LHCb : Introduction for students

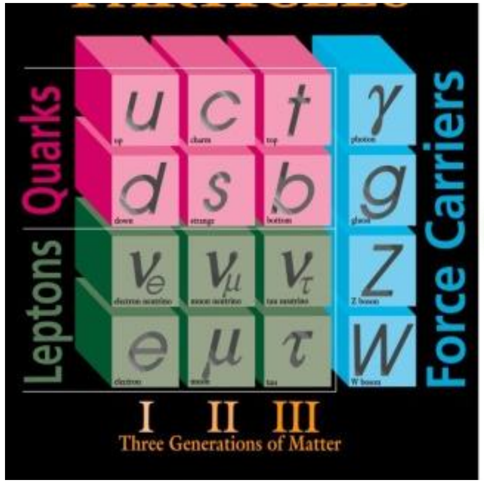
RAL: PPD Open day

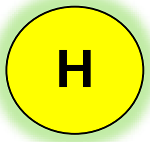
Sajan Easo
21-02-2020

Science and Technology Facilities Council

Why LHCb ?

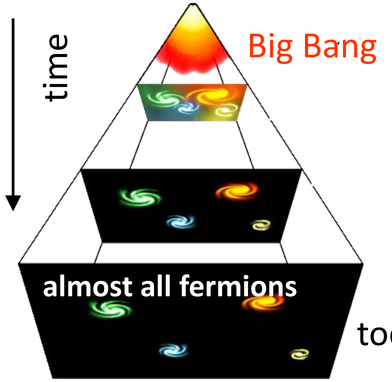
The "Complete" Standard Model (SM)

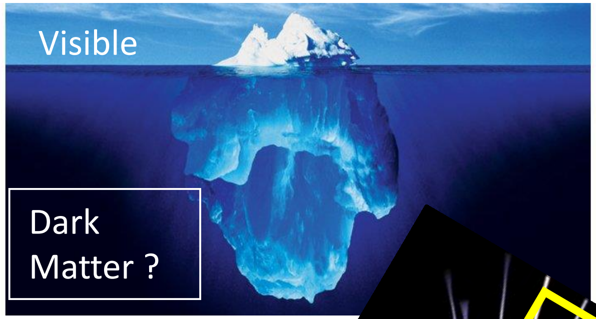




In physics many fundamental questions remain unresolved

Baryogensis ?



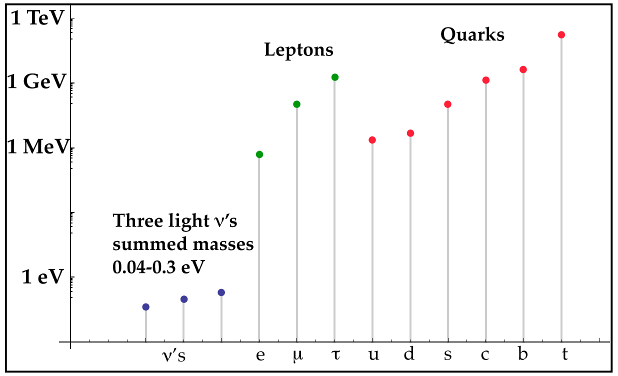


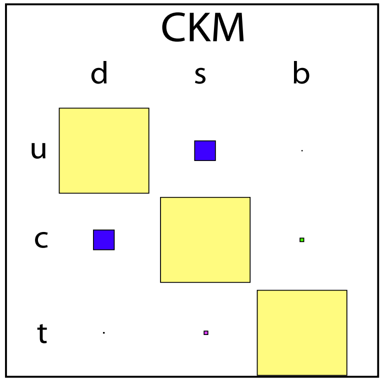
GUT?
How does gravity fit in?

Hierarchy problem ?
$M_H << M_{Planck}$

Neutrinos mass! Dirac? Majorana? CPV, Leptogenesis

Hierarchy of masses and mixing in quark and lepton sectors





12 orders of magnitude differences not explained

SM must be incomplete. New Physics (NP) is needed.

Flavour physics

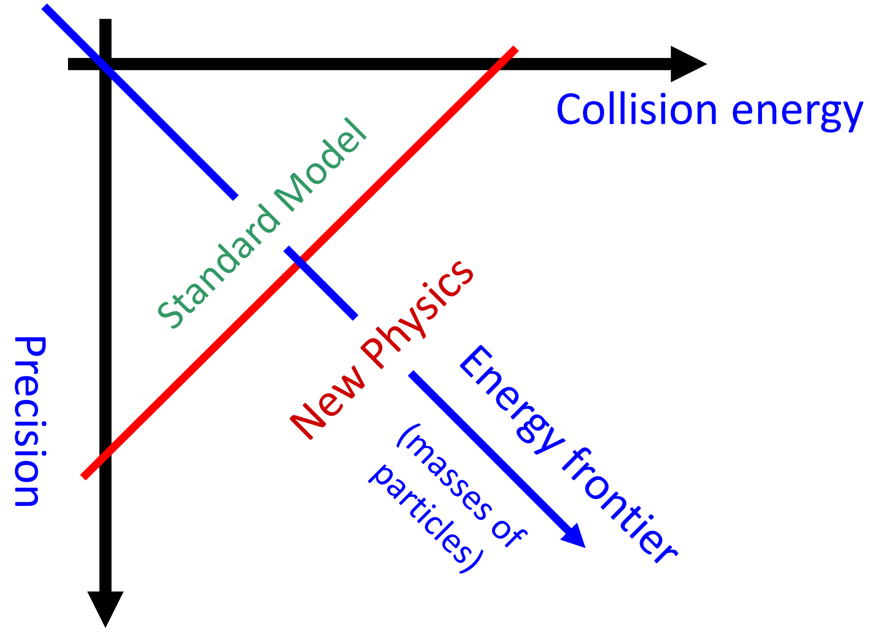
“The term flavour was first used in particle physics in the context of the quark model of hadrons.
It was coined in 1971 by Murray Gell-Mann and his student at the time Harald Fritzsch, at a
Baskin-Robins ice-cream store in Pasadena. Just as ice-cream has both colour and flavour so do quarks”.

Reviews of Modern Physics 81 (2009) 1887

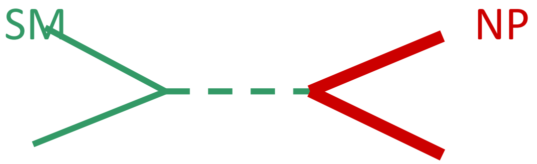
Cabibbo + Kobayashi & Maskawa
Nobel Prize 2008

The study of the flavours of quarks and leptons have led to many important advances in particle physics so far.
LHCb is expecting to make further advances in this field.

NP at accelerator-based experiments



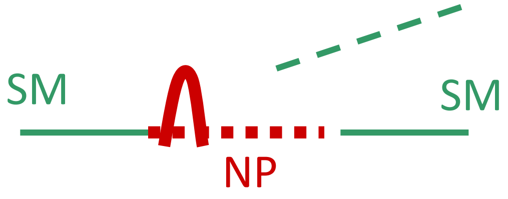
Tree diagrams, for example



Generally need $E_{beam} > M_{NP}$

For low energy observables, we will likely need precision!

Loop diagrams, for example



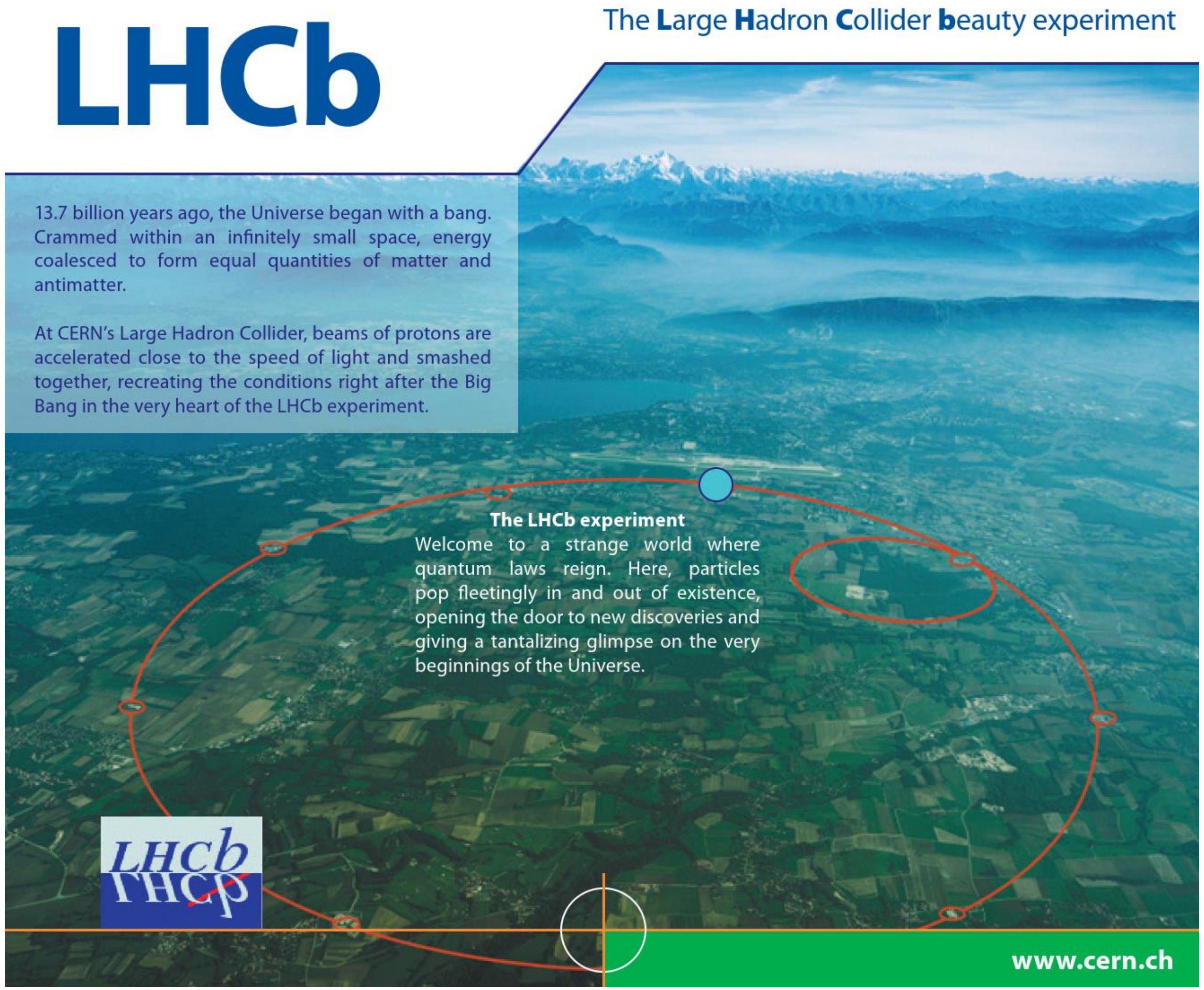
$$L_{eff} = L_{SM} + \frac{c_i}{\Lambda_i^2} O_i$$

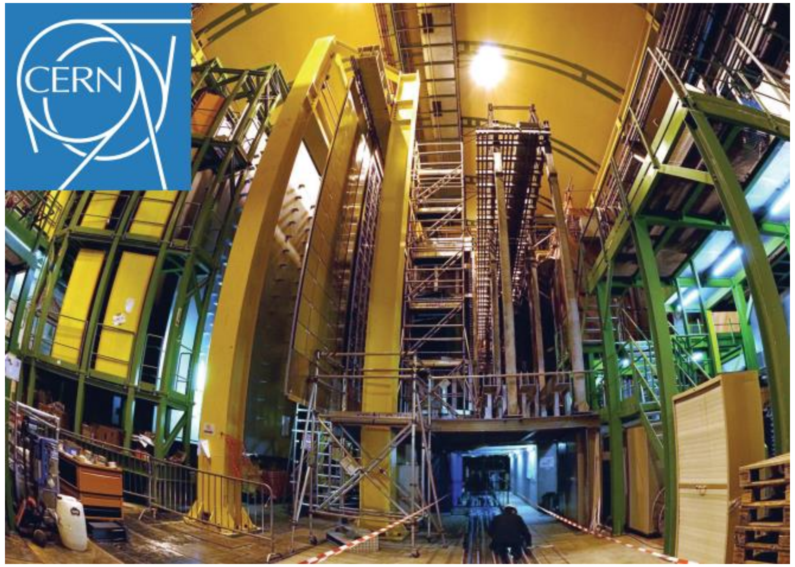
This would involve flavour physics

NP at LHCb : search for:

- Dark matter
- Deviations from SM predictions
- Signals of rare processes driven by NP

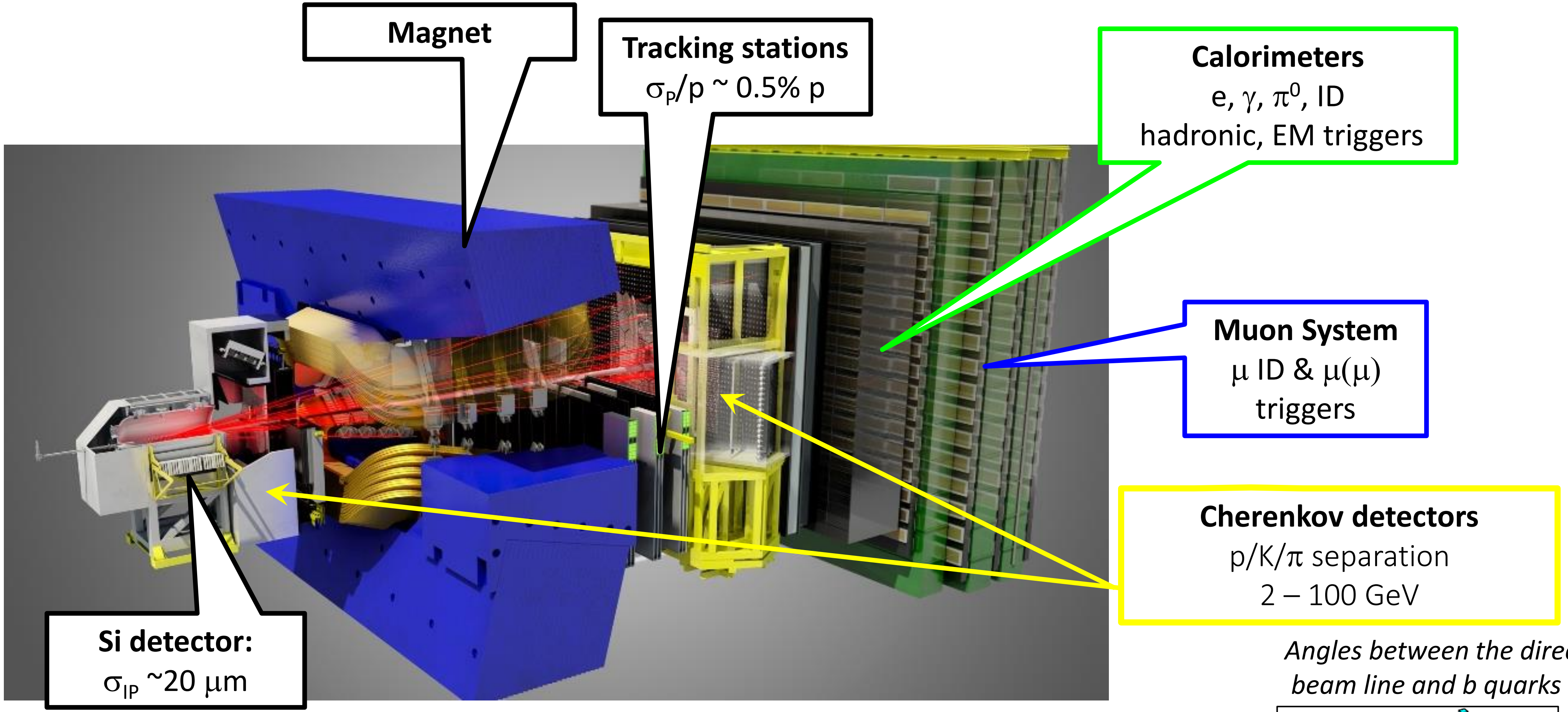
This requires an upgrade of LHCb



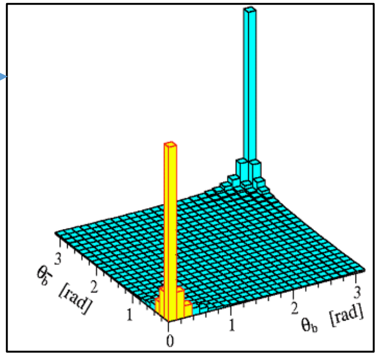


- LHCb is located in a cavern 100 m underground and it stretches for 20 m.
- Expecting to collect signals of interesting events
  from the 40 million proton-proton collisions that happen every second.

LHCb detector: Key aspects



Angles between the directions of beam line and b quarks



- The beauty quarks from proton-proton collisions tend to stay close to the line of the beam pipe. This is reflected in the design of LHCb
- (~ 50000 /second b-$\bar{b}$ into LHCb during a previous a RUN of the experiment).
- Excellent vertex resolutions
- Excellent hadron particle identification capability

LHCb collaboration

- As of February 2020, LHCb has 1377 members from 83 institutes in 19 countries

- LHCb-UK institutes:

  Birmingham, Bristol, Cambridge, Warwick, STFC-RAL, Edinburgh, Glasgow, Liverpool, Imperial College, Manchester and Oxford.

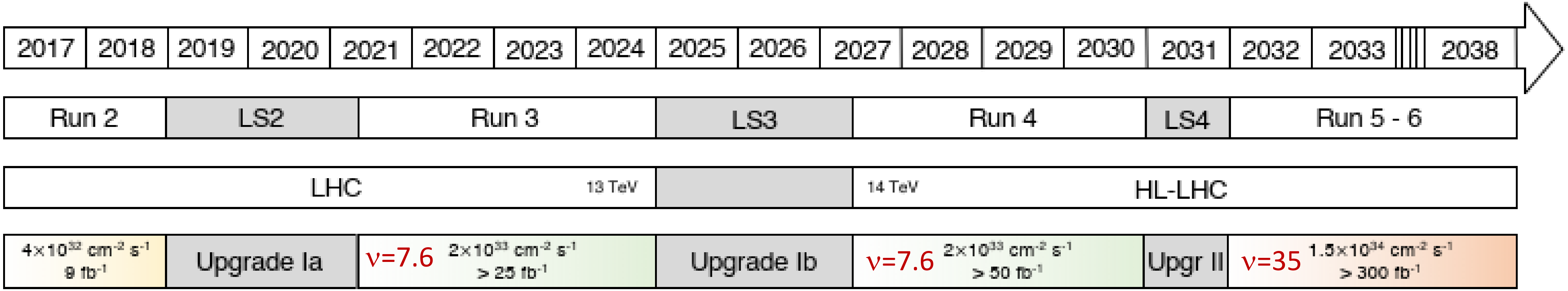
- STFC-RAL- PPD: Fergus Wilson,
  Antonis Papanestis, Raja Nandakumar , Sajan Easo, Stefania Ricciardi

  STFC-RAL-TD:

- Cambridge : Valerie Gibson,
  Fionn Bishop, Michele Blago, Harry Cliff, Blaise Delaney, Chris Jones, Floris Keizer, George Lovell, John Smeaton, Yuan Wang, Ifan Williams, Stephen Wotton

- Stephen and Sajan: More than 21 years in LHCb.

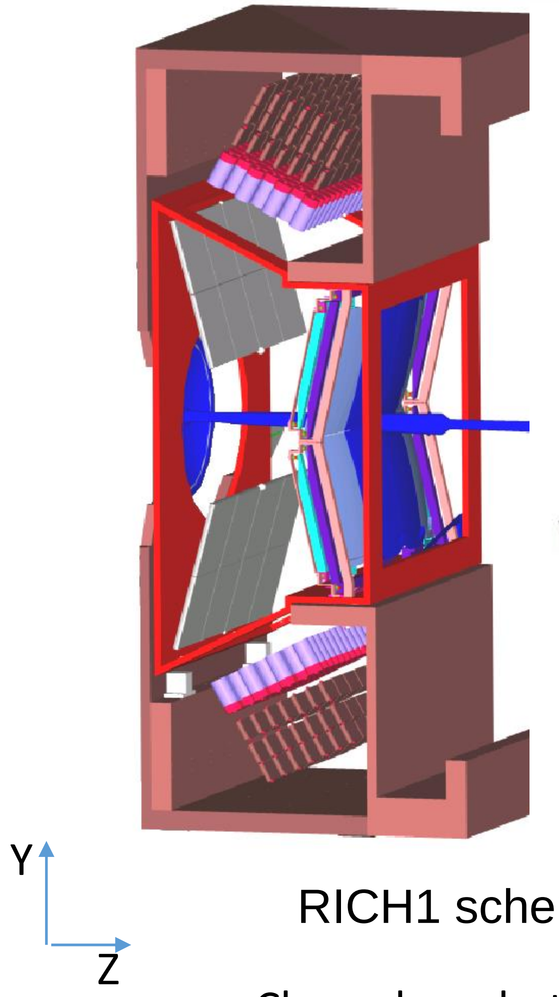
LHCb Timeline

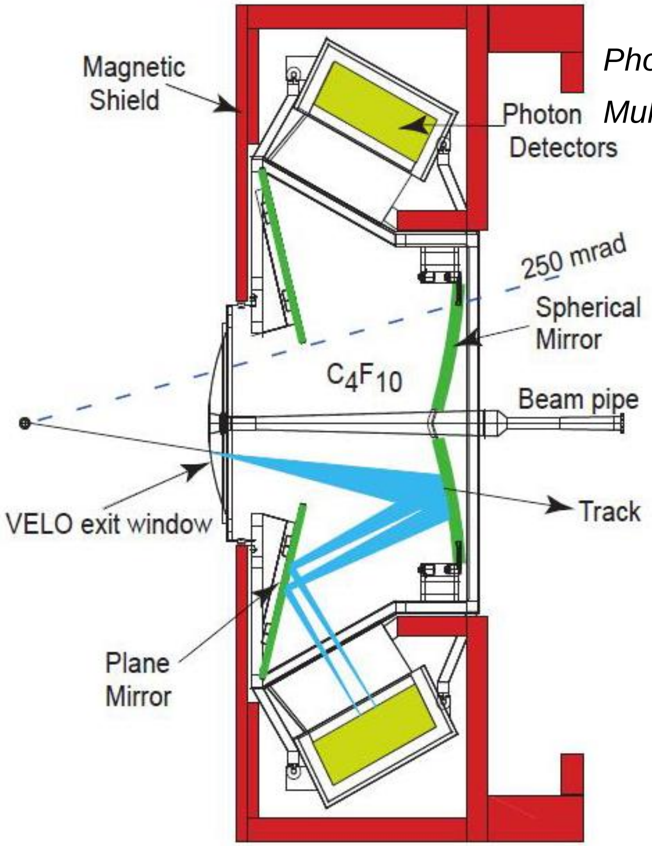


- The detectors in LHCb are being upgraded, before collecting data from 2021 onwards.
- From 2021: Trigger fully controlled by software. This enables to increase the amount of useful events collected.
- The R&D for a further upgrade in 2026, is starting now.
- For upgrade II a major redesign of LHCb, is being envisaged.
- Detectors that can record hits with a time resolution at the level of 50-100 pico seconds, are being designed for upgrade II.

Particle identification (PID) in LHCb

Hadron PID in the 2-100 GeV/c range, using Ring imaging Cherenkov (RICH) detector is a unique feature of LHCb and is used for most of the physics results from LHCb

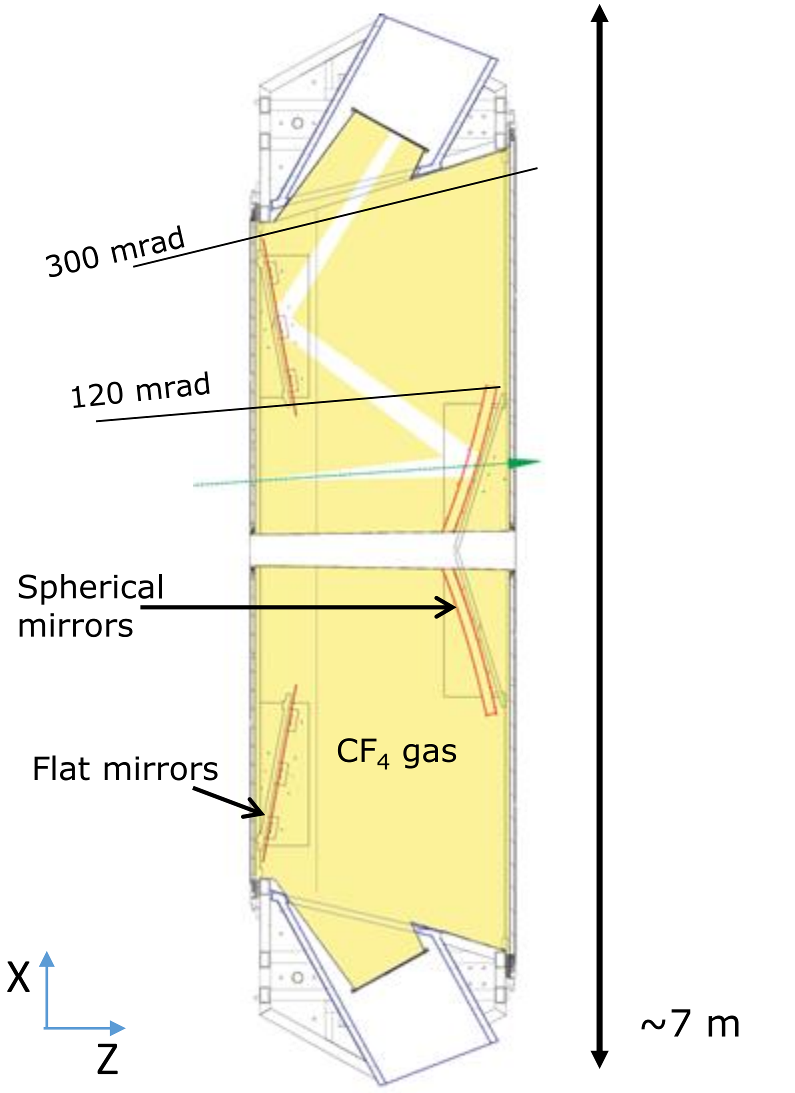




Photon detectors:
Multi-anode photomultipliers (MaPMTs)

RICH1 schematic diagrams

RICH2 schematic diagram



Cherenkov photon production: $\cos(\theta) = 1/n\beta$ where $\beta = p/\sqrt{p^2 + m^2}$

Particle identification coverage: RICH1 : 2- 40 GeV/c, RICH2: 15-100 GeV/c in general.

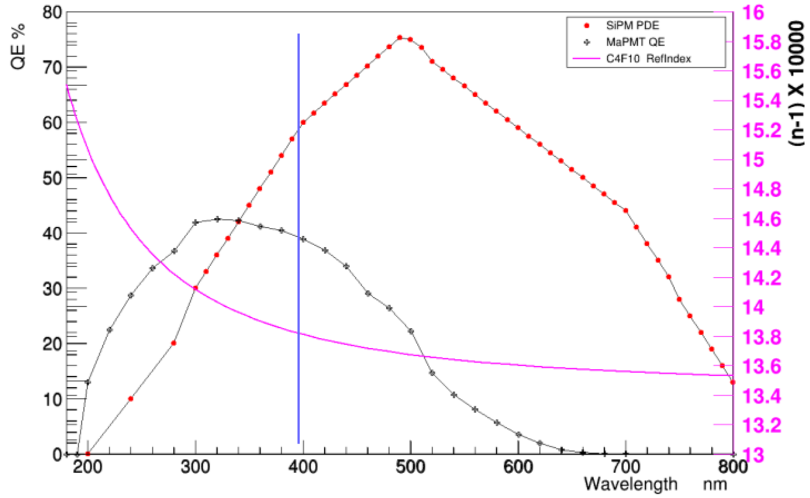
RICH upgrade project

- **Some of the options for improving the RICH**

  - Use new photon detectors named silicon photomultipliers (SiPM) which are being developed by the industry.

  - Improvements in the optical geometry and radiators used for the RICH system. Designing this requires detailed simulation studies.

  - These studies will be followed up with testing prototypes.



Comparison of the efficiencies of SiPM and MaPMT

- LHCb uses GEANT4 software tool kit to perform full simulations for all detectors
  This will be used to design and implement various options for the upgrade.

- The LHCb simulation and reconstruction programs are written in C++
  In the future they may be adapted for usage on GPUs, for improved CPU performance.

RICH upgrade project

- **Improving RICH time resolution**

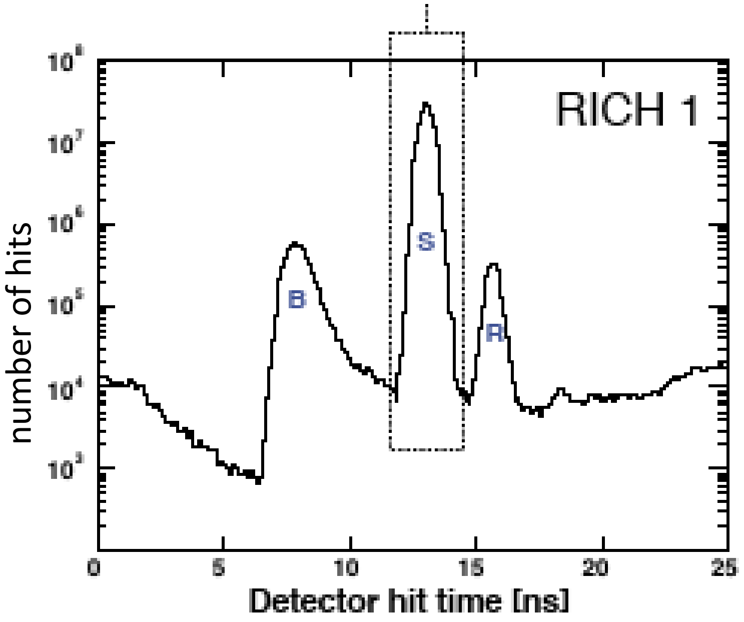
- In the RUN3, each ‘event’ will normally contain data from p-p collisions collected during 25 ns by each of the detectors in the experiment.

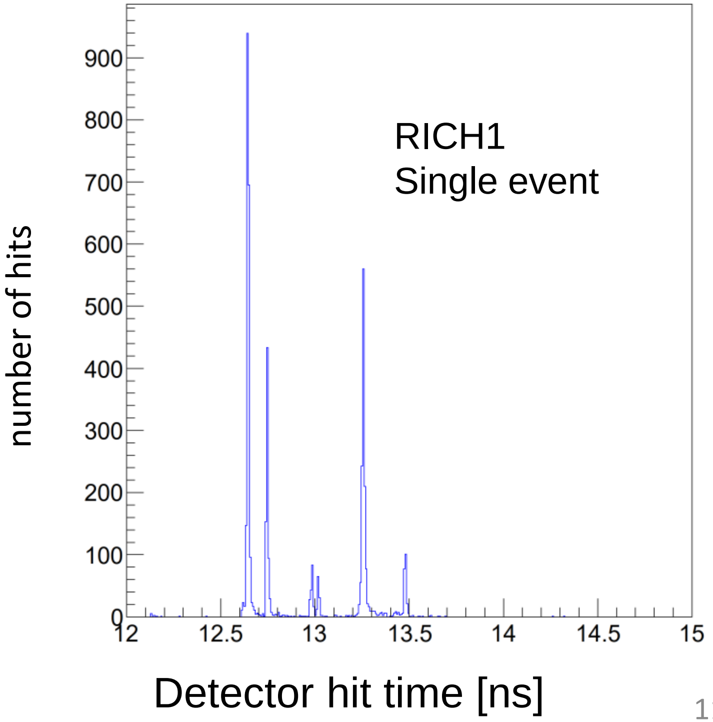
- In the RUN3 we plan to pioneer the implementation of a nano-gating scheme. This will select single photon signals in a time gate whose width is in the range of 3 – 6 ns.

- This requires adaptations in both software and hardware.

- RUN4 and beyond: We plan to measure the time of the primary vertex (where the p-p interaction occurred) using tracking detectors. This will enable to reduce the width of the time gate to ~300 ps with MaPMTs in RUN4 and to ~80 ps with SiPMs in RUN5.

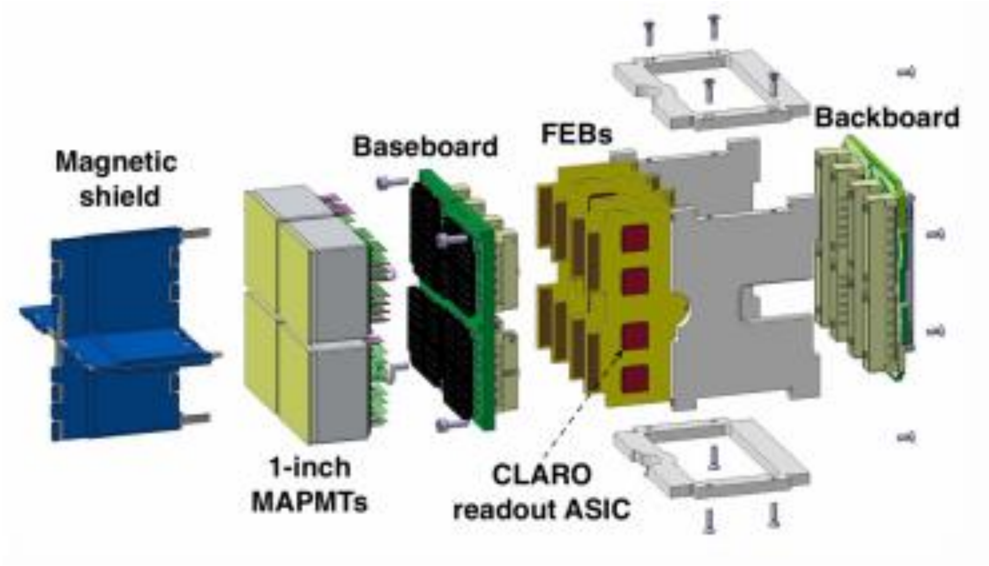
- Reducing the time gate, without loosing the signal , has been shown to improve the PID performance of the RICH system.



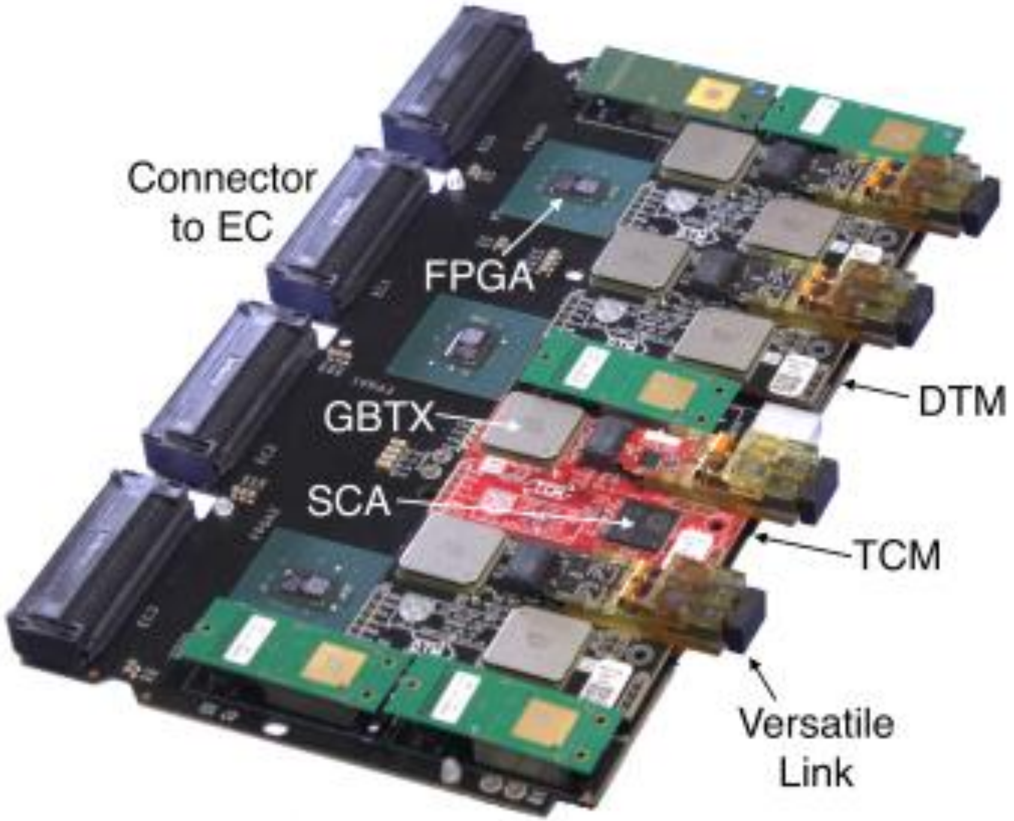


RICH upgrade project: readout hardware

Scheme for RUN3



Photon detector module digital board (PDMDB)



- Readout scheme for MaPMTs in RUN3
- Analogue signals from MaPMT are converted to digital signals by a readout chip and then sent to a digital readout board named PDMDB which contain FPGAs.
- Hardware time gates for signal selection, will be implemented in the readout boards
- The project will involve working on readout hardware and gaining expertise on the FPGAs.

Opportunities for the student

- Design and assemble a modern RICH detector using state-of-the-art technology for the future runs of LHCb.

- Develop expertise in readout hardware and detector software :
  - *Work on FPGAs and other readout hardware*
  - *Use modern C++ software and use packages like GEANT4*
  - *Options to work on modern GPUs*
  - *Work on new photon detectors in collaboration with industry*

- The skills developed in this project are useful assets for a career in particle physics. They also provide many transferable skills for working in other fields.

Examples of projects for the student

Year 1:

- Extend the simulations of the timing characteristics of electronics and MaPMTs in order to verify the improvements in physics performance.
- Contribute to the design and development of sub-nanosecond timing in the readout electronics

Year 2:

- Prepare and perform lab measurements with prototypes of sensors and electronics. Analyse the data collected, refine the simulations and PID software.
- Contribute to the design, installation and operation of RICH prototypes in the CERN beam test facilities.
- Evaluate the performance of novel photon detectors like silicon photomultipliers.
- Contribute to the development of GPU based simulations.

Year 3:

- Continue with refinements of readout hardware and analysis of data from test beams and laboratories.
- Test new radiators which may extend the momentum range for particle identification
- Finalize the design of the RICH detectors that could be installed in LHCb in RUN4 and RUN5 using simulations.

Beam tests at CERN

Detector prototypes will be operated at the CERN beam facilities.

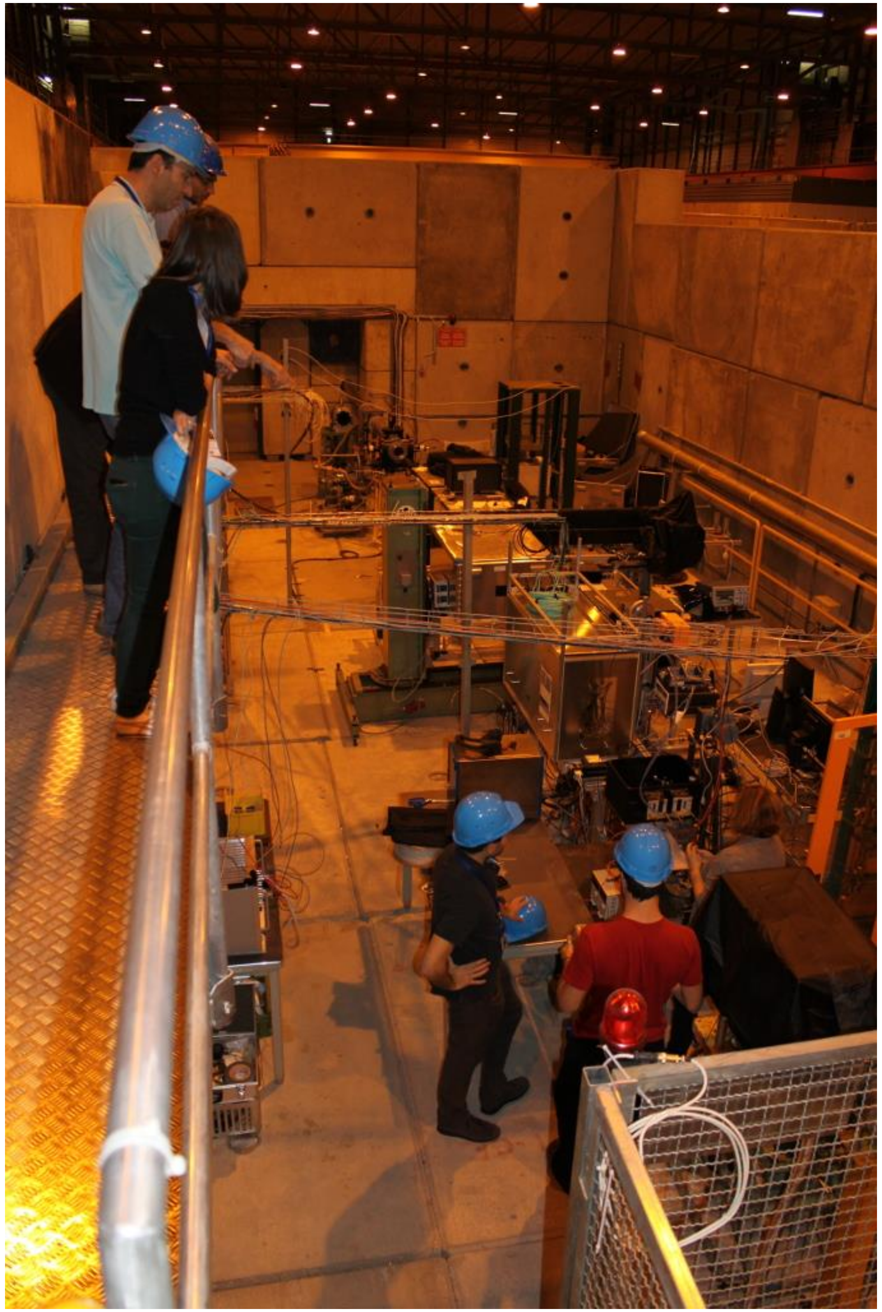
Photon sensors and readout electronics for LHCb RICH future upgrades will be tested there.

Presents exciting opportunities for PhD student to take a central role.

Work in a small team of talented and (mainly) young experts.

Develop unrivalled experience and expert insight into the detector performance under real life conditions.

Hard work but fun too…



Student profile - Floris Keizer

Cambridge PhD student in LHCb, 2015-2019

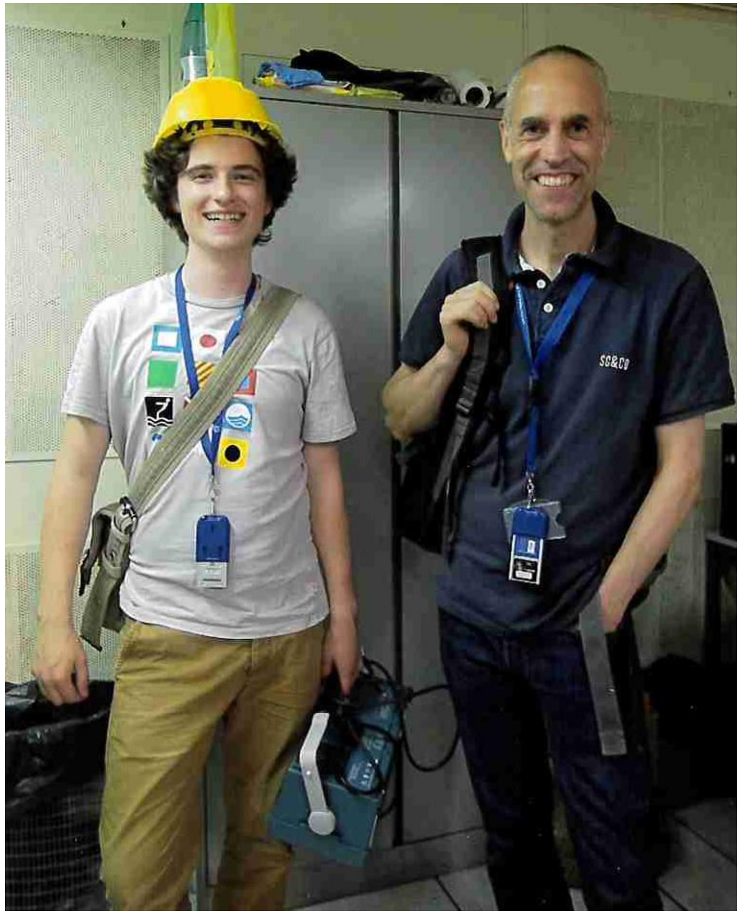
Designed and built tracking system for RICH beam tests.

Best poster at ICFA school of instrumentation, Havana, 2017.

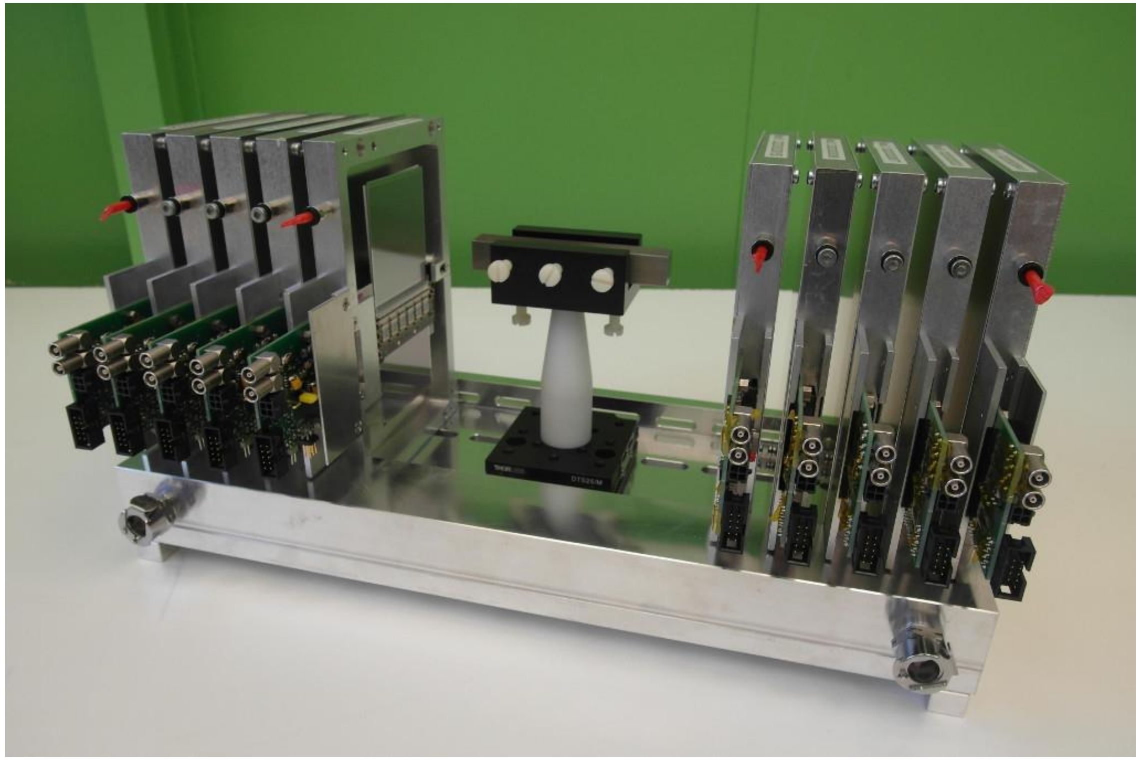
Pioneered simulations, studies and measurements of RICH detector photon time of arrival.

Provide the silicon sensor quality assurance system for the FASER experiment.

Now post-doctoral researcher at CERN in LHCb



Floris and Steve ready for beam



Floris' semi-conductor tracker being prepared for beam

Student profile – Michele Blago

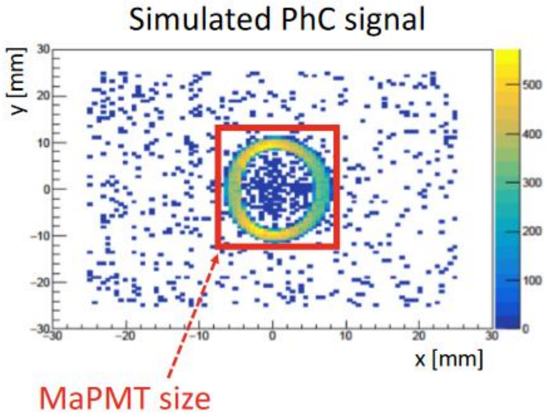
Cambridge/CERN PhD student in LHCb, 2017-

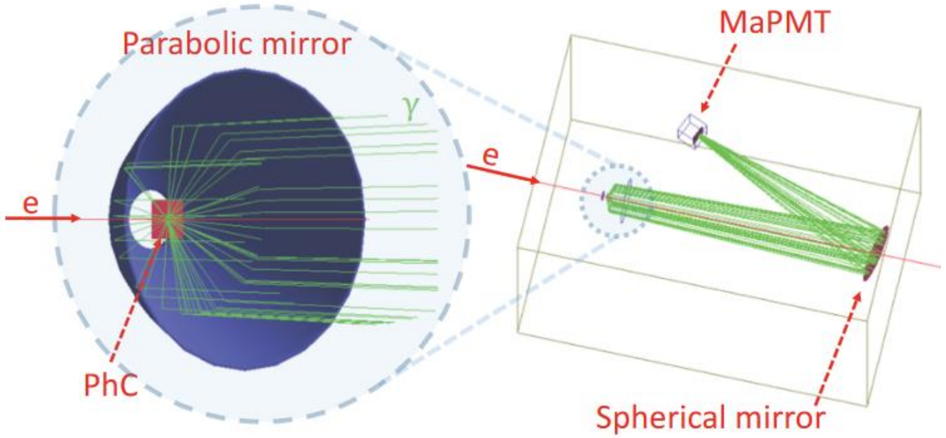
Built apparatus to measure properties of novel Cherenkov radiators (photonic crystals).

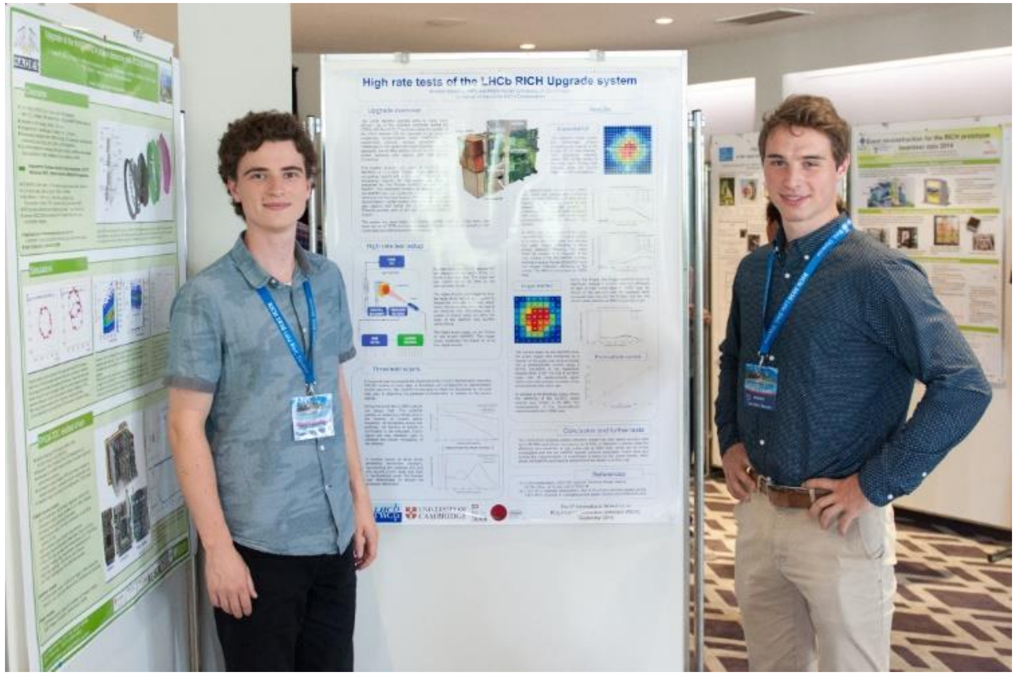
Performed analysis of photon yield measurements.

Developing machine-learning techniques for particle identification using RICH data.

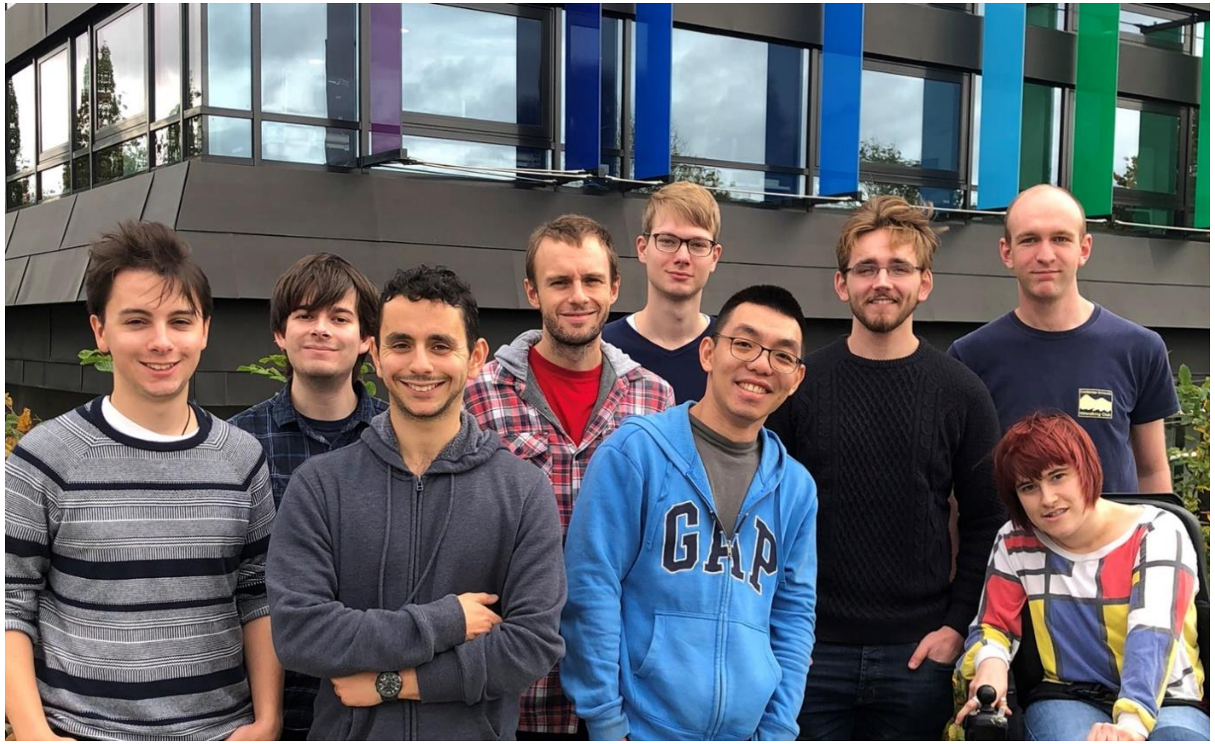
Commissioning of LHCb RICH photon detector columns for RUN3.







Floris and Michele presenting their research at RICH2016, Lake Bled, Slovenia



Would you like to join us ?

Please sign up and have a chat with Stephen and me today.

Formal interviews at Cambridge university on March 2 .

For this, we shall send invitations with the details soon.

EXTRA PAGES

RICH upgrade project

General strategy:

- Improve single photon resolutions and yield

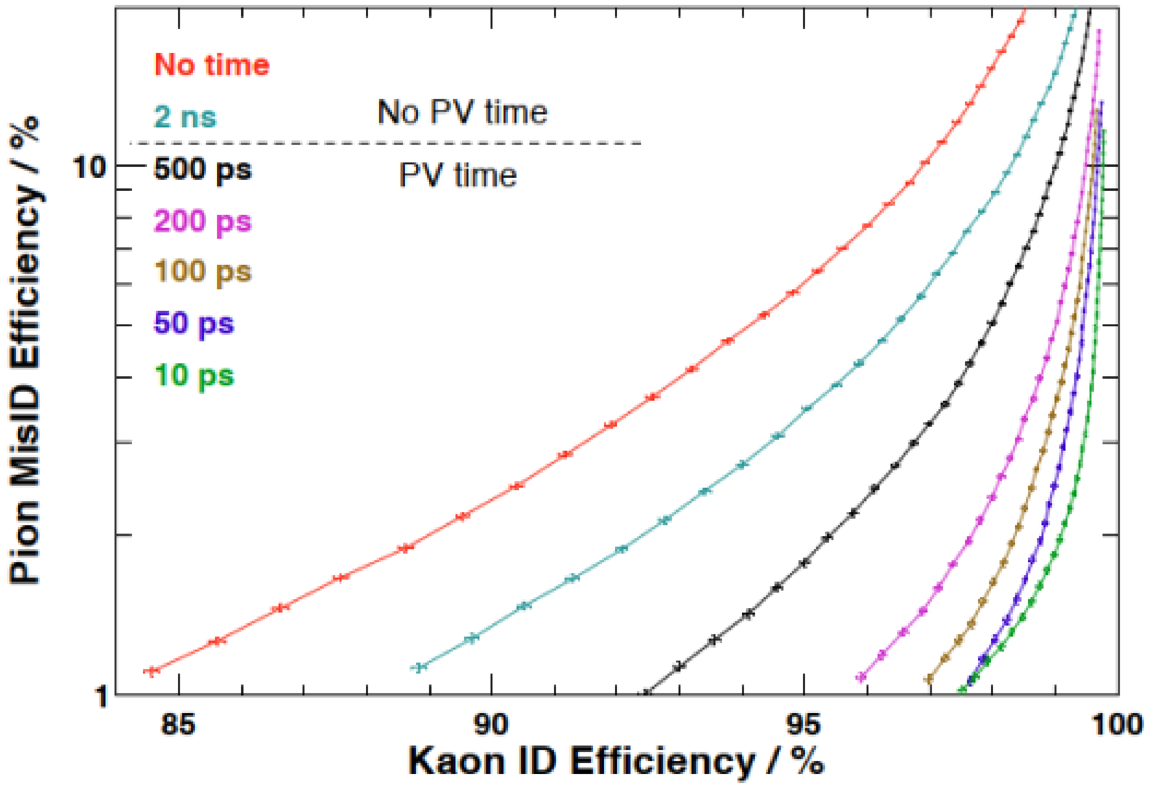
$$\sigma_p = \sigma_{\text{chromatic}} \oplus \sigma_{\text{emission point}} \oplus \sigma_{\text{pixel}}$$

$$\sigma_t = \frac{\sigma_p}{\sqrt{N}} + \text{Const.}$$

- Reduce the hit occupancy
  - Measure the hit time coordinate and apply time gates
  - Improve the RICH optics
- Upgrade the coverage at low and high momenta
  - Upgrading the radiators is one of the options
- All these require corresponding upgrades in the tracking system also.

RICH upgrade project

- Typical expectations of PID performance in RUN4:



- A time gate applied at the level of 300 ps would improve the PID performance.