Studies of excited states of beauty hadrons at CMS

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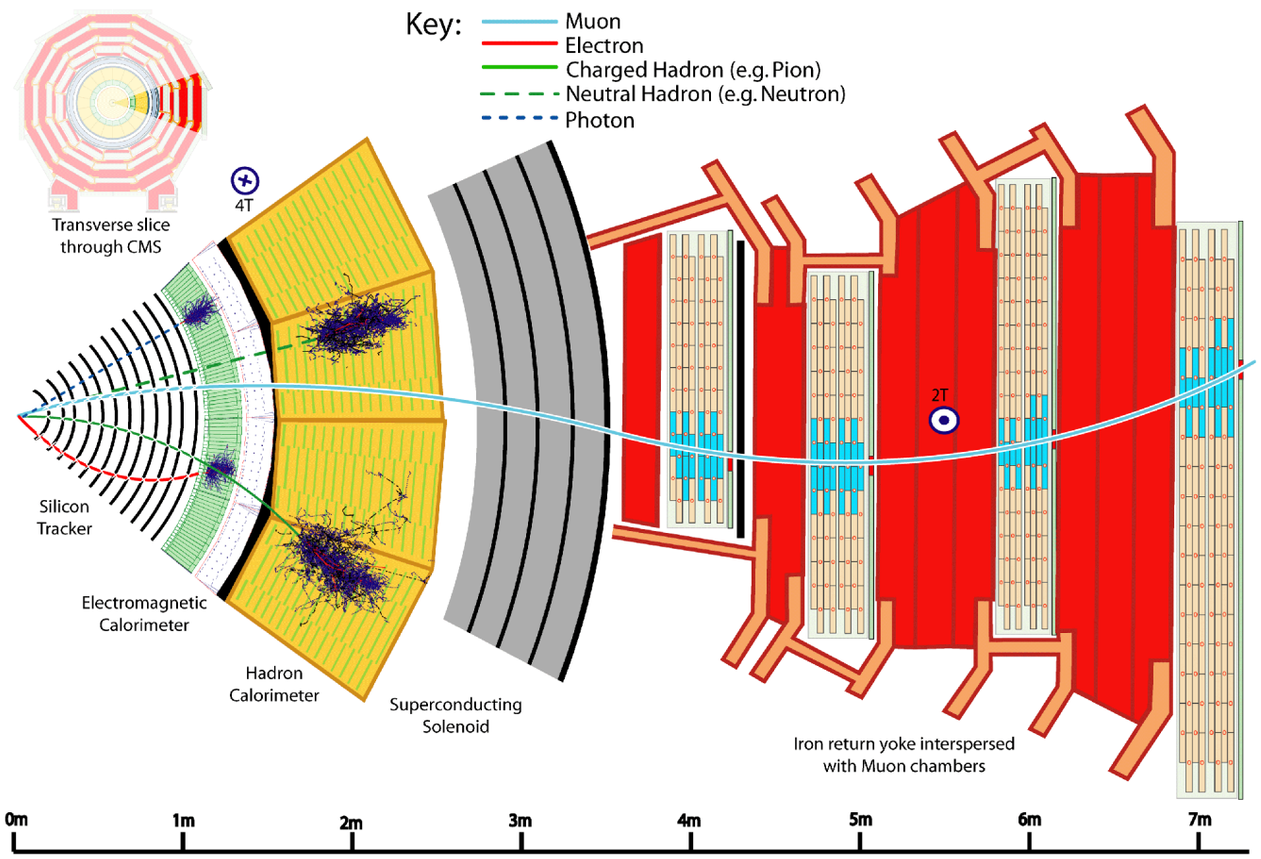
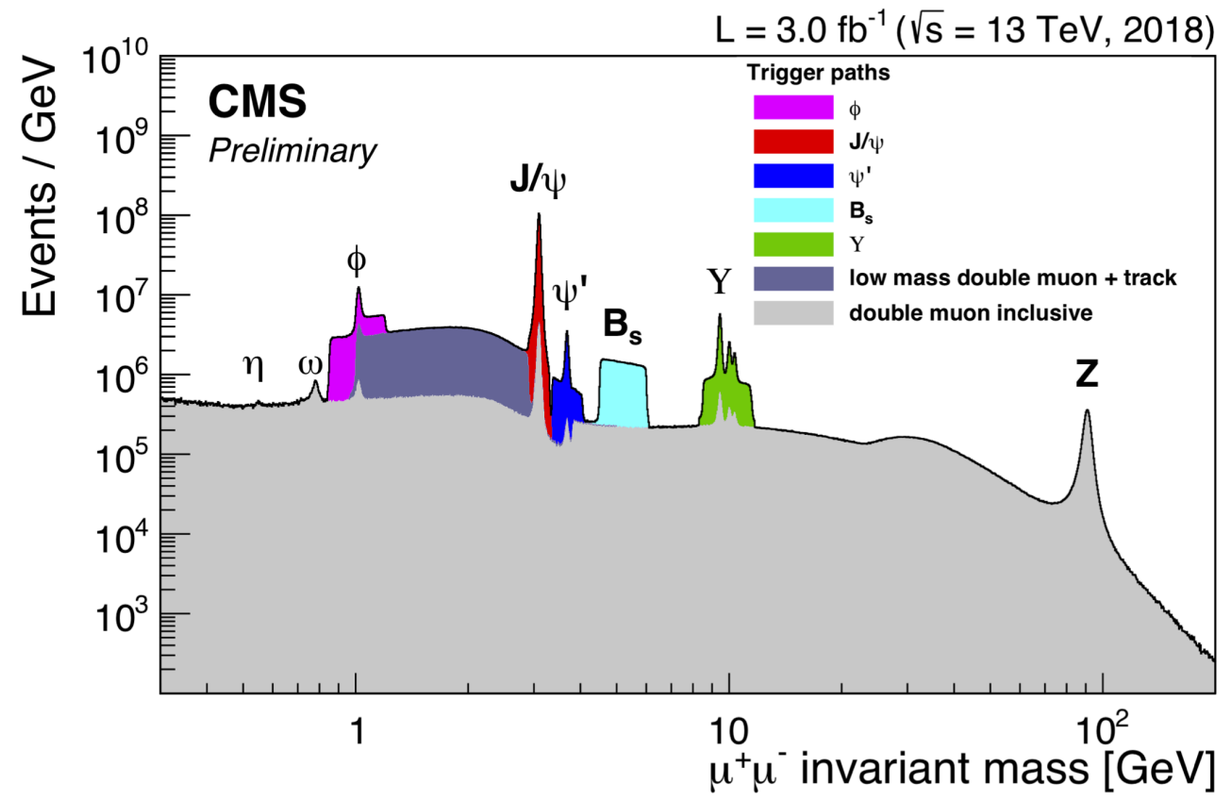
Introduction and overview

- The CMS Experiment
- Observation of two excited B_c^+ states and measurement of the $B_c^+(2S)$ mass in pp collisions at $\sqrt{s}$ = 13 TeV
- Study of excited Λ_b^0 states decaying to $\Lambda_b^0\pi^+\pi^-$ in proton-proton collisions at $\sqrt{s}$ = 13 TeV
- Conclusion and summary

The CMS Experiment



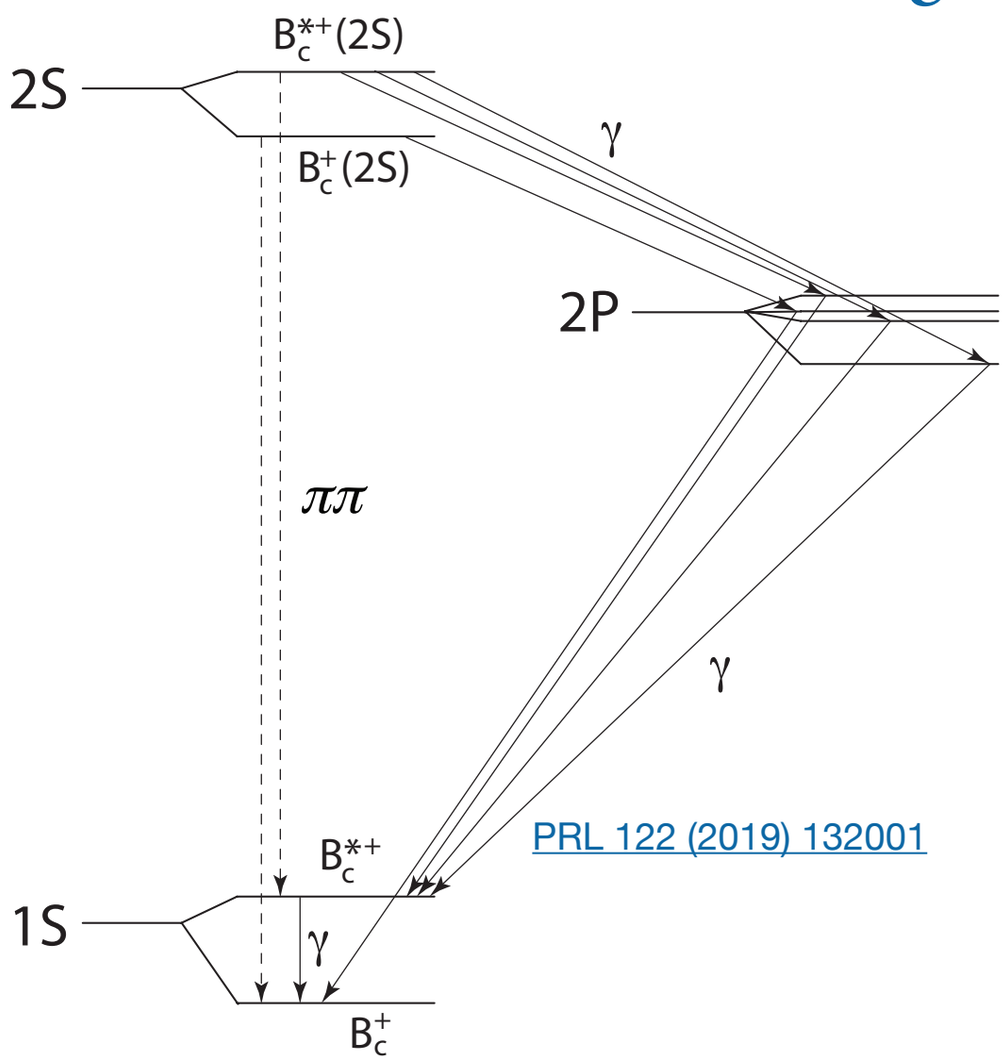


- The CMS Experiment at the LHC was designed mainly for high-p_T physics (Higgs, top-quark, SM precision measurement, New Physics searches etc)
- However, robust muon system, good p_T resolution and perfect vertex reconstruction provide promising opportunities for heavy flavour and quarkonia-related analyses
- In the present talk, two recent results from the CMS Collaboration about excited beauty hadrons studies are reported

Observation of two excited B_c^+ states and measurement of the $B_c^+(2S)$ mass in pp collisions at $\sqrt{s}$ = 13 TeV

CMS-BPH-18-007, Phys. Rev. Lett. 122 (2019) 132001

About B_c spectroscopy



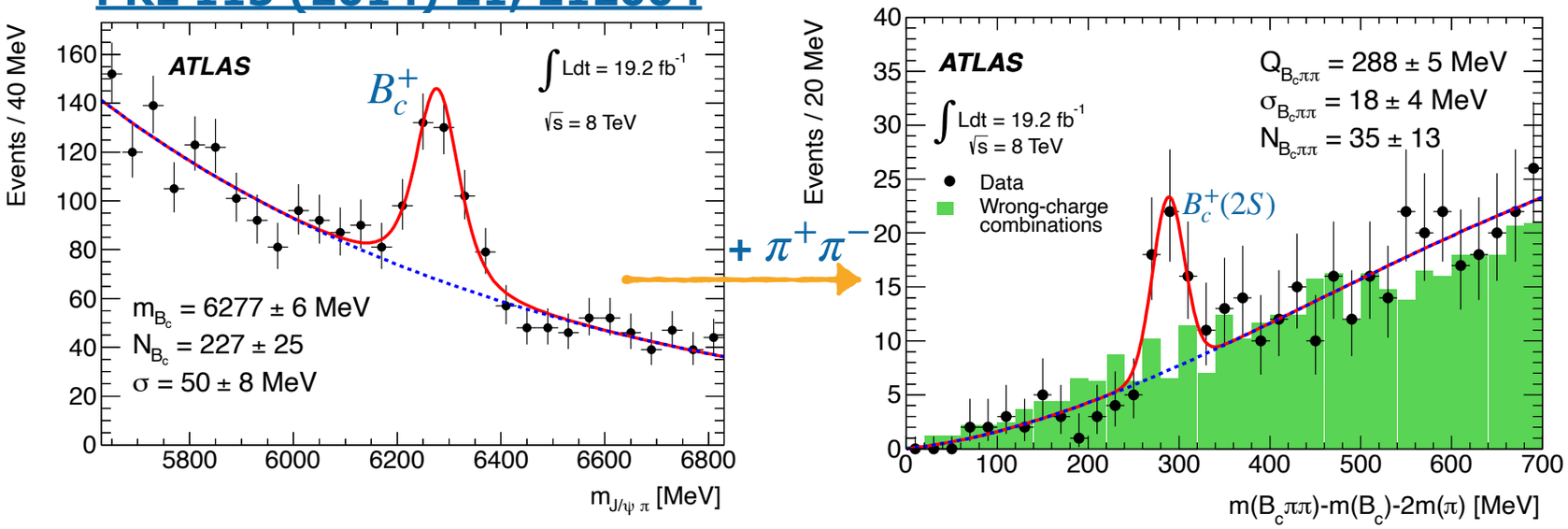
PRL 122 (2019) 132001

- B_c^+ meson ($c\bar{b}$ quarks) is the lightest double heavy hadron
- The study of its properties and search for its excited states are very interesting for theories of strong interactions
- Excited B_c states are expected to decay predominantly via cascades of photon emissions, hard to reconstruct
- However, reconstruction of strong decays of 2S states via two pions is accessible at the LHC

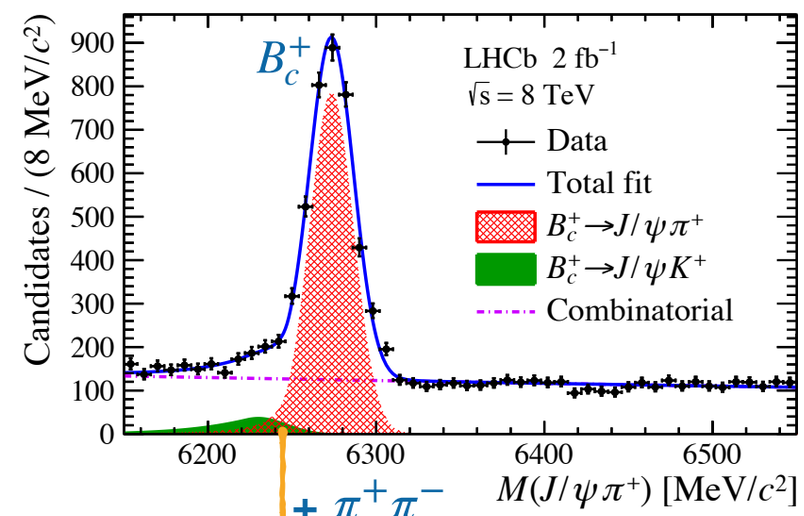
- $B_c^+(2S)$ is expected to decay directly to $B_c^+\pi^+\pi^-$
- $B_c^{*+}(2S)$ will decay to $B_c^{*+}\pi^+\pi^-$ with the following $B_c^{*+} \to B_c^+\gamma$, where very soft photon will be lost
- If $\Delta M \equiv [M(B_c^{*+}) - M(B_c^+)] - [M(B_c^{*+}(2S) - M(B_c^+(2S)]$ is larger than detector resolution, the $B_c^{*+}(2S)$ is expected to be observed lower the $B_c^+(2S)$ state in $B_c^+\pi^+\pi^-$ invariant mass spectrum

Previous results

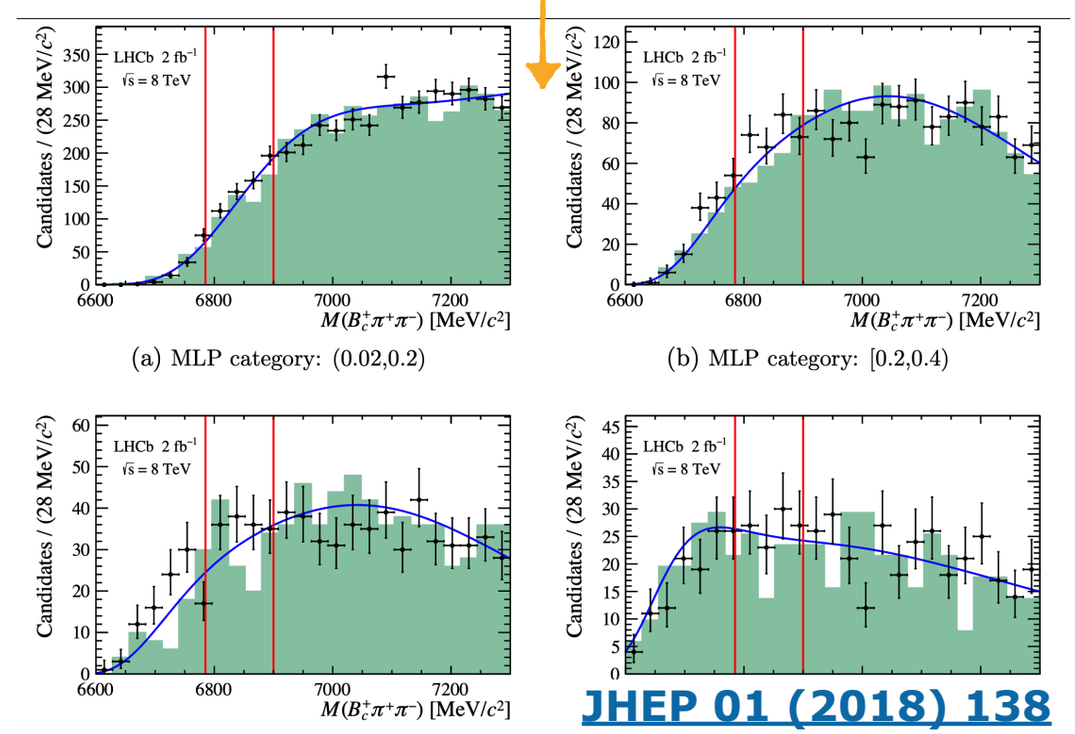
PRL 113 (2014) 21, 212004



$N(B_c^+) = 3325 \pm 73$



$+\,\pi^+\pi^-$



(a) MLP category: (0.02,0.2)

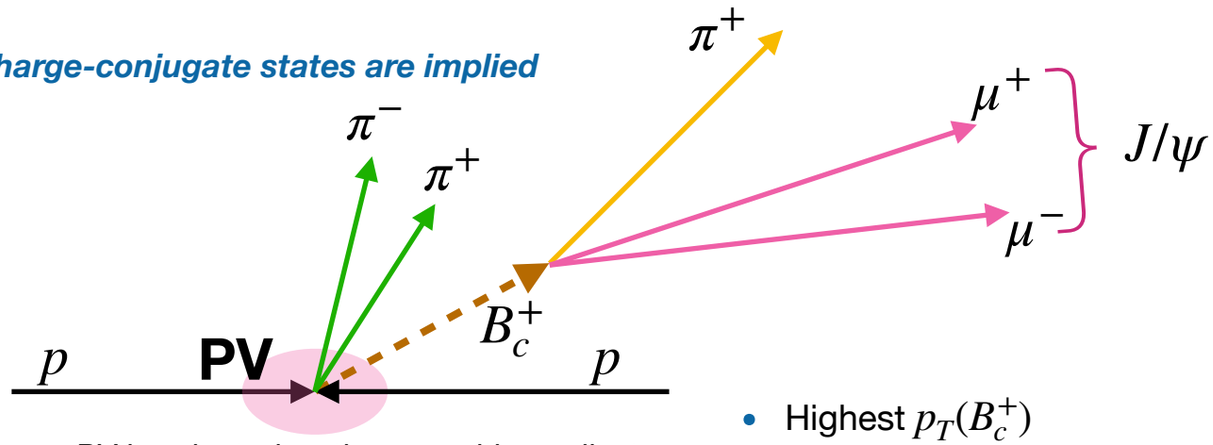
(b) MLP category: [0.2,0.4)

JHEP 01 (2018) 138

- In 2014 ATLAS Collaboration presented single-peak observation in $B_c^+\pi^+\pi^-$ invariant mass The mass of this new state is consistent with $B_c^+(2S)$ predictions
- Later LHCb Collaboration with much larger B_c^+ statistics released a paper with no significant $B_c^+(2S)$ signal found
- Both results are based on Run-1 LHC statistics

The $B_c^+ \to J/\psi\pi^+$ signal at CMS Run-2

Charge-conjugate states are implied

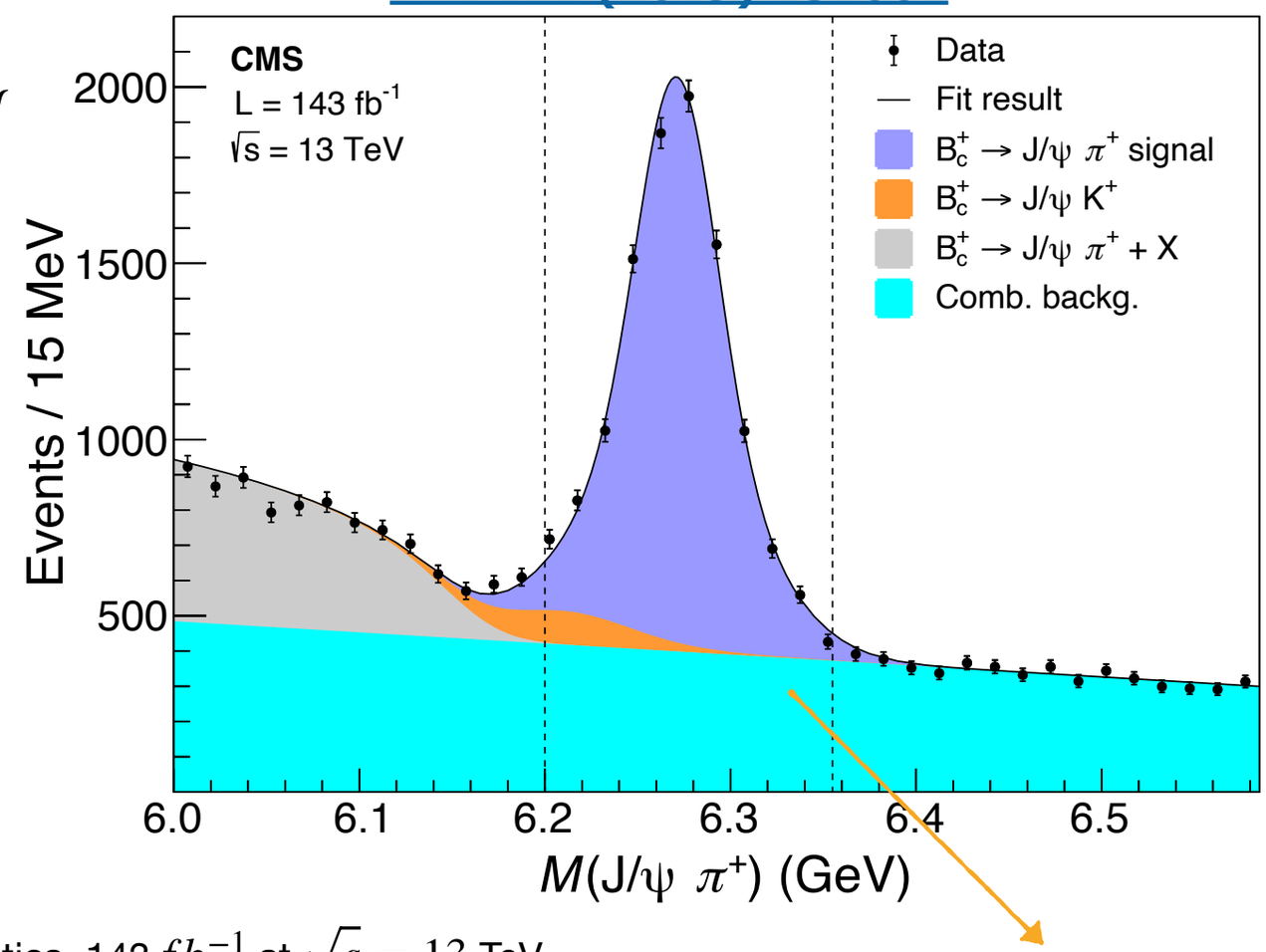


PV is selected as the one with smallest 3D pointing angle

- High-purity tracks
- $|\eta(\mu^\pm)| < 2.4$
- $p_T(\pi^+) > 3.5\ GeV/c$
- $d_{xy} > 2\sigma_{d_{xy}}$

- Highest $p_T(B_c^+)$ candidate is kept only
- $p_T(B_c^+) > 15\ GeV/c$
- $|y(B_c^+)| < 2.4$
- $l_{xy}(B_c^+) > 100\ \mu m$
- $P_{vtx}(B_c^+) > 10\,\%$

PRL 122 (2019) 132001



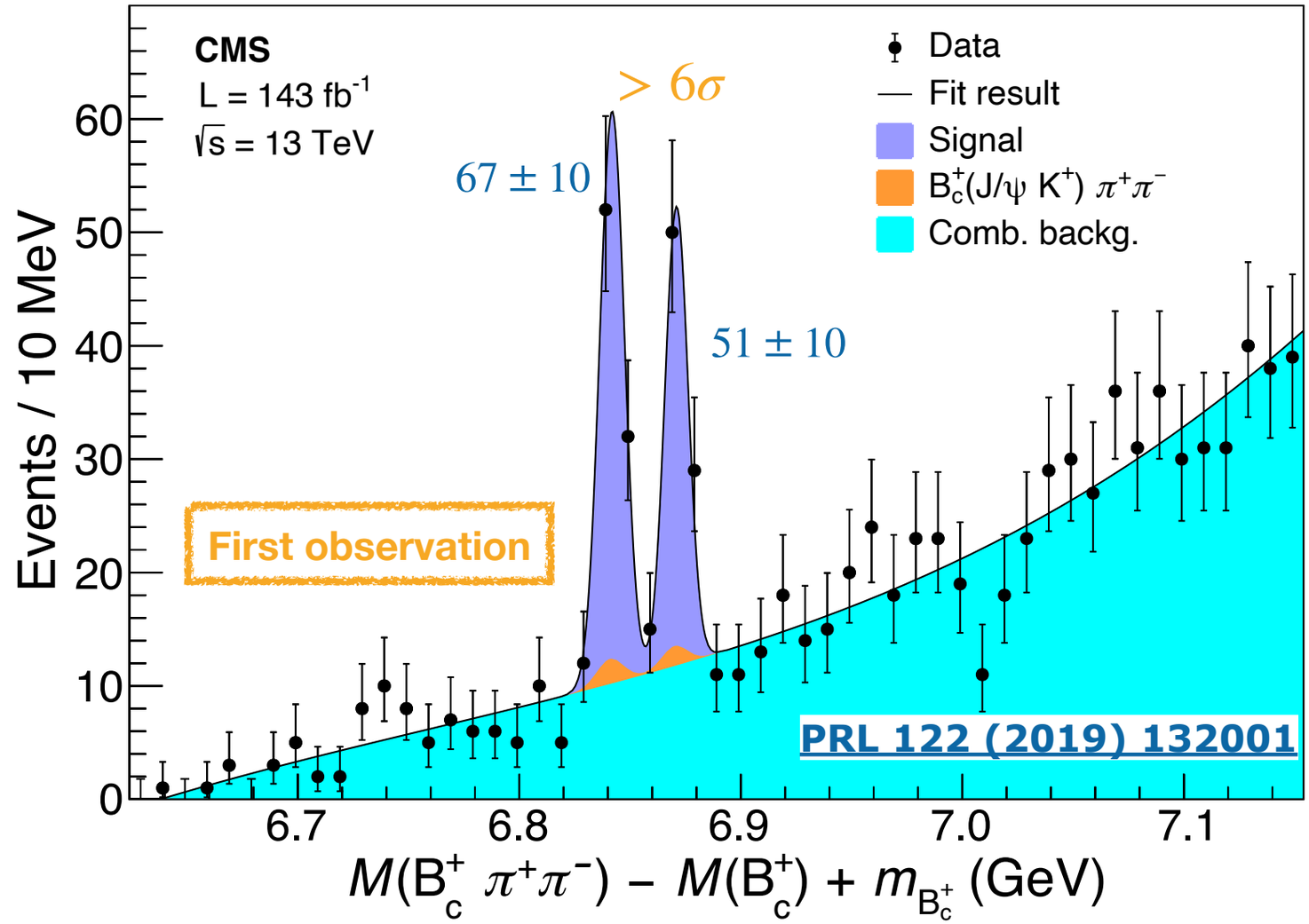
[6.2-5.355] GeV mass window for $B_c^+\pi^+\pi^-$ studies

- Early 2019 CMS presented $B_c^+\pi^+\pi^-$ analysis using full Run-2 statistics, 143 fb^{-1} at $\sqrt{s} = 13$ TeV
- $7629 \pm 225\ B_c^+ \to J/\psi\pi^+$ events obtained
- UML fit, Signal is double Gaussian with common mean, background:
  - 1st order polynomial for comb. bkg.
  - ARGUS $\otimes$ Gaussian resolution for partially reconstructed $B_c^+ \to J/\psi\pi^+X$ decays below 6.2 GeV
  - The latter one corresponds to $B_c^+ \to J/\psi K^+$ reflection, normalisation fixed to $B_c^+ \to J/\psi\pi^+$ Br. fr., shape obtained in simulation

$$m_{B_c^+} = 6271.1 \pm 0.5 \text{ MeV}$$
$$\sigma_{eff} = 33.5 \pm 2.5 \text{ MeV}$$

$B_c^{(*)+}(2S) \to B_c^+\pi^+\pi^-$ observation

- $B_c^+\pi^+\pi^-$ vertex fit, $P_{vtx} > 10\,\%$
- $6.2\ GeV < M(J/\psi\pi^+) < 6.355\ GeV$
- $|y(B_c^+\pi^+\pi^-)| < 2.4$
- $p_T(\pi_2) > 0.8\ GeV/c$
- $p_T(\pi_3) > 0.6\ GeV/c$
- Highest $p_T(B_c^+\pi^+\pi^-)$ candidate is kept only
- Mass variable $M(B_c^+\pi^+\pi^-) - M(B_c^+) + m_{B_c^+}$ is used to cancel the B_c^+ signal resolution



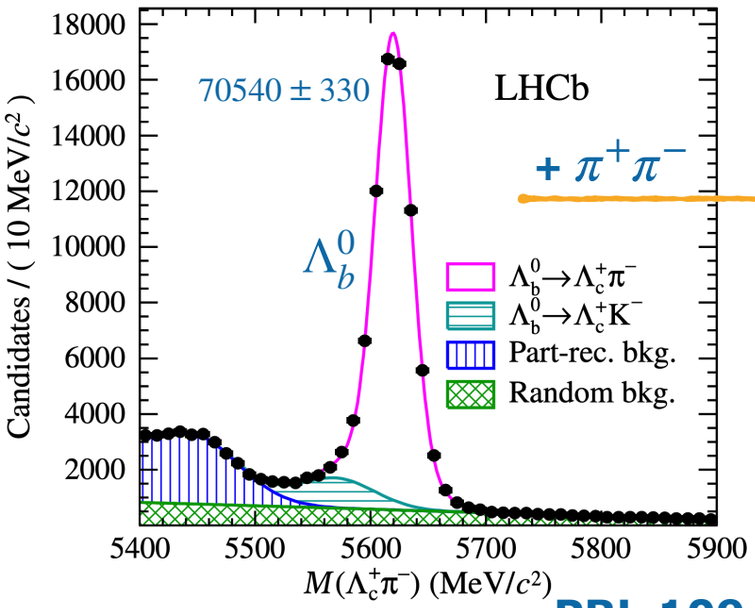
- Two well-resolved peaks are observed in $B_c^+\pi^+\pi^-$ invariant mass, position is consistent with ATLAS single peak
- UML fit: signals are Gaussians, bkg: 3rd order polynomial for comb.bkg. and signal shapes with fixed from Br.fr. normalisation for $B_c^+ \to J/\psi K^+$ contributions
- The $\Delta M = 29.1 \pm 1.5\ (stat)\ \pm 0.7\ (syst)$ MeV, the resolutions are about 6 MeV ⟶ the lower-mass peak is $B_c^{*+}(2S)$ with photon from $B_c^{*+} \to B_c^+\gamma$ decay is lost, true $M(B_c^{*+}(2S))$ is unknown
- The higher-mass peak is $B_c^+(2S)$ state with $M(B_c^+(2S)) = 6871.0 \pm 1.2\ (stat)\ \pm 0.8\ (syst)\ \pm 0.8\ (B_c^+)$

Recently, CMS reported the measurement of $B_c^+(2S)$ and $B_c^{*+}(2S)$ cross section ratios, see backup

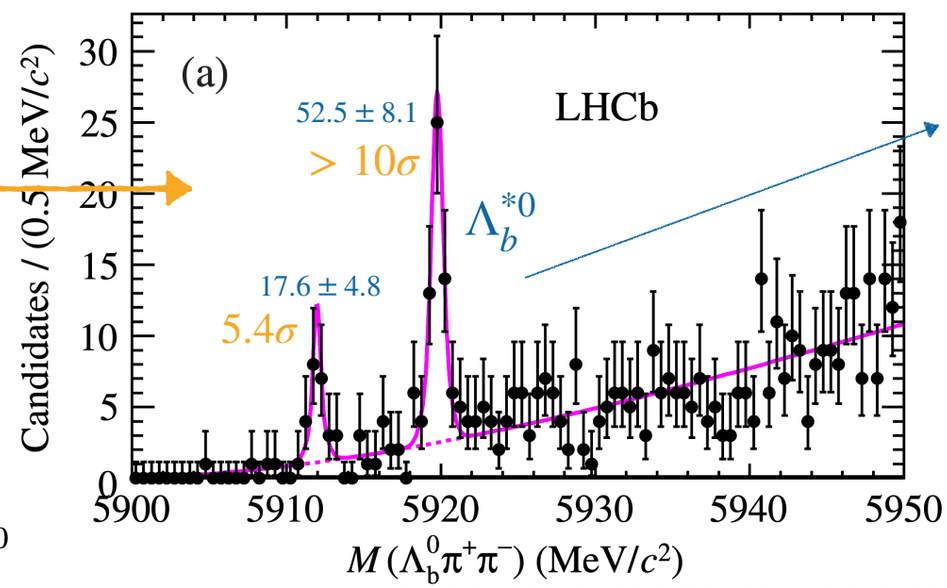
Study of excited Λ_b^0 states decaying to $\Lambda_b^0\pi^+\pi^-$ in proton-proton collisions at $\sqrt{s}$ = 13 TeV

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

Historical $\Lambda_b\pi^+\pi^-$ overview

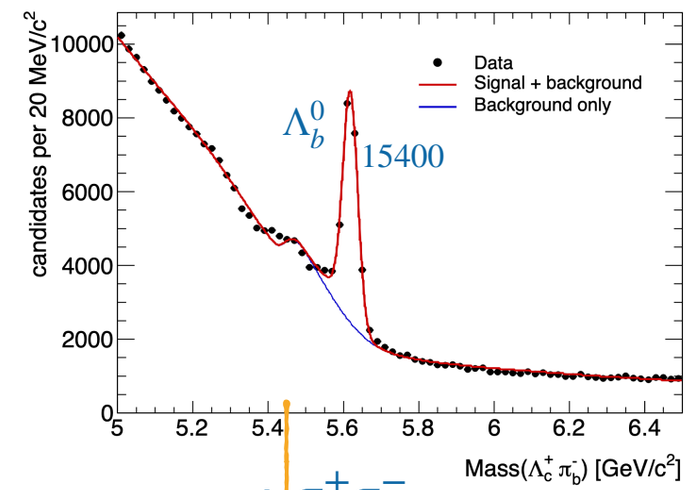


+ $\pi^+\pi^-$

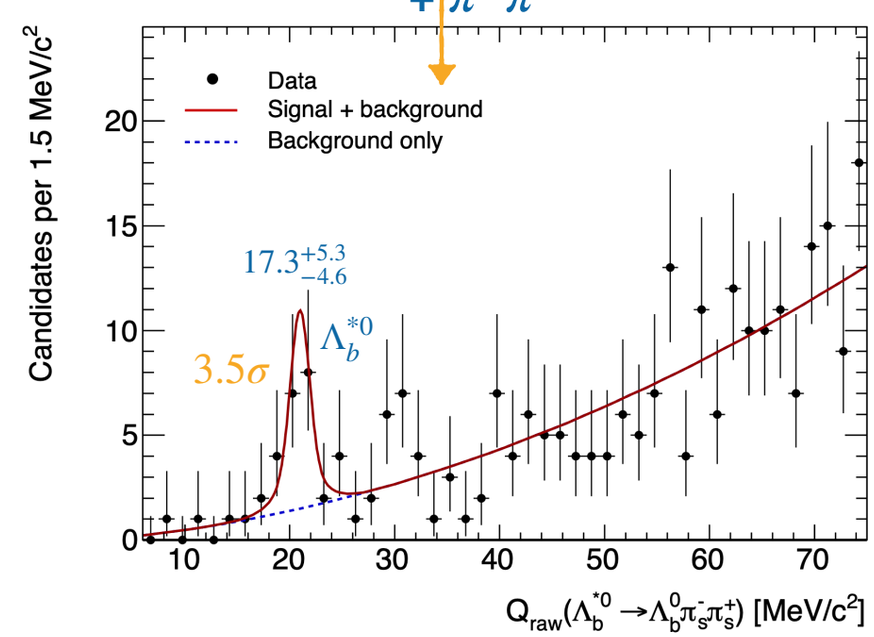


$$M_{\Lambda_b^{*0}(5912)} = 5911.97 \pm 0.12 \pm 0.02 \pm 0.66 \text{ MeV}/c^2,$$
$$M_{\Lambda_b^{*0}(5920)} = 5919.77 \pm 0.08 \pm 0.02 \pm 0.66 \text{ MeV}/c^2,$$

PRL 109 (2012) 172003



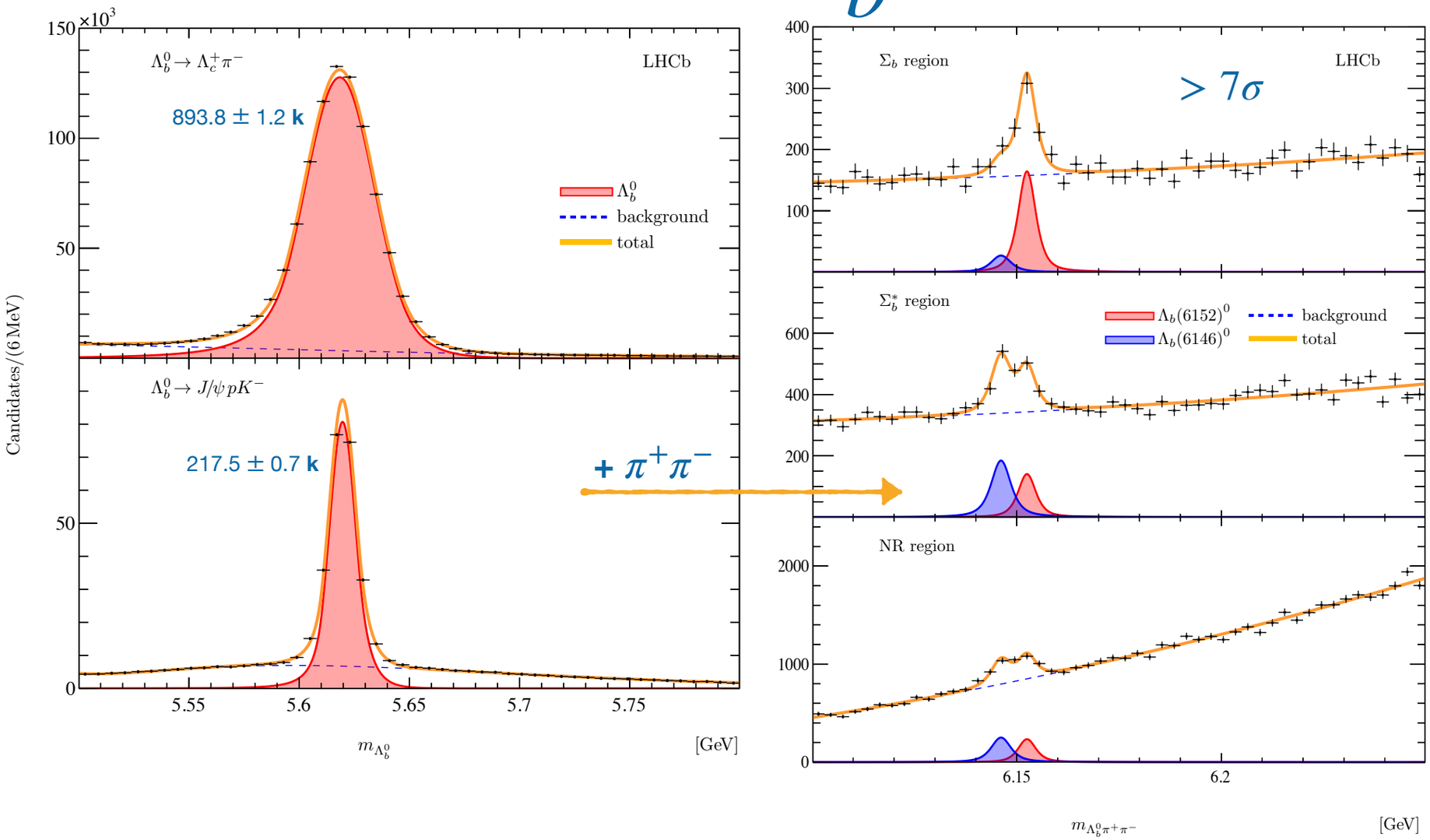
+ $\pi^+\pi^-$



PRD 88, 071101 (2013)

- Study of excited beauty baryons is very interesting to understand strong interquark interaction and baryons formation mechanisms
- There are many theoretical predictions for the excited Λ_b^0 baryons, but their predicted masses are in a wide range, no particular mass windows where to search
- First excited beauty baryons $\Lambda_b(5912)^0$ and $\Lambda_b(5920)^0$ were observed by LHCb Collaboration in 2012 in $\Lambda_b\pi^+\pi^-$ invariant mass
- In 2013 CDF Collaboration confirmed only the heavier $\Lambda_b(5920)^0$ state

Historical $\Lambda_b\pi^+\pi^-$ overview



PRL 123 (2019) 152001

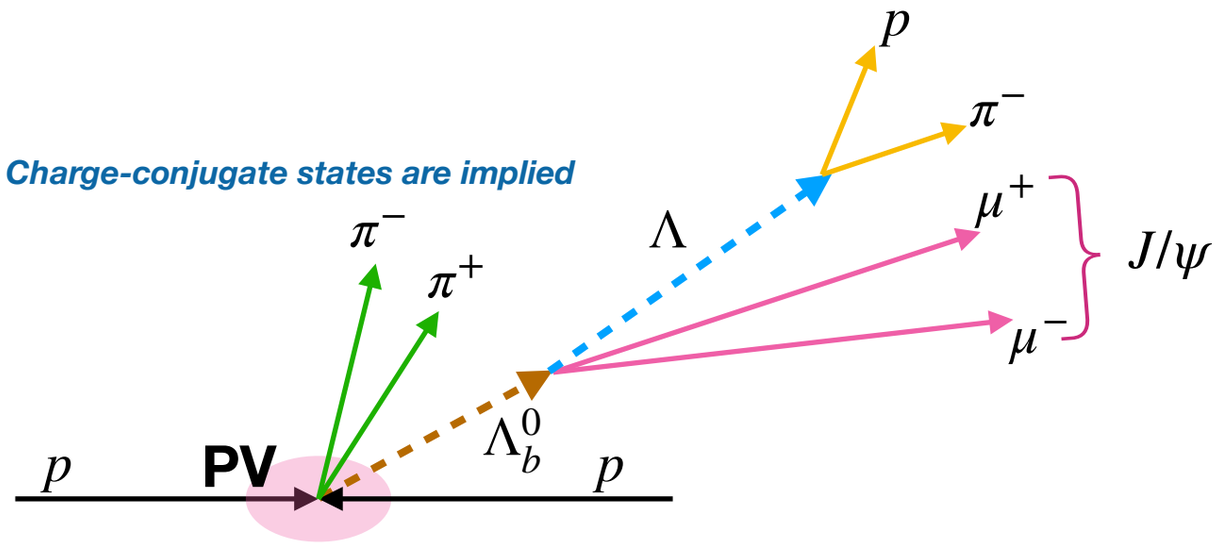
$$m_{\Lambda_b(6146)^0} = 6146.17 \pm 0.33 \pm 0.22 \pm 0.16\,\text{MeV},$$
$$m_{\Lambda_b(6152)^0} = 6152.51 \pm 0.26 \pm 0.22 \pm 0.16\,\text{MeV},$$
$$\Gamma_{\Lambda_b(6146)^0} = 2.9 \pm 1.3 \pm 0.3\,\text{MeV},$$
$$\Gamma_{\Lambda_b(6152)^0} = 2.1 \pm 0.8 \pm 0.3\,\text{MeV},$$

$$\Delta m = 6.34 \pm 0.32 \pm 0.02\ \text{MeV}$$

	Σ_b region	Σ_b^* region	NR region
$N_{\Lambda_b(6146)^0}$	67 ± 40	460 ± 92	624 ± 136
$N_{\Lambda_b(6152)^0}$	357 ± 52	305 ± 70	510 ± 109

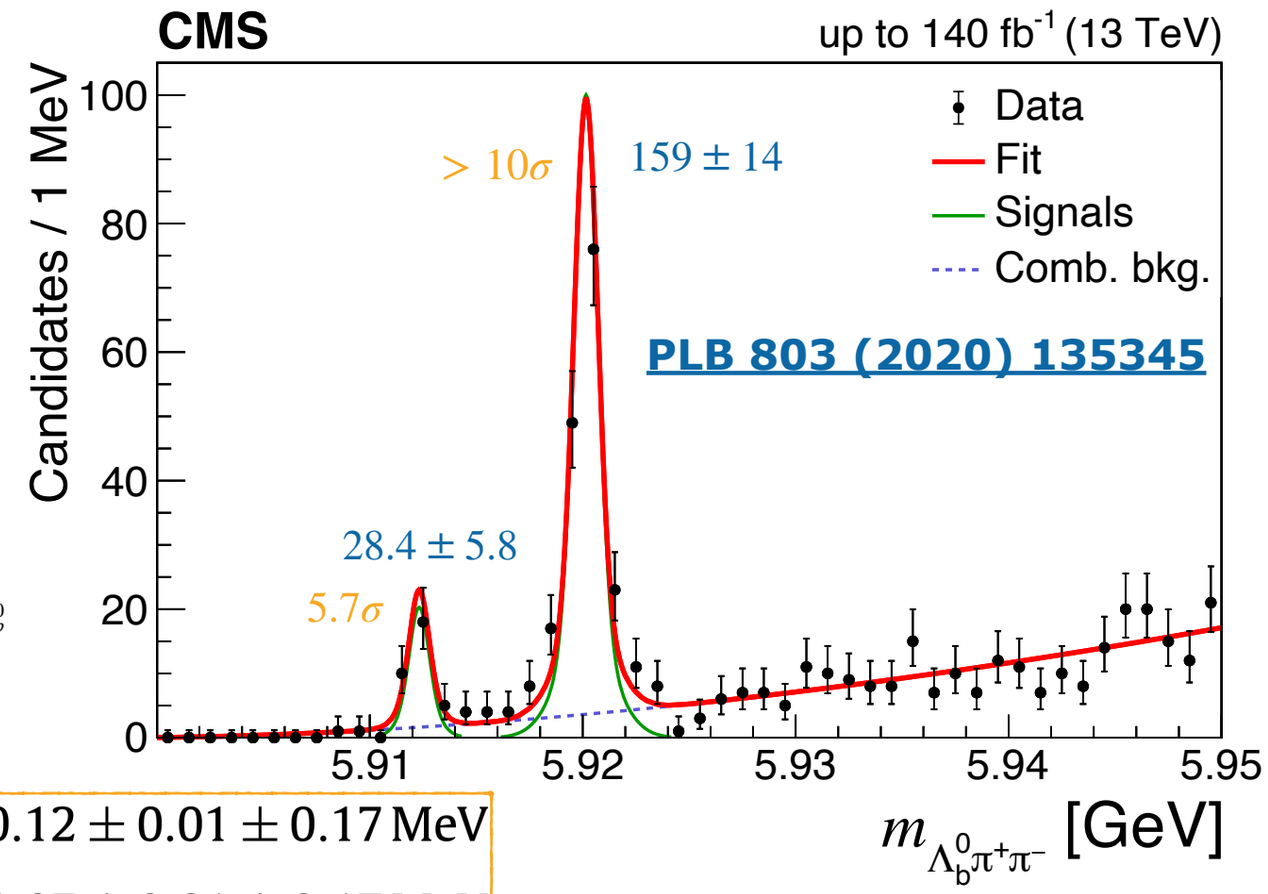
- In 2019 LHCb Collaboration presented the observation of two new very close excited Λ_b^0 states in $\Lambda_b\pi^+\pi^-$ higher-mass region: $\Lambda_b(6146)^0$ and $\Lambda_b(6152)^0$
- Full Run-1 + Run-2 statistics, more than 1.1M Λ_b^0 ground state candidates
- Some theoretical predictions and intermediate Σ_b and Σ_b^* decays are consistent with the possible doublet of $\Lambda_b(1D)^0$ states

CMS $\Lambda_b\pi^+\pi^-$ near-threshold study



PV is selected as the one with smallest 3D pointing angle

Mass variable $M(\Lambda_b^0\pi^+\pi^-) - M(\Lambda_b^0) + m_{\Lambda_b^0}$ and PV refit technique (see backup) are used to cancel the Λ_b^0 signal resolution

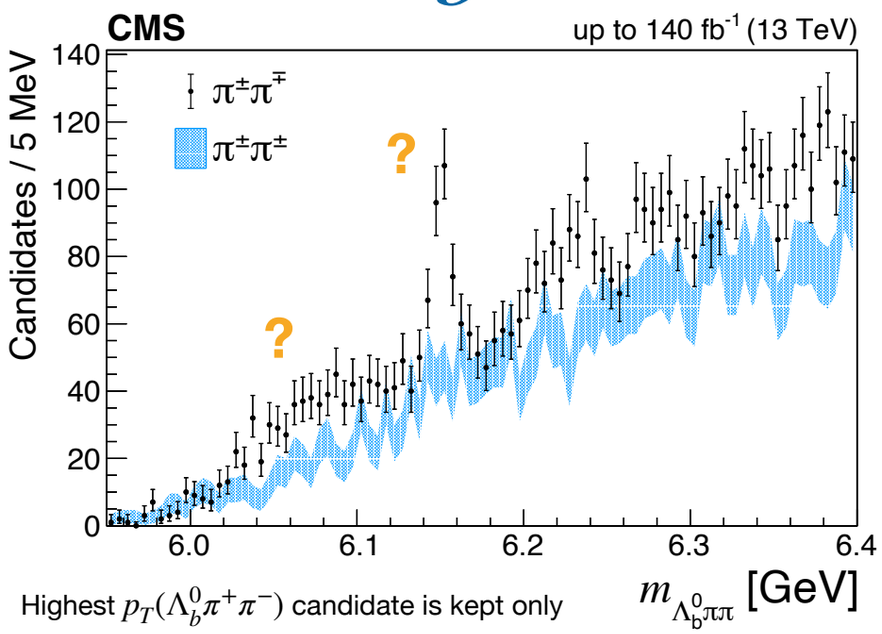


Selection criteria were optimised using Punzi FOM $S/(5/2+\sqrt{B})$

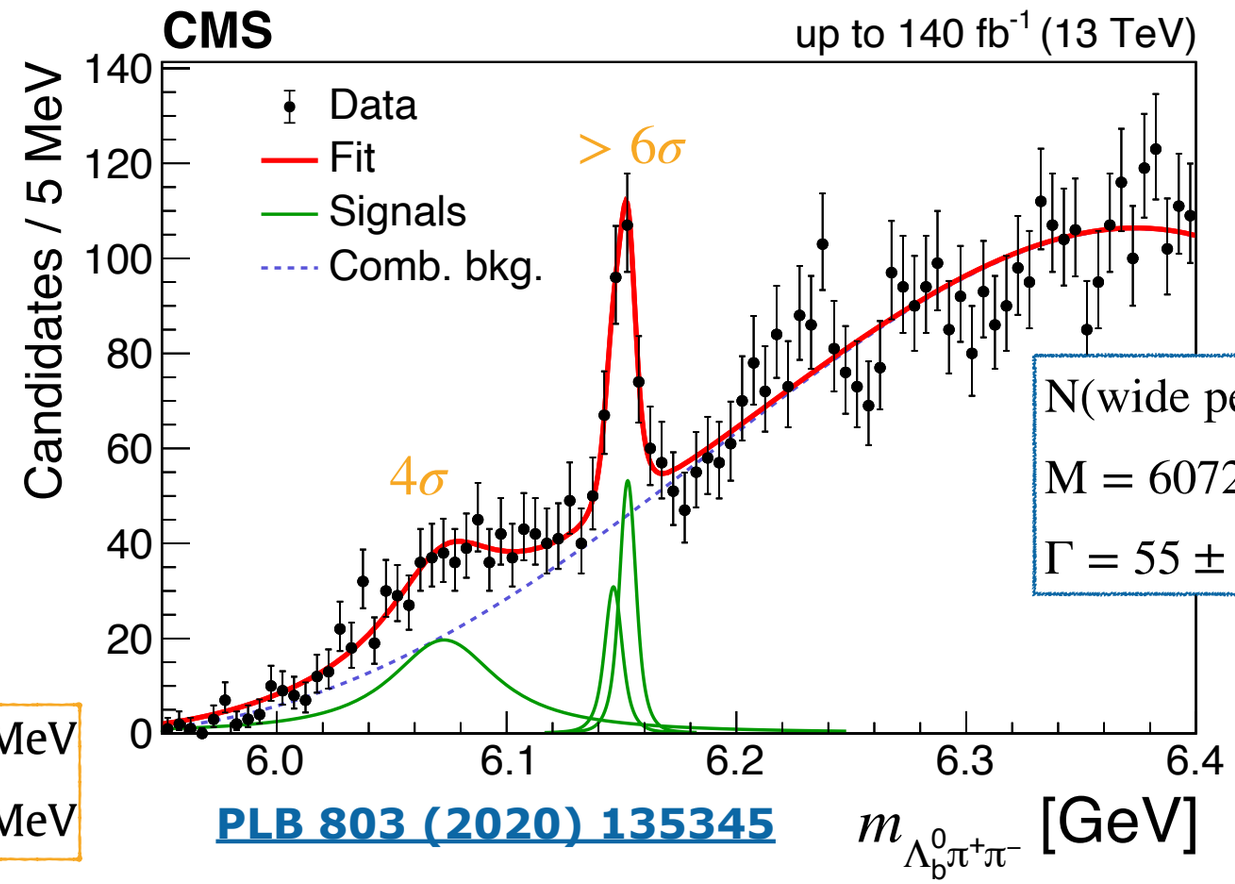
$$M(\Lambda_b^0(5912)^0) = 5912.32 \pm 0.12 \pm 0.01 \pm 0.17\,\text{MeV}$$
$$M(\Lambda_b^0(5920)^0) = 5920.16 \pm 0.07 \pm 0.01 \pm 0.17\,\text{MeV}$$

- Early 2020 CMS Collaboration presented Run-2 $\Lambda_b\pi^+\pi^-$ analysis, 140 fb^{-1} with $\sqrt{s} = 13$ TeV
- $\Lambda_b \to J/\psi\Lambda$ and $\Lambda_b \to \psi(2S)\Lambda$ channels are used, ≈46k Λ_b^0 ground state candidates
- Two peaks are observed near the $\Lambda_b\pi^+\pi^-$ mass threshold: first confirmation of $\Lambda_b(5912)^0$ state and 2nd for $\Lambda_b(5920)^0$ state
- UML fit: 2 double-Gaussians with a common mean for signals (shape fixed from MC) + threshold function $(x - x_0)^\alpha$ for the comb. bkg.

CMS $\Lambda_b\pi^+\pi^-$ higher-mass region study



Highest $p_T(\Lambda_b^0\pi^+\pi^-)$ candidate is kept only



PLB 803 (2020) 135345

$N(\Lambda_b(6146)) = 70 \pm 35$

$N(\Lambda_b(6152)) = 113 \pm 35$

N(wide peak) $= 301 \pm 72$

M $= 6072.8 \pm 4.8$ MeV

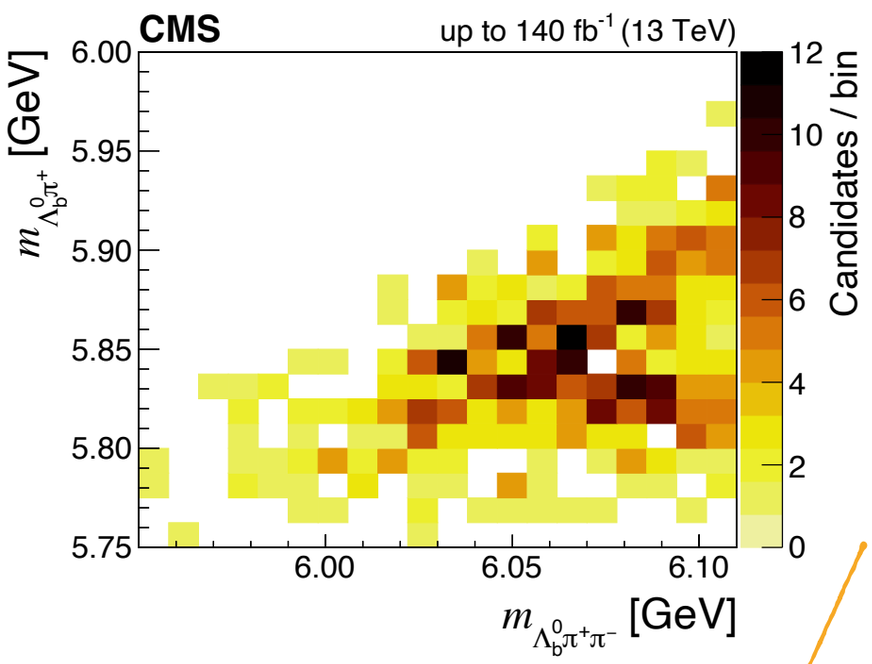
$\Gamma = 55 \pm 11$ MeV

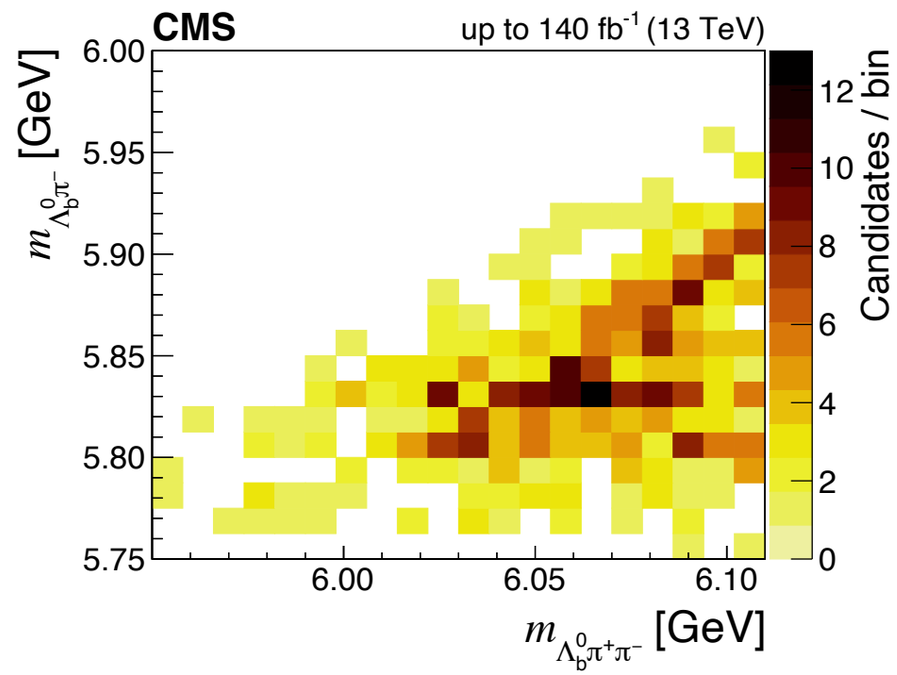
$M(\Lambda_b^0(6146)^0) = 6146.5 \pm 1.9 \pm 0.8 \pm 0.2$ MeV

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

- The $\Lambda_b\pi^+\pi^-$ higher-mass region up to 6.4 GeV is studied as well
- A structure near 6.15 GeV is observed, consistent with the overlap of $\Lambda_b(6146)^0$ and $\Lambda_b(6152)^0$ states observed by LHCb Experiment
- A broad enhancement in 6040-6100 MeV region is observed as well, unlike in the same-sign distribution
- UML fit: 2 Breit-Wigner $\otimes$ double Gaussian resolution (fixed from MC), Γ fixed to LHCb results, for 6.15 GeV structure + Breit-Wigner $\otimes$ double Gaussian resolution (fixed from MC), for the broad enhancement + $(x - x_0)^\alpha \cdot \mathrm{Pol}_1(x)$ function for the comb. bkg.

Additional studies of broad excess





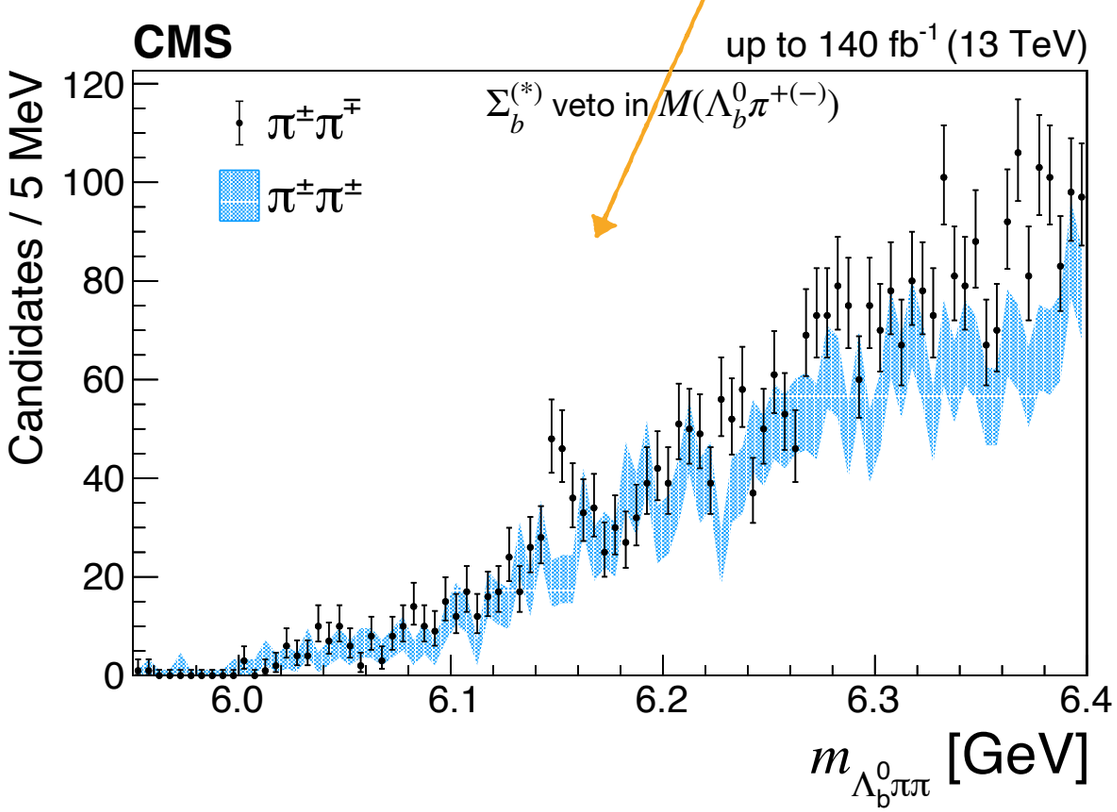
PLB 803 (2020) 135345

PDG:

Mass $m(\Sigma_b^+) = 5810.56 \pm 0.25$ MeV
Mass $m(\Sigma_b^-) = 5815.64 \pm 0.27$ MeV

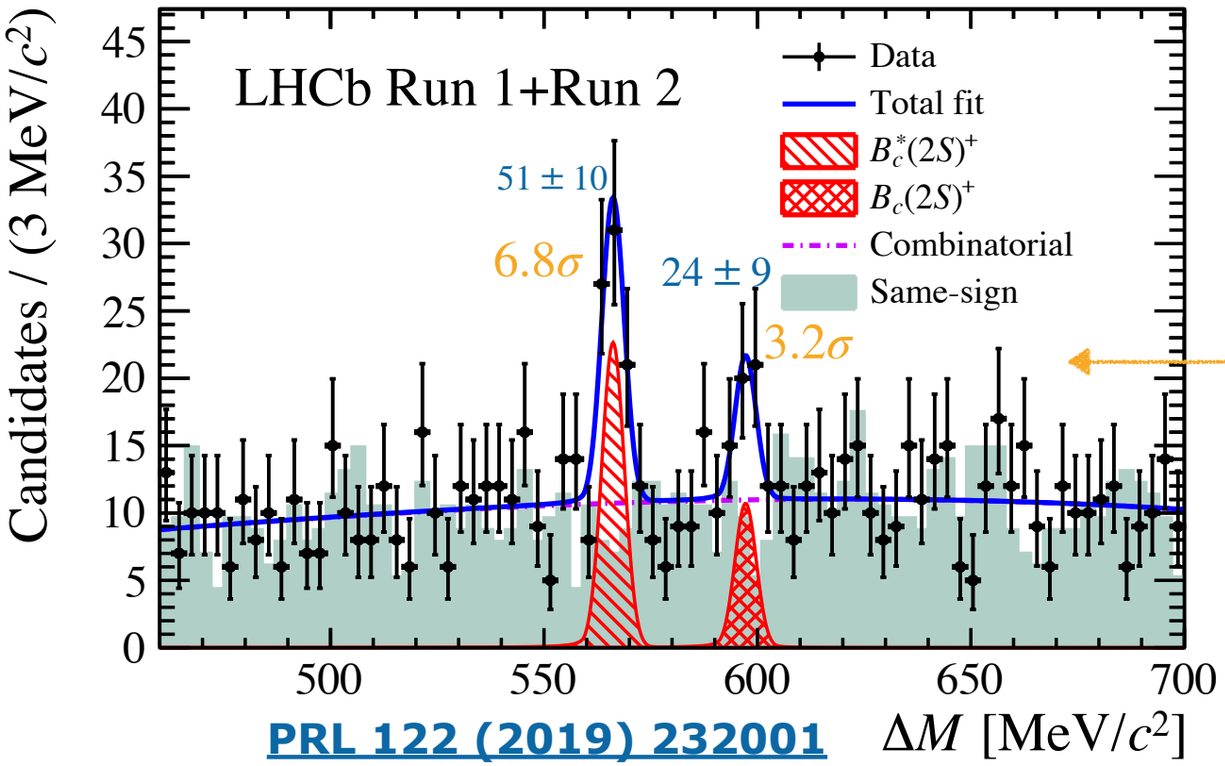
Mass $m(\Sigma_b^{*+}) = 5830.32 \pm 0.27$ MeV
Mass $m(\Sigma_b^{*-}) = 5834.74 \pm 0.30$ MeV

PLB 803 (2020) 135345



- Additional studies of the broad enhancement were carried out
- 2D-plot for $M(\Lambda_b^0\pi^+\pi^-)$ versus $M(\Lambda_b^0\pi^{+(-)})$ indicate possible correlation
- The broad excess may be may be related with the presence of intermediate $\Sigma_b^{(*)\pm}\pi^\mp \to \Lambda_b^0\pi^\pm\pi^\mp$ decays
- If $\Sigma_b^{(*)}$ in $M(\Lambda_b^0\pi^{+(-)})$ is vetoed, the broad enhancement disappears, but its true origin cannot be discerned with the present data

Confirmation of CMS results



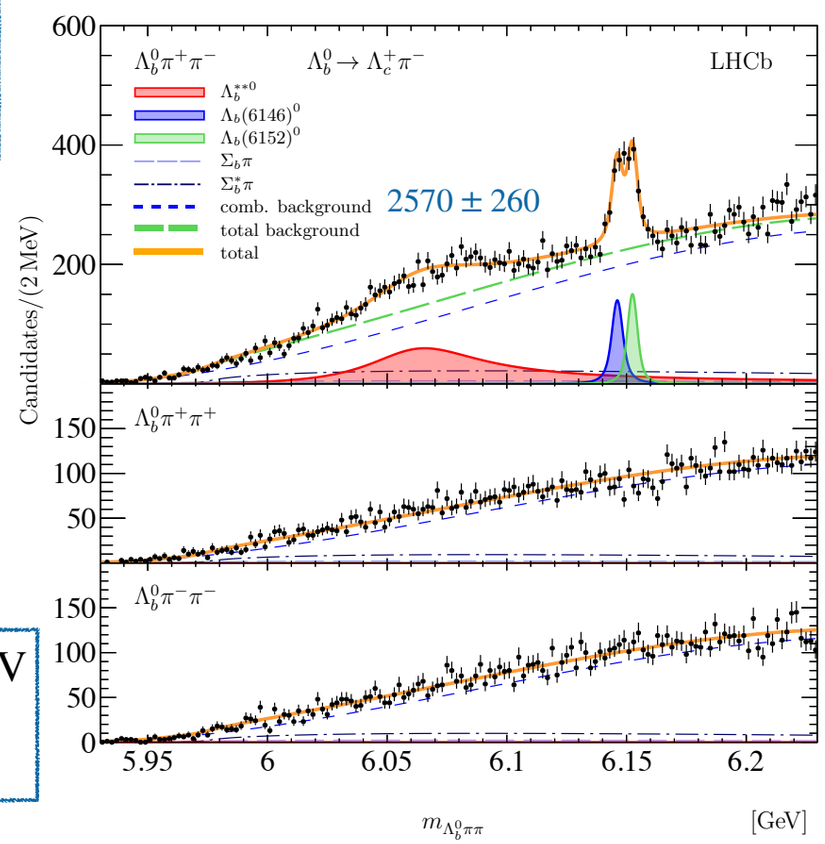
PRL 122 (2019) 232001

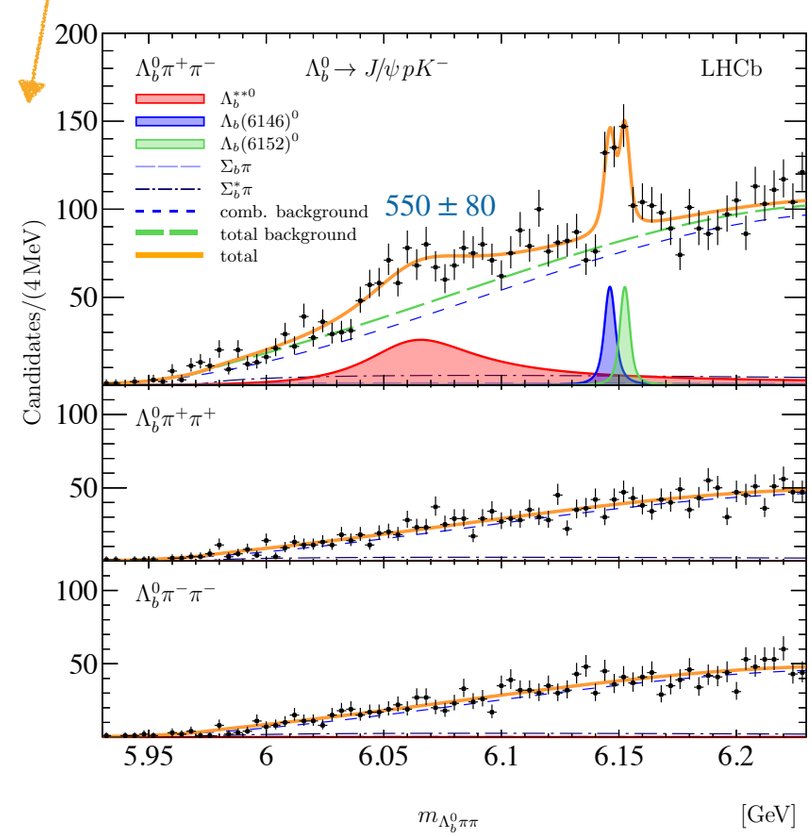
Later the LHCb Collaboration confirmed:

- Two-peak structure in $B_c^+\pi^+\pi^-$ invariant mass
- A broad excess presence in $M(\Lambda_b^0\pi^+\pi^-)$, interpreted as Λ_b^{**0} baryon, possible $\Lambda_b^0(2S)$ state

$$M(B_c^+(2S)) = 6872.1 \pm 1.3 \pm 0.1 \pm 0.8\,(B_c^+)\ \text{MeV}$$

$$\Delta M = 31.0 \pm 1.4 \pm 0.0\ \text{MeV}$$





JHEP 06 (2020) 136

$$m(\Lambda_b^{**0}) = 6072.3 \pm 2.9 \pm 0.6 \pm 0.2\ \text{MeV}$$

$$\Gamma_{\Lambda_b^{*0}} = 72 \pm 11 \pm 2\ \text{MeV}$$

Conclusion and summary

- CMS Experiment is contributing actively to for the excited heavy hadrons spectroscopy:

- Two new well-resolved $B_c^+(2S)$ and $B_c^{*+}(2S)$ mesons were observed for the first time in $B_c^+\pi^+\pi^-$ invariant mass spectrum, consistent with previous ATLAS result of a single peak, later confirmed by LHCb

- Recently, CMS also reported the measurement of $B_c^+(2S)$ and $B_c^{*+}(2S)$ cross section ratios

- $\Lambda_b(5912)^0$ and $\Lambda_b(5920)^0$ states near $M(\Lambda_b^0\pi^+\pi^-)$ threshold are confirmed, their masses are measured and reported

- A 6.15 GeV structure is observed at $M(\Lambda_b^0\pi^+\pi^-)$, consistent with the overlap of $\Lambda_b(6146)^0$ and $\Lambda_b(6152)^0$ states; their masses are measured and reported

- A broad enhancement in the 6040-6100 MeV of $M(\Lambda_b^0\pi^+\pi^-)$ region is reported (4 std. dev. $\longrightarrow$ first evidence), later confirmed by LHCb as possible Λ_b^{**0} baryon state

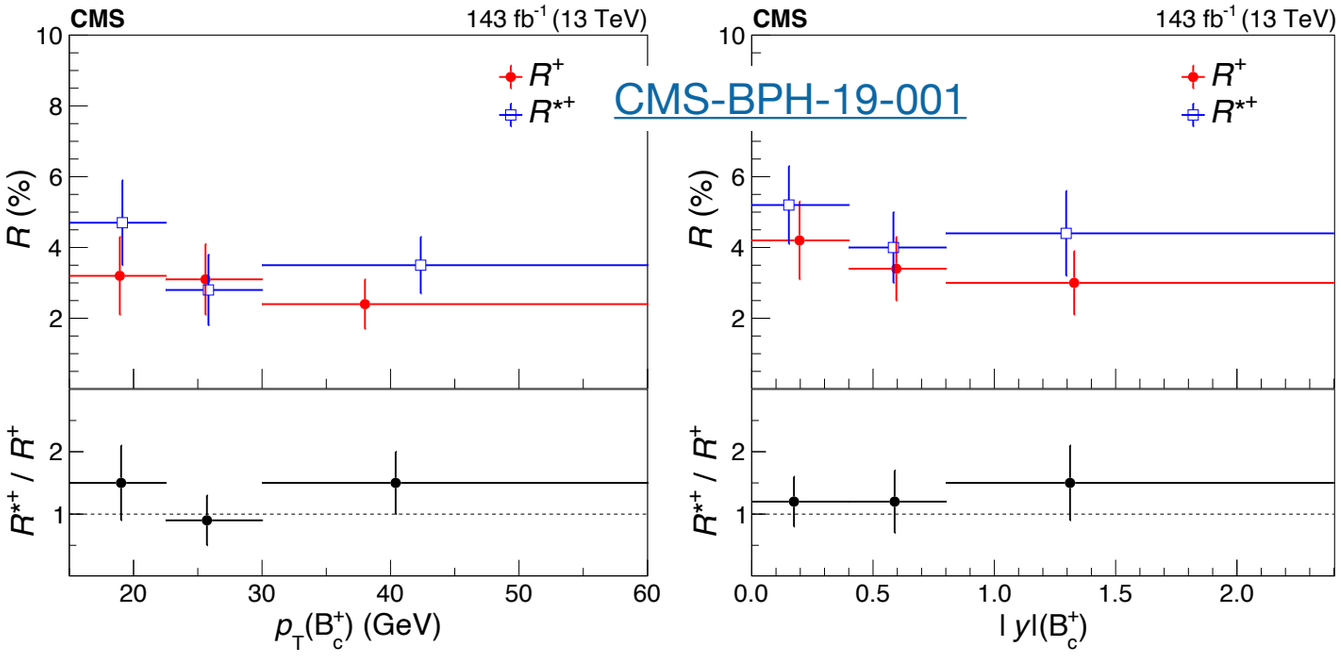
- Stay tuned for new beautiful and charming CMS results from the CMS Collaboration to be reported soon!

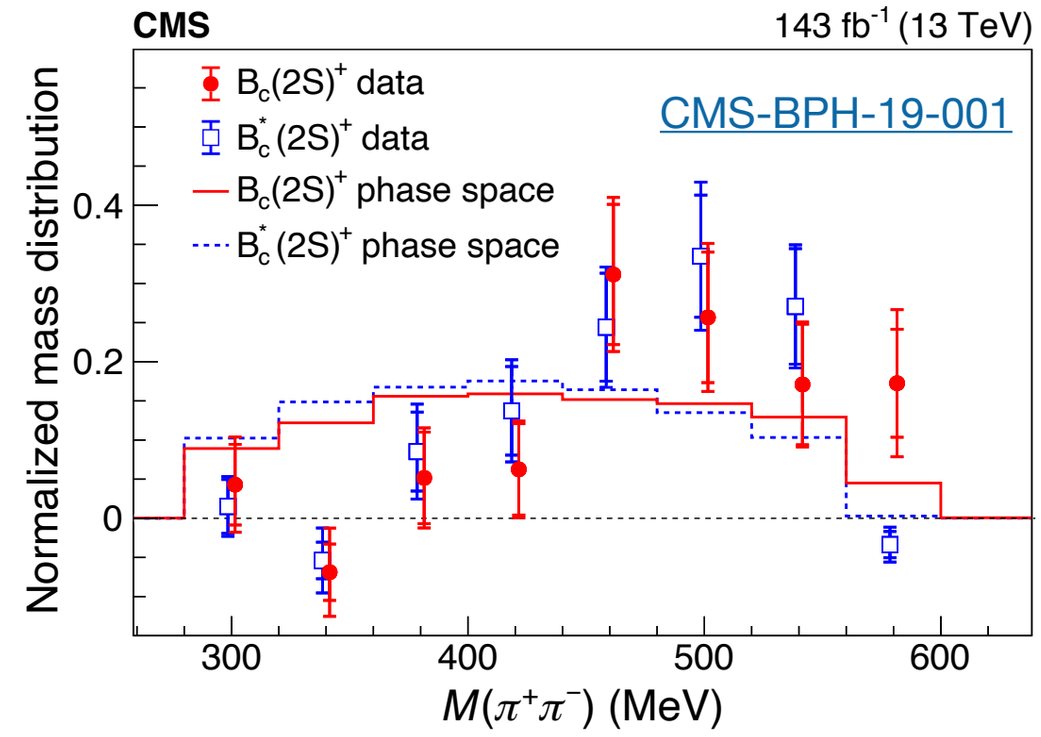
Thank you for your attention!

Do you have any questions?

Backup slides

$B_c^+(2S)$ and $B_c^{*+}(2S)$ cross section ratios





- Recently, the CMS Collaboration presented new results of measurement of $B_c^+(2S)$ and $B_c^{*+}(2S)$ cross section ratios (CMS-BPH-19-001, *accepted by PRD*), based on discussed B_c^+ and $B_c^{(*)+}(2S)$ Run-2 signals

- The $\mathrm{B_c(2S)^+}$ to $\mathrm{B_c^+}$, $\mathrm{B_c^*(2S)^+}$ to $\mathrm{B_c^+}$, and $\mathrm{B_c^*(2S)^+}$ to $\mathrm{B_c(2S)^+}$ cross section ratios are measured to be:

$$R^+ \equiv \frac{\sigma\left(\mathrm{B_c(2S)^+}\right)}{\sigma\left(\mathrm{B_c^+}\right)}\mathscr{B}\left(\mathrm{B_c(2S)^+} \to \mathrm{B_c^+}\pi^+\pi^-\right) = \frac{N\left(\mathrm{B_c(2S)^+}\right)}{N\left(\mathrm{B_c^+}\right)}\frac{\epsilon\left(\mathrm{B_c^+}\right)}{\epsilon\left(\mathrm{B_c(2S)^+}\right)} = (3.47 \pm 0.63 \pm 0.33)\,\%$$

$$R^{*+} \equiv \frac{\sigma\left(\mathrm{B_c^*(2S)^+}\right)}{\sigma\left(\mathrm{B_c^+}\right)}\mathscr{B}\left(\mathrm{B_c^*(2S)^+} \to \mathrm{B_c^{*+}}\pi^+\pi^-\right) = \frac{N\left(\mathrm{B_c^*(2S)^+}\right)}{N\left(\mathrm{B_c^+}\right)}\frac{\epsilon\left(\mathrm{B_c^+}\right)}{\epsilon\left(\mathrm{B_c^*(2S)^+}\right)} = (4.69 \pm 0.71 \pm 0.56)\,\%$$

$$R^{*+}/R^+ = \frac{\sigma\left(\mathrm{B_c^*(2S)^+}\right)}{\sigma\left(\mathrm{B_c(2S)^+}\right)}\frac{\mathscr{B}\left(\mathrm{B_c^*(2S)^+} \to \mathrm{B_c^{*+}}\pi^+\pi^-\right)}{\mathscr{B}\left(\mathrm{B_c(2S)^+} \to \mathrm{B_c^+}\pi^+\pi^-\right)} = \frac{N\left(\mathrm{B_c^*(2S)^+}\right)}{N\left(\mathrm{B_c(2S)^+}\right)}\frac{\epsilon\left(\mathrm{B_c(2S)^+}\right)}{\epsilon\left(\mathrm{B_c^*(2S)^+}\right)} = 1.35 \pm 0.32 \pm \pm 0.09$$

- No significant dependence the p_T or $|y|$ of the B_c^+ meson is observed

- The normalised dipion invariant mass distributions from the $\mathrm{B_c^{(*)}(2S)^+} \to \mathrm{B_c^{(*)+}}\pi^+\pi^-$ are reported

Different approaches for exited B-hadrons mass calculation

- We can extract "raw" 4-momenta from prompt PV's tracks or make exited B-hadron vertex fit and extract 4-momenta from fit for signal enhancement (used in $B_c^+\pi^+\pi^-$ PRL 122 (2019) 132001 analysis)

- New approach for exited B-hadrons study is applied for the $\Lambda_b^0\pi^+\pi^-$ PLB 803 (2020) 135345 analysis:

- We fit ALL the tracks forming the PV + B-candidate (about 20-100 tracks in each) and use 4-momenta from this vertex fit. The PV refitting procedure has improved the $\Lambda_b^0\pi^+\pi^-$ mass resolution by up to 50%