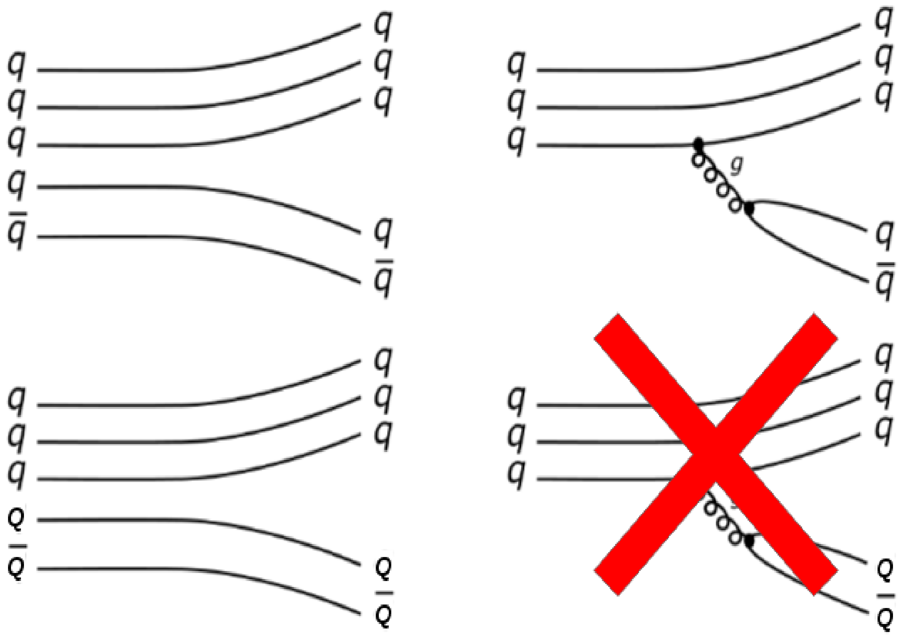
Perspectives and Challenges for Studies of Quarkonium(-like) states with the LHCb Upgrade

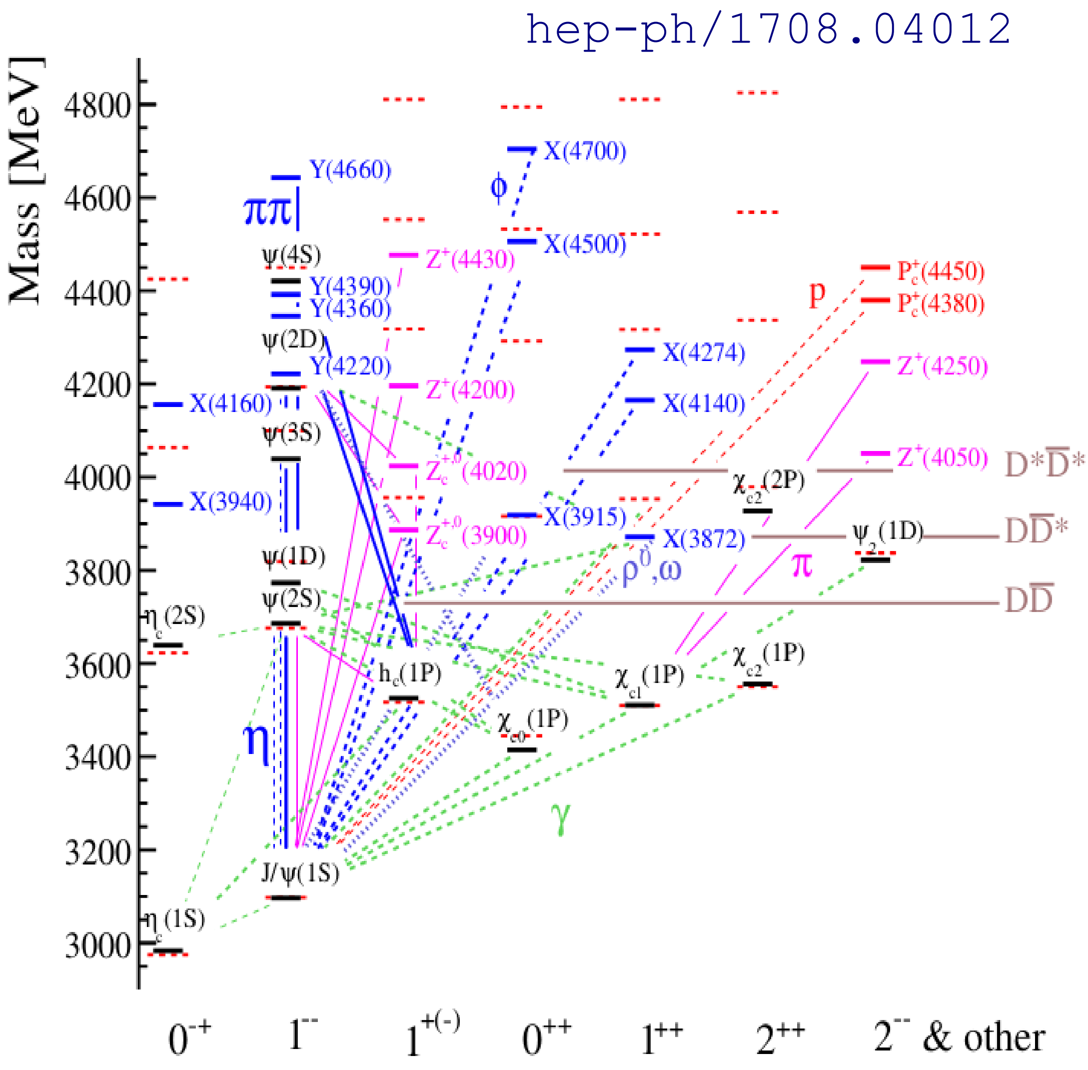
Lucio Anderlini

Seminario INFN – CdS di Dicembre

A first renaissance of Hadron Spectroscopy

Many new states were observed since the **b-factories** and the **LHC** made possible to produce a large amount of heavy hadrons.



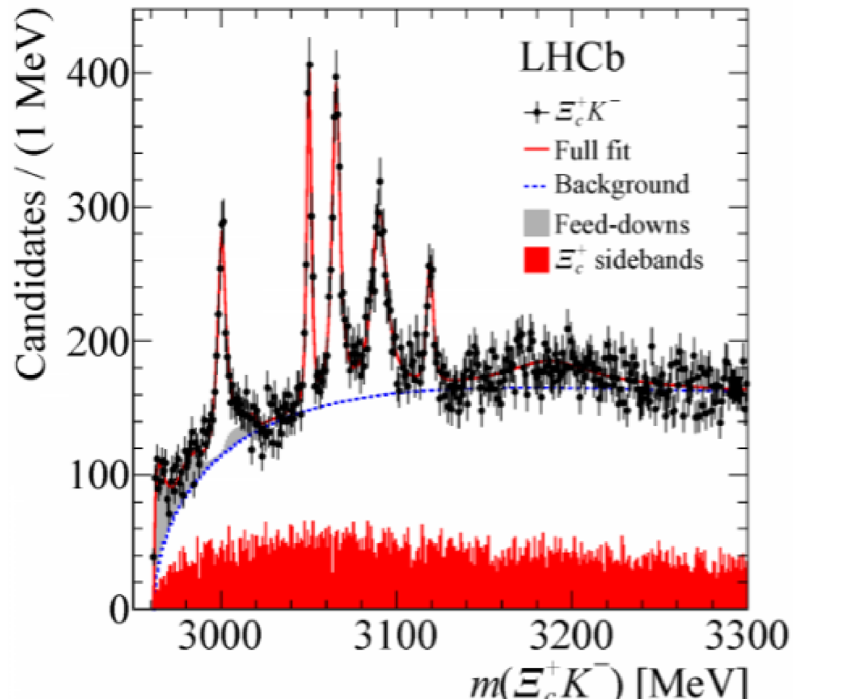


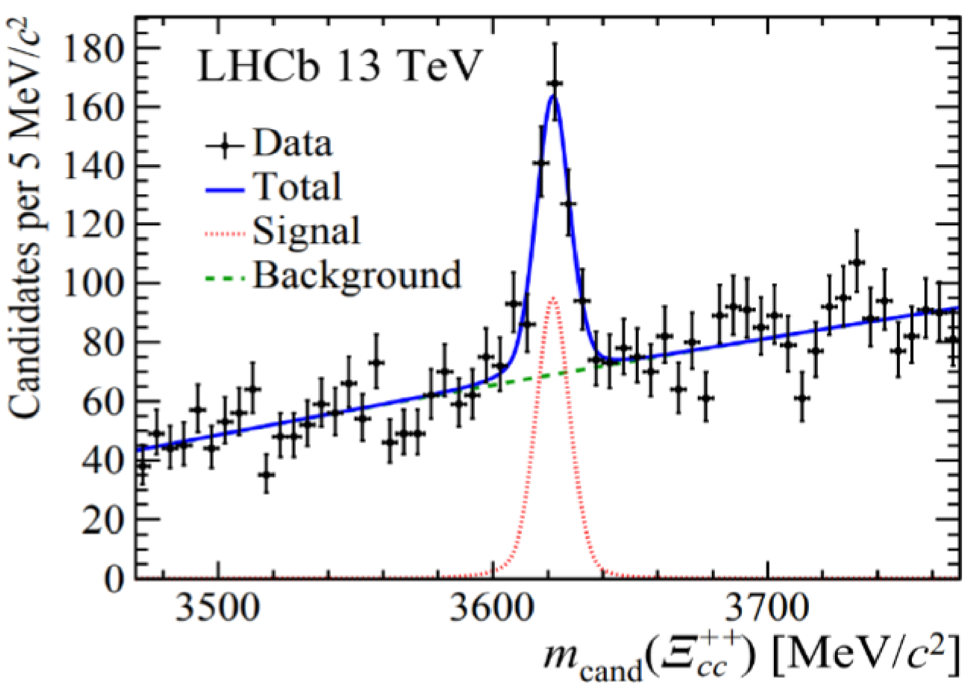
Thanks to heavy quarks, for the first time it was possible to unambiguously identify **exotic hadrons: multiquark states.**

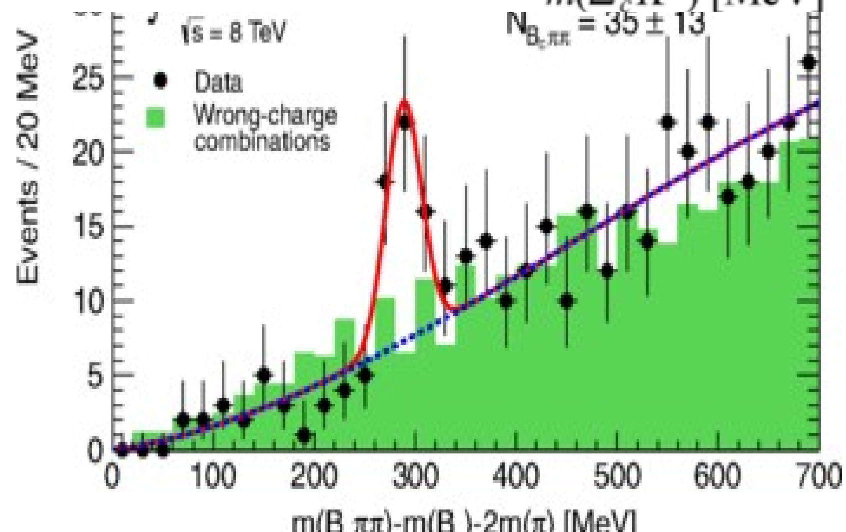
A second thrust to Hadron Spectroscopy

Studying heavy flavors at an hadronic machine opened new fields:

- Baryons (including pentaquarks)
- Doubly heavy hadrons (B_c and Ξ_{cc})







Outline

- Theoretical context
- The LHCb experiment
- The upcoming upgrade of the LHCb experiment
- Perspective and challenges for Heavy Hadron Spectroscopy

Theoretical Context

Quarkonium Production in hadron collisions

Prompt production

Quarkonium production is described with Non-Relativistic QCD (NRQCD) and the factorization hypothesis

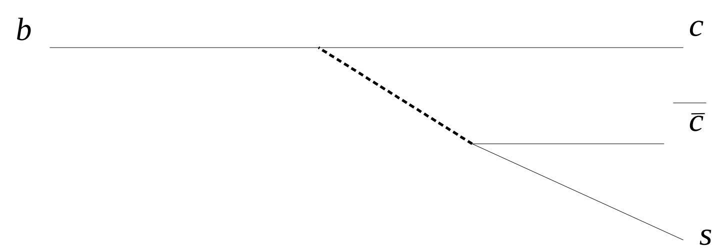
$$d\sigma_{pp\to Q+X} = \sum_n d\hat{\sigma}_{pp\to Q\bar{Q}[n]+X}\langle \mathcal{O}^Q(n)\rangle$$

Assuming “factorisable”:

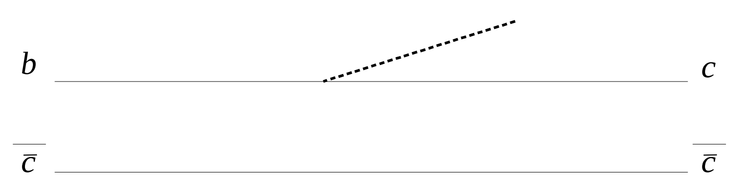
- Perturbative QCD diquark production (computed as QCD scattering)
- Non-perturbative hadronization (fitted from data)

Charmonium production in *b*-decays

Charmonium can be produced in *b*-hadron decays in $b\to c\bar{c}s$ transitions



Recently, also production from B_c decays became observables.



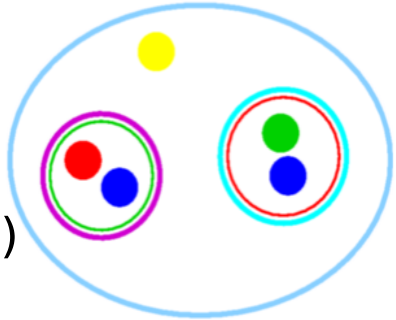
Nature of the exotic hadrons

It is well agreed that there are quarkonium-like states that do not fit the conventional hadrons, baryons qqq and mesons $q\bar{q}$ but several model exist to decribe (some) of these states.

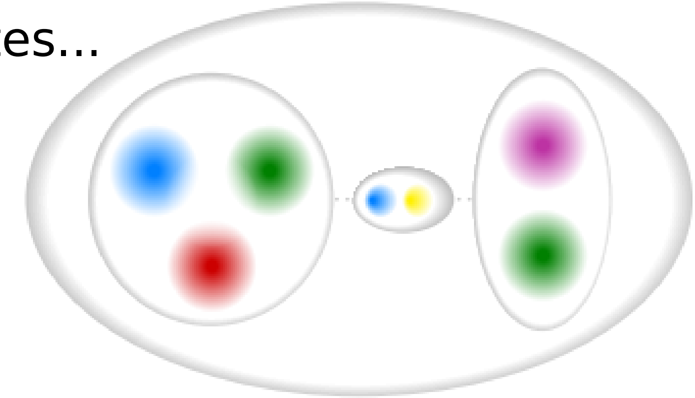
Fact: all the observed states lay at some threshold, *e.g.* $m_{X(3872)} \sim m_D + m_{D^{star}}$

Broadly speaking, there are three families of models:

- Rescattering effects (or cusps)
- Tightly bound tetraquarks (similar to conventional hadrons)
- Molecular states (similar to light nuclei)



... or it could be a combination of these states...



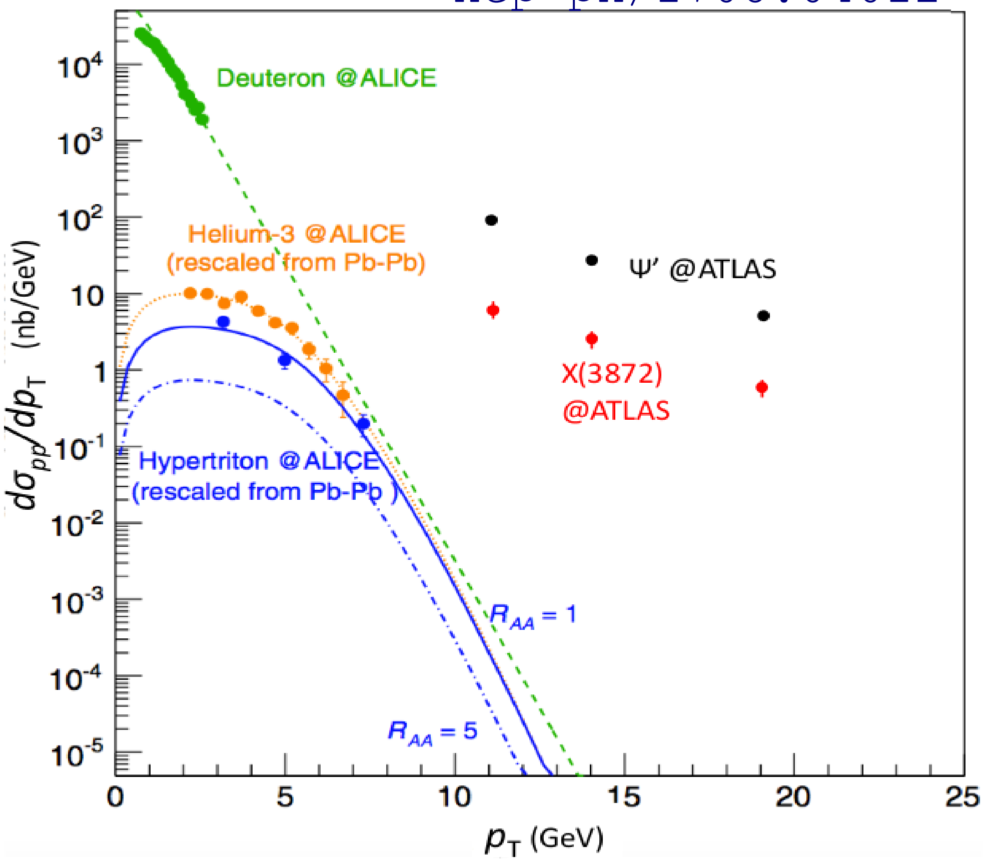
Do the observed state share the same nature?
Or are we seeing different phenomena
without a unique pattern?

1. Study the production measurements

The theoretical predictions on quarkonium production have improved a lot in the last ten years. Today they can be used as baseline to infer the nature of the quarkonium-like states.

For example, important difference between the pT spectra of X(3872) and light nuclei disfavors the molecular interpretation.

hep-ph/1708.04012



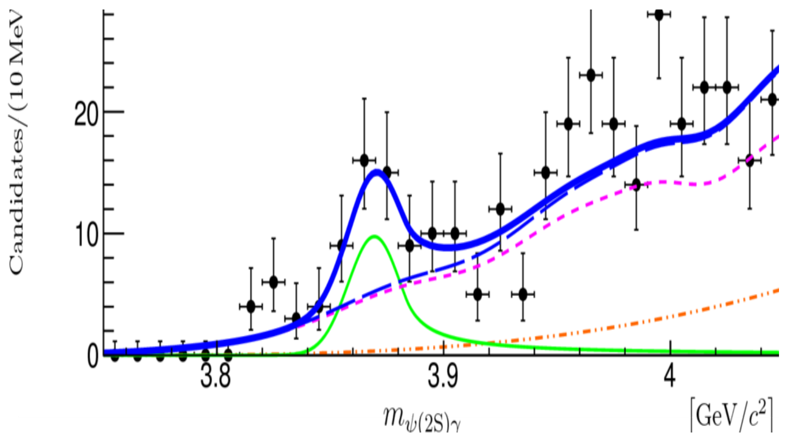
2. Search for more decays of exotic hadrons

An important set of constraints on exotic hadrons comes from the decay pattern.

Examples:

- X(3872) → $\psi(2S)\,\gamma$ is favored over X(3872) → $J/\psi\,\gamma$
  - This favors pictures with radial cc excitations over molecular interpretation
  - Observing the state in more final states, speaks against rescattering

Evidence of X(3872) → $\psi(2S)\,\gamma$
hep-ex/1404.0275



- The observed pentaquark $P_c \to J/\psi\, p$ could be observed as $P_c \to \chi_c\, p$
  - If observed it would speak against rescattering interpretation of the pentaquark

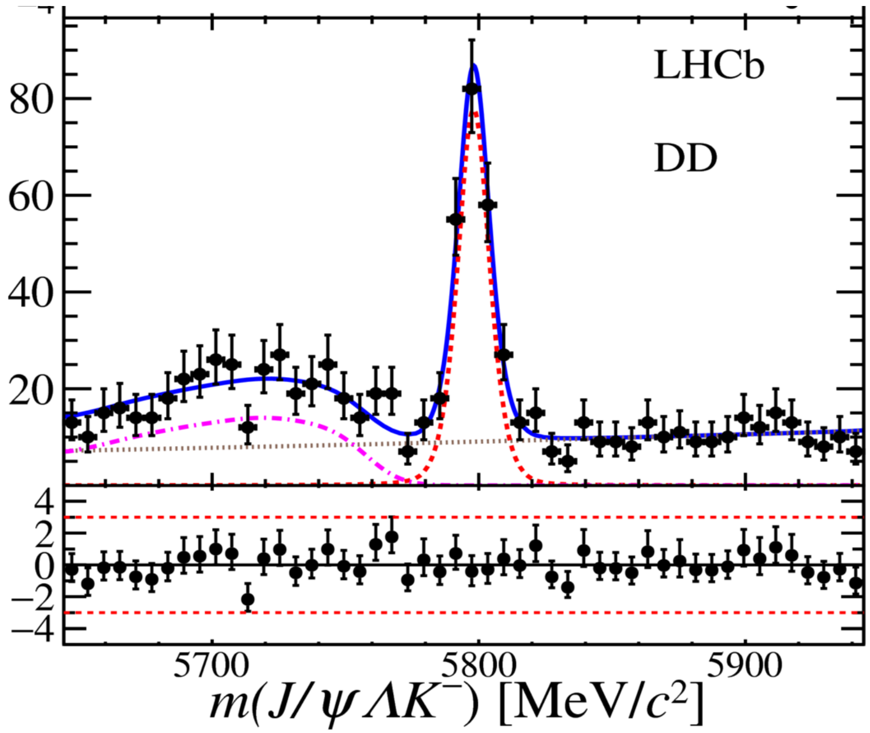
3. Search for more states

In the tight-hadron picture, we expect exotic hadrons to sit in isospin multiplets.

The exploration of new decay modes is necessary.

Example:

Search for P_{cs} pentaquark states decaying to $J/\psi\,\Lambda$ in the final state of $\Xi_b \to J/\psi\,\Lambda\,K$



LHCb-Run1 Statistics not enough to conclude, but very interesting prospects for a Run2 analysis.

The LHCb experiment

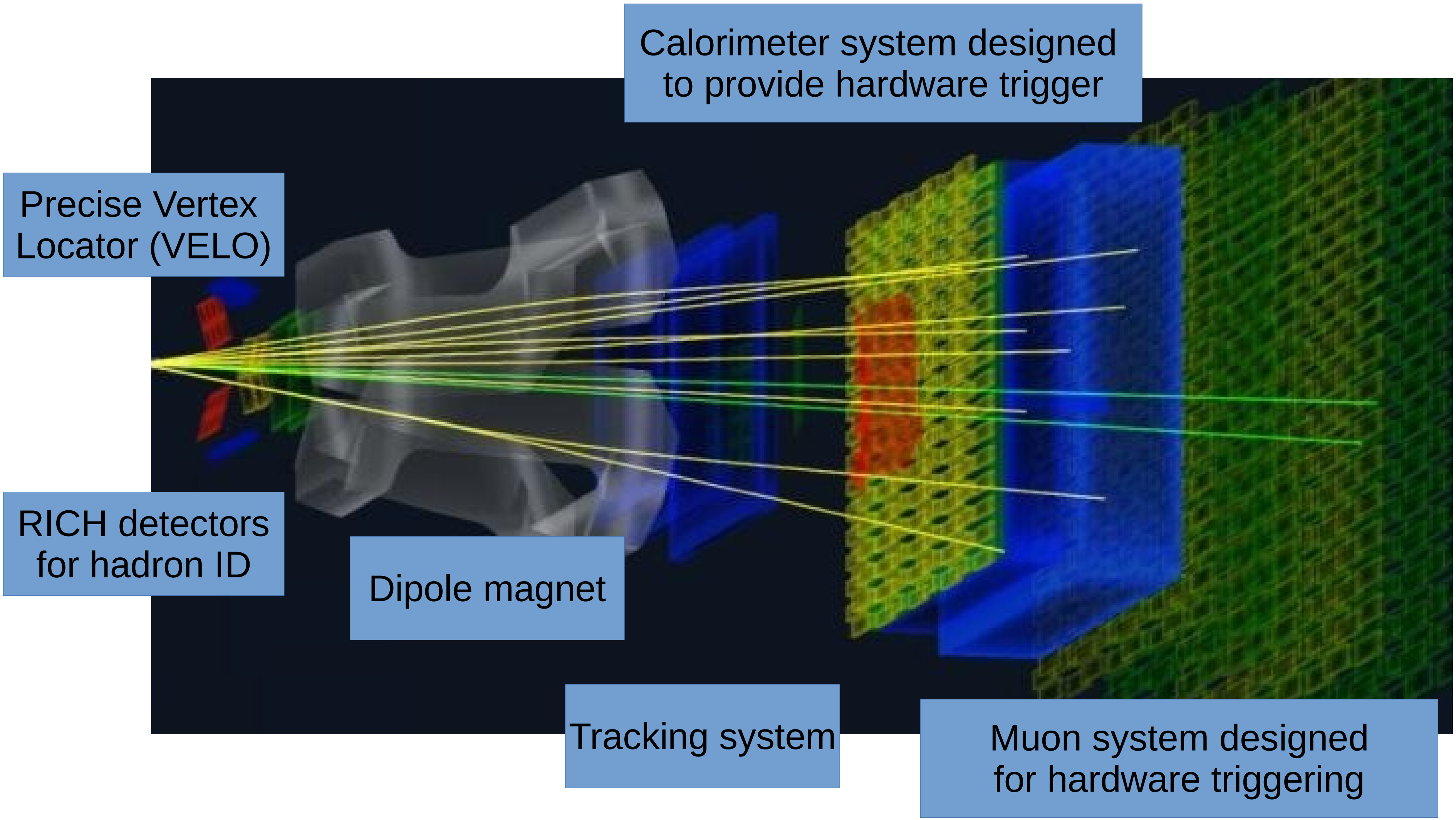
The Large Hadron Collider (LHC)

World's largest collider.

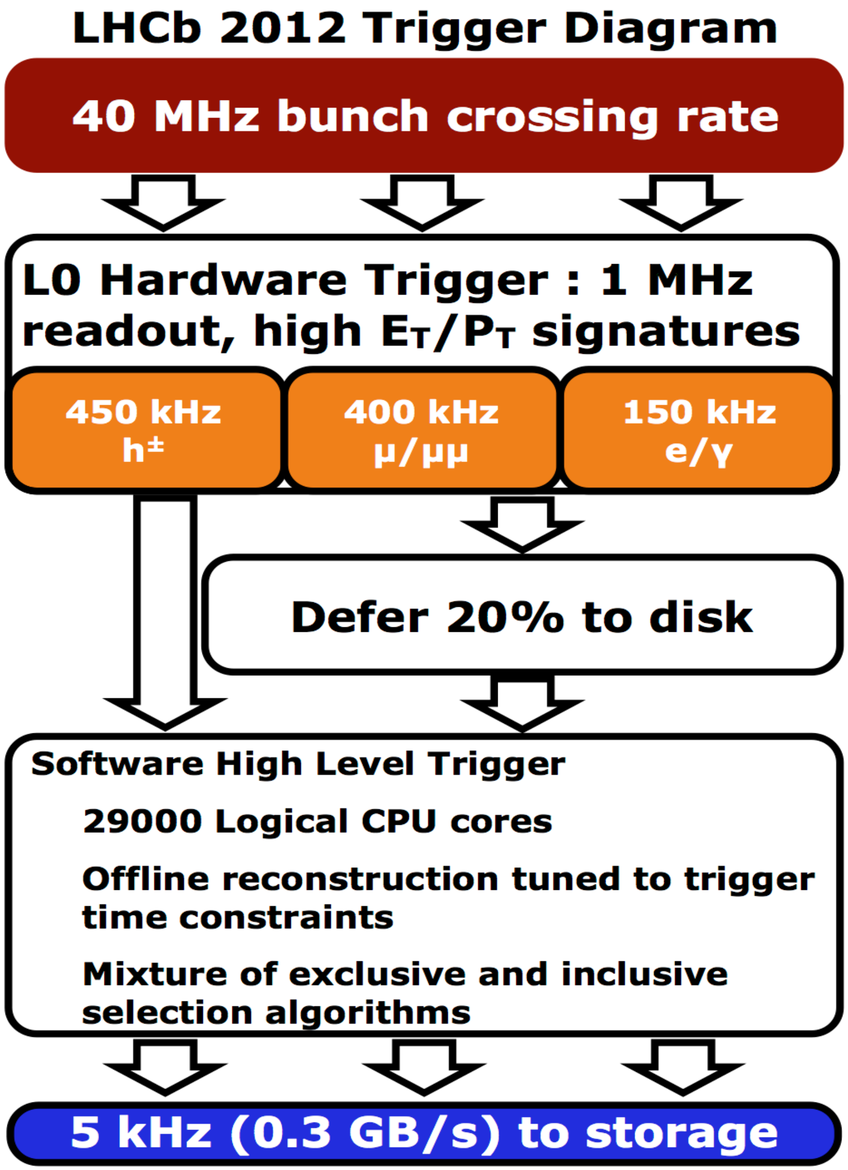
Proton – proton collisions in collider mode at up to 13 TeV in the center of mass

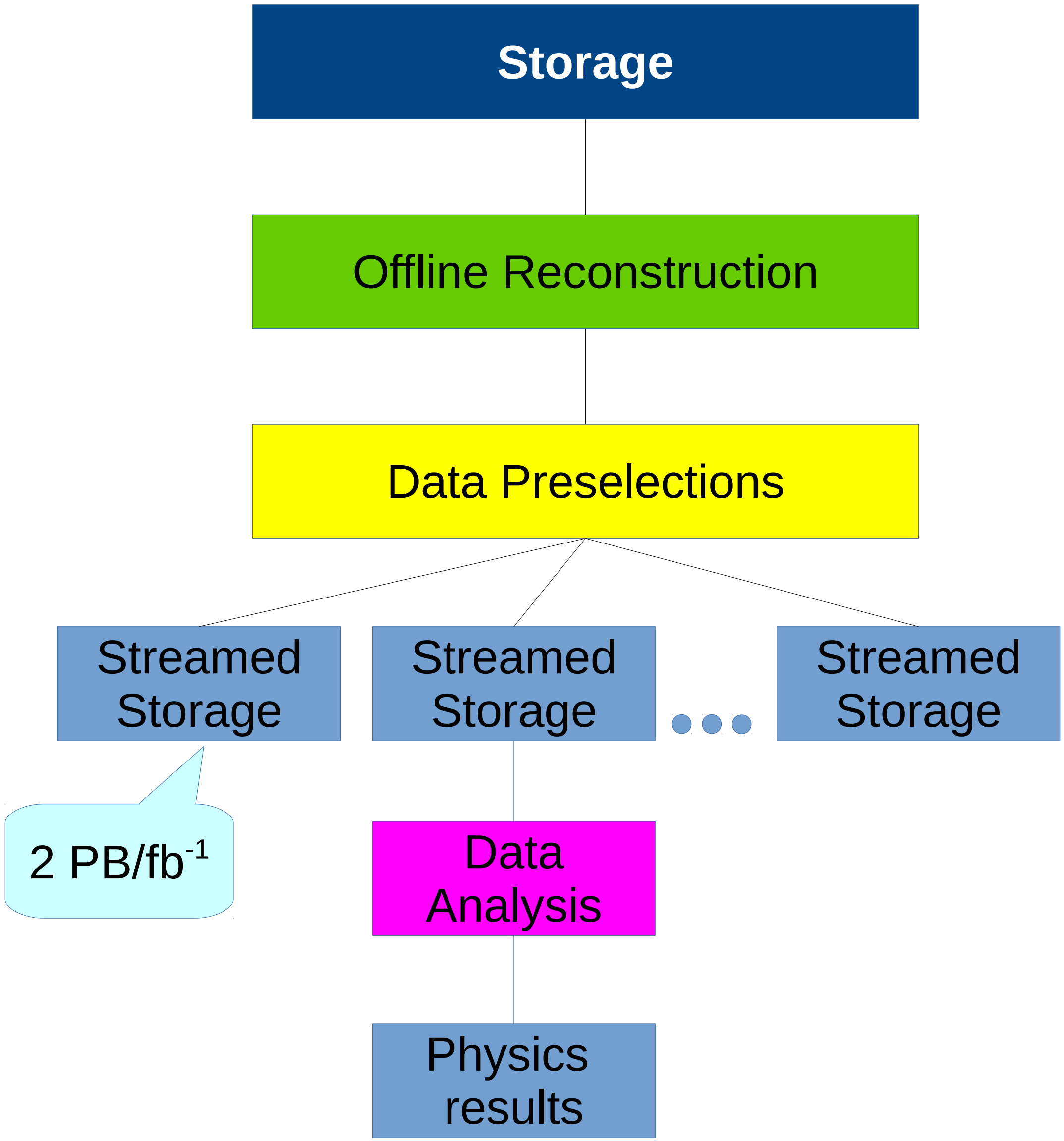
Four interaction points where beams cross, large detector built around the interaction points.

The LHCb detector



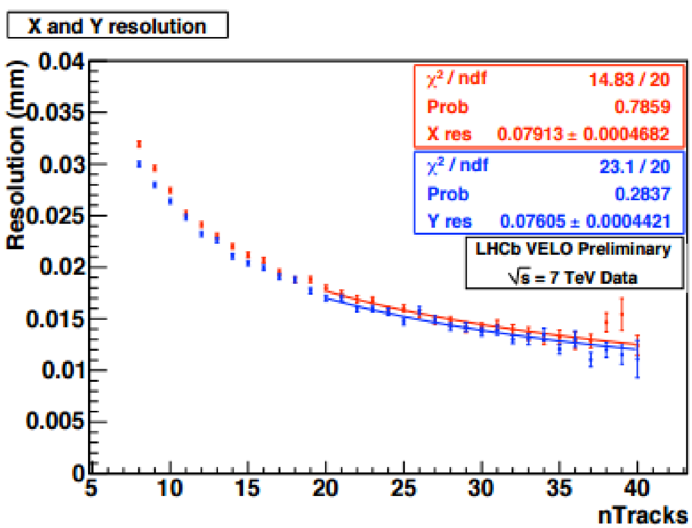
The LHCb trigger and computing model

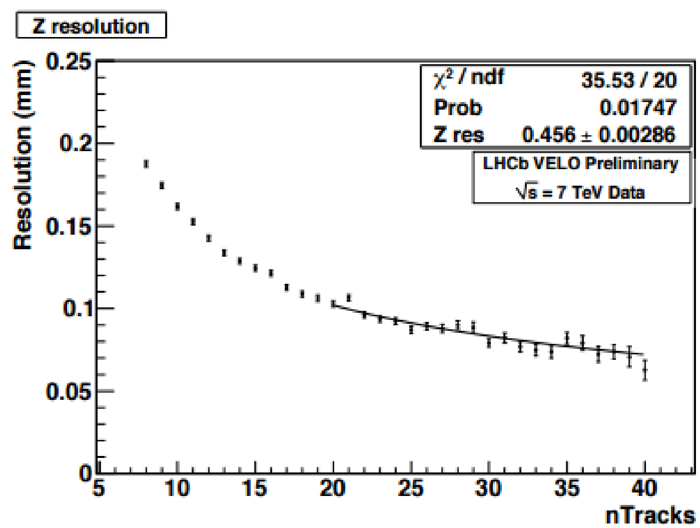




Designed to reconstruct (and trigger) *b*-hadron decays

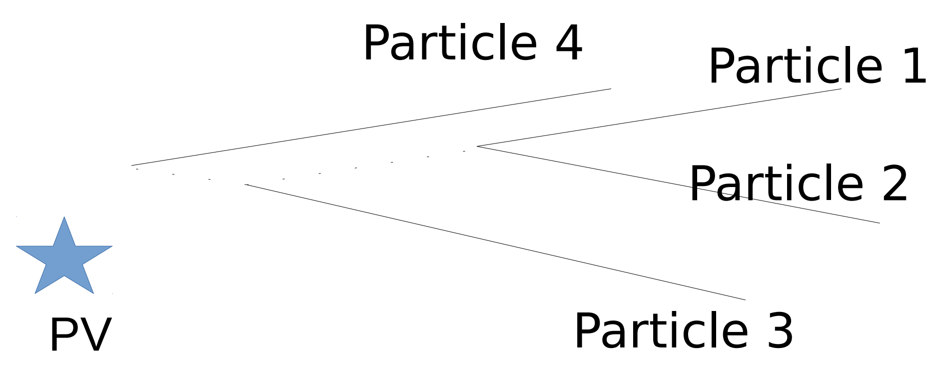
To enhance efficiency on *b*-hadrons it is crucial to reject the background from the primary vertex (proton-proton collision).





To profit from excellent vertex resolution at trigger level, *topological trigger lines* based on *machine learning techniques* were introduced.

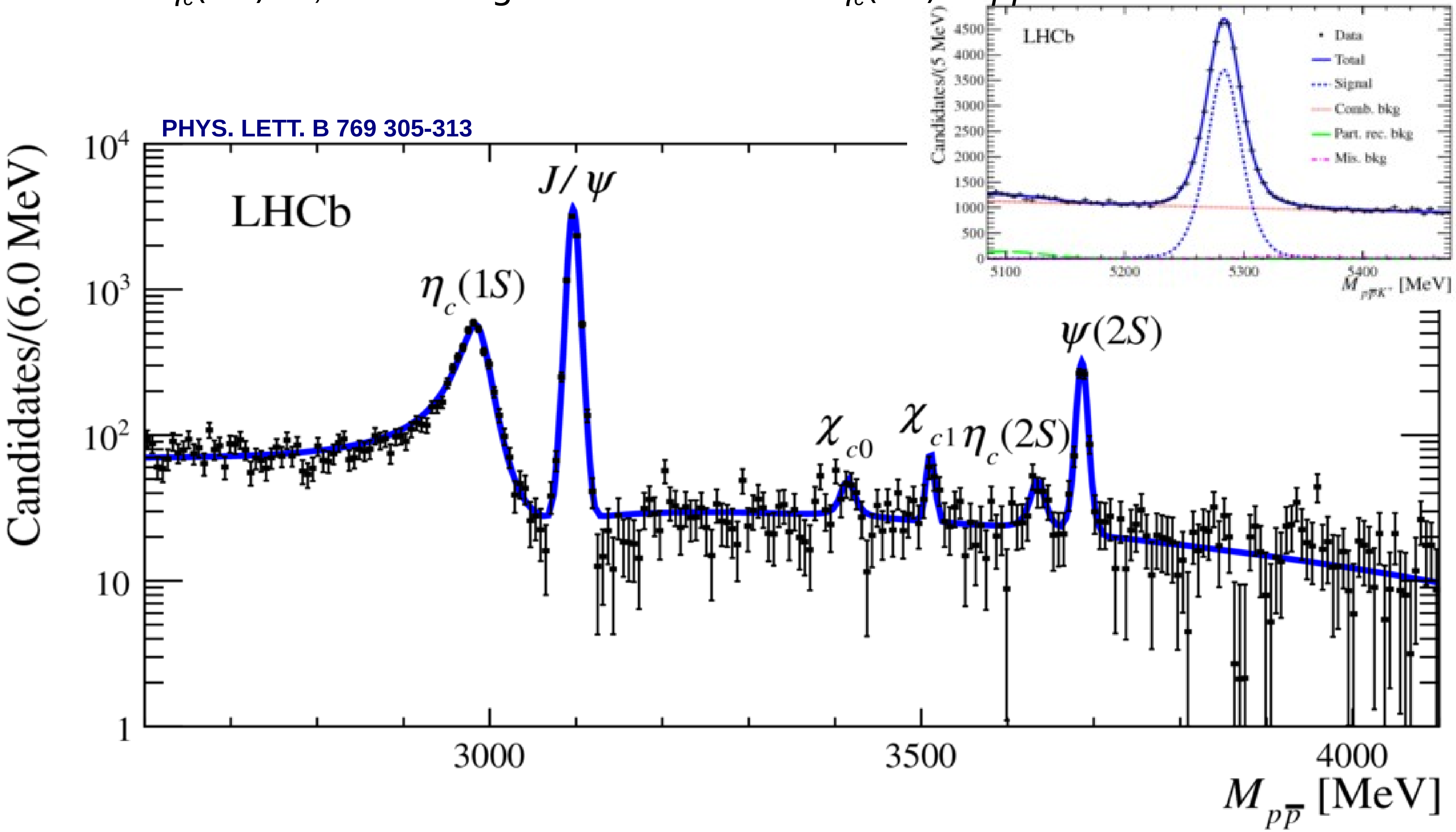
Iterative combination of tracks pair with *Boosted-Decision Tree criteria.*



Can be very fast using only tracking information

Charmonium in *b*-decays relying on *topo-triggers*

Topological trigger lines were used for example to reconstruct the decay $B^+ \to \eta_c(2S) K^+$, observing for the first time $\eta_c(2S) \to p\bar{p}$.



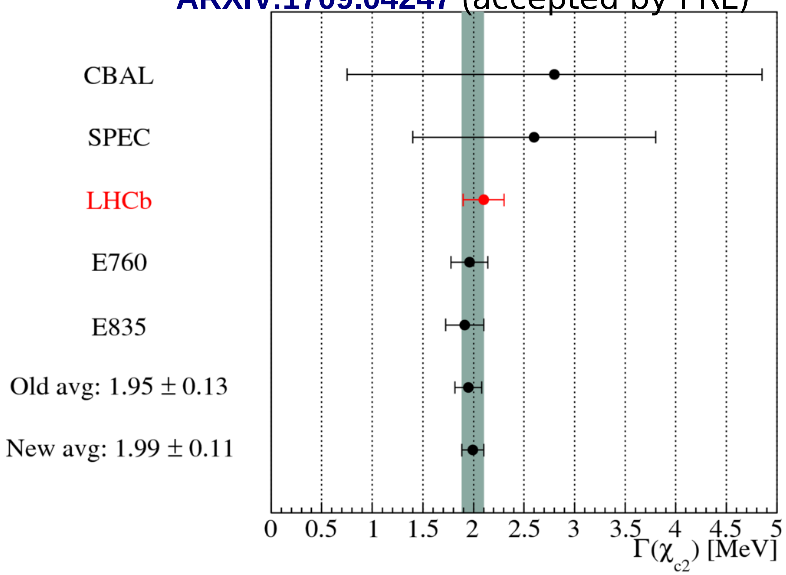
High mass resolution and muons for prompt studies

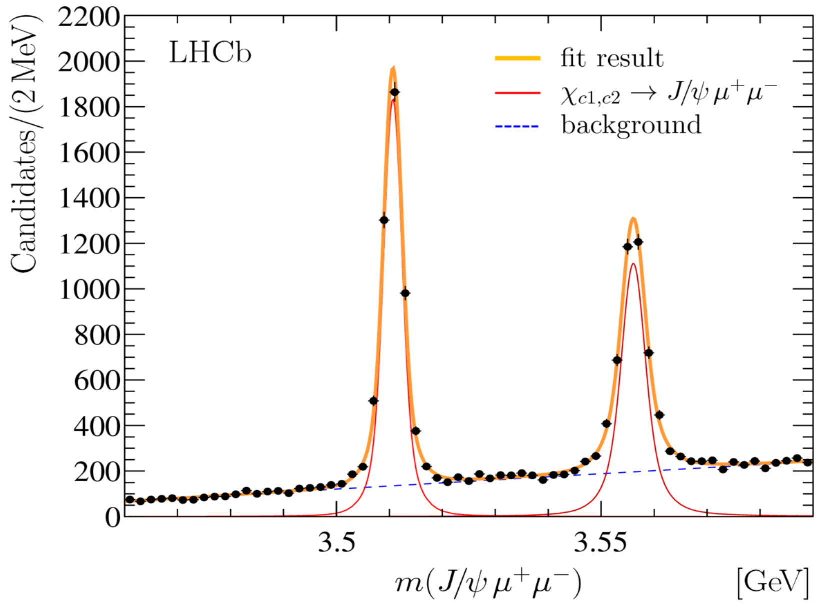
Life is made much easier using muons, thanks to the excellent Muon System performance (and to the relative rarity of muons in the final state of QCD processes).

For example, LHCb recently observed **prompt** decays $\chi_{c1} \to J/\psi\ \mu\mu$ and $\chi_{c2} \to J/\psi\ \mu\mu$.

The small energy release and the the **excellent momentum resolution** allowed to measure mass of χ_{c1} and χ_{c2} and width of χ_{c2}, with an uncertainty for the first time **competitive** with **total-annihilation experiments.**

ARXIV:1709.04247 (accepted by PRL)



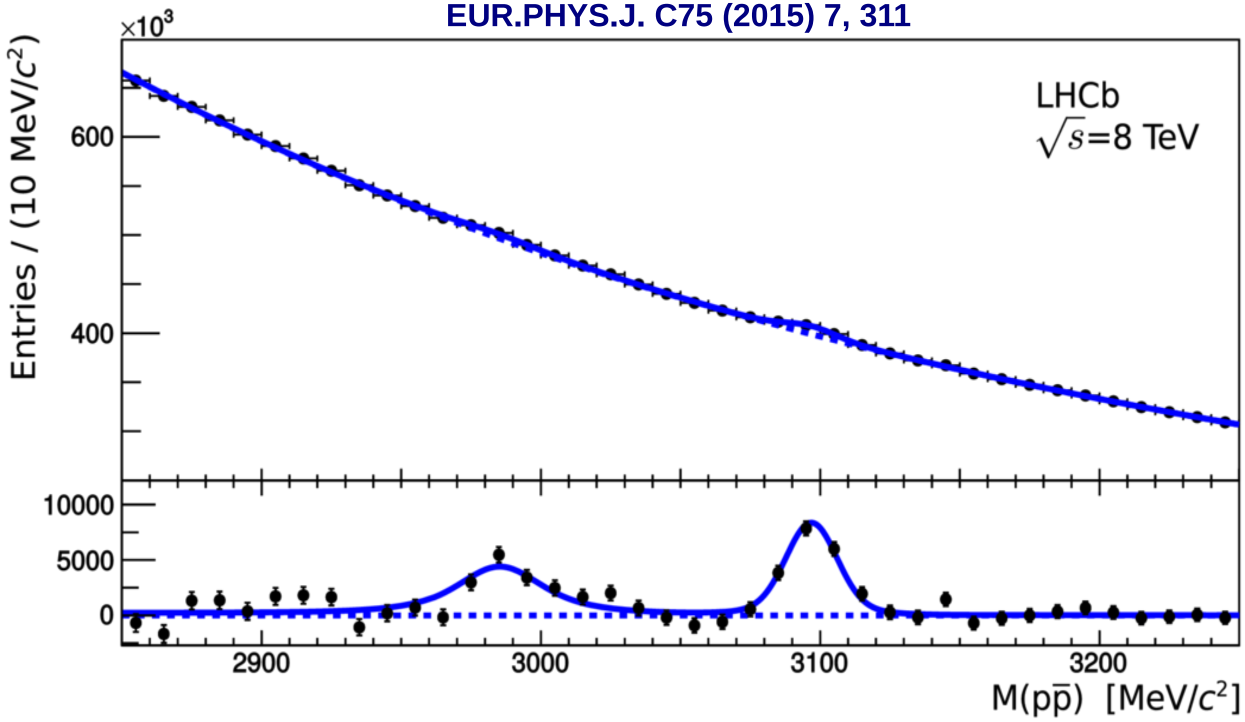


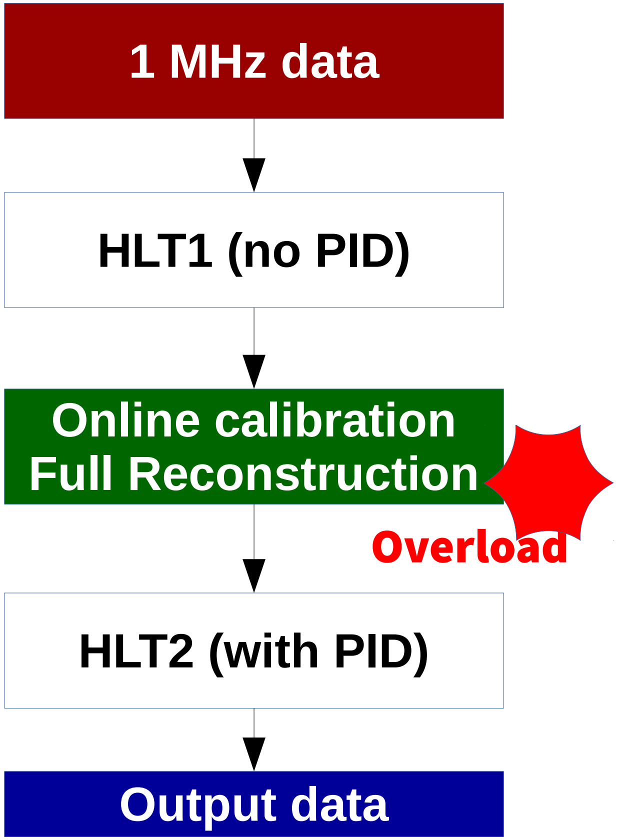
Challenging fully hadronic prompt decays, $\eta_c \to p\bar{p}$

When looking for prompt decays with no muons in the final state, large background is expected, but measurements are possible using **dedicated trigger lines**.

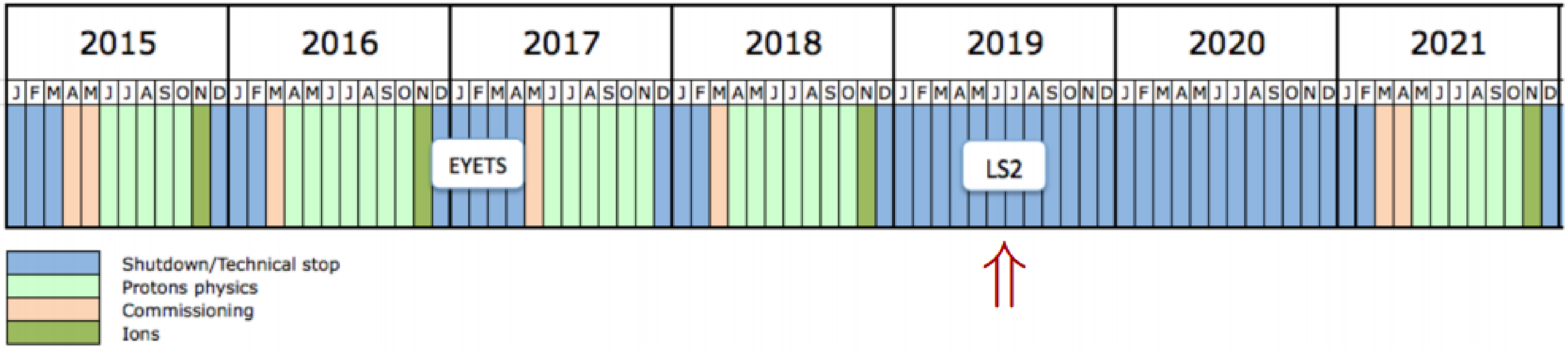
As an example: the measurement of the $\eta_c \to pp$ production cross-section in pp collisions was performed with a dedicated *dihadron* trigger line.

EUR.PHYS.J. C75 (2015) 7, 311





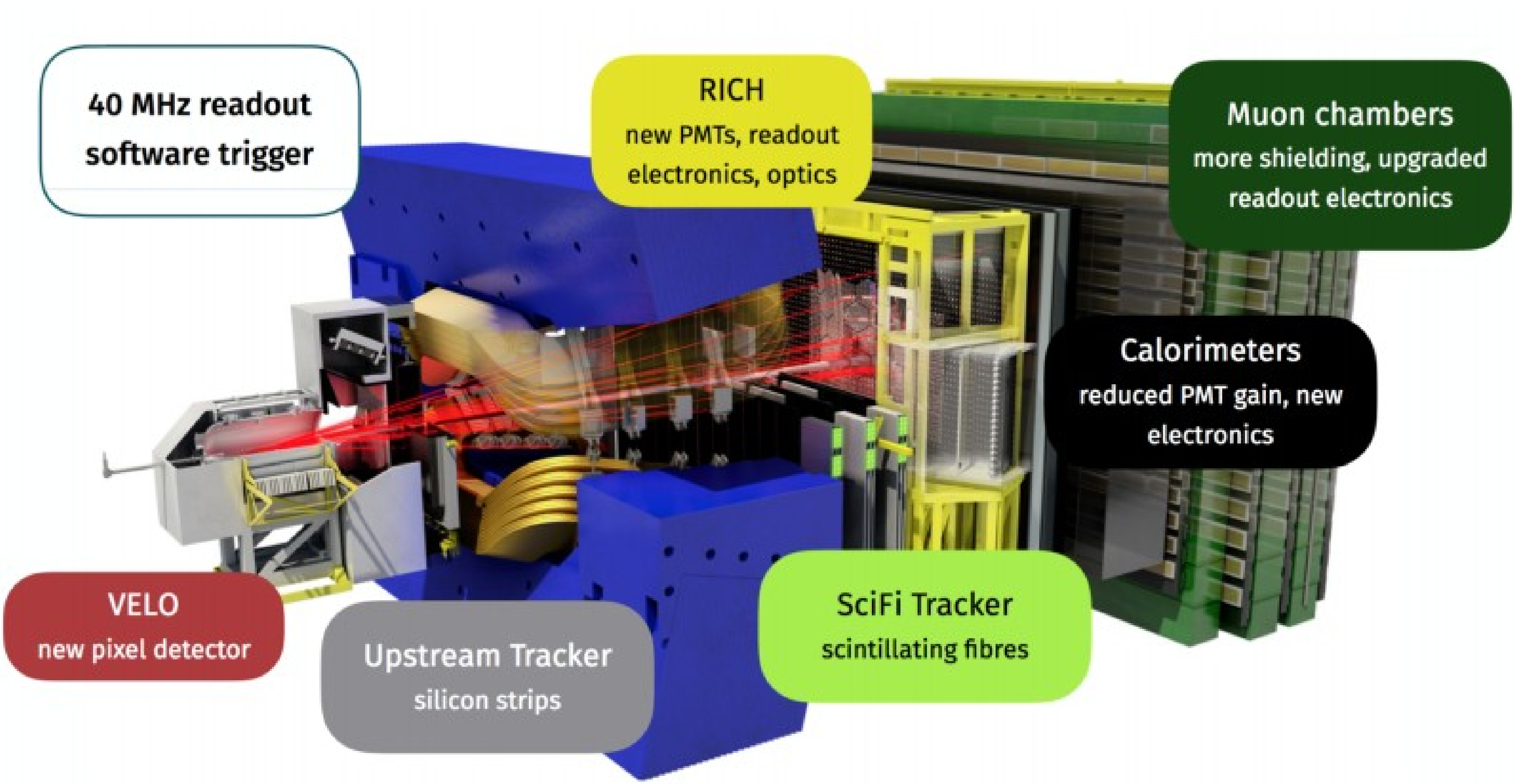
The Upgrade of the LHCb experiment



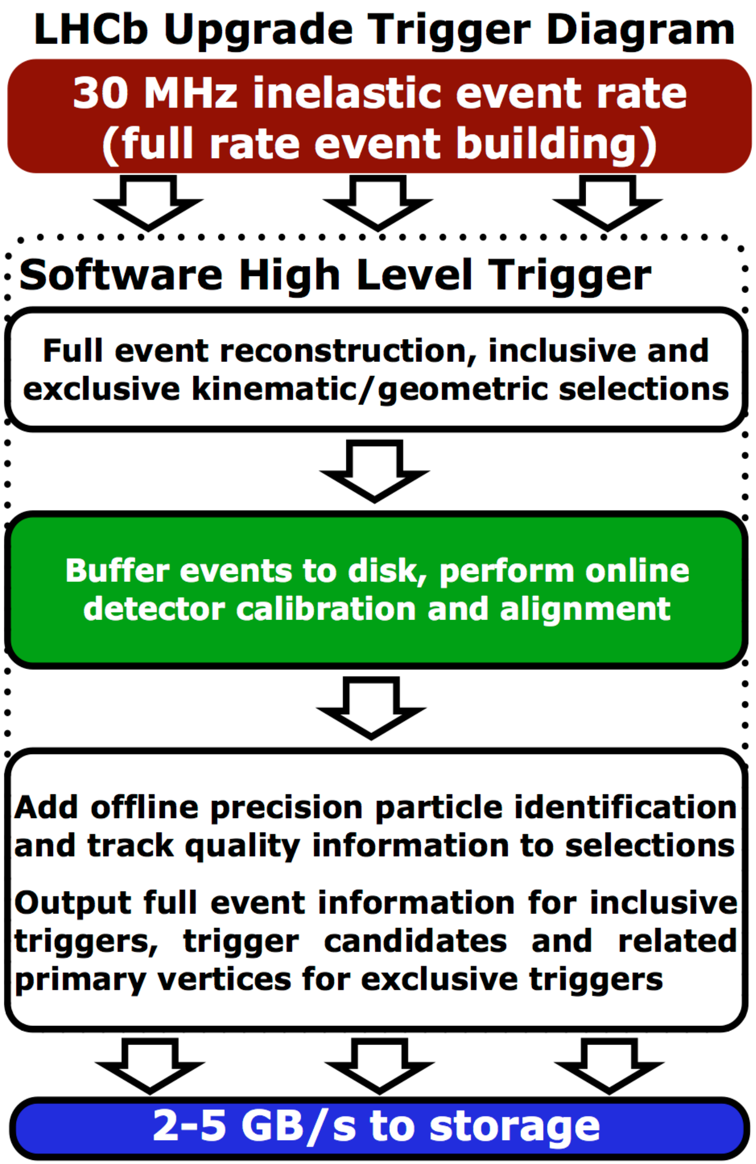
The 40 MHz challenge

- The main goal is to enhance the **instantaneous luminosity** (up to 2×10^{33} cm^{-2} s^{-1}), **in order to integrate 30 fb^{-1} by the end of Run3** (end of 2023)**.**
- More luminosity requires **higher pile-up** (*pp* collisions in the same bunch crossing)
  *Resulting in **higher occupancy of the detector**.*
- Every event will contain at least a heavy hadron (either c- or b-flavored)
  Implying that hardware trigger rejecting soft-QCD events would be uneffective.
  Moving to a purely software trigger implies
  full read-out of the whole detector at the bunch-crossing frequency of 40 MHz.

The detector upgrade in one slide



Fully software trigger



The offline reconstruction is totally moved to the online, trigger reconstruction.

The detector data (*raw event)* will be discarded and only high-level post-reconstruction information will be kept.

The technique (*Turbo)* has been successfully employed during Run 2 for a limited list of decay modes and it was proved to work effectively.

Inclusive selections (such as *dimuons)* are ineffective.

Exclusive selections will be requiring a very careful planning.

Particle identification since the first trigger layer

Considering again the prompt $\eta_c \to p\bar{p}$,
one notice that this decay
(prompt and with purely hadronic final state)
becomes as easy as decays to muons for the
upgrade computing model.

It could become easier to design analyses
for prompt decay channels.

Combined with the higher statistics, the new
trigger scheme will allow to observe $\Lambda_b \to \eta_c\, p\, K^-$
which could provide indication for $P_c \to \eta_c\, p$ decays.

30 MHz data

↓

HLT1 (with PID)

↓

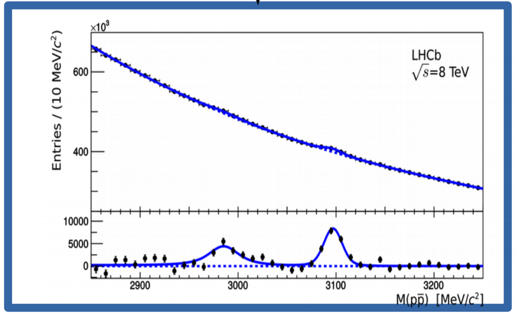
Online calibration
Full Reconstruction

~~Overload~~

↓

HLT2 (with PID)

↓



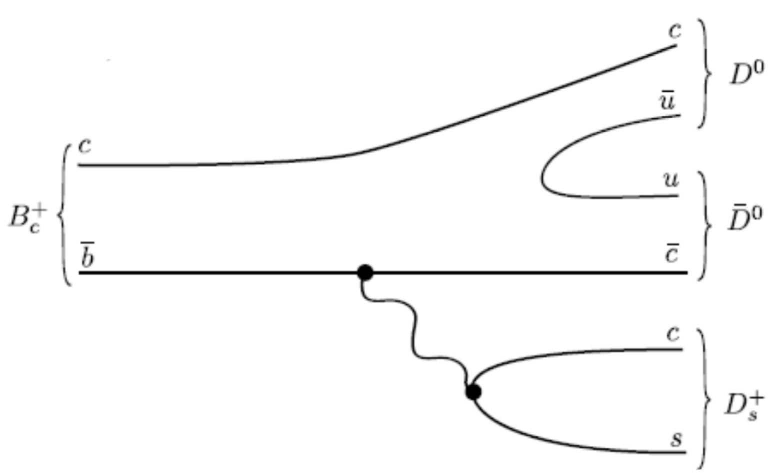
Phys. Rev. D 88, 054029 (2013)

Spectroscopy using B_c decays

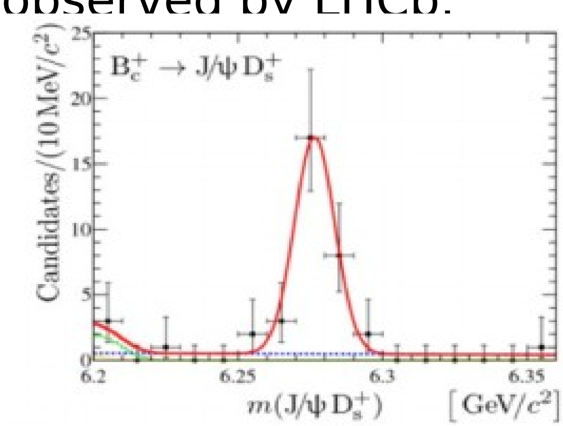
Why wasn't the pentaquark observed before LHCb?

- Because LHCb is the first experiment collecting thousands of Λ_b decays.
  A new *b*-hadron might imply new spectroscopy.

The B_c meson can become the "Λ_b of the LHCb upgrade", opening to **doubly-charmed tetraquark searches**: $B_c \to T_{ccs}\,\bar{D}^0$ with $T_{ccs} \to D^0\, D_s^+$.



LHCb could achieve a first observation already in 2023 with O(10) events, extrapolating (accounting for an additional 5% BF) from $B_c \to J/\psi\, D_s$ already observed by LHCb.



Spectroscopy with the upgraded LHCb detector

Requirements and constraints

- More decay modes of exotic states
- More decay modes of heavy hadrons (to search for other exotic states)
- More heavy hadrons with increasing number of possible final states (with small BF)
- Explore more the prompt-production of exotic states

- Precise definition of the selection strategy: at regime, only exclusive selections (order of 5000).

  We developed more than 1300 different selection strategies, only on Run 1.

- Maintainable (and robust) trigger

  Challenging, but LHCb always loved challenges :)

The simulation challenge

Developing thousands of selection strategies, before starting collecting data requires

a lot of Simulated samples for the signal;

huge Background samples to populate the tails of the distributions.

With the current fast-simulation options, even moving the whole production to fast-simulation (unrealistic), would <u>not</u> be <u>sufficient</u> to cover the extrapolated needs with the available pledges.

LHCb is exploring:

- *parametric-simulation* techniques for samples good enough for the selection strategy

  e.g. RapidSim or Delphes

- *Machine-learning techniques* to correct the simulation with calibration data promptly after the start of data-taking.

  e.g. Meerkat (2015 JINST 10 P02011)

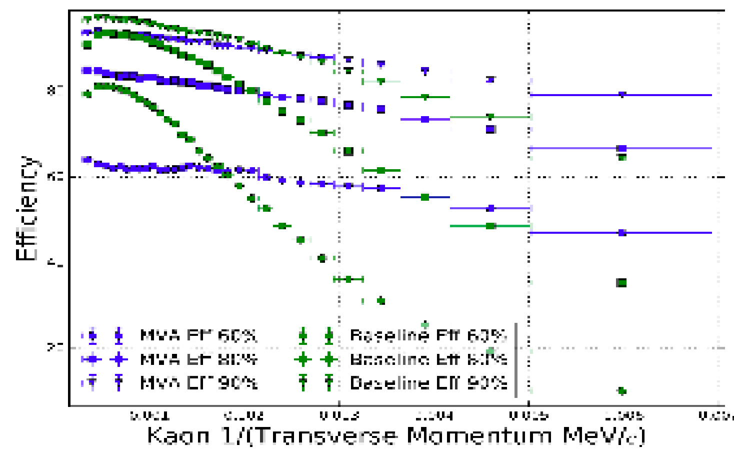
Extending the Topological Trigger using PID

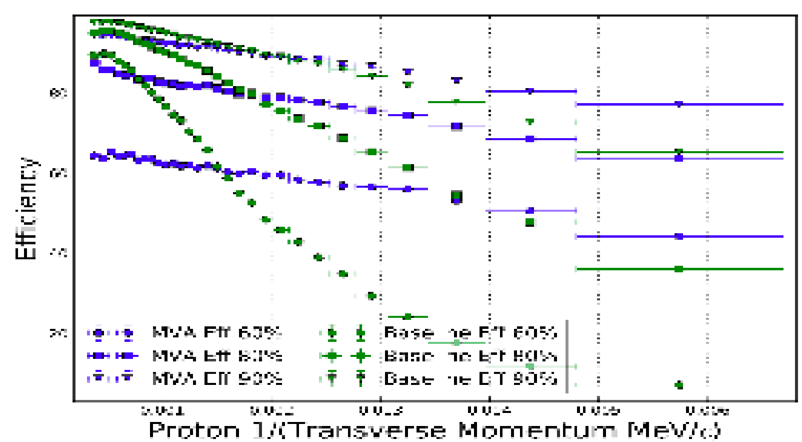
The topological trigger approach has been demonstrated to be very powerful, and the efficiency can be determined effectively.

The offline-quality particle identification could now be included in the selection strategy, based on a similar algorithm.

LHCb has developed *machine-learning algorithms* combining the *particle-identification* information for several sub-detectors with (*almost*) flat efficiency as a function of the kinematic variables, to ease efficiency determination

[poster at ACAT 2017]



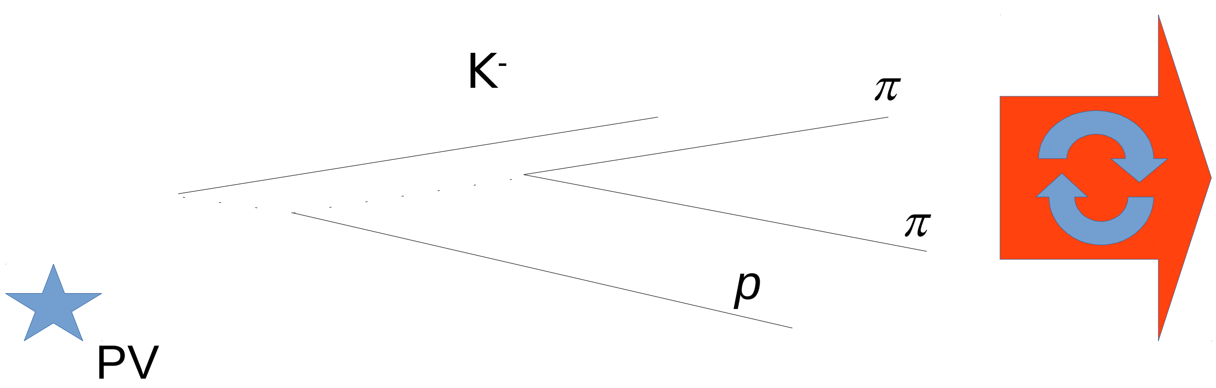


A very long-term view

Combining

- fast and accurate parametric simulation
- Particle-Identification-Aware topological triggers
- Modern large-scale *machine learning systems* with thousands of classes

one can hope to build an automatic classifier of decay chains.



$\Xi_b^0 \to \Lambda_c K^-$

with $\Lambda_c \to K_S^0 p$

with $K_S^0 \to \pi\pi$

Summary and conclusion

LHCb upgrade a “third renaissance” for spectroscopy?

The LHCb experiment at the LHC is being playing a key role in heavy hadron spectroscopy.

The upcoming upgrade offers great opportunity of enhancing the physics reach thanks to **higher luminosity, earlier application of particle identification, less selection layers.**

Big challenges are being faced for Trigger, Data processing and Simulation.