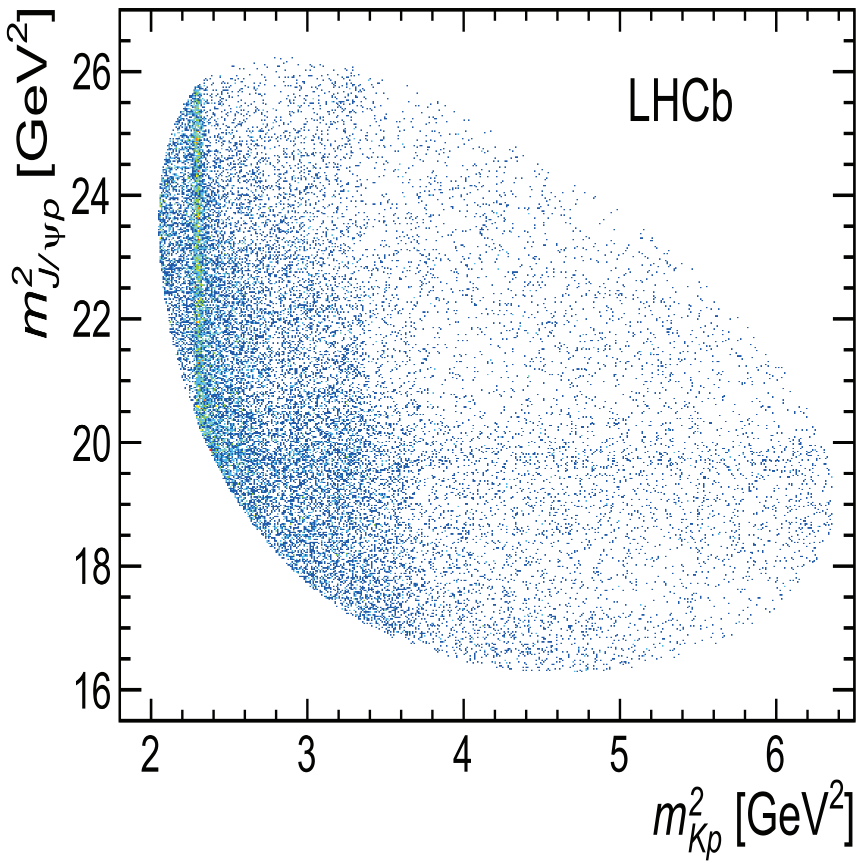
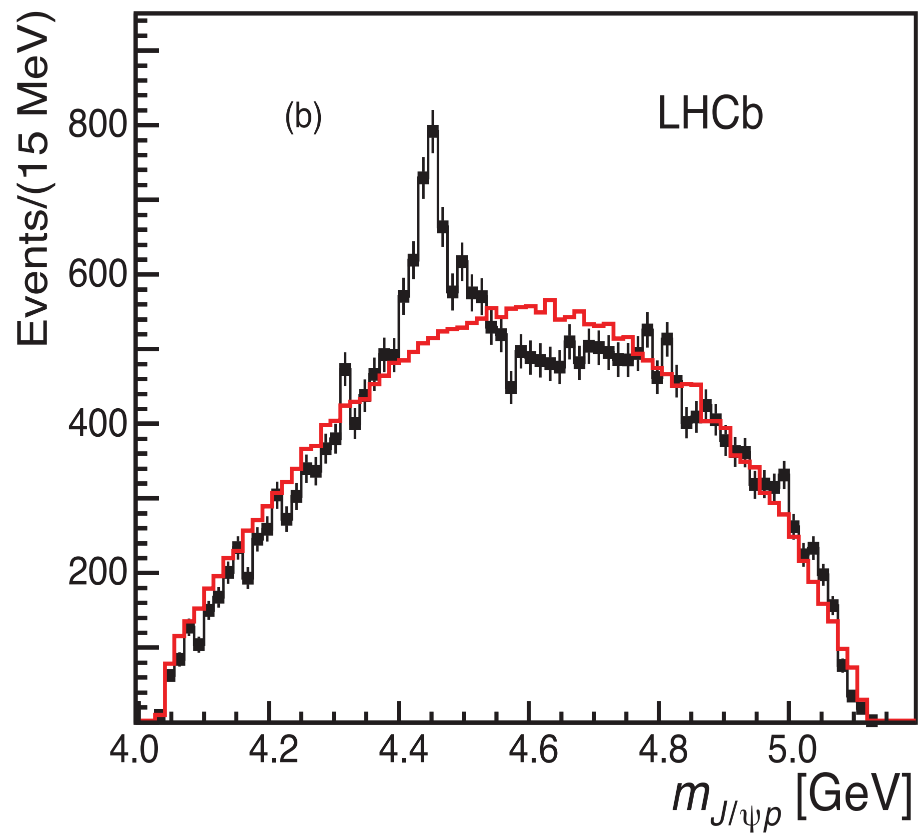
R. Aaij *et al.* **[LHCb Collaboration]**

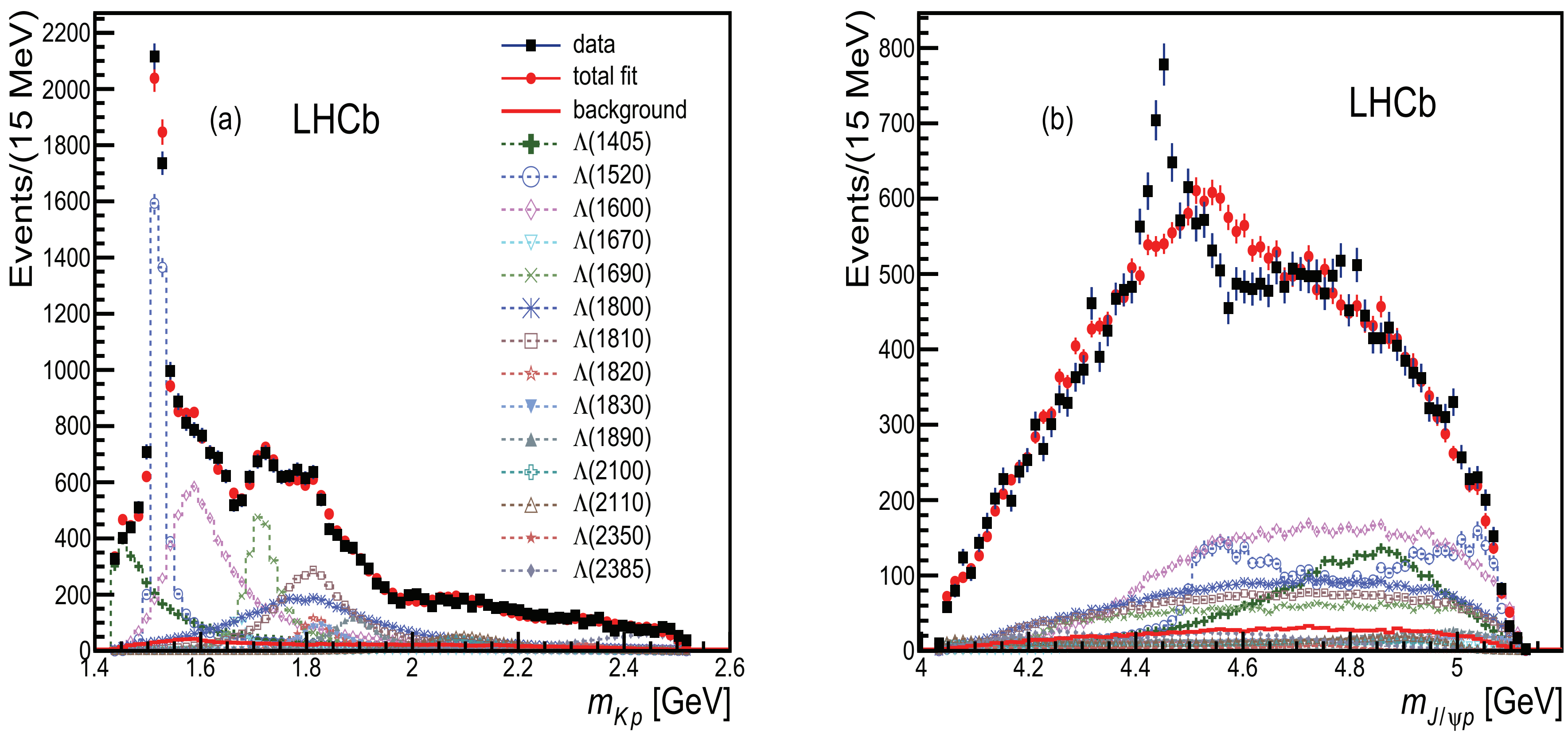
"Observation of $J/\Psi\, p$ Resonances Consistent with Pentaquark States in $\Lambda_b^0 \to J/\Psi K^- p$ Decays"



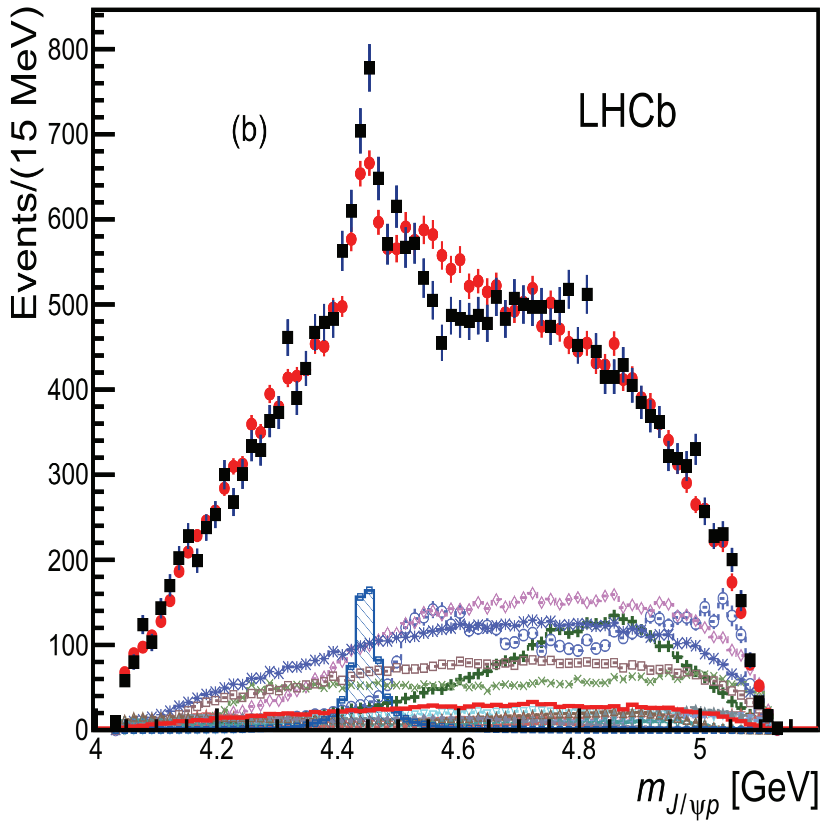


LHCb pentaquark...

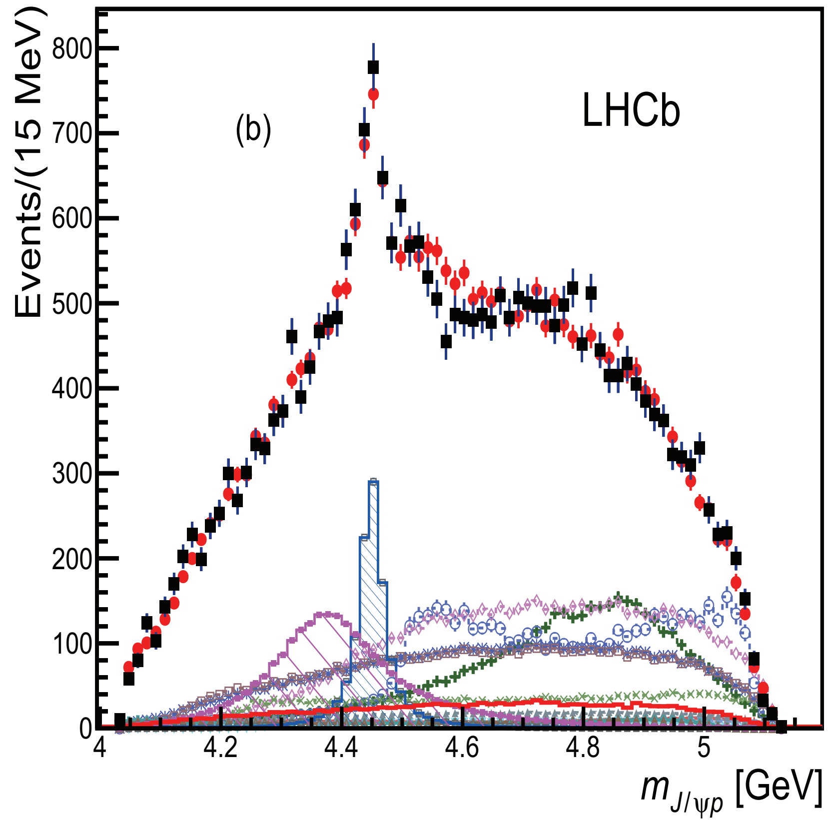
Only Λ^* states



Added 1 or 2 pentaquark states



7/2+ or 7/2-



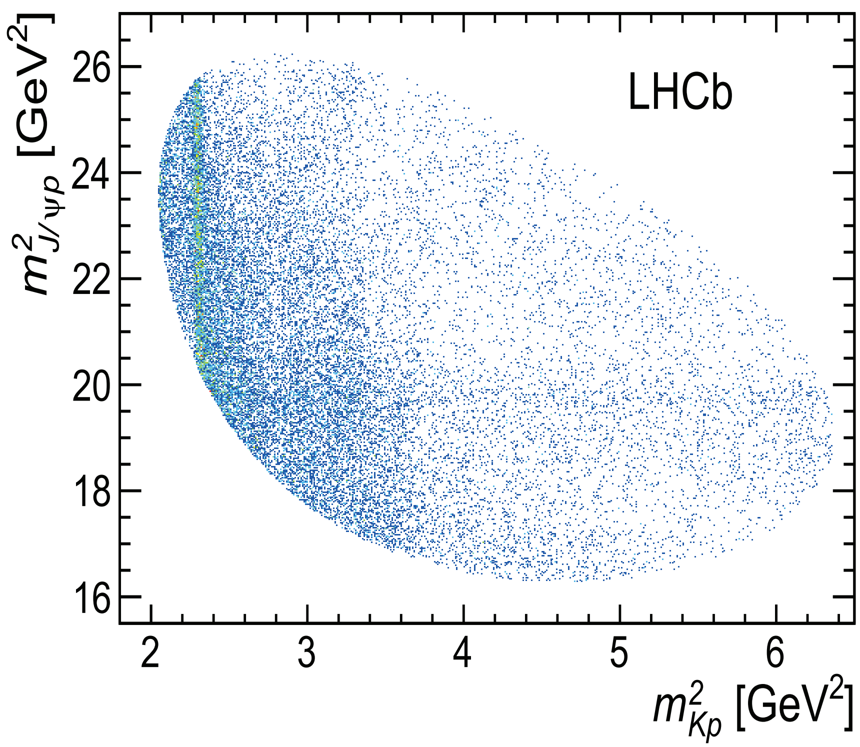
Best (3/2-,5/2+) $M = 4380 \pm 8 \pm 29$**,**

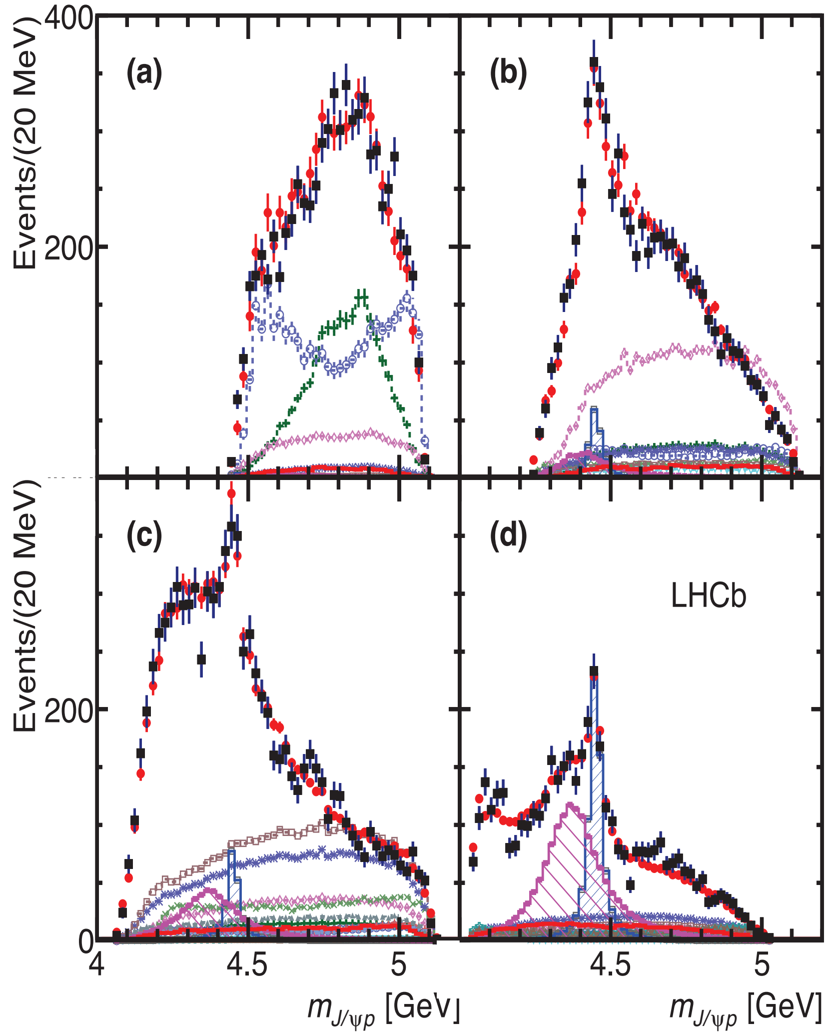
$\Gamma = 205 \pm 18 \pm 86$ **MeV,**

$M = 4449.8 \pm 1.7 \pm 2.9 \, \Gamma = 39 \pm 5 \pm 19$

Acceptable (3/2+, 5/2-) or (5/2+,3/2-)

Description of mass distributions

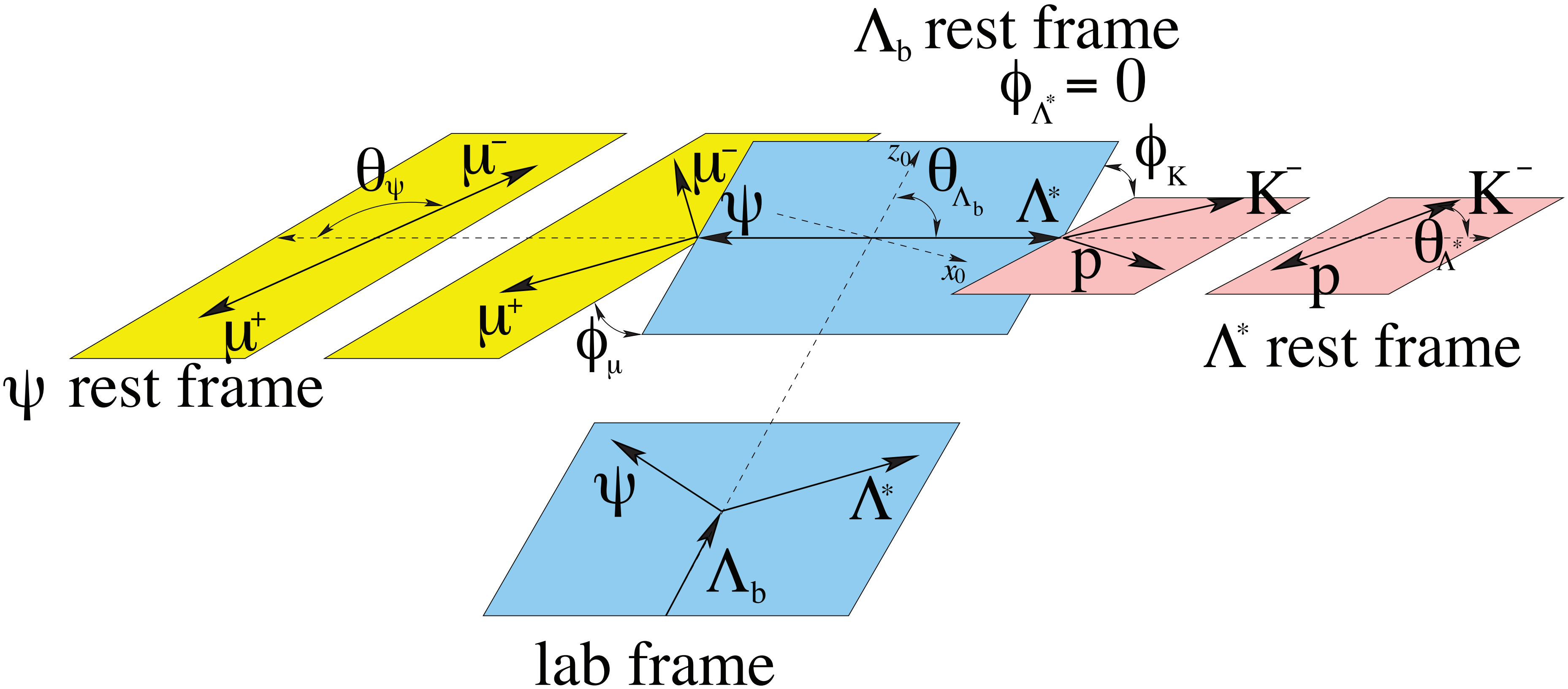




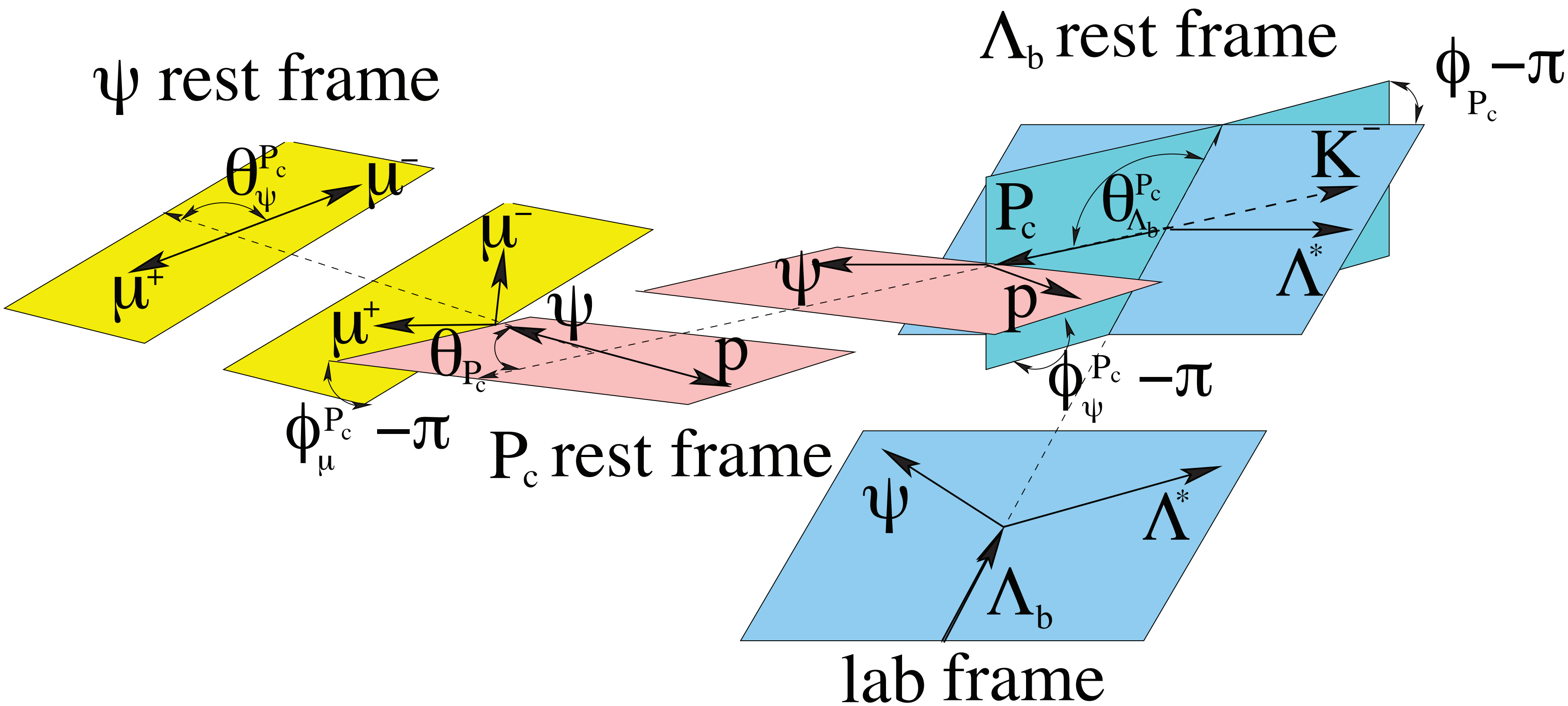
(a) $m^2_{Kp} < 2.4$ **(b)** $2.4 < m^2_{Kp} < 2.9$

(c) $2.9 < m^2_{Kp} < 4.0$ **(d)** $m^2_{Kp} > 4.0$ **GeV^2.**

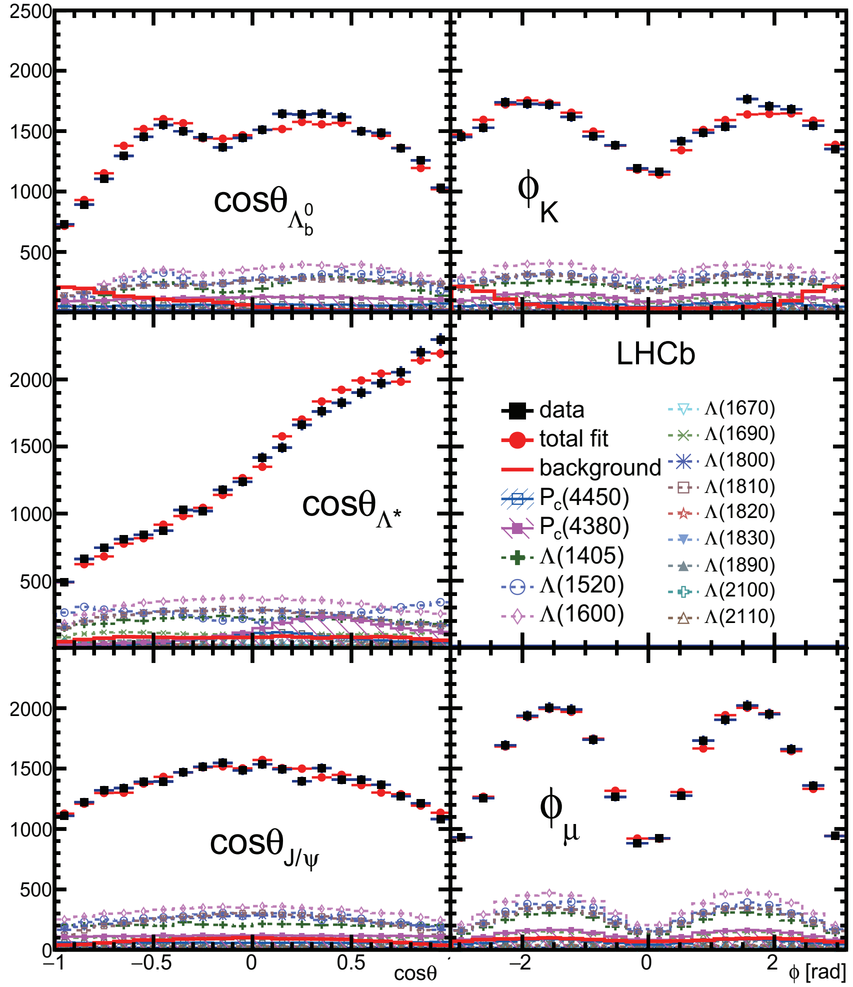
This system describes properties of Λ^* states



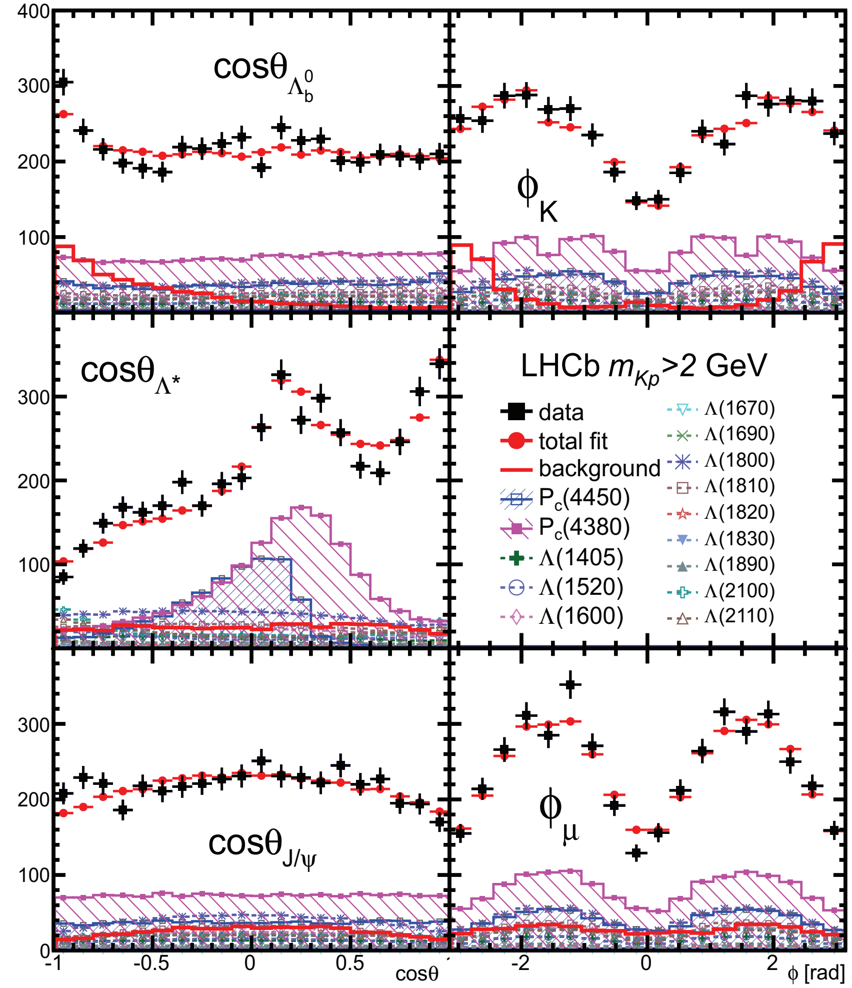
This system describes properties of P_c states



Angular distributions are shown only for Λ^* production

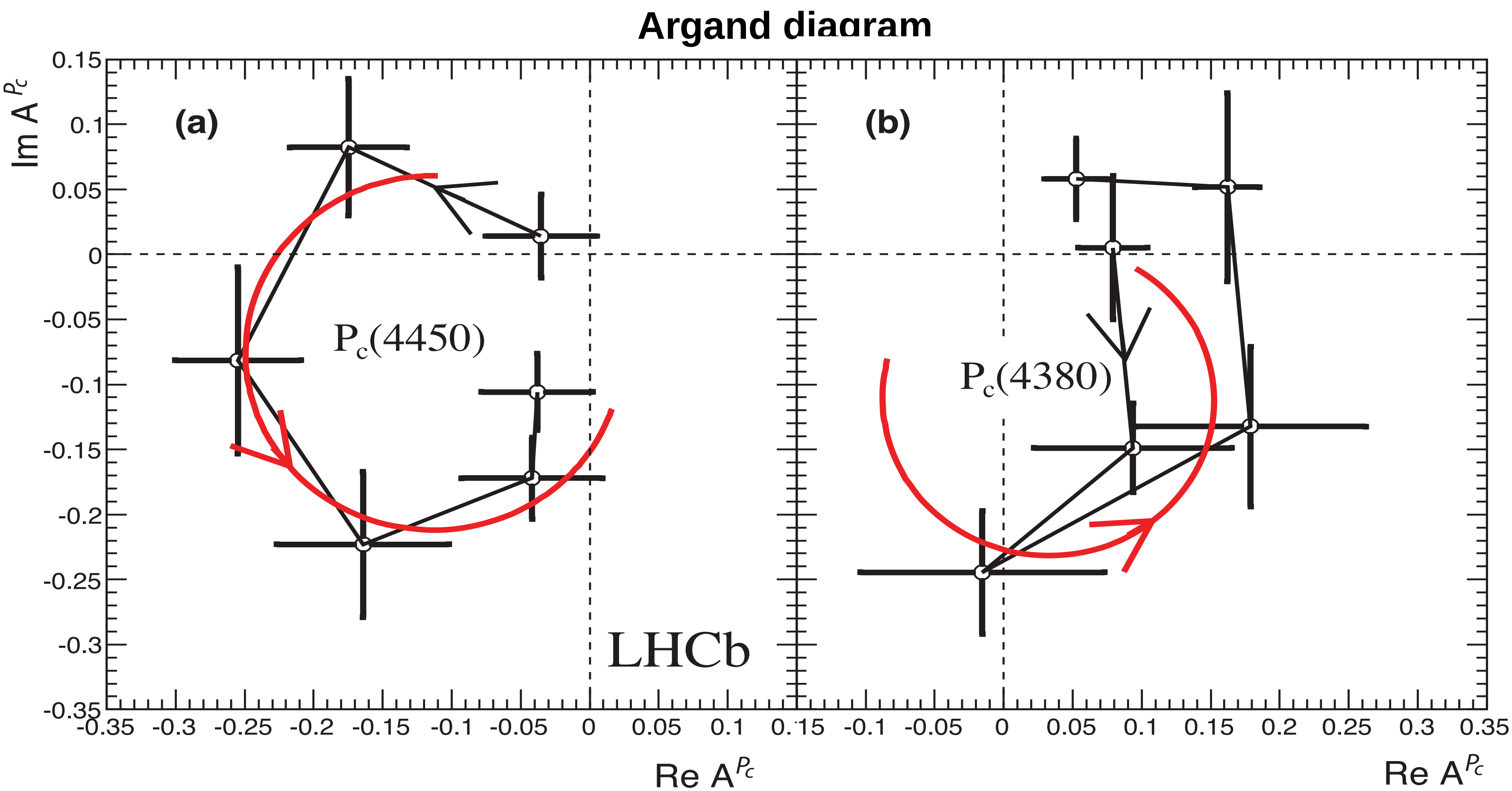


All



$m^2_{Kp} > 4.0$ **GeV^2**

LHCb pentaquark...

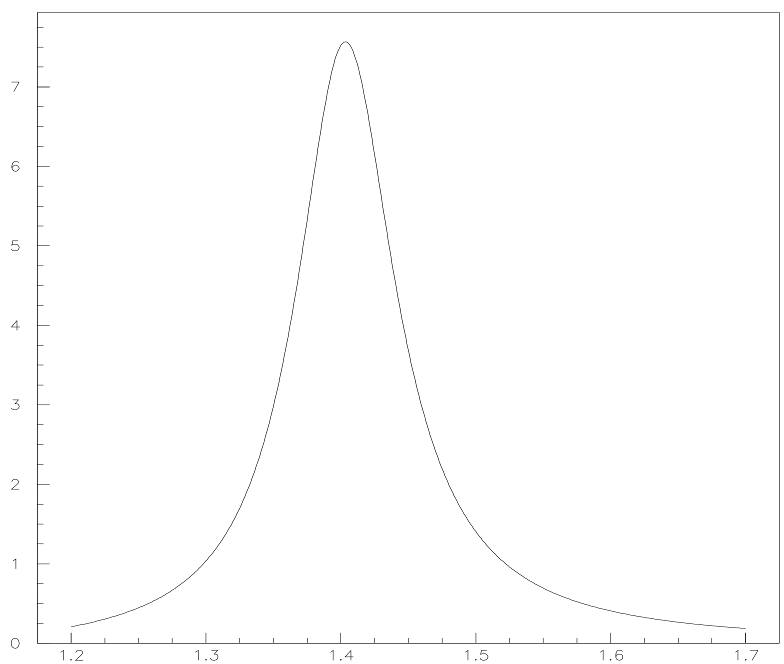


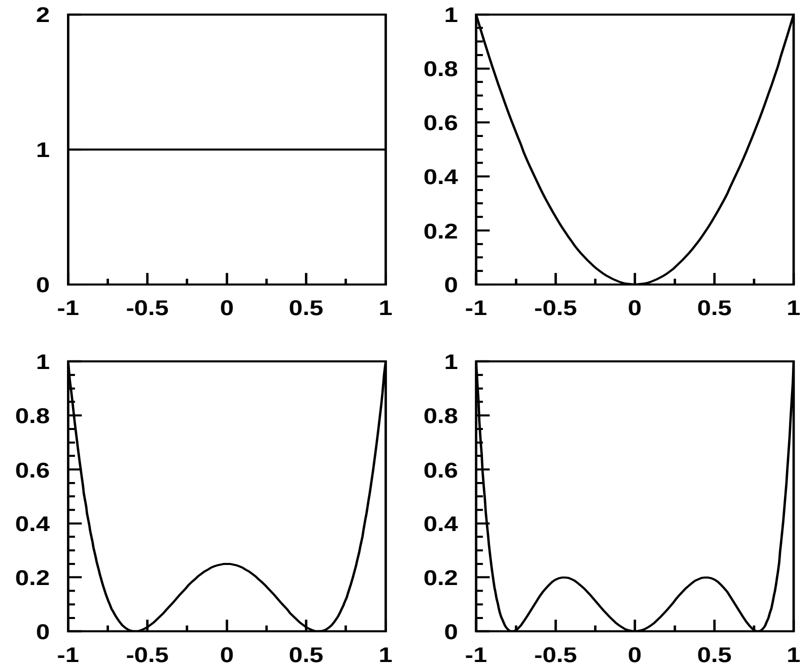
Scattering amplitude for spinless particles

The quantum numbers are defined by the angular distribution in c.m.s. of the resonance

$$A_L = BW(s)P_L(z)$$

$$|A_0|^2 = BW^2(s), \quad |A_1|^2 = BW^2(s)z^2, \quad |A_2|^2 = BW^2(s)\frac{1}{4}(3z^2-1)^2 \ldots$$





The πN interaction. Three measurements are needed to fix quantum numbers

$$A_{\pi N} = \omega^* \left[G(s,t) + H(s,t) i(\vec{\sigma}\vec{n}) \right] \omega' \qquad \vec{n}_j = \varepsilon_{\mu\nu j} \frac{q_\mu k_\nu}{|\vec{k}||\vec{q}|} \,.$$

$$G(s,t) = \sum_L \left[(L+1) F_L^+(s) + L F_L^-(s) \right] P_L(z) \,,$$

$$H(s,t) = \sum_L \left[F_L^+(s) - F_L^-(s) \right] P_L'(z) \,.$$

Differential cross section in c.m.s. of the reaction

$$|A|^2 = \frac{1}{2} \mathrm{Tr} \left[A_{\pi N}^* A_{\pi N} \right] = |G(s,t)|^2 + |H(s,t)|^2 (1 - z^2)$$

the recoil asymmetry:

$$P = \frac{\mathrm{Tr} \left[A_{\pi N}^* \sigma_2 A_{\pi N} \right]}{2|A|^2 \cos\phi} = \sin\Theta \frac{2Im \left(H^*(s,t) G(s,t) \right)}{|A|^2} \,.$$

and the rotation parameter.

$$|A|^2 = |G(s,t)|^2 + |H(s,t)|^2(1-z^2) \qquad |A|^2 \frac{P}{\sin\Theta} = 2Im\left(H^*(s,t)G(s,t)\right) .$$

$$\underline{S_{1,1}}; \quad G = F_0^+; \quad H = 0; \quad |A|^2 = |F_0^+|^2 \tag{1}$$

$$\underline{P_{1,1}}; \quad G = F_1^- z; \quad H = -F_1^-; \quad |A|^2 = |F_1^-|^2 \tag{2}$$

$$\underline{P_{1,3}}; \quad G = 2F_1^+ z; \quad H = F_1^+; \quad |A|^2 = |F_1^+|^2(3z^2+1)$$

Both S_{11} and P_{11} distributions are flat. Recoil asymmetry is zero for single partial wave.

$$\underline{S_{1,1}+P_{1,1}}: \quad P\frac{|A|^2}{\sin\Theta} = -2Im(F_0^+ F_1^{-*}) \quad |A|^2 = |F_0^+|^2 + |F_1^-|^2 + 2zRe(F_0^{+*}F_1^-)$$

$$\underline{S_{1,1}+P_{1,3}}: \quad P\frac{|A|^2}{\sin\Theta} = 2Im(F_0^+ F_1^{+*}) \quad |A|^2 = |F_0^+|^2 + |F_1^+|^2(3z^2+1) + 4zRe(F_0^{+*}F_1^+)$$

$$\underline{P_{1,1}+P_{1,3}}: \quad P\frac{|A|^2}{\sin\Theta} = 6zIm(F_1^{+*}F_1^-) \quad |A|^2 = |F_1^+ - F_1^-|^2 + z^2\left(3|F_1^+|^2 - 2Re(F_1^{+*}F_1^-)\right) .$$

S and P-waves can be extracted from the differential cross section and recoil asymmetry. For higher partial waves the rotation parameter is needed.

Production of vector mesons. Differential cross section, recoil asymmetry, rotation parameter and spin density matrix elements are needed

$$\frac{d\sigma}{d\Omega_\omega\, d\Omega_{dec}} = \frac{d\sigma}{d\Omega_\omega} W(\cos\Theta_{dec}, \Phi_{dec})$$

$\pi p \to n\omega(\pi^+\pi^-\pi^0)$ **or** $\gamma p \to p\omega(\pi^+\pi^-\pi^0)$

$$W(\cos\Theta, \Phi) = \frac{3}{4\pi}\left(\frac{1}{2}(1-\rho_{00}) + \frac{1}{2}(3\rho_{00}-1)\cos^2\Theta - \sqrt{2}Re\rho_{10}\sin 2\Theta\cos\Phi - \rho_{1-1}\sin^2\Theta\cos 2\Phi\right).$$

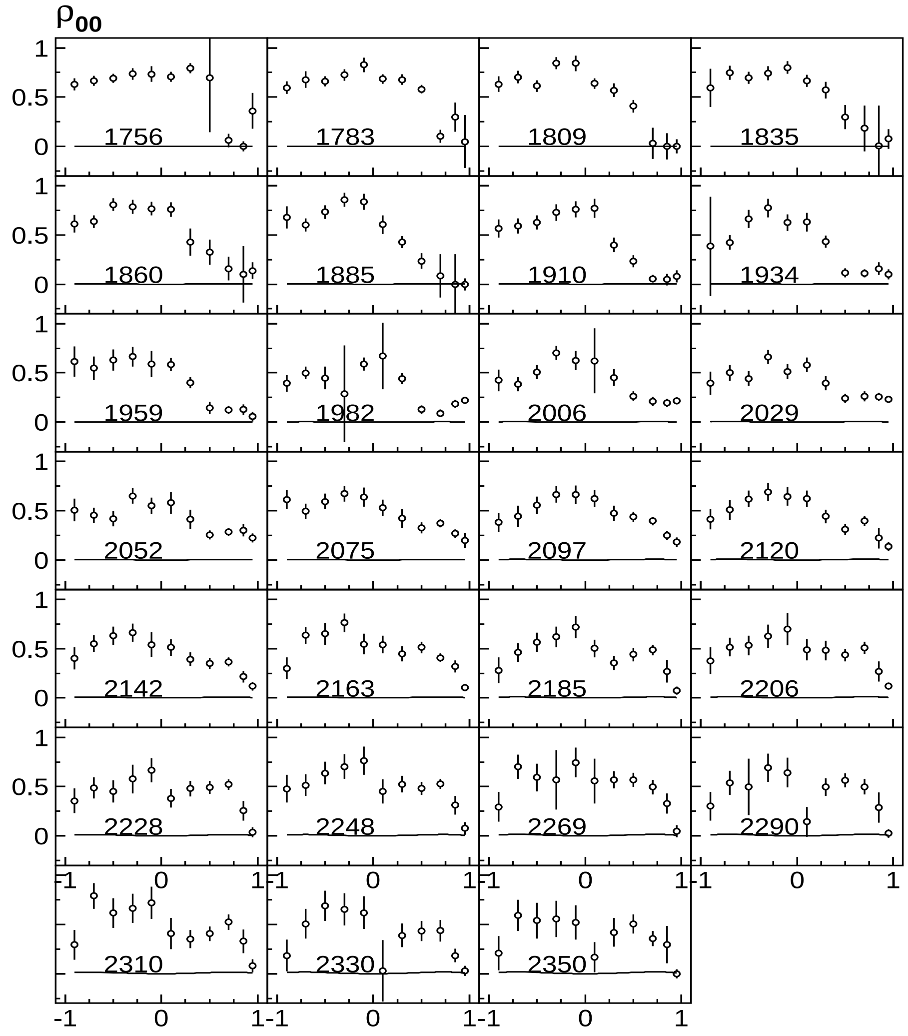
$\cos\Theta, \Phi$ **direction of the vector** $n = \varepsilon_{ijkm} p_j^{\pi^+} p_k^{\pi^-} p_m^{\pi^0}$ **in the** ω **rest frame.**

$\pi p \to n\omega(\gamma\pi^0)$

$$W(\cos\Theta, \Phi) = \frac{3}{8\pi}\left(\frac{1}{2}(1+\cos^2\Theta) + \frac{1}{2}(1-3\cos^2\Theta)\rho_{00} + \sqrt{2}Re\rho_{10}\sin(2\Theta)\cos\Phi + \rho_{1-1}\sin^2\Theta\cos 2\Phi\right).$$

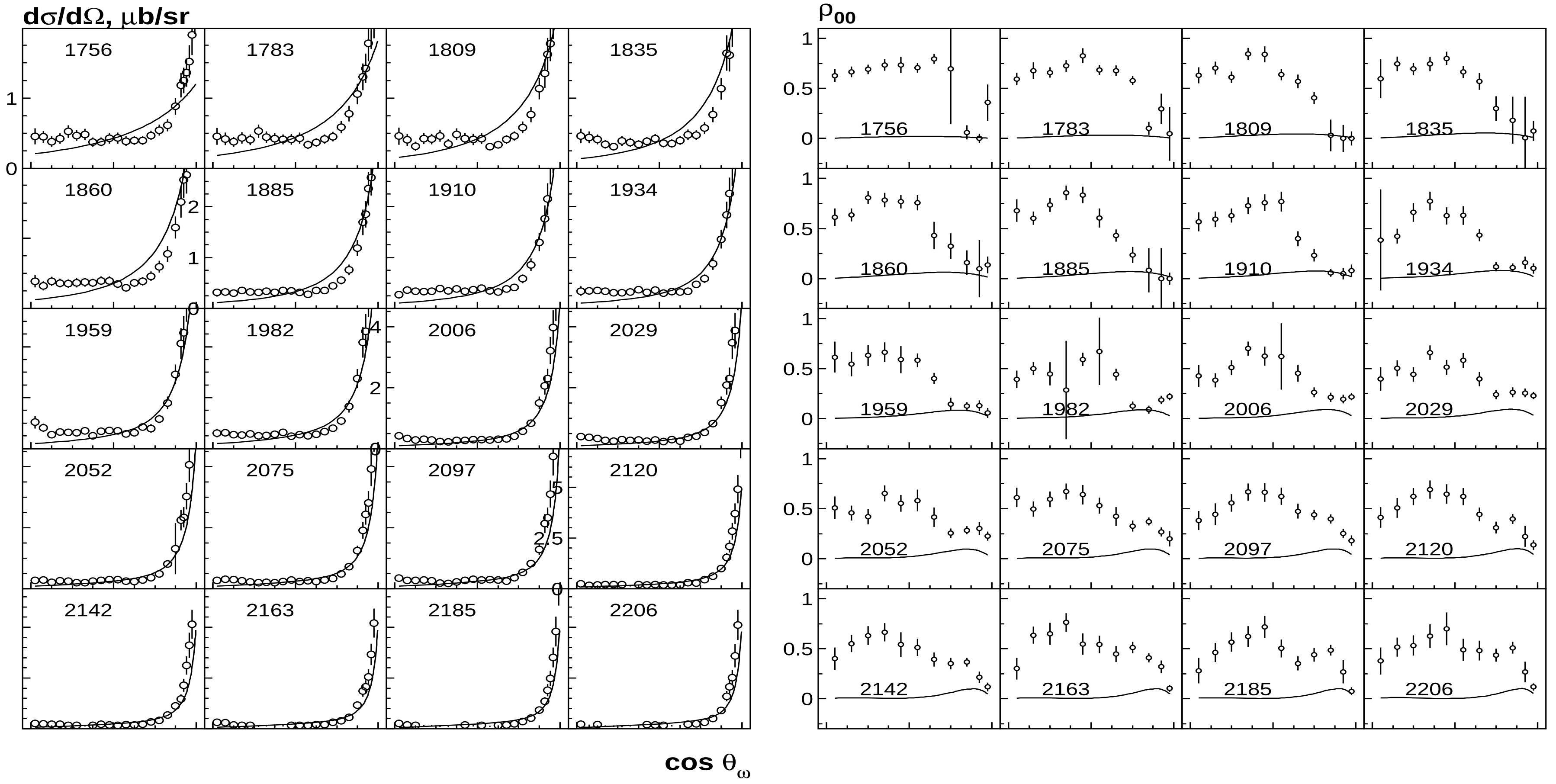
$\cos\Theta, \Phi$ **angles of photon from** ω **decay in the** ω **rest frame**

Density matrix elements are very important. For example the ρ_{00} for the Pomeron exchange in $\gamma p \to p\omega$ is identically 0 while data are not



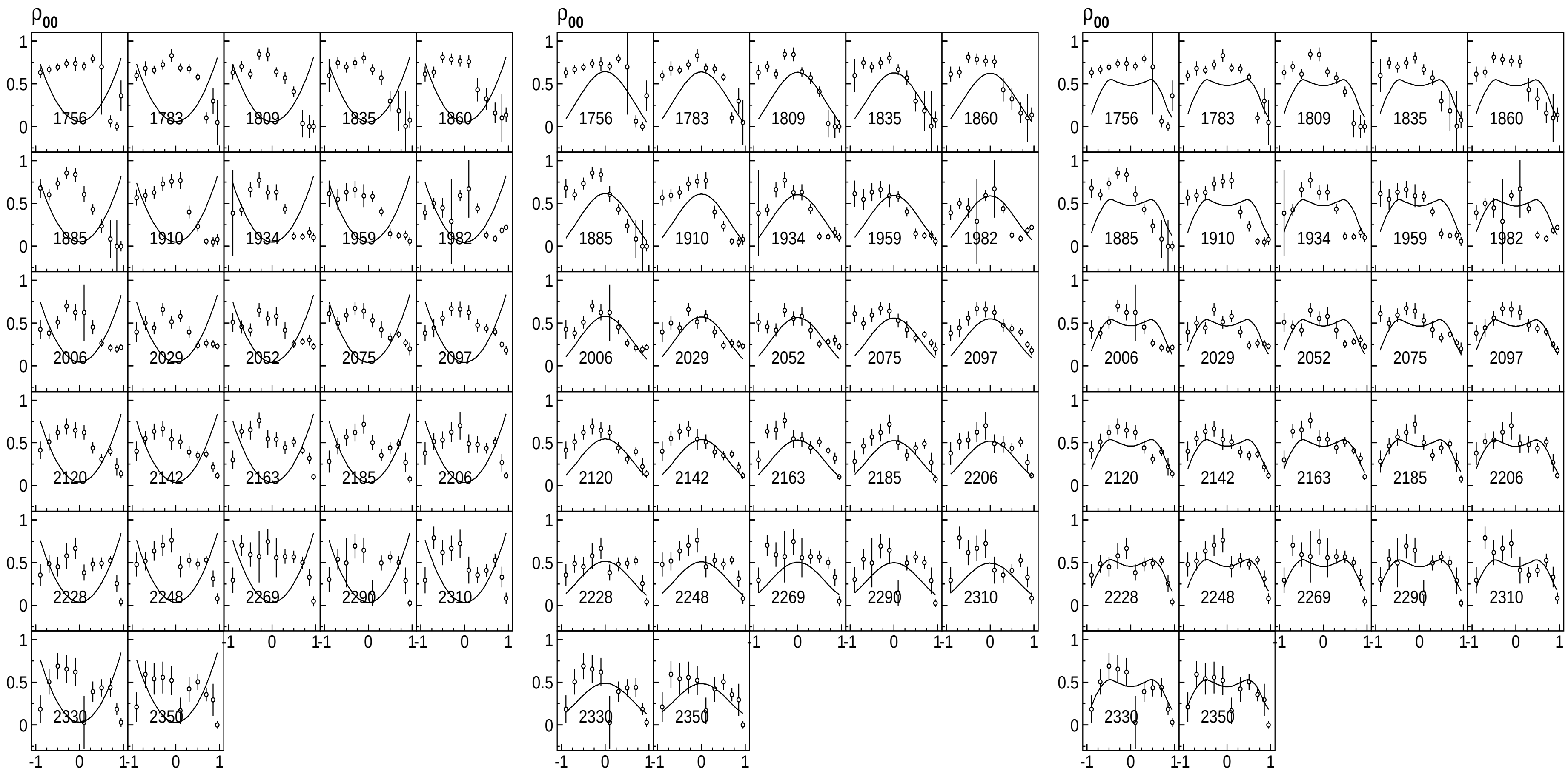
An example: the π and Pomeron exchanges can describe the differential cross section of the $\gamma p \to p\omega$ reaction but not density matrix elements

$d\sigma/d\Omega_\omega$ ρ_{00}



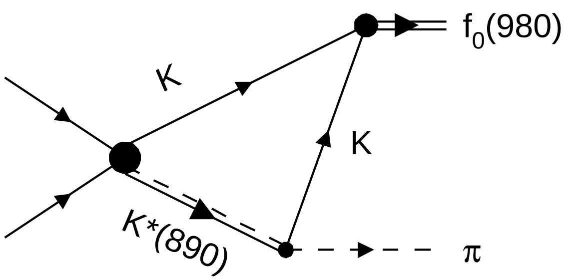
Simulation of ρ_{00} for resonance production $\gamma p \rightarrow Resonance \rightarrow p\omega$. It provides important information about resonance quantum numbers

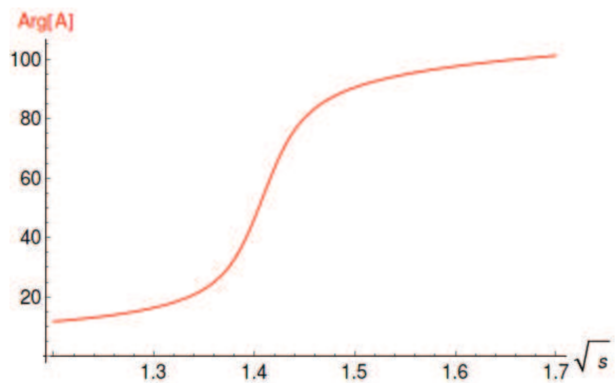
1/2+ **3/2+** **5/2-**

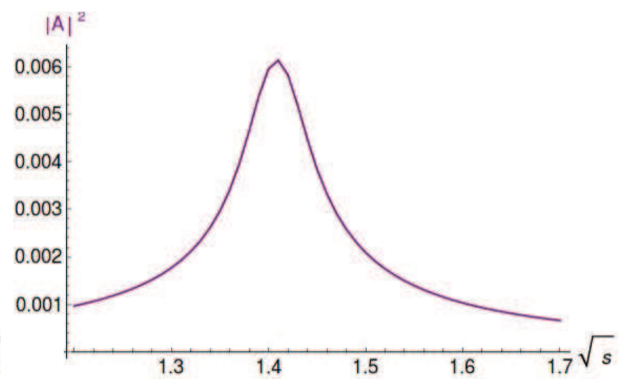


Triangle singularity?

The triangle singularity defined by the $a_1(1260) \to K^*(890)K$ transition generates the signal with effective mass, width and intensity which corresponds exactly to the $a_1(1420)$ state observed by the COMPASS collaboration.







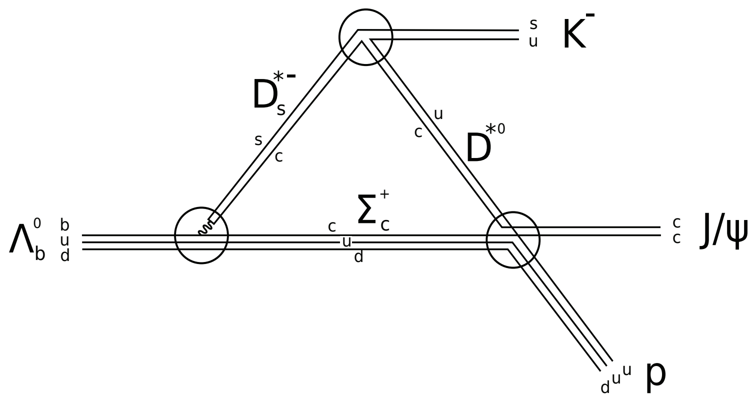
3. M. Mikhasenko, B. Ketzer, A. Sarantsev. Phys.Rev. D91 (2015) 9, 094015

Triangle diagrams. $M(\Lambda_b) = 5.619$ GeV

M. Mikhasenko

“A triangle singularity and the LHCb pentaquarks,”

arXiv:1507.06552 [hep-ph].



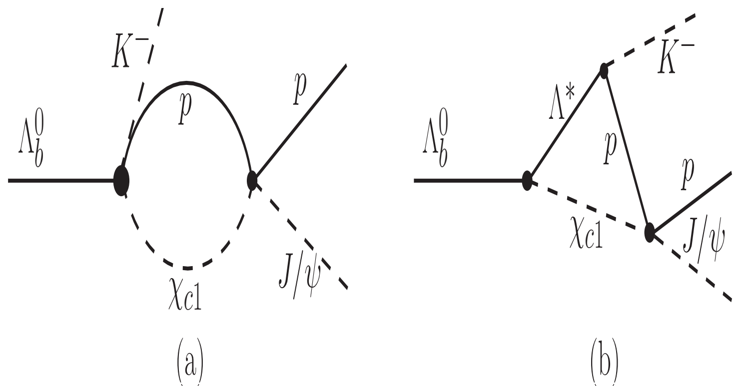
$$M(D_s^*)+M(\Sigma_c)=3.044+2.453=5.497$$
$$M(D_0^*)+M(\Sigma_c)=2.007+2.453=4.460$$
$$0^+ + 1/2^+ = 1/2^+ \quad \Gamma(D_s^*) = 240 \text{ MeV}$$

However it violates isospin conservation and should be small.

F. K. Guo, U. G. Meißner, W. Wang and Z. Yang

“How to reveal the exotic nature of the P$_c$(4450),”

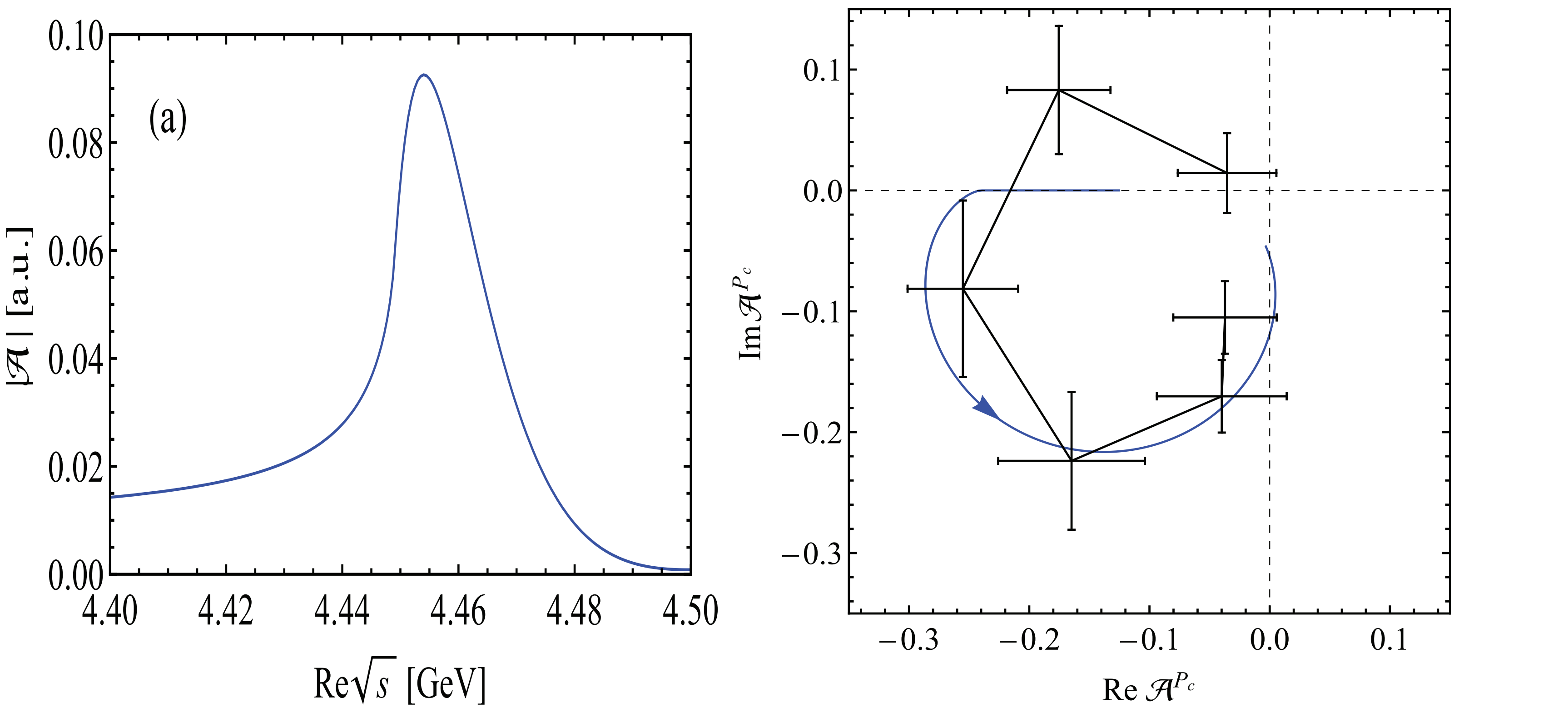
Phys. Rev. D 92 (2015) 7, 071502



$$M(\Lambda^*)+M(\chi_{c1}) = 1.890+3510 = 5.400$$
$$M(p)+M(\chi_{c1}) = 0.940+3510 = 4.450$$
$$1^+ + 1/2^+ = 1/2^+ \text{ or } 3/2^+$$
$$\Gamma(\Lambda^*) = 60 - 200 \text{ MeV}$$

LHCb pentaquark...

F. K. Guo, U. G. Meißner, W. Wang and Z. Yang



$\Gamma(\Lambda^*) = 100$ **MeV**

Diquark-antidiquark mesons: masses and spin splitting parameter

$$m_{S(q'q'')} = 650 \pm 50 \text{ MeV}, \quad m_{A(q'q'')} = 750 \pm 50 \text{ MeV},$$
$$m_{S(cq)} = 2000 \pm 50 \text{ MeV}, \quad m_{A(cq)} = 2050 \pm 50 \text{ MeV}$$

$$M_B = \sum_{j=1,2,3} m_{q(j)} + b \sum_{j>\ell} \frac{\vec{s}_j \vec{s}_\ell}{m_{q(j)} m_{q(\ell)}},$$

where $\vec{s}_j$ and $m_{q(j)}$ refer to spins and masses of the constituents. b is characterized by a size of the color-magnetic interaction in the discussed hadron.

Masses of diquark-diquark subsystems $(cq) \cdot (q'q'')$. For the diquark-diquark subsystem we write:

$$M_{(cq)\cdot(q'q'')} = m_{(cq)} + m_{(q'q'')} + J_{(cq)\cdot(q'q'')} \left(J_{(cq)\cdot(q'q'')} + 1 \right) \Delta_{(cq)\cdot(q'q'')} ,$$

with the splitting parameter being of the order of that for the diquark-antidiquark system, $\Delta_{(cq)\cdot(q'q'')} \sim 70$ MeV.

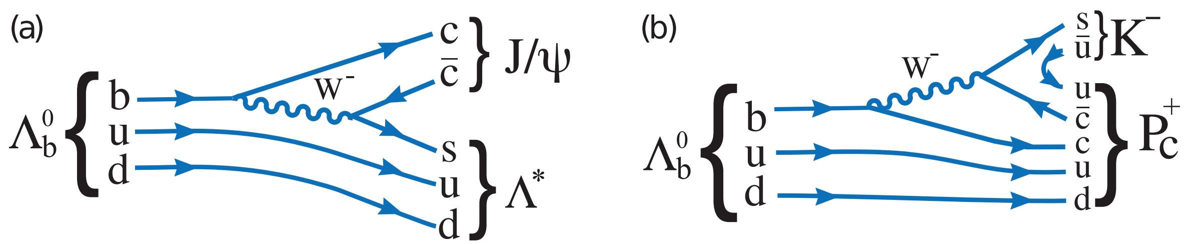
Masses of the pentaquarks as a sum of masses of the constituents plus spin splitting

$$M_{\bar{c}\cdot(cq)(q'q'')} \quad = \quad m_{\bar{c}} + M_{(cq)\cdot(q'q'')} + J_{\bar{c}\cdot(cq)(q'q'')}\left(J_{\bar{c}\cdot(cq)(q'q'')}+1\right)\Delta_{\bar{c}\cdot(cq)(q'q'')}$$

$P_{\bar{c}\cdot(cq)(q'q'')}, \quad I=\frac{1}{2}$	$P_{\bar{c}\cdot(cq)(q'q'')}, \quad I=\frac{3}{2}$
$P^{(\frac{1}{2},\frac{1}{2}^-)}_{\bar{c}S_{cq}S_{q'q''}}(3800)$	
$P^{(\frac{1}{2},\frac{1}{2}^-)}_{\bar{c}S_{cq}A_{q'q''}}(4190)$, $P^{(\frac{1}{2},\frac{3}{2}^-)}_{\bar{c}S_{cq}A_{q'q''}}(4190)$	$P^{(\frac{3}{2},\frac{1}{2}^-)}_{\bar{c}S_{cq}A_{q'q''}}(4190)$, $P^{(\frac{3}{2},\frac{3}{2}^-)}_{\bar{c}S_{cq}A_{q'q''}}(4190)$
$P^{(\frac{1}{2},\frac{1}{2}^-)}_{\bar{c}A_{cq}S_{q'q''}}(4140)$, $P^{(\frac{1}{2},\frac{3}{2}^-)}_{\bar{c}A_{cq}S_{q'q''}}(4140)$	
$P^{(\frac{1}{2},\frac{1}{2}^-)}_{\bar{c}A_{cq}A_{q'q''}}(4100)$	$P^{(\frac{3}{2},\frac{1}{2}^-)}_{\bar{c}A_{cq}A_{q'q''}}(4100)$
$P^{(\frac{1}{2},\frac{1}{2}^-)}_{\bar{c}A_{cq}A_{q'q''}}(4240)$, $P^{(\frac{1}{2},\frac{3}{2}^-)}_{\bar{c}A_{cq}A_{q'q''}}(4240)$	$P^{(\frac{3}{2},\frac{1}{2}^-)}_{\bar{c}A_{cq}A_{q'q''}}(4240)$, $P^{(\frac{3}{2},\frac{3}{2}^-)}_{\bar{c}A_{cq}A_{q'q''}}(4240)$
$P^{(\frac{1}{2},\frac{3}{2}^-)}_{\bar{c}A_{cq}A_{q'q''}}(4520)$, $P^{(\frac{1}{2},\frac{5}{2}^-)}_{\bar{c}A_{cq}A_{q'q''}}(4520)$	$P^{(\frac{3}{2},\frac{3}{2}^-)}_{\bar{c}A_{cq}A_{q'q''}}(4520)$, $P^{(\frac{3}{2},\frac{5}{2}^-)}_{\bar{c}A_{cq}A_{q'q''}}(4520)$

Masses are given in MeV units, the uncertainty in the determination of masses is of the order $\pm$150 MeV. We consider the state $P^{(\frac{1}{2},\frac{5}{2}^-)}_{A_{(cq)}A_{(q'q'')}}(4520 \pm 150)$

LHCb pentaquark...



Possible other reactions:

$$\Lambda_b \to P_C \pi^- \to J/\Psi p \pi^-$$

$$\Lambda_b \to P_{CS}(I=0)\pi^- \to J/\Psi \Lambda \phi$$

$$\Sigma_b \to P_C K^- \to J/\Psi p K$$

$$\Sigma_b \to P_C(I=3/2)K^- \to J/\Psi \Delta(1232) K \to J/\Psi p \pi K$$

$$\Sigma_b \to P_{CS}(I=1)\phi \to J/\Psi \Sigma \phi$$

Summary

1. **If it is a genuine state, then it should be a spectrum of the pentaquark states. Therefore other states should be searched in corresponding reaction.**

2. **The proper angular distributions (in c.m.s.) of the pentaquark should be given.**

3. **The density matrix elements should be extracted and shown.**

4. **The contribution from the triangle diagrams should be investigated. The best, if it is done on the level of the partial wave analysis to take into account not only energy dependence but also angular distributions from these diagrams.**