

Heavy Baryons (experimental)

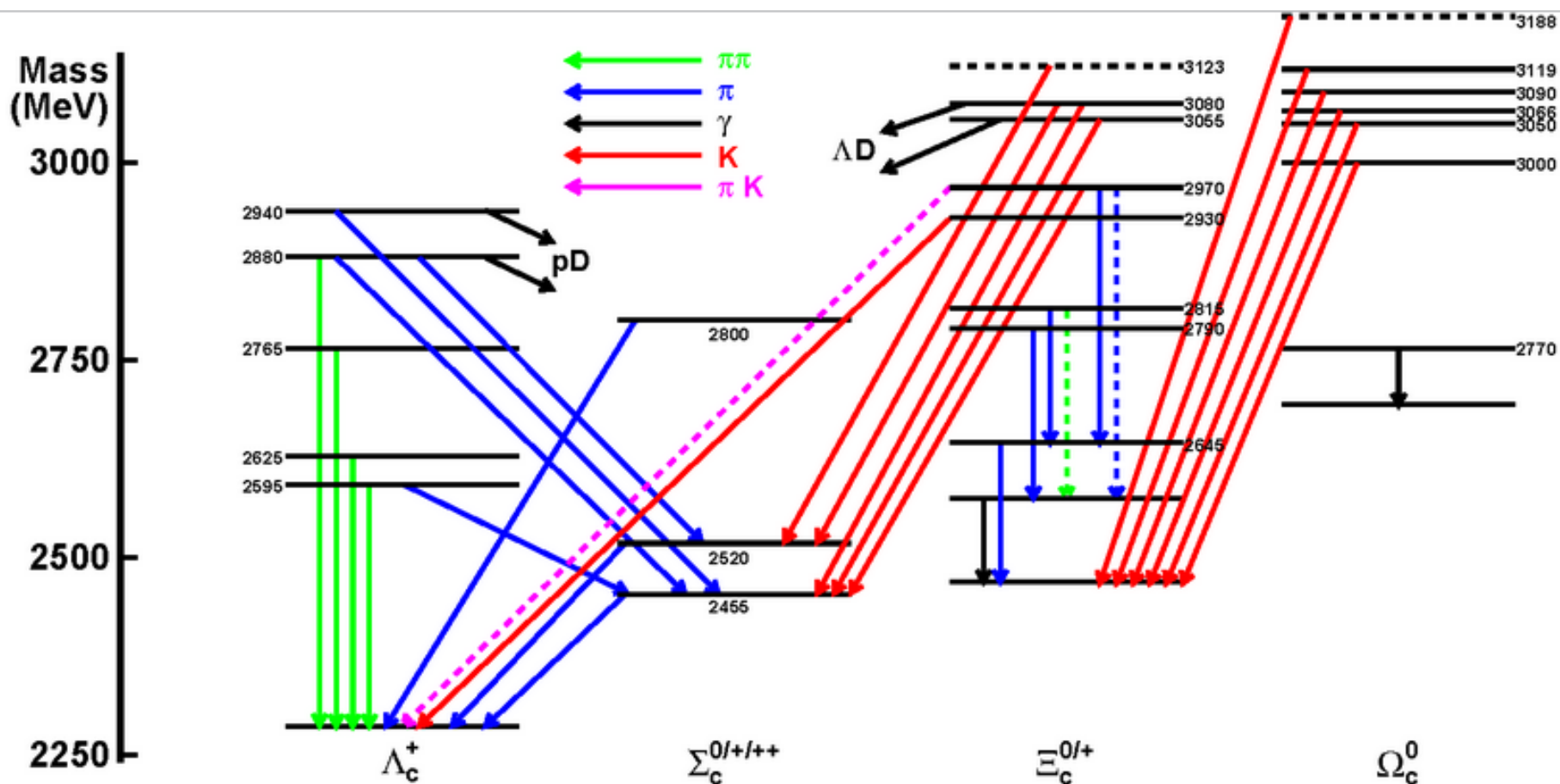
Ruslan Chistov

LPI RAS, Moscow

Outline

1. Charm baryons and prospects
2. Exotic baryons with hidden charm
3. Beauty baryons and prospects
4. Summary

Charm Baryons: today's landscape



Picture taken from Heavy Flavor Averaging Group Web Page

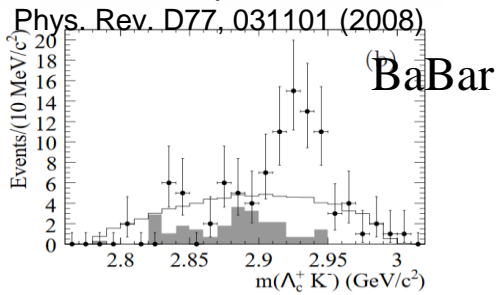
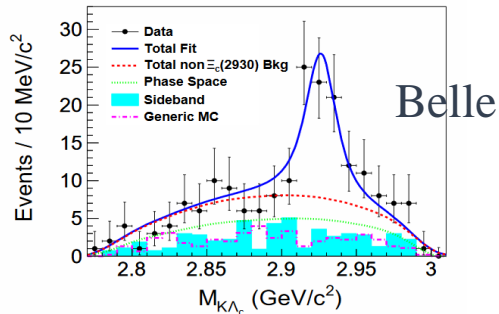
Compared to ~20 years ago picture (ARGUS, CLEO, CDF) several interesting features added:

- Decay modes with light baryon+charm meson: $D^0 p$, $D\Lambda$ (BaBar, Belle)
- Decays of excited Ξ_c not only to $\Xi_c \pi$ or $\Xi_c \pi \pi$ but also to $\Lambda_c K(\pi)$. And these modes dominate! (sq diquark is cutting so that s-quark go to form K meson) (Belle, [PRL 97, 162001 \(2006\)](#))
- Unexpectedly *narrow* 5 new Ω_c states were observed by LHCb

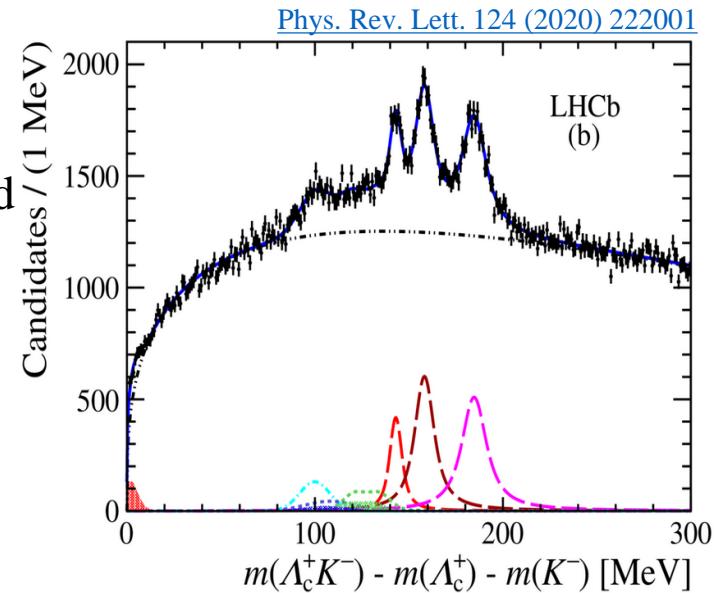
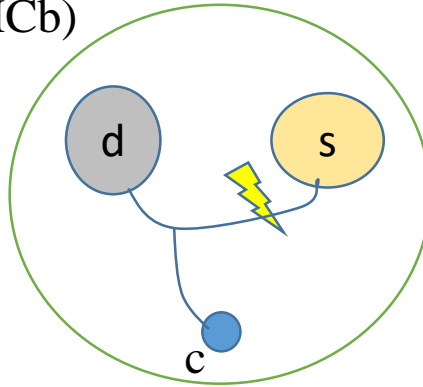


Charm Baryons: selected recent results

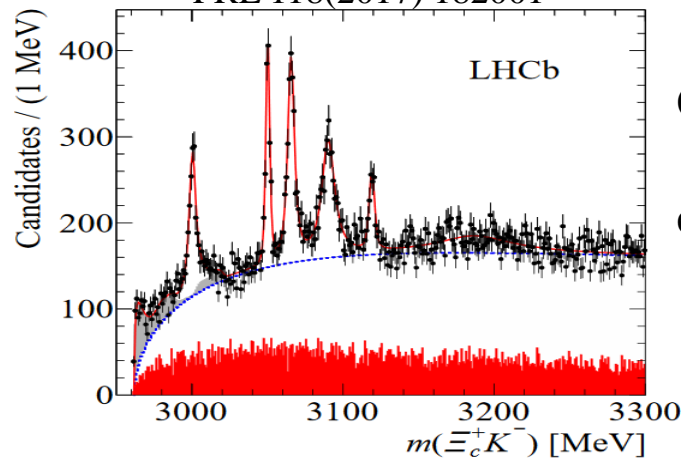
EPJC78, 252 (2018)



$\Xi_c(2930) \rightarrow \Lambda_c^+ K^-$ now resolved into two new states (in total 3 new states observed by LHCb)

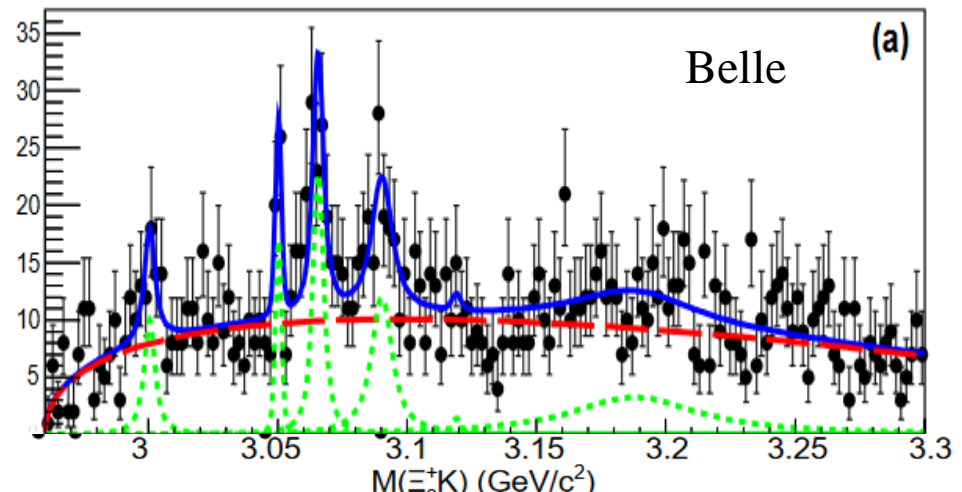


Unexpected 5 new narrow Ω_c excitations
PRL 118(2017) 182001



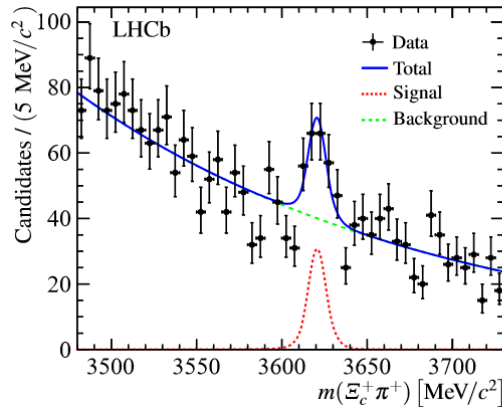
Consistent with P-wave excitations

Confirmed by Belle (PRD 97 051102 (2018))

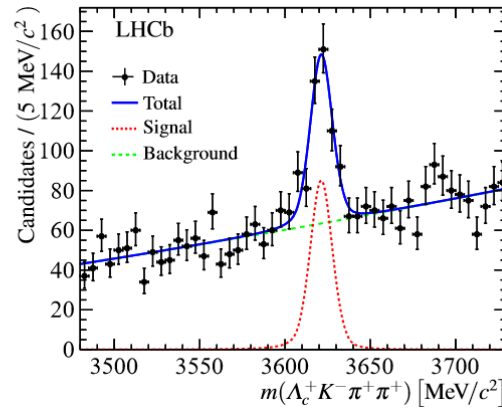


Charm Baryons: **selected** recent results

$$\Xi_{cc}^{++} \rightarrow \Xi_c^+ \pi^+$$



$$\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+$$



Double charm baryons
 Ξ_{cc}^{++} observed by LHCb!

PRL 121, 162002(2018)

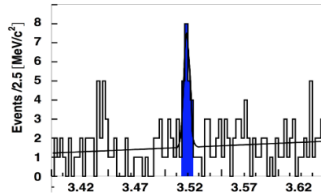
3621.24 ± 0.65 (stat) ± 0.31 (syst) MeV/c²

Mass is consistent with theoretical predictions
(Marek Karliner and Jonathan L. Rosner,
PRD 90, 094007(2014))

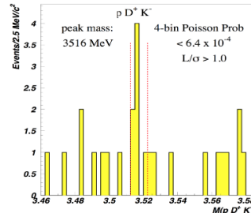
SELEX claimed to observe $\Xi_{cc}^+(ccd)$ in $\Xi_{cc}^+ \rightarrow \Lambda_c^+ K^- \pi^+$ and $p D^+ K^-$ decays

➤ Mass: 3518.7 ± 1.7 MeV PRL 89 (2002) 112001, PLB 628 (2005) 18

$$\Xi_{cc}^+ \rightarrow \Lambda_c^+ K^- \pi^+$$



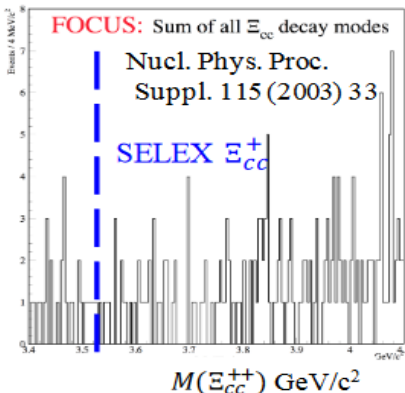
$$\Xi_{cc}^+ \rightarrow p D^+ K^-$$



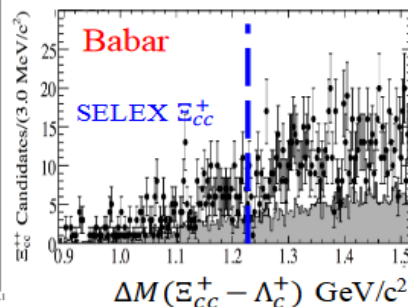
Where is the isospin partner Ξ_{cc}^+ ?

Not confirmed by FOCUS, BaBar, Belle and LHCb in much larger Λ_c^+ samples

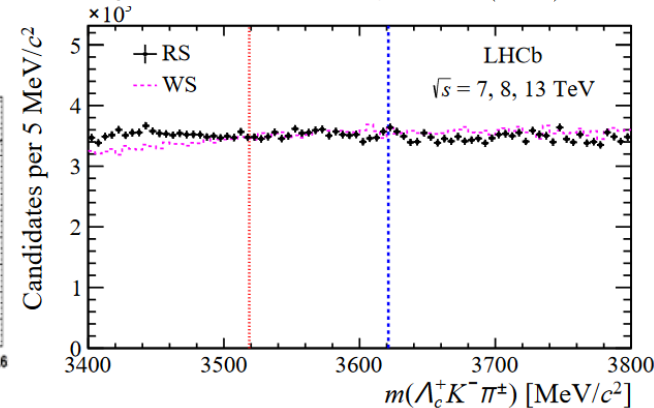
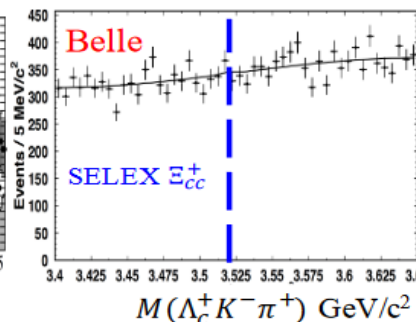
Sci. China-Phys. Mech. Astron. 63, 221062 (2020)



PRD 74 (2006) 011103



PRL 97 (2006) 162001



Charm Baryons: future possible developments and advances

Next decade evolution in **conventional** charm baryons (LHCb & Belle II):

- (1) **Determination of J^P quantum numbers**: in an amplitude analysis of corresponding b-hadron decays or through the study of decay angle distributions;
- (2) One should **study the predicted (expected) levels and their decay modes** – to test theoretical models... sometimes in searching for the classical “simple” levels one can observe something unexpected;
- (3) Search for (new) excited states decaying with ss-bar pair popping (e.g. $\Lambda_c^{**+} \rightarrow D_s^+ \Lambda$)
[PRD 76, 051102 \(2007\)](#)
- (4) **Confirmation (Belle II) of double charm baryons Ξ_{cc}^{++}**
and search for its new decay modes - important to collect as much as possible Ξ_{cc} for the search for **excited states $\Xi_{cc}^* \rightarrow \Xi_{cc} \pi(\pi)$** ; **Search for Ξ_{cc}^+**
- (5) Weak decays of ground states is important in determination of J^P of light baryons;
- (6) Study of production properties of conventional (& exotic?)
charm baryons in PbPb collisions (LHC) – important for better understanding of its structure and also in test of the models of QGP.

Exotic Charm Baryons: future possible developments and advances

Next decade evolution in **exotic** charm baryons:

(1) **We await for the confirmation of the observations**, especially of exotic states like pentaquarks.

Particular these confirmations have almost equal importance as the observations itself.

Also search for (new?) P_c in $\Lambda_b \rightarrow \chi_{c1} p K^- / \psi(2S) p K^-$.

(2) **Test $\Sigma^{(*)+} D^{(*)0}$ thresholds at Belle II ?**

(π^0 reconstruction $\Sigma_c^+ \rightarrow \Lambda_c^+ \pi^0$)

(3) **Search for charm strange pentaquark $P_{cs} \rightarrow J/\psi \Lambda$**

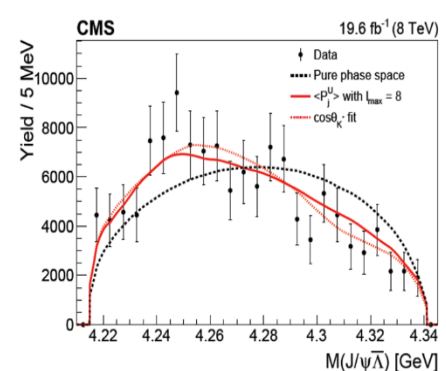
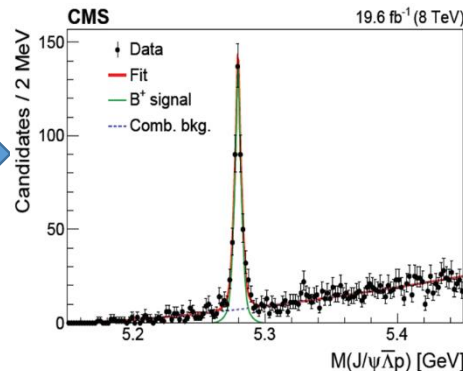
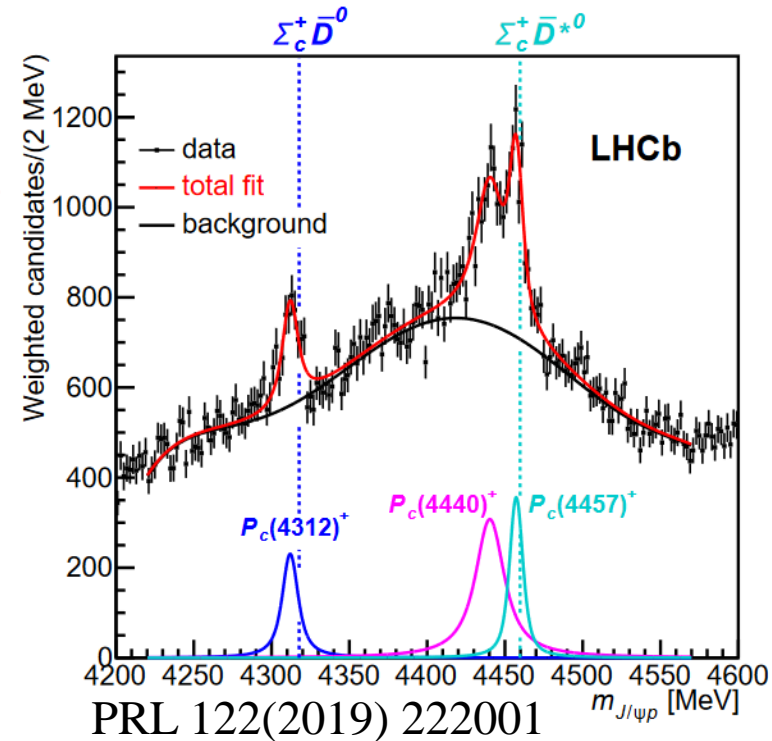
The base for it is already exists: new decay modes found

$\Xi_b^- \rightarrow J/\psi \Lambda K^-$ (LHCb) and $\Lambda_b \rightarrow J/\psi \Lambda \phi$ (CMS).

Phys. Lett. B 772
(2017) 265-273

Phys. Lett. B 802
(2020) 135203

Also, angular analysis in
 $B^+ \rightarrow J/\psi \text{ anti-}\Lambda p$ (CMS)



Beauty Baryons: today's landscape

Ground states discovered by UA1, CDF, D0,
but their excitations observed by LHCb, 2 of them by CMS

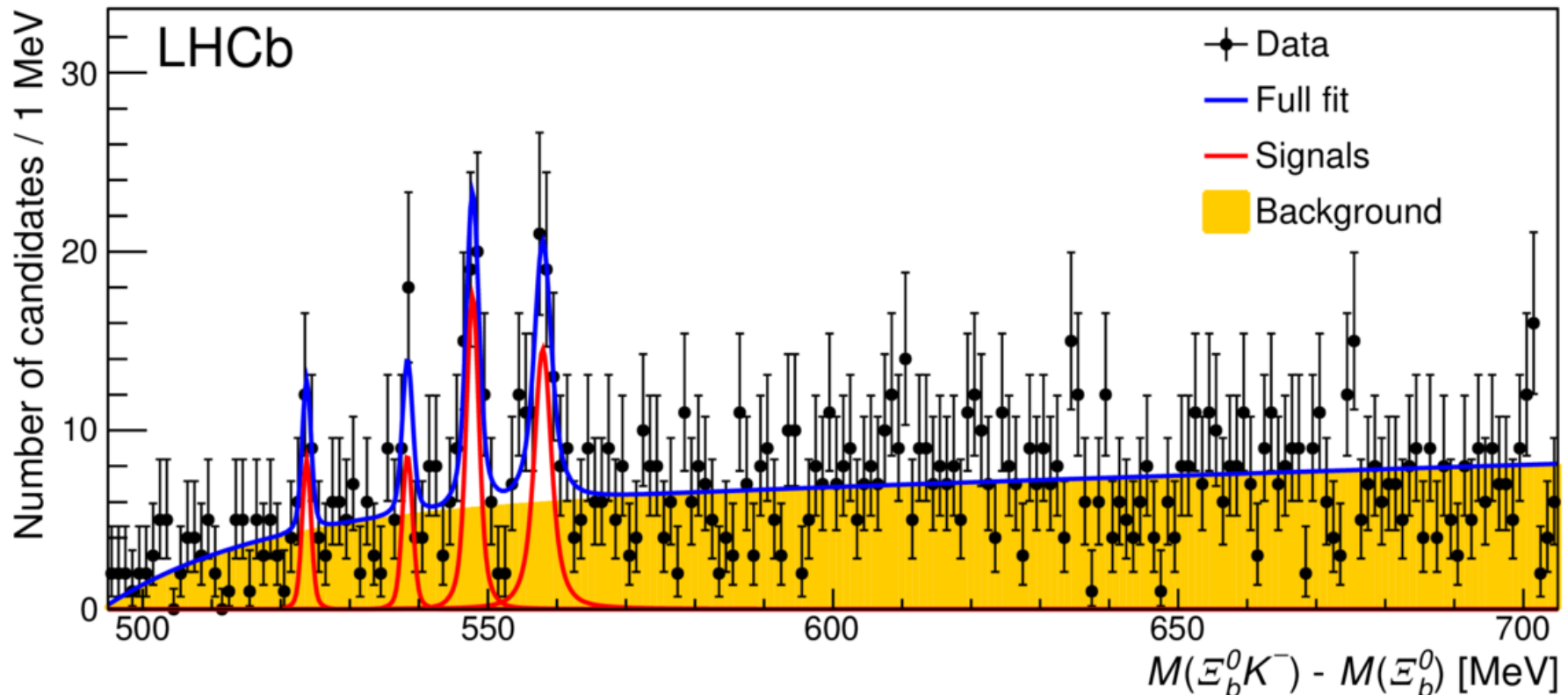
State	Quarks	Decay mode	Mass, MeV	Observation (with links)
Ξ_{cc}^{++}	$u\ c\ c$	$\Lambda_c^+ K^- \pi^+ \pi^+$ $\Xi_c^+ \pi^+$	3620.6 ± 1.5 3621.40 ± 0.72	LHCb, 2017, 13 TeV LHCb, 2018, 13 TeV
$\Lambda_b(5912)$ $\Lambda_b(5920)$	$u\ d\ b$	$\Lambda_b \pi^+ \pi^-$	5912.20 ± 0.21 5919.92 ± 0.19	LHCb, 2012, 7 TeV CMS, 2020, 13 TeV
$\Lambda_b(6146)$ $\Lambda_b(6152)$	$u\ d\ b$	$\Lambda_b \pi^+ \pi^-$	6146.17 ± 0.43 6152.51 ± 0.37	LHCb, 2019, 7, 8, 13 TeV CMS, 2020, 13 TeV
Λ_b^{**70}	$u\ d\ b$	$\Lambda_b \pi^+ \pi^-$	6073 ± 5 6072.3 ± 3.0	CMS, 2020, 13 TeV LHCb, 2020, 7, 8, 13 TeV
$\Sigma_b(6097)^-$ $\Sigma_b(6097)^+$	$d\ d\ b$ $u\ u\ b$	$\Lambda_b \pi^-$ $\Lambda_b \pi^+$	6098.0 ± 1.8 6095.8 ± 1.7	LHCb, 2018, 7, 8 TeV
$\Xi'_b(5935)^-$ $\Xi'_b(5955)^-$	$d\ s\ b$	$\Xi_b^0 \pi^-$	5935.02 ± 0.05 5955.33 ± 0.13	LHCb, 2015, 7, 8 TeV
$\Xi_b(5945)^0$	$u\ s\ b$	$\Xi_b^- \pi^+$	5951.4 ± 1.2 5952.2 ± 0.9	CMS, 2012, 7 TeV LHCb, 2016, 7, 8 TeV
$\Xi_b(6227)$	$u\ s\ b$	$\Xi_b^0 \pi^-$ $\Lambda_b K^-$	6226.9 ± 2.0	LHCb, 2018, 7, 8, 13 TeV

Beauty Baryons: **selected** recent results

Search for analogous to new narrow excited Ω_c^0 states in beauty sector:
charm sector continuously motivates beauty.

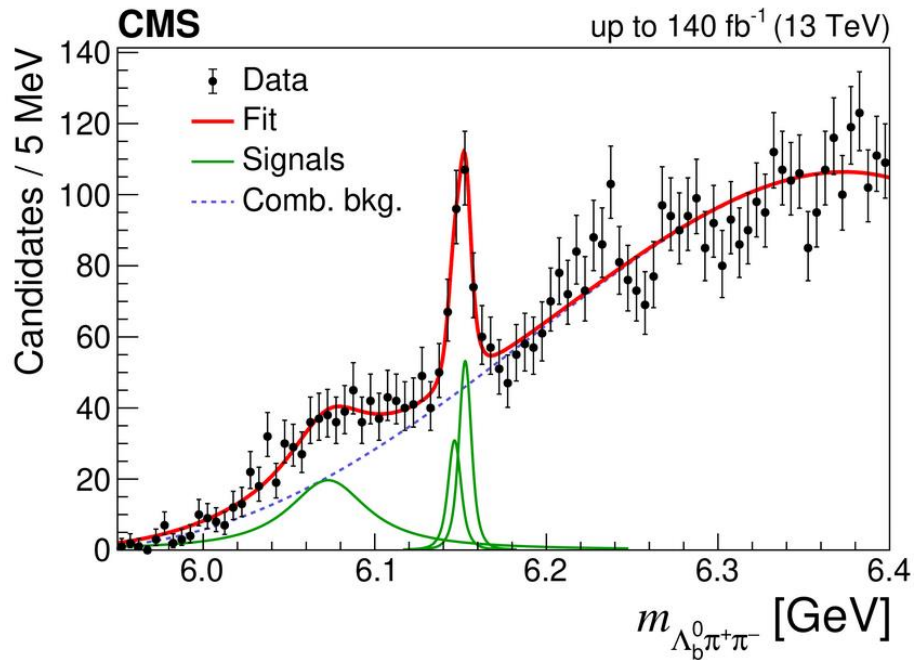
LHCb reports 4 new narrow states decaying into $\Xi_b^0 K^-$, consistent with P-wave excitations

PRL 124 (2020) 082002



New Ω_b^- states should be added to the table in the previous slide

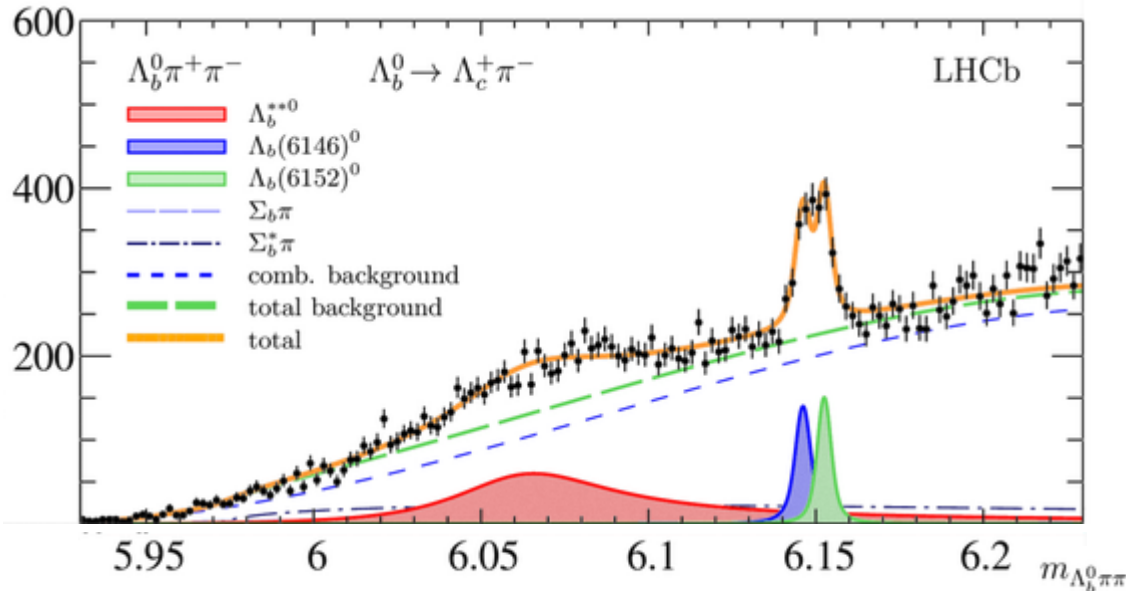
Beauty Baryons: selected recent results



[*Phys. Lett. B* 803 \(2020\) 135345](#)

2020 hot beauty baryon topic:

Observation by LHCb and CMS of 3 new excited Λ_b states, broad one is probably 2S state and two narrow are candidates for 1D doublet.



[*JHEP* 06 \(2020\) 136](#)

Beauty Baryons: future possible developments and advances

Next decade possible evolution in **conventional beauty baryons (LHC):**

(1) **Determination of J^P quantum numbers** through the study of decay angle distributions;

(2) One should study the **predicted (expected) levels and their decay modes** – to test theoretical models... sometimes in searching for the classical “simple” levels one can observe something unexpected;

(3) **Search for Ξ_{bc} , Ξ_{bb} and their excited states.**

First search in D^0 pK- by LHCb [arXiv:2009.02481](https://arxiv.org/abs/2009.02481). Possible future modes are: $\Xi_{bc}^0 \rightarrow \Xi_b^- \pi^+ / J/\psi \Xi_c / B^0 \Lambda / \Lambda_b K_s^0$ (LHCb but in principle reachable in ATLAS, CMS), $D^0 \Lambda / \Lambda_c^+ K^- / \Xi_c \pi / \Xi_{cc} \pi$ (LHCb)

(4) Weak decays of ground states is important in determination of J^P of charm baryons;

(5) Study of production properties of conventional (&exotic?)

beauty baryons in PbPb collisions (LHC) – important for better understanding of its structure and also in test of the models of QGP.

(6) **Search for exotic beauty (di)baryons:** Marek Karliner, Jonathan Rosner

-- check $B_c p / B_c \pi / \Upsilon p / \Upsilon \pi$ modes in the vicinity of $\Sigma_c B^* / \Sigma_b D^* / \Lambda_b\text{-bar} \Sigma_c / \Sigma_b \Lambda_b\text{-bar}$

Summary

- *Many conventional charm and beauty baryon states observed by LHCb await for their confirmation by Belle II, ATLAS and CMS*
- *Searches for missing excited conventional heavy baryon states and its new decay modes will be continued and also searches for double heavy baryons Ξ_{cc}^+ and $\Xi_{bc}^{+/-0}$ will be performed*
- *P_c pentaquarks await for their confirmation by ATLAS and CMS.*
(It is not so clear whether Belle II can do it
– search for P_c in $e^+e^- \rightarrow c\bar{c}$ continuum production)
- *New thresholds like heavy meson- heavy baryon and heavy baryon – heavy baryon should be tested in different decay modes.*



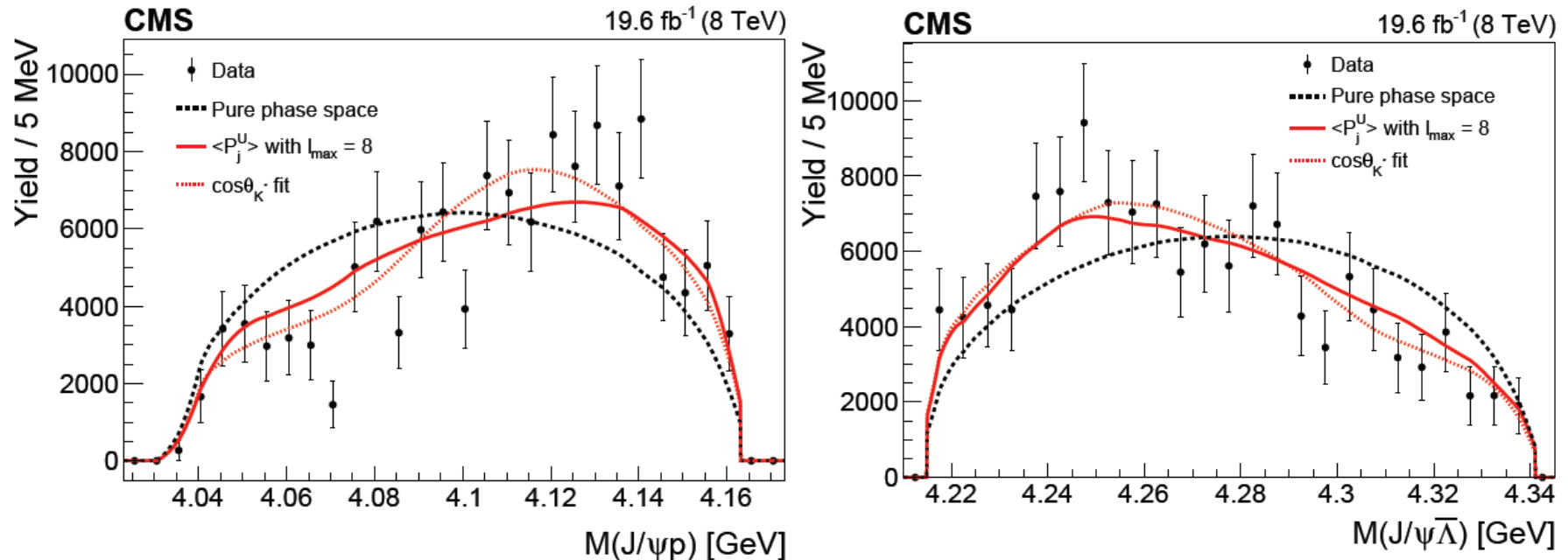
Good news for heavy hadrons aficionados - very exciting next 10 years ahead

Backup slides

CMS: Study of $B^+ \rightarrow J/\psi \bar{\Lambda} p$

JHEP 12 (2019) 100

Simulation reweighting according to the observed structure in Λp



A model-independent approach that accounts for the contribution from known K^* 's with spins up to 4 in the Λp system improves the agreement with data significantly!

Compatibility with data (incompatibility $< 2.8 \sigma$ including syst.)
eliminating the need for exotic resonances in this 3-body decay