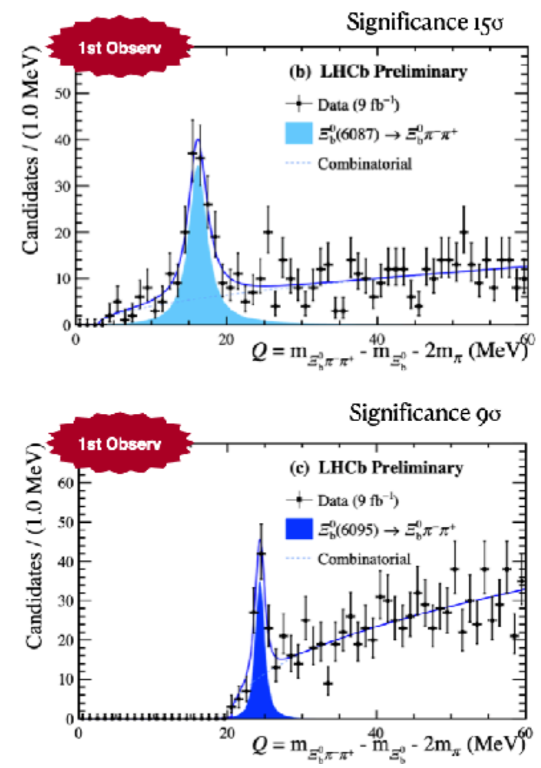
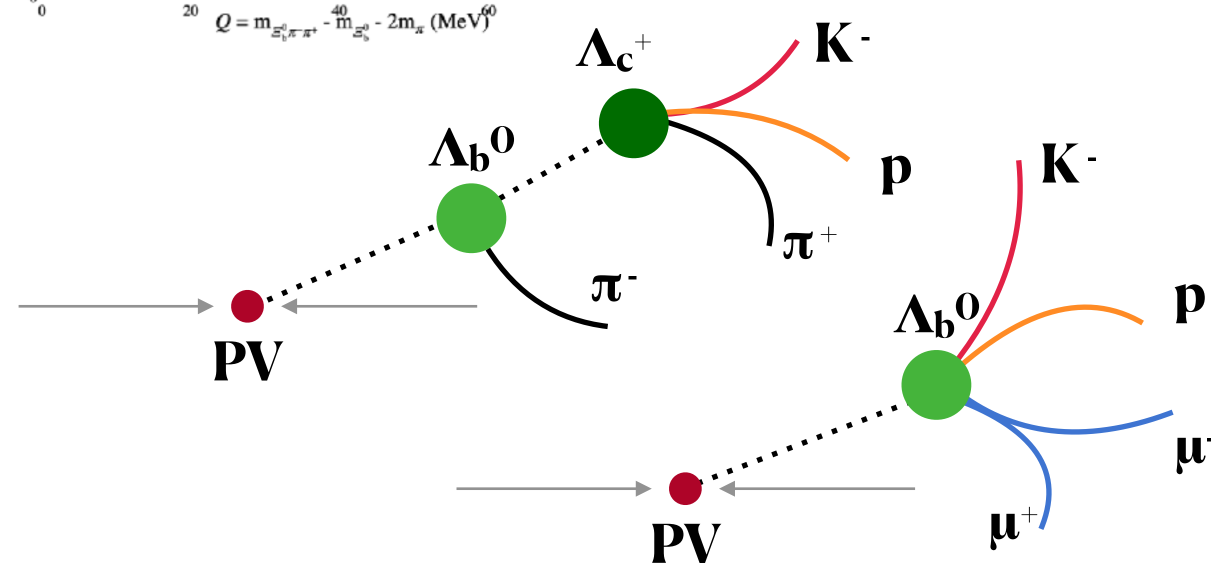
LHCb on technical aspects how to search and find resonances (also using AI techniques)

Paolo Gandini
INFN - Sezione di Milano
On behalf of the LHCb collaboration

6th - 10th November 2023
WPCF & Resonance Joint Workshop 2023





Outline

- Really broad topic to condense in a single talk
- Covers many different aspects in data analysis at LHCb:

  - Exotic & SM resonances
  - Technical aspects & experimental strategies
  - AI techniques et similia

- Heavily borrows from presentations of many people
- Also dedicated talk at this workshop →
- Here I will cover more technical and general aspects

Exotic Spectroscopy at LHCb

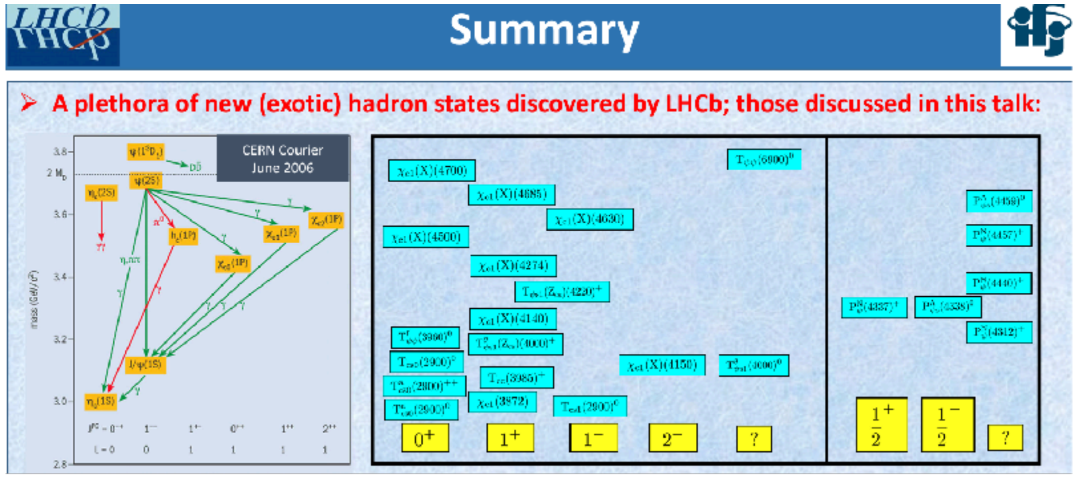
6 Nov 2023, 14:30
25m
Invited Day 1 - Afternoon

Speaker

Tadeusz Lesiak

Description

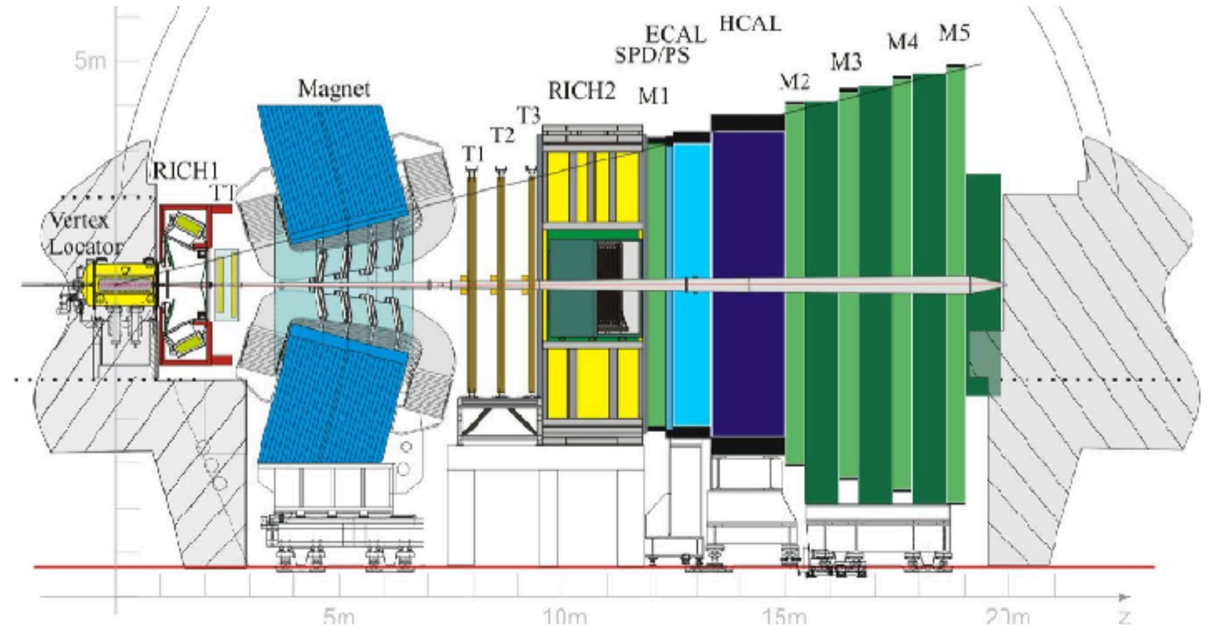
Studies of exotic hadrons comprise a natural and privileged playground for a more thorough elucidation of the nature of quantum chromodynamics. In this contest the LHCb experiment, dedicated to study heavy flavor hadrons produced from pp collision at the LHC, plays a vital role, already providing evidence for several exotic hadrons.
The talk will deliver an overview of the selected, latest LHCb on the subject of exotic hadron spectroscopy. It encompasses, in particular, the observations of pentaquarks, tetraquarks and the status of experimental knowledge about the state xc1(3872).



The LHCb detector

- LHCb designed as forward spectrometer covering the pseudo rapidity range $2<\eta<5$
- The LHCb experiment is an extraordinary spectroscopy gym both for "conventional" and "exotic" states
- **At LHC *b* and *c* baryons are produced in unprecedented quantities (high xsections & luminosity)**
- **Perfect conditions for both precision measurements & observations of new states**
- **Drawbacks: reconstructing neutrals is experimentally challenging (but doable)**

LHCb Detector Performance
Int. J. Mod. Phys. A 30 (2015) 1530022



Ingredients for good spectroscopy measurements

- **Excellent tracking** → mass and lifetime resolutions
- **Particle Identification** → important when dealing with charged hadrons in final states
- **Trigger efficiency** → use of muons & topological trigger give excellent efficiency

Asking to a modern AI to give a pictorial view...

an expressionist painting of a CERN physicist discovering new particles

https://openai.com/dall-e-2

Images generated
by DALL-E artificial intelligence

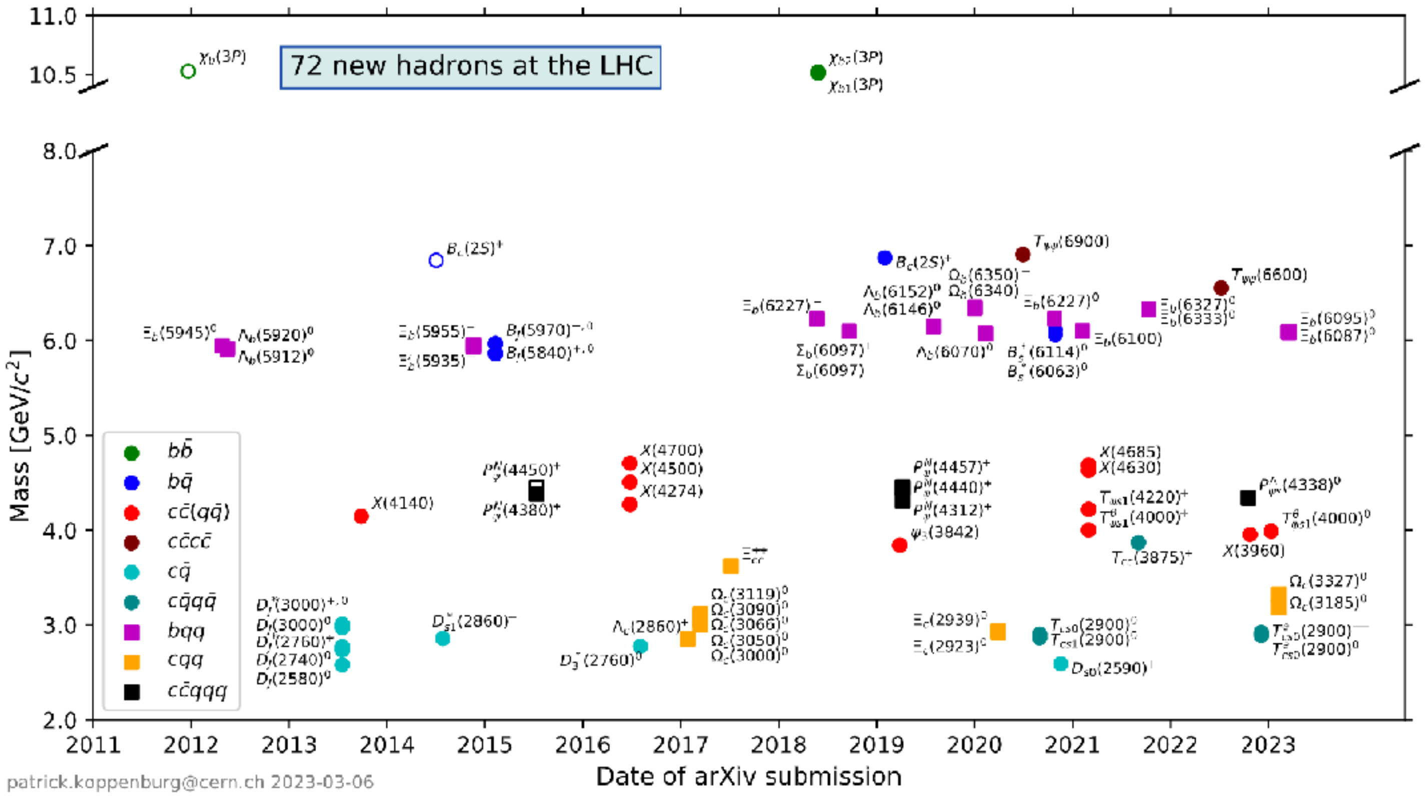
https://www.midjourney.com

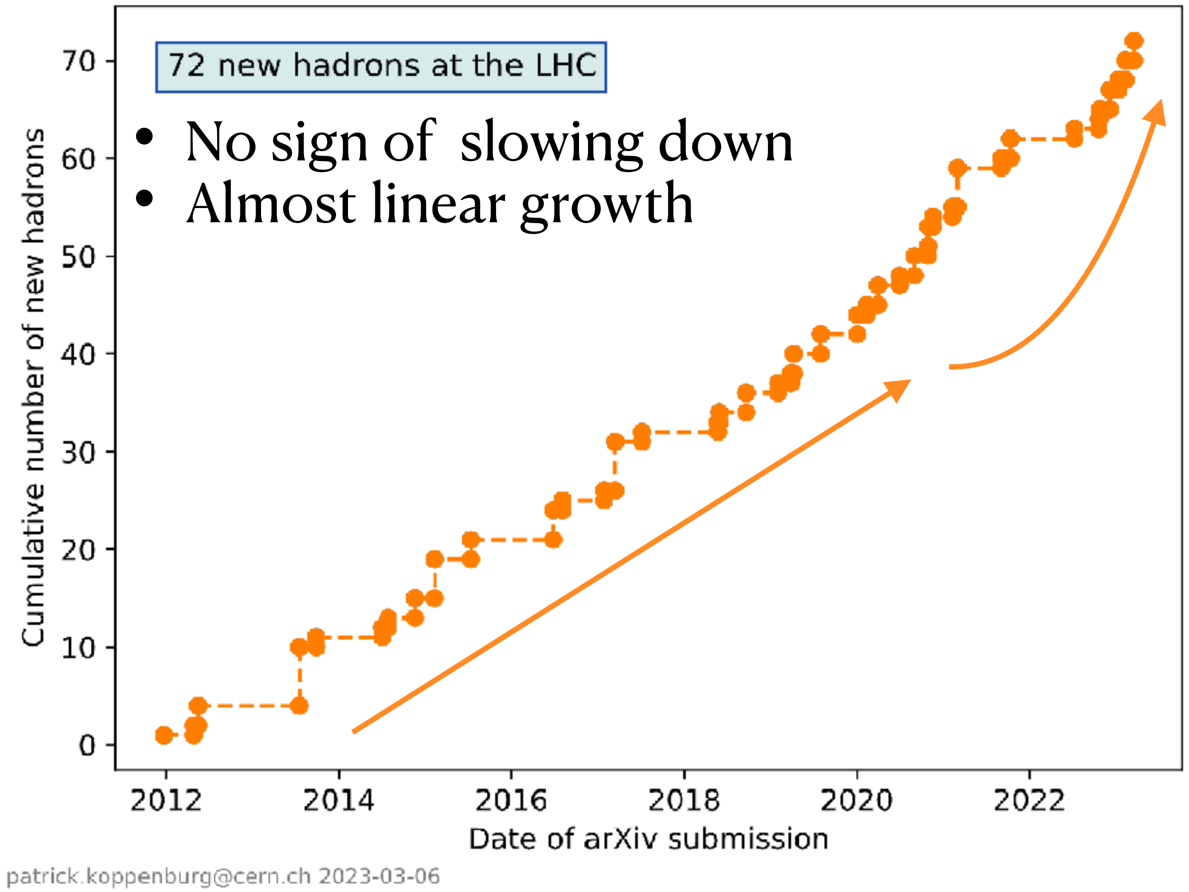
Images generated
by Midjourney

New observations at LHC

- **Spectroscopy is a super-active field at LHC and all the experiments are contributing!**
- So far 72 hadrons have been discovered at the LHC, of which 64 by LHCb
- The list is growing… All sector represented

Shown several times…



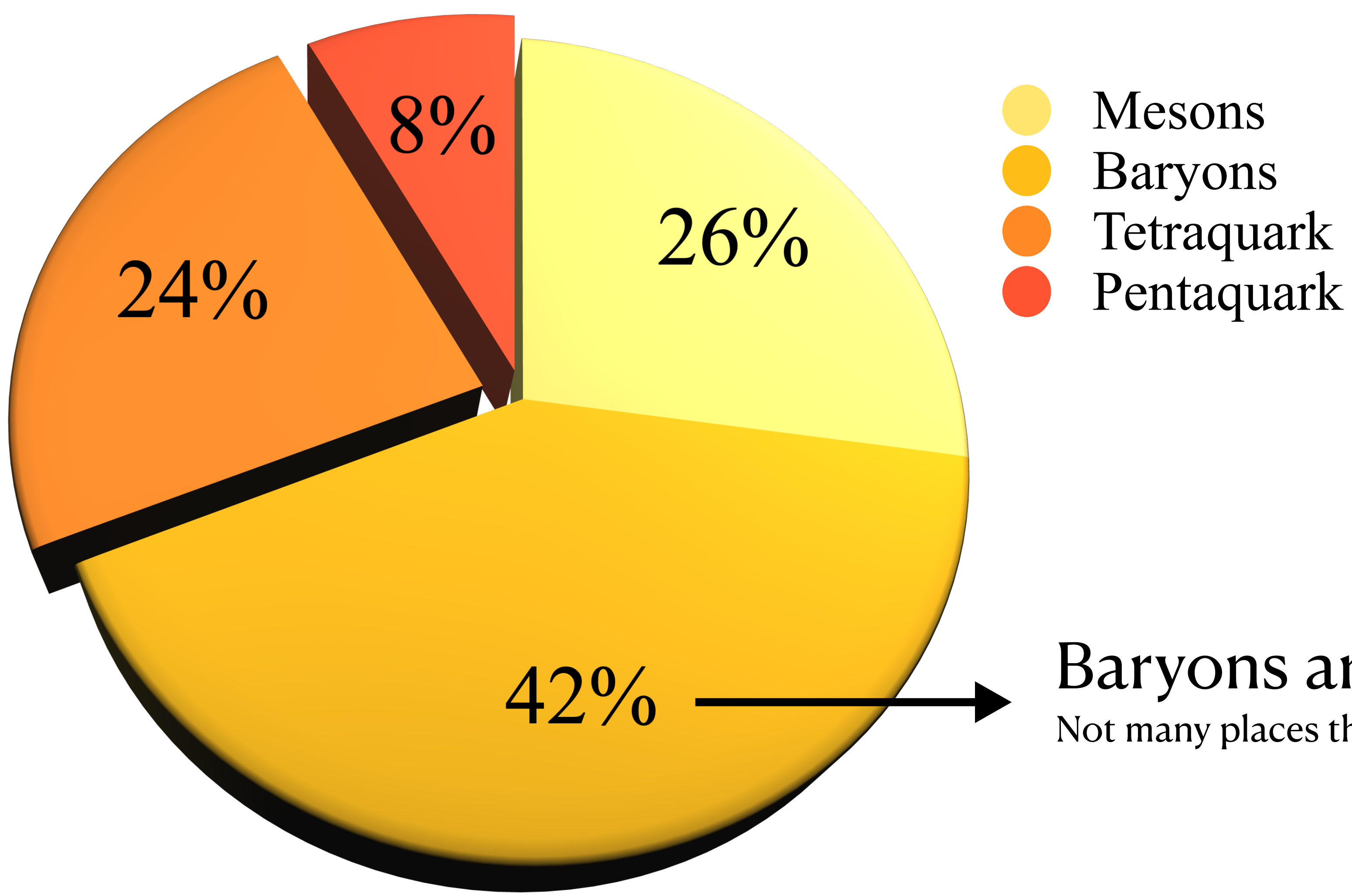


LHCb collaboration, P. Koppenburg, List of hadrons observed at the LHC, LHCb-FIGURE-2021-001, 2021, and 2023 updates.

+ new naming convention proposed: arXiv:2206.15233

New observations at LHC

- Key facts:
  - Observations in both the charm and the bottom sector
  - Baryons represented quite abundantly → no competition from other sources than LHC
  - Exotics are being observed copiously in channels not available before
  - Also different analysis methods (in production, in decay)



Baryons are the key players!

Not many places that can be used to produce and study them!

LHCb collaboration, P. Koppenburg, List of hadrons observed at the LHC, LHCb-FIGURE-2021-001, 2021, and 2023 updates.

Prompt production & decay

- Two main ways to do spectroscopy:

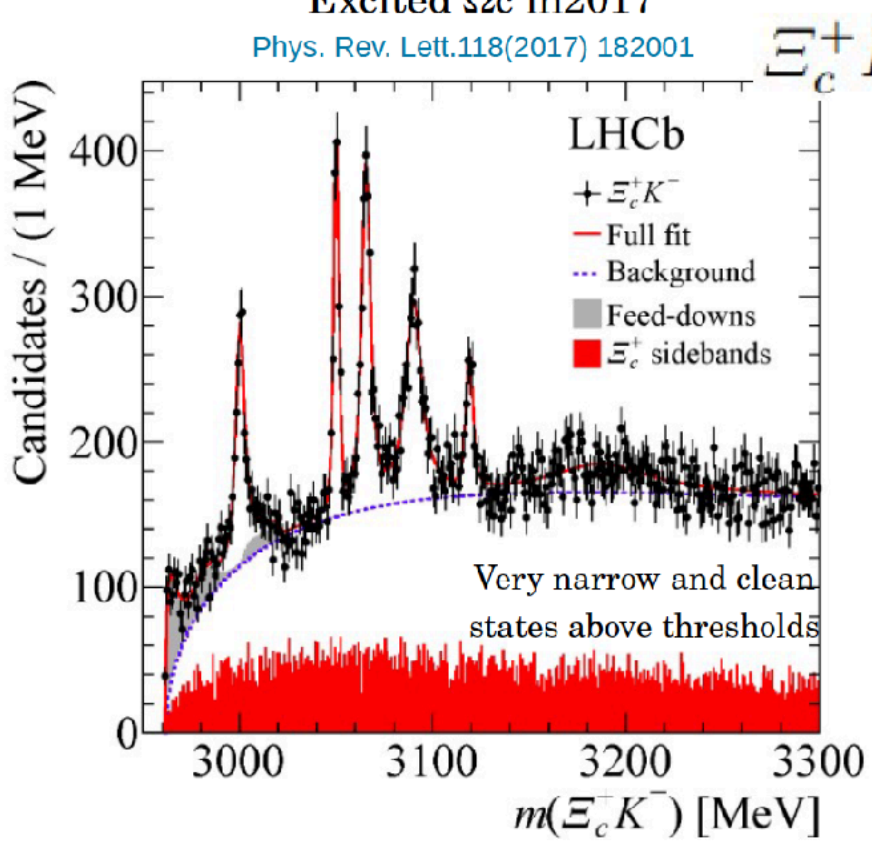
Prompt Production	Dalitz decays

Prompt Production

PROs:
- Huge production rate
- Main production mechanism for b-hadrons
- Appealing for strong decaying baryons

CONs:
- Large background

Excited Ωc in2017
Phys. Rev. Lett.118(2017) 182001



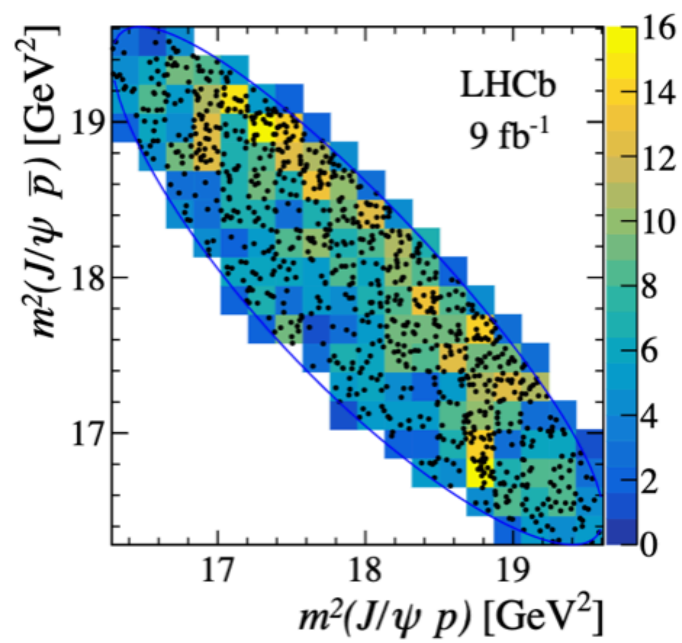
Dalitz decays

PROs:
- Clean samples
- Detailed study of quantum numbers
- Conservation rules

CONs:
- Only c-hadron available
- Usually less abundant than prompt (if also produced promptly)

Editors' Suggestion
PRL 128, 062001 (2022)

$B_s^0 \to J/\psi p\bar{p}$



Some history of LHCb spectroscopy efforts

This talk is not meant to be just a chronological collection of results
Rather and organic description of highlights and some successful techniques

Pentaquarks and Tetraquarks

- Several results drew attention in press
- Some results were actually unforeseen from the initial LHCb roadmap → LHCb is truly a GPD
- Here is just a small recap: milestones

2015

Phys. Rev. Lett. 115, 072001

822

Featured in Physics | Editors' Suggestion | Open Access

Observation of $J/\psi p$ Resonances Consistent with Pentaquark States in $\Lambda_b^0 \to J/\psi K^- p$ Decays

R. Aaij *et al.* (LHCb Collaboration)
Phys. Rev. Lett. **115**, 072001 – Published 12 August 2015

Physics See Viewpoint: Elusive Pentaquark Comes into View

Was $P_c(4450)^+$. Later resolved into $P_\psi^N(4440)^+$ and $P_\psi^N(4457)^+$.

2016

Phys. Rev. Lett. 118, 022003

136

Editors' Suggestion | Open Access

Observation of $J/\psi\phi$ Structures Consistent with Exotic States from Amplitude Analysis of $B^+ \to J/\psi \phi K^+$ Decays

R. Aaij *et al.* (LHCb Collaboration)
Phys. Rev. Lett. **118**, 022003 – Published 11 January 2017

\+ **many other more recent observations**

Really difficult to make justice to so many nice results

Angular analysis

- Use power of Dalitz plot analysis to extract properties of the intermediate resonances
- More powerful and refined tool compared to simple bump-hunting
- In this case:
  - Look for J/ ΨΦ final state
  - The data cannot be described by a model that contains only excited K states → ΦK
  - Four J/ΨΦ structures are observed
  - Very complex amplitude analysis in 6D (including invariant masses and decay angles)
  - Extract quantum numbers → fundamental to rule out some of the models on the nature of the states
  - E.g X(4140) is consistent with 1++ hypothesis

Phys Rev D.95.012002

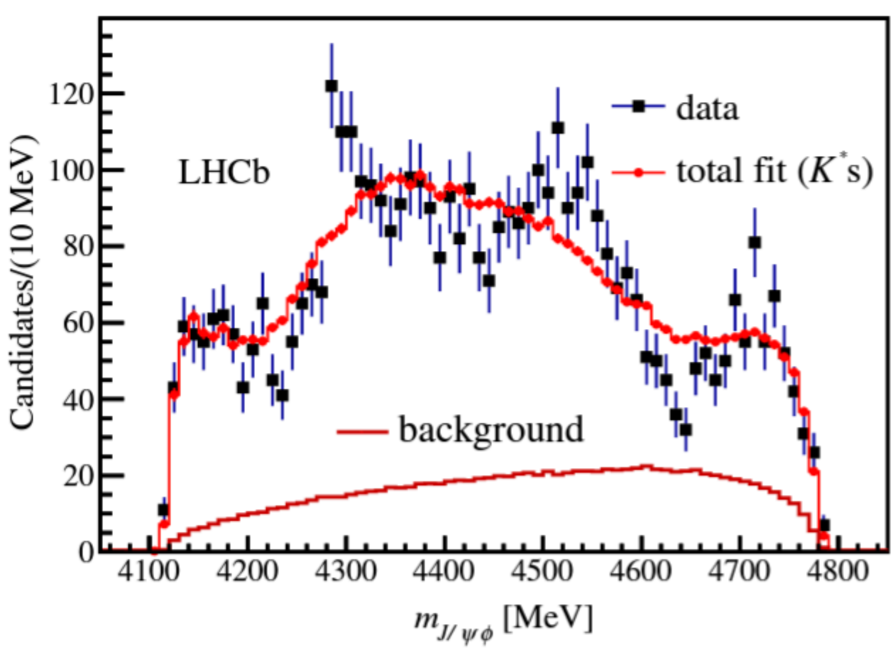


FIG. 1. Distribution of $m_{J/\psi\phi}$ for the data and the fit results with a model containing only $K^{*+} \to \phi K^+$ contributions.

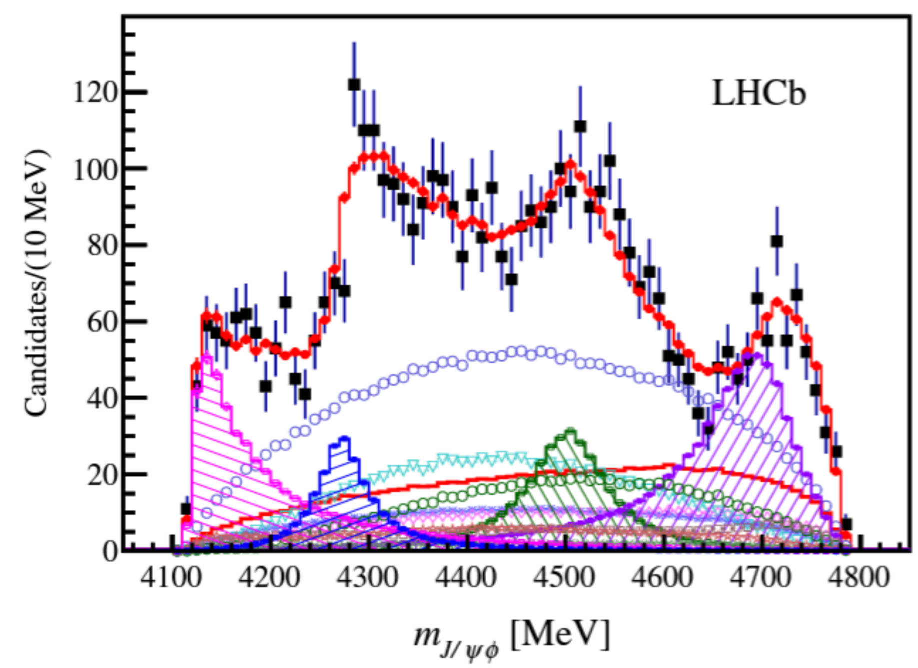
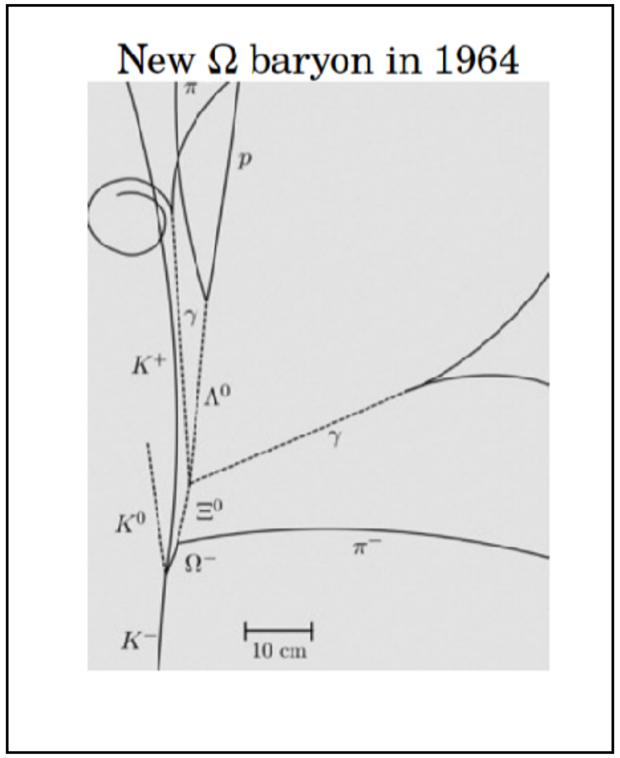


FIG. 3. Distributions of (top) ϕK^+, (middle) $J/\psi K^+$ and (bottom) $J/\psi\phi$ invariant masses for the $B^+ \to J/\psi\phi K^+$ candidates (black data points) compared with the results of the default amplitude fit containing eight $K^{*+} \to \phi K^+$ and five $X \to J/\psi\phi$ contributions. The total fit is given by the red points with error bars. Individual fit components are also shown.

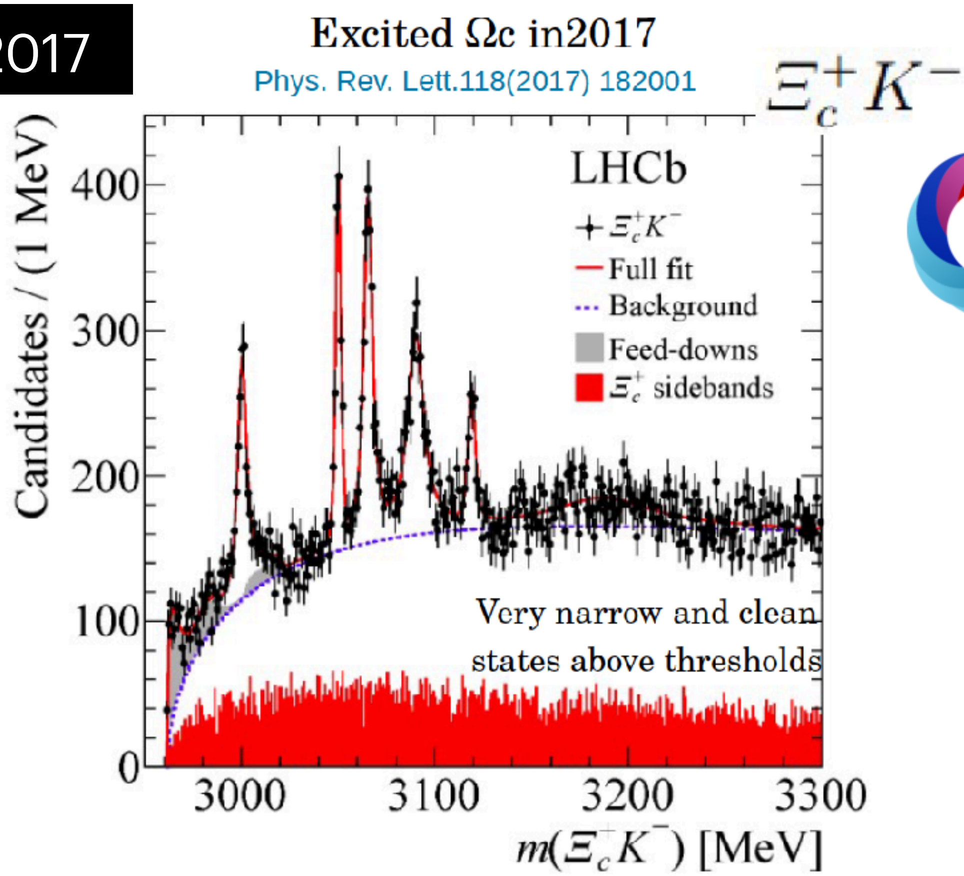
Observation of five new narrow Ω^0_c states → $\Xi_c^+ K^-$

- Surprises even in “conventional” baryon spectroscopy… 5 states at the same time!

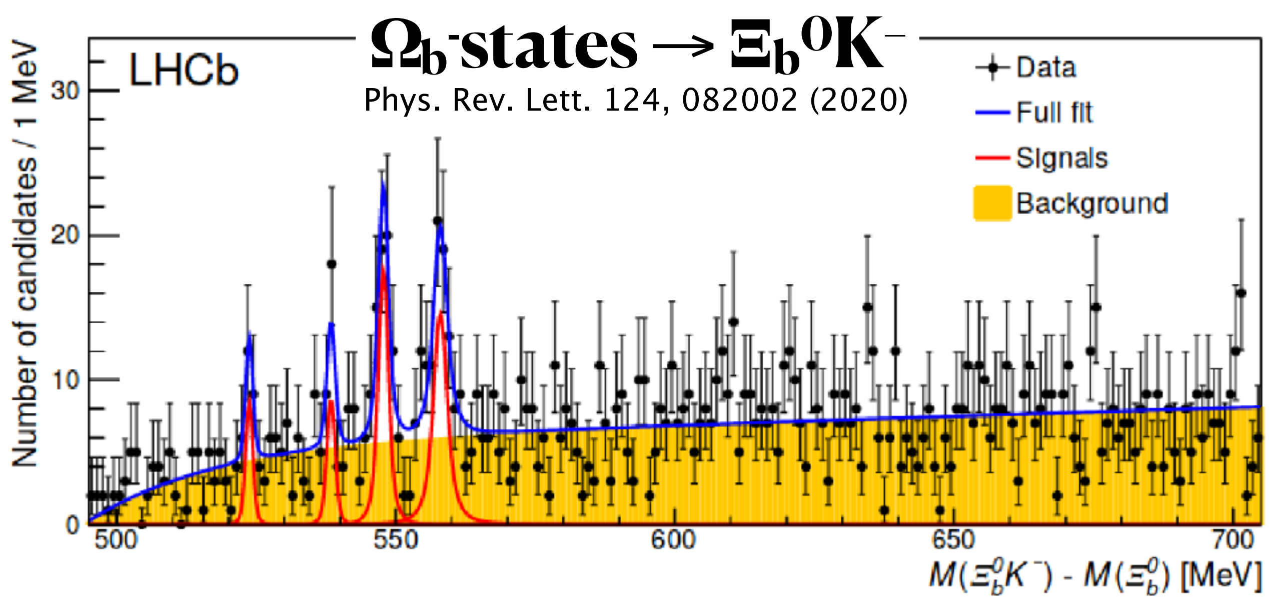
First observation of sss state



2017



2020



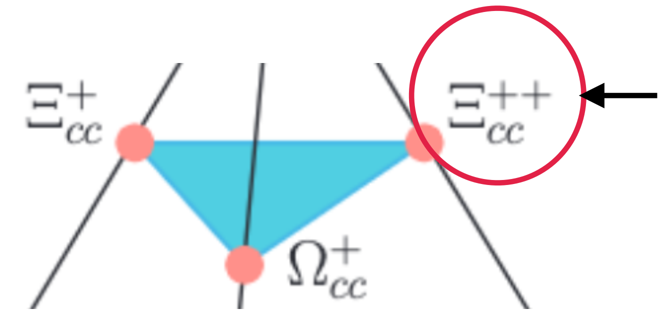
Doubly heavy Ξcc^{++}

2017

- Not only strong decays → first observation of double-heavy baryons
- Start of a new field of spectroscopy…

Ξ_{cc}^{++}

- Well established in 2 different modes (as required by PDG)
- Lifetime measured as well



3621.6 ± 0.4 MeV

$(2.56 \pm 0.27) \times 10^{-13}$ s

	Mode
Γ_1	$\Lambda_c^+ K^- \pi^+ \pi^+$
Γ_2	$\Xi_c^+ \pi^+$, $\Xi_c^+ \to p K^- \pi^+$
Γ_3	$D^+ p K^- \pi^+$

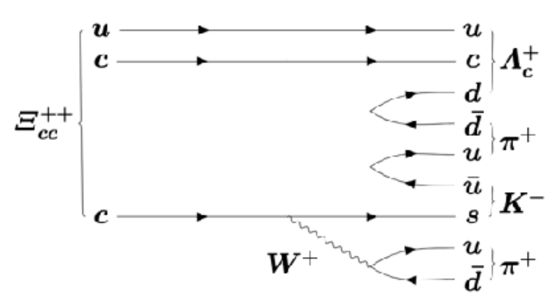
+

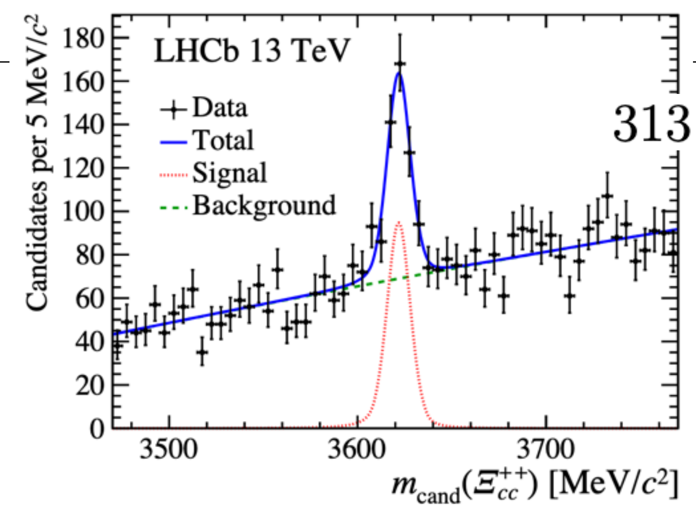
$\Xi_{cc}^{++} \to \Xi_c'^{+} \pi^+$

JHEP 05 (2022) 038

Phys. Rev. Lett. 119, 112001 **(2017)**

$\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$

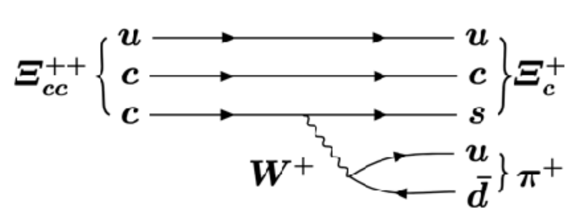


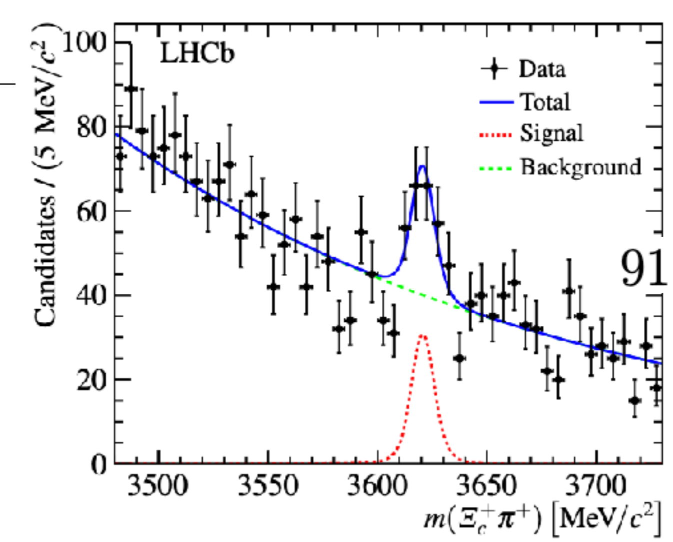


313 ± 33

Phys. Rev. Lett. 121, 162002 (2018)

$\Xi_{cc}^{++} \to \Xi_c^+ \pi^+$





91 ± 20

Observation of a new T_{cc}^+ state

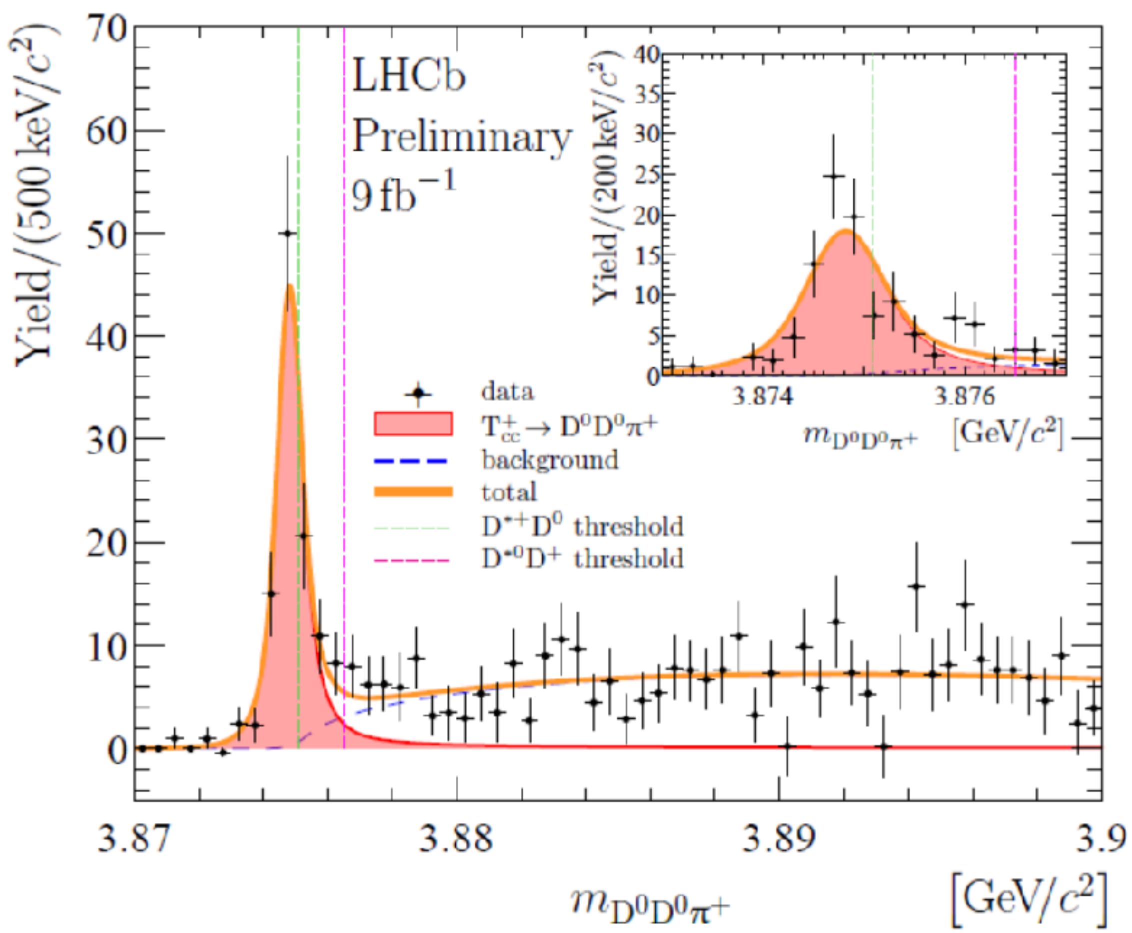
2021

Nature Physics volume 18, pages 751–754 (2022)

- Charged state with double charm content (two D meson with same "charge" in the same final state)
- Flavour not "hidden"
- Very narrow peak just above the threshold with striking significance over background

29 July 2021: Observation of an exceptionally charming tetraquark.

This week at the European Physical Society conference on high energy physics, EPS-HEP 2021 the LHCb Collaboration presented the first observation of a doubly charmed tetraquark, T_{cc}^+, with a new quark content $cc\bar{u}\bar{d}$. The newly discovered particle containing two heavy charm quarks is manifestly exotic, *i.e.* beyond the conventional pattern of hadron formation found in mesons and baryons. The tetraquark particle manifests itself as a narrow peak in the $D^0D^0\pi^+$ meson mass spectrum, just below $D^{*+}D^0$ mass threshold, with a statistical significance exceeding 20 standard deviations. The full Run 1 and Run 2 dataset was used to obtain this discovery.



- T_{cc}^+, with a new quark content $cc\bar{u}\bar{d}$
- Charged double-charmed state is manifestly exotic
- **Narrow peak in the $D^0D^0\pi^+$ meson mass spectrum**
- The new state is just below $D^{*+}D^0$ mass threshold
- Sample is extremely pure

- Subtract fake-D background using 2D fit to ($m_{K\pi}$, $m_{K\pi}$)
- No evidence in opposite sign sample

Ingredients for a successful analysis
An example…

- High yields + Clean samples
- Good momentum resolution (for m_0 and Γ)
- Good ideas and guestimations

+

- Example on how things evolve with data becoming available

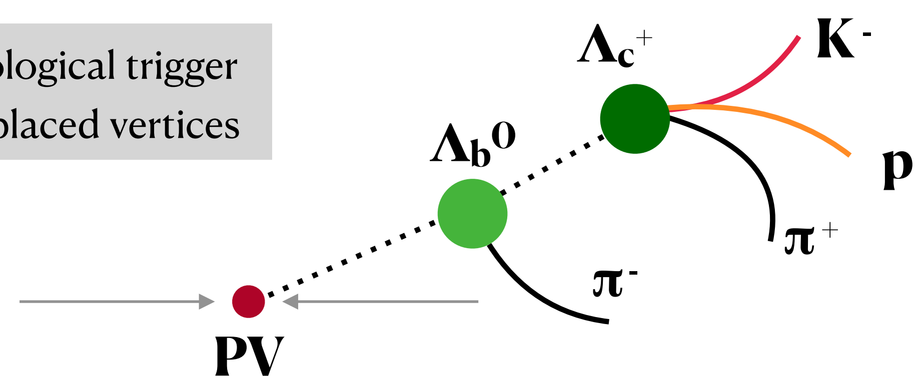
Di-Muon vs Topological triggers

JHEP 06 (2020) 136

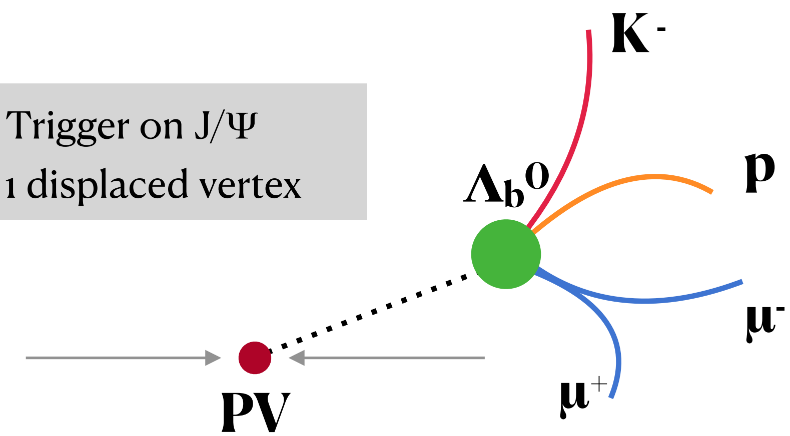
- **First job is to gather high yields to access rare states**
- Also, S/B ratio is important, especially for the most intricate analyses
- **As an example we can consider the Λ_b baryon. Standard candle for many b-baryon analyses**
- Also a clean control sample for many different tasks (calibration/BF measurements)
- **Use Λ_b to show Pros and Cons of Di-Muon vs Fully hadronic triggers**

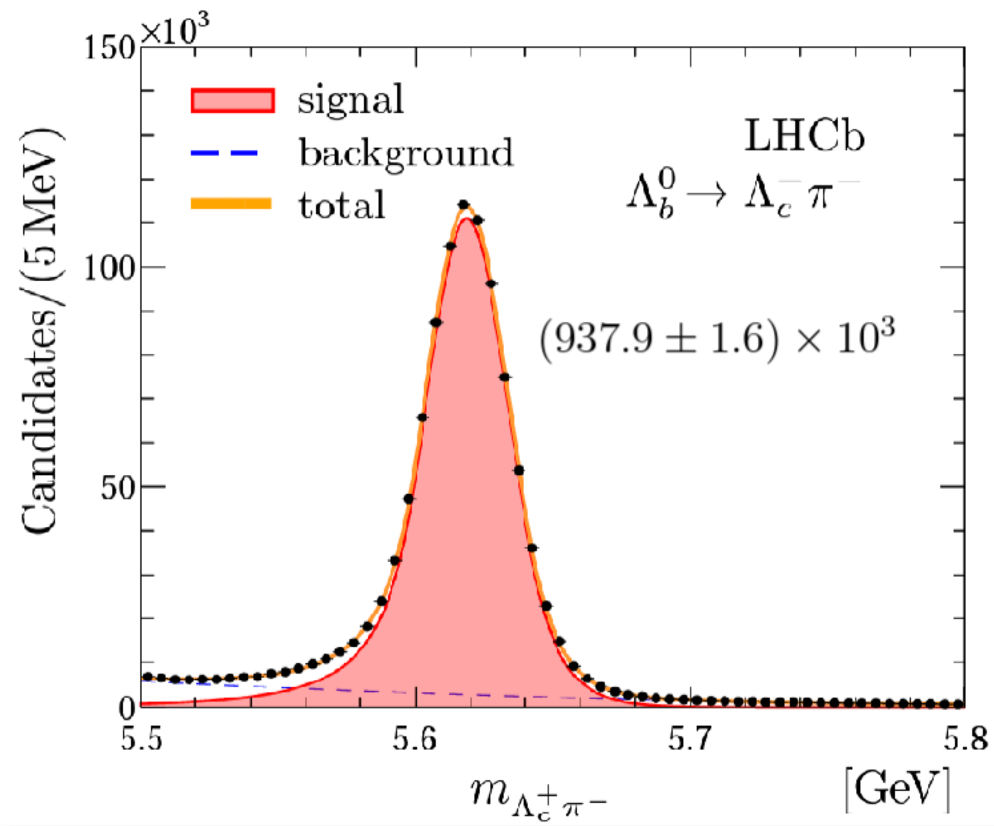
Most abundant b-baryon

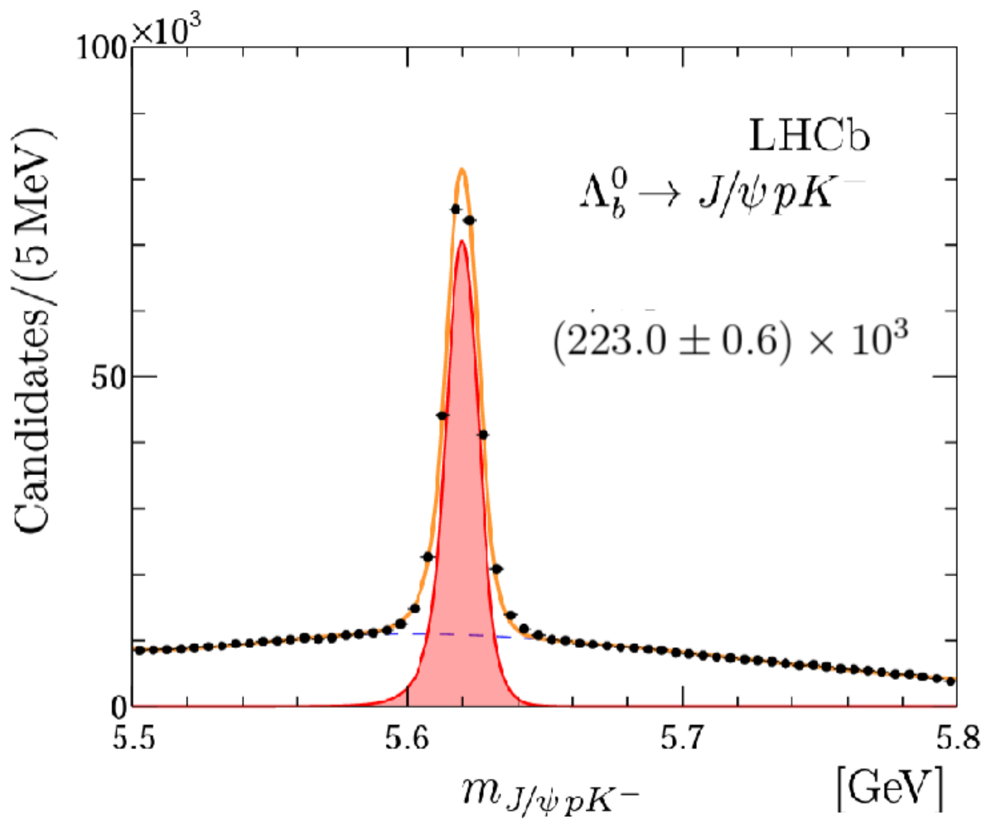
- Topological trigger
- 2 displaced vertices



- Trigger on J/Ψ
- 1 displaced vertex



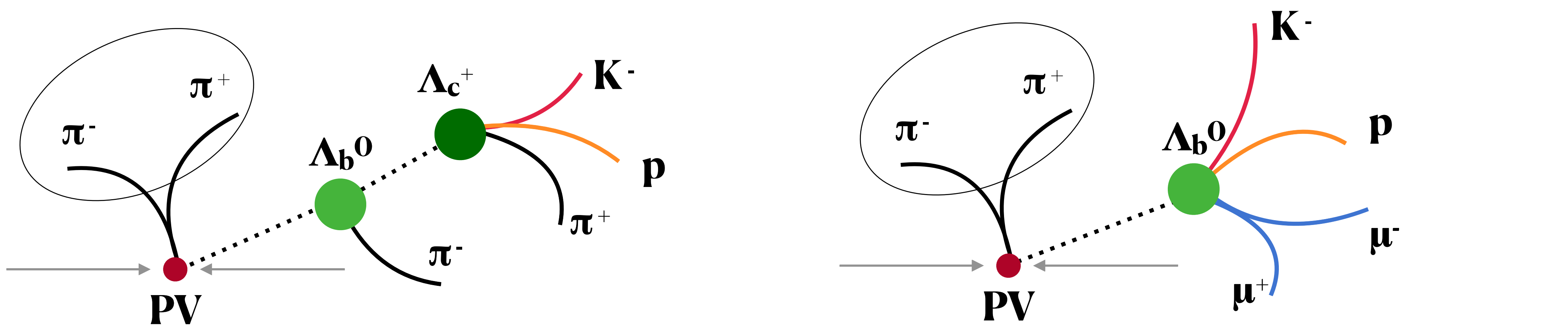


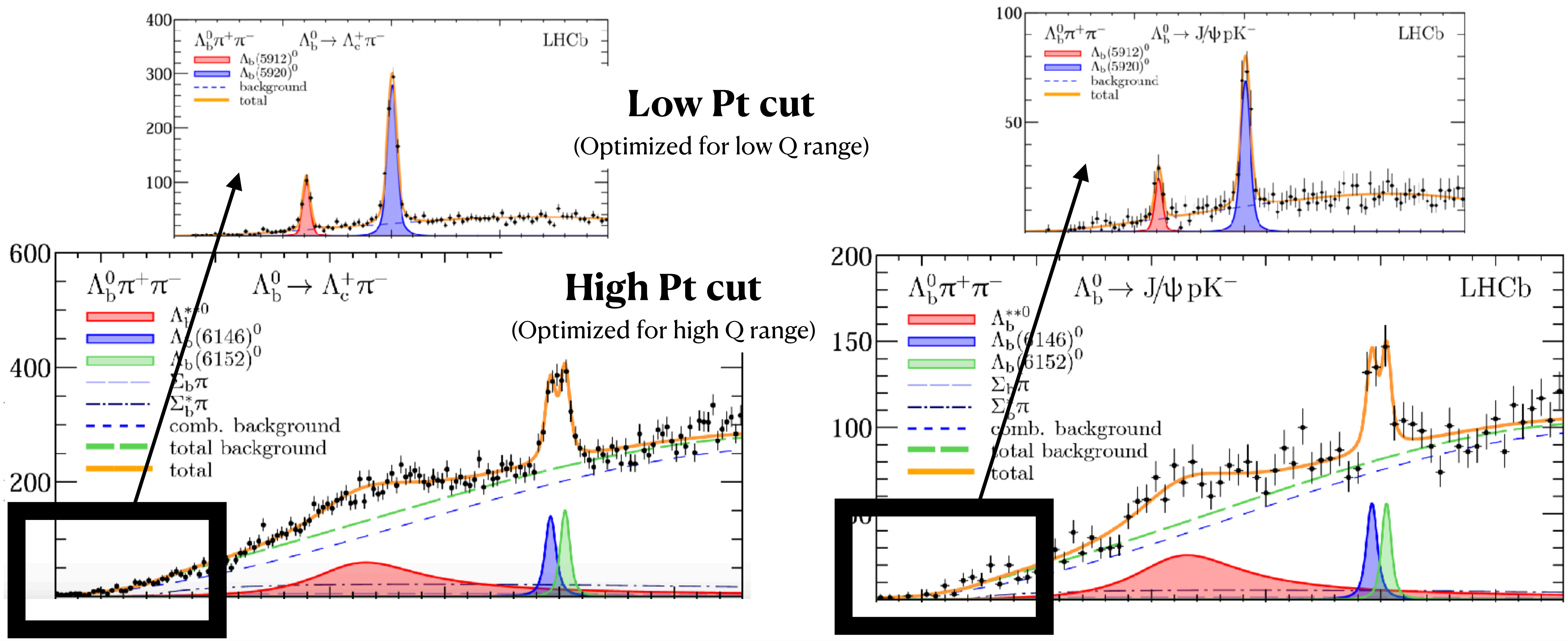


Extending the Q value regions

JHEP 06 (2020) 136

- **Again.. as an example one can look for resonances above threshold → Strong decays**
- Rich system of resonances!
- Actually interesting to show the time evolution of observation





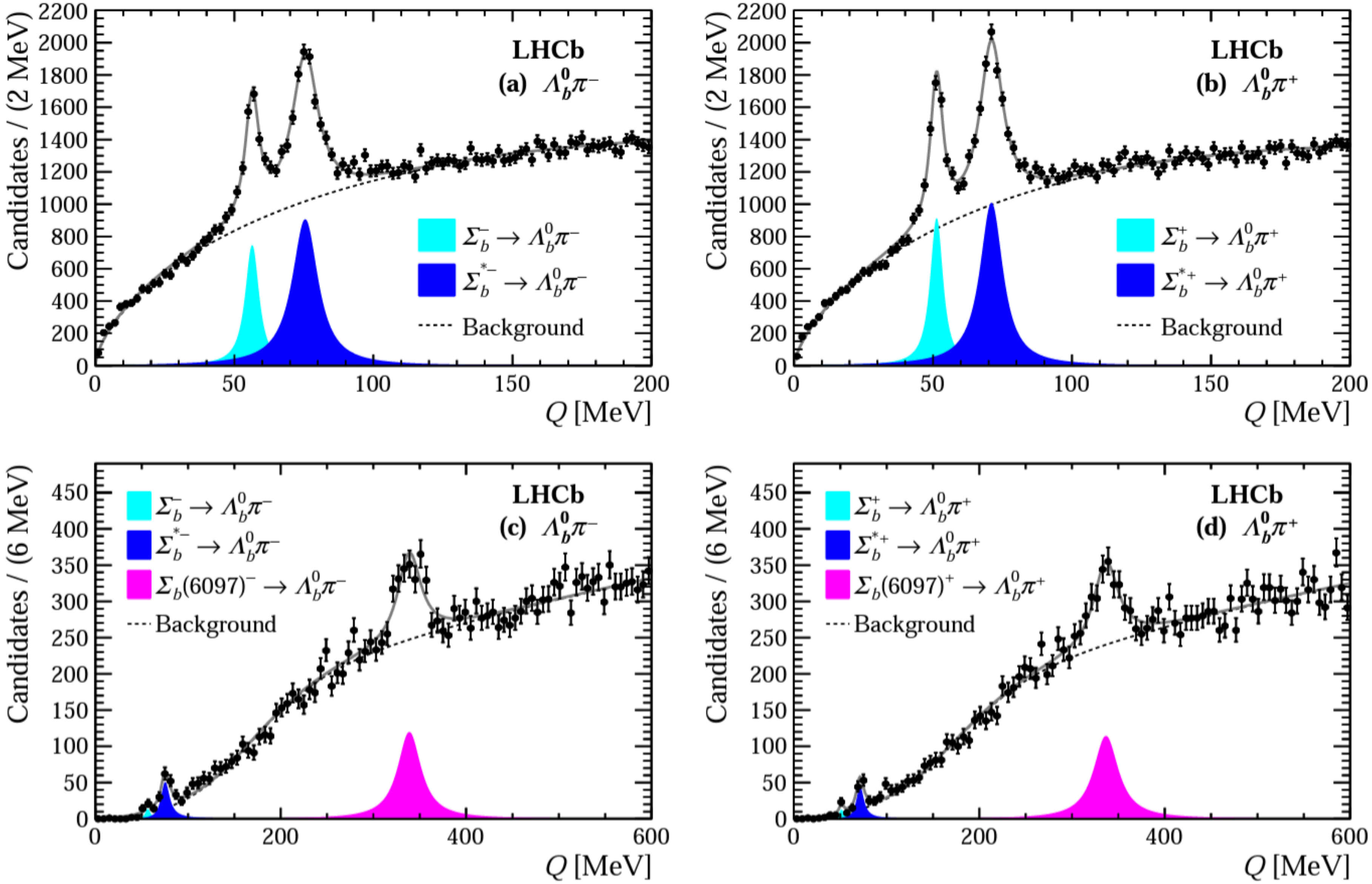
Missing States: example Σ_b^0

(buu, bdd, bud)

- Some states still eluding experimental observation
- E.g. neutral Σ_b states are likely to decay strongly in $\Lambda_b\pi^0$
- Experimentally challenging to reconstruct prompt π^0
- One could look at charged case and guesstimate
- **Combinatorial of photons too severe...**

First observed by CDF
Searches then extended by LHCb

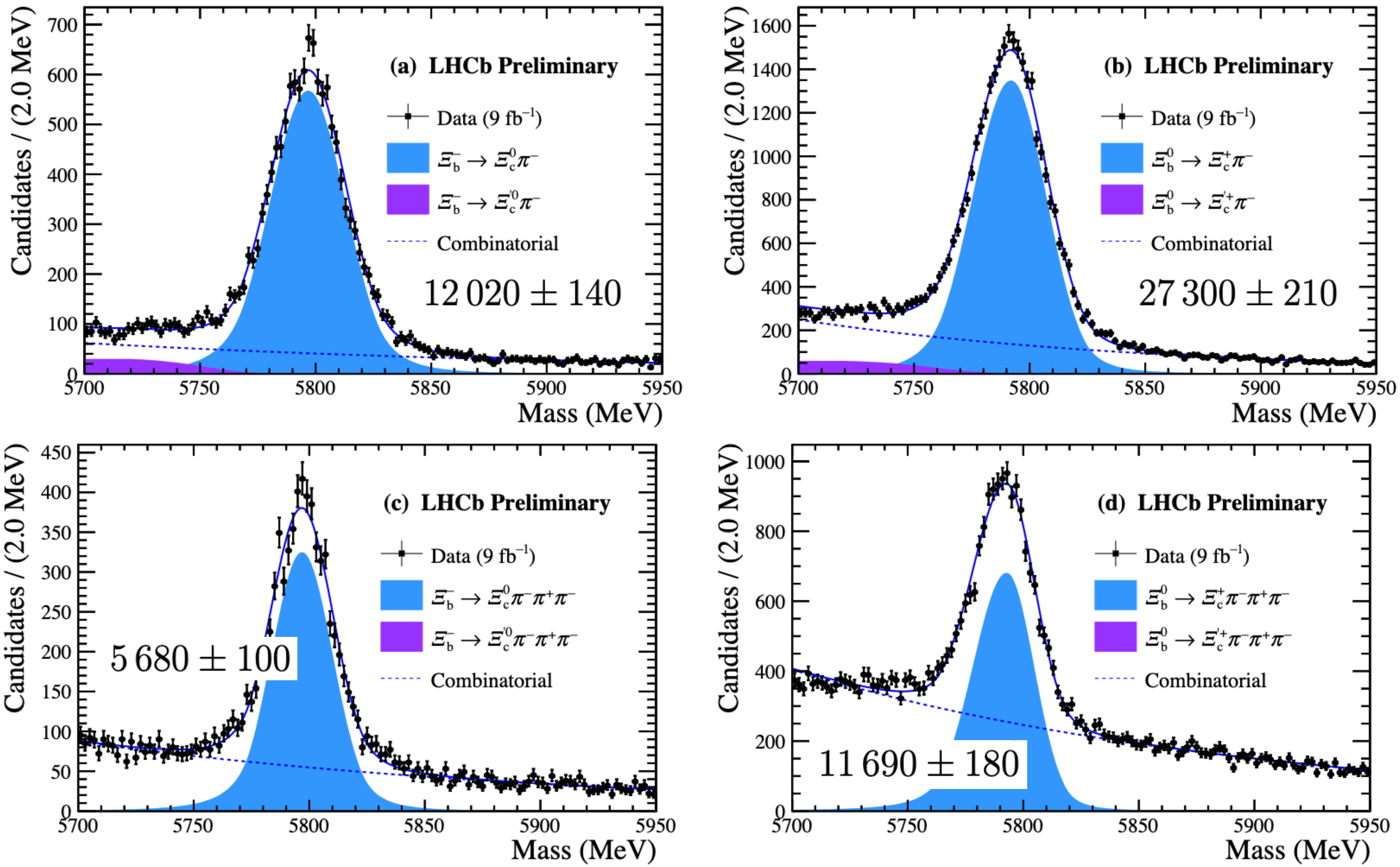
Phys. Rev. Lett. 122, 012001 (2019)



Phys. Rev. Lett. 131, 171901

New baryons in $\Xi_b^-\pi^+\pi^-$ and $\Xi_b^0\pi^+\pi^-$

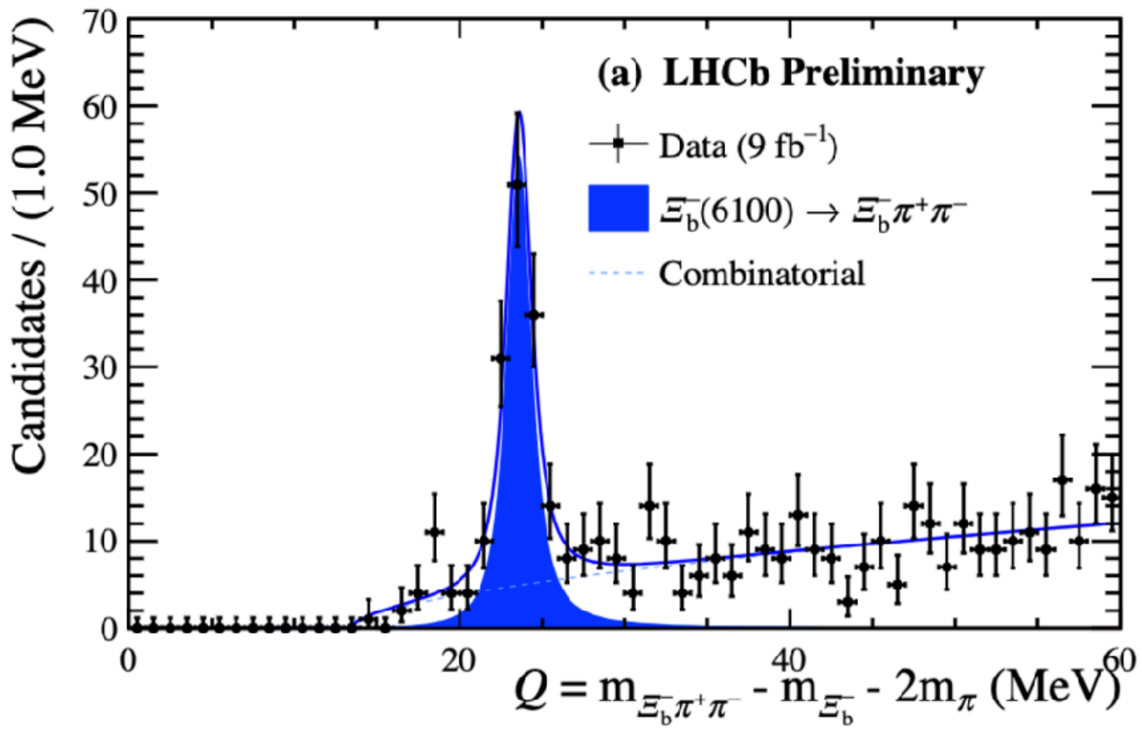
- Reconstruct nice samples of Ξ_b charged and neutral
- Selection based on BDT algorithms trained on simulation for signal and DATA sidebands for background
- Additional vetoes to suppress contributions from Λ_b, where required



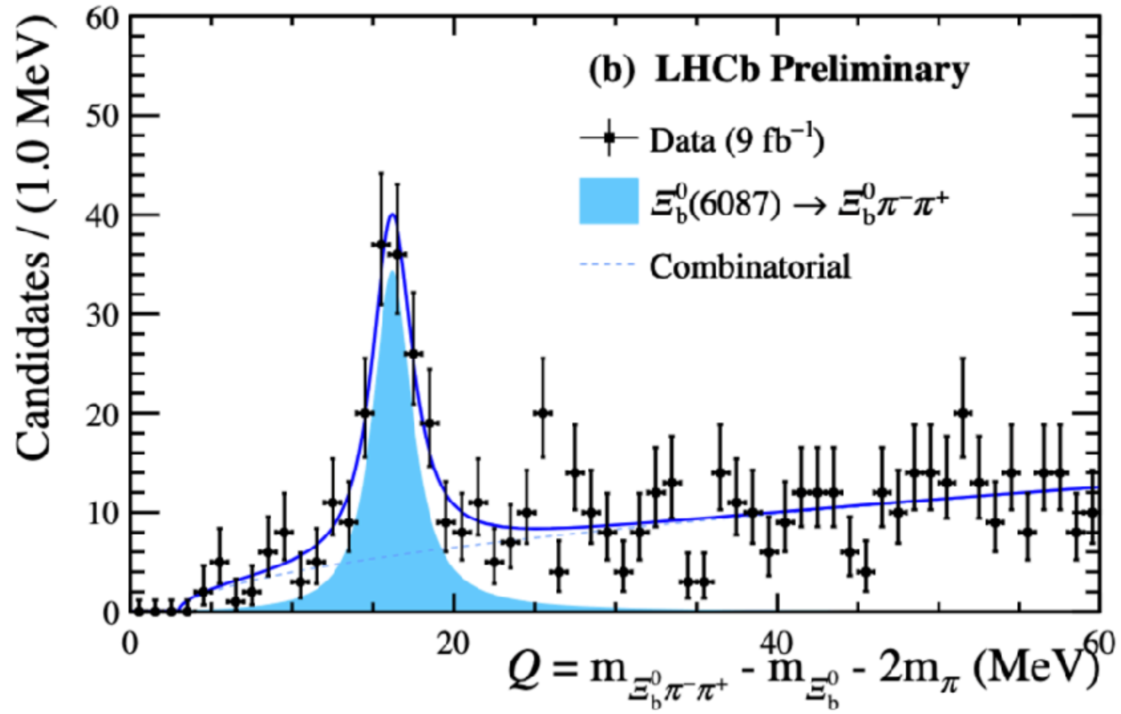
Phys. Rev. Lett. 131, 171901

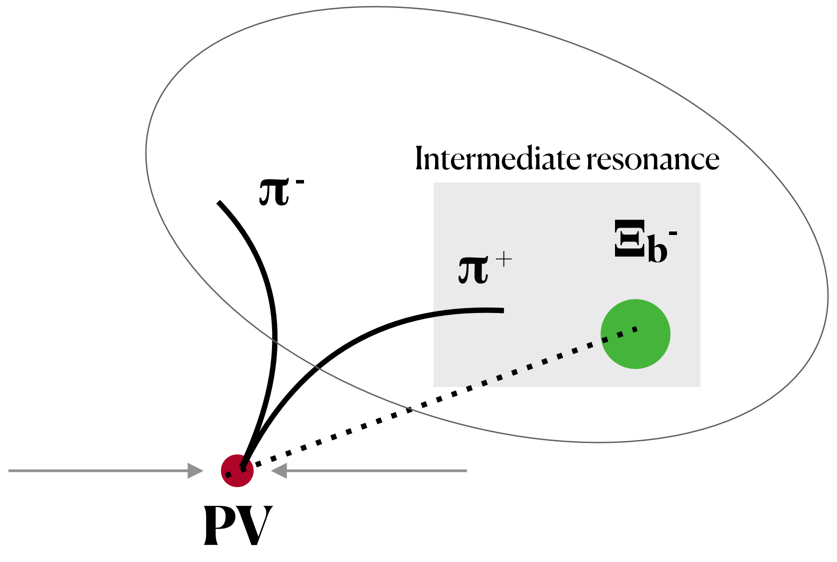
New baryons in $\Xi_b^-\pi^+\pi^-$ and $\Xi_b^0\pi^+\pi^-$

Significance 18σ

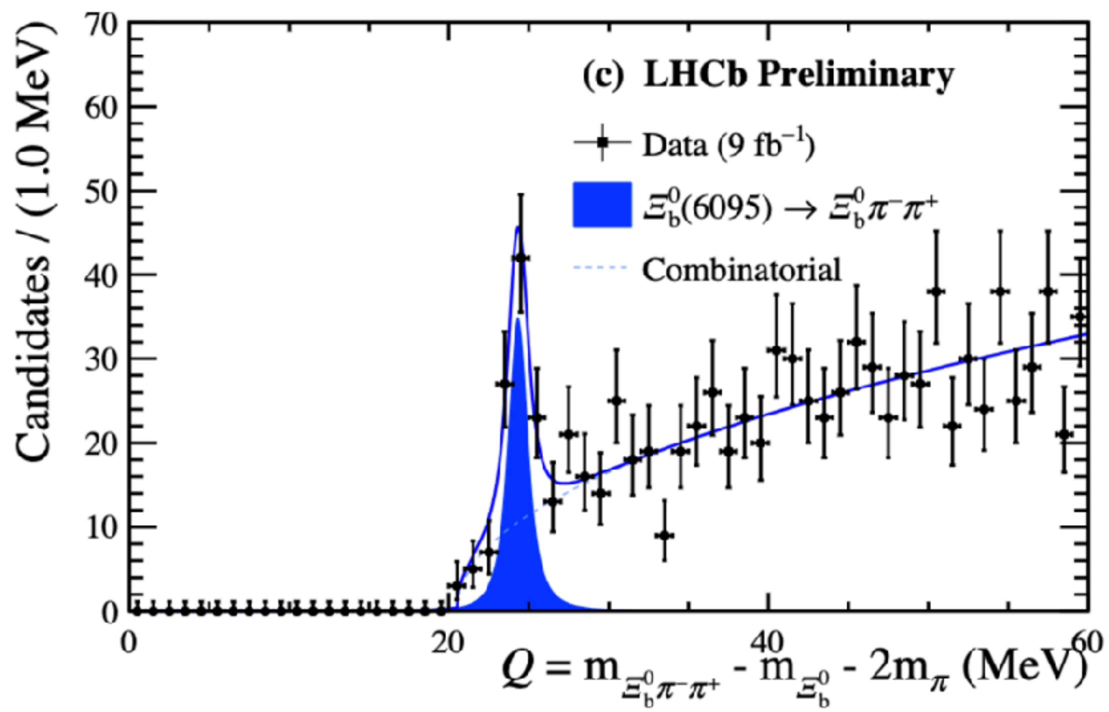


Significance 15σ





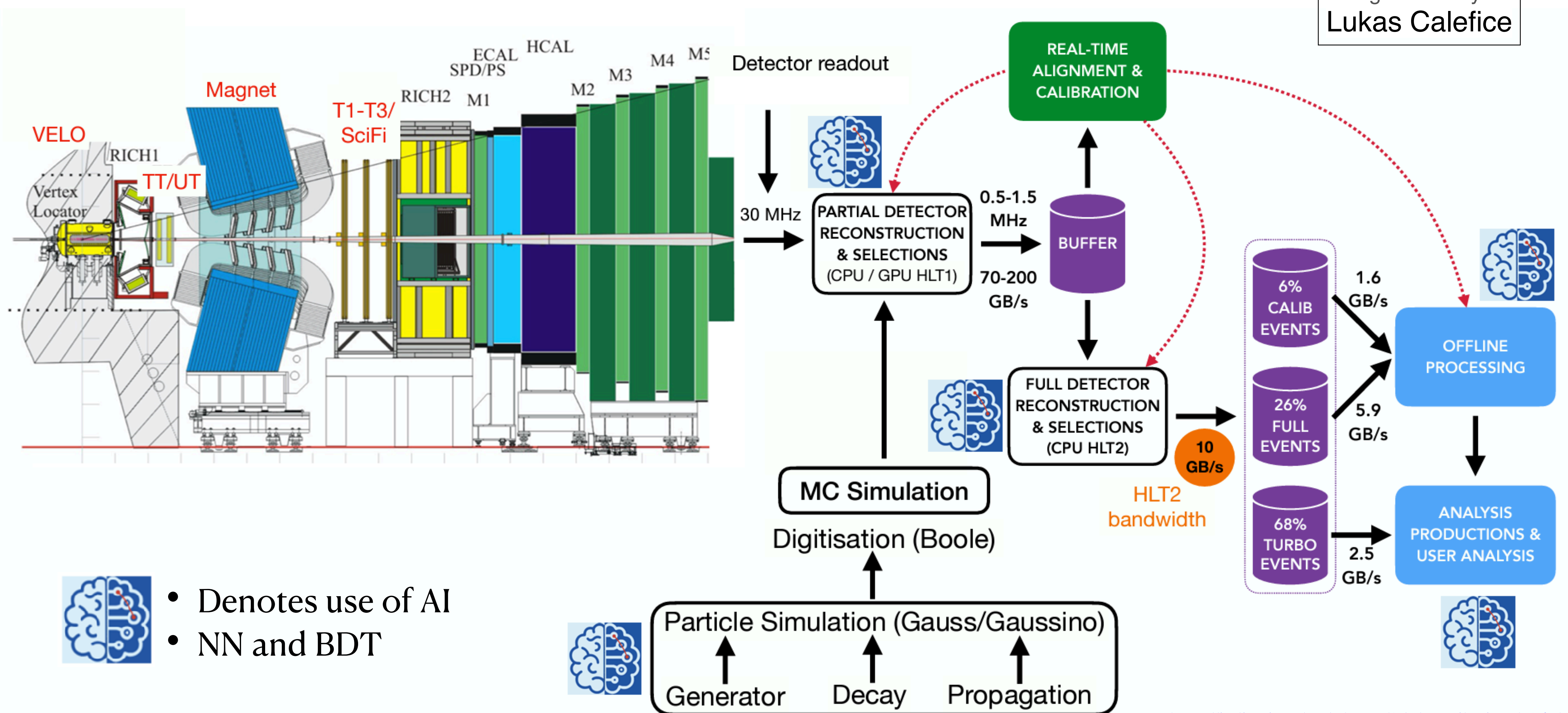
Significance 9σ



AI techniques

- Machine learning is widely used in LHCb in many aspects
- A detailed description is beyond the scope of this talk (see links)
- **Main customers are trigger (online) + PID + event selection (offline)**
- Usage is generic, not targeting specific searches, rather improving the algorithm required to run the detector
- Nice summary at the recent dedicated ML Workshop at ICCUB 24/10/2023
- Run3 → Full software trigger (HLT1 in GPU & HLT2 in CPU)

Image courtesy of
Lukas Calefice



https://indico.icc.ub.edu/event/251/contributions/1961/

AI techniques

- Diversified history of ML application in every aspect of the detector
- Main customer… Trigger
  - ML-based algorithms (BDT) in inclusive particle selections already during Run1 & Run 2 covering the majority of the collaboration's published analyses in Run 1 already
  - New paradigm in Run 3 with full software trigger implementation; 326 GPUs reduce incoming data rate from 5 to approximately 0.1 TB/s
  - All subdetectors data available now at trigger level
- Opened window for ML application (inference) at earliest selection level as possible directly in the online environment

2nd CERN IT Machine Learning Infrastructure Workshop

mercoledì 11 ott 2023, 09:00 → 13:00 Europe/Zurich

40/S2-A01 - Salle Anderson (CERN)

Descrizione The High Energy Physics community has started introducing Deep Learning techniques for improving different aspects in the experiments and accelerators life cycle and data processing steps.

The availability of reliable, user-friendly and scalable resources, including full software and hardware stacks, is critical to fully support activities in the ML/DL domain. In this context, the CERN IT department has launched an initiative to gather information about the status of its ML/DL dedicated infrastructure, the state-of-the-art and the needs of the HEP ML/DL community at CERN.

A first workshop focused on the current status of ML/DL activities and infrastructure solutions in CERN IT. This second workshop tries to collect information about on-going and planned AI-research within the different departments and experiments at CERN.

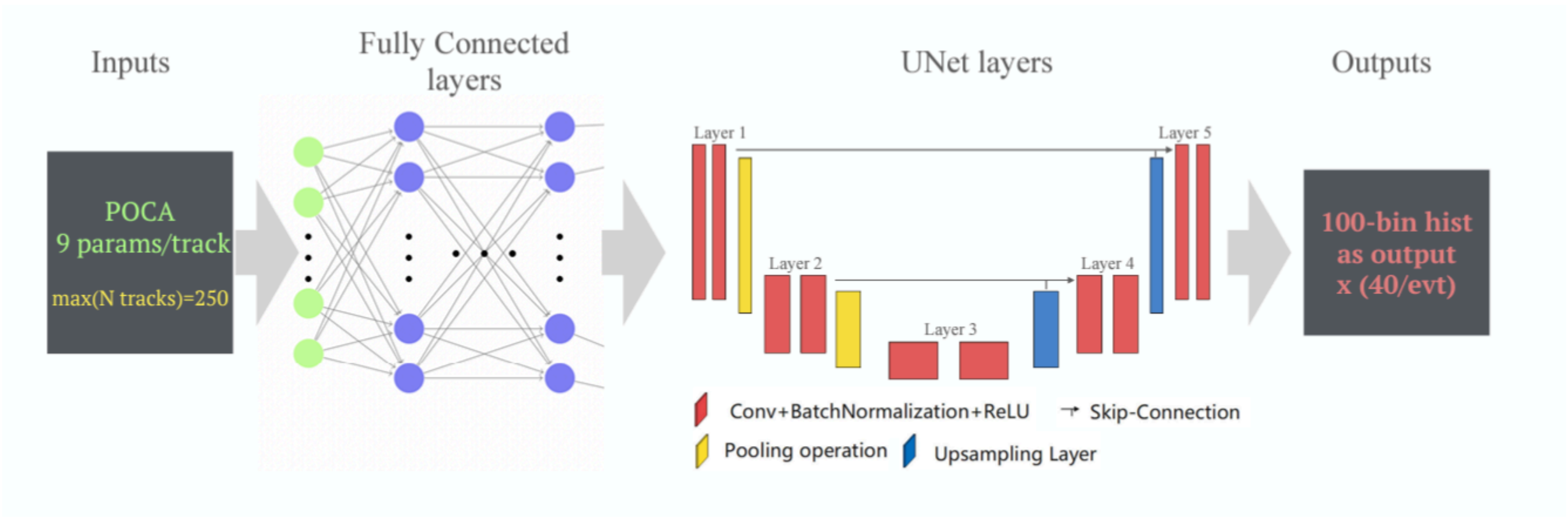
AI techniques: Example 1 - Tracking

- **High-throughout Graph Neural Network track reconstruction at LHCb: [talk@CTD2023]**
  - Track reconstruction in the Velo (high-granularity tracking system)
  - Using GNN pipeline is based on the work of the Exa.TrkX collaboration
  - Training performed using PyTorch on local ressources (LIP6 Paris — Sorbonne Université)
  - Inference on low-level features
  - High parallelization over hits / edges ⇒ adapted to GPUs
  - Very promising preliminary physics performances
  - On-going R&D to run inference on GPUs in Allen (HLT1)

AI techniques: Example 2 - PV finding

- **DNN for finding primary vertices in pp collisions at the LHC: [talk@CHEP2023]**
  - Identify PV positions from tracks low-level features
  - High parallelization over tracks / events ⇒ adapted to GPUs
  - Non trivial hybrid MLP + CNN architecture

- Common training platform for LHCb and ATLAS
- Training performed using PyTorch on local ressources (University Cincinnati)
- Very promising preliminary physics performances
- On-going R&D to run inference for LHCb on GPUs in Allen (HLT1)



Conclusions

- Let me take the opportunity to introduce the upgraded detector
- Spectroscopy analyses will benefit both for increased luminosity and performance
- Full software trigger improves efficiency and flexibility

Upstream Tracker closing completes installation of the LHCb Upgrade 1 detector

First plots with Run3 data