Heavy baryons at LHCb (non exotic)

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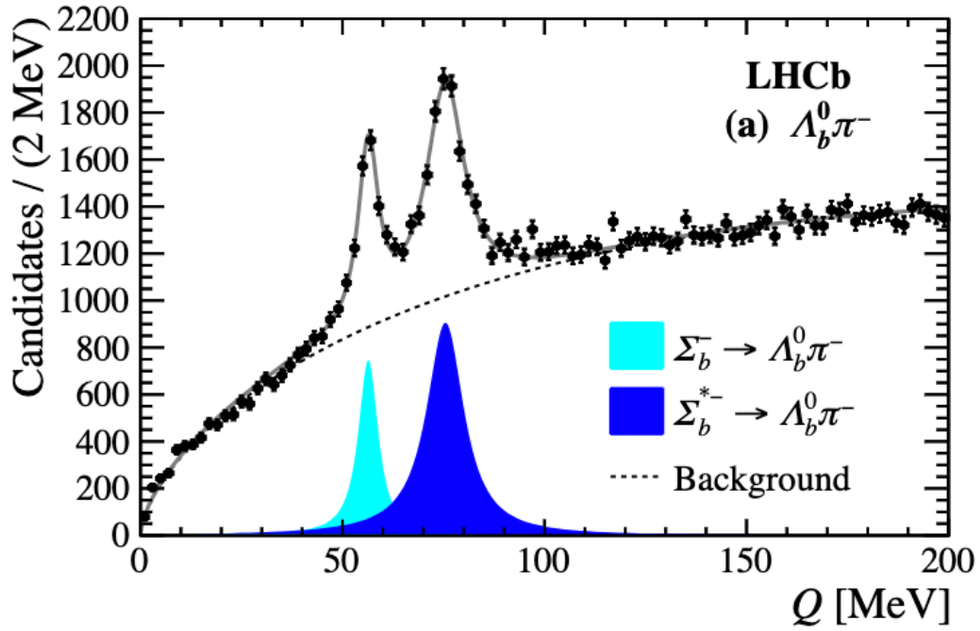
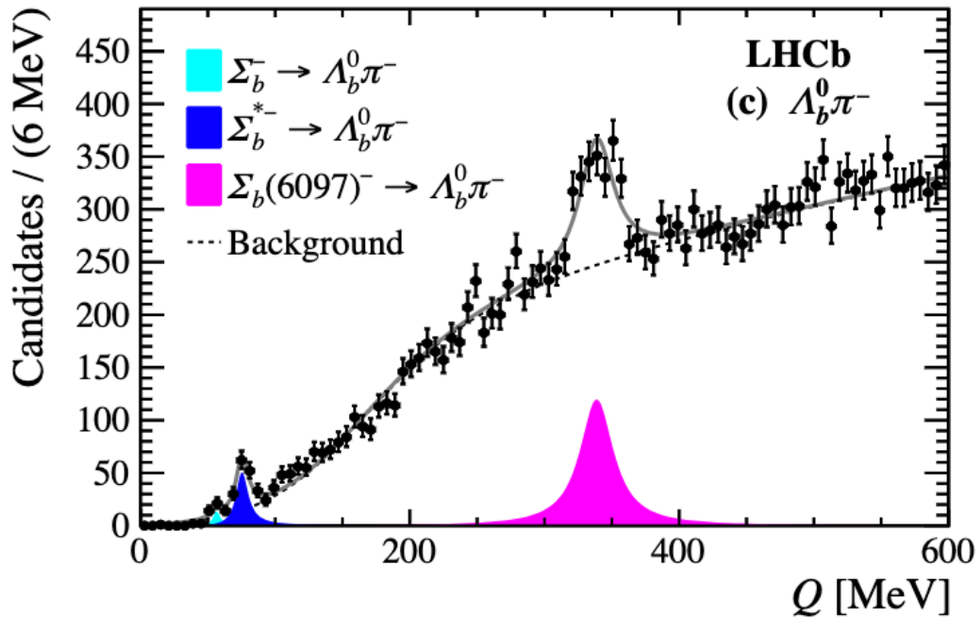
On behalf of the LHCb collaboration

The International Workshop on
Partial Wave Analysis and Advanced Tools
for Hadron Spectroscopy
PWA12/ATHOS7

September, 6th-10th 2021





"Conventional" spectroscopy at LHCb

- This summer had quite some striking results by LHCb
- E.g. see LHCb highlight talk by Franz Muheim at EPS2021

https://inspirehep.net/literature/1915457 : arxiv 2109.01038
https://inspirehep.net/literature/1915358 : arxiv 2109.01056

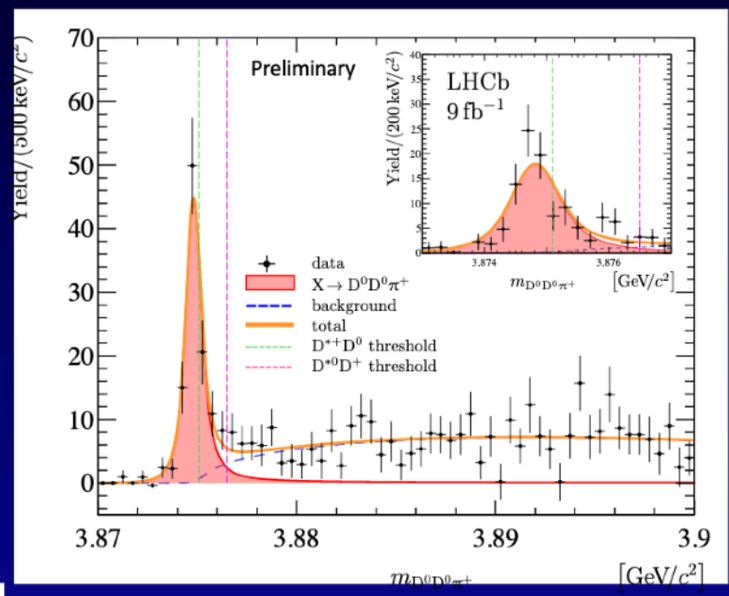
Observation of T_{cc}^+ state

- **First observation of a same-sign doubly charmed tetraquark T_{cc}^+**
  - Very narrow state in $D^0 D^0 \pi^+$ mass spectrum
  - Consistent with $cc\bar{u}\bar{d}$ tetraquark
  - Mass very close to $D^{*+}D^0$ mass thresholds
  - Manifestly exotic
- **Parameters of T_{cc}^+**
  - Fit structure with P-wave relativistic Breit-Wigner

$$\begin{aligned} \delta m_{\rm BW} &= -273 \pm 61 \pm 5\,^{+11}_{-14}\,{\rm keV}/c^2\,, \\ \Gamma_{\rm BW} &= 410 \pm 165 \pm 43\,^{+18}_{-38}\,{\rm keV}\,, \end{aligned}$$

  - Uncertainties stat, syst and due $J^P = 1^+$ assumption
  - Significance for signal > 10 σ
  - Significance for $\delta m_{BW} < 0$ 4.3 σ

NEW LHCb-PAPER-2021-031

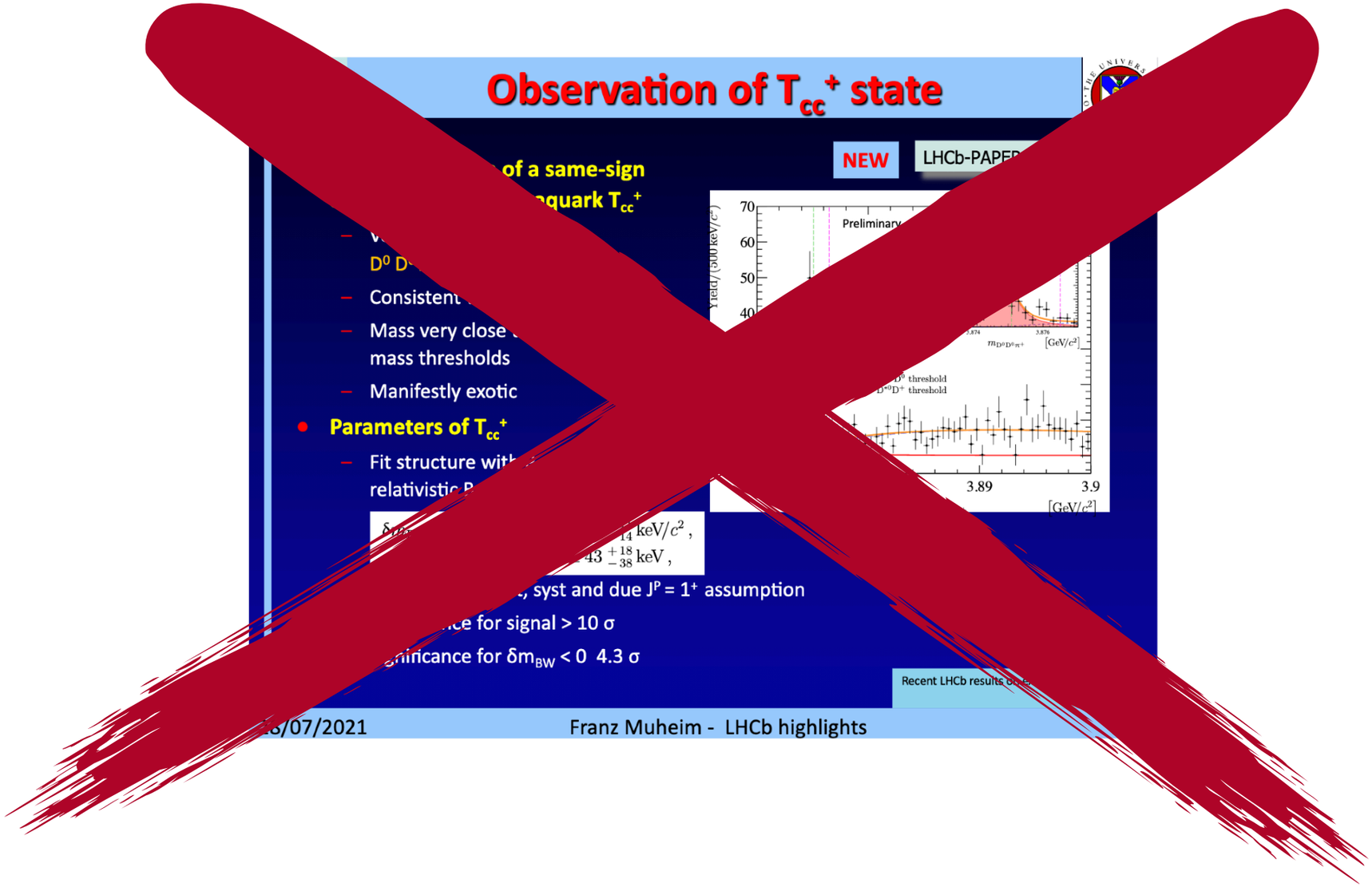


Recent LHCb results on exotic meson candidates
Ivan Polyakov

28/07/2021 Franz Muheim - LHCb highlights 23

“Conventional” spectroscopy at LHCb

- But I will talk about “conventional” heavy baryons, so no **tetraquark/pentaquark here!**
- Please refer to Nicola’s talk for exotica states

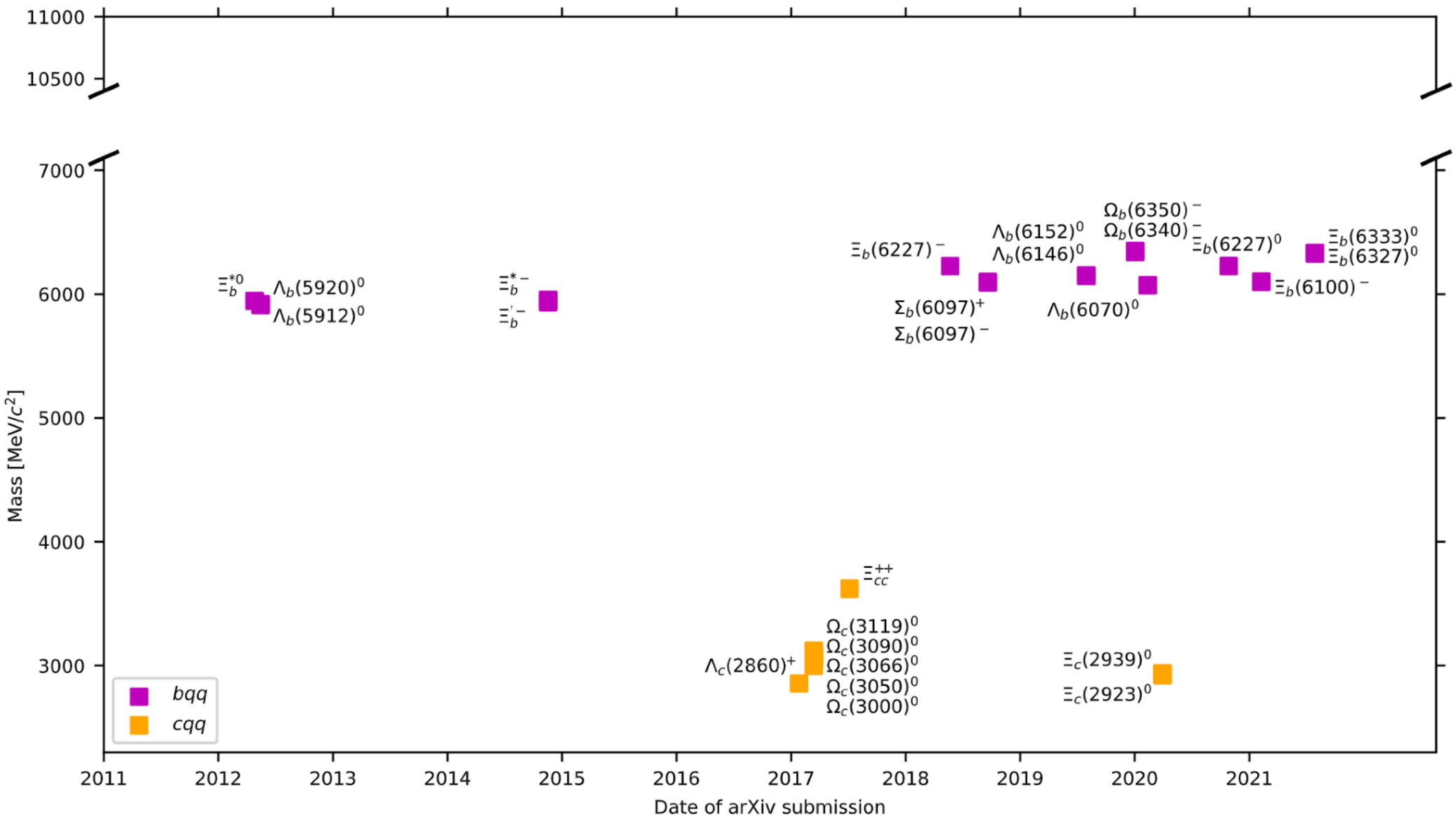


- **On the other hand LHCb is still a key player even for states predicted by SM**
- **New decay modes → new resonances and sometimes even ground states!**

New states observed at LHC

- I cannot start without showing the updated famous plot by our colleague Patrick Koppenburg
- **This plot only shows the new observations of baryons at LHC (baryons only)**
- **Really nice progression with time (as new data arrives)**

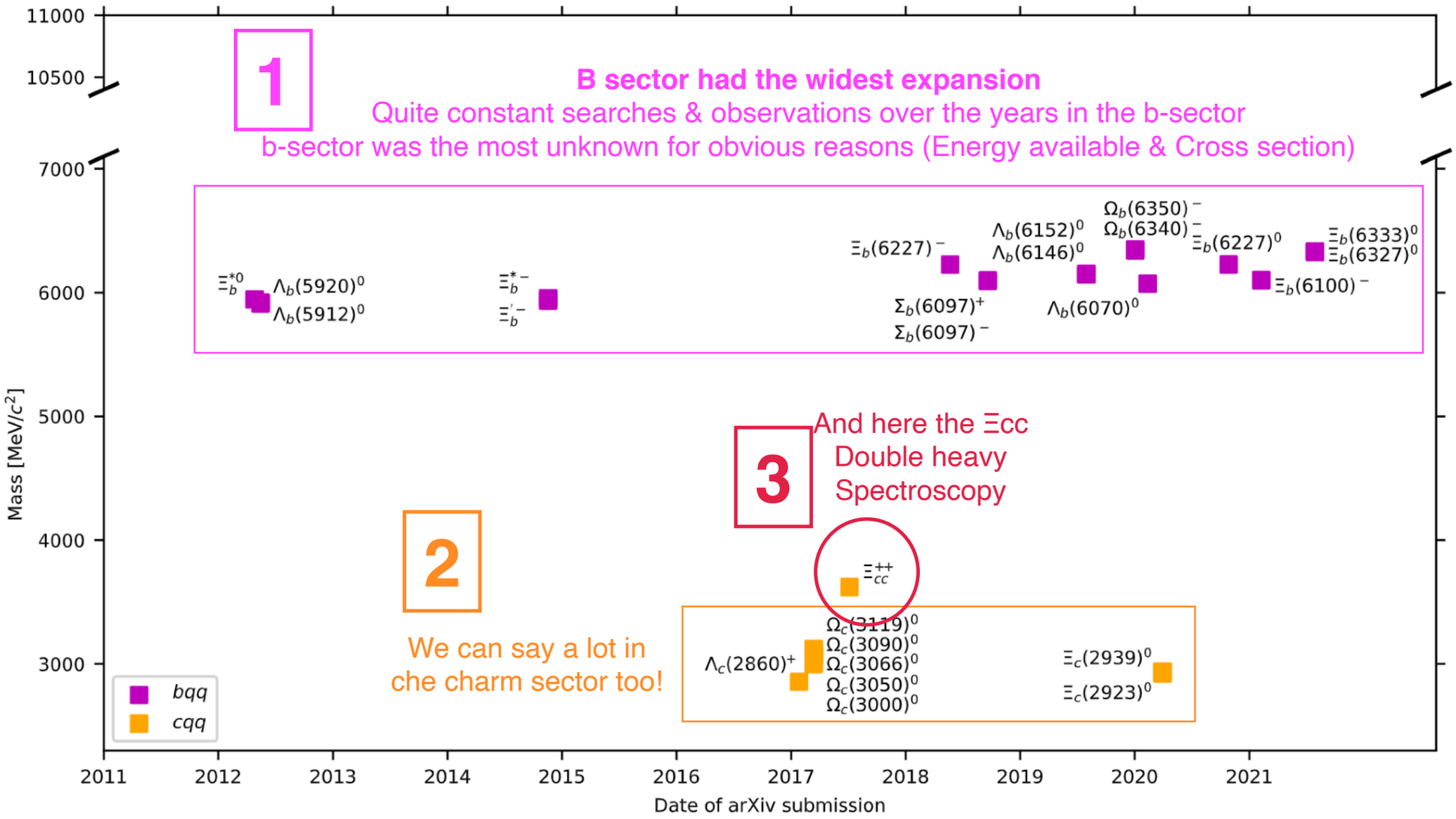
Masses and discovery date for conventional baryons observed at the LHC. Hollow markers indicate superseded states.



New states observed at LHC

- I cannot start without showing the updated famous plot by our colleague Patrick Koppenburg
- **This plot only shows the new observations of baryons at LHC (baryons only)**
- **My personal interpretation of the plot…**

Masses and discovery date for conventional baryons observed at the LHC. Hollow markers indicate superseded states.



Outline

- **Very hands-on talk**
  - What we have done… (just one recent example)
  - What we are doing…
  - What can we do for the future… (especially in the upgrade scenario)

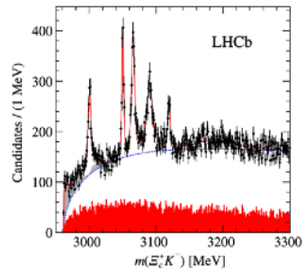
- **Putting things in order…**

CHARMED BARYONS ($C = +1$)

$\Lambda_c^+ = udc$, $\Sigma_c^{++} = uuc$, $\Sigma_c^+ = udc$, $\Sigma_c^0 = ddc$,
$\Xi_c^+ = usc$, $\Xi_c^0 = dsc$, $\Omega_c^0 = ssc$

- Mostly explored
- But sometimes still interesting surprises

inclusive observation
Phys. Rev. Lett. 118, 182001 (2017)



BOTTOM BARYONS ($B = -1$)

$\Lambda_b^0 = udb$, $\Xi_b^0 = usb$, $\Xi_b^- = dsb$, $\Omega_b^- = ssb$

- Resonances & Ground states

DOUBLY CHARMED BARYONS ($C = +2$)

$\Xi_{cc}^{++} = ucc$, $\Xi_{cc}^+ = dcc$, $\Omega_{cc}^+ = scc$

Ξ_{cc}^{++}

- Double heavy spectroscopy is a fact now
- LHCb is a key player on double-heavy searches

Charmed Baryons

CHARMED BARYONS ($C = +1$)

$\Lambda_c^+ = udc$, $\Sigma_c^{++} = uuc$, $\Sigma_c^+ = udc$, $\Sigma_c^0 = ddc$,
$\Xi_c^+ = usc$, $\Xi_c^0 = dsc$, $\Omega_c^0 = ssc$

- "Most" states now known from previous experiments
- Inclusive searches + Dalitz decays from b-baryons
- Energy and Cross sections are not a problem for most experiments → states accessible at B factories
- Exotic states in the charm sector (Tetra and Penta states not covered in this talk)

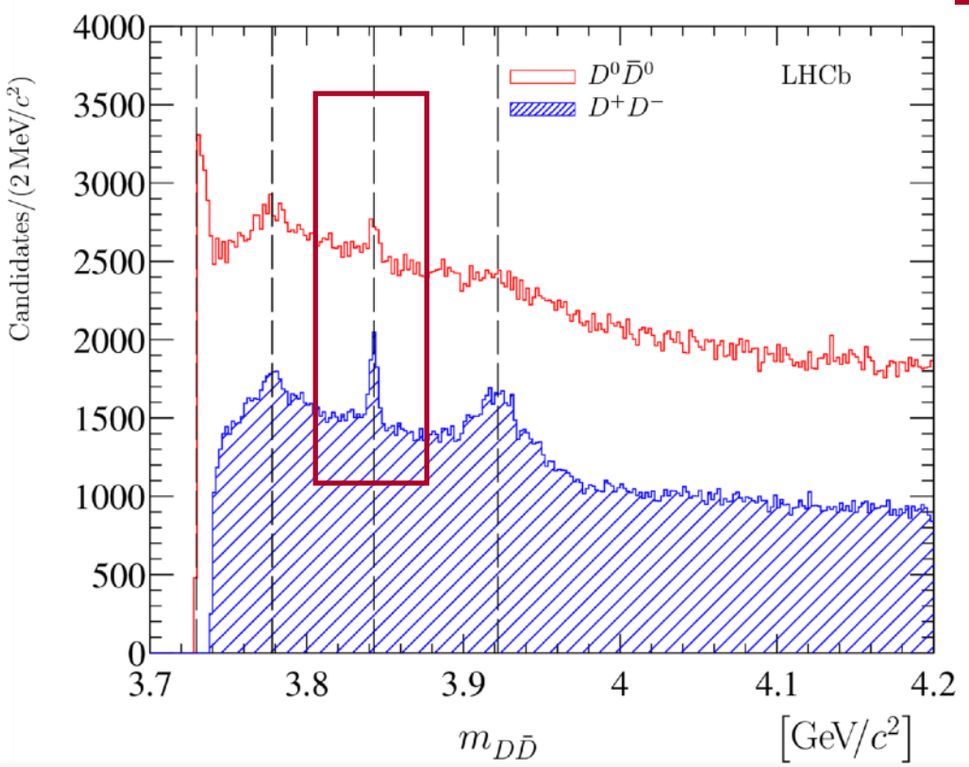
- One could think everything is done for conventional SM → but surprises can happen!
- E.g. DD states, etc... (you can look for Tcc but even conventional ccbar states above threshold)
- For the future we could even try Triple-charm and similar

JHEP **2019,** 35 (2019)

Abstract

Using proton-proton collision data, corresponding to an integrated luminosity of $9fb^{-1}$, collected with the LHCb detector between 2011 and 2018, a new narrow charmonium state, the $X(3842)$ resonance, is observed in the decay modes $X(3842) \to D^0\bar{D}^0$ and $X(3842) \to D^+D^-$. The mass and the natural width of this state are measured to be

$m_{X(3842)} = 3842.71 \pm 0.16 \pm 0.12 MeV/c^2$, $\Gamma_{X(3842)} = 2.79 \pm 0.51 \pm 0.35 MeV$,



The mass spectra for selected $D\overline{D}$ combinations. The open red histogram corresponds to $D^0\overline{D}^0$ pairs, while the hatched blue histogram corresponds to D^+D^- pairs. Vertical black dashed lines help to identify the peaks from (left to right) $\chi_{c1}(3872) \to D^{*0}\overline{D}^0$, $\psi(3770) \to D\overline{D}$, X(3842) $\to D\overline{D}$ and $\chi_{c2}(3930) \to D\overline{D}$ decays.

Bottom Baryons

BOTTOM BARYONS ($B = -1$)

$\Lambda_b^0 = udb$, $\Xi_b^0 = usb$, $\Xi_b^- = dsb$, $\Omega_b^- = ssb$

- Ground states are almost all known, with some exceptions (see below)
- A lot of resonances have been found, identified with radial and orbital excitations
- **With higher luminosities collected, we can have access to states with lower cross section**
- **Explore wider Q value ranges and multi-particle states, where background is severe**
- I will go through a list of what's available and what can be done (or not)

Panoramic view

Λ_b^0	Σ_b	Ξ_b^-	Ω_b^-
$\Lambda_b(5912)^0$	Σ_b^*	Ξ_b^0	$\Omega_b(6316)^-$
$\Lambda_b(5920)^0$	$\Sigma_b(6097)^+$	$\Xi_b'(5935)^-$	$\Omega_b(6330)^-$
$\Lambda_b(6070)^0$	$\Sigma_b(6097)^-$	$\Xi_b(5945)^0$	$\Omega_b(6340)^-$
$\Lambda_b(6146)^0$		$\Xi_b(5955)^-$	$\Omega_b(6350)^-$
$\Lambda_b(6152)^0$		$\Xi_b(6227)^-$	
		$\Xi_b(6227)^0$	

Λ_b states: $\Lambda_b\pi\pi$

- Example of time evolution of searches and new observations once more data is available
- At LHCb we collected order of 1M-2M Λb signal events in various final states

Λ_b^0 Ground state

$\Lambda_b(5912)^0$

$\Lambda_b(5920)^0$

$\Lambda_b(6070)^0$

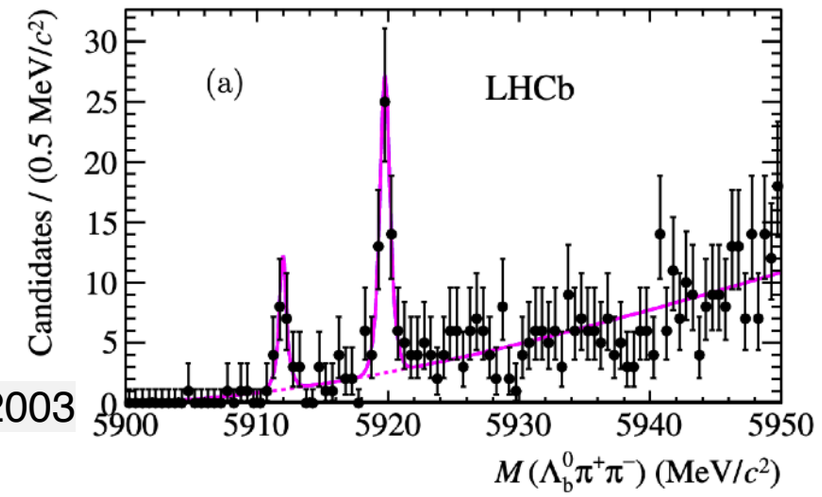
$\Lambda_b(6146)^0$

$\Lambda_b(6152)^0$

2012

$\Lambda_b^0\pi^+\pi^-$

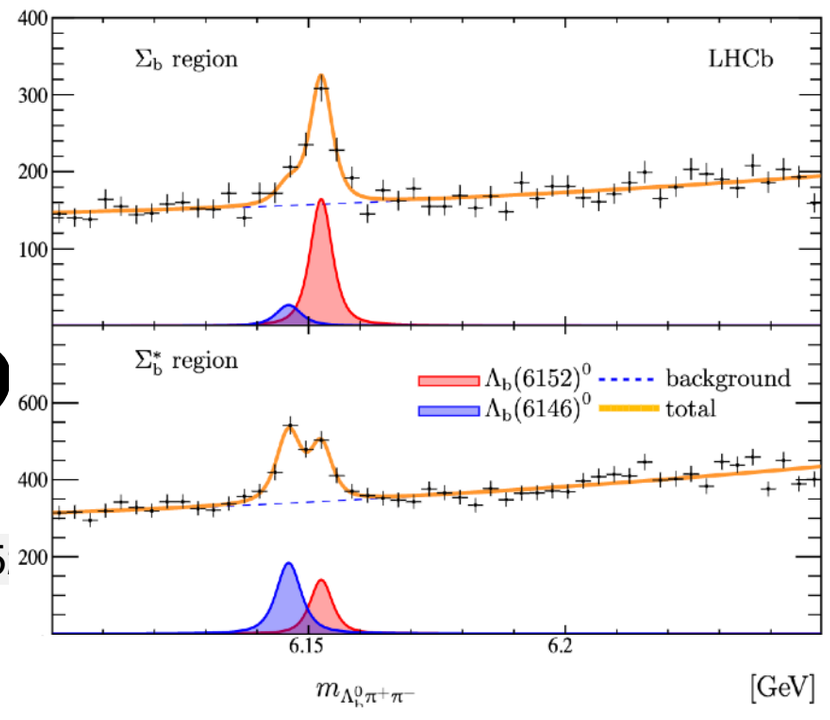
PRL 109 172003



2019

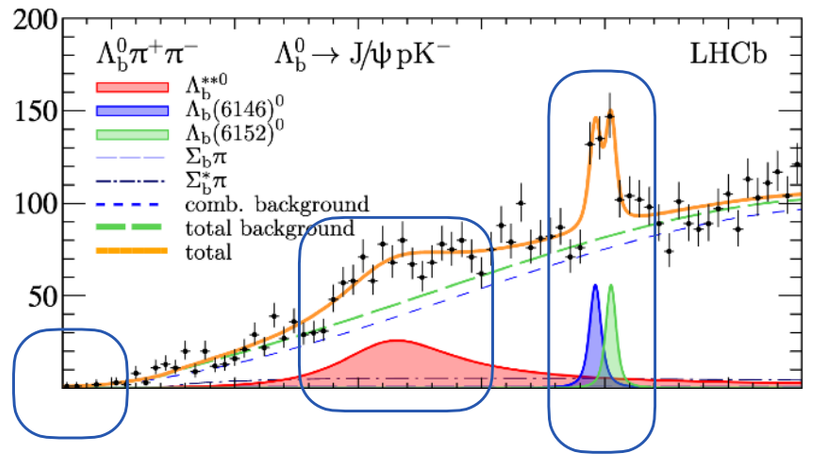
$\Lambda_b^0\pi^+\pi^-$

PRL 123, 15



2020

JHEP 2006 136



Σ_b states: $\Lambda_b\pi$

- Ground state observed by CDF
- Confirmed + new states observed by LHCb

Σ_b

Σ_b^*

$\Sigma_b(6097)^+$

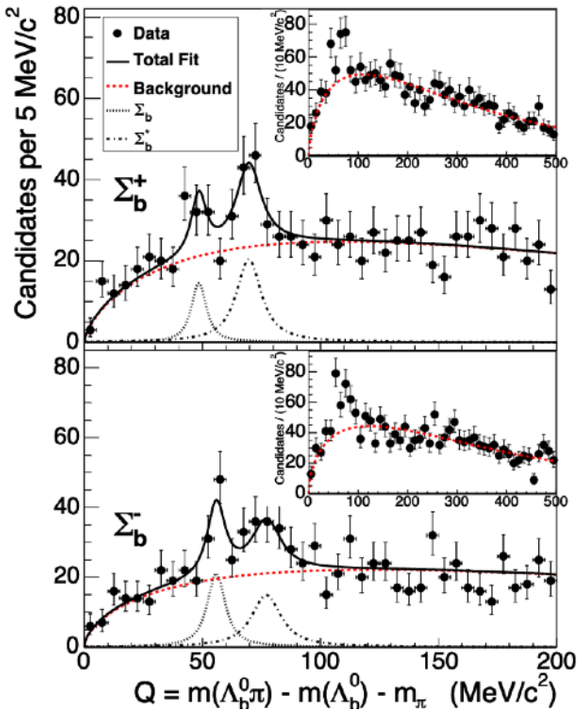
$\Sigma_b(6097)^-$

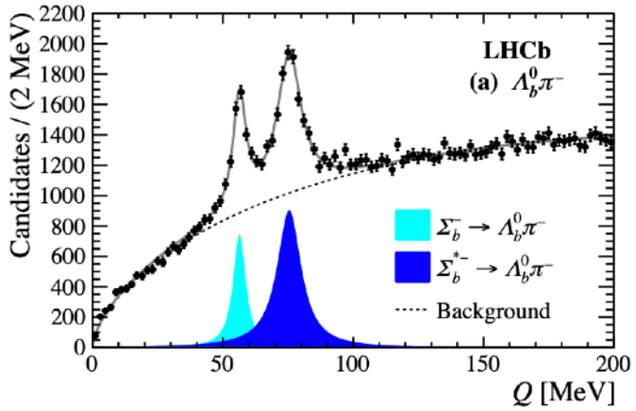
2007

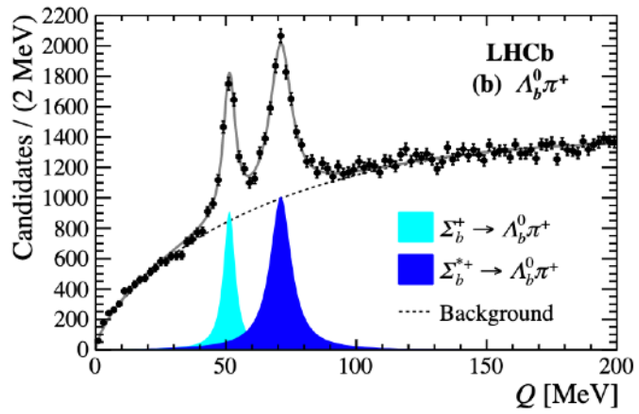
PRL 99:202001

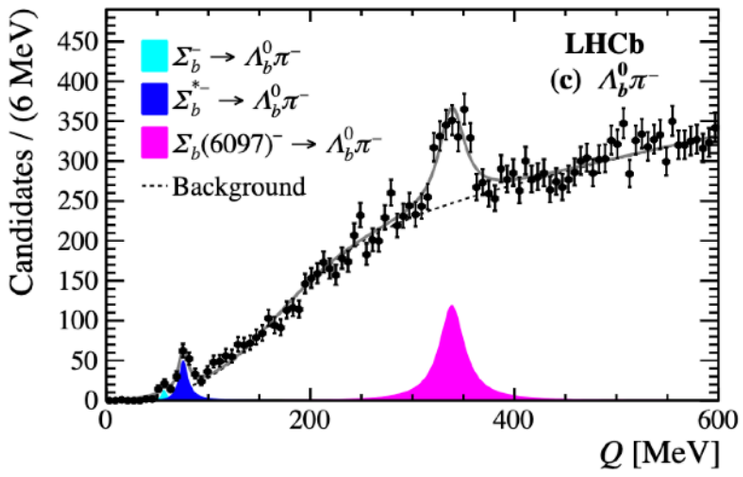
2019

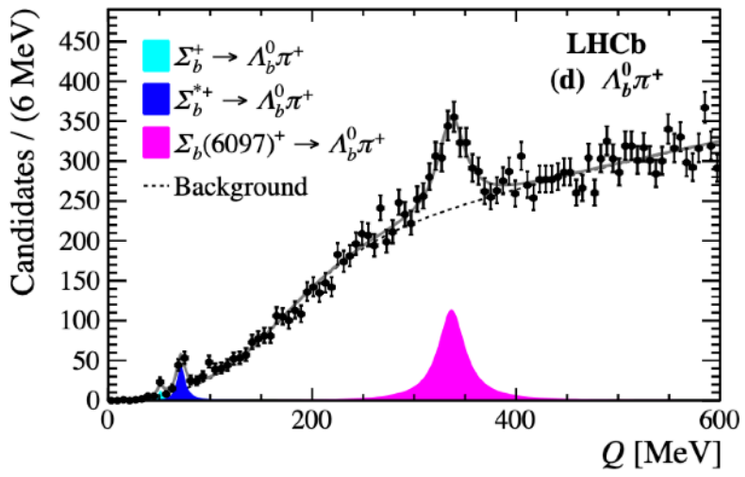
PRL 122, 012001











- **Σ_b^0 doublet still unobserved experimentally**
- **Experimentally very challenging as neutral Σb is expected → $\Lambda_b\,\pi^0$**

Ξ_b states: $\Xi_b\pi$ and others

- Several observations of ground states and excitations
- Missing ground state Ξb' (probably below threshold)
- Multi particle modes interesting (see next slide)

Ξ_b^-

Ξ_b^0

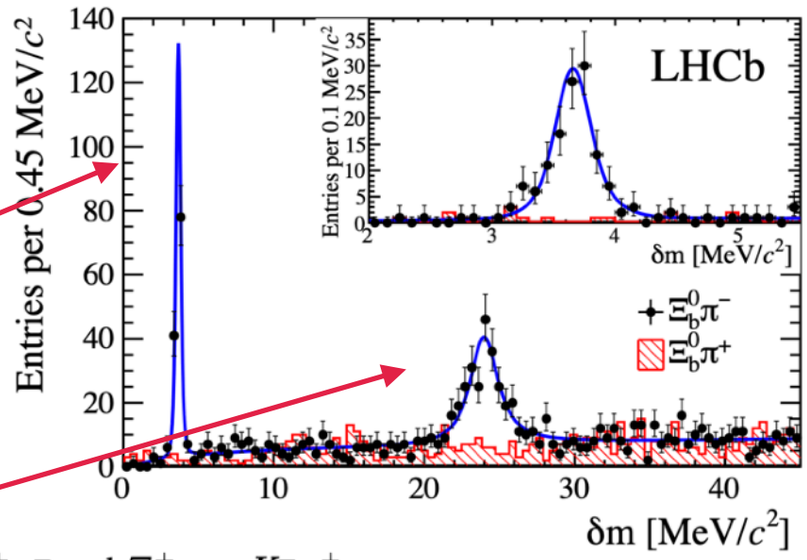
$\Xi_b'(5935)^-$

$\Xi_b(5955)^-$

2015

PRL 114 062004

Observed in $\Xi_b^0\pi^-$ channel with $\Xi_b^0 \to \Xi_c^+\pi^-$ and $\Xi_c^+ \to pK^-\pi^+$



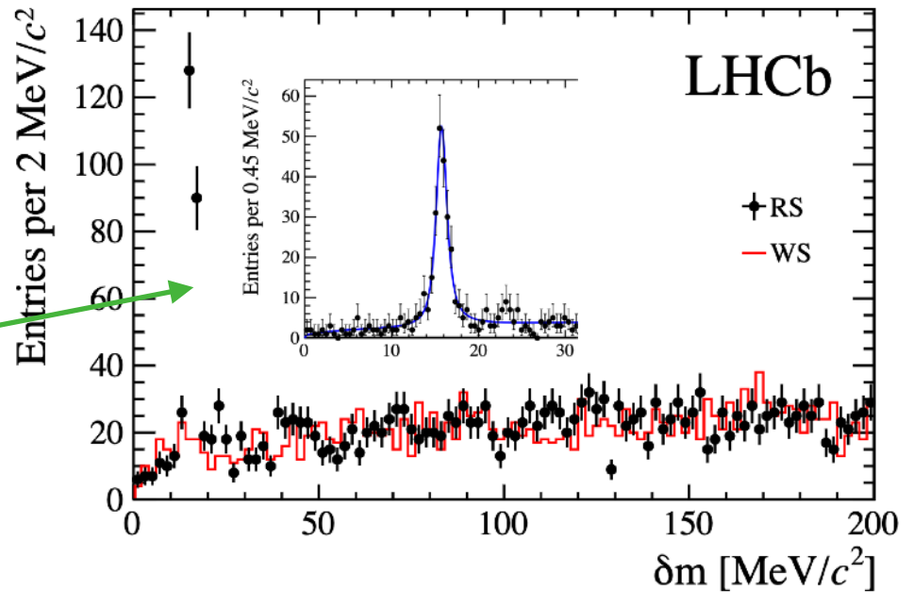
?

$\Xi_b(5945)^0$

2016

2016AE JHEP 1605 161

2012S PRL 108 252002



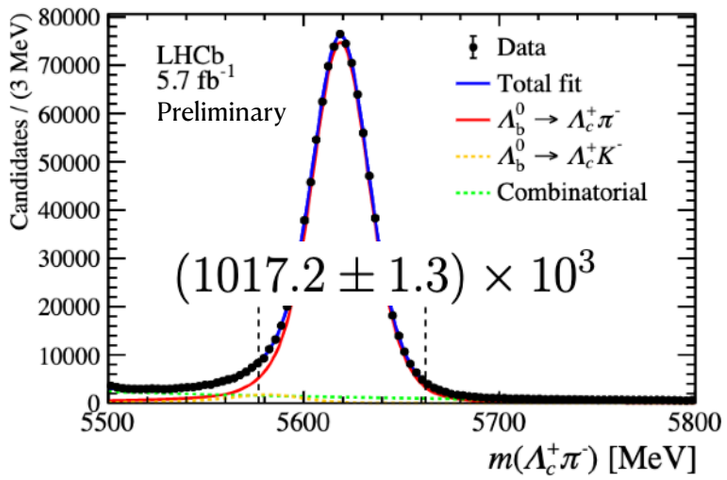
Ξ_b'^{o} is probably below $\Xi_b\pi$ threshold and decay either $\Xi_b{}^o\pi^o$ or $\Xi_b{}^o\gamma$

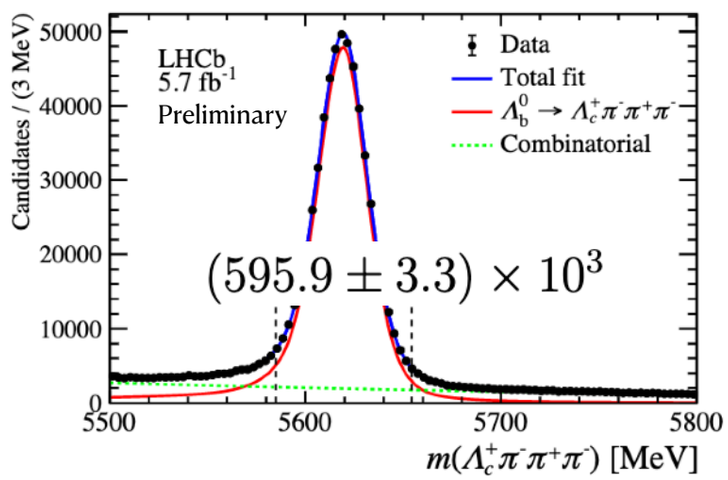
Observation of two new excited Ξ_b^0 states decaying to $\Lambda_b^0 K^- \pi^+$

Paper in Preparation
LHCb-PAPER-2021-025

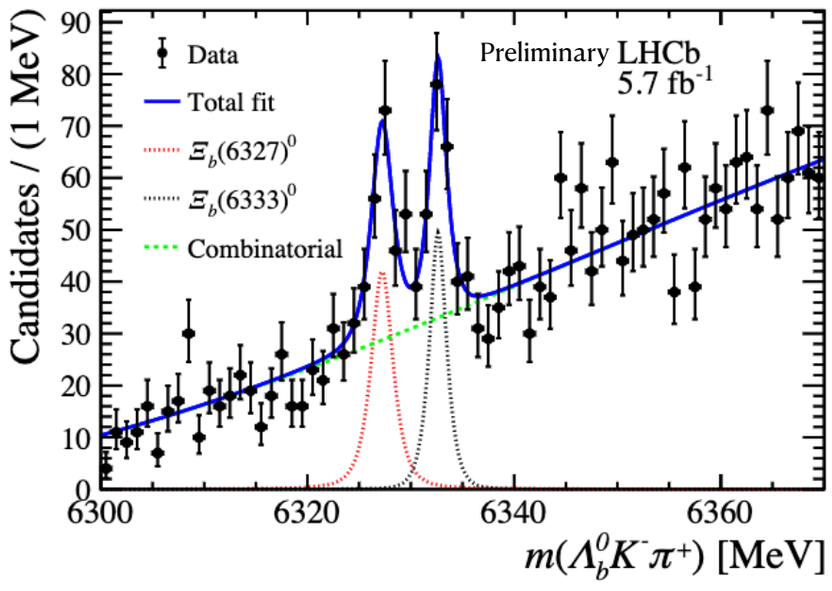
- Example of a resent search (arXiv this August)
- Use the very abundant samples of Λ_b saved on disk
- Use both:
  - $\Lambda_b \to \Lambda_c \pi$
  - $\Lambda_b \to \Lambda_c \pi \pi^+ \pi$

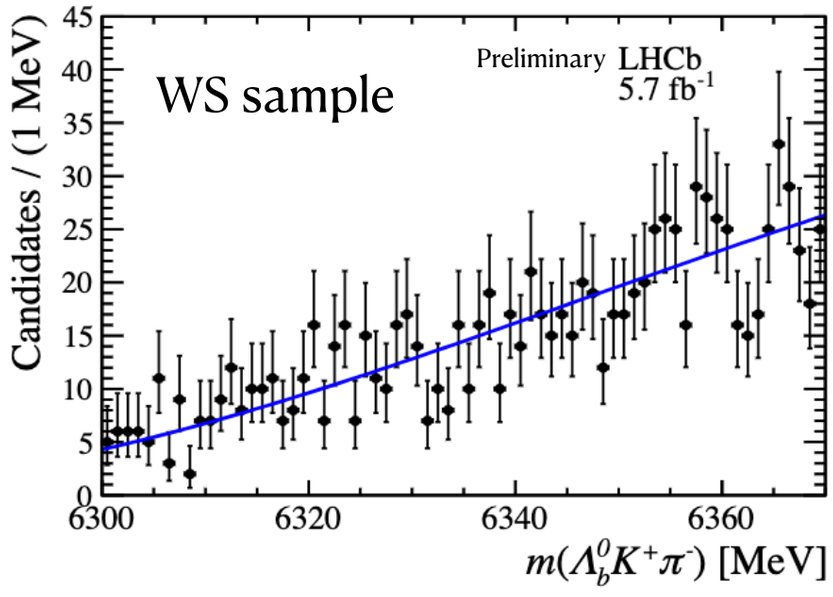
$\Lambda_b^0 K^- \pi^+$





- Two narrow peaks in the Λ_b K- π+ mass spectrum are observed

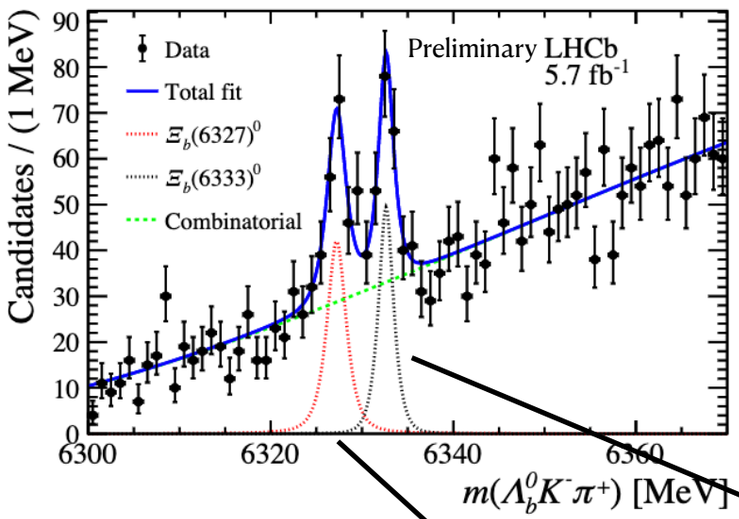


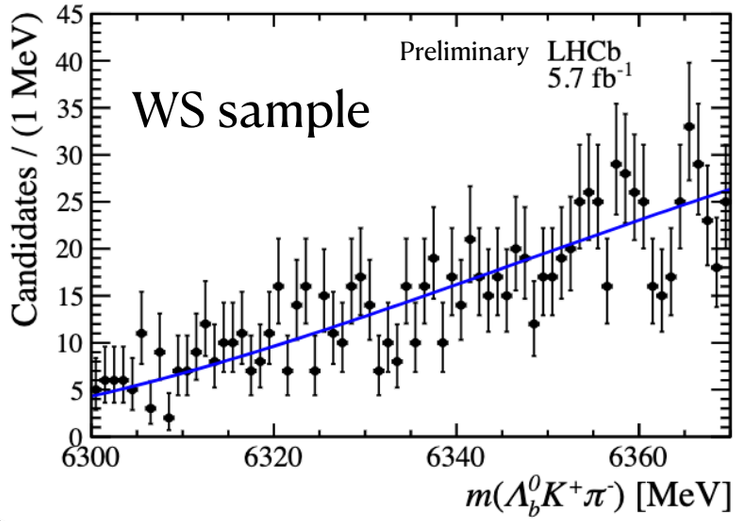


Observation of two new excited Ξ_b^0 states decaying to $\Lambda_b^0 K^- \pi^+$

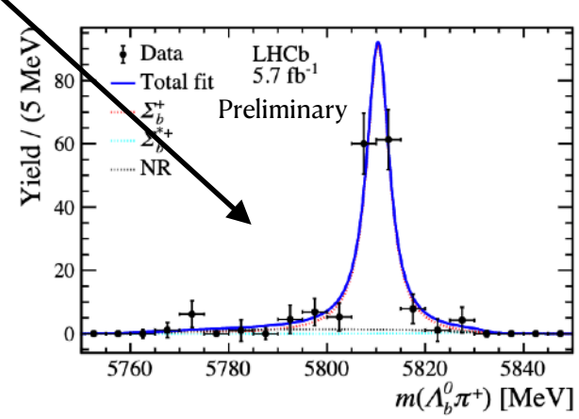
- The states are consistent with the theoretical predictions to the 1D excited Ξ_b^0 doublets

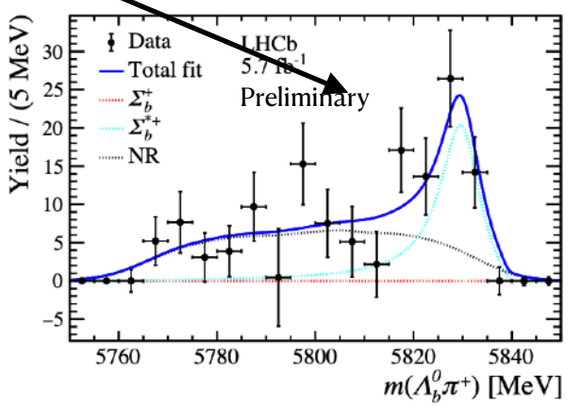
Paper in Preparation
LHCb-PAPER-2021-025





Confirmed decay patterns of the two peaks via intermediate resonances





$$m_{\Xi_b(6327)^0} = 6327.28^{+0.23}_{-0.21} \pm 0.08 \pm 0.24\,\text{MeV},$$
$$m_{\Xi_b(6333)^0} = 6332.69^{+0.17}_{-0.18} \pm 0.03 \pm 0.22\,\text{MeV},$$
$$\Gamma_{\Xi_b(6327)^0} < 2.20\ (2.56)\,\text{MeV at 90\% (95\%) CL},$$
$$\Gamma_{\Xi_b(6333)^0} < 1.55\ (1.85)\,\text{MeV at 90\% (95\%) CL},$$

Ωb are rare objects

- **Ωb and where to find them...**
- Ωb state appear in the PDG, but yields are still very low
- New decay modes observed, they help measuring mass and lifetime
- LHCb has roughly 100 - 200 signal events per mode in the full Run1+Run2 dataset

Ω_b^- MASS	6046.1 ± 1.7 MeV
$m_{\Omega_b^-} - m_{\Lambda_b^0}$	426.4 ± 2.2 MeV
$m_{\Omega_b^-} - m_{\Xi_b^-}$	247.3 ± 3.2 MeV
Ω_b MEAN LIFE	$(1.64^{+0.18}_{-0.17}) \times 10^{-12}$ s
$\tau(\Omega_b^-)/\tau(\Xi_b^-)$ mean life ratio	1.11 ± 0.16

	Mode	
Γ_1	$J/\psi\Omega^- \times \mathrm{B}(b \to \Omega_b)$	← Golden dimuon mode
Γ_2	$pK^-K^- \times \mathrm{B}(\bar{b} \to \Omega_b)$	
Γ_3	$p\pi^-\pi^- \times \mathrm{B}(\bar{b} \to \Omega_b)$	
Γ_4	$pK^-\pi^- \times \mathrm{B}(\bar{b} \to \Omega_b)$	
Γ_5	$\Omega_c^0\pi^-$	← Golden hadronic mode

- Ω_b^-
- $\Omega_b(6316)^-$
- $\Omega_b(6330)^-$
- $\Omega_b(6340)^-$
- $\Omega_b(6350)^-$

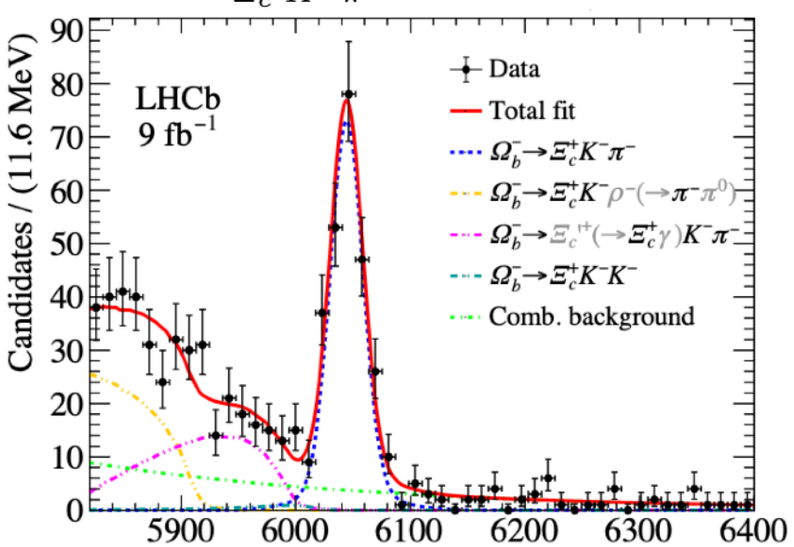
Example: $\Omega_b^- \to \Xi_c^+ K^- \pi^-$ decays

- New mode considered → first observation
- Four excited Ωc baryons are observed in the $\Xi_c^+ K^-$ mass projection
- Their relative production rates, masses and natural widths are measured + Precise mass measurement

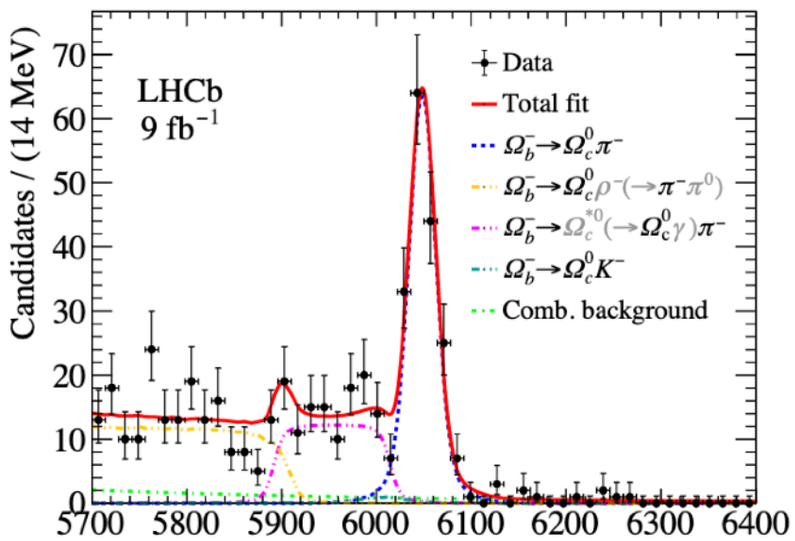
arXiv:2107.03419

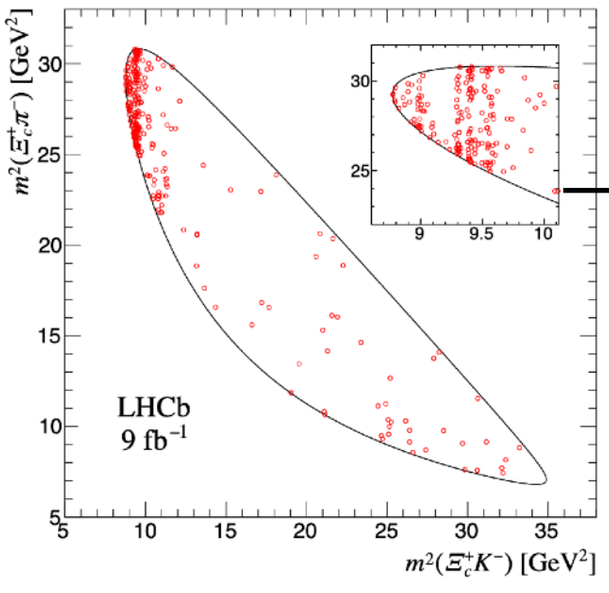
More than the actual control mode!

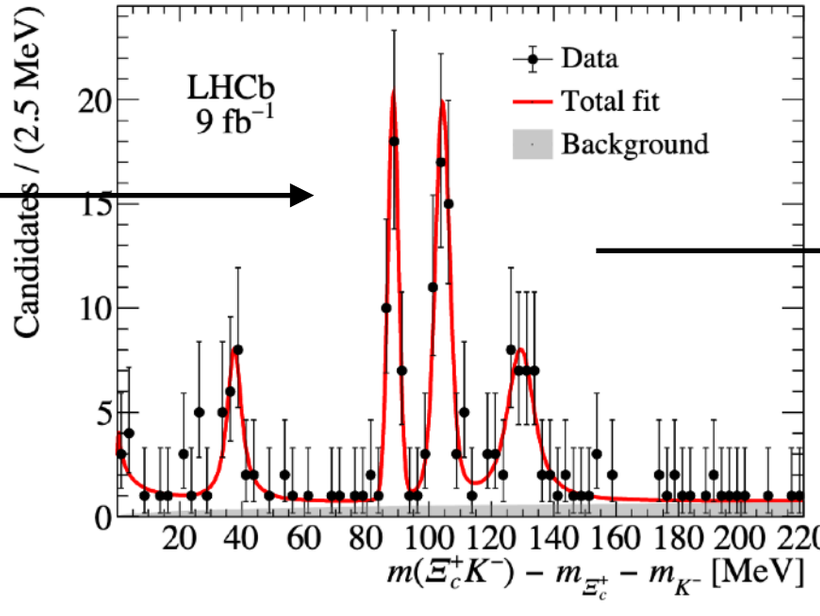
$N_{\Xi_c^+ K^- \pi^-} = 240 \pm 17$



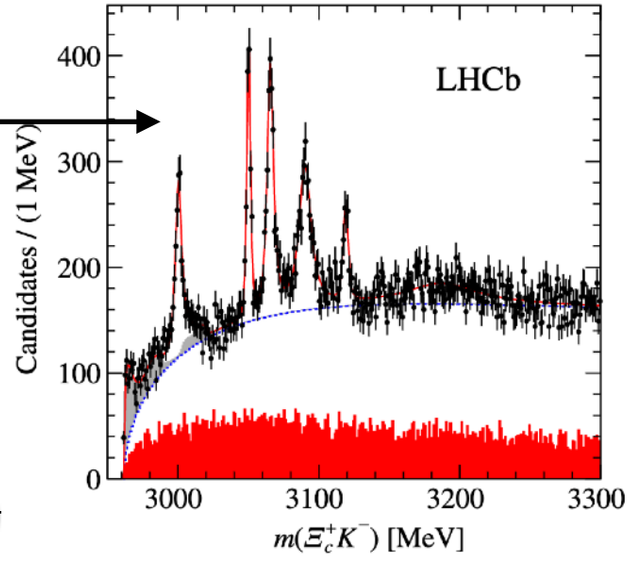
$N_{\Omega_c^0 \pi^-} = 174 \pm 14$







Comparison wrt the inclusive observation
Phys. Rev. Lett. 118, 182001 (2017)



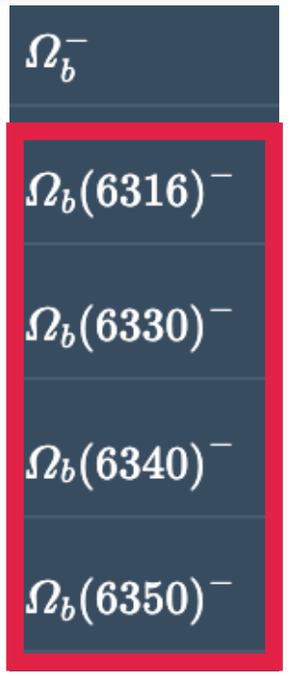
Ωb excited states

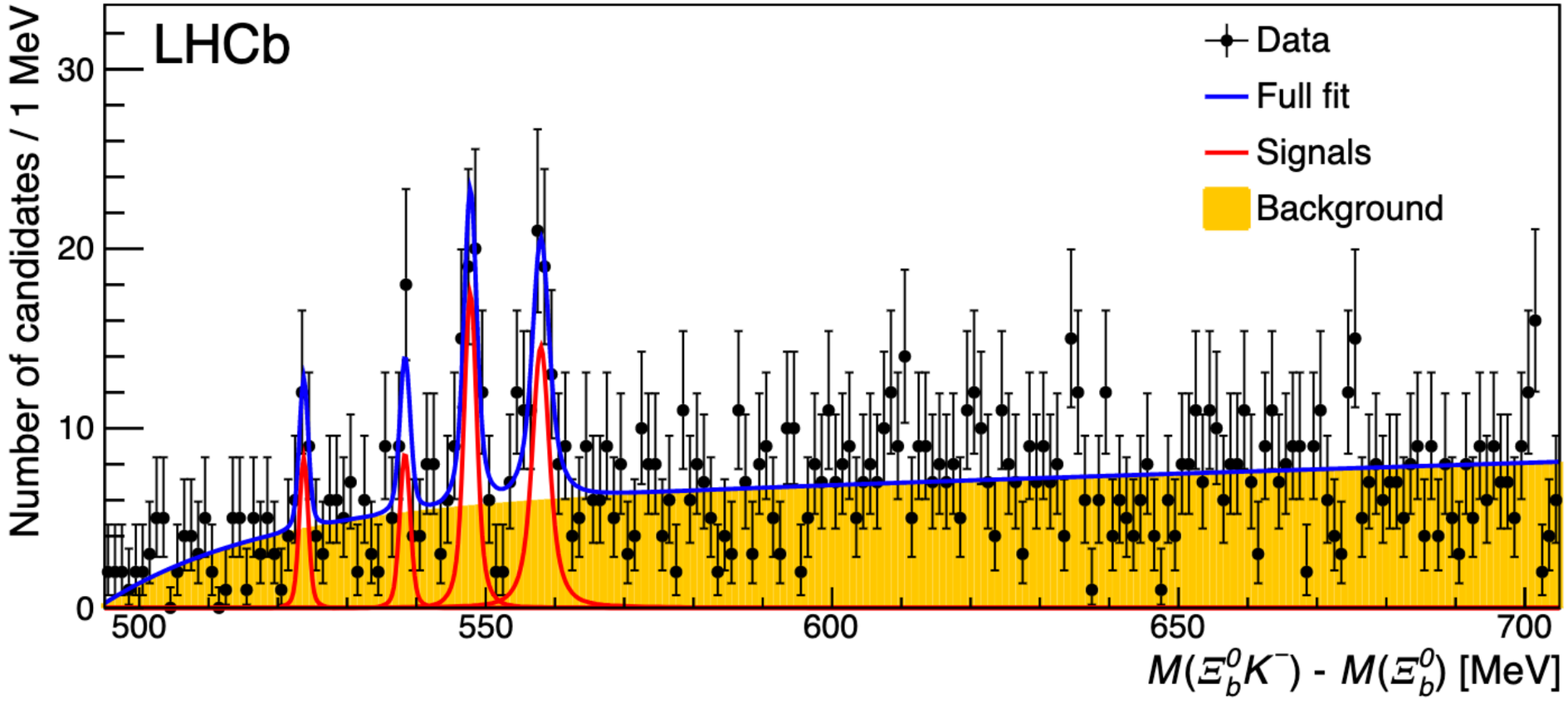
- Replicate what done in the charm sector
- Same ideas but yields are expected much lower

We report four narrow peaks in the $\Xi_b^0 K^-$ mass spectrum obtained using pp collisions at center-of-mass energies of 7, 8 and 13 TeV, corresponding to a total integrated luminosity of $9\,\text{fb}^{-1}$ recorded by the LHCb experiment. Referring to these states by their mass, the mass values are

$$
\begin{aligned}
m(\Omega_b(6316)^-) &= 6315.64 \pm 0.31 \pm 0.07 \pm 0.50\,\text{MeV},\\
m(\Omega_b(6330)^-) &= 6330.30 \pm 0.28 \pm 0.07 \pm 0.50\,\text{MeV},\\
m(\Omega_b(6340)^-) &= 6339.71 \pm 0.26 \pm 0.05 \pm 0.50\,\text{MeV},\\
m(\Omega_b(6350)^-) &= 6349.88 \pm 0.35 \pm 0.05 \pm 0.50\,\text{MeV},
\end{aligned}
$$

PRL 124 082002





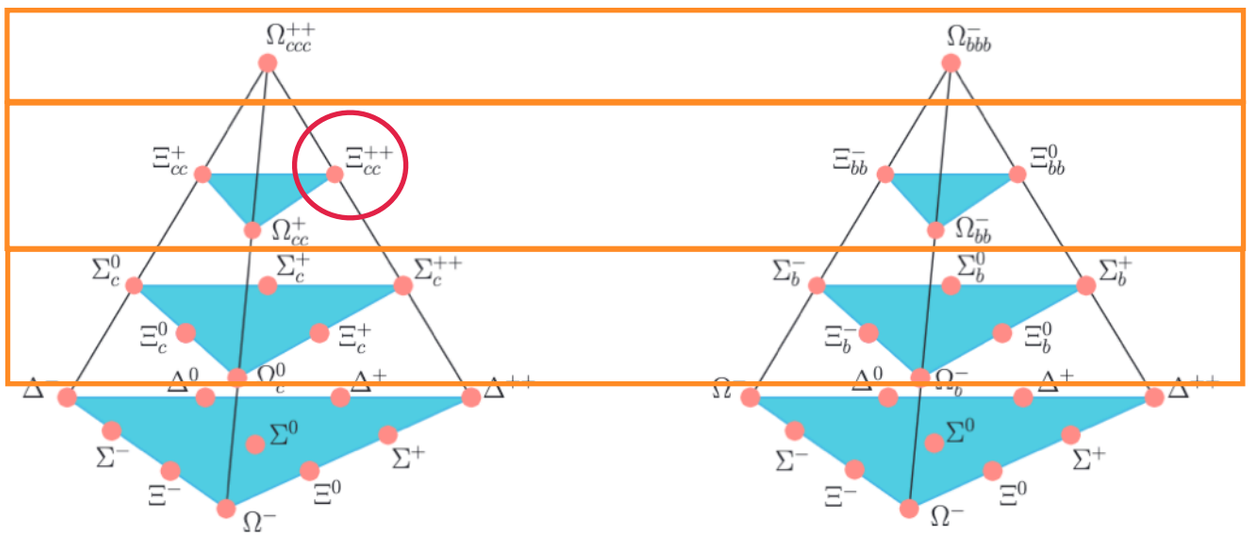
“Multiple” Heavy States

- Searches ongoing, cross sections are at the limit of what we can do
- Double-bottom and Triple-charm (at the moment) are more just like a dream

Triple

Double

Single



+ the equivalent with bottom+charm

Baryon	Quark Content	S_h^π	J^P	Baryon	Quark Content	S_h^π	J^P
Ξ_{cc}	$\{cc\}q$	1^+	$1/2^+$	Ξ_{bb}	$\{bb\}q$	1^+	$1/2^+$
Ξ_{cc}^*	$\{cc\}q$	1^+	$3/2^+$	Ξ_{bb}^*	$\{bb\}q$	1^+	$3/2^+$
Ω_{cc}	$\{cc\}s$	1^+	$1/2^+$	Ω_{bb}	$\{bb\}s$	1^+	$1/2^+$
Ω_{cc}^*	$\{cc\}s$	1^+	$3/2^+$	Ω_{bb}^*	$\{bb\}s$	1^+	$3/2^+$
Ξ_{bc}'	$\{bc\}q$	0^+	$1/2^+$	Ω_{bc}'	$\{bc\}s$	0^+	$1/2^+$
Ξ_{bc}	$\{bc\}q$	1^+	$1/2^+$	Ω_{bc}	$\{bc\}s$	1^+	$1/2^+$
Ξ_{bc}^*	$\{bc\}q$	1^+	$3/2^+$	Ω_{bc}^*	$\{bc\}s$	1^+	$3/2^+$

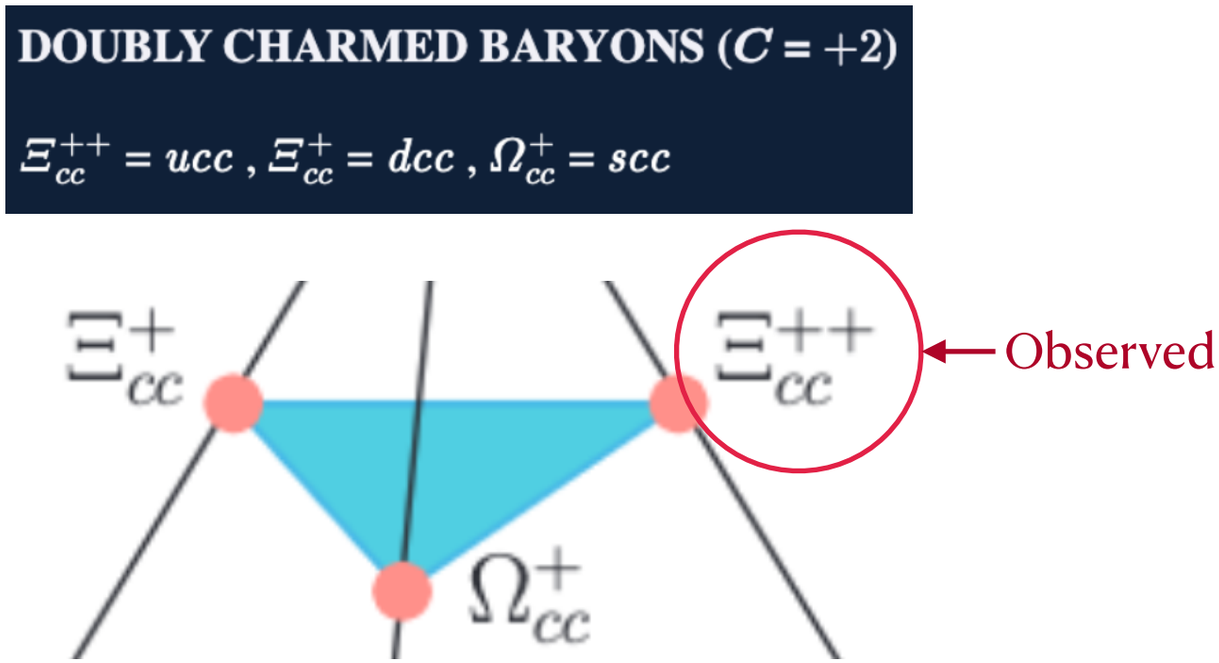
- Interesting ideas are appearing
- It’s important to keep in mind what can be done experimentally when providing expected rates/decay widths

- Also, there are appearing prediction of triple-heavy states
- Most of them clearly too optimistic from the experimental point of view
- E.g. Example using a triple-charm state in a cascade type of decay

$$\Omega_{ccc}^{++} \to \Omega_{ccs}^{+} + \pi^+ \to \Omega_{css}^{0} + 2\pi^+ \to \Omega_{sss}^{-} + 3\pi^+ .$$

$$\Omega_{ccc} \to (\Xi_{cc}^{++}\overline{K}^0, \Xi_{cc}^{++}K^-\pi^+, \Omega_{cc}^{+}\pi^+, \Xi_c^+D^+, \Xi_c'D^+, \Lambda_cD^+\overline{K}^0, \Xi_c^+D^0\pi^+, \Xi_c^0D^+\pi^+)$$

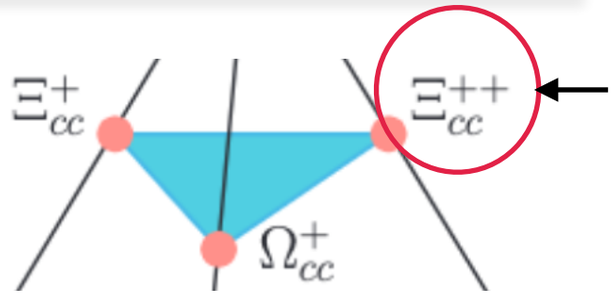
Double Charmed



- 3 baryons to be observed (ground states), **so far only one experimentally**
- All analyses of this type are performed blind in LHCb
- If no signal is found, UL are put on the interesting mass region on production

Double Charmed

- Ξ_{cc}^{++}
  - Well established in 2 different modes (as required by PDG)
  - Lifetime measured as well



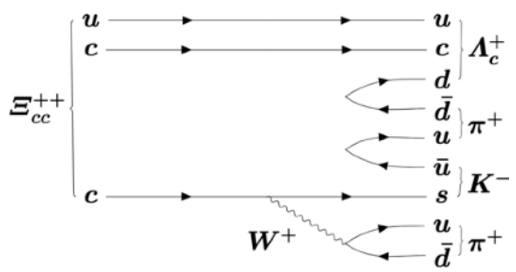
3621.6 ± 0.4 MeV

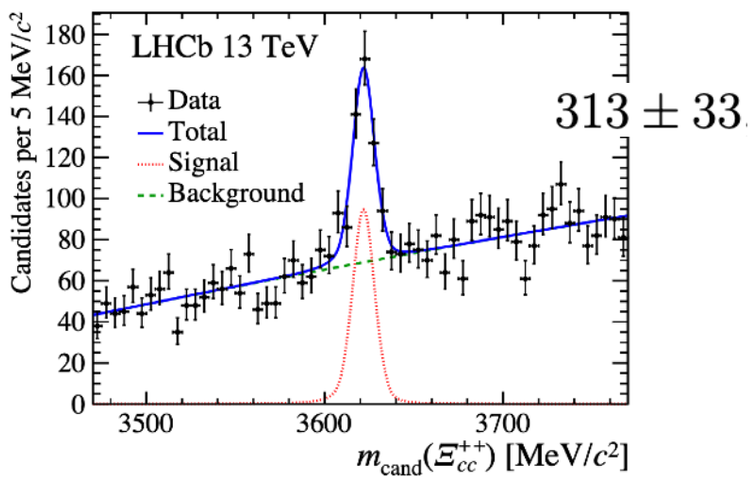
$(2.56 \pm 0.27) \times 10^{-13}$ s

	Mode
Γ_1	$\Lambda_c^+ K^- \pi^+ \pi^+$
Γ_2	$\Xi_c^+ \pi^+$, $\Xi_c^+ \to p K^- \pi^+$
Γ_3	$D^+ p K^- \pi^+$

Phys. Rev. Lett. 119, 112001 **(2017)**

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

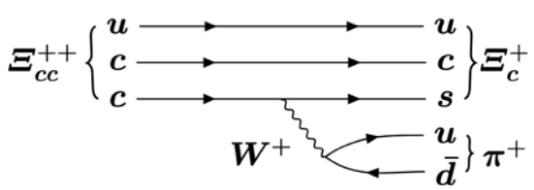


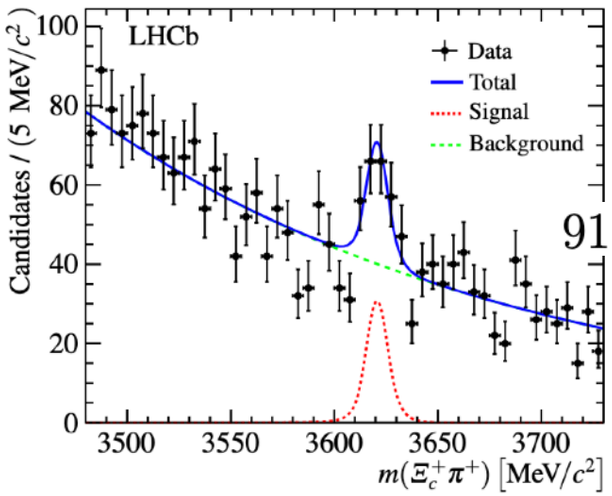


313 ± 33

Phys. Rev. Lett. 121, 162002 (2018)

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





91 ± 20

JHEP10(2019)124

$\Xi_{cc}^{++} \to D^+ p K^- \pi^+$ decays

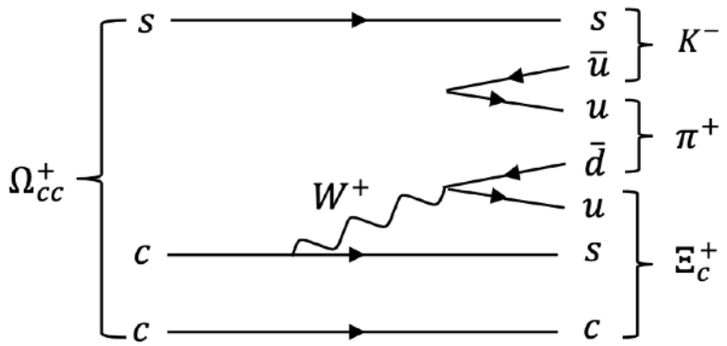
No significant signal is observed
Upper limit set

Double Heavy rearches

Search for the doubly charmed baryon Ω_{cc}^+

arXiv:2105.06841

$\Omega_{cc}^+ \to \Xi_c^+ K^- \pi^+$



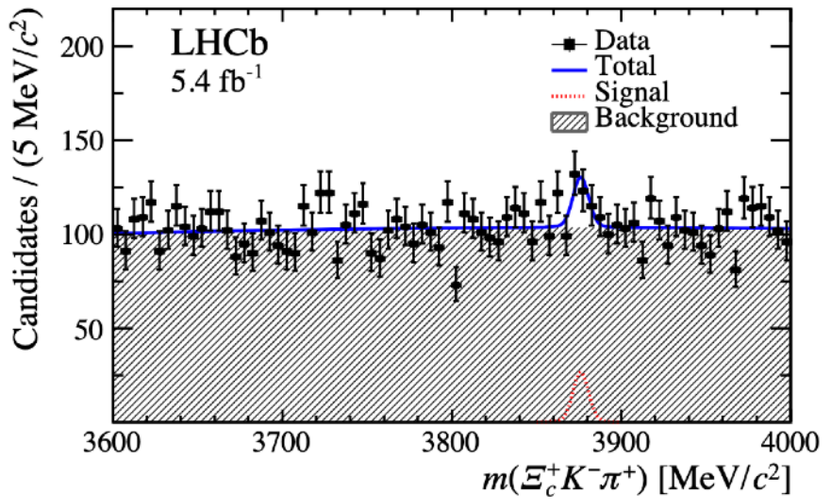
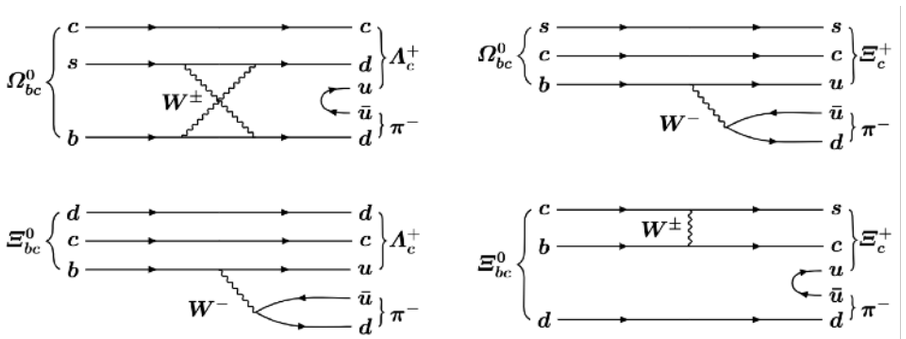
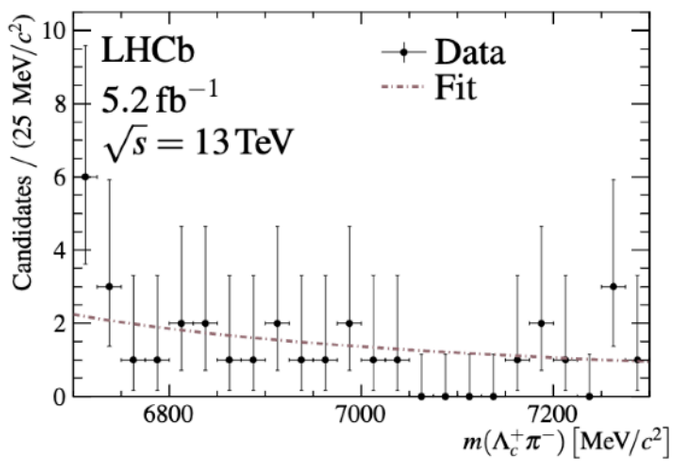


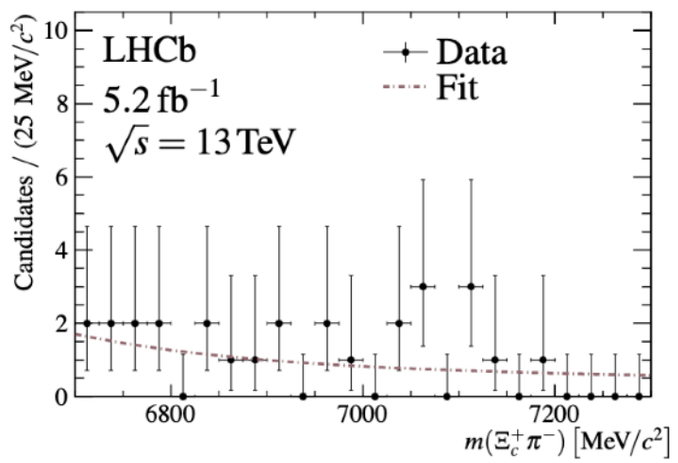
Figure 2: Invariant mass $m(\Xi_c^+ K^- \pi^+)$ distribution of selected Ω_{cc}^+ candidates from (black points) selection A, with (blue solid line) the fit with the largest local significance at the mass of 3876 MeV/c^2 superimposed.

Search for the doubly heavy baryons Ω_{bc}^0 and Ξ_{bc}^0 decaying to $\Lambda_c^+ \pi^-$ and $\Xi_c^+ \pi^-$

arXiv:2104.04759

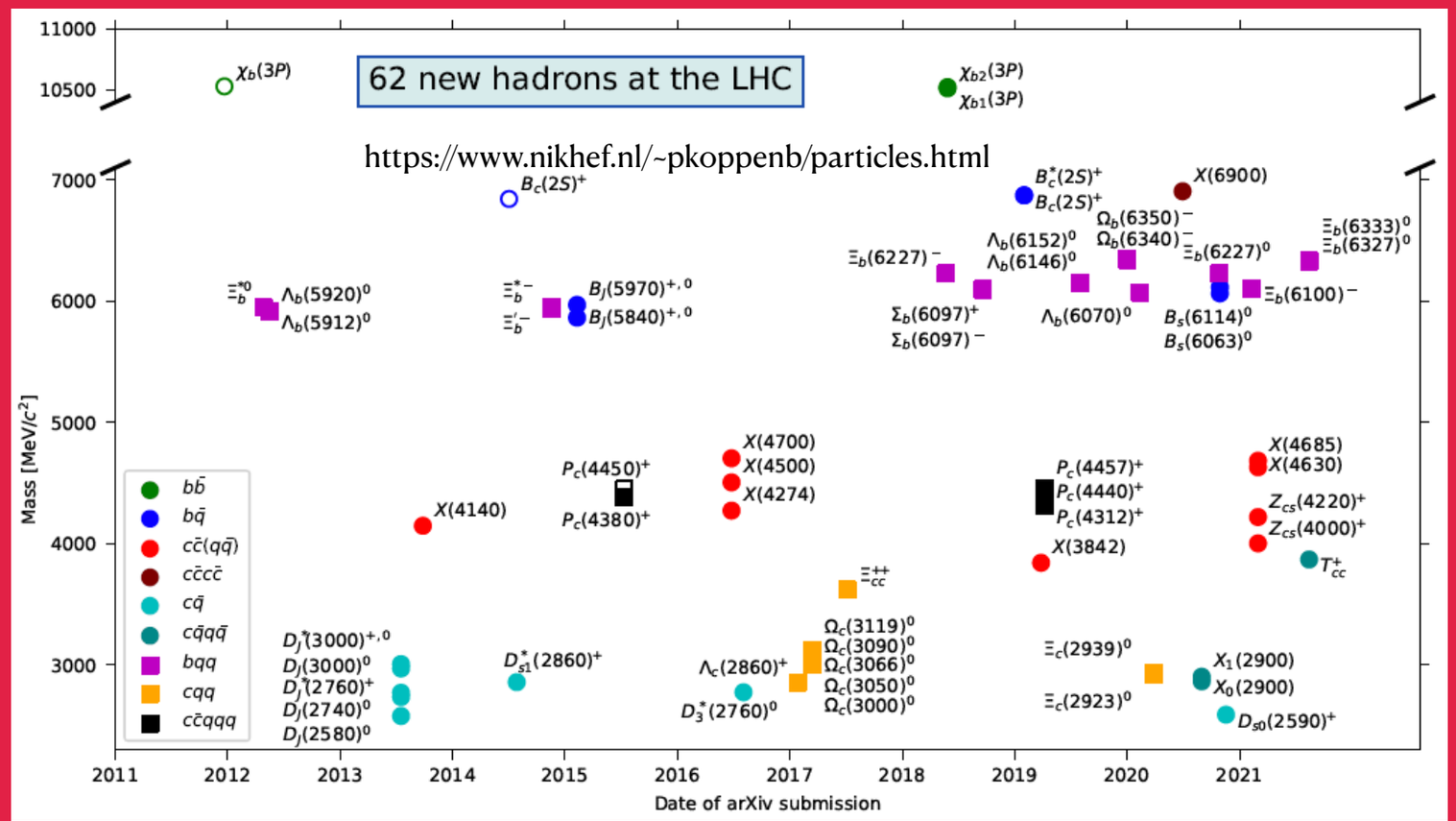






Conclusions

This summer → 3 more hadrons have been added to the list
Growing extremely fast!



- Research is speeding up with new results coming at a fast pace
- Meanwhile, upgrade is speeding up to be ready for next year's data taking!

- **We need to be sure to include all modes in our upgraded trigger**
- **Due to computing resources available → all selections should be almost offline like**

Please stay tuned!