Latest Results in Spectroscopy

Adriano Di Florio

On Behalf of The CMS, LHCb and ATLAS Collaborations

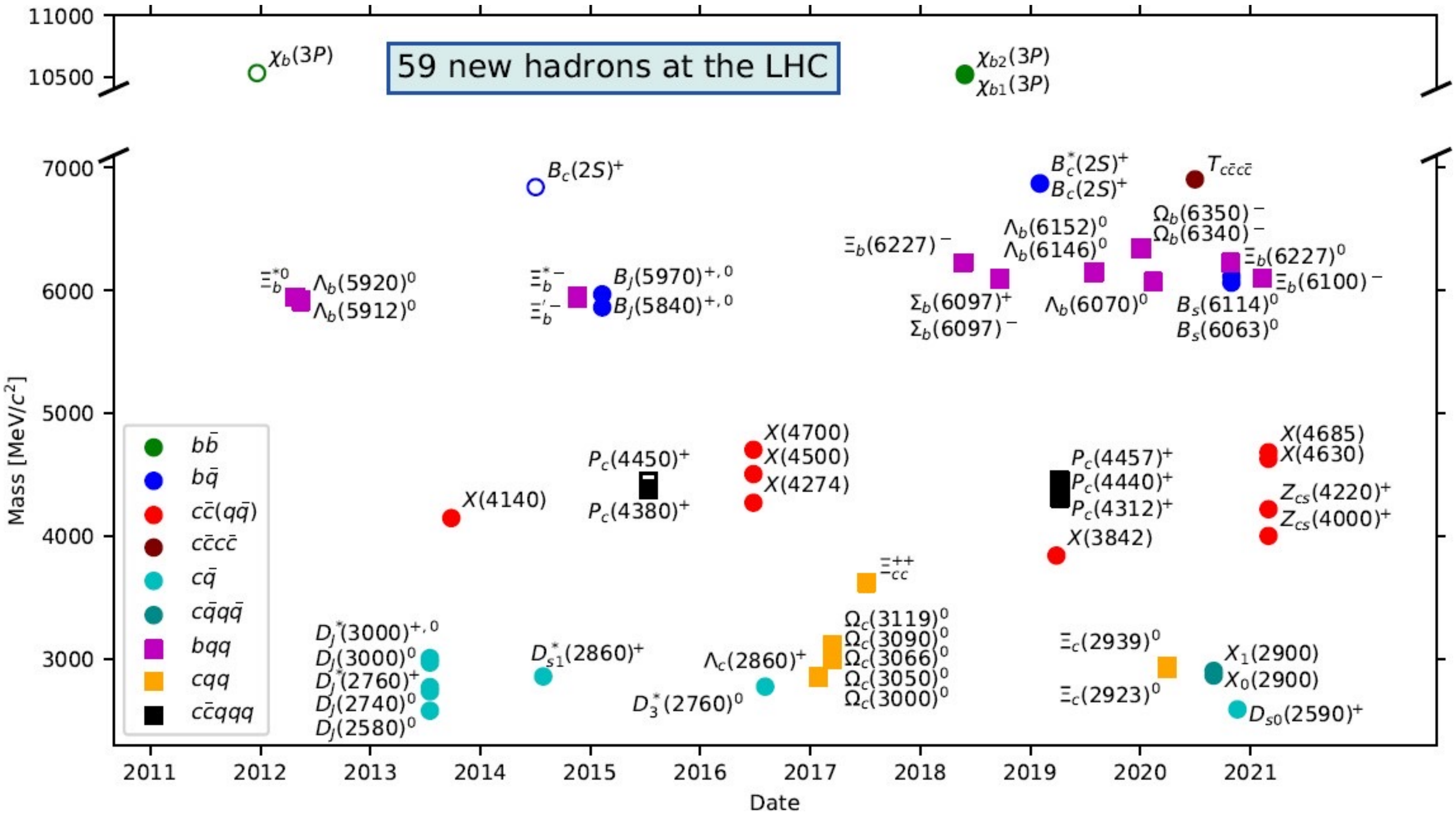
New results in conventional and exotic spectroscopy

Experiment	Result	Publication	Reference	Period	$\mathcal{L}$	$\sqrt{s}$
CMS	Excited Λ_b^0 states	Phys. Lett. B 803 135345	10.1016/j.physletb.2020.135345	Run II	140	13
CMS	Excited Ξ_b states	Accepted by PRL	arXiv:2102.04524	Run II	140	13
CMS	Observation of the $B_s^0 \to X(3872)\phi$ Decay	Phys. Rev. Lett. 125 152001	10.1103/PhysRevLett.125.152001	Run II	140	13
LHCb	Study of $B_s^0 \to J/\psi\pi^+\pi^-K^+K^-$ decays	JHEP 02 (2021) 024	10.1007/JHEP02(2021)024	Run I + II	9	7; 8; 13
LHCb	Observation of the decay $\Lambda_b^0 \to \chi_{c1}\, p\pi^-$	Submitted to JHEP	arXiv:2103.04949	Run II *	5.2	13
LHCb	Search for the doubly heavy baryons Ξ_{bc}^0 and Ω_{bc}^0	Submitted to JHEP	arXiv:2104.04759	Run II	6	13
LHCb	Observation of new resonances decaying to $J/\psi K$ and $J/\psi\phi$	Submitted to PRL	arxiv:2103.01803	Run I + II	9	7; 8; 13
ATLAS	Study of $J/\psi p$ resonances in the $\Lambda_b^0 \to J/\psi pK^-$ decays	ATLAS-CONF-2019-048	cdsweb.cern.ch/record/2693957	Run I	4.9 + 20.6	7; 8

* 2016 - 2018

conventional | both | exotic

LHC results in conventional and exotic spectroscopy



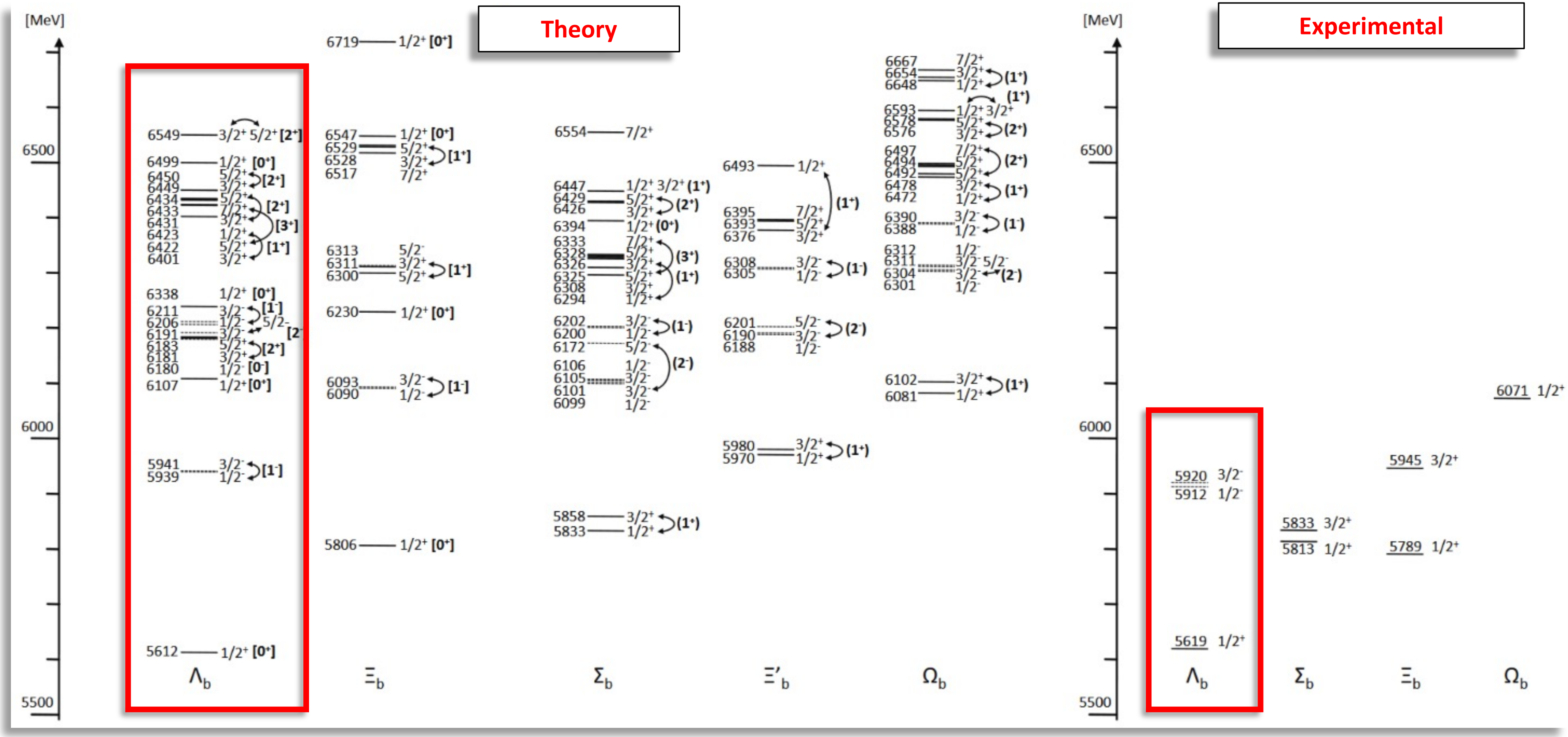
from CERN Courier

(udb) spectroscopy : excited Λ_b^0 states

Phys. Lett. B 803 (2020) 135345

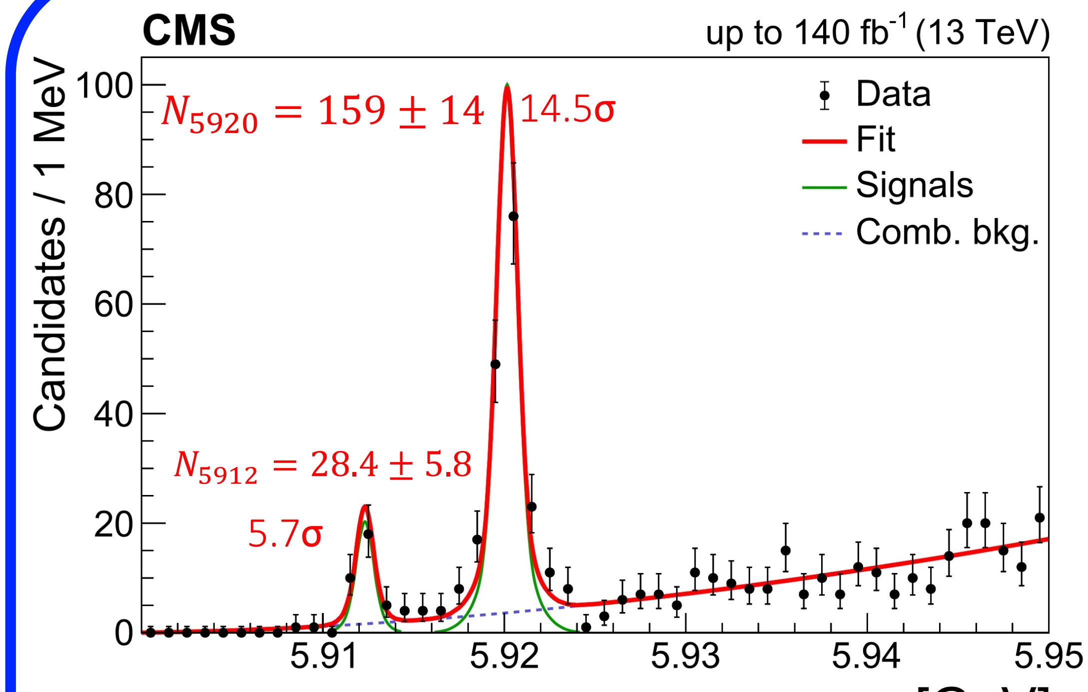
Introduction to Λ_b^0 excited states

Studies of excited heavy baryon spectrum **are an important test** of Heavy Quark Effective Theory. 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 narrow window** to search for a signal.



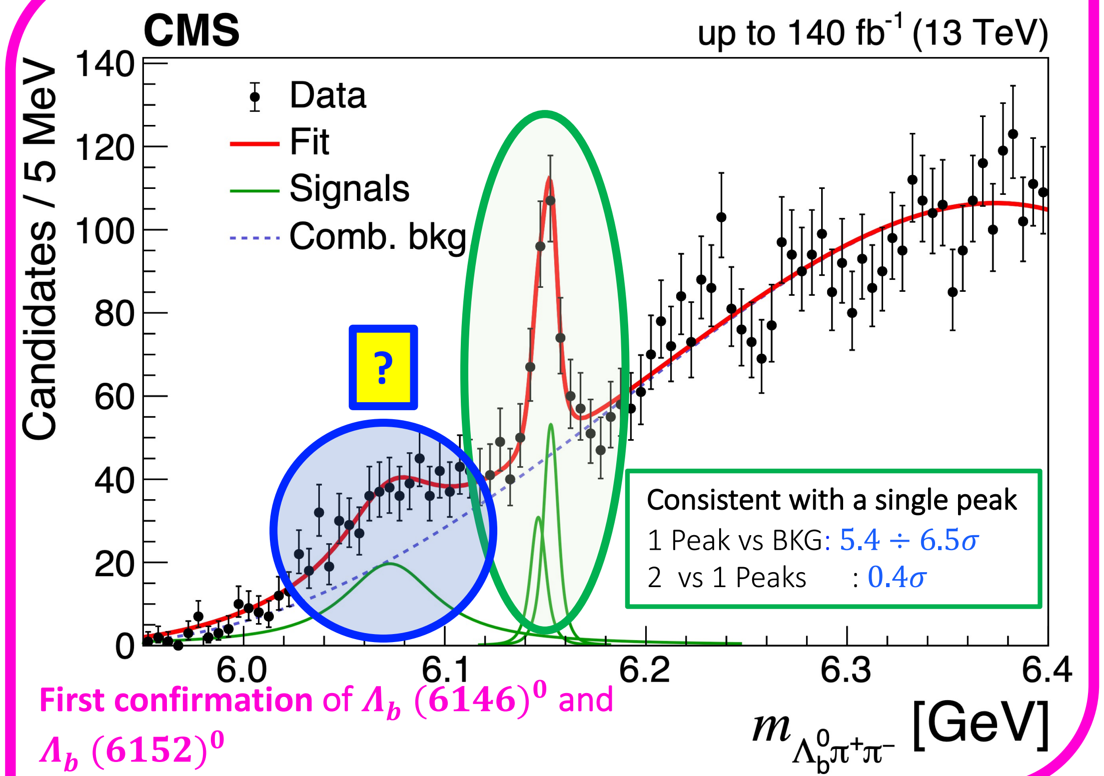
- To study the exticed Λ_b states, CMS used $\Lambda_b^0 \to J/\psi\Lambda$ and $\Lambda_b^0 \to \psi(2S)\Lambda$ channels with $\psi(2S) \to \mu\mu$ or $\psi(2S) \to J/\psi\pi^+\pi^-$
- $m_{\Lambda_b^0\pi^-\pi^+} = M(\Lambda_b^0\pi^-\pi^+) - M(\Lambda_b^0) + M_{\Lambda_b^0}^{PDG}$ ⊕ a new PV refit technique, i.e. fitting all the tracks forming the **PV + *B candidate*** and use 4-momenta from this vertex fit; crucial to improve detector resolution

at **low masses** (near threshold)



First confirmation of $\Lambda_b\,(5912)^0$ and confirmation of $\Lambda_b\,(5920)^0$

at **high masses** (higher background)



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

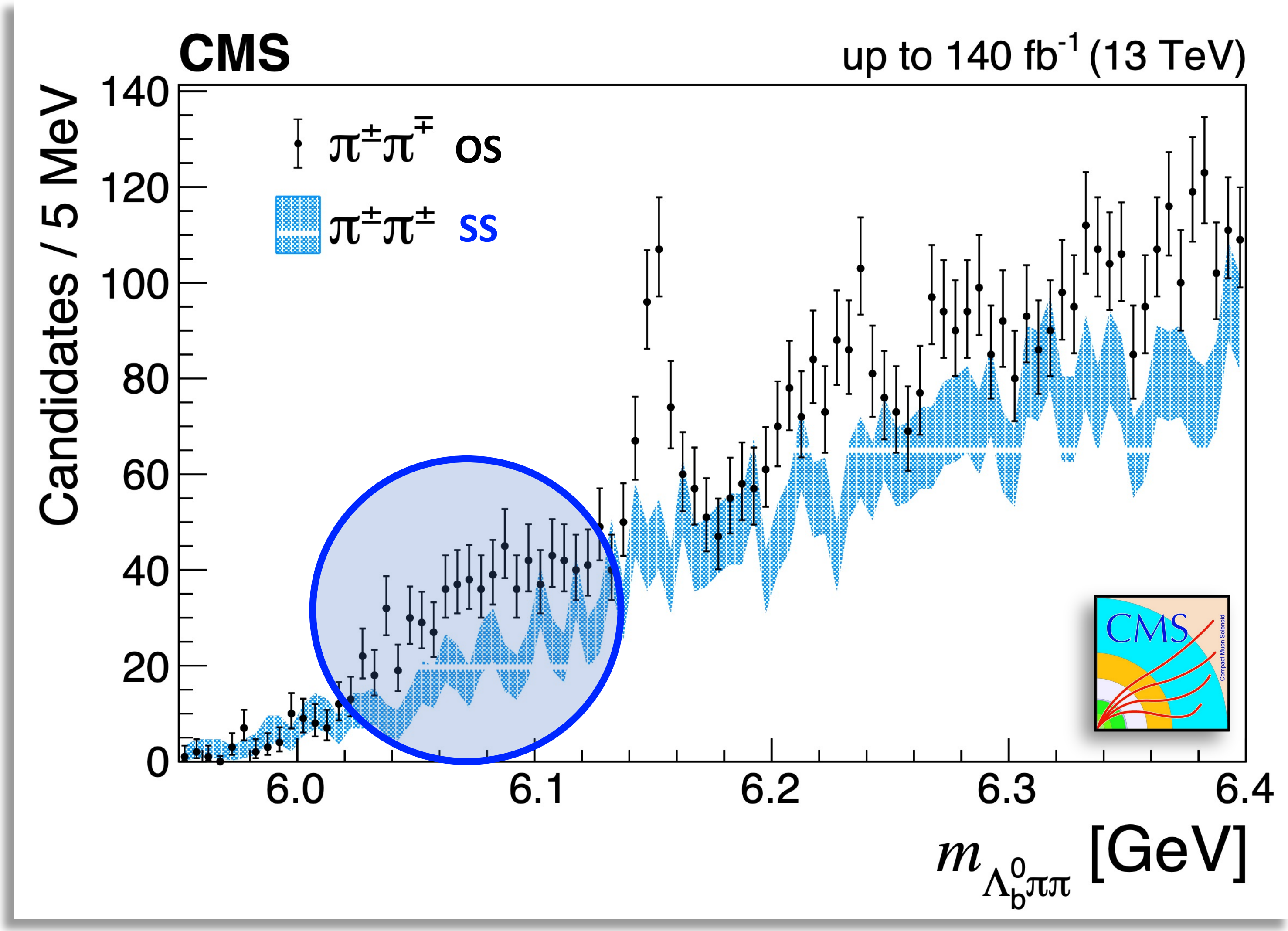
$M(\Lambda_b(5912)^0) = [5912.32 \pm 0.12(stat) \pm 0.01(syst) \pm 0.17(m_{PDG}(\Lambda_b^0))]\mathrm{MeV}$

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

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

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

Same Sign $\pi^{\pm}\pi^{\pm}$ Distributions



The *bump* in the $\Lambda_b^0\pi^{\pm}\pi^{\mp}$ invariant mass spectrum is **not present in the same sign spectrum** $\Lambda_b^0\pi^{\pm}\pi^{\pm}$

Assuming a single broad resonance X_b and using the same signal fit model as before:

$$M(X_b) = [6073 \pm 5(stat)]MeV$$

$$\Gamma(X_b) = [55 \pm 11(stat)]MeV$$

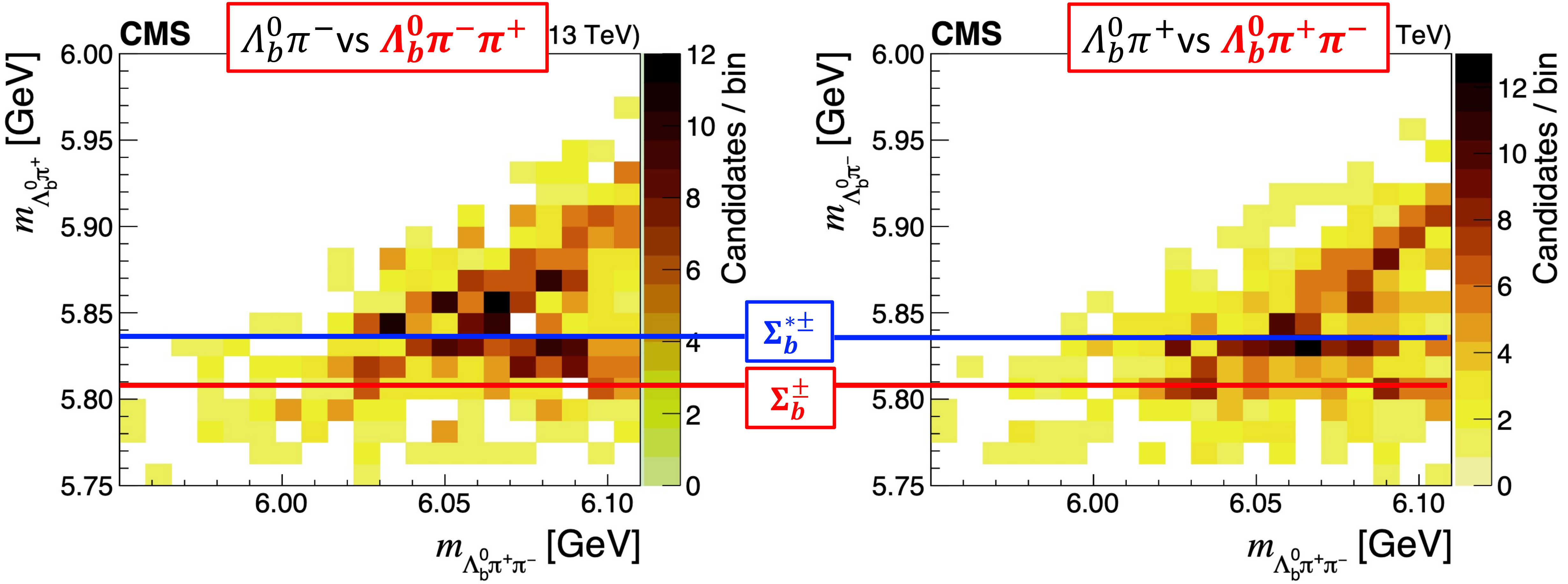
with **4σ** statistical significance

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 **not necessarily** be a single state but - instead - a **superposition or several nearby broad states**.

$\Sigma_b^{(*)\pm}$ Contributions

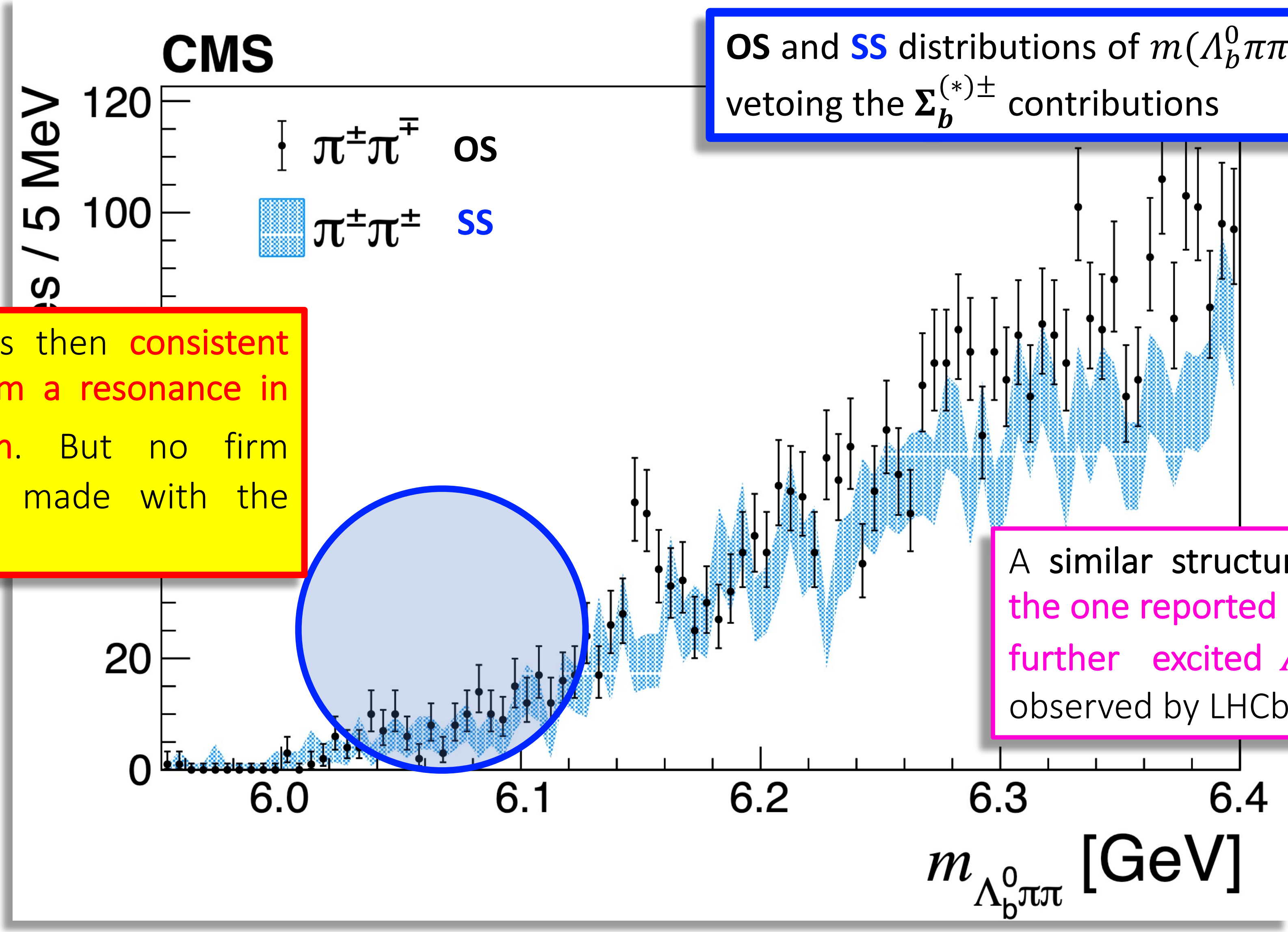
Inspecting the scatter plots $\Lambda_b^0\pi^\pm$ vs $\Lambda_b^0\pi^\pm\pi^\mp$ in the region of interest ($m_{\Lambda_b^0\pi^\pm\pi^\mp} < 6.11$ GeV)



Horizontal bands corresponding to the $\Sigma_b^{(*)\pm} \longrightarrow \Lambda_b^0\pi^\pm$ are visible and if we veto them …

$\Sigma_b^{(*)\pm}$ Veto

… we see that the «bump» **disappear**



OS and **SS** distributions of $m(\Lambda_b^0\pi\pi)$ vetoing the $\boldsymbol{\Sigma_b^{(*)\pm}}$ contributions

The **broad excess** is then 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.

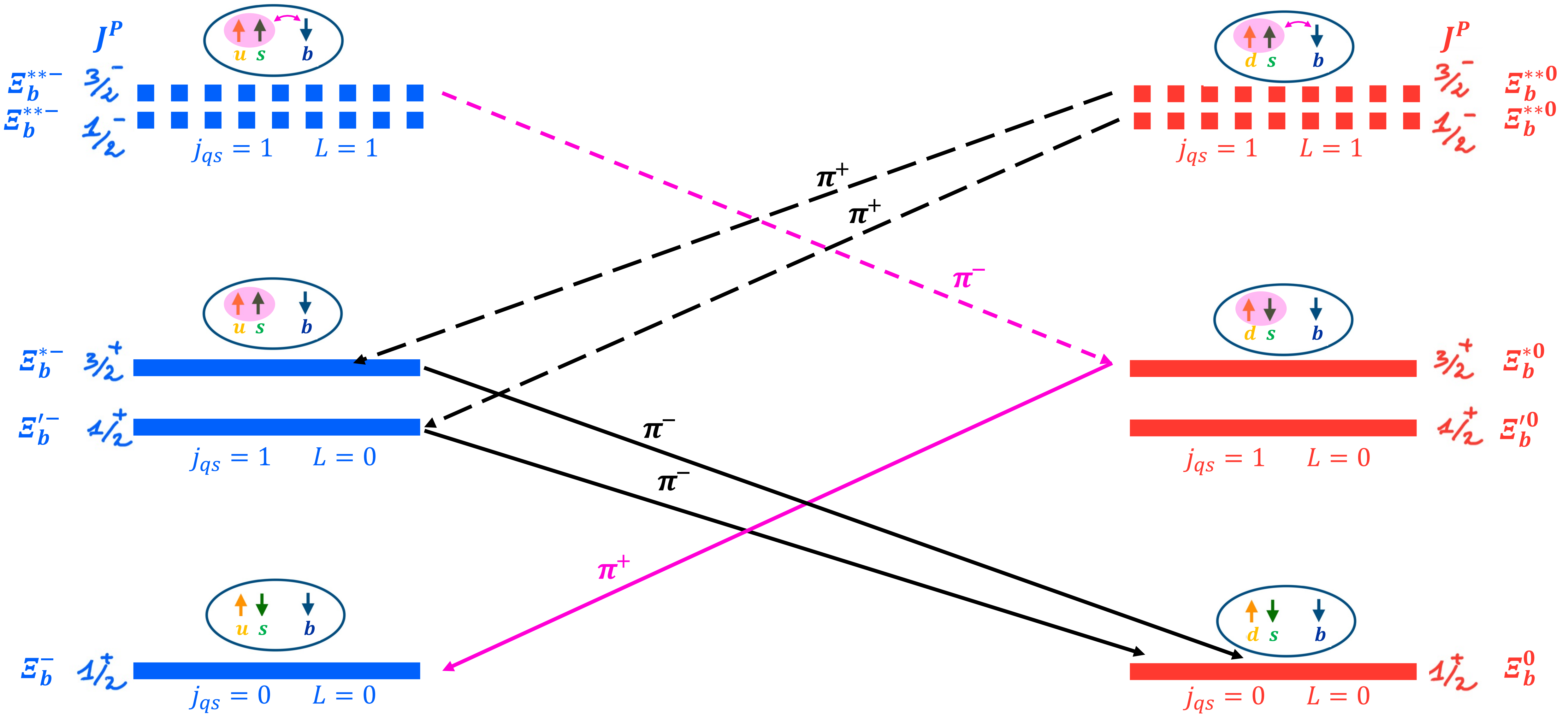
A **similar structure**, consistent with the one reported here and possibly a further excited Λ_b^0 state has been observed by LHCb (see backup).

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

arXiv:2102.04524

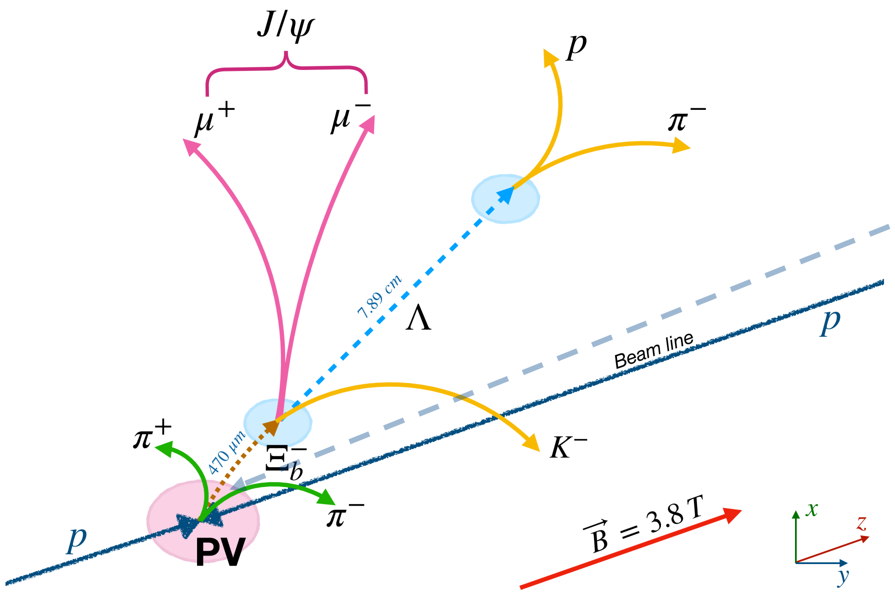
(submitted to PRL)

- Ξ_b^0 and Ξ_b^- forms isodoublet of (qsb) bound states $q = u \lor d$.



Search for $\Xi_b^{**-} \to \Xi_b^{*0}\,\pi^- \to \Xi_b^-\pi^-\,\pi^+$

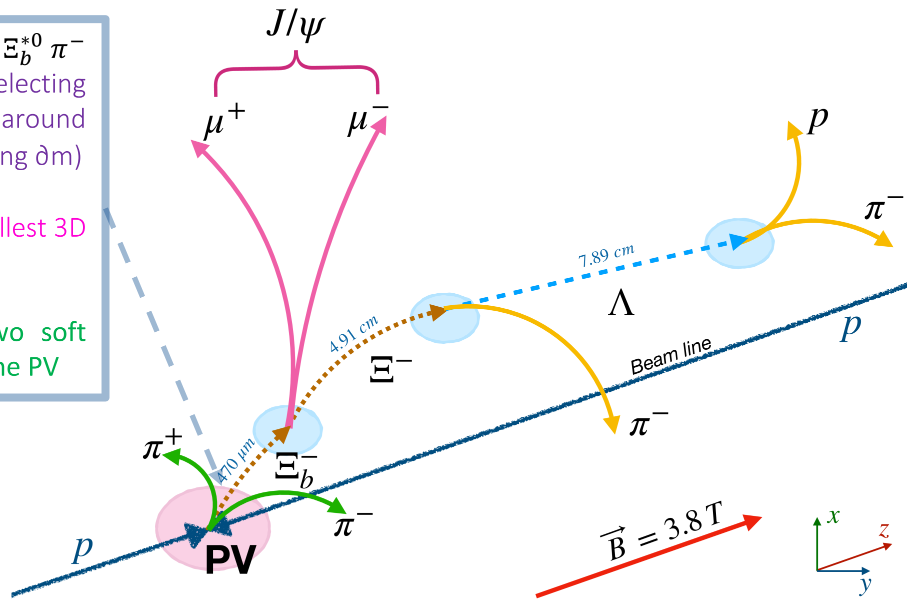
- A **new resonance** is searched through $\Xi_b^{**-} \to \Xi_b^{*0}\,\pi^- \to \Xi_b^-\pi^-\,\pi^+$ (charge conjugate states are implied)
- Ξ_b^- is then reconstructed via its decays $\Xi_b^- \to J/\psi\Xi^-$ and $\Xi_b^- \to J/\psi\Lambda K^-$(with a contribution from partially reconstructed $\Xi_b^- \to J/\psi\Sigma^0 K^-$channel) with $J/\psi \to \mu\mu$,$\Xi^- \to \Lambda\pi^-$ and $\Lambda \to p\pi^-$



The intermediate $\Xi_b^{**-} \to \Xi_b^{*0}\,\pi^-$ is taken into account by selecting a 5 MeV mass window around the Ξ_b^{*0} for the $\Xi_b^{*0}\,\pi^-$ (using ∂m)

PV is the one with the smallest 3D pointing angle

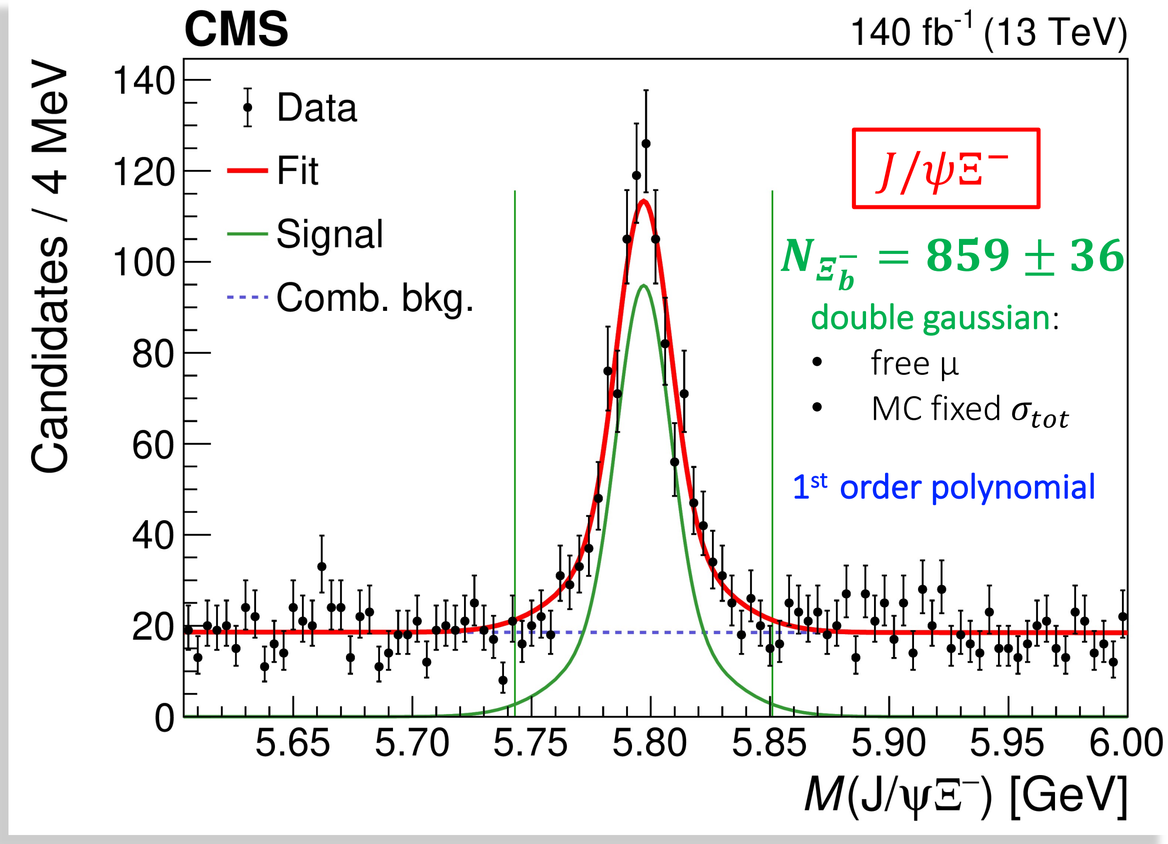
Ξ_b^- is combined with two soft pion tracks coming from the PV

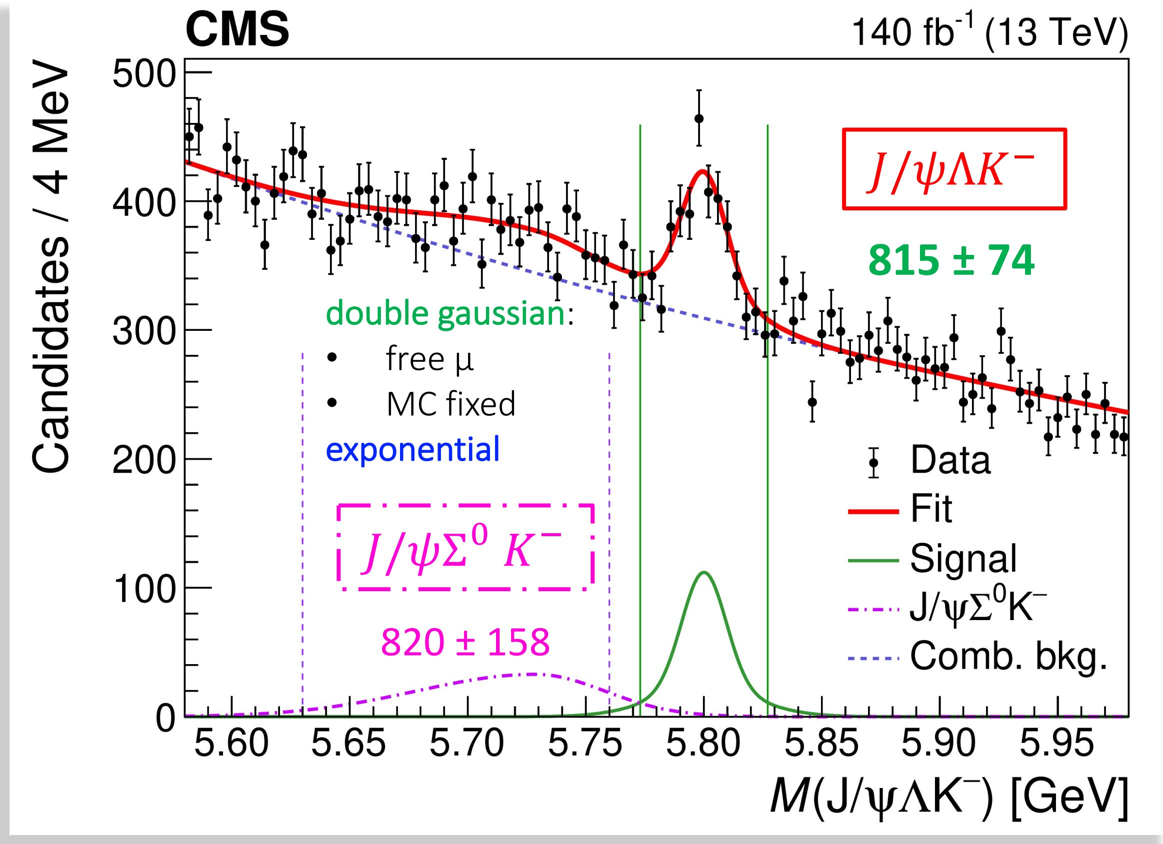


- Selection criteria (shown in backup) are optimised using Punzi Figure of Merit $f = S/(463/13 + 4\ B + 5\ 25 + 8\ B + 4B)$

See backup for selection

Ξ_b^- signals

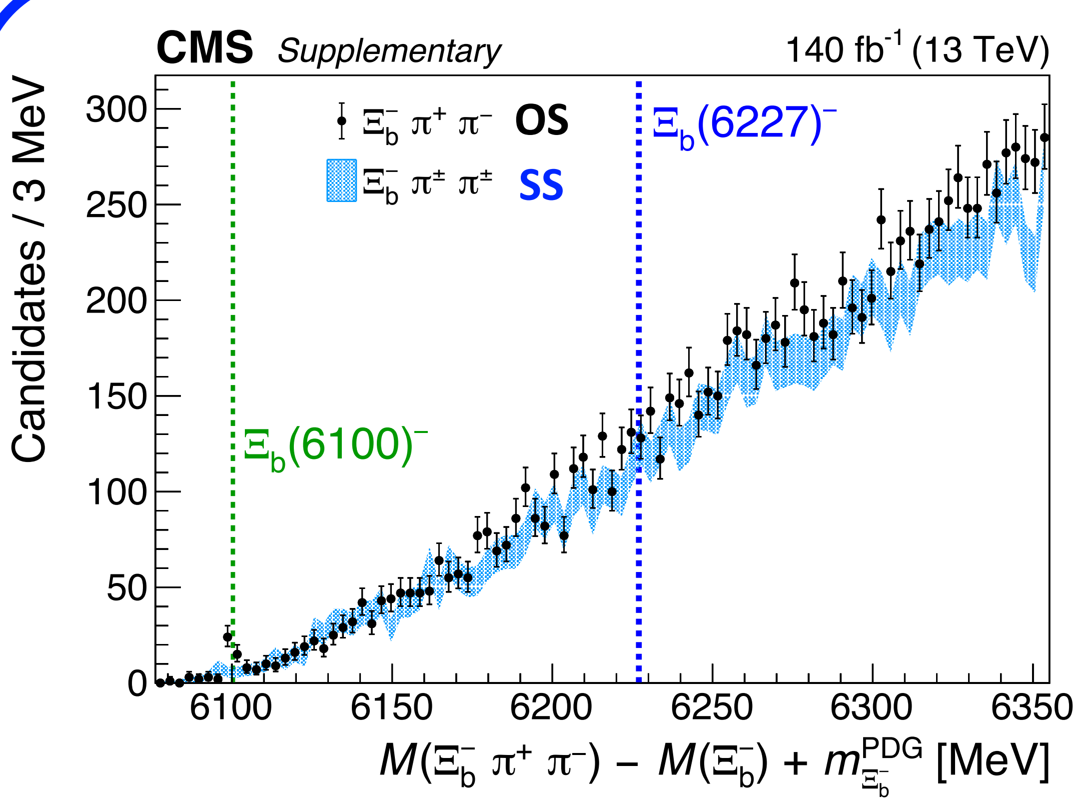




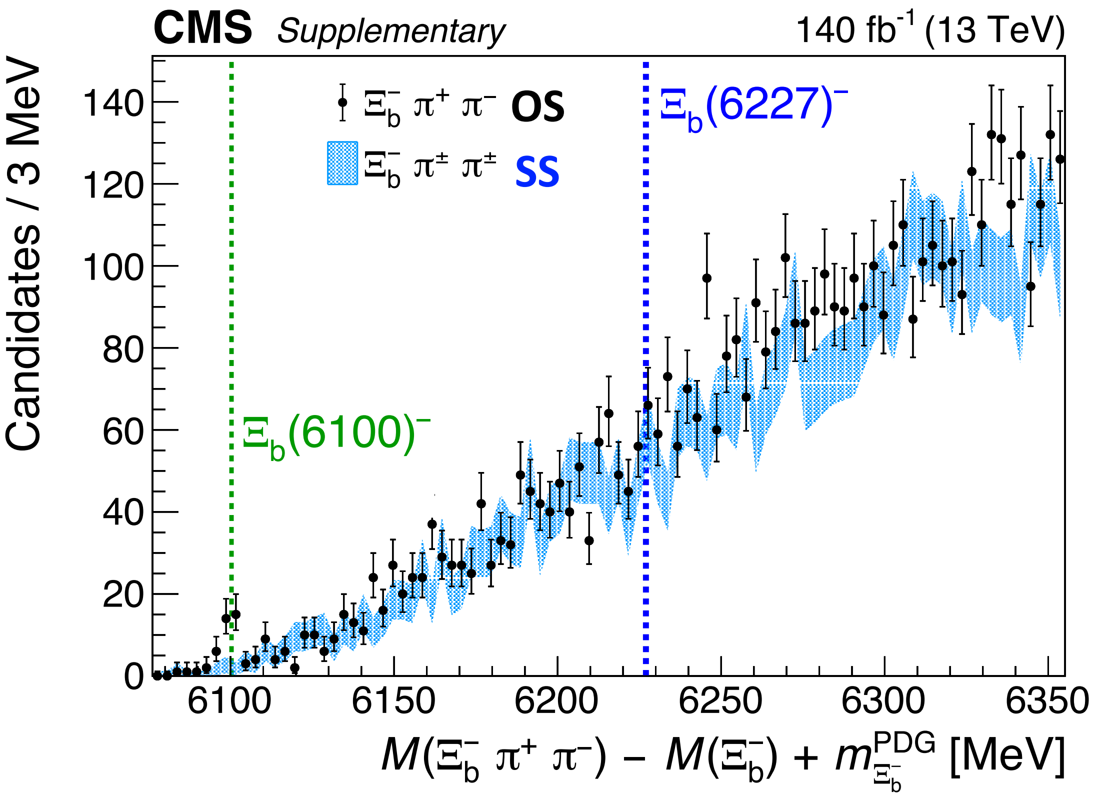
- The $\Xi_b^- \to J/\psi\Sigma^0 K^-$ is partially reconstructed due to the soft photon in $\Sigma^0 \to \Lambda\gamma$ and is modelled with an asymmetrical gaussian.
- Both the fully reconstructed and partially reconstructed decays are used to build the $\Xi_b^-\pi^-\pi^+$ candidates (see mass selection on the plots)

Same Sign $\pi^{\pm}\pi^{\pm}$ and Opposite Sign $\pi^{+}\pi^{-}$ distributions

$\Xi_b^- \to J/\psi\Xi^-$ and $\Xi_b^- \to J/\psi\Lambda K^-$



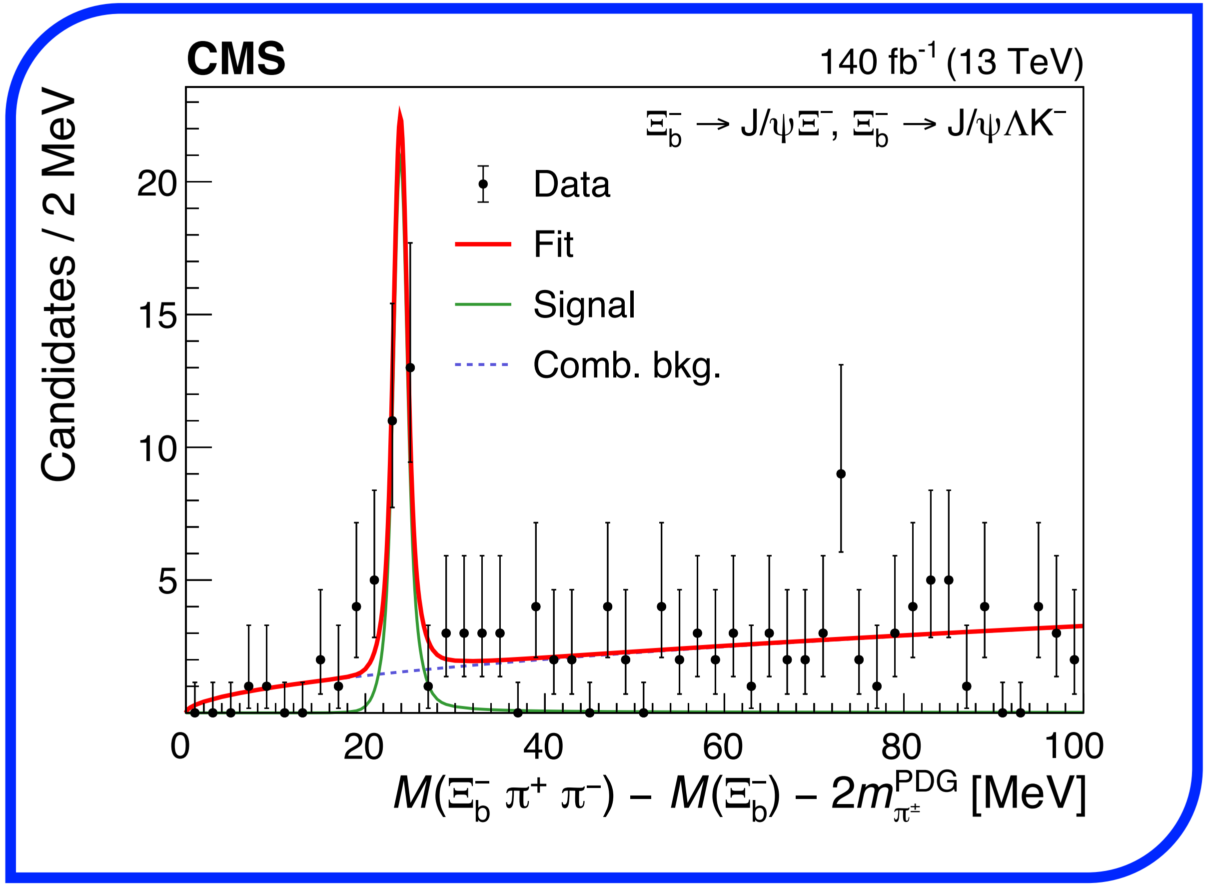
$\Xi_b^- \to J/\psi\Sigma^0 K^-$



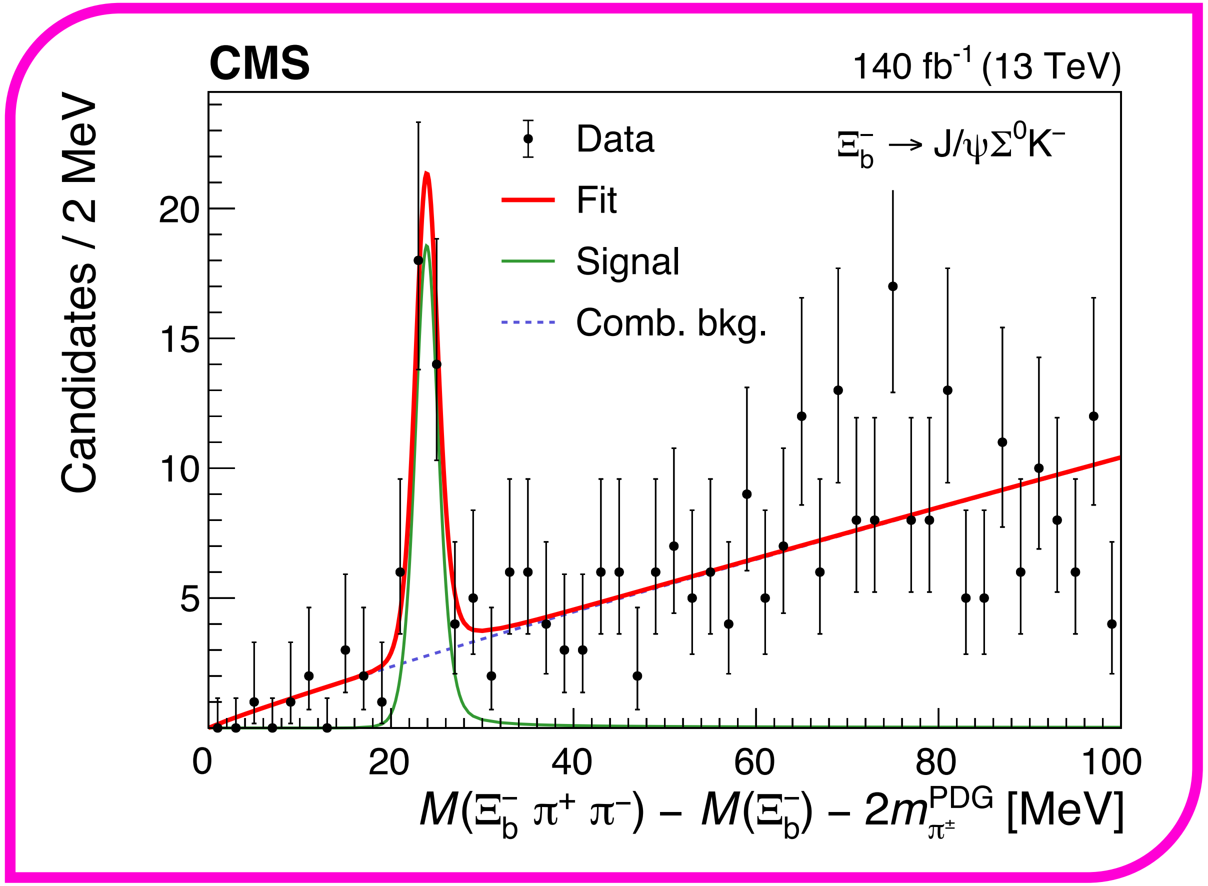
- No Ξ_b^{*0} mass cut on $\Xi_b^- \pi^+$
- Only peaking structure at ~ 6100 MeV
- No hint of $\Xi_b(6227)^-$ reported by LHCb in PhysRevD.103.012004

$\Xi_b(6100)^-$

$\Xi_b^- \to J/\psi\Xi^-$ and $\Xi_b^- \to J/\psi\Lambda K^-$



$\Xi_b^- \to J/\psi\Sigma^0 K^-$



- Simultaneous fit to the two distribution :common **mean** and **width**

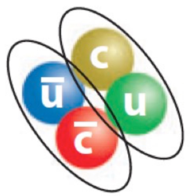
$$M(\Xi_b(6100)^-) = 6100.3 \pm 0.2 \pm 0.1 \pm 0.6\ MeV \qquad \Gamma(\Xi_b(6100^-) < 1.9\ MeV\ @95\%\ CL$$

- Significance $> 6\sigma$: **first observation of $\Xi_b(6100)^-$** compatible with the orbitally excited Ξ_b^- with $J^P = \frac{3^-}{2}$ analogue of $\Xi_c(2815)$
- $\Delta M = M(\Xi_b^-\pi^-\pi^+) - M(\Xi_b^-\pi^-) - 2m_{\pi^\pm}^{PDG})$ $\oplus$ a new PV refit technique crucial to improve detector resolution

Observation of the $B_s^0 \to X(3872)\phi$ Decay

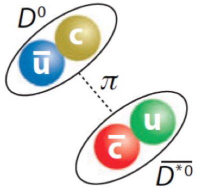
PhysRevLett.125.152001

$B_s^0 \to X(3872)\phi$ and $B_s^0 \to \psi(2S)\phi$: signal and normalization



- $X(3872)$ was discovered by Belle in 2003. What we know

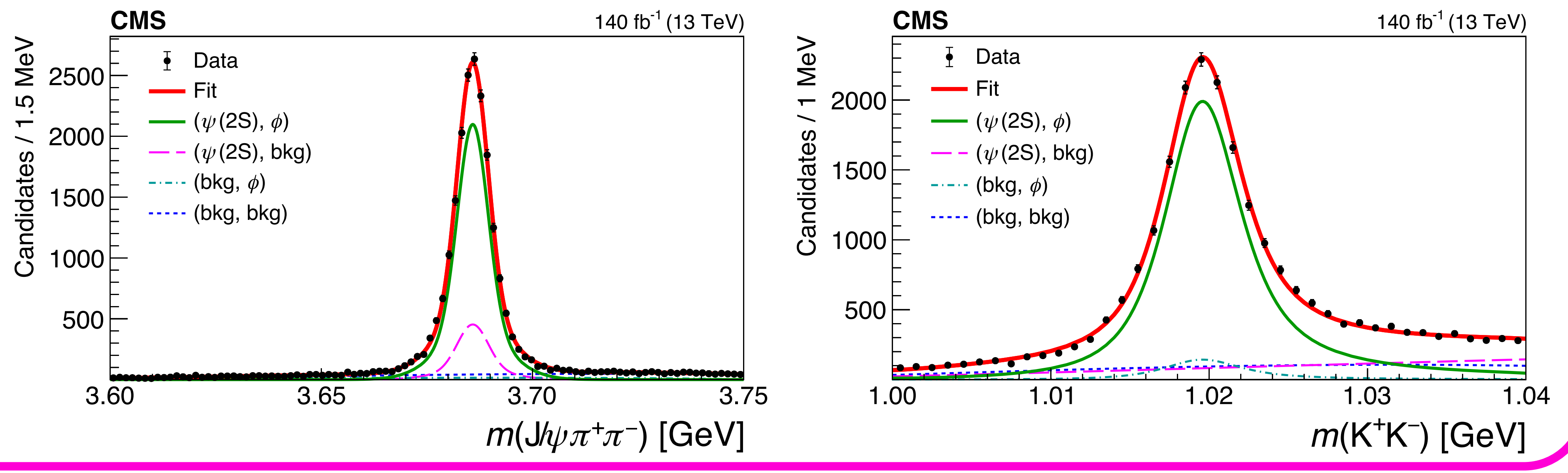
  $m(X)$ very near to $m(D^0 D^{0*})$ $\Gamma < 1.2$ MeV $J^{PC} = 1^{++}$



- What we **don't know (yet): its nature.** A tetraquark, a molecule, a mixture, a conventional charmonium state [$\chi_{c1}(3872)$] ?
- Evidence for inclusive production **in** $PbPb$, observed prompt in pp and nonprompt in pp from B^+, B^0, Λ_b^0 but not from B_s^0.
- **Two channels studied (with $\phi \to KK$ and $X \to J/\psi(\to \mu\mu)\pi\pi$)** with very similar topologies and same event selection (see backup)

  $B_s^0 \to X(3872)\phi$ (signal) $B_s^0 \to \psi(2S)\phi$ (normalization)

- With a 2D fit to $m(KK)$ in the ϕ mass region and to $m(J/\psi\pi\pi)$ in the $\psi(2S)$ mass region



$B_s^0 \to \psi(2S)\phi$

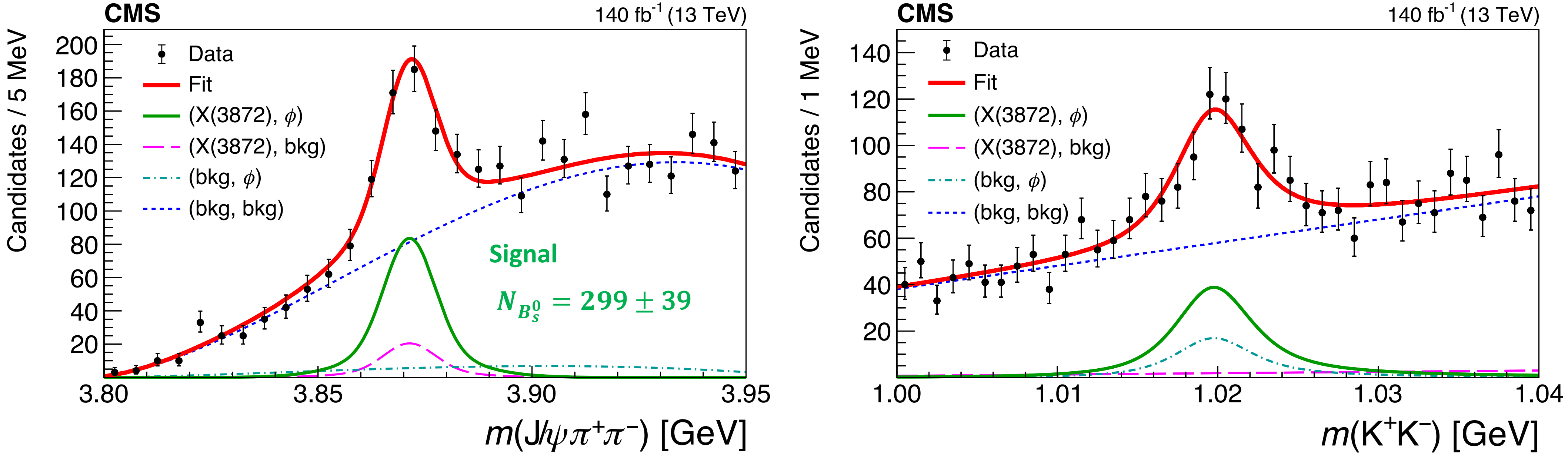
Signal

$N_{B_s^0} = 15359 \pm 171$

$B_s^0 \to X(3872)\phi$ observation

- With a 2D fit to $m(KK)$ in the ϕ mass region and to $m(J/\psi\pi\pi)$ in the $X(3872)$ mass region

$B_s^0 \to X(3872)\phi$



- **First observation with significance $> 6\sigma$**

- Using the yields measured and corrected with the relative efficiencies, the branching fraction ratio $\mathcal{R}$ is calculated:

$$R \equiv \frac{\mathcal{B}[B_s^0 \to X(3872)\phi]\mathcal{B}[X(3872) \to J/\psi\pi^+\pi^-]}{\mathcal{B}[B_s^0 \to \psi(2S)\phi]\mathcal{B}[\psi(2S) \to J/\psi\pi^+\pi^-]} = [2.21 \pm 0.29(\text{stat}) \pm 0.17(\text{syst})]\%$$

Also later confirmed by LHCb (see next slides)

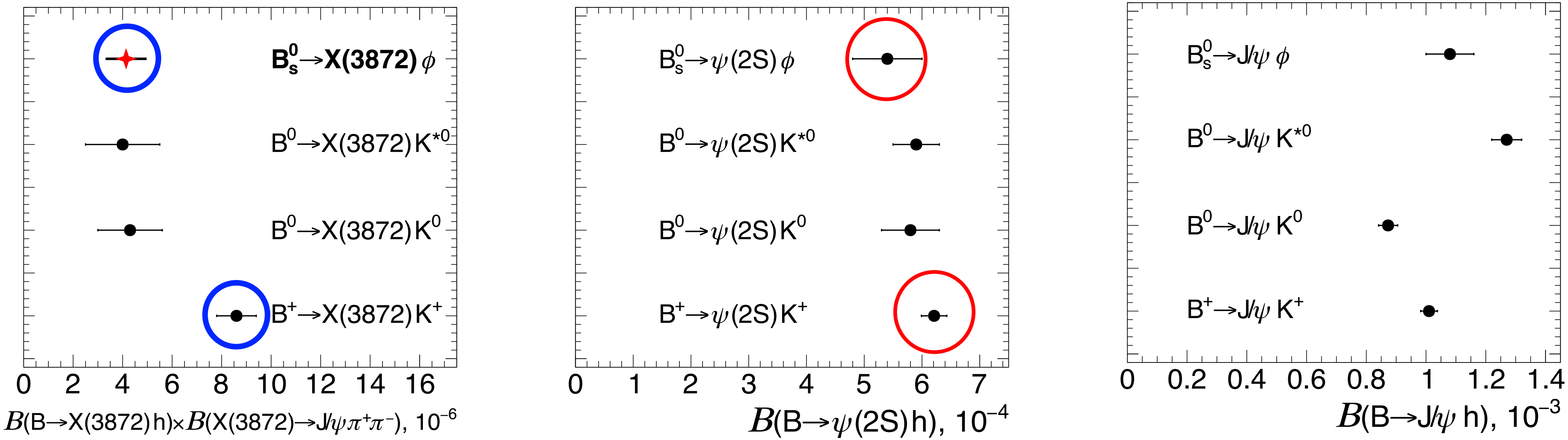
$\mathcal{R}$ calculations and comparisons

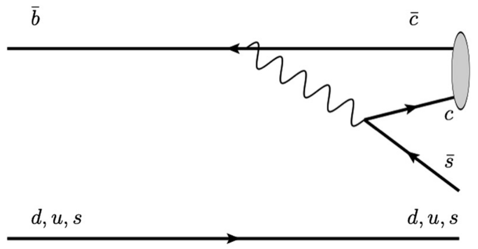
- Multiplying $\mathcal{R}$ for the known $\mathcal{B}[B_s^0 \to \psi(2S)\phi]$ and $\mathcal{B}[\psi \to J/\psi\pi\pi]$ the $\mathcal{B}$ product is calculated:

$$\mathcal{B}(B_s^0 \to X(3872)\phi)\,\mathcal{B}(X(3872) \to J/\psi\,\pi^+\pi^-) = (4.14 \pm 0.54\,(\text{stat}) \pm 0.32\,(\text{syst}) \pm 0.46\,(\mathcal{B})) \times 10^{-6}$$

- The measured value is consistent with B^0 but two times smaller than the one for B^+ **(not for $\psi(2S)$ instead)**

$$\frac{\mathcal{B}(B_s^0 \to X(3872)\phi)}{\mathcal{B}(B^+ \to X(3872)K^+)} = 0.482 \pm 0.063\,(\text{stat}) \pm 0.037\,(\text{syst}) \pm 0.070\,(\mathcal{B})$$





- In PhysRevD.102.034017 this results is interpreted as possibly favouring the **compact tetraquark hypothesis**

Study of $B_s^0 \to J/\psi\pi^+\pi^-K^+K^-$ decays

JHEP 02 (2021) 024

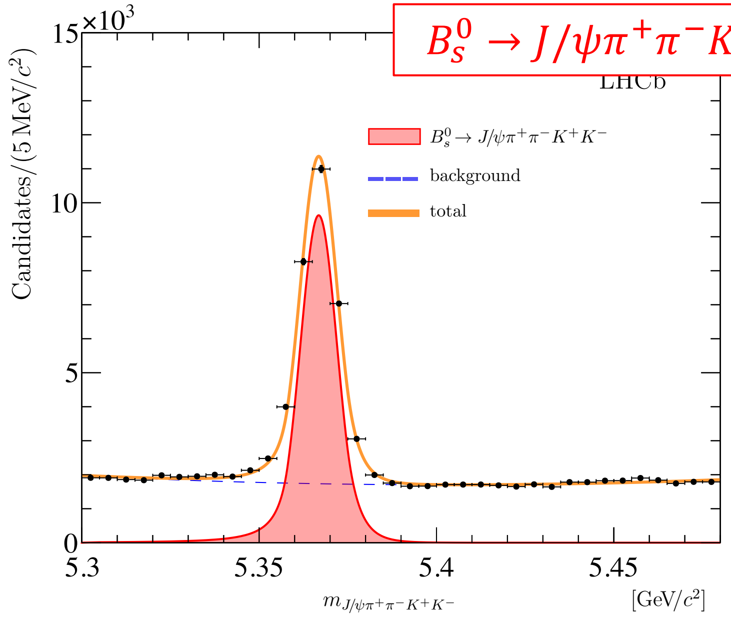
Study of $B_s^0 \to J/\psi\pi^+\pi^-K^+K^-$ decays

- Motivation:
  - $\chi_{c1}(3872)$ and $J/\psi\phi$ structures can be studied in this decay
  - Production rate measurements can shed light on the nature of exotic states

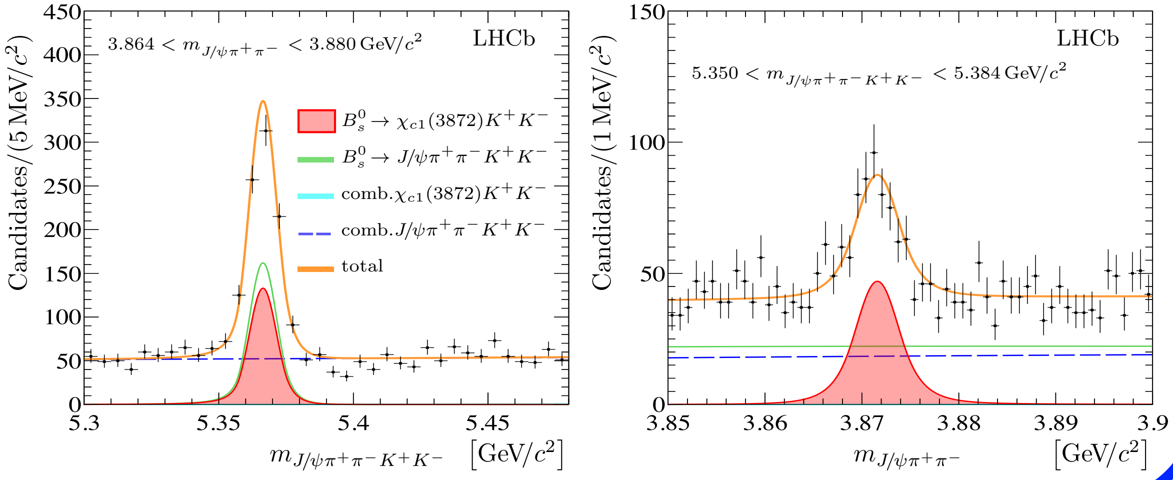
- Multiple channels studied, multiple branching fractions measured (see backup for $\mathcal{R}$)
  - $B_s^0 \to X_{c\bar{c}}\phi$ $X_{c\bar{c}} = [\chi_{c1}(3872), \psi(2S)]$ $X_{c\bar{c}} \to J/\psi\pi\pi$ with
  - $\boldsymbol{B_s^0 \to \chi_{c1}(3872)K^+K^-}$ (non resonant KK) First Observation
  - $\boldsymbol{B_s^0 \to J/\psi K^{*0}\overline{K}^{*0}}$ First Observation
  - $B_s^0 \to J/\psi\pi^+\pi^-K^+K^-$ (non resonant $J/\psi\pi\pi$, see next slide)

- **Most precise** single measurement of $\boldsymbol{B_s^0}$ **mass** $m_{B_s^0} = 5366.98 \pm 0.07 \pm 0.13\,\mathrm{MeV}/c^2$
  [from samples enriched in $B_s^0 \to \psi(2S)\,\phi$]

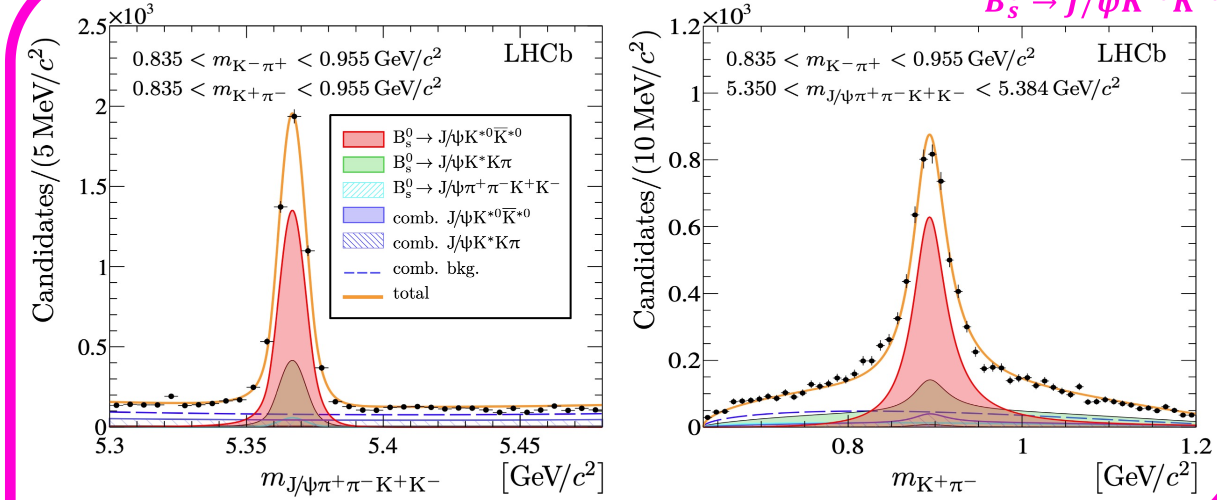
$B_s^0 \to J/\psi\pi^+\pi^-K^+K^-$



$B_s^0 \to \chi_{c1}(3872)K^+K^-$



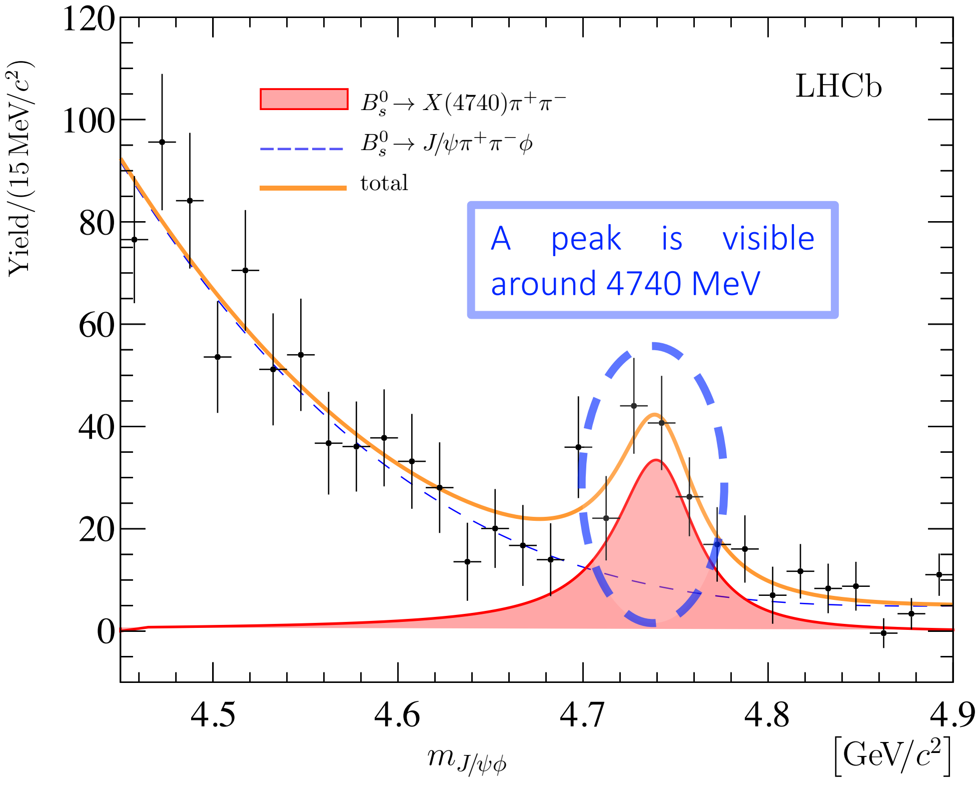
$B_s^0 \to J/\psi K^{*0}\overline{K}^{*0}$



for $K^-\pi^+$ see backup

$J/\psi\phi$ mass spectrum

- The $J/\psi\phi$ spectrum is investigated using $J/\psi\pi^+\pi^-K^+K^-$ sample (excluding $\psi(2S)$ and $\chi_{c1}(3872)$ resonances)

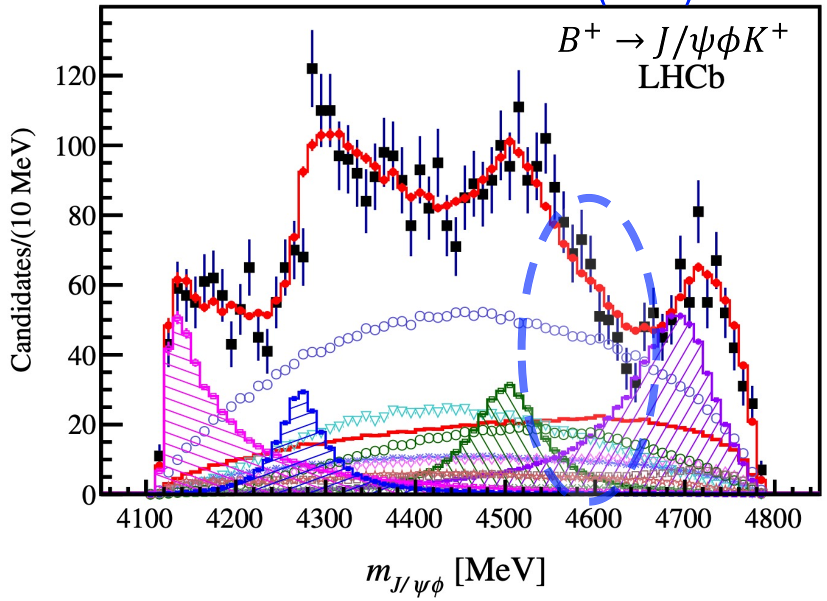


- Fitting with the Breit-Wigner lineshape

$$m_{X(4740)} = 4741 \pm 6 \pm 6 \ \mathrm{MeV}/c^2 ,$$
$$\Gamma_{X(4740)} = 53 \pm 15 \pm 11 \, \mathrm{MeV} ,$$

- Significance $> 5\sigma$

PRL 118 (2017) 022003



- Further studies would be needed to understand if it is the same X(4700) found in $B^+ \to J/\psi\phi K^+$

$\mathcal{R}$ ratios

- $\mathcal{R}$ branching ratios

Compatible with CMS result

$$\mathcal{R}^{\chi_{c1}(3872)\phi}_{\psi(2S)\phi} = \frac{N_{B^0_s\to\chi_{c1}(3872)\phi}}{N_{B^0_s\to\psi(2S)\phi}} \times \frac{\varepsilon_{B^0_s\to\psi(2S)\phi}}{\varepsilon_{B^0_s\to\chi_{c1}(3872)\phi}}$$

$$= (2.42 \pm 0.23 \pm 0.07) \times 10^{-2}\,,$$ (LHCb)

$$= [2.21 \pm 0.29(\text{stat}) \pm 0.17(\text{syst})]\%$$ (CMS)

$$\mathcal{R}_{K^+K^-} = \frac{1}{f_\phi} - 1 = 1.57 \pm 0.32 \pm 0.12\,,$$ (non resonant)

$$\mathcal{R}^{J/\psi K^{*0}\overline{K}^{*0}}_{\psi(2S)\phi} = \frac{N_{B^0_s\to J/\psi K^{*0}\overline{K}^{*0}}}{N_{B^0_s\to\psi(2S)\phi}} \times \frac{\varepsilon_{B^0_s\to\psi(2S)\phi}}{\varepsilon_{B^0_s\to J/\psi K^{*0}\overline{K}^{*0}}} = 1.22 \pm 0.03 \pm 0.04\,,$$

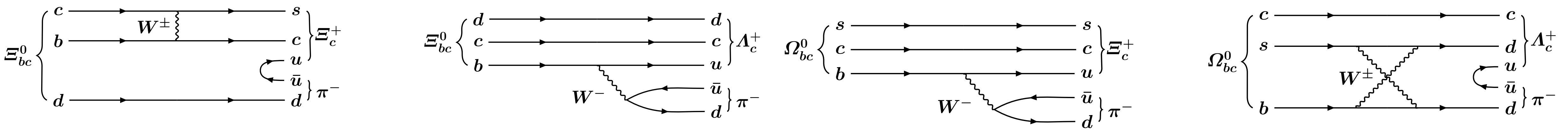
Search for the doubly heavy baryons Ξ_{bc}^{0} and Ω_{bc}^{0} decaying to $\Lambda_c^+ \pi^-$ and $\Xi_c^+ \pi^-$

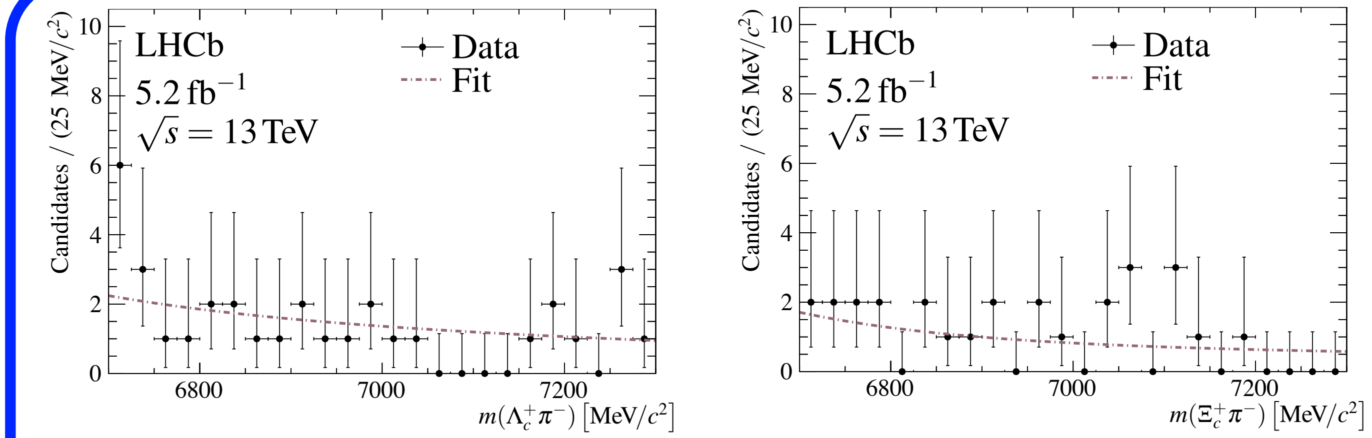
arXiv:2104.04759

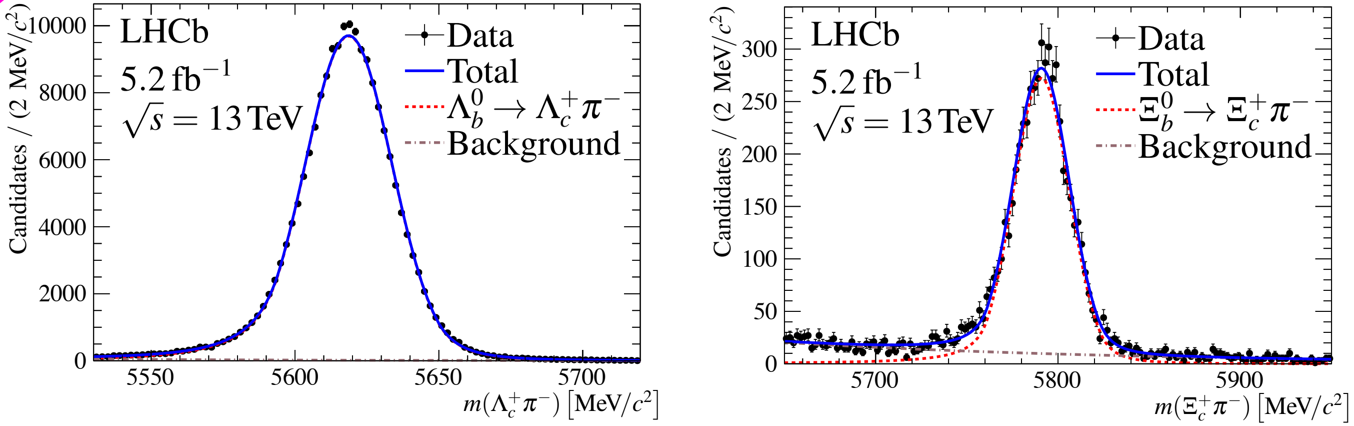
(submitted to JHEP)

Ξ_{bc}^0 and Ω_{bc}^0 search: signal and control channels

- Search for Ξ_{bc}^0 and Ω_{bc}^0 in $\Xi_c^+\pi^-$ and $\Lambda_c^+\pi^-$ spectra







- Theory predictions:

	m	$c\tau$
Ξ_{bc}^0	6700 ÷ 7200 MeV	0.20 ÷ 0.33 ps
Ω_{bc}^0	~100MeV above Ξ_{bc}^0	0.22 ± 0.04 ps

- Final states $pK^-\pi^+\pi^-$

- Control channels
  - $\Xi_b^0 \to \Xi_c^+\pi^-$
  - $\Lambda_b^0 \to \Lambda_c^+\pi^-$

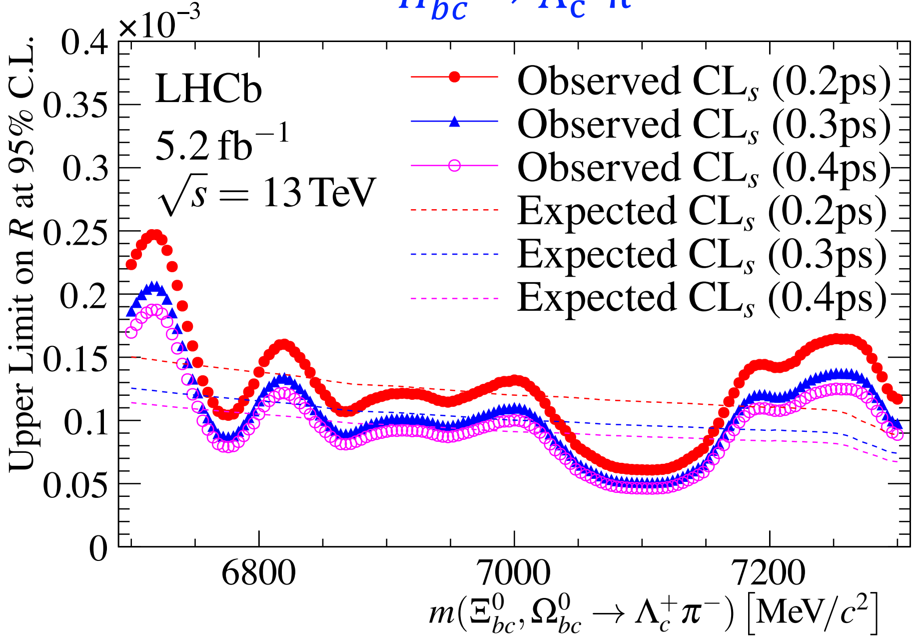
$\mathcal{R}$ limits

- No evidence of signal is found for both searches ($\boldsymbol{\Xi_{bc}^0}$ and $\boldsymbol{\Omega_{bc}^0}$)
- The $\mathcal{R}$ ratios of $\mathcal{B}\times\sigma$ of the $H_{bc}^0 \to \Xi_c^+\pi^-$ relative to $\Xi_{bc}^0 \to \Xi_c^+\pi^-$ and $H_{bc}^0 \to \Lambda_c^+\pi^-$ relative to $\Lambda_b^0 \to \Lambda_c^+\pi^-$ (with $H_{bc}^0 = [\boldsymbol{\Xi_{bc}^0}\,;\boldsymbol{\Omega_{bc}^0}]$) are calculated using the measure yield corrected by the relative reconstruction efficiencies

$$\mathcal{R}(\Xi_c^+\pi^-) \equiv \frac{\sigma(pp\to H_{bc}^0 X)\,\mathcal{B}(H_{bc}^0\to\Xi_c^+(\to pK^-\pi^+)\pi^-)}{\sigma(pp\to\Xi_b^0 X)\,\mathcal{B}(\Xi_b^0\to\Xi_c^+(\to pK^-\pi^+)\pi^-)} \qquad \mathcal{R}(\Lambda_c^+\pi^-) \equiv \frac{\sigma(pp\to H_{bc}^0 X)\,\mathcal{B}(H_{bc}^0\to\Lambda_c^+(\to pK^-\pi^+)\pi^-)}{\sigma(pp\to\Lambda_b^0 X)\,\mathcal{B}(\Lambda_b^0\to\Lambda_c^+(\to pK^-\pi^+)\pi^-)}$$

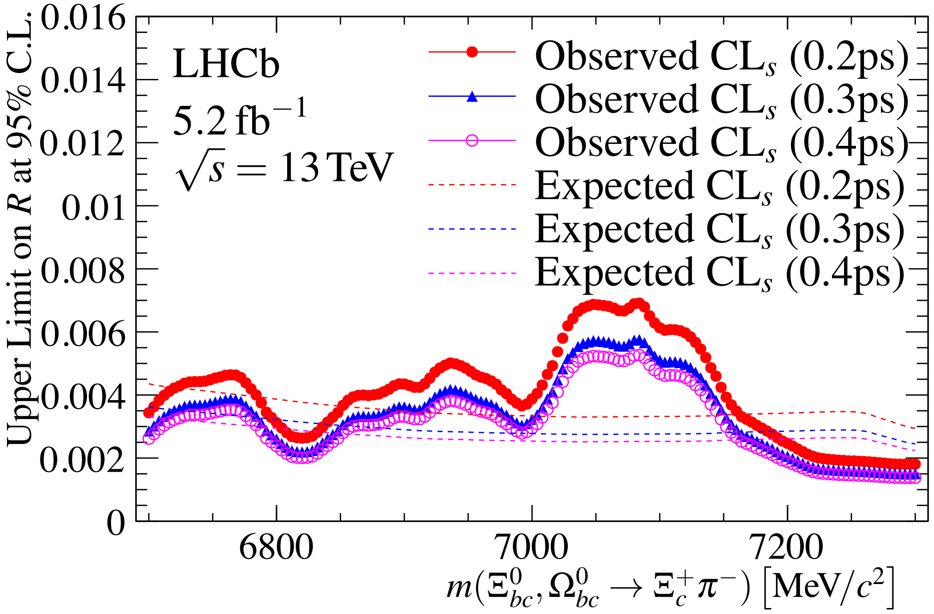
- Limits set with the asymptotic CL_s method at 95 % confidence level for running masses and multiple lifetimes

$H_{bc}^0 \to \Lambda_c^+\pi^-$



$0.5\times10^{-4} \div 2.5\times10^{-4}$

$H_{bc}^0 \to \Xi_c^+\pi^-$



$1.4\times10^{-3} \div 6.9\times10^{-3}$

All the systematics in the backup

Observation of the decay $\Lambda_b^0 \to \chi_{c1} p \pi^-$

arXiv:2103.04949

(submitted to JHEP)

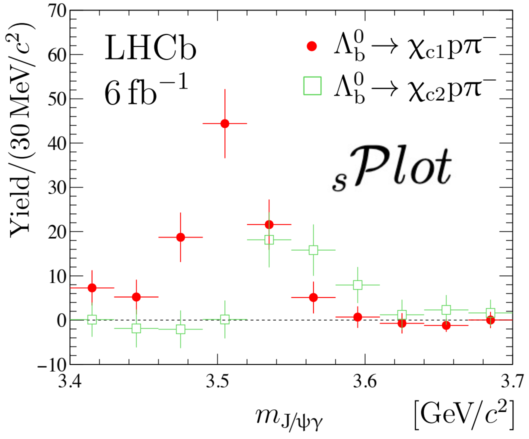
$\Lambda_b^0 \to \chi_{c1,2}\, p\pi^-$ and $\Lambda_b^0 \to \chi_{c1,2}\, pK^-$

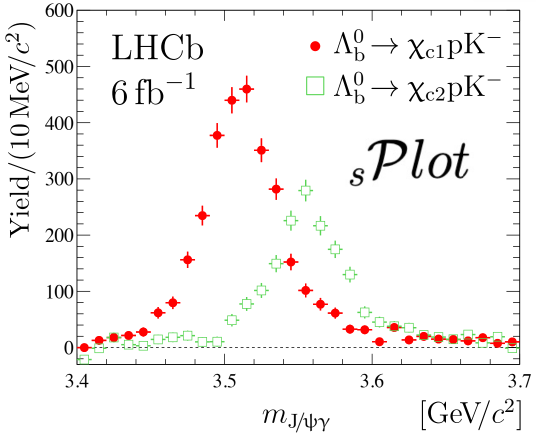
- Two channels studied (**with** $\chi_{c1,2} \to J/\psi\gamma \to \mu\mu$ **)**

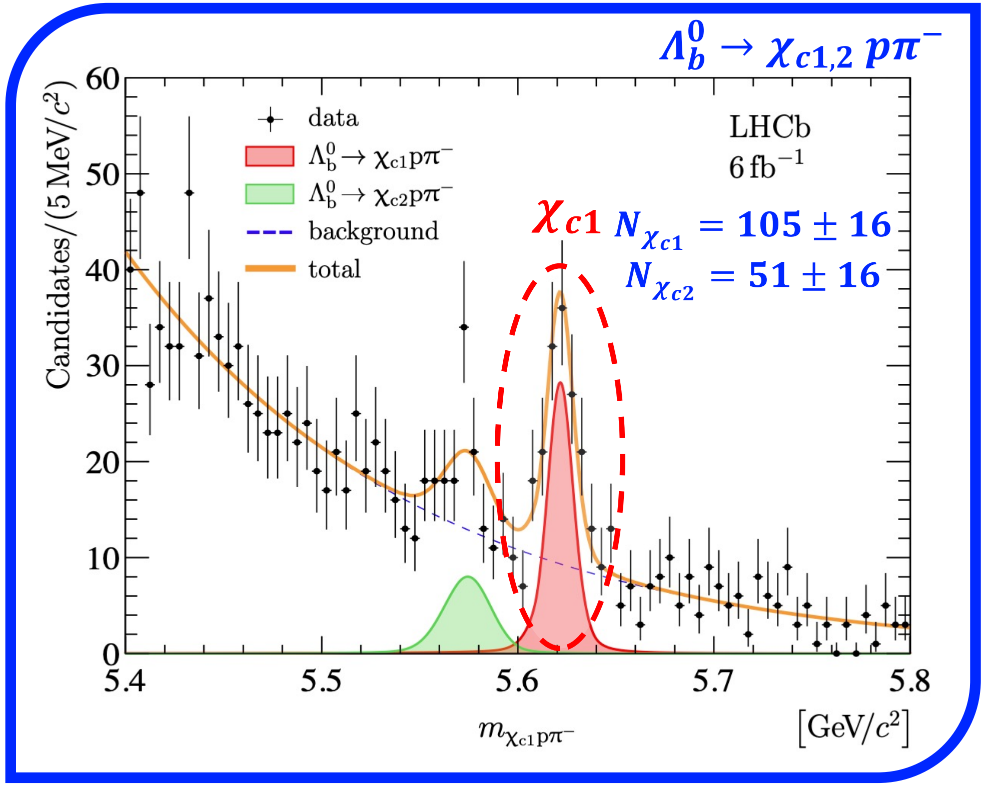
  $\Lambda_b^0 \to \chi_{c1,2}\, p\pi^-$ (signal) $\Lambda_b^0 \to \chi_{c1,2}\, pK^-$ (normalization)

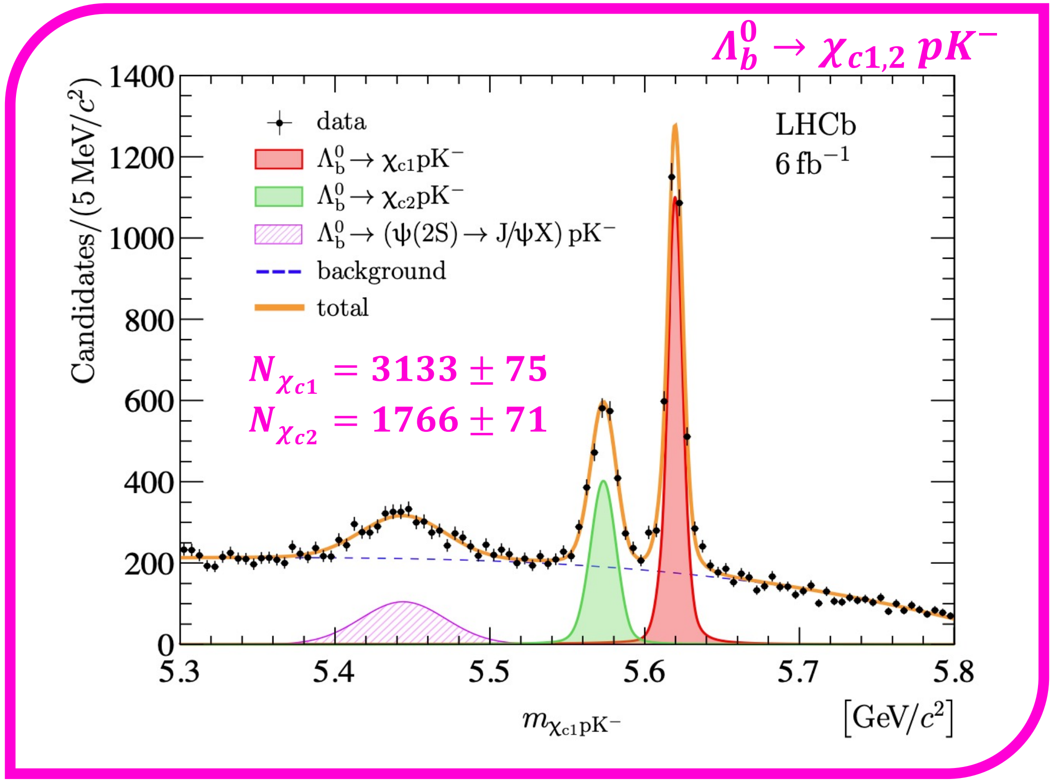
- Background rejection achieved via $c\tau(\Lambda_b^0)$, kinematics and PID

- Significance: $> 9\sigma$ **for** $\chi_{c1}\, p\pi^-$ 3.5σ for $\chi_{c1}\, p\pi^-$





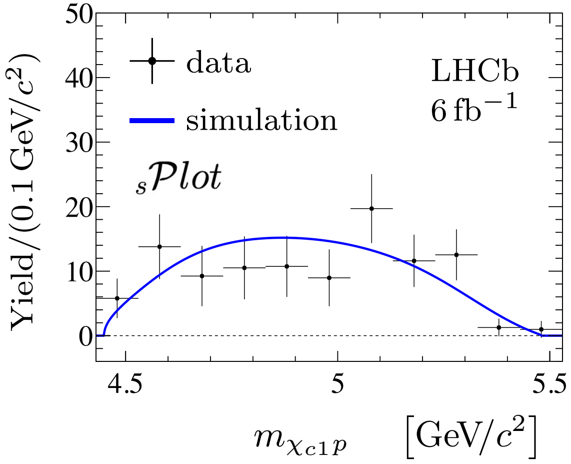


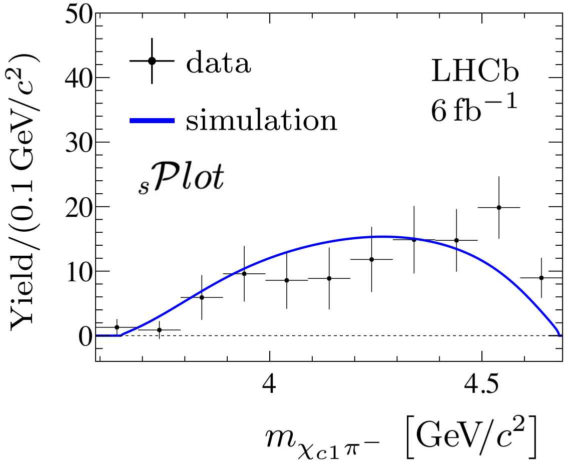


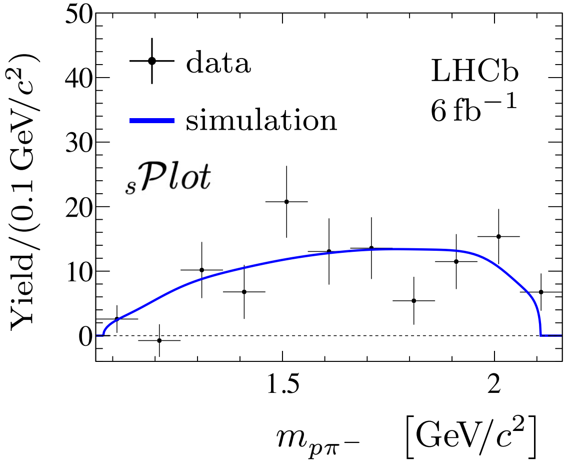
NB χ_{c0} is not expected to give a sizeable contribution: suppressed & much smaller BF to $J/\psi\gamma$ (w.r.t. χ_{c1})

Intermediate masses: $\chi_{c1}\,p$ & $\chi_{c1}\,\pi^-$ & $p\pi^-$

- Background subtracted intermediate masses

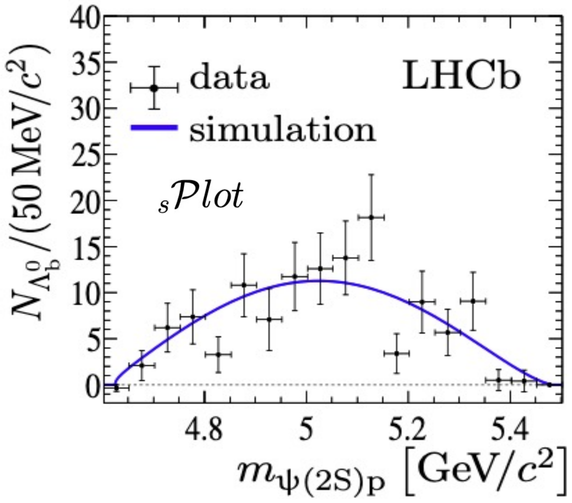


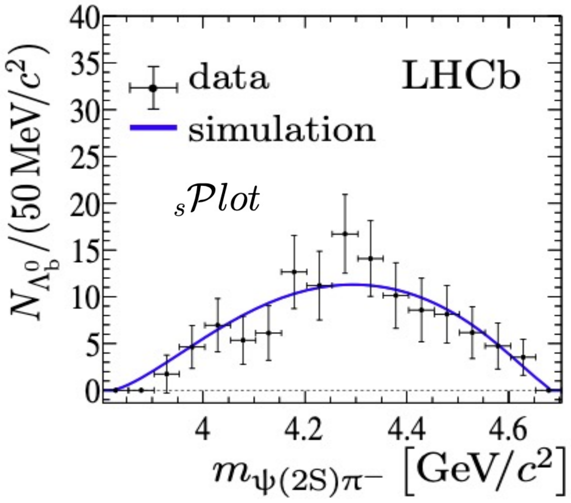


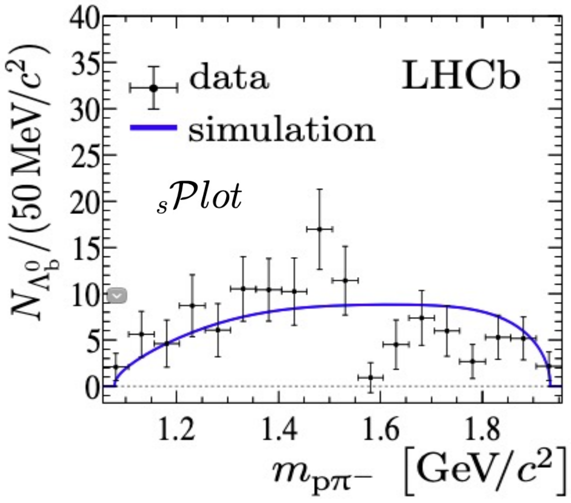


- Overall no evident peaking structure
- A search for small contributions from exotic states would be possible with a **larger data sample**

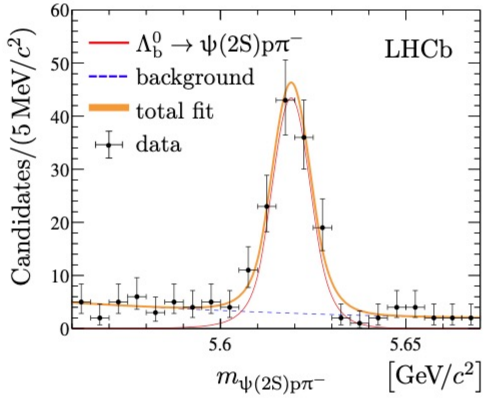
- Analogous to what was reported in JHEP 1808 (2018) 131







- From $\Lambda_b^0 \to \psi(2S)p\pi^-$



$\mathcal{R}$ calculations and comparisons

- Yields measured and corrected for efficiencies from MC (see backup), are used to calculate the branching ratios for χ_{c2}/χ_{c1}:

$$\mathcal{R}^{\pi}_{2/1} = \frac{\mathcal{B}(\Lambda_b^0 \to \chi_{c2} p \pi^-)}{\mathcal{B}(\Lambda_b^0 \to \chi_{c1} p \pi^-)} = 0.95 \pm 0.30 \pm 0.04 \pm 0.04$$

No suppression

$$\mathcal{R}^{K}_{2/1} = \frac{\mathcal{B}(\Lambda_b^0 \to \chi_{c2} p K^-)}{\mathcal{B}(\Lambda_b^0 \to \chi_{c1} p K^-)} = 1.06 \pm 0.05 \pm 0.04 \pm 0.04$$

In agreement with PRL 119 (2017) 062001

- and for Cabibbo suppression

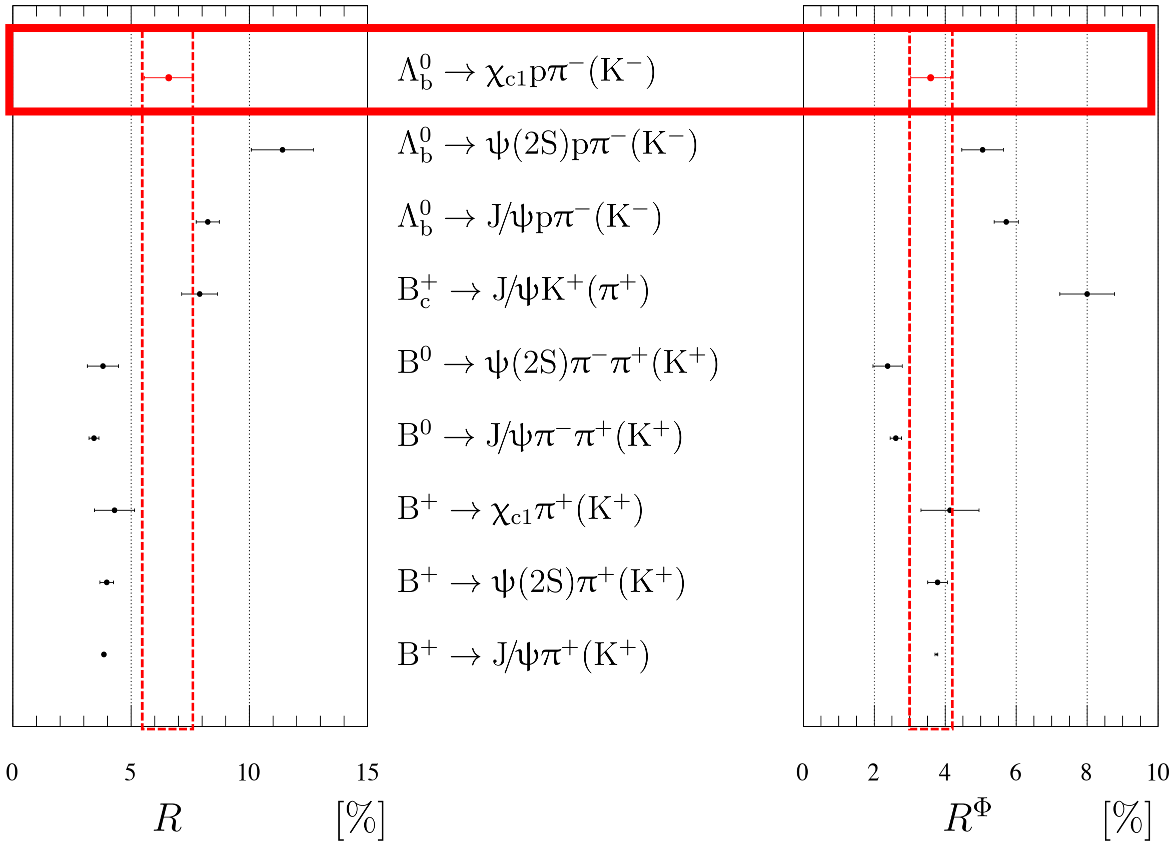
$$\mathcal{R}_{\pi/K} = \frac{\mathcal{B}(\Lambda_b^0 \to \chi_{c1} p \pi^-)}{\mathcal{B}(\Lambda_b^0 \to \chi_{c1} p K^-)} = (6.59 \pm 1.01 \pm 0.22) \times 10^{-2}$$

also phase space corrected

$$R \equiv \frac{\mathcal{B}(\text{suppressed})}{\mathcal{B}(\text{favoured})} \qquad R^{\Phi} \equiv \frac{\mathcal{B}(\text{suppressed})}{\mathcal{B}(\text{favoured})} \times \frac{\Phi(\text{favoured})}{\Phi(\text{suppressed})}$$

3body phase space neglecting resonant structure

a new measurement added to the picture.



All the systematics in the backup

Observation of new resonances decaying to $J/\psi K$ and $J/\psi \phi$

arxiv:2103.01803

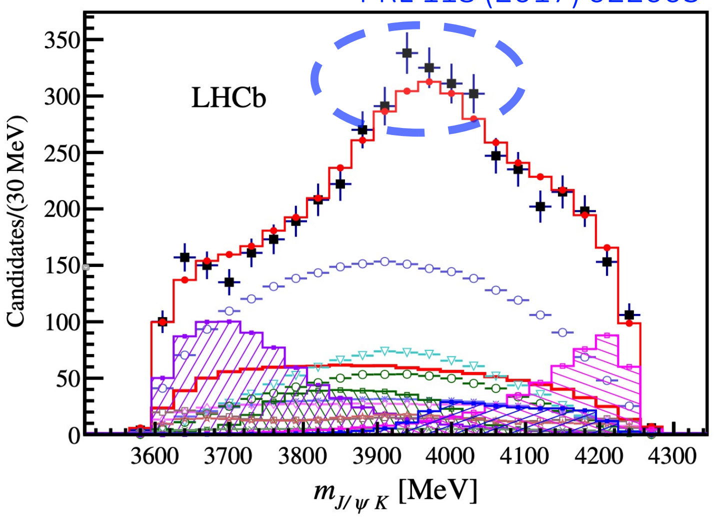
(submitted to PRL)

Z_{cs}

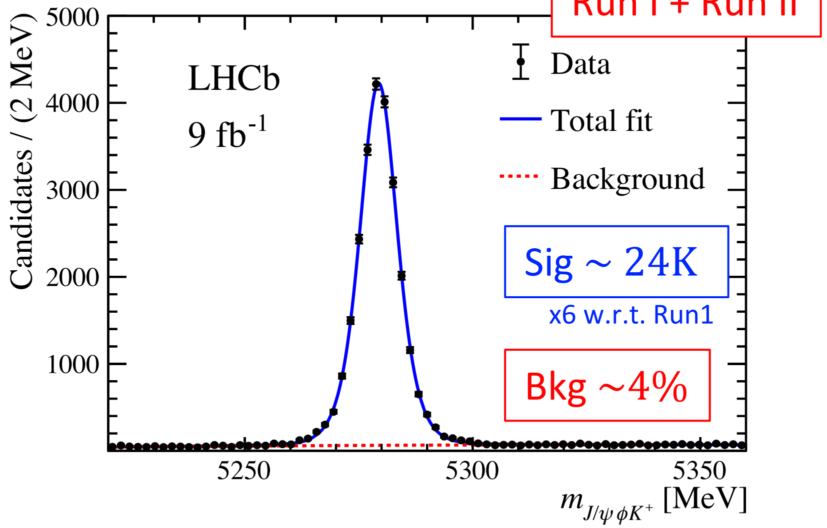
$B^+ \to J/\psi\phi K^+$ with Run1+Run2 data

- The channel $B^+ \to J/\psi\phi K^+$ was studied at LHCb using Run I sample
  - The width of $X(4140)$ larger than the value measured from other experiments [**PRD 95 (2017) 012002**]
  - Hint of structure in $J/\psi K^+$

PRL 118 (2017) 022003

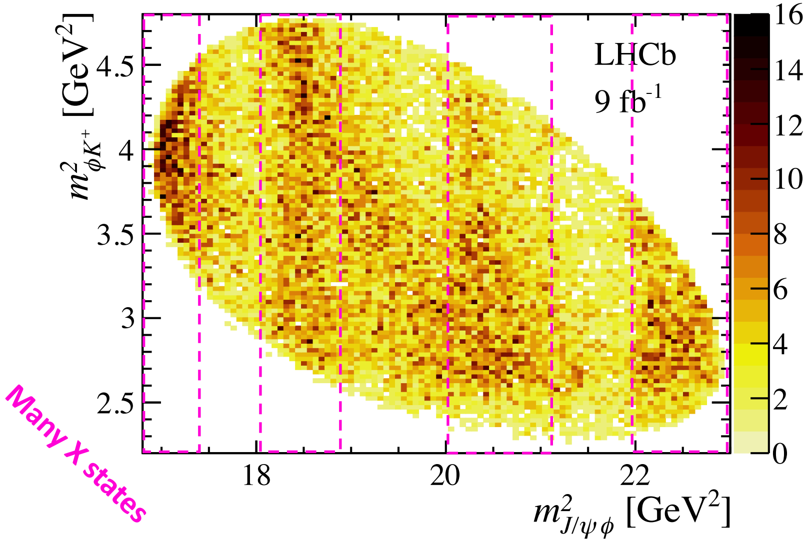


Run I + Run II

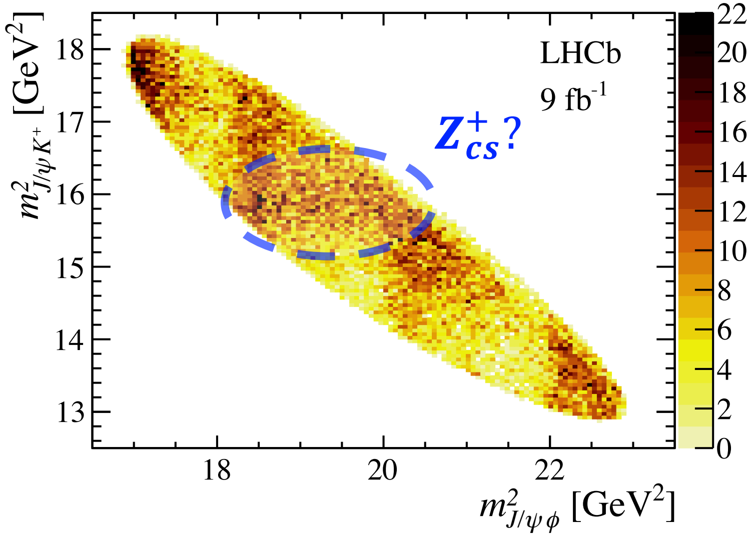


- $B^+ \to J/\psi\phi K^+$ with Run1+Run2 data. Clear structures in the Dalitz plots

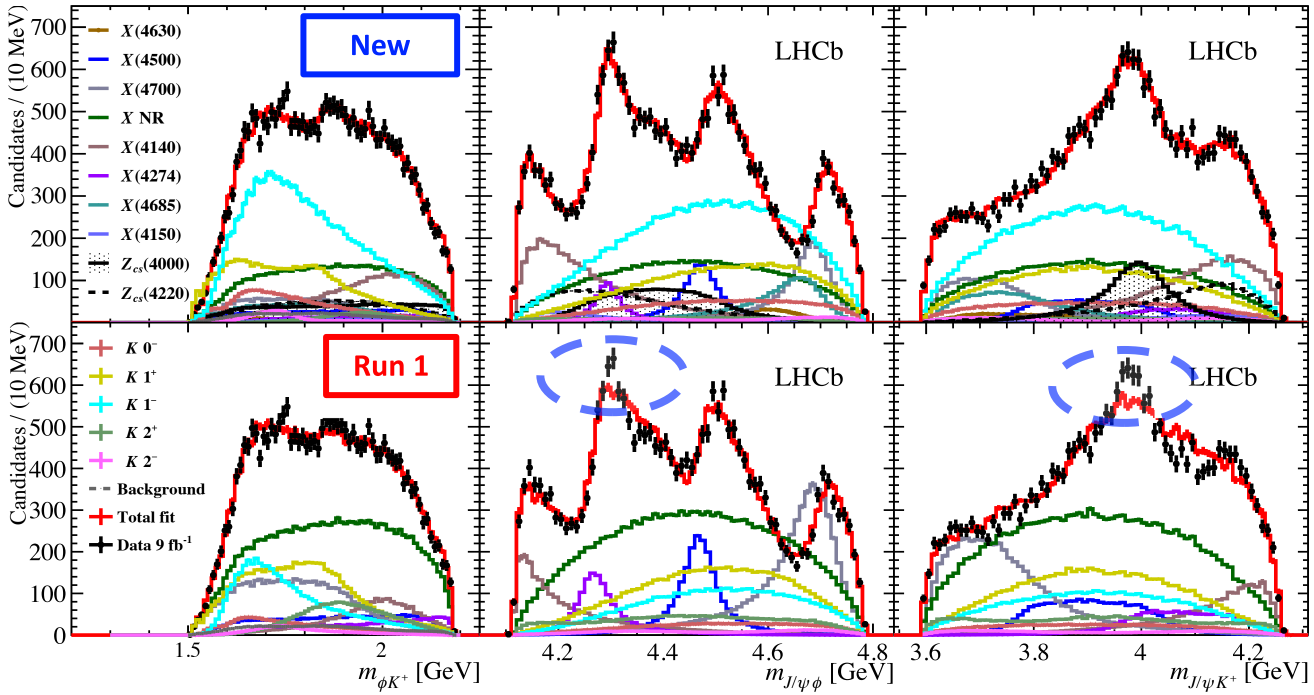
4 structures in $\boldsymbol{J/\psi\phi}$



Structure in $\boldsymbol{J/\psi K^+}$



New fit and Z_{cs}^{+} signal

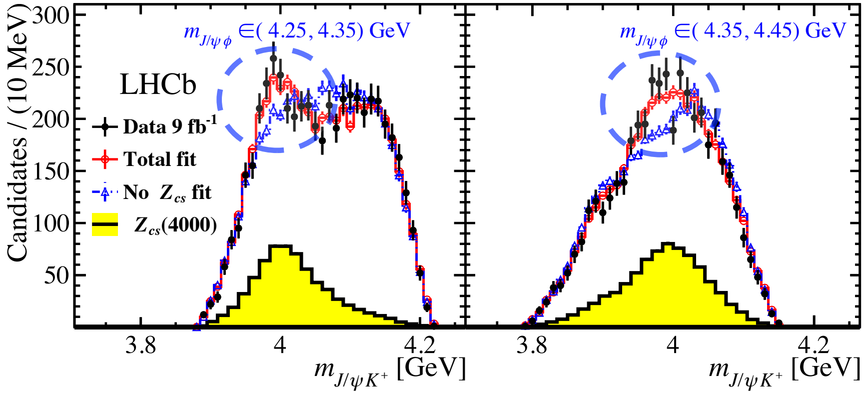


- The fitting model was optimized based on previous analysis using Run 1 sample. More K^* states cannot improve the fitting: testing the contributions from other states

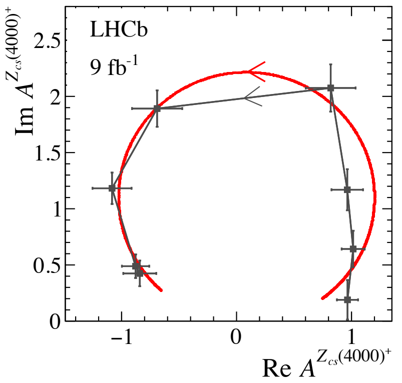
Contribution	Significance $[\times\sigma]$	M_0 [MeV]	Γ_0 [MeV]	FF [%]
$X(2^-)$				
$X(4150)$	4.8 (8.7)	$4146 \pm 18 \pm 33$	$135 \pm 28\,^{+59}_{-30}$	$2.0 \pm 0.5\,^{+0.8}_{-1.0}$
$X(1^-)$				
$X(4630)$	5.5 (5.7)	$4626 \pm 16\,^{+18}_{-110}$	$174 \pm 27\,^{+134}_{-73}$	$2.6 \pm 0.5\,^{+2.9}_{-1.5}$
All $X(0^+)$				$20 \pm 5\,^{+14}_{-7}$
$X(4500)$	20 (20)	$4474 \pm 3 \pm 3$	$77 \pm 6\,^{+10}_{-8}$	$5.6 \pm 0.7\,^{+2.4}_{-0.6}$
$X(4700)$	17 (18)	$4694 \pm 4\,^{+16}_{-3}$	$87 \pm 8\,^{+16}_{-6}$	$8.9 \pm 1.2\,^{+4.9}_{-1.4}$
$\mathrm{NR}_{J/\psi\phi}$	4.8 (5.7)			$28 \pm 8\,^{+19}_{-11}$
All $X(1^+)$				$26 \pm 3\,^{+8}_{-10}$
$X(4140)$	13 (16)	$4118 \pm 11\,^{+19}_{-36}$	$162 \pm 21\,^{+24}_{-49}$	$17 \pm 3\,^{+19}_{-6}$
$X(4274)$	18 (18)	$4294 \pm 4\,^{+3}_{-6}$	$53 \pm 5 \pm 5$	$2.8 \pm 0.5\,^{+0.8}_{-0.4}$
$X(4685)$	15 (15)	$4684 \pm 7\,^{+13}_{-16}$	$126 \pm 15\,^{+37}_{-41}$	$7.2 \pm 1.0\,^{+4.0}_{-2.0}$
All $Z_{cs}(1^+)$				$25 \pm 5\,^{+11}_{-12}$
$Z_{cs}(4000)$	15 (16)	$4003 \pm 6\,^{+4}_{-14}$	$131 \pm 15 \pm 26$	$9.4 \pm 2.1 \pm 3.4$
$Z_{cs}(4220)$	5.9 (8.4)	$4216 \pm 24\,^{+43}_{-30}$	$233 \pm 52\,^{+97}_{-73}$	$10 \pm 4\,^{+10}_{-7}$

- Two Z_{cs}^{+} states were observed in $J/\psi K^+$; with significance$> 5\sigma$
- New X(4630) and X(4685); with significance $>5\sigma$
- Larger significance for Xs w.r.t. Run I results
- J^P for $Z_{cs}(4000)^+$ found 1^+ ; J^P for $Z_{cs}(4220)^+$ found 1^+ or 1^-

$J/\psi K^+$ fit in $J/\psi\phi$ slices



Argand Plot



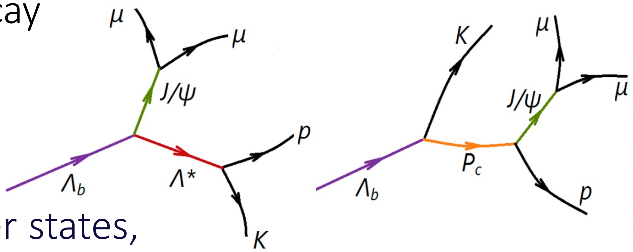
Study of $J/\psi p$ resonances in the $\Lambda_b^0 \to J/\psi p K^-$ decays

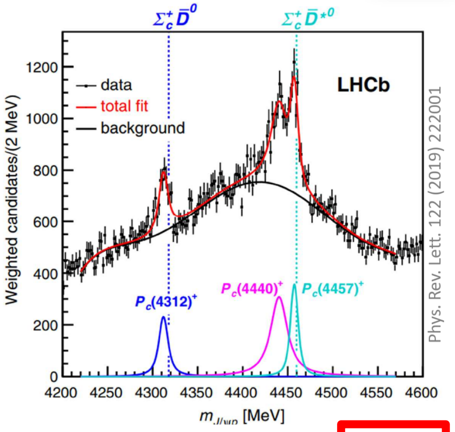
ATLAS-CONF-2019-048

P_c

Search for P_c in ATLAS

- LHCb: new resonances $P_c(\bar{c}cuud)$ in $J/\psi p$ system from $\Lambda_b^0 \to J/\psi p K^-$ decay





- $P_c(4380)^+$ and $P_c(4450)^+$
  - LHCb reported that the $P_c(4450)^+$ signal may represent two narrower states, $P_c(4440)^+$ and $P_c(4457)^+$ and claimed the existence of another narrow resonance, $P_c(4312)^+$

- Caveat: no PID in ATLAS – reconstruct $J/\psi h_1 h_2$ candidates where
  - $h_{1,2} = (p, K^\pm, \pi^\pm)$

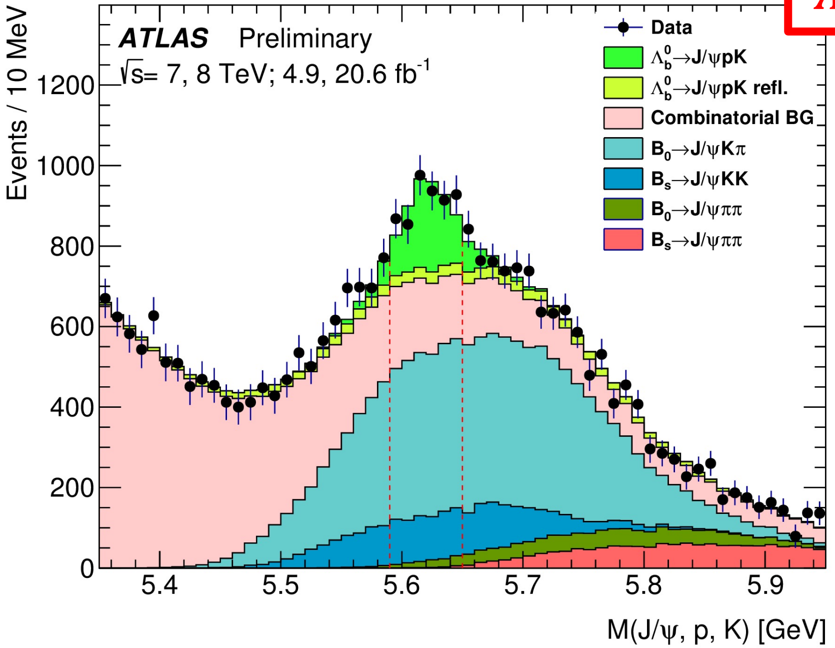
- Quite crowded:

  - $\Lambda_b^0 \to J/\psi p K^-$ [via intermediate Λ_b^{*0} and P_c]
  - $B^0 \to J/\psi K^+\pi^-$ [via intermediate K^{*0} and Z_c]
  - $B_s^0 \to J/\psi K^+K^-$ [via intermediate f^0 and ϕ]
  - $B^0 \to J/\psi \pi^+\pi^-$ [via intermediate f^0 and ρ]
  - $B_s^0 \to J/\psi \pi^+\pi^-$ [via intermediate f^0 and ρ]

- Same-sign $h_1 h_2$ background is subtracted

- To suppress light Λ_b^{*0}, K^{*0}, f^0, ϕ : remove events with $M(\pi K) < 1.55$ GeV

Λ_b^0

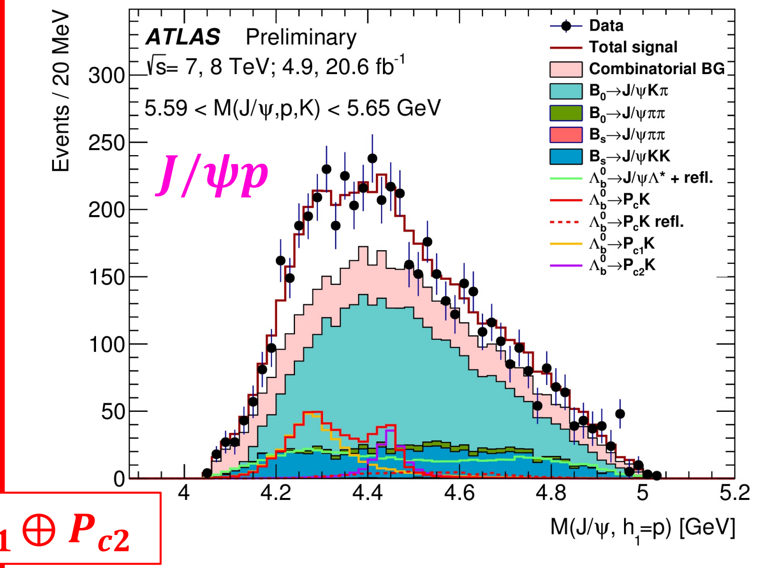


1010 ± 140 Λ_b^0 candidates in the signal region

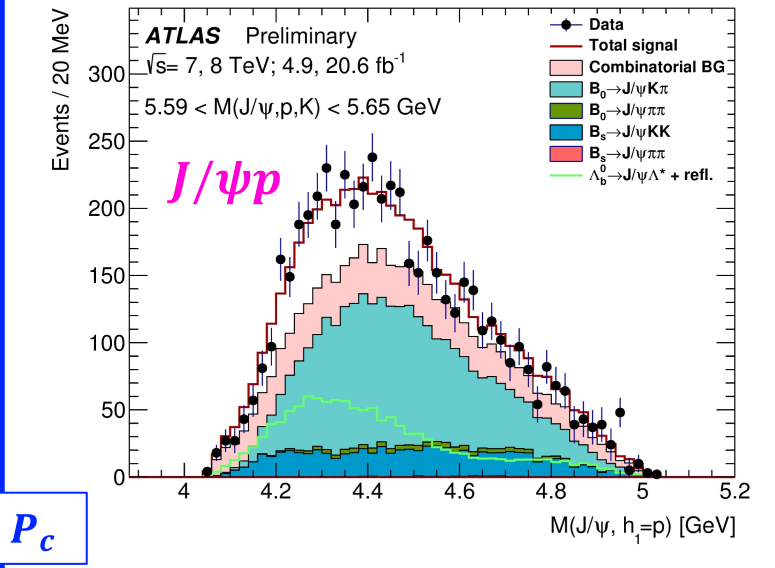
Two Pentaquark Hypothesis

- Multiple models are tested: **best agreement** for the two or more pentaquark states hypothesis:
  - Model with two pentaquarks: $\frac{\chi^2}{n.d.f} = \frac{37.1}{39} \Longrightarrow p = 55.7\%$
  - Equally fine with four-pentaquarks hypothesis
  - Model w/o pentaquarks still not excluded: $\frac{\chi^2}{n.d.f} = \frac{42.0}{23} \Longrightarrow p = 9.1 \cdot 10^{-3}$
- P_{c1} mass slightly lower than LHCb result
- Fit with all masses and widths fixed to LHCb gives $\frac{\chi^2}{n.d.f} = \frac{49.0}{39} \Longrightarrow p = 24.5\%$

Parameter	Value	LHCb value [5]
$N(P_{c1})$	$400^{+130}_{-140}(\text{stat})^{+110}_{-100}(\text{syst})$	–
$N(P_{c2})$	$150^{+170}_{-100}(\text{stat})^{+50}_{-90}(\text{syst})$	–
$N(P_{c1}+P_{c2})$	$540^{+80}_{-70}(\text{stat})^{+70}_{-80}(\text{syst})$	–
$\Delta\phi$	$2.8^{+1.0}_{-1.6}(\text{stat})^{+0.2}_{-0.1}(\text{syst})$ rad	–
$m(P_{c1})$	$4282^{+33}_{-26}(\text{stat})^{+28}_{-7}(\text{syst})$ MeV	$4380 \pm 8 \pm 29$ MeV
$\Gamma(P_{c1})$	140^{+77}_{-50} (stat)$^{+41}_{-33}$ (syst) MeV	$205 \pm 18 \pm 86$ MeV
$m(P_{c2})$	4449^{+20}_{-29} (stat)$^{+18}_{-10}$ (syst) MeV	$4449.8 \pm 1.7 \pm 2.5$ MeV
$\Gamma(P_{c2})$	51^{+59}_{-48} (stat)$^{+14}_{-46}$ (syst) MeV	$39 \pm 5 \pm 19$ MeV



$P_{c1} \oplus P_{c2}$



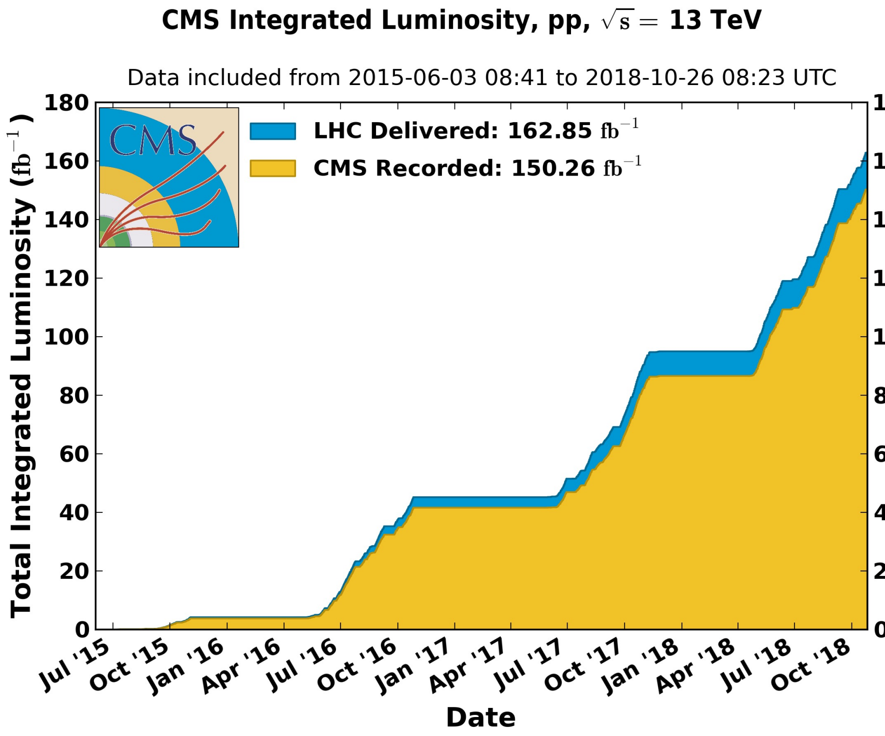
No P_c

See backup for other hypotheses and fitting model

Back Up

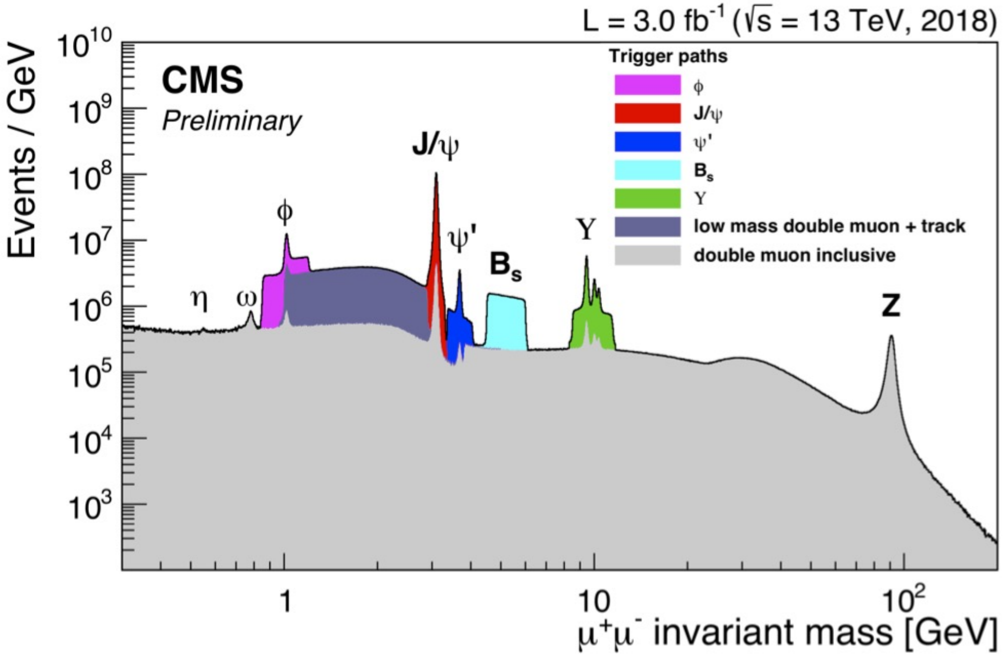
Compact Muon Solenoid

The CMS experiment has recorded 150 fb^{-1} at 13 TeV of data of which ~143 fb^{-1} have been certified for physics



Tracking system

- Good p_T **resolution** (down to $\Delta p_T/p_T \approx 0.01$ in barrel)
- Tracking efficiency >99% for central muons
- Good vertex reconstruction & impact parameter resolution O(μm)



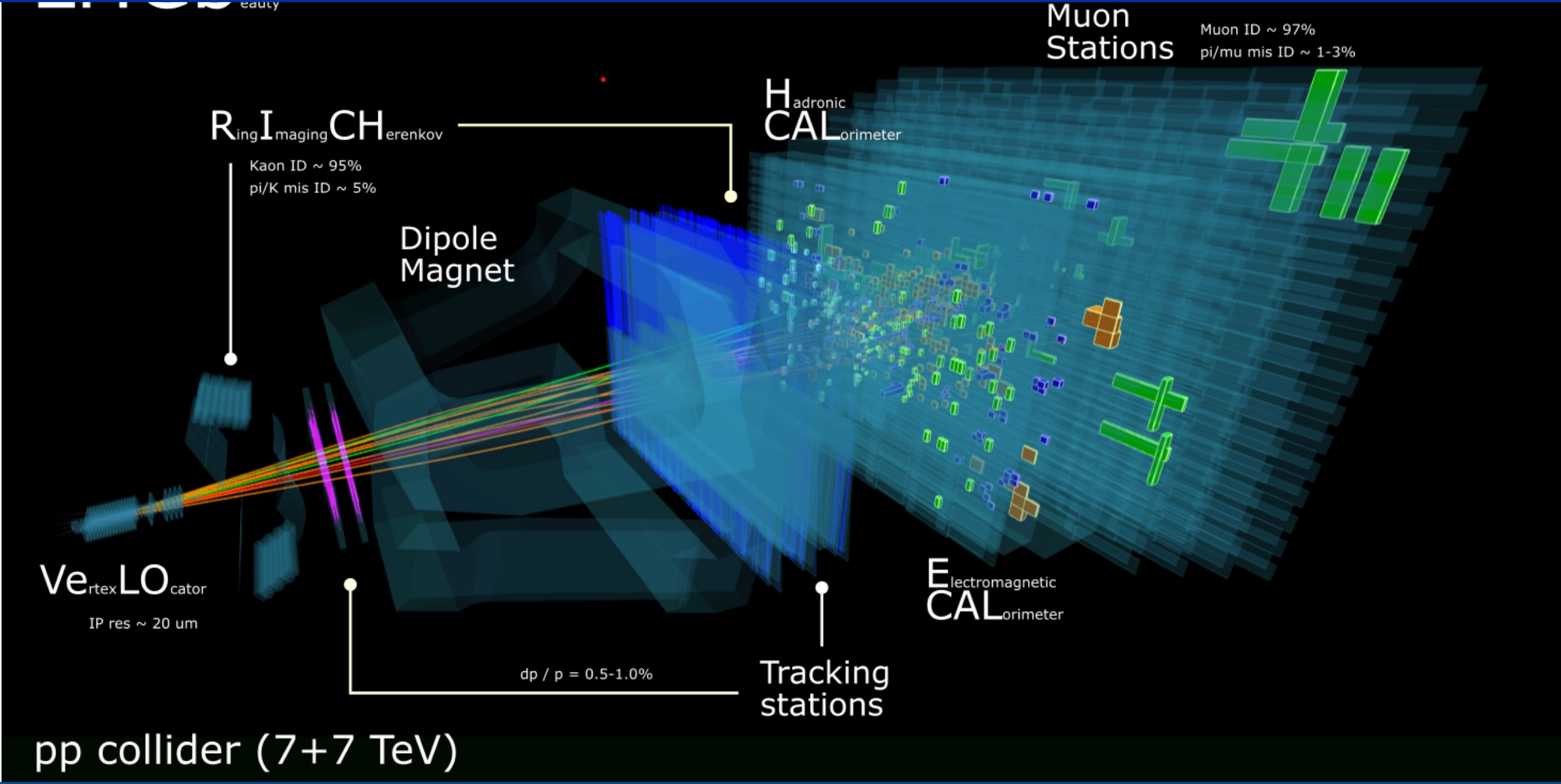
Muon system

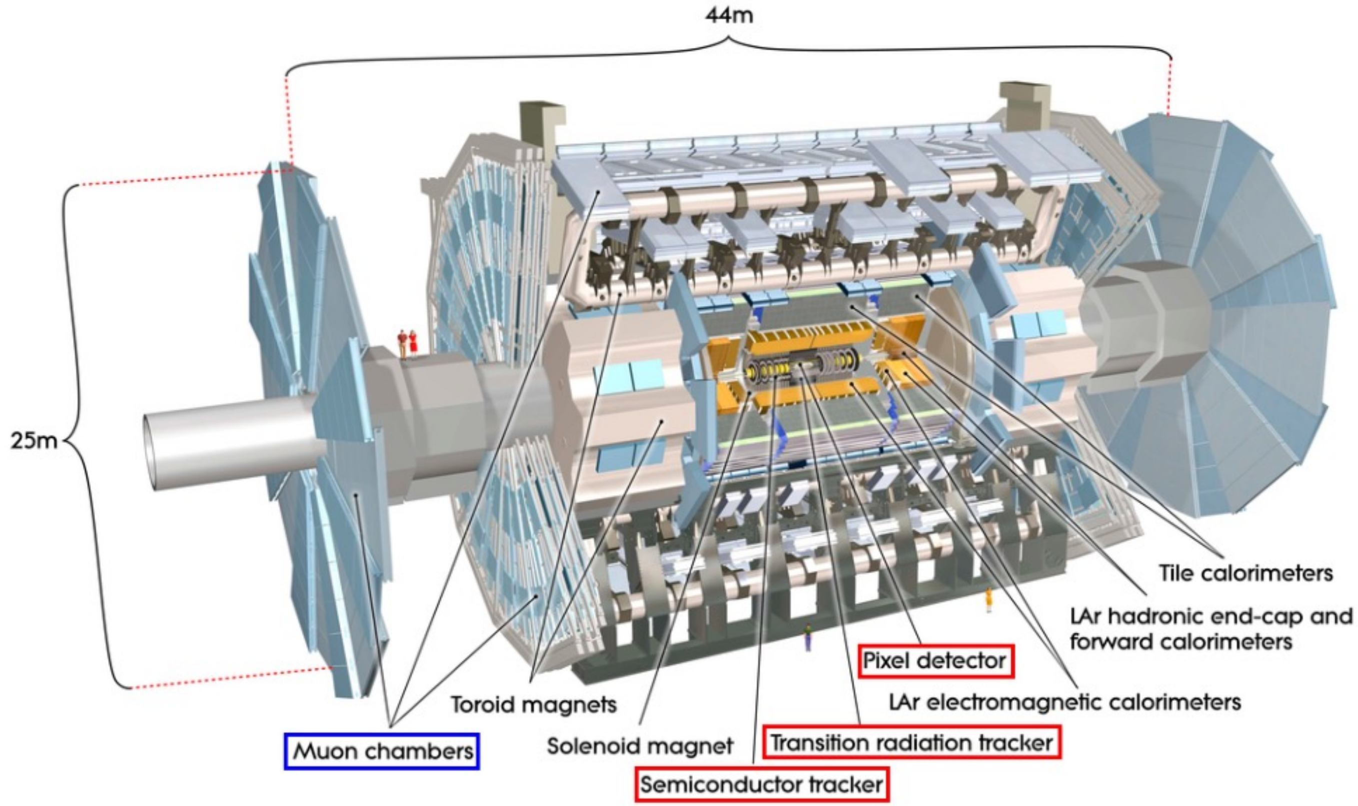
- Muon candidates reconstructed by matching muon segments and a silicon track in a large rapidity coverage ($|\eta|$<2.4)
- Good dimuon mass resolution ($|\eta|$ dependent):

$$\Delta M/M \sim 0.6 \div 1.5\% \longrightarrow \Delta M(J/\psi) \approx (20 \div 70) MeV$$

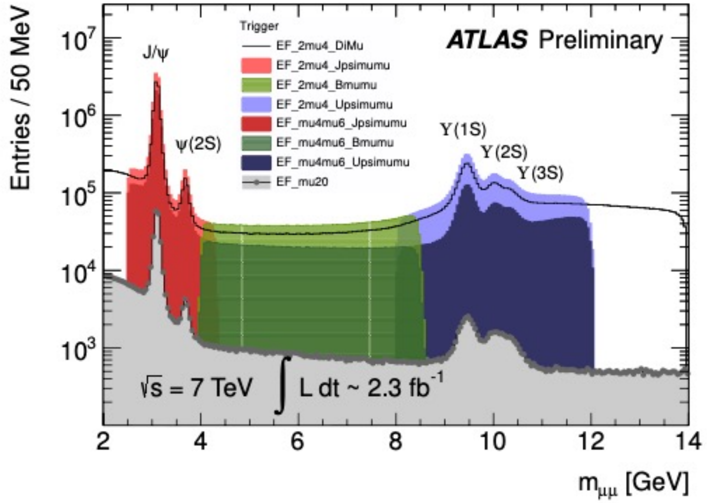
- Excellent muon-ID: $\varepsilon(\mu | \pi, K, p) \leq (0.1 \div 0.2)\%$

LHCb Detector

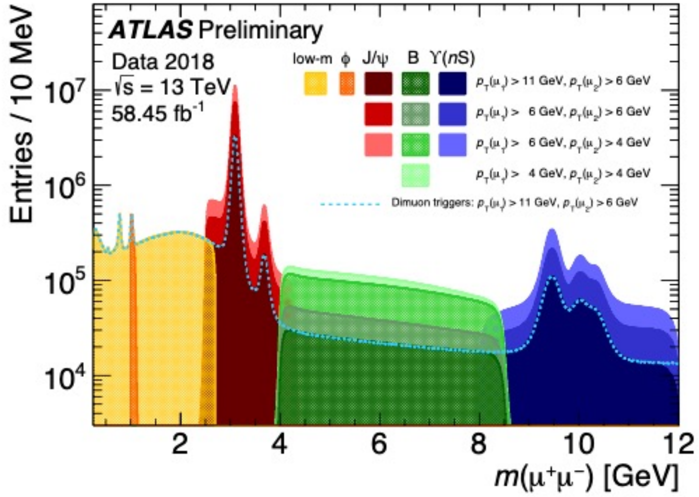




44m
25m
Tile calorimeters
LAr hadronic end-cap and forward calorimeters
Pixel detector
LAr electromagnetic calorimeters
Toroid magnets
Muon chambers
Solenoid magnet
Transition radiation tracker
Semiconductor tracker



ATLAS Preliminary
Trigger
EF_2mu4_DiMu
EF_2mu4_Jpsimumu
EF_2mu4_Bmumu
EF_2mu4_Upsimumu
EF_mu4mu6_Jpsimumu
EF_mu4mu6_Bmumu
EF_mu4mu6_Upsimumu
EF_mu20
J/ψ
ψ(2S)
Υ(1S)
Υ(2S)
Υ(3S)
√s = 7 TeV
∫ L dt ~ 2.3 fb-1
Entries / 50 MeV
m_μμ [GeV]



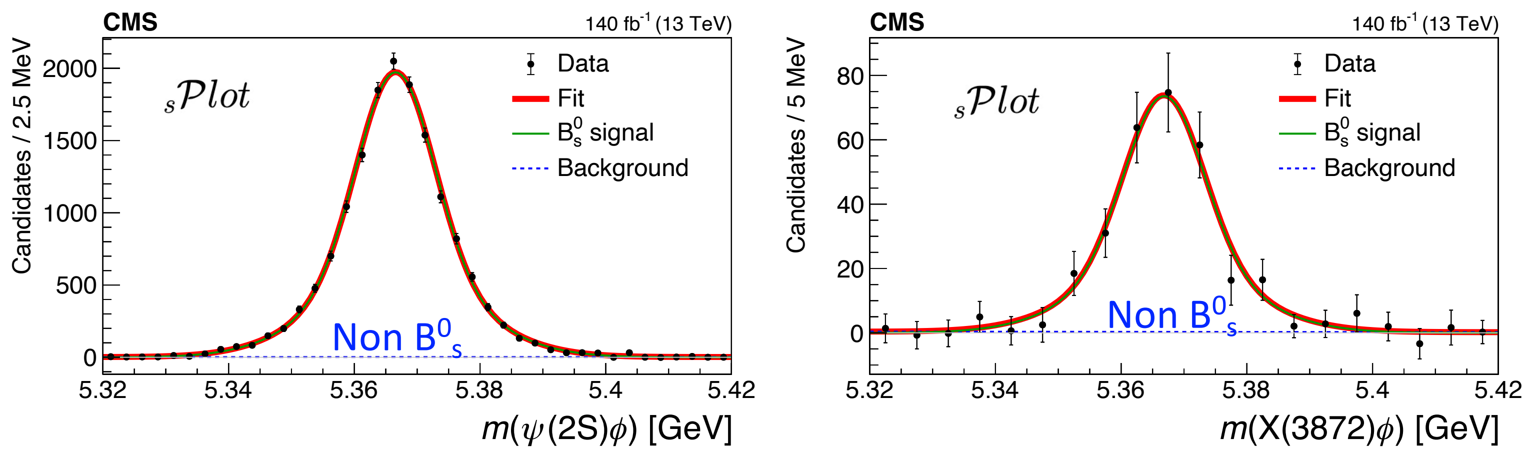
ATLAS Preliminary
Data 2018
√s = 13 TeV
58.45 fb-1
low-m φ J/ψ B Υ(nS)
Dimuon triggers
Entries / 10 MeV
m(μ+μ−) [GeV]

Ξ_{bc}^{0} and Ω_{bc}^{0} searches systematics

	$H_{bc}^{0} \to \Lambda_{c}^{+}\pi^{-}$	$H_{bc}^{0} \to \Xi_{c}^{+}\pi^{-}$
Fit model	0.1%	0.9%
Size of simulated samples	1.6%	0.7%
Particle identification efficiency	1.7%	2.1%
Mass resolution	$<$ 0.1%	0.2%
Simulation model	1.6%	3.0%
χ^{2}_{IP} simulation	5.0%	5.0%
Total	5.7%	6.3%

Systematics in JHEP 12 (2019) 100

Source	Uncertainty (%)
$m(K^+K^-)$ signal model	< 0.1
$m(K^+K^-)$ background model	2.5
$m(J/\psi\pi^+\pi^-)$ signal model	5.3
$m(J/\psi\pi^+\pi^-)$ background model	4.3
Non-B_s^0 background	1.2
Simulated sample size	2.2
Total	7.7



JHEP 02 (2021) 024 Systematics

- $\mathcal{R}$ ratios

Source	$\mathcal{R}^{\chi_{c1}(3872)\phi}_{\psi(2S)\phi}$	$\mathcal{R}^{J/\psi K^{*0}\overline{K}^{*0}}_{\psi(2S)\phi}$	$\mathcal{R}_{K^+K^-}$
Fit model	1.8	2.6	7.3
Efficiency corrections	0.3	0.1	0.3
Trigger efficiency	1.1	1.1	1.1
Data-simulation difference	2.0	2.0	2.0
Simulated sample size	1.0	0.9	1.3
Sum in quadrature	3.1	3.6	7.8

$$\mathcal{R}^{\chi_{c1}(3872)\phi}_{\psi(2S)\phi} = (2.42 \pm 0.23 \pm 0.07) \times 10^{-2}\,,$$
$$\mathcal{R}_{K^+K^-} = 1.57 \pm 0.32 \pm 0.12\,,$$
$$\mathcal{R}^{J/\psi K^{*0}\overline{K}^{*0}}_{\psi(2S)\phi} = 1.22 \pm 0.03 \pm 0.04\,,$$

- B_s^0 mass

Source	$\sigma_{m_{B_s^0}}$ [keV/c^2]
Fit model	51
Momentum scale	122
Energy loss	15
Kaon mass	27
$\psi(2S)$ mass	10
Sum in quadrature	133

- $X(4740)B_s^0$ mass

Source	$\sigma_{m_{X(4740)}}$ [MeV/c^2]	$\sigma_{\Gamma_{X(4740)}}$ [MeV]
Fit model	2.8	8.4
$\psi(2S)$, $\chi_{c1}(3872)$ veto	4.6	5.1
Interference	1.2	5.1
Sum in quadrature	5.5	11.1

- $\mathcal{R}$ ratios

$$\mathcal{R}^{\chi_{c1}(3872)\phi}_{\psi(2S)\phi} = \frac{N_{B^0_s\to\chi_{c1}(3872)\phi}}{N_{B^0_s\to\psi(2S)\phi}} \times \frac{\varepsilon_{B^0_s\to\psi(2S)\phi}}{\varepsilon_{B^0_s\to\chi_{c1}(3872)\phi}}$$

$$\mathcal{R}_{K^+K^-} = \frac{1}{f_\phi} - 1$$ (non resonant)

$$\mathcal{R}^{J/\psi K^{*0}\overline{K}^{*0}}_{\psi(2S)\phi} = \frac{N_{B^0_s\to J/\psi K^{*0}\overline{K}^{*0}}}{N_{B^0_s\to\psi(2S)\phi}} \times \frac{\varepsilon_{B^0_s\to\psi(2S)\phi}}{\varepsilon_{B^0_s\to J/\psi K^{*0}\overline{K}^{*0}}}$$

- $\mathcal{R}$ Systematics

Source	$\mathcal{R}^{\chi_{c1}(3872)\phi}_{\psi(2S)\phi}$	$\mathcal{R}^{J/\psi K^{*0}\overline{K}^{*0}}_{\psi(2S)\phi}$	$\mathcal{R}_{K^+K^-}$
Fit model	1.8	2.6	7.3
Efficiency corrections	0.3	0.1	0.3
Trigger efficiency	1.1	1.1	1.1
Data-simulation difference	2.0	2.0	2.0
Simulated sample size	1.0	0.9	1.3
Sum in quadrature	3.1	3.6	7.8

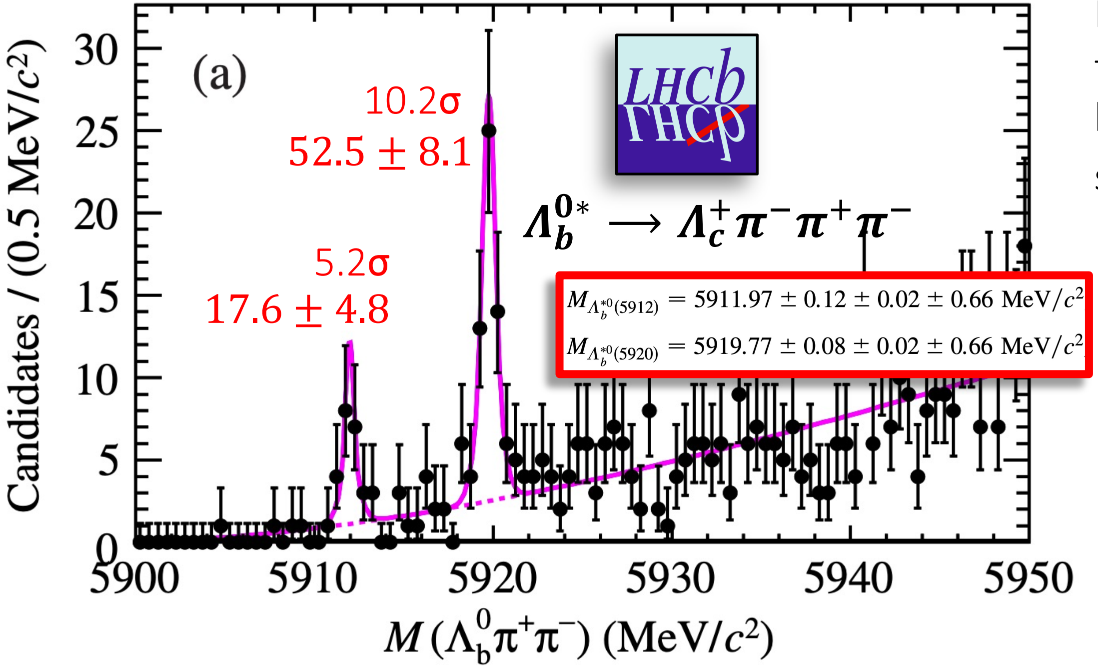
- $\mathcal{R}$ results

$$\mathcal{R}^{\chi_{c1}(3872)\phi}_{\psi(2S)\phi} = (2.42 \pm 0.23 \pm 0.07) \times 10^{-2},$$

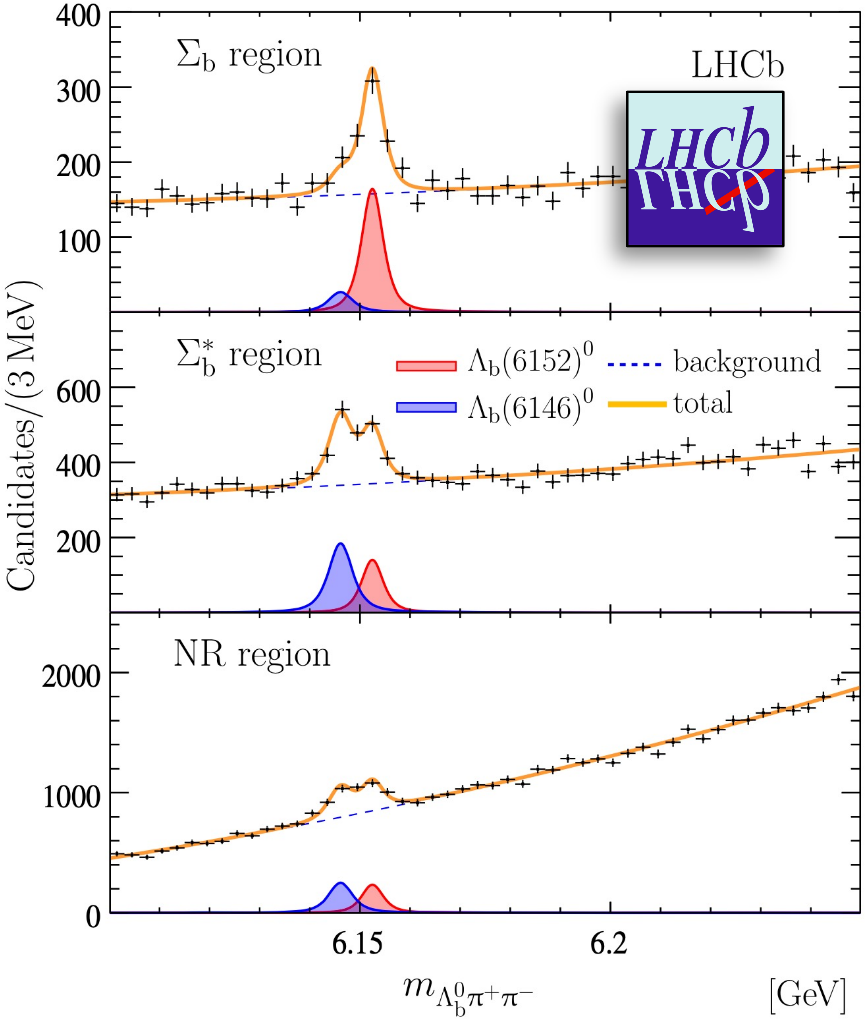
$$\mathcal{R}_{K^+K^-} = 1.57 \pm 0.32 \pm 0.12,$$

$$\mathcal{R}^{J/\psi K^{*0}\overline{K}^{*0}}_{\psi(2S)\phi} = 1.22 \pm 0.03 \pm 0.04,$$

Λ_b^0 excited states – LHCb first results



In PhysRevLett.109.172003 LHCb (2012)using $1fb^{-1}$ of 2011 data observed for the first time excited $\Lambda_b^{0*} \longrightarrow \Lambda_b^0\pi^+\pi^-$ using $\Lambda_b^0 \longrightarrow \Lambda_c^+\pi^-$ channel. Shortly later, in PhysRevD.88.071101 CDF (2013): confirmed **only the higher mass** state $\Lambda_b\,(5920)^0 \longrightarrow \Lambda_b^0\pi^+\pi^-$ with a significance of **3.5σ (see backup)**



In 2019 in PRL 123 (2019) 152001 LHCb **using full Run-I+II dataset observed two new excited states decaying to $\Lambda_b^0\pi^+\pi^-$ final state:**

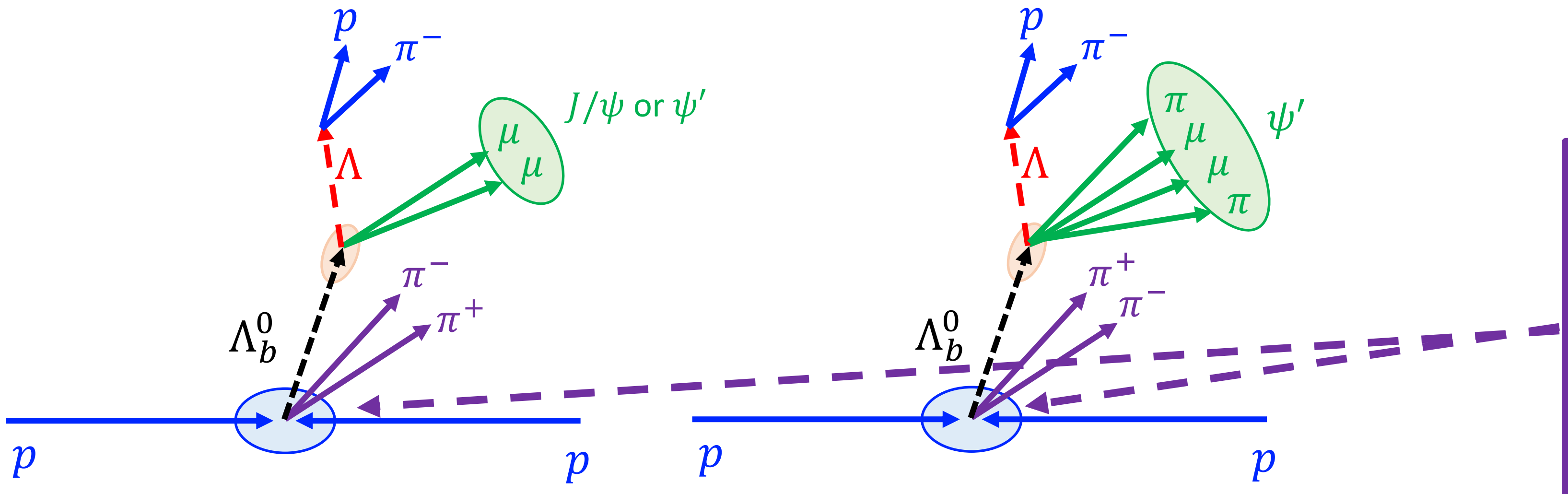
$\Lambda_b\,(6146)^0$ and $\Lambda_b\,(6152)^0$

using both channels $\boldsymbol{\Lambda_b^0 \longrightarrow \Lambda_c^+\pi^-}$ and $\boldsymbol{\Lambda_b^0 \longrightarrow J/\psi p K^-}$ with about **$1.1M$ Λ_b^0** in total

In CMS **we cannot** use these most copious channels since **no dedicated trigger** (for $\boldsymbol{\Lambda_b^0 \longrightarrow \Lambda_c^+\pi^-}$) is possible: the backgrounds are too large due to the lack of hadronic PID

Phys. Lett. B 803 (2020) 135345 – Λ_b^0 reconstruction at CMS

In **CMS** the most copious channels such as $\boldsymbol{\Lambda_b^0 \longrightarrow J/\psi p K^-}$ and $\boldsymbol{\Lambda_b^0 \longrightarrow \Lambda_c^+ \pi^-}$ cannot be used use **mainly because** the backgrounds are too large due to the lack of hadronic PID. Good channels are $\boldsymbol{\Lambda_b^0 \longrightarrow J/\psi \Lambda}$ and $\boldsymbol{\Lambda_b^0 \longrightarrow \psi(2S)\Lambda}$ with $\boldsymbol{\psi(2S)}$ decaying both in dimuon ($\longrightarrow \mu\mu$) channel and hadronic ($\longrightarrow J/\psi\pi^+\pi^-$) using a combination of various $\boldsymbol{J/\psi + X}$ and $\boldsymbol{\psi(2S) + X}$ triggers



Two additional OS prompt tracks (with pion mass hypothesis) are selected from the tracks forming the PV, chosen as 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

The analysis has used **full Run II** pp **collision data** and has **been optimized differently**

- at **low masses**, near threshold where **backgrounds** level is low
- at **high masses** where background is large

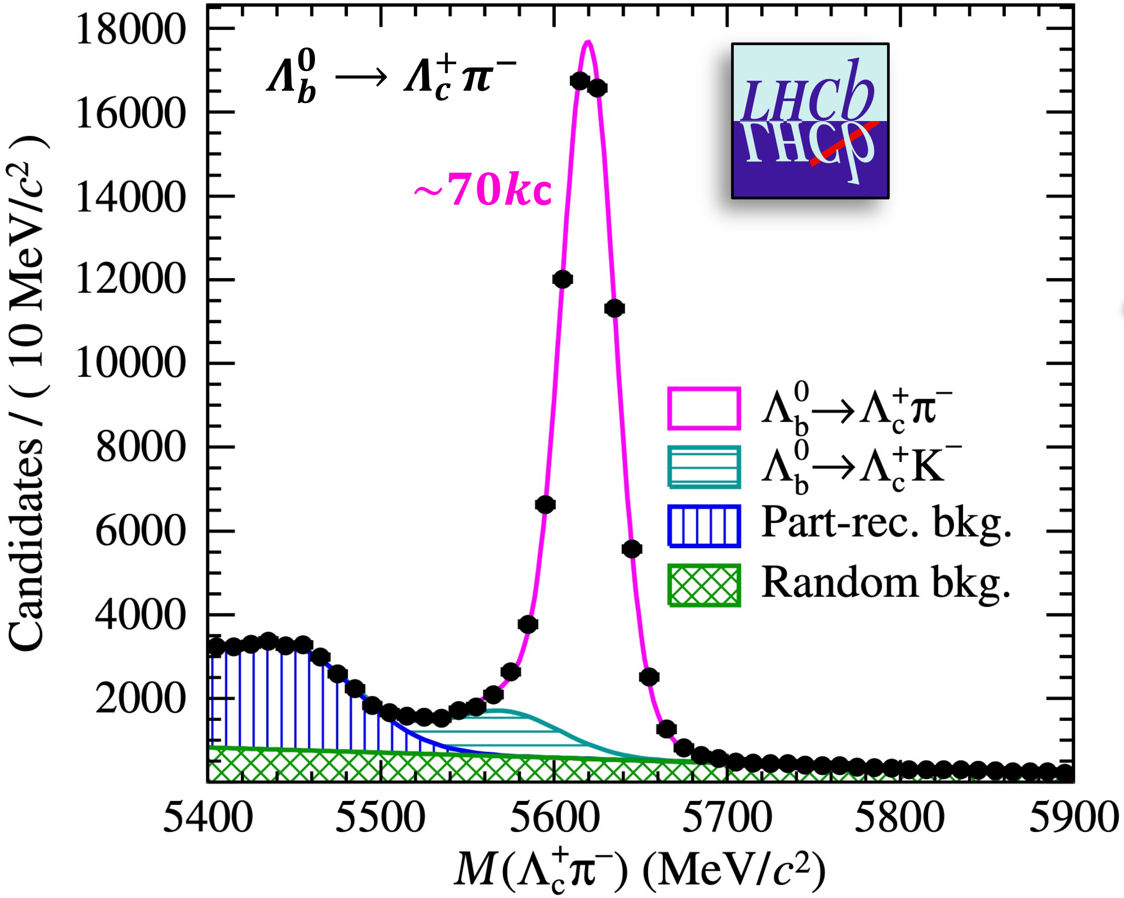
Phys. Lett. B 803 (2020) 135345 - Systematic Uncertainties for Λ_b^0 excited states

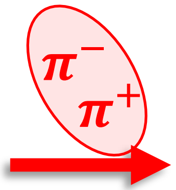
Source	$M(\Lambda_b(5912)^0)$	$M(\Lambda_b(5920)^0)$	$M(\Lambda_b(6146)^0)$	$M(\Lambda_b(6152)^0)$
Signal model	0.005	0.011	0.21	0.23
Background model	0.004	0	0.16	0.14
Inclusion of the wide bump region	—	—	0.35	0.14
Fit range	0	0	0.40	0.02
Mass resolution	0.007	0.001	0.01	0.09
Knowledge of Γ	—	—	0.43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

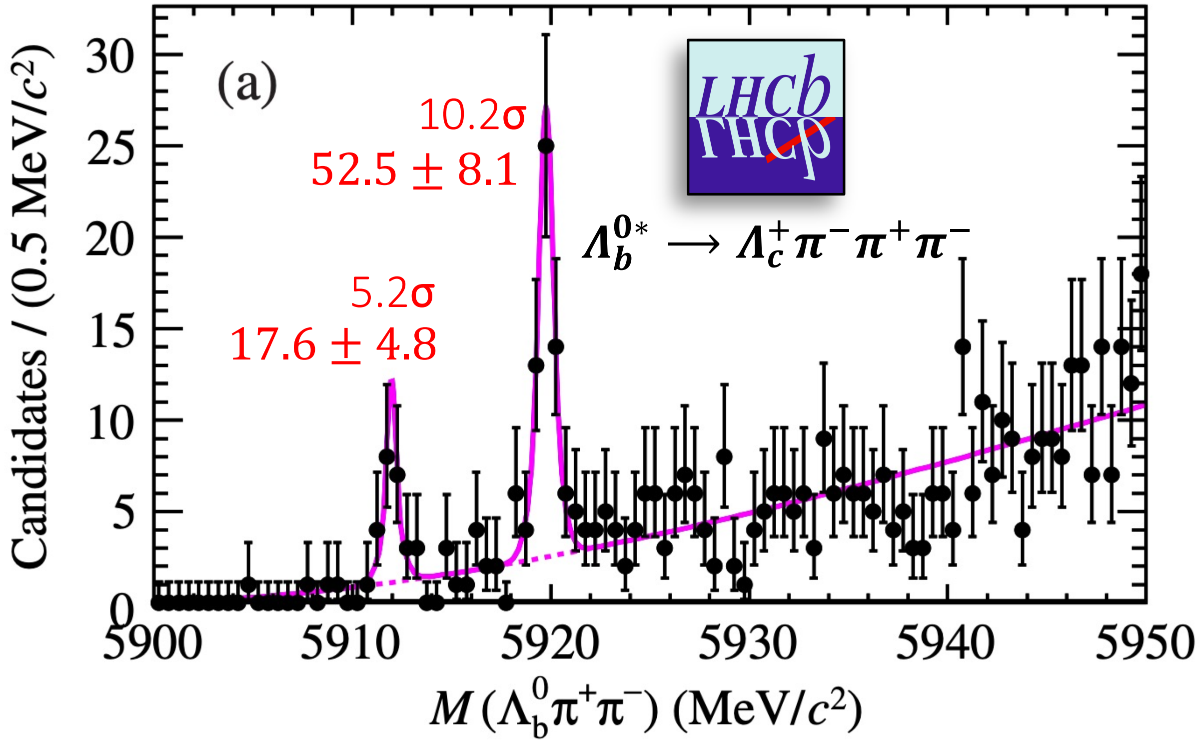
Introduction to Λ_b^0 excited states – LHCb first results

Studies of excited heavy baryon spectrum **are an important test** of Heavy Quark Effective Theory. 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 narrow window** to search for a signal.

In PhysRevLett.109.172003 LHCb (2012)using $1fb^{-1}$ of 2011 data observed for the first time excited $\Lambda_b^{0*} \longrightarrow \Lambda_b^0\pi^+\pi^-$ using $\Lambda_b^0 \longrightarrow \Lambda_c^+\pi^-$ channel







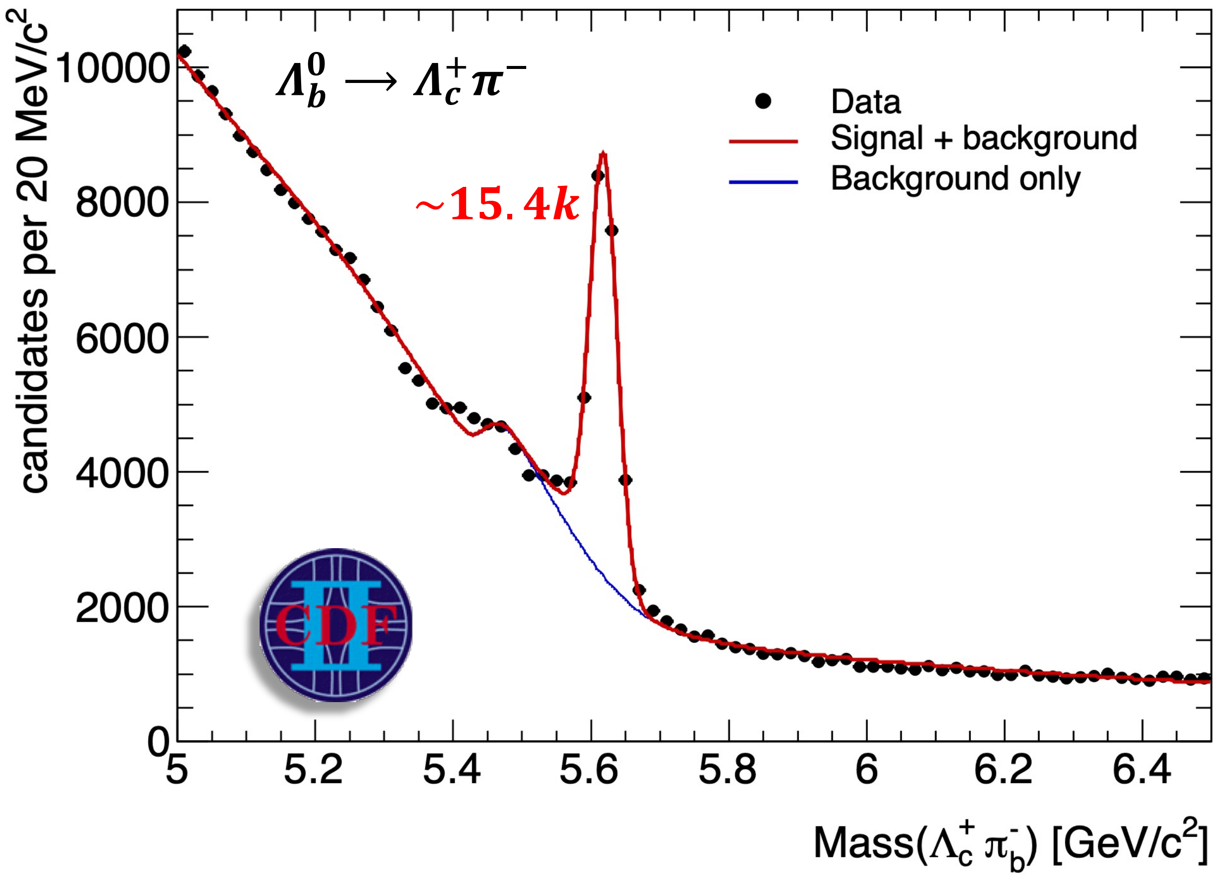
$$M_{\Lambda_b^{*0}(5912)} = 5911.97 \pm 0.12 \pm 0.02 \pm 0.66 \text{ MeV}/c^2$$

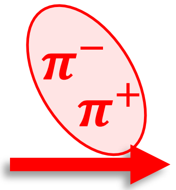
$$M_{\Lambda_b^{*0}(5920)} = 5919.77 \pm 0.08 \pm 0.02 \pm 0.66 \text{ MeV}/c^2$$

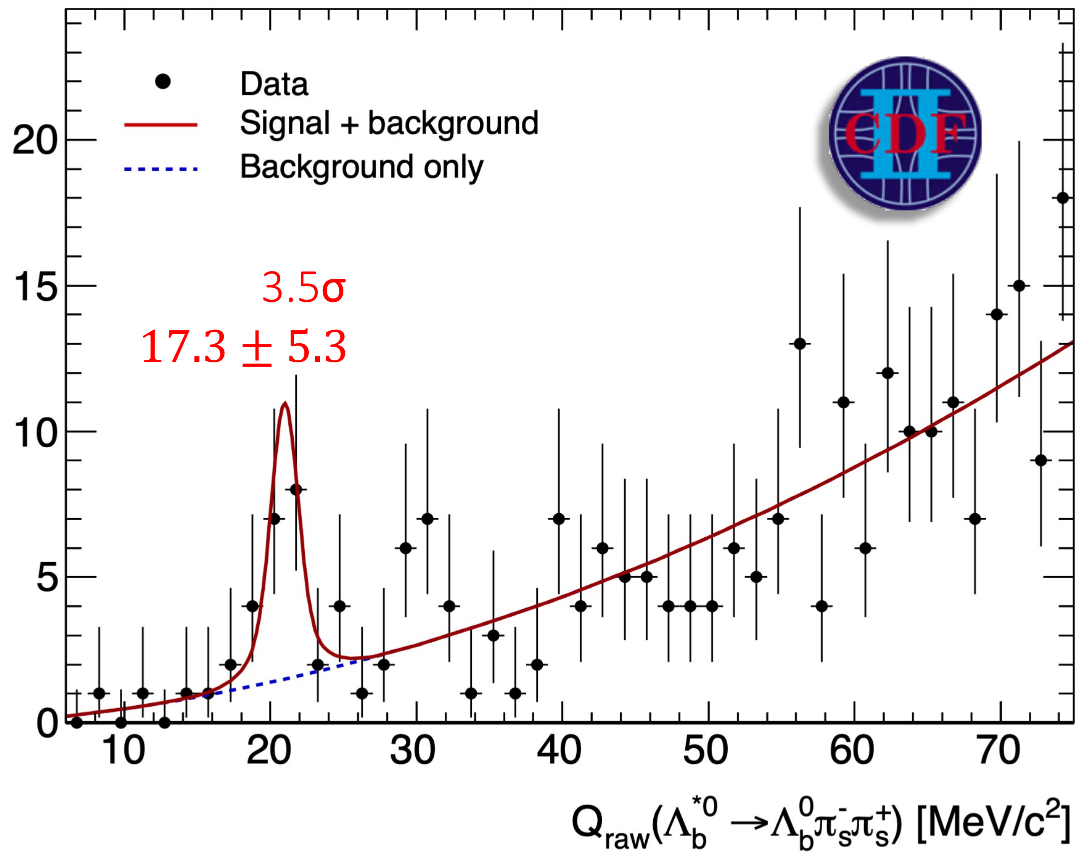
Introduction to Λ_b^0 excited states – CDF confirmations

Studies of excited heavy baryon spectrum **are an important test** of Heavy Quark Effective Theory. 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 narrow window** to search for a signal.

In PhysRevD.88.071101 CDF (2013): confirmed **only the higher mass state** $\Lambda_b\,(5920)^0 \longrightarrow \Lambda_b^0\pi^+\pi^-$ with a significance of **3.5σ**





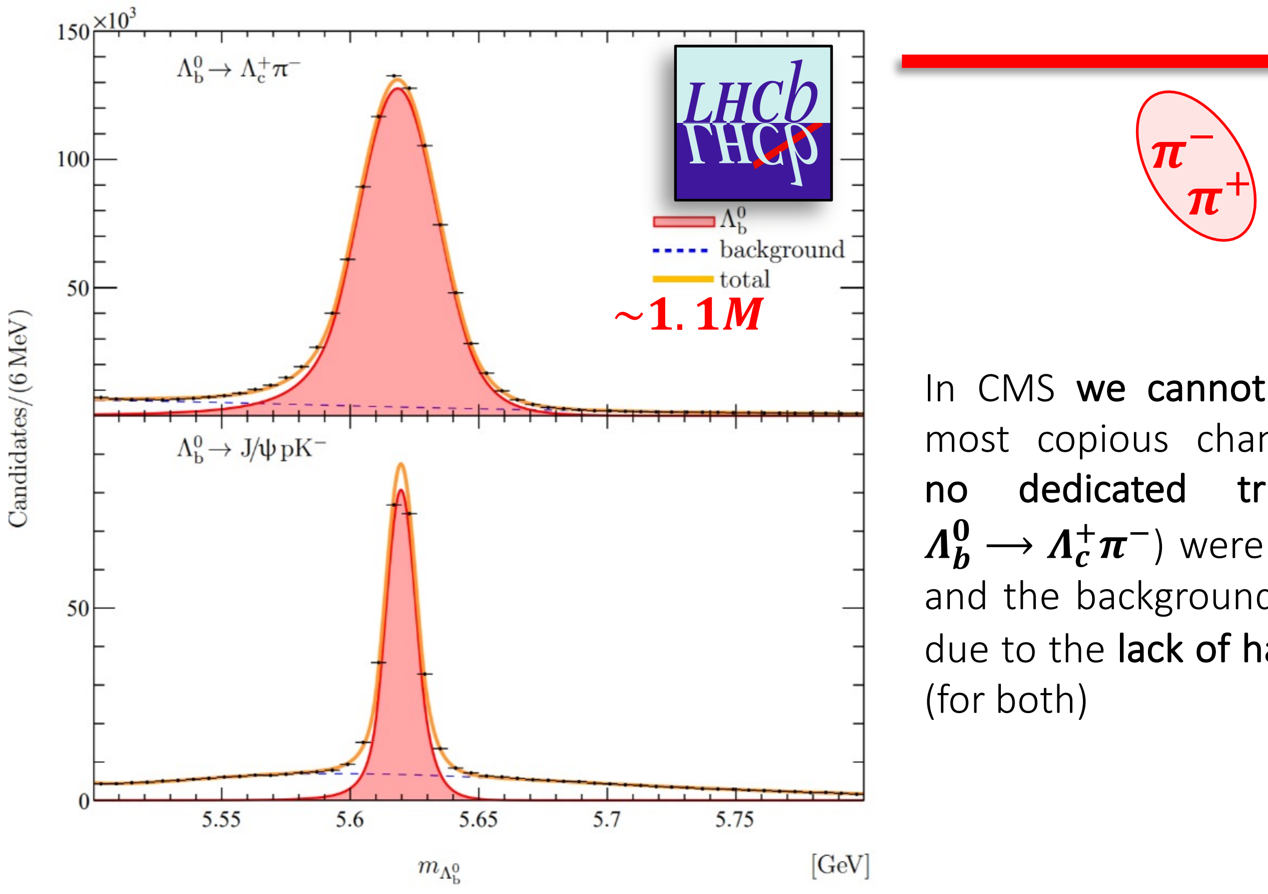


LHCb 2019: Two More States

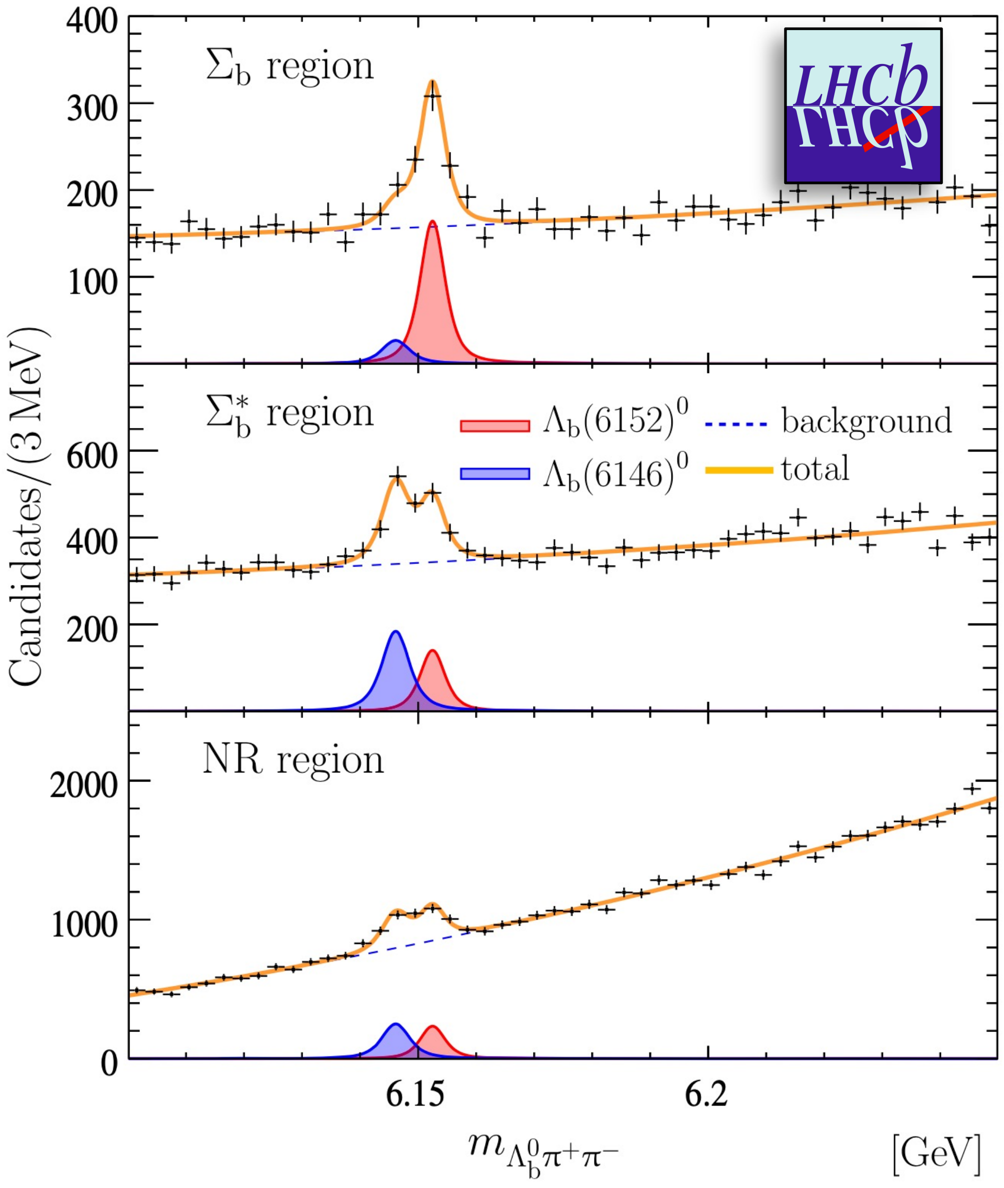
In 2019 in PRL 123 (2019) 152001 LHCb **using full Run-I+II dataset observed two new excited states** decaying to $\Lambda_b^0\pi^+\pi^-$ final state:

$\Lambda_b\,(6146)^0$ and $\Lambda_b\,(6152)^0$

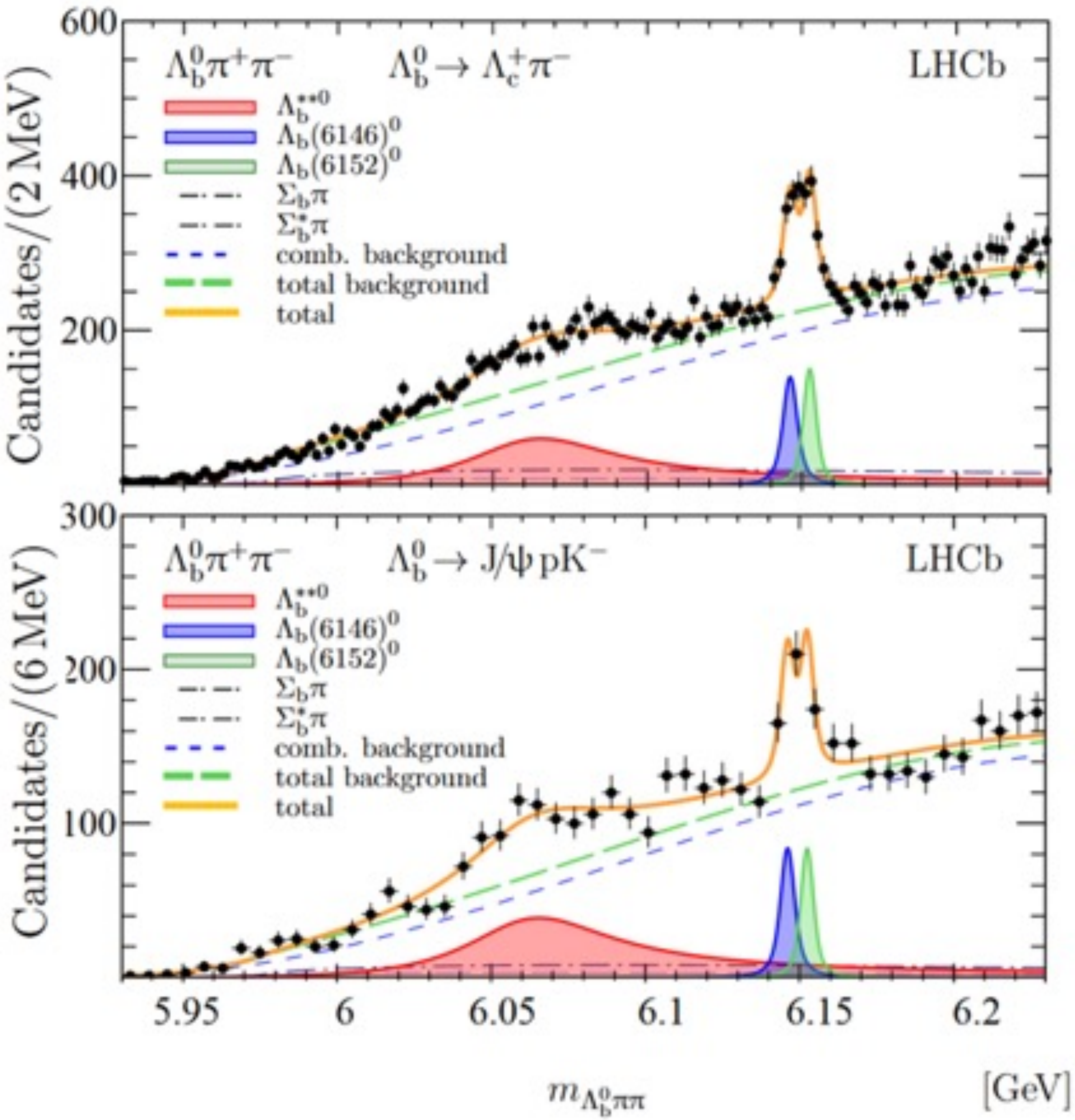
using both channels $\boldsymbol{\Lambda_b^0 \longrightarrow \Lambda_c^+\pi^-}$ and $\boldsymbol{\Lambda_b^0 \longrightarrow J/\psi p K^-}$ with about $\mathbf{1.1M}$ $\boldsymbol{\Lambda_b^0}$ in total



In CMS **we cannot** use these most copious channels since **no dedicated trigger** (for $\boldsymbol{\Lambda_b^0 \longrightarrow \Lambda_c^+\pi^-}$) were configured and the backgrounds are large due to the **lack of hadronic PID** (for both)

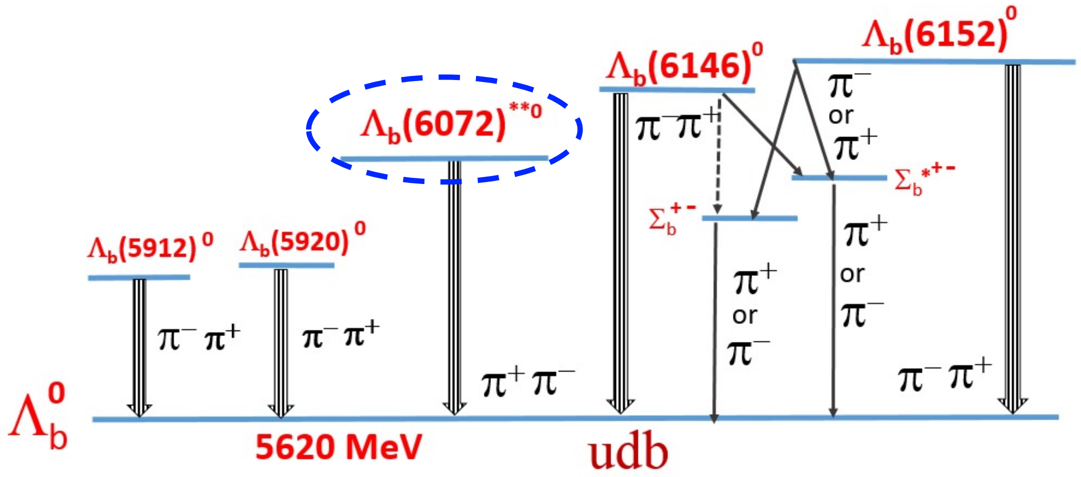


$\Lambda_b^0\pi^\pm\pi^\mp$ wide structure in LHCb



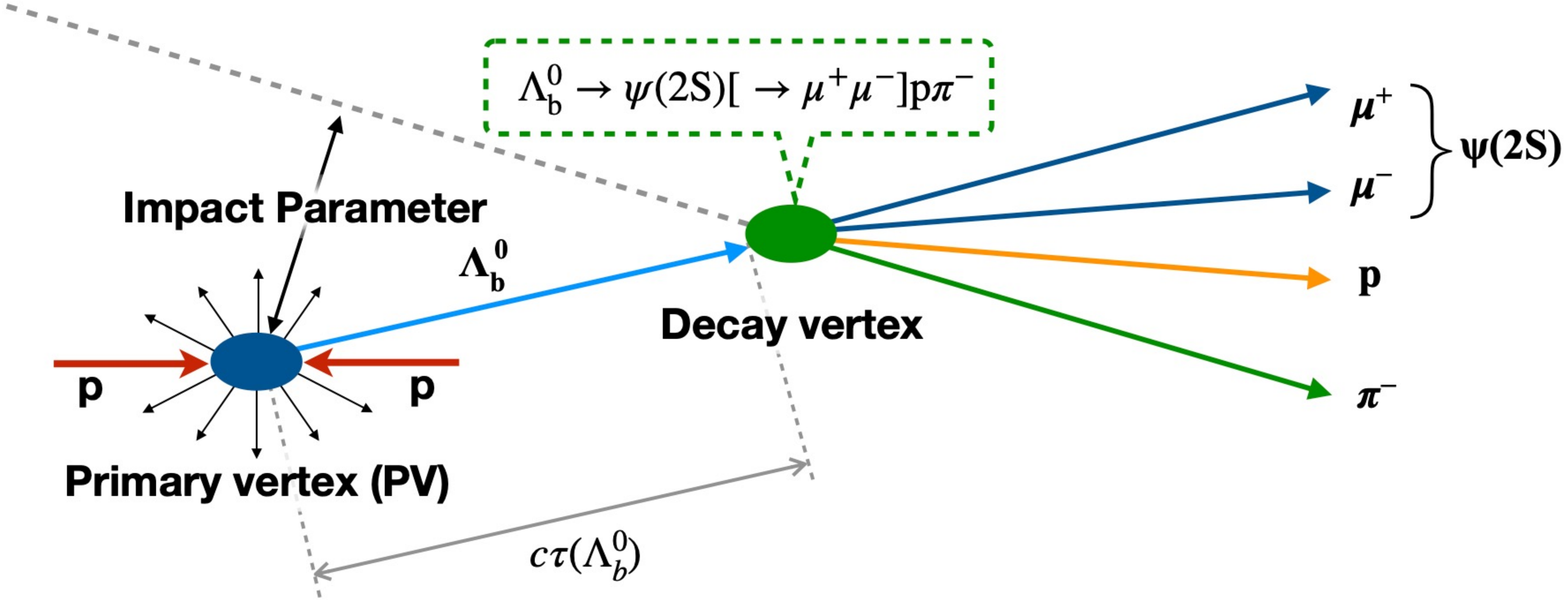
Later confirmed the wide structure in the $\Lambda_b^0\pi^\pm\pi^\mp$ spectrum and …

… possibly interpreted it as a further excited Λ_b^0 with mass and width compatible with expectations for the $\Lambda_b^0(2S)$ state



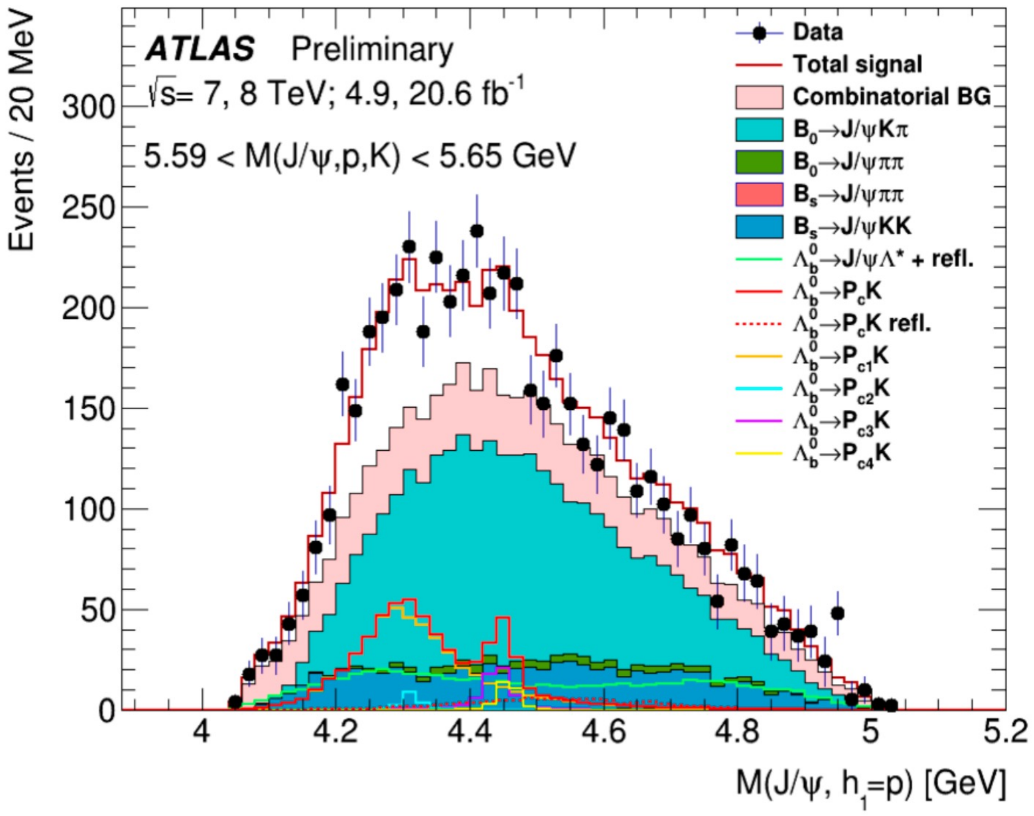
http://lhcb-public.web.cern.ch

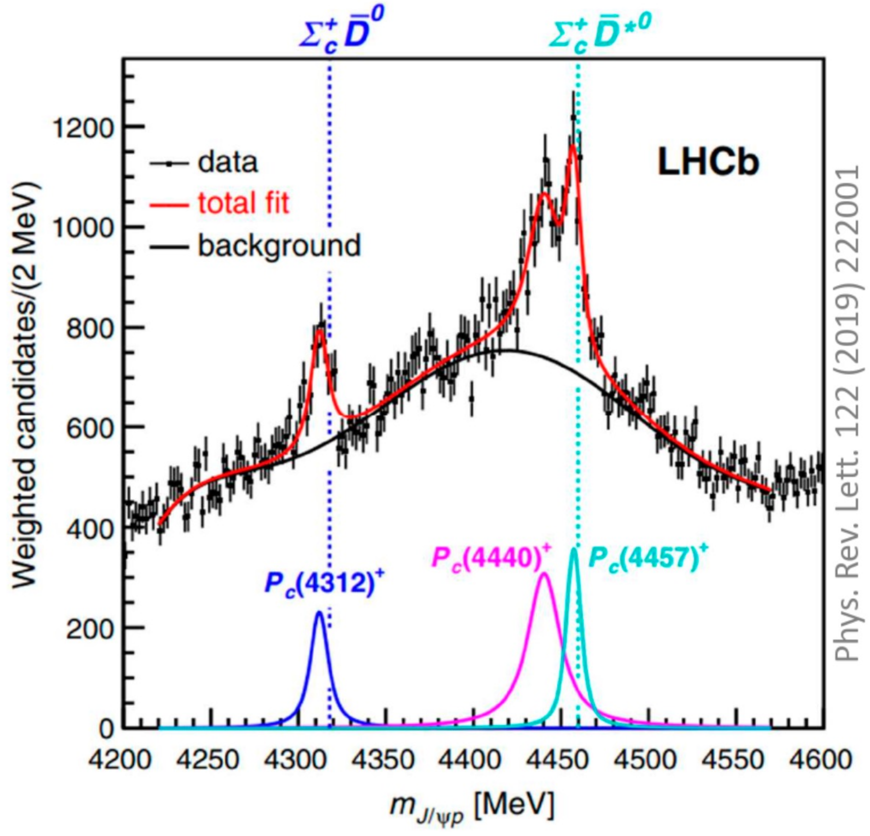
ATLAS-CONF-2019-048 $\Lambda_b^0 \to J/\psi p K^-$ Topology



(credits to Viacheslav Matiunin)

MC Reweigthing: a Model-independent Approach





State	M [MeV]	Γ [MeV]	(95% CL)	$\mathcal{R}$ [%]
$P_c(4312)^+$	$4311.9 \pm 0.7^{+6.8}_{-0.6}$	$9.8 \pm 2.7^{+\ 3.7}_{-\ 4.5}$	(< 27)	$0.30 \pm 0.07^{+0.34}_{-0.09}$
$P_c(4440)^+$	$4440.3 \pm 1.3^{+4.1}_{-4.7}$	$20.6 \pm 4.9^{+\ 8.7}_{-10.1}$	(< 49)	$1.11 \pm 0.33^{+0.22}_{-0.10}$
$P_c(4457)^+$	$4457.3 \pm 0.6^{+4.1}_{-1.7}$	$6.4 \pm 2.0^{+\ 5.7}_{-\ 1.9}$	(< 20)	$0.53 \pm 0.16^{+0.15}_{-0.13}$

Fit procedure for pentaquark searches

Fit uses signal region ($5.59 < m(J/\psi p K^-) < 5.65$ GeV) and two control regions for B^0 and B^0

Global fit

Fitting decay coupling constants for B-meson decays. Λ_b decay couplings are fixed

Information included:
2D: $M(J/\psi,K,K)$, $M(J/\psi,\pi,\pi)$
2D: $M(J/\psi,K,\pi)$, $M(J/\psi,\pi,K)$;
2D: $M(J/\psi,K)$, $M(J/\psi,\pi)$ in B_d CR
2D: $M(J/\psi,1K)$, $M(J/\psi,2K)$ in B_s CR
1D: $M(K,\pi)$ and $M(\pi,K)$ separately in B_d CR
1D: $M(K,\pi)$ in B_d CR

$M(J/\psi,p,K)$ fit

Obtain yields of Λ_b, B_d, B_s decays;
All decay coupling constants fixed;

Information included:
2D: $M(J/\psi,p,K)$, $M(J/\psi,\pi,\pi)$;
2D: $M(J/\psi,K,\pi)$, $M(J/\psi,\pi,K)$;

Λ_b decays fit

Fit of Λ_b decay couplings;

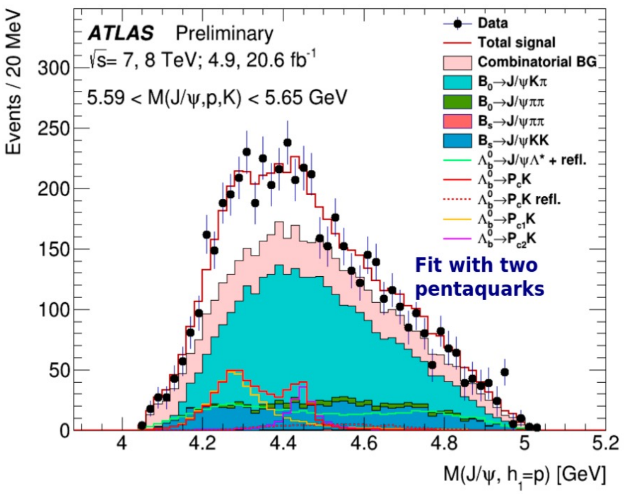
Information included:
2D: $M(J/\psi,p)$, $M(J/\psi,K)$ in Λ_b CR
OR: 1D: $M(p,K)$ in Λ_b CR

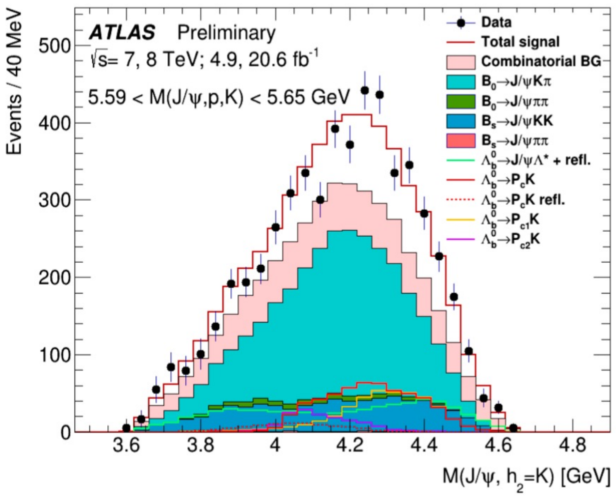
$M(J/\psi,p)$ fit

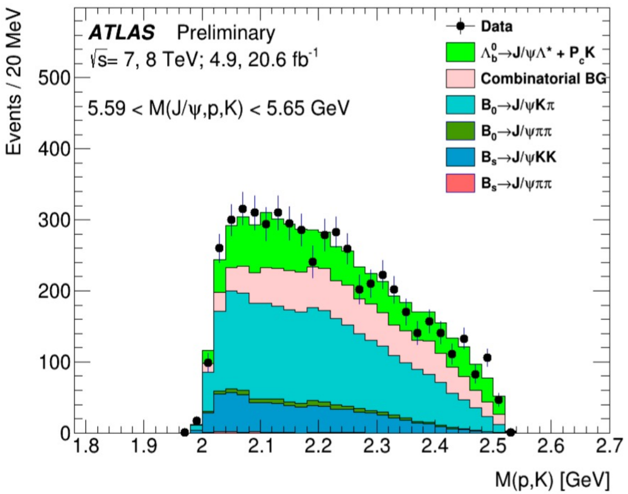
Fit of pentaquark signal parameters and yields.

Information included:
2D: $M(J/\psi,p)$, $M(J/\psi,K)$ in Λ_b CR
OR: 1D: $M(p,K)$ in Λ_b CR

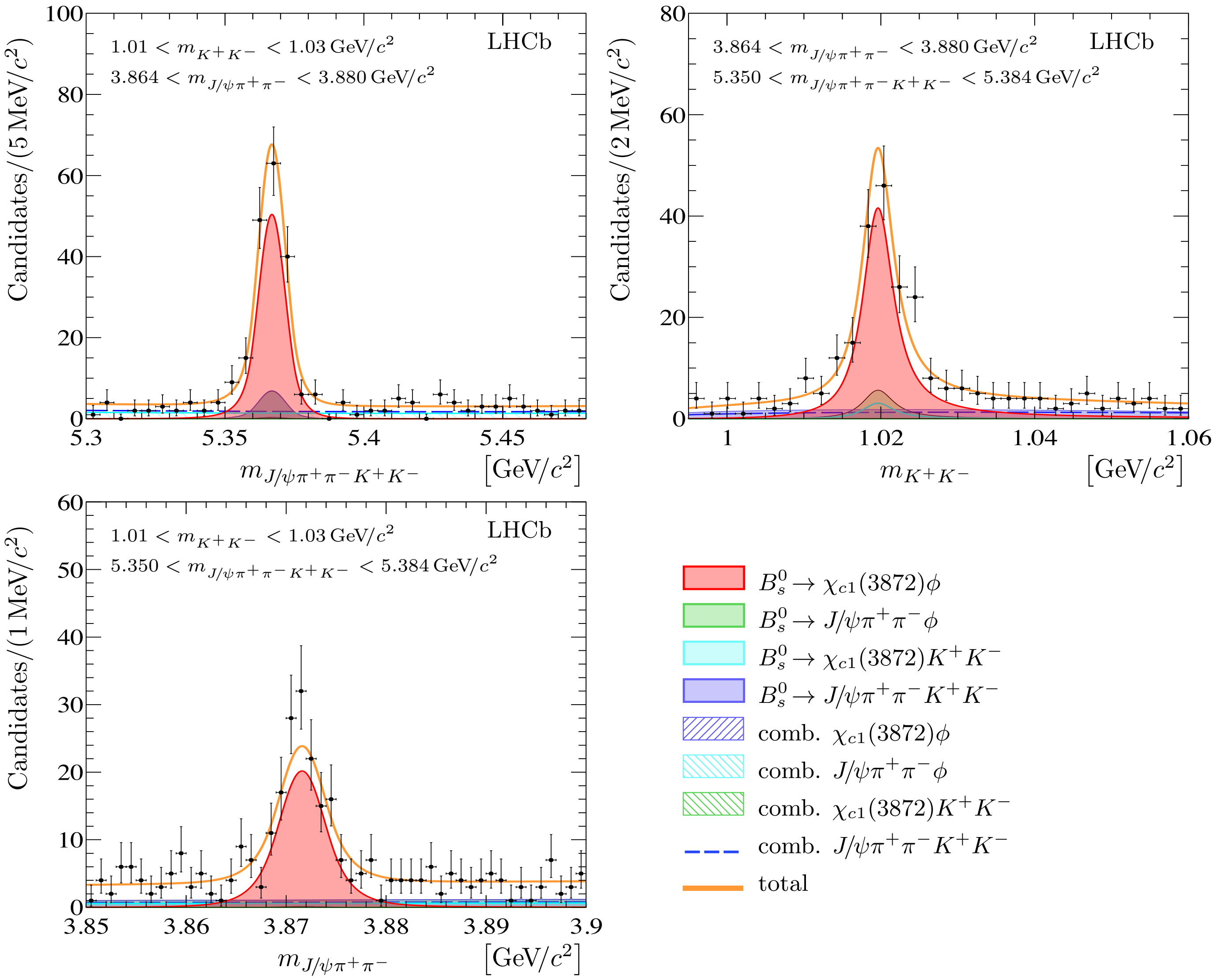
(credits to I.Yeletskikh)



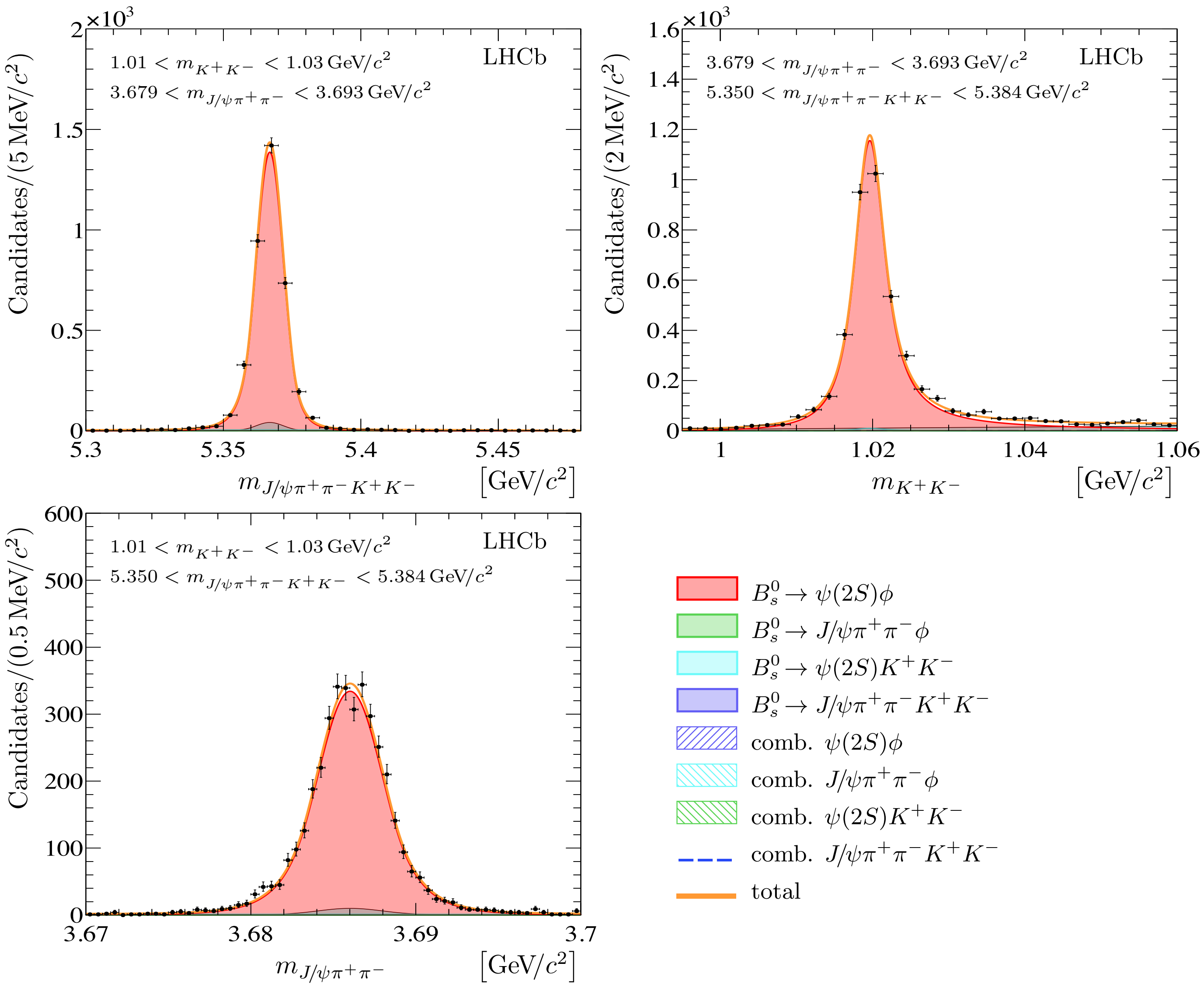


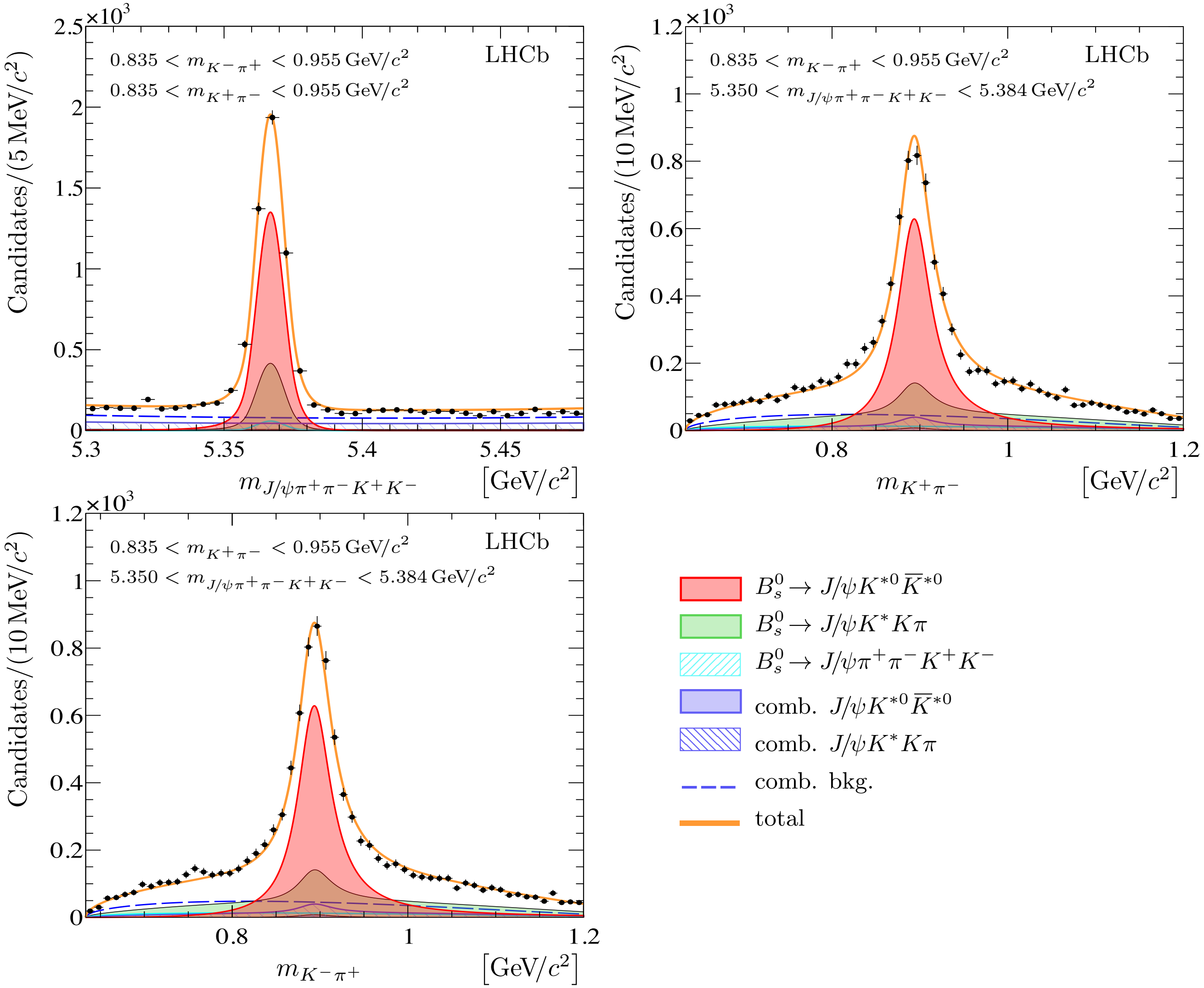


JHEP 02 (2021) 024 - $B_s^0 \to \chi_{c1}(3872)\phi$



JHEP 02 (2021) 024 - $B_s^0 \to \psi(2S)\,\phi$





$0.835 < m_{K^-\pi^+} < 0.955$ GeV/c^2
$0.835 < m_{K^+\pi^-} < 0.955$ GeV/c^2
LHCb
Candidates/(5 MeV/c^2)
$\times 10^3$
$m_{J/\psi\pi^+\pi^-K^+K^-}$ [GeV/c^2]
$0.835 < m_{K^-\pi^+} < 0.955$ GeV/c^2
$5.350 < m_{J/\psi\pi^+\pi^-K^+K^-} < 5.384$ GeV/c^2
LHCb
Candidates/(10 MeV/c^2)
$m_{K^+\pi^-}$ [GeV/c^2]
$0.835 < m_{K^+\pi^-} < 0.955$ GeV/c^2
$5.350 < m_{J/\psi\pi^+\pi^-K^+K^-} < 5.384$ GeV/c^2
LHCb
Candidates/(10 MeV/c^2)
$m_{K^-\pi^+}$ [GeV/c^2]
$B_s^0 \to J/\psi K^{*0}\overline{K}^{*0}$
$B_s^0 \to J/\psi K^* K\pi$
$B_s^0 \to J/\psi \pi^+\pi^- K^+K^-$
comb. $J/\psi K^{*0}\overline{K}^{*0}$
comb. $J/\psi K^* K\pi$
comb. bkg.
total

arXiv:2103.04949 - $\Lambda^0 \to \chi\, p\pi$ systematics

Source	$\mathcal{R}_{\pi/K}$	$\mathcal{R}^{\pi}_{2/1}$	$\mathcal{R}^{K}_{2/1}$
Fit model	2.4	3.7	3.7
Λ^0_b production spectra	< 0.1		
$\Lambda^0_b \to \chi_{cJ} p K^-$ decay models	< 0.1		< 0.1
Track reconstruction	< 0.1		
Hadron identification	0.3		
Trigger efficiency	1.1		
Data-simulation agreement	2.0		
Simulation sample size	0.4	0.6	0.7
Sum in quadrature	3.3	3.8	3.8

N.B. Systematic uncertainties largely cancel for the ratios

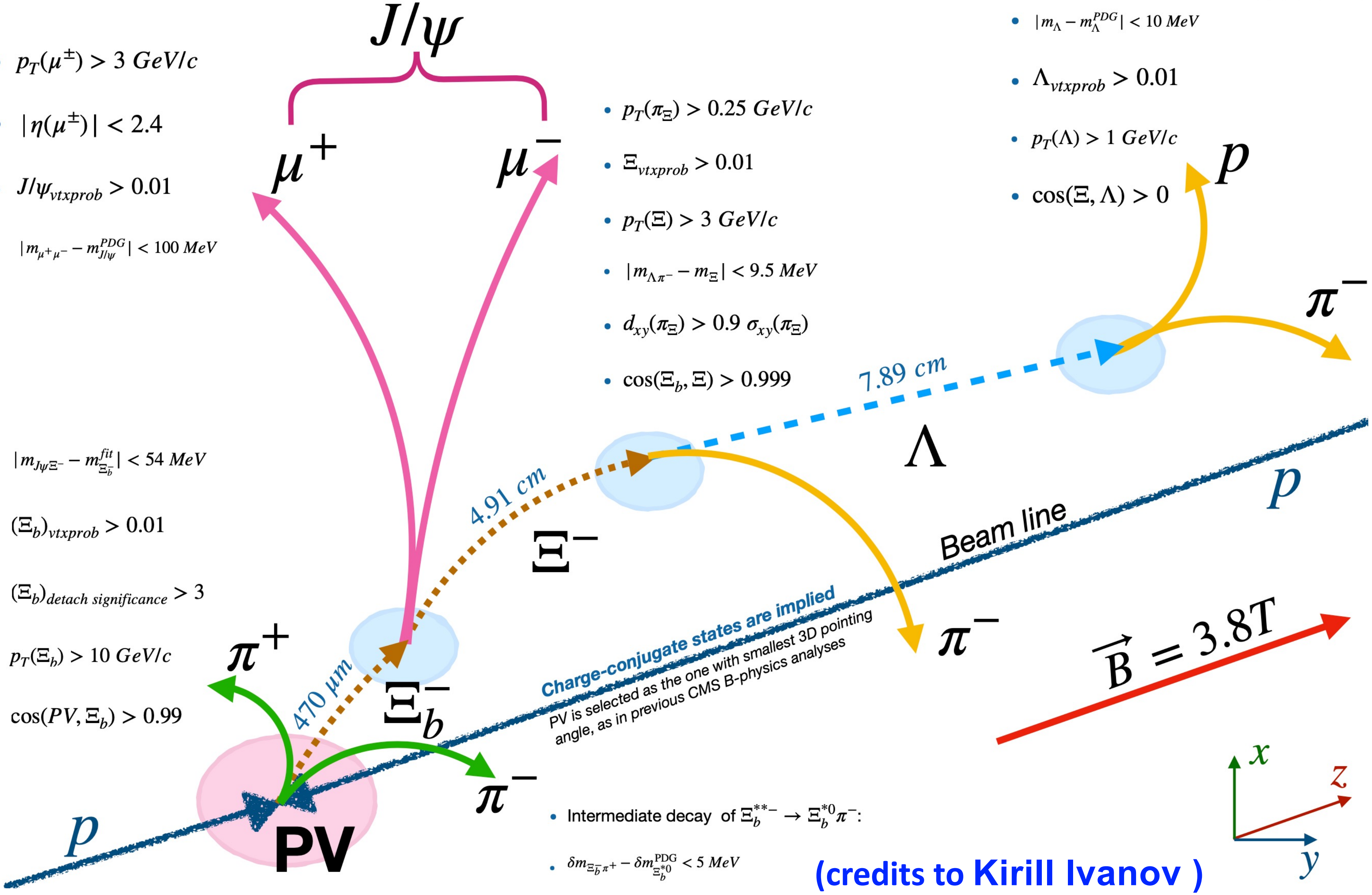
JHEP 12 (2019) 100 – Selection

- $p_T(\mu^{\pm}) > 3\ GeV/c$
- $|\eta(\mu^{\pm})| < 2.4$
- $J/\psi_{vtxprob} > 0.01$
- $|m_{\mu^+\mu^-} - m_{J/\psi}^{PDG}| < 100\ MeV$

- $p_T(\pi_\Xi) > 0.25\ GeV/c$
- $\Xi_{vtxprob} > 0.01$
- $p_T(\Xi) > 3\ GeV/c$
- $|m_{\Lambda\pi^-} - m_\Xi| < 9.5\ MeV$
- $d_{xy}(\pi_\Xi) > 0.9\ \sigma_{xy}(\pi_\Xi)$
- $\cos(\Xi_b, \Xi) > 0.999$

- $|m_\Lambda - m_\Lambda^{PDG}| < 10\ MeV$
- $\Lambda_{vtxprob} > 0.01$
- $p_T(\Lambda) > 1\ GeV/c$
- $\cos(\Xi, \Lambda) > 0$

- $|m_{J\psi\Xi^-} - m_{\Xi_b^-}^{fit}| < 54\ MeV$
- $(\Xi_b)_{vtxprob} > 0.01$
- $(\Xi_b)_{detach\ significance} > 3$
- $p_T(\Xi_b) > 10\ GeV/c$
- $\cos(PV, \Xi_b) > 0.99$



- Intermediate decay of $\Xi_b^{**-} \to \Xi_b^{*0}\pi^-$:
- $\delta m_{\Xi_b^-\pi^+} - \delta m_{\Xi_b^{*0}}^{PDG} < 5\ MeV$

(credits to Kirill Ivanov)