Istituto Nazionale di Fisica Nucleare
SEZIONE DI FIRENZE

Tetra- and Pentaquark studies at LHCb

Lucio Anderlini
on behalf of the LHCb Collaboration

Istituto Nazionale di Fisica Nucleare, Sezione di Firenze

Thursday May, 16th – Quarkonium Working Group
Torino, Italy

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Tetraquark studies at LHCb are covered in detail by:

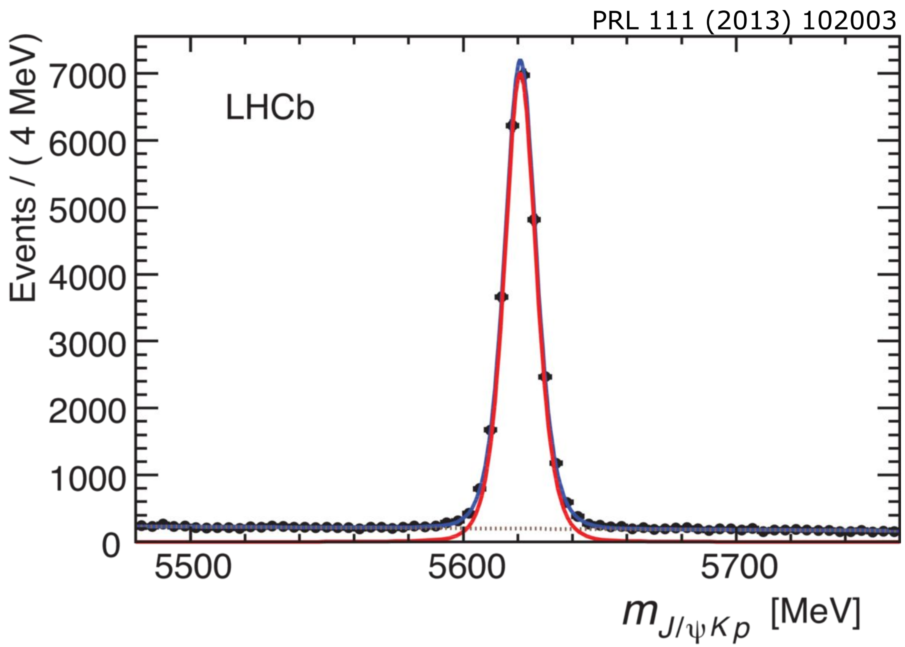
Roberta Cardinale, "Observation of a new charmonium and evidence of a new charged charmonium-like state at LHCb", on May, 15th

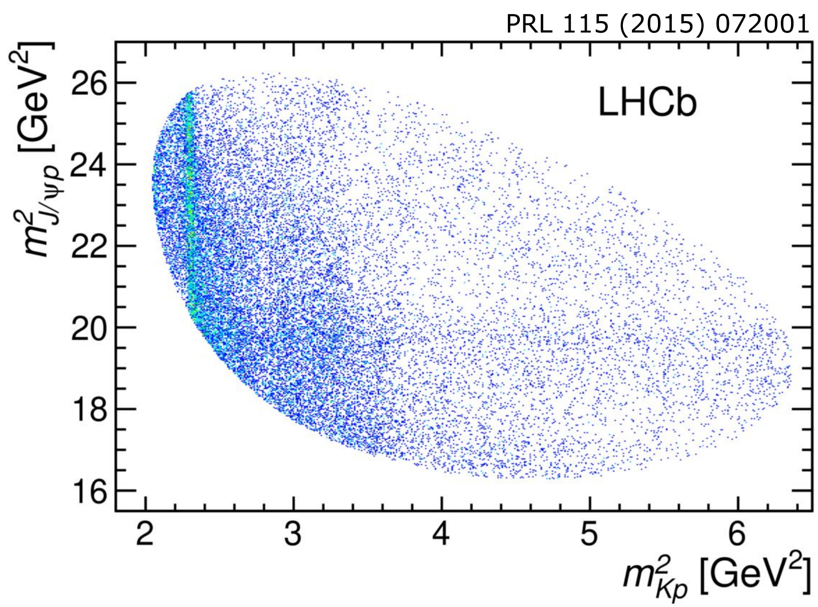
Marco Pappagallo, "Perspectives for hadron spectroscopy at LHCb" on May, 17th

First P_c observation in $\Lambda_b^0 \to J/\psi\, p\, K^-$ decays (2015)

The decay $\Lambda_b^0 \to J/\psi p K^-$ was first observed at LHCb and used for lifetime measurements in 2013 [PRL 111 102003].

Combining the data sets collected in 2011 and 2012, corresponding to 3 fb^{-1},
26 000 decay candidates were selected.
[PRL 115 (2015) 072001]





The Dalitz plot shows a clear horizontal band that points towards *some activity* in the J/ψ *p* dynamics.

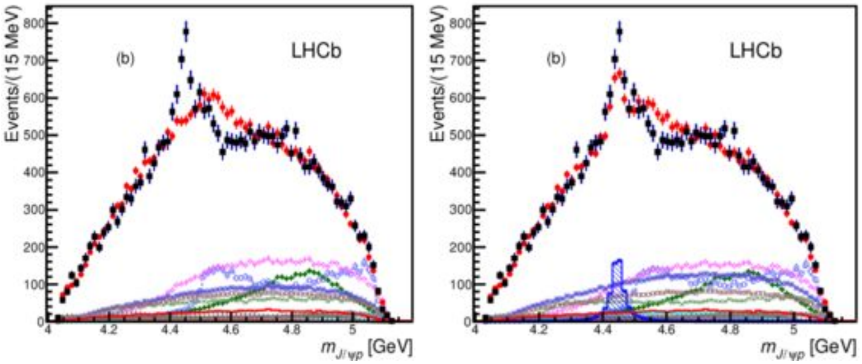
Amplitude analysis: *model dependent observation*

Full amplitude analysis, demonstrated the need of two *interfering resonance-like* structures to accommodate that J/ψ *p band.*

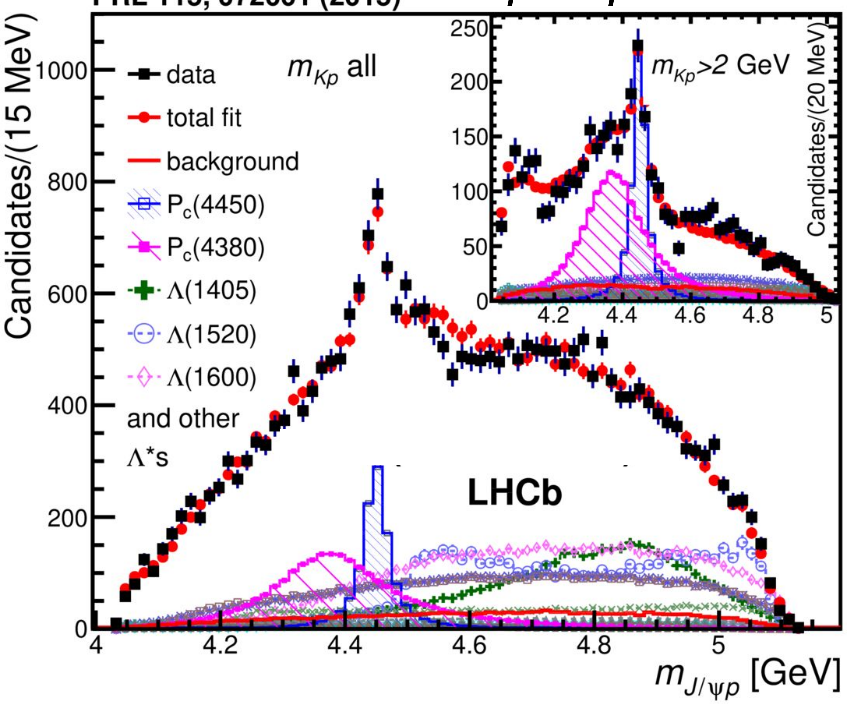
The six-dimensional fit (including masses and angles) brought to the following statements:

PRL 115 (2015) 072001

No pentaquark ***Only 1 pentaquark***



PRL 115, 072001 (2015) ***Two pentaquark resonances***



1. *All models including any combination of known and predicted Λ^* resonances is excluded with a statistical significance of more than 9 σ*

2. *Any model with a single J/ψ p resonance (a pentaquark) is not sufficient to provide a satisfactory interpretation of the data.*

3. *A second pentaquark resonance is needed to describe the data, at the point that any single-pentaquark model is excluded with a statistical significance of more than 9 σ.*

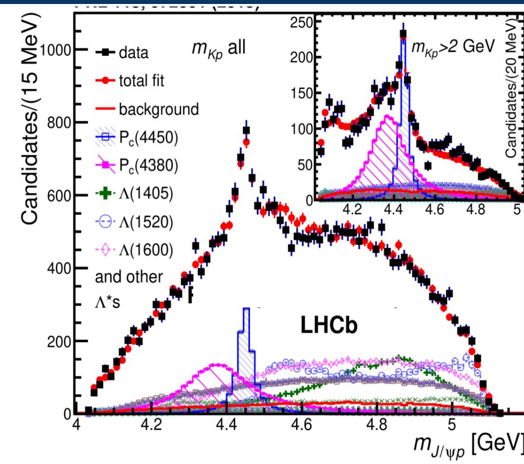
Amplitude analysis: *conclusions*

When describing the data with a model including two pentaquark resonances, these must have the following properties:

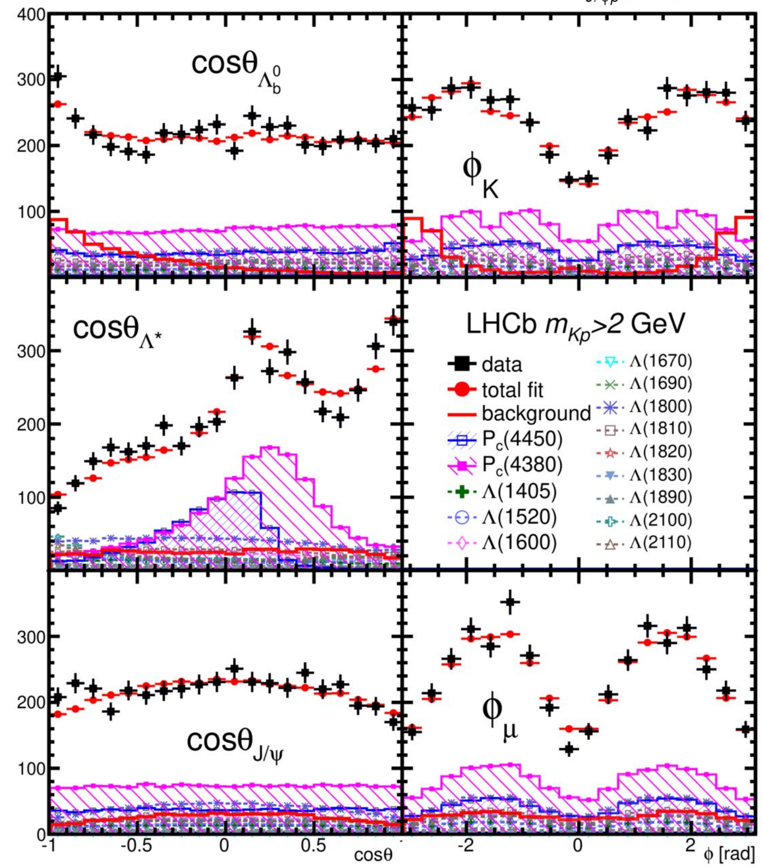
- A narrow resonance, with
  - Mass: 4380 ± 8 ± 29 MeV
  - Width: 205 ± 18 ± 86 MeV

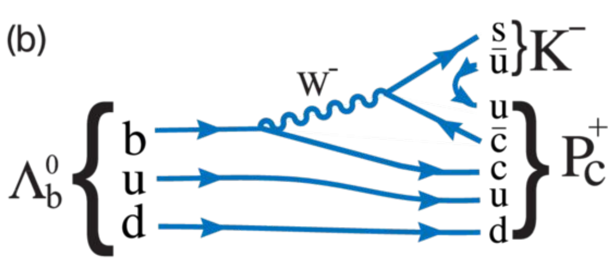
- A broader resonance, with
  - Mass: 4449.8 ± 1.7 ± 2.5 MeV
  - Width: 39 ± 5 ± 19 MeV

With opposite parity, and spin $\frac{3}{2}$ and $\frac{5}{2}$



PRL 115 (2015) 072001



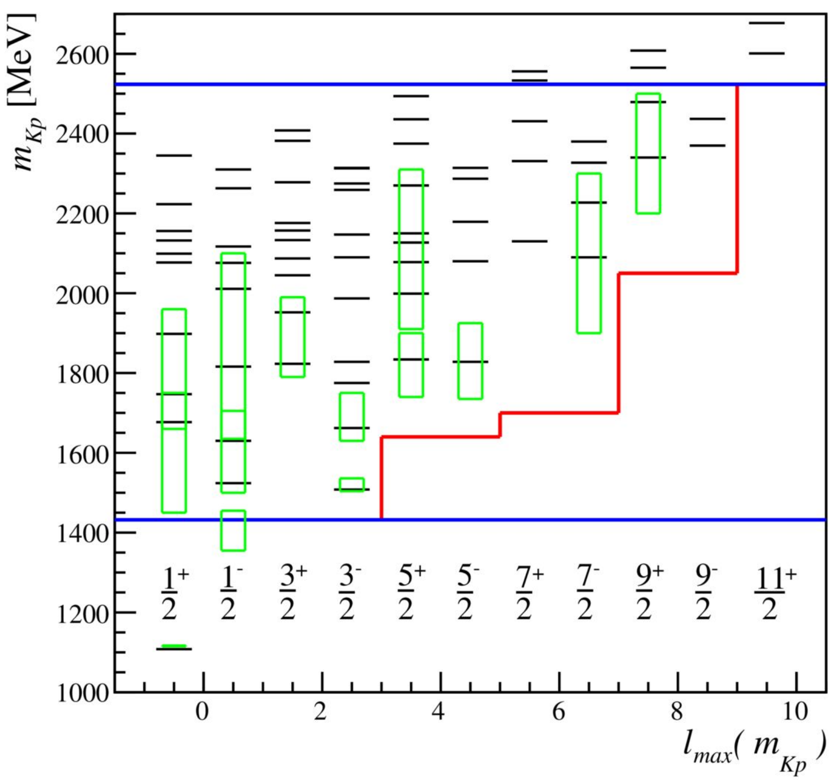


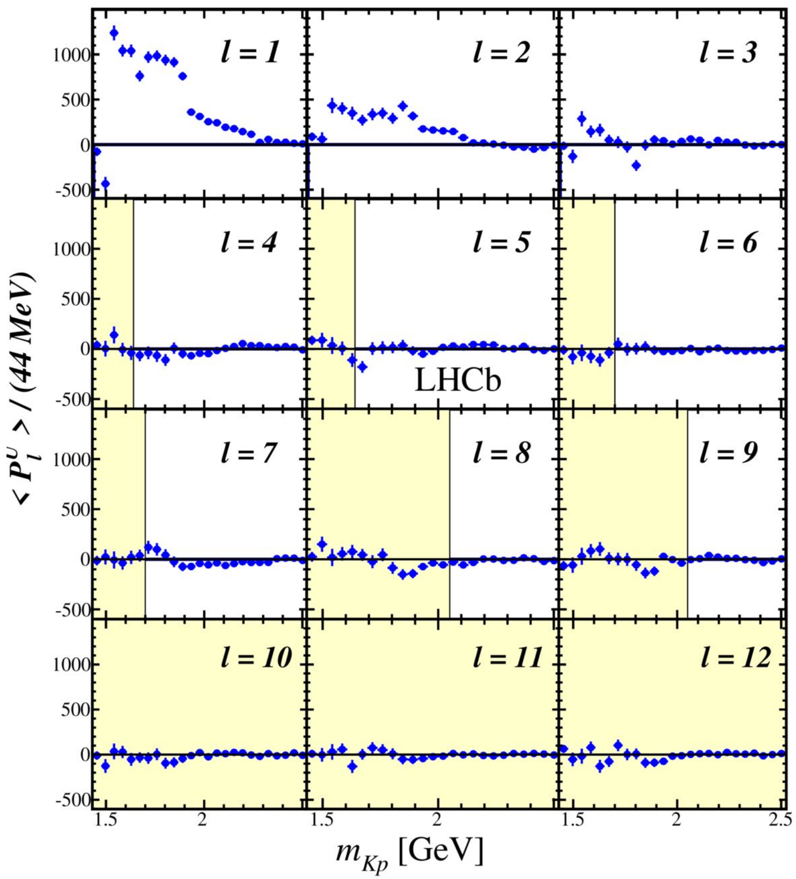
Model independent confirmation of $J/\psi\, p$ resonances

To strengthen the evidence of pentaquarks, LHCb has developed an analysis independent of any assumption on the *pK* dynamics, encoded above as **known** or **predicted** Λ^* resonances.

In fine bins of m_{Kp} the decay is decomposed in partial wave, with or without unphysical orbital momentum.

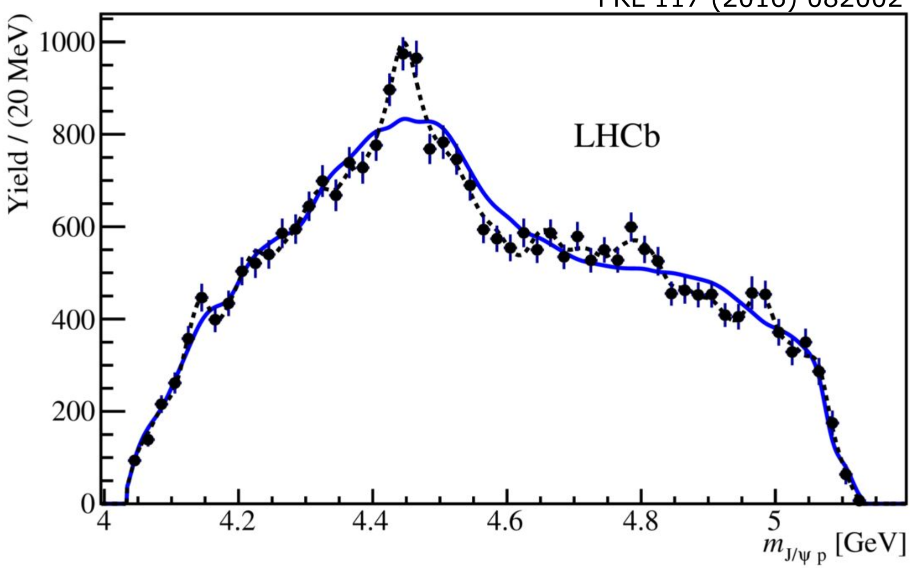
PRL 117 (2016) 082002

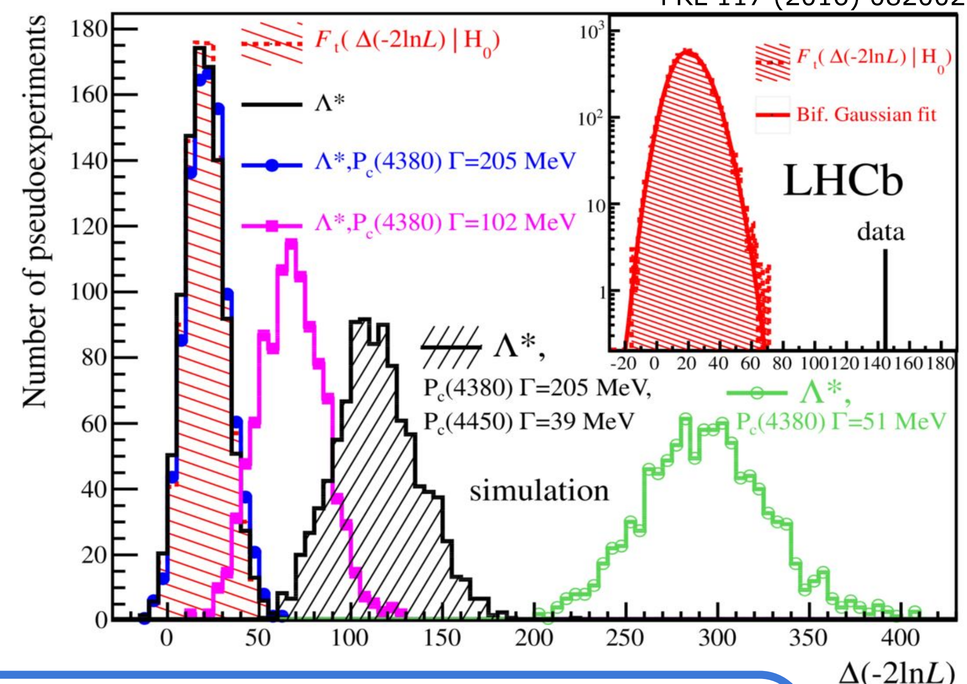




Model independent confirmation of $J/\psi\ p$ resonances

Comparing the model for the $m_{J/\psi p}$ obtained with and without unphysical orbital momentum we assessed the statistical significance of J/ψ p dynamics in a model-independent way.





The statistical significance is assessed with pseudo-experiments (MC toys), generated according to the *null hypothesis*, rejected with more than 9 σ.

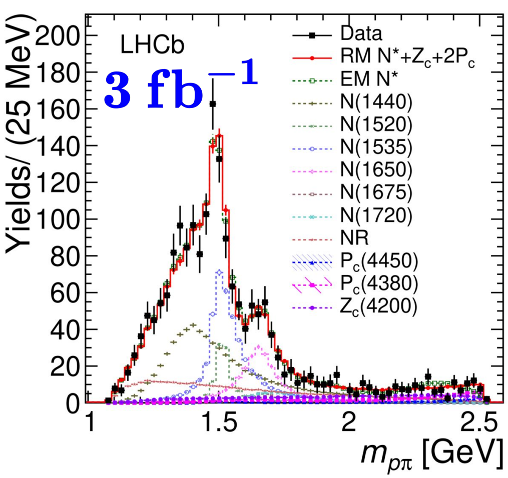
Distributions for some *model-dependent hypotheses* are also shown.

Pentaquarks beyond $\Lambda_b^0 \to J/\psi\, pK^-$

In the meanwhile, during the long shutdown (2013, 2014), LHCb started to explore *b*-baryon decays with lower statistics to confirm the existence of pentaquarks.

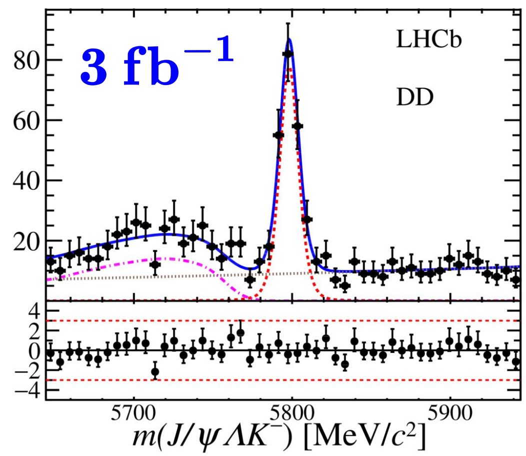
PRL 117 (2016) 082003

$\Lambda_b^0 \to J/\psi\, p\, \pi^-$



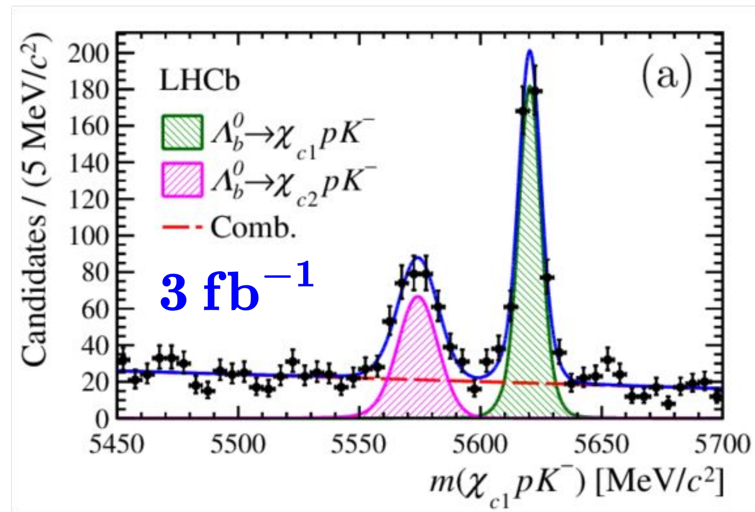
PLB 772 (2017) 265

$\Xi_b^0 \to J/\psi\, \Lambda K^-$



PRL 119 (2017) 062001

$\Lambda_b^0 \to \chi_{c1,c2}\, p\, K^-$



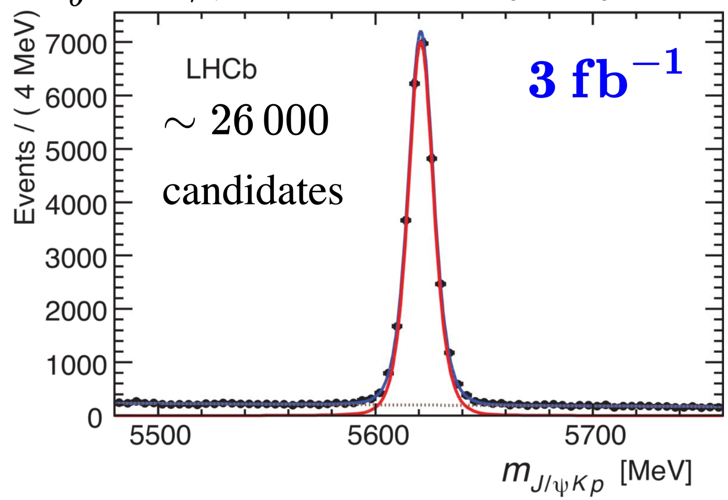
While no unambiguous observation has been achieved because of limited statistics, these new decays pave the way for the upcoming high-luminosity runs of the LHC.

A great effort to perfect the selection strategy of final states involving protons.

Improvement in the selection

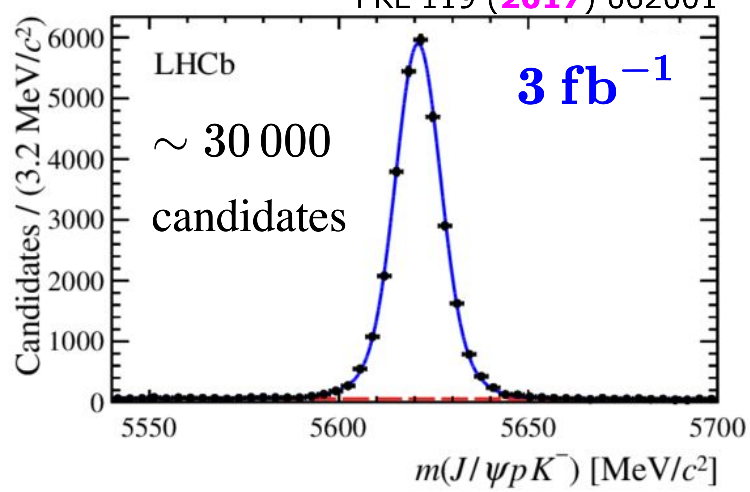
Motivated by the need of statistics to achieve observation of $\Lambda_b^0 \to \chi_{c1,c2}\, p\, K^-$, we selected $\sim 30\,000$ $\Lambda_b^0 \to J/\psi p K^-$ decay candidates in the datasets collected in 2011 and 2012.

$\Lambda_b^0 \to J/\psi\, p\, K^-$ PRL 111 (**2013**) 102003



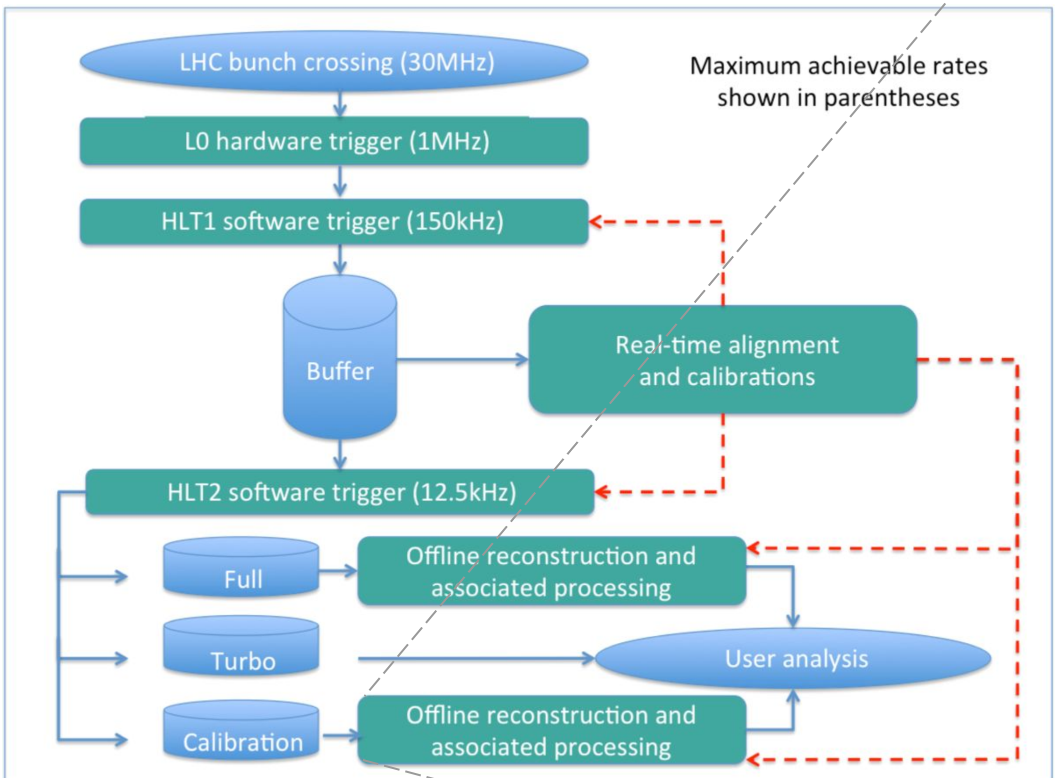
Significant improvement in the Signal−Background separation including the **particle identification** in the multivariate selection algorithm (**Gradient BDT**), but larger uncertainty on the selection efficiency come from small *imperfections in the Simulation*, mitigated through **resampling** from the distributions of detector response in calibration samples (*real data*).

$\Lambda_b^0 \to J/\psi\, p\, K^-$ PRL 119 (**2017**) 062001



Upgrade of the data processing: *improving Particle ID*

Novel dedicated data processing to select and analyze the calibration samples already at trigger level.



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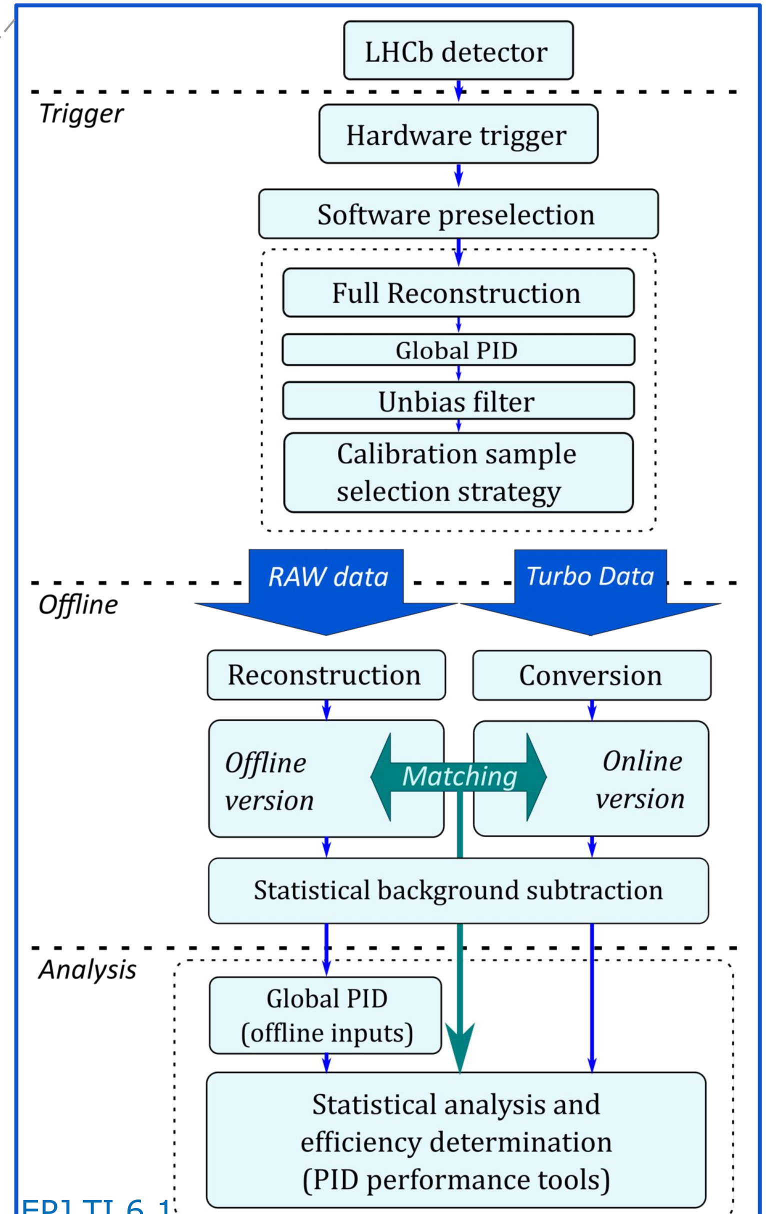

EPJ TI 6 1

Upgrade of the data processing: *improving Particle ID*

Novel
the

Allows selection of pure and abundant calibration samples to measure and **model the PID detector response**.

Selecting the samples at trigger level allows to shape the kinematic coverage on the needs of heavy hadron physics downscaling selectively.

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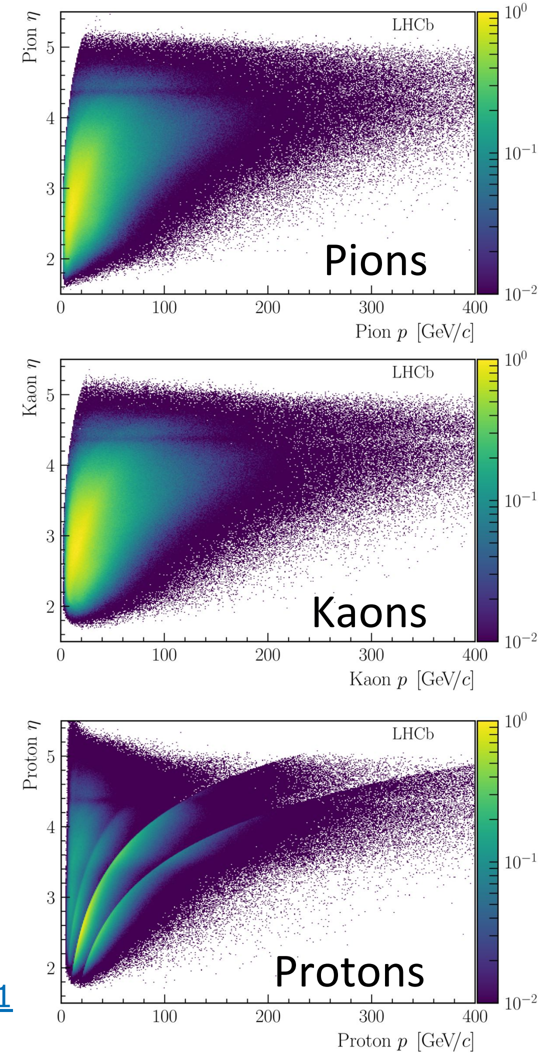

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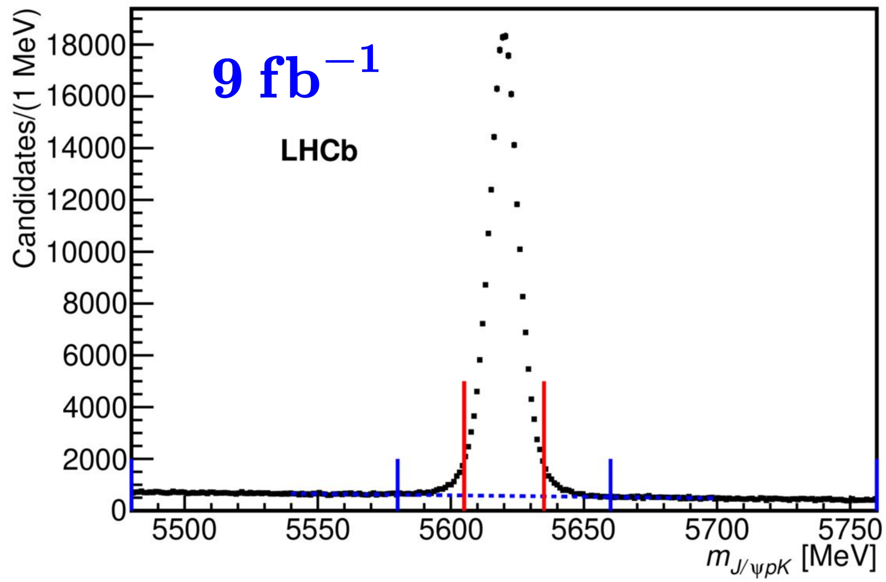
EPJ TI 6 1

New sample of $\Lambda_b^0 \to J/\psi\, pK^-$ decays: *×10 larger*

Combining:

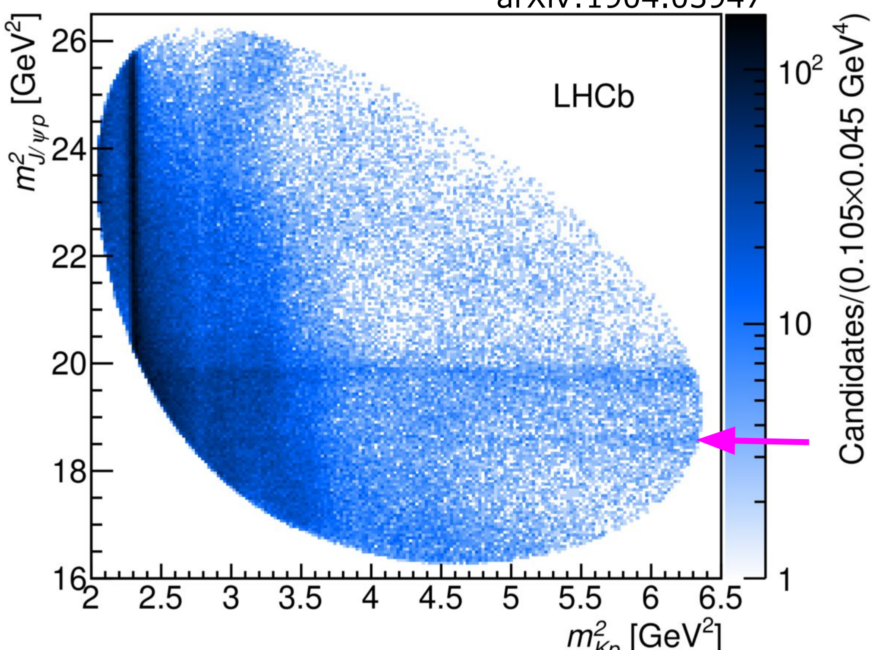
- data collected from 2011 to 2018
- improvements trigger strategy
- improvements in the multivariate selection strategy
- improvement of the calibration samples

arXiv:1904.03947



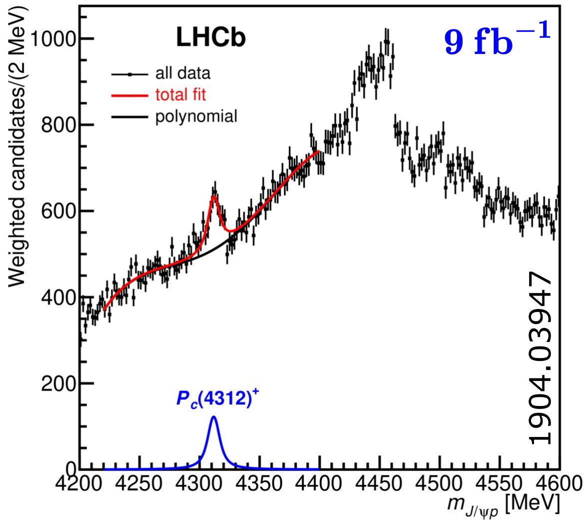
Selected $\sim 246\,000\ \Lambda_b^0 \to J/\psi pK^-$ decay candidates.

arXiv:1904.03947



In the Dalitz plot it is now evident a second horizontal stripe.

A new narrow peak at 4312 MeV/c^2

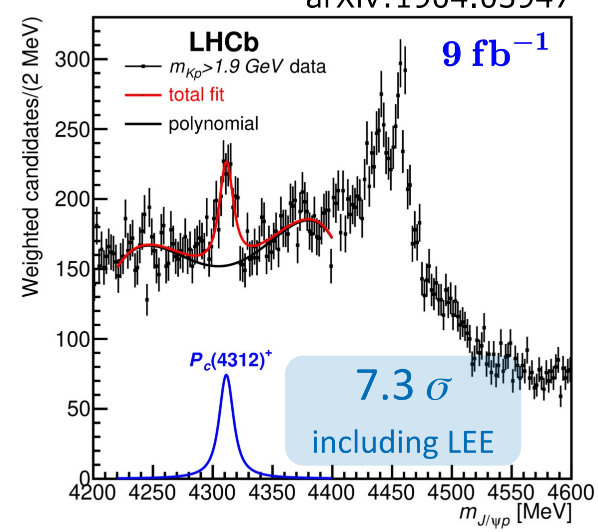


The stripe in the Dalitz plot is a peak in the $m_{J/\psi\, p}$ distribution.

It is more visible when removing the decay candidates with $m_{pK} < 1.9$ GeV/c^2 where the contribution from Λ^* dominates.

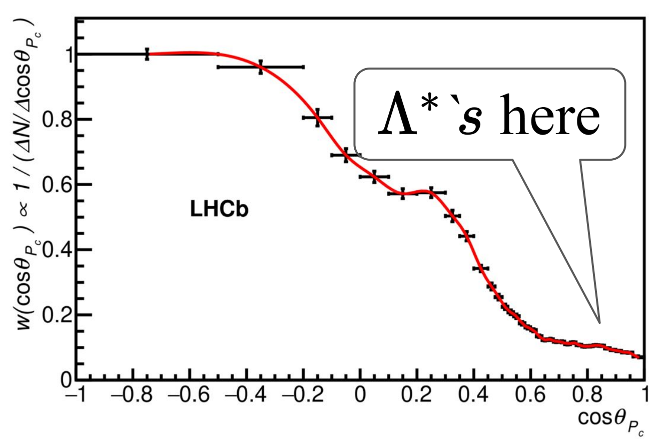
$m_{pK} > 1.9\mathrm{GeV}/c^2$

arXiv:1904.03947



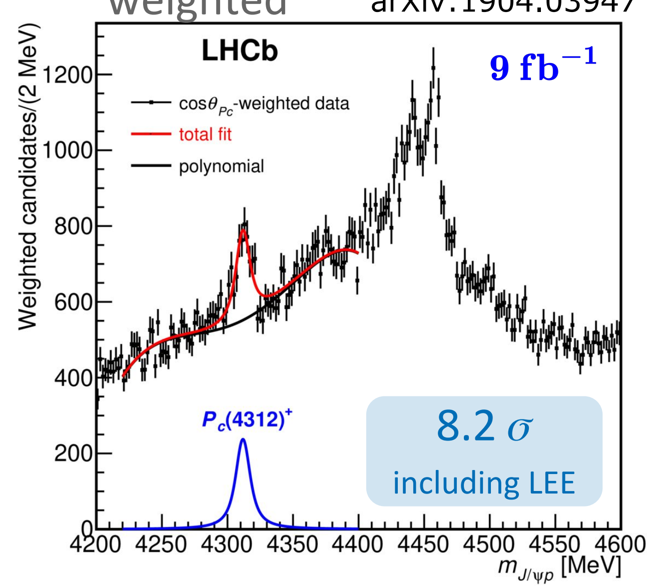
Statistical significance from the variation of the χ^2 fit to the $m_{J/\psi p}$ distribution.
Look-elsewhere-effect assessed with mass scan.

Best statistical significance achieved weighing events to suppress the Λ^* dominated region.



weighted

arXiv:1904.03947



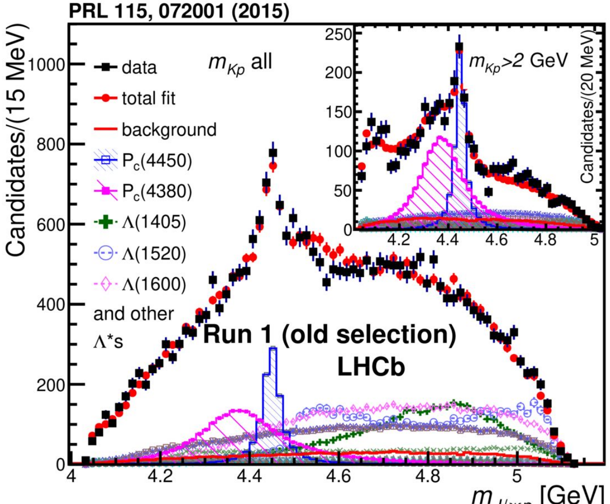
Another two peaks

Significance of the two-peak interpretation: 5.4 σ

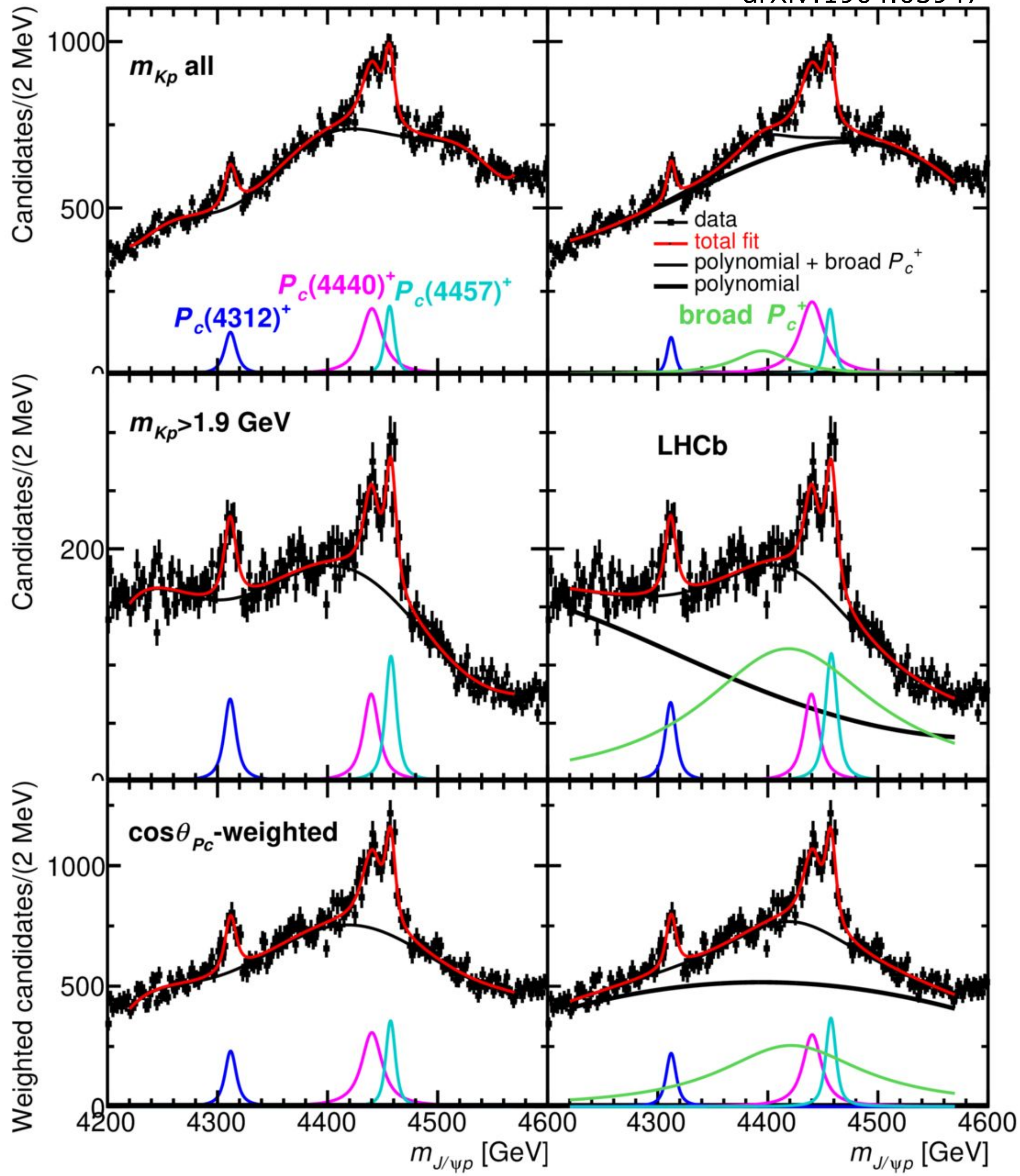
Fitting well with or without a broad resonance:
not conclusive on $P_c(4380)$

Ongoing full amplitude analysis to measure properties and quantum numbers.

PRL 115, 072001 (2015)



arXiv:1904.03947

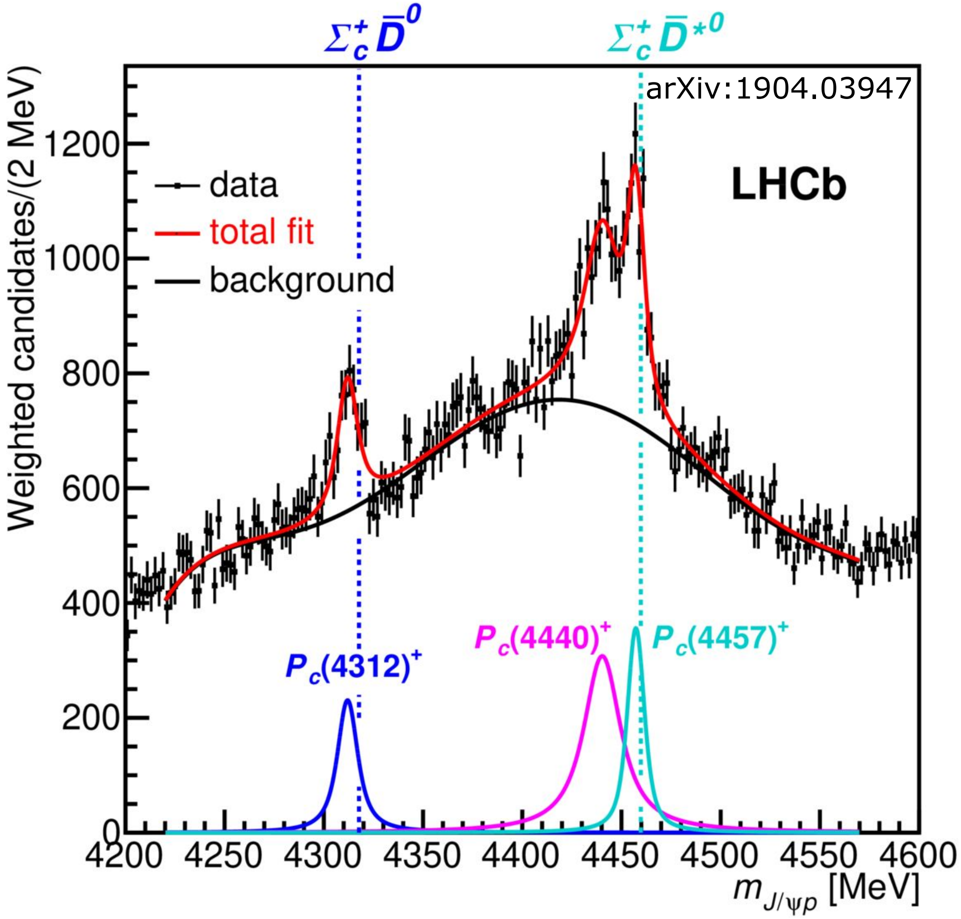


Properties of the peaks

Best model: three relativistic Breit-Wigner convolved with the resolution function.

All the three peaks are too narrow to resolve their natural width.

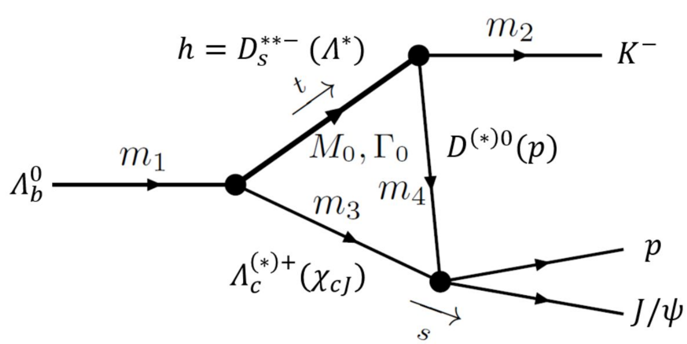
Despite the *large statistics*, the properties of the fits are affected by large uncertainties, dominated by the ***unknown interference pattern***, and model of the "non-resonant-or-large-resonance" component.



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

Suggestive proximity to thresholds of the $\Sigma_c D$ system

Non-resonant interpretation: *worse but not excluded.*

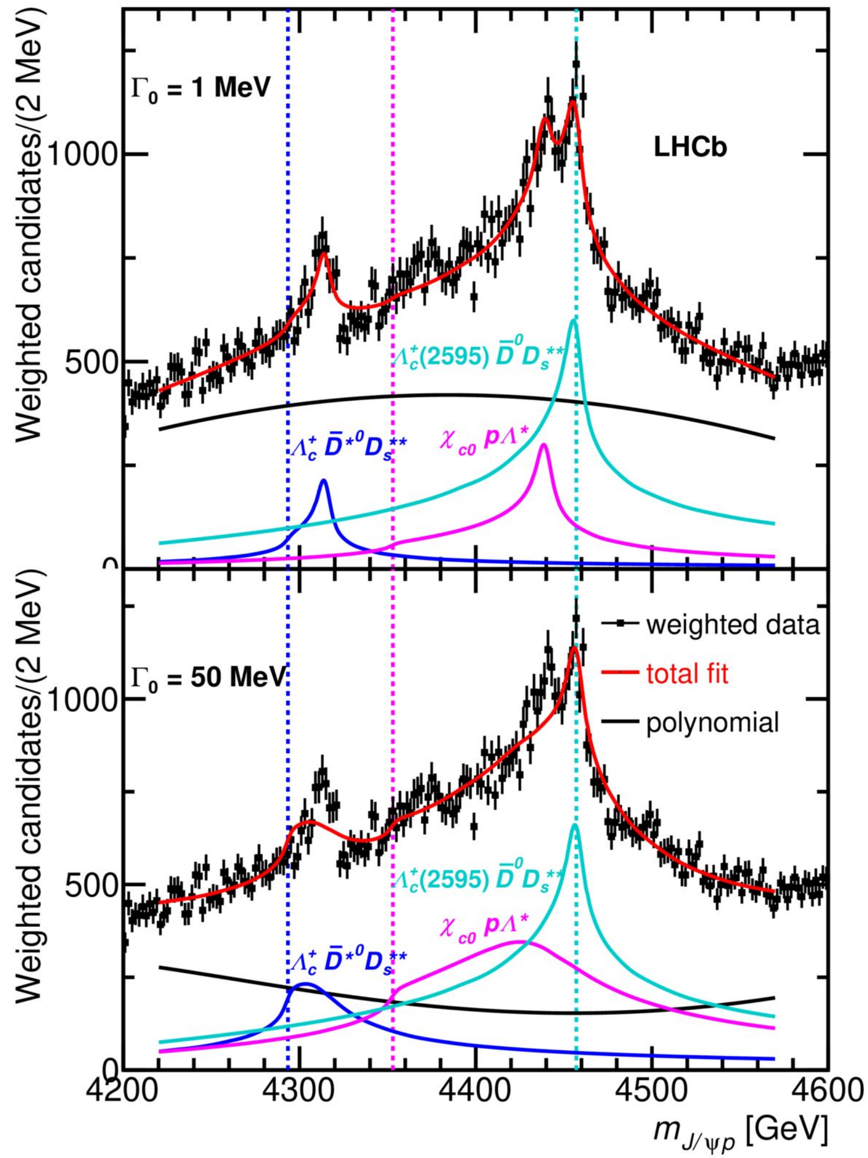


Cusp effects and rescattering of the final state can give raise to structures in the mass distribution that cannot be excluded without a full amplitude analysis.

Though, an unrealistically narrow intermediate resonance is necessary to fit Pc (4312) and Pc (4440).

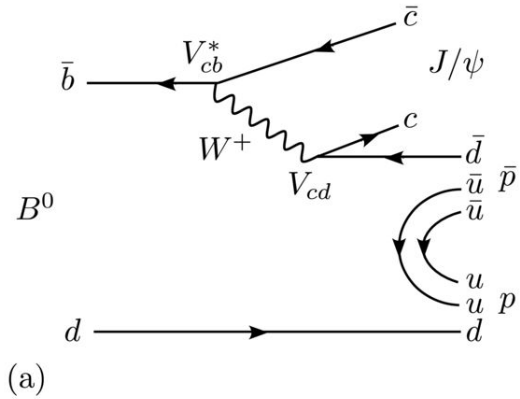
Pc (4457) can be fitted with a realistic cusp, but the goodness-of-fit favors its interpretation as a resonance.

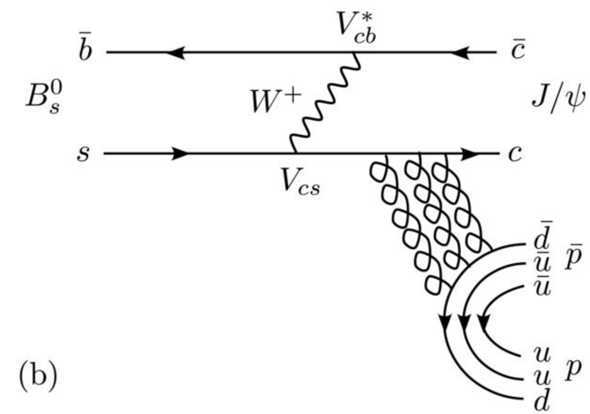
arXiv:1904.03947



Pentaquarks from beauty mesons

Analysing the data collected from 2011 to 2016, observed two new decays with a final state potentially affected by pentaquark resonances.





The branching fraction was measured

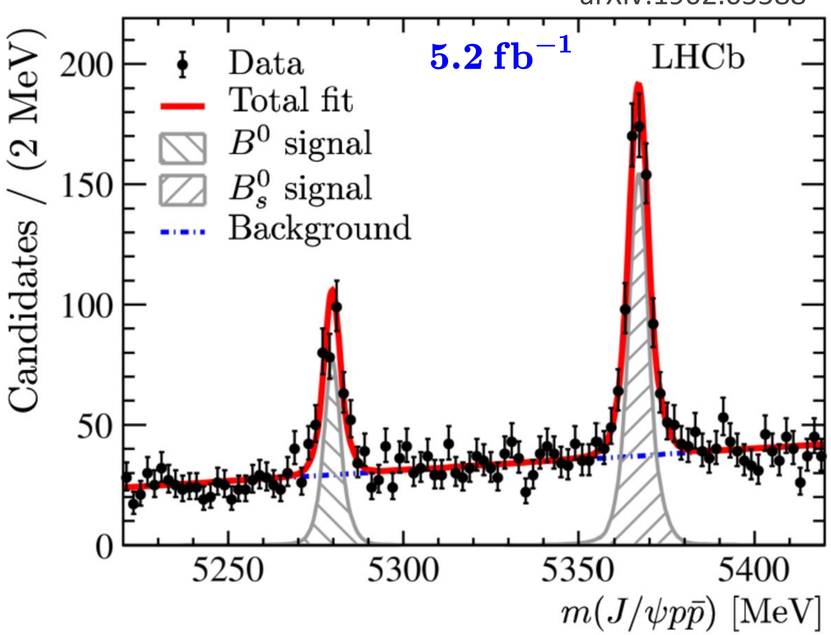
$$\mathcal{B}(B^0 \to J/\psi p\bar{p}) = (4.51 \pm 0.40\ (\text{stat}) \pm 0.44\ (\text{syst})) \times 10^{-7}$$
$$\mathcal{B}(B_s^0 \to J/\psi p\bar{p}) = (3.58 \pm 0.19\ (\text{stat}) \pm 0.33\ (\text{syst})) \times 10^{-6}$$

The small Q-value of the decay modes results into excellent precision on the mass

$$m(B^0) = 5279.74 \pm 0.30\,(\text{stat}) \pm 0.10\,(\text{syst})\ \text{MeV}/c^2$$
$$m(B_s^0) = 5366.85 \pm 0.19\,(\text{stat}) \pm 0.13\,(\text{syst})\ \text{MeV}/c^2$$

Full amplitude analysis is ongoing exploiting the full dataset (9 fb^{-1}).

arXiv:1902.05588



Pentaquar

Analysing the d
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The branching fr

$\mathcal{B}(B^0 \to J/\psi p\bar{p}) = (4.5$

$\mathcal{B}(B^0_s \to J/\psi p\bar{p}) = (3.5$

The small Q-valu
into excellent pr

$m(B^0) = 5279.74$

$m(B^0_s) = 5366.85$

Full amplitude ar
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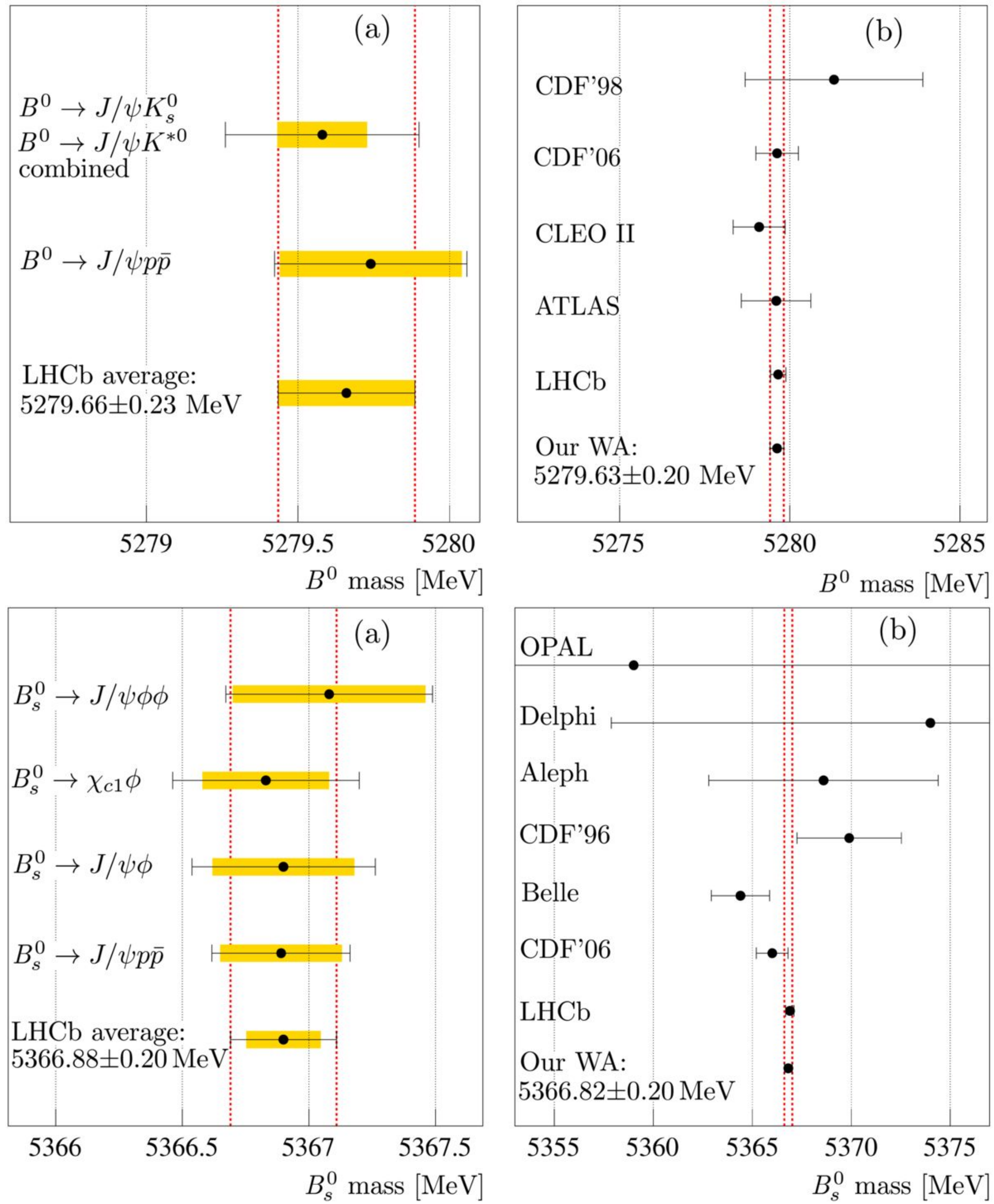
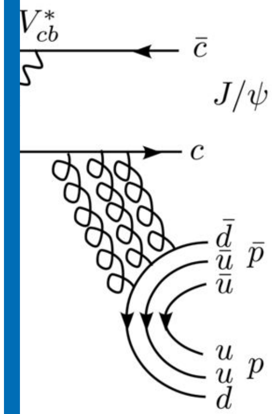
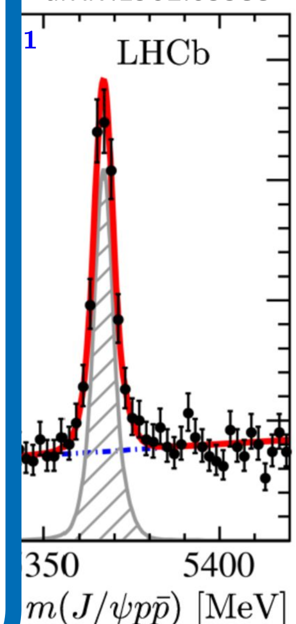




arXiv:1902.05588



Conclusion

LHCb is currently leading the studies on pentaquarks: **discovering a new narrow state** and **observing several decays to be studied with more statistics**, in the future Runs.

Data processing and calibration are critical to the study of these states.
LHCb is focussing on these aspects, both on LS1 and for the upcoming upgrade pushing the software trigger to 30 MHz with upfront data reconstruction.

Amplitude analyses are necessary (and ongoing) to draw conclusions on the nature of broad pentaquarks, but they depend on the hadronic scattering model for both development and interpretation. Large statistics challenges the assumptions underlying the isobar model.