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

The Λ_b -> J/Ψ K^- p reaction
The LHCb experiment claiming two pentaquark states
Theoretical analysis of the experimental data
The Λ_b -> J/Ψ π^- p reaction
Ξ_b^- -> J/Ψ K^- Λ and a hidden charm strange pentaquark
Λ_b -> J/Ψ η Λ
Λ_b -> J/Ψ K^0 Λ

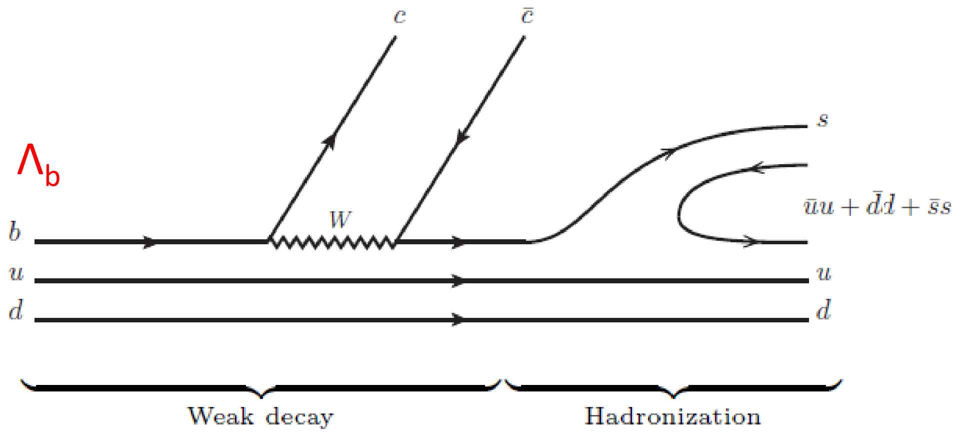
Predictions for the $\Lambda_b \to J/\psi\, \Lambda(1405)$ decay

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

Cabibbo suppressed

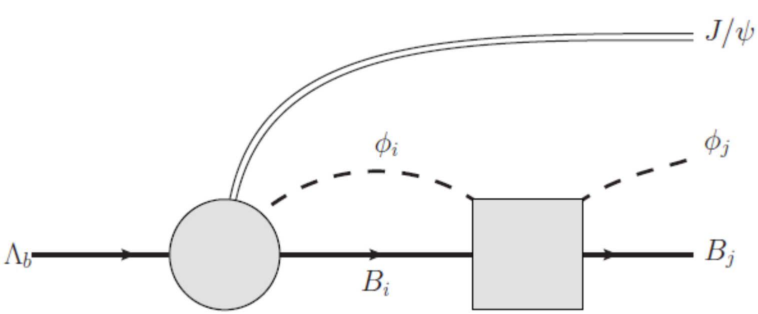
u c t
d s b

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) 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

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

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

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

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

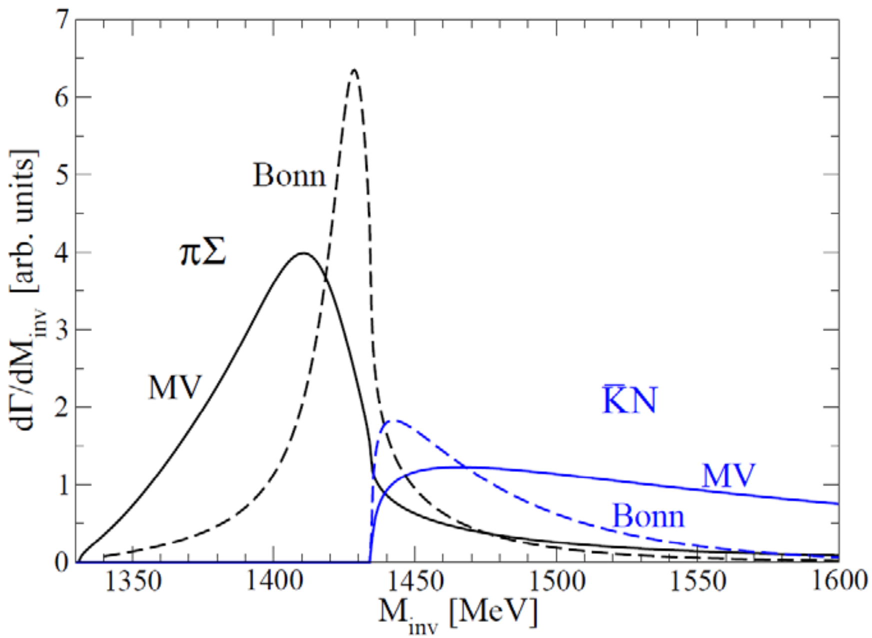
$$|H\rangle = \frac{1}{\sqrt{2}}\Big(K^-u(ud-du)+\bar{K}^0d(ud-du)$$
$$+\frac{1}{\sqrt{3}}\left(-\eta+\sqrt{2}\eta'\right)s(ud-du)\Big)$$

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

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

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/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

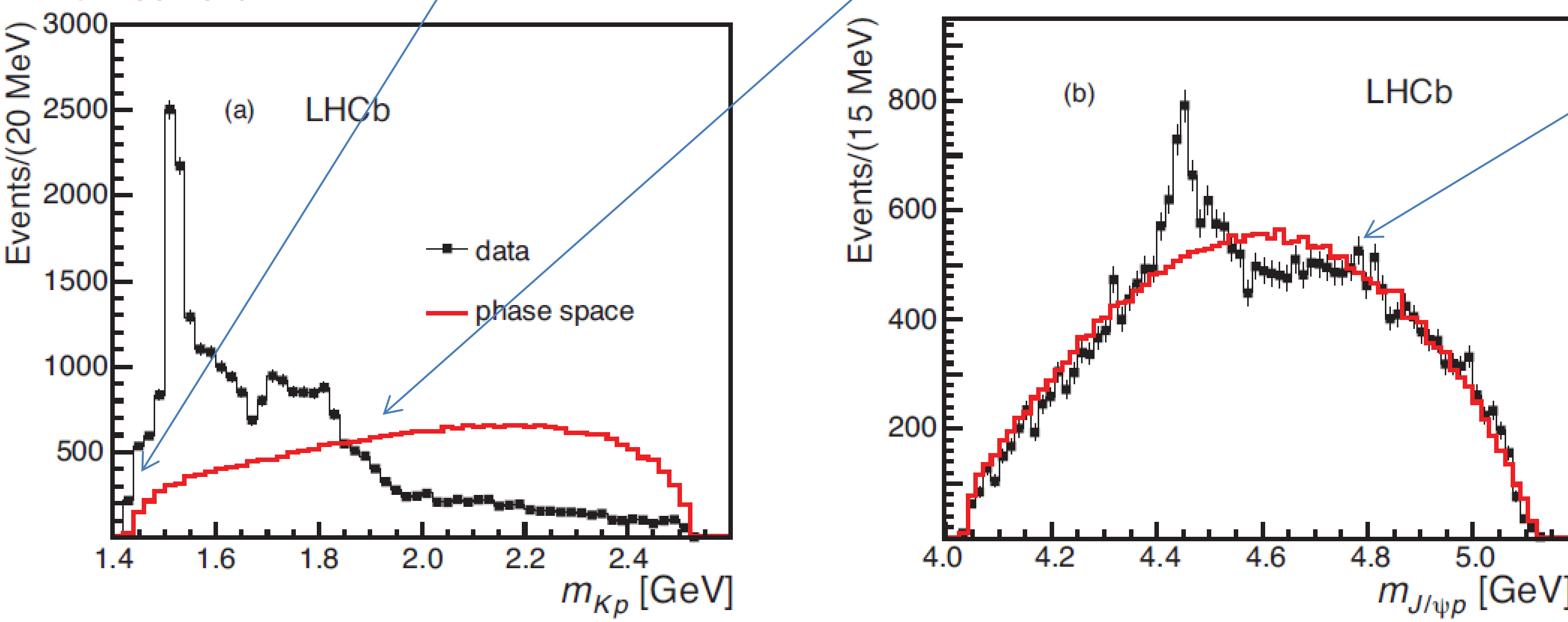
LHCb Collaboration

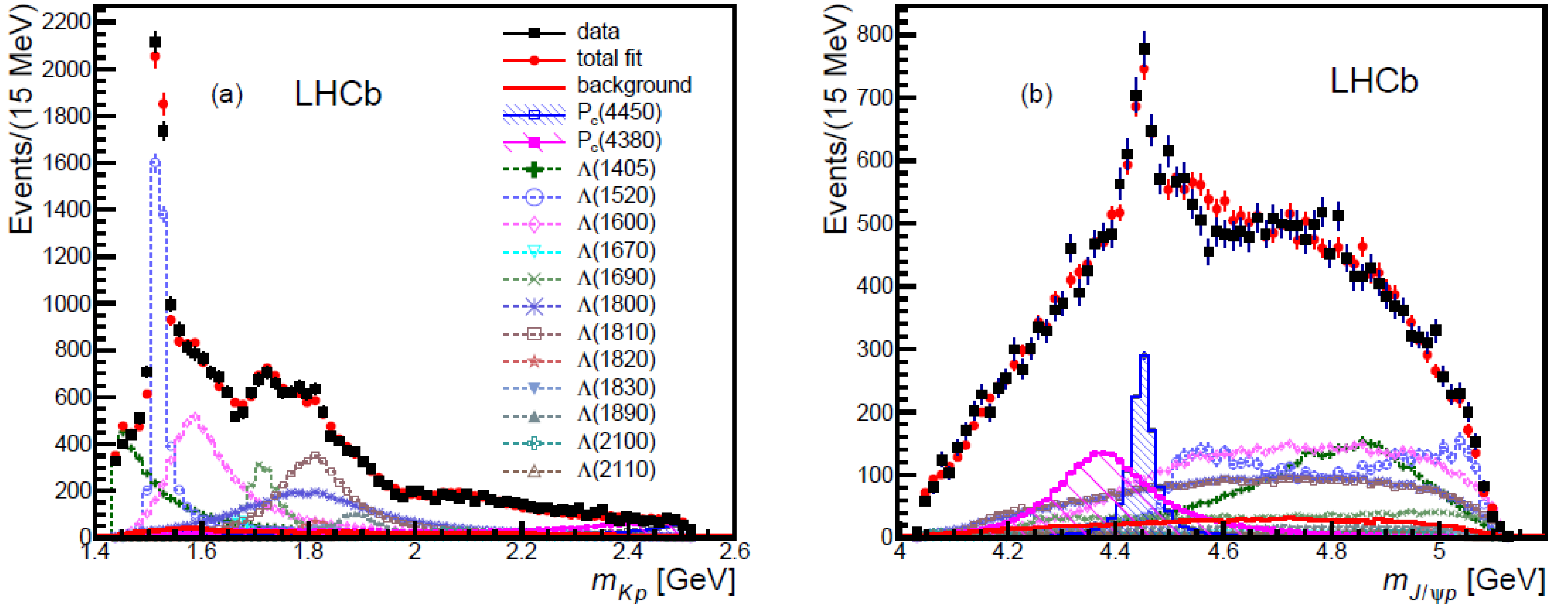
Phys.Rev.Lett. 115 (2015) 072001

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

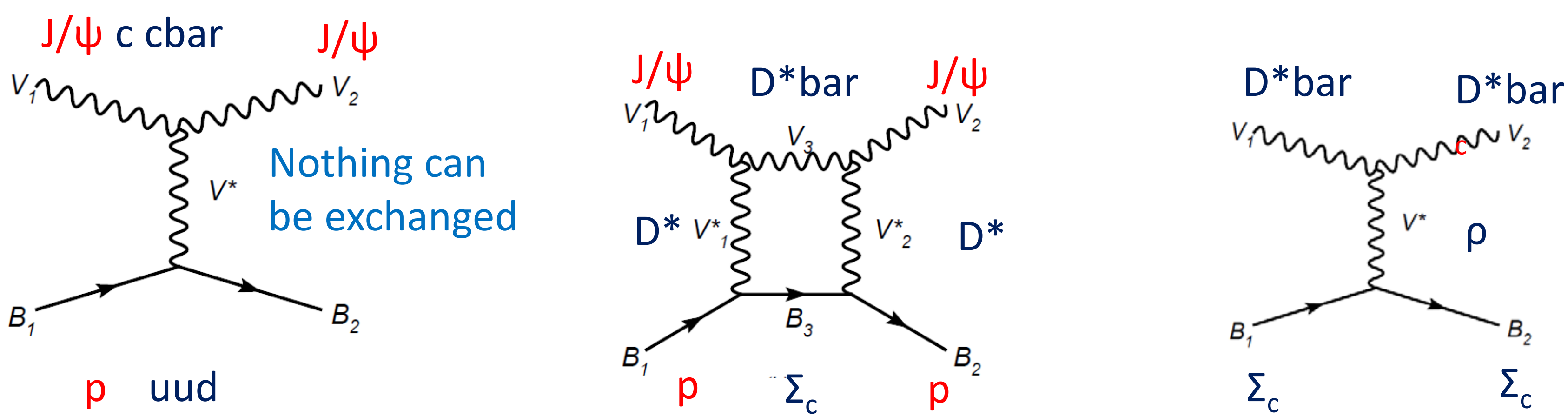




Two states claimed: Pc(4380), Γ=205 MeV ; Pc(4450), Γ=40 MeV

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

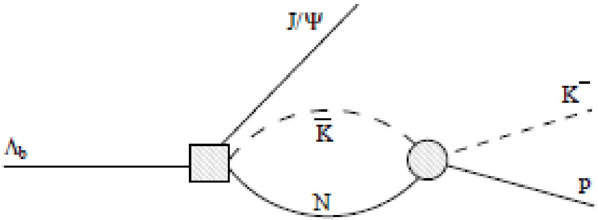
J J Wu, R Molina, E. O, B S Zou, PRL (2010)

(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

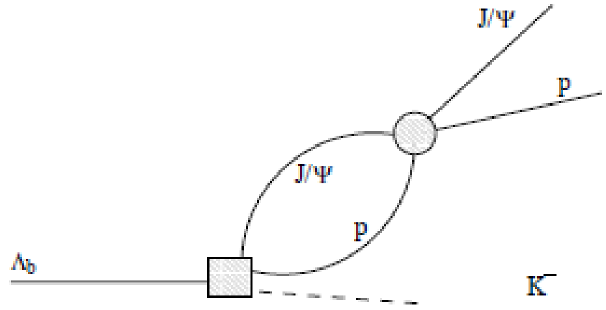
In s-wave: $3/2^-$

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



(b)

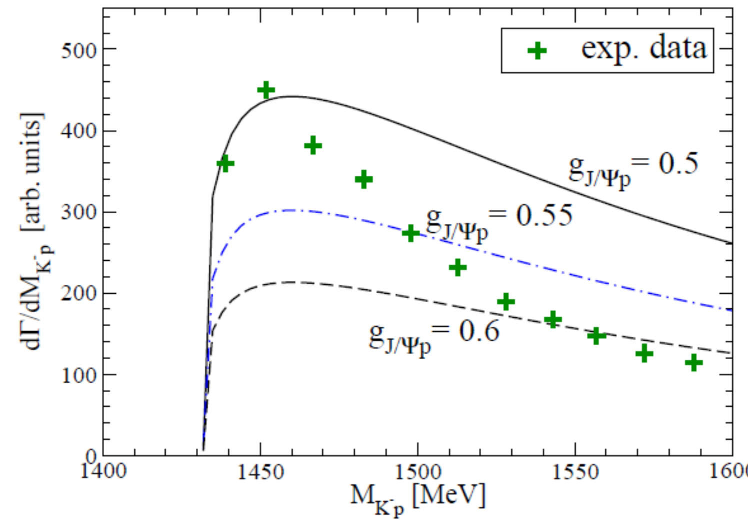


(c)

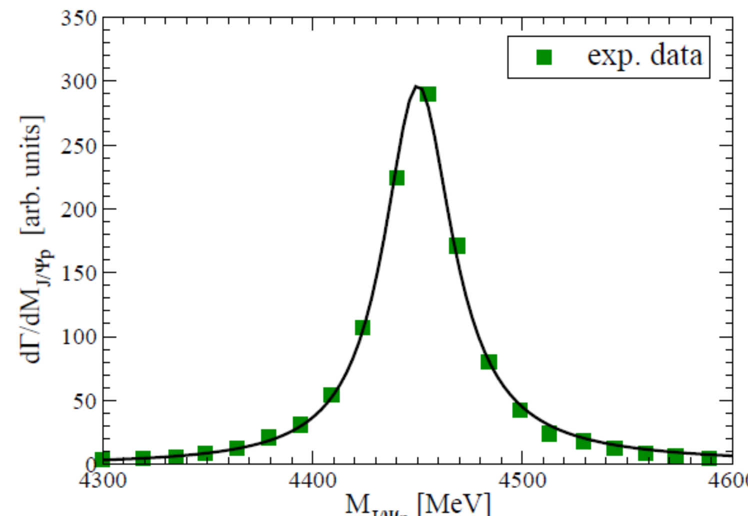
L. Roca, J. Nieves, E. O
PRD 92, 094003 (2015)

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

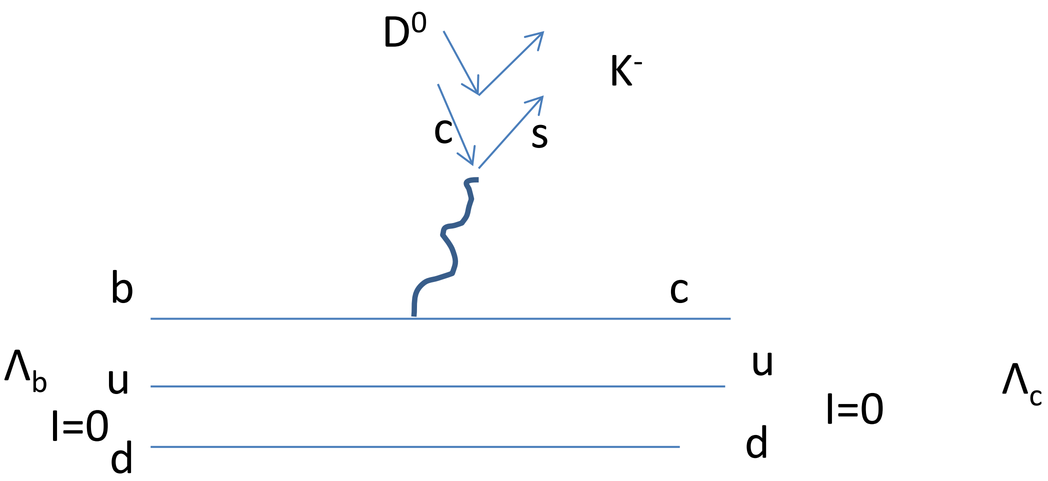
$$t_{J/\psi\, p \to J/\psi\, p} = \frac{g^2_{J/\psi\, p}}{M^2_{J/\psi\, p} - M_R^2 + i M_R \Gamma_R} \quad 2M_R$$



(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

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

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

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

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

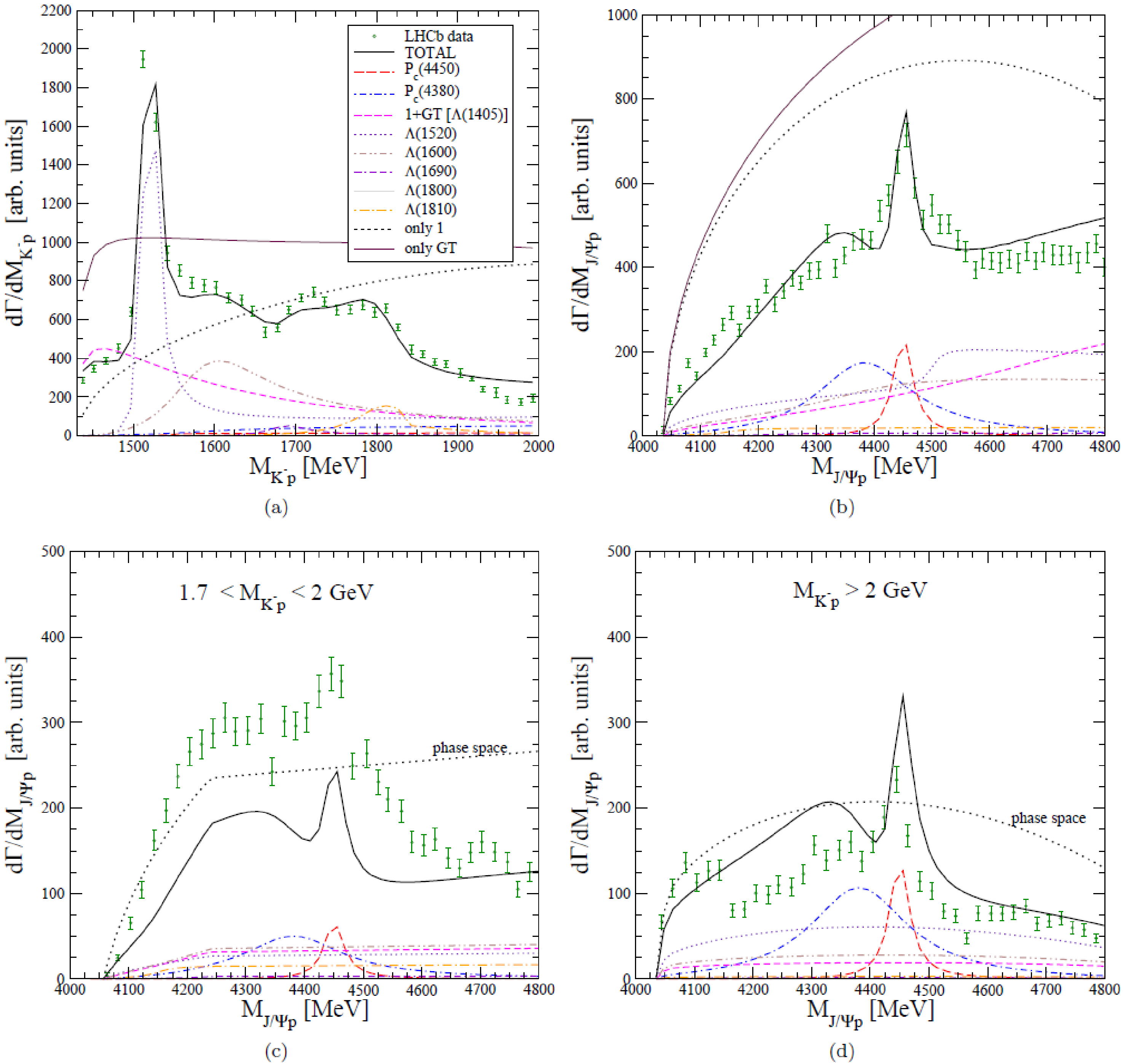
$\Lambda(1690)$ $(3/2^-)$

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

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

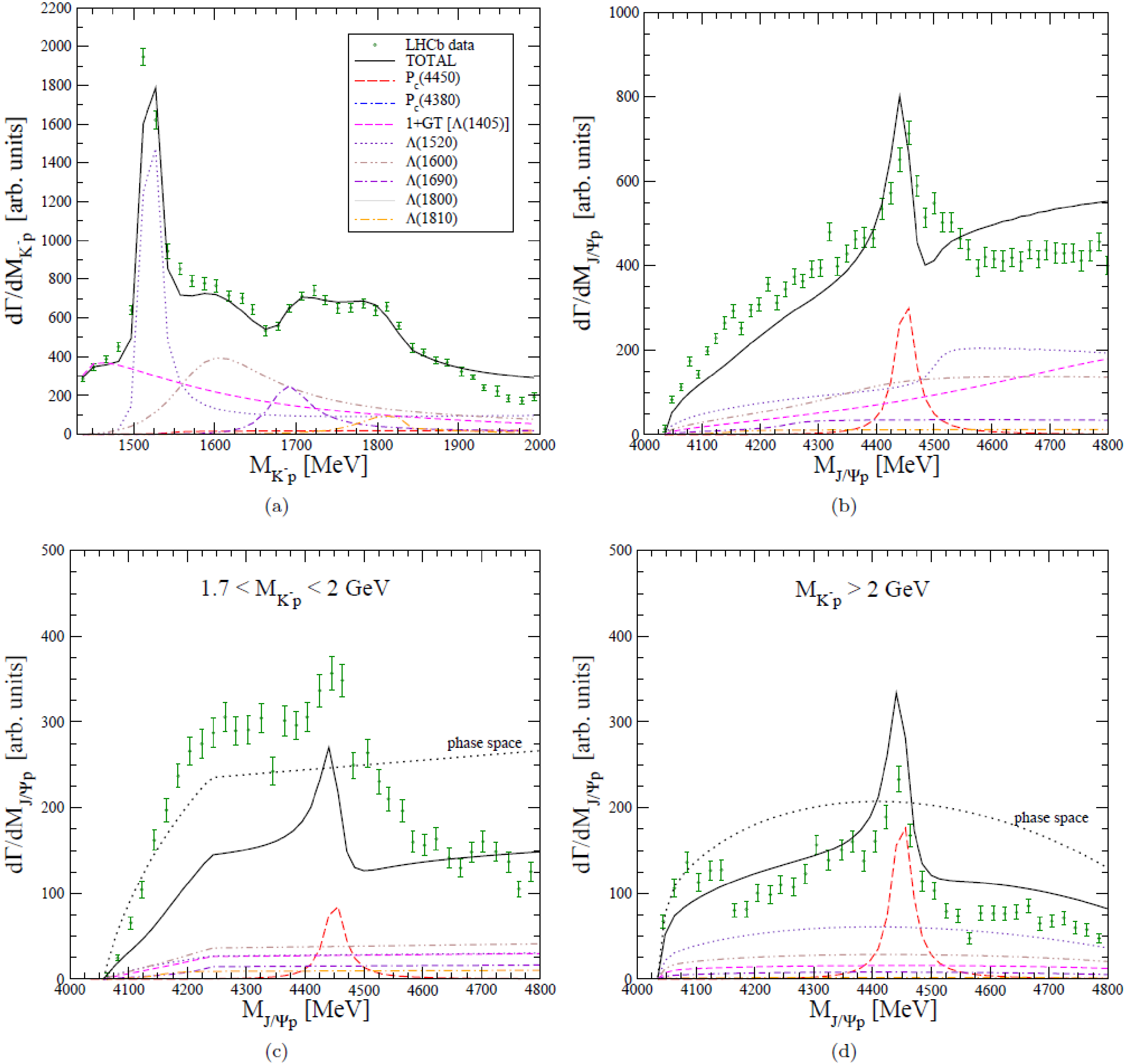
This assumes the two pentaquark states to be in S-wave in J/Ψ p

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



Fit with two Pentaquarks

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



Fit removing the Pc(4380)

This could be 3/2⁻, 5/2⁺

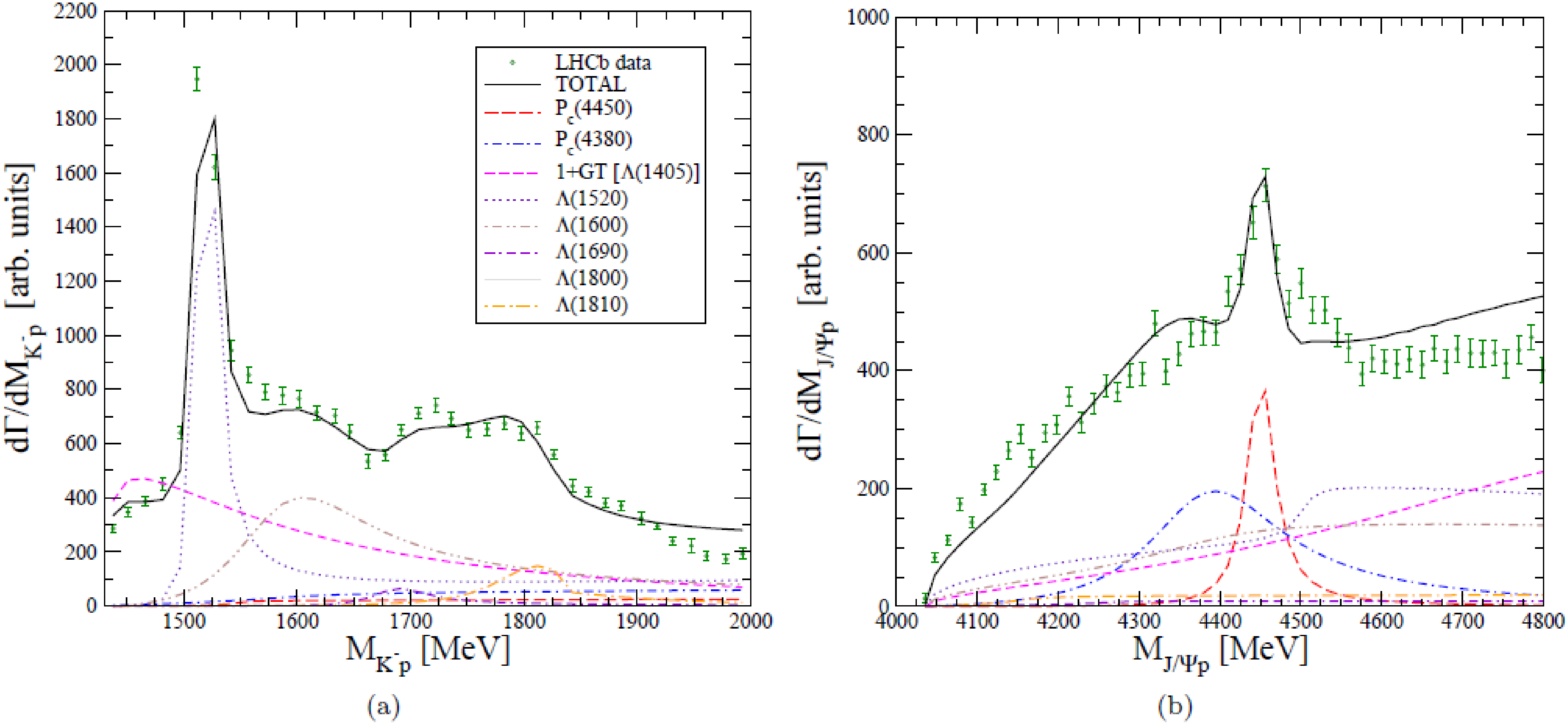


FIG. 5: (Color online). Same as Fig. 3a and b but considering $P_c(4380)$ in s-wave and $P_c(4450)$ in p-wave.

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

Lucky experimental analysis

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

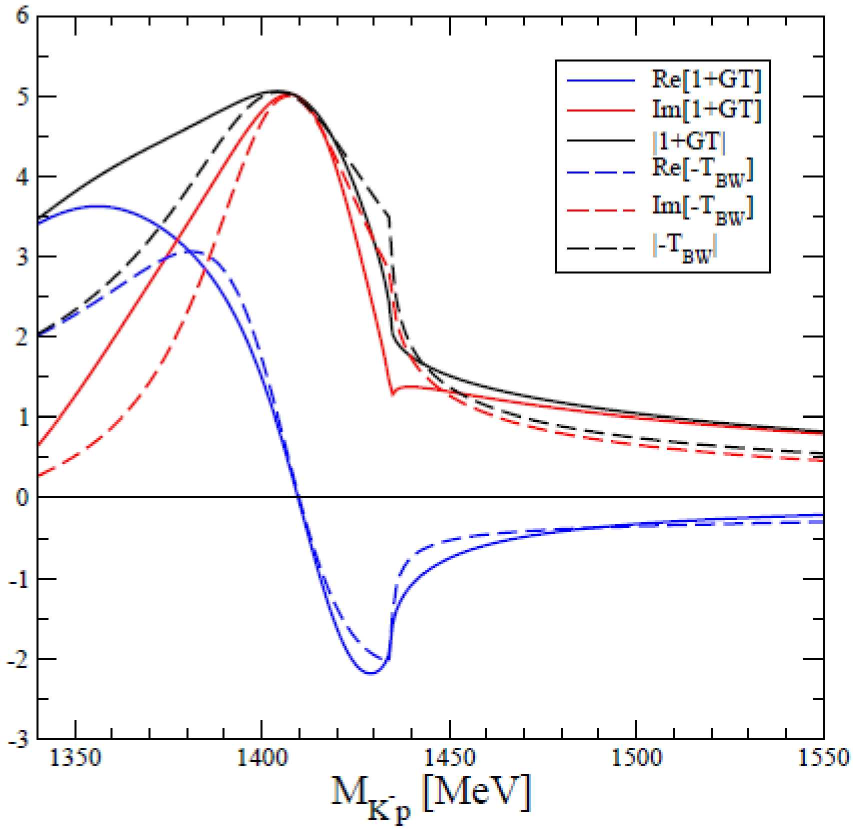
$$T_{12} \simeq \frac{g_1^A g_2^A}{\sqrt{s} - \sqrt{s_0^A}} + \frac{g_1^B g_2^B}{\sqrt{s} - \sqrt{s_0^B}}$$

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

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

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

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



11: Kbar N -> Kbar N

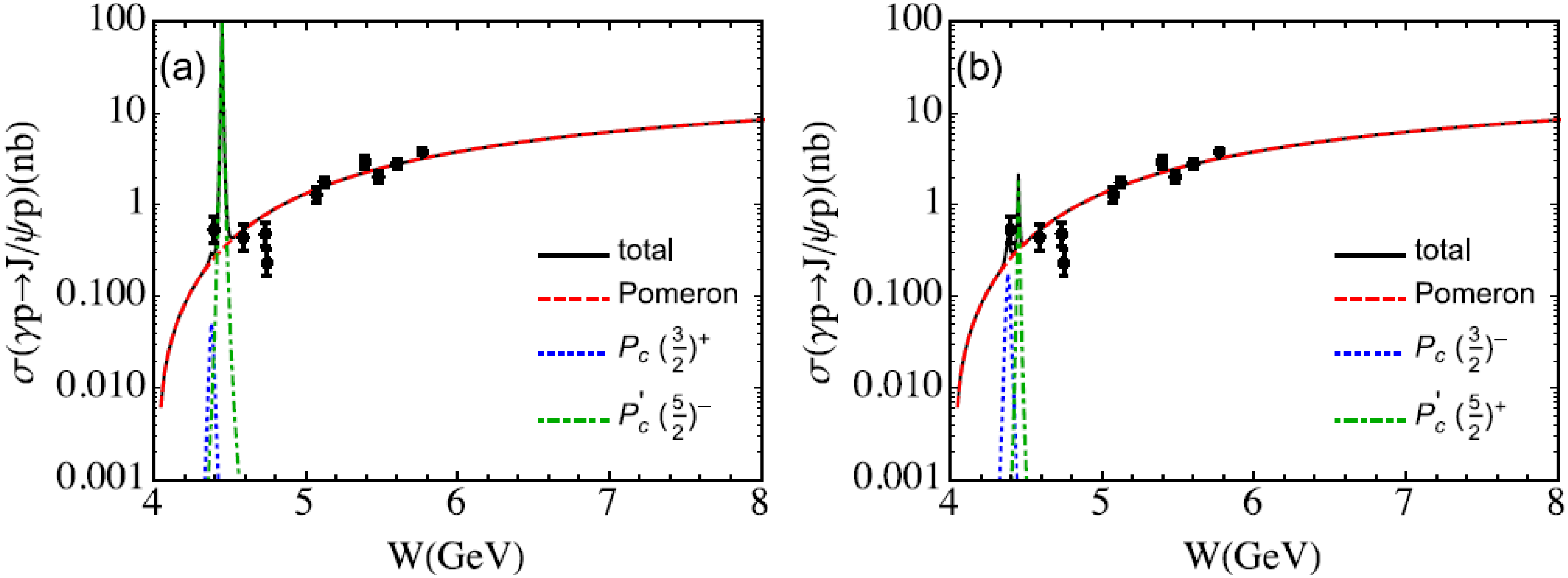
12: Kbar N -> πΣ

and recall the Λ(1405) has two poles.

Wang, Li , Q Zhao, arXiv 1508.00339

Photoproduction of J/psi

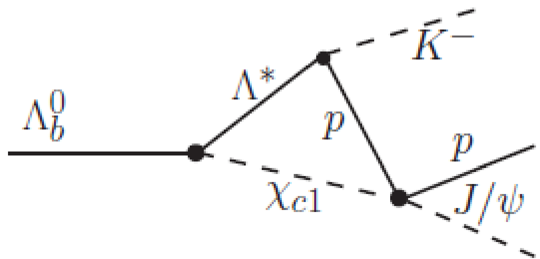
Theory assuming that only 5% of the width goes into J/psi N



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

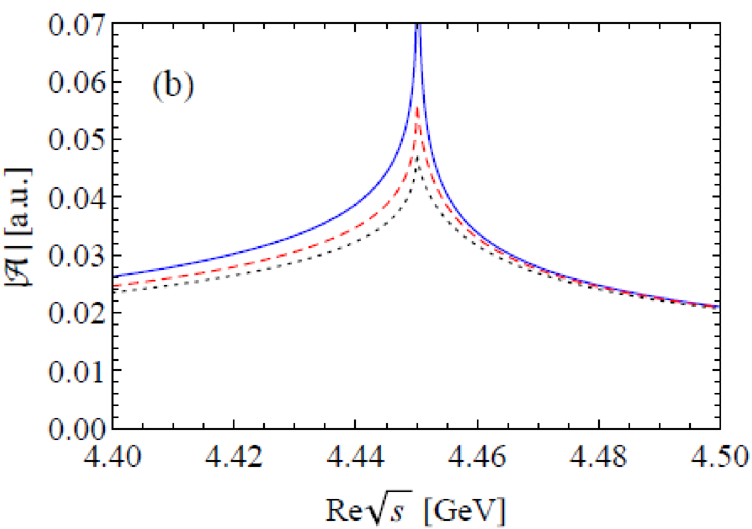
Feng-Kun Guo[1,2,*] Ulf-G. Meißner[2,3,†] Wei Wang[4,1,‡] and Zhi Yang[2,§]

PRD 2015



(b)

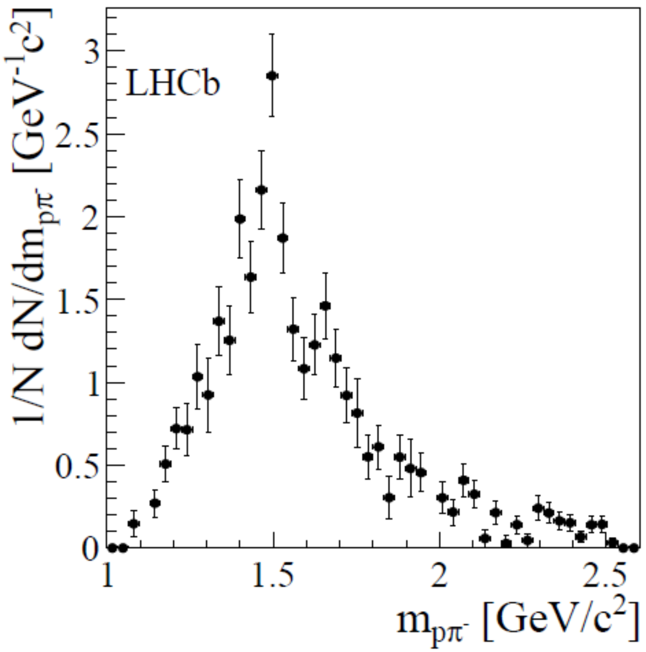
assume the $\Lambda(1890)$ with a mass of 1.89 GeV is exchanged in the triangle diagram



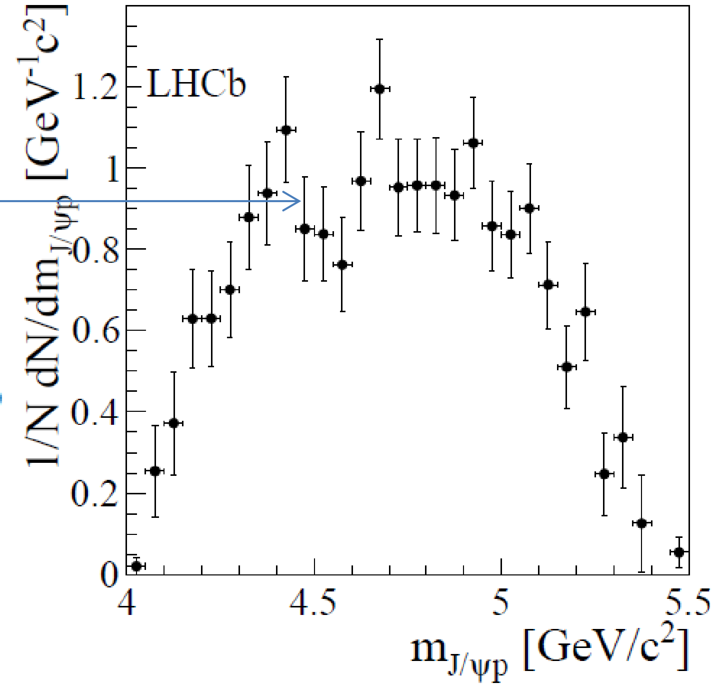
Lower curve is for Γ=100 MeV (exp value)

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

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

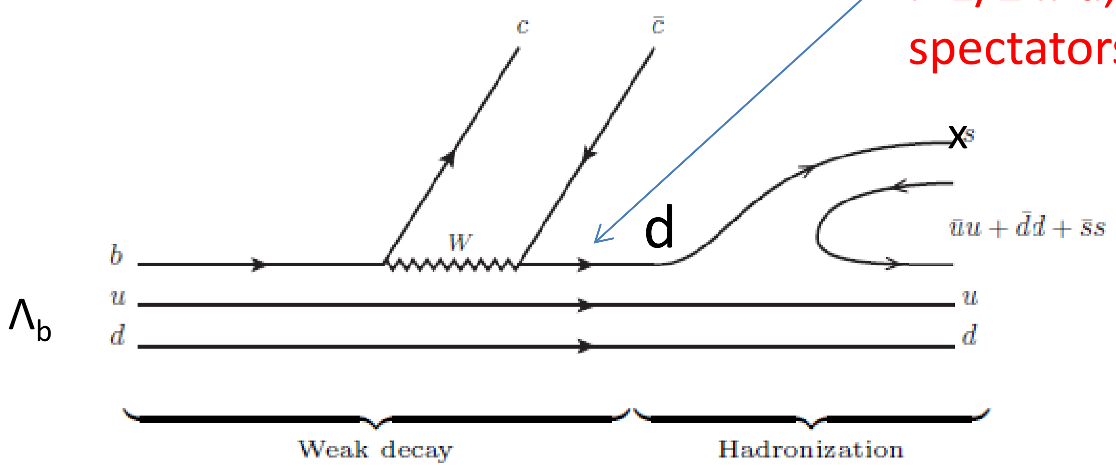


Peak at the same energy as in $\Lambda_b \to J/\psi\ K^- p$

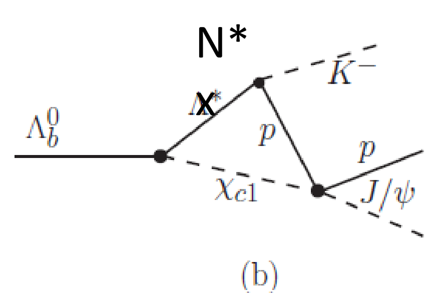


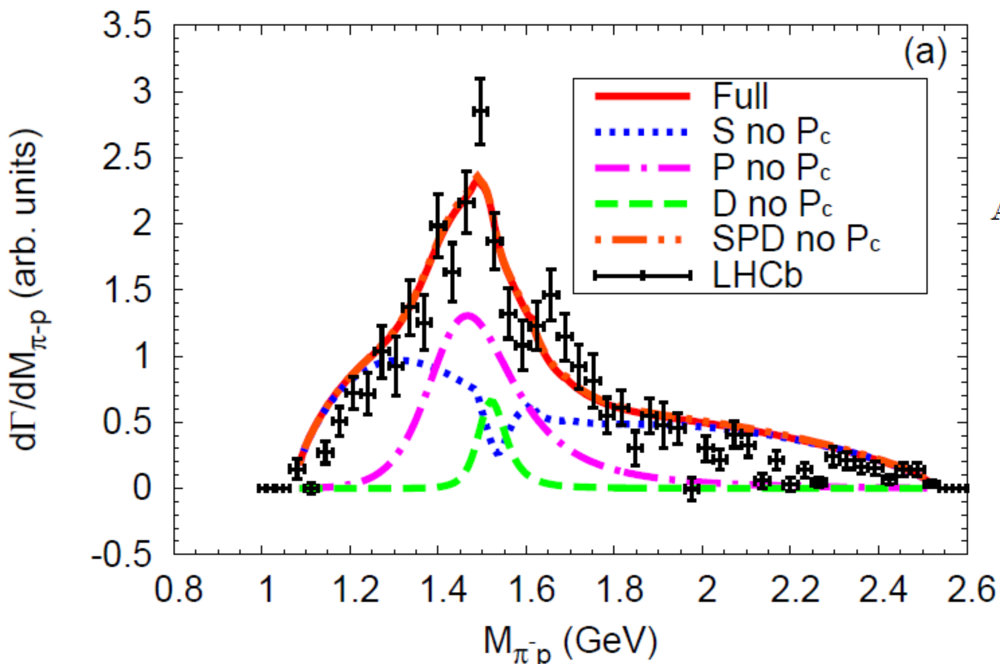
Note: No Δ(1232) !!

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



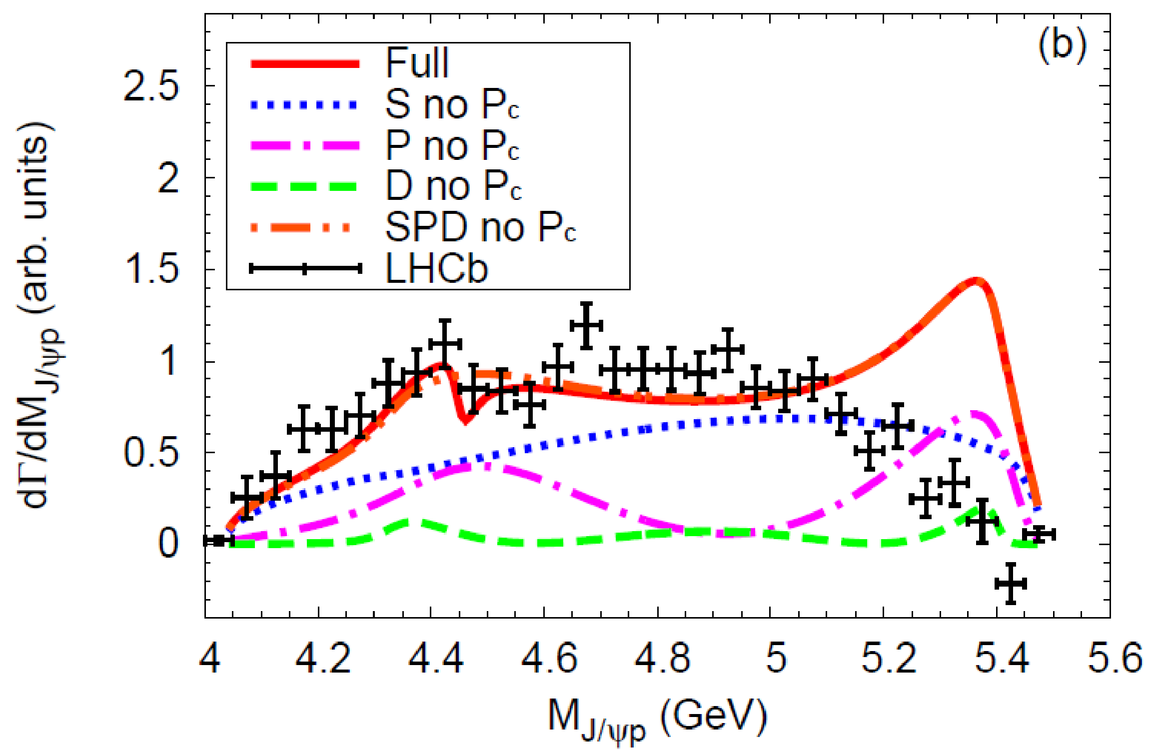
Triangle singularity Is different now





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

Wang, Chen, Geng, Li, E. O. , 1512.01959



More pentaquarks?

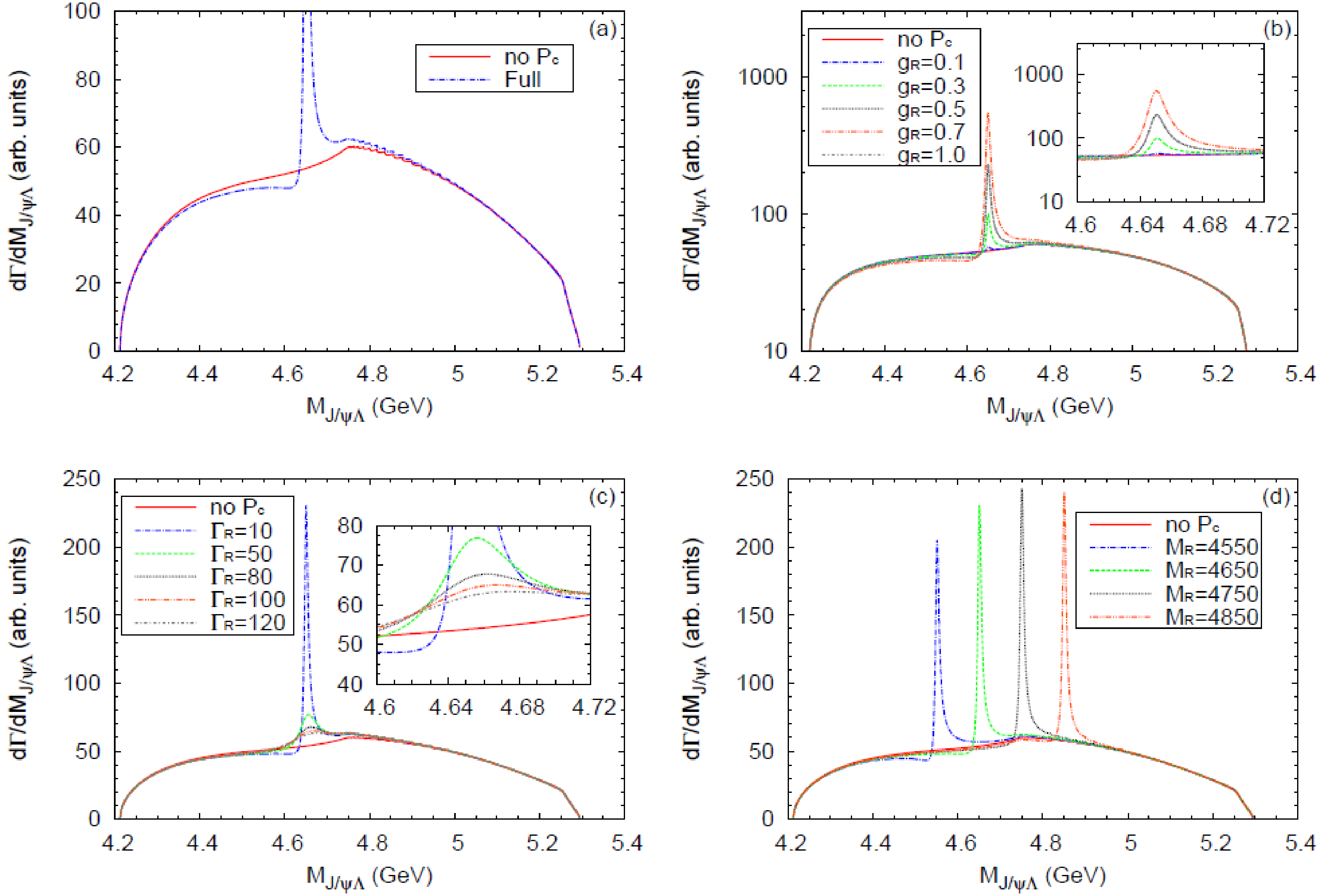
Dynamically generated N^* and Λ^* resonances in the hidden charm sector around 4.3 GeV

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

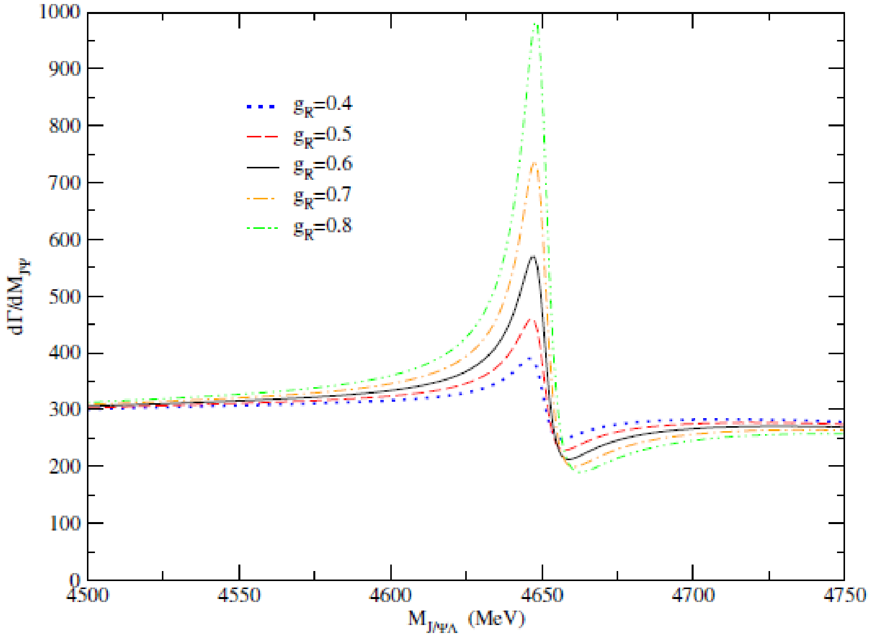
Looking for a hidden-charm pentaquark state with strangeness $S = -1$ from Ξ_b^- decay into $J/\psi K^- \Lambda$

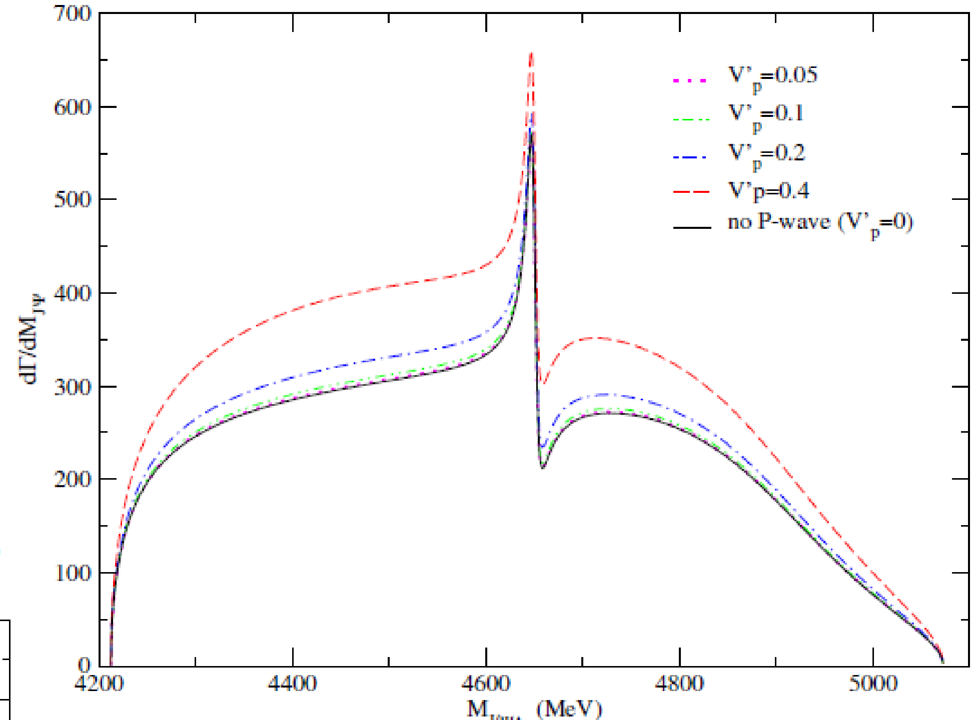
Chen, Geng, Liang, E.O. Wang, Xie, 1510. 01803

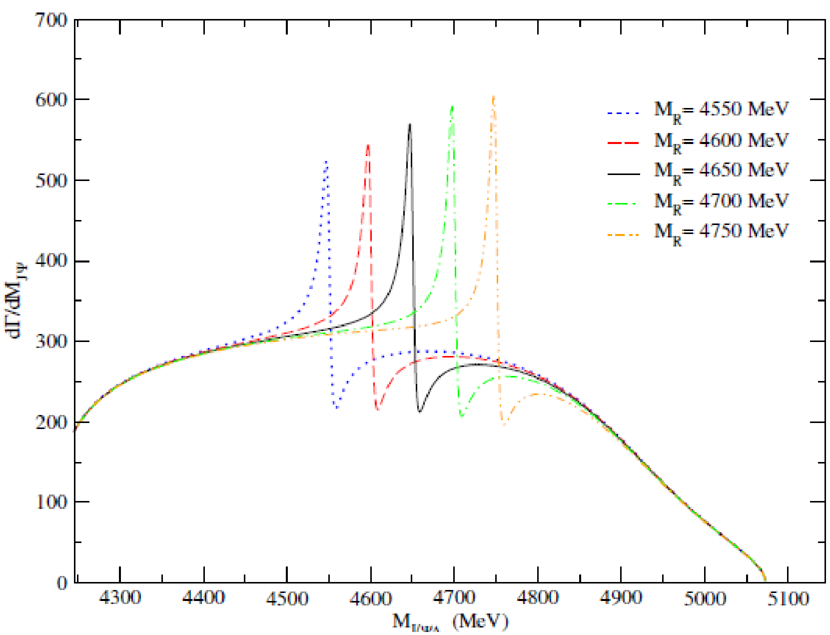


A hidden-charm $S = -1$ pentaquark from the decay of Λ_b into $J/\psi\eta\Lambda$ states

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

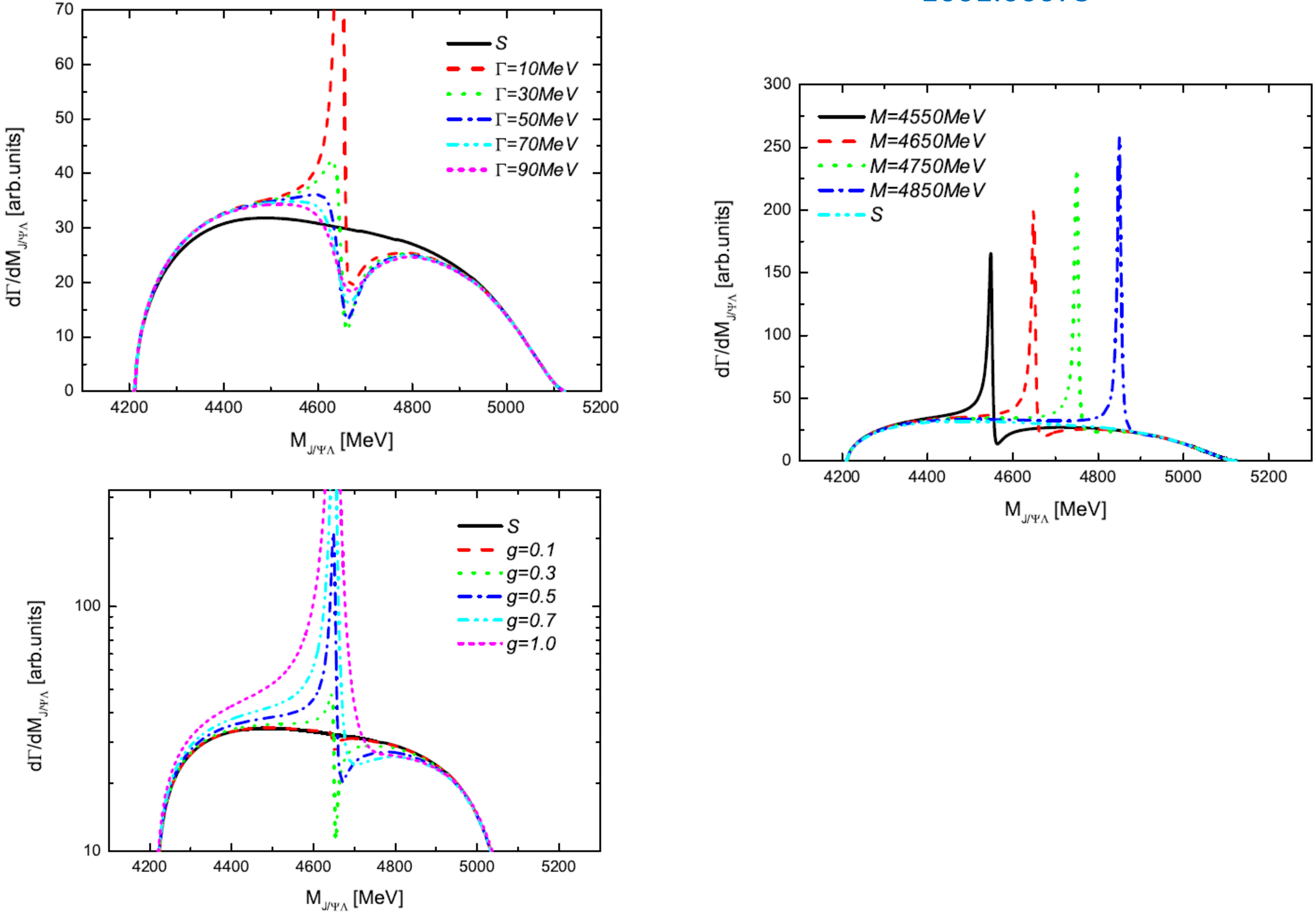






The $\Lambda_b \to J/\psi K^0 \Lambda$ reaction and a hidden-charm pentaquark state with strangeness

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



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 backs the experimental claims
for two pentaquark states.

The Λ_b -> J/ψ π^- p decay shows the same peak as the Λ_b -> J/ψ K^- p .
This rules out the triangle singularity interpretation, and makes more likely the interpretation as a new state.

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.