Particle identification in LHCb

CEPC workshop, Hangzhou, China

On behalf of LHCb-RICH collaboration

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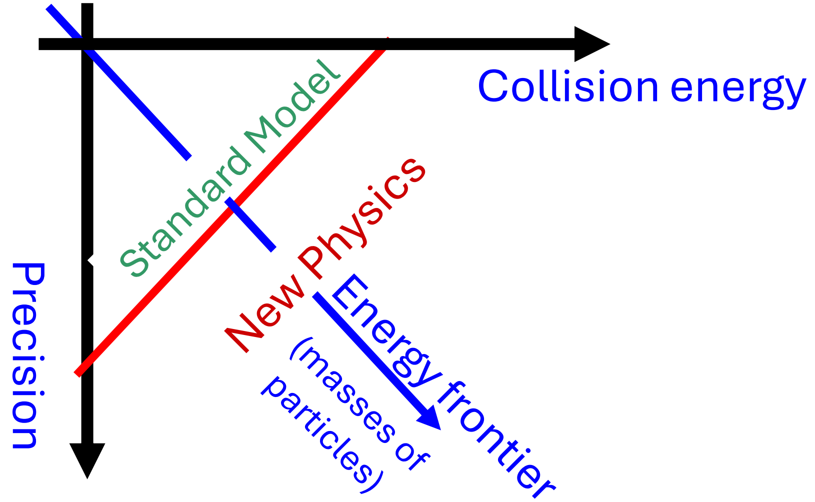
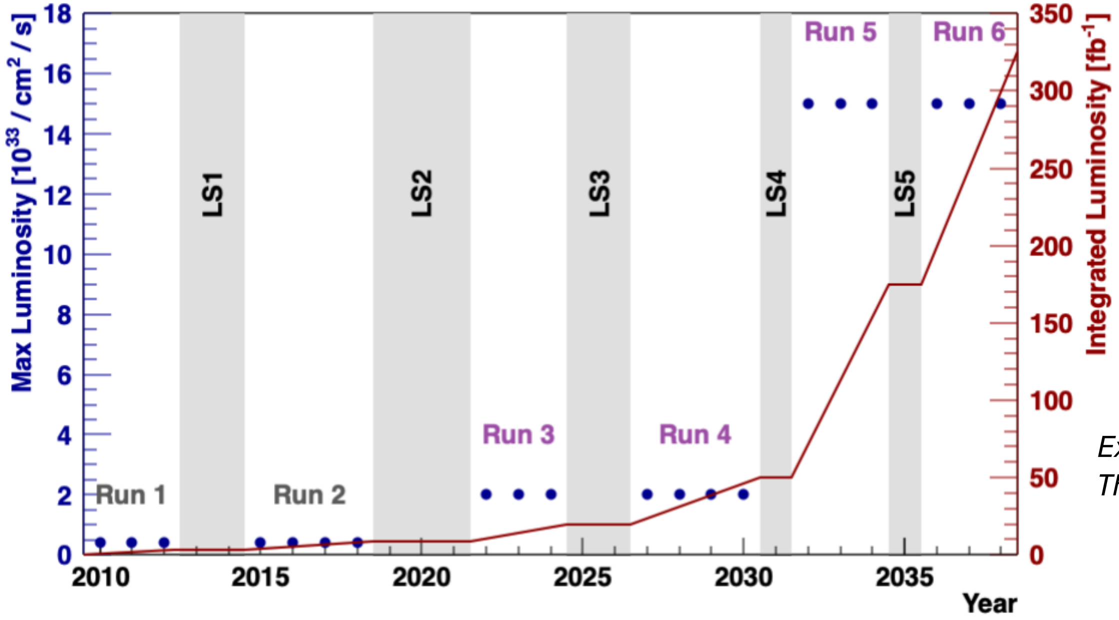
25-10-2024

LHCb : goals and timeline

- Search for signals of new physics(NP) beyond the standard model (SM) in high energy physics
  - Indirect search from the decays of hadrons with b and c quarks
- Large sources of flavour symmetry breaking are excluded at TeV scale, from the current measurements
- Hence, we aim for a significant increase in the precision of LHCb measurements in RUN3 and future upgrades. This requires collecting large amount of data.





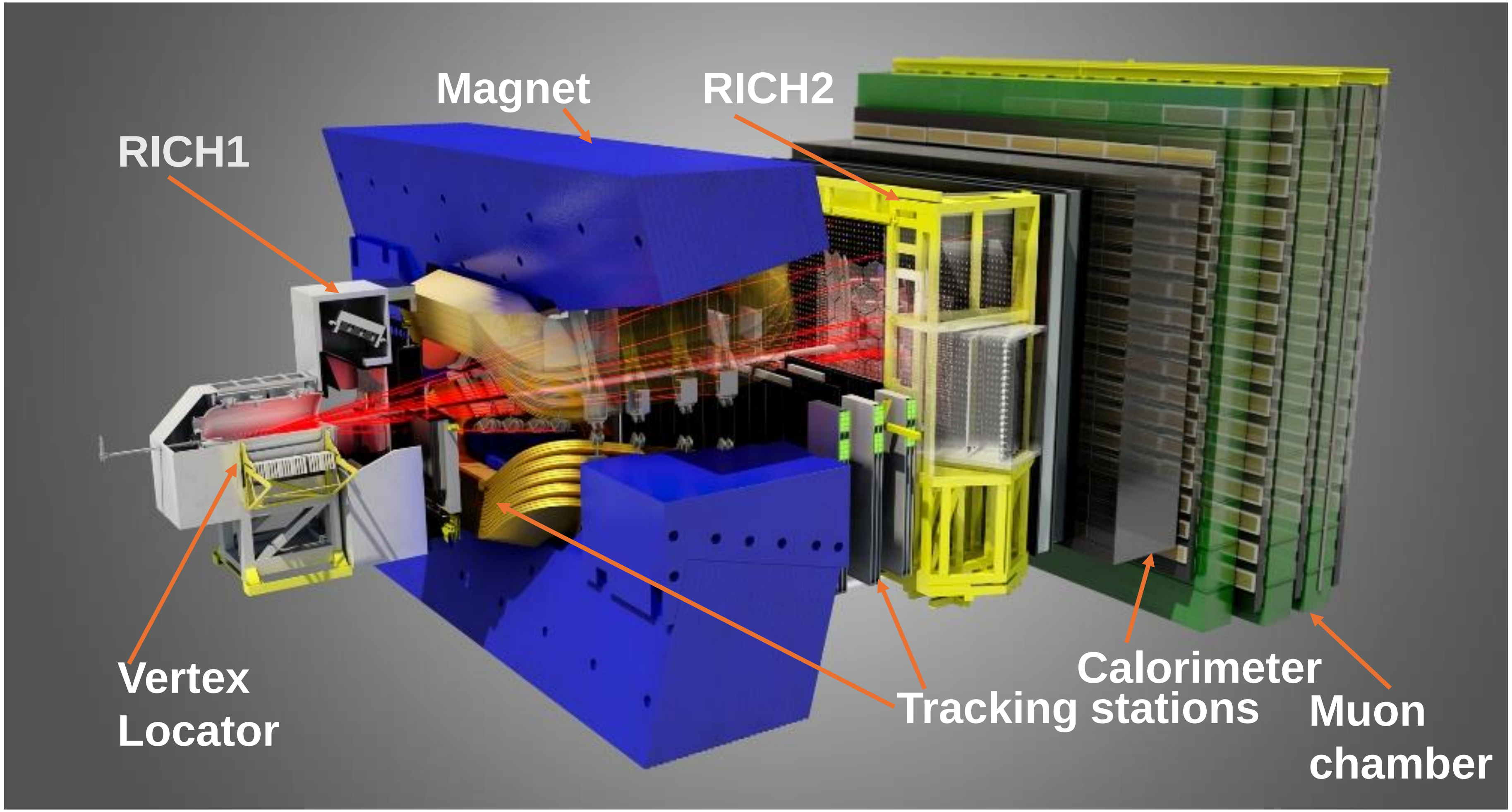
Exact schedule of LHC is evolving.
This is just a recent version

- At present LHCb has more than 1700 members from 103 institutes in 22 countries, including China

Outline

- Brief introduction to the LHCb detector
- Particle identification in LHCb
- Description and performance of the current RICH system
- Plans for upgrades in the coming years
- Summary

The LHCb detector



At present:

- pp : $\sqrt{s}$ = 13.6 TeV
- RICH1:
  C_4F_{10} < ~ 60 GeV/c
  Photodetectors:
  Top + Bottom
- RICH2:
  CF_4: < ~ 100 GeV/c
  Photodetectors:
  Left+ Right

Forward spectrometer with $2 < \eta < 5$.

Overall acceptance ~ 10→300 mrad, Momentum range : 2-100 GeV/c

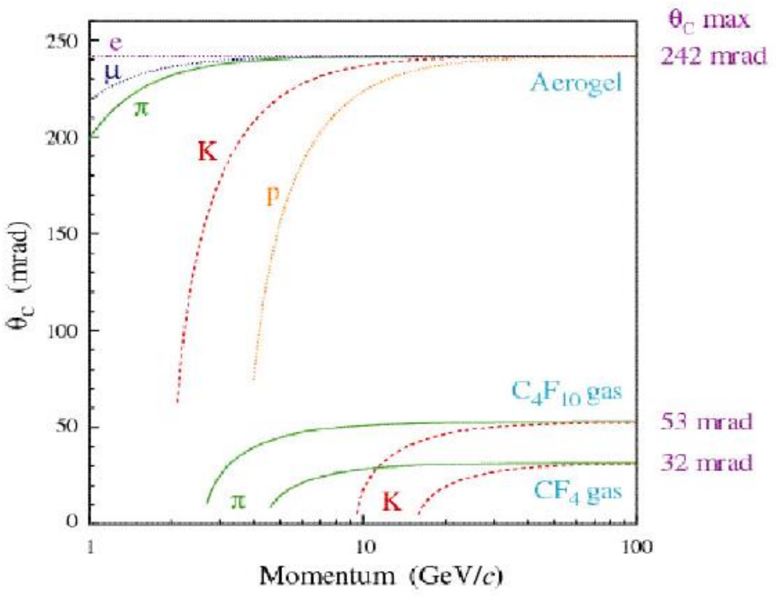
Particle identification in LHCb

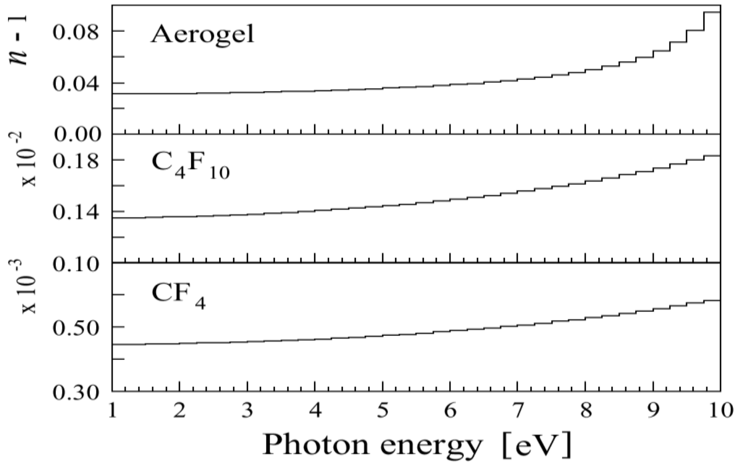
JINST 19 (2024) P05065.
Also, presentation yesterday, on 'LHCb calorimeter upgrade'

- For particle identification (PID), LHCb has:
  - A RICH system
  - A calorimeter system which consists of an electromagnetic and hadron calorimeters
  - A set of muon chamber stations at the downstream end of LHCb.
- This presentation focuses on the RICH system in LHCb
  - Hadron PID in the 2-100 GeV/c range is a unique feature of LHCb and continues to be an essential part of its physics programme.
  - This is achieved essentially using the data from two RICH detectors named RICH1 and RICH2. They also contribute to the identification of muons, deutrons etc.

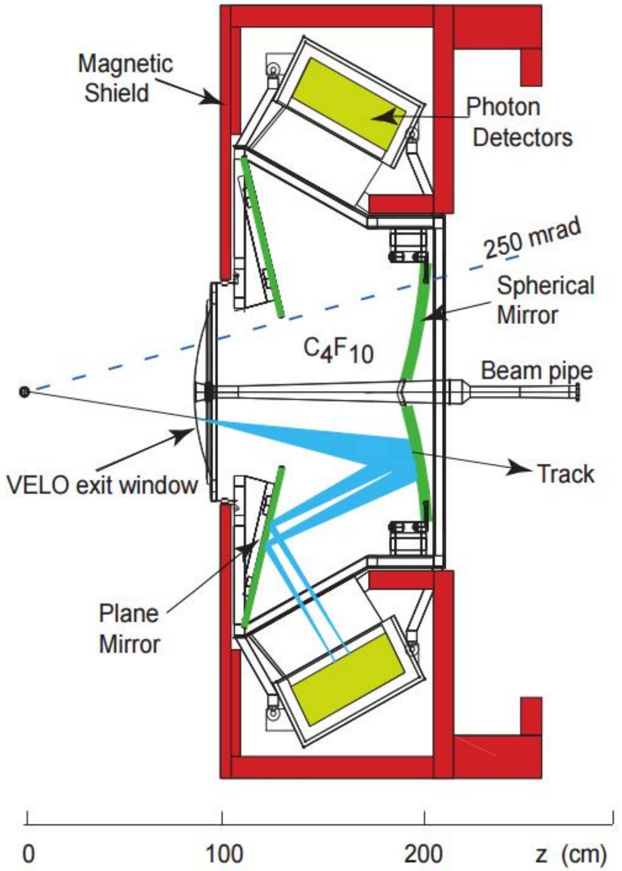
RICH1: Aerogel 2→10 GeV/c (until 2014)
C_4F_{10} gas < 70 GeV/c

RICH2: CF_4 gas <100 GeV/c.



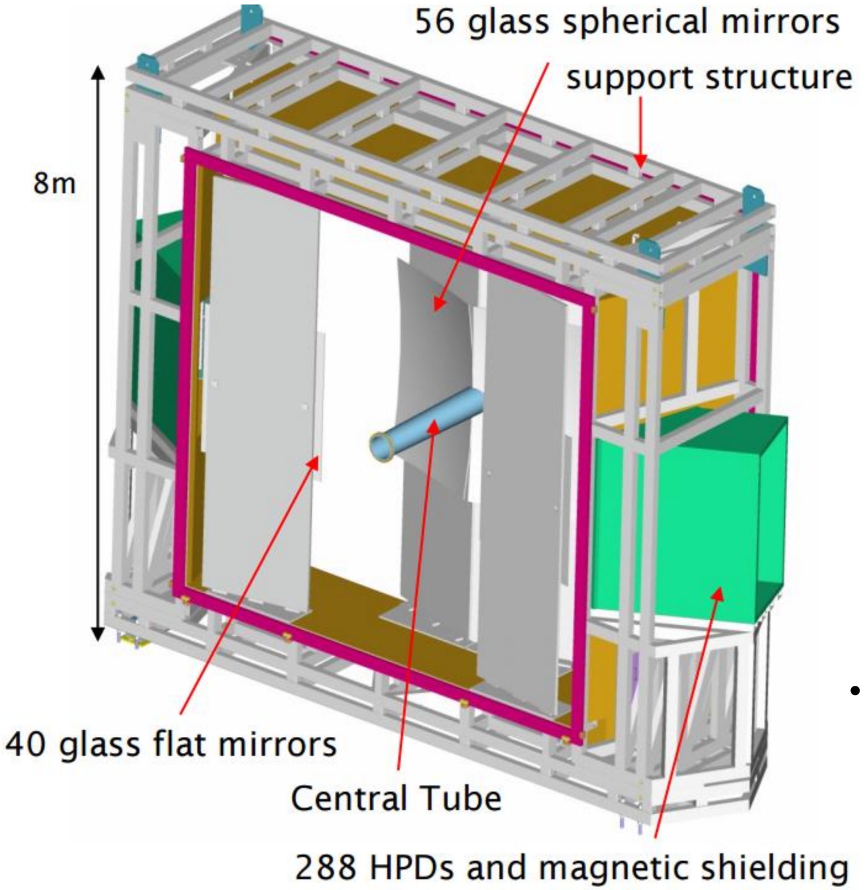


RICH system in LHCb



RICH-1 (25-300 mrad)

4 m^3 C_4F_{10} n = 1.0014, up to 60 GeV



RICH-2 (15-120 mrad)

100 m^3 CF_4 n = 1.0005, up to ~100 GeV

- *Scintillation in CF_4 quenched by adding a small amount of CO_2* *Nucl.Inst.Meth. A. 791 (2015) 27-31*

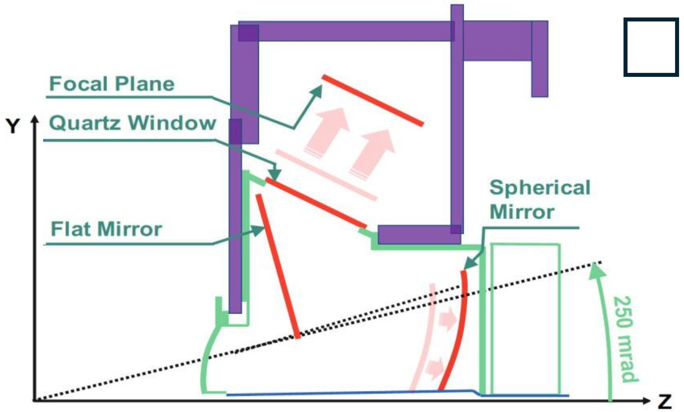
- Mirrors tilted to keep photon detectors outside the acceptance of the charged particles.
- Flat mirrors are used to limit the foot-print of the detector along the beamline.
- Spherical mirrors in RICH1 are made of light carbon-fibre material to limit the material budget.

RICH in different RUNs of LHCb

Arrays of HPDs

- Photon detectors :
  - In RUN1 and RUN2, Hybrid photodiodes (HPDs) were used as photon detectors
  - They were equipped with front-end readout working at 1 MHz rate
  - MaPMTs connected to an external readout at 40 MHz, were installed for RUN3.
    They are expected to be used also for RUN4.
    They are also being considered for RUN5 for some regions of the detector plane

- RICH1 in RUN3
  - RUN2 → RUN3 : nominal luminosity (~4 → 20) X 10^{22} cm^{-2} s^{-1}
  - RICH1 was rebuilt with an improved optics for RUN3.

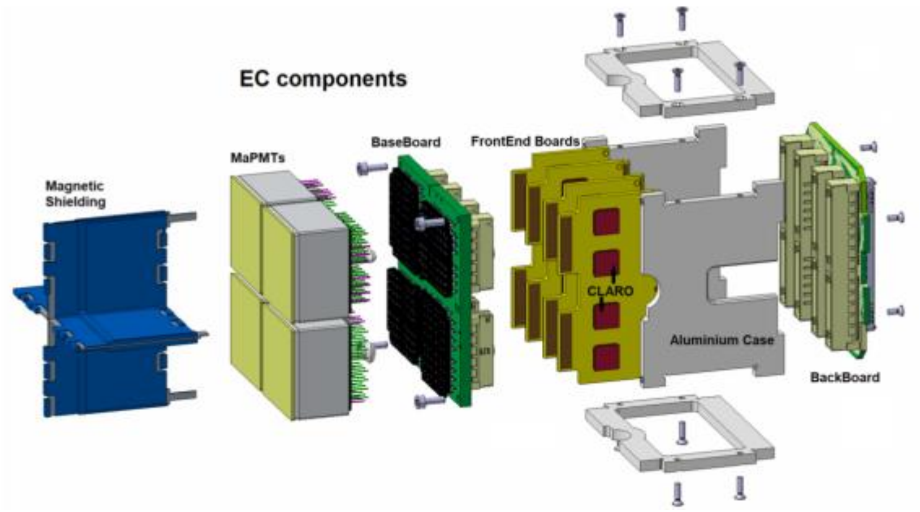


- Details of the performance of RICH in RUN1 and RUN2 :

  RUN1 : Eur. Phys. J. C 73 (2013) 2431
  RUN2 : JINST 17 P07013

- This presentation : Detector description is mostly focused on RUN3 and RUN4

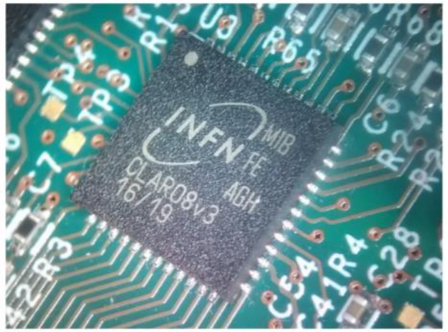
RICH readout system in RUN3



CLARO: custom made 8 channel ASIC

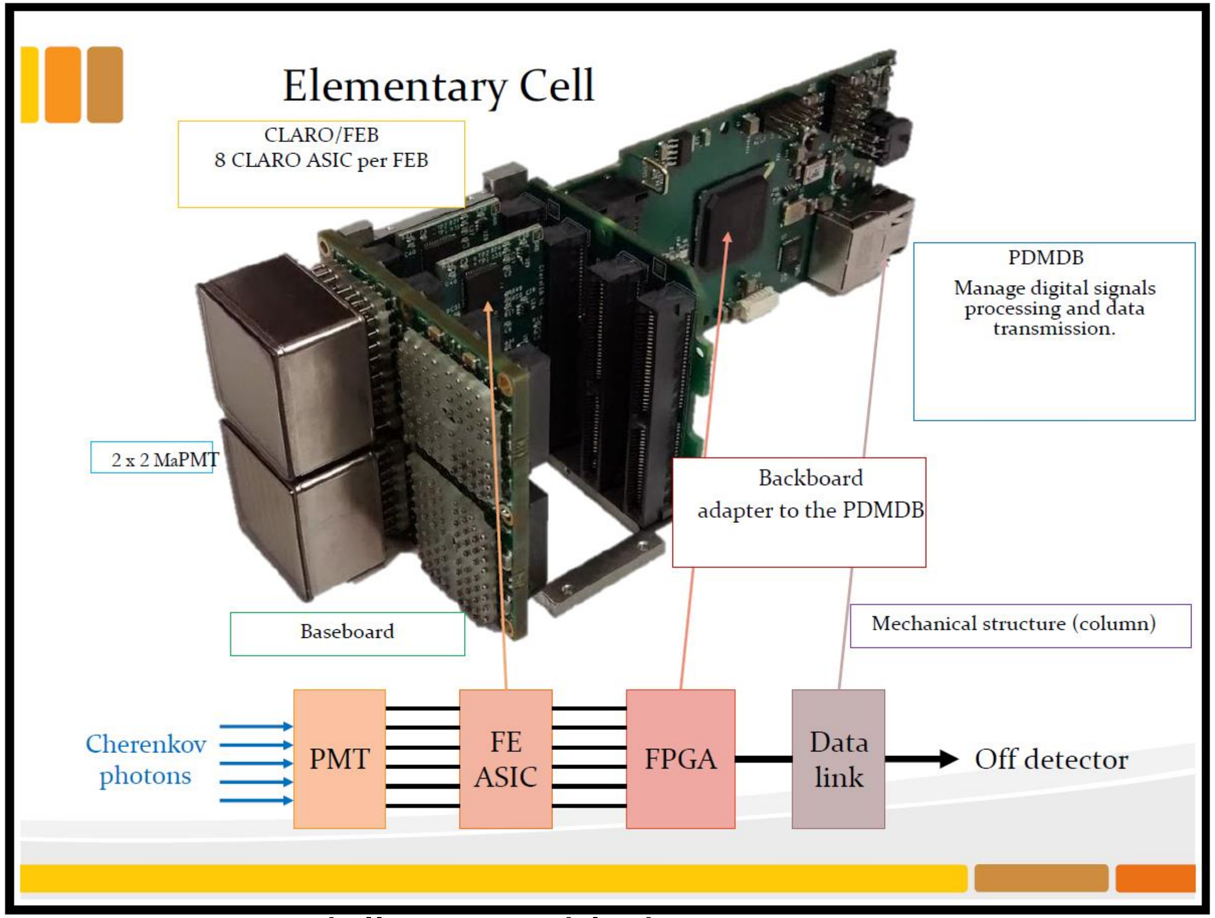
JINST 8 C01029 (2013)

More details in backup pages



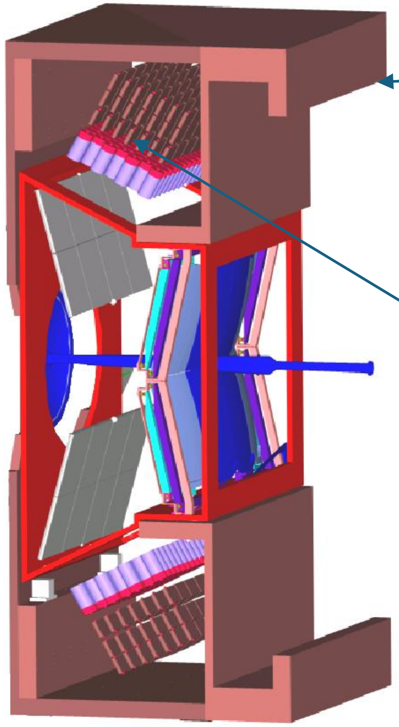
- A base board to house the MaPMTs.
- Front-end boards (FEBs) equipped with CLARO chips
- A backboard which interfaces FEBs to a digital board for configuration and readout. The backboard uses FPGAs.

- Columns of modules assembled from EC's populate the detector plane



Partially assembled structure

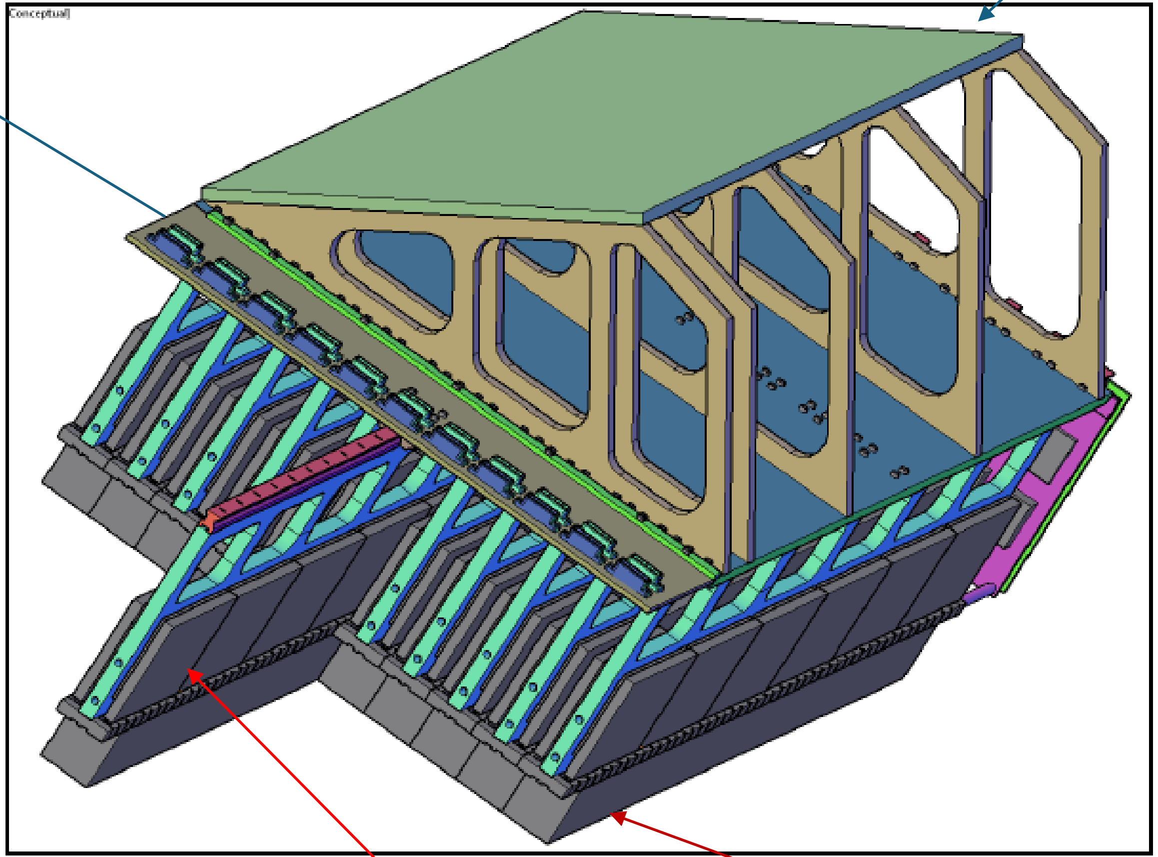
RICH1 Mechanics



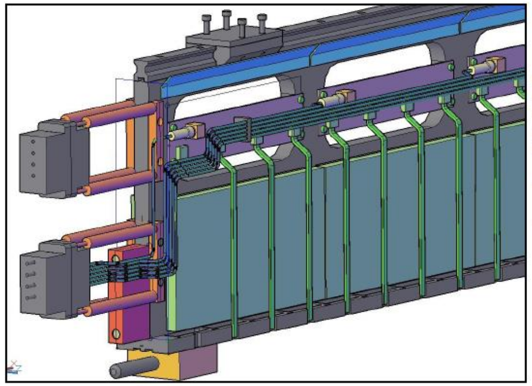
RICH1

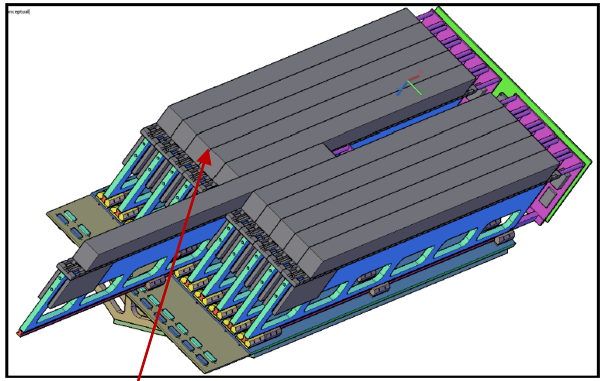
Magnetic shielding plates

Mechanical structure attached to the shielding plates



Column of PDM



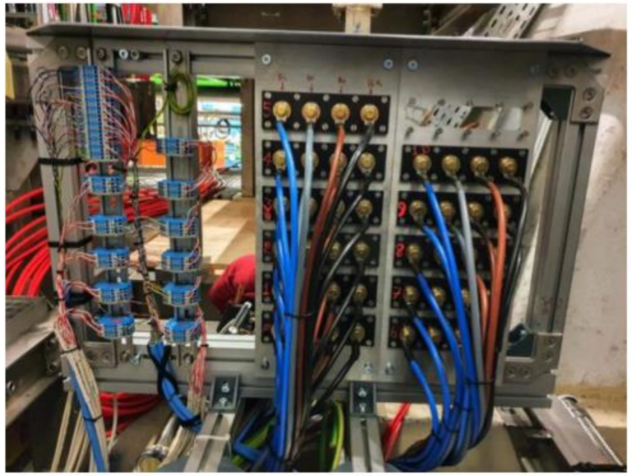


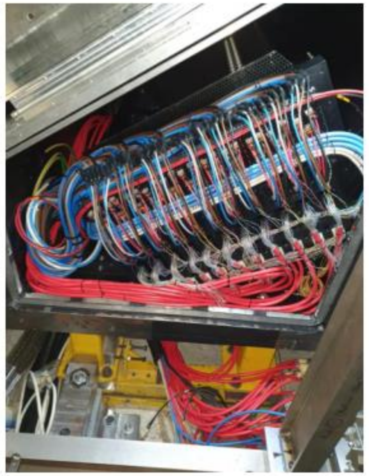
Readout boards

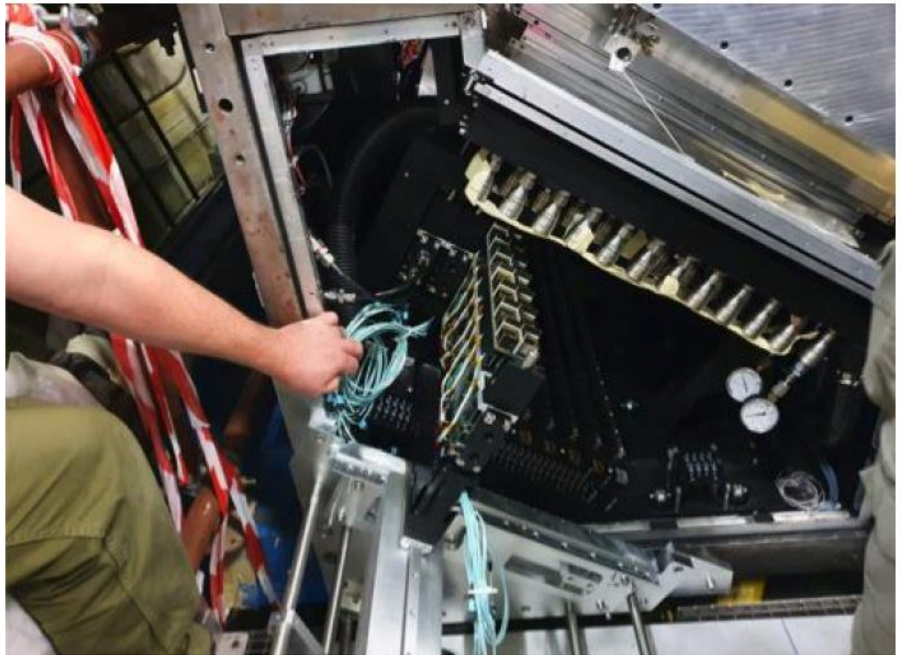
Easy to remove a column for maintenance operations

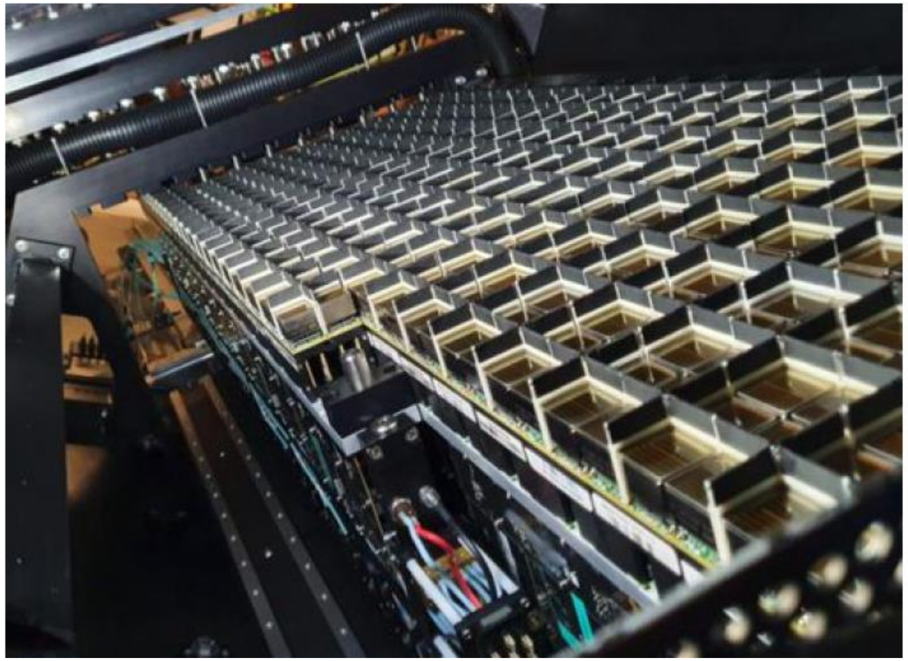
Arrays of MaPMT modules (PDM) in columns

RICH1 Installation: Down Box (12/2021)







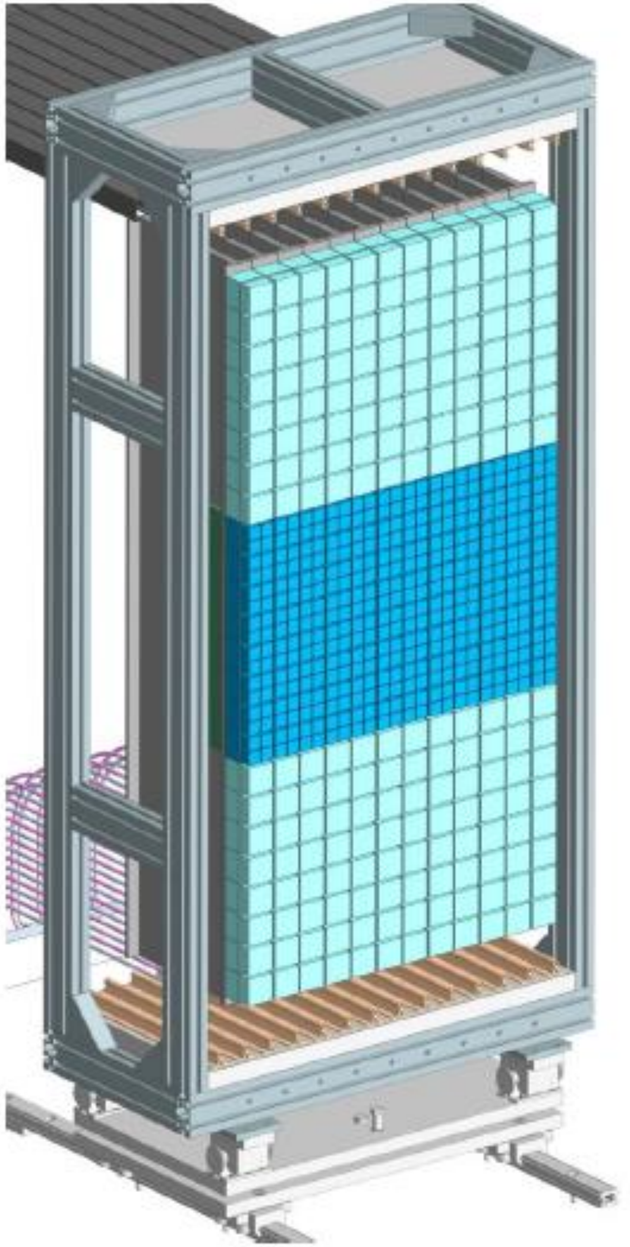


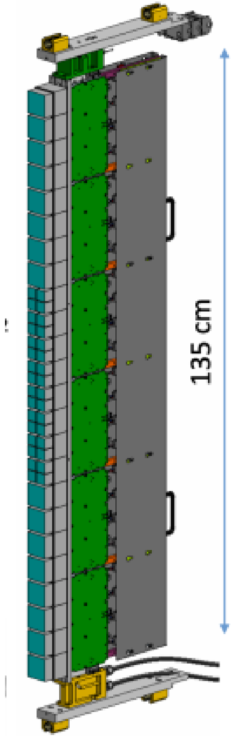
RICH2 Mechanics

- RICH2 optical layout same as that in previous RUNs

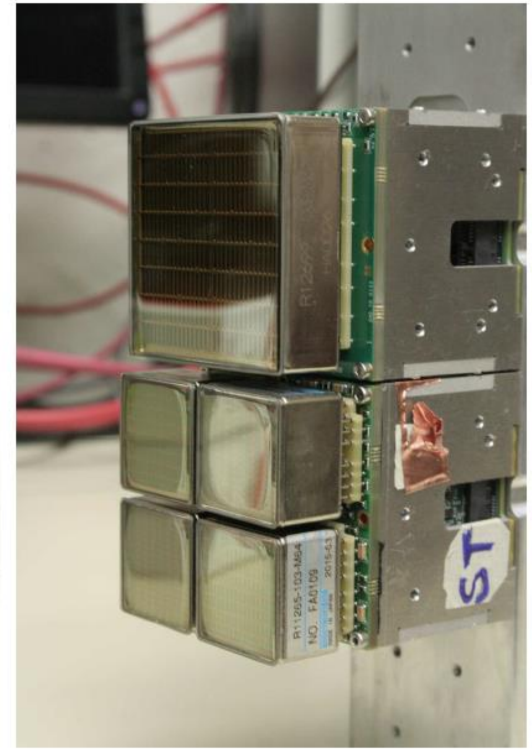
- Two types of MaPMTs :
  - Central region with R13742 , same as that for RICH1.
    Pixel size 2.875 X2.875 mm

  - Peripheral region R13743 with pixel size 6.06 mm X 6.06 mm





Arrays of MaPMTs



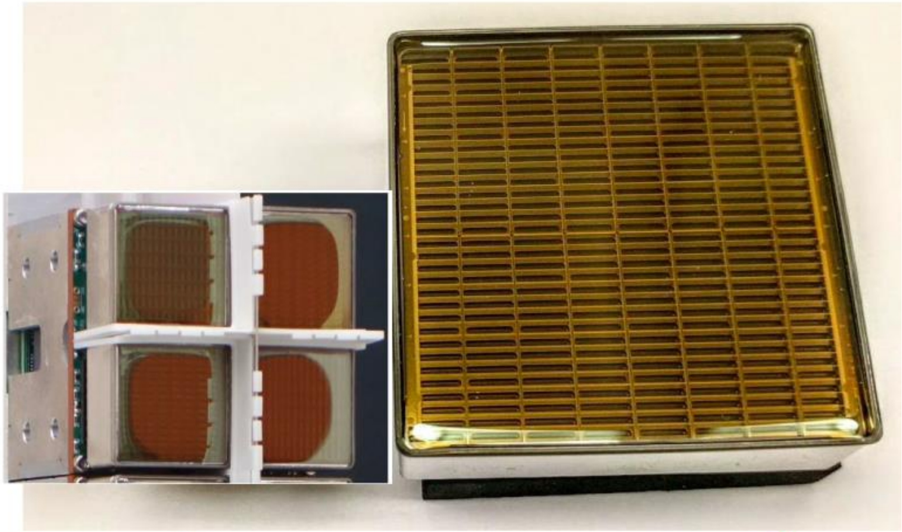
Photos of MaPMTs on ECs

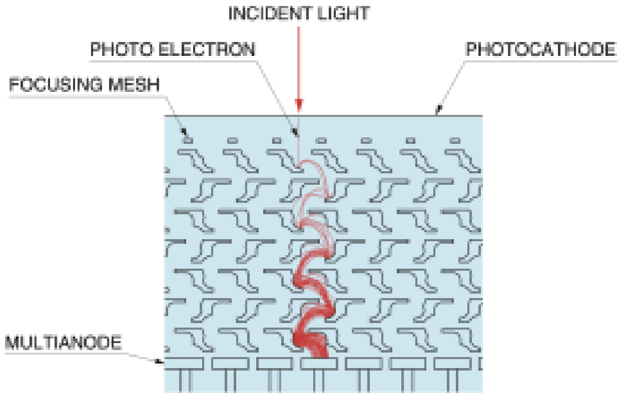
RICH photon detectors in RUN3

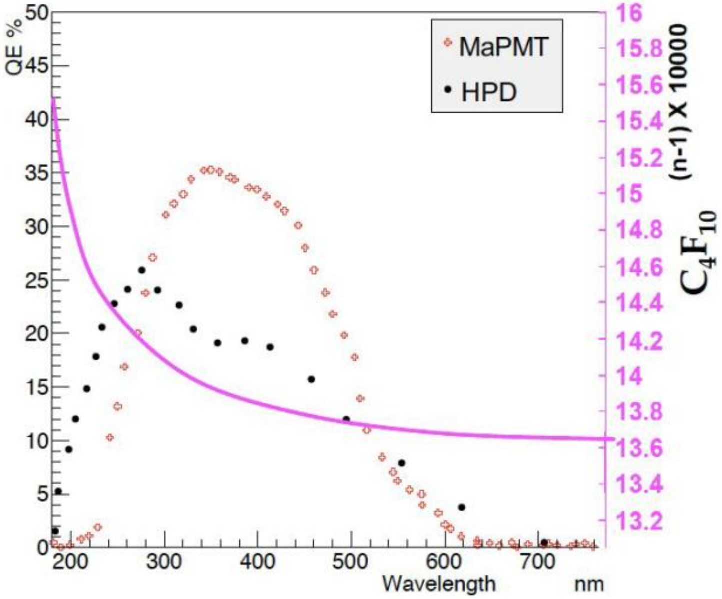
MultiAnode PhotoMultipliers

- Hamamatsu MaPMTs
  - 3100 R13742 and 450 R13743, including spares
  - Super-bialkali photocathode
  - UV glass window
  - Minimum gain 1×10^6 at 1 KV
  - 1:4 pixel gain spread in 1" PMTs, 1:3 pixel gain spread in 2" PMTs
  - Low dark count rate (< 2.5 kHz/cm^2)
  - Single photon spectrum well separated from the noise pedestal
- Higher QE of MaPMT in the green
  - Chromatic error reduction
- Sensitive to magnetic fields
  - Shielding applied

Radiation levels : 3×10^{12} 1 MeV n_{eq}/cm^2





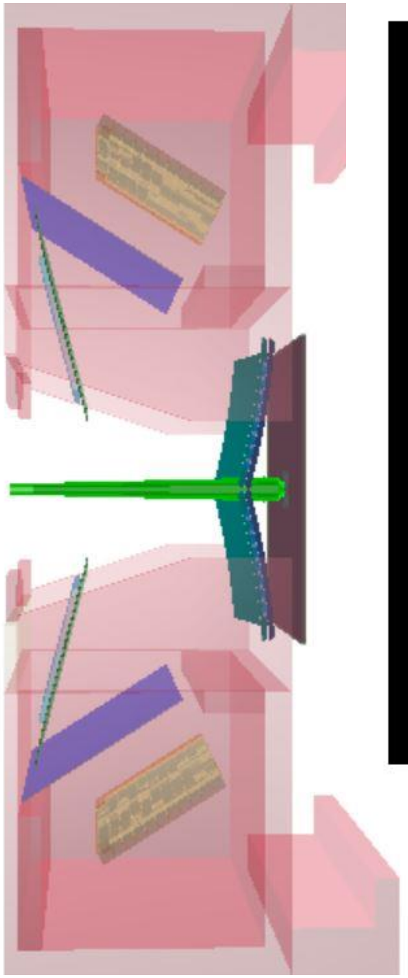


- Active area ~ 80 %

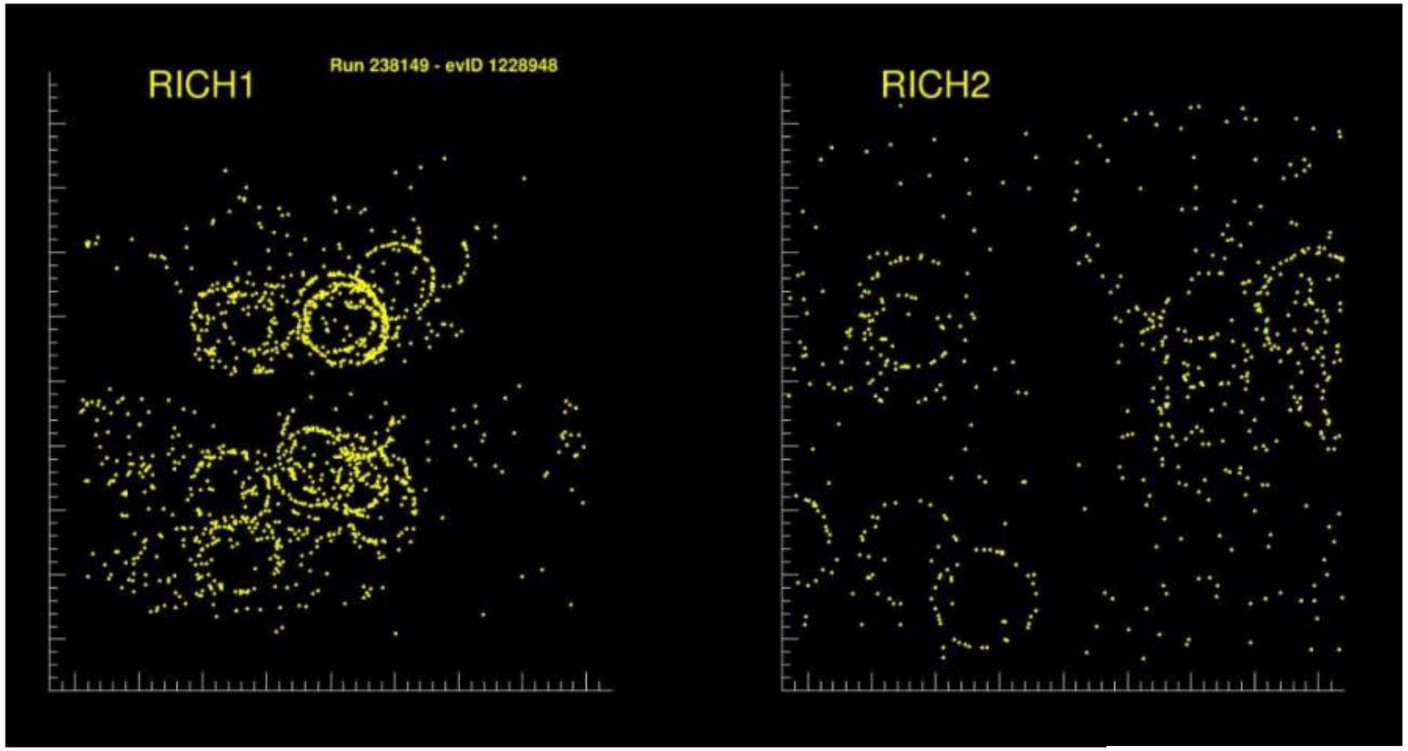
Further details in backup pages

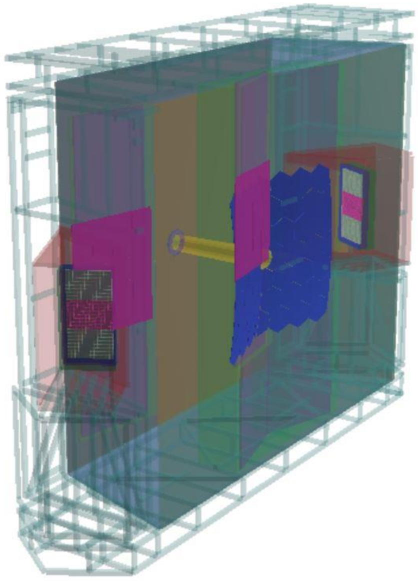
RICH data from RUN3

Some of the first set of Cherenkov rings from RUN3

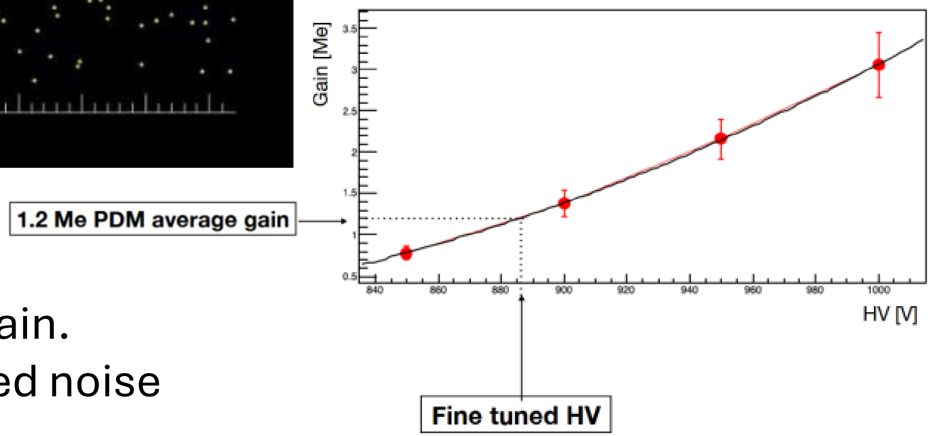


RICH1 in LHCb software





RICH2 in LHCb software



RICH commissioning :

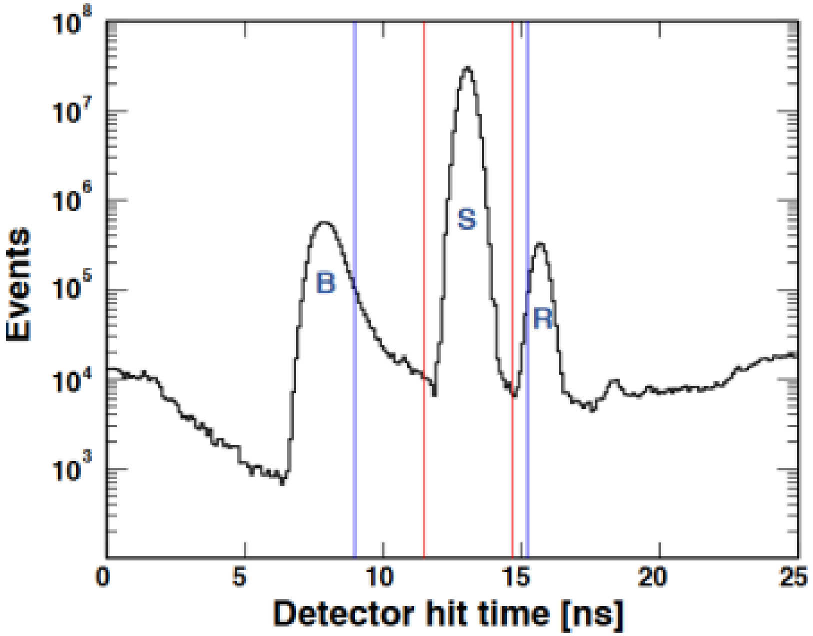
- This includes calibrating the CLARO chip gain.
- Some of the MaPMTs showed signal induced noise in a few channels.
- The HV applied, was tuned to get optimal gain and noise levels

RICH commissioning in RUN3

Time alignment :

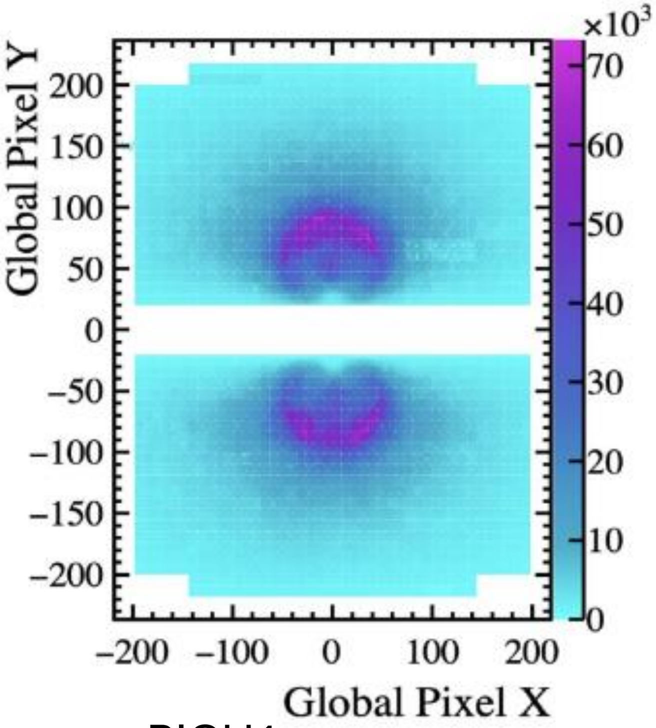
- At first a coarse time alignment was obtained within the 25ns that is needed for each LHC bunch crossing.
- In order to reduce the background in the RICH data, applying an effective time gate of 6.25 ns is applied.

Time of arrival on RICH1

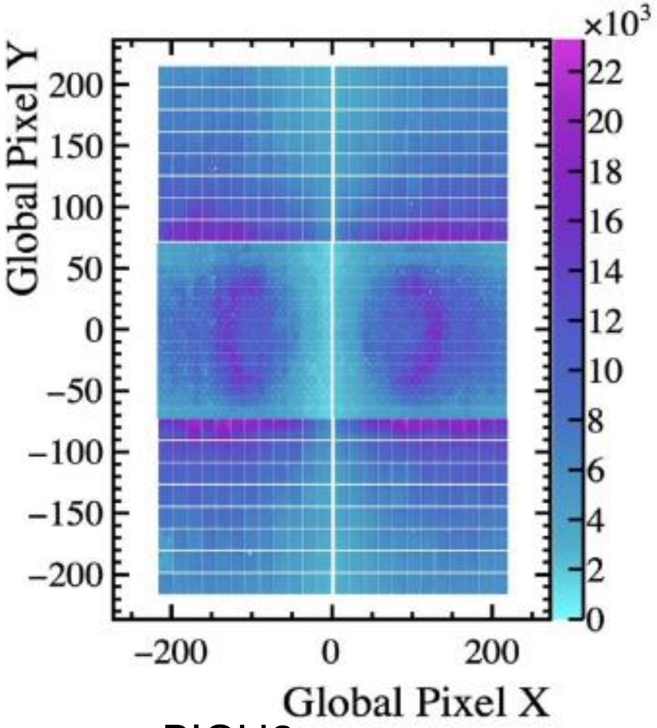


From LHCb simulations

RICH hit distributions from RUN3 data



RICH1



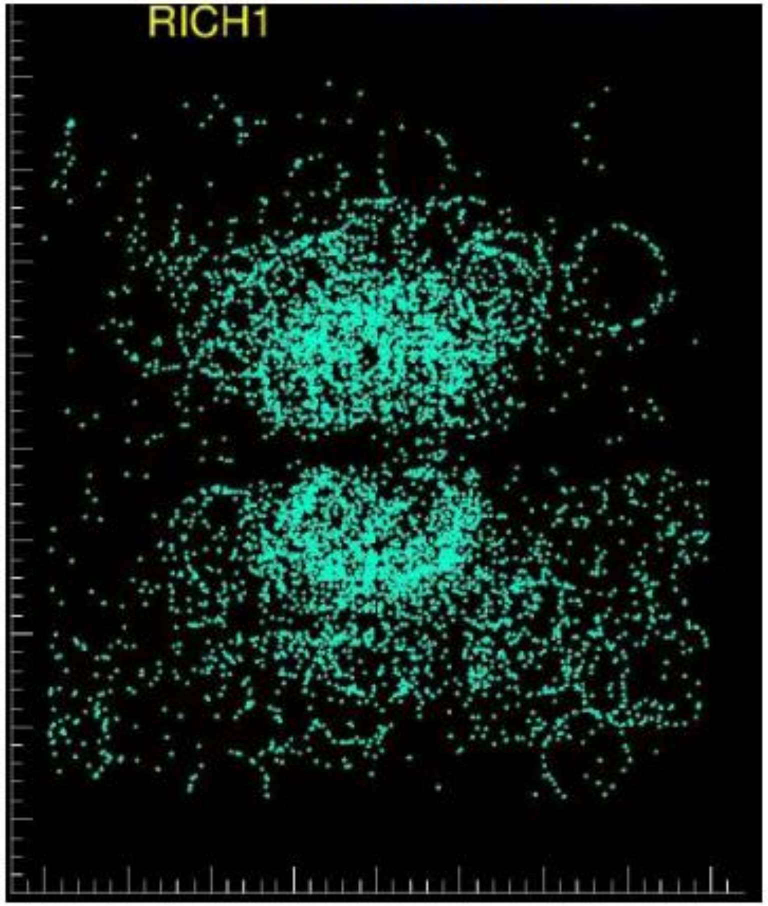
RICH2

- The RICH reconstruction is running as part of the HLT2 software.
- The RICH alignment is also performed as part of online procedures.

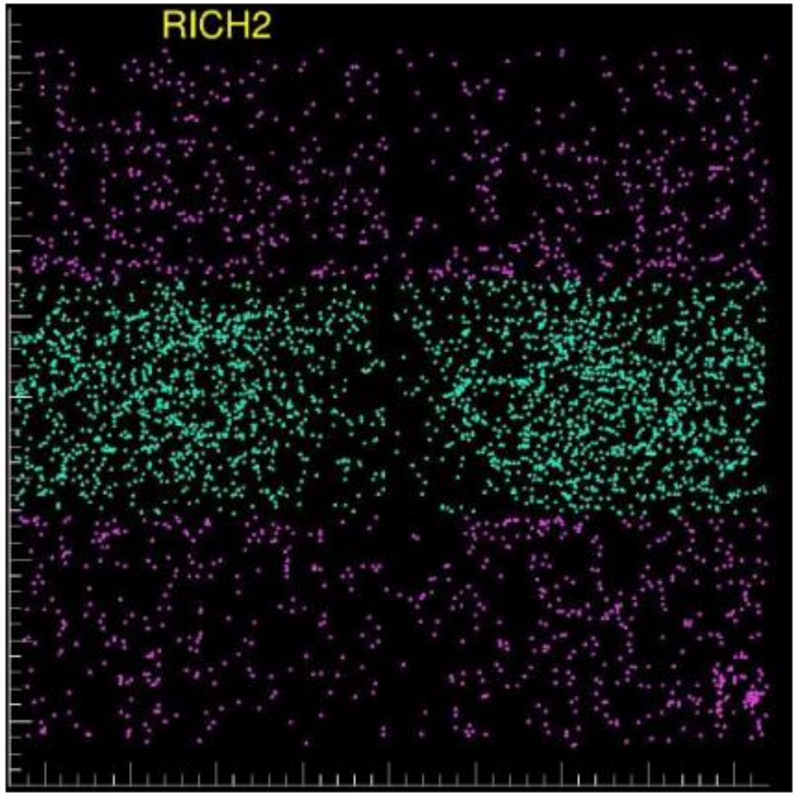
RICH data from RUN3

Typical hit distribution in physics triggered events

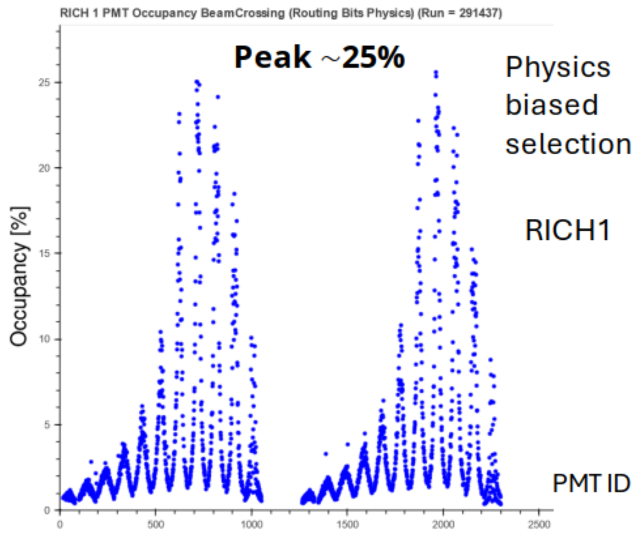
5720 hits in RICH1

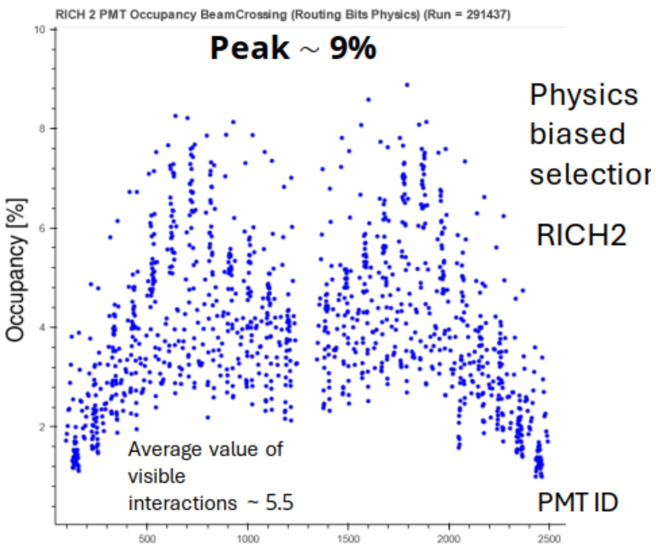


3733 hits in RICH2



Occupancy in MaPMTs





RICH expected performance

Typical yields and single photon resolutions from LHCb-simulation:

Resolution (in mrad)	RICH1-RUN3	RICH2-RUN3
Chromatic	0.52	0.34
Pixel	0.36	0.32 (small PMT)
Emission point	0.50	0.22
Overall (RICH alone)	0.81	0.52 (small PMT) 0.58 (all PMTS)
From tracking	0.1→ >1.2	0.14 → >0.26
Yield	63	34
	RICH1-RUN2	RICH2-RUN2
Overall (RICH alone)	1.60	0.65
Yield	32	24

Resolution components:

Chromatic : From the variation of refractive index with wavelength

Pixel : From the pixel granularity

Emission point : From the tilt of the spherical mirror and other geometry factors

Tracking : Track angular resolution, multiple scattering, curvature in the magnetic field etc.

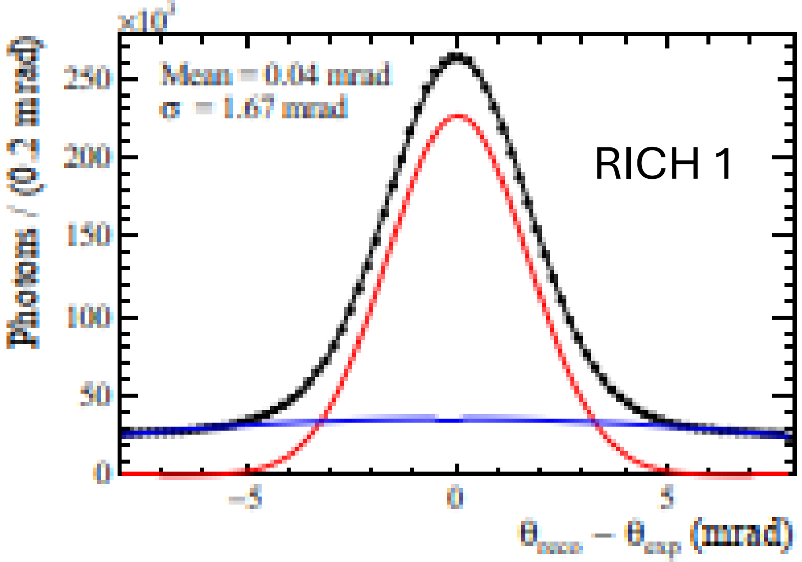
Nominal Configuration	Luminosity 10^{32} cm^{-2}s^{-1}	nominal # of Bunches	E TeV	ν
LHCb in Run 2	4.0	2300	13	1.6
LHCb in Run 3	20	2400	13.6	7.6

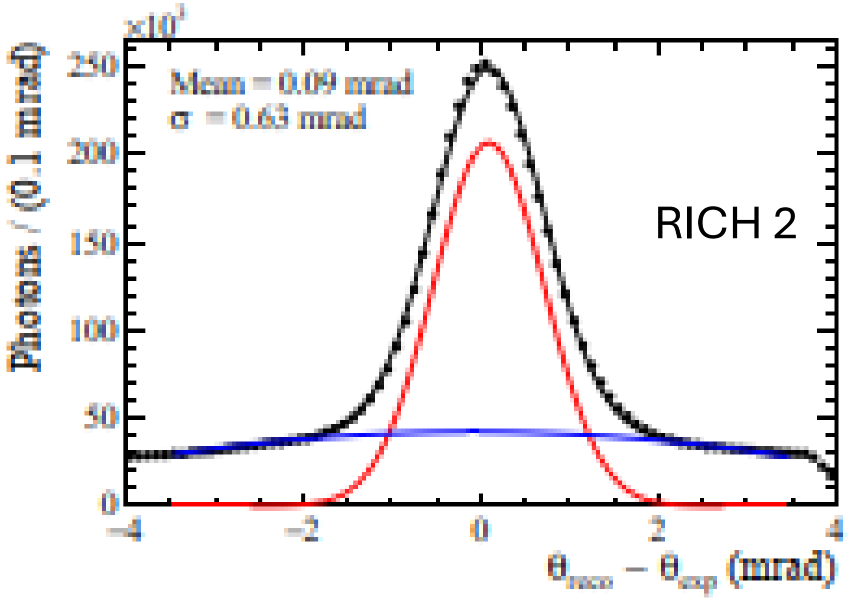
The resolution contributions from tracking depend on the track momentum
Here, for RICH2 , small MaPMT refer to R13742 type MaPMTs

ν= number of pp collisions per bunch crossing

RICH resolutions in real data

From LHCb-RUN2 data using low multiplicity events:



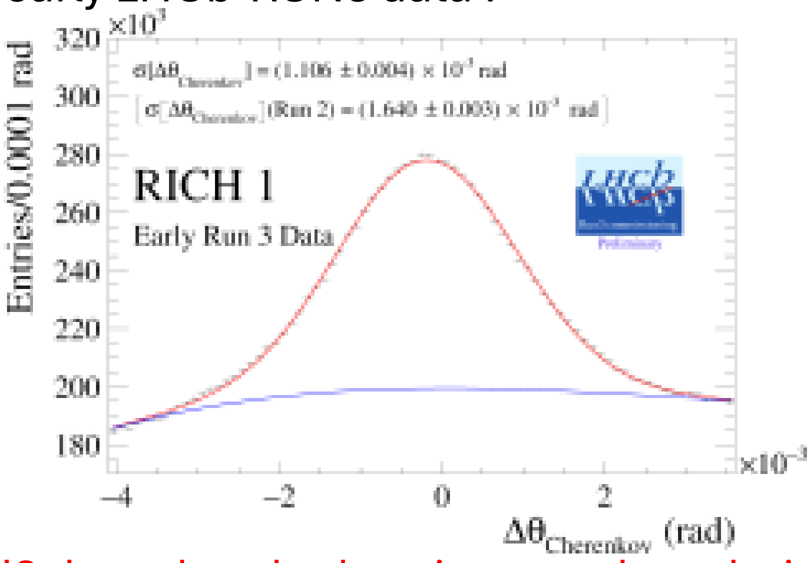


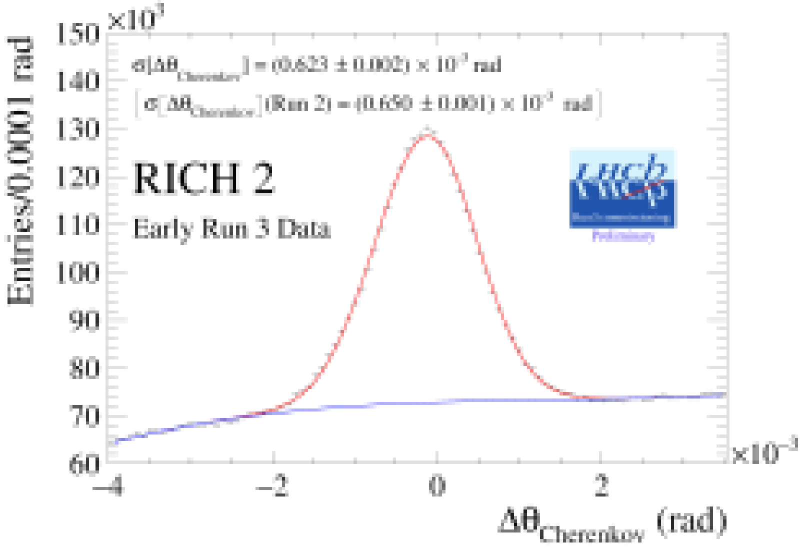
RICH1 resolution:

RUN2: 1.67 mrad

RUN3: 1.1 mrad (preliminary)

From early LHCb-RUN3 data :

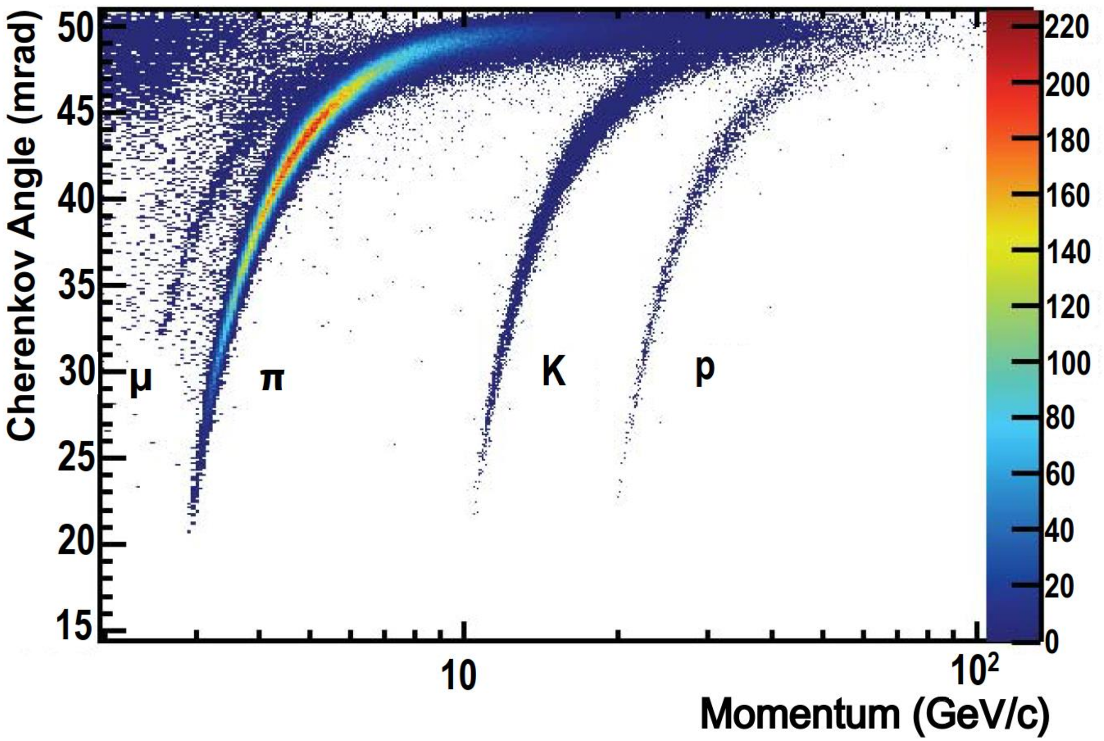




RUN3 data already show improved resolutions compared to those from RUN2

PID from RICH

From LHCb-RUN1 data :



Using isolated tracks from C_4F_{10} in RICH1

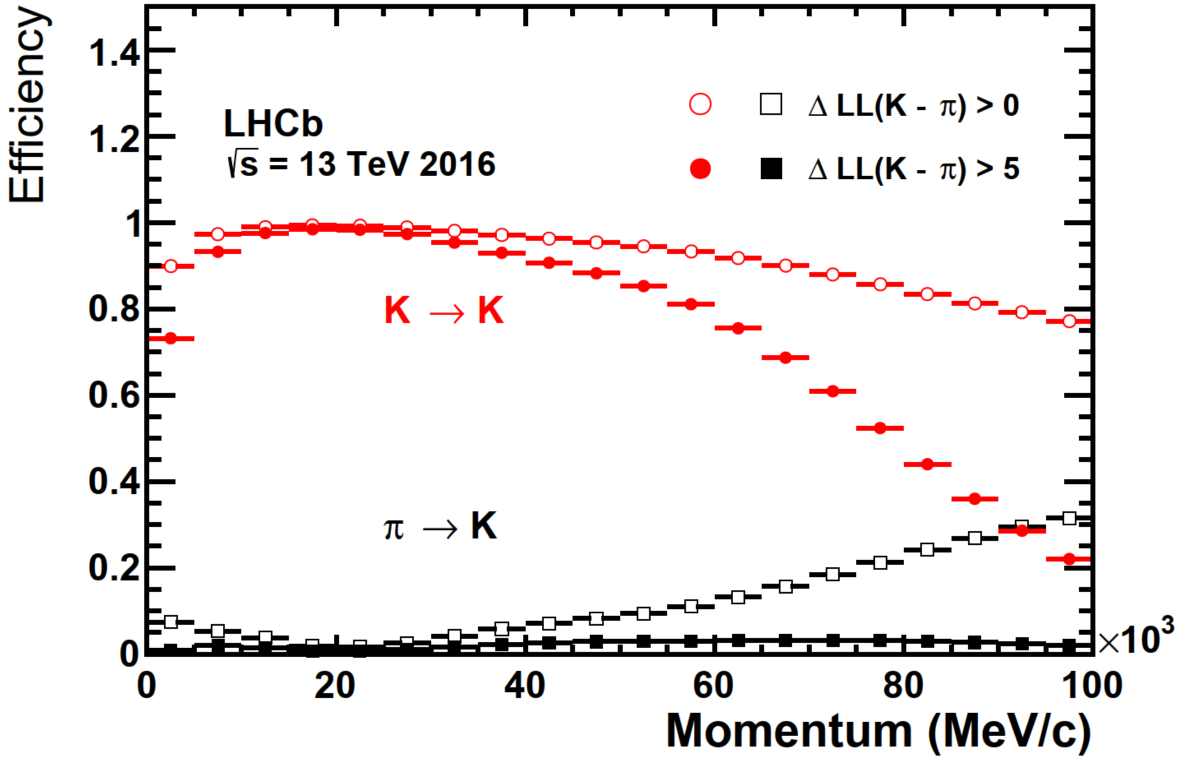
Eur.Phys.J.C. (2013) 73:2431

- In general, there are many tracks close to one another, and this makes it difficult to associate tracks with hits.
- As a result, the PID algorithm uses a 'maximum-likelihood' technique. *NIMA 433 (1999) 257-261*
- This uses all combinations of tracks and mass hypotheses for estimating the expected signals on the pixels.
- These are compared with the actual signals to create likelihood estimates and to find 'maximum-likelihood' for the event.
- The results are quoted for each track in terms of the logarithm of likelihood ratios.

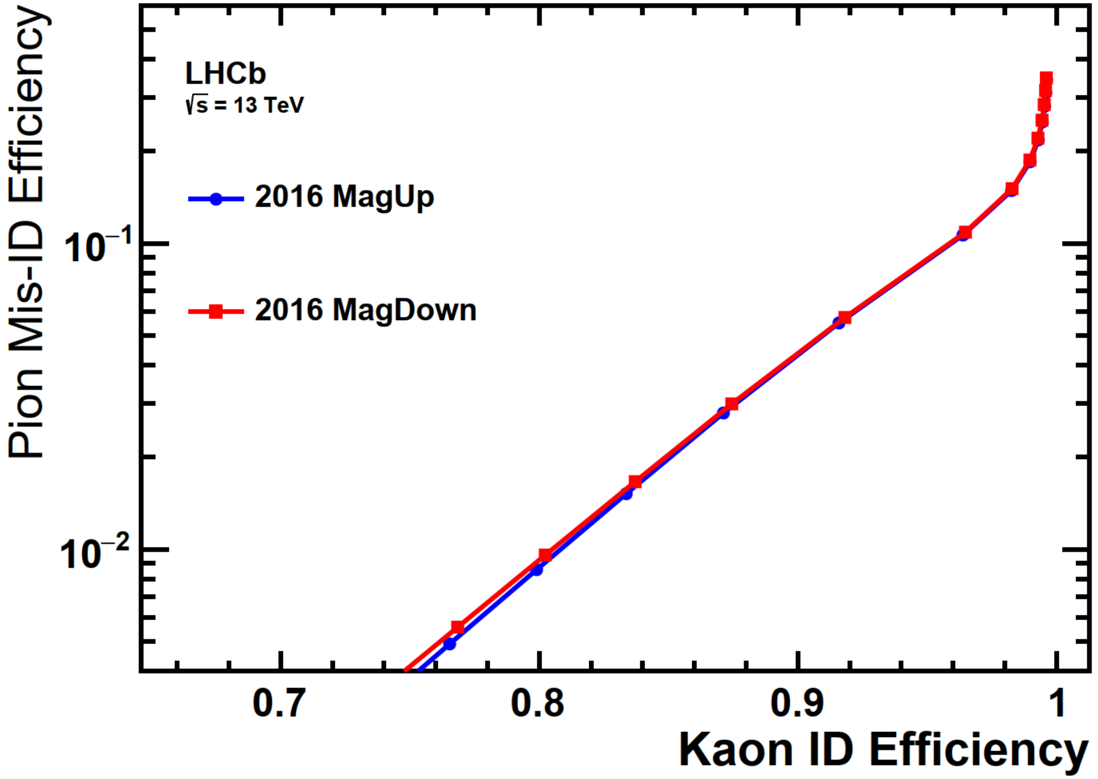
$$\Delta \ln \mathrm{L}_{K\pi} = \ln \mathrm{L}(K) - \ln \mathrm{L}(\pi)$$ = Δ LL (K-π)

Typical PID performance from real data

From data collected in 2016 (RUN2)



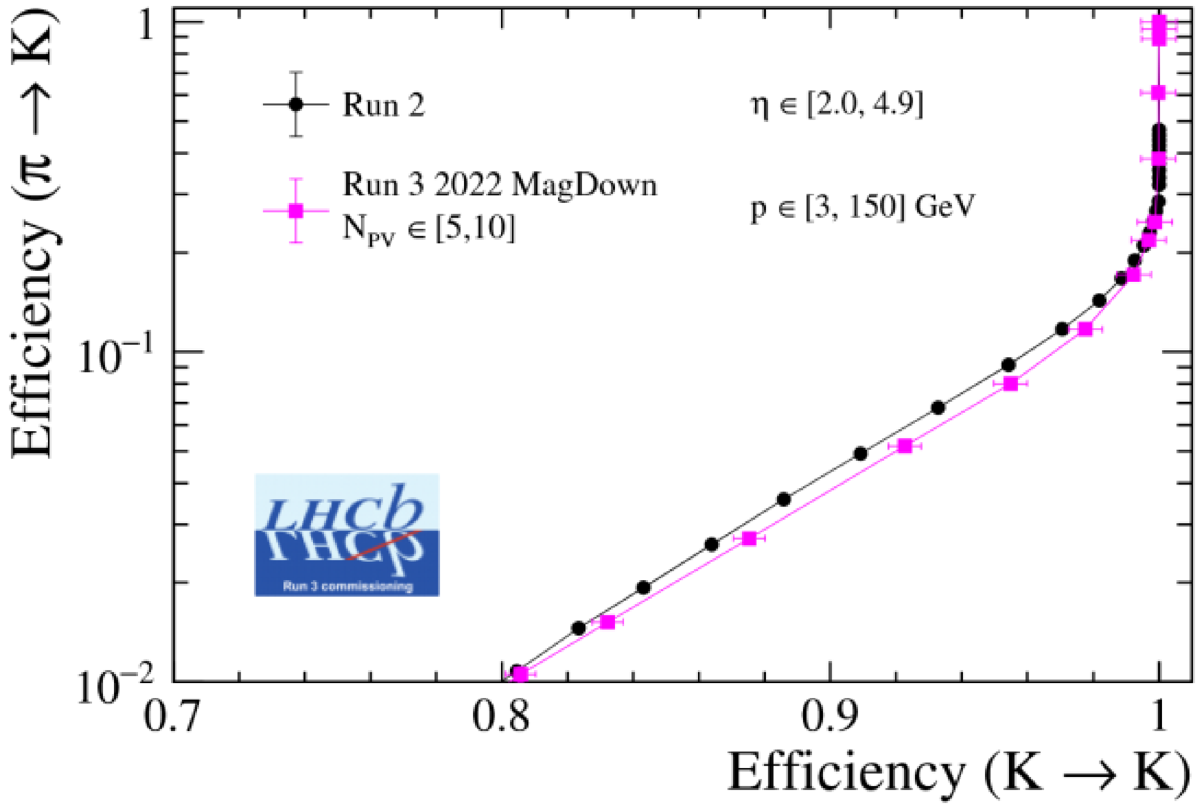
PID performance as a function of momentum
Illustrated for two different Δ LL cuts

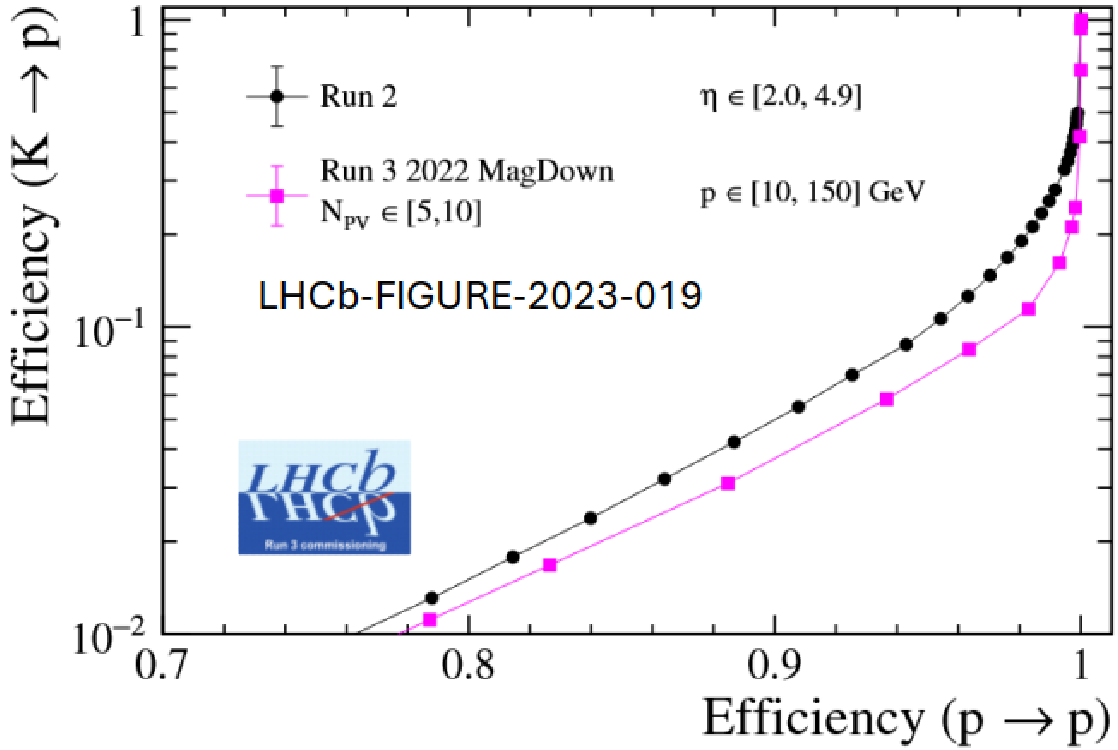


PID performance averaged over the full momentum range.
The dots shown represent performances at different ΔLL cuts.

Typical PID performance from real data

From data collected in 2022 (RUN3) and RUN2

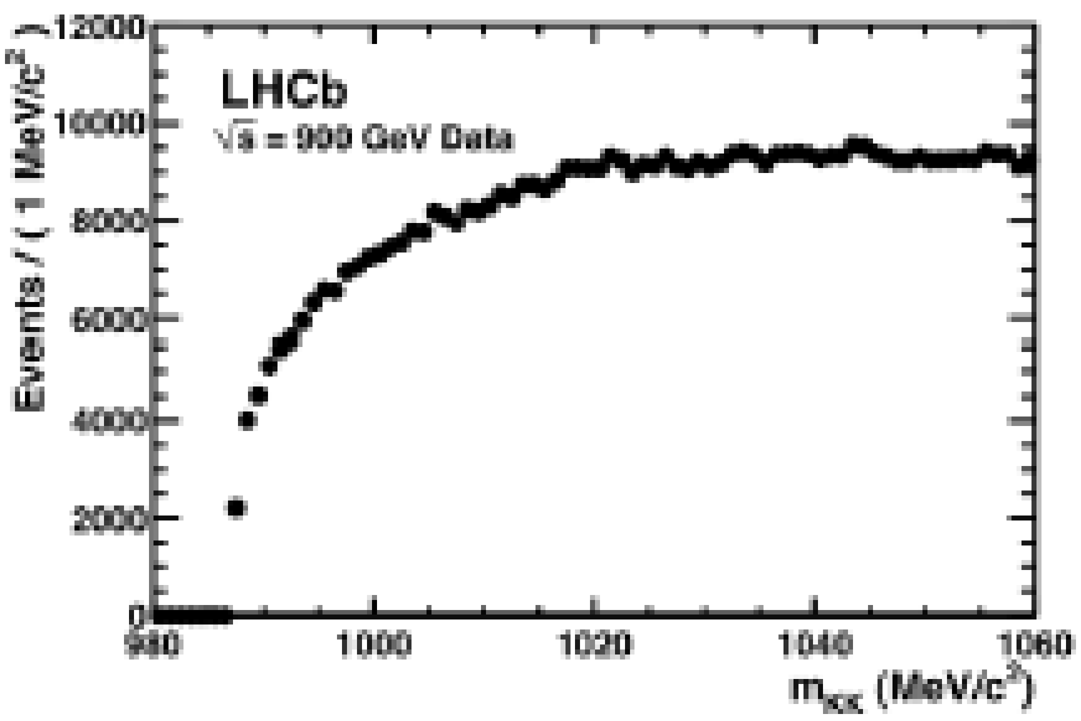




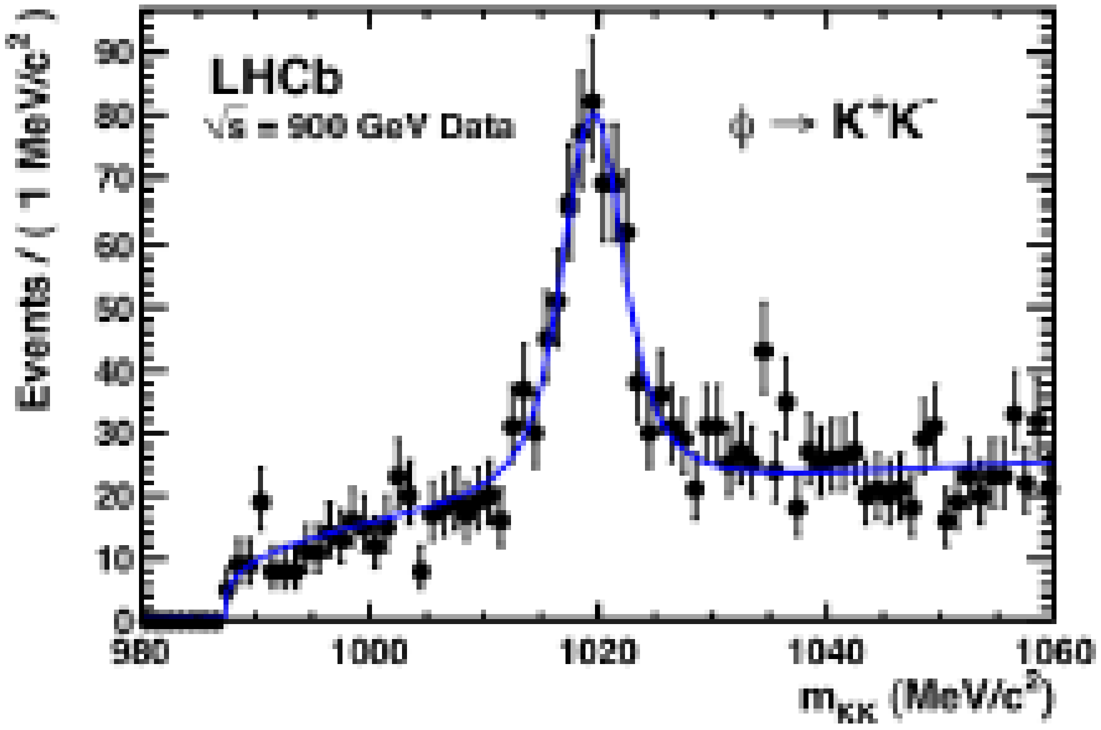
PID performance averaged over the full momentum range.
The dots shown represent performances at different ΔLL cuts.
Here, average number of PV per event in RUN2 ~ 1.8,
in RUN3 ~ 5 - 10

Usefulness of RICH in physics analysis

Without RICH data

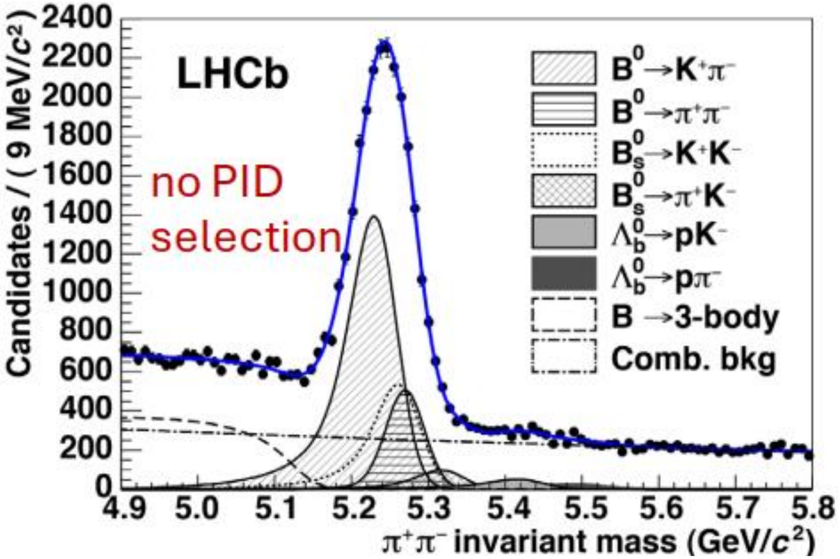


With RICH data

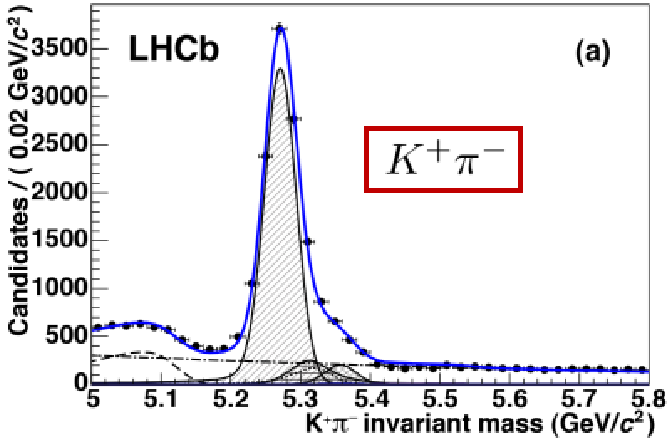


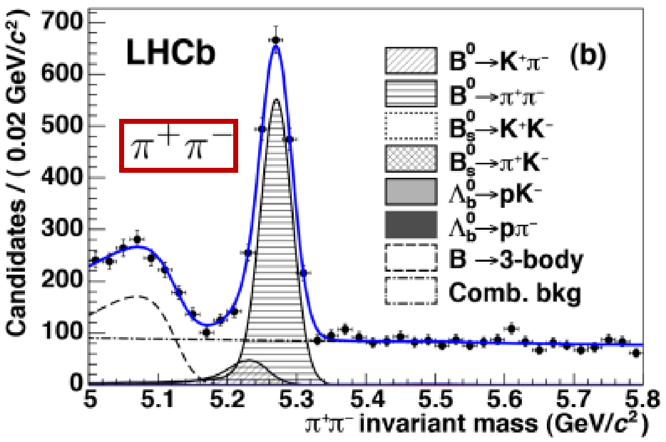
Usefulness of RICH in physics analysis

JHEP 10 (2012) 37

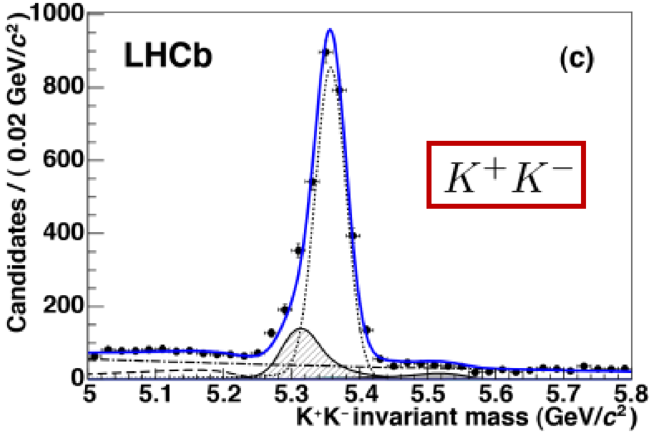


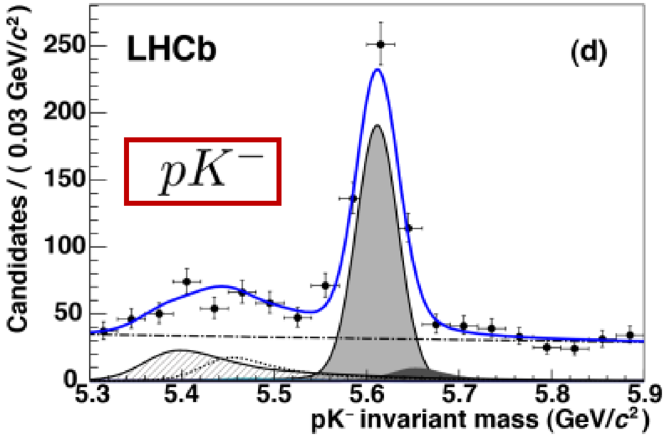
With selections using PID,
one can see the different signals of B^0, B_s^0 and Λ_b

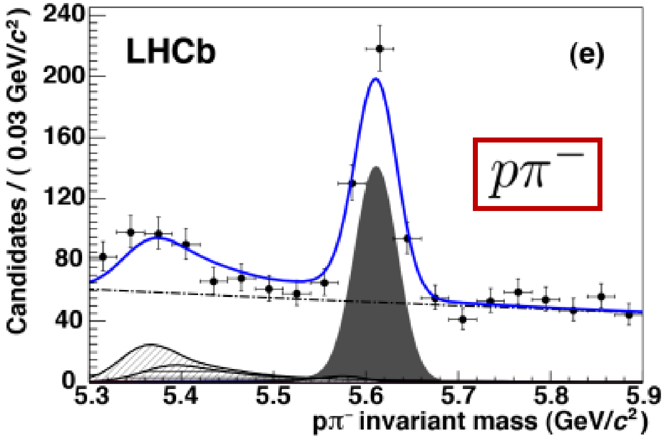




Using RUN1 data



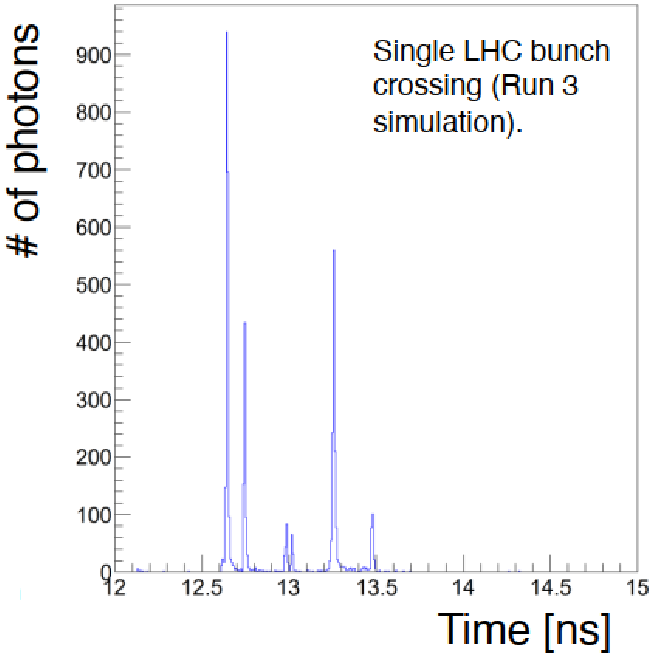


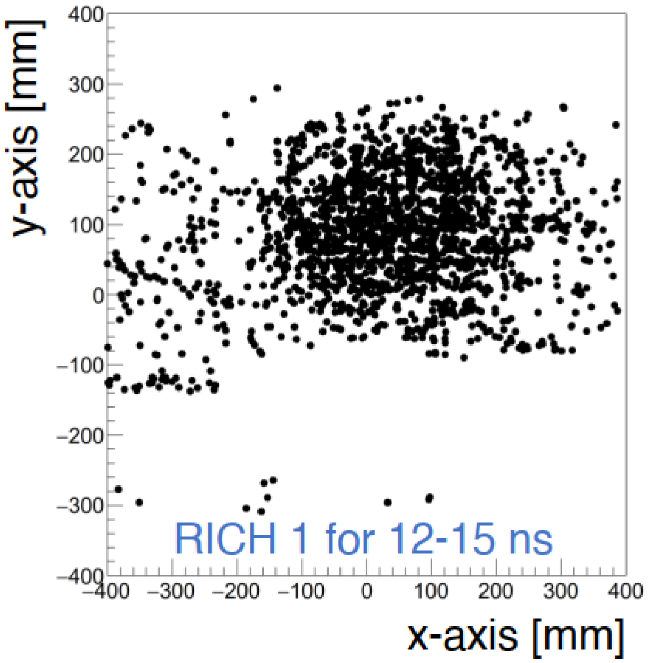


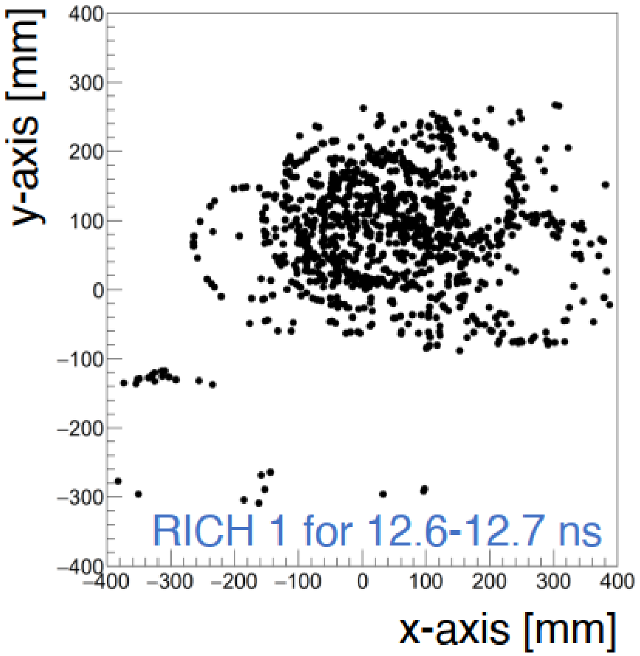
RICH data is used to reduce the combinatorial backgrounds and to distinguish between final states with similar event topology.

Future upgrades of the RICH system

- Introduction of fast timing :
  - Photons from the same track arrive at detector plane at the same time.
  - This feature can be used to reduce backgrounds by selecting hits within an expected time window for each track.
  - Illustration from RUN3 simulations which show the time and space coordinates on RICH1 using a photon detector with zero time jitter.



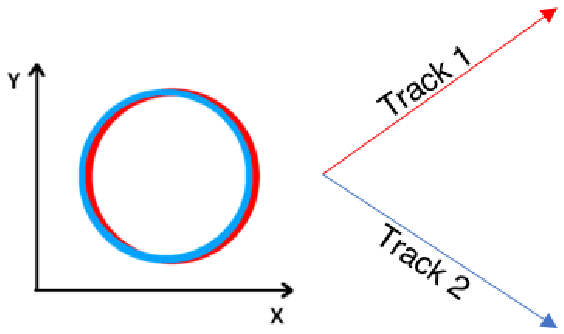


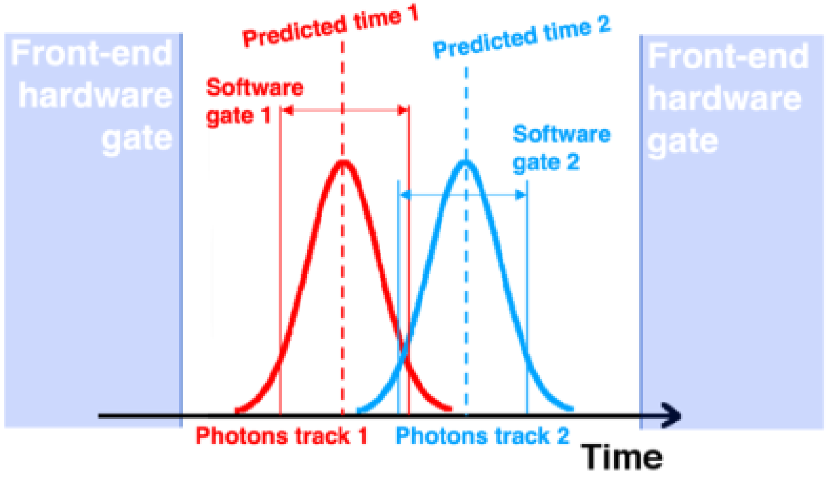


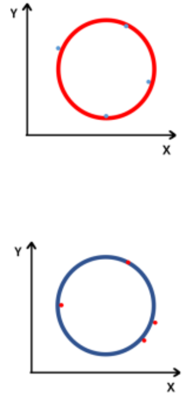
- The distinct peaks show tracks originating from different primary vertices (PV).
- Applying a time window cut improves the PID capability.

RICH upgrades in RUN4

- In RUN4, the readout hardware will be upgraded such that time and space coordinates for each hit will be recorded.
- At the front-end ASIC a nanosecond-scale time gate will be applied.
- In software, the time of arrival (TOA) of the photon at the detector plane can be predicted within 10 ps.
- This facilitates the implementation of a ‘software time gate’ during data reconstruction.
- In RUN4 the size of this time gate will be mainly determined by MaPMT time resolution.

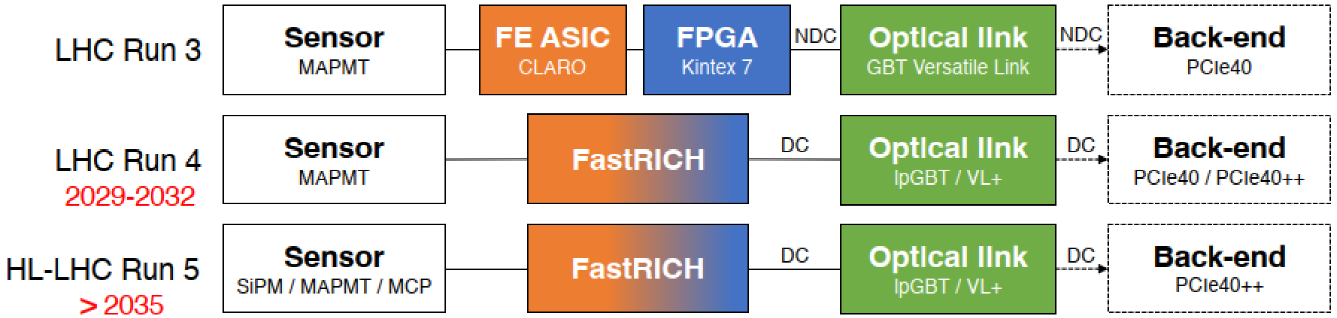


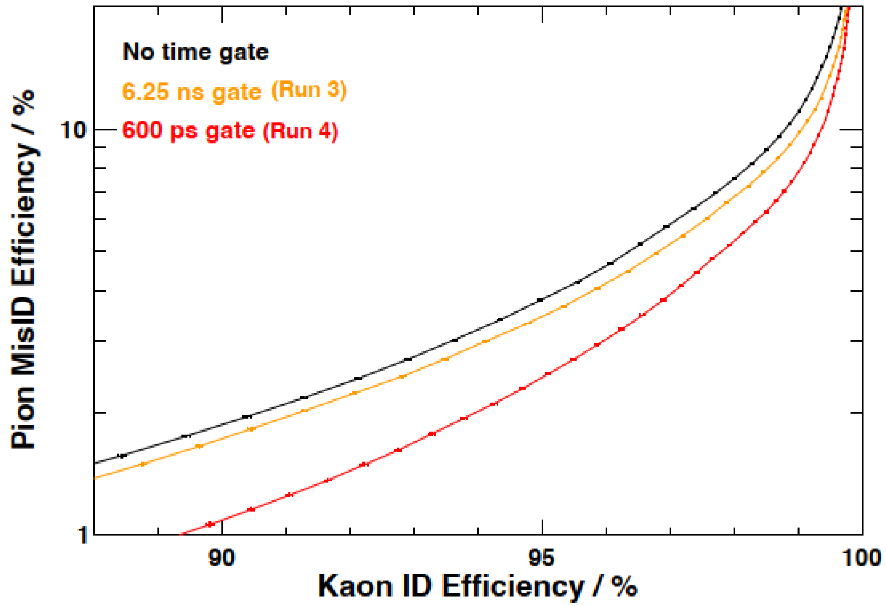




RICH upgrades in RUN4

- The time gate used at the front-end in RUN3 is 6.25 ns
- Considering the MaPMTs have a time resolution of ~150 ps, the optimal software time gate would be ~600 ps.
- This can result in an improvement in PID performance, assuming one knows the PV time.
- In RUN4, RICH is the only detector in LHCb with time coordinate measurement. This would require the PV time to be determined from RICH data.
- For RUN4 a readout chip named FastRICH is being developed that can timestamp the hits within 25 ps time bins.
- The upgrades to the readout hardware in RUN4 are part of the upgrades towards RUN5.



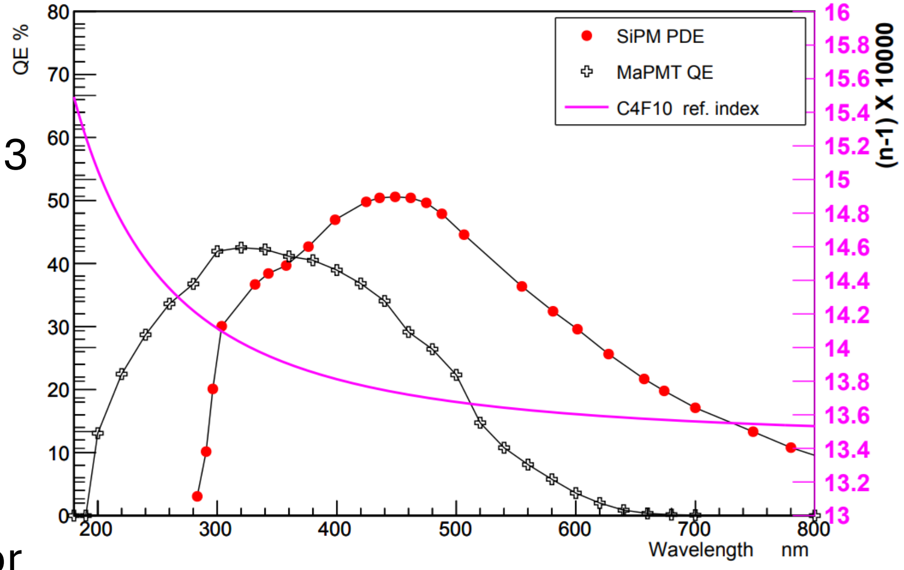


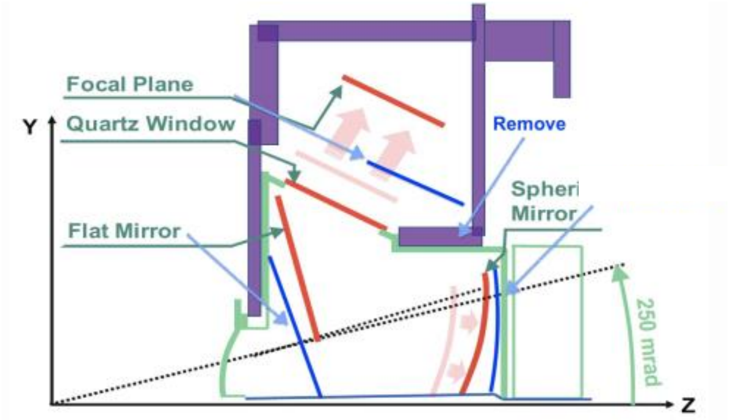
- A TDR is created for RICH upgrade in RUN4.

- Prototypes of the various parts of the new readout are being tested using test beams.

RICH upgrades in RUN5

- In RUN5, the luminosity is increased by a factor of ~ 5 to 7, compared to that in RUN3
- Potential improvements in angular resolutions :
  - The usage of SIPM can reduce the chromatic error and improve the yield, compared to those from MaPMTs used in RUN3
  - The SiPM can have reduced pixel size, for example 1 mm compared to the 2.875 mm of MaPMTs
  - However, they would need to operate at cryogenic temperatures to reduce the dark count rates to a good level.
  - Other photon detectors such as MCPs are also being considered for achieving similar improvements.
    (More details in a backup page)
  - Geometry changes to improve resolutions are also planned.
    Examples:
    - Increase the focal length
    - Reduce the tilt of the spherical mirror
      and make corresponding changes to the flat mirror





- R&D also planned to replace the gas radiators with more eco-friendly gases in the next decade, without changing their performance.

RICH upgrades in RUN5

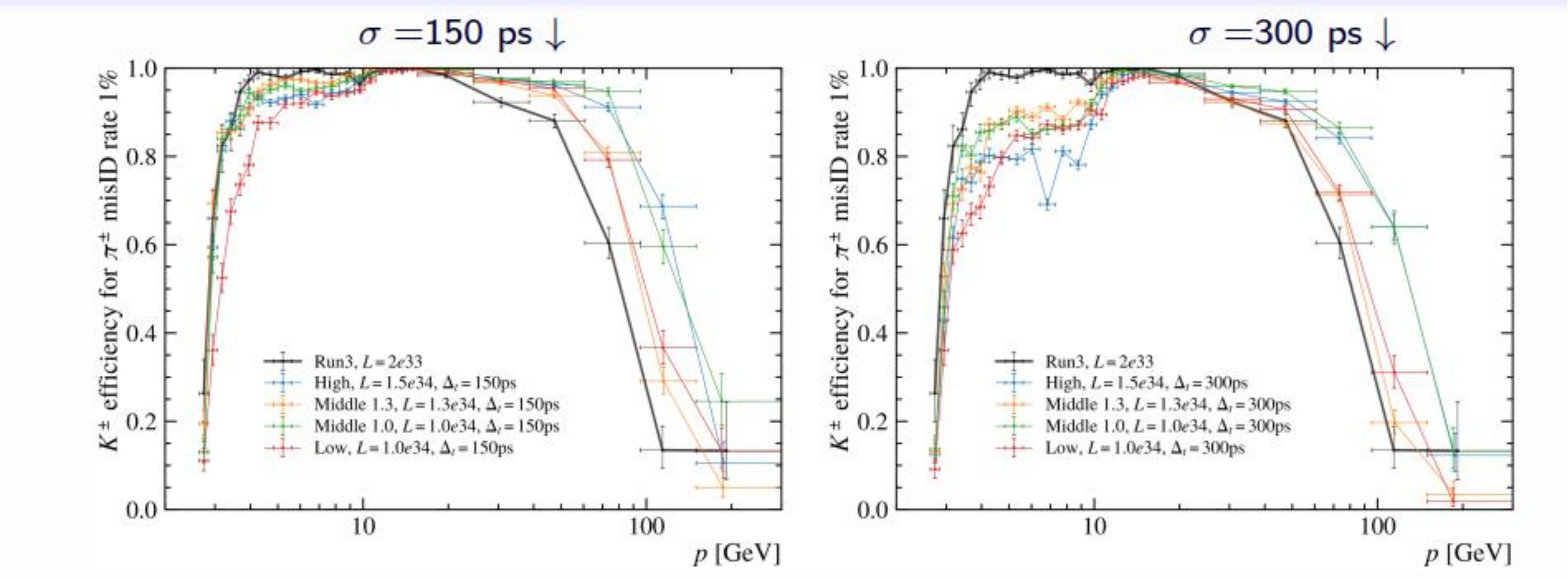
- Example of resolutions and yields in RUN5 from simulations:

Configuratio n	Overall [mrad]	Chromatic [mrad]	Emission pt [mrad]	Pixel [mrad]	Yield
RICH 1					
MaPMT	0.8	0.52	0.36	0.5	63
SiPM	0.40	0.11	0.36	0.15	47
SiPM+geom	0.22	0.11	0.12	0.15	34
RICH2					
MaPMT	0.50	0.34	0.32	0.22	34
SiPM+geom	0.13	0.10	0.05	0.07	20-30

Realizing such resolutions would require corresponding improvements in LHCb tracking also.
Here, usage of SiPM is considered for photons above 400 mrad, as an example.

- Potential improvements in time resolutions:
  - Usage of SiPMs or MCPs can reduce the software time gate that is applied to a level in the range of 100-300 ps.

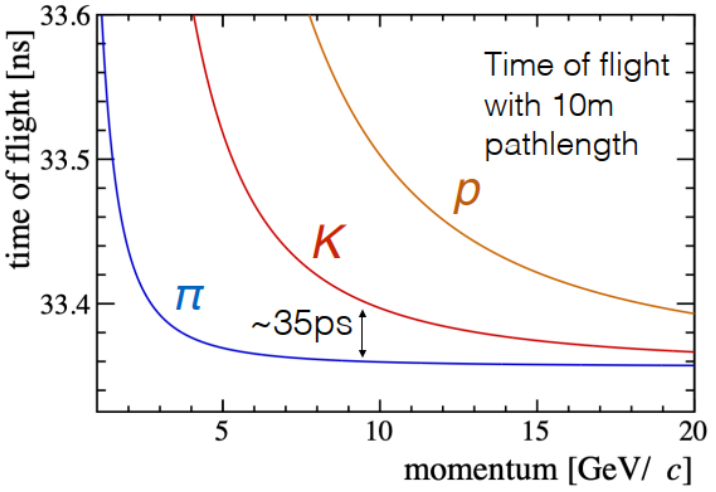
Examples of PID performances expected in RUN5

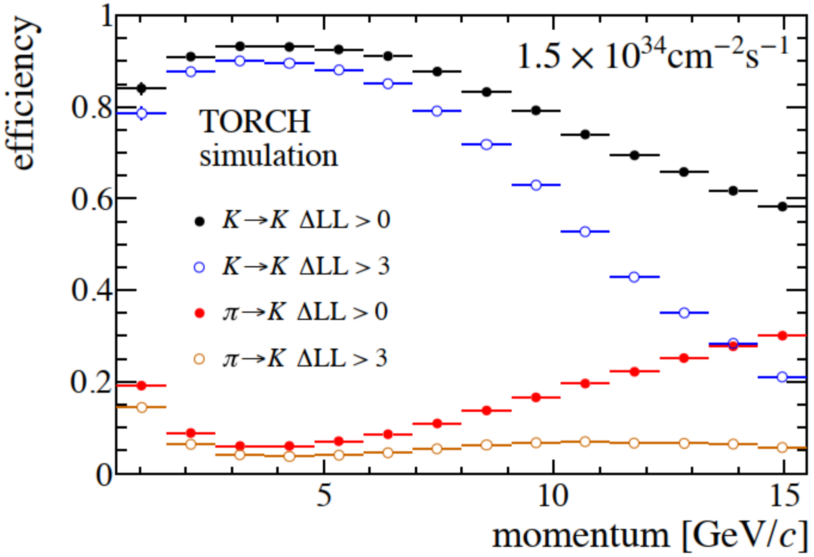


- These show the PID performances as function of momentum for different combinations of resolutions.
- Different scenarios being considered to balance cost and performance at different values of luminosity

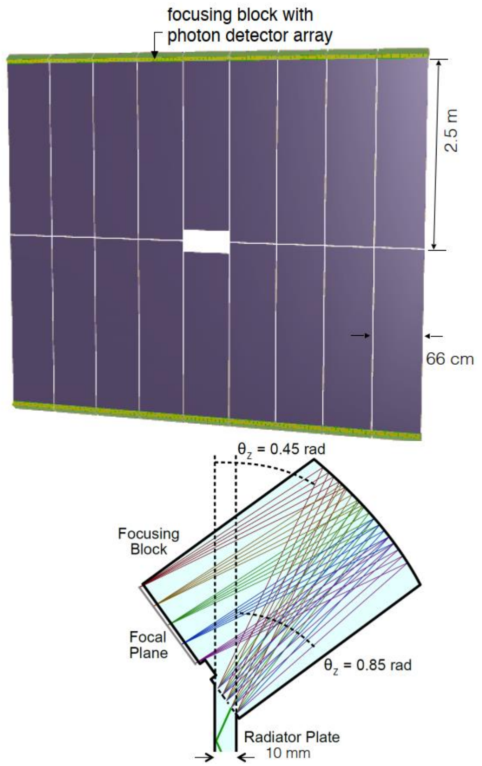
TORCH : Time-of-flight detector for RUN5

- For improving PID in the low-momentum region which is below K/p threshold in the gas radiators.
- Detector concept :
  - For K-pi separation over 10 m, aim for a single photon resolution of 70 ps , which can potentially give a resolution of 15 ps per track.
  - Cherenkov photons produced in a fused silica bar are propagated to a cylindrical focusing block and then on to a detector plane. *NIM A 639 (1) (2011) 173*
- R&D status :
  - Prototypes are being developed and tested. *NIMA 1050 (2023) 168181*
  - At present the prototypes use custom made MCP-PMTs . *JINST 10 (2015) C05003*





Typical PID performance from initial simulation studies

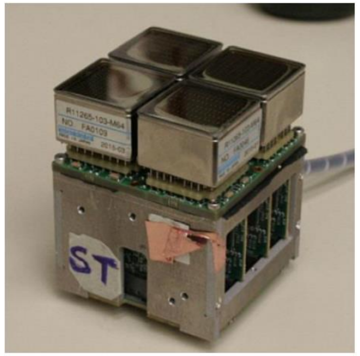


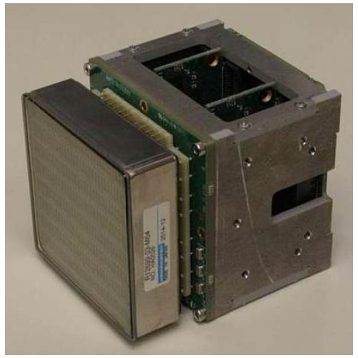
SUMMARY

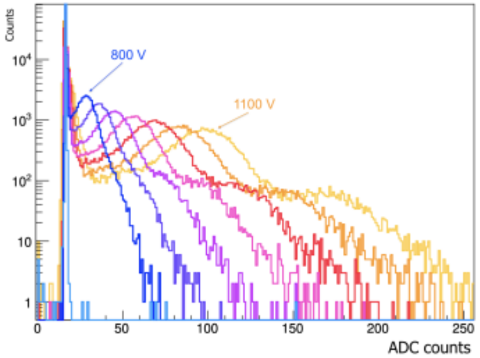
- Particle identification using the data from the RICH detectors has been an essential part of the LHCb physics programme.
- The RICH system performed reasonably well in the last 14 years. Excellent PID performance seen from data.
- There was a major upgrade for RUN3. The new system has been operational for the past couple of years.
- For the upgrades in RUN4 for the RICH system, a TDR was created.
- For the upgrades in RUN4 and RUN5 , prototypes are being tested.

BACKUP PAGES

MaPMTs for RICH







MaPMT response

HAMAMATSU

TENTATIVE DATA SHEET

Dec. 2015

MULTIANODE PHOTOMULTIPLIER TUBE

R13742

Exclusive for HPF-BS/ CERN and HPI/ INFN MILANO (for LHCb/RICH)

Super Bialkali Photocathode (SBA), UV Window, 1 Inch Square 8 x 8 Multianode and Fast Time Response

General

Parameter		Description	Unit
Spectral Response Range		185 to 650	nm
Peak Wavelength		350	nm
Photocathode Material		Bialkali	-
Window	Material	UV Glass	-
	Thickness	0.8	mm
Dynode	Structure	Metal Channel Dynode	-
	Number of Stage	12	-
Anode	Number of Pixels	64 (8 x 8 Matrix)	-
	Pixel Size	2.88 x 2.88	mm
Effective Area		23 x 23	mm
Dimensional Outline (W x D x H)		26.2 x 26.2 x 17.4	mm
Packing Density (Effective Area / External Size)		77	%
Weight		27	g
Operating Ambient Temperature		-30 to +50	deg C
Storage Temperature		-80 to +50	deg C

Maximum Ratings (Absolute Maximum Values)

Parameter	Value	Unit
Supply Voltage (Between Anode and Cathode)	1100	V
Average Anode Output Current in Total	0.1	mA

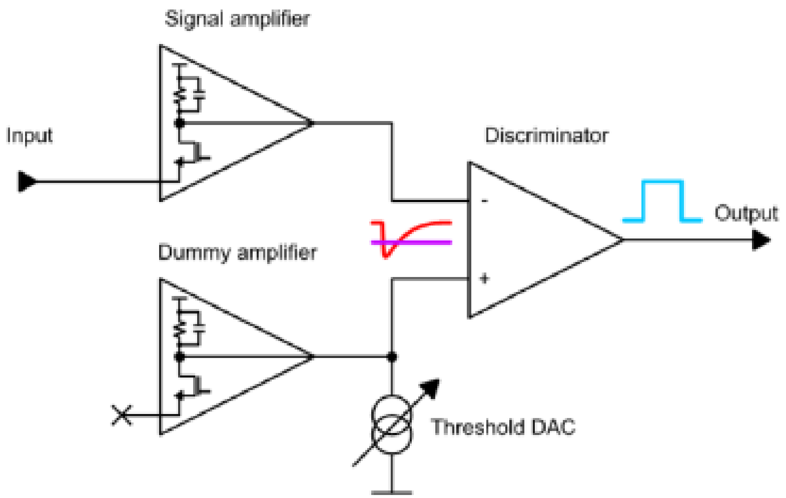
Nucl. Inst. Meth. A 876 (2017) 206-208

RICH Readout

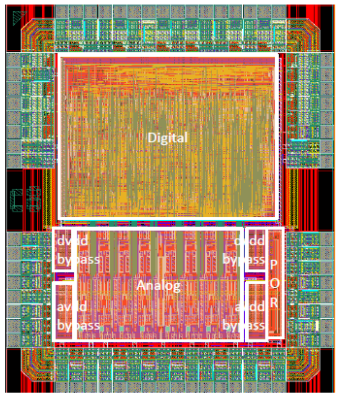
JINST 8 C01029 (2013)

CLARO : 8 channel ASIC

- 64 possible threshold settings from 30 ke$^-$ to 2 M e$^-$
- 3 attenuation levels
- Power consumption only ~ 1 mW per channel
- Recovery time less than 25 ns.
- Radiation tolerant up to ~ 1 Mrad (10 k Gy) TID
  (*Even better results obtained from recent tests*)



- Performances of prototypes verified using lab tests and beam tests



- LHCb-RICH needed about 28000 chips. They were all characterised before installation

Photon detectors for RUN5

Features of photon detectors candidates, that are considered for RUN5

	MaPMT	SiPM	MCP/LAPPD
σ_t [ps]	150	60	30
Pixel size [mm]	$\geq$ 2.8	$\geq$ 1	Custom (R&D)
QE	> 35% at 350 nm	> 45% at 460 nm	20-30% at 350 nm
Dark count rate [Hz mm^{-2}]	1	10^5 - 10^7	1
Typical operating voltage	1 kV	< 100 V	1 kV
B-field	< 5 mT	Insensitive	< 2 T
Radiation tolerance	Entrance window	Lattice defects	Entrance window
Gain ageing limits	I_{anode} 100 μA	N/A	10 C cm^{-2}

- SiPM would be required to operate in cryogenic temperatures, in order to reduce the dark count rates to an acceptable level

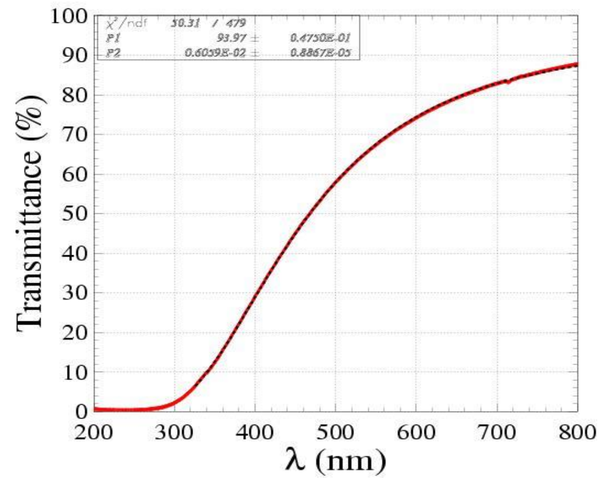
NIM A 922 (2019) 243-249

- MCP's have excellent time resolution, but at present there are drawbacks related to lifetime and rate capability.
- Further R&D is planned for realizing a photon detector that meets all the requirements of LHCb upgrade2.

LHCb RICH radiators

	Aerogel	C_4F_{10}	CF_4	
L	5	86	196	cm
θ_c^{max}	242	53	32	mrad
π_{Th}	0.6	2.6	4.4	GeV/c
K_{Th}	2.0	9.3	15.6	GeV/c

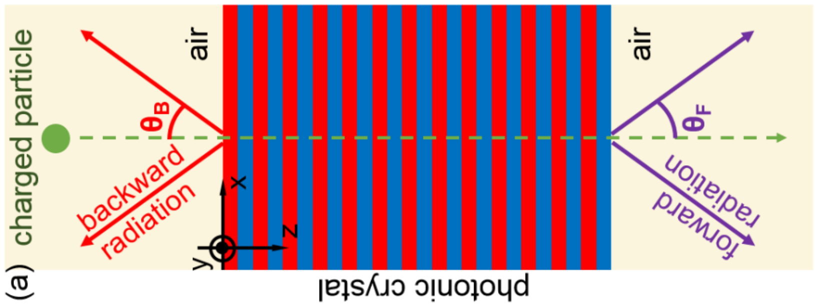
Aerogel Transmission



$$T = A\,e^{(-C\,t/\lambda^4)}$$

Typically: A= 0.94, C =0.0059 mm^4 /cm

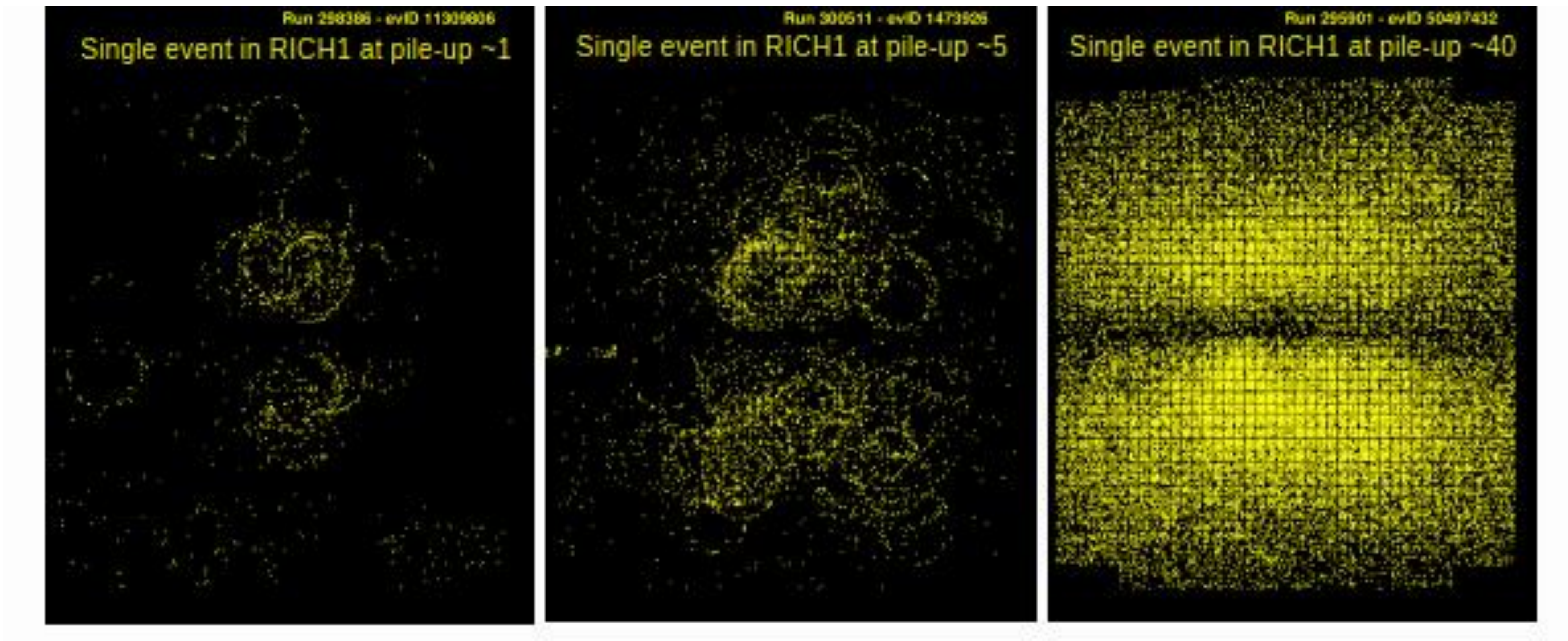
R&D on novel radiators: meta materials



Resonance Transition Radiation :

- *Has the features of conventional Cherenkov radiation*
- *Both forward and backward radiation are possible*   *Nature physics 14, 816-821 (2018)*
- *Possibility to create a structure with the desired refractive index*

RICH hit distributions in different RUNs



- For RUN5, one would need a significant improvement in the angular resolutions and time resolutions.

- It will involve developing novel photon detectors such as SiPM or MCP for single photon detection. These photon detectors could be subjected to high radiation environment, corresponding to 10^{13} /cm^2 1-MeV-equivalent neutron fluence.