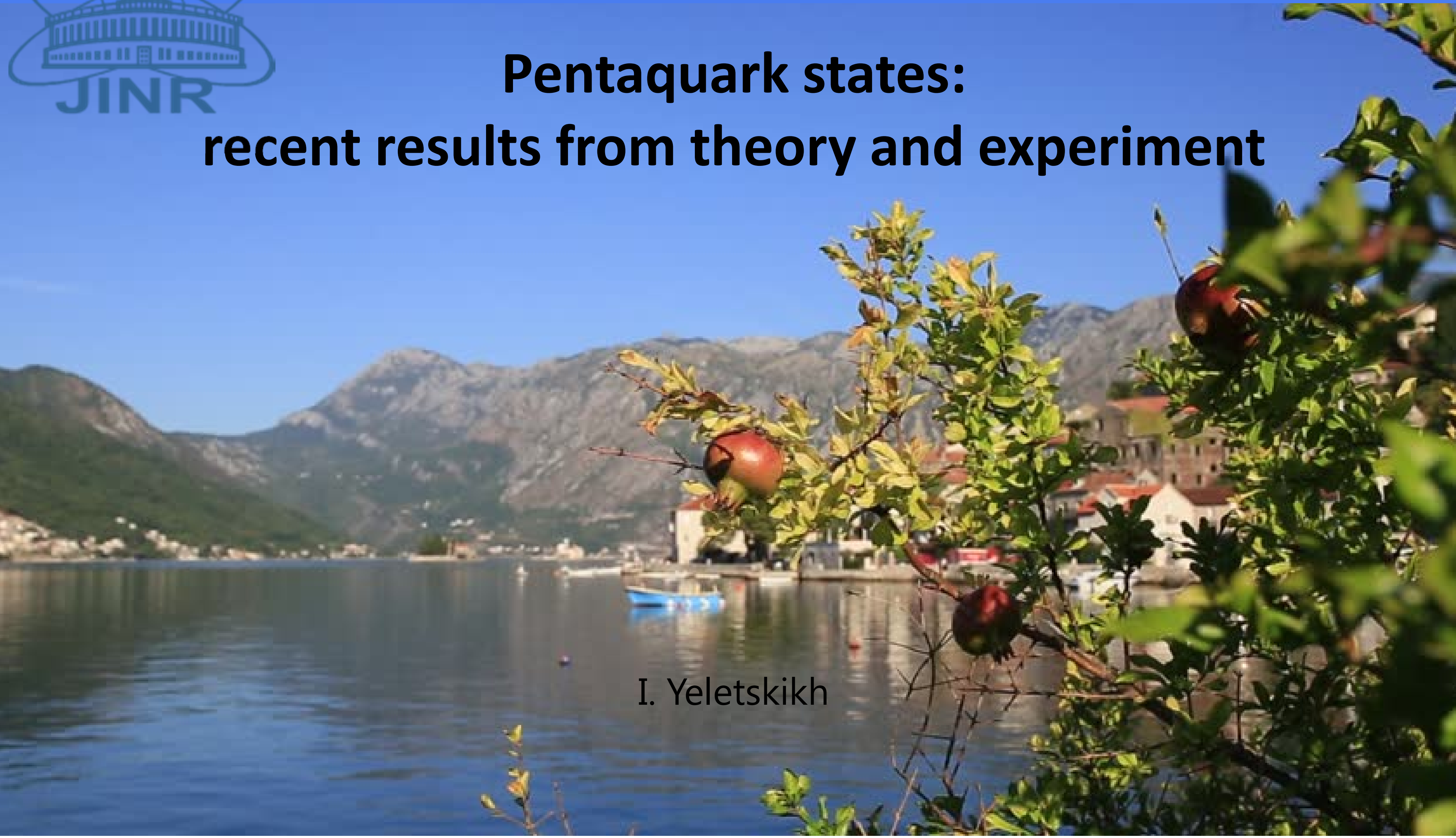
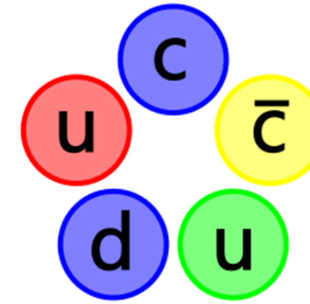
Pentaquark states: recent results from theory and experiment



I. Yeletskikh

New Trends in High Energy Physics, 24-30.09.2018, Budva, Becici, Montenegro

1. Experimental results:
    - discovery of hidden charm pentaquarks;
    - further studies;
2. Theoretical models:
    - rescattering;
    - molecules;
    - compact structures;
    - predictions of new states;
3. Experimental perspectives:
    - new studies for known states;
    - searches for new states;



P_c quark content

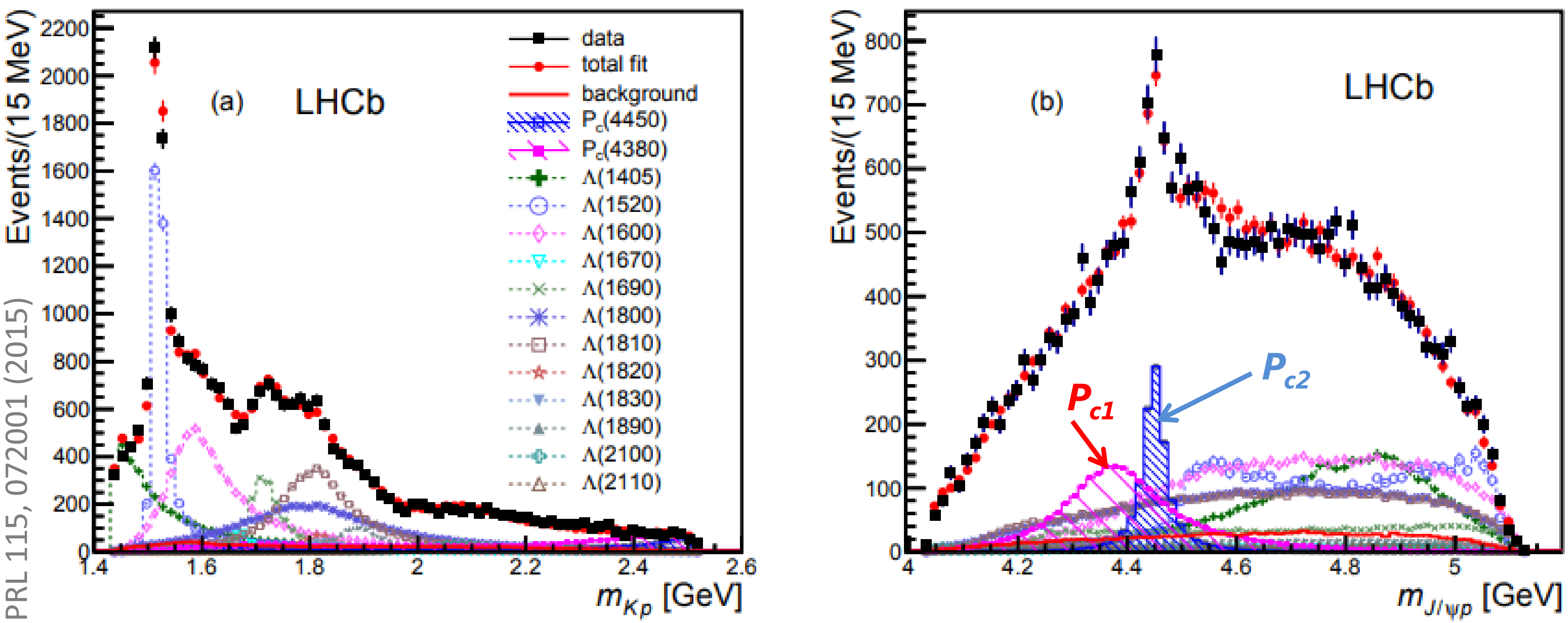
In 2015 LHCb discovered two states in the decays of $\Lambda_b \rightarrow J/\psi, p, K$:

P_{c1}: M = 4380 MeV, Γ = 205 MeV; J=3/2;

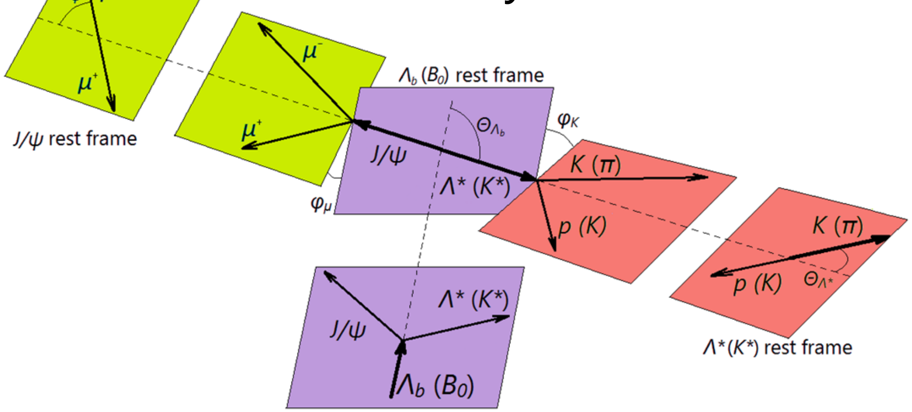
P_{c2}: M = 4450 MeV, Γ = 39 MeV; J=5/2;

Opposite parity

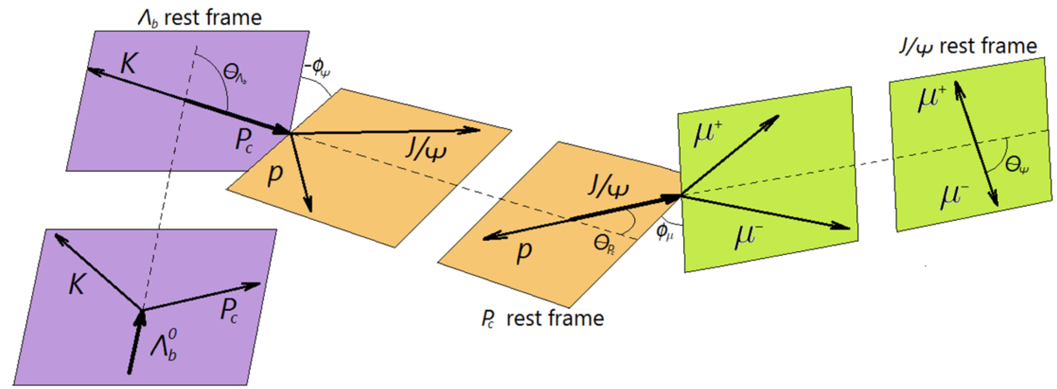
Statistical significance is *9σ* and *12σ* respectively for lower and higher mass states.



Λ^* decay chain



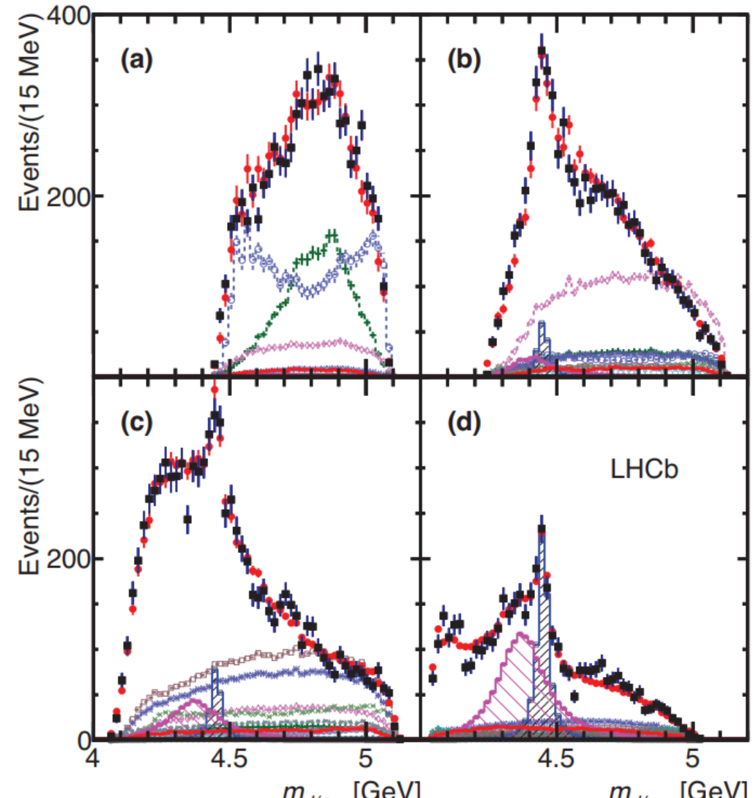
P_c decay chain



P_c decay kinematics is totally different from that of known Λ^* decays;

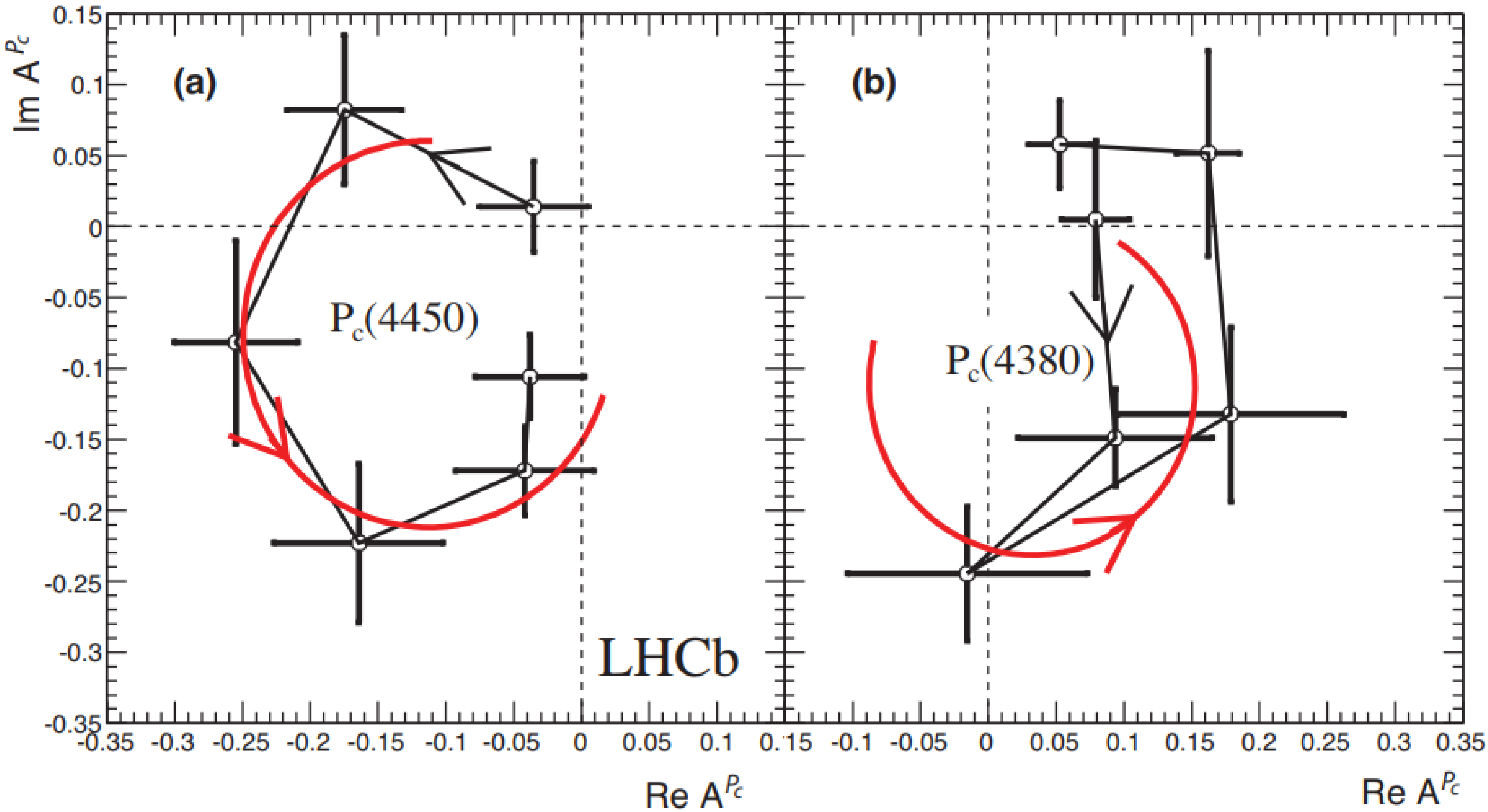
P_c contributes to higher masses of proton-kaon system;
Plot shows signal in different M(*p*,*K*) regions:

a) M_{pK} < 1.55GeV
b) 1.70 GeV < M_{pK} < 1.55 GeV
c) 2.00 GeV < M_{pK} < 1.70 GeV
d) M_{pK} > 2.00 GeV

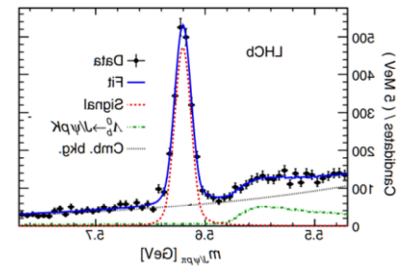


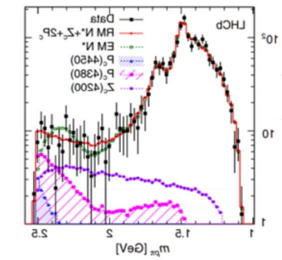
PRL 115, 072001 (2015)

Full amplitude analysis has been performed to describe $\Lambda_b \to J/\psi, p, K$ in P_c and Λ^* decay chains. Argand diagram for $P_c(4450)$ is well consistent with it's resonant nature. Amplitude behavior of $P_c(4380)$ is less clear…



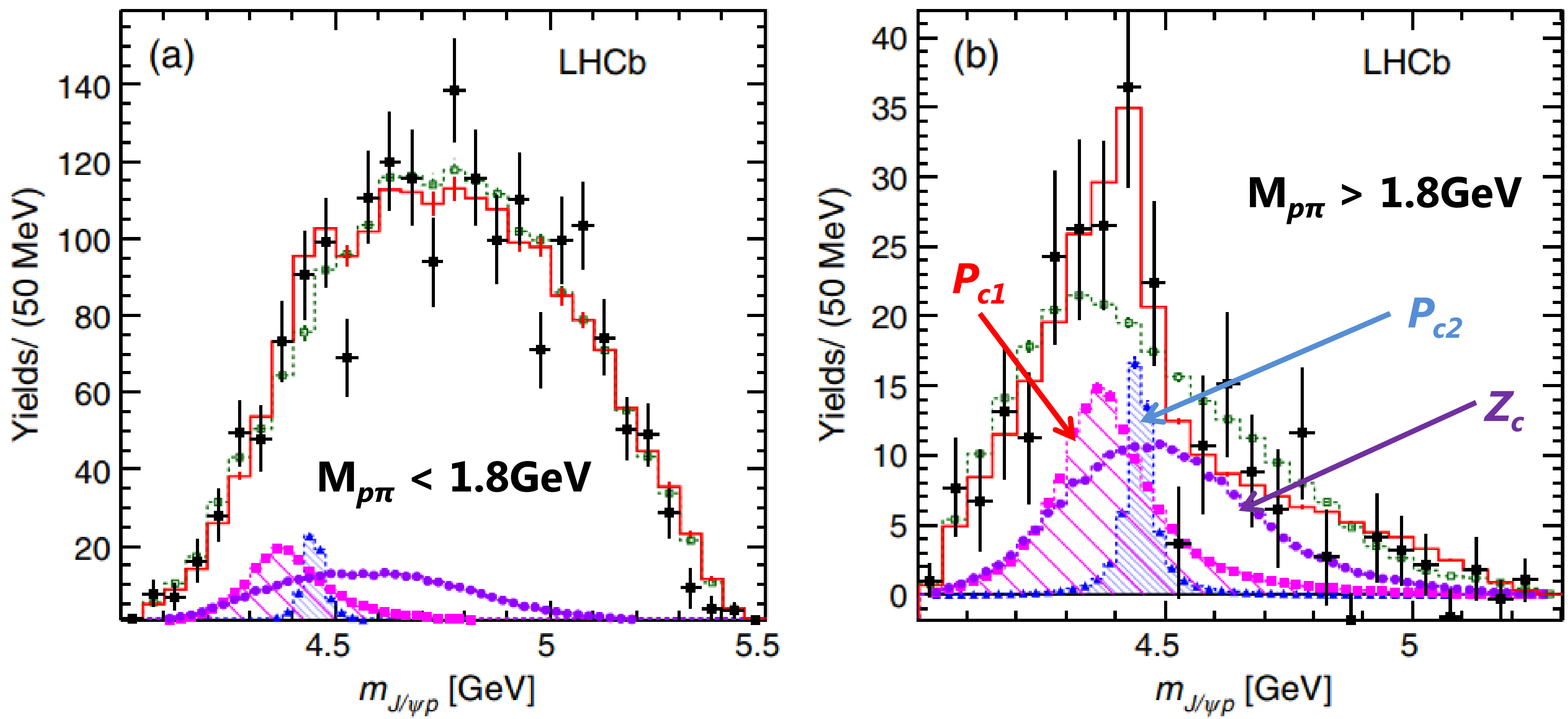
PRL 115, 072001 (2015)





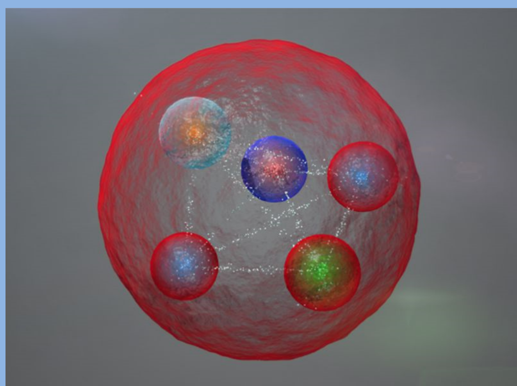
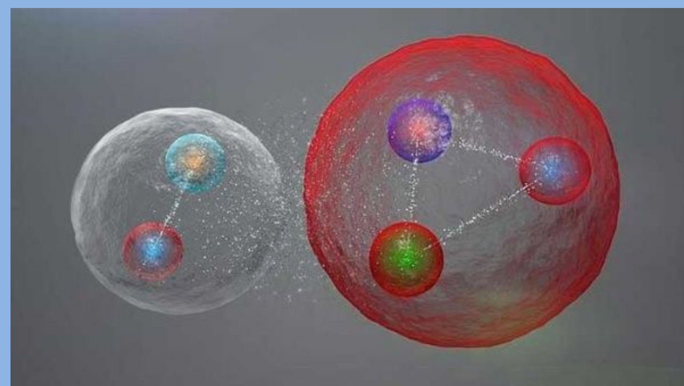
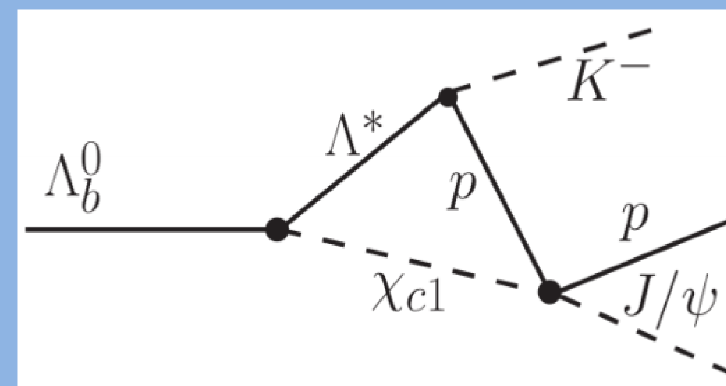
Pentaquark states has also been studied in the Cabibbo-suppressed channel $\Lambda_b \to J/\psi, p, \pi$.

Statistics of these decays doesn't allow amplitude analysis. Moreover, tetraquark state $Z_c(4200)$ seems to contribute significantly to the process.
Still, pentaquark model is in favor with at least **3.1σ**.



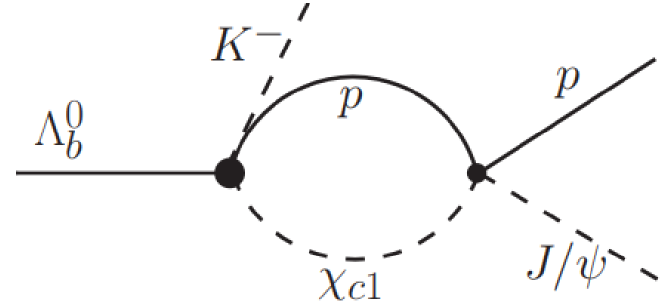
PRL 117, 082003 (2016)

Differences in mass, width and amplitude behavior imply different structures for $P_c(4380)$ and $P_c(4450)$ states;

Tightly bound state	Meson-baryon sparse structure	Rescattering effect
		

Some of the proposed pentaquark structure and producton mechainsm hypotheses have been already excluded…

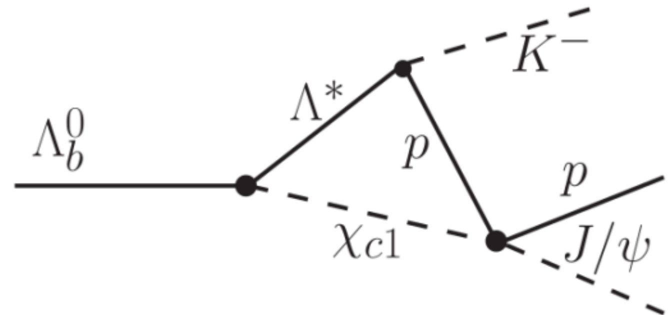
Pentaquark signal from rescattering effects

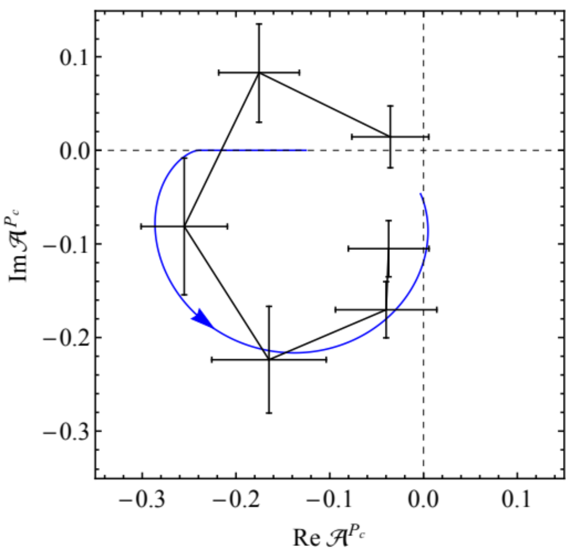


$P_c(4450)$ is located exactly at the threshold of $\chi_{c1}+p$ production:

M(P_c(4450)) – M(χ_{c1}) – M(p) = 0.9±3.1 MeV

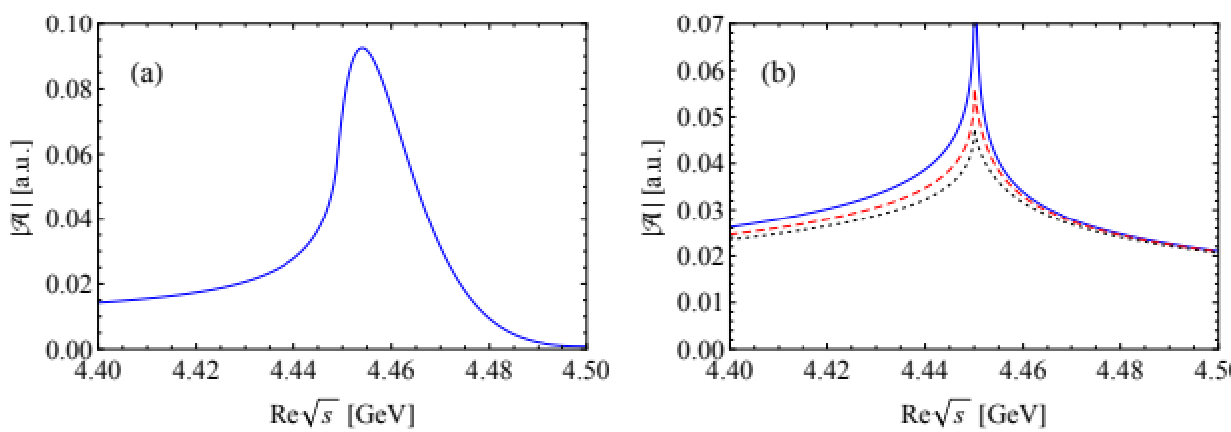
Rescattering mechanism can explain narrow peak of $P_c(4450)$ and can produce 'resonant-like' Argand plot:





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

It was shown that triangular diagram produces further enhancement of the signal being mediated by $\Lambda^*(1890)$ state.



Signals produced by loop (a) and triangle (b) diagrams.

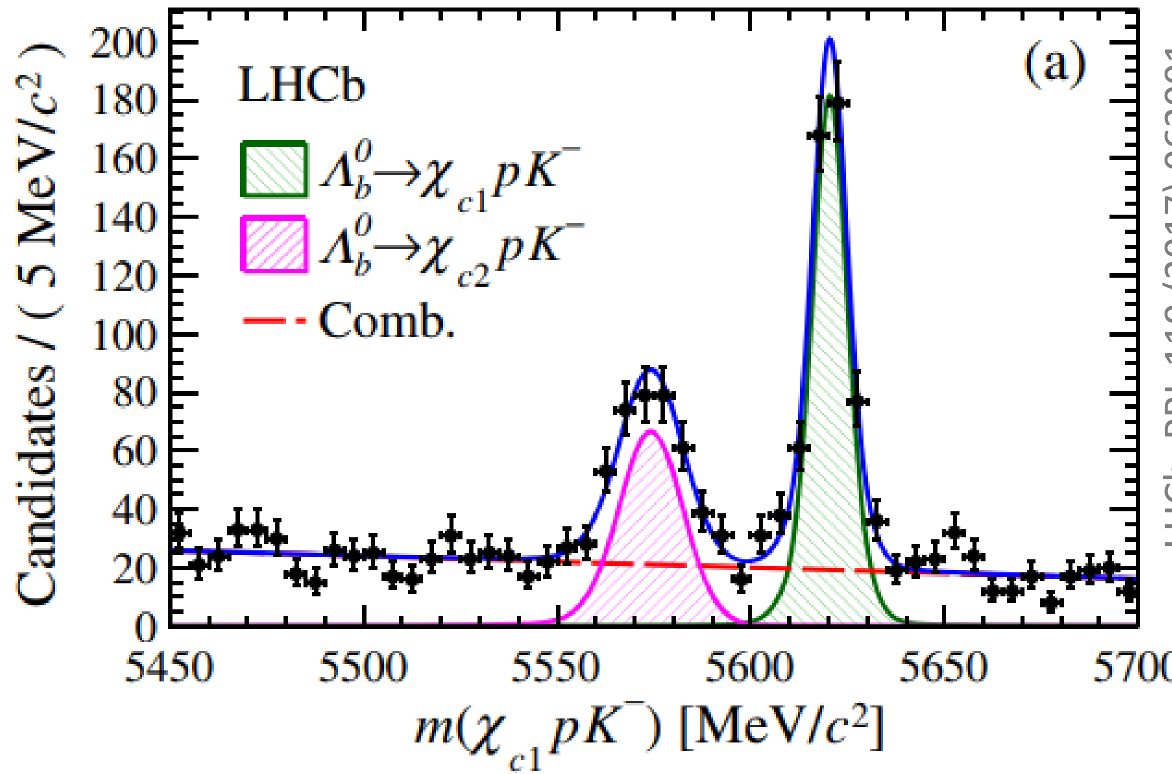
Best test to this hypothesis of $P_c(4450)$ nature is search for the signal in the $\chi_{c1}p$ final state.

Decays $\Lambda_b \to \chi_{c1} pK$ are seen by LHCb in LHC Run I data.
Branching fractions are measured (~25% of $\Lambda_b \to J/\psi pK$);
Signal yield is 453 ± 25 candidate events;

Search for P_c in these decays and its amplitude analysis can be performed with LHC Run II data;

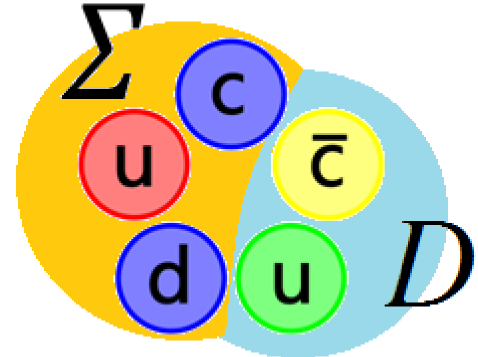
If P_c signal is seen in this mode, it means that rescattering hypothesis is false…

Still, $P_c(4380)$ cannot be explained via rescattering mechanism…

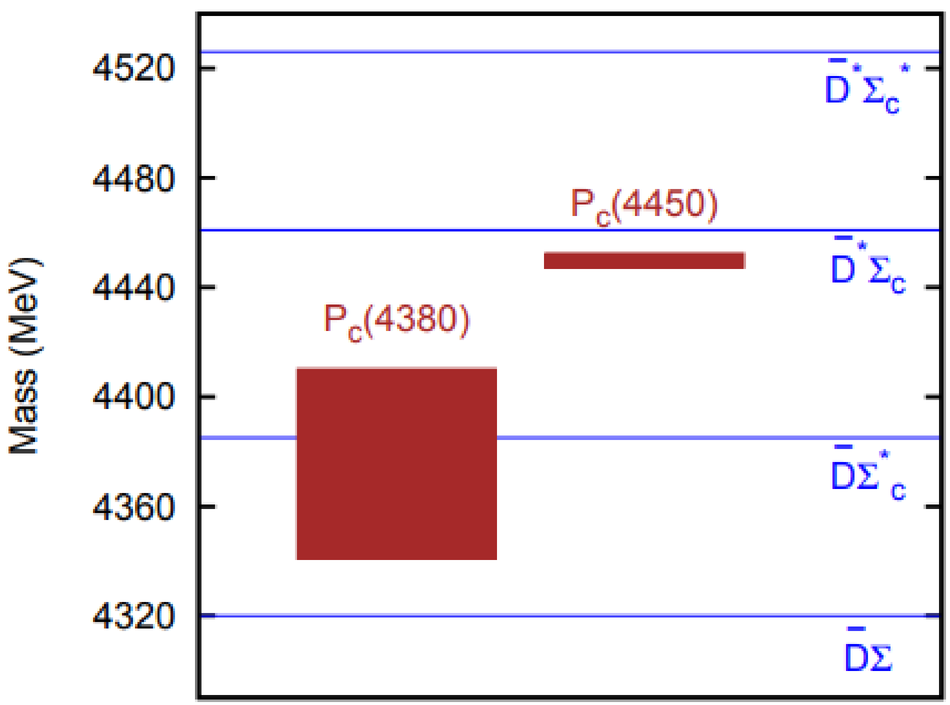


LHCb, PRL 119 (2017) 062001

Pentaquarks as $D\Sigma_c$ 'molecular' bound states



- Many exotic states are close to the thresholds of 2 heavy hadrons;
- P_c(4380) and P_c(4450) are close to the thresholds of the $\bar{D}\Sigma^*(2520)$ and $\bar{D}^*\Sigma$ (2455) combinations respectively.
- P_c(4450) was predicted within such model before it's actual discovery. Model also suggests ground state P_c near 4320MeV.



- The common 'molecular' model involves light meson exchange potential plus heavy quark-antiquark binding…

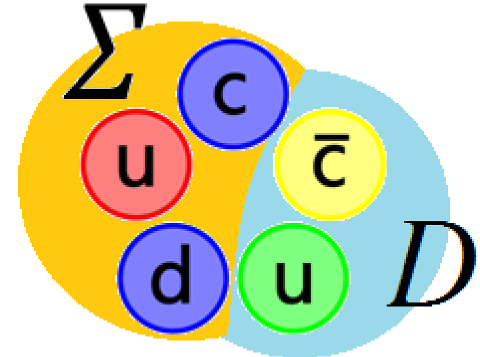
- In 'molecular' model the multiquark state is below (or very close above) molecular threshold, so it cannot decay quickly into two heavy hadrons;
- On the other hand, the 'molecular' structure is sparse enough, so that decays into quarkonia + light state are also supressed;
- That's how the model explains narrow enough multiquark states…

PLB753 (2016) 547

PRD92(2015)094003

PRL115(2015)172001

PRD 88 (2013) 056012

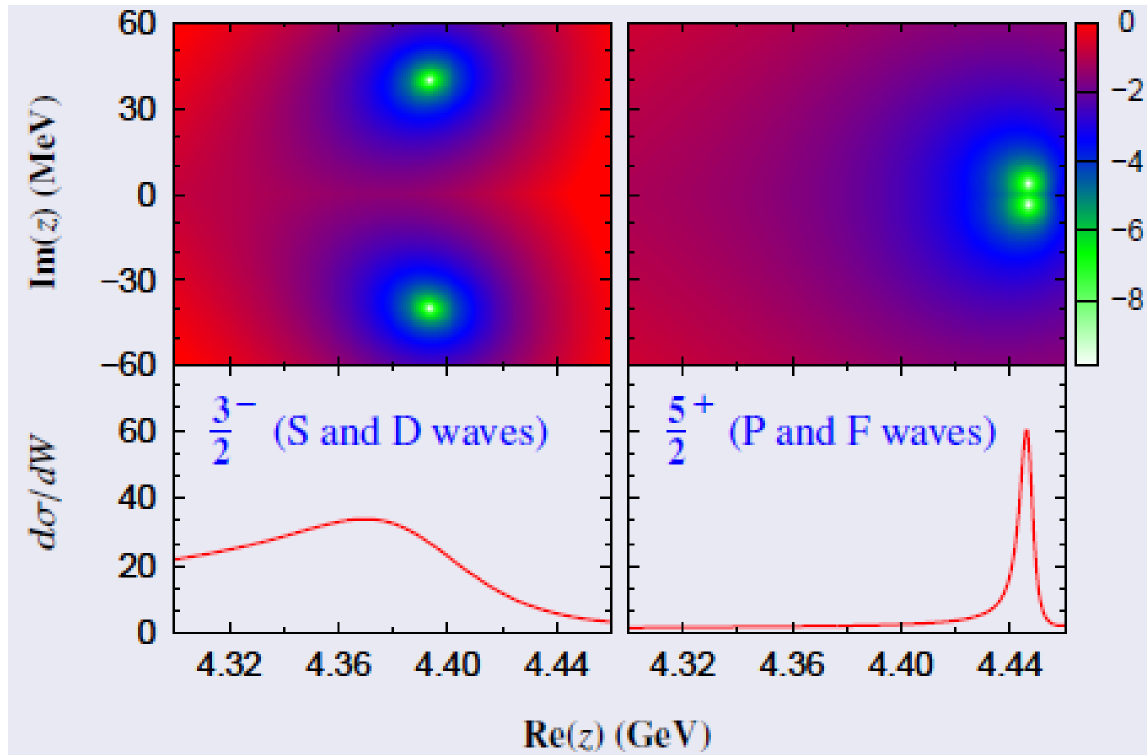


- Simple S-wave meson-baryon interaction gives negative parity of the pentaquark state… while experimental data are strongly in favor of opposite parity for the two P_c states;

- In more sophisticated models, higher-wave interactions can be included;

- $P_c(4450)$ in the model is a $5/2^+$ state from P-wave $\bar{D}^*\Sigma\,(2455)$ interaction;

- $P_c(4380)$ can be a mixture of $3/2^-$ states from $\bar{D}\Sigma^*(2520)$ and $\bar{D}^*\Sigma\,(2455)$ interactions; and, thus, it has more complicated structure;

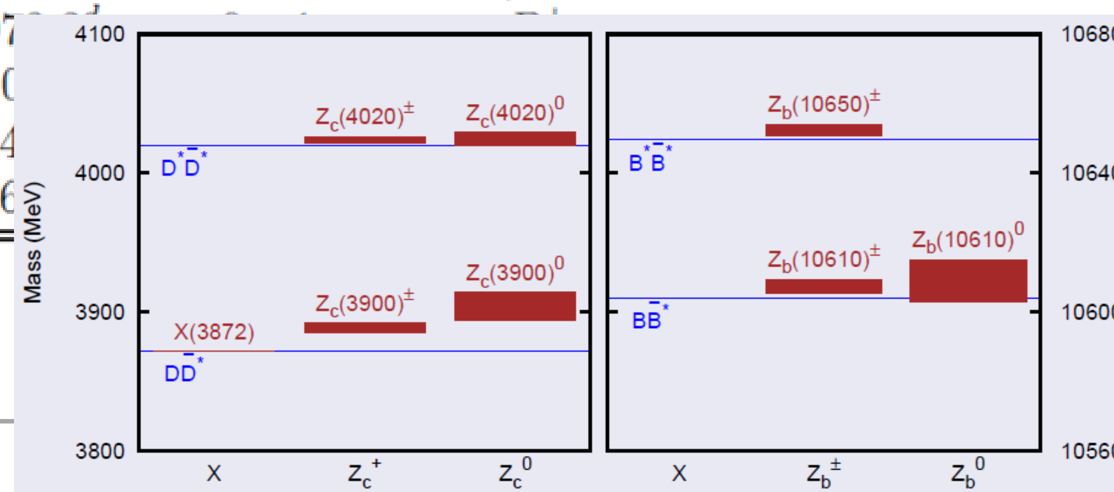


Pentaquarks as $D\Sigma_c$ 'molecular' bound states

Predictions from the simple S-wave potential model:

Channel	Minimum isospin	Minimal quark content[a,b]	Threshold (MeV)[c]	S-wave J^P	Example of decay mode
$D\bar{D}^*$	0	$c\bar{c}q\bar{q}$	3875.8	1^+	$J/\psi\,\pi\pi$
$D^*\bar{D}^*$	0	$c\bar{c}q\bar{q}$	4017.2	$0^+,1^+,2^+$	$J/\psi\,\pi\pi$
D^*B^*	0	$c\bar{b}q\bar{q}$	7333.8	$0^+,1^+,2^+$	$B_c^+\omega$
$\bar{B}B^*$	0	$b\bar{b}q\bar{q}$	10604.6	1^+	$\Upsilon(nS)\omega$
$\bar{B}^*B^*$	0	$b\bar{b}q\bar{q}$	10650.4	$0^+,1^+,2^+$	$\Upsilon(nS)\omega$
$\Sigma_c\bar{D}^*$	1/2	$c\bar{c}qqq'$	4462.4	$1/2^-,3/2^-$	$J/\psi\,p$
Σ_cB^*	1/2	$c\bar{b}qqq'$	7779.5	$1/2^-,3/2^-$	B_c^+p
$\Sigma_b\bar{D}^*$	1/2	$b\bar{c}qqq'$	7823.0	$1/2^-,3/2^-$	B_c^-p
Σ_bB^*	1/2	$b\bar{b}qqq'$	11139.6	$1/2^-,3/2^-$	$\Upsilon(nS)p$
$\Sigma_c\bar{\Lambda}_c$	1	$c\bar{c}qq'\bar{u}\bar{d}$	4740.3	$0^-,1^-$	$J/\psi\,\pi$
$\Sigma_c\bar{\Sigma}_c$	0	$c\bar{c}qq'\bar{q}\bar{q}'$	4907.6	$0^-,1^-$	$J/\psi\,\pi\pi$
$\Sigma_c\bar{\Lambda}_b$	1	$c\bar{b}qq'\bar{u}\bar{d}$	807		
$\Sigma_b\bar{\Lambda}_c$	1	$b\bar{c}qq'\bar{u}\bar{d}$	810		
$\Sigma_b\bar{\Lambda}_b$	1	$b\bar{b}qq'\bar{u}\bar{d}$	114		
$\Sigma_b\bar{\Sigma}_b$	0	$b\bar{b}qq'\bar{q}\bar{q}'$	116		

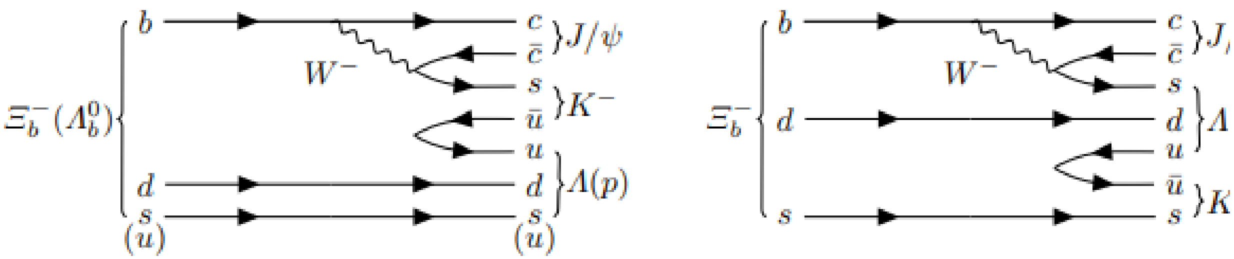
Known states



Phys.Rev.Lett. 108 (2012) 122001
Phys.Rev.Lett. 110 (2013) 252001
Phys.Rev.Lett. 111 (2013) no.24, 242001
Phys.Rev.Lett. 113 (2014) no.21, 212002

Existence of $P_c(4380)$ and $P_c(4450)$ firmly suggests also the existence of charmonium open strangeness pentaquarks…

One of the perspective channels to look for it is Ξ_b baryon decays, with strange P_{cs} decaying into $J/\psi\Lambda^0$ with roughly same decay rate as P_c

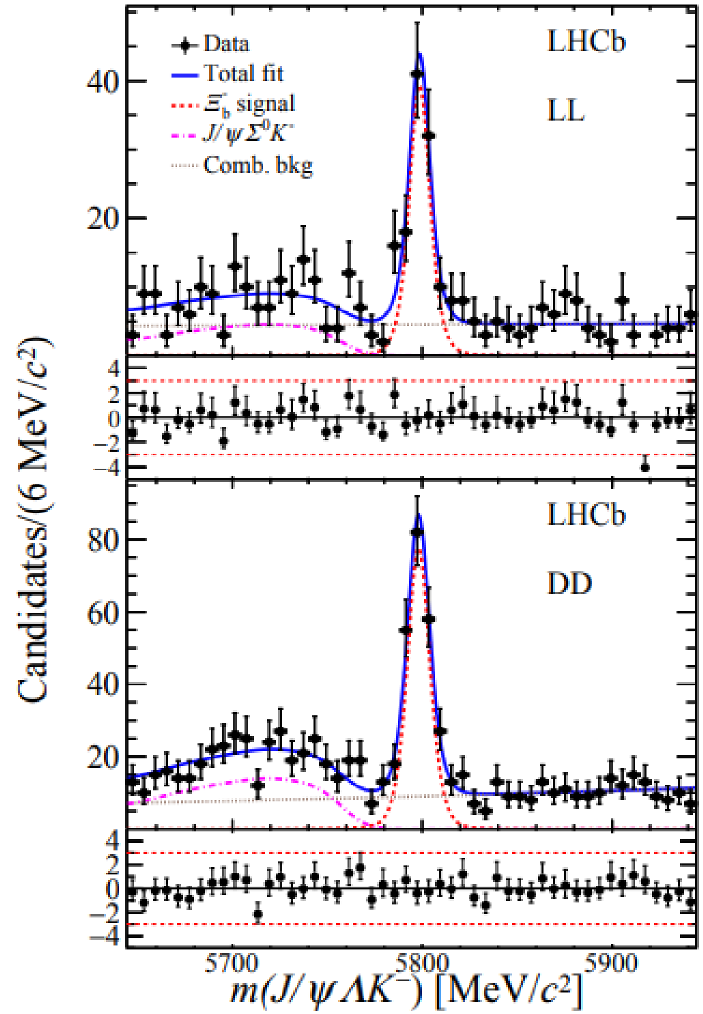


(a) (b)

Ξ_b baryon production is ~200 times suppressed compared to Λ_b baryon.

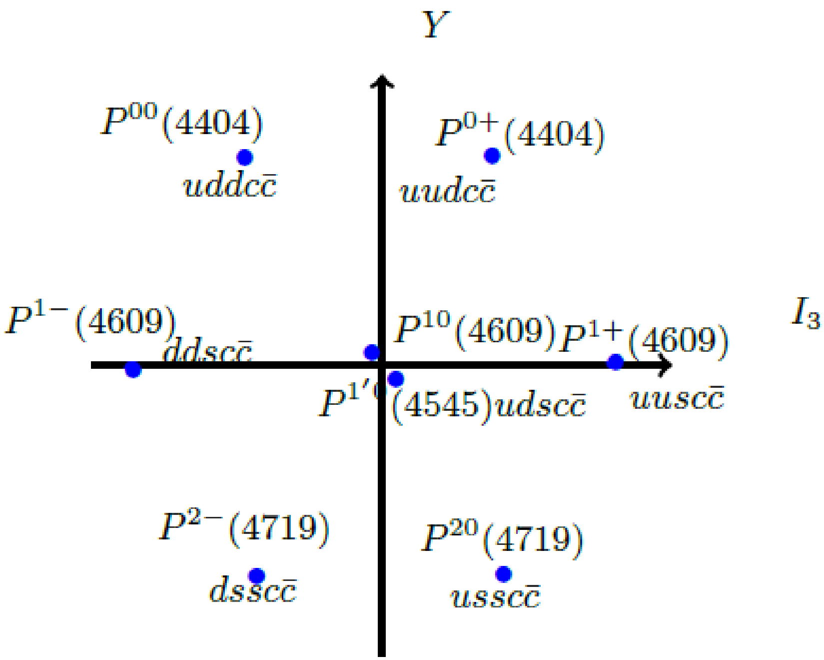
LHCb has reconstructed 99±12 + 209±17 Ξ_b candidates in $J/\psi\Lambda^0K^{\pm}$ channel with Run I data;

Amplitude analysis of these decays is possible with LHC Run II statistics and (depending on the existence of P_{cs}) can definitely shed more light on P_c structure;

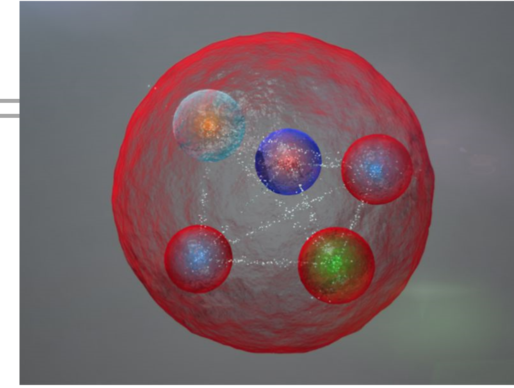


Phys. Lett. B 772, 265 (2017)

Pentaquarks as compact structures



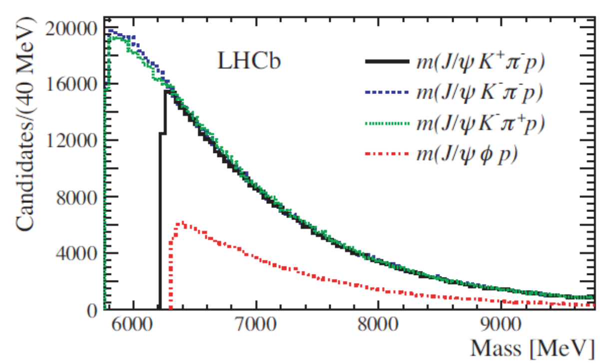
Molecular models cannot accurately describe some of the observed states ($P_c(4380)$), on the other hand, they predict many states, that have not been observed…

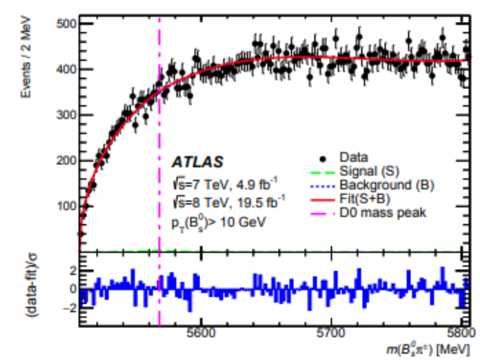


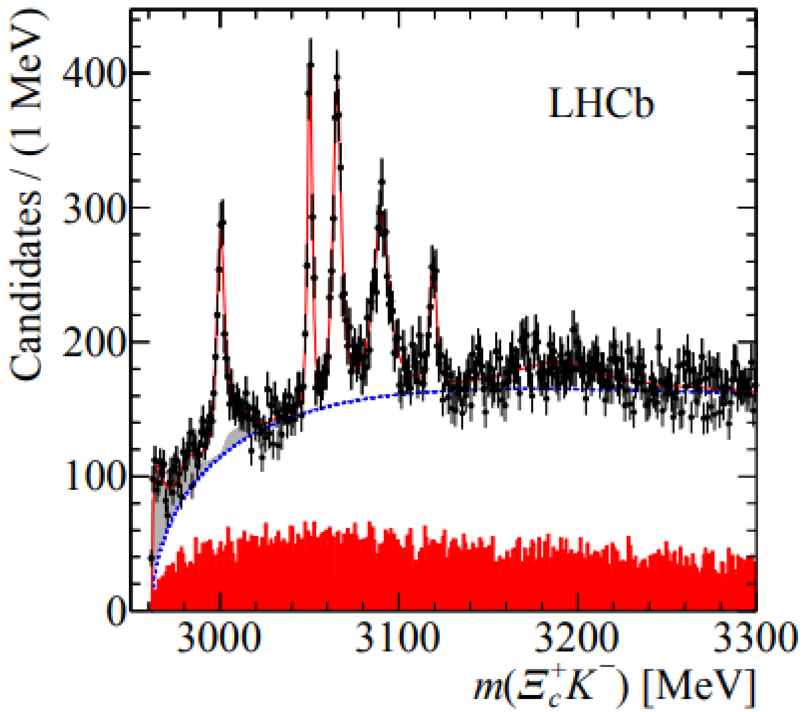
To address the problem, the models of compact structure of exotic states are suggested.

Such models usually suggest existence of the multiplets of exotic states… e.g., one can expect existence of open-strangeness pentaquarks at ~4.55—4.60GeV as well as doubly-strange pentaquarks at ~4.7GeV;
Observation of such states is in principle possible in decays of Ξ_b and Ω_b baryons;

However, no proved open heavy-flavor multiquark states so far…







Phys. Rev. Lett. 118 (2017) 182001

- Discovery of the 5 new Ω_c states made by LHCb in the final state of $\Xi_c K$;
- $\Omega_c(3000)$, $\Omega_c(3050)$, $\Omega_c(3066)$, $\Omega_c(3090)$, $\Omega_c(3119)$
- Evidence for additional broad state at 3188;
- *Evidence of* $\Omega_c(3066)$, $\Omega_c(3090)$, $\Omega_c(3119)$ decaying into $\Xi'_c K$;
- Amplitude analysis has not been performed yet;

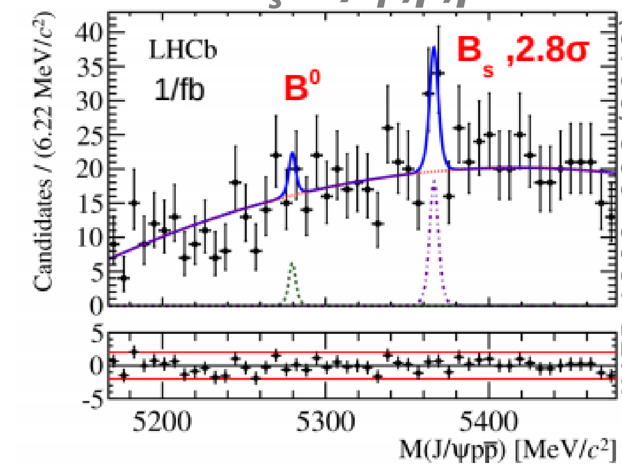
Resonance	Mass (MeV)	Γ (MeV)	Yield	N_σ
$\Omega_c(3000)^0$	$3000.4 \pm 0.2 \pm 0.1^{+0.3}_{-0.5}$	$4.5 \pm 0.6 \pm 0.3$	$1300 \pm 100 \pm 80$	20.4
$\Omega_c(3050)^0$	$3050.2 \pm 0.1 \pm 0.1^{+0.3}_{-0.5}$	$0.8 \pm 0.2 \pm 0.1$	$970 \pm 60 \pm 20$	20.4
		< 1.2 MeV, 95% CL		
$\Omega_c(3066)^0$	$3065.6 \pm 0.1 \pm 0.3^{+0.3}_{-0.5}$	$3.5 \pm 0.4 \pm 0.2$	$1740 \pm 100 \pm 50$	23.9
$\Omega_c(3090)^0$	$3090.2 \pm 0.3 \pm 0.5^{+0.3}_{-0.5}$	$8.7 \pm 1.0 \pm 0.8$	$2000 \pm 140 \pm 130$	21.1
$\Omega_c(3119)^0$	$3119.1 \pm 0.3 \pm 0.9^{+0.3}_{-0.5}$	$1.1 \pm 0.8 \pm 0.4$	$480 \pm 70 \pm 30$	10.4
		< 2.6 MeV, 95% CL		

- Some theoretical works suggest these states are open-charm pentaquarks having diquark-diquark-antiquark structure…;

arXiv:1706.01336

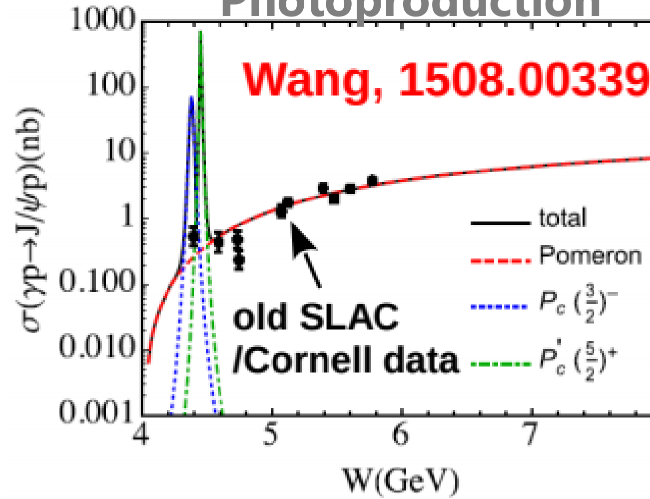
- Precise measurements in the discovery mode;
- Amplitude analysis of the $\Lambda_b \to J/\psi,p,\pi$;
- Search for different decay modes:
  $\Lambda_b \to \chi_{c1} pK$; $\Lambda_b \to \Lambda_c D^0 K$;
- Search for different production modes:
  $\Lambda_b \to J/\psi,p,K^*$;
  $\{Y,B_s\} \to J/\psi,p,p$; $\Xi_b \to J/\psi,p,K,K$; etc.
- Direct photoproduction of P_c states:
  $p\gamma \to P_c \to J/\psi,p$; (JLab)
- P_c in *ee*-collisions (BELLE-II).

$B_s \to J/\psi,p,p$



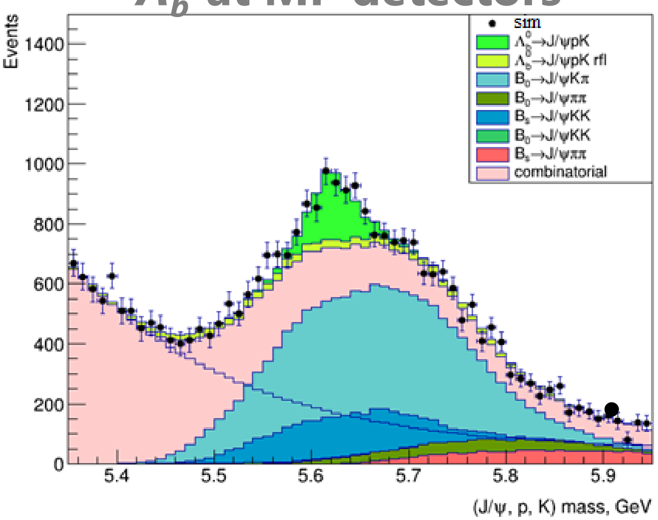
JHEP 1309, 006 (2013)

Photoproduction



Phys. Rev. D 92, 034022 (2015)

Λ_b at MP detectors



- Multipurpose experiments (e.g., ATLAS, CMS) suffer from absence of hadron ID. They can only benefit from high luminosity and try special decays, e.g.,
  $B_s \to J/\psi,p,p$; $\Lambda_b \to J/\psi \Lambda^0 \varphi$
  $\Xi_b \to \Lambda_b \pi \to J/\psi,p,K,\pi$;

- Search for P_c partners, e.g., $\overline{D}\Sigma$ ground state around 4320MeV…
- Very promising is search for charmonium open-strangeness pentaquarks: $\Xi_b \to J/\psi \Lambda^0 K^\pm$; $\Lambda_b \to J/\psi \Lambda^0 \varphi$; and further – charmonium doubly-strange states…
- Search for hidden-bottom pentaquarks, dibaryon states, etc., suggested by molecular models…
- Search for exotic states in rare decays;
- Search for open-heavy-flavor states;

- P_c states are discovered with 9σ and 12σ respectively, confirmed by different analysis strategies and firmly consistent with data in the suppressed channel; this opened the whole new spectroscopy of new states….
- Model of sparse meson-baryon state (‘molecule’) works very good for the P_c(4450) state; it is also well consistent with a rescattering model, which is straightforward to be tested in experiment…
- ‘Molecular’ models suggest many new exotic states, e.g., hidden-bottom pentaquaks, dibaryon states, etc.
- P_c(4380) is more mysterious… experimental data do not show it’s resonant nature. It can be a mixture of states or have some compact
- Numerous ideas for new measurements and new searches!!!

Thank you for your attention…