LHCb RICH Upgrade II

XI International Workshop on Ring Imaging Cherenkov Detectors,
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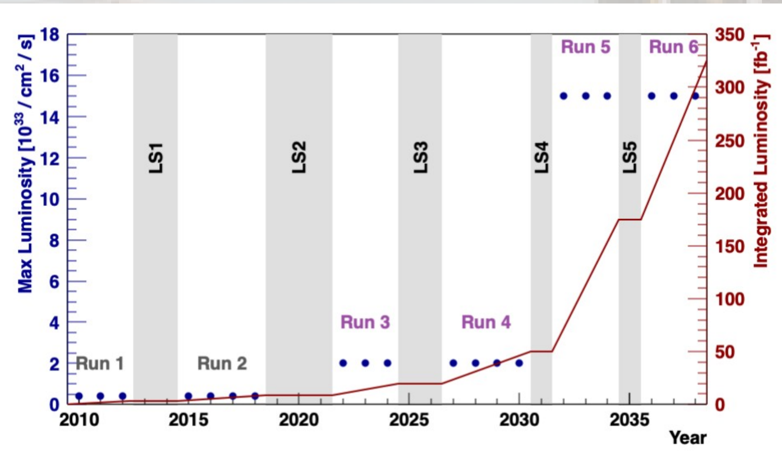
on behalf of the LHCb RICH collaboration

LHCb & the High Luminosity LHC

From around 2035 the LHCb physics program will benefit from a factor 7.5 increased luminosity compared to Run 4. The full Upgrade program is described in the recently published FTDR.

The RICH detectors will remain a vital element of LHCb and will be essential to exploit new physics opportunities in this new high luminosity era (Run 5 & Run 6).



Luminosity: $1.5 \times 10^{34}\,cm^{-2}\,s^{-1}$
RICH1 n-equivalent dose: $\sim 10^{13}\,cm^{-2}$ (1 MeV equivalent)
Total Ionising Dose: $\sim$5 kGy for 350 fb^{-1}

https://cdsweb.cern.ch/record/2776420/

Overview

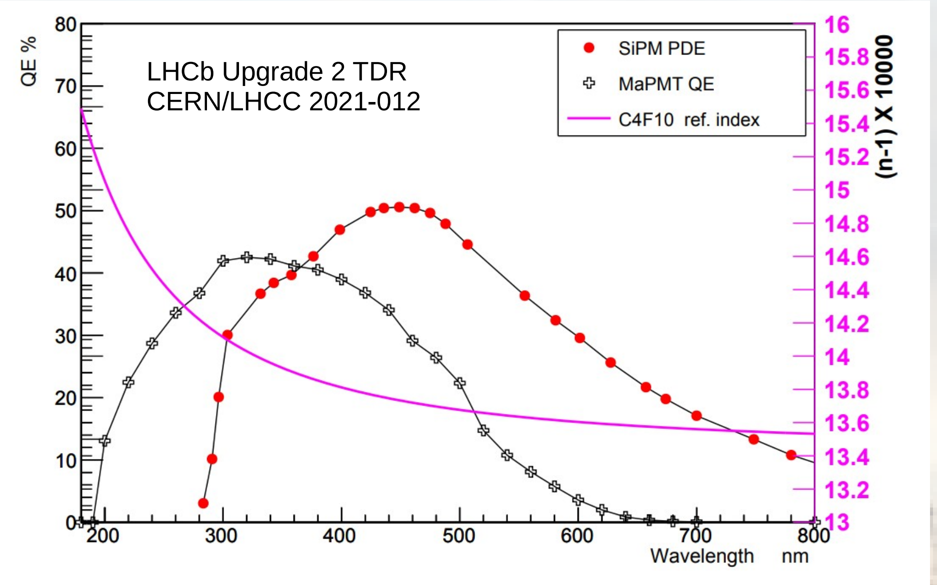
In this presentation I select a few of the challenges that we face and a few early ideas on how to approach them including

- Improvements to the photon detection angular resolution
- The motivation for the addition of time-resolved readout
- A brief review of photon sensor technologies
- Some comments on the front-end electronics and data acquisition

Photon Detection Angular Resolution
Chromatic Error, Emission Point Error & Pixel Error

Chromatic Error

The wavelength dependence of the refractive index gives rise to a chromatic error that can be a significant contribution to the overall error.



This chromatic error is driven by the convolution of:

- Cherenkov photon spectrum;
- spectral sensitivity of the sensor;
- absorption coefficients;
- reflectivity.

There is a clear benefit to operating at longer wavelength where the photon spectrum is flatter.

	Current	Future
RICH1 [mrad]	0.52	0.11
RICH2 [mrad]	0.34	0.10

For example, by using SiPMs as the photon sensor and with optimisation of the optical layout, we estimate a contribution of about 0.1 mrad.

Emission Point Error

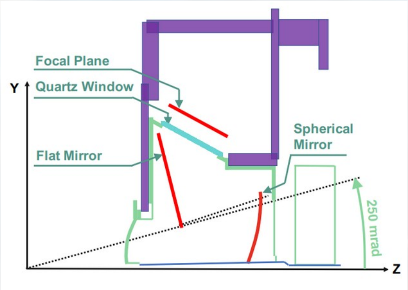
In LHCb, the spherical mirror is tilted to allow the sensor region to be kept outside the detector acceptance.

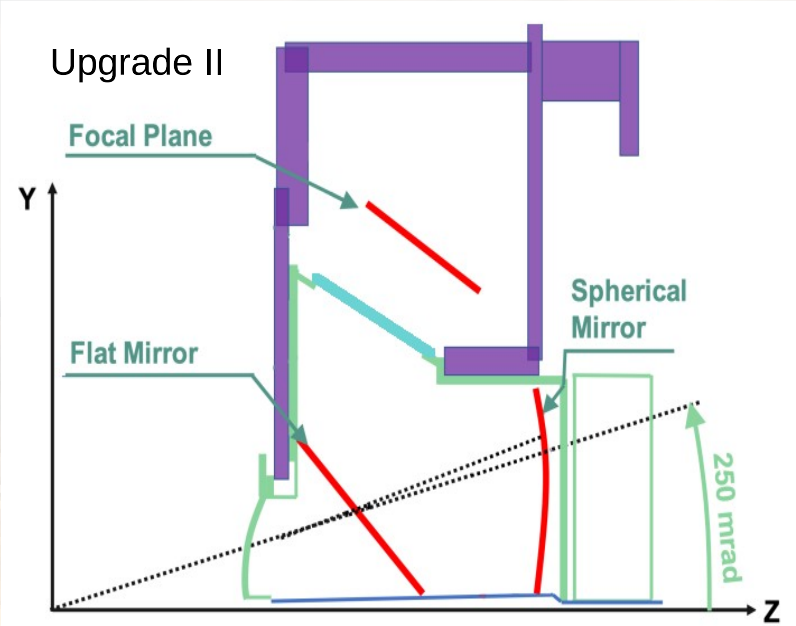
This introduces an error that arises from optical aberrations that make the detected photon position depend on its emission point within the radiator volume.

Closer to ideal geometry can be achieved with smaller mirror tilt:

- Flat mirrors move inside the acceptance
- Must be made of light materials

By making this change we estimate that the emission point error can be reduced to 0.12mrad





https://doi.org/10.17863/CAM.78867

	Current	Future
RICH1 [mrad]	0.36	0.12
RICH2 [mrad]	0.32	0.05

Pixel error

In 1971, Leon Harmon and others tried to figure out how much information can be removed while still being able to recognise an image (motivated by reducing data transmission costs).

In LHCb, the pixel size is also a strong driver of read-out and other costs.

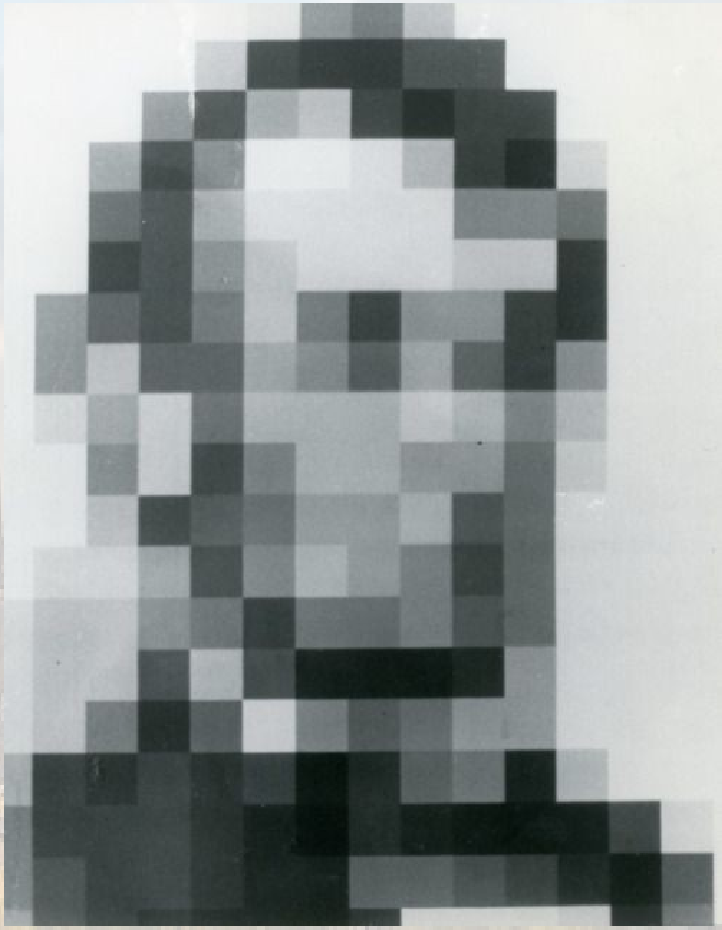
Choose the largest pixel size that does nott dominate the total angular error while maintaining sufficiently low occupancy.

Given the improvements in chromatic and emission point error, pixels around 1mm may be needed.

The high channel density creates engineering challenges:

- Power;
- Cooling;
- Cable density.

Can reduce costs by using larger pixels some regions.



Leon Harmon, Bell Labs, 1971

	Current	Future
RICH 1 [mrad]	0.50	0.15
RICH 2 [mrad]	0.22	0.07

Summary of contributions to angular resolution

Configuration	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

Significant improvements are possible with respect to the current LHCb RICH configuration.

The table compares expectations for the current MaPMT RICH with a possible future design using SiPMs

Realising these improvements also requires corresponding improvements in tracking performance.

Time-resolved read-out

Why time-resolved readout helps

Individual interactions within the same LHC bunch crossing can be resolved spatially by association with primary vertex.

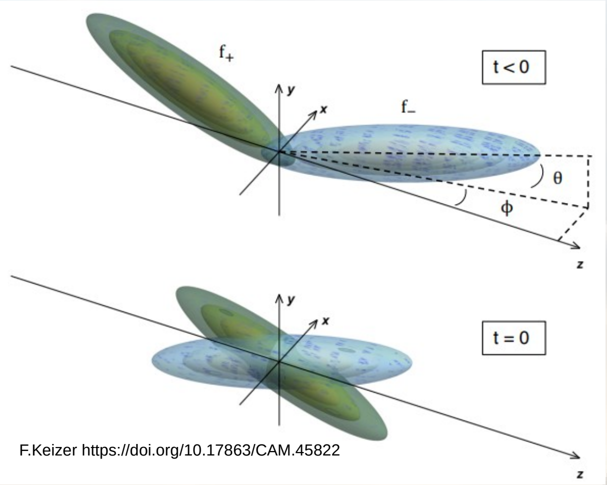
This becomes increasingly difficult as the number of interactions per bunch increases.

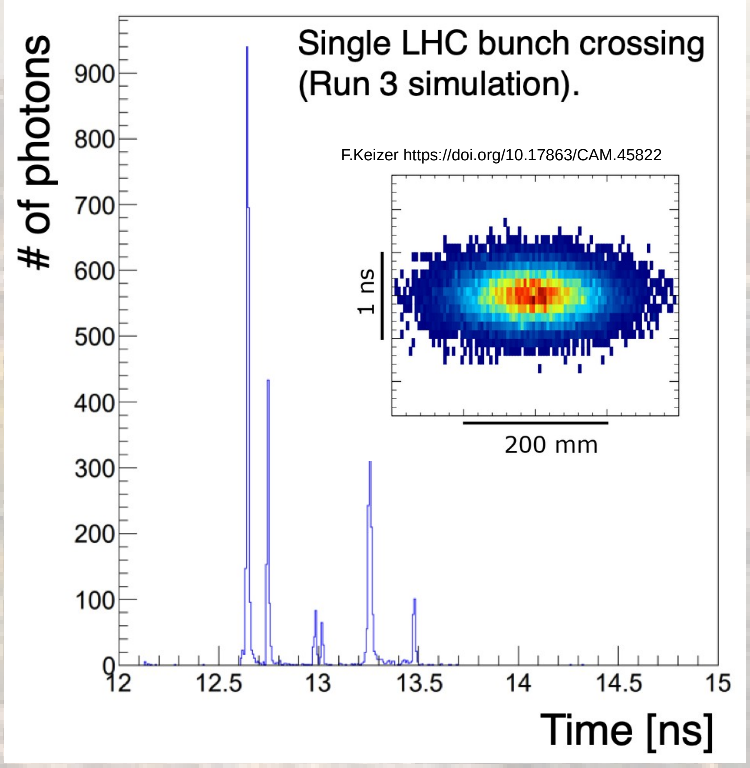
But collisions within the same bunch are distributed in both space and time:

$\sigma_t = 200$ ps

$\sigma_z = 60$ mm

Use the additional time coordinate to separate interactions.





The impact on PID performance

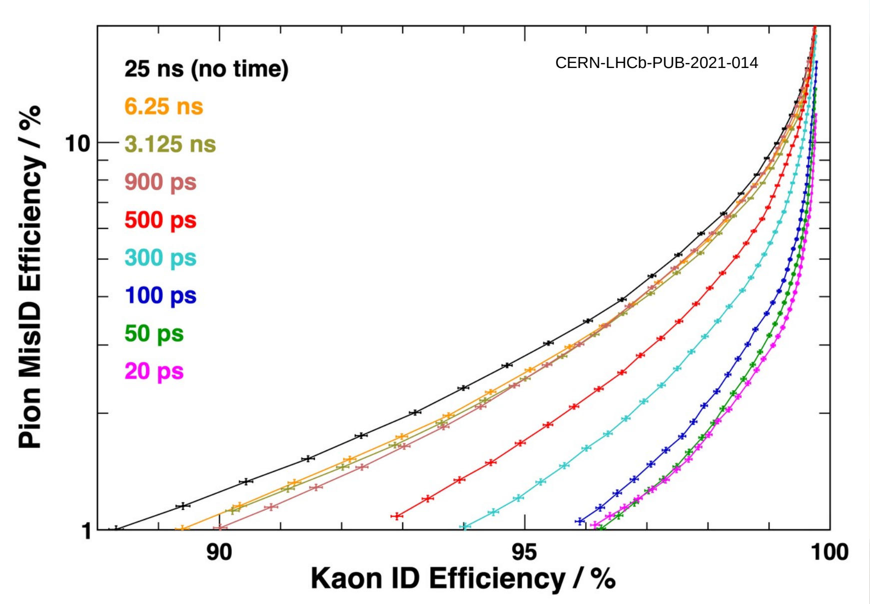
The better the photon time resolution the better the PID performance.

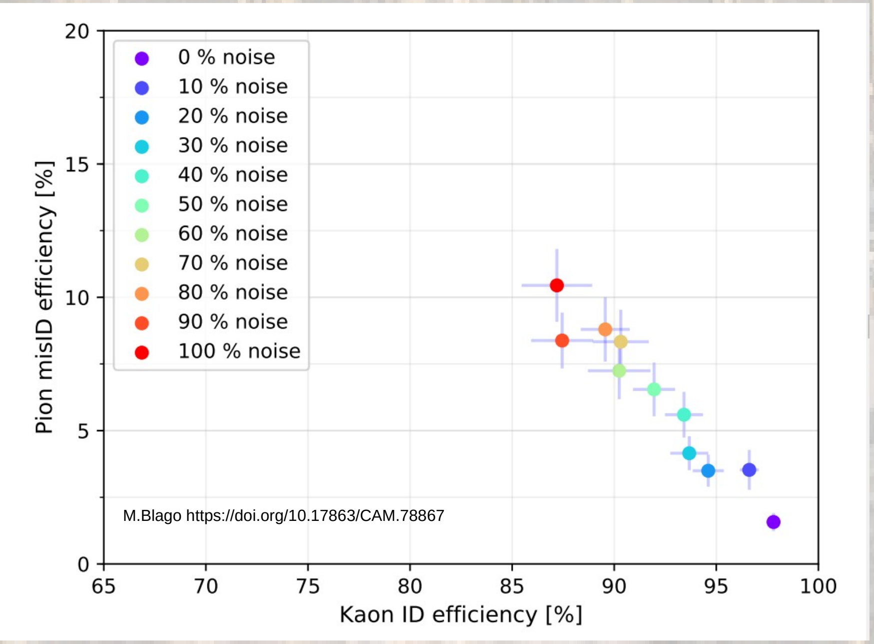
The curves in upper plot are a standard metric that we use in LHCb to characterise PID performance.

- Best performance is furthest to the right and bottom.
- i.e. High Kaon efficiency with low Pion misidentification probability

Effect seen in both conventional (global maximum likelihood) reconstruction and when using CNNs (lower plot).

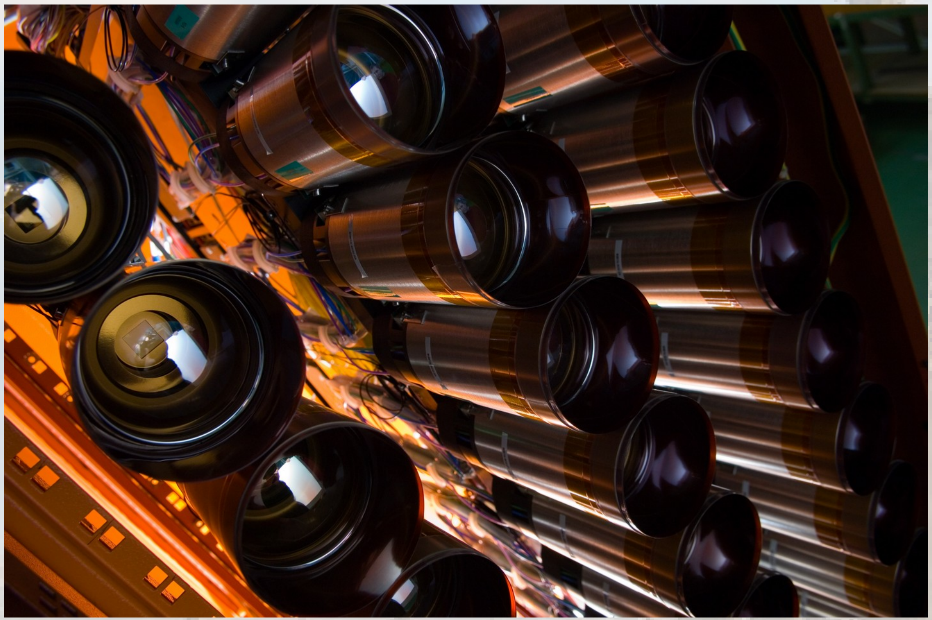
The benefit arises because better timing allows tighter cuts to remove out-of-time photons.





Photon Sensors

HPD, MaPMT



LHCb HPD columns. Photo credit: STFC

Excellent performance during LHCb Run 1 & Run 2

Retired after upgrade to readout architecture for Run 3 (incompatibility of encapsulated readout ASIC).

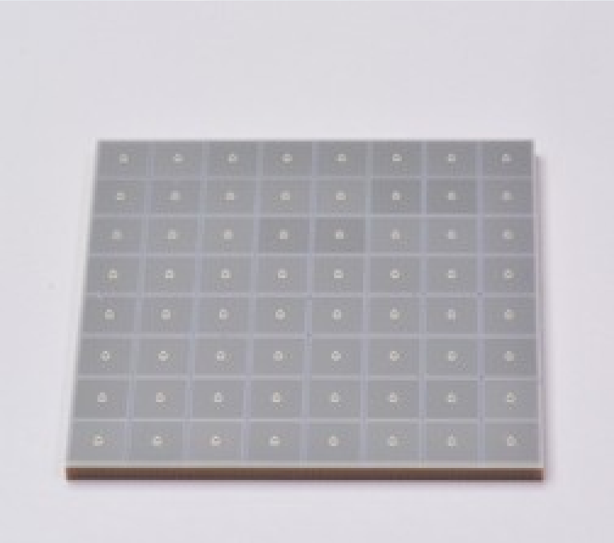
Now installed for Run 3 & Run 4

Dificult to achieve pixel size below 2.8mm

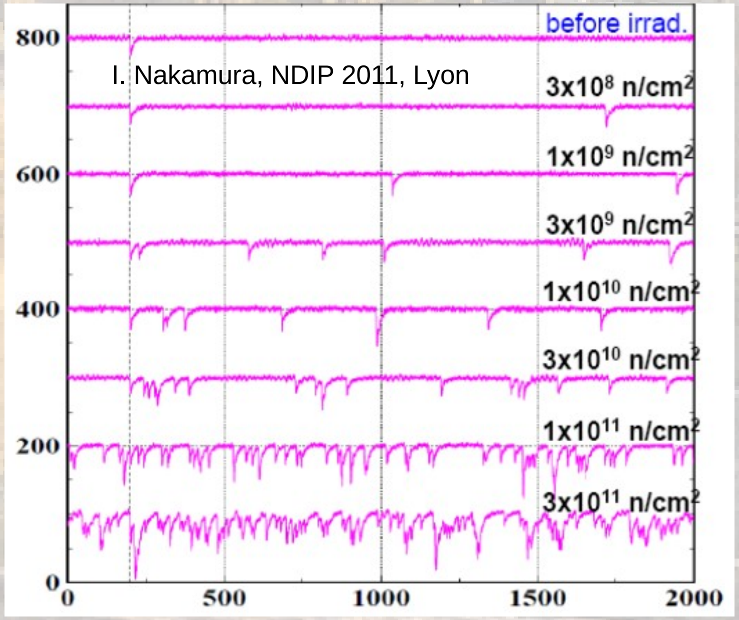
Transit time spread makes them unsuitable for precision photon timing.

SiPM/MPCC

- Solid state
  - Low cost
  - Low dead space
  - Industrial semiconductor process
  - 2D arrays
  - Robust
- Various pixel sizes down to 1 mm
- Low operating voltage
- Insensitive to magnetic fields
- Photon response
  - Photon counting capability
  - High gain
  - High QE in green
  - Fast intrinsic time response
- High Dark Count Rate
  - Increases with irradiation
  - Decreases with temperature
  - Annealing helps
  - Can be periodically replaced

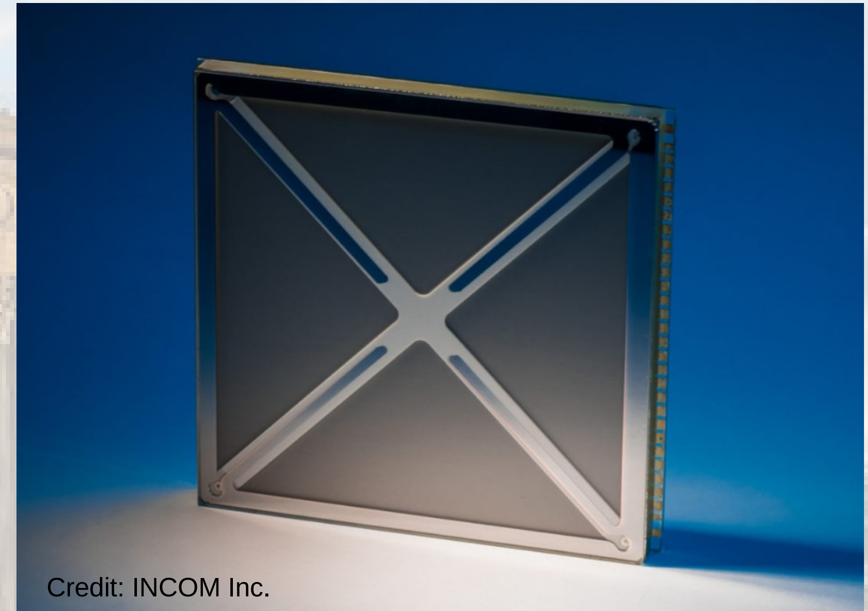


Hamamatsu S14161-3050HS-08

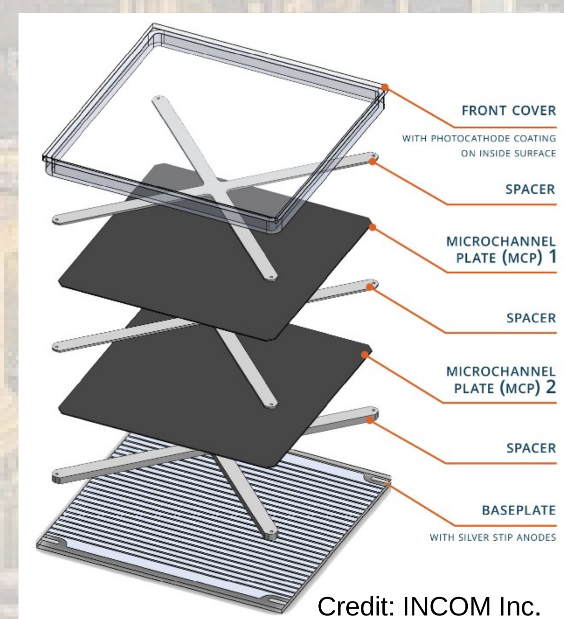


MCP & Large Area Picosecond Photodetector

- Vacuum technology
- High operating voltage
- Very large area (LAPPD 20 cm)
- Multi-channel plates for high gain
- Moderate QE
- Low dark count rate
- Fast time response
- Anode
  - Strips or ...
  - ... highly-customisable capacitatively coupled array
  - Readout electronics integration challenging
- Low volume production
- Shadowing from spacers
- MCP ageing
- [F. Oliva]



Credit: INCOM Inc.



Credit: INCOM Inc.

Summary of Sensor Attributes

	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}

There is not yet a candidate sensor that is proven to meet all LHCb Upgrade 2 requirements but there are candidates that come very close.

Further R&D is needed.

Front-end Electronics & Data Acquisition

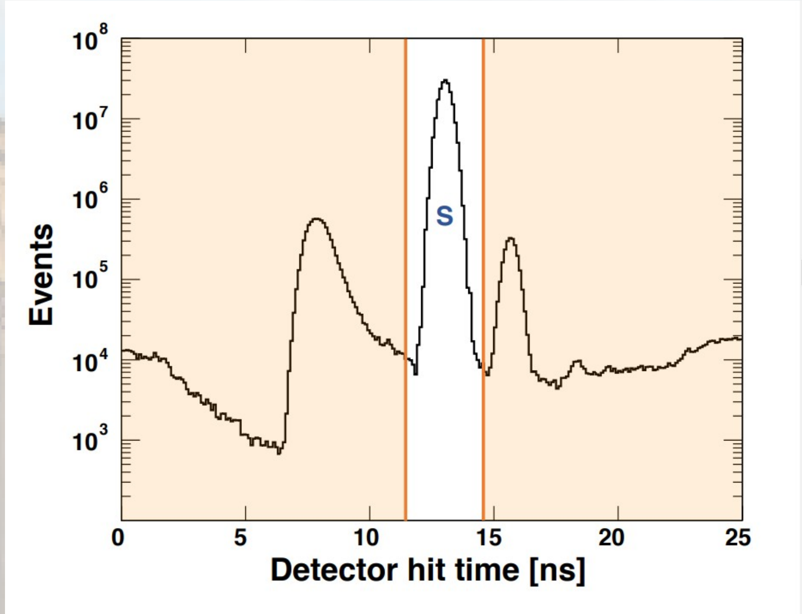
Front-end Electronics

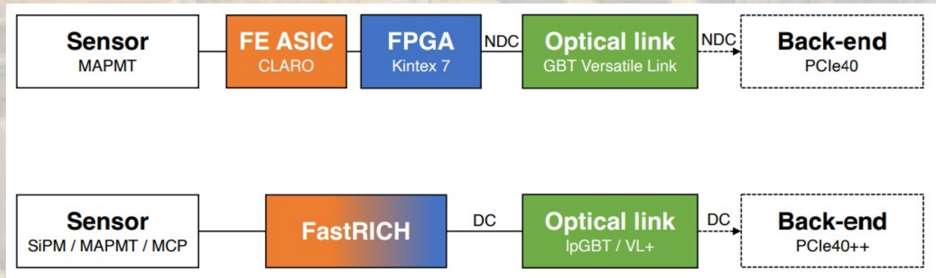
Time-resolved readout imposes stringent requirements on the front-end electronics.

- ~3 ns configurable time gating for suppression of out-of time hits.
- Better than 100 ps time-stamping and time-over-threshold measurement per photon (TDC) ...
- ... or constant-fraction discrimination to avoid need for ToT ...
- ... and/or multi-level discrimination.
- Radiation tolerant.
- Configurable data transmission architecture for different bandwidths (cost optimisation).
- High density, low power (few mW per channel), compatible with cryogenic operation.

Proposal to implement new front-end already during LS3 [F. Keizer].

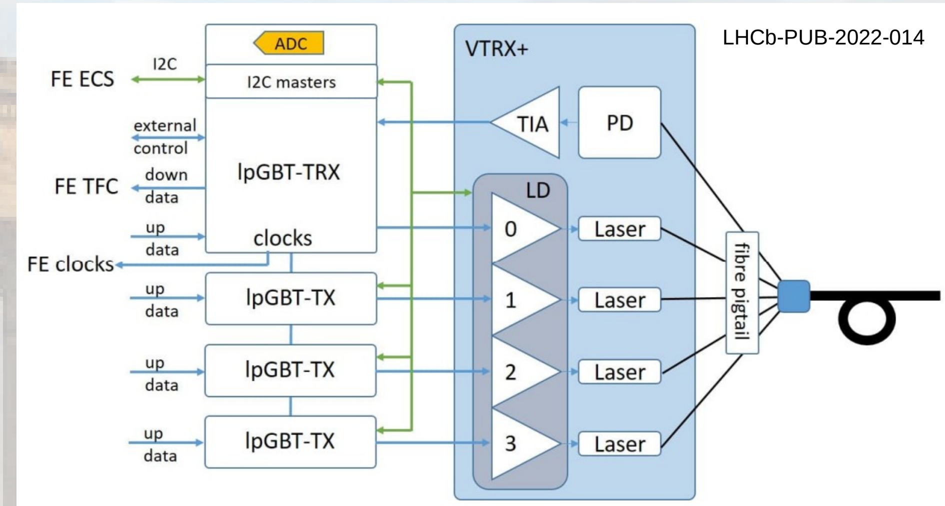
- FastRICH ASIC under development [R.Ballabriga Sune]
- Active program of R&D including recent time-resolved readout in beam tests with 150 ps TDC bins [L. Cojocariu]

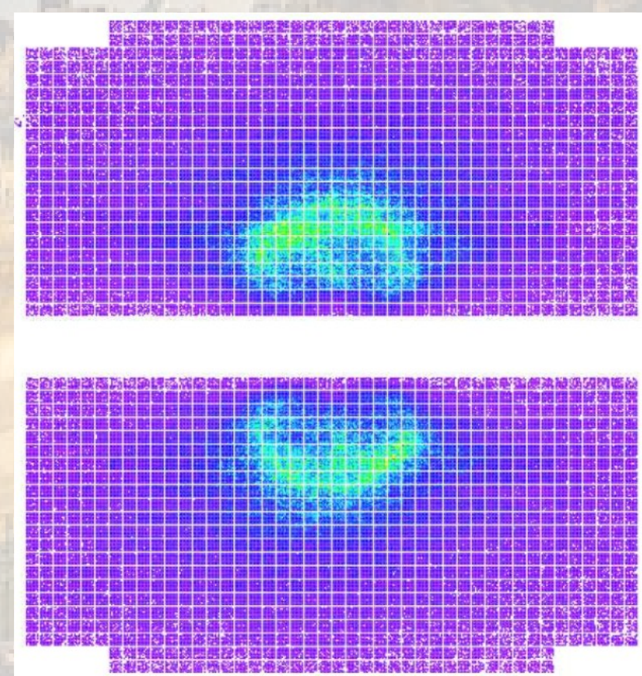




Data Acquisition

- Very high data rate of 30 Tb s^{-1} and very non-uniform across detector.
- Challenging to satisfy bandwidth requirements everywhere without incurring cost penalty.
- Zero-suppression at front-end
- Data transmission based on lpGBT & VTRX+ or their successors
  - Tightly integrated with FE ASIC
  - 10 Gb s^{-1} link speed
  - Asymmetric 4 up, 1 down VTRX+ optical link configuration
  - Transmit >100 m off-detector
- Next generation FPGA back-end readout boards (PCIe40++)
  - Load balancing of input data links
  - Data compression in back-end to match throughput to output bandwidth
  - Adopt commercial solutions





Outlook

The road ahead is challenging but exciting.

Run 4 will be a big step along the way for time-resolved readout.

- ASIC specification/development is well under way (FastRICH, CERN/ICCUB).
- Active test beam and lab program (TDC-in-FPGA, FastIC, sensor studies, aerogel studies).

There is much to do but current technologies are already close to be suitable.

Baseline simulation studies are evolving fast.

More to to explore:

- Cryogenic operation;
- New aerogel [A. Lozar];
- Light collection systems (mirrors, micro-lenses) [R. Cardinale];
- Green gases for radiators & cooling, leak free systems;
- Novel radiators (meta-materials);
- New reconstruction methods (new architectures, faster algorithms, CNNs).

Now is a great time for young researchers to get involved.

Things to do on an excursion in Edinburgh