Upgrade of the LHCb RICH detectors and characterisation of the new opto-electronics chain

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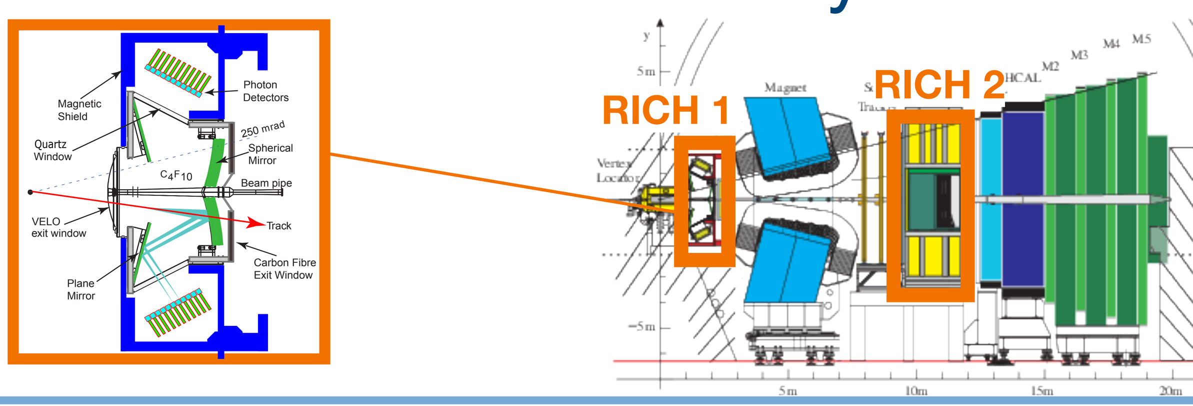
The **two LHCb Ring Imaging Cherenkov detectors**, providing **charged hadron discrimination**, underwent a **major upgrade** to handle the **five-fold increase in the instantaneous luminosity** delivered to the experiment in **Run 3**. The **opto-electronics chain** has been completely **changed** by employing approximately 3100 Multianode Photomultiplier Tubes and brand-new, custom developed, frontend electronics.

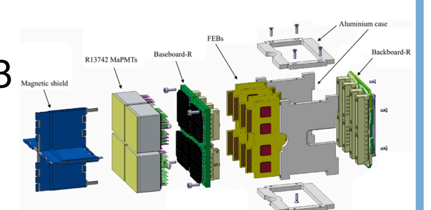
The **stability and uniformity** achieved by optimising the parameters of the **opto-electronics chain** enable the RICH system to function successfully, and provide an **excellent charged hadron identification at instantaneous luminosity equal to $2{\cdot}10^{33}$cm^{-2}s^{-1}**.

The LHCb RICH subsystem



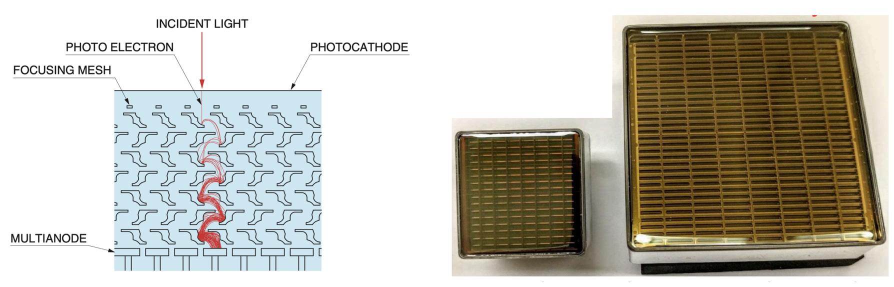
Photon-Detection chain

- **MaPMT** : Hamamatsu R13742 (1 inch) MaPMTs for RICH1 and high occupancy region of RICH2, R13743 (2 inch) MaPMTs for low occupancy region of RICH2
- **CLARO chip:** 8-channel amplifier/discriminator ASIC, adjustable threshold and attenuation for each channel, radiation-hard by design



MaPMTs as RICH Upgrade photo-sensors

Multianode Photomultiplier Tubes (**MaPMTs**) were identified as **optimal candidate** for the **LHCb RICH photo-sensors**, since they fulfill all the desired requirements:



size [mm^2]	26.2 × 26.2	52 × 52
pixel size [mm^2]	2.88 × 2.88	6 × 6
number of devices	2656	384
active area	77%	87%
average gain @ 1 kV	> 1 Me	
gain uniformity	1:4	1:3
peak/valley (P/V) ratio @ 1 kV	no more than 3 pixels with P/V< 1.3	
dark-count rate @ 1 kV	< 2.5 kHz/cm^2	
quantum efficiency	> 30% @ 300 nm	

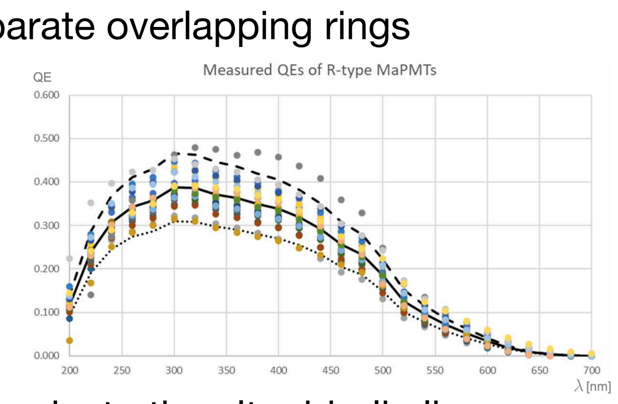
- **single-photon detection at the 40 MHz** LHC bunch crossing rate

  ✓ Achieved with CLARO asic [1]

- **detection rates of O(100 MHz/cm^2) in the high occupancy region**

  ✓ Excellent active area of the order of 80% and spatial granularity, O(10 mm^2)
  Minimise inefficiencies and the pixel size error to separate overlapping rings

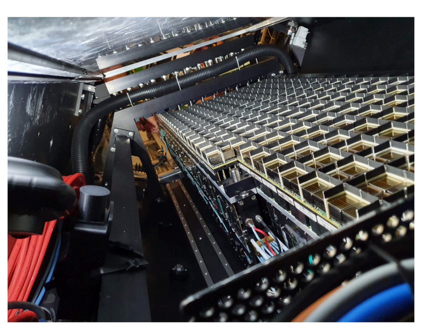
- **appropriate gain and quantum efficiency**
  → to maximise the photon yield per track and keep the chromatic uncertainty under control



  ✓ Gain higher than 10^6 e$^-$ → **Gain equalisation**
  Quantum efficiency of the order of 40% at 300 nm thanks to the ultra bi-alkali photocathodes

- **low dark count rate (O(kHz/cm^2))** and unexpected observation of SIN under control
  → **Observation of Signal Induced Noise**

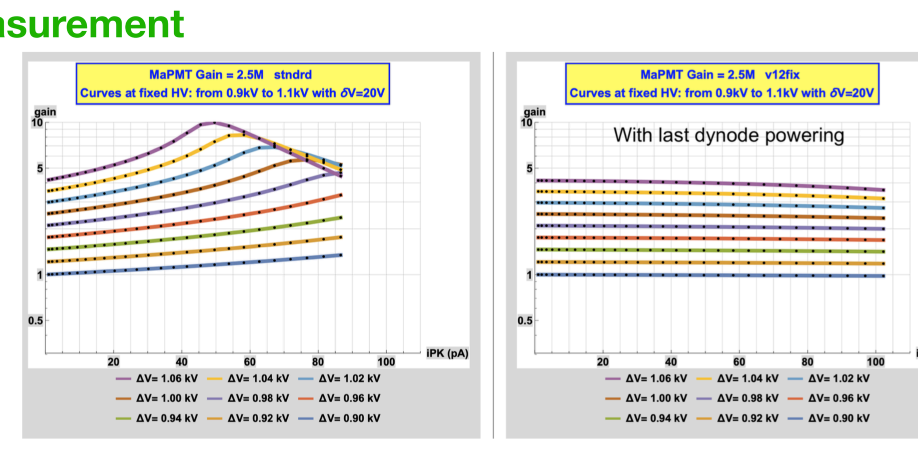
RICH1 down photon detector panel:



RICH2 left photon detector panel:

If the **anode current gets close to the maximum rate** of 100 μA, a **gain non linearity is observed.**

→ MaPMTs are operated **powering the last dynode** to keep **constant the gain and to have a direct control on the average anode current** by measuring the power supply currents
→ **Luminosity measurement**



Conclusions

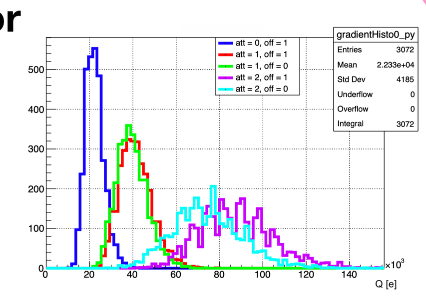
The **LHCb RICH detector's upgrade** effectively **addresses the challenges posed by a five-fold increase in instantaneous luminosity**, ensuring **robust performance** at the full bunch crossing rate of 40 MHz.

- **Enhanced Photon Detection** thanks to the usage of MaPMTs and new front-end electronics
- **Noise Characterisation and Mitigation** due to the detailed characterisation of the photon detection system
- **Innovative Luminosity Evaluation** by estimating anodic currents and correlating them with Cherenkov hits
- **Excellent PID performance** described in Edoardo Franzoso's talk.

Gain equalisation

Threshold scans analysis are a fundamental tool to **optimise the detector performance** since it allows to:

- **fine tune** the **HV**
- check the **ageing** of the sensors



A full gain characterisation implies the acquisition of:

- One **integrated charge spectrum** for **each anode** (threshold scan)
- One **test pulse scan for each anode** , to correlate threshold and charge

x4 **CLARO asic** has **two possible configuration parameters**:

- **Attenuation** (amount of charge for each threshold step)
- **Offset** (shift of CLARO, the front end ASIC, baseline)

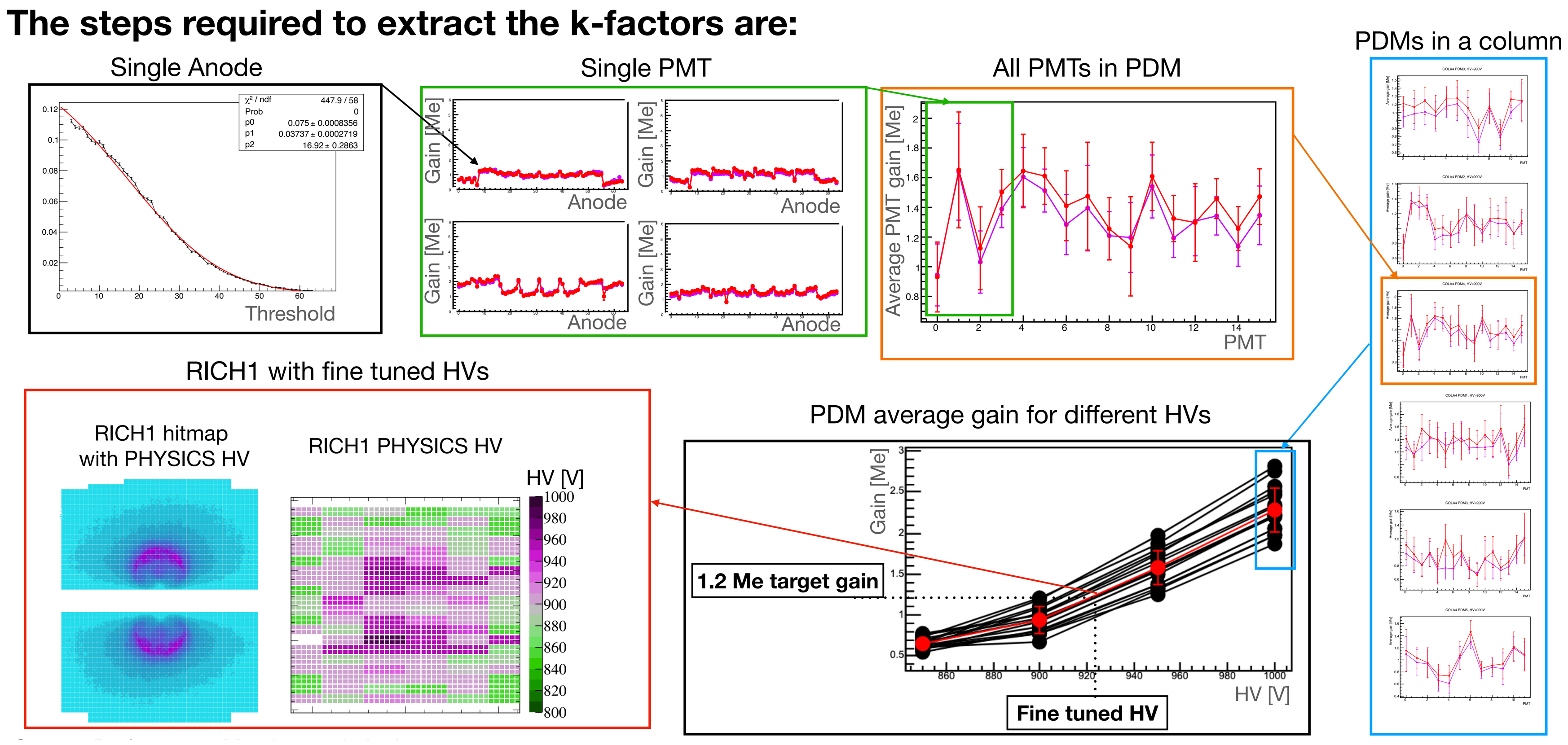
RICH2 (24 columns) 3072 anodes each column x4 configs

RICH1 (22 columns) 5632 anodes each column x4 configs

In order to **fine tune the High Voltage** (HV), it is necessary to **study the gain variations as a function of the applied HV**, namely the study of the **k-factors**.

The relevant quantity to extract is the **average gain of all the PMTs in a Photo Detection Module (PDM)**, since the **HV** can only be **tuned at such level.**

The steps required to extract the k-factors are:

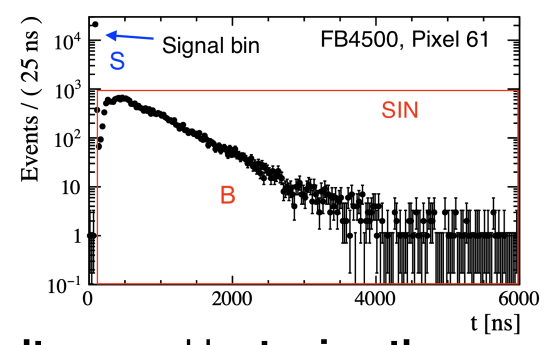


Once chosen as **uniform goal gain 1.2 Me**, it was possible to **estimate the fine tuned HVs of both RICH1 and RICH2.**

Observation of Signal Induced Noise

Out-of-time hits were detected with data acquired in an LHC collision scheme with isolated bunches and with a 3 μs-wide acquisition window: **Signal Induced Noise** [2]

- unexpected source of noise
- characterised by the mean number of SIN pulses μ_{sin}= B/S



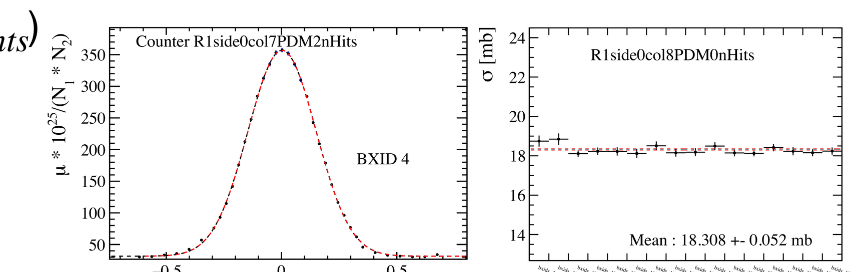
SIN can be mitigated properly by **adjusting the High Voltage** and by **tuning the acquisition time window**.

Luminosity measurement

The **RICH system** is able to provide a **standalone luminosity measurement** for the LHCb experiment.

The luminosity can be expressed as: $L = \frac{\mu_{vis}}{\sigma_{vis}} \times n_{bb} \times \nu_{LHC}$

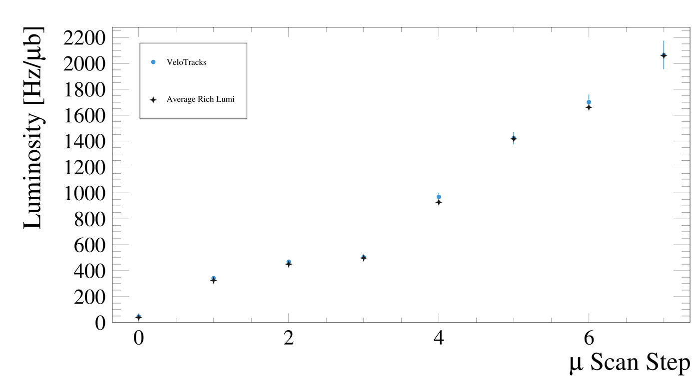
- μ_{vis} is the number of **visible interactions per bunch crossing**. Such quantity follows the Poisson distribution, hence is computed as -log(N$_{empty}$/N$_{events}$)
- σ_{vis} is the **visible cross section at the PDM level**.
- n_{bb} is the number of bunch crossing.
- ν_{LHC} is the LHC bunch crossing rate.

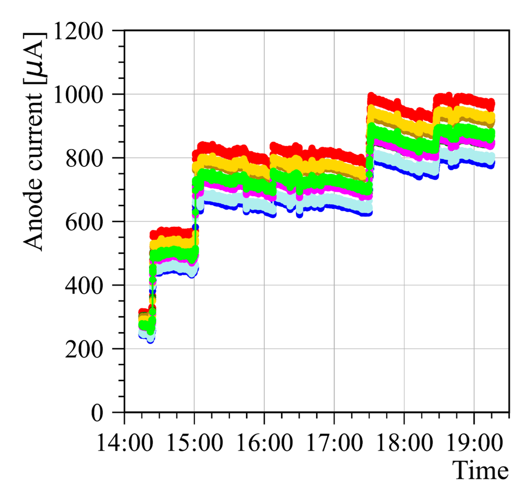


To **perform luminosity calibration**, the **Van der Meer scans are performed**: the two beams separation is varied in x and y direction. In this way it is possible to estimate σ_{vis}.

When the value of μ is changing, it is possible to **extract μ_{vis} at each μ scan step** to provide the **luminosity measurement.**

By averaging all PDMs, the **obtained value** shows **good consistency** with the value obtained from the **number of VErtex LOcator tracks (best lumi counter in Run2)**.





The **RICH MaPMTs anode current** is **sensitive and proportional to the luminosity** as well.

It is possible to **calibrate these variables during a μ scan** by means of the **RICH hits luminosity counter** at the PDM level.

Summarising, **luminosity measurements** can be **provided in two ways** by the RICH sub-detector:

- **Number of hits measurement**: reconstructed variable which allow a more precise offline analysis.
- **Anode currents measurement**: useful tool for luminosity online monitoring with good enough precision.

References:
[1] M. Baszczyk *et al* 2017 *JINST* **12** P08019, "CLARO: an ASIC for high rate single photon counting with multi-anode photomultipliers"
[2] M. Andreotti *et al* 2021 *JINST* **16** P11030, "Characterisation of signal-induced noise in Hamamatsu R11265 Multianode Photomultiplier Tubes"