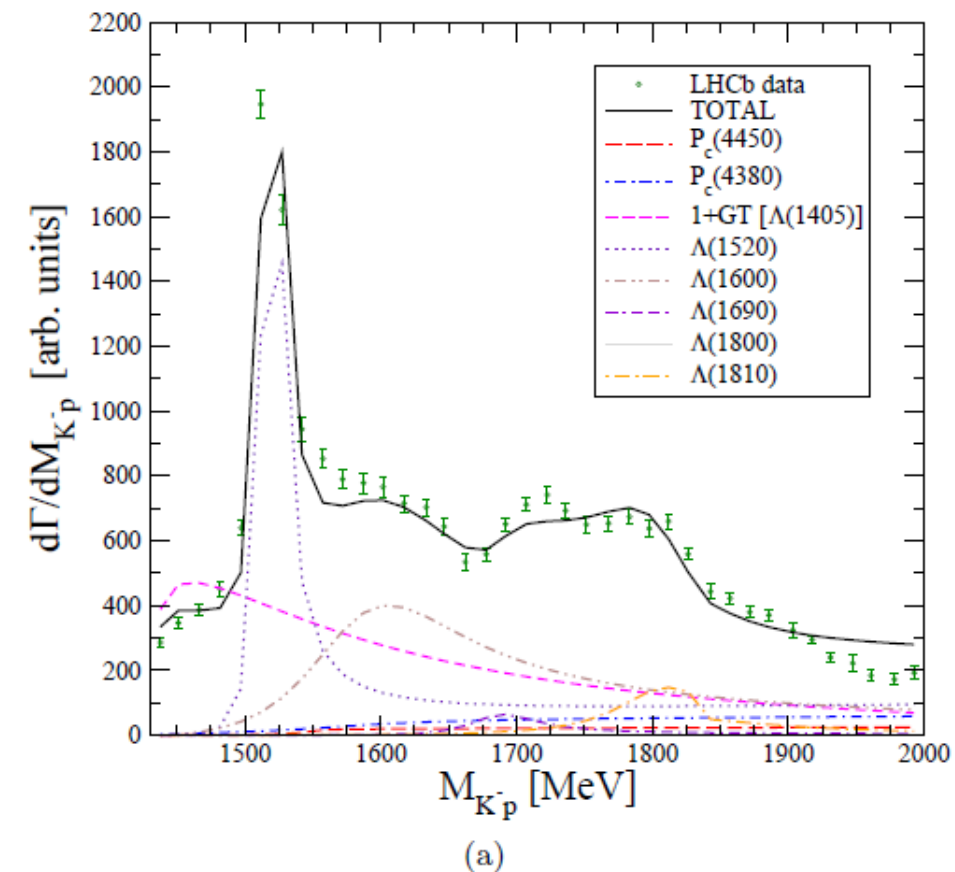


FIG. 5: (Color online). Same as Fig. 3a and b but considering $P_c(4380)$ in s-wave and $P_c(4450)$ in p-wave.

All fits prefer to have the wide state with negative parity, interfering with the $\Lambda(1405)$

Lucky experimental analysis

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

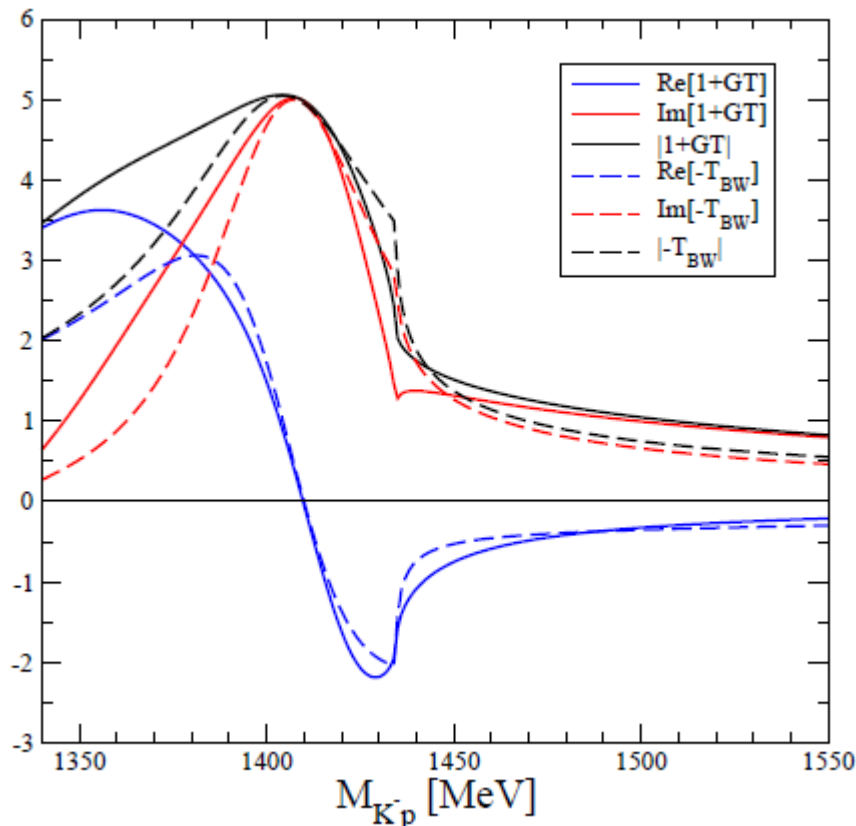
$$(1 + GT)_{11} = (V^{-1}T)_{11} = \frac{T_{11}V_{22} - T_{12}V_{12}}{V_{11}V_{22} - V_{12}^2}$$

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

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

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

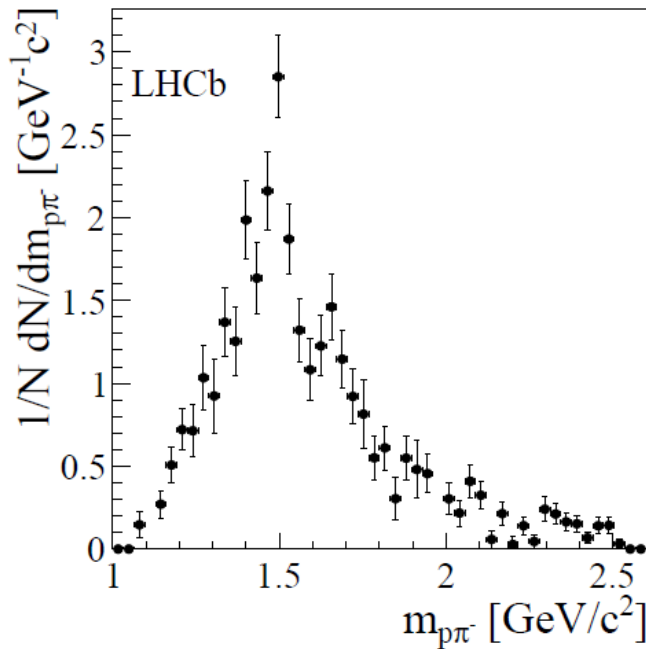
T_{11} and T_{12} are not proportional



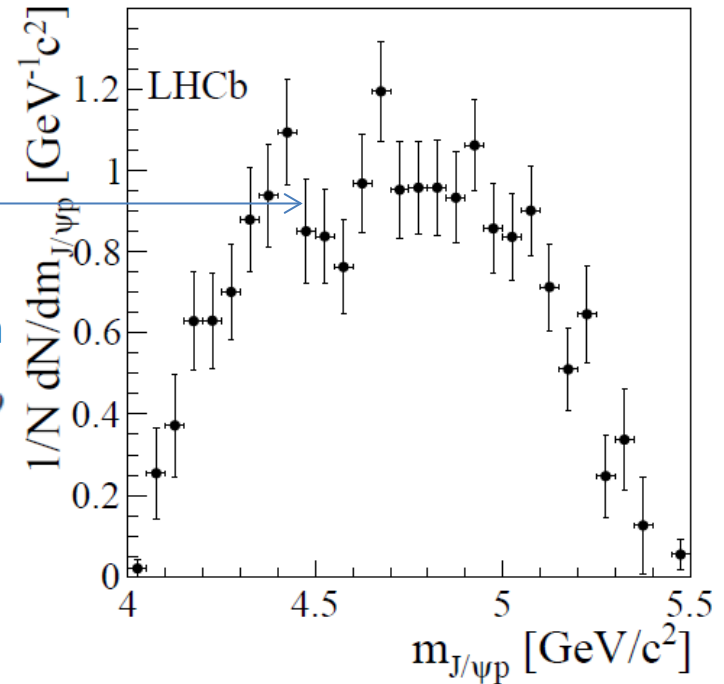
11: $\bar{K} N \rightarrow \bar{K} N$
 12: $\bar{K} N \rightarrow \pi \Sigma$
 and recall the $\Lambda(1405)$ has two poles.

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

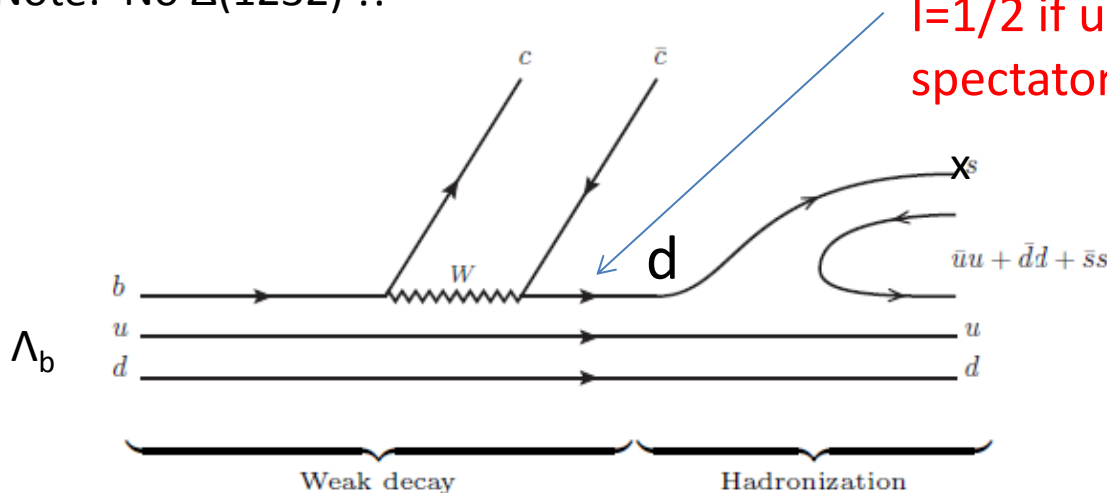
[LHCb Collaboration],
JHEP 1407, 103 (2014)



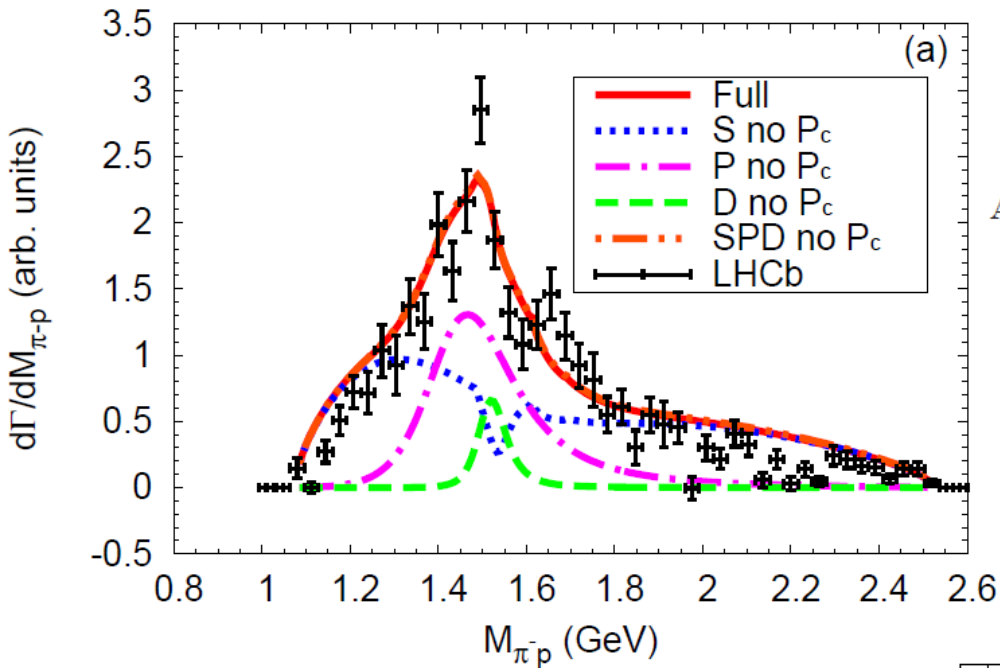
Peak at
the same
energy as in
 $\Lambda_b \rightarrow J/\psi K^- p$



Note: No $\Delta(1232)$!!

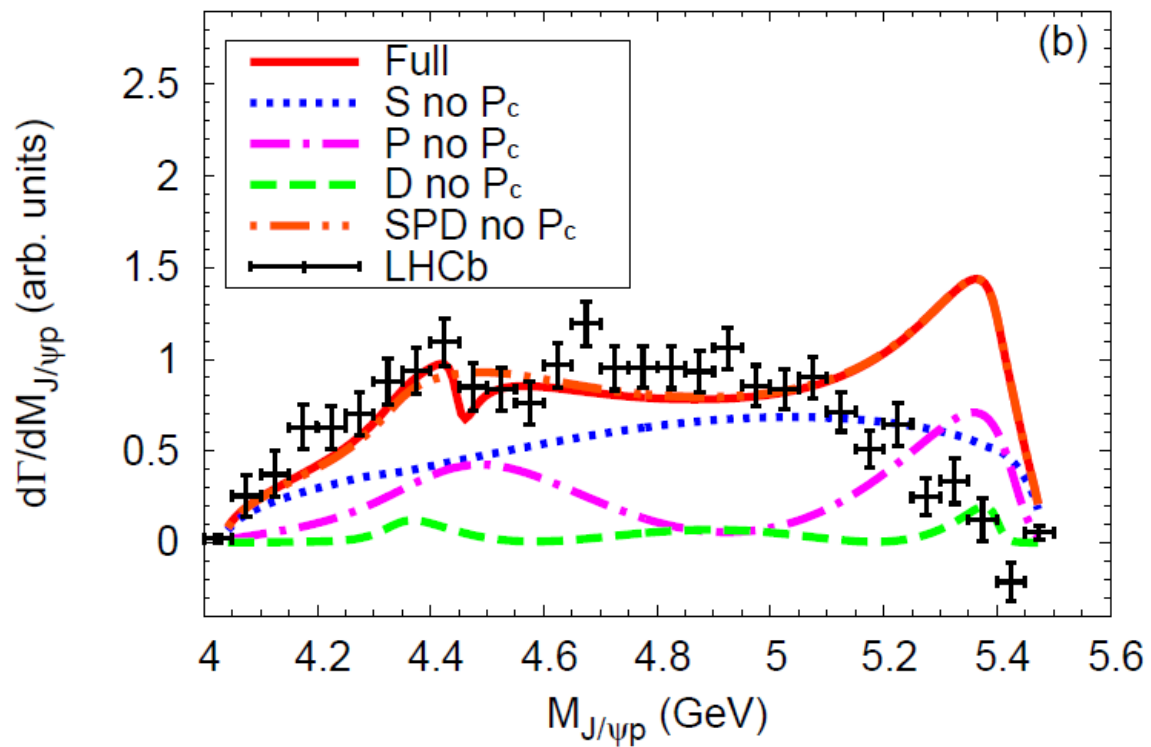


$I=1/2$ if u, d quarks are in $I=0$ and are spectators



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

Wang, Chen, Geng, Li, E. O. , [1512.01959](#)
PRD 2016



More pentaquarks?

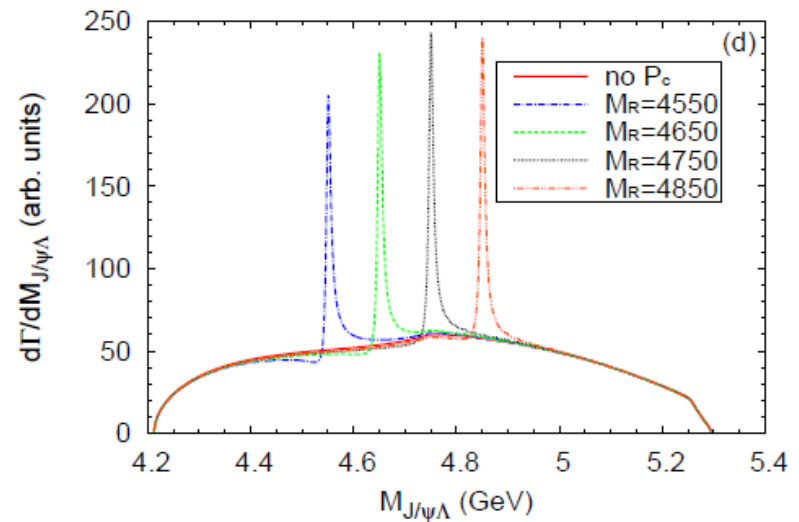
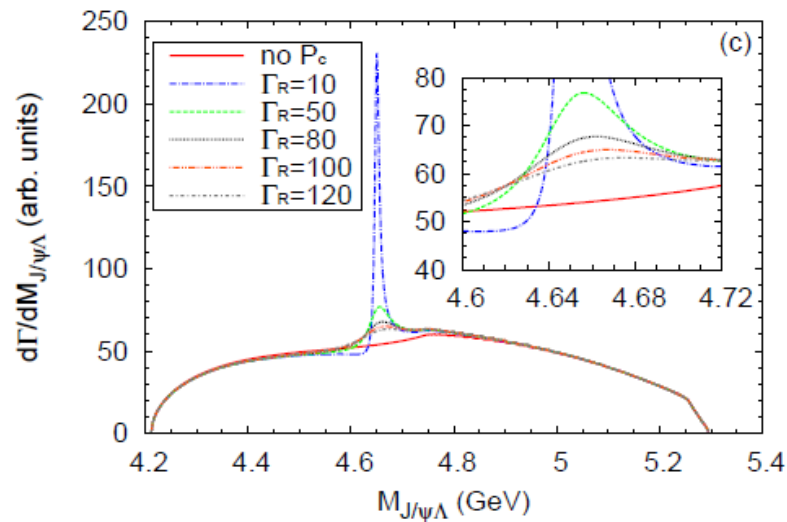
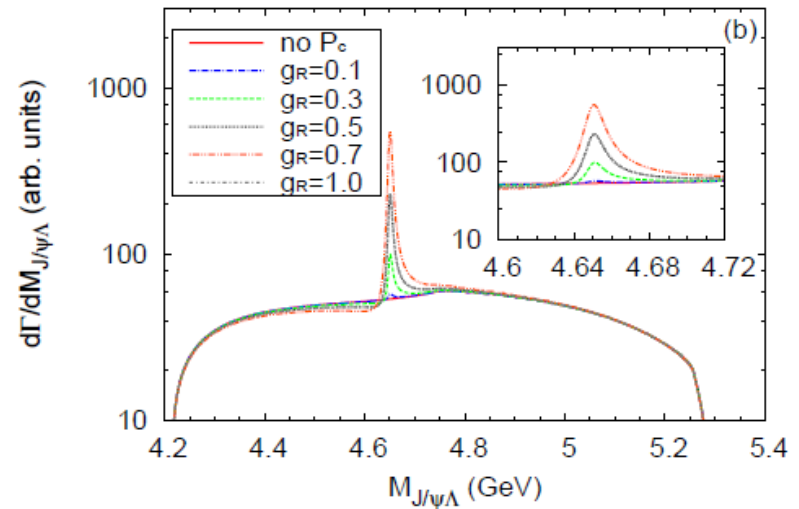
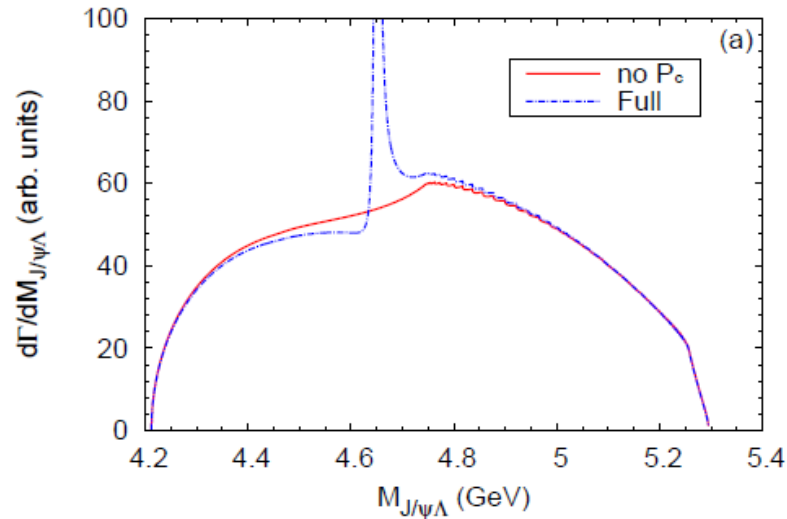
Dynamically generated N^* and Λ^* resonances in the hidden charm sector around 4.3 GeV

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

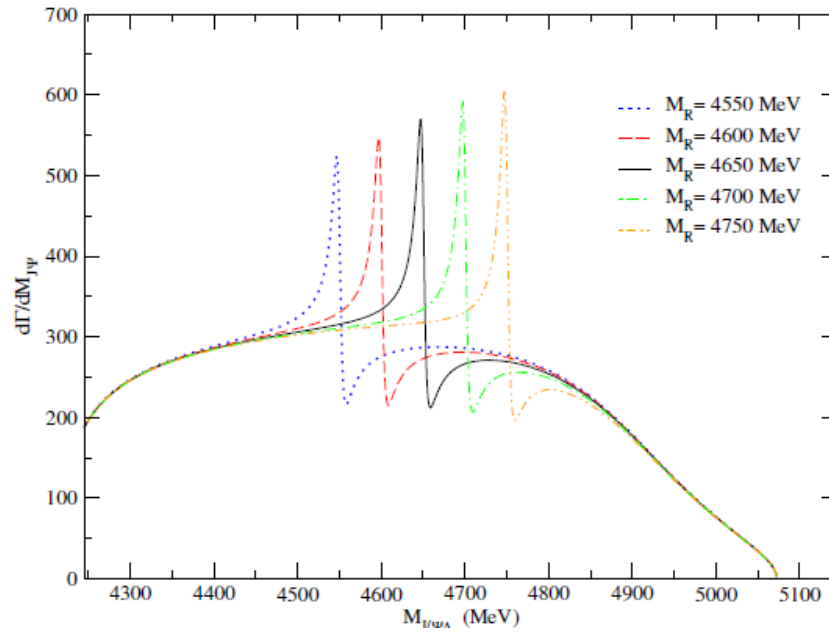
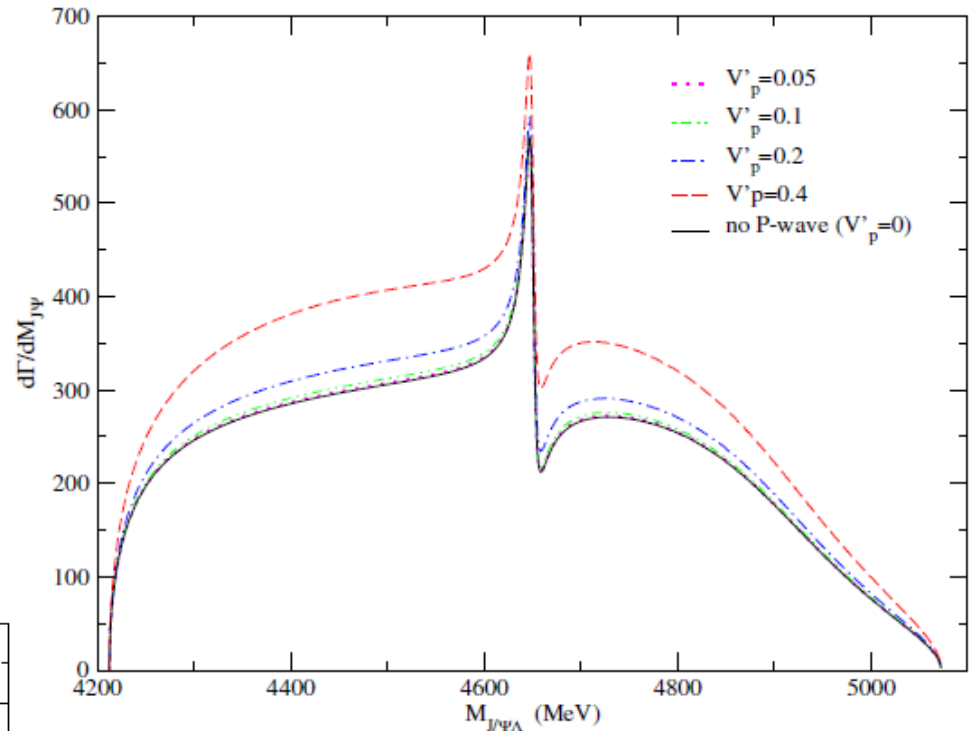
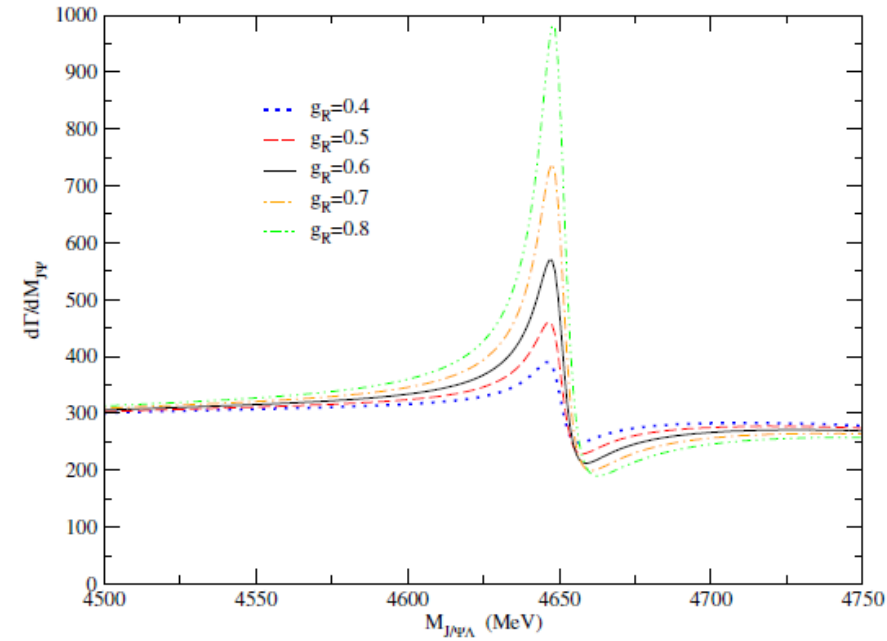
Looking for a hidden-charm pentaquark state with strangeness $S = -1$ from Ξ_b^- decay into $J/\psi K^- \Lambda$

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

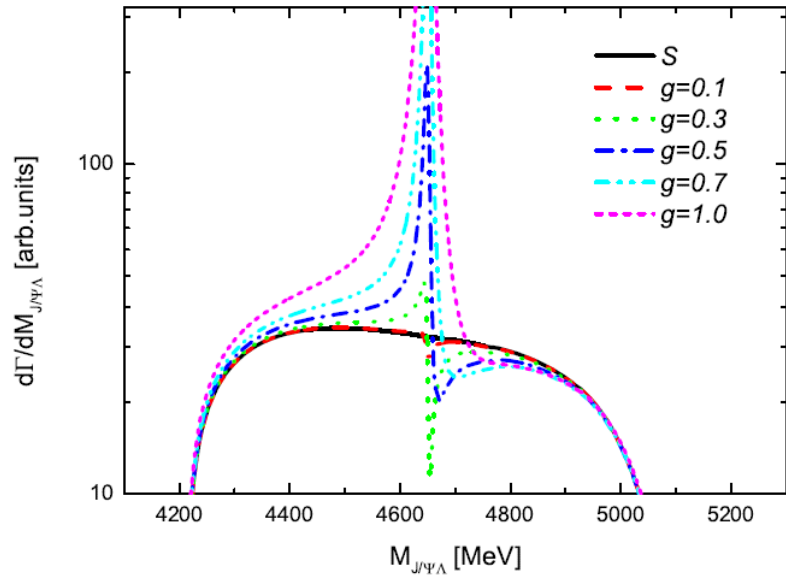
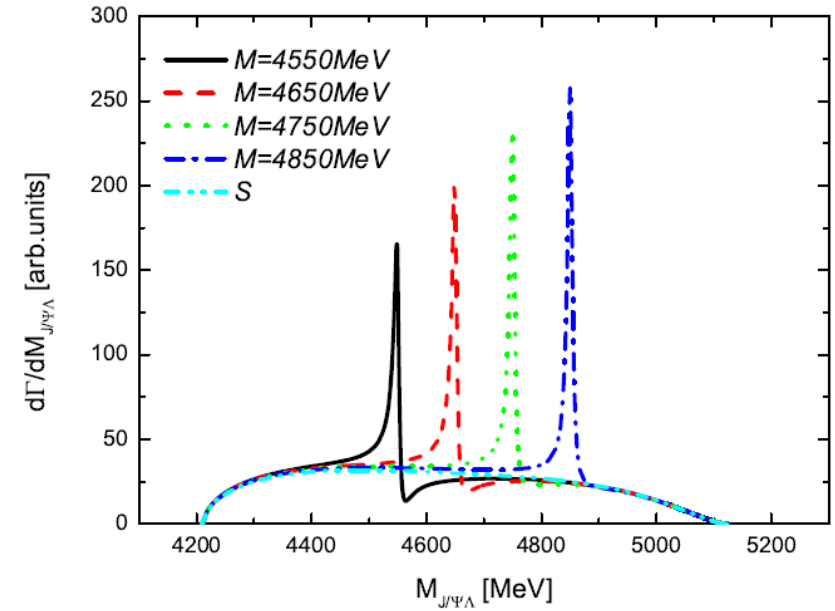
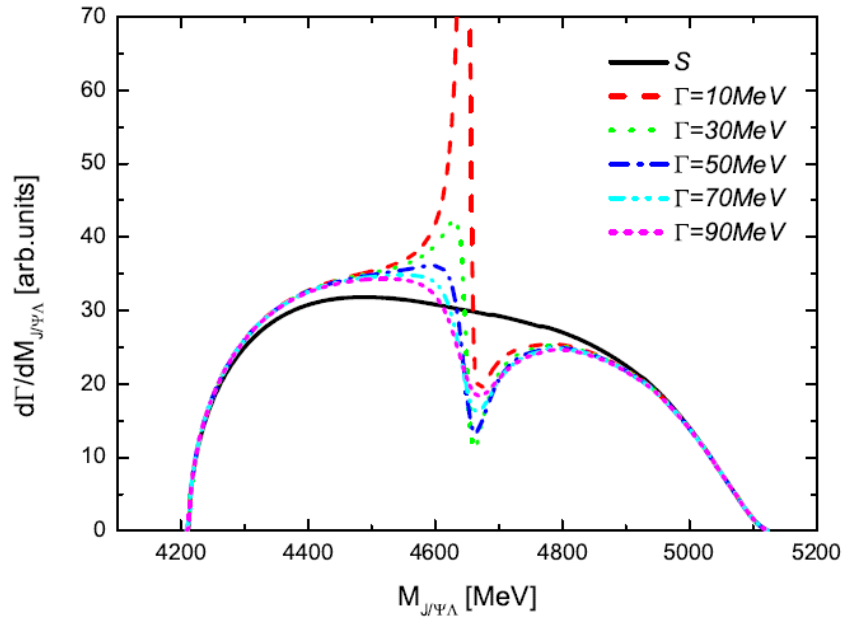
Feijoo, Magas, Ramos, E. O. , [1512.08152](#)



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

with strangeness

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



Conclusions:

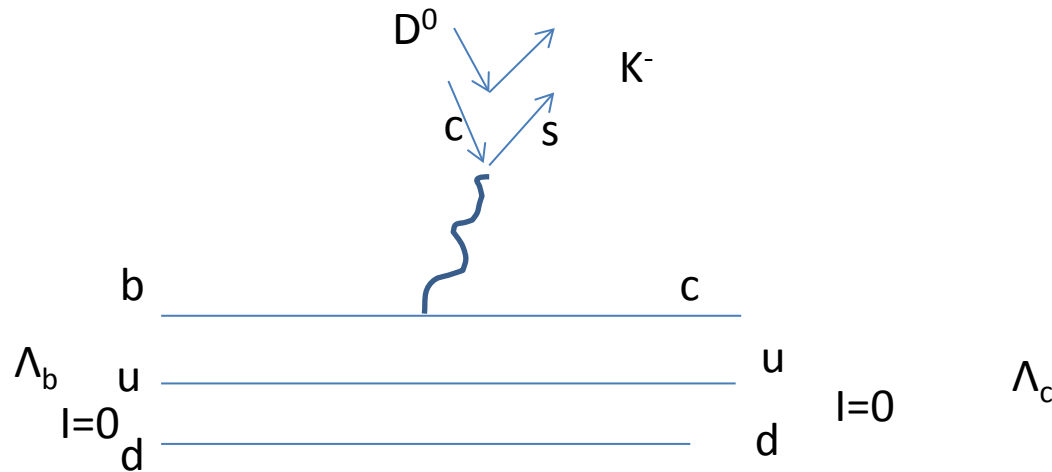
Predictions for $\Lambda_b \rightarrow J/\psi \Lambda(1405)$ made prior to LHCb experiment
Predictions for $D^*\bar{\Sigma}_c$ and $D^*\bar{\Sigma}_c^*$ bound states also made before.
The combination of both matches recent findings of experiment

A recent theoretical analysis backs the experimental claims
for two pentaquark states.

The $\Lambda_b \rightarrow J/\psi \pi^- p$ decay shows the same peak as the $\Lambda_b \rightarrow J/\psi K^- p$.

Predictions are made for different reactions producing $J/\psi \Lambda$ mass in
the final state. The mass distribution of this pair exhibits clear signals
of new pentaquark states with hidden charm and strangeness.

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



Since $D^* \bar{\Sigma}_c$ is the main channel one should start from this production and then make transition to $J/\psi p$, but this configuration is now allowed

$D^* \bar{\Lambda}_c$ is allowed

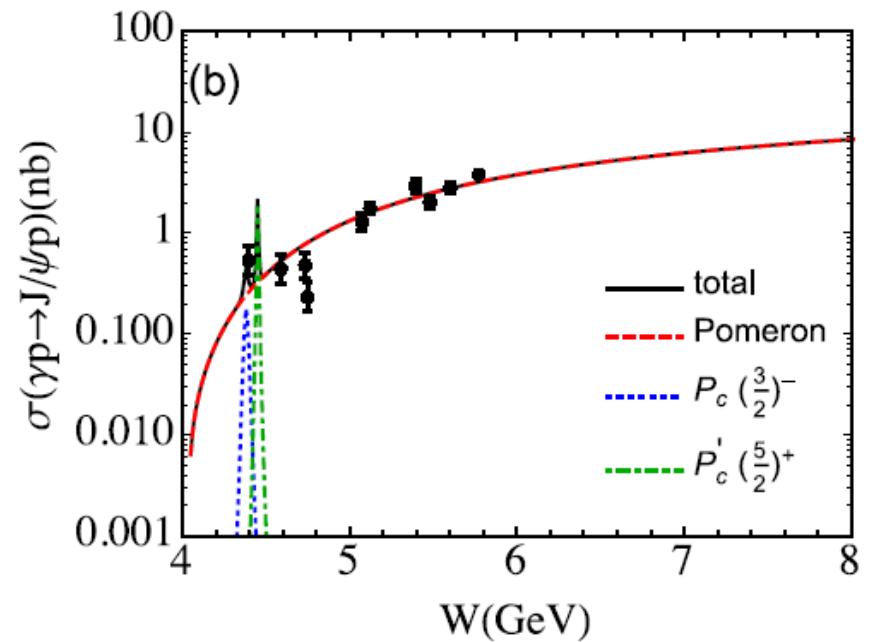
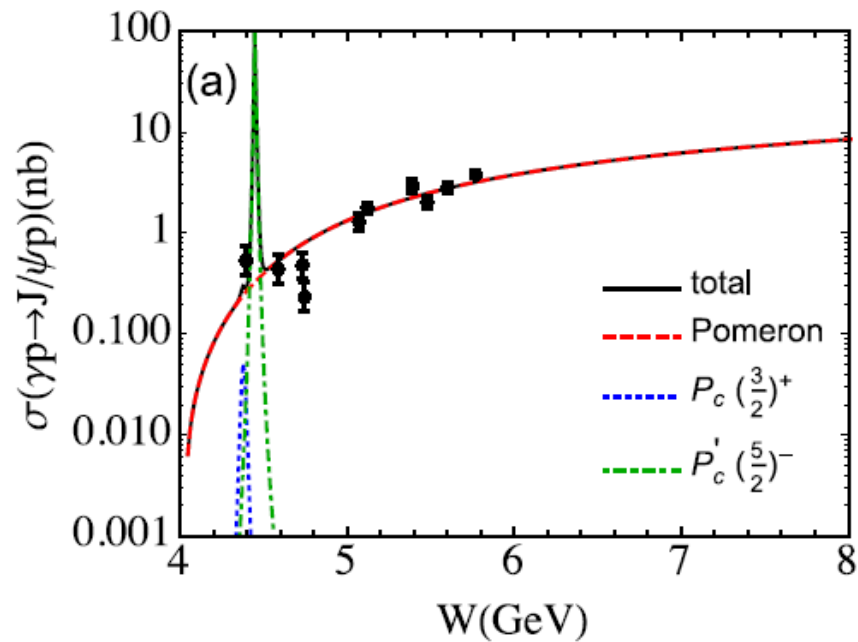
but it has a very small strength in the wave function

This leaves only $J/\psi p$ to initiate the interaction to produce the resonance

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

Photoproduction of J/psi

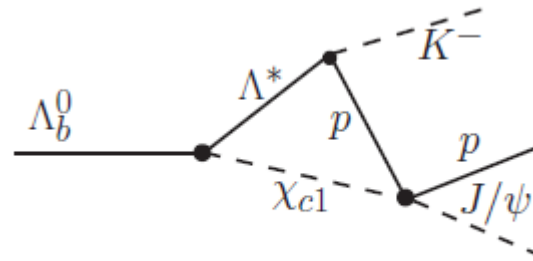
Theory assuming that only 5% of the width goes into J/psi N



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

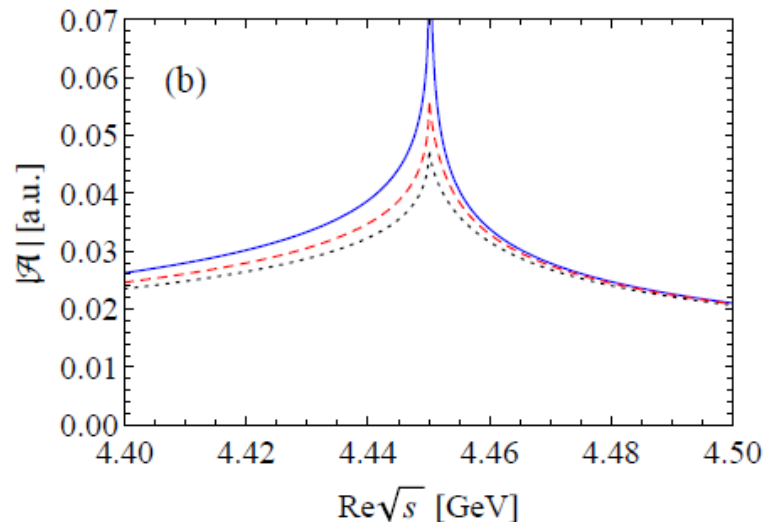
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PRD 2015



(b)

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



Lower curve is for $\Gamma=100$ MeV (exp value)