Observation of Pentaquarks at LHCb

APS: Division of Particles and Fields 2019

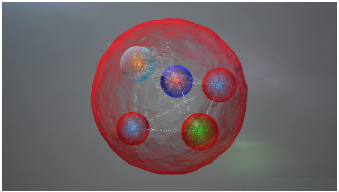
Daniel Craik
on behalf of the LHCb colaboration

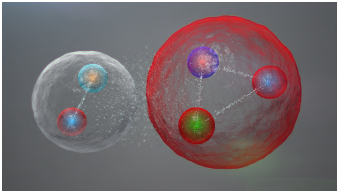
Massachusetts Institute of Technology

31st July, 2019

A brief history of Pentaquarks

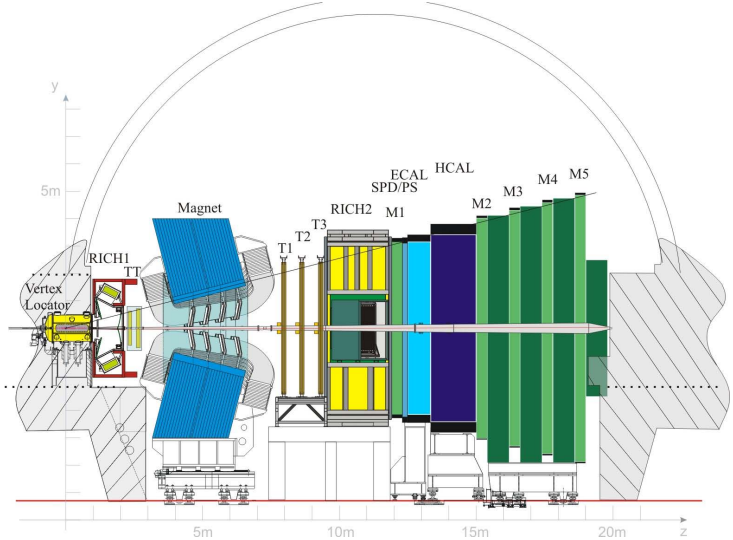
- Exotic hadrons first proposed by Gell-Mann and Zweig in 1964
- Several candidates for (strange) pentaquarks, most notably the $\Theta(1540)^+$, reported over the last $\sim$ 50 years
- None of these candidates born out by further experiments
- Advent of *b*-physics experiments gave easy access to unambiguous hidden-charm exotic states
- First observation of pentaquarks by LHCb in 2015
- Amplitude analyses of Λ_b^0 decays at LHCb now the workhorse for finding pentaquark states
- Ongoing discussion of their structure: tightly-bound pentaquark, molecular, etc





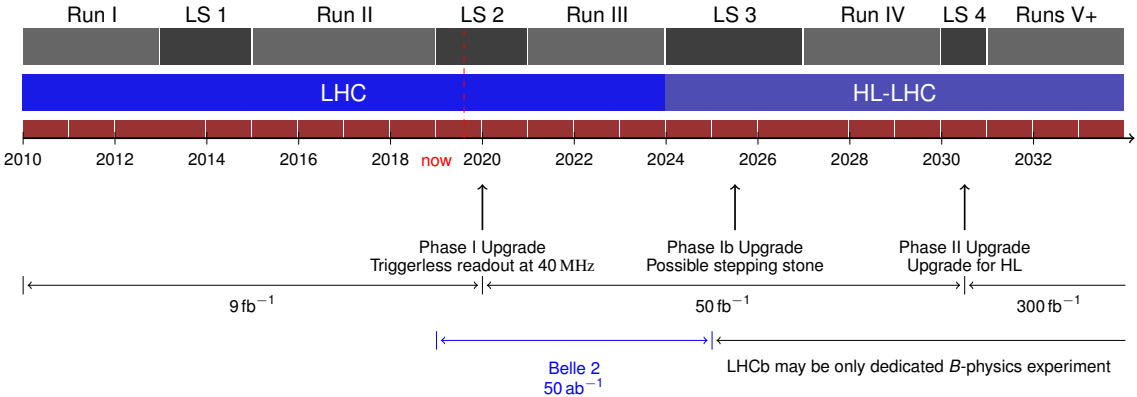
The LHCb Detector

JINST **3** (2008) S08005



- Instrumentation in the forward region ($2 < \eta < 5$)
- Excellent secondary vertex reconstruction
- Precise tracking before and after magnet
- Good PID separation up to $\sim 100\,\mathrm{GeV}/c$

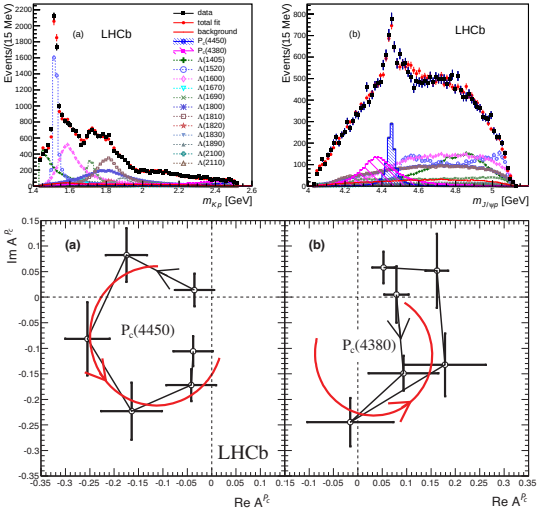
LHCb Timeline



Previously...

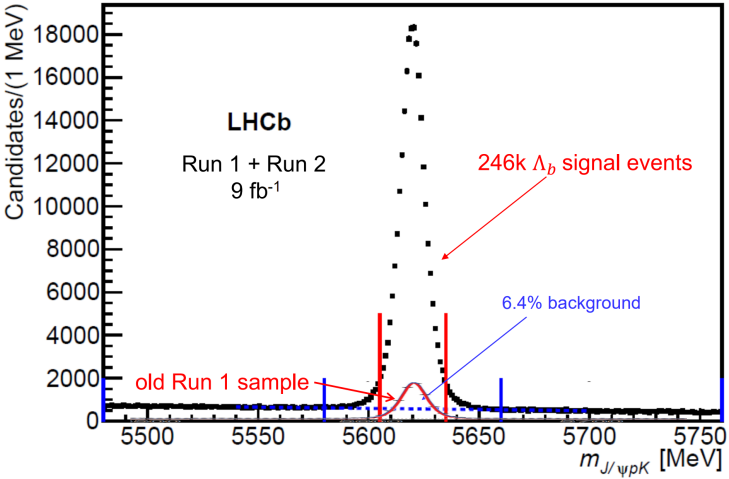
PRL **115** (2015) 072001

- 6D amplitude fit to $3\,\mathrm{fb}^{-1}$ of $\Lambda_b^0 \to J/\psi\, pK^-$ data
- Identified two P_c states
  - One narrow state, $P_c(4450)^+$
  - One broad state, $P_c(4380)^+$
- Both states required by fit with significances in excess of 9σ
- Phase motion consistent with that of a resonance



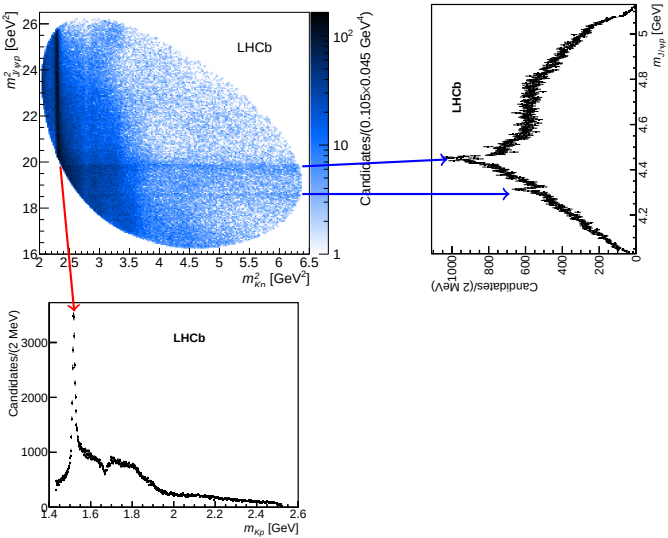
Dataset

Dataset 9× larger than used in previous analysis



- 2× from selection improvements
- 3× from integrated luminosity
- 1.5× from cross-section at $\sqrt{s} = 13\,\mathrm{TeV}$

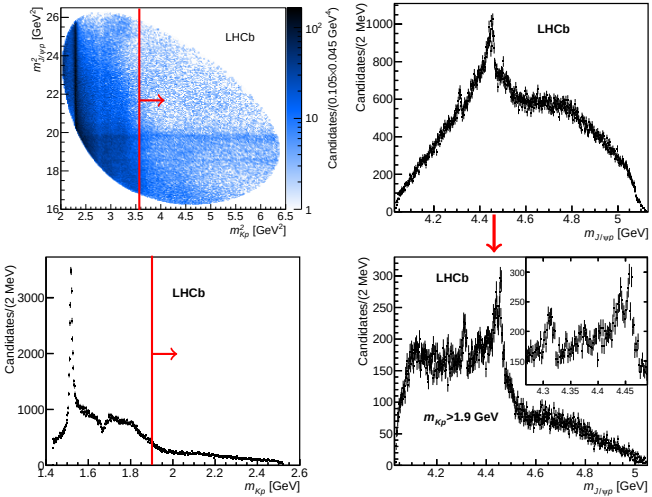
Dataset



- Dalitz plot shows a strong $\Lambda(1520)$ peak
- Also two clear P_c bands
- Low $m(Kp)$ region dominated by Λ^{**} resonances
- Leads to significant background in 1D fits
- Consider different treatments...

Removal of Λ^{**} background

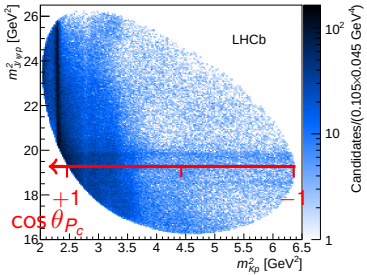
PRL **122** (2019) 222001

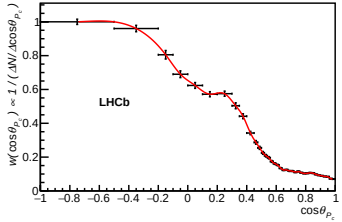


- One option to remove low $m(K^-p)$ data
- Leads to a clear reduction in background to $m(J/\psi\, p)$

Weighting in $\cos\theta_{P_c}$

PRL **122** (2019) 222001



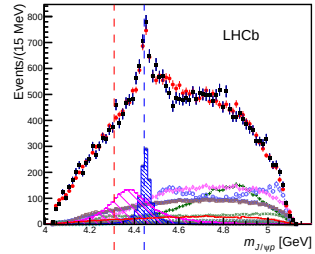


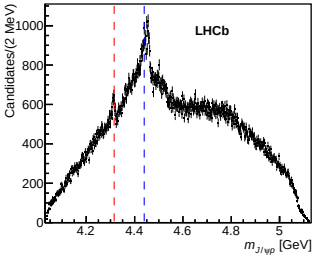
- Weighting in $\cos\theta_{P_c}$ also considered
- Candidates weighted according to the inverse of the Λ^{**} background density
- Λ^{**} density determined from data in wide mass window around the P_c peaks

Comparison to previous dataset

PRL **122** (2019) 222001

- Larger dataset allows finer binning
- Reveals structure of previously observed peak
  - Now resolved into two peaks
- Third peak emerging from previous single-bin “bump”
- Perform 1D fit to $m(J/\psi\, p)$





Fits to the data

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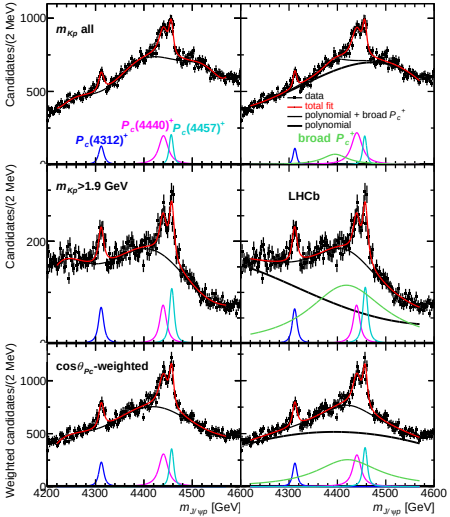

- Fits with different treatments of the Λ** background address possible systematics
- All fits require three narrow states
- Fits agnostic to the presence of broad states
- Widths consistent with resolution
- Upper limits set on natural widths

Results

PRL **122** (2019) 222001

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)	$0.53 \pm 0.16^{+0.15}_{-0.13}$

- Results for mass, width and fraction of each P_c state
- Uncertainties dominated by possible interference effects between P_c states
- J^P not determined

Interpretation: molecules

- Molecular states formed of a bound meson and baryon expected to form narrow resonances just below threshold for the bound hadrons
- Thresholds in the range of the observed P_c states:

$$
\begin{aligned}
m(\Sigma_c^+ \bar{D}^0) &= 4318\,\mathrm{MeV}/c^2, \quad J^P &= \frac{1}{2}^- \\
m(\Sigma_c^+ \bar{D}^{*0}) &= 4460\,\mathrm{MeV}/c^2, \quad J^P &= \frac{1}{2}^-, \frac{3}{2}^- \\
m(\Sigma_c^{*+} \bar{D}^0) &= 4382\,\mathrm{MeV}/c^2, \quad J^P &= \frac{3}{2}^- \\
m(\Sigma_c^{*+} \bar{D}^{*0}) &= 4524\,\mathrm{MeV}/c^2, \quad J^P &= \frac{1}{2}^-, \frac{3}{2}^-, \frac{5}{2}^-
\end{aligned}
$$

- The former two have been predicted to form narrow bound states

Interpretation: molecules

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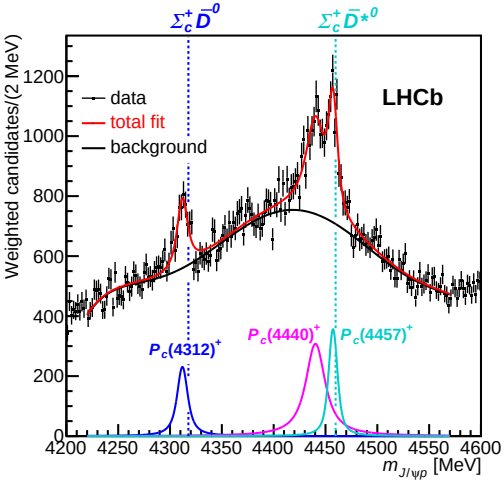
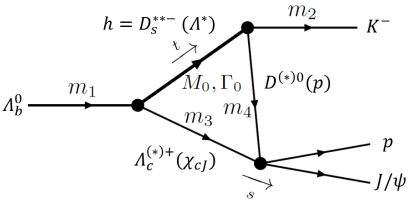


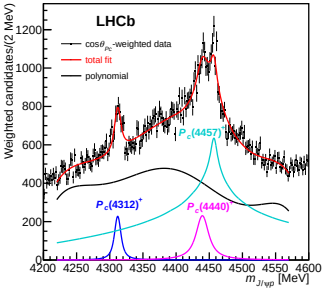
- Near-threshold masses and narrow resonances support molecular structure
- J^P assignments, isospin partners, other decays required to confirm
- Also expect relatively narrow $\Sigma_c^{*+} \bar{D}^{(*)0}$ states
- For $P_c(4312)^+$ and $P_c(4457)^+$, thresholds within widths of peaks
  - Possible virtual states, arXiv:1904.10021

Interpretation: hadronic rescattering

PRL **122** (2019) 222001

- Resonances could also be caused by rescattering of hadrons via a triangle diagram
- Can lead to a peaking structure when the rescattered particles are near to on-shell masses
- Would correspond to a depletion in the non-rescattered final state due to unitarity
- $P_c(4312)^+$ and $P_c(4440)^+$ cannot be described by rescattering
- $P_c(4457)^+$ may be described by $\Lambda_c^+(2595)^+ \bar{D}^0 D_{s1}^*(2860)^-$ triangle diagram
  - However, using three Breit–Wigner functions provides a fit of higher quality
  - Further studies required





Implications for 2015 results

- Previously observed $P_c(4450)^+$ superseded by $P_c(4440)^+$ and $P_c(4457)^+$
- Broad $P_c(4380)^+$ state neither excluded nor confirmed by current analysis
  - However, previous study assumed single narrow state
  - Updated 6D analysis required to identify broad states

Summary and future prospects

- Previously observed resonance resolved into two separate states
- New narrow state observed, $P_c(4312)^+$
- Masses near to thresholds hint at molecular structures
- Updated 6D amplitude analysis required to identify broad states or assign J^P
- Broad states may be tightly bound pentaquarks
- Analyses of decays containing other charmonium states may also shed further light