Recent CMS heavy flavour physics results

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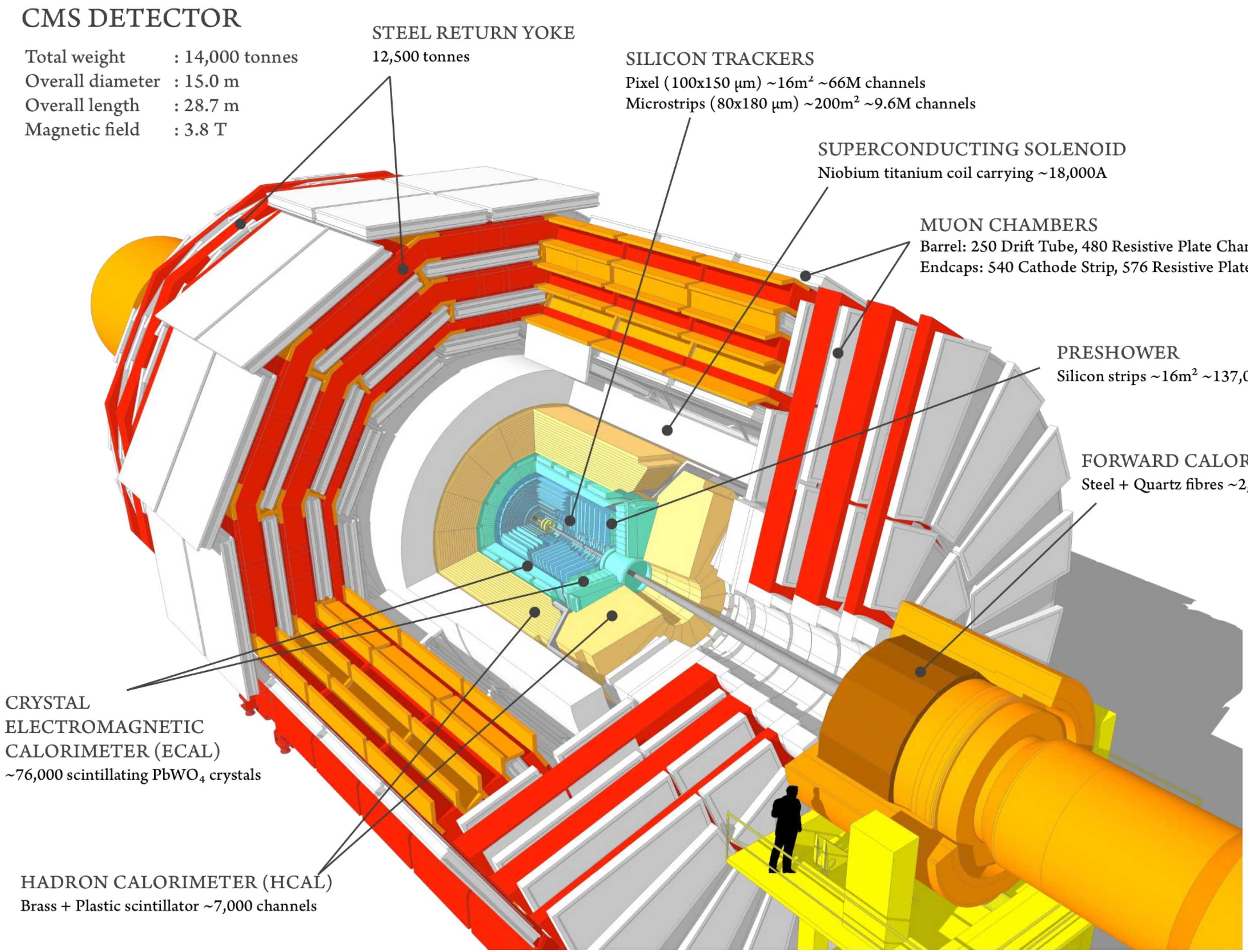
Outline

- CMS experiment
- X(3872) production in PbPb collisions
- Excited B_c^+ states
- Excited Λ_b^0 states

- More – to be presented by Ruslan in the next talk

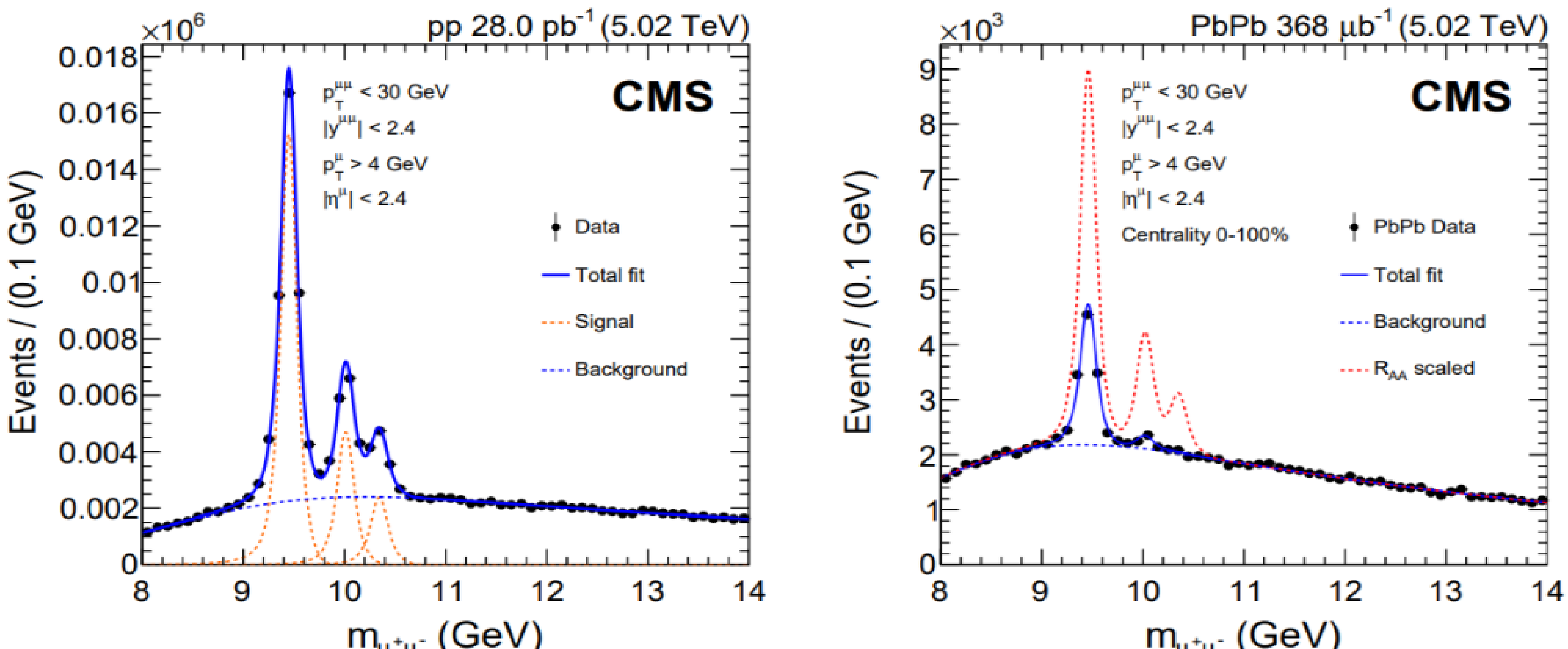
CMS experiment



Quarkonia production in PbPb

Excited quarkonia states production is known to be suppressed in heavy ion collisions

$$R_{\mathrm{AA}}(\Upsilon(1\mathrm{S})) > R_{\mathrm{AA}}(\Upsilon(2\mathrm{S})) > R_{\mathrm{AA}}(\Upsilon(3\mathrm{S}))$$

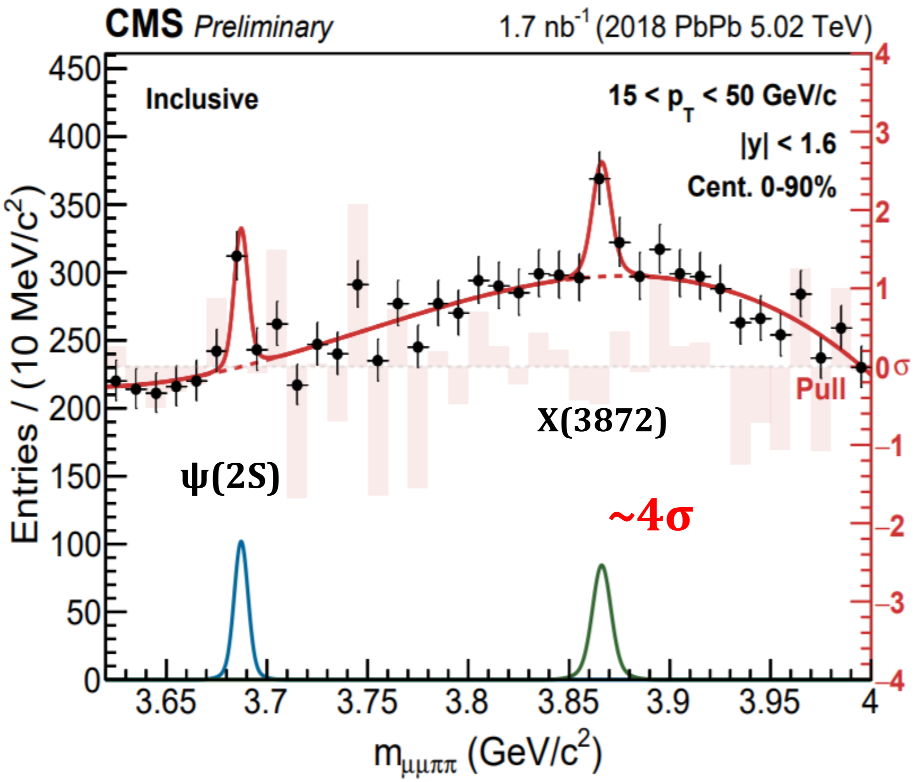


Phys. Lett. B 790 (2019) 270

X(3872) production in PbPb

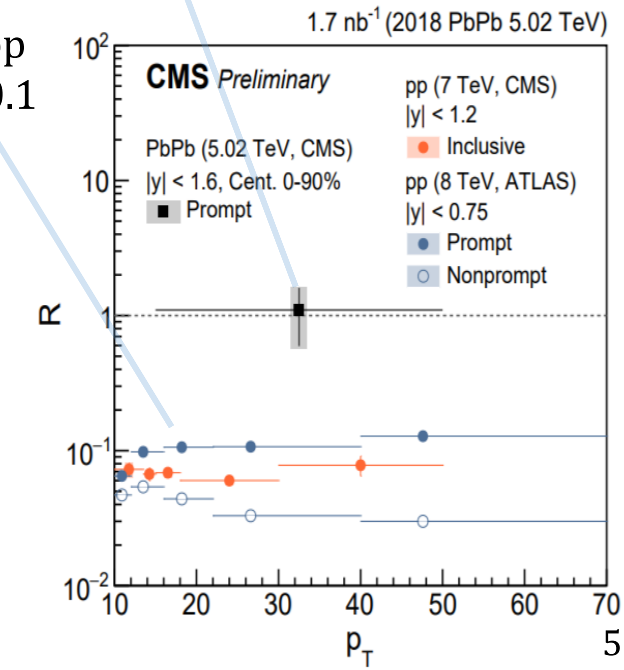
X(3872) state is very close to DD* threshold, its nature is not established

CMS finds a **first evidence** for X(3872) production in PbPb collisions
CMS-HIN-19-005 (Preliminary)



Ratio of efficiency-corrected yields
after non-prompt subtraction
$\mathbf{R_{X/\psi} = 1.10 \pm 0.51 \pm 0.53}$

Same ratio in pp collisions is ≲0.1

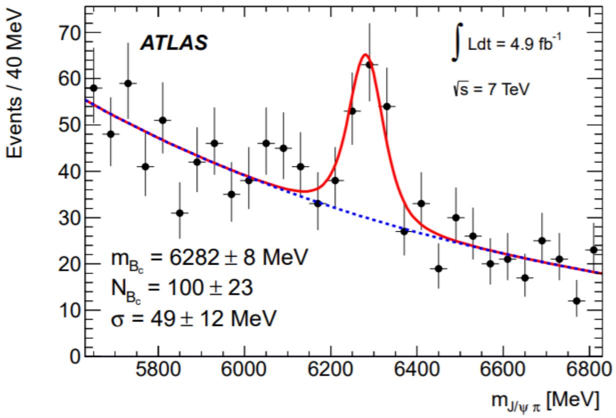


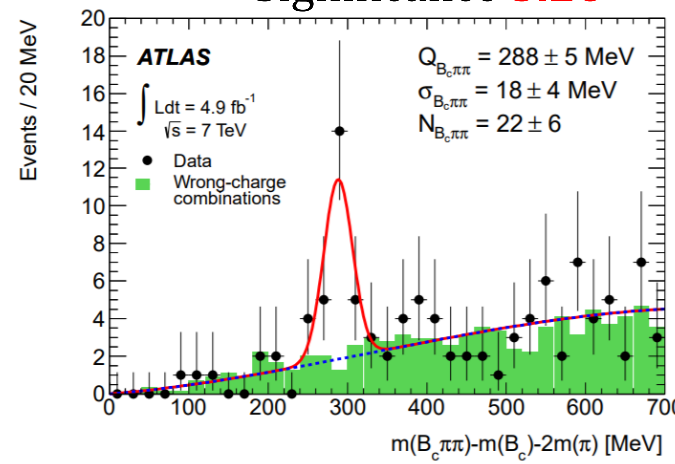
X(3872) production enhanced w.r.t. ψ(2S) in PbPb collisions (2σ), can this give a hint on X(3872) nature ?

Excited B_c^+ states (ATLAS)

ATLAS: 10.1103/PhysRevLett.113.212004

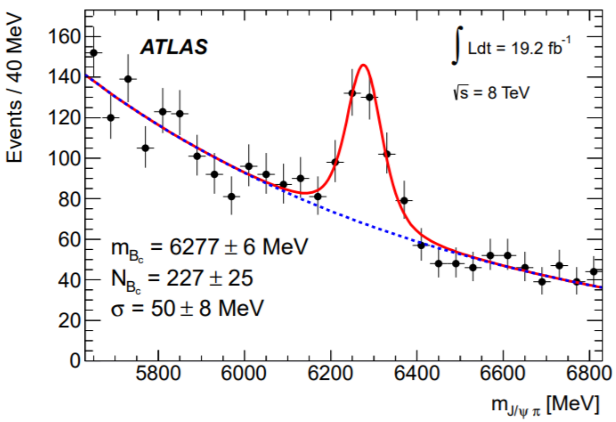
Significance **5.2σ**

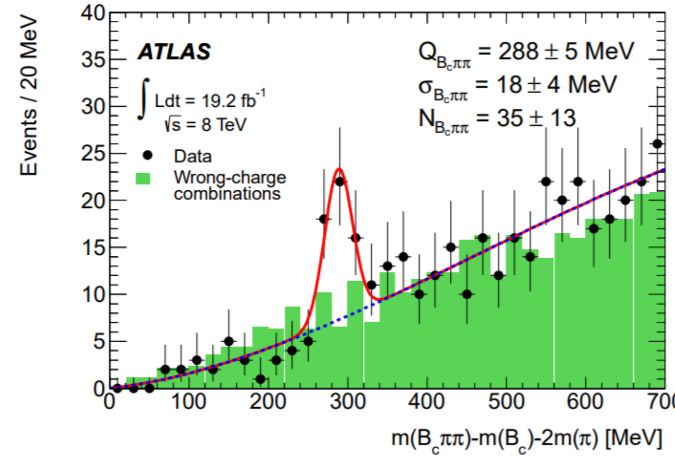




327 B_c^+

57 $B_c(2S)^+$?



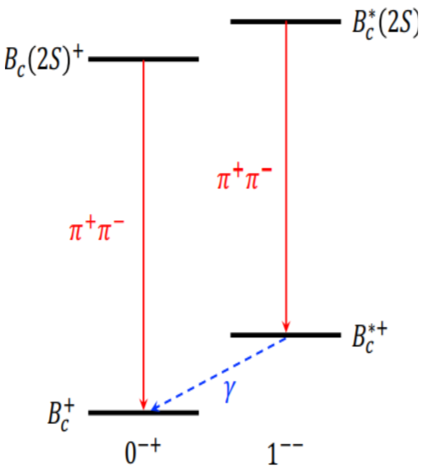


Using Run-1 data, an excited state $B_c(2S)^+$ was observed in $B_c^+\pi^+\pi^-$ spectrum
Mass measured to be 6842 ± 4 ± 5 MeV

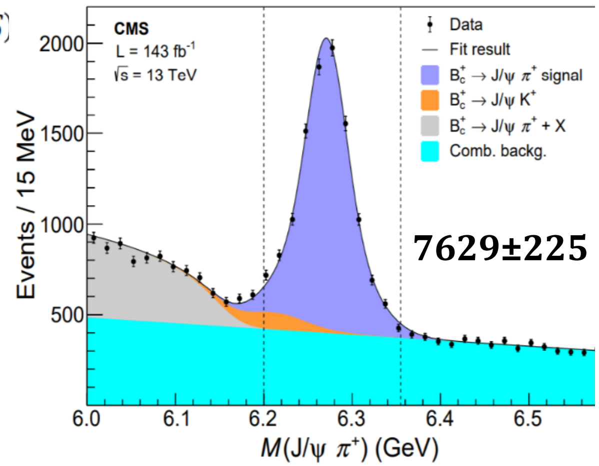
However, the ratio of $B_c(2S)^+$ / B_c^+ yields is unexpectedly large: 17.4%

If efficiency of pion reconstruction is ~0.7, it means that 35% of B_c^+ mesons are produced in $B_c(2S)^+$ decays

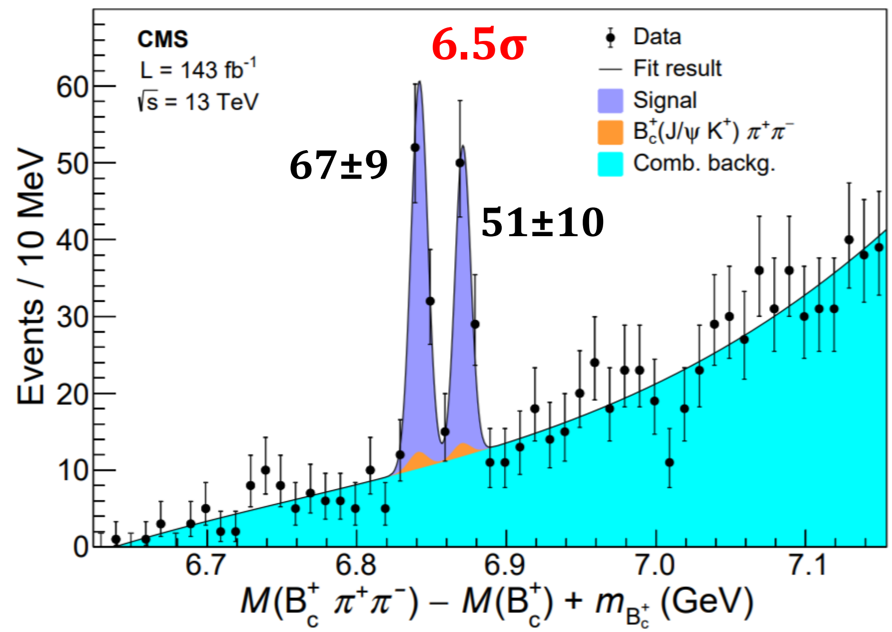
Excited B_c^+ states (CMS)



Phys. Rev. Lett. 122 (2019) 132001



Phys. Rev. Lett. 122 (2019) 132001



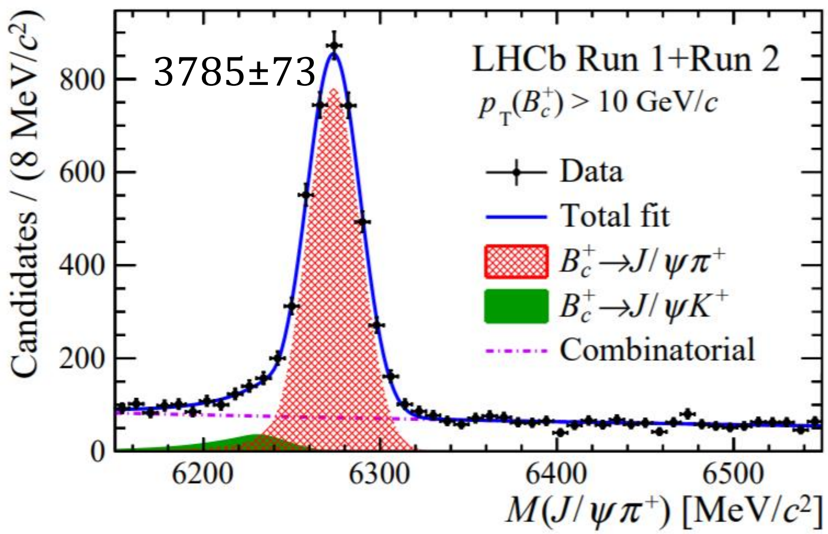
Using 143 fb^{-1} of Run-2 data,
CMS observed TWO peaks (**6.5σ**) in $B_c^+\pi^+\pi^-$ spectrum
There are 2 expected states, $B_c(2S)^+$ and $B_c(2S)^{*+}$, decaying as
$B_c(2S)^+ \to B_c^+\pi^+\pi^-$
$B_c(2S)^{*+} \to B_c^{*+}\pi^+\pi^-$, followed by $B_c^{*+} \to B_c^+\gamma$ *(soft photon not detected)*

Peaks are separated by $\Delta M = M(B_c^{*+}) - M(B_c^+) - [M(B_c(2S)^{*+}) - M(B_c(2S)^+)]$
ΔM is expected to be > 0 → The higher-mass peak is $B_c(2S)^+$, the lower-mass one is $B_c(2S)^{*+}$

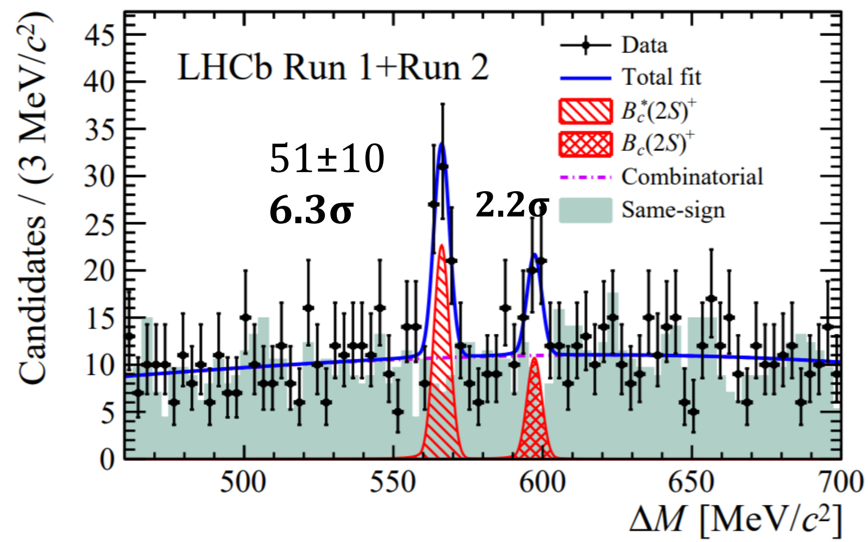
$$\boxed{\begin{aligned} M(B_c(2S)^+) &= 6871.0 \pm 1.2 \pm 0.8 \pm 0.8\,(B_c^+)\ \text{MeV} \\ \Delta M &= 29.1 \pm 1.5 \pm 0.7\ \text{MeV}\end{aligned}}$$

Production ratio measurement in preparation, stay tuned !

Excited B_c^+ states (LHCb)



Phys. Rev. Lett. 122, 232001 (2019)



Using 8.5 fb^{-1} of Rin-1 + Run-2 data, LHCb observed one of the peaks (**6.3σ**) in $B_c^+\pi^+\pi^-$ spectrum, the other has only 2.2σ significance

$M(B_c(2S)^+) = 6872.1 \pm 0.6 \pm 0.1 \pm 0.8\,(B_c^+)$ MeV

$\Delta M = 31.0 \pm 1.4$ MeV

Most precise measurements !

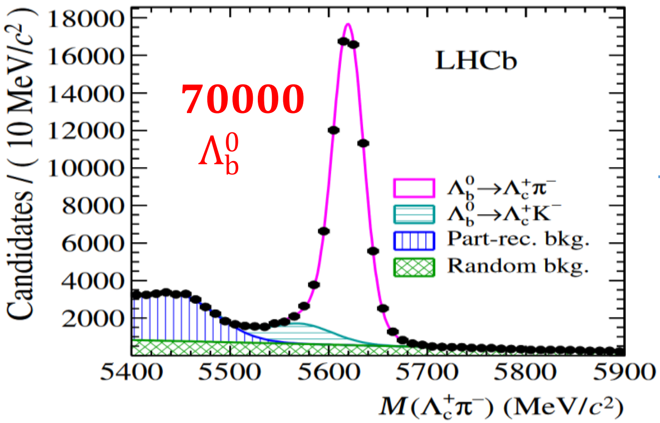
CMS measurements:

$M(B_c(2S)^+) = 6871.0 \pm 1.2 \pm 0.8 \pm 0.8\,(B_c^+)$ MeV

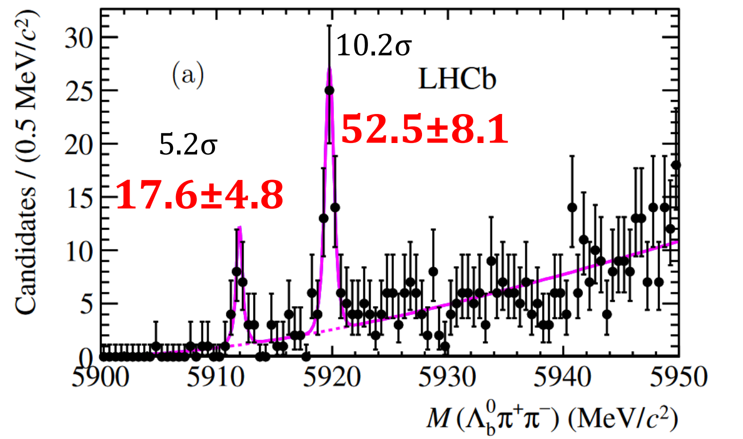
$\Delta M = 29.1 \pm 1.5 \pm 0.7$ MeV

Excited Λ_b^0 states: introduction

LHCb, 2012: using 1fb^{-1} of 2011 data observed excited $\Lambda_b^{*0} \to \Lambda_b^0 \pi^+\pi^-$



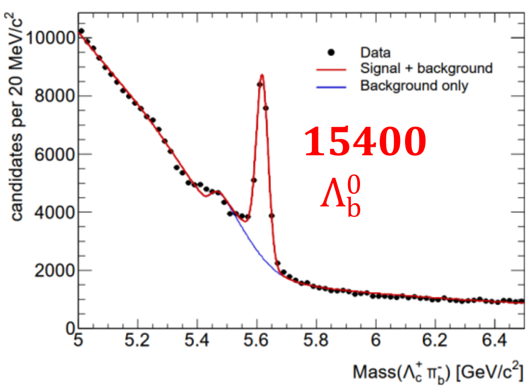
add $\pi^+\pi^-$



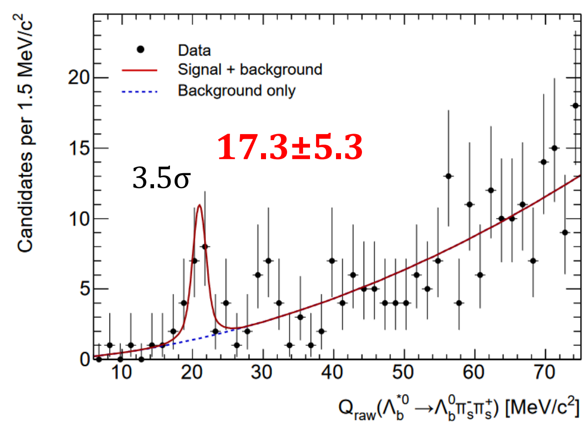
[10.1103/PhysRevLett.109.172003](https://doi.org/10.1103/PhysRevLett.109.172003)

$$M_{\Lambda_b^{*0}(5912)} = 5911.97 \pm 0.12 \pm 0.02 \pm 0.66\ \text{MeV},$$
$$M_{\Lambda_b^{*0}(5920)} = 5919.77 \pm 0.08 \pm 0.02 \pm 0.66\ \text{MeV},$$

CDF, 2013: confirmed (3.5σ) only one, heavier state $\Lambda_b^*(5920)^0 \to \Lambda_b^0 \pi^+\pi^-$



add $\pi^+\pi^-$

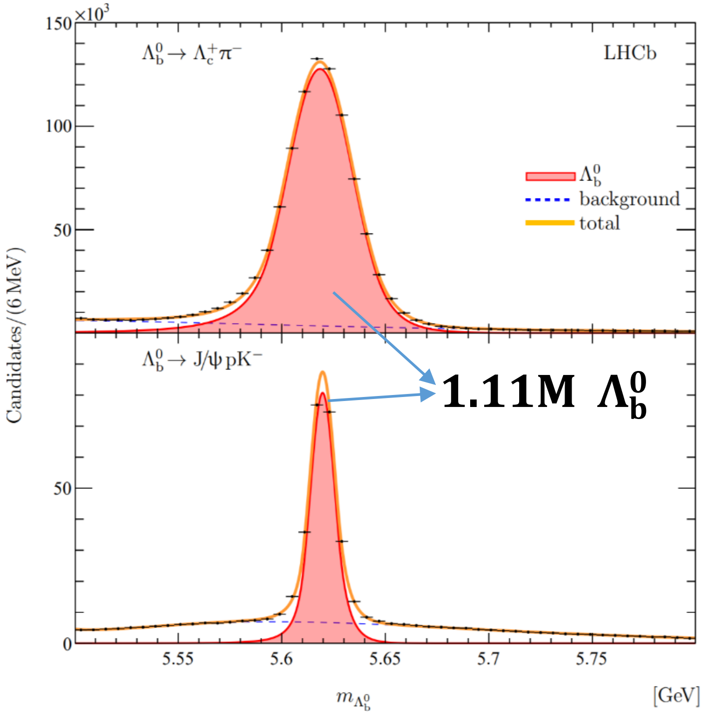


In CMS, we cannot use Λ_c^+: no dedicated trigger, large background since no hadron ID

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

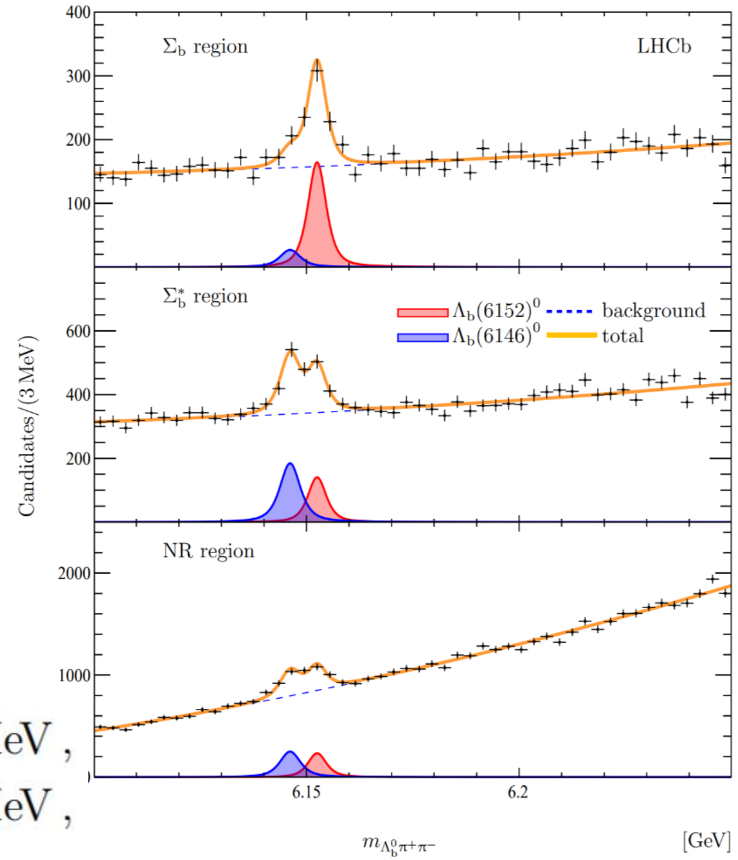
Excited Λ_b^0 states: introduction

LHCb, 2019: using all 9fb^{-1} of 2011-2018 data observed **new** excited $\Lambda_b^{*0} \to \Lambda_b^0 \pi^+\pi^-$



add $\pi^+\pi^-$

[PHYS. REV. LETT. 123 (2019) 152001]



$$
\begin{aligned}
m_{\Lambda_b(6146)^0} &= 6146.17 \pm 0.33 \pm 0.22 \pm 0.16\,\text{MeV}\,,\\
m_{\Lambda_b(6152)^0} &= 6152.51 \pm 0.26 \pm 0.22 \pm 0.16\,\text{MeV}\,,\\
\Gamma_{\Lambda_b(6146)^0} &= 2.9 \pm 1.3 \pm 0.3\ \text{MeV}\,,\\
\Gamma_{\Lambda_b(6152)^0} &= 2.1 \pm 0.8 \pm 0.3\ \text{MeV}\,,
\end{aligned}
$$

In CMS, we cannot use Λ_c^+: no dedicated trigger, large background since no hadron ID

Usage of $\Lambda_b^0 \to J/\psi p K^-$ is very difficult due to high background since no hadron ID

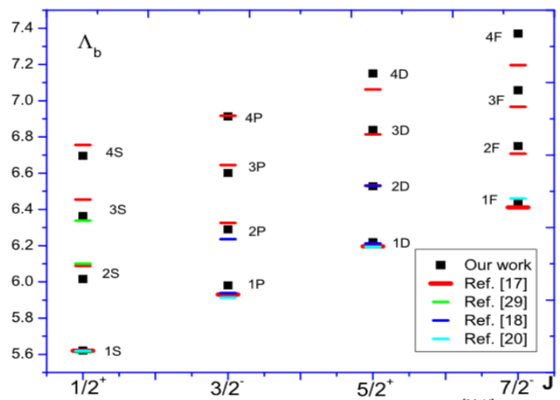
However, we can use $\Lambda_b^0 \to J/\psi\Lambda$ and $\Lambda_b^0 \to \psi(2S)\Lambda$ decays to reconstruct Λ_b^0

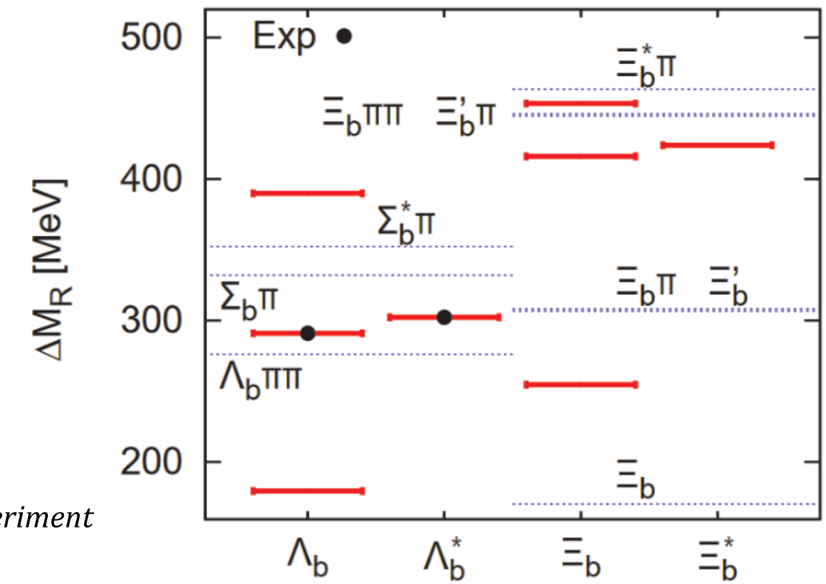
Excited Λ_b^0 states: introduction

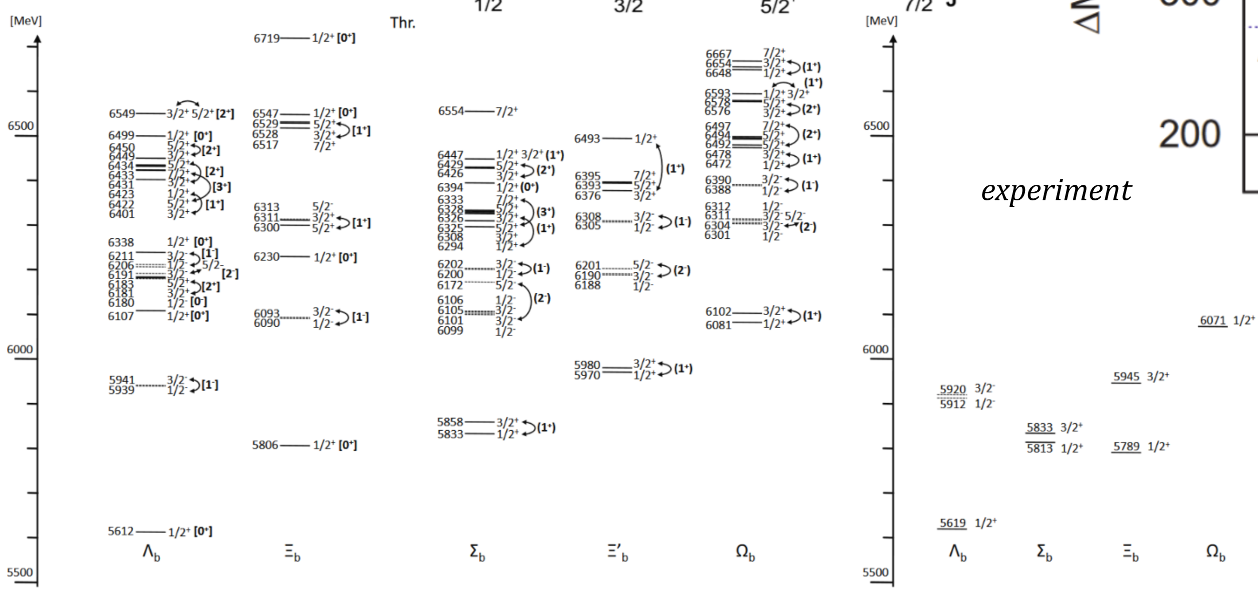
There are many theoretical predictions of excited Λ_b and Σ_b states, but the predicted masses are spread in rather wide regions and do not point to any particular narrow window to search for a signal.

Some of them agree with (or "explain") LHCb measurements, some do not.

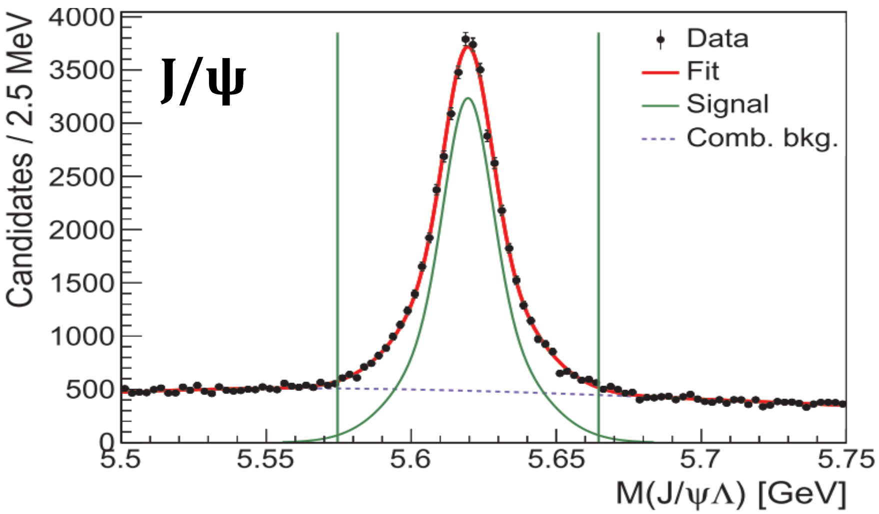
(Most predictions do not have uncertainties so it is often hard to say if there is agreement or not)

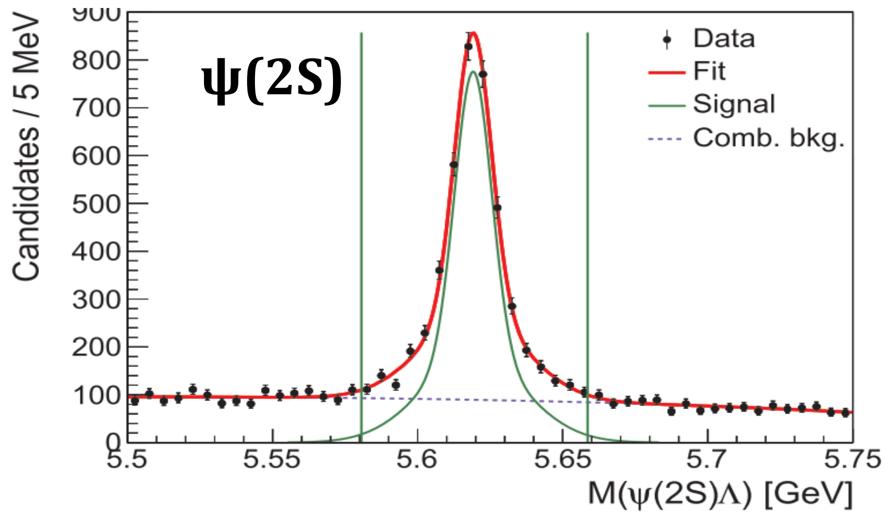


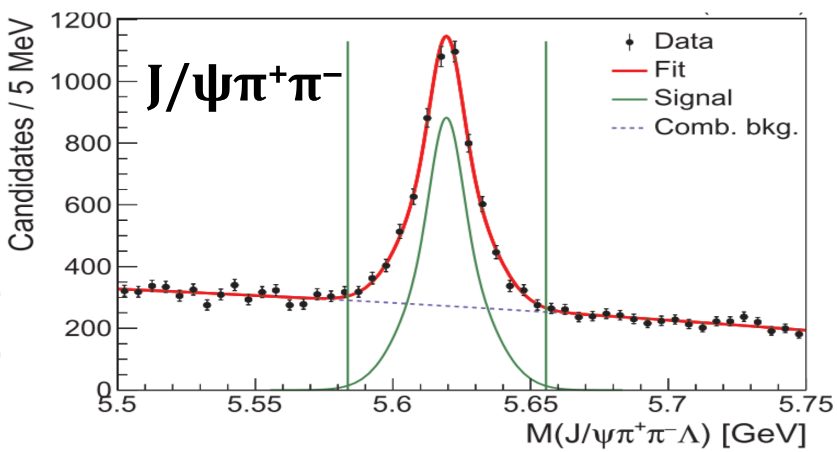




$\Lambda_b^0 \rightarrow \psi\Lambda$ signals







Fit: Double-Gaussian with common mean
+ Exp x Pol_1

$\pm 3\sigma_{eff}$ windows are used in the following

In total ~46K Λ_b^0 events

LHCb: >1M

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

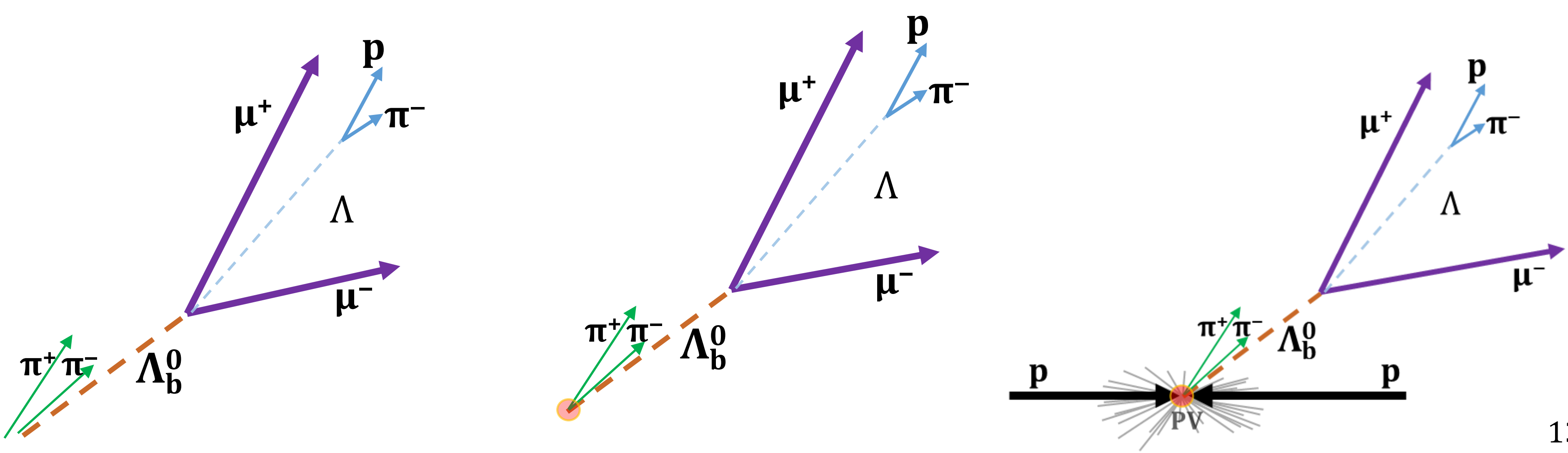
Use the mass difference variable to cancel the resolution in Λ_b^0 mass

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

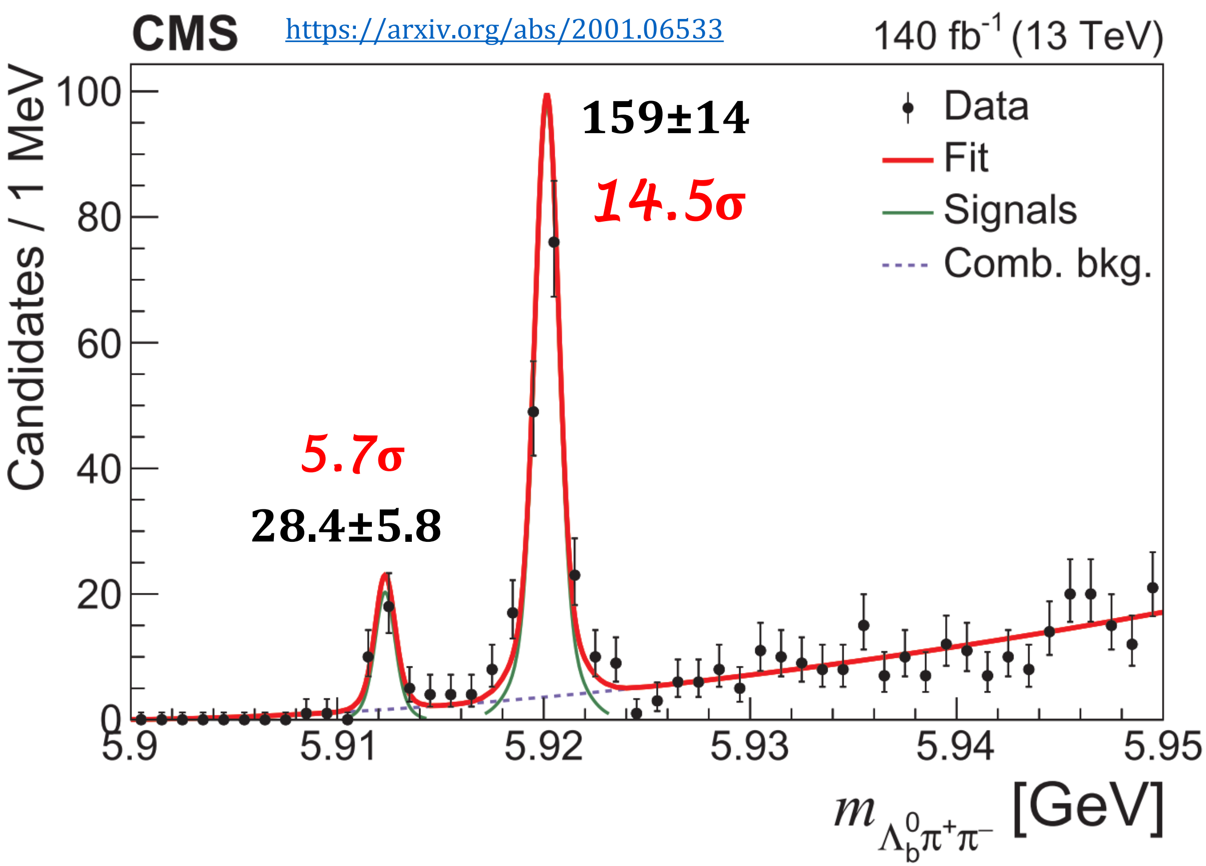
The new approach for the mass calculation:

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.



Near-threshold $\Lambda_b^0\pi^+\pi^-$ invariant mass distribution



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

Fit:

2 double-Gaussian functions for signal, with shapes fixed to MC, free M and N

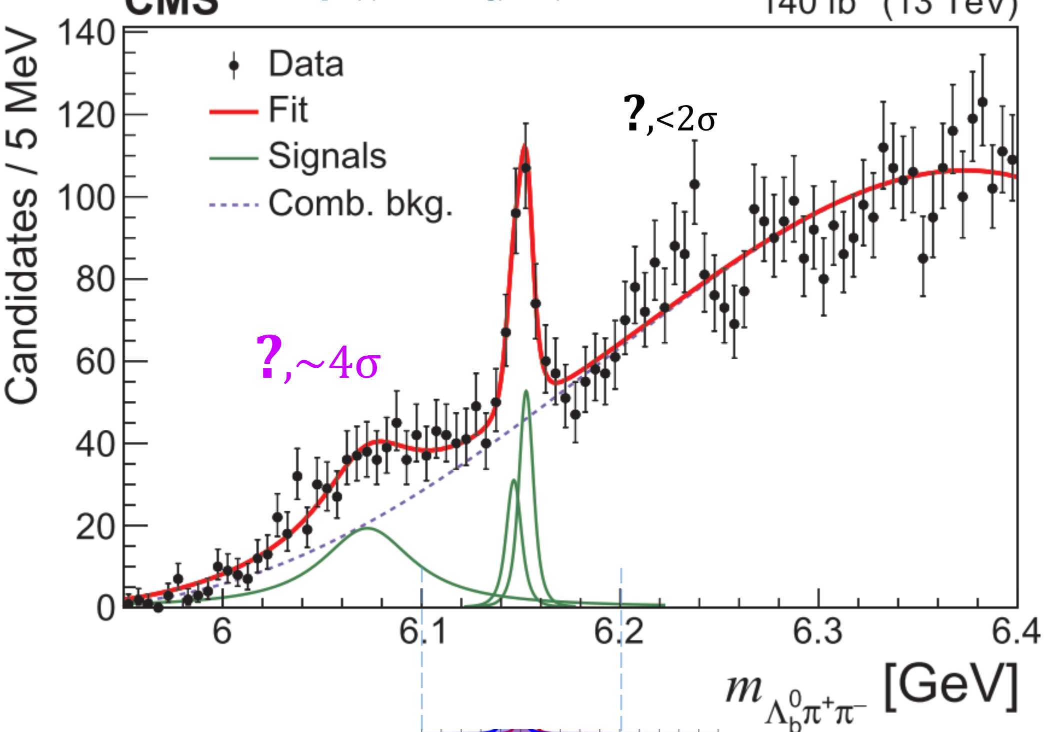
$+ (x-x_0)^\alpha$ for background, x_0 = fixed threshold value, α is free

Results: $M(\Lambda_b(5912)^0)$ = 5912.32±0.12 (stat) MeV

$M(\Lambda_b(5920)^0)$ = 5920.16±0.07 (stat) MeV

High-mass $\Lambda_b^0\pi^+\pi^-$ distribution

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*

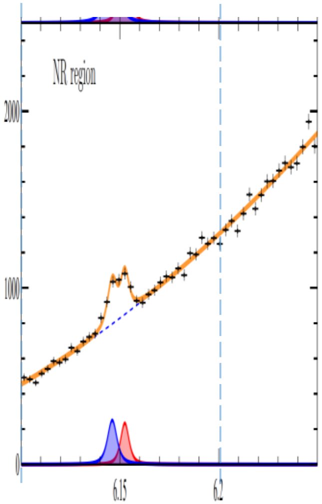
for the wide excess, Γ, N, and M free

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

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

LHCb:

Phys.Rev. Lett. 123 (2019) 152001



Results: N(Λ_b(6146)) = 70±35, M = 6146.5±1.9 MeV

N(Λ_b(6152)) = 113±35, M = 6152.7±1.1 MeV

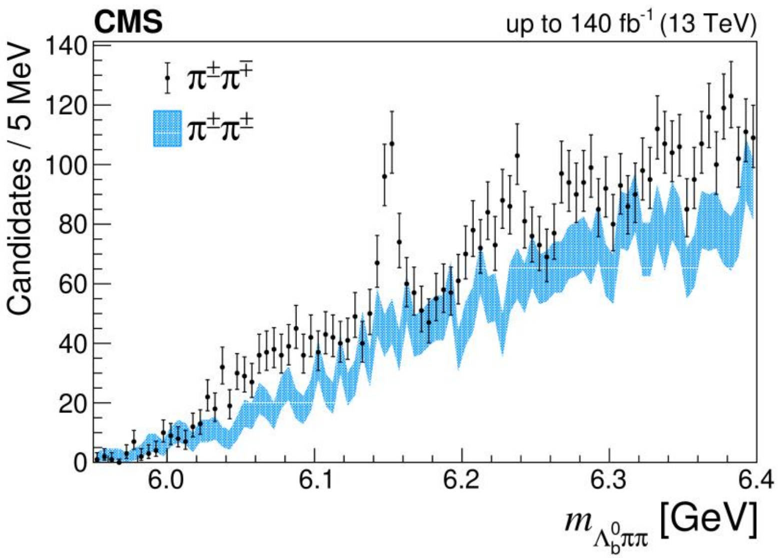
N(wide peak) = 301±72, M = 6073 ± 5 MeV,

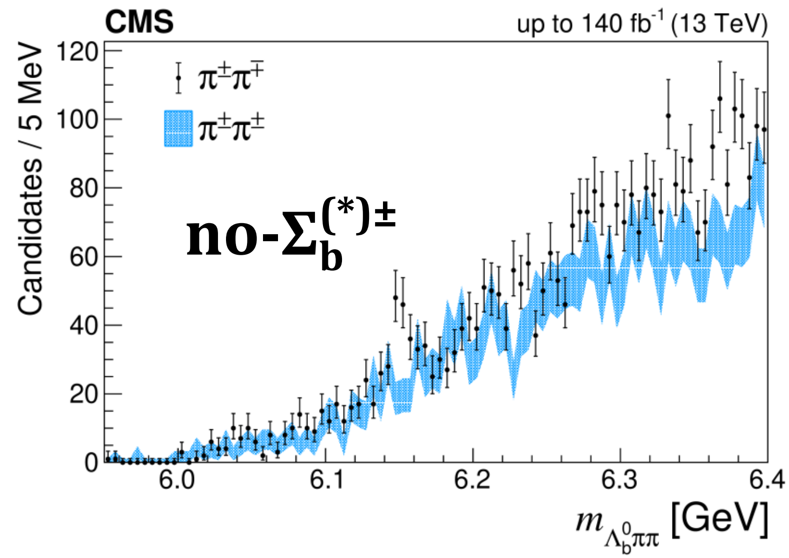
Γ = 55 ± 11 MeV

(statistical-only uncertainties)

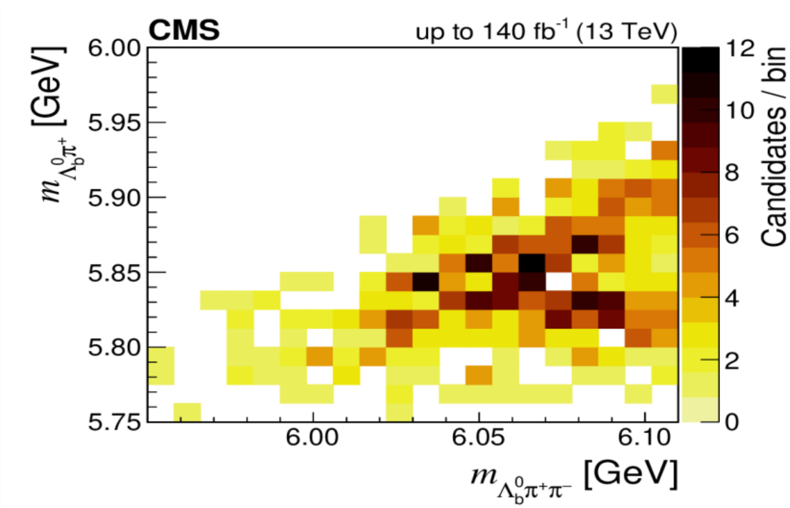
Additional studies to understand the wide enhancement

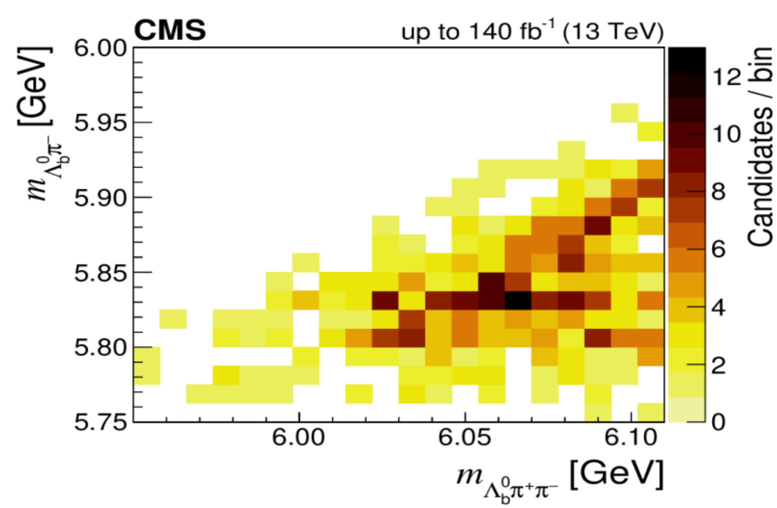
- The nature of enhancement in the <6100 MeV region is unclear
- It is not present in same-sign (SS) distribution
- If the $\Sigma_b^{(*)}$ are vetoed, the SS and OS distribution are in agreement





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





Systematic uncertainties

- 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

Results

A study of excited Λ_b^0 states decaying into $\Lambda_b^0\pi^+\pi^-$ is performed using 2016-2018 data

$\Lambda_b^0 \to J/\psi\Lambda$ and $\Lambda_b^0 \to \psi(2S)\Lambda$ ($\psi(2S)\to\mu^+\mu^-$ and $J/\psi\pi^+\pi^-$) decays are used to reconstruct Λ_b^0

We confirm existence of $\Lambda_b(5912)^0$, $\Lambda_b(5920)^0$, $\Lambda_b(6146)^0$ and $\Lambda_b(6152)^0$ baryons

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

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

$$M(\Lambda_b(6146)^0) = 6146.5 \pm 1.9 \pm 0.8 \pm 0.2\ \text{MeV}$$

$$M(\Lambda_b(6152)^0) = 6152.7 \pm 1.1 \pm 0.4 \pm 0.2\ \text{MeV}$$

Uncertainties are statistical, systematic, due to Λ_b^0 mass, respectively

Our results are in a good agreement with LHCb measurements

In addition, a **broad excess of events is observed in the region 6040–6100MeV**,

with a local significance of about **4σ**.

If interpreted as a single state, M = 6075 ± 5 (stat) MeV and Γ = 55 ±11 (stat) MeV.

However, it can be an overlap of more than one close states...

An excess consistent with this was later reported by LHCb

For more info visit arXiv:2001.06533 and cms-results/public-results/publications/BPH-19-003

Summary

- Evidence is found for X(3872) production in PbPb collisions
  - $X/\psi(2S)$ production enhanced ($\sim 2\sigma$) in heavy ion collisions w.r.t. pp

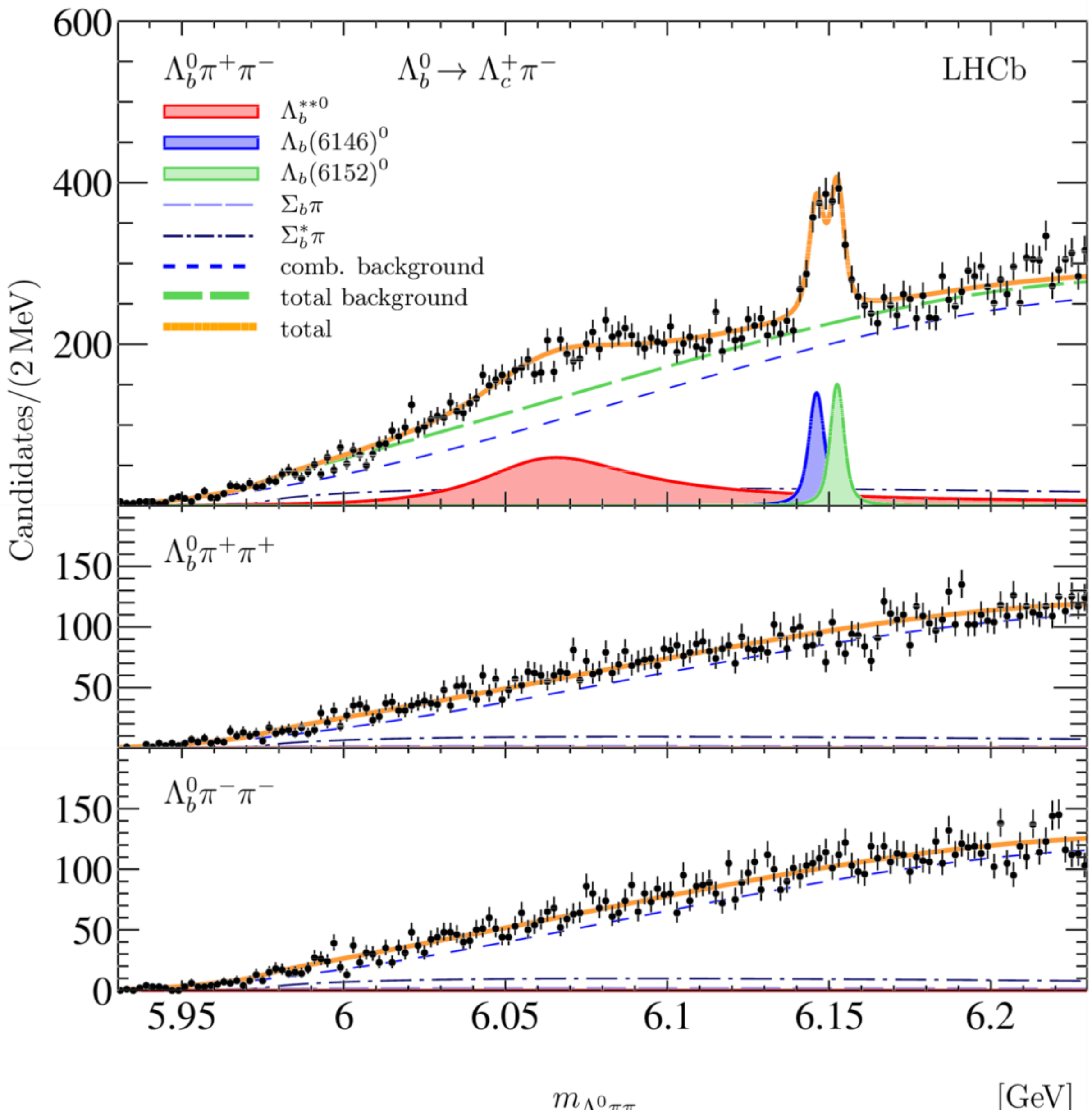
- Two excited B_c^+ states are observed by the CMS experiment
  - Masses close to the mass of a single state reported by ATLAS
  - However, production w.r.t B_c^+ meson appears to be ~x10 lower w.r.t. ATLAS
  - LHCb observes lower-mass peak, the second one has 2.2σ significance

- Excited Λ_b^0 states are studied in the $\Lambda_b^0\pi^+\pi^-$ mass spectrum
  - Existence of four states, $\Lambda_b(5912)^0$, $\Lambda_b(5920)^0$, $\Lambda_b(6146)^0$, and $\Lambda_b(6152)^0$, is confirmed, and their masses are measured
  - A new method of mass resolution improvement is developed and applied
  - A broad excess of events is observed in the region 6040–6100MeV, more data are needed to understand its nature

Thank you !

BACKUP

LHCb result on the broad excess



[ARXIV:2002.05112](https://arxiv.org/abs/2002.05112)

Resulting resonance parameters

$$m = 6072.3 \pm 2.9 \pm 0.6 \pm 0.2 MeV$$

$$\Gamma \;= 72 \pm 11 \pm 2 MeV$$

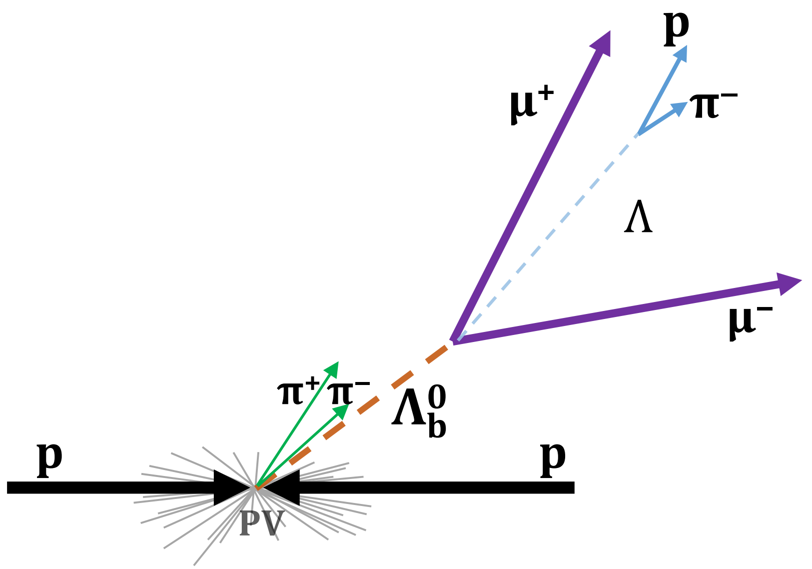
Event selection

Charge-conjugate states are implied

2016-2018 data, 140 fb^{-1}

"standard soft" selection criteria to keep efficiency high

$\Lambda_b^0 \to \psi\Lambda$ ($\mu^+\mu^-$ + $\Lambda\to p\pi^-$)
$p_T(\Lambda) > 1$ GeV,
cos(3D Λ pointing angle to Λ_b^0 vertex) > 0.99,
$L_{xy}/\sigma_{Lxy}(\Lambda$ vtx $\to \Lambda_b^0$ vtx$) > 5$
Λ mass within 10 MeV from PDG
Λ_b^0 vtx fit probability > 1%
$p_T(\Lambda_b^0) > 5$ GeV,
cos(2D Λ_b^0 pointing angle to PV) > 0.99,
$L_{xy}/\sigma_{Lxy}(\Lambda_b^0$ vtx $\to$ PV$) > 3$



No selection of specific trigger path   to increase efficiency

PV selected as the one with smallest 3D pointing angle

Additional two prompt pions are selected from tracks forming the PV

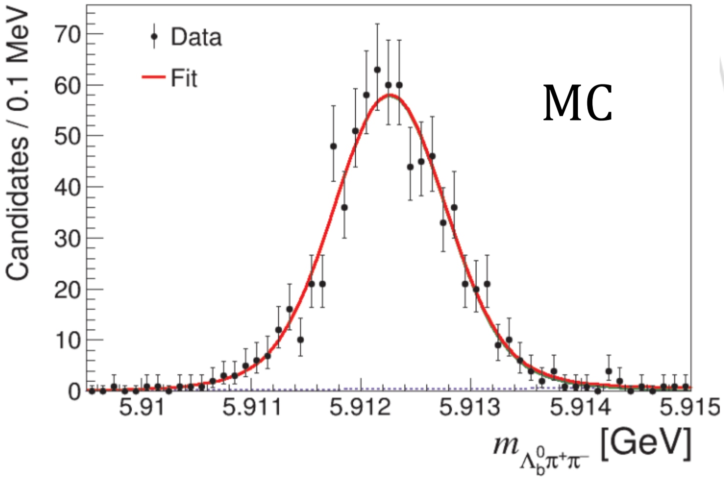
Extra channel $\Lambda_b^0 \to \psi(2S)\Lambda$, $\psi(2S)\to J/\psi\pi^+\pi^-$, $J/\psi\to\mu^+\mu^-$: as above, additional 2 pions – high-purity tracks, p_T>0.35 GeV; Λ_b^0 obtained by vertexing $\mu^+\mu^-\pi^+\pi^-\Lambda$ with J/ψ and Λ mass constraints; 3672<M($J/\psi\pi^+\pi^-$)<3700 MeV

Optimized selection criteria are found using Punzi figure of merit

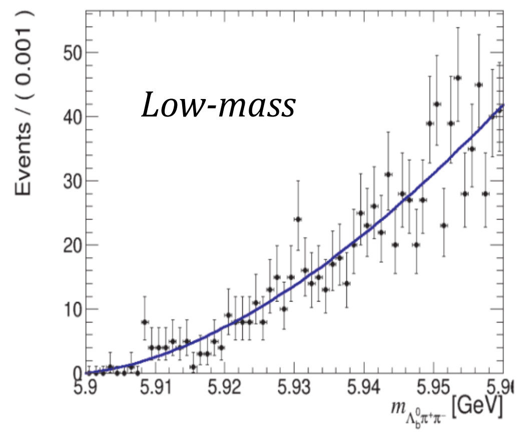
Selection optimization

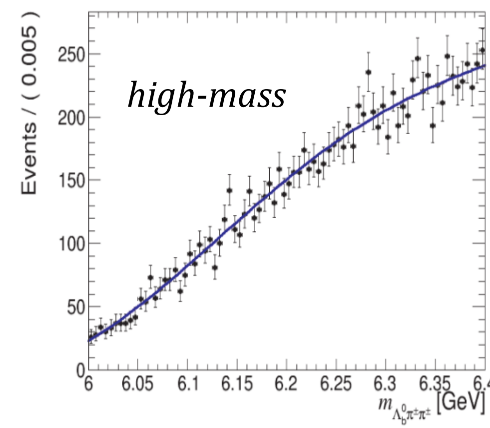
Using Punzi Figure of merit, maximizing $\boldsymbol{f = S \,/\, (5/2+\sqrt{B})}$
Independent of S normalization !

S from MC samples



B *from* control SS region $\Lambda_b^0\pi^\pm\pi^\pm$
Fit the SS distribution and calculate number of events in signal region





Optimization done separately for near-threshold region and high-mass region. Optimal cuts are:

low-mass region m < 5.95 GeV

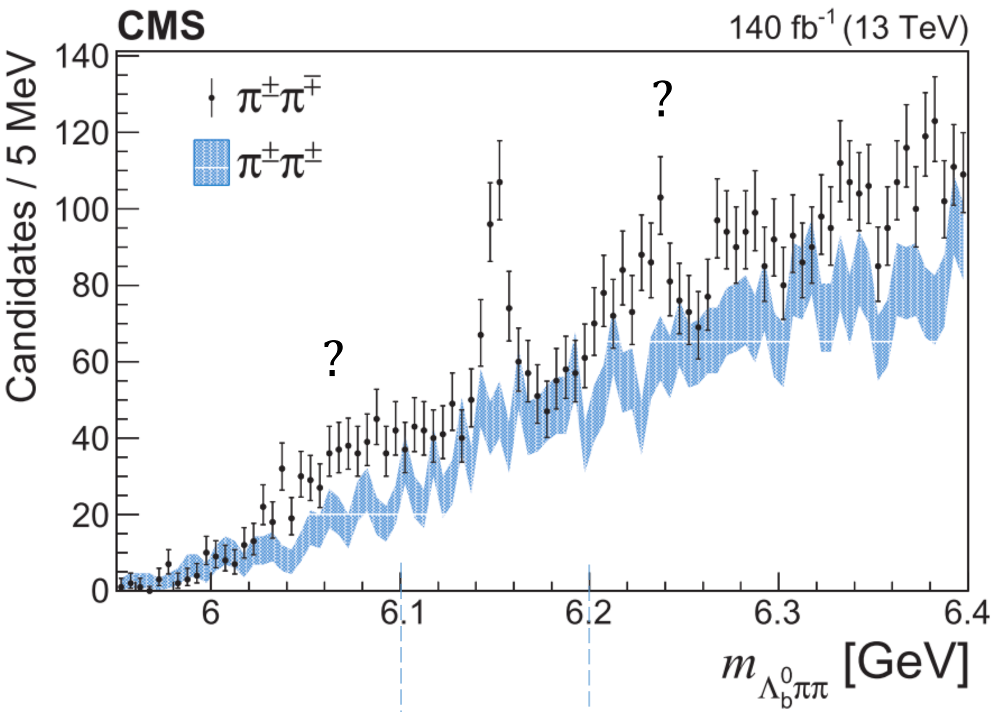
$p_T(\pi_1) > 0.35$ GeV, $p_T(\pi_2) > 0.3$ GeV
cos(3D Λ_b^0 pointing angle to PV) > 0.995
cos(2D Λ_b^0 pointing angle to PV) > 0.995
$p_T(\pi_{\Psi 2S}) > 0.4$ GeV

high-mass region m > 5.95 GeV

$p_T(\pi_1) > 1.4$ GeV, $p_T(\pi_2) > 0.7$ GeV
$p_T(\Lambda_b^0) > 16$ GeV
$P_{vtx}(\Lambda_b^0) > 2\%$
$P_{vtx}(\Lambda_b^0\pi\pi) > 8\%$
If multiple $\Lambda_b^0\pi^\pm\pi^\pm$ candidates found in event, the highest-p_T one is kept

High-mass $\Lambda_b^0\pi^+\pi^-$ distribution

Higher values of $\Lambda_b^0\pi^-\pi^+$ mass are also investigated

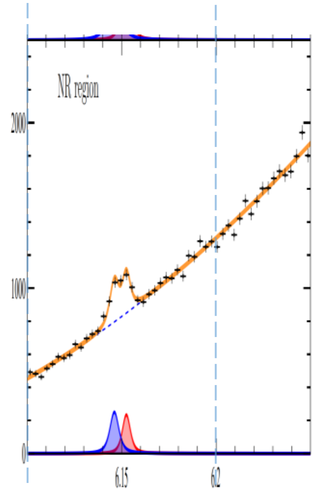


Shapes of SS and OS are different, a distinct peak at ~6150 MeV is seen, consistent with overlap of the recently discovered $\Lambda_b(6146)$ and $\Lambda_b(6152)$ states

An additional wide enhancement in the region < 6100 MeV is seen

an enhancement at ~6.25 GeV is less significant

LHCb:



Systematic uncertainties

- Choice of the signal model
  - Baseline fits use double-Gaussian resolution functions. Change it to single-Gaussian and use the measured difference in masses as syst. uncertainty

- Choice of the background model
  - Vary the order of polynomial, take the largest difference in M as s.u.

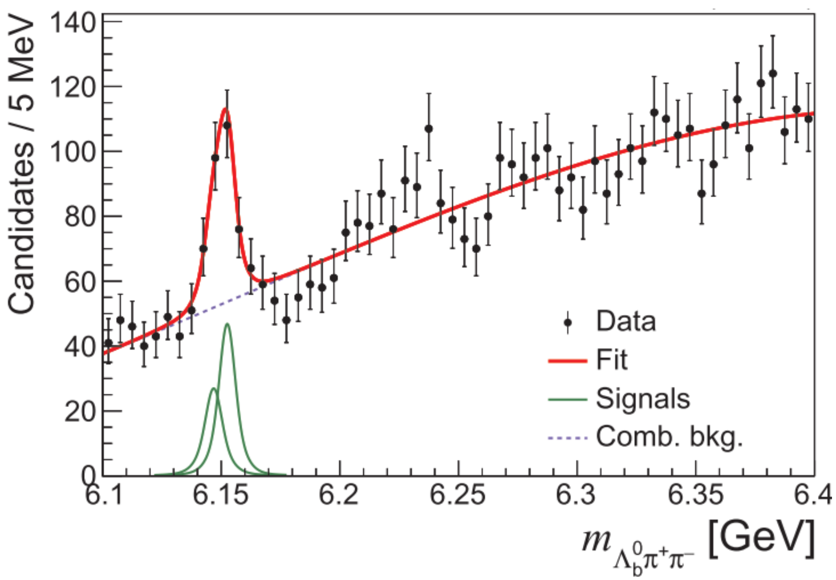
- Difference of the mass resolution between data and MC
  - Compare Λ_b^0 mass resolution agreement between data and MC, in the highest-statistics $\Lambda_b^0 \to J/\psi\Lambda$ signal. The difference of 3.5% is used to estimate the corresponding syst. uncertainty by varying the mass resolution by ±3.5%.

- Detector misalignment
  - The Λ_b^0 mass positions agree, within uncertainties, between the different years (and with PDG).
  - The pixel detector was completely changed between 2016 and 2017 data-taking periods. The detector was also demounted after 2017 data-taking and damaged ROCs were replaced before it was mounted back and put in operation in 2018.
  - Since no significant difference in the measured masses is observed between 2016, 2017, 2018, the uncertainty is neglected.
  - Same approach used un BPH-18-007 (Bc pi pi)

- Knowledge of Γ for $\Lambda_b(6146)^0$ and $\Lambda_b(6152)^0$ states
  - They are fixed in the nominal fits to the LHCb values. Γ are varied by ± the uncertainties, and the largest deviation in M taken as the syst. uncertainty.

Additional source of the systematic uncertainty due to the wide enhancement

- The nature of enhancement in the <6100 MeV region is unclear
- To account for its possible impact on the measured masses of $\Lambda_b(6146)^0$ and $\Lambda_b(6152)^0$ states, the region <6100 MeV is excluded from the fit



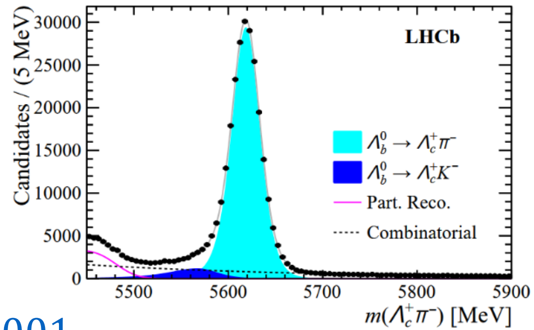
- And the observed differences of 0.35 and 0.14 MeV are used as systematic uncertainties for $\Lambda_b(6146)^0$ and $\Lambda_b(6152)^0$ mass measurements

- Using this fit region, the significance of 6150 MeV peak drops to 5.4σ

Study of Σ_b states by LHCb

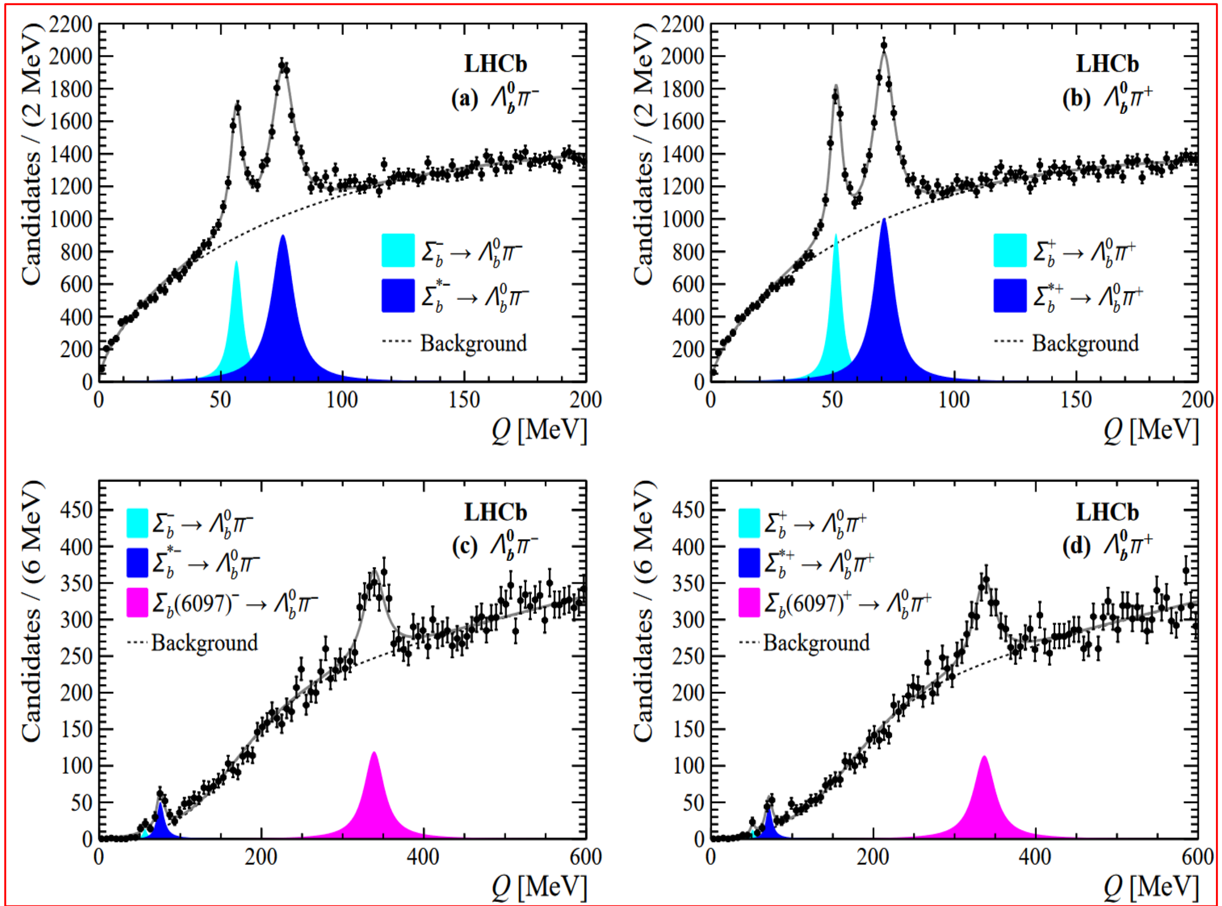
Run-1 dataset (7+8 TeV)

234 000 Λ_b^0 events

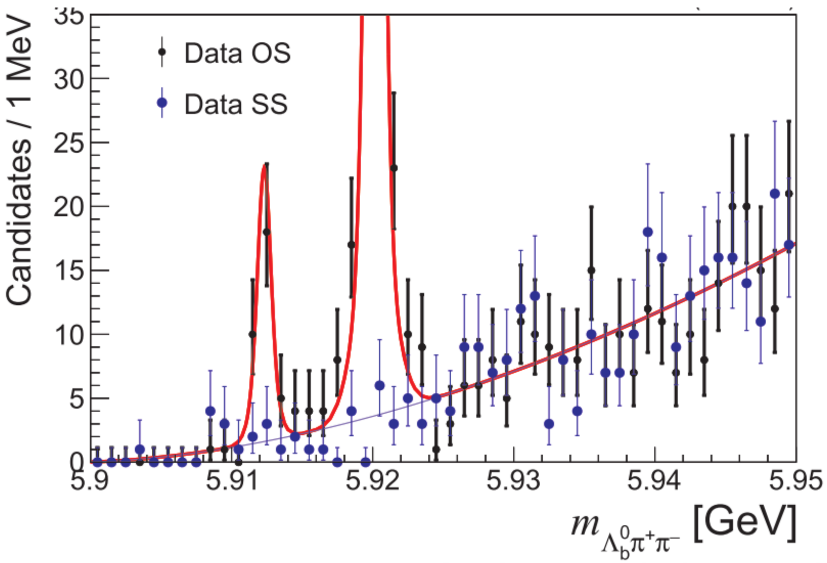


Quantity	Value [MeV]
$m(\Sigma_b(6097)^-)$	$6098.0 \pm 1.7 \pm 0.5$
$m(\Sigma_b(6097)^+)$	$6095.8 \pm 1.7 \pm 0.4$
$\Gamma(\Sigma_b(6097)^-)$	$28.9 \pm 4.2 \pm 0.9$
$\Gamma(\Sigma_b(6097)^+)$	$31.0 \pm 5.5 \pm 0.7$
$m(\Sigma_b^-)$	$5815.64 \pm 0.14 \pm 0.24$
$m(\Sigma_b^{*-})$	$5834.73 \pm 0.17 \pm 0.25$
$m(\Sigma_b^+)$	$5810.55 \pm 0.11 \pm 0.23$
$m(\Sigma_b^{*+})$	$5830.28 \pm 0.14 \pm 0.24$
$\Gamma(\Sigma_b^-)$	$5.33 \pm 0.42 \pm 0.37$
$\Gamma(\Sigma_b^{*-})$	$10.68 \pm 0.60 \pm 0.33$
$\Gamma(\Sigma_b^+)$	$4.83 \pm 0.31 \pm 0.37$
$\Gamma(\Sigma_b^{*+})$	$9.34 \pm 0.47 \pm 0.26$

10.1103/PhysRevLett.122.012001



SS vs OS for low-mass region



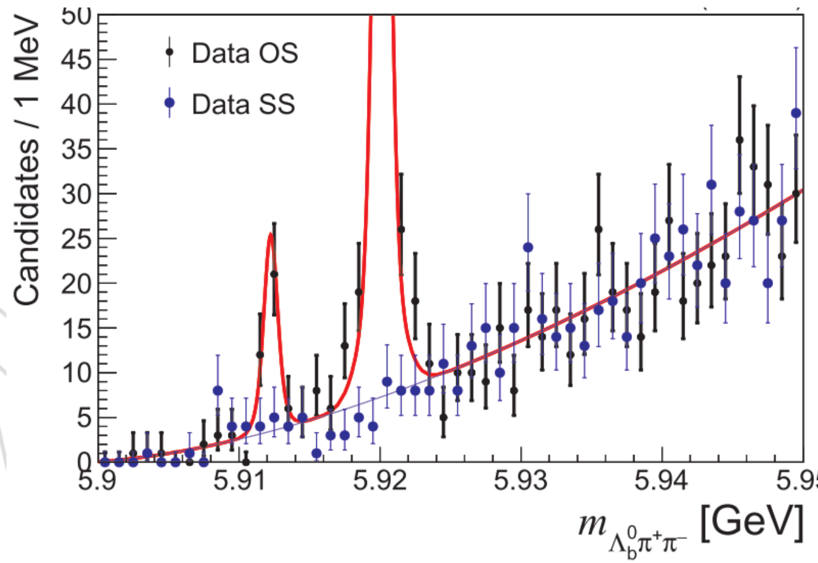


Figure 27: Mass distribution of the selected $\Lambda_b^0\pi^+\pi^-$ candidates in full 2016-2018 data sample overlayed with SS distribution (blue dots). Left: optimized cuts, right: softer cuts used before MC samples became available (Sec. 2.2 but not Sec. 2.3).

<u>Control region (SS) is in a very good agreement with background in signal (OS) region</u>