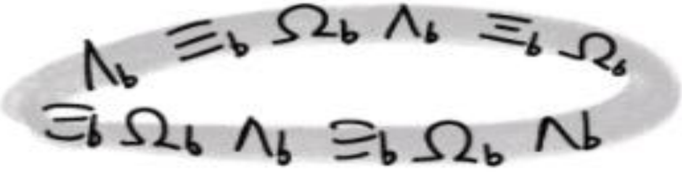
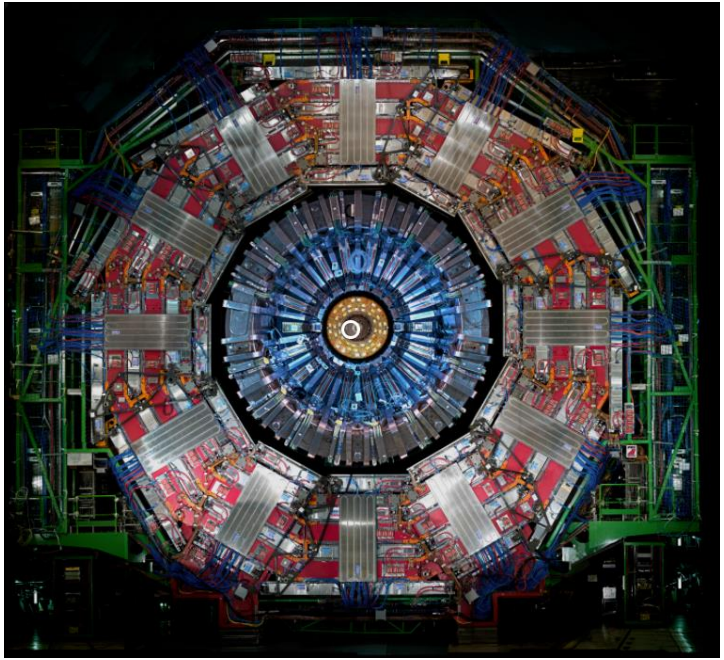
CMS results on beauty baryon spectroscopy





The work was supported by the Ministry of Science and Higher Education of the Russian Federation, Project "Fundamental properties of elementary particles and cosmology" No 0723-2020-0041.

S. Polikarpov (on behalf of the CMS Collaboration)
NRNU MEPhI, LPI RAS

HADRON 2021

27-31 July 2021

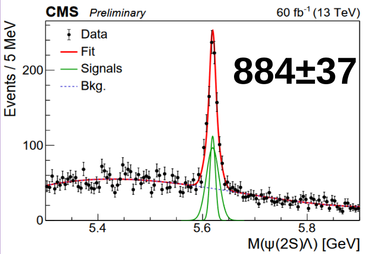
30 July 2021

Outline

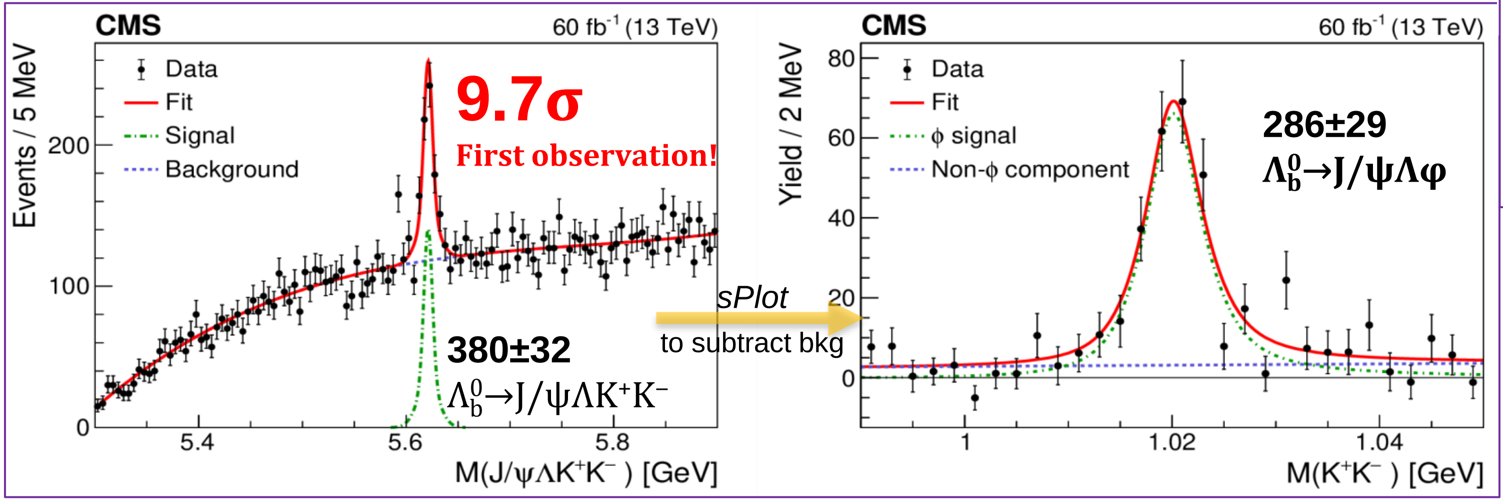
- First observation of the $\Lambda_b^0 \to J/\psi \Lambda \phi$ decay (*Phys.Lett.B* 802 (2020)135203)
- Excited Λ_b^0 states (*Phys.Lett.B* 803(2020)135345)
- New excited Ξ_b^- baryon (*Phys.Rev.Lett.*126(2021)25,252003)

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

- Possibility to search for exotic hadron contributions in the $J/\psi\Lambda$ and $J/\psi\varphi$ mass distributions (pentaquarks $\to J/\psi\Lambda$, tetraquarks $\to J/\psi\varphi$)
- For the BF measurement, $\Lambda_b^0 \to \psi(2S)\Lambda$, $\psi(2S) \to J/\psi\pi^+\pi^-$ channel is used as normalization (same trigger and decay topology)



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



Main systematics: data-MC difference in the mass resolution

$$\frac{\mathcal{B}(\Lambda_b^0 \to J/\psi\Lambda\varphi)}{\mathcal{B}(\Lambda_b^0 \to \psi(2S)\Lambda)} = (8.26 \pm 0.90\,(\text{stat}) \pm 0.68\,(\text{syst}) \pm 0.11\,(\mathcal{B}))\%$$

CMS-BPH-19-002, *Phys.Lett.B 802(2020)135203*

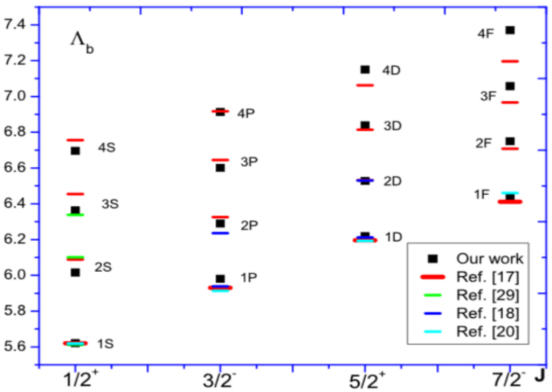
Outline

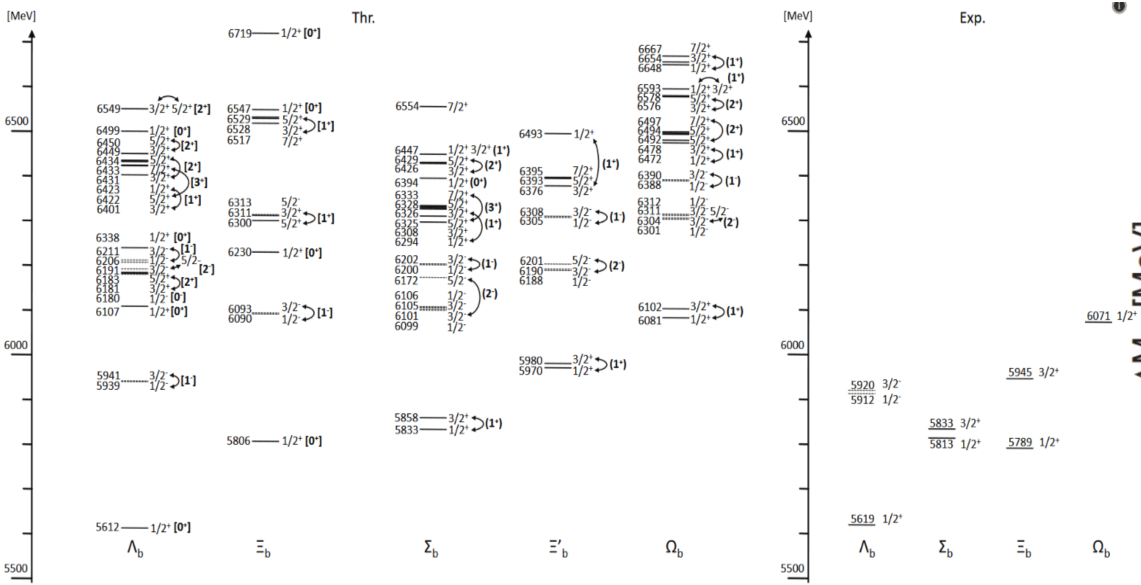
- First observation of the $\Lambda_b^0 \to J/\psi \Lambda \phi$ decay
- **Excited Λ_b^0 states**
- New excited Ξ_b^- baryon

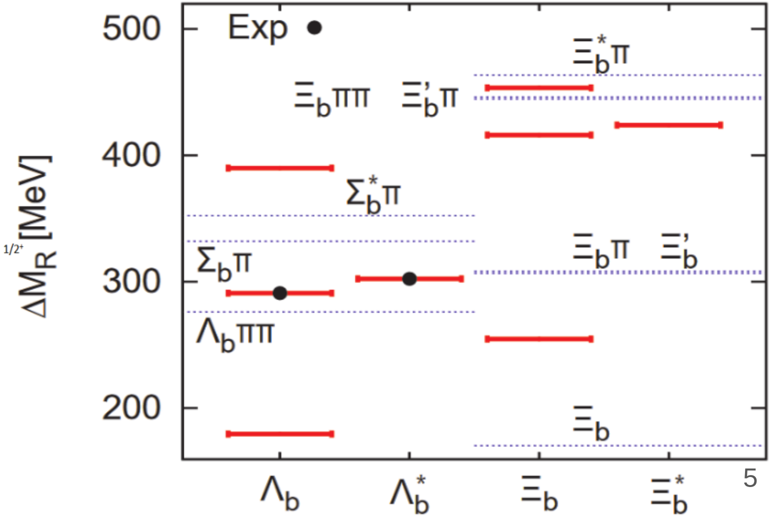
Excited beauty baryons: theory

There are many theoretical predictions of excited Λ_b, Σ_b, Ξ_b, Ω_b states, but the predicted masses are usually spread over rather wide ranges and do not point to any particular narrow window to search for a new signal.

Most predictions do not have uncertainties; new measurements can point to a set of models that are more accurate in describing the data

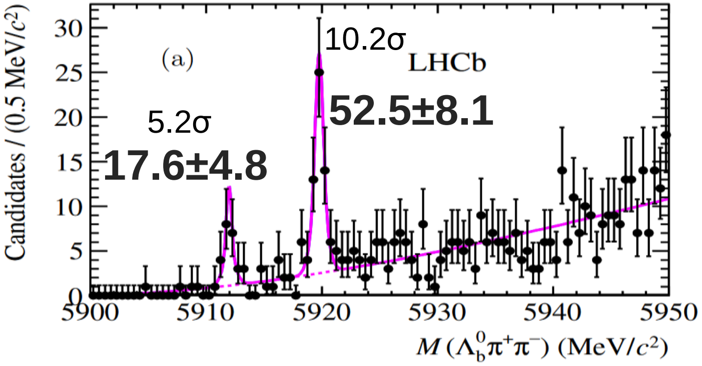






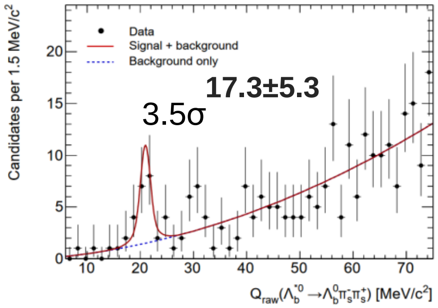
Excited Λ_b^0 states decaying into $\Lambda_b^0\pi\pi$

LHCb, 2012, [10.1103/PhysRevLett.109.172003](https://doi.org/10.1103/PhysRevLett.109.172003)

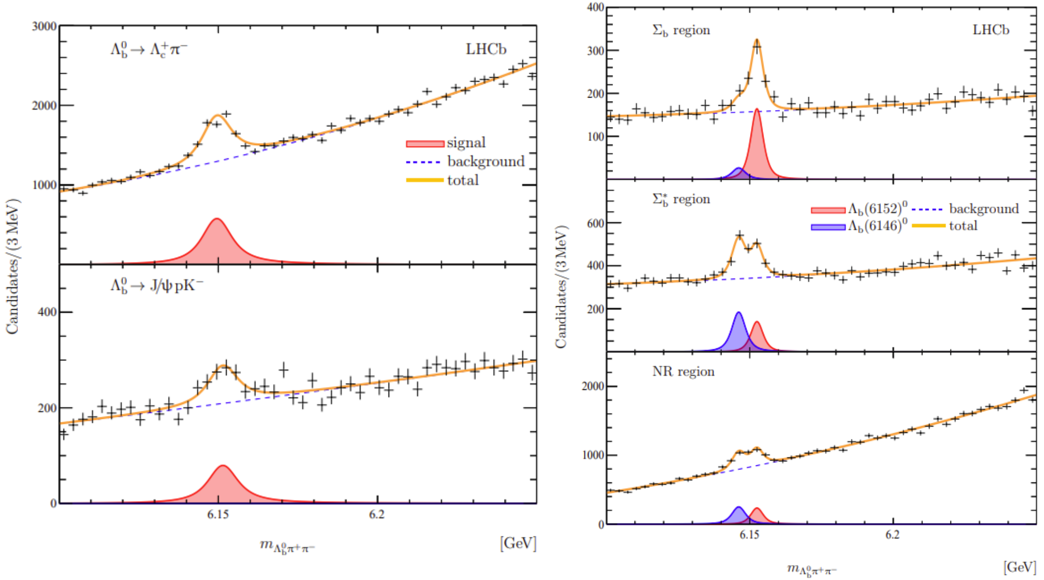


Near kinematic threshold

CDF, 2013, [10.1103/PhysRevD.88.071101](https://doi.org/10.1103/PhysRevD.88.071101)



LHCb, 2019, [10.1103/PhysRevLett.123.152001](https://doi.org/10.1103/PhysRevLett.123.152001)

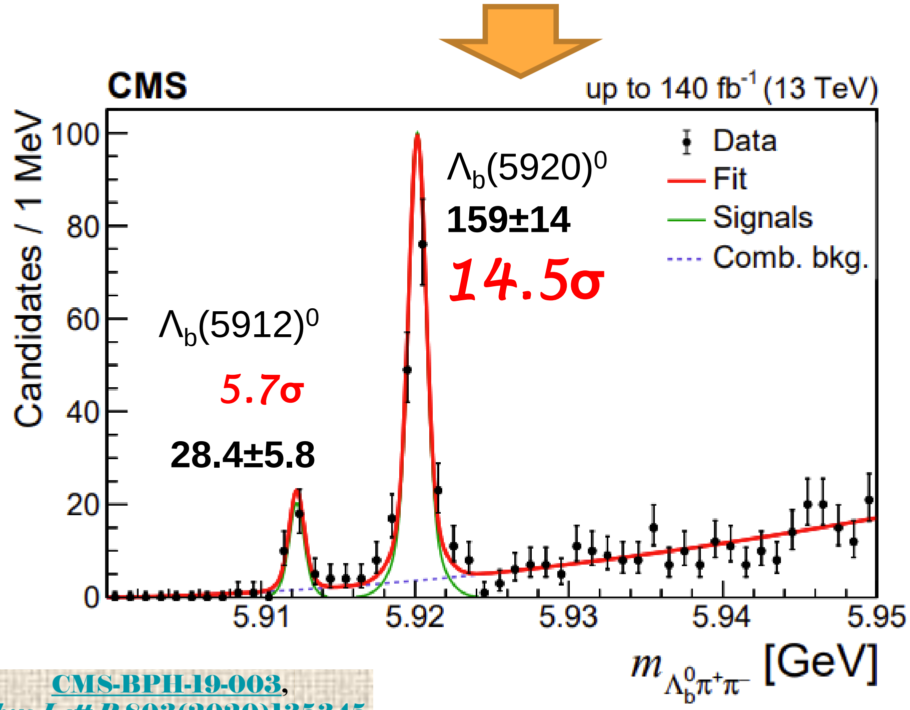


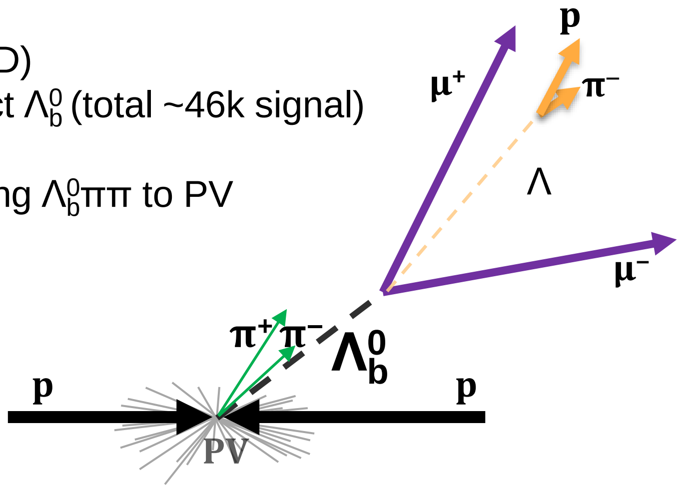
Four excited Λ_b^0 states have been observed, $\Lambda_b(5912)^0$, $\Lambda_b(5920)^0$, $\Lambda_b(6146)^0$, and $\Lambda_b(6152)^0$, with only one of them confirmed (3.5σ)

Excited Λ_b^0 states decaying into $\Lambda_b^0\pi\pi$

CMS: very difficult to use Λ_c^+ (no trigger/hadron PID) or $\Lambda_b^0 \to J/\psi pK^-$ (PID)
However, we can use $\Lambda_b^0 \to J/\psi\Lambda$ and $\Lambda_b^0 \to \psi(2S)\Lambda$ decays to reconstruct Λ_b^0 (total ~46k signal)

Add 2 prompt pions to Λ_b^0 and plot $m(\Lambda_b^0\pi\pi)-m(\Lambda_b^0)+M^{PDG}(\Lambda_b^0)$ after refitting $\Lambda_b^0\pi\pi$ to PV





2nd confirmation of $\Lambda_b(5920)^0$ state,
first confirmation of $\Lambda_b(5912)^0$ state,
mass measurements

$M(\Lambda_b(5912)^0) = 5912.32 \pm 0.12 \pm 0.01 \pm 0.17$ MeV

$M(\Lambda_b(5920)^0) = 5920.16 \pm 0.07 \pm 0.01 \pm 0.17$ MeV

(stat) (syst) (Λ_b^0)

CMS-BPH-19-003, Phys.Lett.B 803(2020)135345

In agreement with LHCb & CDF

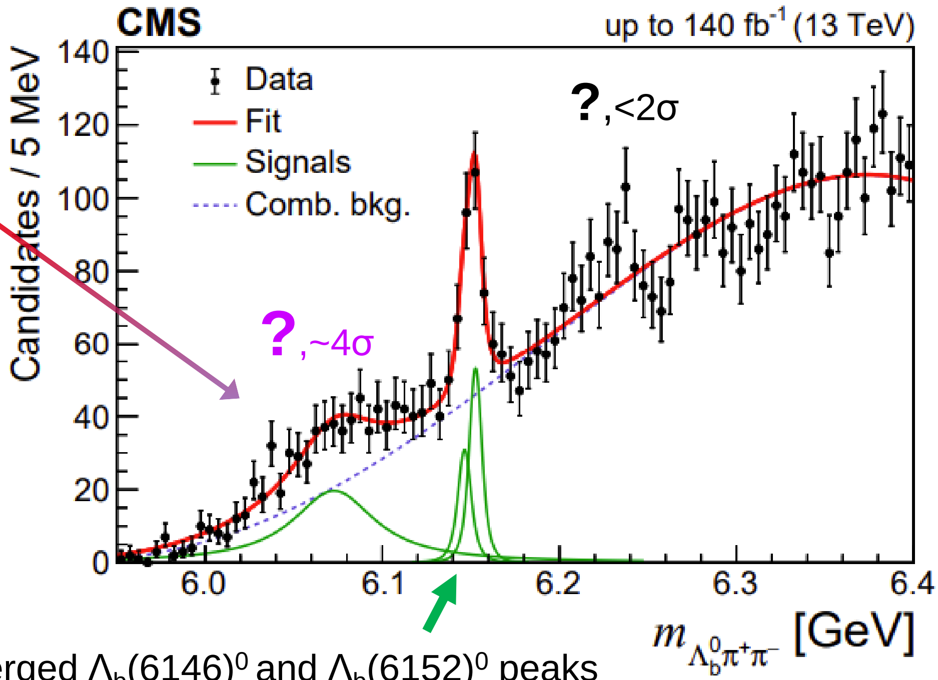
Excited Λ_b^0 states decaying into $\Lambda_b^0\pi\pi$

With tighter cuts on $p_T(\pi)$ and far from threshold:

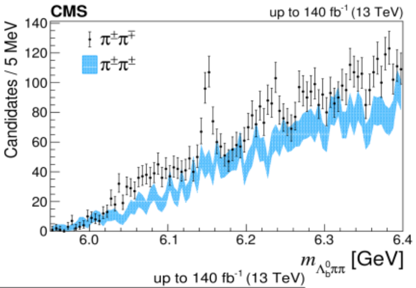
Evidence for a new broad resonance,
M = 6075 ± 5 (stat) MeV and Γ = 55 ±11 (stat) MeV

can also be an overlap of several close/partially-reconstructed states

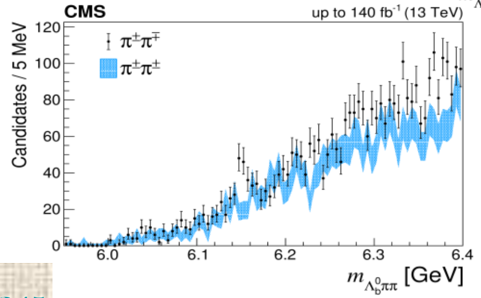
Peak confirmed later by LHCb 10.1007/JHEP06(2020)13



not present in same-sign (SS) distribution



If the $\Sigma_b^{(*)} \rightarrow \Lambda_b^0\pi$ are vetoed, the SS and OS distribution are in agreement



Merged $\Lambda_b(6146)^0$ and $\Lambda_b(6152)^0$ peaks
Confirmation of the resonances , mass measurements

$M(\Lambda_b(6146)^0)$ = 6146.5 ± 1.9 ± 0.8 ± 0.2 MeV

$M(\Lambda_b(6152)^0)$ = 6152.7 ± 1.1 ± 0.4 ± 0.2 MeV

(stat) (syst) (Λ_b^0)

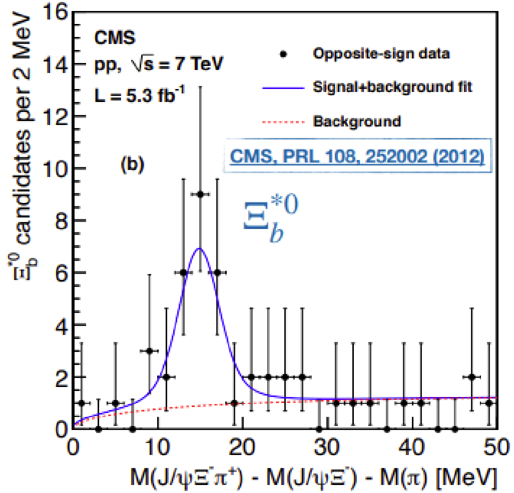
In agreement with LHCb

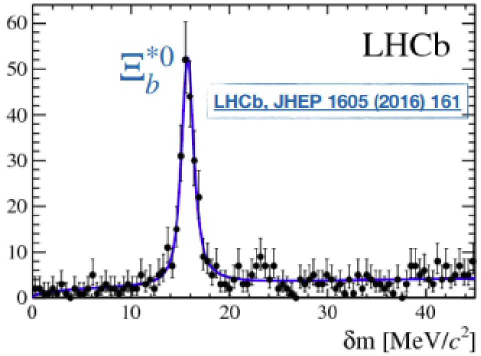
CMS-BPH-19-003, *Phys.Lett.B* 803(2020)135345

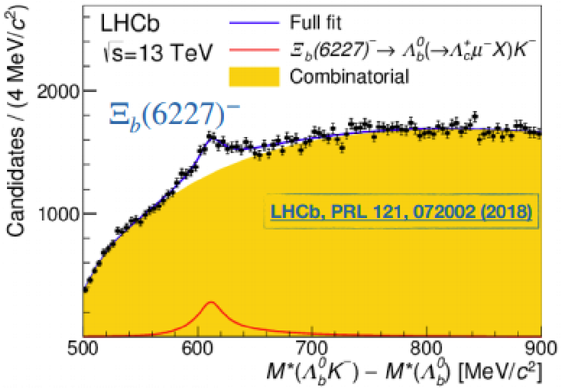
Outline

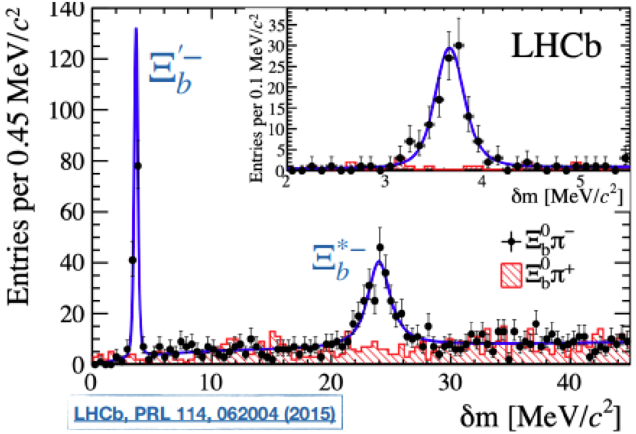
- First observation of the $\Lambda_b^0 \to J/\psi \Lambda \phi$ decay
- Excited Λ_b^0 states
- **New excited Ξ_b^- baryon**

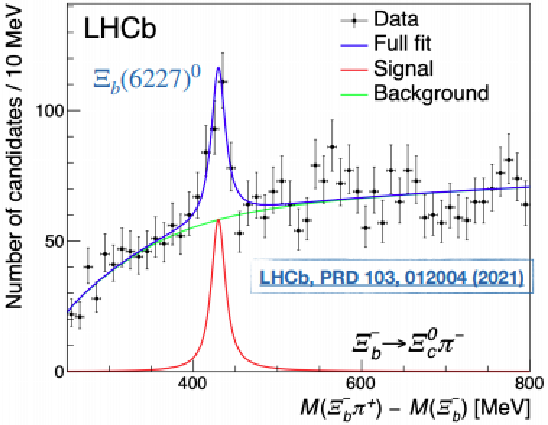
Excited beauty strange (Ξ_b) baryons









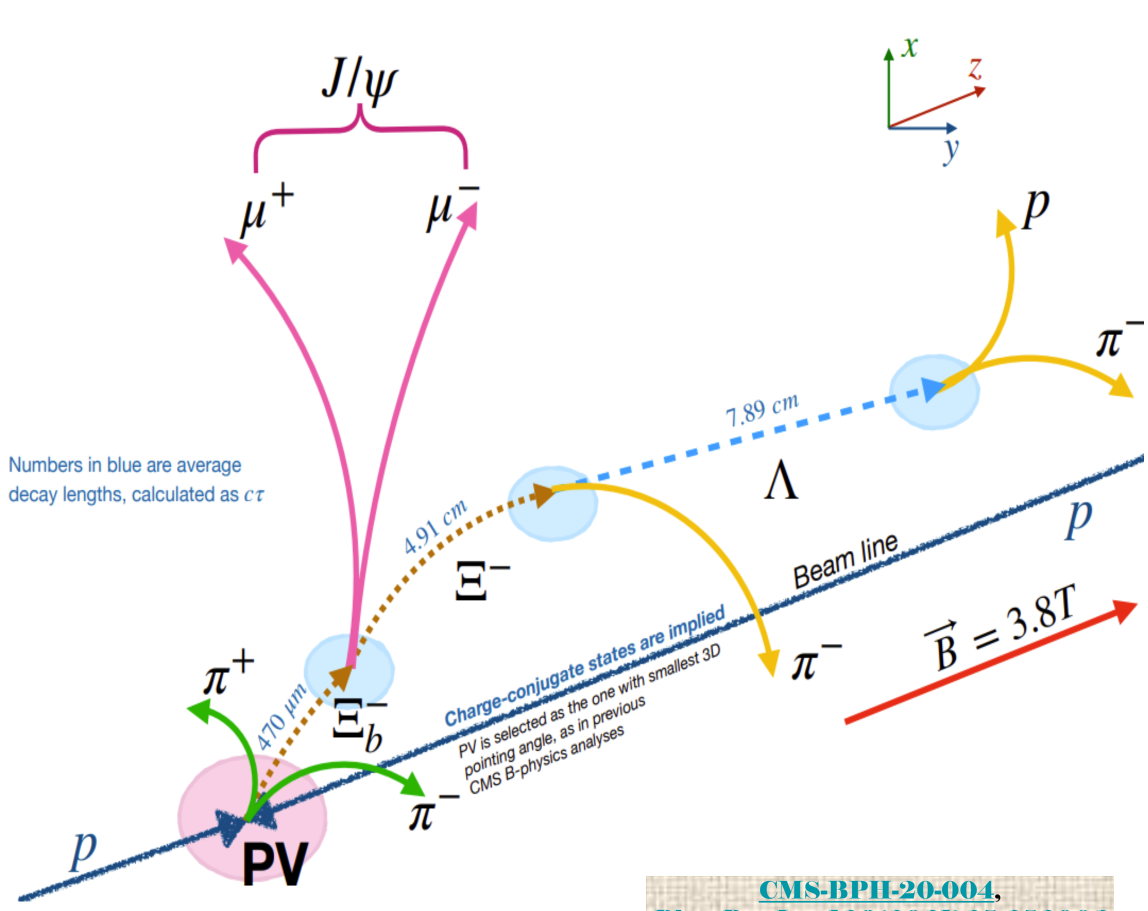


$\Xi_b(6227)$ isodoublet does not unambiguously fit quark model predictions and charm analogies

$\Longrightarrow$

its quantum numbers needs further investigation

Excited Ξ_b baryons: reconstruction at CMS



CMS-BPH-20-004, *Phys.Rev.Lett.*126(2021)25,252003

Cannot use decay channels with charm baryons, using the ones with J/ψ:

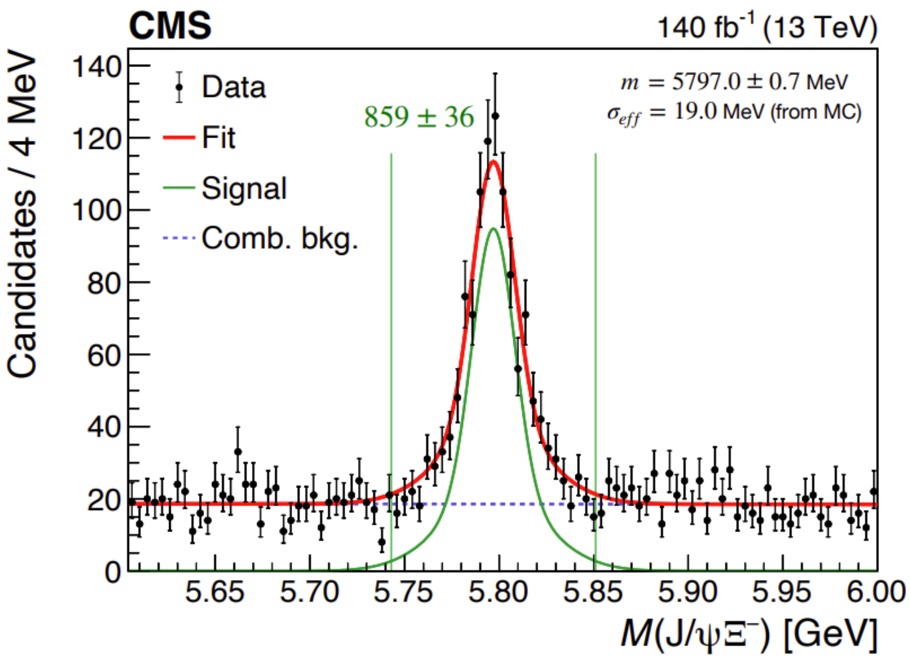
$\Xi_b^- \to J/\psi\Xi^-$ [$\Xi^- \to \Lambda\pi^-$, $\Lambda \to p\pi^-$]
$\Xi_b^- \to J/\psi\Lambda K^-$ [$\Lambda \to p\pi^-$]
(including contribution from $\Xi_b^- \to J/\psi\Sigma^0 K^-$)

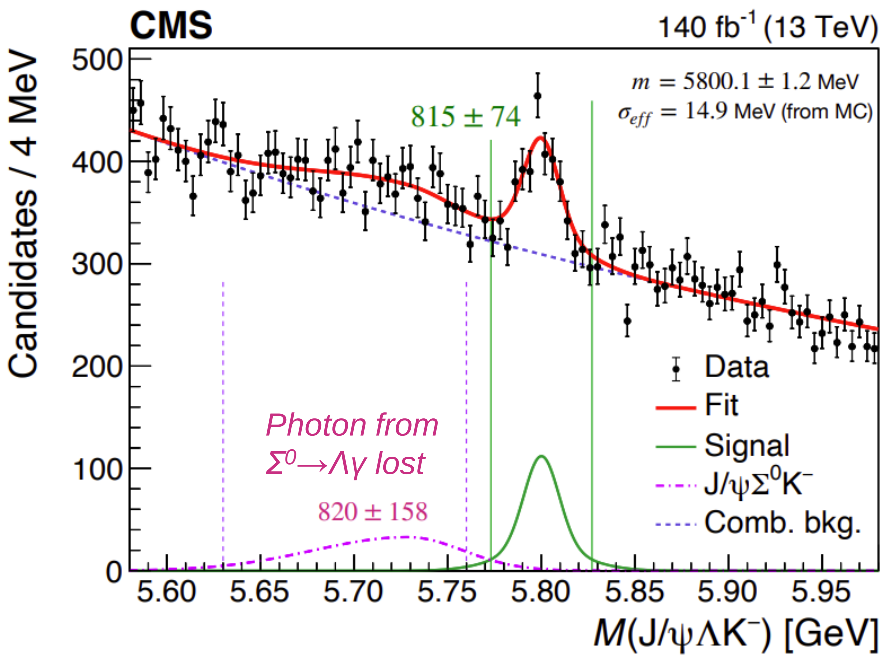
Two additional OS pions from PV, with **$m(\Xi_b^-\pi^+)$ compatible with Ξ_b^{*0}**

Selection criteria optimized using Punzi FOM using the variables characterizing the decay topology and kinematics:

- Flight distances of Ξ_b^-, Ξ^-, Λ
- Alignment of momenta with decay length
- Fit qualities of Ξ_b^-, Ξ^-, Λ, $\Xi_b^-\pi\pi$ vertices
- p_T of candidates

Ξ_b^- signal





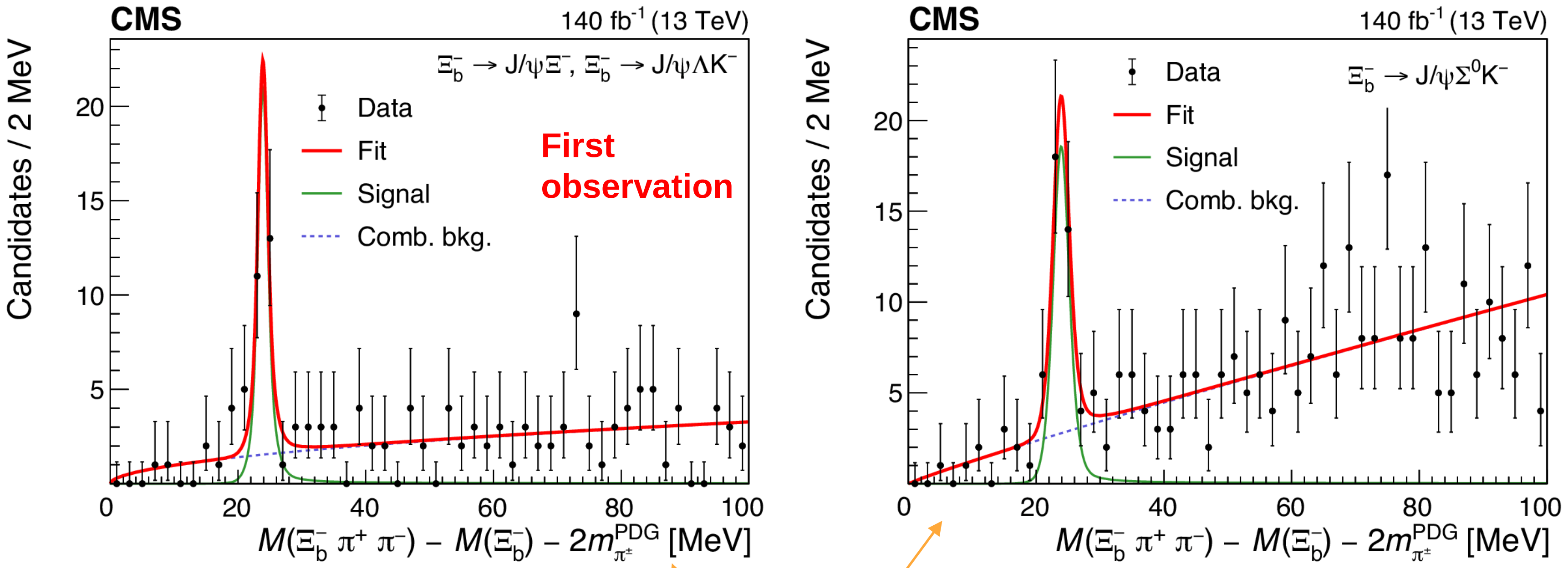
$\Xi_b^- \to J/\psi\Xi^-$: 860 clean signal candidates
$\Xi_b^- \to J/\psi\Lambda K^-$: 815 signal candidates with worse purity
$\Xi_b^- \to J/\psi\Sigma^0K^-$: 820 signal candidates with low purity

Two fully-reconstructed Ξ_b^- channels have the same $\Xi_b^-\pi\pi$ mass resolution

Partially-reconstructed Ξ_b^- channel has worse $\Xi_b^-\pi\pi$ mass resolution

CMS-BPH-20-004,
Phys.Rev.Lett.126(2021)25,252003

Observation of $\Xi_b^{**-} \to \Xi_b^- \pi\pi$



Simultaneous fit to $\Xi_b^- \pi\pi$ candidates from fully- and partially-reconstructed Ξ_b^- channels

A narrow peak is observed near the mass threshold, significance **>6σ**

Measured mass and width are:

$$M(\Xi_b(6100)^-) = 6100.3 \pm 0.2 \pm 0.1 \pm 0.6\ MeV$$
$$\Gamma(\Xi_b(6100^-)) < 1.9\ MeV\ @95\%\ CL$$

CMS-BPH-20-004, *Phys.Rev.Lett.*126(2021)25,252003

Summary

- The decay $\Lambda_b^0 \rightarrow J/\psi \Lambda \phi$ is observed for the 1st time
- Excited Λ_b^0 baryons decaying into $\Lambda_b^0 \pi\pi$ have been studied:

  States $\Lambda_b(5912)^0$, $\Lambda_b(5920)^0$, $\Lambda_b(6146)^0$, and $\Lambda_b(6152)^0$ are confirmed and their masses are measured

  Evidence found for a new broad resonance with M ~ 6075 MeV and Γ ~ 55 MeV

- A **new** excited beauty Ξ_b^- baryon is observed, $\mathbf{\Xi_b(6100)^- \rightarrow \Xi_b^{*0} \pi^-}$

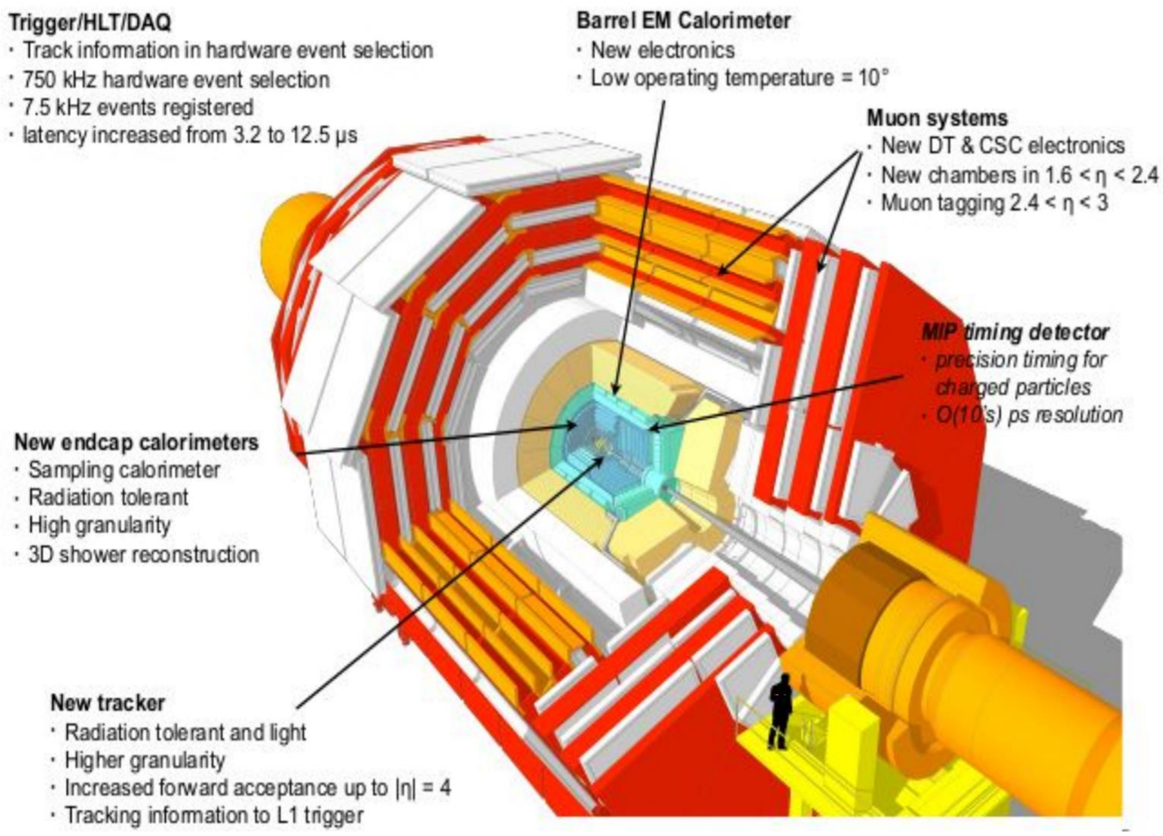
Stay tuned for new results: https://cms-results.web.cern.ch/cms-results/public-results/publications/BPH/index.html

https://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/BPH/index.html

Thank you !

Backup

CMS Phase-II Upgrade (overview)



CMS Phase-II upgrades include:

- a new tracker with improved p_T resolution and radiation hardness, lower material budget, extended coverage
- increased muon coverage
- a new forward calorimeter with high granularity and resolution
- addition of the MIP timing detector (MTD)
- increased trigger bandwidth & latencies
- inclusion of tracking information at L1 trigger
- replacement of electronics

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

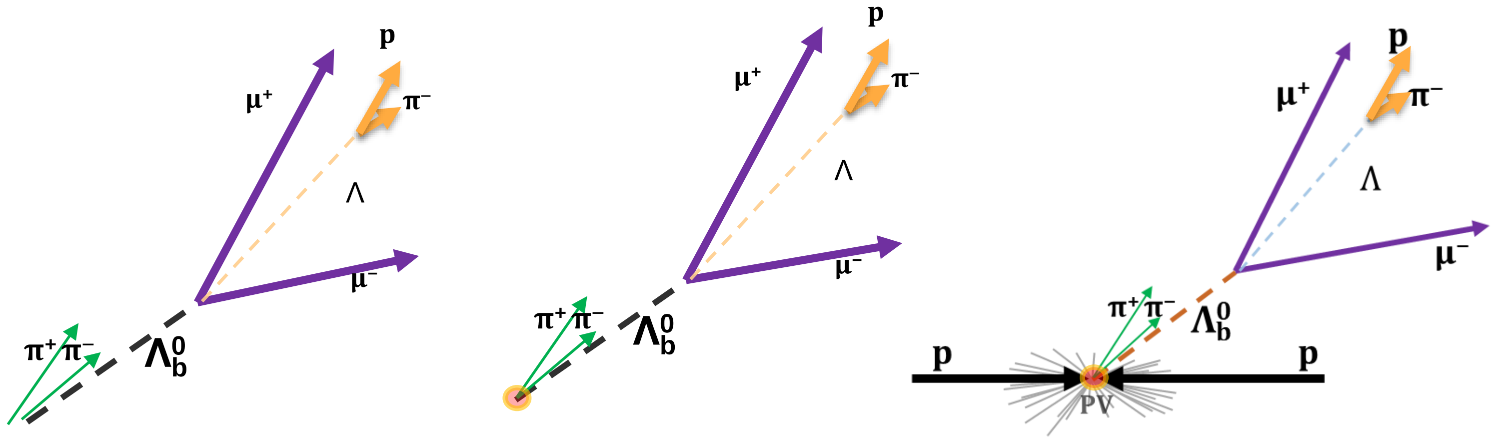
Use the mass difference variable to cancel the resolution in Λ_b^0 mass

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

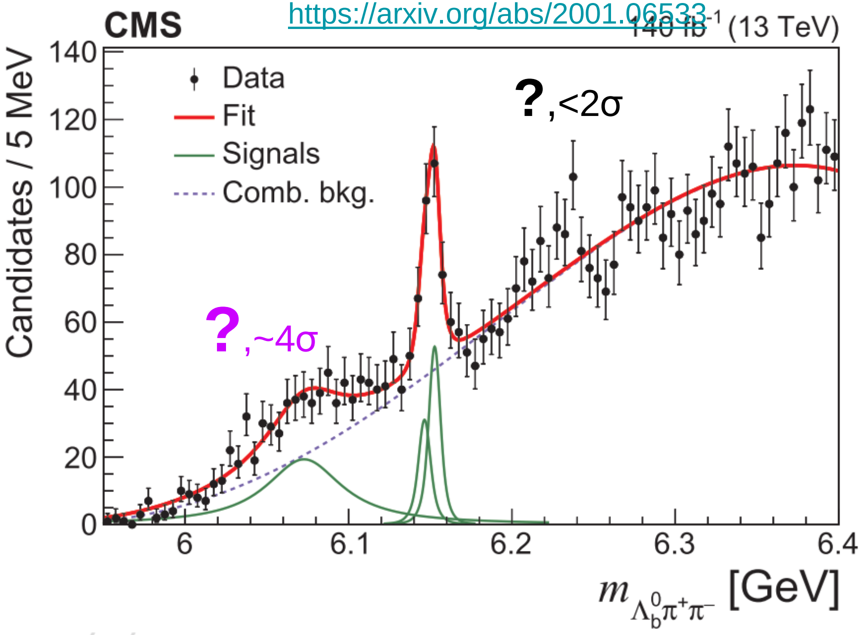
The new approach for the mass calculation:

fit **all** tracks forming the PV + Λ_b^0 candidate into a vertex and use sum of $\Lambda_b^0\pi^+\pi^-$ 4-momenta returned by this vertex fit to measure M

This new method is used for the first time in the CMS collaboration, and it **improves the mass resolution by up to 50%** compared to just using the $\Lambda_b^0\pi\pi$ vertex fit.



Additional studies to understand the wide enhancement



https://arxiv.org/abs/2001.06533

Fit function:

BW convolved with DG*

for $\Lambda_b(6146)$, fixed Γ to LHCb, N and M free

+ BW convolved with DG*

for $\Lambda_b(6152)$, fixed Γ to LHCb, N and M free

+ BW convolved with DG*

for the wide excess, Γ, N, and M free

+ $(x-x_0)^{\alpha}$ • Pol1(x) for bkg

*DG = Double Gaussian, resolution function from MC with all parameters fixed

Results:

$N(\Lambda_b(6146))$ = 70±35, M = 6146.5±1.9 MeV

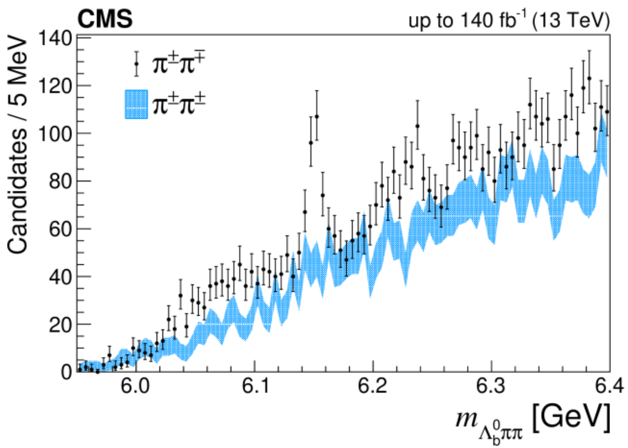
$N(\Lambda_b(6152))$ = 113±35, M = 6152.7±1.1 MeV

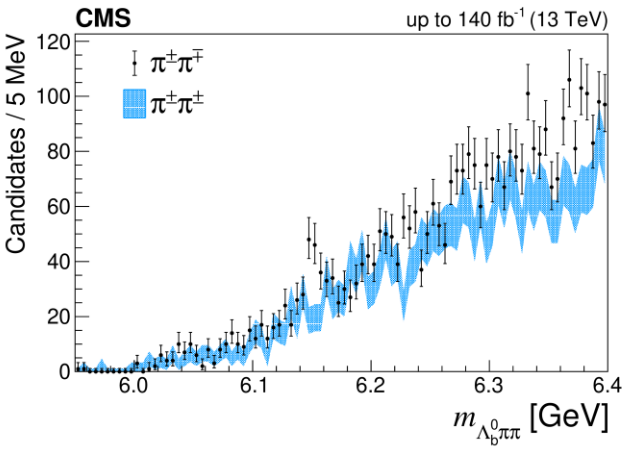
N(wide peak) = 301±72, M = 6073 ± 5 MeV, Γ = 55 ± 11 MeV

(statistical-only uncertainties)

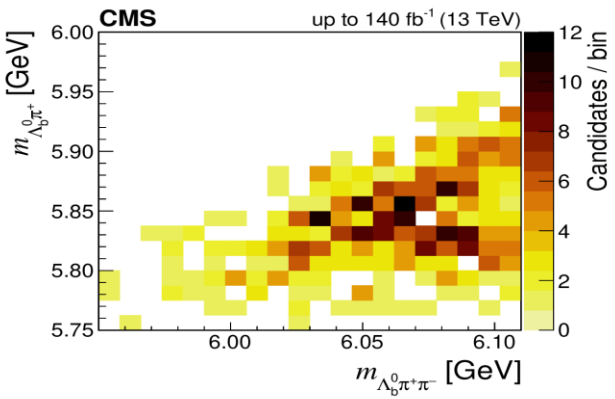
Additional studies to understand the wide enhancement

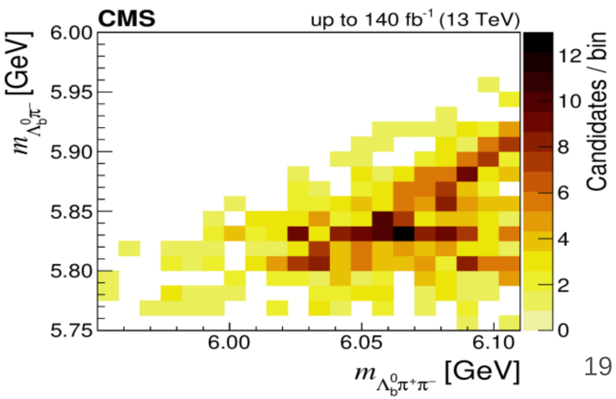
- The nature of enhancement in the <6100 MeV region is unclear
- It is not present in same-sign (SS) distribution
- If the $\Sigma_b^{(*)}$ are vetoed, the SS and OS distribution are in agreement





- 2-dimensional plots also indicate the correlation between the broad excess and $\Sigma_b^{(*)}$





Systematic uncertainties (excited Lb states)

- Choice of the signal model
- Choice of the background model
- Difference of the mass resolution between data and MC
- Detector misalignment (negligible)
- Knowledge of Γ for $\Lambda_b(6146)^0$ and $\Lambda_b(6152)^0$ states
- Fit range
- Presence of the wide enhancement for high-mass region

Table 1: Systematic uncertainties (in MeV) in the measured masses. Zero means that the corre sponding uncertainty is negligible.

Source	$M(\Lambda_b(5912)^0)$	$M(\Lambda_b(5920)^0)$	$M(\Lambda_b(6146)^0)$	$M(\Lambda_b(6152)^0)$
Signal model	0.005	0.011	0.21	0.23
Background model	0.004	0	0.16	0.14
Inclusion of the wide bump region	—	—	0.35	0.14
Fit range	0	0	0.40	0.02
Mass resolution	0.007	0.001	0.01	0.09
Knowledge of Γ	—	—	0.43	0.26
Total	0.009	0.011	0.77	0.41

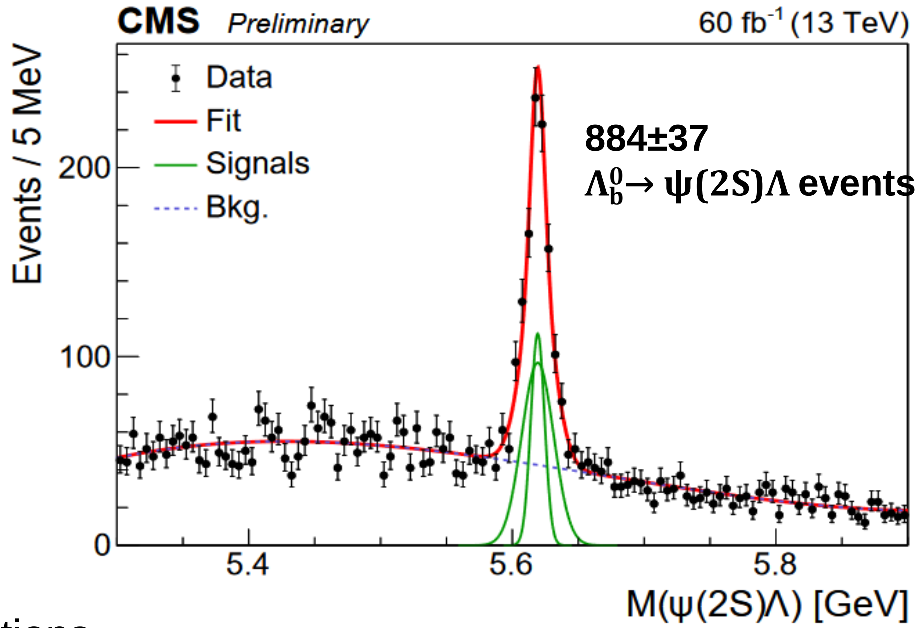
Observation of the $\Lambda_b^0 \to J/\psi \Lambda \varphi$ decay

- Event selection:
  - $\mu^+\mu^-$ form a good quality-vertex, $p_T(\mu)>4$ GeV, $M(\mu\mu)$ in ±100 MeV from J/ψ mass
  - $\Lambda \to p\pi^-$ candidates formed from displaced 2-prong vertices, $p_T(\Lambda) > 1$ GeV
  - Two OS tracks form $\varphi \to K^+K^-$ candidate, $p_T(K) > 0.8$ GeV, $0.99 < M(KK) < 1.05$ GeV
  - Λ_b^0 obtained by vertex fitting $\mu^+\mu^-K^+K^-\Lambda$, with $\mu^+\mu^-$ mass constrained to $m_{J/\psi}$
  - Λ_b^0 vertex $L_{xy}/\sigma_{Lxy} > 3$, $\cos(\Lambda_b^0$ pointing angle$) > 0.99$, vertex fit probability > 1%

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

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

$$\varepsilon \text{ from MC} \rightarrow \frac{\varepsilon(\Lambda_b^0 \to \psi(2S)\Lambda)}{\varepsilon(\Lambda_b^0 \to J/\psi\Lambda\varphi)} = 0.36 \pm 0.01$$



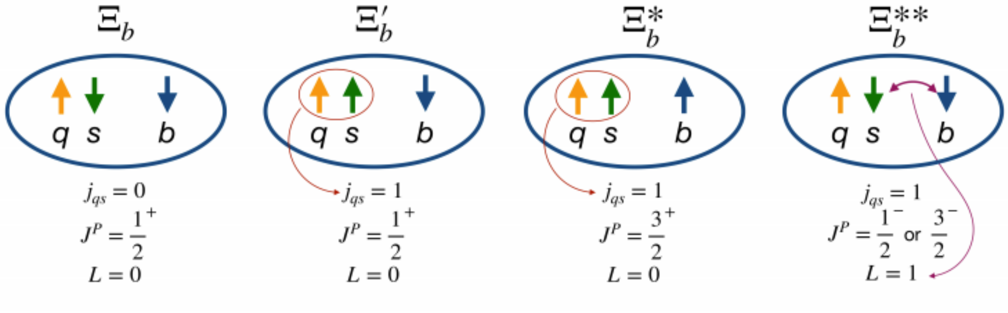
884±37
$\Lambda_b^0 \to \psi(2S)\Lambda$ events

Systematic uncertainties:

- Data/MC difference in mass resolution
- MC sample size
- Variations of background models
- Variations of signal models
- Data/MC difference in kinematic distributions

Total systematic uncertainty
8.2%

Spectroscopy of beauty strange baryons



q denotes u or d quarks for Ξ^0_b or Ξ^-_b. $L = 1$ is the orbital excitation between the light diquark qs and heavy b quark.