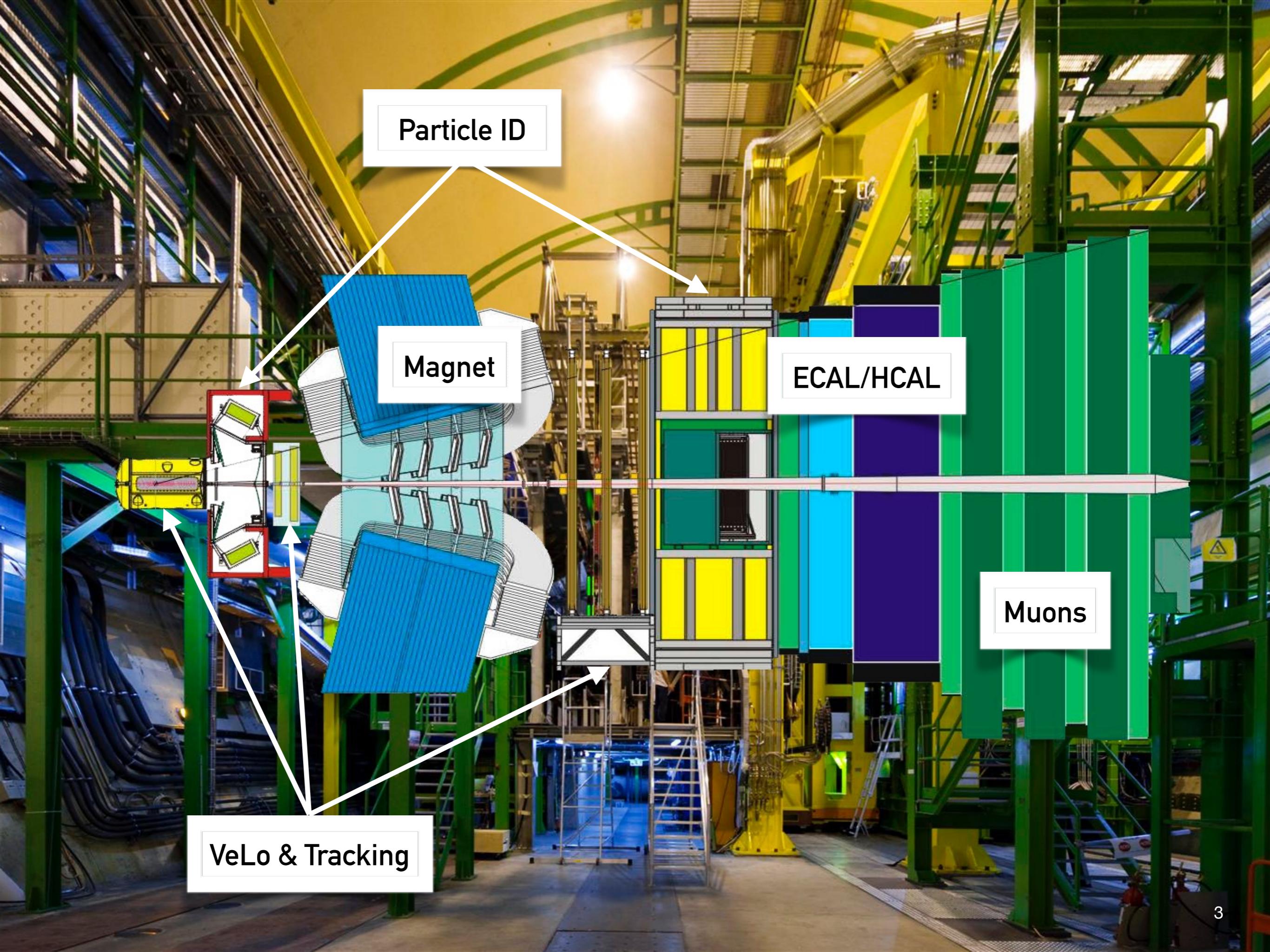


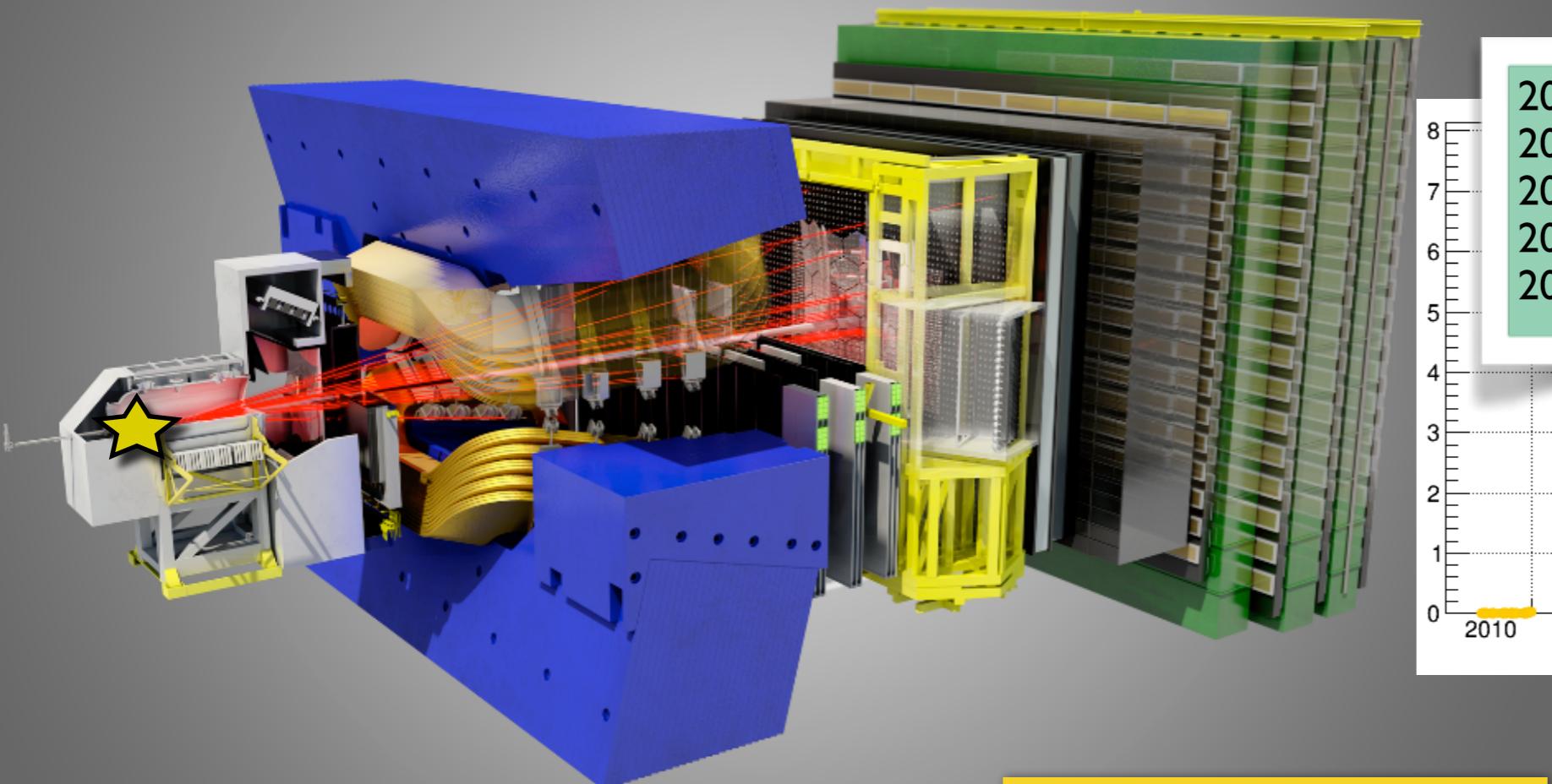


# Heavy Quark Spectroscopy at LHCb

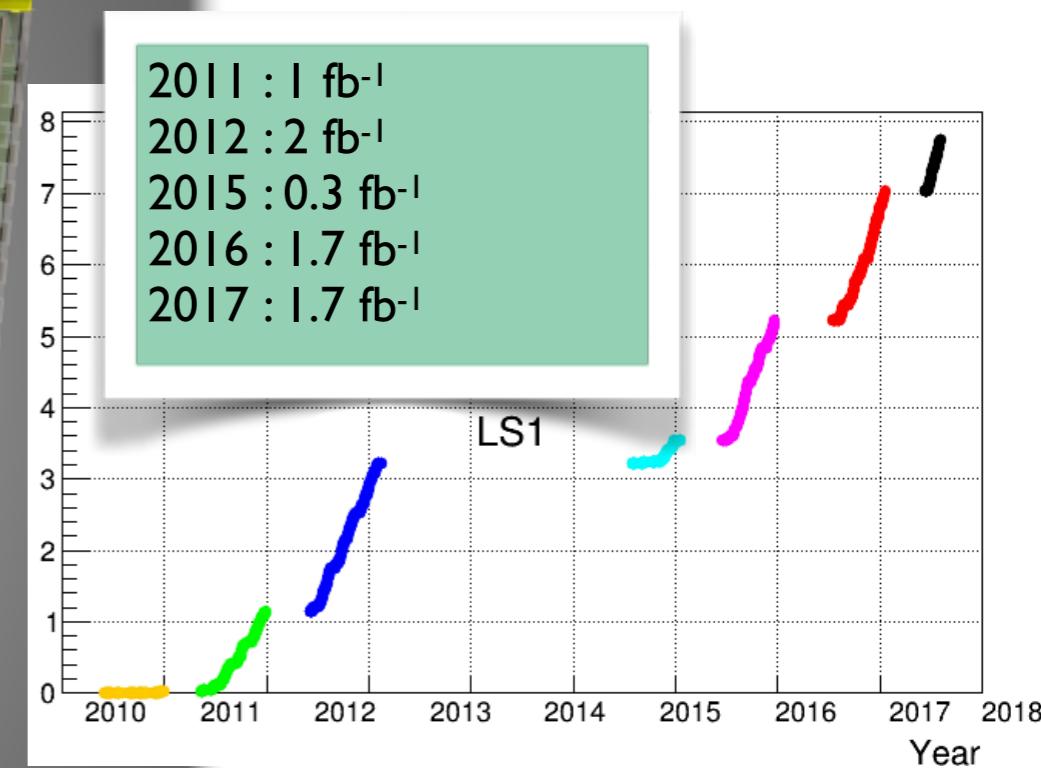
Daniel Johnson, CERN  
on behalf of the LHCb collaboration  
5<sup>th</sup> July 2018, ICHEP, Seoul







2011 : 1 fb<sup>-1</sup>  
 2012 : 2 fb<sup>-1</sup>  
 2015 : 0.3 fb<sup>-1</sup>  
 2016 : 1.7 fb<sup>-1</sup>  
 2017 : 1.7 fb<sup>-1</sup>



Int. J. Mod. Phys. A 30, 1530022 (2015)

Large  $\sigma(b\bar{b})$  @ LHCb in the forward region  
and efficient hadron trigger



Unprecedented samples of b,c-hadrons  
for spectroscopy of prompt & secondaries

Low pile-up and excellent IP resolution  
 $15 + 29/pT(\text{GeV})$



Excellent resolution of B and D vertices

Low p<sub>T</sub> tracking and superb PID  
down to ~300 MeV



Efficient high multiplicity final state  
reconstruction

Good momentum uncertainty  
0.5%-1% @ 200 GeV/c



Precise signal resolution wrt backgrounds

## Trigger strategy:

- ◆ LHC:  $p\bar{p}$  bunch-crossings [11 MHz]
- ◆ Hardware: HCAL, muon information [1 MHz]
- ◆ Software: Full event reconstruction [ $O(1)$  kHz]

# Excited baryons

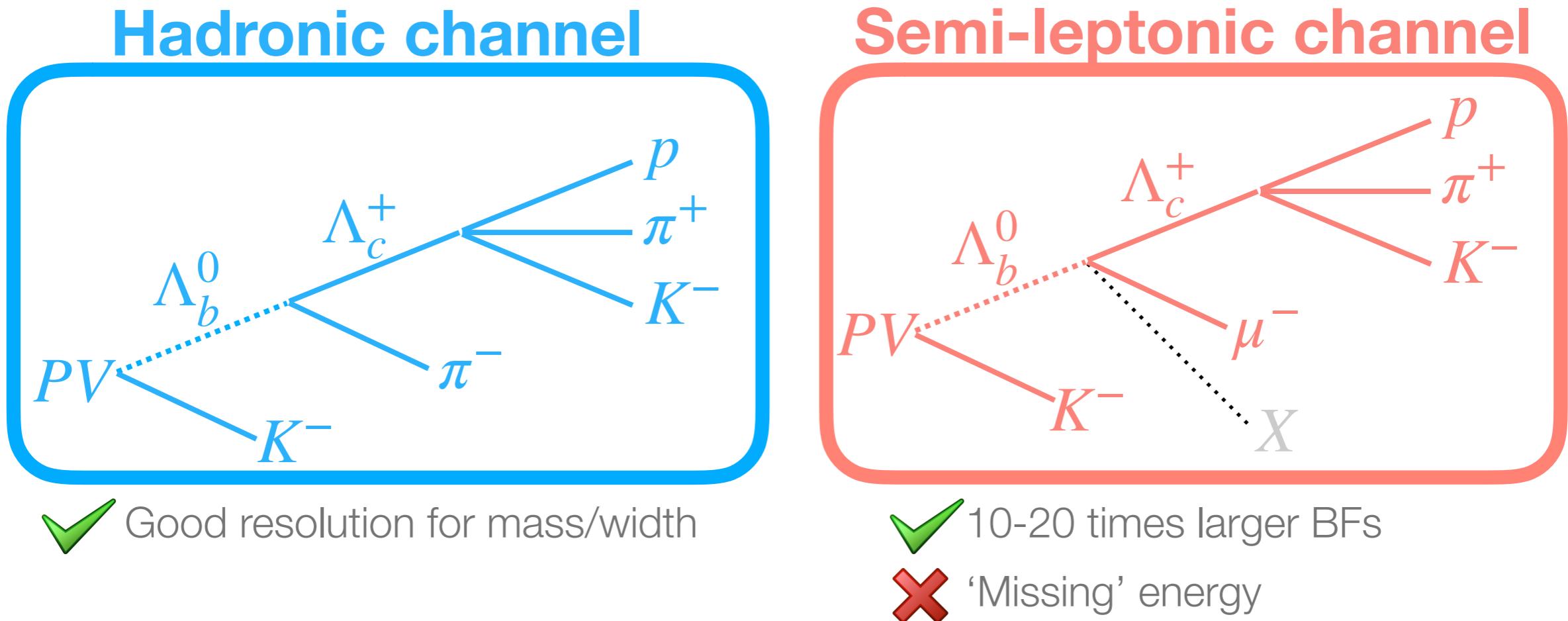
## Observation of a new $\Xi_b^-$ resonance

arXiv:1805.09418

7 TeV      8 TeV      13 TeV  
1 fb<sup>-1</sup> + 2 fb<sup>-1</sup> + 1.5 fb<sup>-1</sup>



- Properties of baryonic multiplets give insights into their internal structure
- A burgeoning field:
  - Observation of two new  $\Xi_b^-$  baryon resonances PRL 114 062004
  - Observation of a new  $\Xi_b$  baryon PRL 108 252002
  - Measurement of the properties of the  $\Xi_b^{*0}$  baryon JHEP 05 161
- Expect spectrum of radially/orbitally excited states;  
only  $\Lambda_b(5912)^0$  and  $\Lambda_b(5920)^0$  discovered

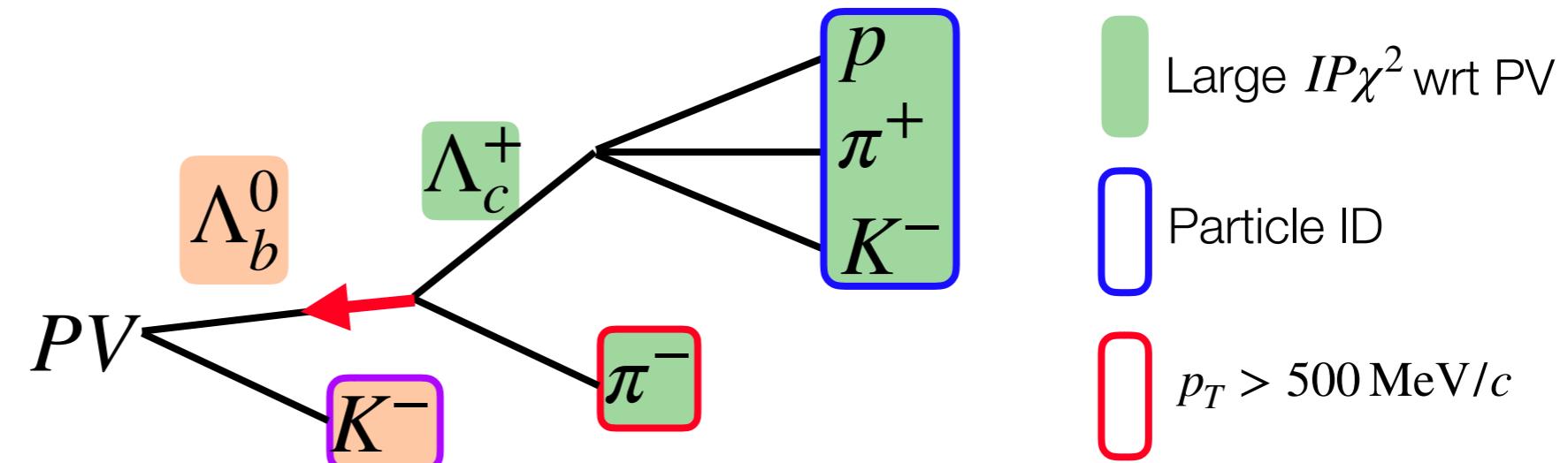


## Selection

Small  $IP\chi^2$  wrt PV



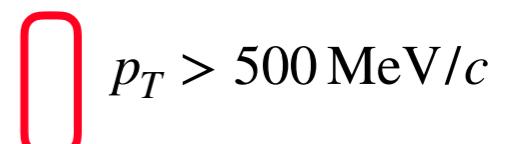
$p_T > 800 \text{ MeV}/c$



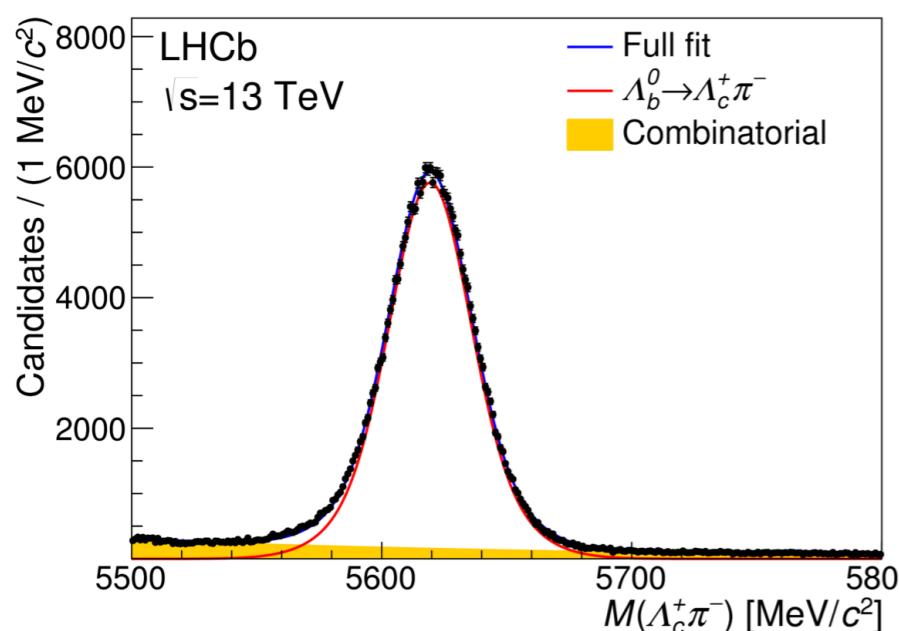
Large  $IP\chi^2$  wrt PV



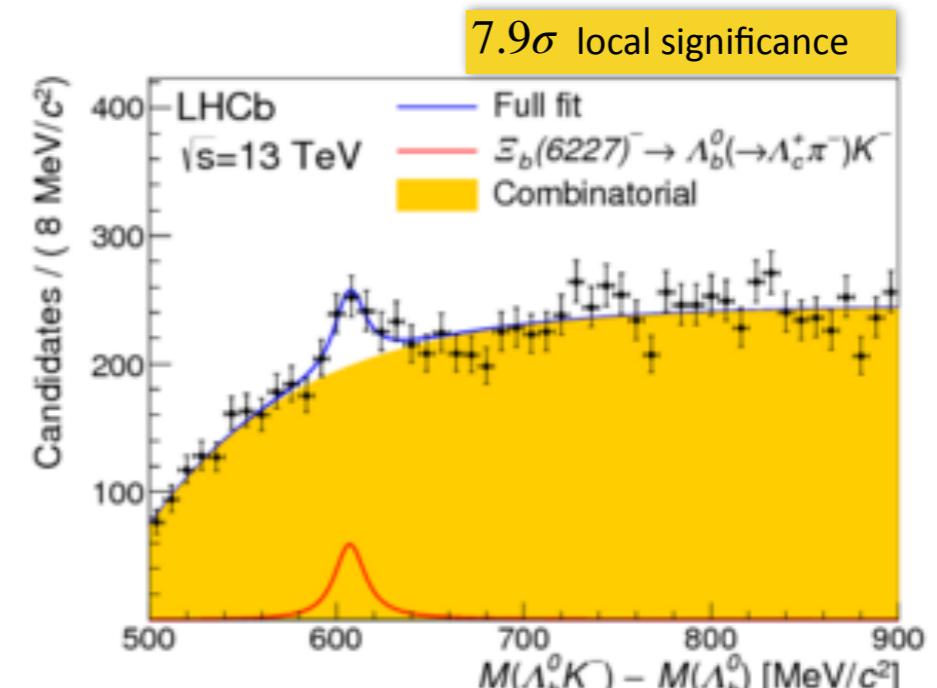
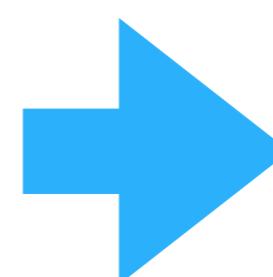
Particle ID



## Fitting



+  $K^-$



## Properties

$$m_{\Xi_b(6227)^-} = 6226.9 \pm 2.0 \text{ (stat)} \pm 0.3 \text{ (syst)} \pm 0.2(\Lambda_b^0) \text{ MeV}/c^2$$

$$\Gamma_{\Xi_b(6227)^-} = 18.1 \pm 5.4 \text{ (stat)} \pm 1.8 \text{ (syst)} \text{ MeV}/c^2$$

- New  $\Xi_b(6227)^-$  state with
- Main systematics from fit model and fitter bias
- Consistent with expectations for  $\Xi_b(1P)^-$  or  $\Xi_b(2S)^-$

# Semi-leptonic channel

## Selection

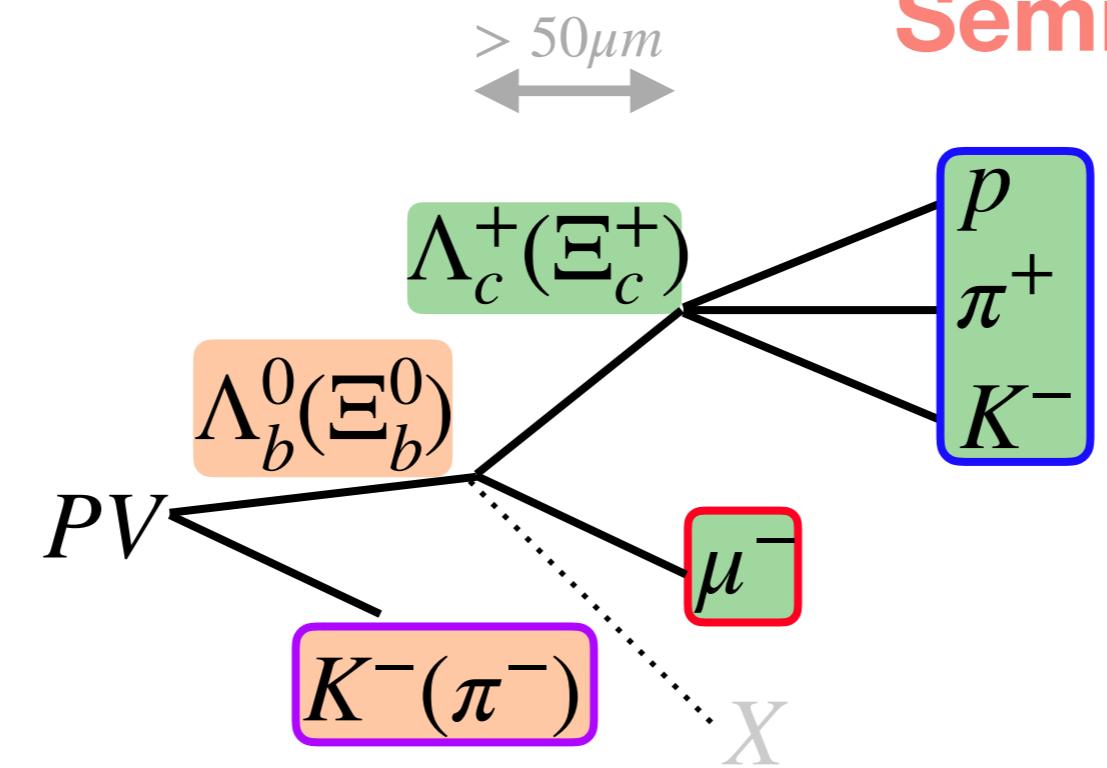
Small  $IP\chi^2$  wrt PV



$p_T > 0.8(0.9) \text{ GeV}/c$



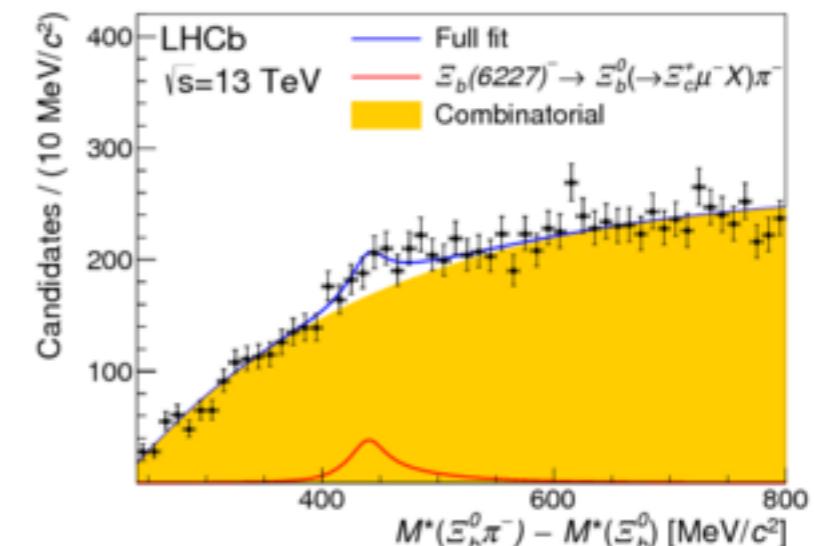
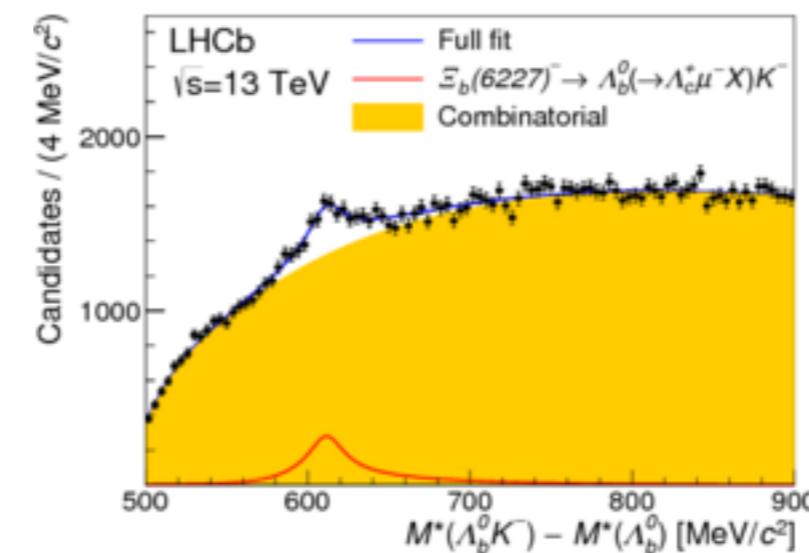
...+ additional BDT to suppress  
 $\Xi_b^0$  combinatorics



- Large  $IP\chi^2$  wrt PV
- Particle ID ( $\Xi_c^+$  specific open-charm PID vetos)
- $p_T > 1 \text{ GeV}/c$

## Fitting

- Missing momentum estimated for massless particle balancing momentum transverse to the  $\Lambda_b^0(\Xi_b^0)$  direction, such that the total invariant mass matches  $m(\Lambda_b^0(\Xi_b^0))$



## Properties

- Mass consistent with **hadronic channel**
- Signal significance  $\sim 25\sigma$ !
- Relative production rates wrt  $\Lambda_b^0(\Xi_b^0)$ :

**Dominant systematic:**  
background model

Quantity [ $10^{-3}$ ]	7, 8 TeV	13 TeV
$R(\Lambda_b^0 K^-)$	$3.0 \pm 0.3 \pm 0.4$	$3.4 \pm 0.3 \pm 0.4$
$R(\Xi_b \pi^-)$	$47 \pm 10 \pm 7$	$22 \pm 6 \pm 3$

# Precision charmonium

Precise measurement  
of  $\chi_{c1}$  and  $\chi_{c2}$  resonance  
parameters

Phys. Rev. Lett. 119 221901

7 TeV      8 TeV      13 TeV

1 fb<sup>-1</sup> + 2 fb<sup>-1</sup> + 1.9 fb<sup>-1</sup>

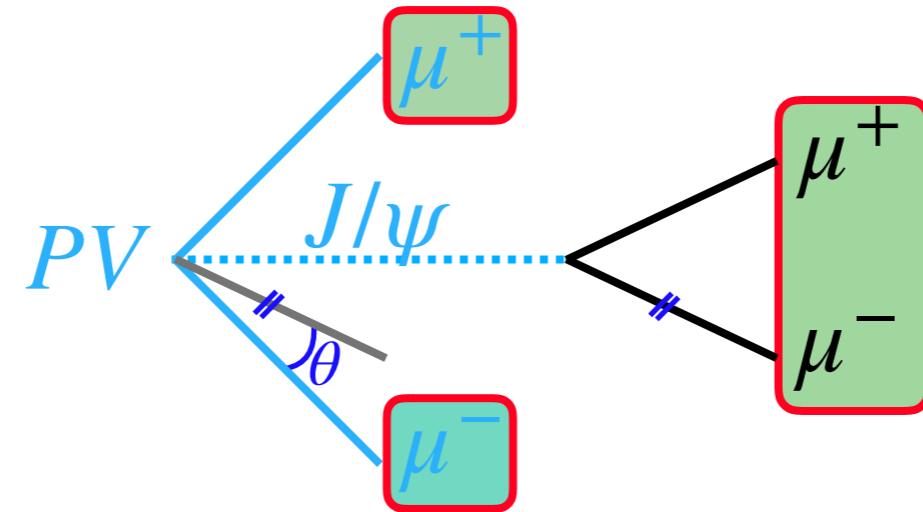


- Quarkonia production/properties allow important QCD tests
  - **Potential models** can be compared to the spectra
  - **Non-rel. eff. field theories** allow calculation of prod. rates
- Follows observation of  $\chi_{c0,1,2} \rightarrow J/\psi e^+e^-$  by BESIII PRL 118 221802

## Selection

### Clean $4\mu^\pm$ signature at a hadron collider

Re-fit candidates,  
constraining  $J/\psi$  mass



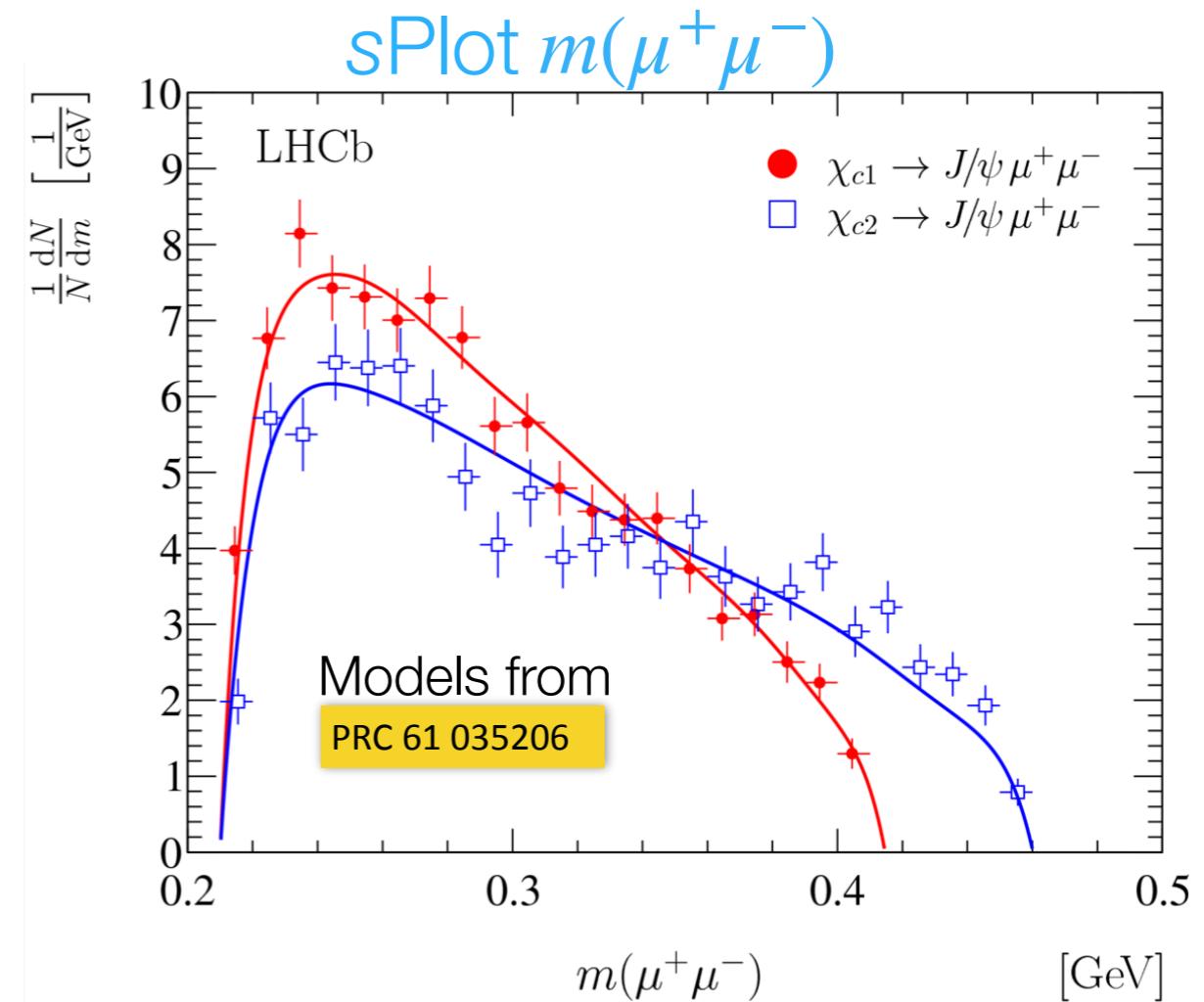
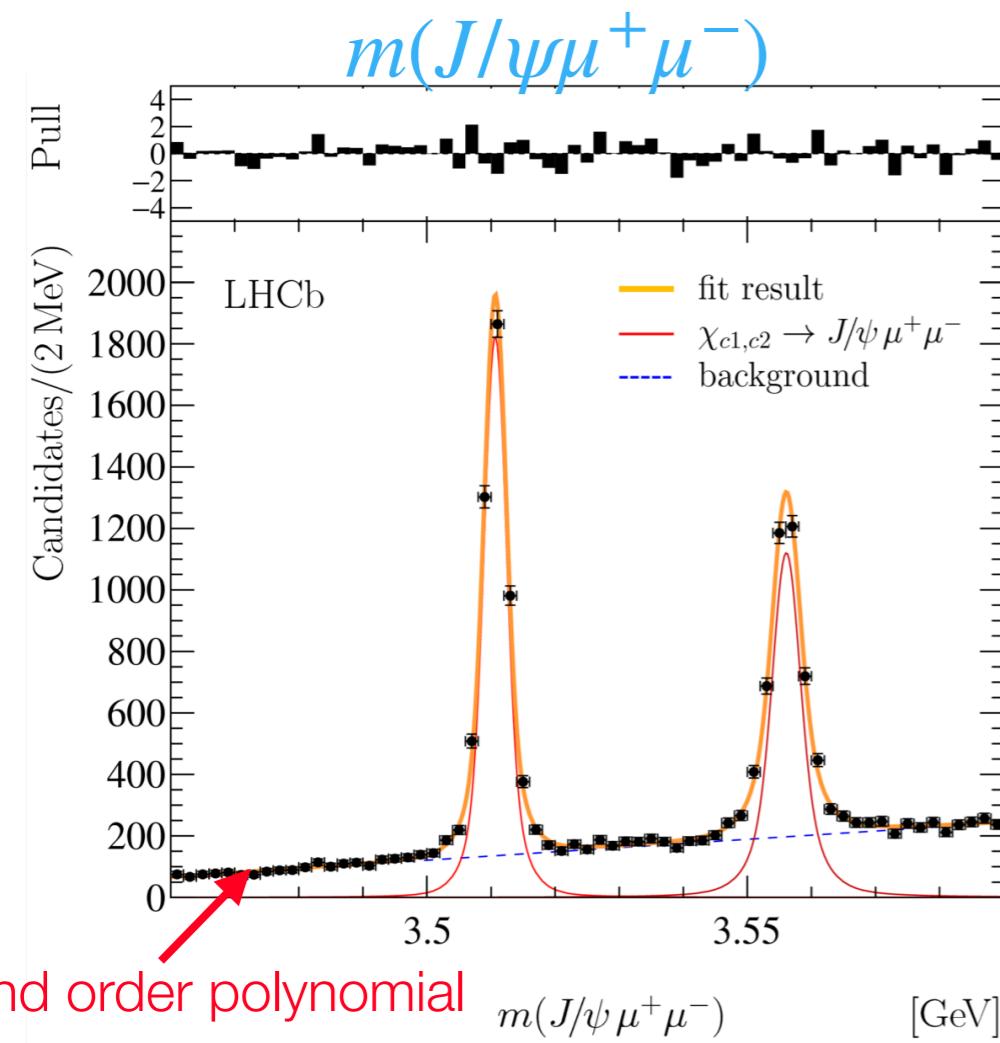
- █ Trigger on any muon, then require consistent with  $J/\psi$
- █ Run II data-taking (full online reconstruction) allows removal of cut  $p_T(J/\psi) > 3 \text{ GeV}/c$
- █  $\eta \in [2.0, 4.9]$
- █ PID to reject hadrons/electrons

## Momentum scale calibration

- Use  $J/\psi \rightarrow \mu^+\mu^-$  and  $B^+ \rightarrow J/\psi K^+$  samples
- Validate with  $K_S^0 \rightarrow \pi^+\pi^-$ ,  $\psi(2S) \rightarrow J/\psi \pi^+\pi^-$ , and  $\psi(2S) \rightarrow \mu^+\mu^-$
- Accurate to  $3 \times 10^{-4}$

# Fitting

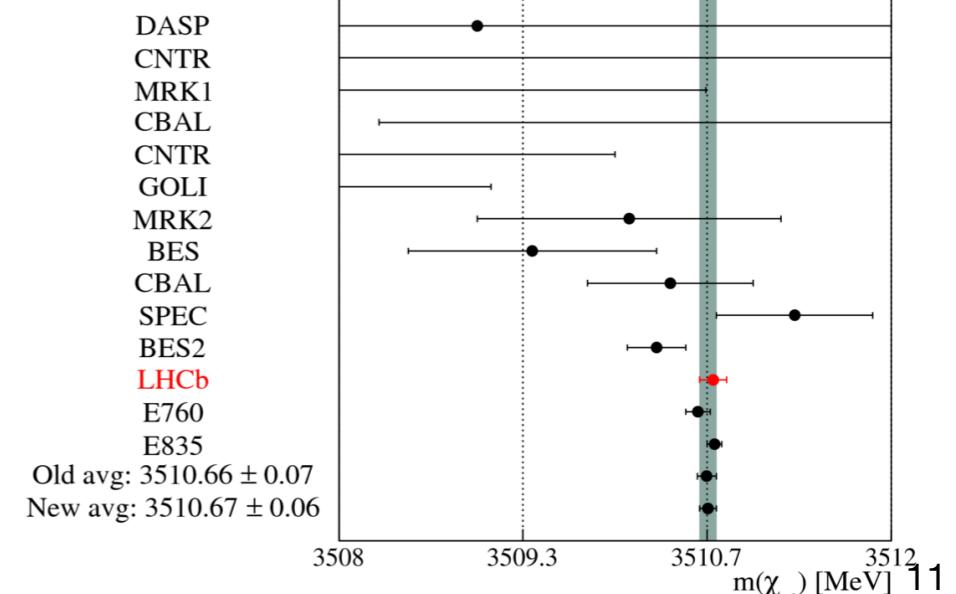
- Fit  $m(J/\psi\mu^+\mu^-)$  with a relativistic Breit-Wigner function
  - convolved with double-Gaussian resolution model



# Properties

$$\begin{aligned} m(\chi_{c1}) &= 3510.71 \pm 0.04 \pm 0.09 \text{ MeV}, \\ m(\chi_{c2}) &= 3556.10 \pm 0.06 \pm 0.11 \text{ MeV}, \\ m(\chi_{c2}) - m(\chi_{c1}) &= 45.39 \pm 0.07 \pm 0.03 \text{ MeV}, \end{aligned}$$

- Comparable to world's best precision
- New future avenue for LHC spectroscopy:**
  - High-precision production rates
  - Will measure very low  $p_T(\chi_c)$
  - Probe transition form factors of this and heavier states



# Tetraquarks

Search for beautiful tetraquarks in the  $\Upsilon(1S)\mu^+\mu^-$  invariant-mass spectrum

---

arXiv:1806.09707

7 TeV

8 TeV

13 TeV

1fb<sup>-1</sup> + 2 fb<sup>-1</sup> + 3.3 fb<sup>-1</sup>

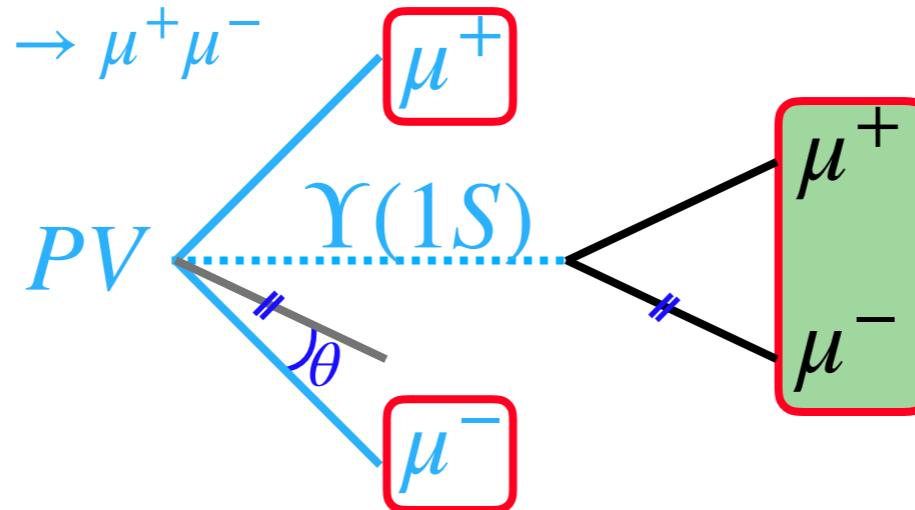


- Since 2003, over 30 exotic hadrons discovered
- Most are **tetraquarks/pentaquarks** around  $4 \text{ GeV}/c^2$
- No exotics found with  $>2$  heavy quarks
- Recent predictions for  $X_{b\bar{b}b\bar{b}}$  state:  $m(X) \in [18.4, 18.8] \text{ GeV}/c^2$ 
  - ... most below  $\eta_b \eta_b$  threshold, so could decay to  $\Upsilon \ell^+ \ell^-$

## Selection

### Normalise to $\Upsilon(1S) \rightarrow \mu^+ \mu^-$

Four muons forming a good vertex, consistent with the same PV



Trigger based on muon  $p, p_T$  and dimuon vertex quality

Good track quality & PID  
 $p_T > 1 \text{ GeV}/c$   
 $p \in [8, 500] \text{ GeV}/c$   
 $\eta \in [2.0, 5.0]$



Fiducial volume:

$$m(2\mu^+ 2\mu^-) \in [16, 22] \text{ GeV}/c^2$$

$$y(2\mu^+ 2\mu^-) \in [2, 4.5]$$

$$p_T(2\mu^+ 2\mu^-) < 15 \text{ GeV}/c$$



Exclude clones amongst  $\mu^+ \mu^+$  and  $\mu^- \mu^-$ :

$$m(\mu^+ \mu^+) > 220 \text{ MeV}/c^2$$

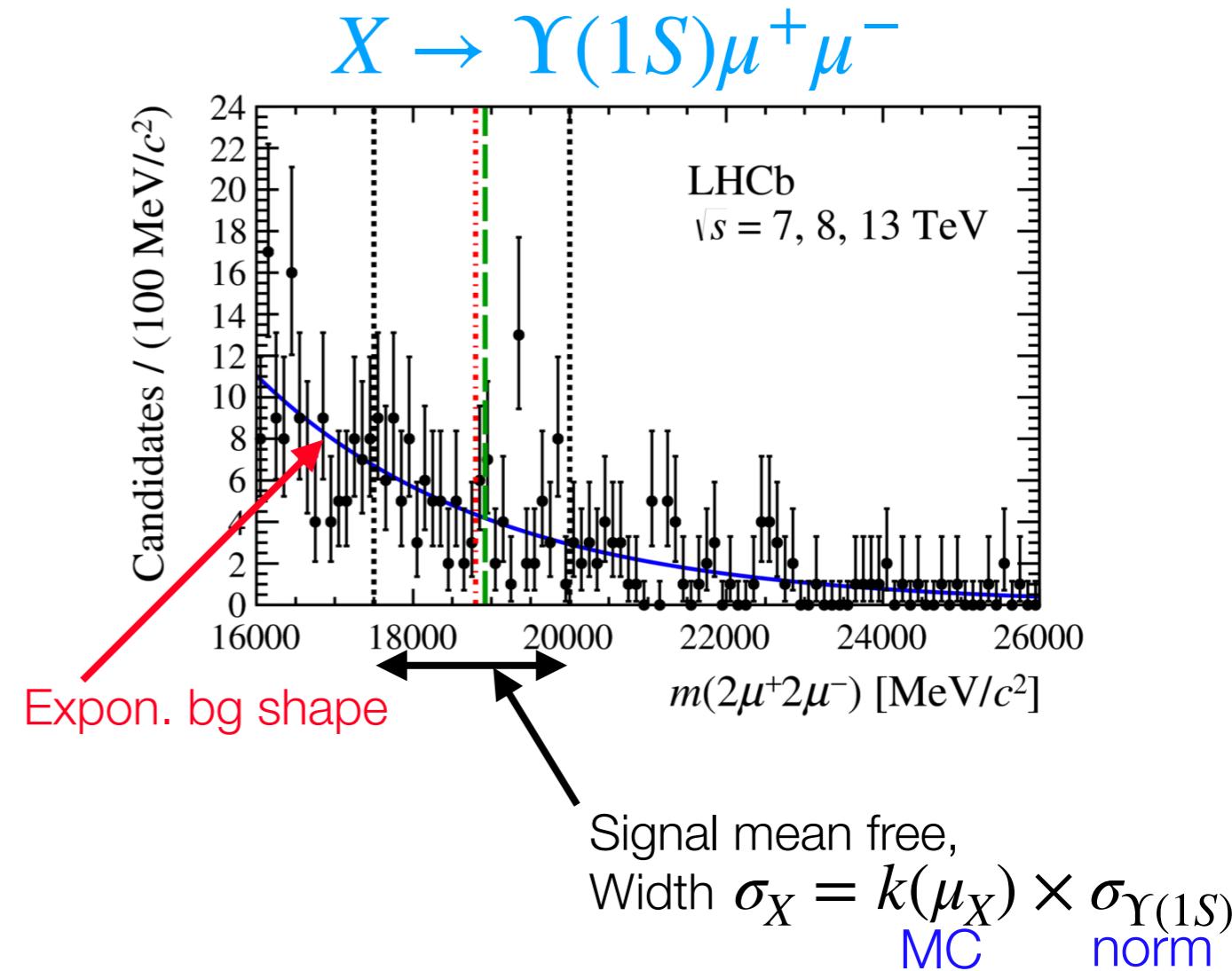
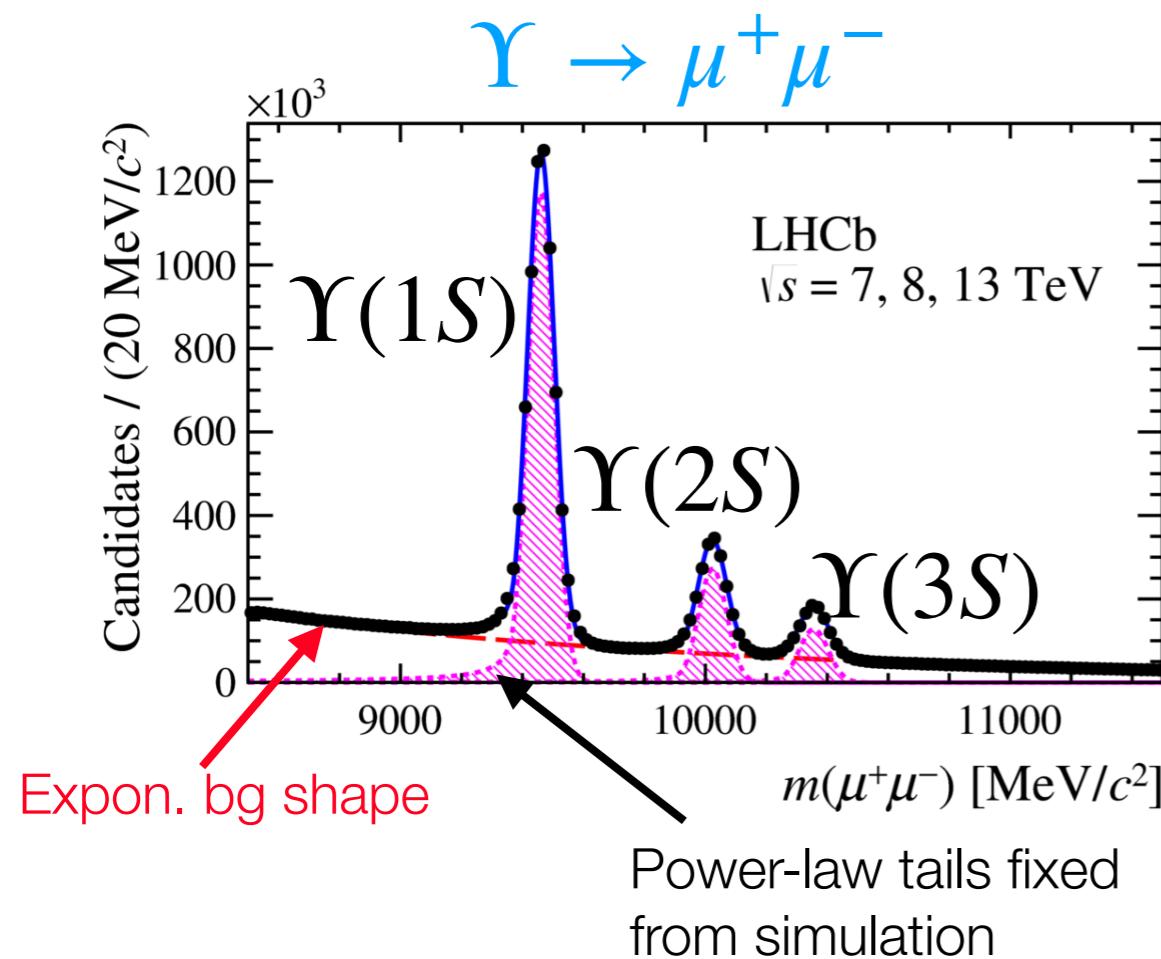
$$\theta > 0.002 \text{ rad}$$

Exclude  $J/\psi$ :

$$m(\mu_Y^+ \mu^-) \not\in [3.05, 3.15] \text{ GeV}/c^2$$

# Fitting

- Fit  $m(\mu^+\mu^-)$  and  $m(2\mu^+2\mu^-)$  in the 7, 8, and 13 TeV data



- No significant excess
- Largest deviation  $2.5\sigma$  (local), above  $\eta_b\eta_b$  and  $\Upsilon(1S)\Upsilon(1S)$

# Limits

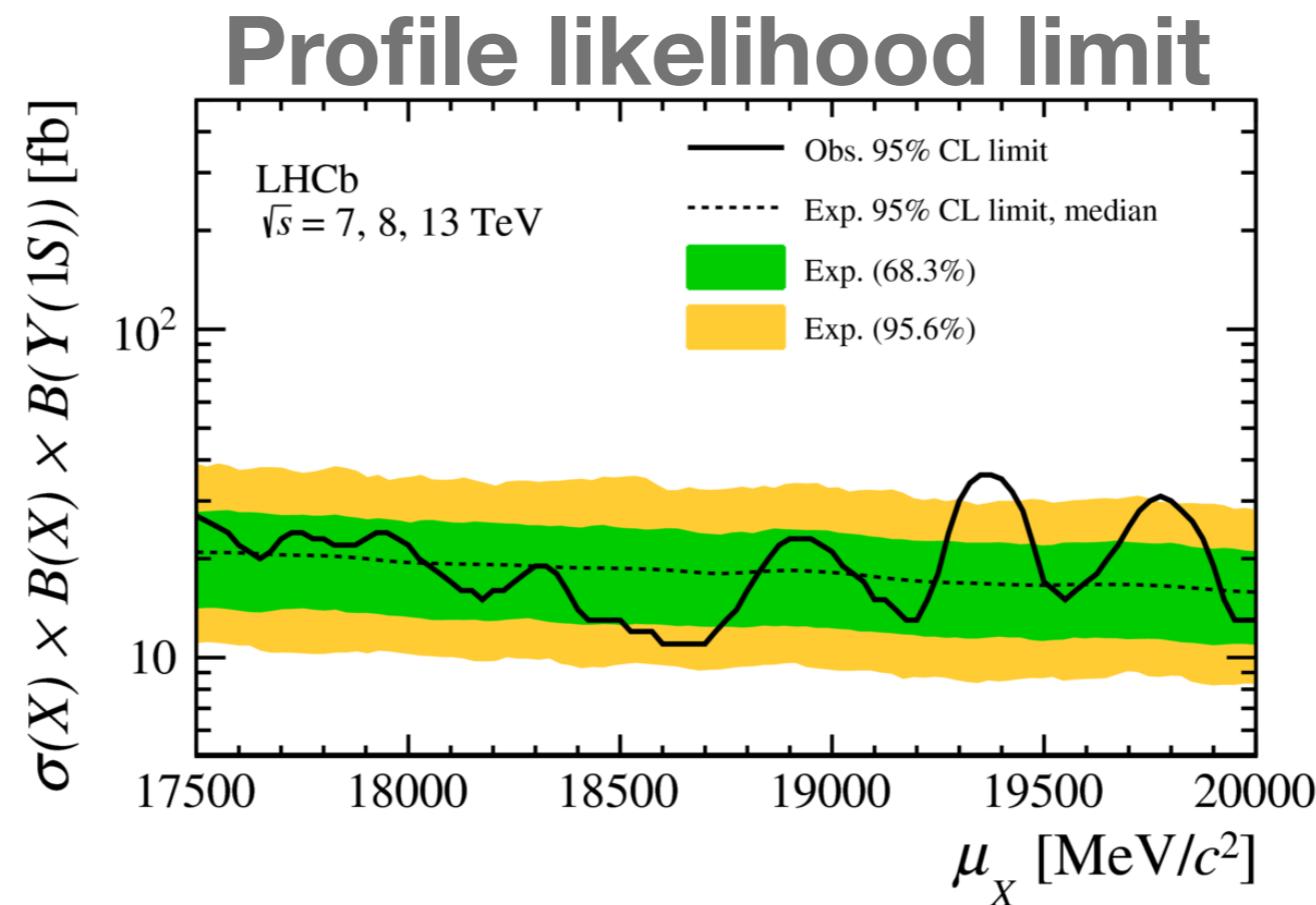
on  $S \equiv \sigma(pp \rightarrow X) \times \mathcal{B}(X \rightarrow \Upsilon(1S)\mu^+\mu^-) \times \mathcal{B}(\Upsilon(1S) \rightarrow \mu^+\mu^-)$

- Parameterise the  $X_{b\bar{b}b\bar{b}}$  signal yield using S:

$$N_{\text{sig}} = N_{\text{norm}} \times \frac{S}{\sigma(pp \rightarrow \Upsilon(1S)) \times \mathcal{B}(\Upsilon(1S) \rightarrow \mu^+\mu^-)} \times \frac{\epsilon_{\text{sig}}}{\epsilon_{\text{norm}}}$$

Acceptance & selection efficiencies from MC  
PID efficiency from calibration data

- Statistically dominated; systematic uncertainty mainly due to uncertainty on  $\sigma(pp \rightarrow \Upsilon(1S))$



# Dibaryons

Observation of the  
decay  $\Lambda_b^0 \rightarrow \Lambda_c^+ p \bar{p} \pi^-$

arXiv:1804.09617



7 TeV

8 TeV

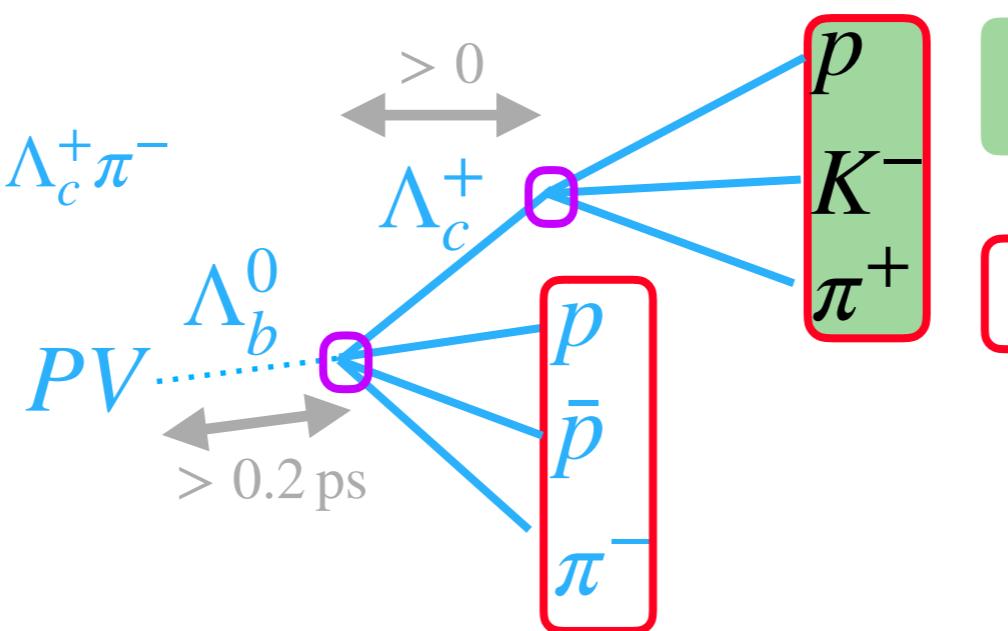
1 fb<sup>-1</sup> + 2 fb<sup>-1</sup>

- Search for charmed dibaryon resonances
  - Could manifest in  $\Lambda_b^0 \rightarrow \bar{p} + [cd][ud][ud]$   $m(\mathcal{D}_c) < 4682 \text{ MeV}/c^2$
  - $\mathcal{D}_c$  decays to  $p\Sigma_c^0$  or  $p\mathcal{P}_c(\bar{u}[cd][ud])$

## Selection

**Normalise to**  $\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-$

Vertex quality requirements



**Trigger:** independent of signal or one displaced, high  $p_T$  track then displaced secondary vertex

○ High  $IP\chi^2$   
Minimum  $p, p_T$  requirements  
Strict PID requirements



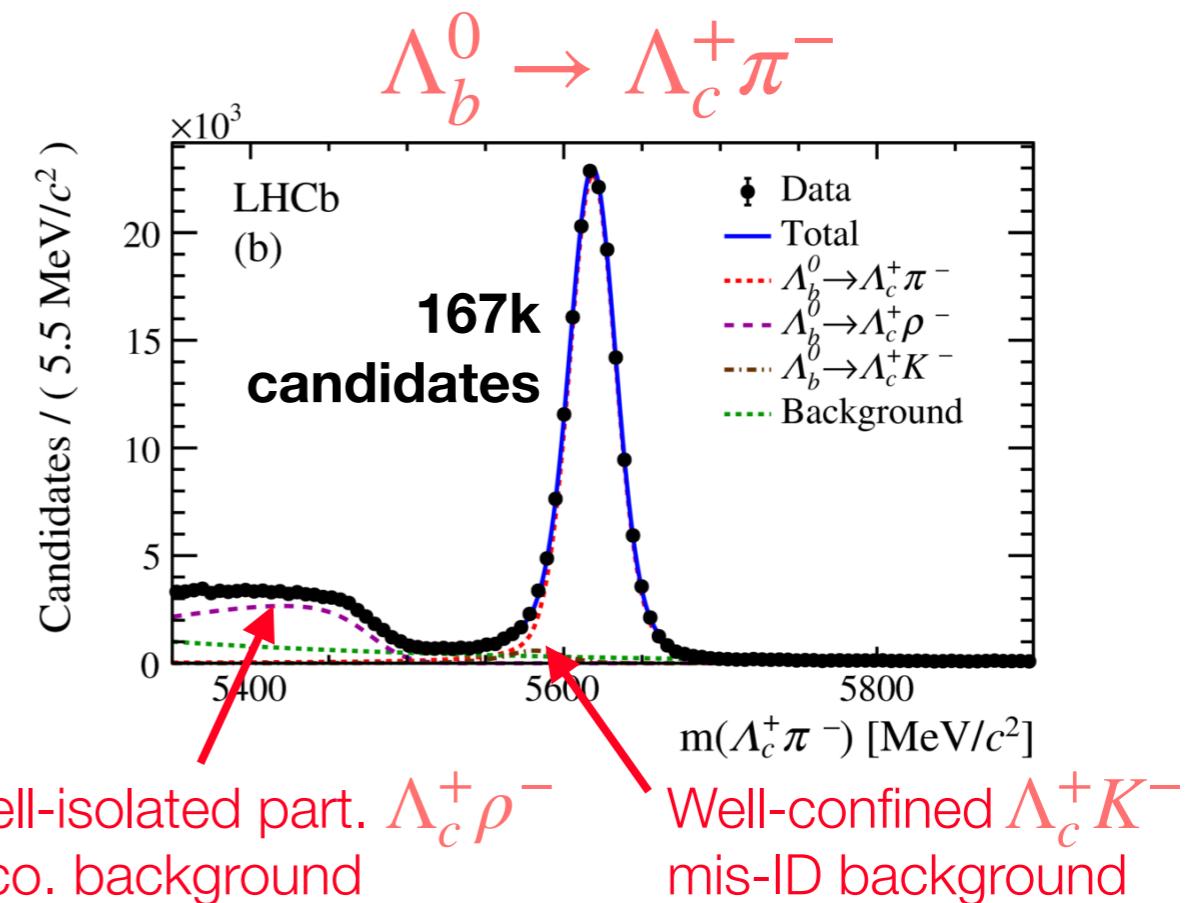
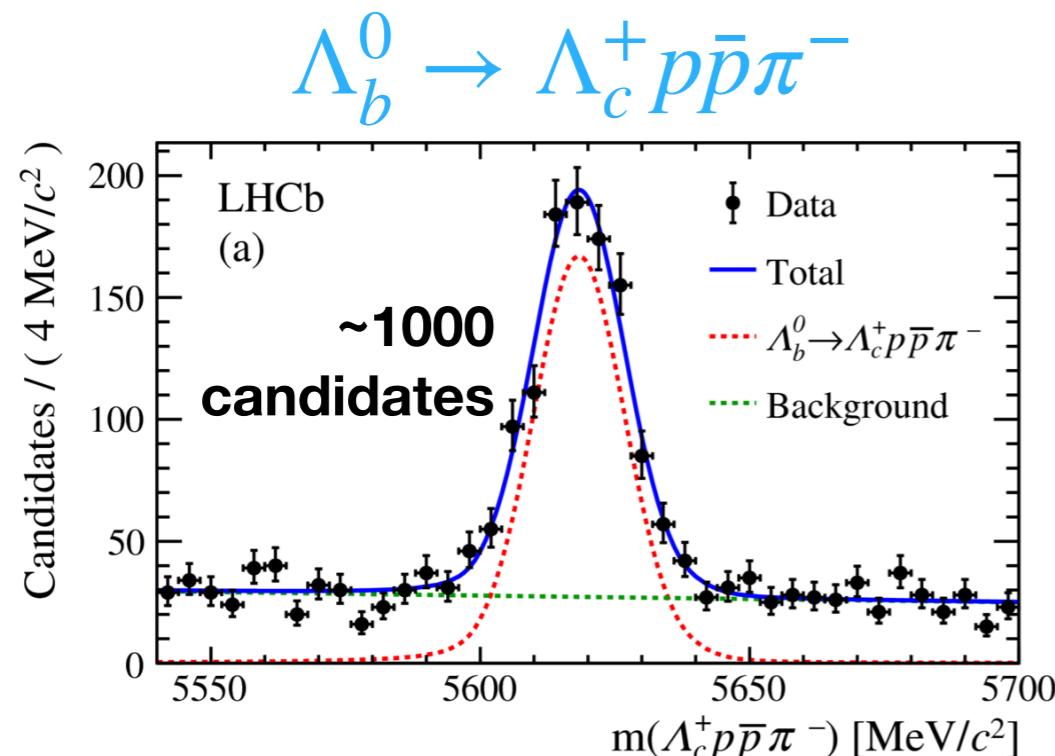
Further background reduction obtained by employing a BDT with a range of kinematic and topological inputs.



Explicitly veto  $\overline{B}_{(s)}^0 \rightarrow D_{(s)}^+ \pi^-$  and  $\overline{B}_{(s)}^0 \rightarrow D_{(s)}^+ p\bar{p}\pi^-$  cross-feeds.  
Suppress clones with requirement on opening angle between tracks with same charge.

# Fitting

- Unbinned M.L. fit to **signal** and **normalisation** channels



# Properties

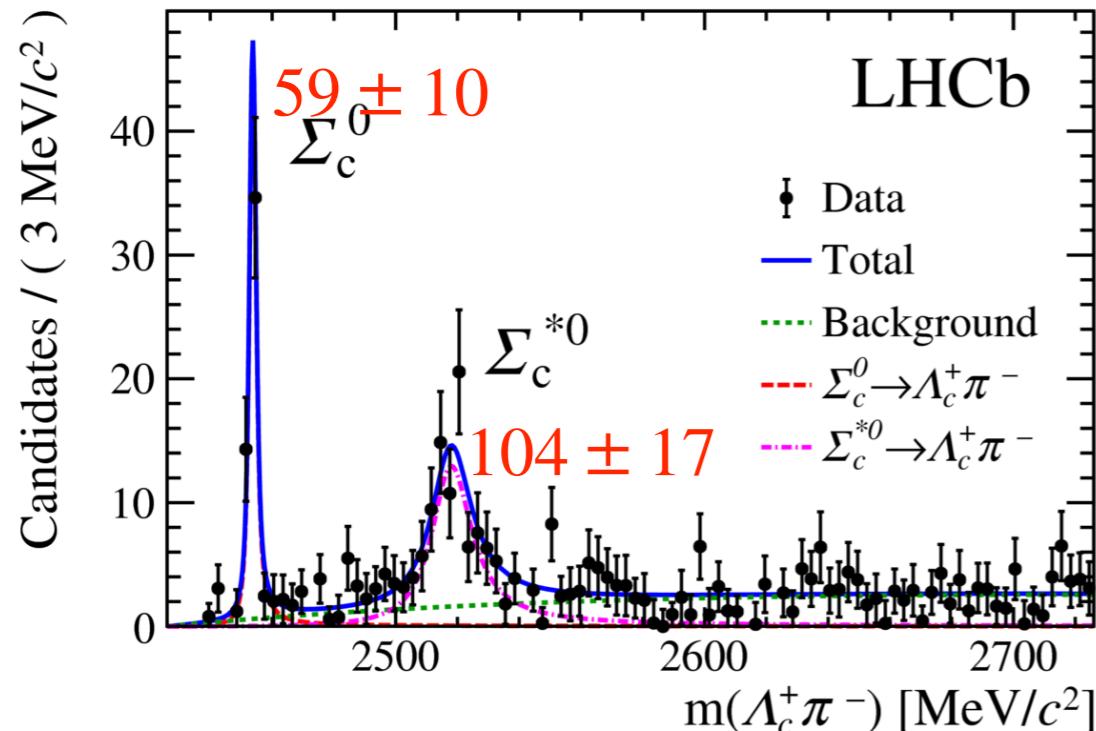
- First observation of  $\Lambda_b^0 \rightarrow \Lambda_c^+ p\bar{p}\pi^-$ :

$$\frac{\mathcal{B}(\Lambda_b^0 \rightarrow \Lambda_c^+ p\bar{p}\pi^-)}{\mathcal{B}(\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-)} = 0.0540 \pm 0.0023 \pm 0.0032.$$

- Main syst: MC model of material interactions

# Resonant structure

- Unbinned M.L. fits to  $\Lambda_c^+ \pi^-$  mass spectrum
- Relativistic B.W.s model  $\Sigma_c^{(*)0}$ , convolved with resolution fn



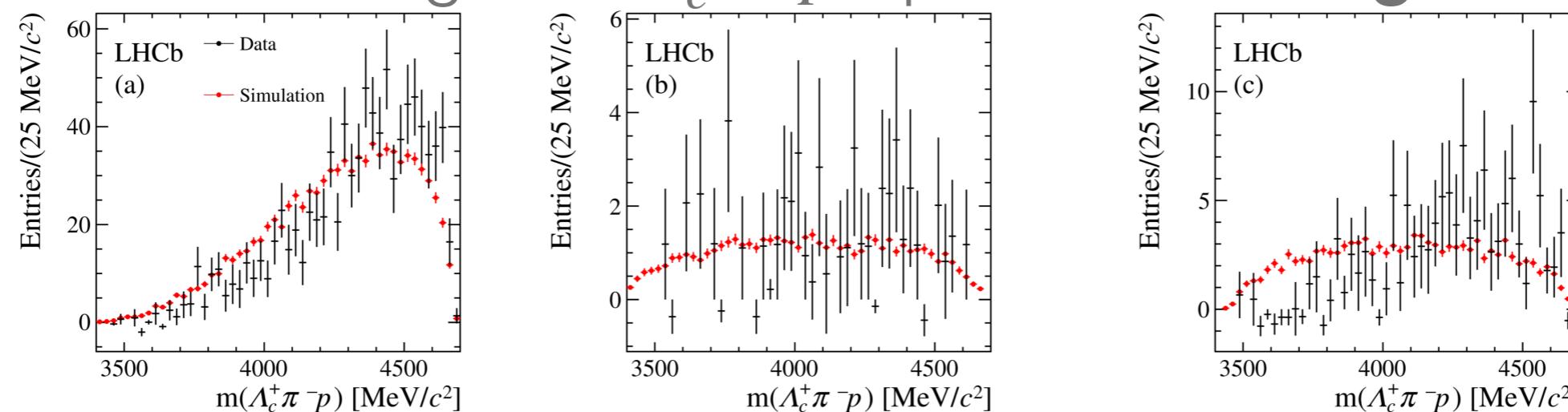
- Measure B.F. ratios
- Dominant systematics from aspects of the sig/bg shapes

$$\frac{\mathcal{B}(\Lambda_b^0 \rightarrow \Sigma_c^0 p\bar{p}) \times \mathcal{B}(\Sigma_c^0 \rightarrow \Lambda_c^+ \pi^-)}{\mathcal{B}(\Lambda_b^0 \rightarrow \Lambda_c^+ p\bar{p}\pi^-)} = 0.089 \pm 0.015 \pm 0.006,$$

$$\frac{\mathcal{B}(\Lambda_b^0 \rightarrow \Sigma_c^{*0} p\bar{p}) \times \mathcal{B}(\Sigma_c^{*0} \rightarrow \Lambda_c^+ \pi^-)}{\mathcal{B}(\Lambda_b^0 \rightarrow \Lambda_c^+ p\bar{p}\pi^-)} = 0.119 \pm 0.020 \pm 0.014.$$

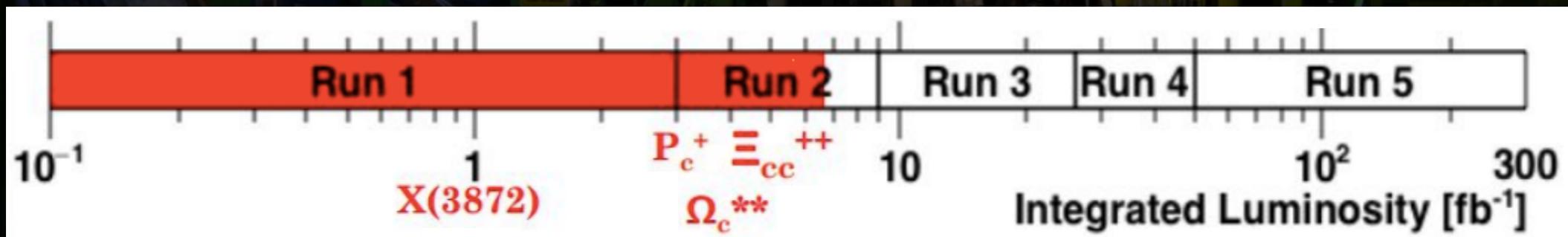
# Exotic structure?

- Consider the sWeighted  $\Lambda_c^+ \pi^- p$  spectrum: **no significant peaks**



# Conclusion & prospects

- Wide range of searches for standard and exotic states achieved with the versatile LHCb detector
- Many more to come (multi-open-charm final states in B decays, new prompt searches)
- Full exploitation of the Run 2 data well underway, as we approach LHC LS2 in a few months' time
- First-fruits of a rich harvest already at hand:



see also talks by Andrii, Daniel(1,2), Jibo(1,2), Paolo(1,2), Veronika