b-Baryons @ CMS

Beautiful and Charming

Baryon Workshop

9-11 Sept. @ IPPP Durham

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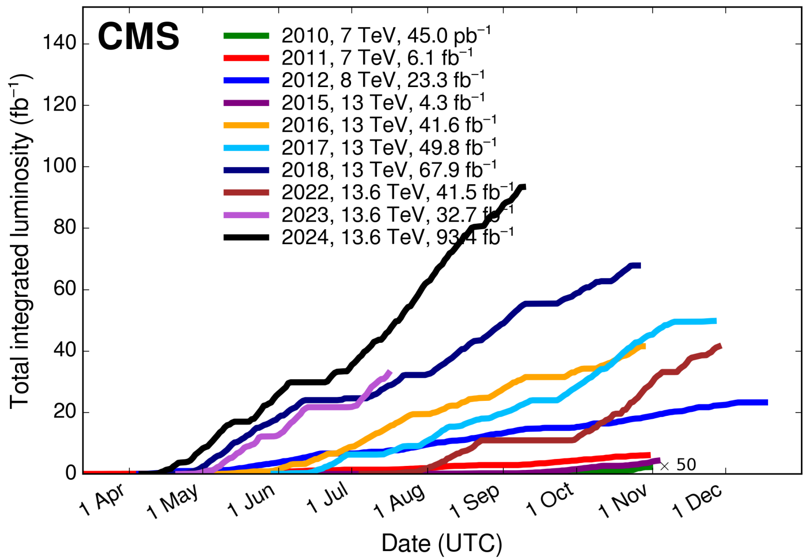
Introduction

- **CMS is providing significant contributions to beauty and quarkonium sectors**, mainly using final states containing muon pairs (trigger constraints).
  - This is possible thanks to :
    - **an excellent tracking and muon identification performances**, combined to
    - **a flexible trigger system** essential to collect data @ increasing luminosity (& pile-up)
    - the possibility to delay the prompt reconstruction (data parking)
    - the large production cross-sections for heavy flavoured particles in *pp* collisions
      [LHC is a "factory" producing quarkonia and beauty hadrons (among them b-baryons)]

- **Selected CMS relevant results are able to integrate and/or complement the LHCb results !**

- Pointers to all CMS Heavy Flavour results can be found here:
  https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsBPH



Outline: CMS results for Beauty Baryons to be discussed today

- Study of the excited Λ_b^0 baryons in the $\Lambda_b^0\,\pi^+\pi^-$ spectrum in pp collisions @ 13 TeV [PLB 803 (2020) 135345]

- Observation of the $\Lambda_b^0 \rightarrow J/\psi\,\Lambda\,\phi$ decay in pp collisions @ 13 TeV [PLB 802 (2020) 135203]

  1st observation

- Observation of the $\Lambda_b^0 \rightarrow J/\psi\,\Xi^- K^+$ decay [arXiv:2401.16303, accepted by EPJC]

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- Observation of the transition $\Xi_b^- \to \psi(2S)\Xi^-$ and studies of the excited baryon Ξ_b^{*0} in pp collisions @ 13 TeV [PRD 110 (2024) 012002]

  1st observation

  - This excited baryon was already discovered by CMS @ 7 TeV: Observation of a New Ξ_b Baryon [PRL 108 (2012) 252002]

- Observation of a new excited beauty strange baryon decaying to $\Xi_b^-\,\pi^+\pi^-$ [PRL 126 (2021) 252003]

- All results are based on the LHC Run-II dataset collected by CMS in the years 2016-2018 (pp collisions @ $\sqrt{s} = 13TeV$; $\mathcal{L}_{int} \approx 135 - 140fb^{-1}$). The 2nd is based only on 2018 data ($60fb^{-1}$).

Other/older CMS results for Beauty Baryons not discussed here (Run-1 based)

- Measurement of the Λ_b^0 lifetime in pp collisions @7 TeV [JHEP 07 (2013) 163 , using $\Lambda_b^0 \to J/\psi\,\Lambda$ decays]

  - The Λ_b^0 lifetime was later measured in pp collisions @8 TeV, using same decays and with higher statistics [Eur. Phys. J. C 78 (2018) 457]

    $c\tau_{\Lambda_b^0} = 442.9 \pm 8.2\,(\text{stat}) \pm 2.8\,(\text{syst})\,\mu\text{m}$ well compatible with world average: $440.7 \pm 3.0\,\mu\text{m}$

- Measurement of the Λ_b^0 polarization and angular parameters in $\Lambda_b^0 \to J/\psi\,\Lambda$ decays from pp collisions @ 7 & 8 TeV [PRD 97 (2018) 072010]

  $P = 0.00 \pm 0.06(\text{stat}) \pm 0.06(\text{syst})$ consistent with LHCb measurement (and theoretical predictions)

- Measurement of the Λ_b^0 cross section and the $\overline{\Lambda}_b^0$ to Λ_b^0 cross sections ratio with $J/\psi\,\Lambda$ decays in pp collisions @7 TeV [PLB 714 (2012) 136-157]

- Study of the $B^+ \to J/\psi\,\bar{\Lambda}p$ decay in pp collisions @ 8 TeV [JHEP 12 (2019) 100]

Reconstruction challenges in CMS for Baryons Physics - I

- The major CMS contribution - so far - is in the field of baryon spectroscopy, in particular the observation of excited states and of new transitions.

  - For Λ_b^0 reconstruction, we cannot use the most copious $\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-$ - as LHCb does - because no dedicated trigger can be built purely on hadronic tracks at an affordable rate.

    However, we can use $\Lambda_b^0 \rightarrow J/\psi\ \Lambda^0$ and $\Lambda_b^0 \rightarrow \psi(2S)\ \Lambda^0$ by exploting the dimuon triggers and the good capability to cleanly reconstruct self-flavour tagging $\Lambda^0 \rightarrow p\pi^-$.

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    - Without having a Λ^0 in the final state, the decay $\Lambda_b^0 \rightarrow J/\psi\, pK^-$ is - instead - characterized by very high backgrounds due to the lack of hadronic PID.
      This makes pentaquarks' search - in this "classic" channel - definitely complicated in CMS.

      In general, typical hadronic transitions that are suitable to trigger on, and can be reconstructed in an enough clean way, are those to a lighter $c\bar{c}$ meson through the emission of light hadrons [$\pi, \pi\pi, K_S^0, \phi, \Lambda$, ... in the final state]. Indeed, these signatures allow to fight the overwhelming backgrounds associated to a tipically huge track multiplicity in the event.

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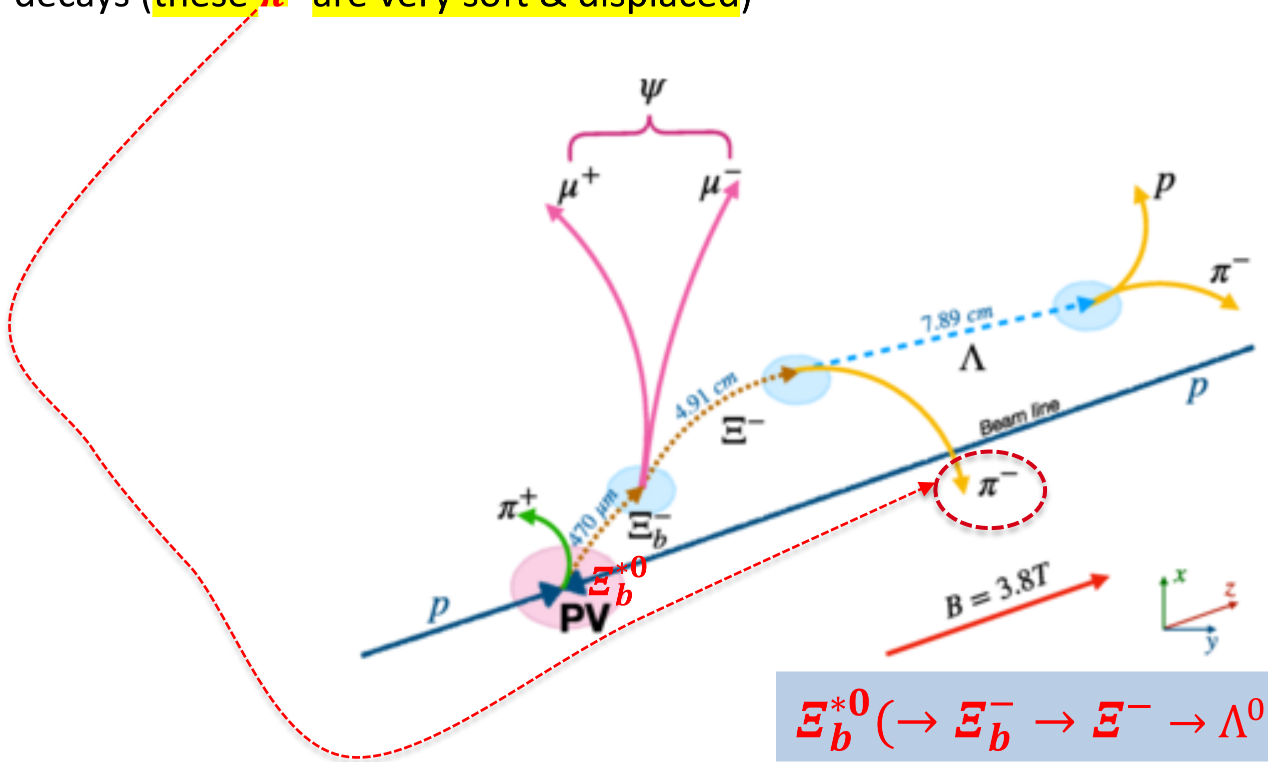
  - For Ξ baryons reconstruction, it is effectively possible to efficiently reconstruct the decay chain $\Xi_b^- \to \Xi^- \to \Lambda^0$ (see next slide).

- **CMS tracking system** has **good efficiency for low-p_T tracks**, both **prompt** and more or less **displaced** from the PV !

A good tracking performance for very displaced and soft tracks is crucial to efficiently reconstruct baryons' decay chains.

The **displaced tracks** are crucial for the reconstruction of

- the $K_S^0 \to \pi^+\pi^-$,
- the self-flavour tagging $\Lambda^0 \to p\pi^-$ decays
- the $\Xi^- \to \Lambda^0 \boldsymbol{\pi^-}$ decays (these $\boldsymbol{\pi^-}$ are very soft & displaced)



$\boldsymbol{\Xi_b^{*0}} (\to \boldsymbol{\Xi_b^-} \to \boldsymbol{\Xi^-} \to \Lambda^0)$ **decay chain**

1. Excited Λ_b^0 baryons in the $\Lambda_b^0 \pi^+ \pi^-$ spectrum

Introduction to Λ_b^0 excited states -

- **Studies of excited heavy baryon spectrum are important test of HQET.**

  There are many - not agreeing ! - predictions of excited Λ_b & Σ_b states

  (masses spread in rather wide regions, most predictions don't have uncertainties' ranges**)**

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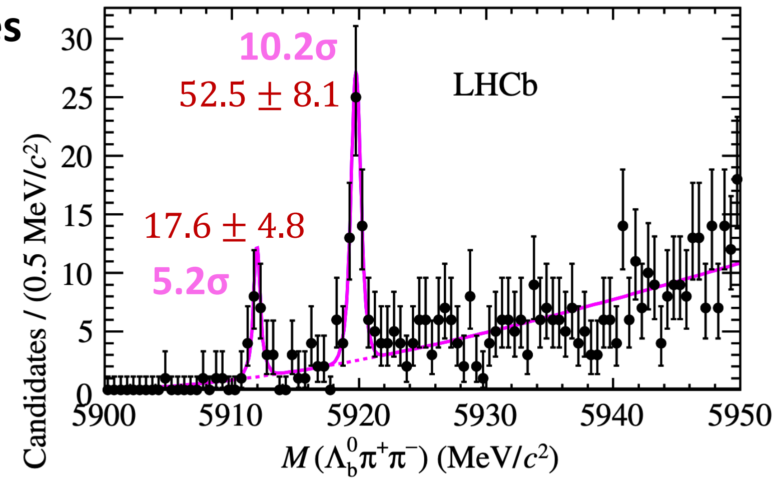
2 near-threshold excited states $\Lambda_b^{0*} \to \Lambda_b^0 \pi^+ \pi^-$

using $\Lambda_b^0 \to \Lambda_c^+ \pi^-$ decays: $\Lambda_b(5912)^0$ & $\Lambda_b(5920)^0$

Only the latter was confirmed (3.5σ) by [PRD88 (2013) 071101]



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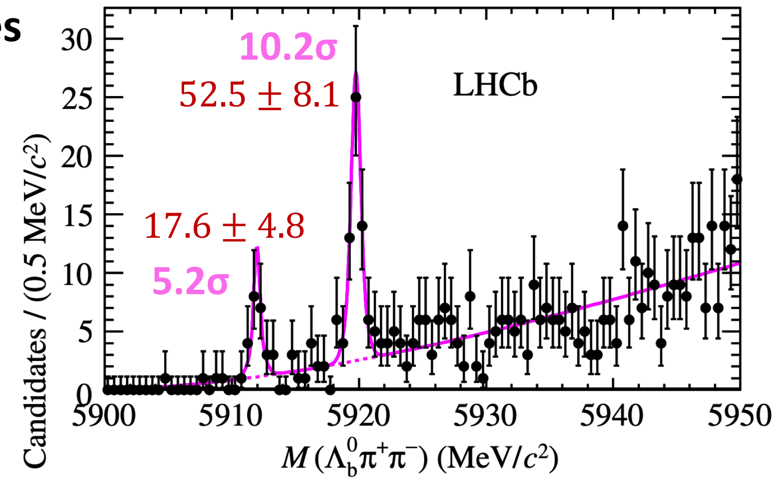

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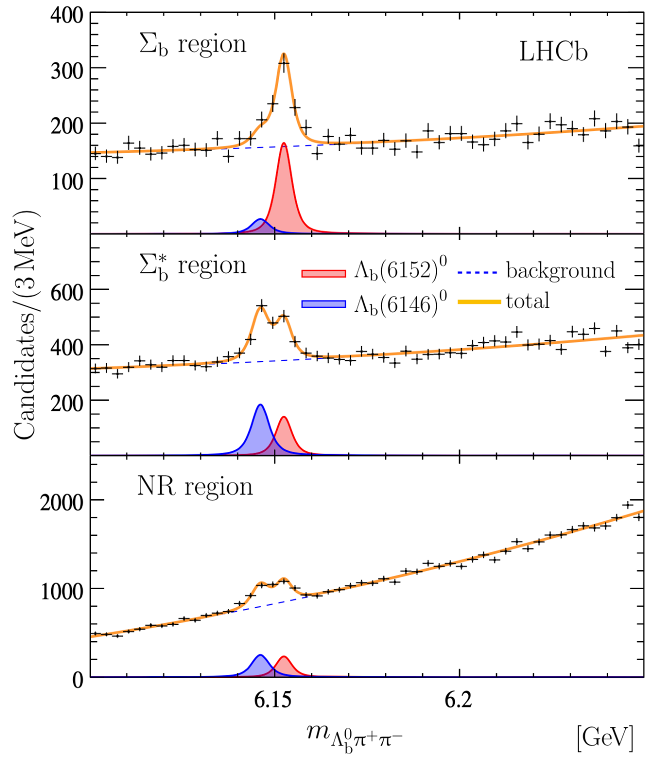
- **More recently** [PRL 123 (2019) 152001] **using full Run-I+II dataset**

  observed 2 new excited states decaying to $\Lambda_b^0\pi^+\pi^-$ **final state**

  using $\begin{cases} \Lambda_b^0 \to \Lambda_c^+\pi^- \text{ (most copious)} \\ \Lambda_b^0 \to J/\psi\, pK^- \end{cases}$ **decays:** $\Lambda_b(6146)^0$ & $\Lambda_b(6152)^0$



Λ_b^0 reconstruction & analysis strategy in CMS

- In CMS we cannot use the most copious $\Lambda_b^0 \to \Lambda_c^+ \pi^-$ because (no dedicated trigger, high bkgs due to no hadronic PID)

  Also, usage of $\Lambda_b^0 \to J/\psi\, pK^-$ is very difficult due to high backgrounds due to the lack of hadronic PID.

  - **However, we can use $\Lambda_b^0 \to J/\psi\, \Lambda$ (~85%) and $\Lambda_b^0 \to \psi(2S)\Lambda$** with $\psi(2S)$ reconstructed via both …

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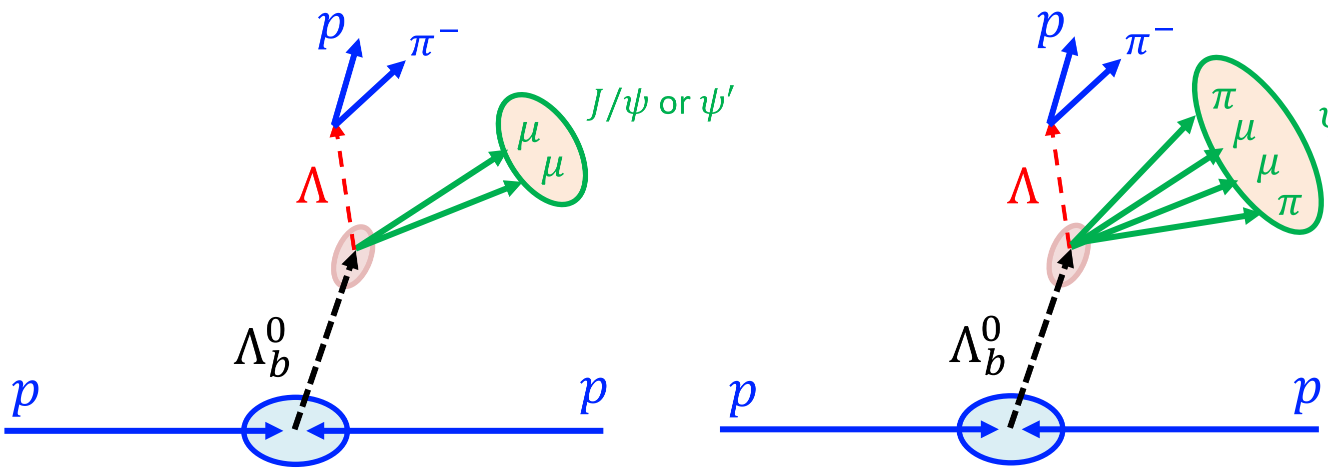

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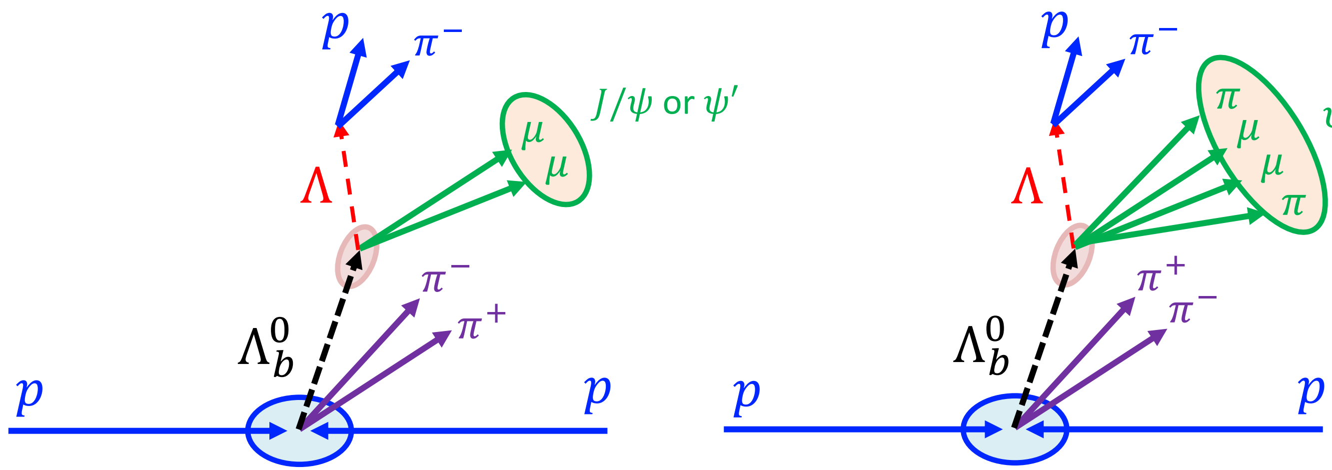

- Additional two OS **prompt** tracks are selected from the tracks forming the PV (specifically, the one with the smallest 3D *pointing angle* of the Λ_b^0 candidate).

- **Combinations with SS prompt pions are used as a control channel**

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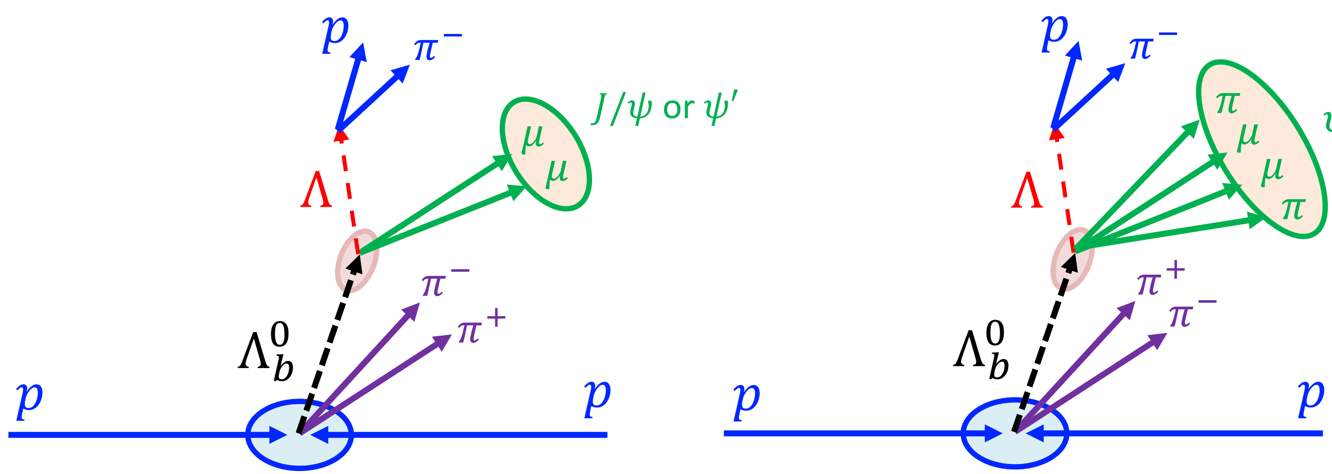

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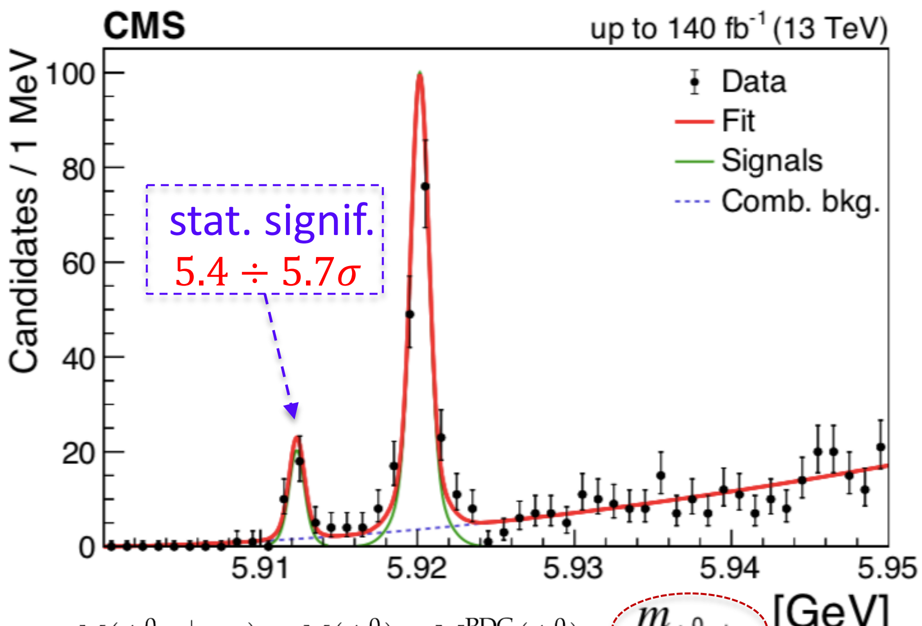
- **Combinations with SS prompt pions are used as a control channel**

- **The analysis has been optimized differently**
  - **at low masses, near threshold where BKGs are low**
  - **at high masses where BKG is large**

Excited states in low-mass region

LOW-MASS REGION (near threshold)



$m_{\Lambda_b^0\pi^+\pi^-} = M(\Lambda_b^0\pi^+\pi^-) - M(\Lambda_b^0) + M^{PDG}(\Lambda_b^0)$

2 double-G with shape fixed from MC (mass & normalization free)

Threshold function $(x - x_0)^{\alpha}$ — α: free; x_0: fixed

Confirmation of $\Lambda_b(5912)^0$

First confirmation of $\Lambda_b(5920)^0$

Mass measurements:

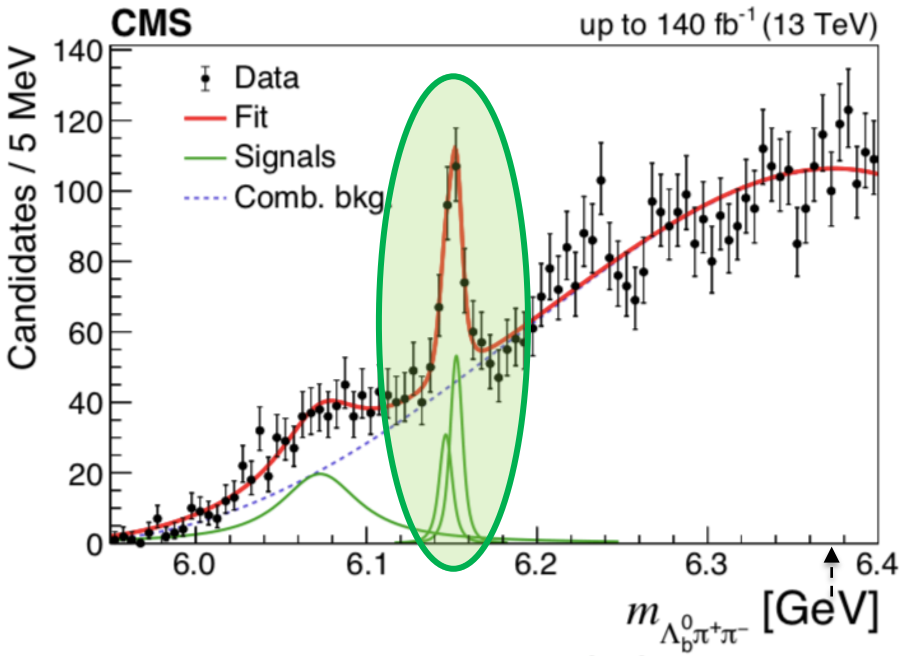
$$M(\Lambda_b(5912)^0) = [5912.32 \pm 0.12(stat) \pm 0.01(syst) \pm 0.17(m_{PDG}(\Lambda_b^0))]\text{MeV}$$

$$M(\Lambda_b(5920)^0) = [5920.16 \pm 0.07(stat) \pm 0.01(syst) \pm 0.17(m_{PDG}(\Lambda_b^0))]\text{MeV}$$

consistent with those by LHCb/PDG & with similar precision

Excited states in high-mass region

HIGH-MASS REGION



Each of the 2 SIGs for the narrow structure :

2 double-G (with mass resolution fixed from MC within gaussian constraits) → 3.8MeV

single Breit-Wigner (Γ fixed to LHCb ones within gaussian constraits)

BGK : $(x - x_0)^{\beta} \cdot poly(1)$: threshold power function x polynomial

(β: free; x_0: fixed)

First confirmation of $\Lambda_b(6146)^0$ & $\Lambda_b(6152)^0$

(discovered by LHCb : Phys. Rev. Lett. 123 (2019) 152001)

Mass measurements:

$$M(\Lambda_b(6146)^0) = [6146.5 \pm 1.9(stat) \pm 0.8(syst) \pm 0.2(m_{PDG}(\Lambda_b^0))]\text{MeV}$$

$$M(\Lambda_b(6152)^0) = [6152.7 \pm 1.1(stat) \pm 0.4(syst) \pm 0.2(m_{PDG}(\Lambda_b^0))]\text{MeV}$$

… in agreement with LHCb values but not as precise as

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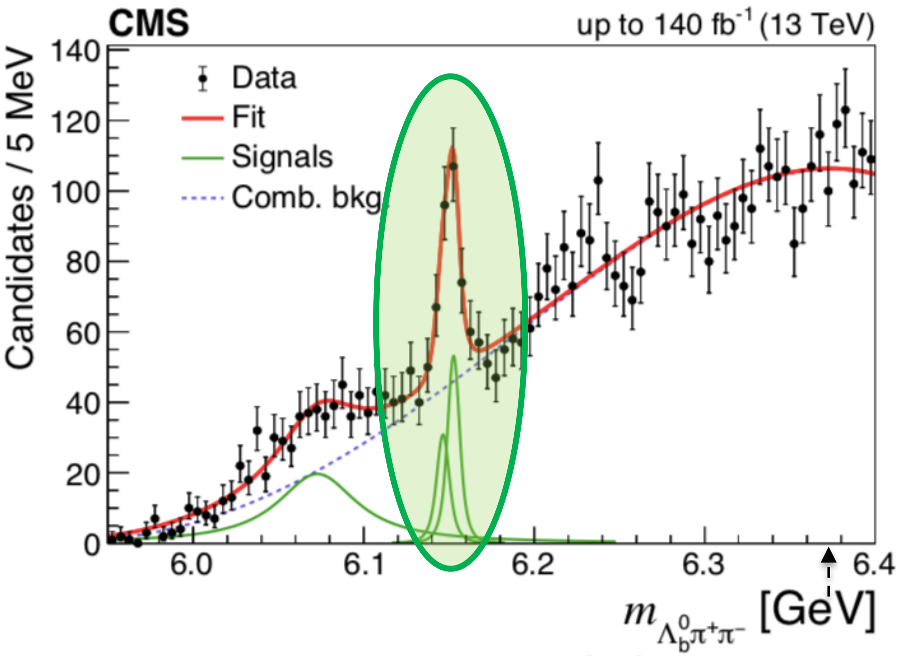

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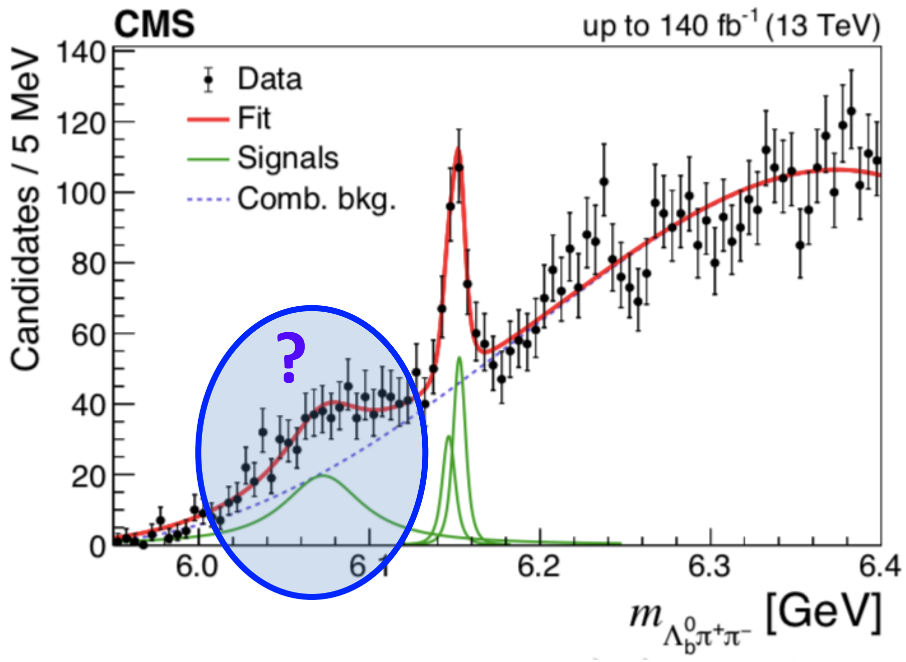
- **Data are consistent with a single peak @6150MeV :**

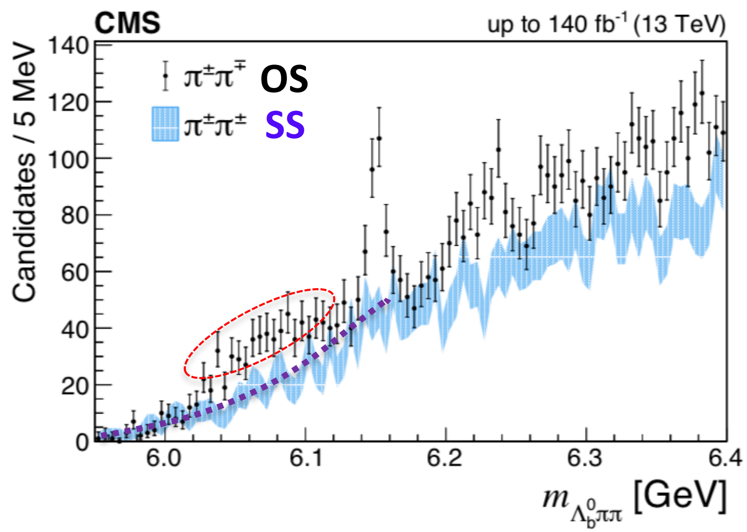
  * 1-peak hypothesis vs BKG-only has significance $> 5.4 \div 6.5\sigma$ (changing fit range & model)

  * 2-peaks vs 1-peak hypotheses (Γ free) has very low significance (0.4σ) : we are not sensitive to the splitting because of the worse mass resolution and much lower statistics w.r.t. LHCb.

Broad structure in high-mass region - I



Firstly this "bump" is **not** present in the $\Lambda_b^0\pi^+\pi^-$ mass spectrum with SS dipions :



Assuming a single broad resonance X_b the fit - with M & Γ free parameter - **provides:**

$M(X_b) = [6073 \pm 5(stat)]MeV$ $\Gamma(X_b) = [55 \pm 11(stat)]MeV$ …. **with stat. signif. ~ 4σ**

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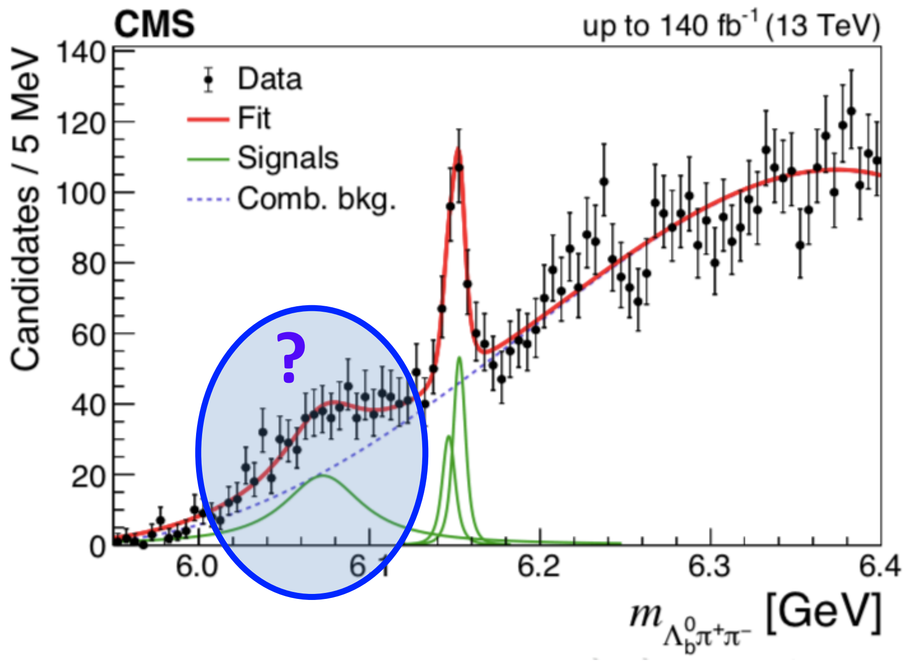

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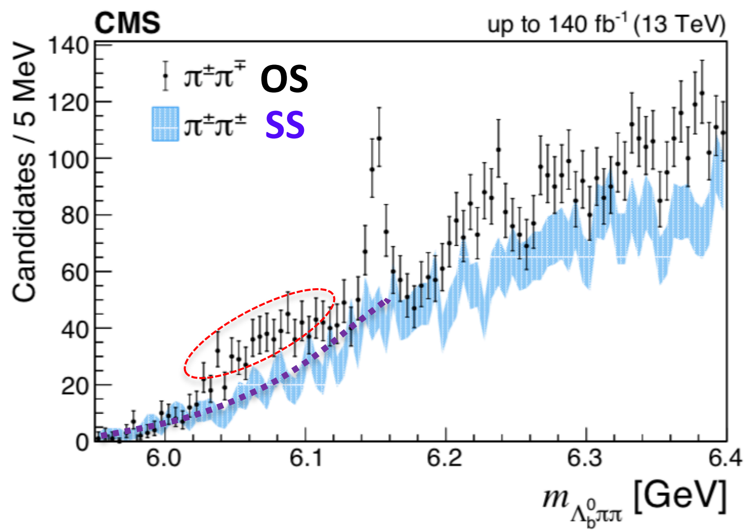

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  - **Various reflections have been thoroughly studied and excluded as the origin/nature of the bump. However, it may be created by partially reconstructed decays of higher-mass states.**
  - **The amount of data is too low to try a proper interpretation of the broad structure as it could be not necessarily a single state but - instead - a superposition or several nearby broad states.**

Broad structure in high-mass region - II

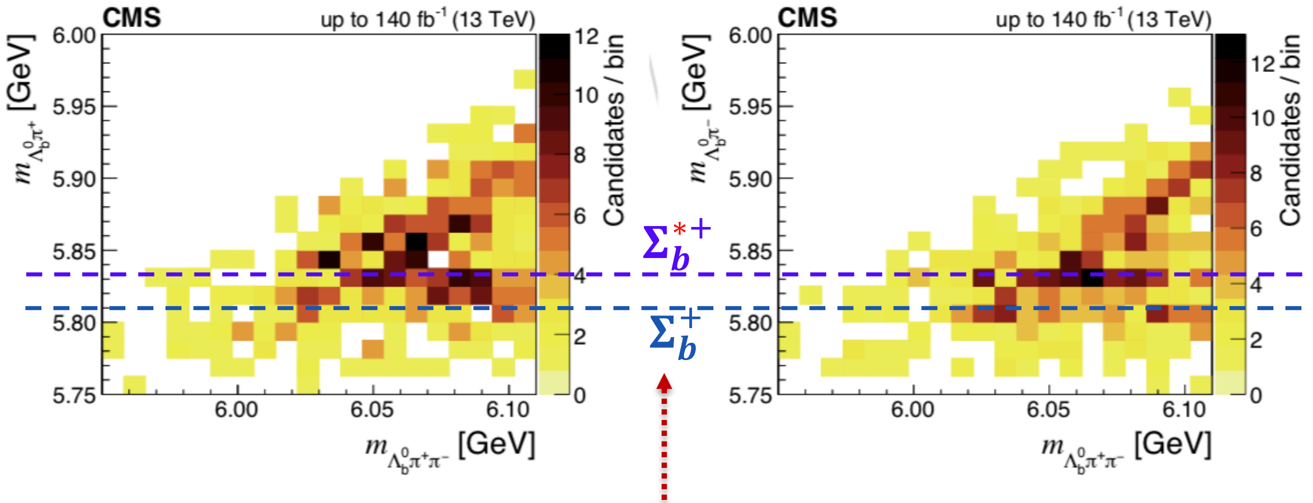
- By inspecting the scatter plots

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

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

  .... in the concerned region

  [$m(\Lambda_b^0\pi^+\pi^-) < 6.11 GeV$]



  - Horizontal bands corresponding to $\Sigma_b^{(*)\pm} \rightarrow \Lambda_b^0\pi^\pm$ can be appreciated

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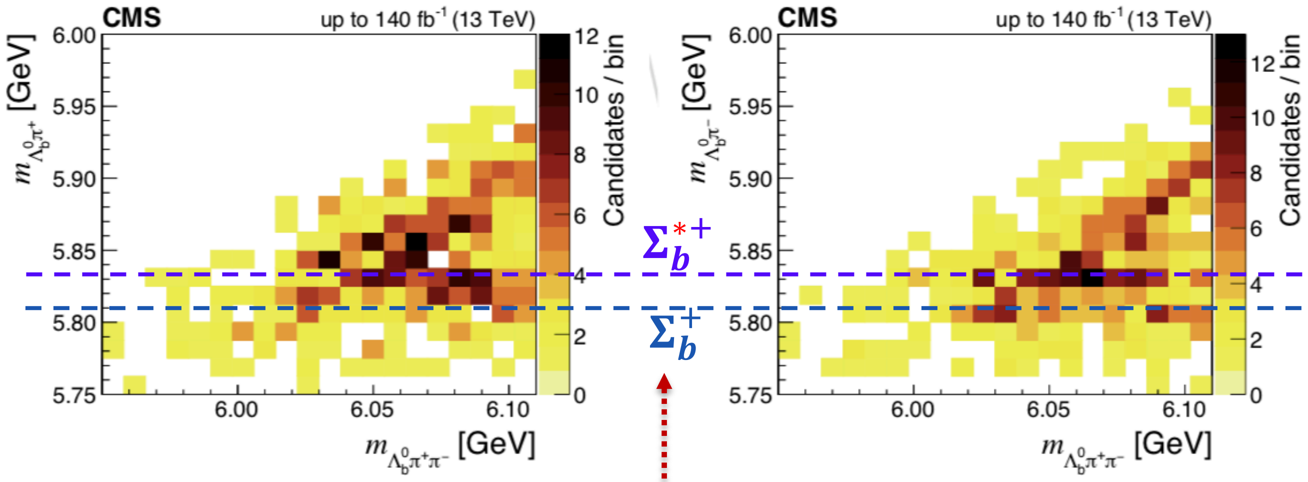

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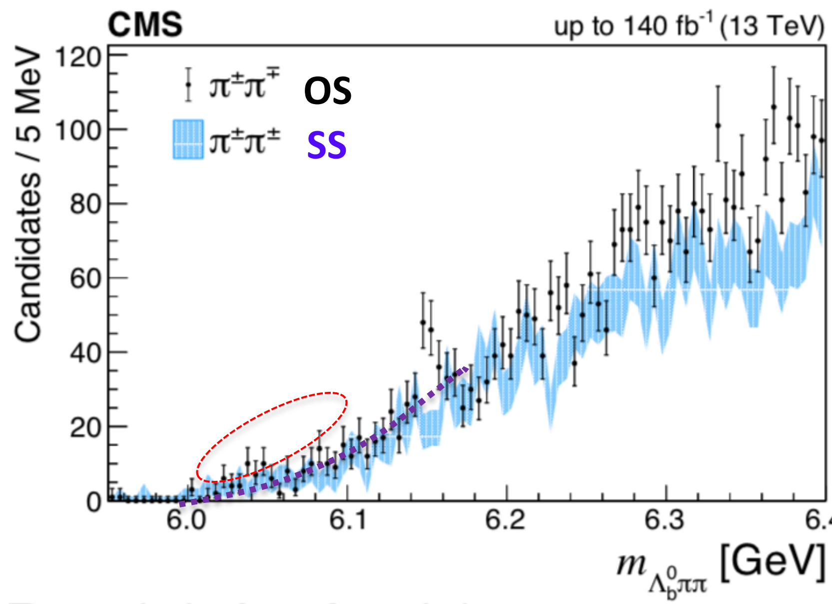
- Comparison between OS & SS distributions of $m(\Lambda_b^0\pi^+\pi^-)$ once the $\Sigma_b^\pm$ & $\Sigma_b^{*\pm}$ contributions are vetoed :

  - the "bump" is consistent with originating from a resonance in the $\Sigma_b^{(*)\pm}\pi^\mp$ system, But no firm conclusion can be made with the present data set

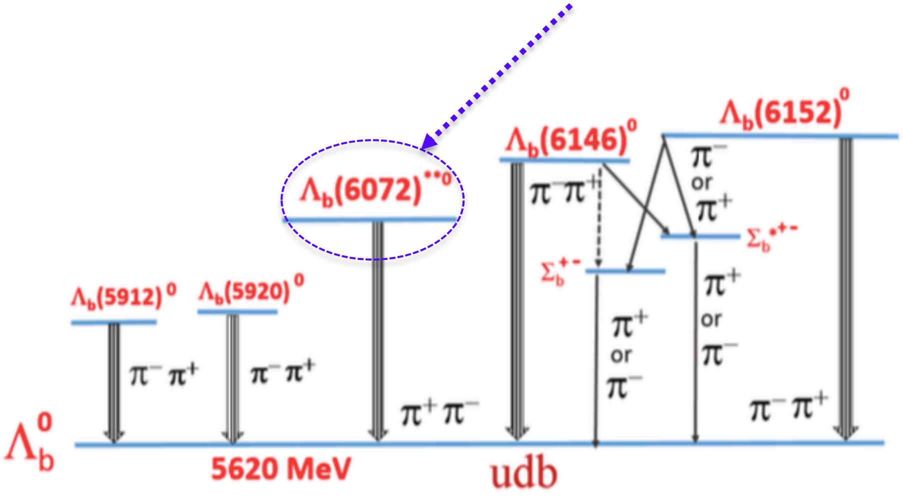


Broad structure @ LHCb

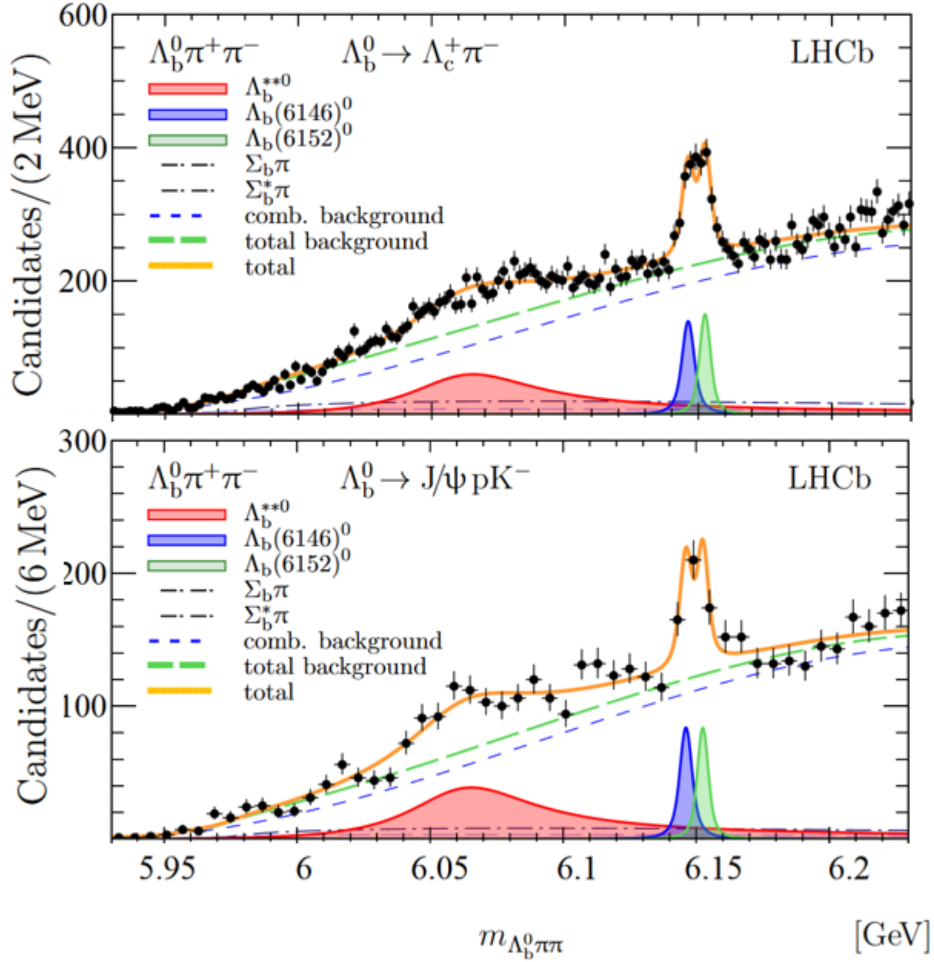
- Few days after CMS paper has appeared on the arXiv, … LHCb confirmed the wide bump with similar parameters [JHEP 06 (2020) 136]

$$m = 6072.3 \pm 2.9 \pm 0.6 \pm 0.2 MeV\,, \Gamma = 72 \pm 11 \pm 2 MeV$$

- … interpreting it as a further excited Λ_b^0 state



http://lhcb-public.web.cern.ch/lhcb-public/Welcome.html#news

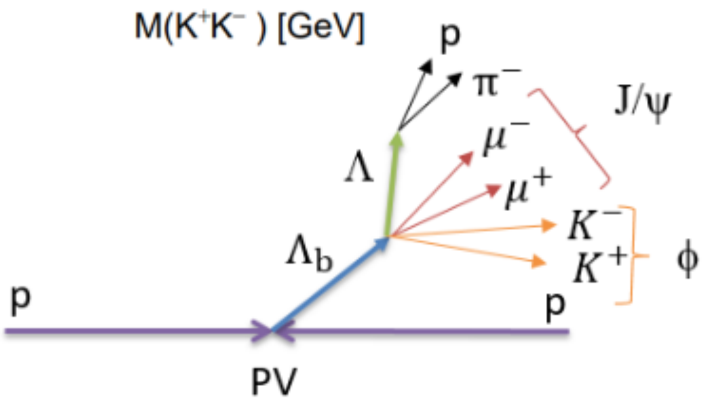


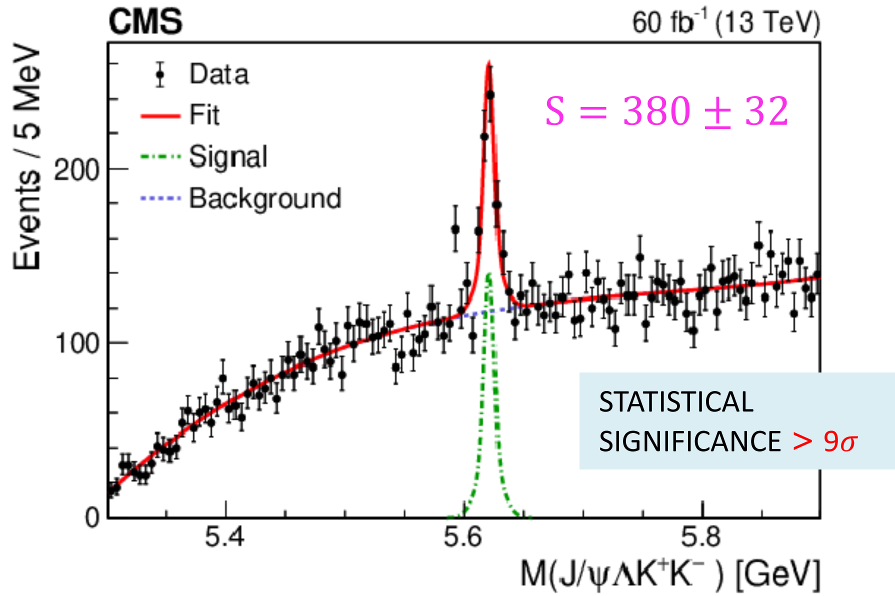
Intepretation non clear,
likely a radial excitation $\Lambda_b^0(2S)$.

2. First observation of the decay $\Lambda_b^0 \to J/\psi\, \Lambda\, \phi$

Observation of the $\Lambda_b^0 \to J/\psi\, \Lambda\, \phi$ decay

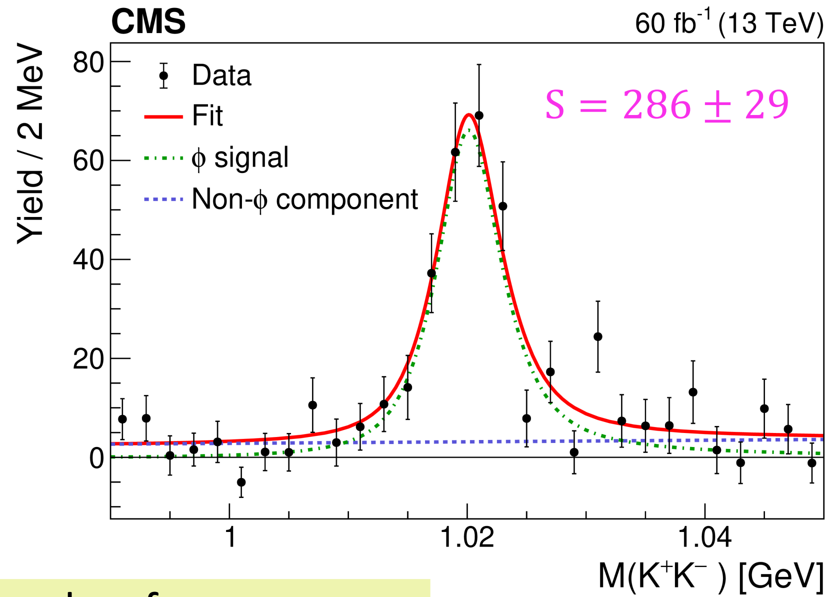
- An UML fit is applied to the invariant $m(J/\psi\, \Lambda K^+ K^-)$:





- Then sPlot technique is used to extract the bkg-subtracted $m(K^+K^-)$ distribution:

The $\Lambda_b^0 \to J/\psi\, \Lambda\, \varphi$ yield is obtained by fitting the bkg-subtracted $m(K^+K^-)$ distribution.

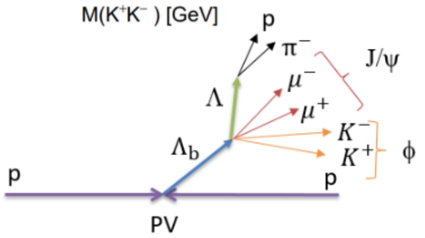


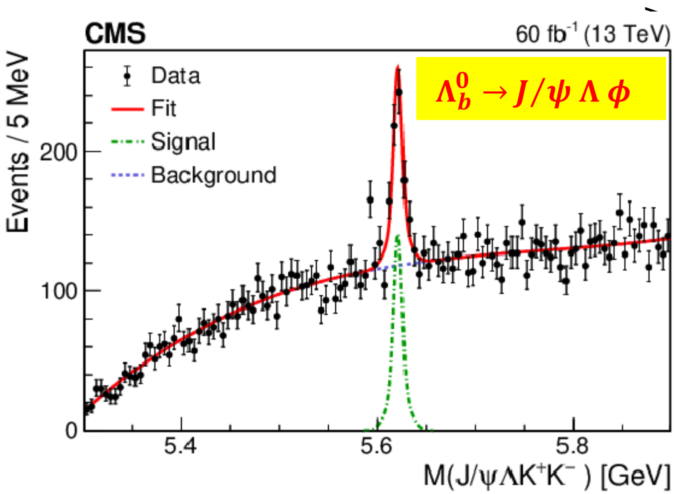
- This observation opens a window on future complementary searches for resonances in the mass spectra once a sufficient number of signal events will be observed.

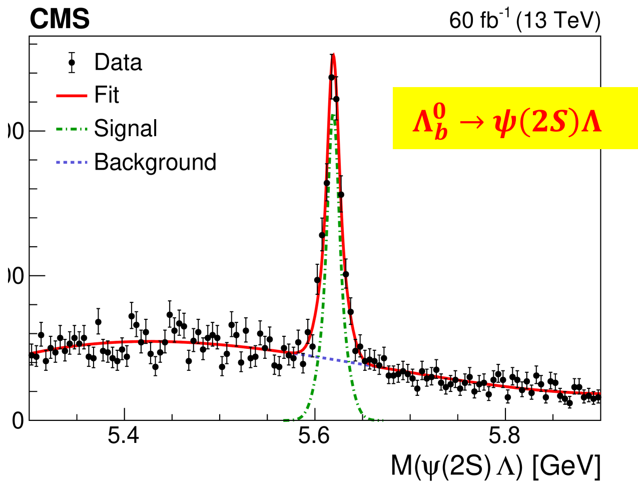
Branching fraction for $\Lambda_b^0 \to J/\psi\,\Lambda\,\phi$ decay

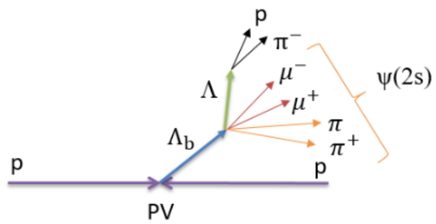
- To measure the BF, $\Lambda_b^0 \to \psi(2S)\Lambda$ used as normalization channel: (more copious, similar topology and kinematics) → **reduced systematics**

  $\psi(2S) \to J/\psi\,\pi^+\pi^-$, $\Lambda \to p\pi^-$









- Branching fraction ratio measurement :

Yields … **corrected by total efficiency** (evaluated on MC)

$$R = \frac{\mathcal{B}(\Lambda_b^0 \to J/\psi\,\Lambda\,\phi)}{\mathcal{B}(\Lambda_b^0 \to \psi(2S)\Lambda)} = \frac{\mathcal{N}(\Lambda_b^0 \to J/\psi\,\Lambda\,\phi)}{\mathcal{N}(\Lambda_b^0 \to \psi(2S)\Lambda)} \cdot \frac{\varepsilon(\Lambda_b^0 \to \psi(2S)\Lambda)}{\varepsilon(\Lambda_b^0 \to J/\psi\,\Lambda\,\phi)} \cdot \frac{\mathcal{B}(\psi(2S) \to J/\psi\,\pi^+\pi^-)}{\mathcal{B}(\phi \to K^+K^-)}$$

from PDG

$$= [8.26 \pm 0.90(stat) \pm 0.68(syst) \pm 0.11(\mathcal{B})]\%$$

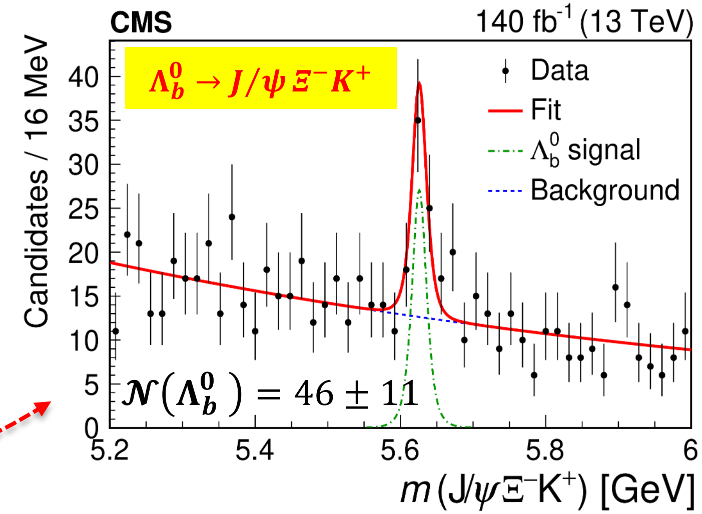
3. First observation of the decay $\Lambda_b^0 \rightarrow J/\psi\, \Xi^- K^+$

Study of the decay $\Lambda_b^0 \rightarrow J/\psi\, \Xi^- K^+$

- First observation of the $\Lambda_b^0 \rightarrow J/\psi\, \Xi^- K^+$ transition through the decay chain :

$J/\psi \rightarrow \mu^+\mu^-$, $\Xi^- \rightarrow \Lambda\pi^-$, $\Lambda \rightarrow p\pi^-$

STATISTICAL SIGNIFICANCE $\sim 5.8\sigma$



- Signal yields extracted by means of UML fits with models:
  - signal: t-Student (μ, σ free; n fixed from MC)
  - background: Exponential

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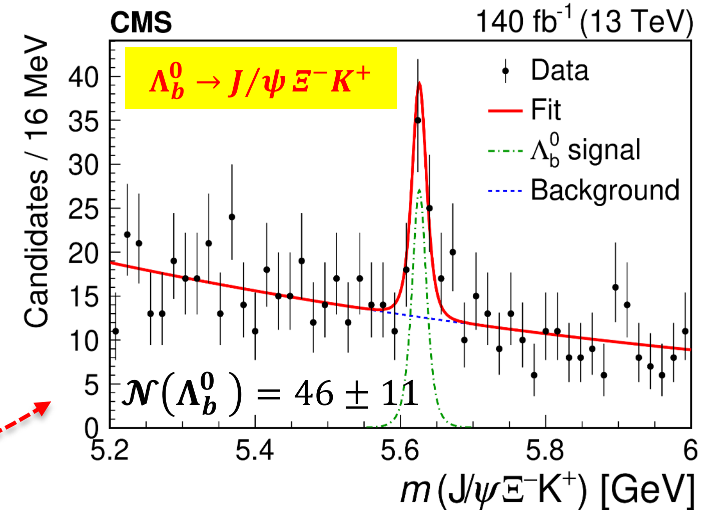
$J/\psi\, \pi^+\pi^-$

Normalization channel : $\Lambda_b^0 \to \psi(2S)\Lambda$

(more copious, similar topology and kinematics) → reduced systematics



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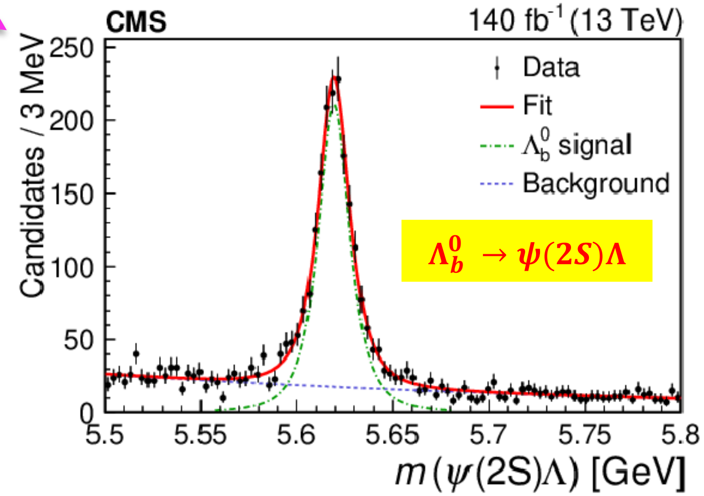

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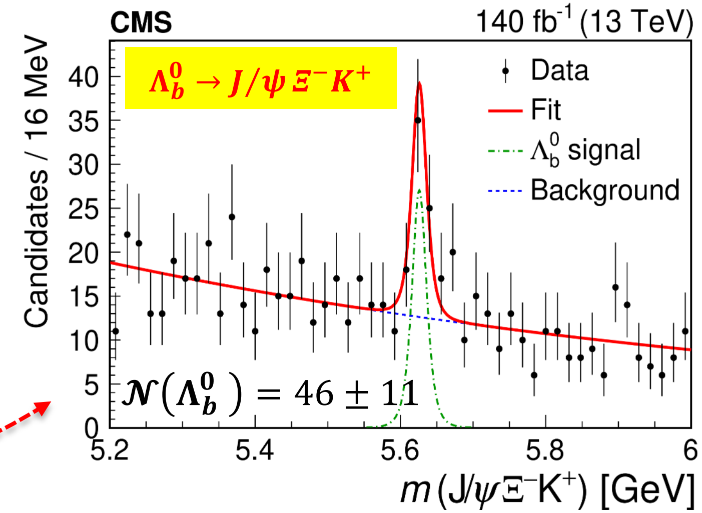

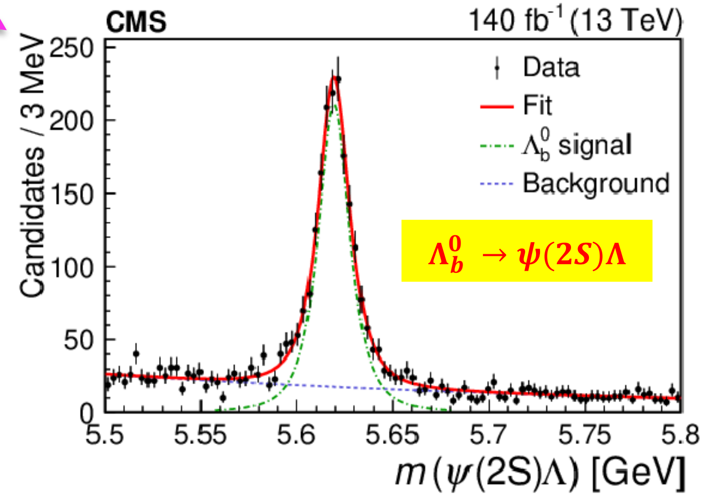

- Branching fraction ratio measurement (with slightly tighter selection):

$$R = \frac{\mathcal{B}(\Lambda_b^0 \rightarrow J/\psi\, \Xi^- K^+)}{\mathcal{B}(\Lambda_b^0 \rightarrow \psi(2S)\Lambda)} =$$

Study of the decay $\Lambda_b^0 \to J/\psi\, \Xi^- K^+$

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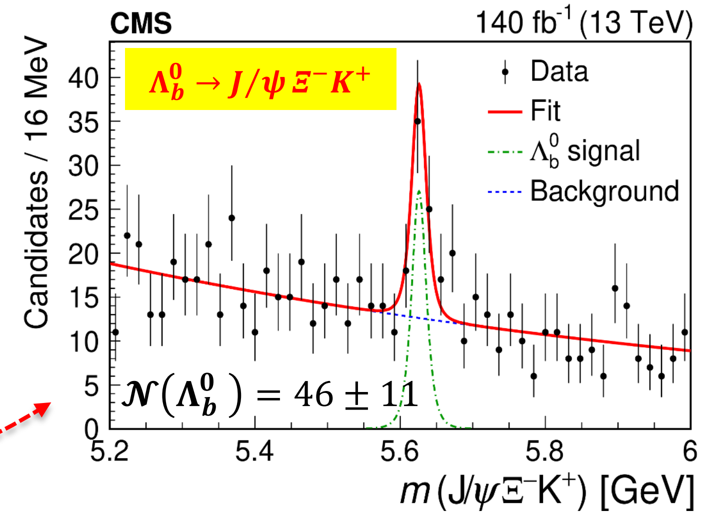

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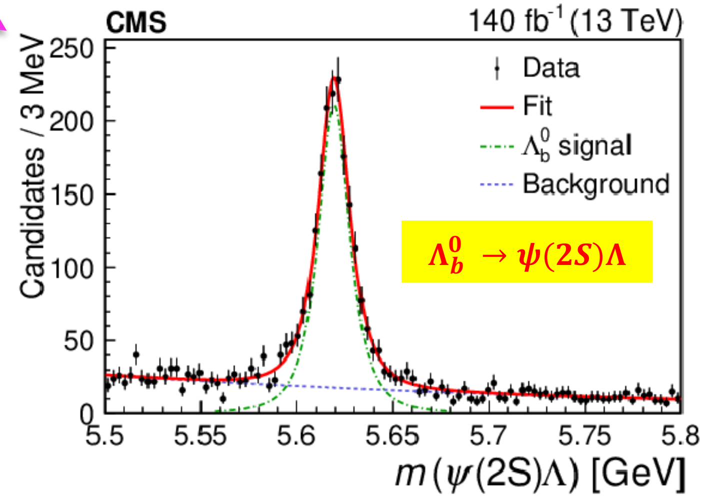

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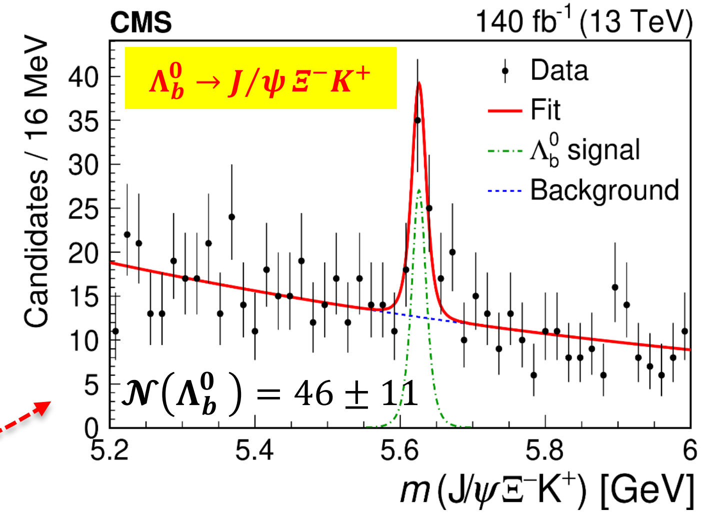

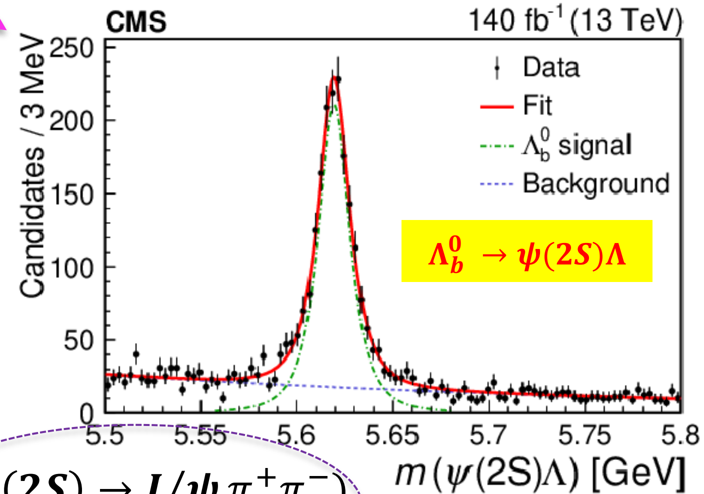

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from PDG

$$= [3.38 \pm 1.02(stat) \pm 0.61(syst) \pm 0.03(\mathcal{B})]\%$$

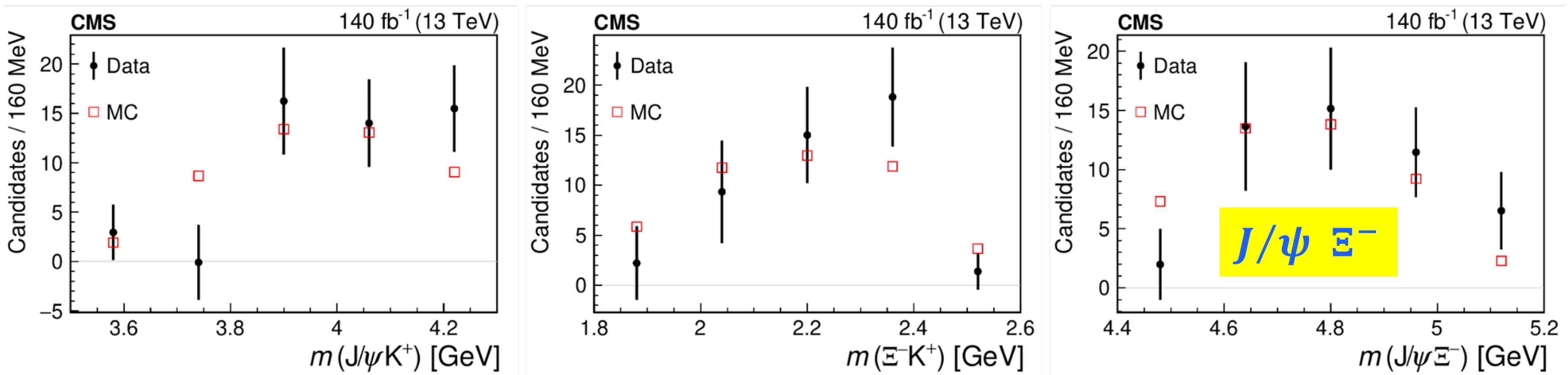
Large statistical uncertaities due to small signal yield

Exploring two-body invariant masses

- **Hidden-charm exotic states** reported by LHCb in $J/\psi\, p$ and $J/\psi\, \Lambda$ **systems**
  (e.g. ***pentaquarks* candidates** in $\Lambda_b \to J/\psi\, p\, K^-$ and $\Xi_b^- \to J/\psi\, \Lambda\, K^-$)

- In principle this new decay represents the first 3-body decay allowing to access the $J/\psi\ \Xi^-$ sub-system

- Background-subtracted mass distributions (**sPlot**), to be used to search for intermediate resonances, are compared with the phase-space model (from simulation):



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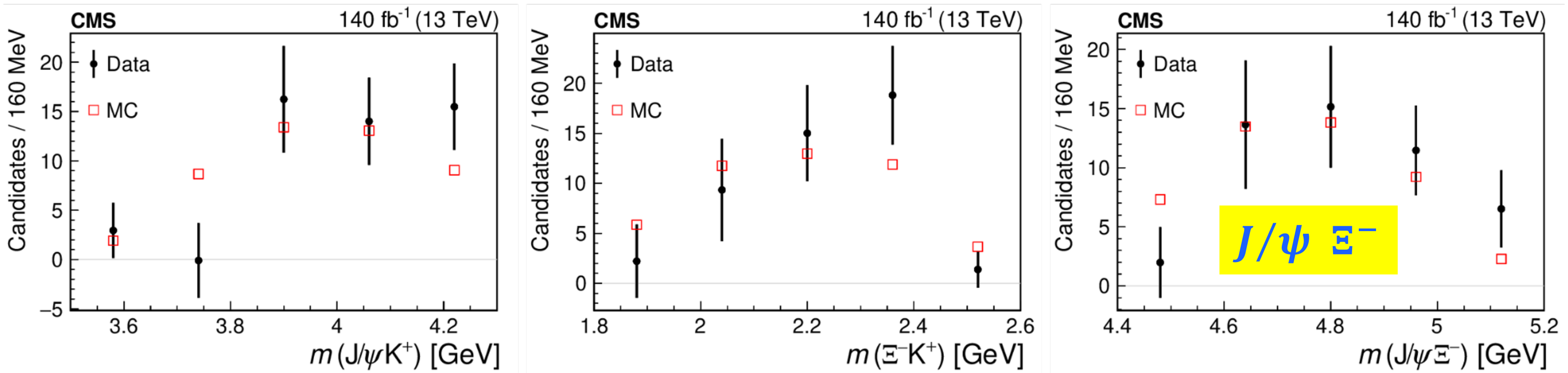


These distributions do not show any relatively narrow peak and agree, within uncertainties, with the predictions from the phase space simulation

- The **sensitivity** of this analysis to potential pentaquark signals in the $J/\psi\, \Xi^-$ intermediate invariant mass distributions is **limited by the low signal yield** for the time being.

4. Observation of the decay $\Xi_b^- \to \psi(2S)\Xi^-$

and studies of $\Xi_b^{*0} \to \Xi_b^{\mp}\, \pi^{\pm}$

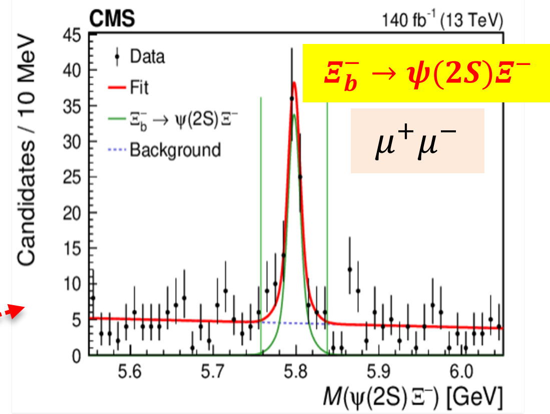
Note: $\Xi_b^{*0} \equiv \Xi_b(5945)^0$

- Ξ_b baryon family: isospin doublets composed of bsq (q light) triplets [Ξ_b (g.s.), Ξ'_b, Ξ^*_b] (according to j_{qs} and J^P)

- First observation of the $\Xi_b^- \to \psi(2S)\Xi^-$ transition through the decay chain :

LOCAL STATISTICAL SIGNIFICANCE > 5σ for both $\psi(2S)$ decays

$\psi(2S) \to \mu^+\mu^-, J/\psi\,\pi^+\pi^-$; $\Xi^- \to \Lambda\pi^-$; $\Lambda \to p\pi^-$



- Signal yields extracted by means of UML fits with models:
  - signal: sum of 2 Gaussians (with common mean)
  - background: 1st order polynomial

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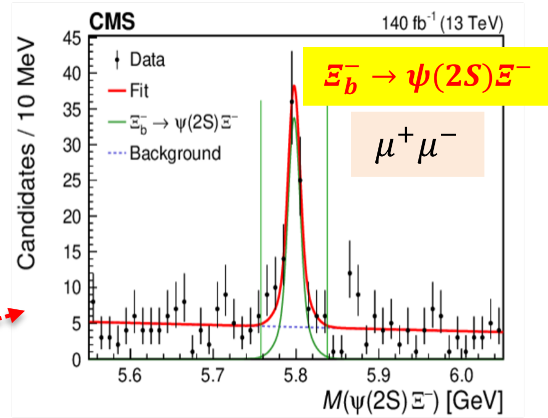

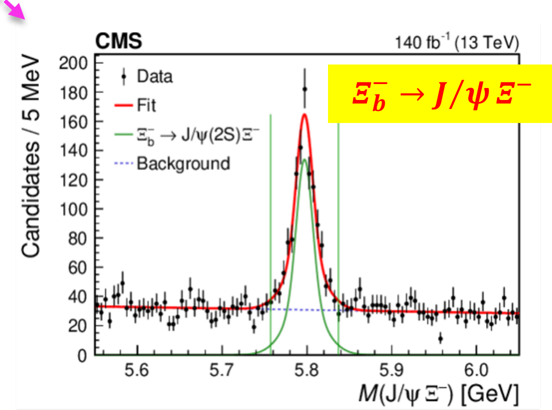

-

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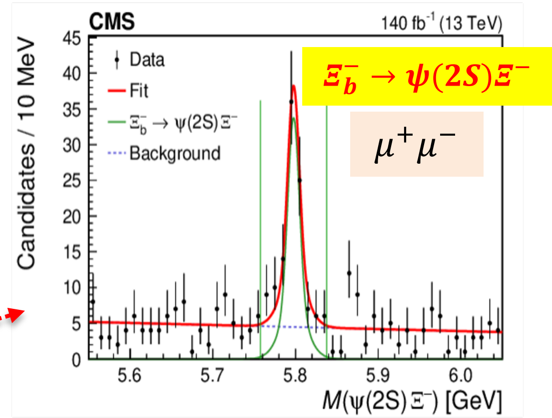

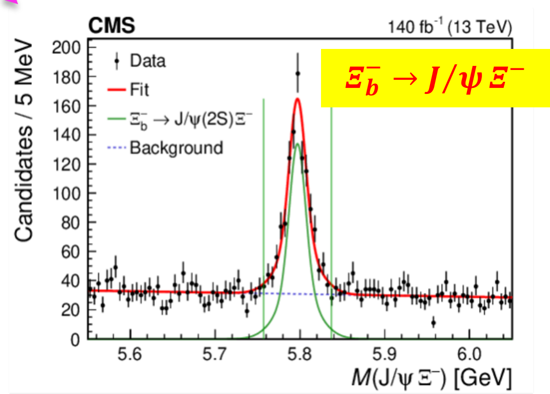

- Branching fraction ratio measurement :

$$R = \frac{\mathcal{B}(\Xi_b^- \to \psi(2S)\Xi^-)}{\mathcal{B}(\Xi_b^- \to J/\psi\,\Xi^-)} =$$

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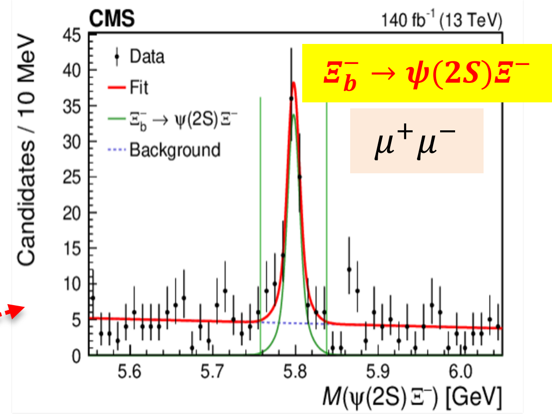

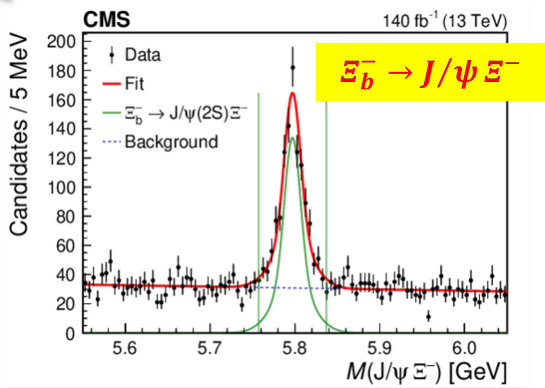

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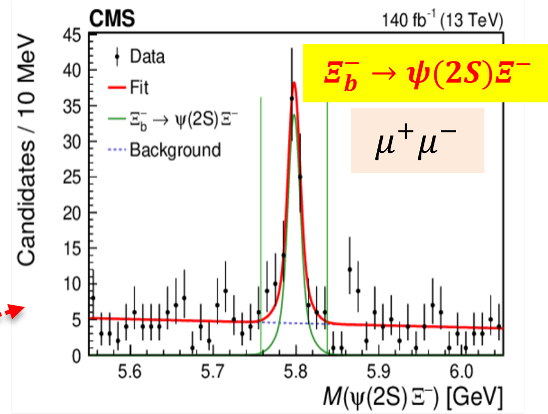

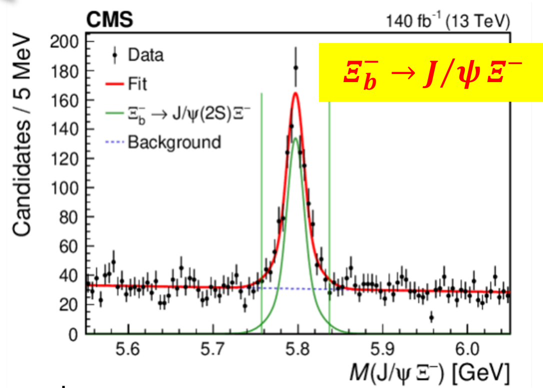

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$$= 0.84^{+0.21}_{-0.19}(stat) \pm 0.10(syst) \pm 0.02(\mathcal{B})$$

Studies of the excited baryon Ξ_b^{*0}

- Ξ_b^{*0} is reconstructed in the $\Xi_b^{\mp}\pi^{\pm}$ final state ($\pi^{\pm}$: any prompt track from PV) with $p_T > 15GeV$

  Ξ_b^- is reconstructed in many decay channels: $J/\psi\,\Xi^-$, $\psi(2S)\Xi^-$, $J/\psi\,\Lambda\,K^-$, $J/\psi\,\Sigma^0\Lambda\,K^-$(partialliy reco'd)

  $\psi(2S) \to \mu^+\mu^-, J/\psi\,\pi^+\,\pi^-$

  $\Sigma^0 \to \Lambda\gamma$ (γ lost)

- No signal present in same-sign mass spectrum $\Xi_b^{\pm}\pi^{\pm}$

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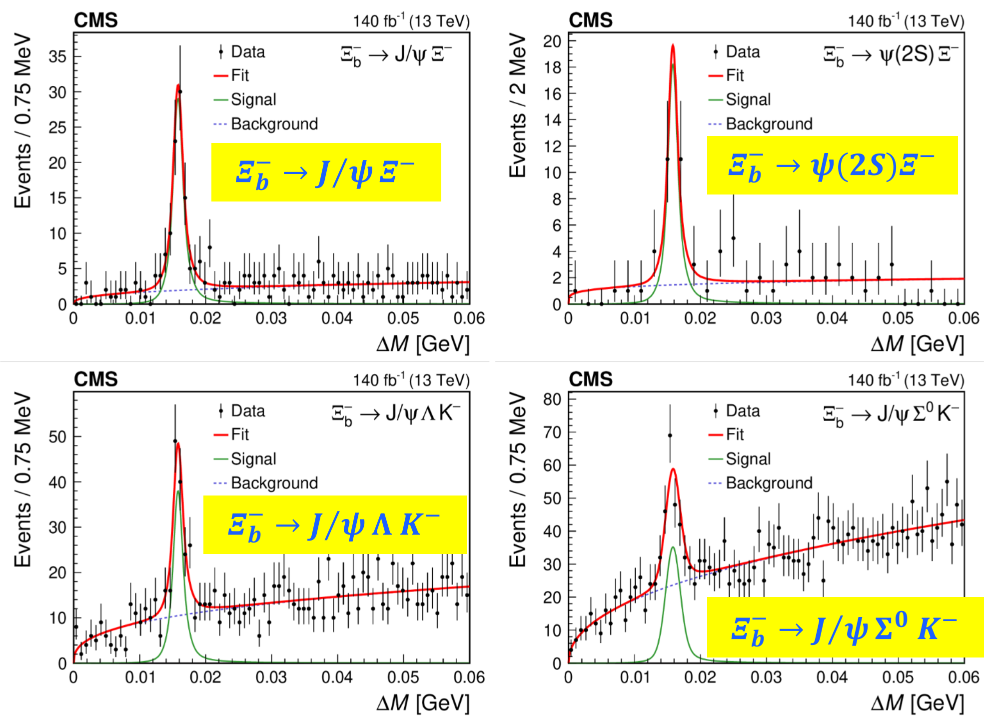
- $\Delta M = M(\Xi_b^-\pi^+) - M(\Xi_b^-) - m_{\pi^+}^{PDG}$ ⇨ **better mass resolution**

  Simultaneous extended UML fit to the 4 ΔM spectra

  Signal Ξ_b^{*0} model : Rel. BW⊗ Gaussian Resolution

  Ξ_b^{*0} **mass & natural width constrained to be equal in 4 fits**



Studies of the excited baryon Ξ_b^{*0} - I

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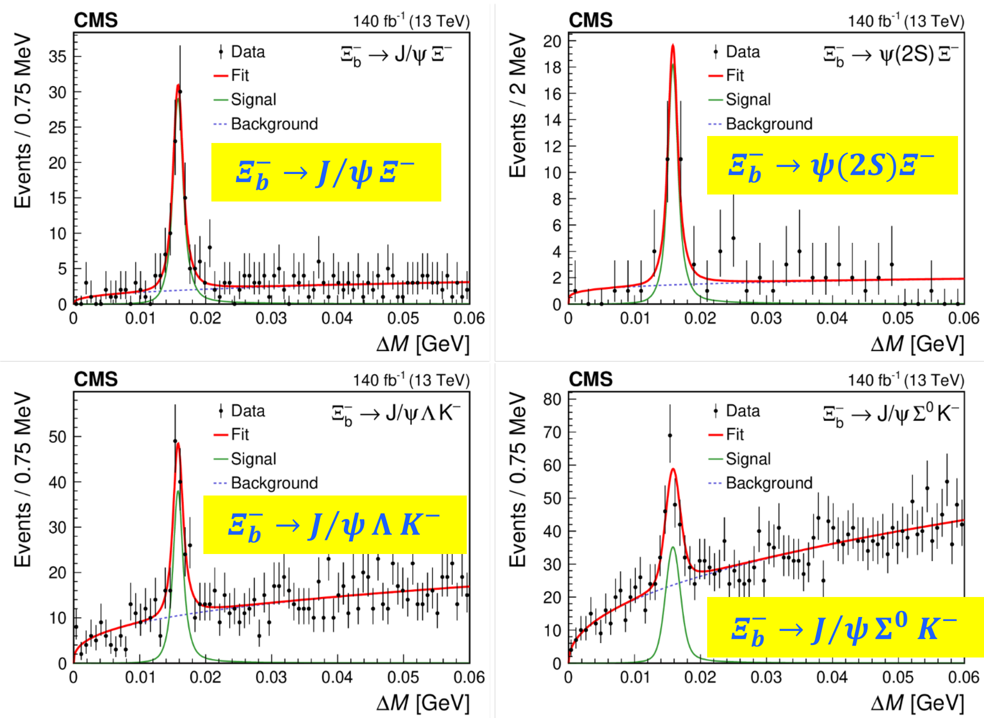
$$m(\Xi_b^{*0}) = 5952.4 \pm 0.1(stat + syst) \pm 0.6(m_{\Xi_b^-})MeV$$

$$\Gamma(\Xi_b^{*0}) = 0.87^{+0.22}_{-0.20}(stat) \pm 0.16(syst)MeV$$



Improved precision on Ξ_b^{*0} mass & width w.r.t. CMS first measurement ($5fb^{-1}$, 2011) [PRL 108 (2012) 252002]

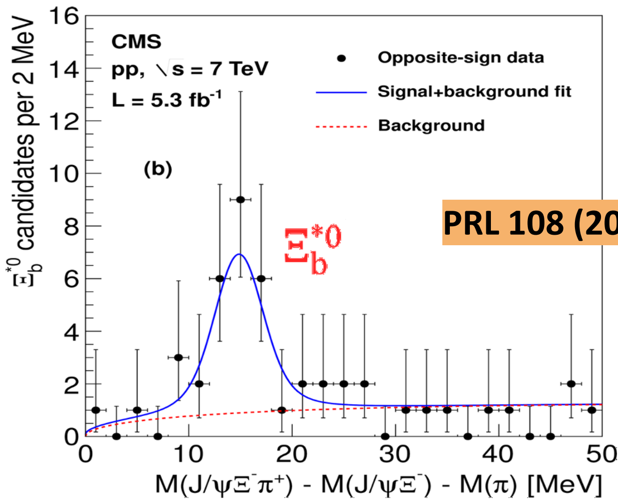
... in agreement with LHCb results [JHEP 05 (2016) 161, PRL 131 (2023) 171901]

Studies of the excited baryon Ξ_b^{*0} - I

- CMS - already with 2011 data (7 TeV) - **observed the Ξ_b^{*0} baryon** [PRL 108 (2012) 252002] **via its strong decay** to $\Xi_b^{\mp}\pi^{\pm}$.

  The ground state Ξ_b baryon was reconstructed via the decay chain $\Xi_b^- \to J/\psi\, \Xi^-, \Xi^- \to \Lambda^0\pi^-, \Lambda^0 \to p\pi^-$.

  - It corresponds to the $J^P = 3/2^+$ **companion** of the Ξ_b.



PRL 108 (2012) 252002

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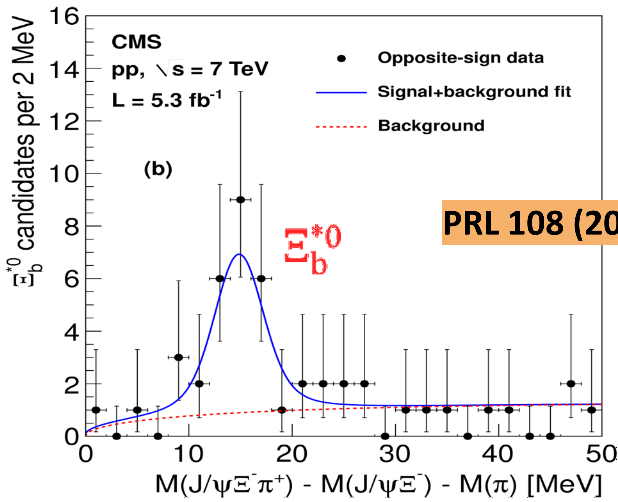


- Inclusive ratio of the Ξ_b^{*0} and Ξ_b^- production Xsections :

(**BLUE** procedure used to combine the results from the different Ξ_b^- decay modes)

$$R_{\Xi_b^{*0}} = \frac{\sigma(pp \to \Xi_b^{*0}X)\cdot\mathcal{B}(\Xi_b^{*0} \to \Xi_b^-\pi^+)}{\sigma(pp \to \Xi_b^- X)} = 0.22 \pm 0.02(stat) \pm 0.02(syst)$$

... in agreement with the LHCb result [JHEP 05 (2016) 161]

This ratio represents the (Ξ_b^{*0} / Ξ_b^-) relative production rate of Ξ_b^- baryons produced from Ξ_b^{*0}

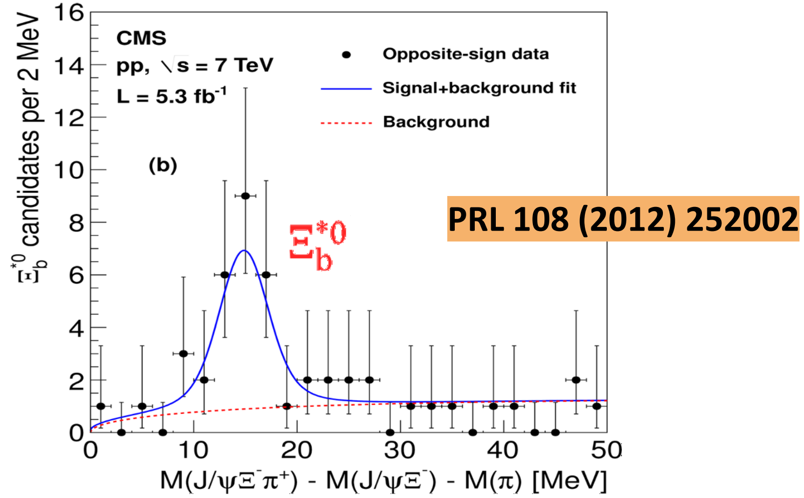
→ fraction of Ξ_b^- baryons produced from Ξ_b^{*0} decays is **~1/4**

Studies of the excited baryon Ξ_b^{*0}

- CMS - already with 2011 data (7 TeV) - **observed the Ξ_b^{*0} baryon** [PRL 108 (2012) 252002] **via its strong decay** to $\Xi_b^{\mp}\pi^{\pm}$.

  The ground state Ξ_b baryon was reconstructed via the decay chain $\Xi_b^- \to J/\psi\,\Xi^-$, $\Xi^- \to \Lambda^0\pi^-$, $\Lambda^0 \to p\pi^-$.

  - It corresponds to the $J^P = 3/2^+$ **companion** of the Ξ_b.



- Inclusive ratio of the Ξ_b^{*0} and Ξ_b^- production Xsections :

(**BLUE** procedure used to combine the results from the different Ξ_b^- decay modes)

$$R_{\Xi_b^{*0}} = \frac{\sigma(pp \to \Xi_b^{*0}X)\cdot\mathcal{B}(\Xi_b^{*0} \to \Xi_b^-\pi^+)}{\sigma(pp \to \Xi_b^- X)} = 0.22 \pm 0.02(stat) \pm 0.02(syst)$$

… in agreement with the LHCb result [JHEP 05 (2016) 161]

This ratio represents the (Ξ_b^{*0} / Ξ_b^-) relative production rate of Ξ_b^- baryons produced from Ξ_b^{*0}

⇒ fraction of Ξ_b^- baryons produced from Ξ_b^{*0} decays is **~1/4**

- From isospin considerations we derive that $\frac{\sigma(pp \to \Xi_b^{*0}X)}{\sigma(pp \to \Xi_b^- X)} \approx \frac{1}{3}$
- **If** the (Ξ_b^{*-} / Ξ_b^-) relative production rate follows **similar** considerations we expect $R_{\Xi_b^{*-}} \approx \frac{1}{9}$

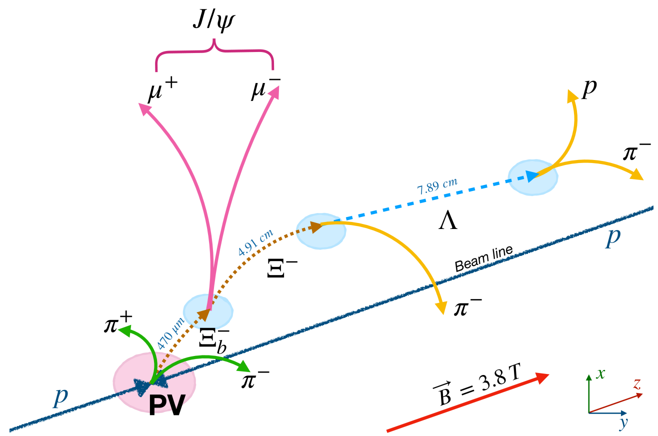
⇒ **~1/3** of Ξ_b^- baryons produced from Ξ_b^{*} decays

- Decays from higher-mass excited states are possible

⇒ **< 2/3 of Ξ_b^- expected promptly produced**

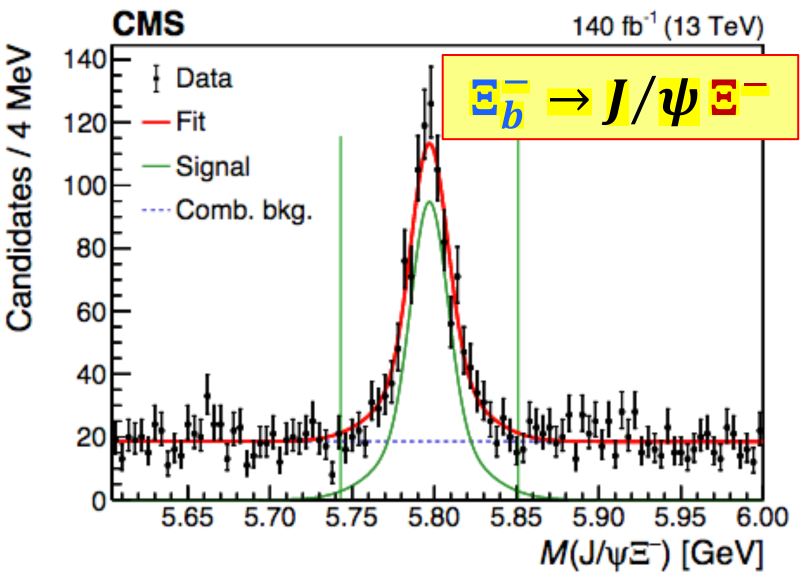
5. Observation of a new excited beauty strange baryon decaying to $\Xi_b^- \pi^+ \pi^-$

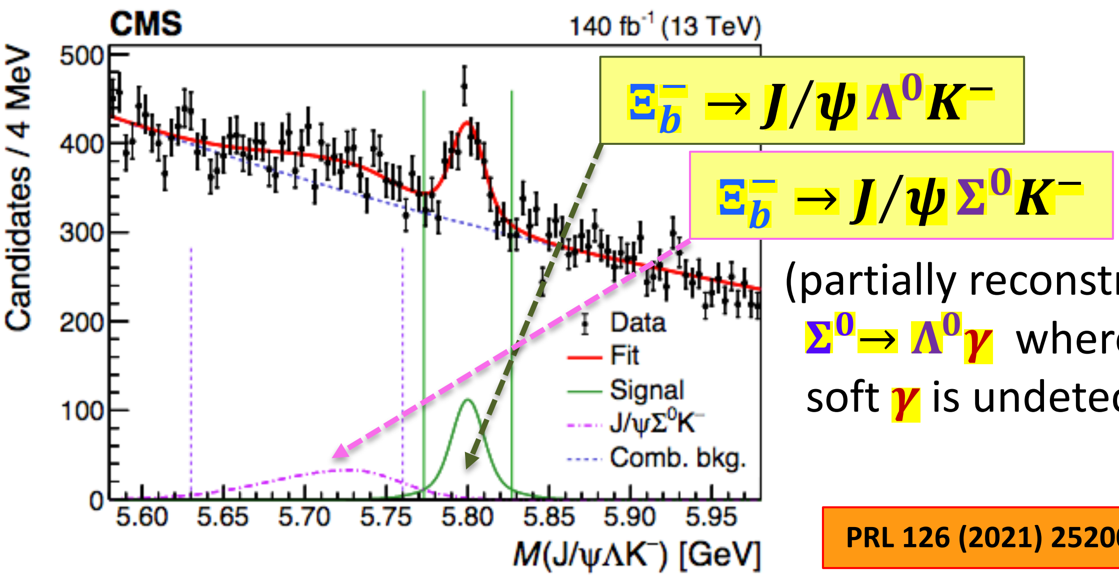
- **Recently CMS observed the lightest orbitally excited beauty strange baryon $\Xi_b^{**}(6100)^- \to \Xi_b^- \pi^+ \pi^-$ (including the - dominant - intermediate resonance $\Xi_b^{*0} \to \Xi_b^- \pi^+$).**



Decay chain from $\Xi_b^{**}(6100)^- \to \Xi_b^- \pi^+ \pi^-$

- The Ξ_b^- baryon is reconstructed via:





(partially reconstructed: $\Sigma^0 \to \Lambda^0 \gamma$ where the soft γ is undetected)

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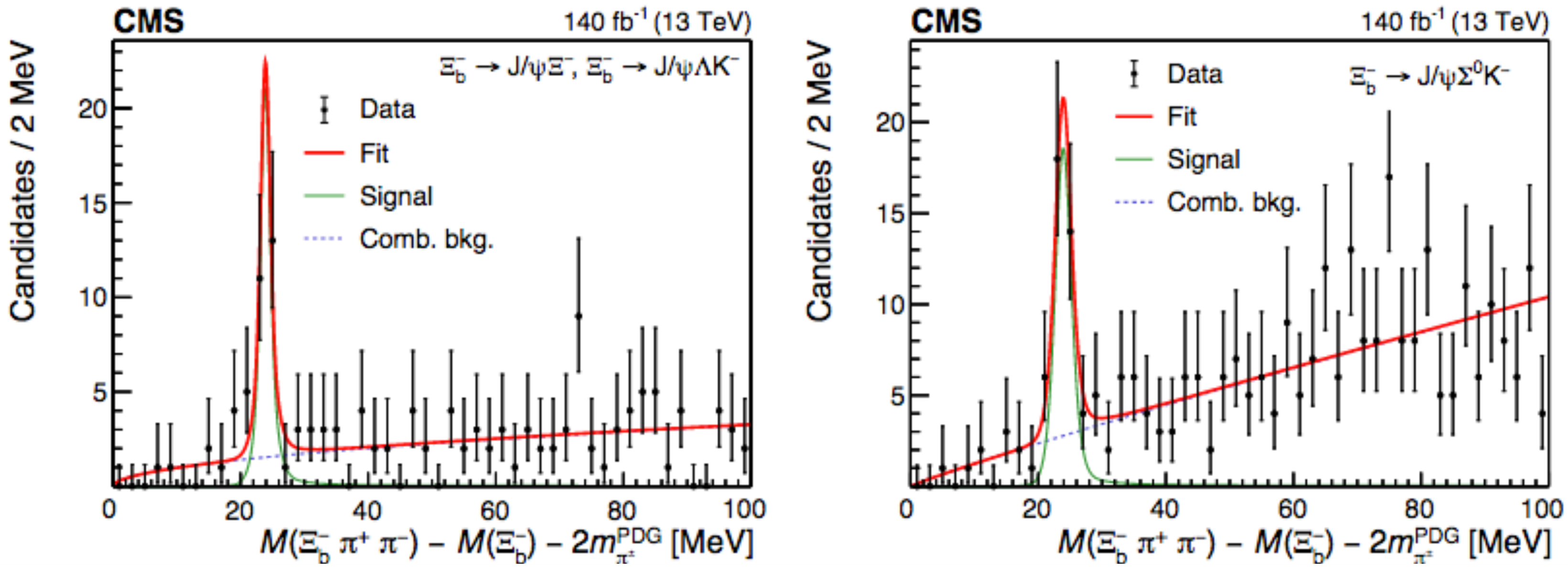
Observation of the excited beauty baryon $\Xi_b^{**}(6100)^-$ - II

- The invariant mass of the final state is build combining the fully reconstructed decays (left) with identical mass resolutions and the partially reconstructed channel (right) with a 30% larger mass resolution.
  The projections of the **simultaneous** extended UML fit (mass parameter is common due to Δm definition):



(local stat. signif. ~6.2-6.7σ)

$m(\Xi_b^{**-}) = [\,6100.3$

$\pm 0.2(\text{stat}) \pm 0.1(\text{sys})$

$\pm 0.6(\Xi_b^-)\,]$ MeV

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- **The natural width** (signal model: RBW⊗2Gauss-resolution) is **too small (consistent with 0) to be measured** with the present data sample and experimental resolution.

  An Upper Limit $\Gamma(\Xi_b^{**-}) < 1.9\text{MeV}$ @95%CL is obtained (systematics included) through the scan of the profiled likelihood.

Observation of the excited beauty baryon $\Xi_b^{**}(6100)^-$ - III

- The low yield does not allow a measurement of the quantum numbers.
  However following analogies with the established Ξ_c baryon states …

  … the new $\Xi_b^{**}(6100)^-$ resonance is the analogue of Ξ_c(2815) and its decay sequence are consistent with lightest the orbitally excited Ξ_b^- baryon with $J^P = 3/2^-$ [L=1 between b-quark and (ds)-diquark]

- This excited baryon has been later confirmed by LHCb : [PRL 131 (2023) 171901]

  (LHCb also observes two new baryonic structures in the neutral final state $\Xi_b^0\pi^+\pi^-$)

Conclusions & perspectives

Conclusions & Perspectives - I

- **CMS has demonstrated to be very competitive also in beauty baryon rare decay chains;**
  We presented here some results among which:
  - the **first observation of the decay $\Lambda_b^0 \to J/\psi\, \Xi^- K^+$**
  - the **first observation of the decay $\Xi_b^- \to \psi(2S)\Xi^-$**.
  These are the two most recent results of a series of analyses dedicated to this sector!

- The Run-3 data being collected will help to achieve very interesting new/updated results, in Heavy Flavour Spectroscopy & Production, integrating and/or complementing LHCb (& ATLAS) results (mainly pp collisions) and ALICE (HI collisions), in spite of huge backgrounds, trigger constraints, particle identification limitations. However, Run-2 data have not yet been fully explored as well.

- Perspectives? Beyond continuing looking for further excited states there are at least two different sectors - not yet explored in CMS - that deal with beauty baryons:

  1. When full Run-III would be available … it may be interesting to study **flavour anomalies** also **with baryonic channels** !

  - $\Lambda_b^0 \to \Lambda^0 \ell\ell \to (p\pi)\ell\ell$
  - $\Xi_b^- \to \Xi^- \ell\ell \to (\Lambda^0\pi^-)\ell\ell \to (p\pi\pi^-)\ell\ell$

  Further investigation is needed though (triggers, efficiencies…), to understand experimental yields (may be still too low).

Conclusions & Perspectives - II

2. Search for **doubly-beauty baryons** (such as $\Xi^0_{bb}(bbu)$, $\Xi^-_{bb}(bbd)$) with full Run-III dataset.

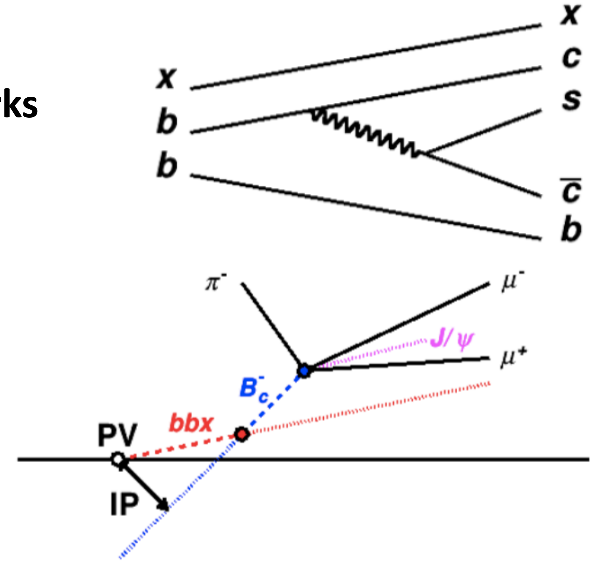
Experimentally, their direct search appear highly challenging:

> The reconstructed final states tend to involve multiple heavy flavoured (beauty or charm) hadrons, so the yield for any exclusive decay mode will be suppressed to unobservable low levels by the product of several branching fractions, each of which is typically 10^{-3}–10^{-2}.

Following Gershon & Poluetkov [JHEP01(2019)019], since the decays of double beauty hadrons are the only possible source of $B_c^\pm$ mesons **that** are displaced from the primary vertices of pp collisions, a more promising inclusive search strategy can be considered not only by LHCb, taking into account that CMS is rather competitive in the $B_c^\pm$ mesons physics:

Displaced B_c^- mesons can be produced only when one of the b quarks in a bbx hadron decays via a $b \to \bar{c}$ transition and the produced antiquark hadronizes with the remaining b quark:
(the transition $b \to c\bar{c}s$ will be dominant (CKM!)**)**

Experimentally the signature is a tail in the distribution of the proper time or IP of the $B_c^\pm$ candidates (dedicated trigger is crucial)



Conclusions & Perspectives - III

- As a mere exercise it is possible to roughly estimate the yields that could be expected for displaced $B_c^{\pm}$ mesons as signature of weakly decaying doubly-beauty hadrons.

  The potential yields can be roughly estimated following the logic in Gershon's paper. as done in the out-of-the-box calculation (characterized by relevant theoretical and experimental uncertainties and assumptions) adapted to the CMS experiment.

  The naïve estimation procedure and the involved assumptions are summarized here:

Numeric input	LHCb	CMS
Run2+3 Integrated Luminosity	$30 fb^{-1}$	$300 fb^{-1}$
bbx hadron production cross section	$\sim\mathcal{O}(1nb)$	$\sim\mathcal{O}(1nb)$
branching fraction for inclusive $bbx \to B_c^+ X$	$\sim 10\%$	$\sim 10\%$
branching fraction: $B_c^+ \to J/\psi\pi^-$	$\sim 2\%$	$\sim 2\%$
further branching fractions: $J/\psi \to \mu^+\mu^-$	$\sim 6\%$	$\sim 6\%$
overall detection efficiency	$\sim 10\%$	$\sim 0.5\%$

factor +10

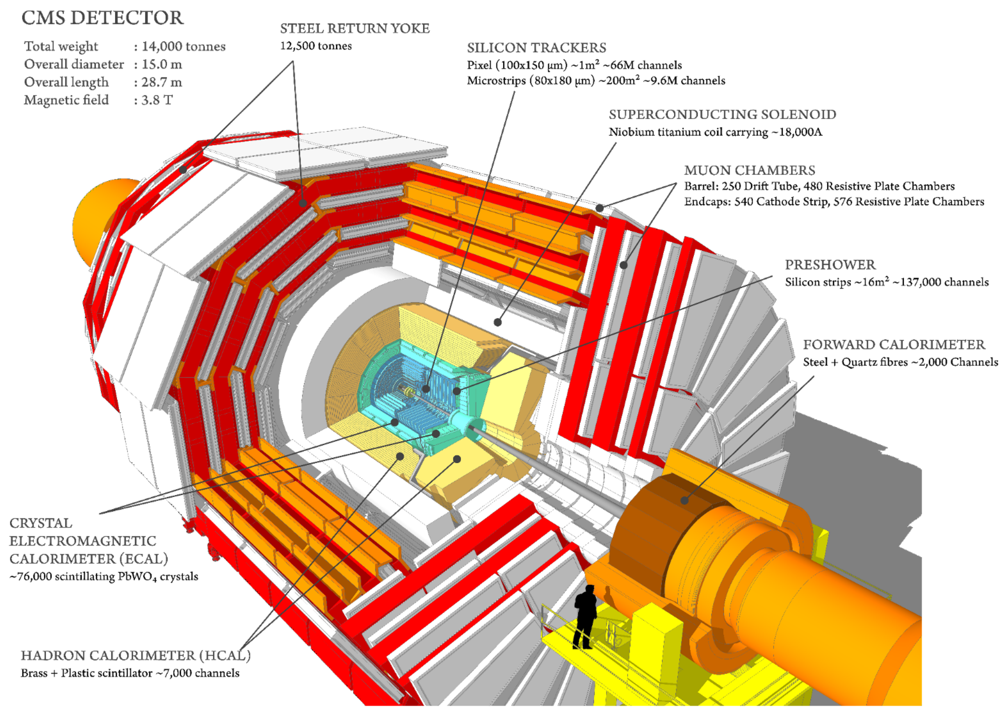
factor -20

300 displaced $B_c^{\pm}$ mesons

LHCb should be favoured by "only" a factor 2 .

Backup material

- **General purpose detector** with **cylindrical symmetry** and (almost) **full coverage of the solid angle**



Strengths (for the discussed analyses):

- muon reconstruction and identification
- large muons' acceptance
- high-performance tracking & vertexing