Experimental Flavour Physics

Lecture I: Where to study flavour and how to do it

Guy Wilkinson
University of Oxford

TIFR, September 2023

Lecture plan

Lecture I	Why study flavour and where ? Focus on how to do this at hadron machines, in particular the LHC and LHCb. Closing digression on hadron spectroscopy.
Lecture II	Unitarity Triangle metrology and CPV measurements
Lecture III	New Physics searches through studies of Flavour-Changing Neutral Currents (and other processes)
Lecture IV	Charm physics, and future prospects for experimental flavour studies

Upfront admission: I will be saying a lot about LHCb.

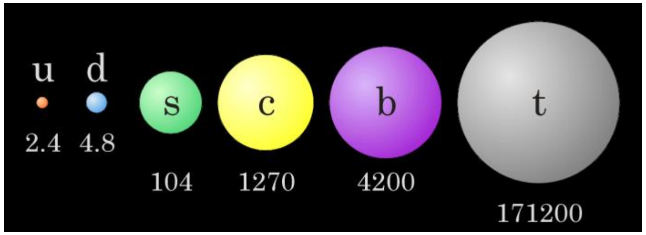
Lecture-I outline

- Why study flavour, and where ?
- Why do we need a dedicated flavour experiment at the LHC ?
- Some historical notes
- Essential attributes of LHCb:
    - geometry and choice of luminosity
    - instrumentation
    - the data challenge and the trigger
- Not quite flavour: hadron spectroscopy at the LHC

Why flavour ? A puzzle of the SM

Flavour encompasses many of the open questions of the Standard Model.

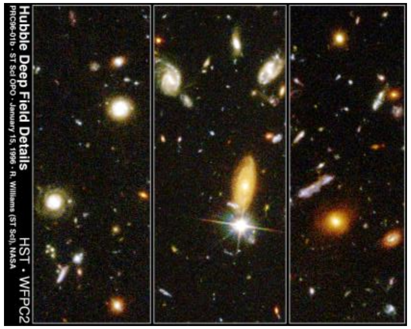
- Why 3 generations of quarks, and why the extreme hierarchy of masses ?



- What determines the hierarchical structure of the CKM matrix ?

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 0.9705-0.9770 & 0.21-0.24 & 0-0.014 \\ 0.21-0.24 & 0.971-0.973 & 0.036-0.070 \\ 0-0.014 & 0.036-0.070 & 0.997-0.999 \end{pmatrix}$$

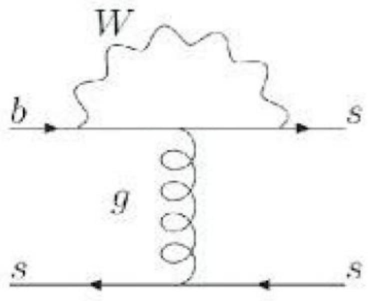
- The CKM paradigm accommodates CP violation, but it does not really explain it. Furthermore, can the study of quark flavour tell us anything about the matter-antimatter asymmetry of the universe ?

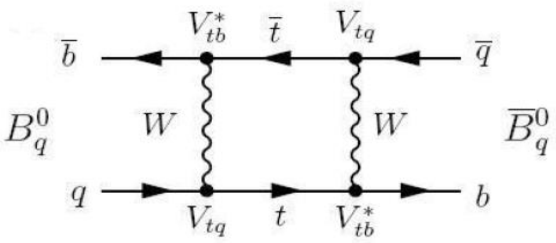


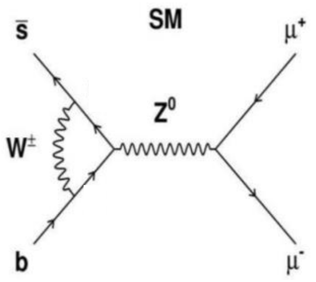
Most importantly, flavour physics is a tool of discovery !

Why flavour ? A tool of discovery

In flavour physics the guiding principle is to probe processes where loop diagrams are important, as here non-SM particles may contribute.





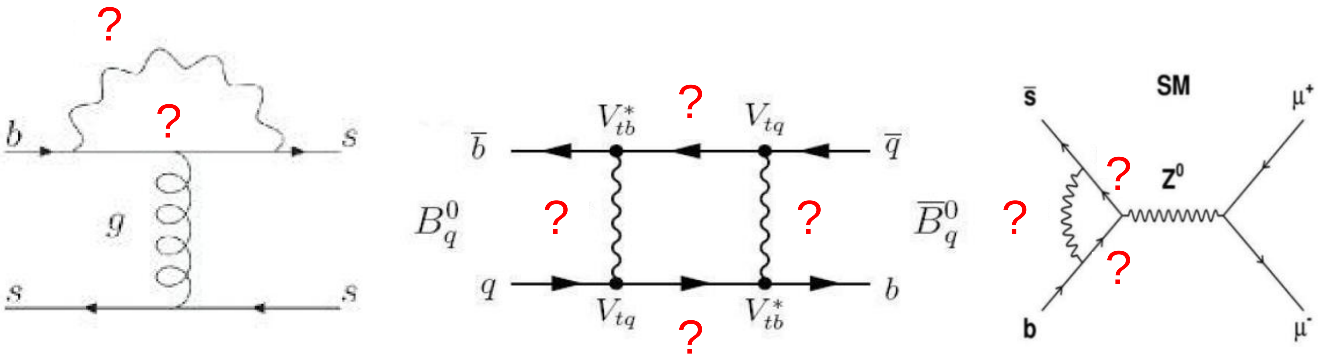


(but as we will see, tree-mediated decays also have their role to play).

Indirect search principle ➡ Precise measurements of low energy phenomena tells us about unknown physics at (potentially *much*) higher energies

Why flavour ? A tool of discovery

In flavour physics the guiding principle is to probe processes where loop diagrams are important, as here non-SM particles may contribute.



(but as we will see, tree-mediated decays also have their role to play).

Indirect search principle ➡ Precise measurements of low energy phenomena tells us about unknown physics at (potentially *much*) higher energies

These lectures will address how these measurements are made. We will focus on colliders, and on heavy quarks (charm and beauty). But there is still much to be learned from kaons, and the mysteries of flavour extend to lepton sector too.

Collider options for flavour (main players)

	$e^+e^- \to Z^0 \to b\bar{b}$	$e^+e^- \to \Upsilon(4S) \to b\bar{b}$ (or at $\Psi(3770)$ if want to study charm only)	$p\overset{(-)}{p} \to b\bar{b}X$
Past	ALEPH, OPAL, DELPHI, L3 at LEP	ARGUS, CLEO BaBar, Belle	UA1, UA2 at Sp$\bar{p}$S CDF, D0 at Tevatron
Current	/	Belle II BESIII (charm threshold)	LHCb, ATLAS, CMS at LHC
Future	FCC-ee	Belle II upgrades Super Tau Charm Factory	LHCb, ATLAS, CMS upgrades FCC-hh

Collider options for flavour (main players)

	$e^+e^- \to Z^0 \to b\bar{b}$	$e^+e^- \to \Upsilon(4S) \to b\bar{b}$	$\overset{(-)}{p}p \to b\bar{b}X$
Past	ALE DELPH		2 at Sp$\bar{p}$S at Tevatron
Current			, ATLAS, S at LHC
Future	FCC-ee	Belle II upgrades Super Tau Charm Factory	LHCb, ATLAS, CMS upgrades FCC-hh

I have chosen to focus the discussion on the LHC and LHCb in particular.

This is largely because of personal bias, but also because the hadronic environment poses the most interesting experimental challenges.

But don’t lose sight of fact that a huge number of leading results have emerged from the $\Upsilon(4S)$!

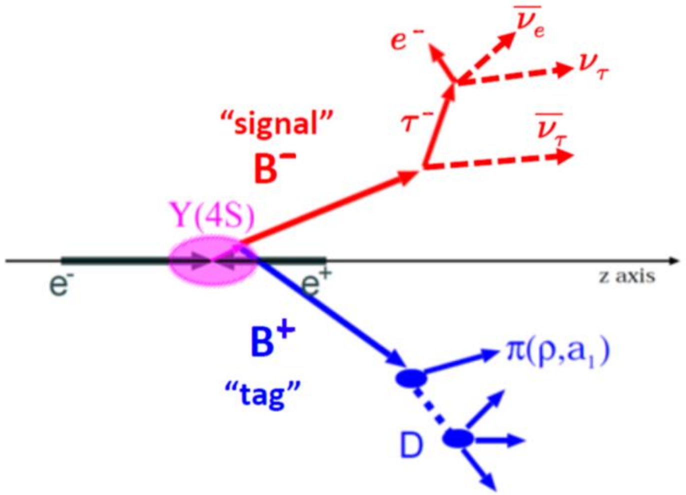
We will discuss b-physics at the Z^0 in Lecture IV.

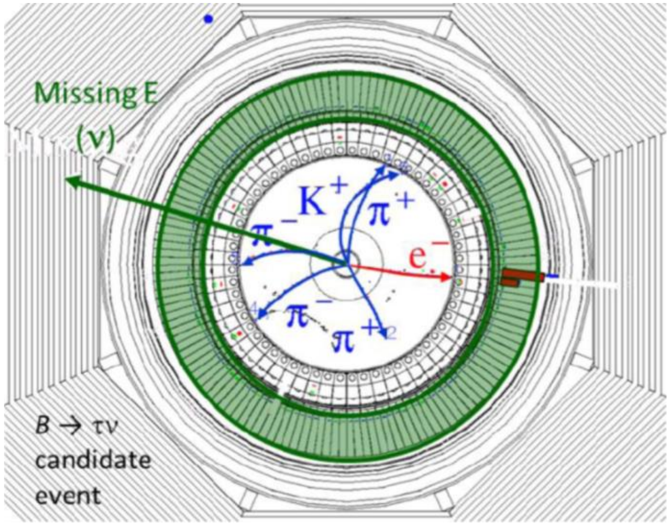
Why perform B physics at Υ(4S) ?

B production at the Υ(4S) presents several very advantageous features:

- Can reconstruct full event, which is beneficial for missing energy modes and also inclusive measurements (typically lower theory uncertainties).

e.g. B→τν





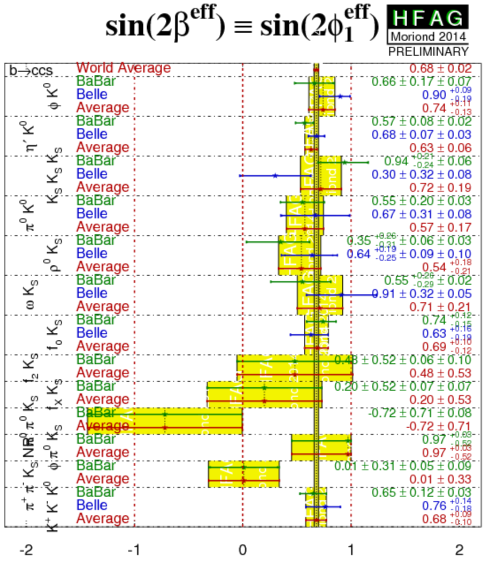
Also B→Kννbar: very topical ! See latest Belle II result [Glazov, EPS 2023, Hamburg].

Why perform B physics at $\Upsilon(4S)$?

B production at the $\Upsilon(4S)$ presents several very advantageous features:

- Can reconstruct full event, which is beneficial for missing energy modes and also inclusive measurements (typically lower theory uncertainties).
- Low multiplicity environment permits excellent performance for final states with π^0s, η’s, photons. Also, good efficiency for long-lived particles K_S and K_L.

e.g. most modes suitable for sin2β measurements involving Penguin loops (b→ccbar s) are rather tough at LHCb…



…and other important decays *e.g.* $D^0 \to \gamma\gamma$, $B^0 \to \pi^0\pi^0$… are essentially inaccessible.

Why perform B physics at ϒ(4S) ?

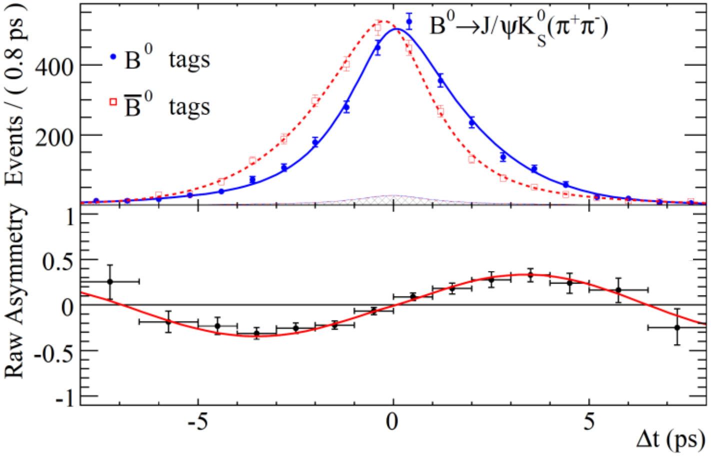
B production at the Y(4S) presents several advantages over hadron environment

- Can reconstruct full event, which is beneficial for missing energy modes and also inclusive measurements (typically lower theory uncertainties).
- Low multiplicity environment permits excellent performance for final states with π^0s, η's, photons. Also, good efficiency for long-lived particles K_S and K_L.
- Coherent B^0B^0bar production at Y(4S) benefits flavour tagging (see Lecture II).

e.g. in sin2β measurement with $B^0 \to J/\psi K_S$

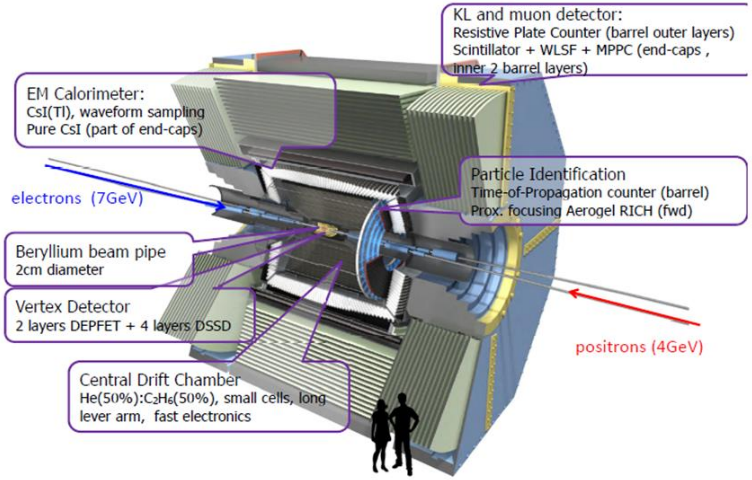
ε (tag effective) BaBar ~ 31 %
[PRD 79 (2009) 072009]

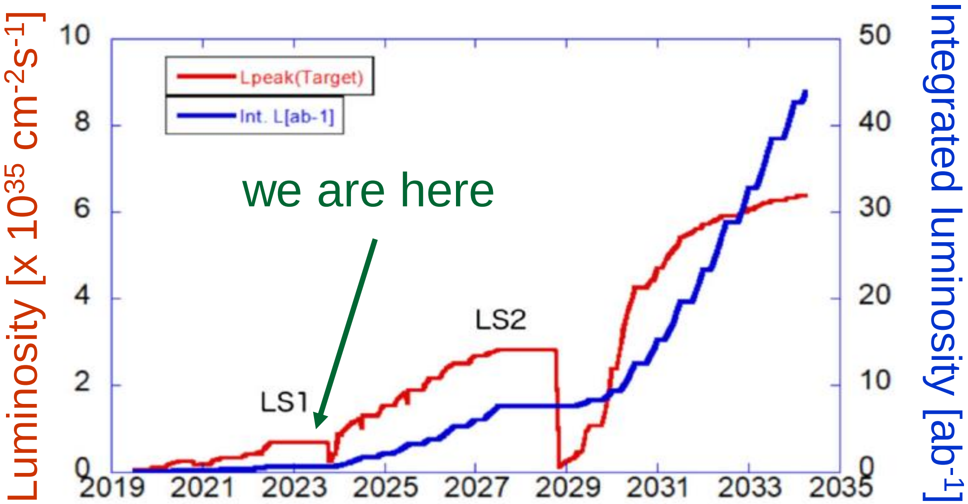
ε (tag effective) LHCb ~ 3 %
[PRL 115 (2015) 031601]



Why perform B physics at $\Upsilon(4S)$?

For these reasons, the BaBar and Belle experiments were enormously successful. Therefore, it makes great sense to continue this programme with a next generation experiment – Belle II – at a next generation collider – SuperKEKb.

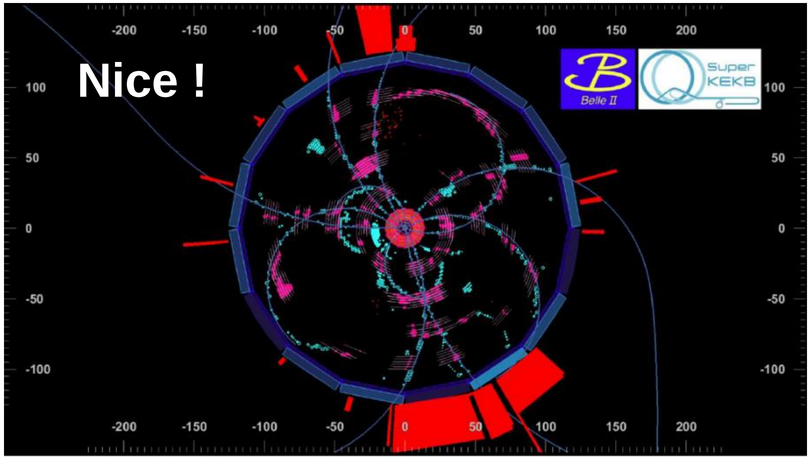


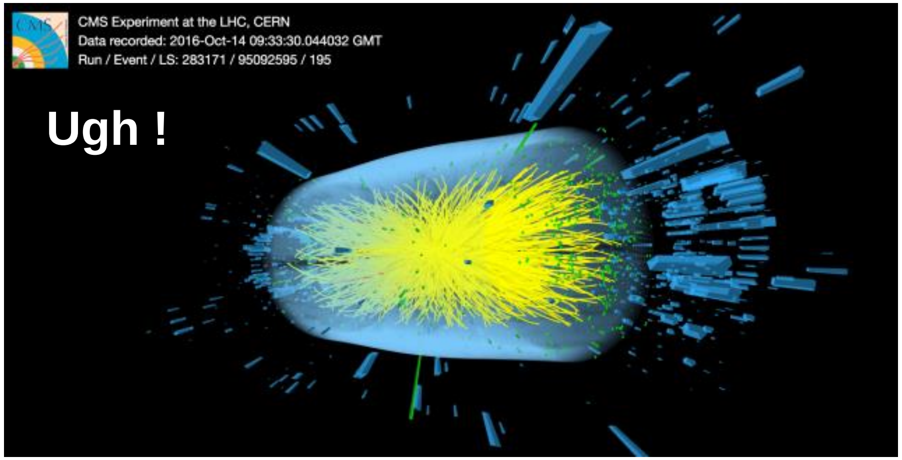


Soon to resume data taking after ~one year shutdown (LS1). Machine has reached instantaneous luminosity of 4.7 x 10^{34} $cm^{-2}s^{-1}$ and has delivered 428 fb^{-1} (similar to BaBar). Still a long way to go. Aim for 5 –10 fb^{-1} in coming ~ five years.

So why flavour physics at a hadron machine ?

Flavour-physics studies often consist of precise measurements of delicate and rare processes. Therefore, the choice of environment is surely a no brainer ?



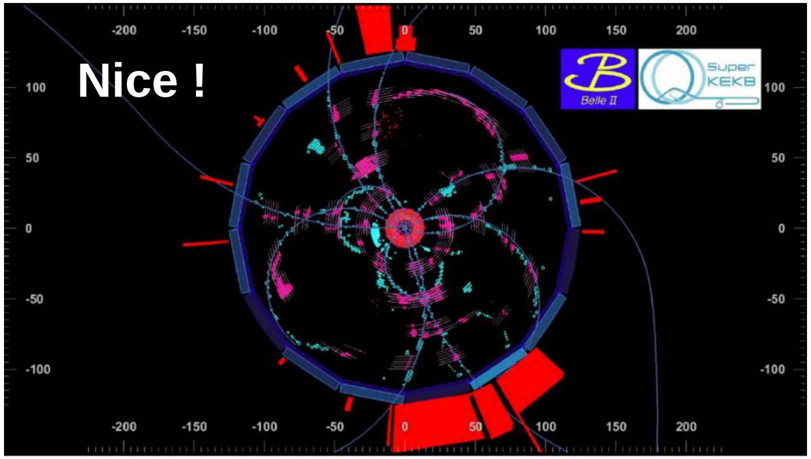


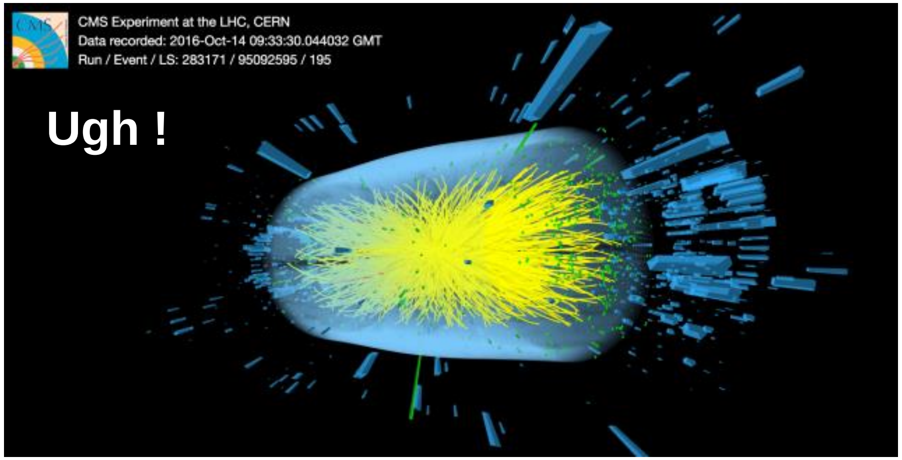
Related to this event complexity / furthermore (to recap):

- (Initial) backgrounds much higher, particularly for studies with neutrals;
- Much more severe trigger challenge;
- Coherent production is valuable for flavour tagging (see Lecture II).

So why flavour physics at a hadron machine ?

Flavour-physics studies often consist of precise measurements of delicate and rare processes. Therefore, the choice of environment is surely a no brainer ?





Related to this event complexity / furthermore (to recap):

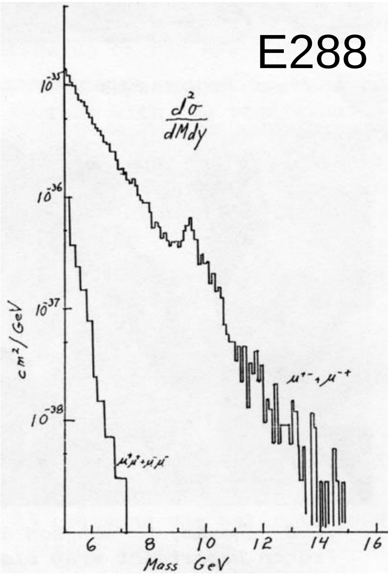
- (Initial) backgrounds much higher, particularly for studies with neutrals;
- Much more severe trigger challenge;
- Coherent production is valuable for flavour tagging (see Lecture II).

Nonetheless:

- *Much* higher cross section: $\sigma_{b\bar{b}}[\Upsilon(4S)] \approx 1$ nb $\sigma_{b\bar{b}}[\mathrm{LHC@14\ TeV}] \approx$ 600 μb ;
- In contrast to the Υ(4S), all b-hadron species are produced ;
- High boost.

Hadron beams and colliders have a strong tradition in b-physics

[E288, PRL 35 (1977) 252]

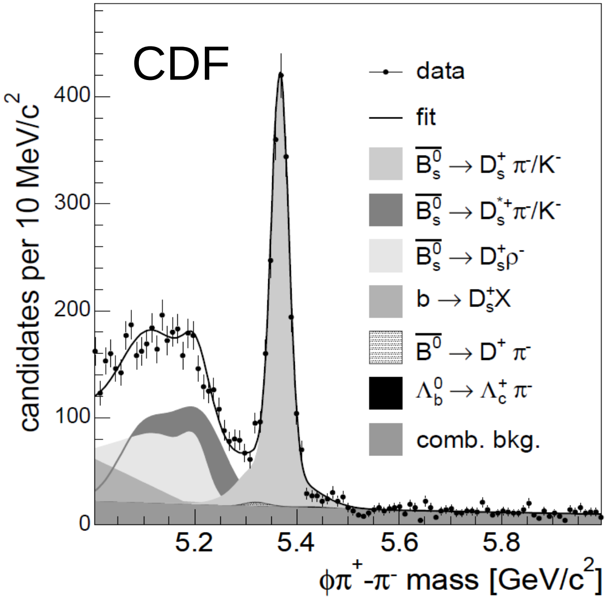


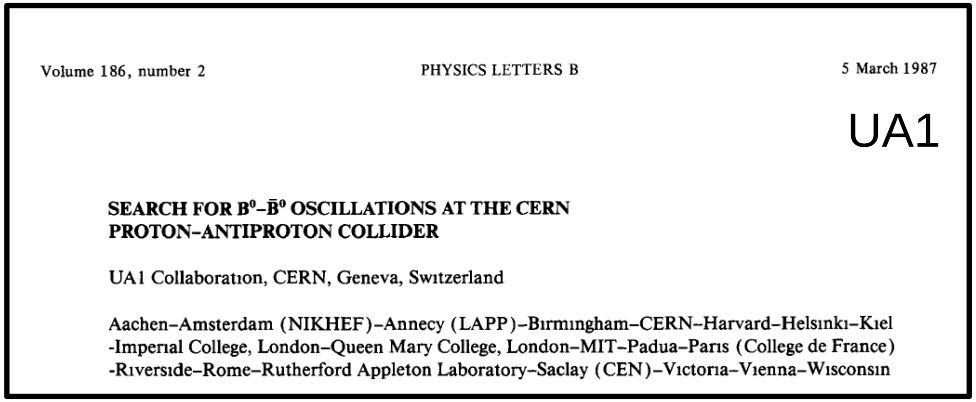
Discovery of b quark (ϒ) by Lederman and E288 in 1977.

Discovery of neutral B oscillations by UA1 in 1987.

Discovery of resolved B_s oscillations by CDF in 2006.

[CDF, PRL 97 (2006) 242003]





Volume 186, number 2 PHYSICS LETTERS B 5 March 1987

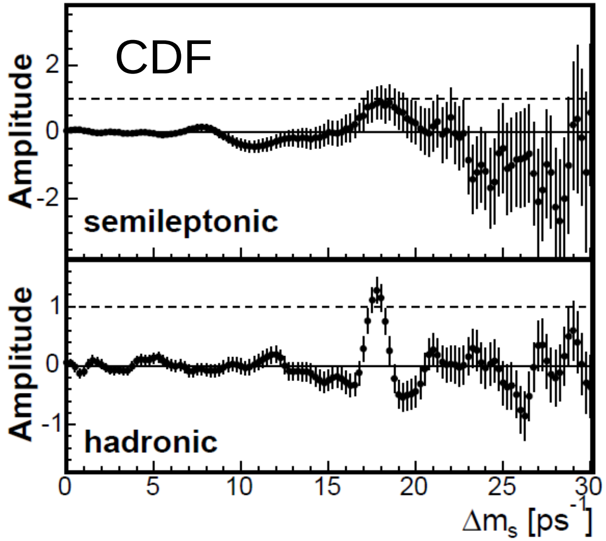
UA1

SEARCH FOR B^0–$\bar{B}^0$ OSCILLATIONS AT THE CERN PROTON–ANTIPROTON COLLIDER

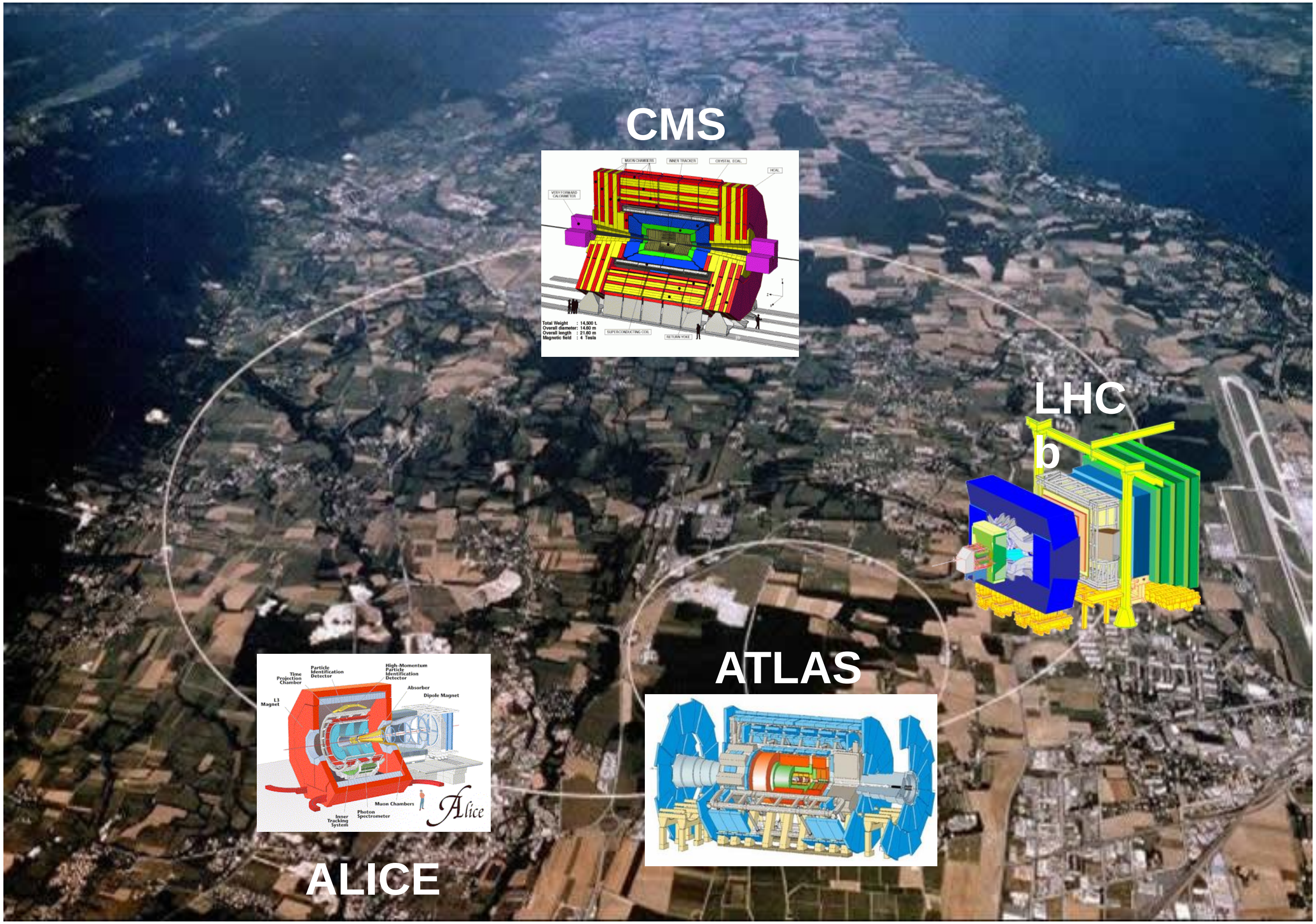
UA1 Collaboration, CERN, Geneva, Switzerland

Aachen–Amsterdam (NIKHEF)–Annecy (LAPP)–Birmingham–CERN–Harvard–Helsinki–Kiel
-Imperial College, London–Queen Mary College, London–MIT–Padua–Paris (College de France)
-Riverside–Rome–Rutherford Appleton Laboratory–Saclay (CEN)–Victoria–Vienna–Wisconsin

[UA1, PLB 186 (1987) 247]



The LHC: a multipurpose machine



Why do we need a 'dedicated' flavour physics experiment at the LHC ?

CMS and ATLAS can! They are exceptionally versatile experiments that (as we shall see) have produced high quality results in flavour physics. However their studies are restricted to final states involving di-muons, and they have no hadron identification capabilities. This puts many important measurements out of reach.

Towards a dedicated b-physics experiment at the LHC

In early 1990s three ideas took shape for dedicated b-physics experiment at LHC.

GAJET	Fixed target – LHC protons impinging on gas jet. Calorimeter trigger, giving efficiency for hadron final states.
LHB	Fixed target – extracting LHC beam halo with bending crystal.
COBEX	Forward collider experiment, benefitting from full $\sqrt{s}$ =14 TeV cross section. Equipped with vertex detector sitting inside secondary vacuum. Muon trigger, followed by vertex trigger.

Towards a dedicated b-physics experiment at the LHC

In early 1990s three ideas took shape for dedicated b-physics experiment at LHC.

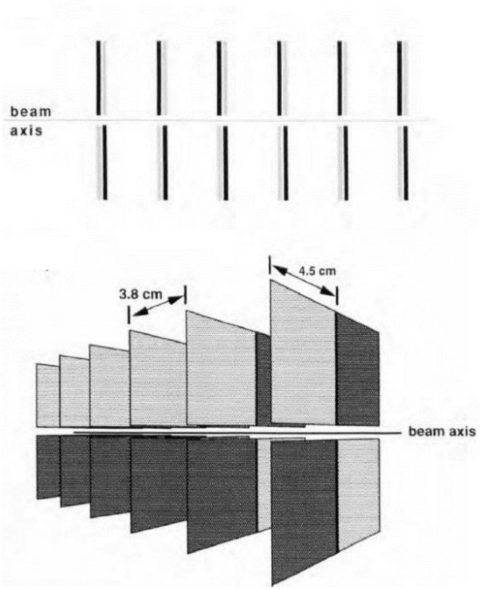
GAJET	Fixed target – LHC protons impinging on gas jet. Calorimeter trigger, giving efficiency for hadron final states.
LHB	Fixed target – extracting LHC beam halo with bending crystal.
COBEX	Forward collider experiment, benefitting from full $\sqrt{s}$ =14 TeV cross section. Equipped with vertex detector sitting inside secondary vacuum. Muon trigger, followed by vertex trigger.

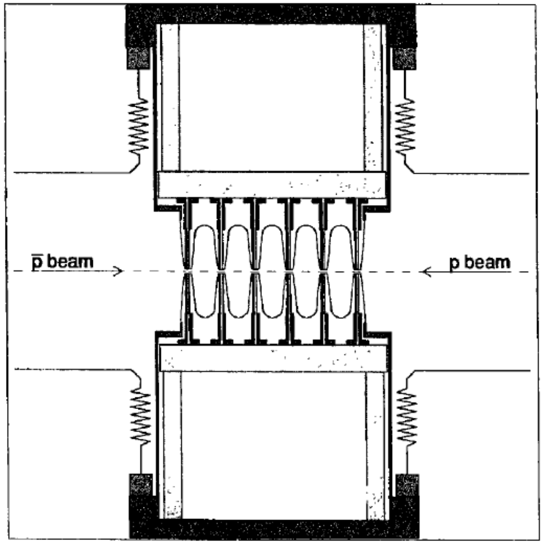
These aspects of proposal had a compelling proof-of-principle coming from P238 project at SPS.

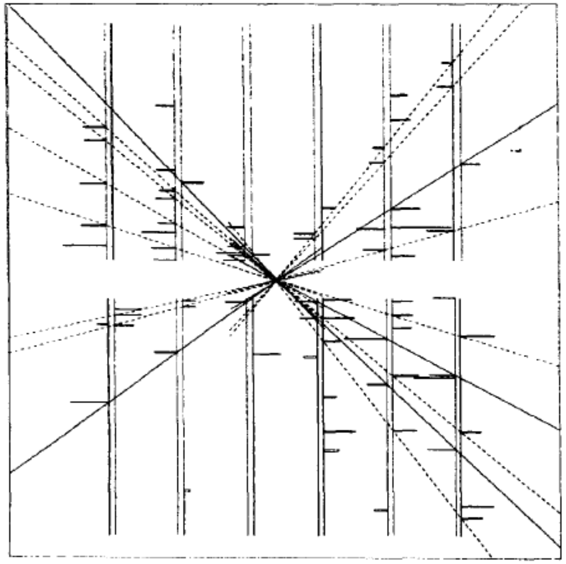
P238 – towards the LHCb VELO

‘Development and test of a large silicon strip system for a hadron collider beauty Trigger’, P. Schlein *et al.*, NIM A 317 (1992) 28

Large aperture forward spectrometers with planar geometry perpendicular to the beam line are the natural detectors to accomodate the expected forward peaking of Beauty particle production at high energy hadron colliders. We have designed, built and tested a prototype planar silicon strip vertex detector for triggering such a spectrometer system. The test system consisted of 43000 channels, configured in six planes, each with four quadrants, perpendicular to the beam line and installed inside the SPS-collider vacuum pipe at the center of an interaction region. Events recorded with the rf shield of the silicon system 1.5 mm from the circulating beams show negligible event-unrelated background.







Towards a dedicated b-physics experiment at the LHC

In early 1990s three ideas took shape for dedicated b-physics experiment at LHC.

GAJET	Fixed target – LHC protons impinging on gas jet. Calorimeter trigger, giving efficiency for hadron final states.
LHB	Fixed target – extracting LHC beam halo with bending crystal.
COBEX	Forward collider experiment, benefitting from full $\sqrt{s}$ =14 TeV cross section. Equipped with vertex detector sitting inside secondary vacuum. Muon trigger, followed by vertex trigger.

These proto-collaborations were encouraged to join forces and develop a detector concept that merged the best features of each, in particular collider operation and good trigger efficiency across a wide range of b-hadron decays.

Towards a dedicated b-physics experiment at the LHC

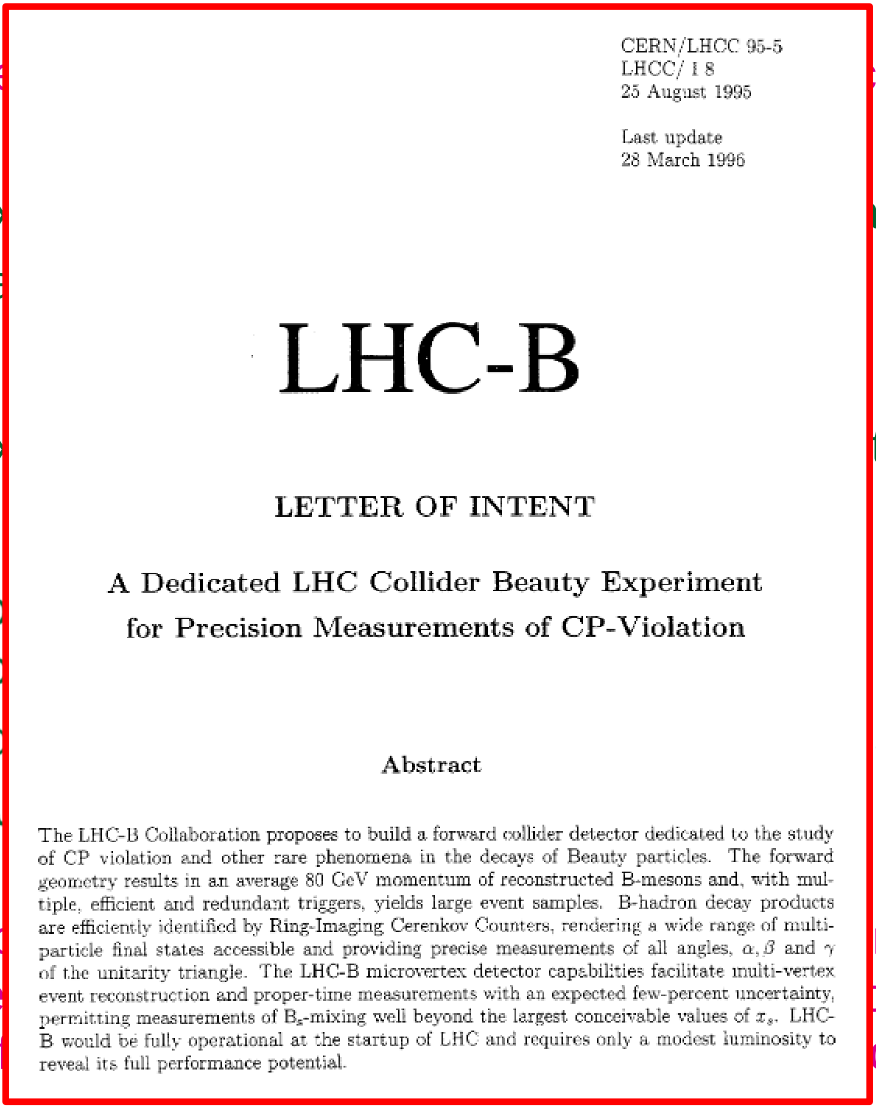
In early 1990s three
s experiment at LHC.

GAJET
Fi
s jet.
Ca
ron final states.

LHB
Fi
th bending crystal.

COBEX
Fo
fro
Ec
secondary vacuum.
Mu

These proto-collabo
nd develop a detector
concept that merge
collider operation
and good trigger ef
decays.



CERN/LHCC 95-5
LHCC/ I 8
25 August 1995

Last update
28 March 1996

LHC-B

LETTER OF INTENT

A Dedicated LHC Collider Beauty Experiment for Precision Measurements of CP-Violation

Abstract

The LHC-B Collaboration proposes to build a forward collider detector dedicated to the study of CP violation and other rare phenomena in the decays of Beauty particles. The forward geometry results in an average 80 GeV momentum of reconstructed B-mesons and, with multiple, efficient and redundant triggers, yields large event samples. B-hadron decay products are efficiently identified by Ring-Imaging Cerenkov Counters, rendering a wide range of multi-particle final states accessible and providing precise measurements of all angles, α, β and γ of the unitarity triangle. The LHC-B microvertex detector capabilities facilitate multi-vertex event reconstruction and proper-time measurements with an expected few-percent uncertainty, permitting measurements of B_s-mixing well beyond the largest conceivable values of x_s. LHC-B would be fully operational at the startup of LHC and requires only a modest luminosity to reveal its full performance potential.

Meanwhile, at DESY, Hamburg…

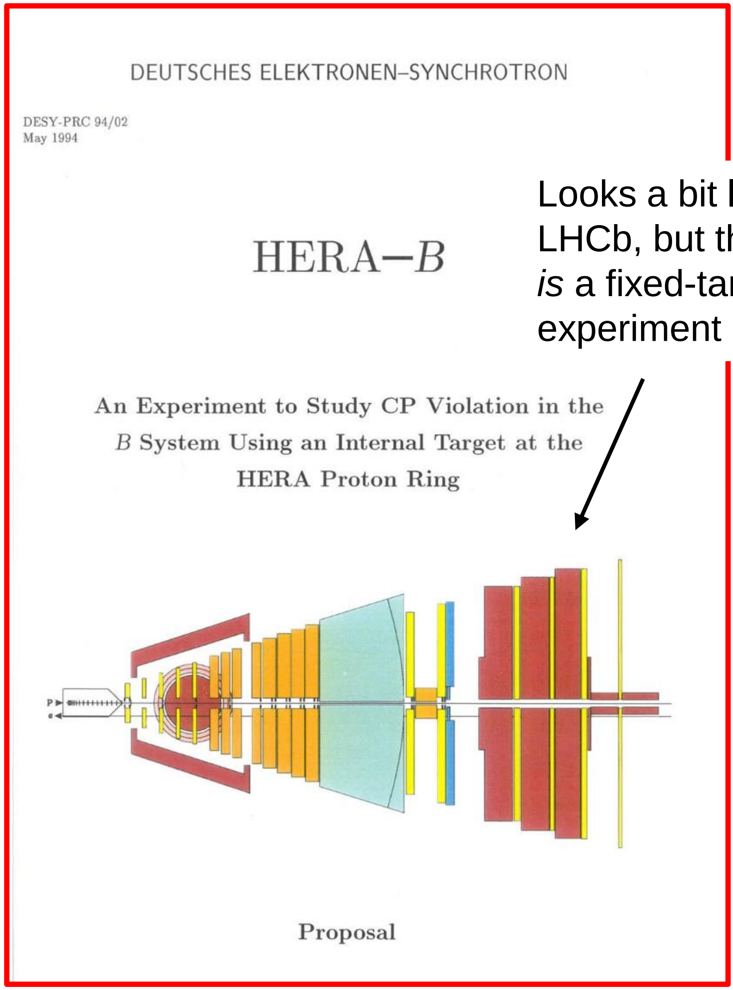
HERA-B, first proposed in 1992, starting ~2000, operated with HERA proton beam on fixed-wire target.

Principal goal was to be first experiment to see CP violation in $B^0 \to J/\psi K_S^0$.

Hugely demanding (harder than LHCb !), as $b\bar{b}$ / minimum bias cross-section ratio at $\sqrt{s}$ = 920 GeV is 10^{-6} , and interaction rate, with pileup, was 10s of MHz.

Much was learned, concerning:

- triggering;
- vertex detectors and RICHes;
- challenges of operating MSGCs in high radiation environments;
- why too much material is bad.



DEUTSCHES ELEKTRONEN–SYNCHROTRON

DESY-PRC 94/02
May 1994

HERA–*B*

An Experiment to Study CP Violation in the
B System Using an Internal Target at the
HERA Proton Ring

Proposal

Looks a bit like LHCb, but this *is* a fixed-target experiment

Many of these lessons were very valuable for LHCb. But for HERA-B it was too late. The B factories started too well and quickly, and HERA-B data taking ceased in 2003.

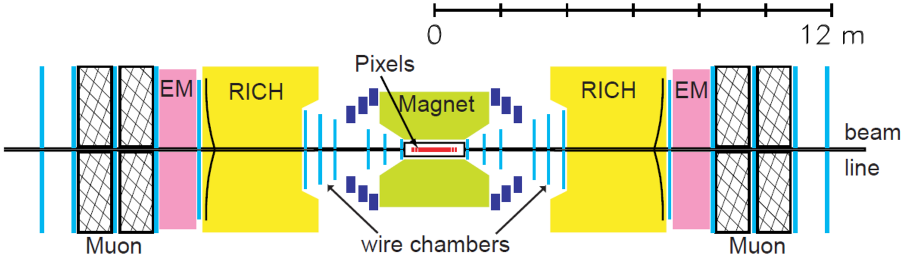
…and at FNAL, Illinois

BTeV was proposed as a dedicated B physics experiment at the Tevatron.

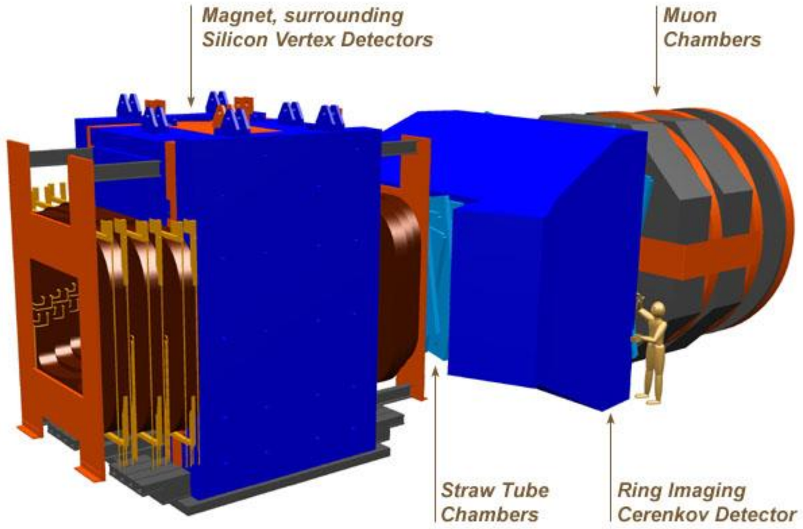
Differences w.r.t. LHCb:

- Two-arm spectrometer;
- Pixel, not strip, vertex detector and intention to use vertex signatures at earliest trigger stage;
- Higher emphasis on ECAL physics.

Given first-stage approval in 2004, but cancelled soon after. Some aspects of BTeV are central to LHCb Upgrades.



One arm of BTeV

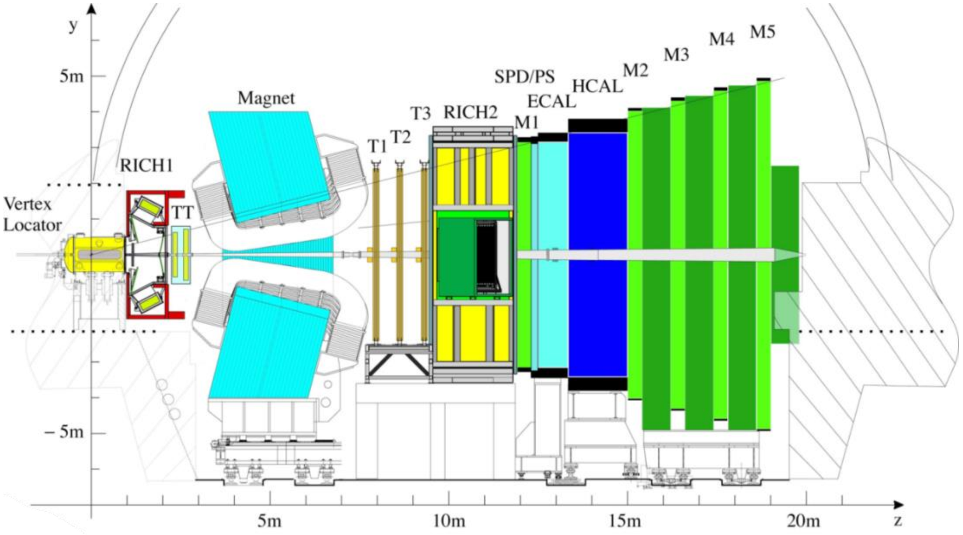


LHCb: a dedicated experiment for flavour physics at the LHC

Designed to be a *dedicated* experiment for b- and c-physics at the LHC.

Dedicated in the sense of the following attributes:

- Acceptance
- Operating luminosity
- Instrumentation
- Trigger

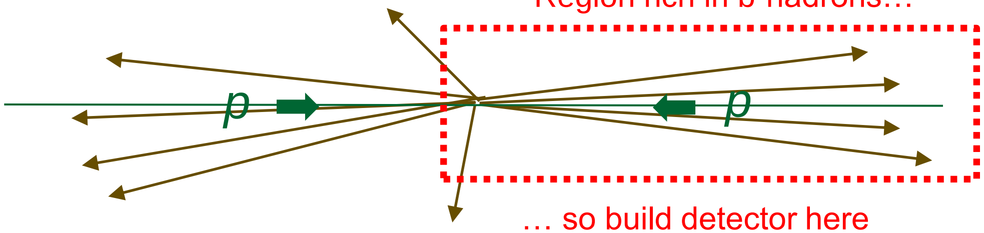


These capabilities give the experiment high sensitivity in other studies apart from flavour, but describing these goes beyond the scope of these lectures (although we will be saying a few words about spectroscopy).

A dedicated experiment for flavour physics at the LHC – general considerations

Go forward ! This collects a large fraction of the $b\bar{b}$ pairs, which are predominantly produced by gluon fusion at low angles. This choice of geometry brings other benefits:

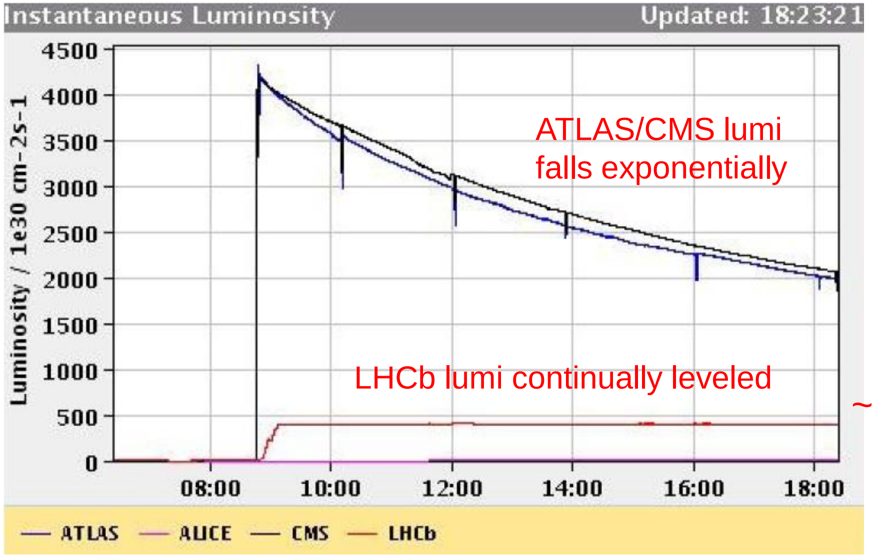
- Vertex detector can get *really* close to beamline;
- High boost;
- Lots of space (very helpful for RICH detectors);
- 'High p_T' can be redefined to mean a few GeV, which is typical p_T of b-decay products.



Region rich in b-hadrons…

… so build detector here

This necessitates operating at lower luminosity than ATLAS / CMS (also needed for trigger – see later).

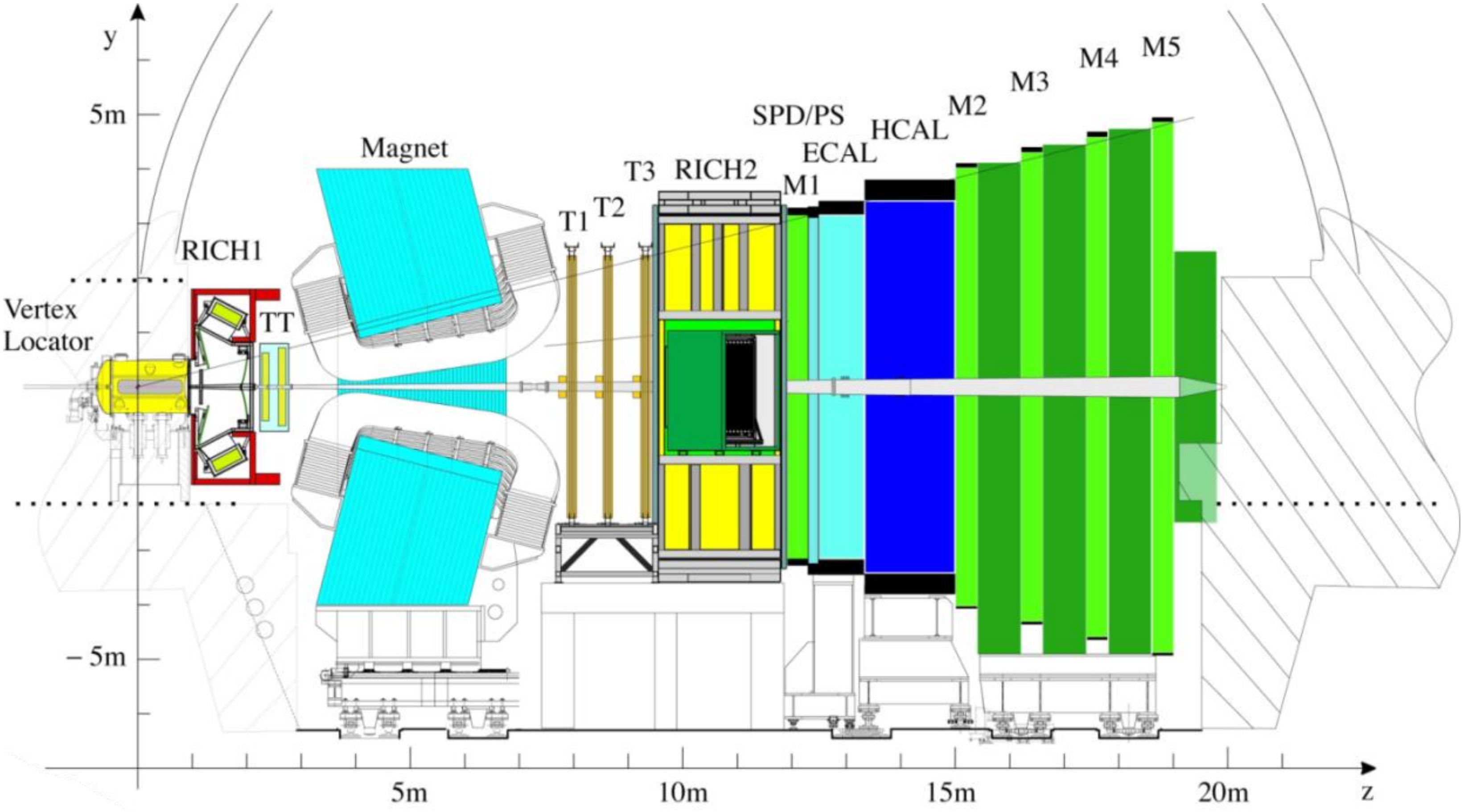


ATLAS/CMS lumi falls exponentially

LHCb lumi continually leveled

~4 x 10^{32} $cm^{-2}s^{-1}$

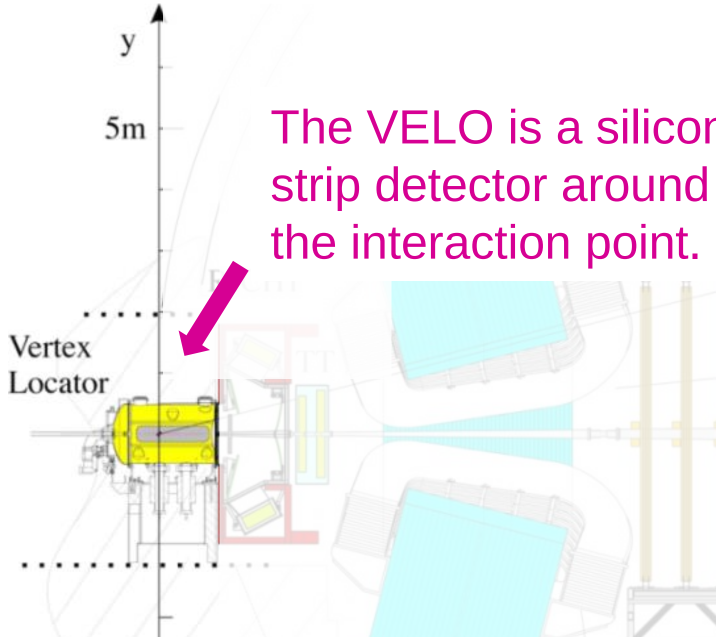
LHCb – a forward spectrometer for flavour physics



LHCb – a forward spectrometer for flavour physics

This is the experiment that operated for Runs 1 & 2 of the LHC. It *no longer exists* ! We will find out what has replaced it in Lecture IV.

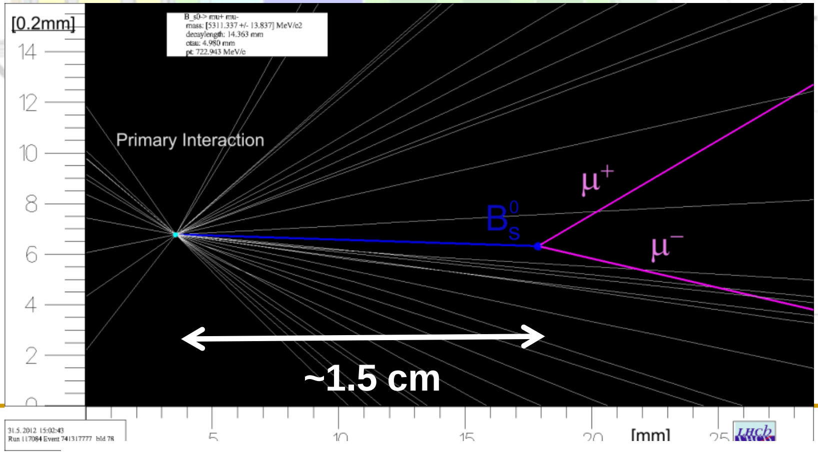
LHCb – a forward spectrometer for flavour physics



The VELO is a silicon strip detector around the interaction point.

One-half of the VELO under construction

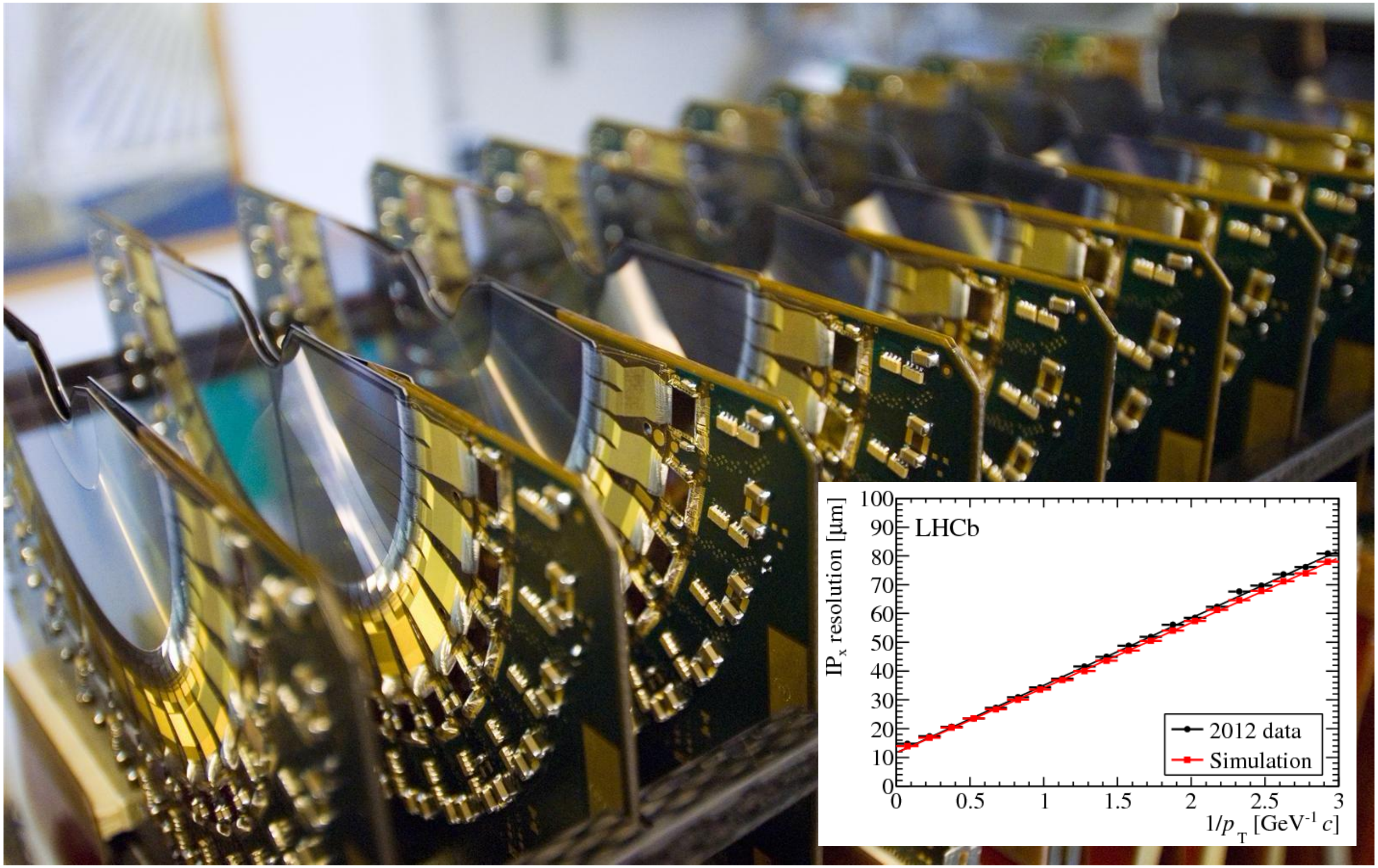
It approaches within 8 mm of the beamline, sits in a secondary vacuum, and reconstructs the *b*-hadron decay vertex precisely.



A reconstructed *b*-hadron decay vertex

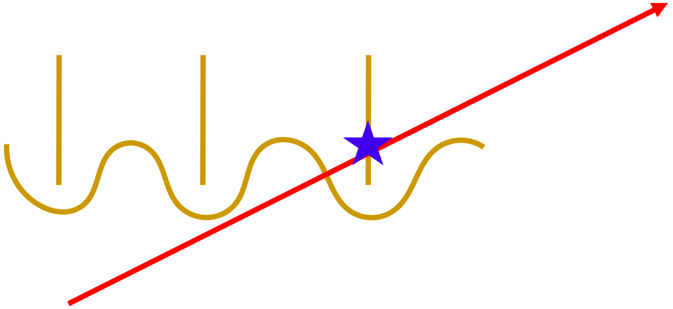
VELO – built for precision

Closest measurement point has 4 μm precision and is 8.1 mm from beam. There material is minimal – only the sensor, no electronics or cooling.

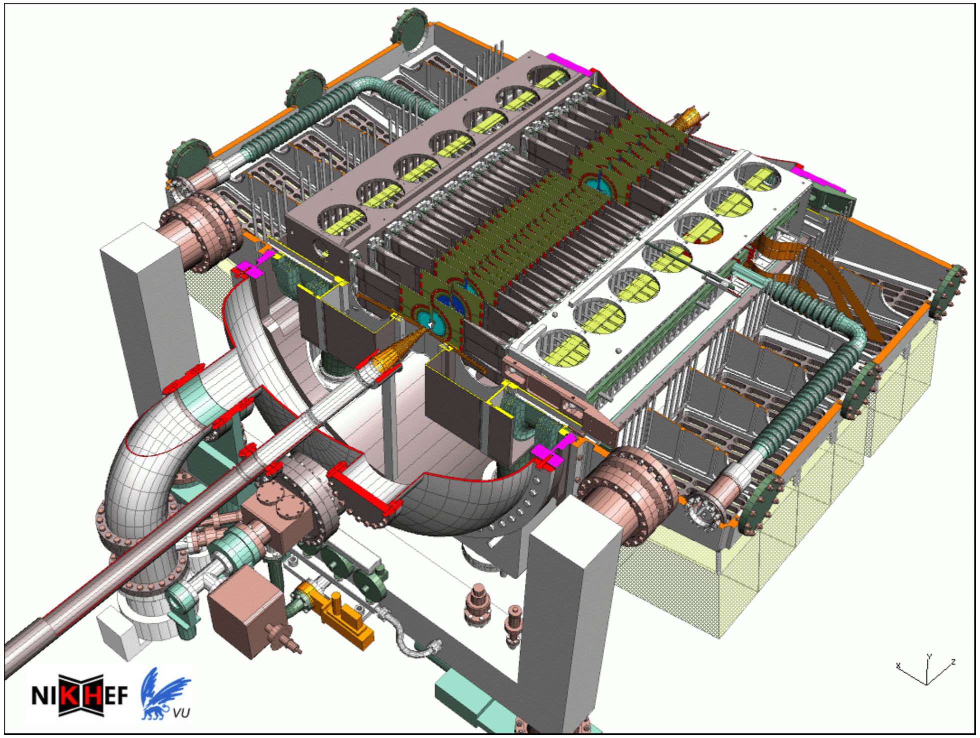


VELO – close to beam

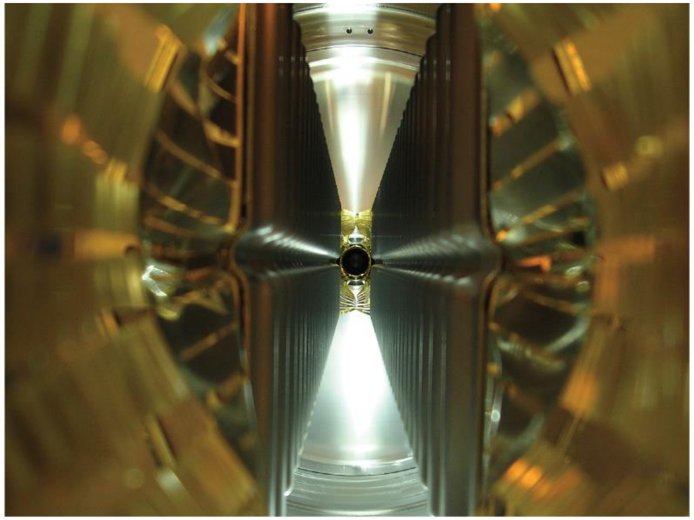
VELO is moveable and operates in vacuum.
The RF foil “beampipe” surrounding it
is ultra-thin, and corrugated.



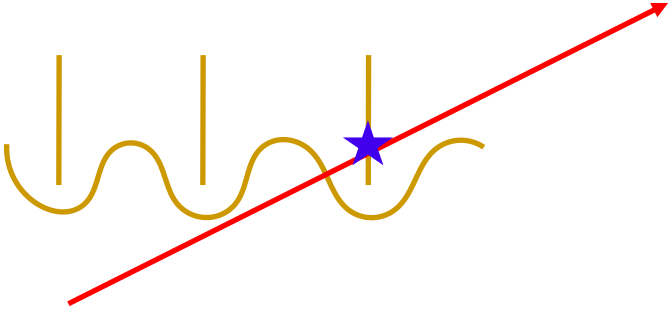
Track passes through RF foil perpendicularly – good for multiple coulomb scattering.



What the protons see in injection

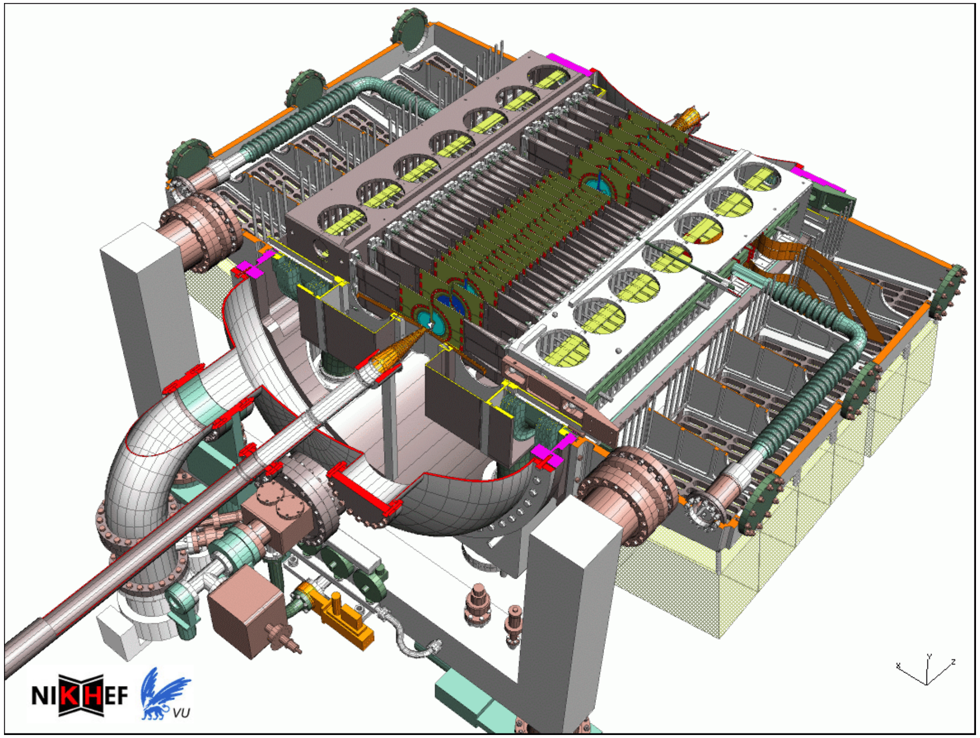


VELO – close to beam

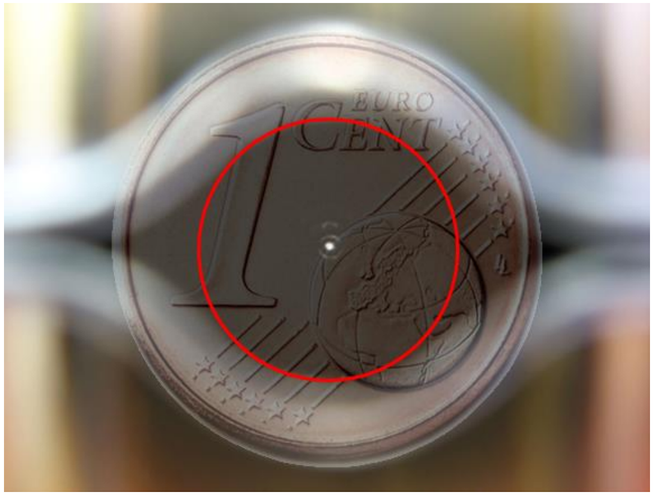


VELO is moveable and operates in vacuum.
The RF foil “beampipe” surrounding it
is ultra-thin, and corrugated.

Track passes through RF foil perpendicularly – good for multiple coulomb scattering.

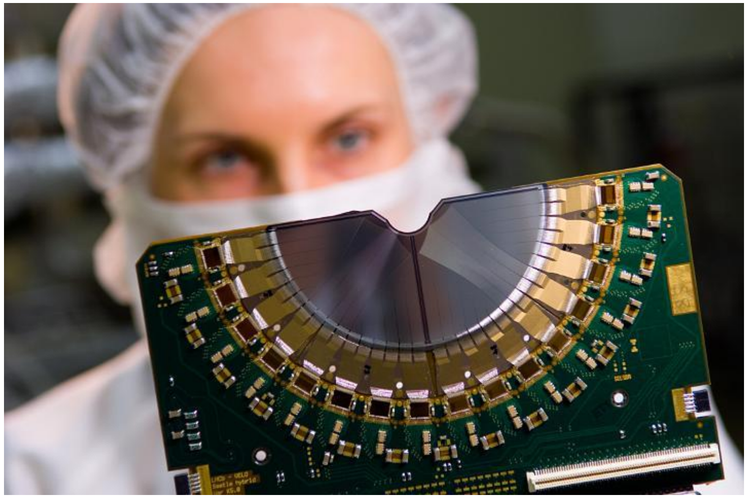


What the protons see in collisions

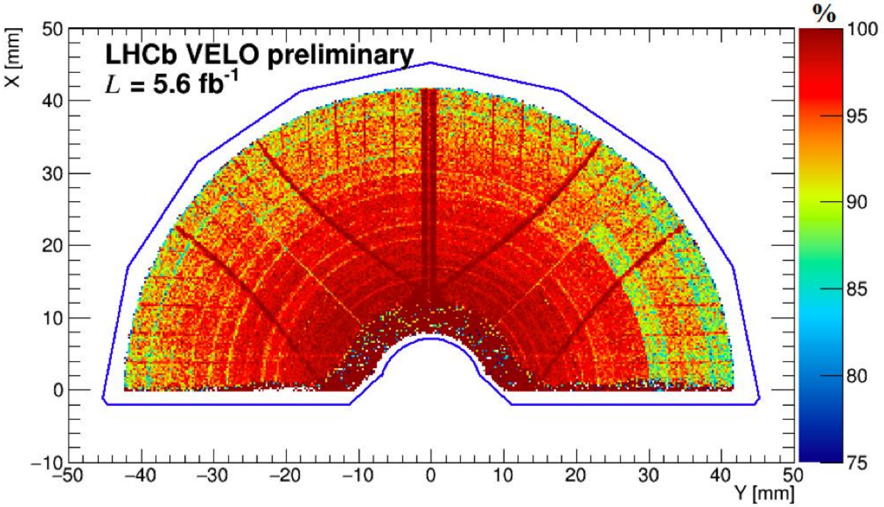


Size of beam aperture compared with one Euro.

VELO – built to last

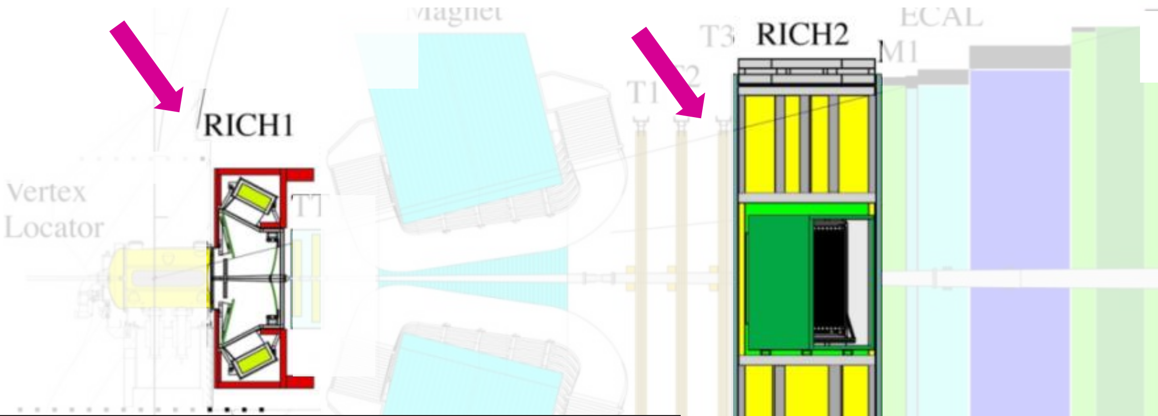


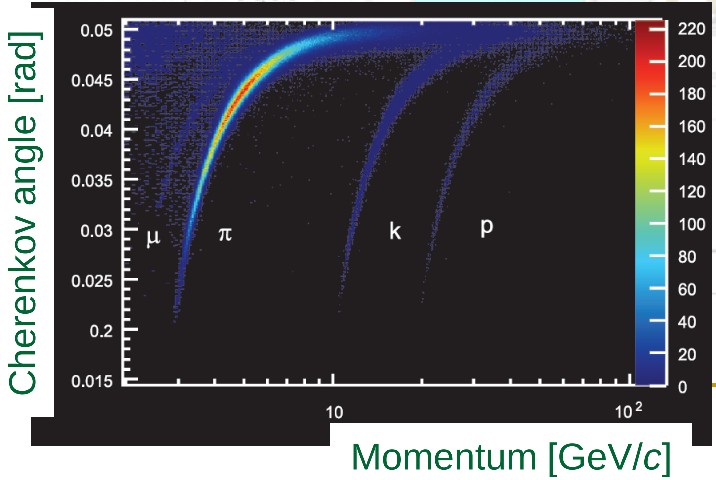
Efficiency after being blasted by LHC



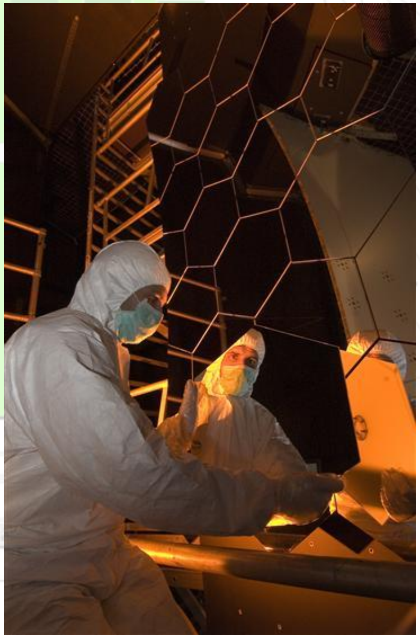
LHCb – a forward spectrometer for flavour physics

Two Ring Imaging Cherenkov (RICH) detectors detect Cherenkov radiation and measure the emission angle, which gives the particle’s velocity, and hence mass.





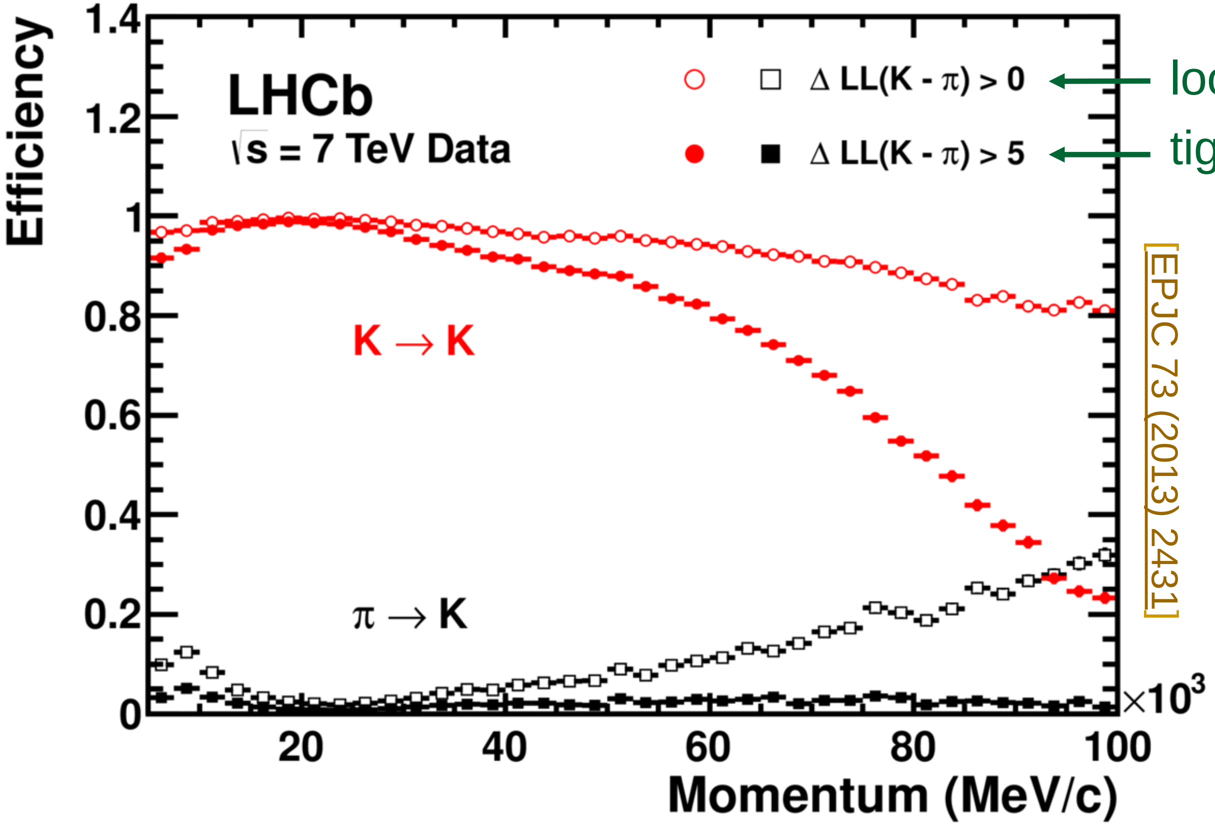
Array of RICH photodetectors



Assembling RICH 2; note the mirrors

More about the RICH system

Hadron-identification requirements are very different at LHC compared to B-factories, as there is a *much* greater spread in momentum, going to *much* higher momenta.



loose cut

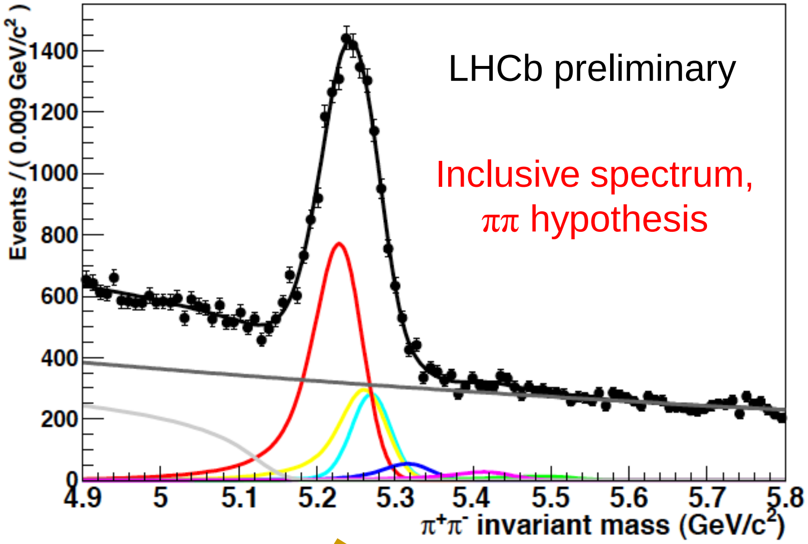
tight cut

[EPJC 73 (2013) 2431]

Two RICHes, one optimised for lower momentum (C_4F_{10}), the other downstream (CF_4) optimised for higher momentum, span a range of $1 < p < 100$ GeV/*c*.

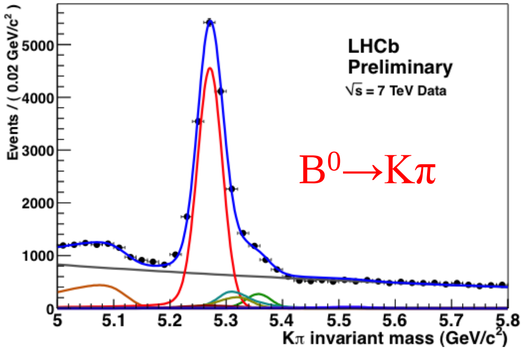
RICH in action

Two-body charmless B decays are central goal of LHCb physics.
Identical topologies require RICH to separate.

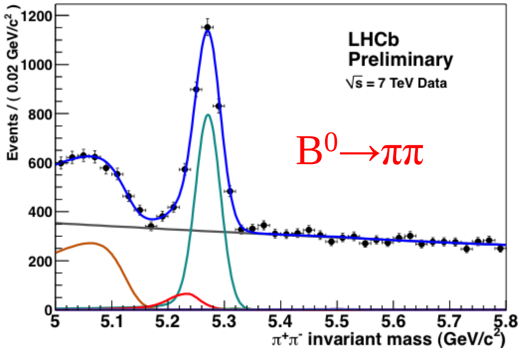


Inclusive spectrum,
ππ hypothesis

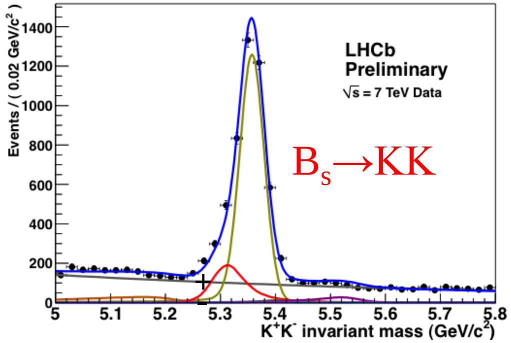
Deploy
RICH to
isolate
each
mode !



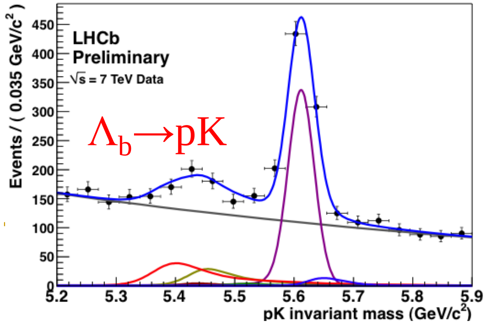
$B^0 \rightarrow K\pi$



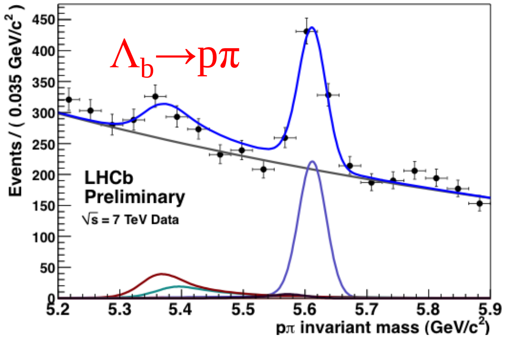
$B^0 \rightarrow \pi\pi$



$B_s \rightarrow KK$



$\Lambda_b \rightarrow pK$



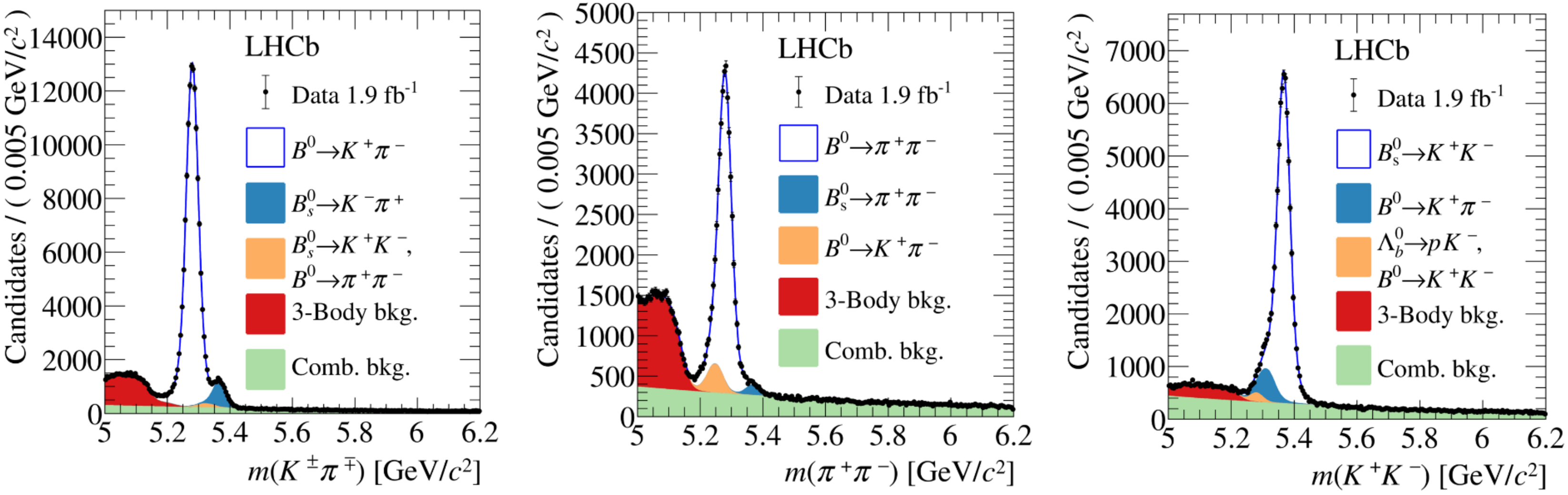
$\Lambda_b \rightarrow p\pi$

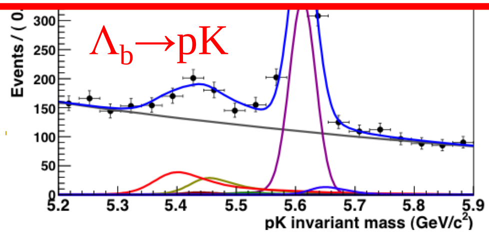
RICH in action

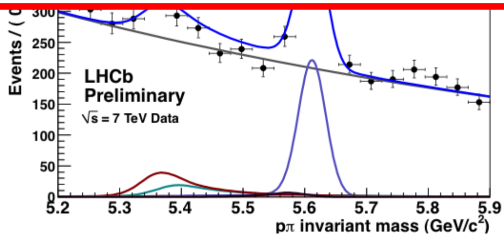
Two-body charmless B decays are central goal of LHCb physics.

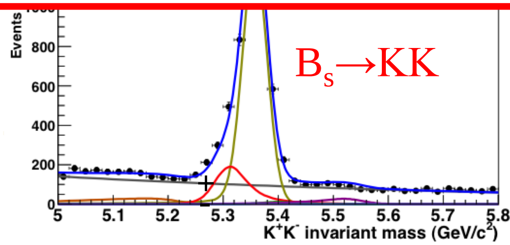
Identical topologies require RICH to separate

Those plots were from early Run I data. Here are some more recent examples from Run II [JHEP 03 (2021) 075] , with better control of background.



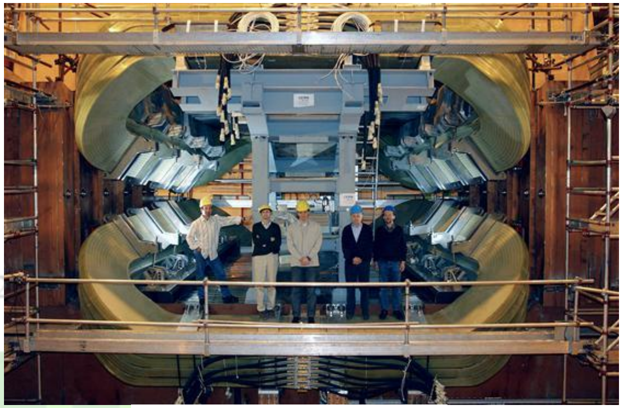




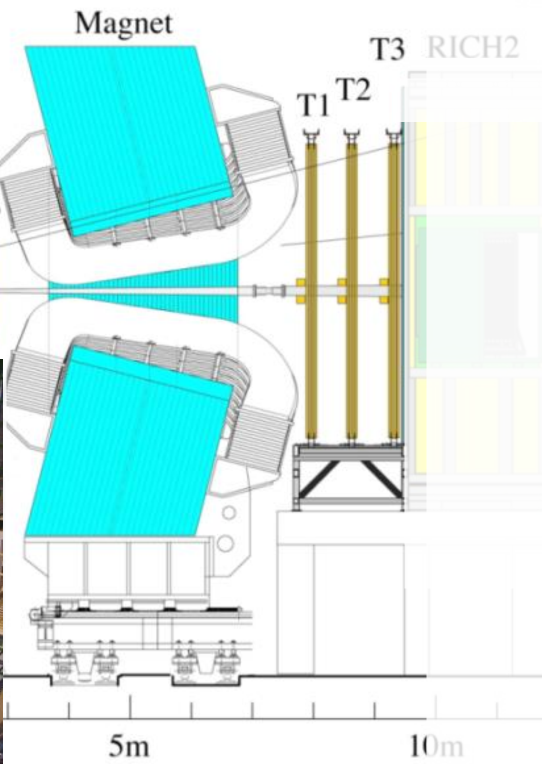


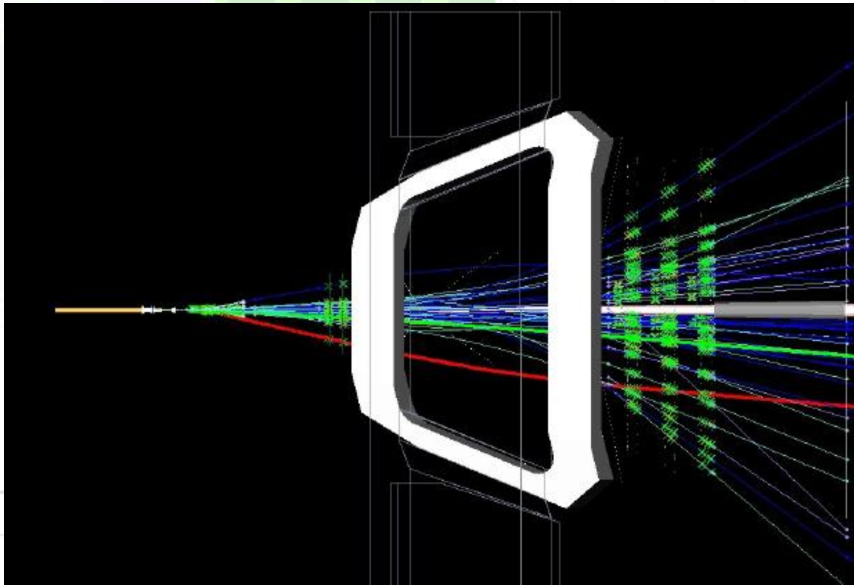
LHCb – a forward spectrometer for flavour physics

A 4 Tm dipole, and the tracking detectors reconstruct the trajectory of charged particles, and allows their momentum to be determined.

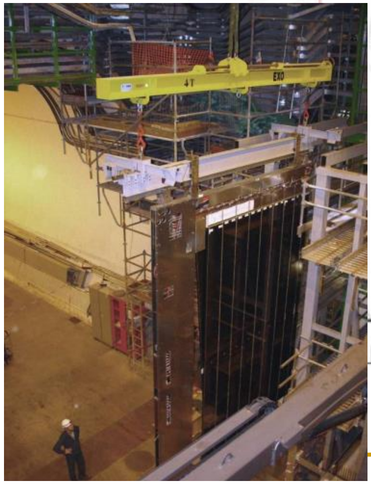


Dipole magnet





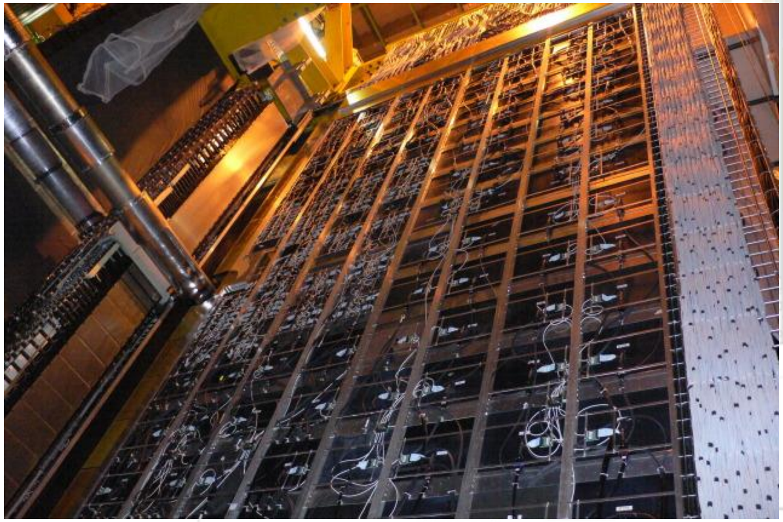
Reconstructed tracks



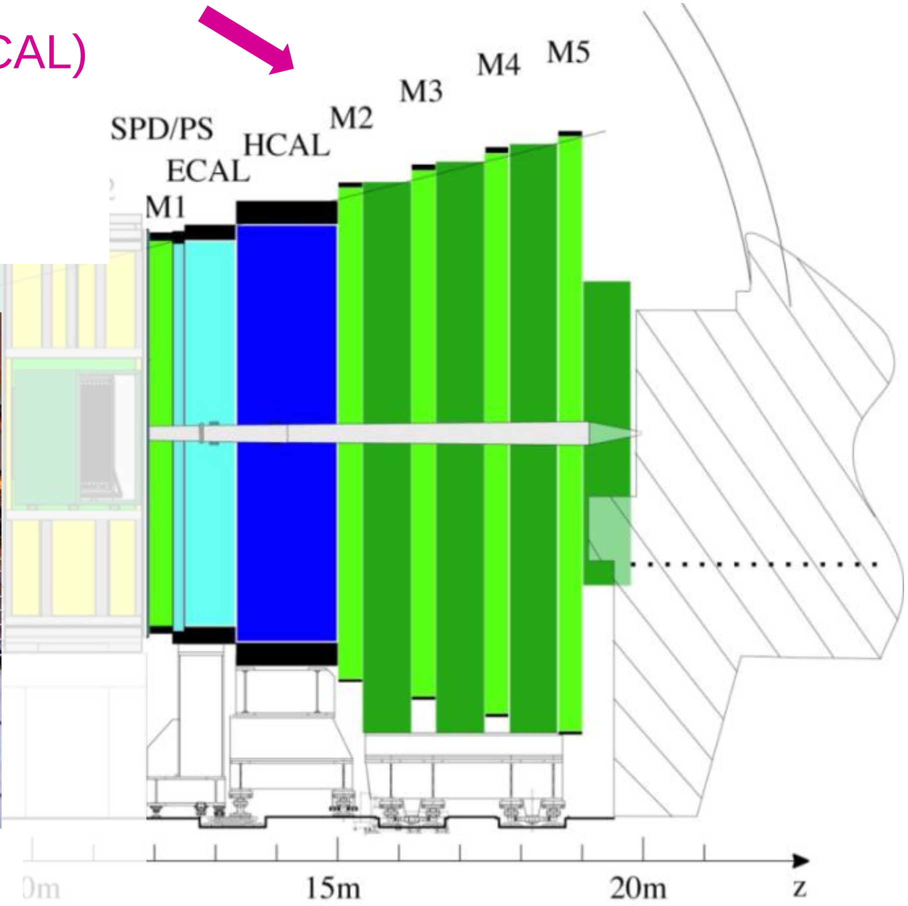
Part of outer tracker

LHCb – a forward spectrometer for flavour physics

The calorimeter system (ECAL & HCAL) reconstructs the energy of photons, electrons and hadrons. The muon system (M1-M5) identifies muons.



Part of calorimeter system (preshower)



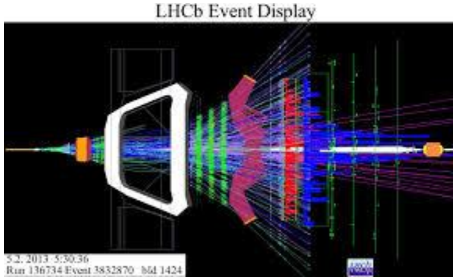
These detectors are particularly important for the role they play in the LHCb trigger

The data challenge

LHC operates at 40 MHz and does so for ~15% of year

LHCb raw event size ~100 kBytes

×

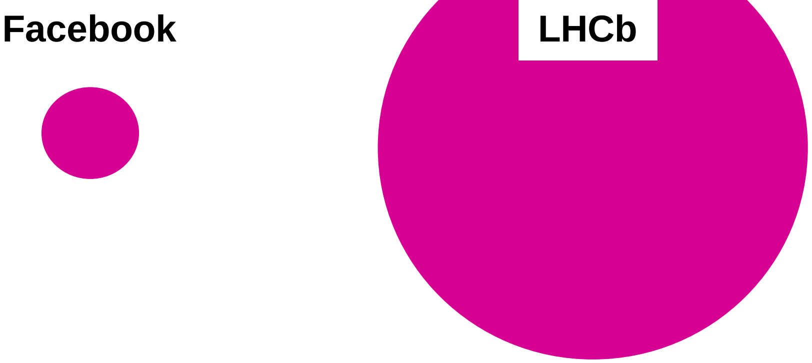


→

~ 15000 PetaBytes /yr (raw data alone)

~ 15000 PetaBytes/year is less than dealt with by search engines, but still considerably more than *e.g.* Facebook (~ 1500 PB/year in 2022).

Data rate	LHCb ~15000 PB.yr Facebook ~1500 PB / yr

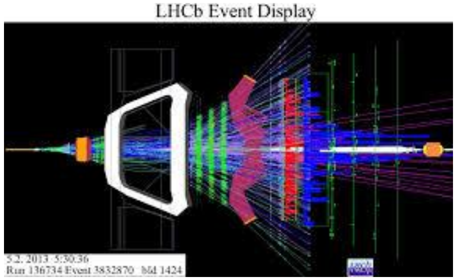


The data challenge

LHC operates at 40 MHz and does so for ~15% of year

LHCb raw event size ~100 kBytes

✖



➡

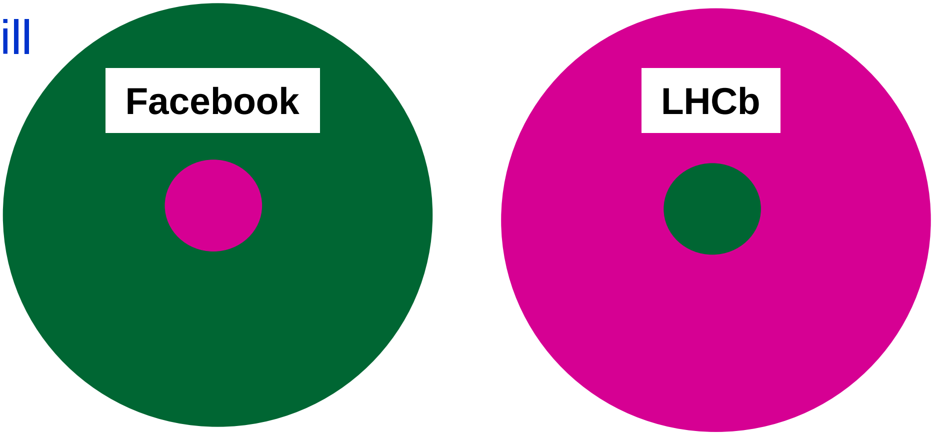
~ 15000 PetaBytes /yr (raw data alone)

~ 15000 PetaBytes/year is less than dealt with by search engines, but still considerably more than *e.g.* Facebook (~ 1500 PB/year in 2022).

Public science has less money to spend on computing than Facebook.

Storage costs money. Better to process as much as possible in ‘real time’, hence the need for the trigger.

Data rate	LHCb ~15000 PB.yr Facebook ~1500 PB / yr

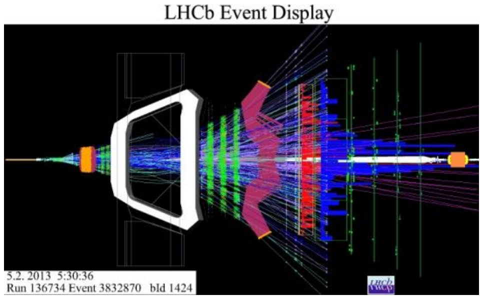


Computing budget	LHCb ~10M$ / yr Facebook ~1000 M$ /yr

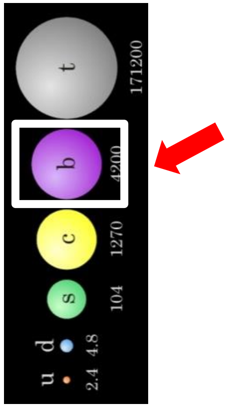
Not all collisions are equally interesting

Core business of LHCb is beauty physics, and here we can be selective

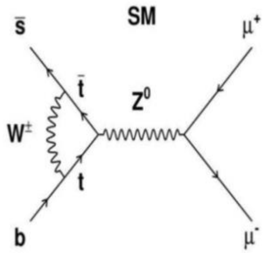
Collision rate 40 MHz
(currently a little less,
but this sets the ballpark)



b-hadrons produced
about once every
~150 *pp* collisions



And most *b*-hadrons
decays don't interest us.



$B_s \rightarrow \mu\mu$
occurs every
4×10^{-9}
B_s decays

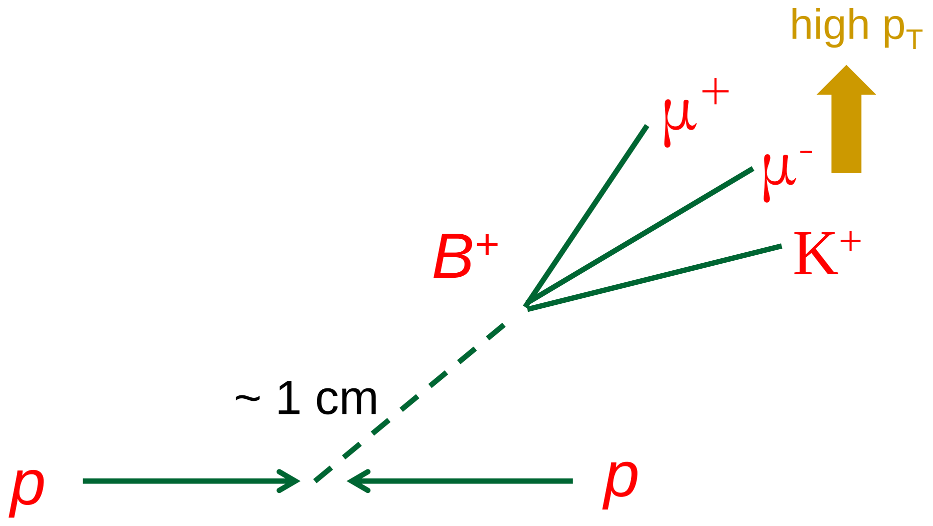
The ones that do, occur
every 10^{-3} -10^{-10} of time.

(Situation is complicated by the fact we also want to study charm physics.
Charm is much more abundant, and the decays of interest are more common).

So we only save to disk the potentially interesting collisions – task of the trigger.

Triggering on beauty

There exist characteristics of increasing complexity than can be searched for to determine if the collision is of interest and should be preserved for offline analysis.



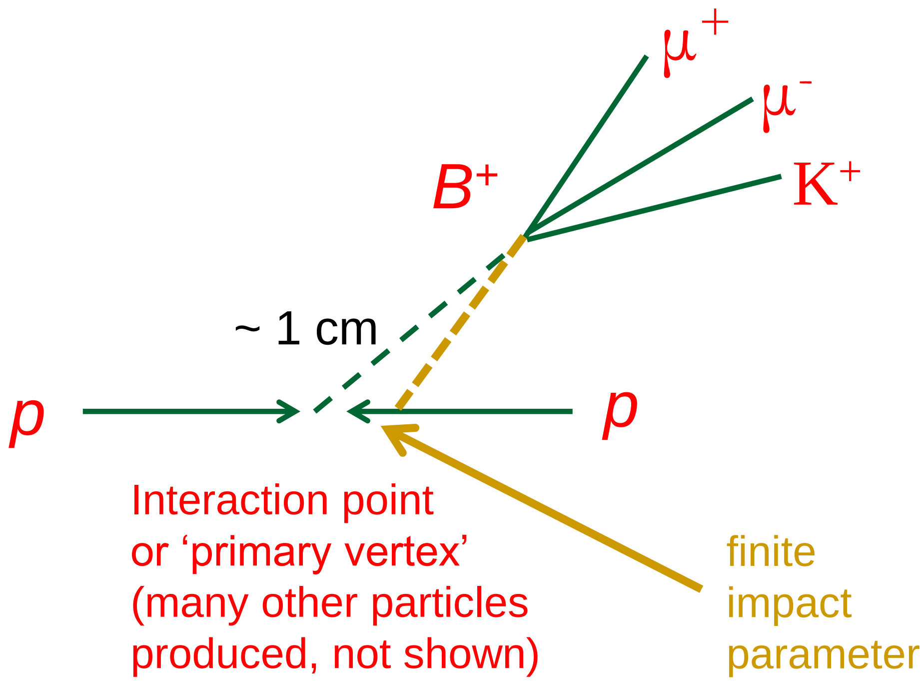
Interaction point
or ‘primary vertex’
(many other particles
produced, not shown)

1. Look for ‘high’ transverse energy (E_T) or momentum (p_T) in calorimeters or muon system from decay products.

.

Triggering on beauty

There exist characteristics of increasing complexity than can be searched for to determine if the collision is of interest and should be preserved for offline analysis.

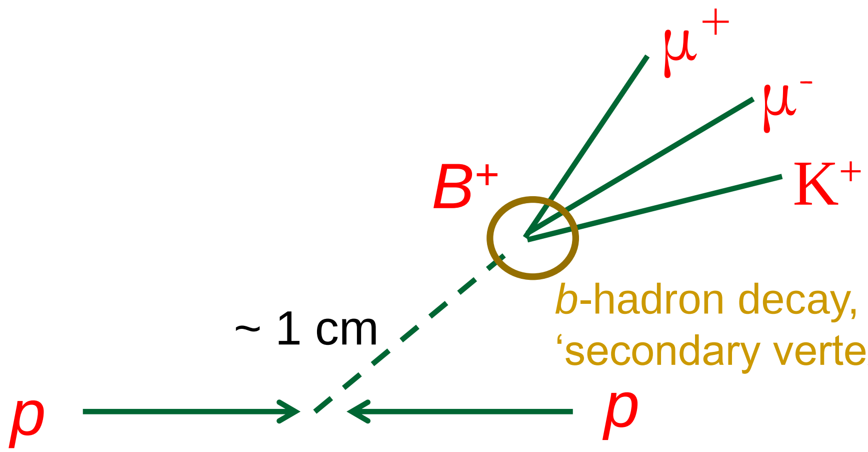


1. Look for ‘high’ transverse energy (E_T) or momentum (p_T) in calorimeters or muon system from decay products.

2. Look for tracks with significant ‘impact parameter’ with respect to primary vertex.

Triggering on beauty

There exist characteristics of increasing complexity than can be searched for to determine if the collision is of interest and should be preserved for offline analysis.



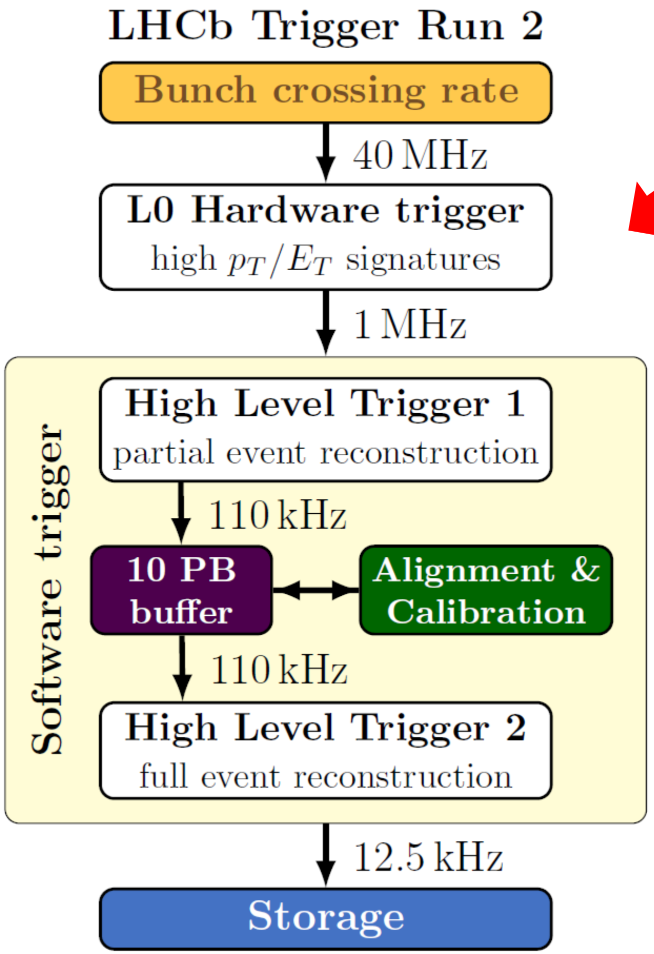
b-hadron decay, or 'secondary vertex'

Interaction point
or 'primary vertex'
(many other particles
produced, not shown)

1. Look for 'high' transverse energy (E_T) or momentum (p_T) in calorimeters or muon system from decay products.
2. Look for tracks with significant 'impact parameter' with respect to primary vertex.
3. Reconstruct secondary vertex and full *b*-hadron decay products.

Each successive step provides improved discrimination, but requires more information & time to execute. In LHCb the first step is performed by the L0 (hardware) Trigger and the next two in the High Level (software) Trigger.

LHCb trigger



LHCb Trigger Run 2

Bunch crossing rate

40 MHz

L0 Hardware trigger

high p_T/E_T signatures

1 MHz

Software trigger

High Level Trigger 1

partial event reconstruction

110 kHz

10 PB buffer

Alignment & Calibration

110 kHz

High Level Trigger 2

full event reconstruction

12.5 kHz

Storage

Earliest trigger stage, 'L0', makes decisions in hardware based on simple high E_T, high p_T signatures.

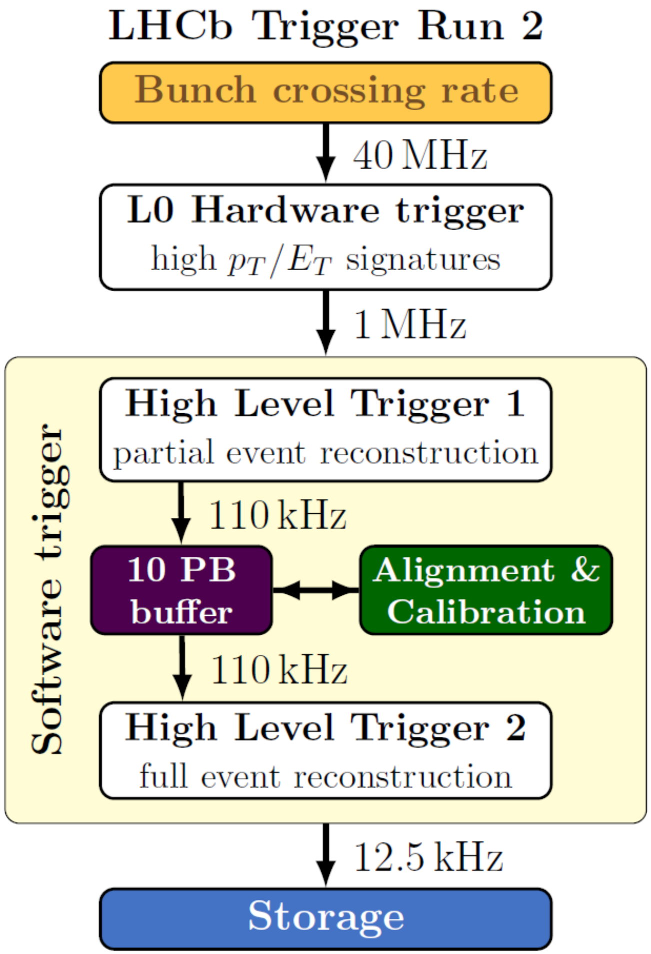
Decision made with partial detector information. No time to build full event.

Trigger decision made within 4 μs synchronous with bunch crossing rate.

While decision is being made local detector information is retained in a pipeline within front-end electronics.

Reduces data rate down to 1 MHz (= rate at which full event is read out, *c.f.* ATLAS where earliest trigger level operates at max rate of 75 kHz).

LHCb trigger



The High Level Trigger (HLT) is a software trigger (C++) that runs on the Event Filter Farm (EFF)

The EFF is a farm of multiprocessor PCs (~1700 nodes), located at LHCb

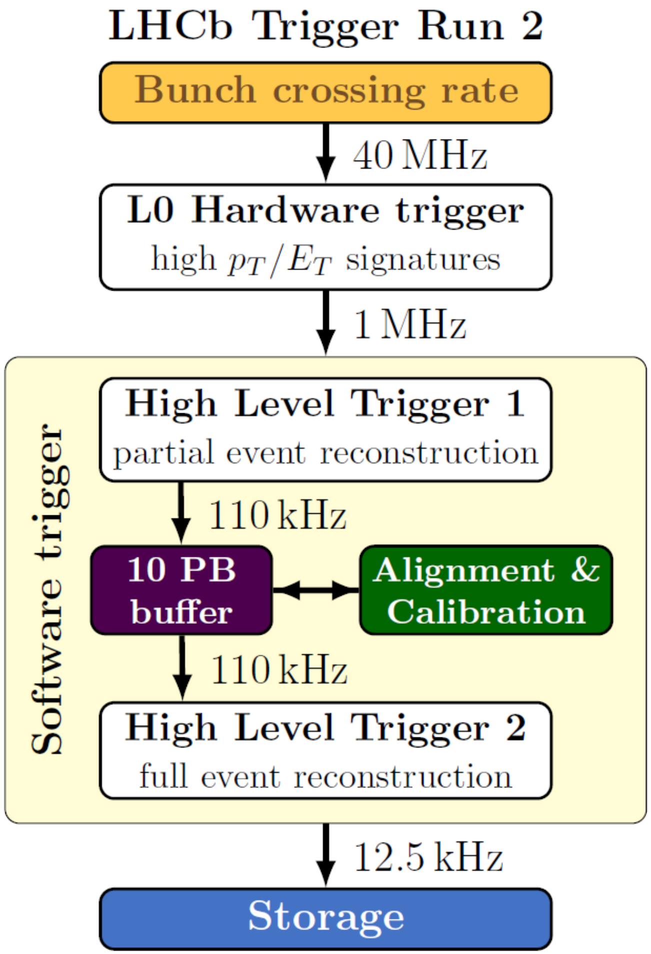
L0-accepted event assembled on the EFF. Placed in buffer that is accessed by HLT programs.

Two steps:

- HLT1: track reconstruction, impact parameter and muon id used to reduce rate to ~110-150 kHz
- HLT2: *full* event information used to reduce rate to ~12 kHz

Then written offline.

LHCb trigger



Something very novel, whose design and scope evolved through Run 2.

After HLT1, events are temporarily stored on a 10 PB disk buffer, enough to hold two weeks of data.

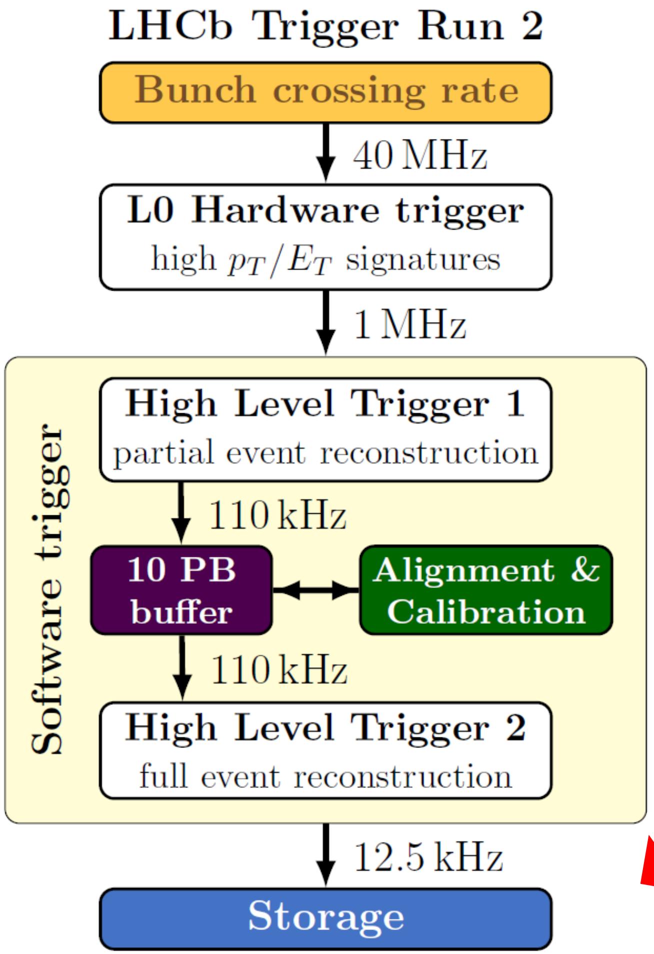
Alignment and calibration is performed for the full detector using dedicated event streams.

Some detector components need alignment each fill (*e.g.* VELO), some less frequently (*e.g.* RICH mirrors).

When all OK, the event is fully reconstructed. Two benefits:

- trigger uses offline quality information to make decision;
- no need for further offline processing step.

LHCb trigger



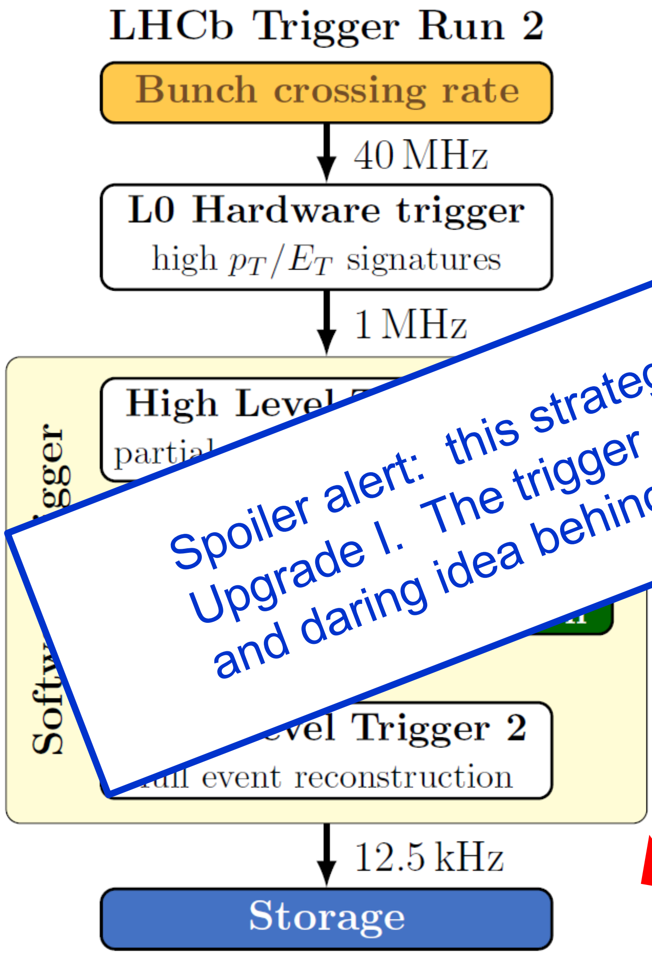
12.5 kHz is a very high output rate, and reflects the wide scope and large sample sizes of flavour physics (*c.f.* ATLAS outputs at 600 Hz).

For the highest rate lines, *e.g.* those of charm meson decays, the events are written out with a reduced format ('TURBO') containing only:

- tracks, neutral objects and PID line that relate to the decay chain of interest;
- tracking detector clusters to permit refits, if necessary.

This, and the overall HLT scheme represents a paradigm shift in physics experiments ('Real Time Analysis') that is sure to become more widespread.

LHCb trigger



Spoiler alert: this strategy changes dramatically for LHCb Upgrade I. The trigger upgrade is the most important, and daring idea behind this project. See Lecture IV.

12.5 kHz is a very high output rate, and reflects the wide scope and large sample sizes of flavour physic
(*c.f.* ATLAS outputs at

For the hig
thos
ced
ng only:

objects and PID
at relate to the decay
chain of interest;

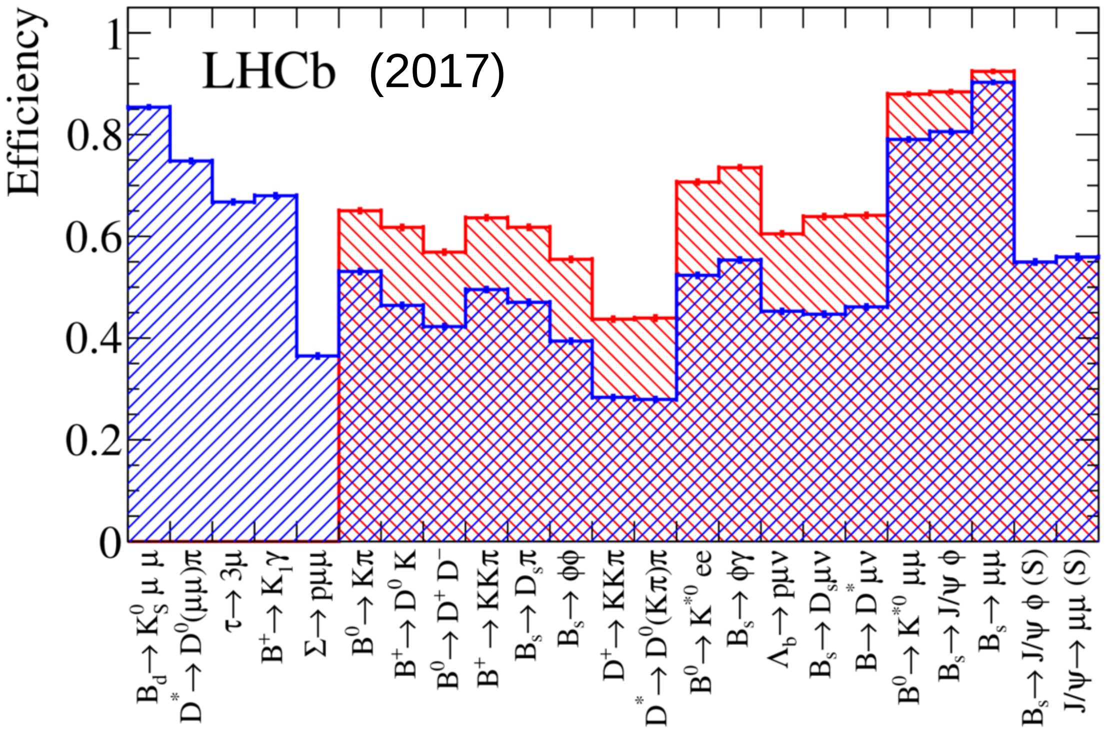
- tracking detector clusters to permit refits, if necessary.

This, and the overall HLT scheme represents a paradigm shift in physics experiments ('Real Time Analysis') that is sure to become more widespread.

Performance of LHCb trigger

[JINST 14 (2019) P04013]

It is LHCb's ability to trigger on hadrons, electrons, photons and single muons from b decays (not just dimuons) that gives it sensitivity to the widest range of channels.



Red – efficiency if all L0 bandwidth were to be devoted to this channel (not evaluated for all).

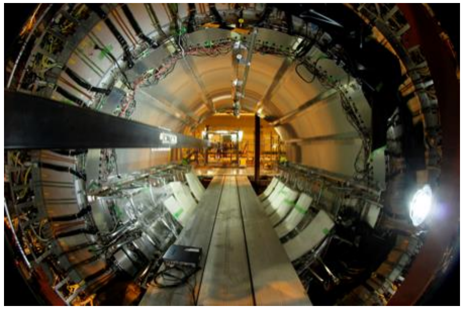
Blue – more realistic case: efficiency if L0 bandwidth is shared between channels.

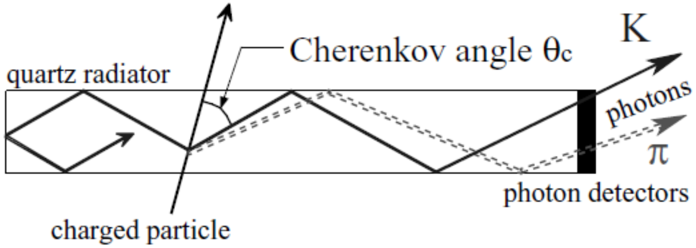
The efficiency varies and is generally higher for low multiplicity decays. Although rarely close to 100%, it is perfectly adequate for bringing a huge range of physics within reach. Improving these efficiencies, and allowing the trigger to function at higher luminosities, is the goal of the LHCb Upgrade (see Lecture IV).

What is *really* different at Belle II ?

1) Geometry: much greater proportion of b production happens in barrel region at e^+e^- machine, than at hadron collider.

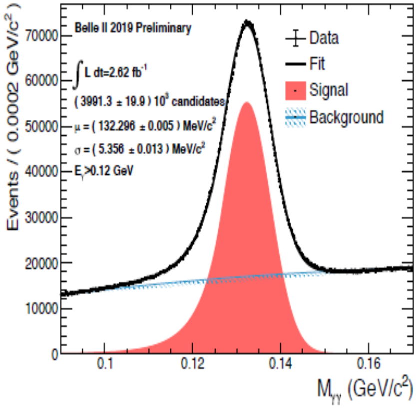
2) Particle identification: need to cover a much narrower (and lower) range of momenta (up to a few GeV/*c*). Single thin radiator is sufficient, which in barrel is quartz (TOP detector) and aerogel in end caps.





~2 cm thick

3) Calorimetry: in low multiplicity e^+e^- environment, there is much to be done with photons and π^0s, and little emphasis on jet physics, so use high-performance CsI(Tl) crystal ECAL.



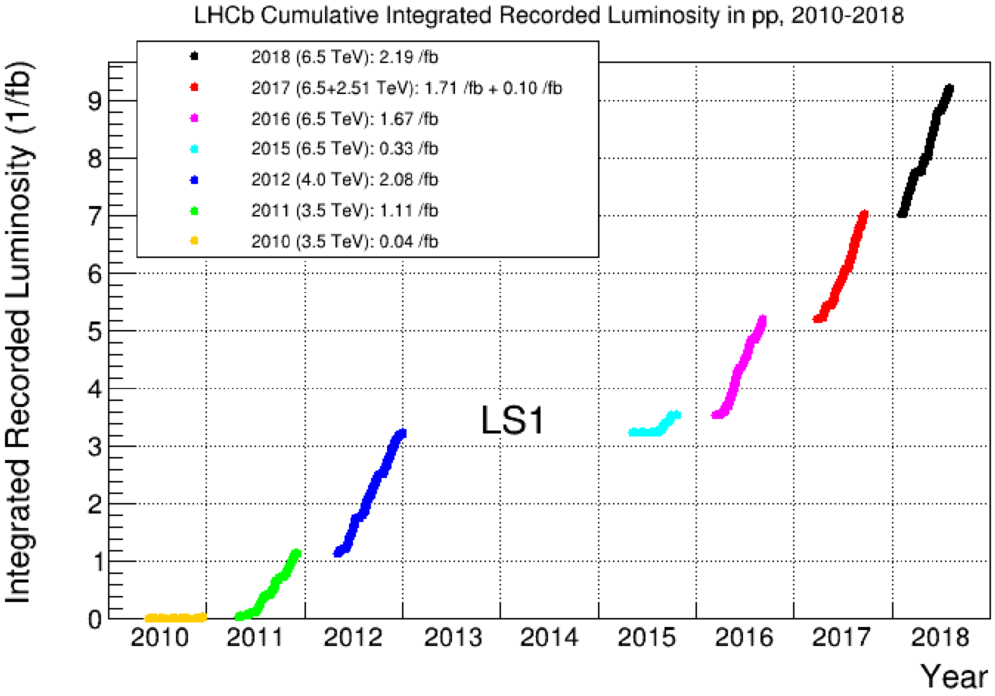
[Miyabayashi, JINST 15 (2020) C10016]

π^0 peak about twice as narrow as at LHCb

4) Trigger: not an issue in an e^+e^- experiment !

LHCb – the story so far

LHC Run 1 went from 2010 to 2012 at E_{CM} = 7 and 8 TeV, and Run 2 went from 2015-18 at E_{CM} = 13 TeV (giving a ~ x 1.7 increase in $b\bar{b}$ cross section).

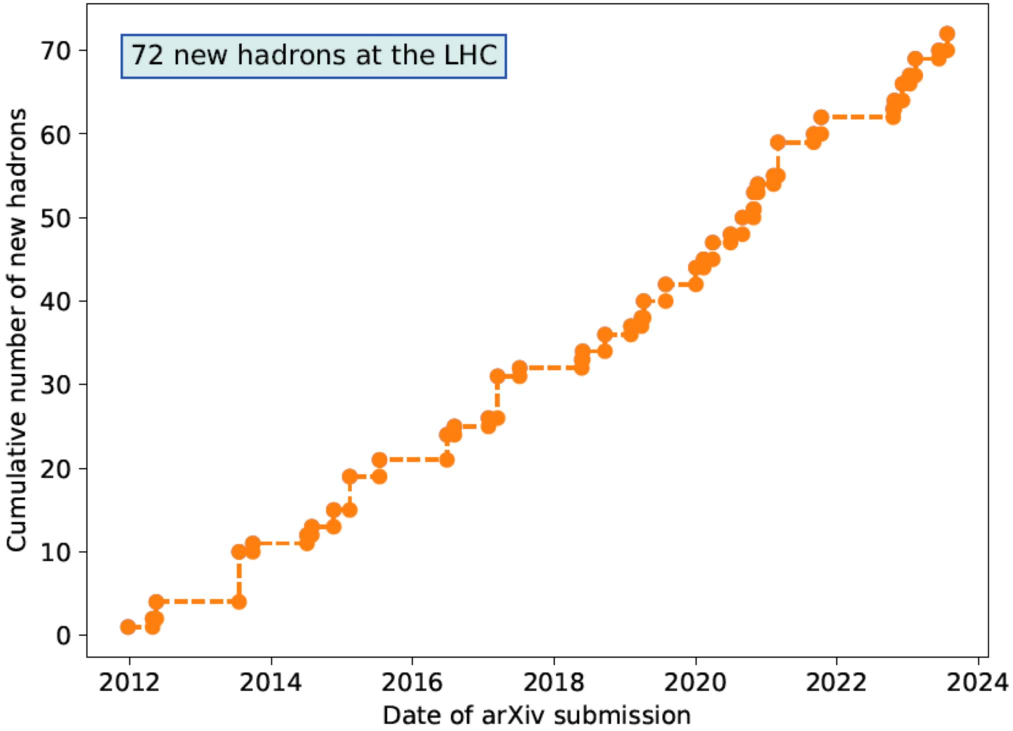


9 fb^{-1} collected (~10^{12} $b\bar{b}$ pairs produced within LHCb). Much less than integrated luminosity of ATLAS/CMS, but delivered in conditions ideal for b-physics.

OK, so we have our detector. What can we do with it ?

Instead of immediately turning to the core topics of flavour physics, we will conclude today's lecture by considering these experiments' contributions to spectroscopy. This is non-perturbative QCD, not flavour, however the most interesting studies concern states with heavy quark content. Ideally suited to flavour experiments !

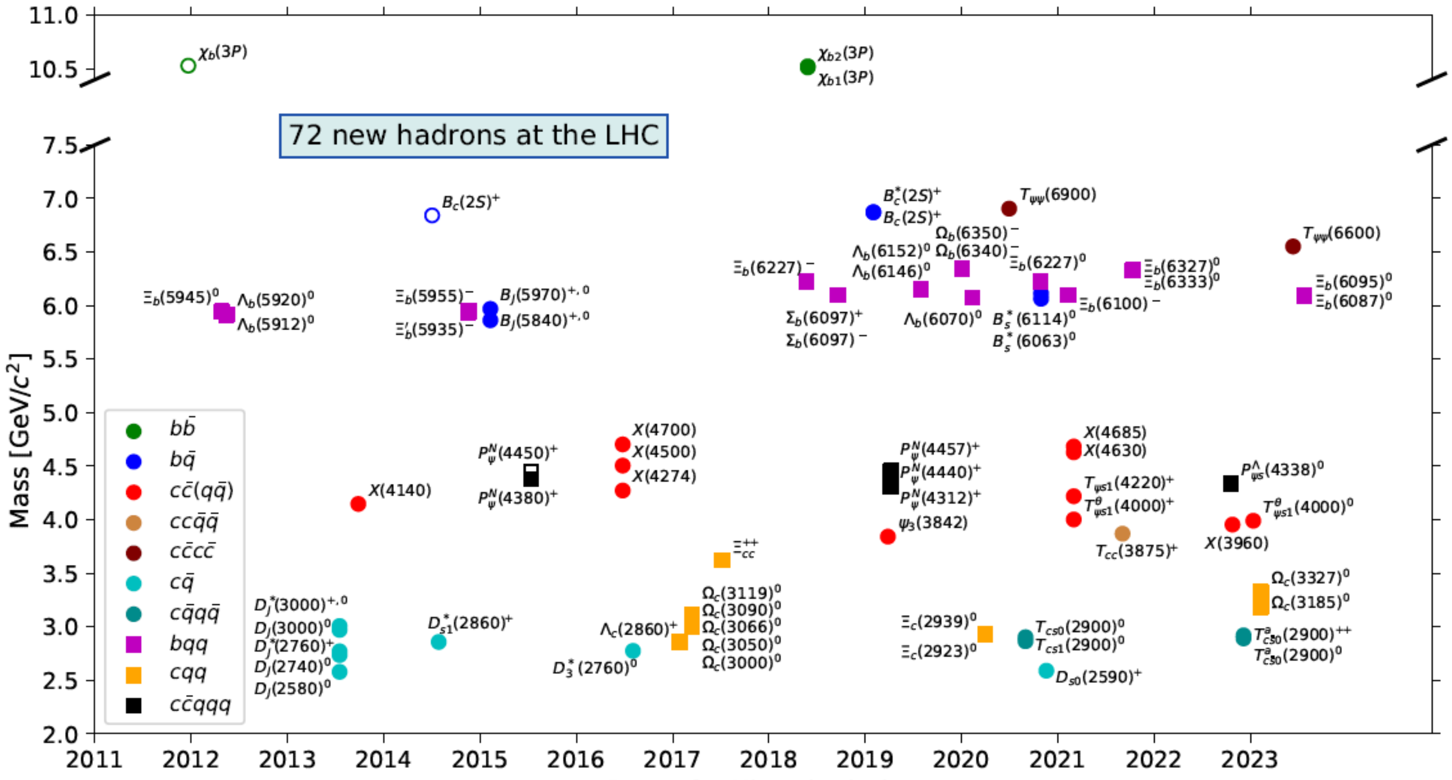
The LHC has truly been a gold mine for spectroscopy studies, something not at all foreseen prior to turn on.



patrick.koppenburg@cern.ch 2023-08-16

New particles discovered at the LHC

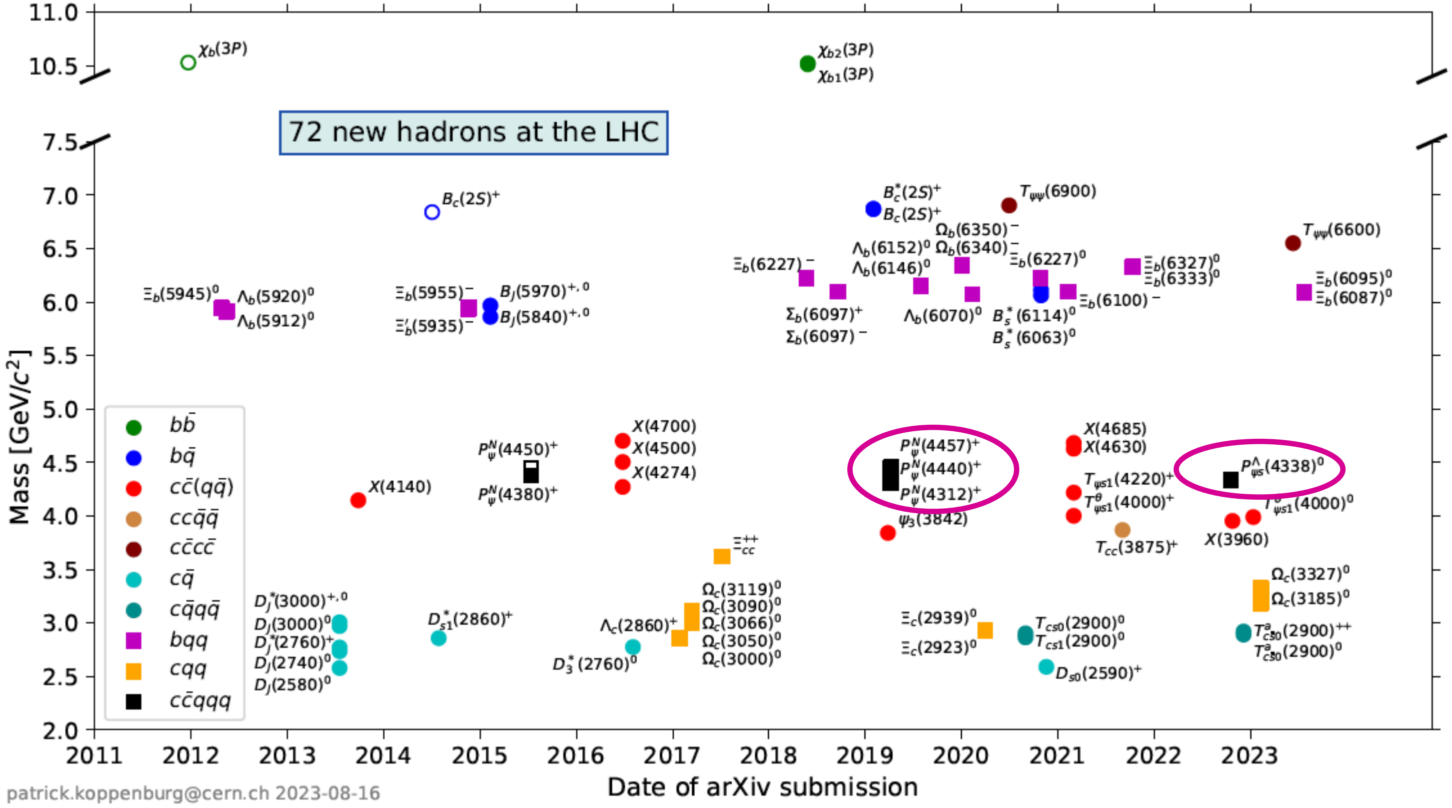
It's not just the Higgs by any means !



patrick.koppenburg@cern.ch 2023-08-16

New particles discovered at the LHC

It’s not just the Higgs by any means !

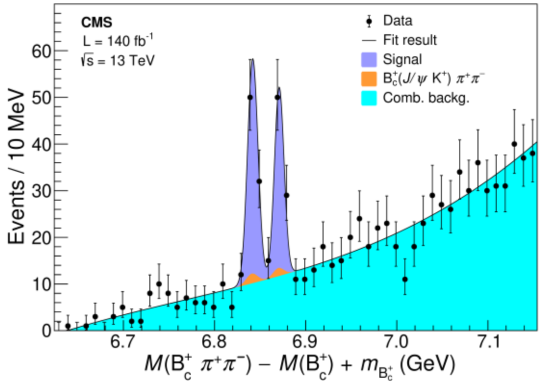


Impossible to be comprehensive, so I will focus on exotic baryons – unique to LHC.

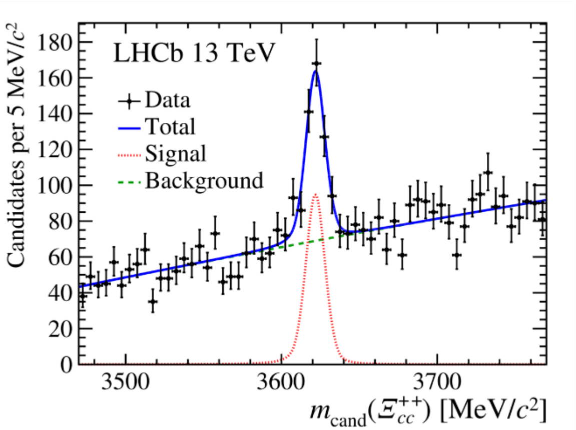
Spectroscopy - the conventional

Many new states found at the LHC, most of which fit within the ‘vanilla’ quark model

CMS discovery of excited B_c states [PRL 122 (2019) 132001]



LHCb discovery of the Ξ_{cc}^{++} [PRL 119 (2017) 112001]



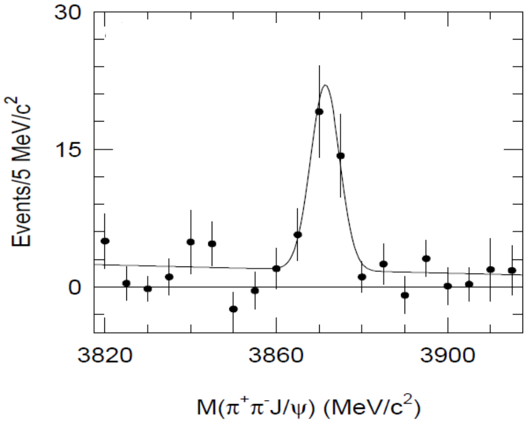
> “Baryons can now be constructed from quarks by using the combinations qqq, $qqq\bar{q}q$, etc, while mesons are made out of $q\bar{q}$, $q\bar{q}q\bar{q}$, etc.”
>
> **Murray Gell-Mann**

Spectroscopy - the exotic

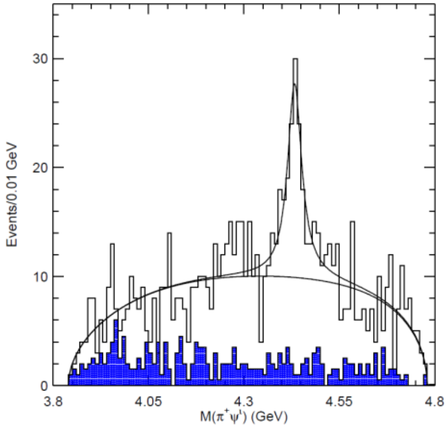
Other states, many discovered in e^+e^-, are good candidates to be ‘exotic’:

Both are strong candidates to be four-quark states

Observation of the X(3872) at Belle [PRL 91 (2003) 262001]



Observation of the $Z(4430)^+$ at Belle [PRL 100 (2008) 142001]



> “Baryons can now be constructed from quarks by using the combinations qqq, $qqq\bar{q}q$, etc, while mesons are made out of $q\bar{q}$, $q\bar{q}q\bar{q}$, etc.”
>
> **Murray Gell-Mann**

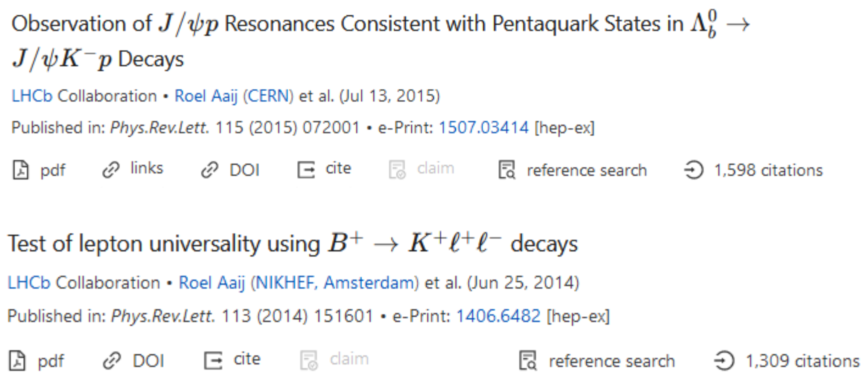
Spectroscopy results – provoke great interest among physicists

Top cited Belle physics papers

1. Observation of a narrow charmonium-like state in exclusive $B^\pm \to K^\pm \pi^+ \pi^- J/\psi$ decays
   Belle Collaboration • S.K. Choi (Gyeongsang Natl. U.) et al. (Sep, 2003)
   Published in: *Phys.Rev.Lett.* 91 (2003) 262001 • e-Print: hep-ex/0309032 [hep-ex]
   2,353 citations

2. Observation of large CP violation in the neutral B meson system
   Belle Collaboration • Kazuo Abe (KEK, Tsukuba) et al. (Jul, 2001)
   Published in: *Phys.Rev.Lett.* 87 (2001) 091802 • e-Print: hep-ex/0107061 [hep-ex]
   1,176 citations

Top cited LHCb physics papers



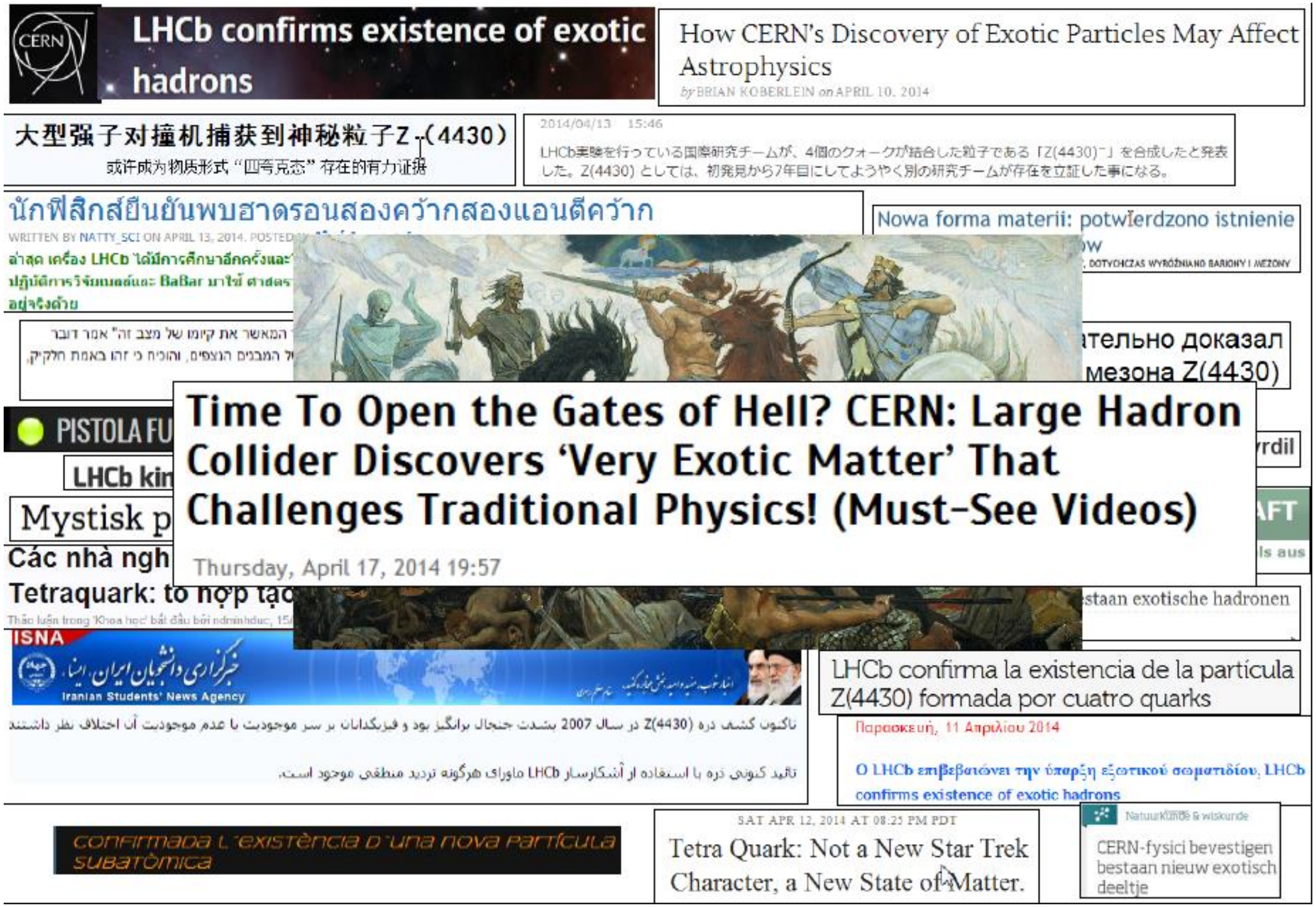
1. Observation of $J/\psi p$ Resonances Consistent with Pentaquark States in $\Lambda_b^0 \to J/\psi K^- p$ Decays
   LHCb Collaboration • Roel Aaij (CERN) et al. (Jul 13, 2015)
   Published in: *Phys.Rev.Lett.* 115 (2015) 072001 • e-Print: 1507.03414 [hep-ex]
   1,598 citations

2. Test of lepton universality using $B^+ \to K^+ \ell^+ \ell^-$ decays
   LHCb Collaboration • Roel Aaij (NIKHEF, Amsterdam) et al. (Jun 25, 2014)
   Published in: *Phys.Rev.Lett.* 113 (2014) 151601 • e-Print: 1406.6482 [hep-ex]
   1,309 citations

[citation count as of 28/8/23]

Spectroscopy results – provoke great interest among public too

e.g. reactions to LHCb study of resonant nature of $Z(4430)^-$ [PRL 112 (2013) 222002]



LHCb confirms existence of exotic hadrons

How CERN's Discovery of Exotic Particles May Affect Astrophysics

by BRIAN KOBERLEIN on APRIL 10, 2014

大型强子对撞机捕获到神秘粒子Z-(4430)

或许成为物质形式“四夸克态”存在的有力证据

2014/04/13 15:46

LHCb実験を行っている国際研究チームが、4個のクォークが結合した粒子である「Z(4430)⁻」を合成したと発表した。Z(4430) としては、初発見から7年目にしてようやく別の研究チームが存在を立証した事になる。

นักฟิสิกส์ยืนยันพบฮาดรอนสองคว้ากสองแอนตีคว้าก

WRITTEN BY NATTY_SCI ON APRIL 13, 2014. POSTED

ล่าสุด เครื่อง LHCb ได้มีการศึกษาอีกครั้งและ

ปฏิบัติการวิจัยเบลล์และ BaBar มาใช้ ศาสตร

อยู่จริงด้วย

Nowa forma materii: potwierdzono istnienie

ów

, DOTYCHCZAS WYRÓŻNIANO BARIONY I MEZONY

המאשר את קיומו של מצב זה" אמר דובר

ל המבנים הנצפים, והוכיח כי זהו באמת חלקיק,

ательно доказал

мезона Z(4430)

PISTOLA FU

LHCb kin

Mystisk p

Các nhà ngh

Tetraquark: tổ hợp tạo

Thảo luận trong 'Khoa học' bắt đầu bởi ndminhduc, 15/

Time To Open the Gates of Hell? CERN: Large Hadron Collider Discovers 'Very Exotic Matter' That Challenges Traditional Physics! (Must-See Videos)

Thursday, April 17, 2014 19:57

rdil

AFT

ls aus

staan exotische hadronen

ISNA

خبرگزاری دانشجویان ایران، ایسنا،

Iranian Students' News Agency

تاکنون کشف ذره (Z(4430 در سال 2007 بشدت جنجال برانگیز بود و فیزیکدانان بر سر موجودیت یا عدم موجودیت آن اختلاف نظر داشتند

تائید کنونی ذره با استفاده از آشکارساز LHCb ماورای هرگونه تردید منطقی موجود است.

LHCb confirma la existencia de la partícula Z(4430) formada por cuatro quarks

Παρασκευή, 11 Απριλίου 2014

Ο LHCb επιβεβαιώνει την ύπαρξη εξωτικού σωματιδίου, LHCb confirms existence of exotic hadrons

Confirmada l'existència d'una nova partícula subatòmica

SAT APR 12, 2014 AT 08:25 PM PDT

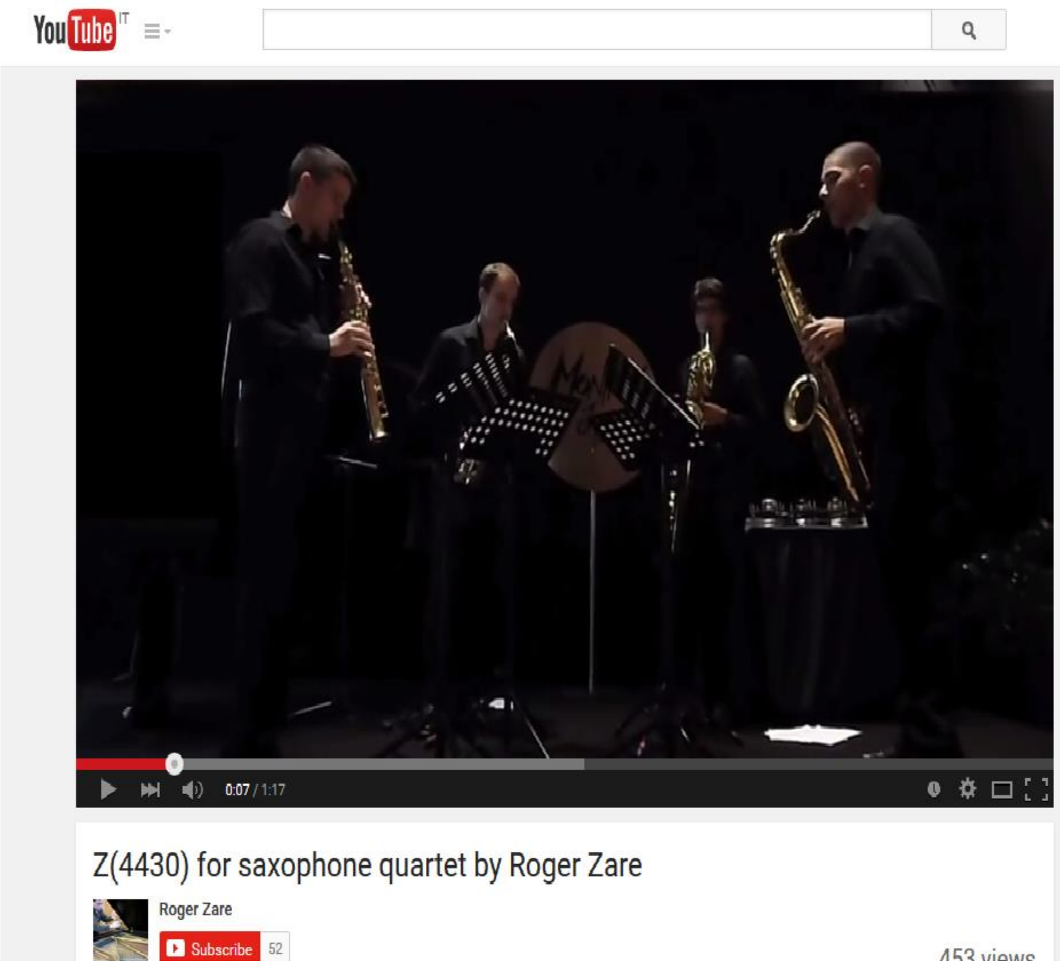
Tetra Quark: Not a New Star Trek Character, a New State of Matter.

Natuurkunde & wiskunde

CERN-fysici bevestigen bestaan nieuw exotisch deeltje

Spectroscopy results – provoke great interest among public too

e.g. reactions to LHCb study of resonant nature of $Z(4430)^-$ [PRL 112 (2013) 222002]



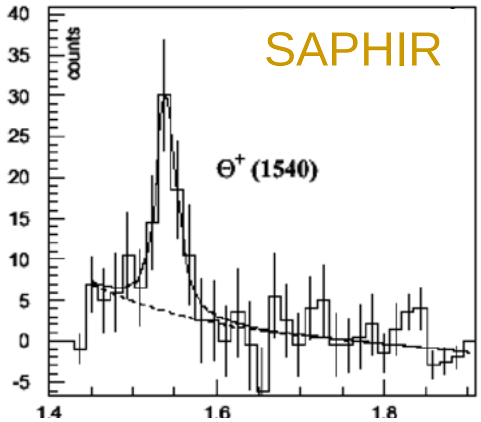
Z(4430) for saxophone quartet by Roger Zare

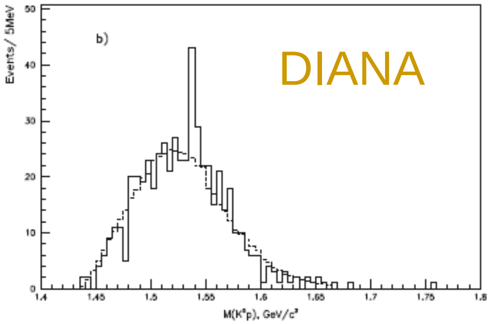
Roger Zare

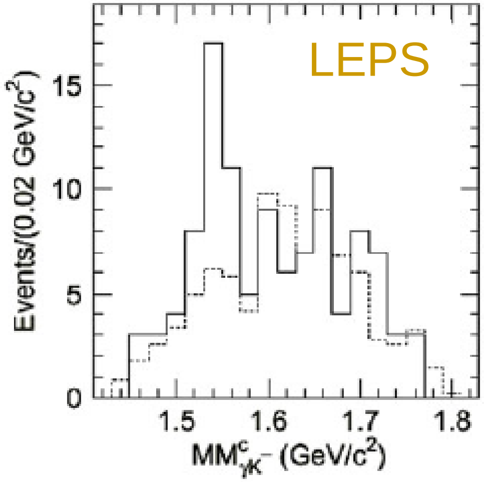
Montreux jazz festival, 2014

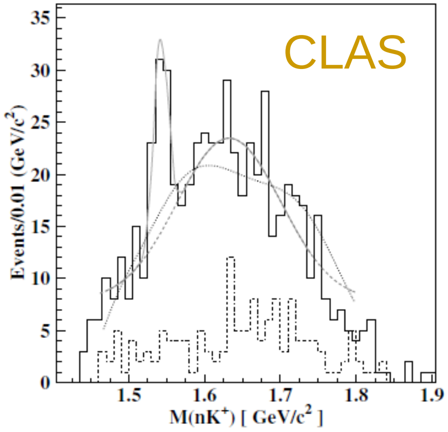
The hunt for pentaquarks – a long journey with several cul-de-sacs

Pentaquark signals have been claimed before, for example the θ^+ (sbar uudd) ‘seen’ by several experiments in the early 2000s.







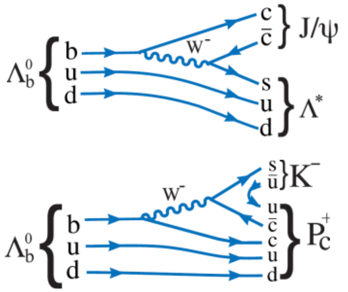


After an initial rush of confirmations, null results from more sensitive experiments appeared, & eventually it was accepted to be non-existent.

> “ The whole story – the discoveries themselves, the tidal wave of papers by theorists and phenomenologists that followed, and the eventual ‘undiscovery’ - is a curious episode in the history of science.” PDG 2008

[for more information, see Hicks, Eur. Phys. J. H 37 (2012) 1]

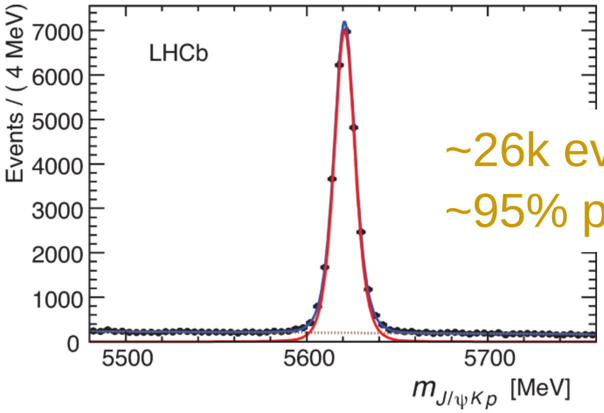
J/Ψp resonances consistent with pentaquark states



[PRL 115 (2015) 072001]

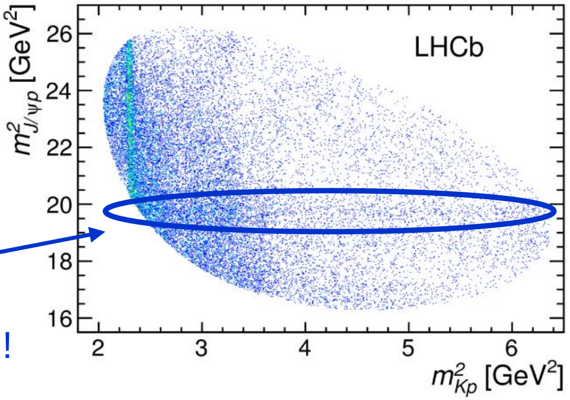
Large & pure sample of $\Lambda_b \to J/\Psi pK$ decays

Distinctive structure in J/Ψp spectrum

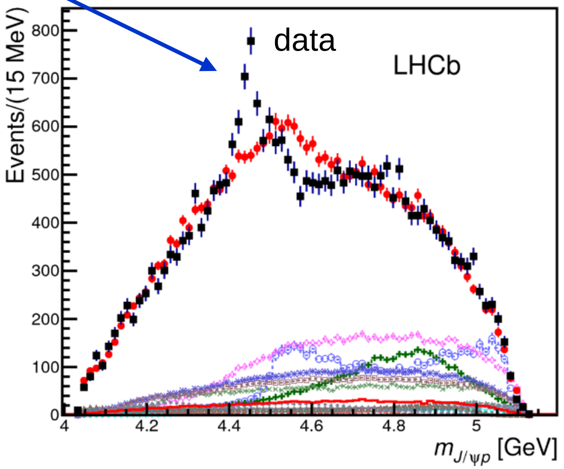


~26k events

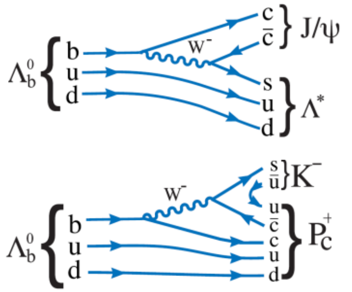
~95% purity



Naïve first impression: this is exotic ! (uudccbar).

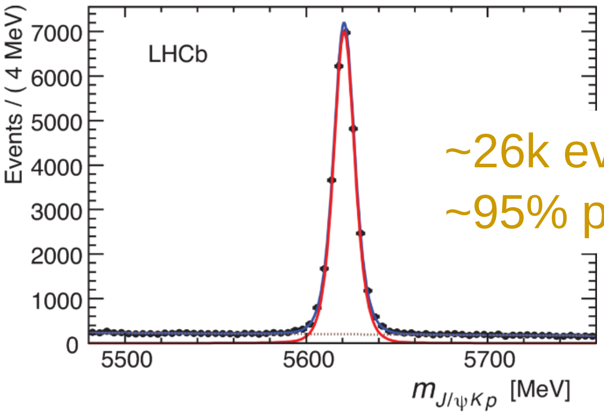


J/Ψp resonances consistent with pentaquark states



[PRL 115 (2015) 072001]

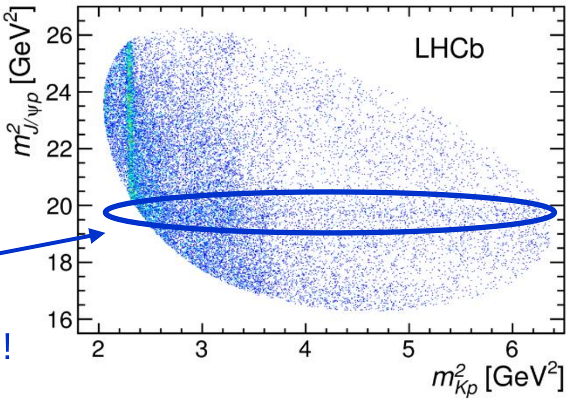
Large & pure sample of $\Lambda_b \to J/\Psi pK$ decays



~26k events

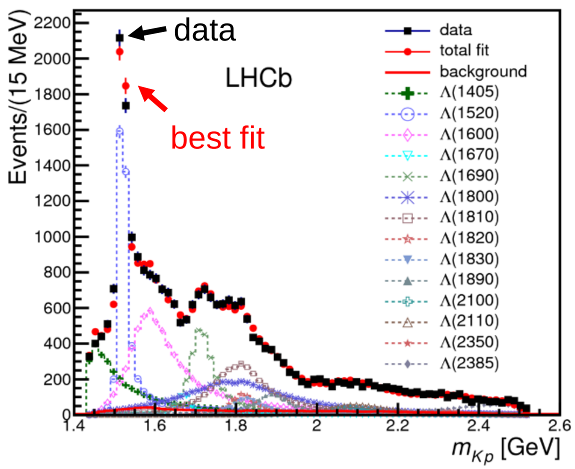
~95% purity

Distinctive structure in J/Ψp spectrum

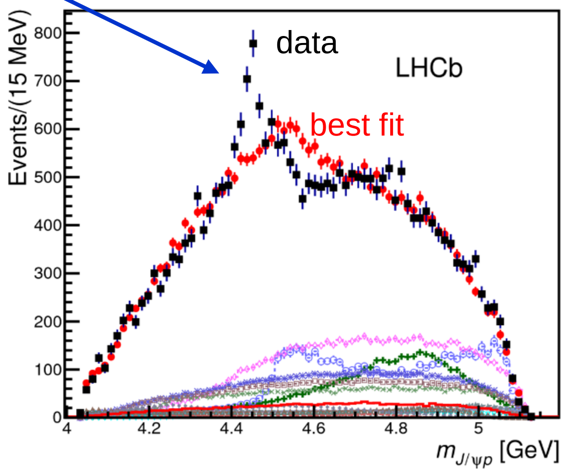


Naïve first impression: this is exotic ! (uudccbar).

Amplitude model of conventional states can reproduce Kp spectrum well enough…



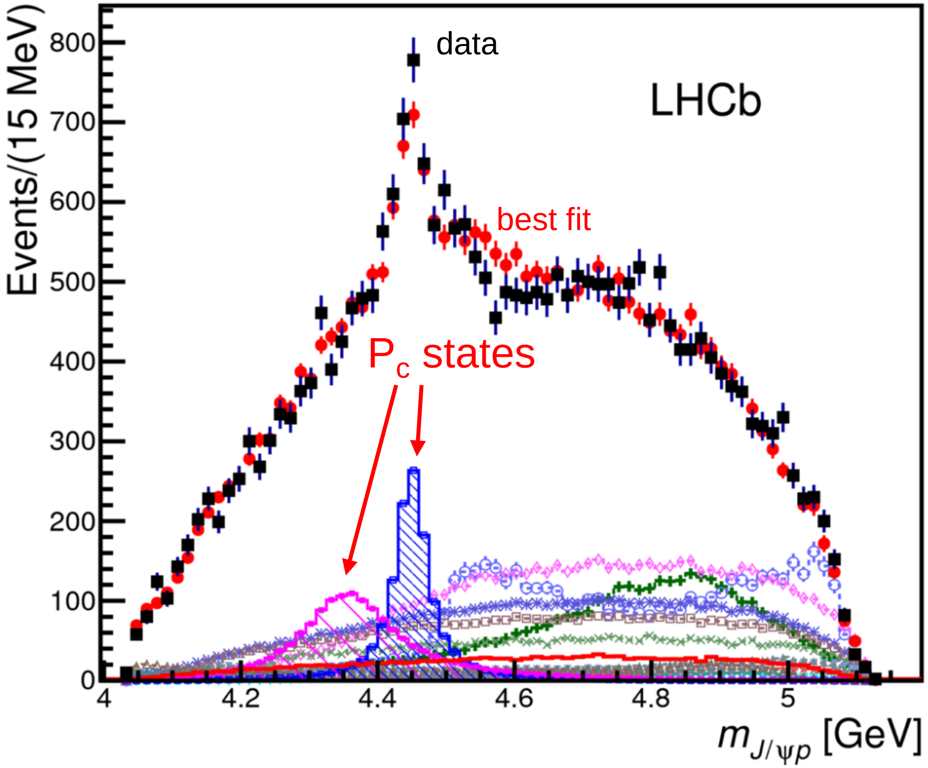
…but cannot describe the J/Ψ projection at all.



J/Ψp resonances consistent with pentaquark states

[PRL 115 (2015) 072001]

Can only describe data satisfactorily by adding two exotic pentaquark states with content uudccbar. Best fit has J=3/2 and 5/2 with opposite parities.



$P_c(4380)$:

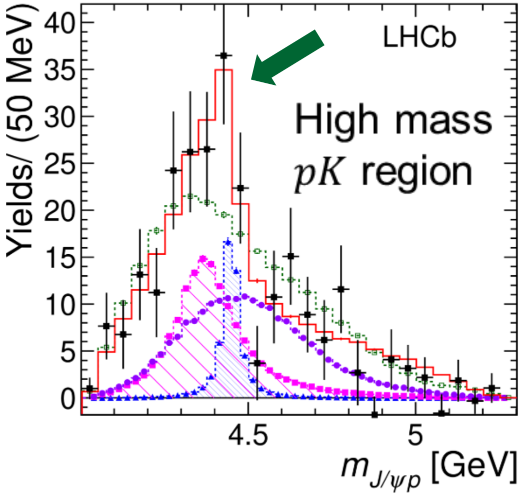
$$M = 4380 \pm 8 \pm 29\,\mathrm{MeV},$$
$$\Gamma = 205 \pm 18 \pm 86\,\mathrm{MeV}$$

$P_c(4450)$:

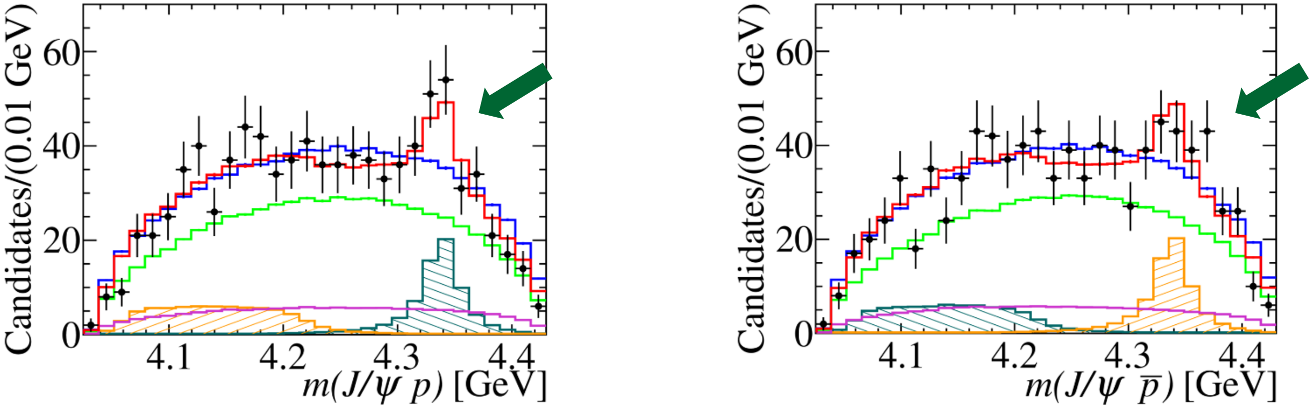
$$M = 4449.8 \pm 1.7 \pm 2.5\,\mathrm{MeV}$$
$$\Gamma = 39 \pm 5 \pm 19\,\mathrm{MeV}$$

Appearance in other channels ?

These same resonances should appear in the Cabibbo-suppressed channel $\Lambda^0_b \to J/\psi p\pi^-$, and indeed there is evidence of a signal at the level expected with this lower yield sample [PRL 117 (2016) 082003].



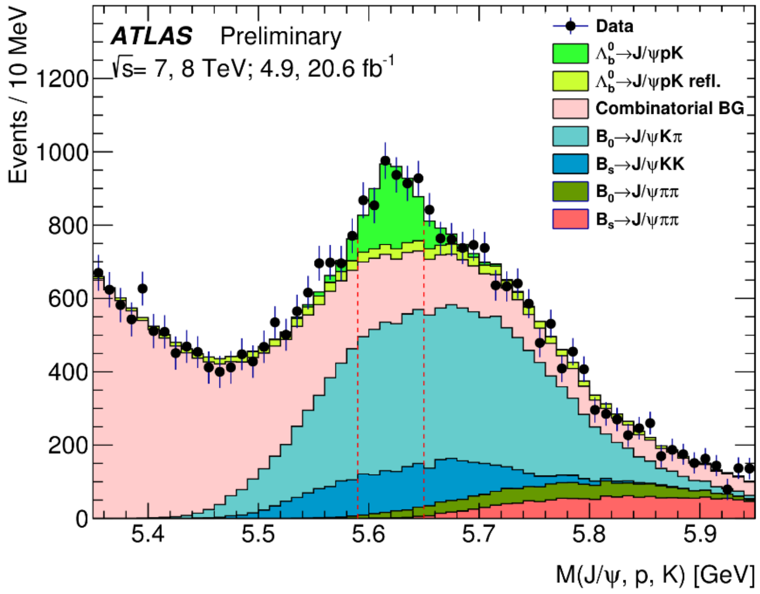
The mode $\Lambda^0_b \to J/\psi p\bar{p}$ has also been studied [PRL 128 (2022) 062001]. Curiously, the (now established) P_c resonances are not present, but there is evidence of a structure at slightly higher mass. An excited P_c ?

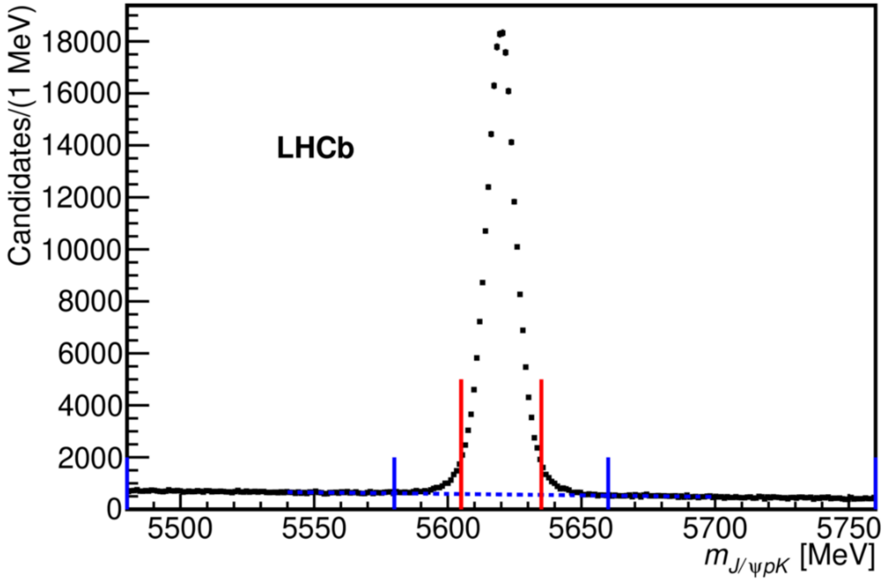


Reminder – the importance of PID

ATLAS have come to the party with a preliminary analysis [ATLAS-CONF-2019-048].

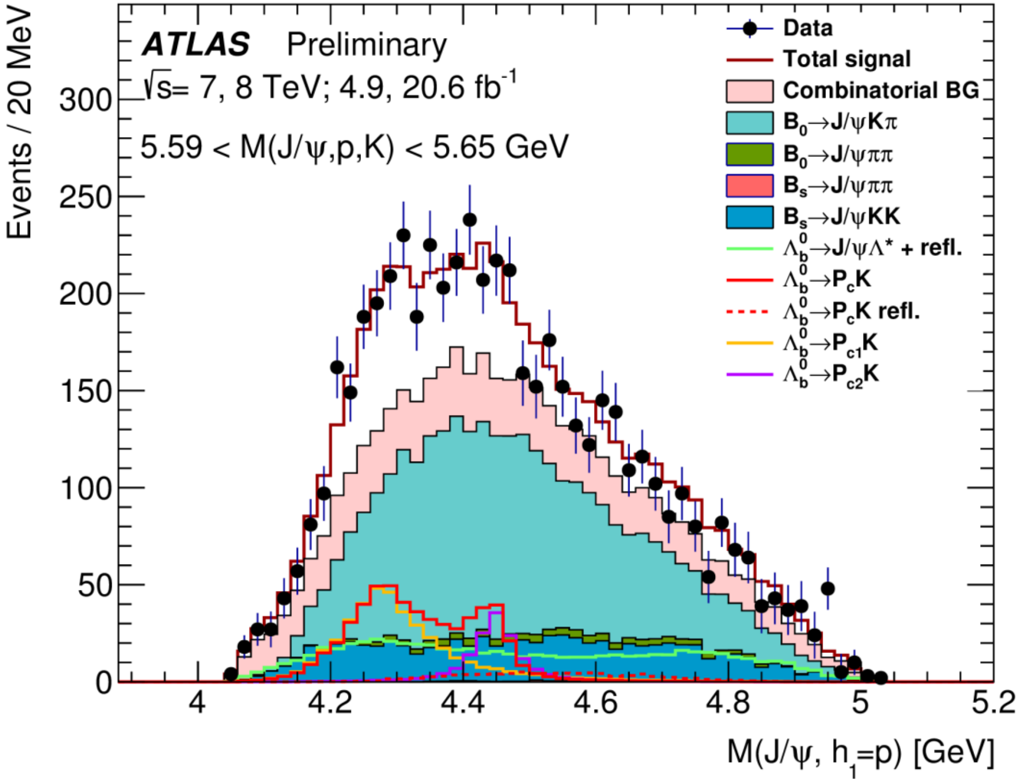
Without a RICH system the background challenge is substantial.





ATLAS preliminary pentaquark study

Nonetheless, a signal region can be isolated and fits performed – a heroic task !

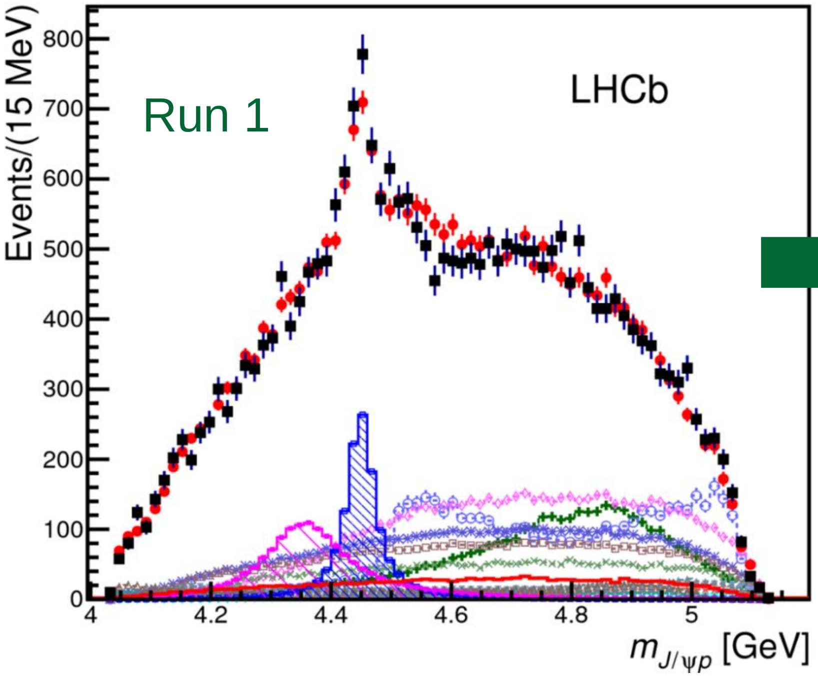


[ATLAS-CONF-2019-048]

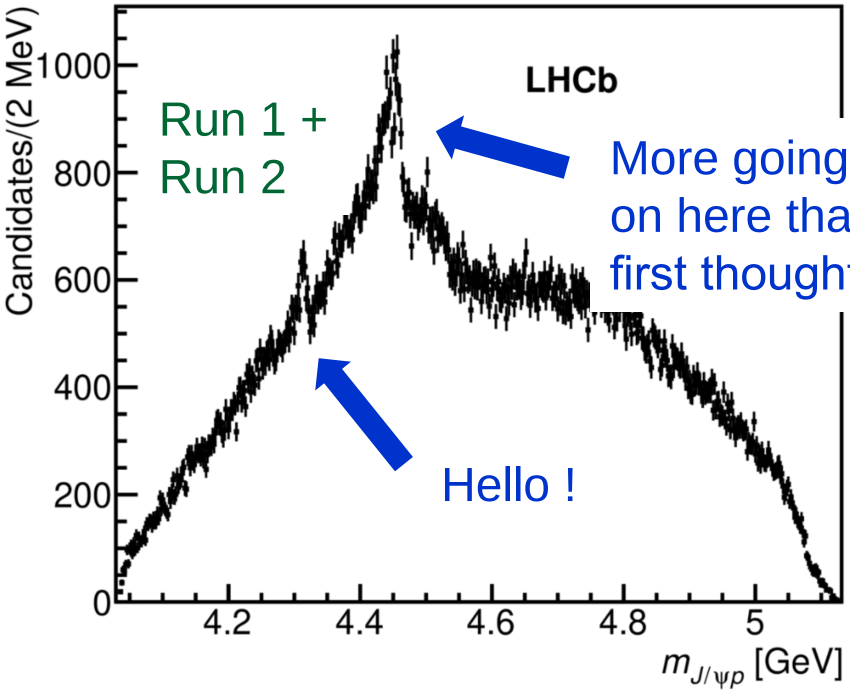
Results compatible with LHCb model, but other solutions are not excluded.

Pentaquarks – why more data matters

Run 2 data and improved selection provide x9 increase in signal



[PRL 115 (2015) 072001]



More going on here than first thought…

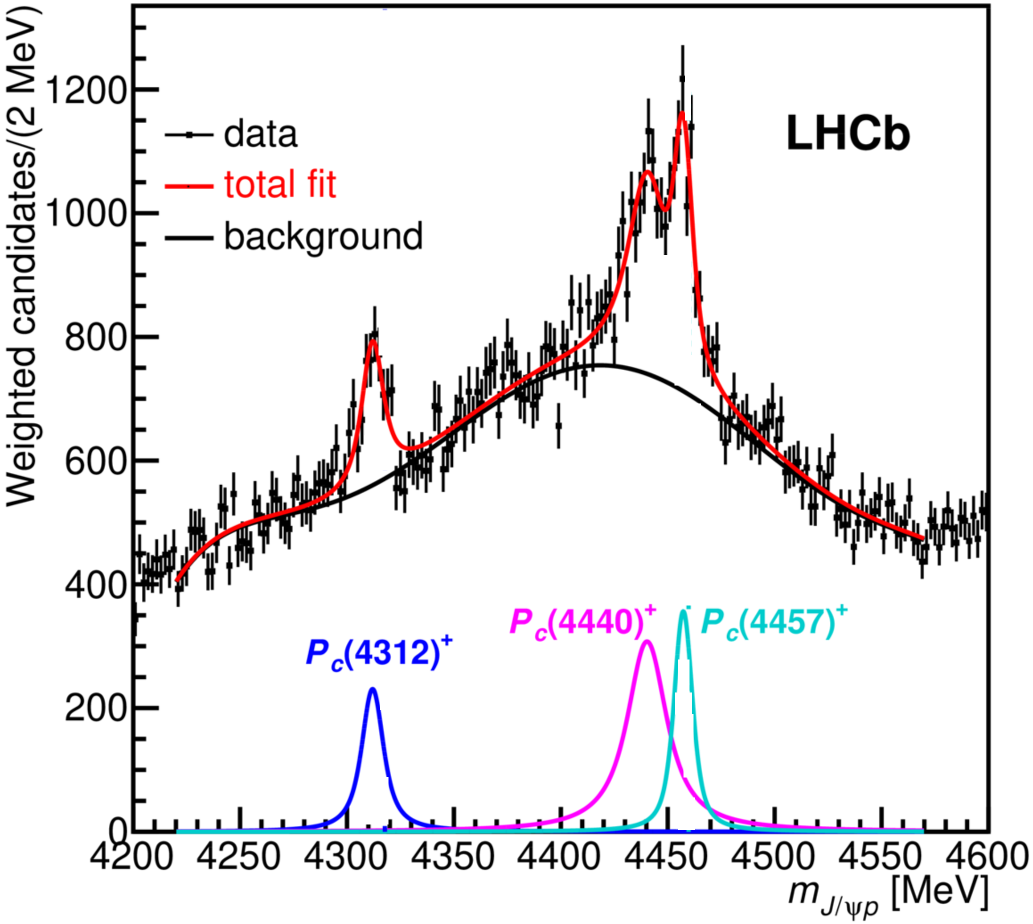
Hello !

[PRL 122 (2019) 222001]

Not one narrow state, but three

A closer look at Run 2 data, after weighting to suppress effect of Λ* background.

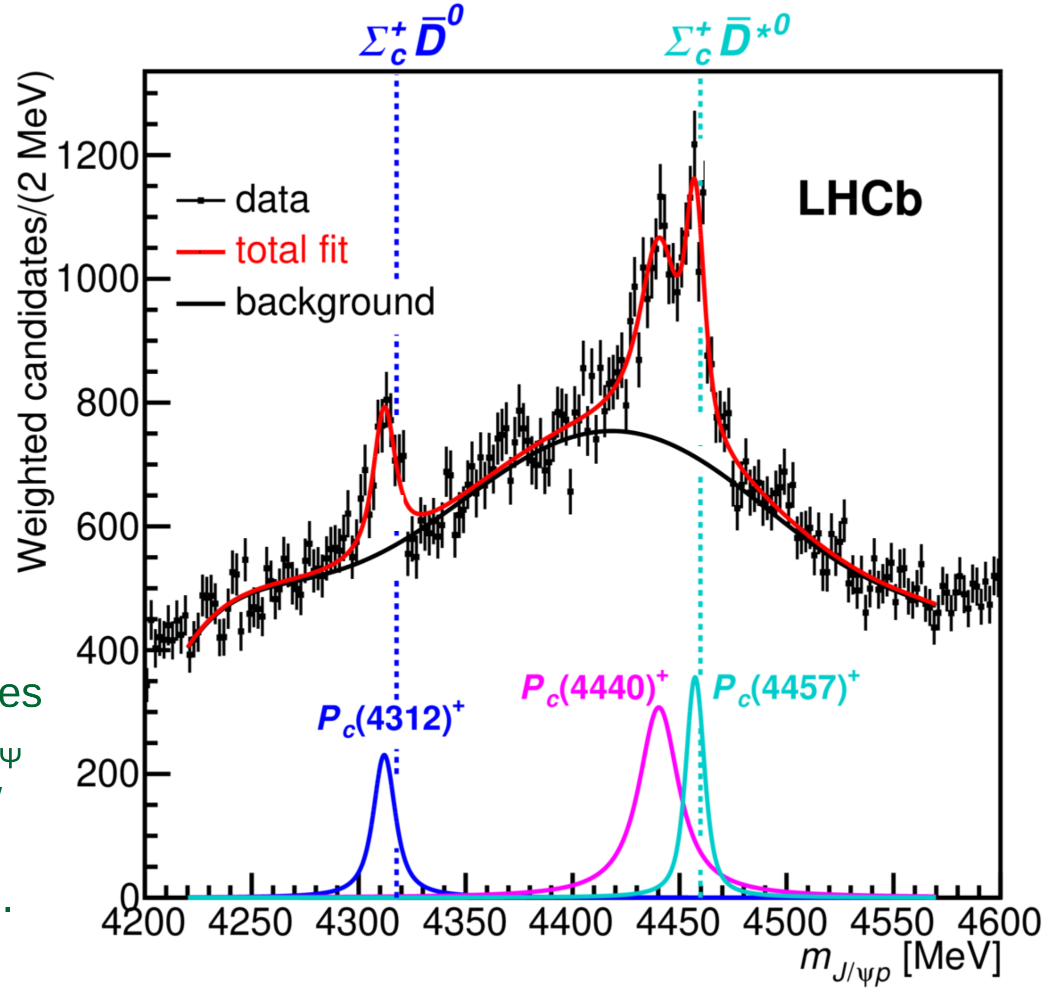
[PRL 122 (2019) 222001]



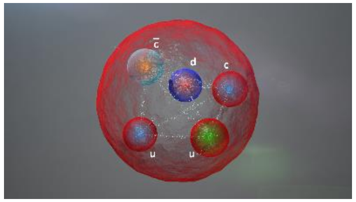
A new narrow state is observed at 4312 MeV, and the previous narrowish state is resolved into two close-lying narrower states. An amplitude analysis is required to determine J^P and decide on whether broad $P_c(4380)$ still required.

Not one narrow state, but three

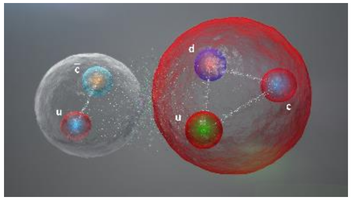
[PRL 122 (2019) 222001]



tightly-bound model



molecular model



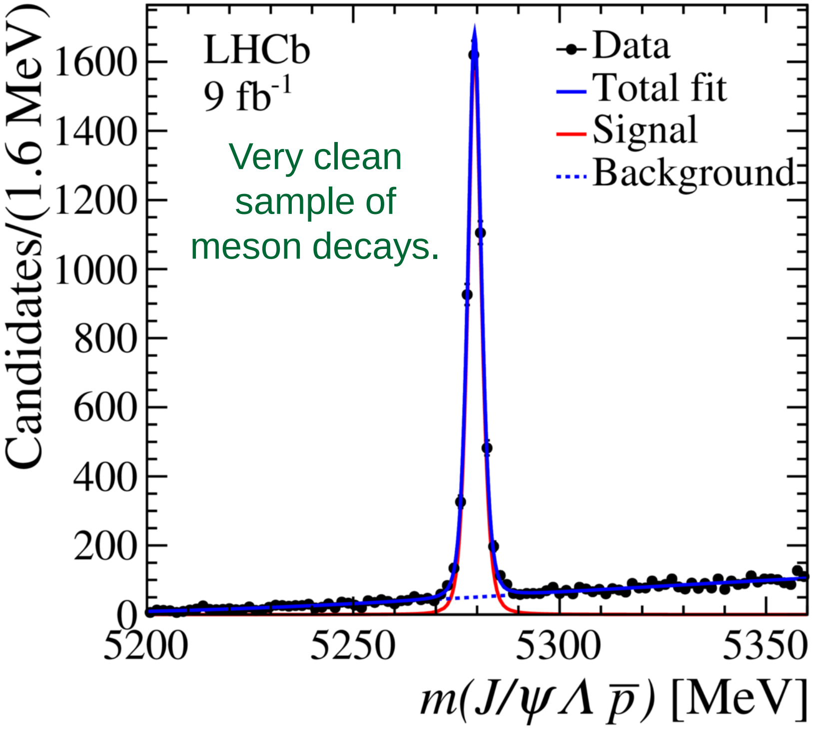
Note, all these states now labelled as P^N_ψ according to a new naming convention [arXiv:2206.15233].

Intriguingly, two of the states lie just below the $\Sigma_c D^{(*)0}$ thresholds, which supports a molecular meson-baryon bound state picture of the pentaquarks. See *e.g.*

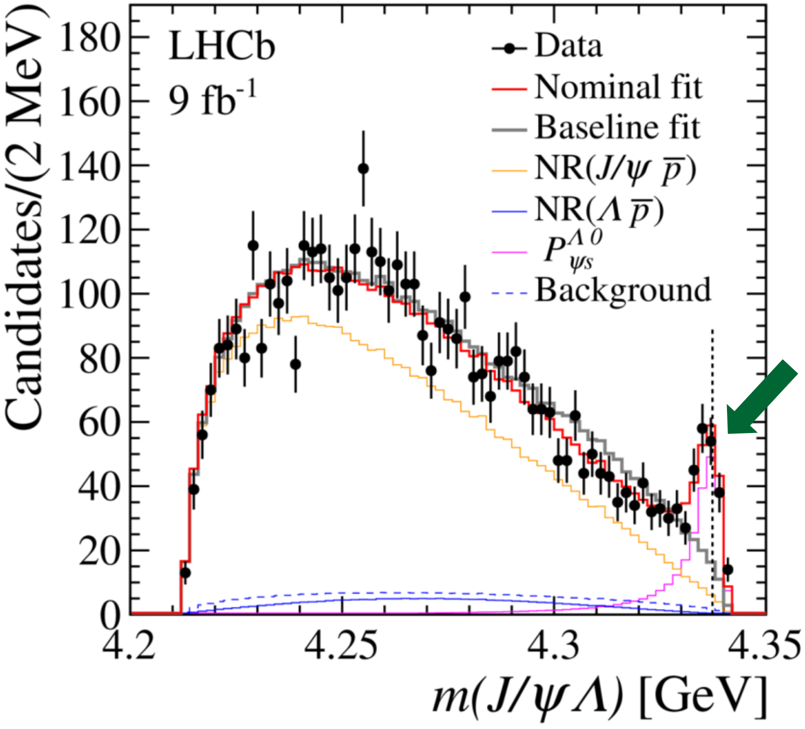
[Wang *et al.*, PRC 84 (2011) 015203], [Zhang *et al.*, CPC 36 (2012) 6], [Wu *et al.*, PRC 85 (2012) 044002].

The strange pentaquark comes to the party

Recently, a new discovery has been made [PRL 131 (2023) 031901] – the observation of a pentaquark of content ccuds has been made in $B^- \to J/\psi \Lambda \bar{p}$ decays.



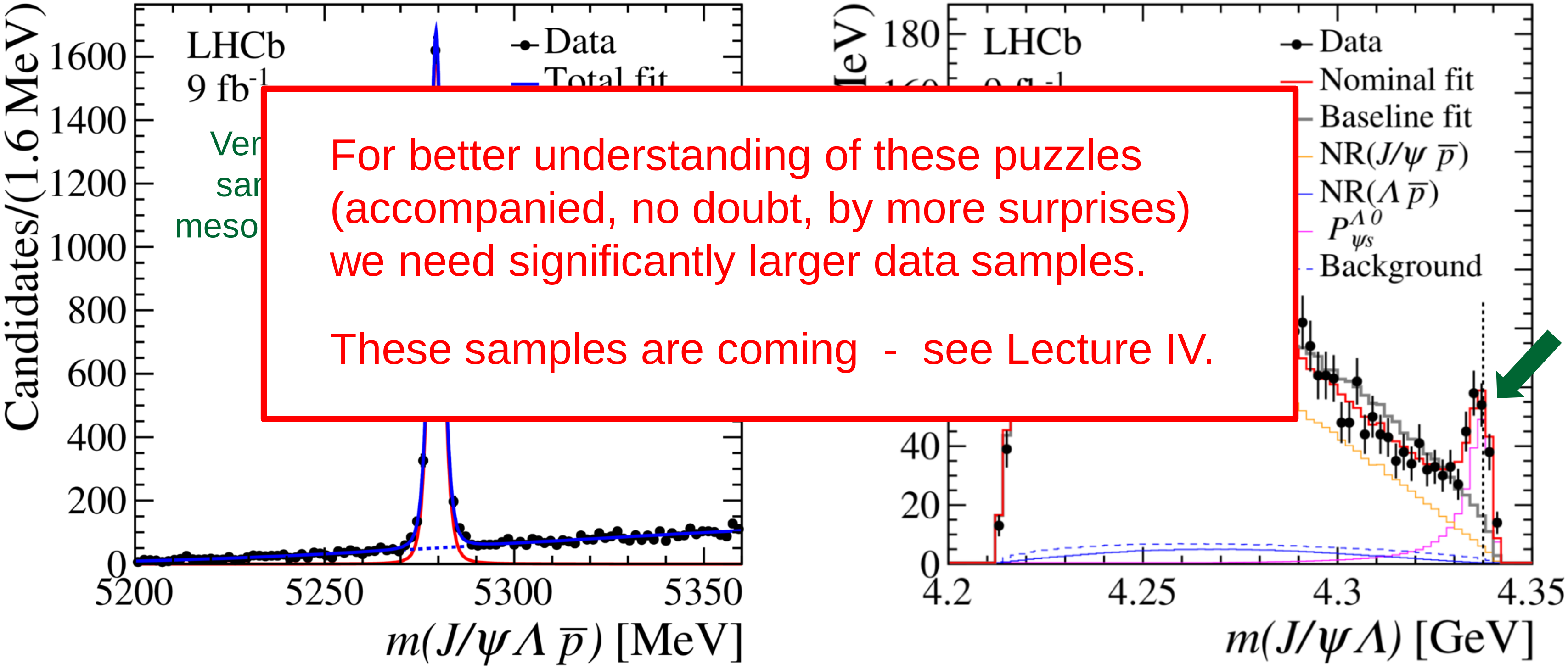
Very clean sample of meson decays.



$P^\Lambda_{\psi s}(4338)^0$ Mass = $4338.2 \pm 0.7 \pm 0.4\,\mathrm{MeV}$, width = $7.0 \pm 1.2 \pm 1.3\,\mathrm{MeV}$.

The strange pentaquark comes to the party

Recently, a new discovery has been made [PRL 131 (2023) 031901] – the observation of a pentaquark of content ccbaruds has been made in $B^- \rightarrow J/\psi \Lambda \bar{p}$ decays.



For better understanding of these puzzles (accompanied, no doubt, by more surprises) we need significantly larger data samples.

These samples are coming - see Lecture IV.

$\mathrm{P^\wedge}_{\psi s}(4338)^0$ Mass = $4338.2 \pm 0.7 \pm 0.4\,\mathrm{MeV}$, width = $7.0 \pm 1.2 \pm 1.3\,\mathrm{MeV}$.

Conclusions

Flavour physics can be conducted in a variety of environments: the Z^0, e^+e^- threshold (*e.g.* the Υ(4S)) and at hadron machines. Hadron machines, *e.g.* the LHC, present formidable experimental challenges, but offer (in many areas) unbeatable opportunities for flavour-physics studies.

To exploit this potential fully requires a dedicated experiment, with optimised geometry, instrumentation and trigger. LHCb is such an experiment.

Hadron spectroscopy is not flavour physics, but it is a topic of incredible richness ideally suited to flavour-physics experiments. Hadron spectroscopy has been one of the most interesting and unexpected success stories of the LHC.

Next lecture: Unitarity Triangle metrology and CPV measurements.