RICH evolution towards Upgrade Ib and II

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With many thanks to the RICH group,
in particular Steve Wotton, Chris Jones, Carmelo D'Ambrosio and Sajan Easo

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Introduction

The upgrades of the RICH detectors will include improved single photon resolutions and yield, new photon detectors and improved optics. R&D studies towards e.g. new radiators are ongoing.

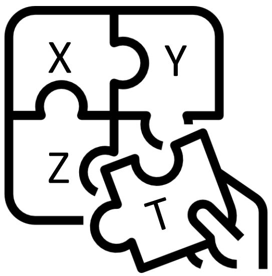
In this presentation, the focus will be on a novel feature of the RICH detectors :

The photodetector hit time

The future RICH detector will be the first ever time-resolved RICH with gas radiators. It is a powerful tool to enhance our particle ID performance.

Outline

- Simulation of the photon hit time and the ultimate time resolution of 10 ps.
- Front-end hardware time gate.
- Proposed scenario for the evolution from Upgrade Ib to Upgrade II.
- Prospect for the particle ID performance.
- Implications for the data bandwidth.



Prediction of the RICH photon detector hit time

The RICH particle ID algorithms in the HLT already reconstruct the track and photon paths through the detector, for example the track entry (A), photon emission (E) and mirror reflection (M1 and M2) points.

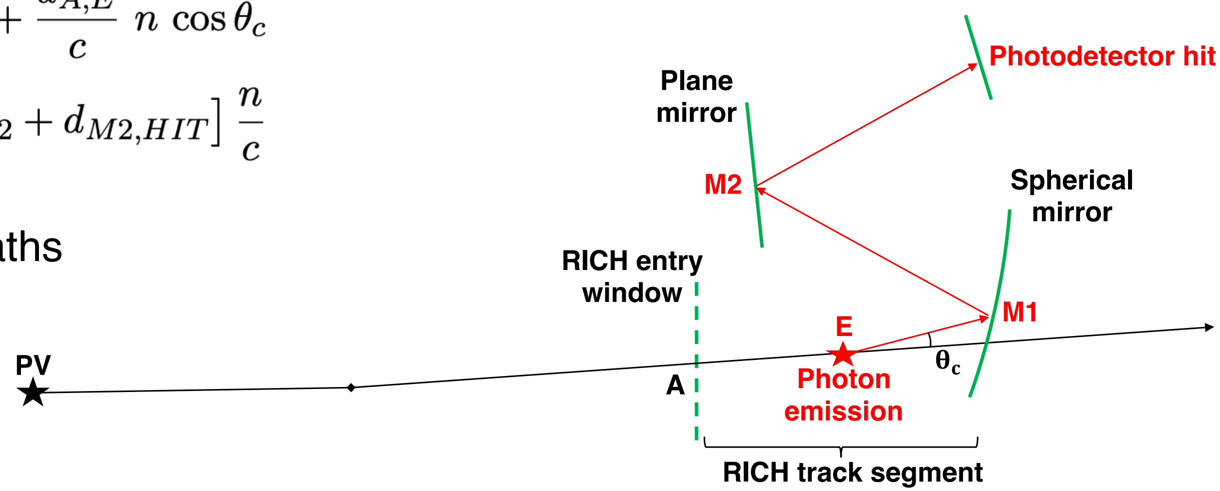
Using these points, together with the Primary Vertex time and z-coordinate, a highly accurate prediction of the photodetector hit time can be made.

Primary Vertex

Track outside and inside the RICH

$$t_{pred} = t_{pv} + \frac{d_{pv,A}}{c}\sqrt{1+\left(\frac{mc}{p}\right)^2} + \frac{d_{A,E}}{c}\, n \cos\theta_c$$
$$+\left[d_{E,M1} + d_{M1,M2} + d_{M2,HIT}\right]\frac{n}{c}$$

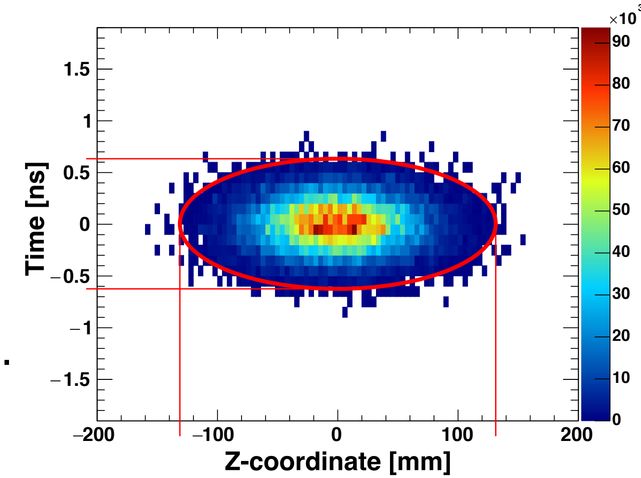
Reconstructed photon paths

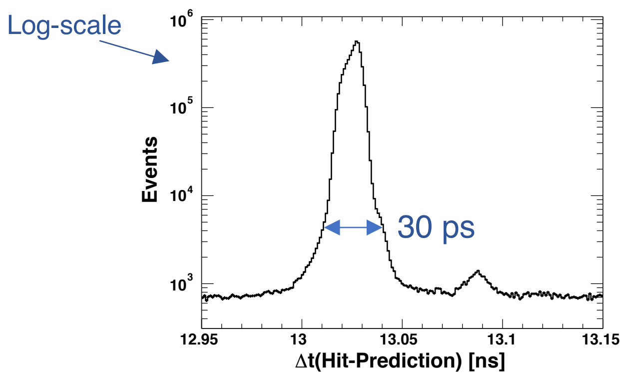


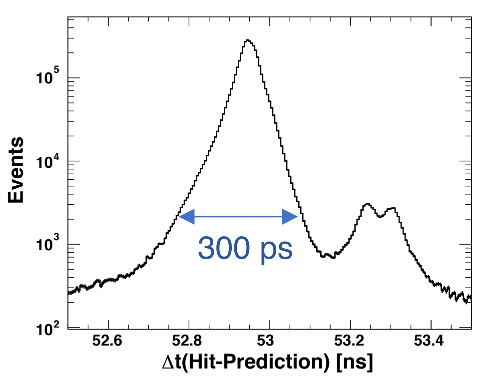
Contributions to the RICH hit time (1/2)

The primary vertex spread : ~ 1 ns.

- Developed a tool to simulate the 4-dimensional PV distribution.
  $\sigma_t = 210$ ps and $\sigma_z = 57$ mm.
- ***Subtracted*** using a timestamp from tracking or RICH reconstruction.



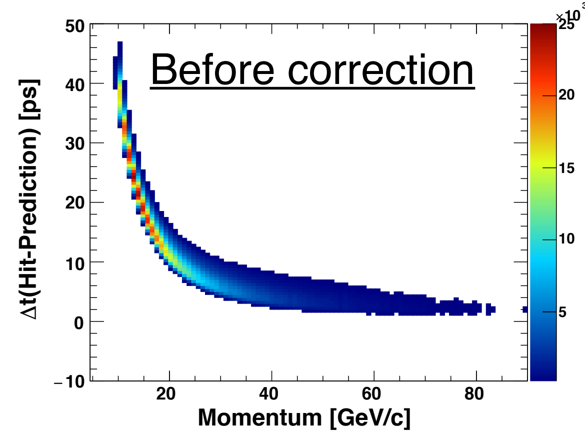




Photon path length variations :
~ 30 ps (*full range* for RICH 1) and ~ 300 ps (*full range* for RICH 2).

- Observed by plotting: $\Delta t = t_{hit} - t_{pv} + \frac{z_{pv}}{c}$
- More spread in the physically larger RICH 2 detector.
- Simulation is based on the Run 3 geometry.
  The spread is expected to be smaller for Upgrade II.
- ***Subtracted*** using RICH reconstructed mirror reflection points.

Contributions to the RICH hit time (2/2)

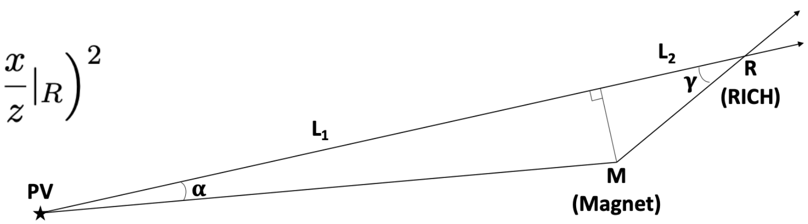


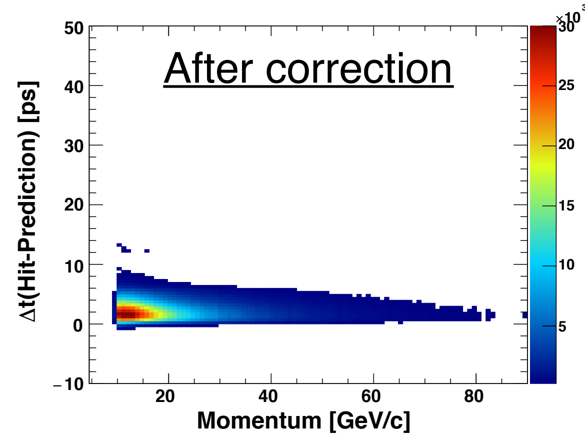
Curvature of low momentum tracks reaching RICH 2 : ~ 50 ps (*full range*).

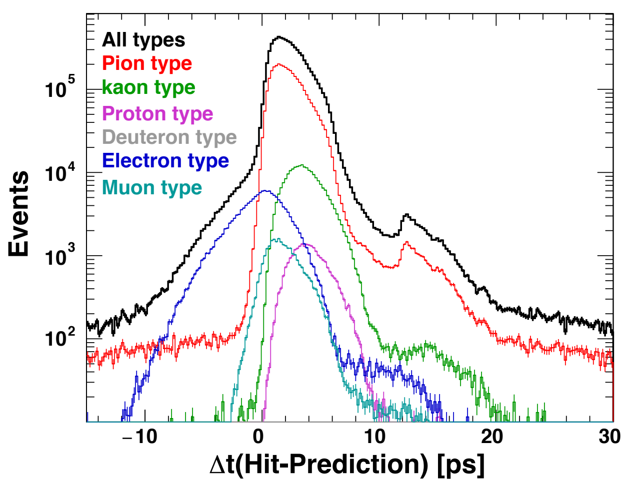
- Low momentum tracks bend in the LHCb magnet and deviate from the assumed straight trajectory to the RICH entry point.

- ***Corrected*** using the tracking information and a geometric argument to scale the path length of the particle to the RICH 2 detector.

$$\therefore \frac{L'}{L} = 1 + \frac{s}{2}\left(\frac{z_R}{z_M} - 1\right)\left(\frac{dx}{dz}|_R - \frac{x}{z}|_R\right)^2$$







The particle mass : negligible (< 10 ps for electrons).

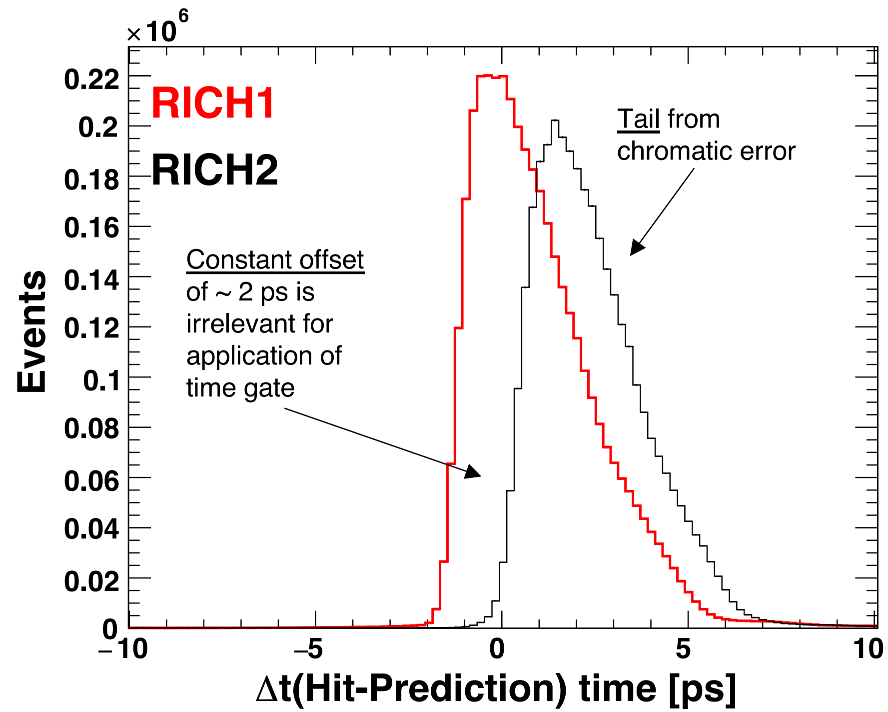
- The relatively high momentum range of the RICH detectors means that a TOF measurement cannot be performed.

- Time should therefore not enter in the particle ID algorithms, but instead be used for photon-to-track association.

The RICH intrinsic resolution

Taking all contributions into account : **resolution < 10 ps.**

- All contributions in the previous slides are successfully removed in reconstruction.
- Dominated by tail from chromatic error, which is expected to get even smaller in the future.
- Faster photon detectors are better.
  Time resolution of the photon detector or readout electronics is not taken into account in this plot.



The high potential of RICH time information can be gradually 'unlocked' as more information about the event becomes available from the detector front-end to the High-Level Trigger.

- Nanosecond scale at the front-end readout.
- Picosecond scale at the event reconstruction algorithms.

Front-end hardware time gate: the first step!

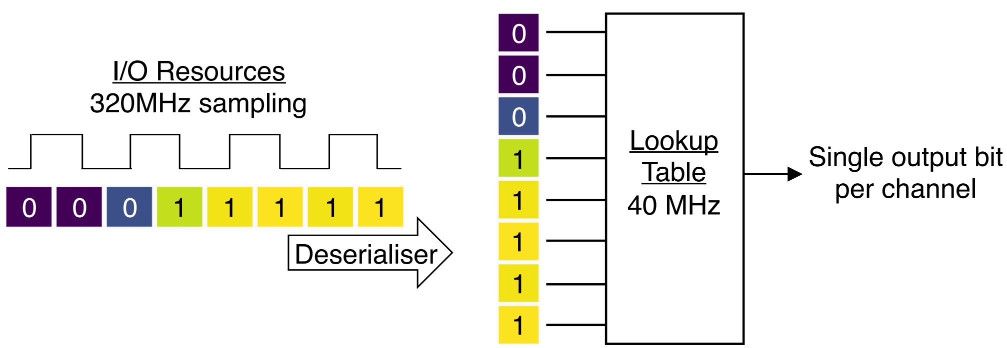
Time information is already used in the Run 3 detector to improve the particle ID performance.

The signal arrives at a fixed time w.r.t. the LHC clock.

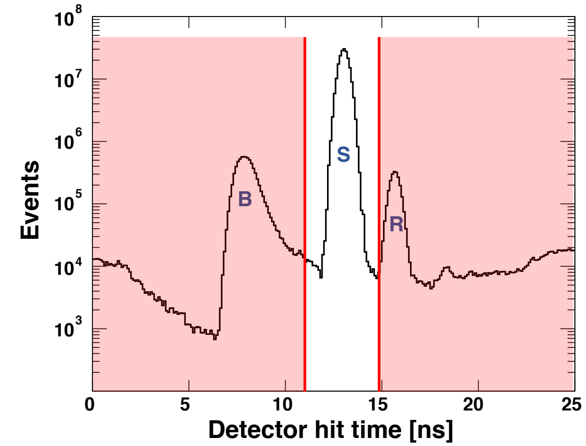
- Width of the peak ~ 1 to 2 ns.
- Time gate reduces background photons due to reflections, scintillation, scattering etc.
- Time gate reduces sensor noise (not shown but important effect).

The programmable FPGA logic in the digital readout board samples the incoming signal at 320 Mbit/s using the I/O deserialisers.

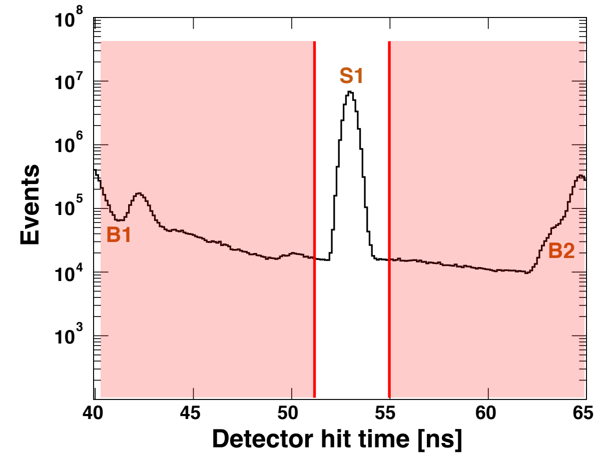
- Byte from the deserialiser addresses a lookup table.
- The FPGA is programmed to write a hit for a specific input pattern.
- The minimum gate is 3.125 ns.



RICH 1 photon hit time distribution



RICH 2 photon hit time distribution



Front-end hardware time gate

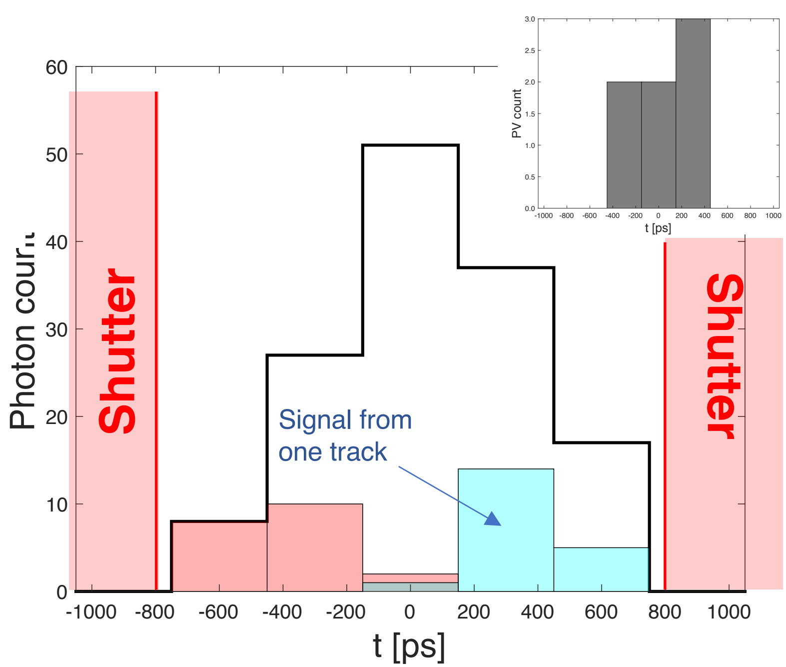
The Run 3 time gate is close to the fundamental limit of ~ 1 to 2 ns at the front-end.

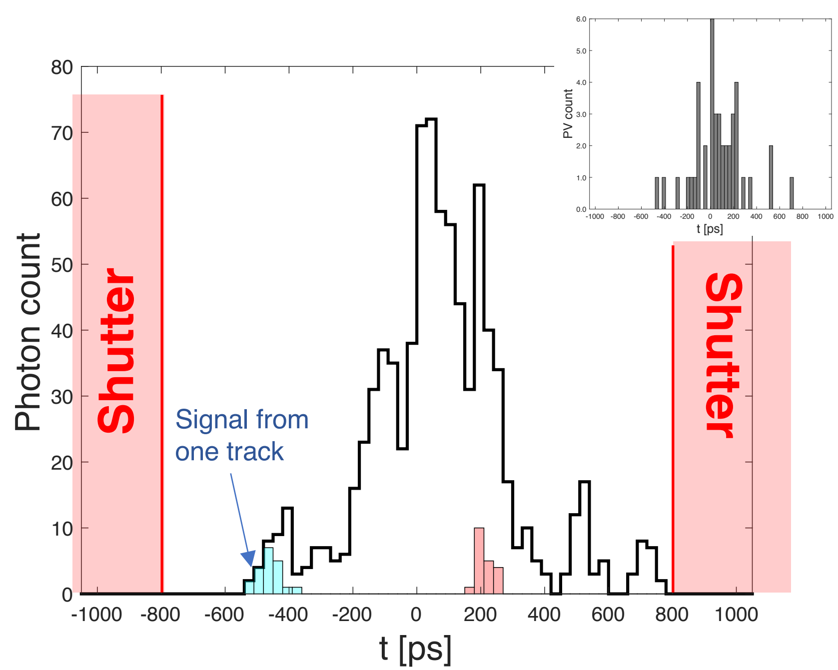
- This limit is dominated by the PV spread.
- The signal is spread over this range and we must keep our shutter open to read all of it. Also in Upgrade Ib and Upgrade II (as shown below).
- Fine-tuning will happen as the electronics time resolution improves.

There is of course much more to gain using time in the reconstruction software.

Upgrade Ib

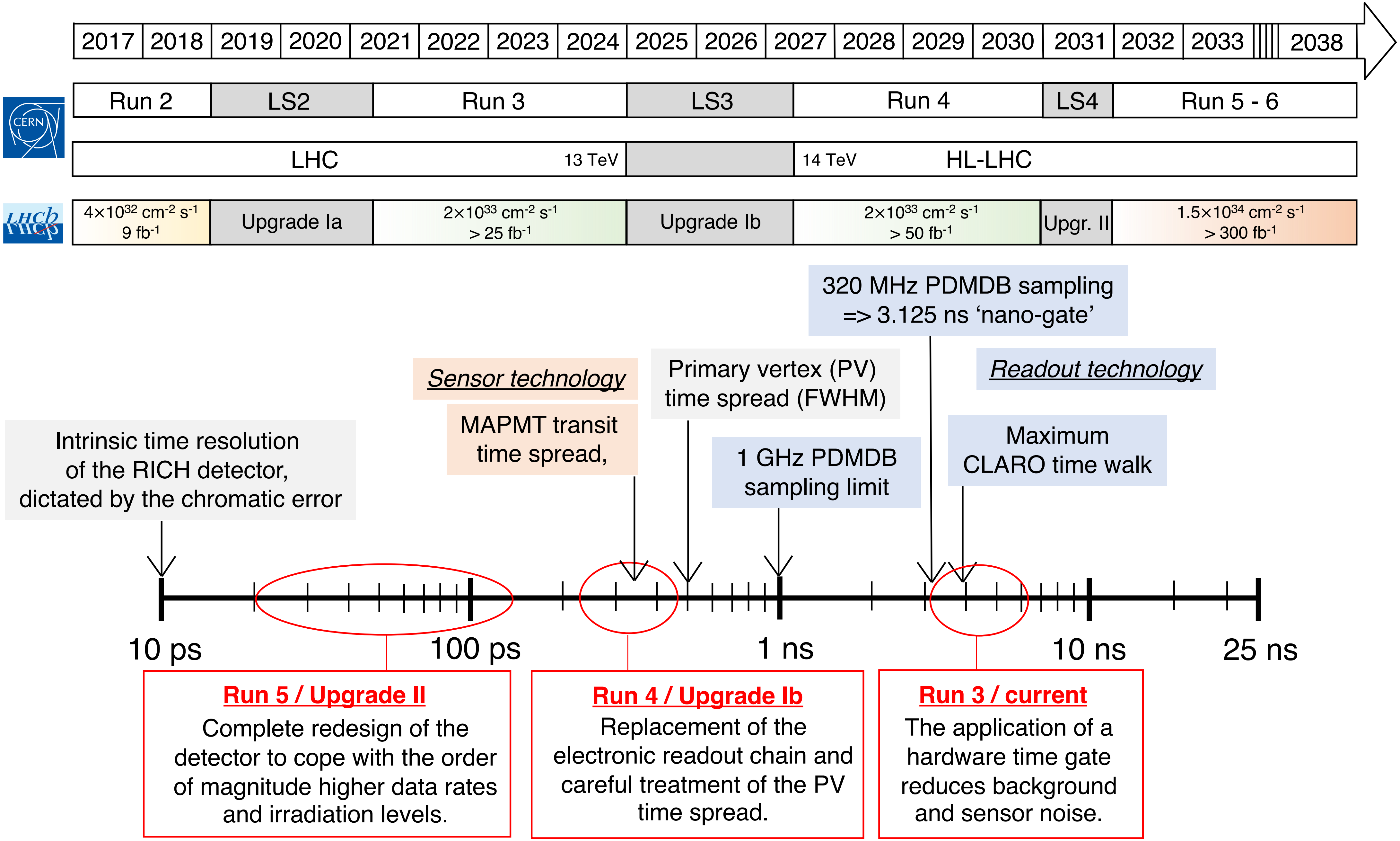
$\sigma_{\text{sensor}} = 150$ ps,
$\Delta t_{\text{bin}} = 300$ ps,
$N_{\text{pv}} = 7$





Upgrade II

$\sigma_{\text{sensor}} = 150$ ps,
$\Delta t_{\text{bin}} = 30$ ps,
$N_{\text{pv}} = 42$



2017 2018 2019 2020 2021 2022 2023 2024 2025 2026 2027 2028 2029 2030 2031 2032 2033 2038
Run 2
LS2
Run 3
LS3
Run 4
LS4
Run 5 - 6
LHC
13 TeV
14 TeV
HL-LHC
4×10^{32} cm^{-2} s^{-1} 9 fb^{-1}
Upgrade Ia
2×10^{33} cm^{-2} s^{-1} > 25 fb^{-1}
Upgrade Ib
2×10^{33} cm^{-2} s^{-1} > 50 fb^{-1}
Upgr. II
1.5×10^{34} cm^{-2} s^{-1} > 300 fb^{-1}
320 MHz PDMDB sampling => 3.125 ns 'nano-gate'
Sensor technology
Primary vertex (PV) time spread (FWHM)
Readout technology
MAPMT transit time spread,
1 GHz PDMDB sampling limit
Maximum CLARO time walk
Intrinsic time resolution of the RICH detector, dictated by the chromatic error
10 ps
100 ps
1 ns
10 ns
25 ns
Run 5 / Upgrade II
Complete redesign of the detector to cope with the order of magnitude higher data rates and irradiation levels.
Run 4 / Upgrade Ib
Replacement of the electronic readout chain and careful treatment of the PV time spread.
Run 3 / current
The application of a hardware time gate reduces background and sensor noise.

Scenarios for upgrades of the RICHes

The role of time information can gradually evolve within the LHCb upgrade programme.

- Consolidate the current detector with sub-ns electronics in Upgrade Ib.
- An important transition towards the HL-LHC Run 5.

	Sensor σ resolution [ps]	Electronic readout [ps]	Track t_0	FE gate [ns]	Software gate [ps]	Bandwidth	Particle ID
Run 3	150	3125	No	3 to 6	N/A	No zero-suppression	+
Upgrade Ib	150	200-300 *	RICH rec	1.5	~ 900	Zero-suppression => Similar but non-uniform	++
Upgrade Ib	150	30	RICH rec	1.5	~ 900 #	–	++
Upgrade II	30	30	Timestamp	1.5	90	– –	+

* 30 ps sampling at the front-end, but slower readout to reduce bandwidth.

The software gate can be better tuned using 30 ps readout, but the width is still dictated by the sensor resolution.

These scenarios are discussed in more detail in the rest of the presentation.

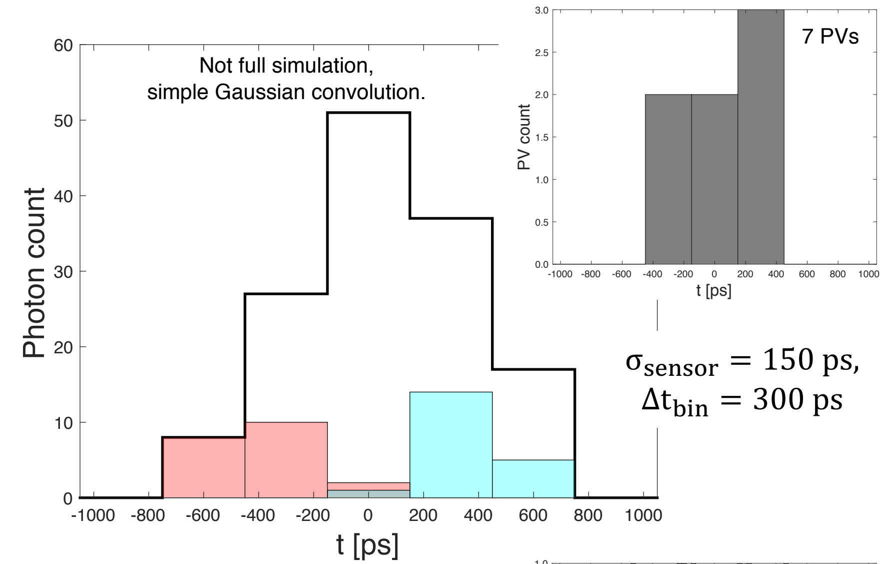
The Upgrade Ib proposal

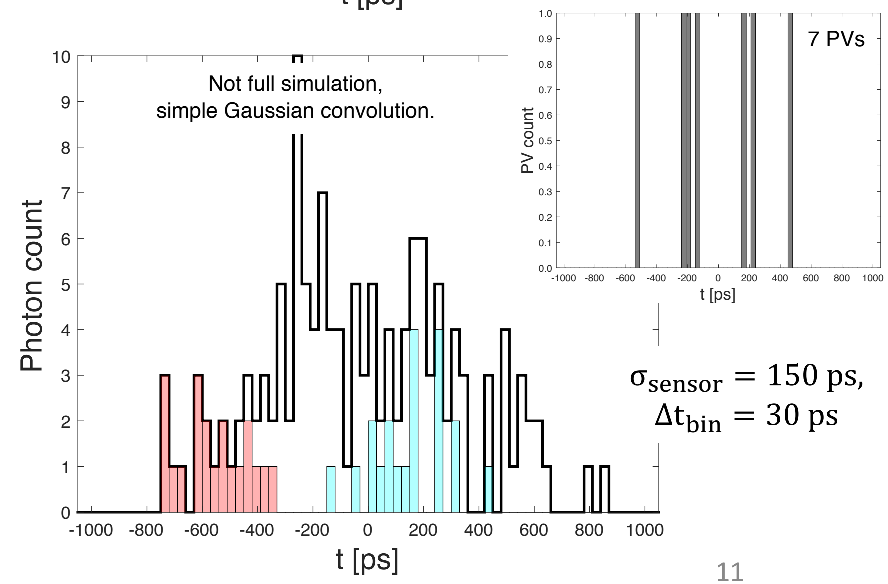
	Sensor σ resolution [ps]	Electronic readout [ps]	Track t_0	FE gate [ns]	Software gate [ps]	Bandwidth	Particle ID
Run 3	150	3125	No	3 to 6	N/A	No zero-suppression	+
Upgrade Ib	150	200-300 *	RICH rec	1.5	~ 900	Zero-suppression => Similar but non-uniform	++
Upgrade Ib	150	30	RICH rec	1.5	~ 900 #	–	++
Upgrade II	30	30	Timestamp	1.5	90	– –	+

The electronic readout chain is upgraded:
- Front-end ASIC with picosecond resolution.
- Coupled to a picosecond TDC.
- We propose to save bandwidth by transmitting data with 200-300 ps time resolution.

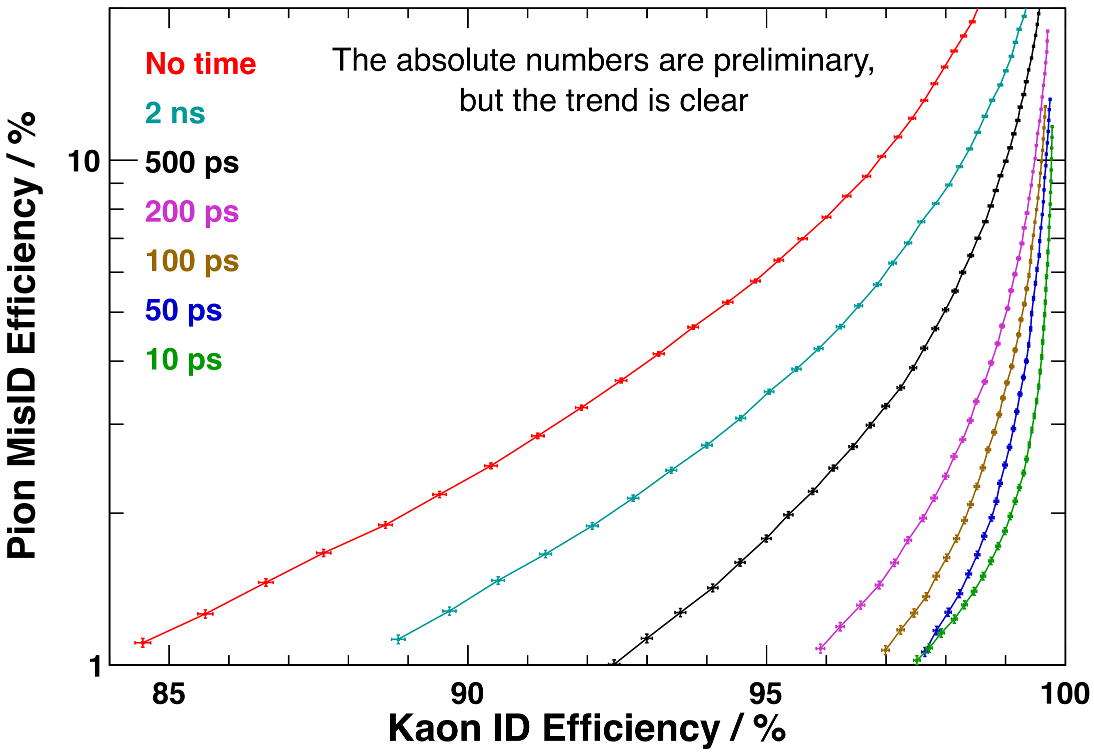
Main spread arises from the MAPMTs.
- σ ~ 150 ps (datasheet).
- Same order in recent measurements.

Spatial information provides good photon-to-track association, then fine-tuned using time information to improve particle ID.
- Since we have 20 to 40 photons per track, the track t_0 can be extracted in software. "$\frac{\sigma_{\text{sensor}}}{\sqrt{40}}$"
- Simulation studies are being prepared.
- The alternative to install a track timing layer, potentially inside the RICH detector, will also be investigated.





Particle ID performance simulation for Run 4 / Upgrade Ib



Timing information improves particle ID through better assignment of hits to tracks.

Particle ID curves produced in the LHCb simulation framework.

- The absolute numbers deviate from the latest release (work ongoing), but the trend is clear.
- Run 3 geometry and spatial granularity of MAPMTs are also applicable to Run 4.

The labels indicate the width of the time gate around the predicted hit time (on slide 3).

- Assumes that the track t_0 has been previously inferred from the data.

By design, the photon detector time spread is not included.

- For MAPMTs, we expect a performance between the turquoise and black curves.
- In the limit of excellent resolution, a nearly perfect particle ID can be achieved.

Zero suppression at the front-end

Run 3: The PDMDB transmits data across six optical links. No zero-suppression at the front-end: it adds FPGA logic and compromises the radiation hardness.

Suppose we apply zero-suppression
- 7 bit encoding of the MAPMT hit position (512 / 6 = 85 to 86 channels / link).
- Below 14 % occupancy, zero suppression reduces bandwidth.
- At the highest occupancy, the additional headers double the bandwidth.

512 MAPMT channels

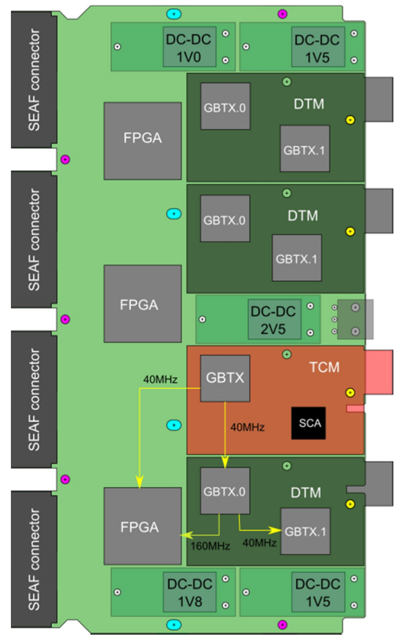
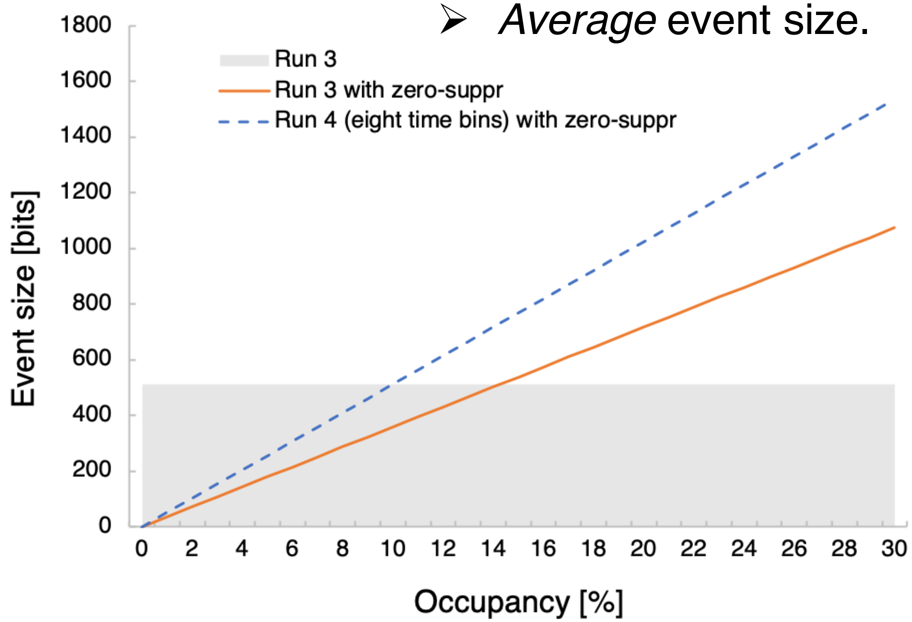


Figure 2 Clock distribution scheme

- *Average* event size.



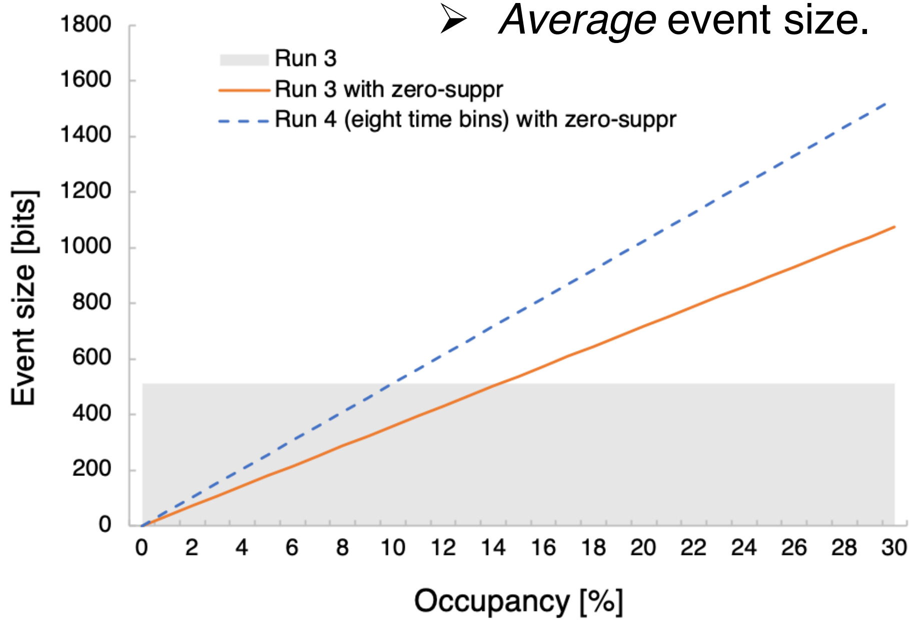
Upgrade Ib: Without zero-suppression, the bandwidth would increases linearly with the number of time bins. Factor of 8 (not shown) for the 200-300 ps readout.

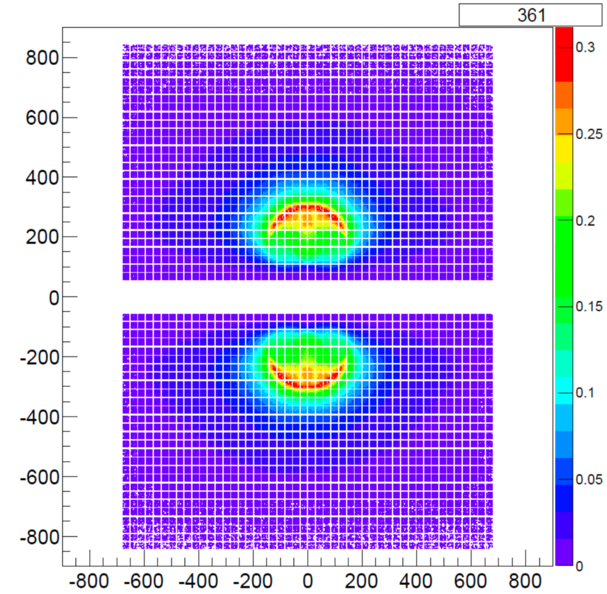
Suppose we apply zero-suppression
- 3 additional bits for time (i.e. 8 bins of 200-300 ps).
- Below 10 % occupancy, zero suppression reduces bandwidth *with respect to Run 3 without time*.
- At the highest occupancy, the additional headers triple the bandwidth.

Zero suppression at the front-end

The region with occupancy >10 % is only ~10% of the whole detector plane.

➢ *Average* event size.





RICH (1) occupancy distribution is extremely non-uniform.

➢ For most of the detector, addition of time and zero-suppression therefore reduces the average bandwidth.

The bandwidth requirement will be non-uniform across the detector with most the bandwidth concentrated in the RICH 1 high-occupancy region.

➢ We can introduce the lpGBT with VL+ and/or install additional links.

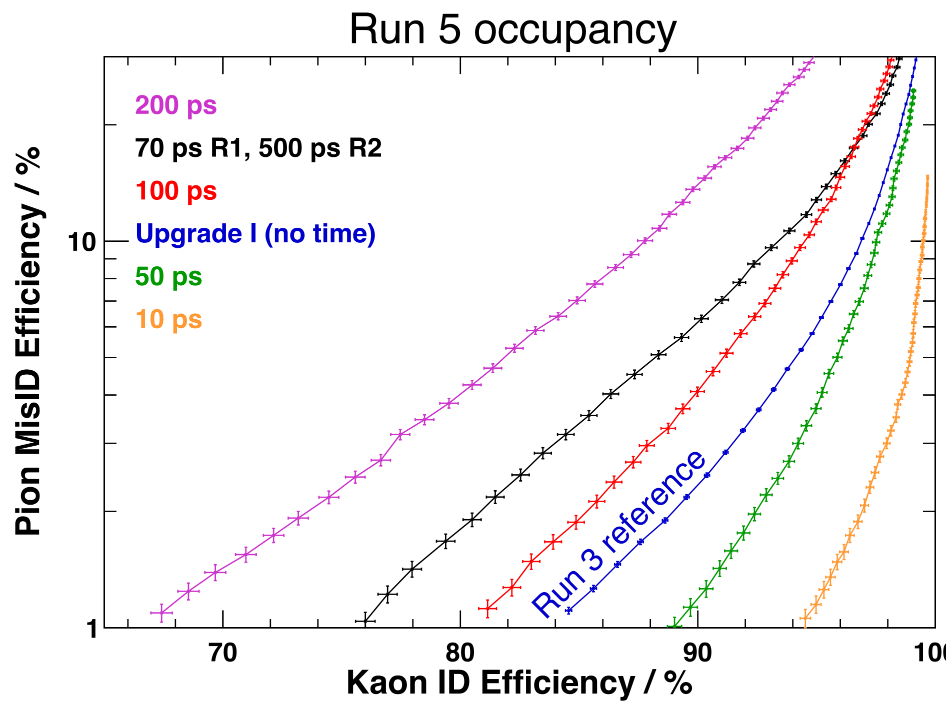
Upgrade II

For upgrade II, the challenge is clear: factor seven increase in the number of particle tracks and photons.

- MAPMTs saturate and need replacement.
- Electronic readout upgrade to increase bandwidth.
- All components need to be radiation hard.

The particle ID curves are made by overlapping seven Run 3 events. This approximation of Upgrade II uses MAPMT pixels and the Run 3 optics.

- With 1.0 x 1.0 mm^2 pixels and improved geometry, the particle ID would improve and the timing requirements would relax.



The Run 5 'no time' curve would be off-scale and is not shown.

The possibility of worse time resolution in RICH 2 (the black curve) is being considered.

In Upgrade II, 4D 'space-time' photon-to-track association is required due to the high track multiplicity and photon occupancy. The track t_0 then becomes an important input for the reconstruction algorithms.

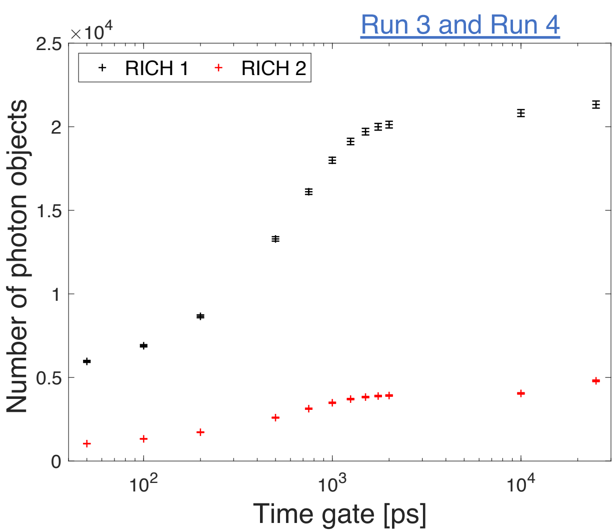
Upgrade II

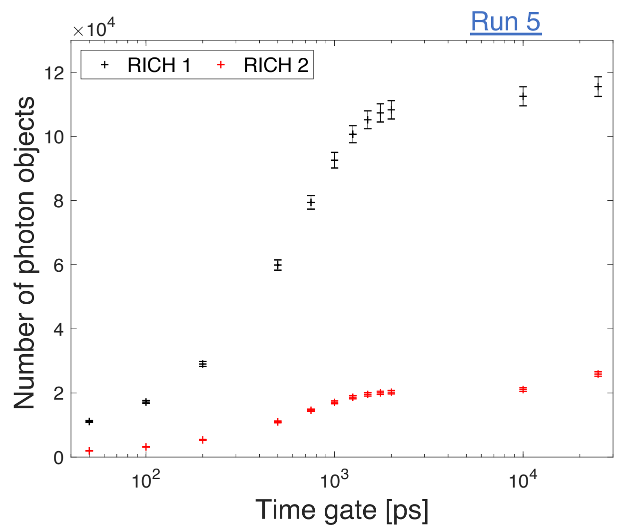
	Sensor σ resolution [ps]	Electronic readout [ps]	Track t_0	FE gate [ns]	Software gate [ps]	Bandwidth	Particle ID
Run 3	150	3125	No	3 to 6	N/A	No zero-suppression	+
Upgrade Ib	150	200-300 *	RICH rec	1.5	~ 900	Zero-suppression => Similar but non-uniform	++
Upgrade Ib	150	30	RICH rec	1.5	~ 900 #	–	++
Upgrade II	30	30	Timestamp	1.5	90	– –	+

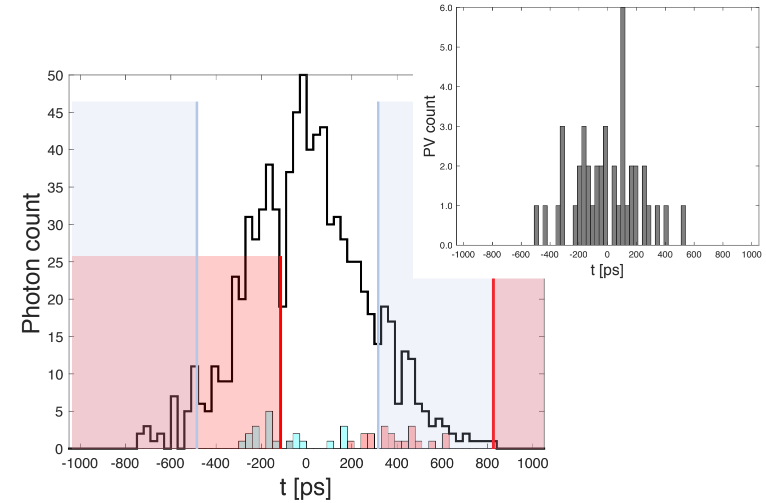
Faster photon detectors are better.

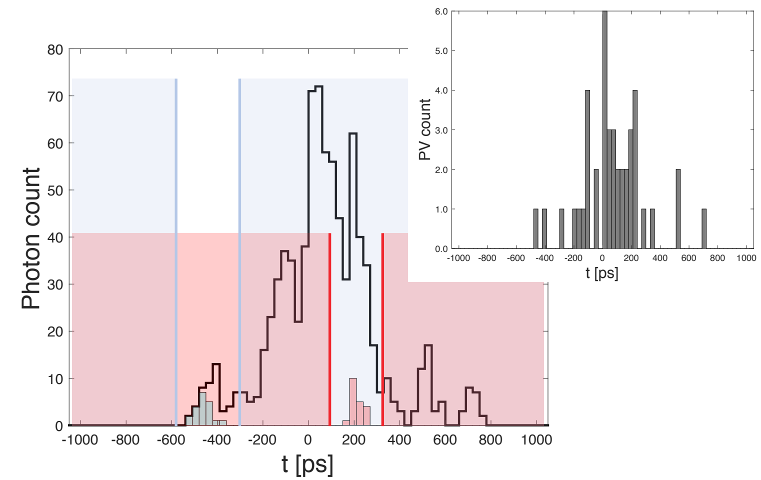
➢ The time gate in reconstruction can be smaller, hence significantly reducing combinatorial background.

Trend is clear from the number of photon objects below. Since the cut is applied at the first stage of the reconstruction algorithms, improvement in reconstruction speed can be expected.

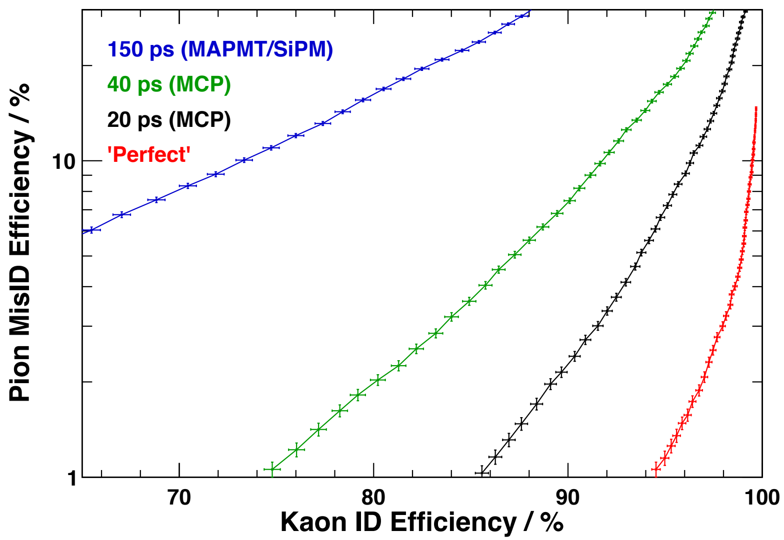








Upgrade II photon sensor technologies



The absolute numbers are preliminary, but the trend is clear

The particle ID curves include a Gaussian time spread reflecting different technology time resolutions, combined with a 3σ time gate.

A time gate of order 100 ps around a photon detector with 20 to 40 ps resolution would match the Run 3 particle ID performance in the HL-LHC using time alone.

- Since this result is for MAPMT pixel sizes, work is in progress to merge it in simulation with Upgrade II granularity and quantum efficiency of SiPMs example.

	MAPMT	SiPM	MCP
Time res. [ps]	~ 150	~ 100	~ 30
Pixel size [mm]	2.88	~ 1	~ 1
Peak quantum efficiency	30 to 35 % at 350 nm	45 % at 400 nm	~ 30 % at 350 nm
Dark-count rate [Hz/mm^2]	< 1	$\mathcal{O}(10^5 - 10^7)$ at room T	$\mathcal{O}(1)$
Radiation hardness	UV glass window	Lattice defects	UV glass window
Gain ageing (50% loss) [C/cm^2]	~ 10^3	SPAD	$\mathcal{O}(10)$ ALD
Max anode current [μA/cm^2]	~ 20	Quenched	$\mathcal{O}(0.1)$
Bias voltage [V]	$\mathcal{O}(10^3)$	10-100	$\mathcal{O}(10^3)$
Robustness in B-field	RICH 1 shielding (< 5 mT)	Not affected	Micro-channel (< 2 T)

MCP-PMTs have the best time resolution.
SiPMs have many other attractive properties.

- R&D is ongoing for both options.

Estimate of the Upgrade II data rates

	RICH 1			RICH 2		
	Current	Upgrade I	Upgrade II	Current	Upgrade I	Upgrade II
N_{pe}	32	42	60-30	24	22	30
Chromatic	0.84	0.58	0.24-0.18	0.48	0.31	0.10
Pixel	1.04	0.44	0.15	0.35	0.19	0.07
Emission	0.76	0.37	0.10	0.27	0.27	0.05
Total [mrad]	1.60	0.78	0.30-0.24	0.65	0.45	0.13

Numbers in table obtained from
doi.org/10.1016/j.nima.2017.02.076

With the anticipated improvements in geometry and chromatic error, the pixel error should be reduced to achieve a higher overall Cherenkov angle resolution.

Suppose basic zero-suppression scheme at the front-end and
1.0×1.0 mm^2 pixel size --> 10 bit position (cf. 7 bits for MAPMT pixel sizes).
100 ps over a 1.6 ns range --> 4 bit time (cf. 3 bits for the Run 4 proposed readout).
Average increase in bandwidth in Run 5 compared to Run 4:
1.4 (increase in bits per hit) x 7 (increase in luminosity) ~ factor of 10.

- ➢ We are trying to find other methods of data-suppression at the front-end, as well as more sophisticated zero-suppression schemes.

Conclusion and outlook

	Sensor σ resolution [ps]	Electronic readout [ps]	Track t_0	FE gate [ns]	Software gate [ps]	Bandwidth	Particle ID
Run 3	150	3125	No	3 to 6	N/A	No zero-suppression	+
Upgrade Ib	150	200-300 *	RICH rec	1.5	~ 900	Zero-suppression => Similar but non-uniform	++
Upgrade II	30	30	Timestamp	1.5	90	– –	+

The excellent time resolution of the RICH detectors can be gradually unlocked from the nanosecond level at the front-end to the picosecond level in the HLT reconstruction.
This strongly improves the particle ID.

Run 3 : a front-end hardware time gate of 3 to 6 ns for background reduction.
- The positive effect on particle ID is being simulated with a realistic detector and readout description.

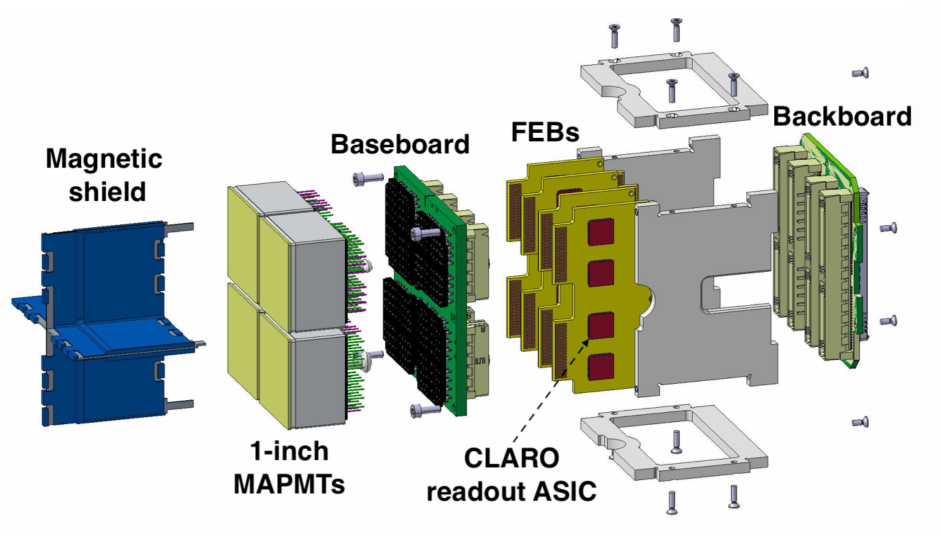
Run 4 / Upgr Ib : upgrade of the readout electronics to achieve 200 to 300 ps time resolution.
- Electronics R&D into a picosecond front-end ASIC + TDC, digital processing and bandwidth control.
- Simulation efforts will focus on the reconstruction: extraction of t_0 from RICH data and optimisation of the particle ID using time resolution.

Run 5 / Upgr II : redesign of the detector aiming for a time resolution below 100 ps.
- A lot of important R&D, including timing capabilities of new photon sensors (SiPM / MCP / …).
- Evolution of the readout electronics building on experience in Run 4.
- Simulation in progress to combine timing studies with smaller pixels and improved quantum efficiency. Until a full LHCb Upgr II simulation framework is available, we will combine extrapolations (photon detector occupancy) and MC information (for tracking) to make our estimates.

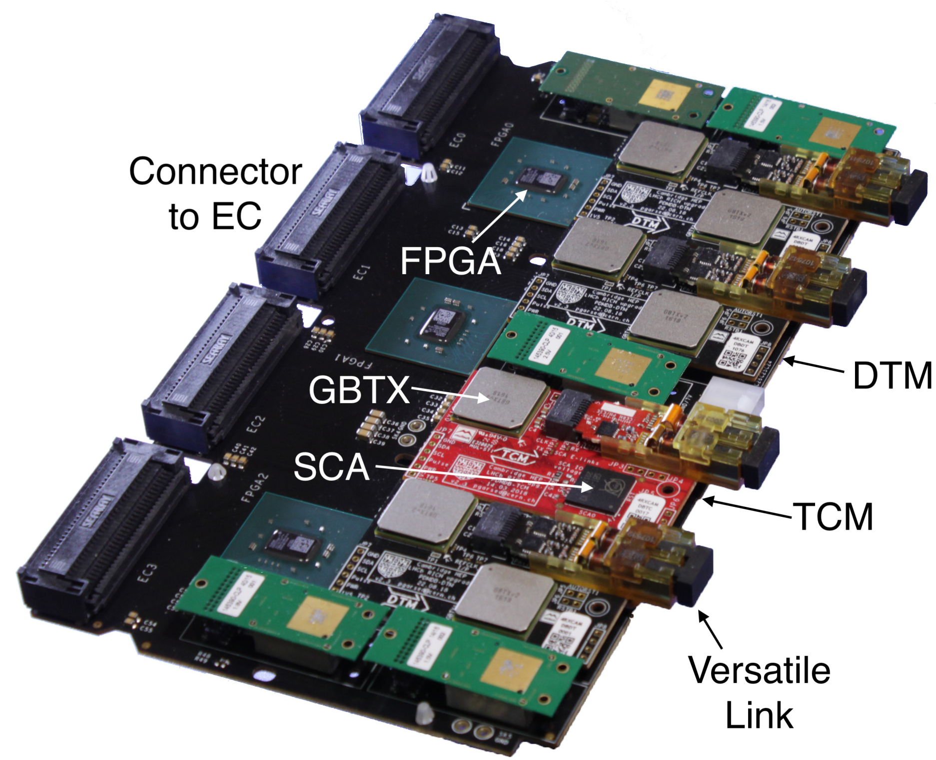
BACKUP

Run 3 electronic readout chain

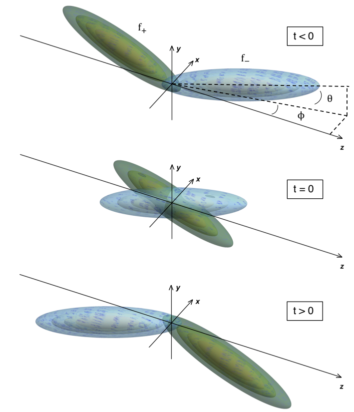
The RICH photon detector consists of elementary cells of multi-anode photon multiplier tubes (MAPMTs). The MAPMT signals are shaped and discriminated by the CLARO readout ASICs.



The PDMDB provides the interface between the CLAROs and the Versatile Links to the LHCb readout. The FPGAs capture the digital signals, format the data and transmit it using GBTX transceiver ASICs.



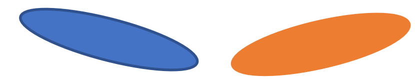
Novel PV simulation tool for LHCb upgrade studies



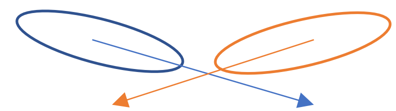
The first step for time in the simulation is a new **primary vertex (PV) generation** tool:

1) Take two Gaussian bunches.
   (write down the spatial Probability Density Function, PDF)

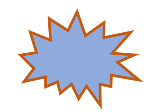
2) Rotate each bunch about the bunch crossing angles.
   (rotate the covariance matrices)



3) Set the centre of mass of each bunch into motion.
   (this step introduces time)



4) Collide the bunches.
   (take the product of the PDFs)



5) Sample from the 4-dimensional distribution of primary vertices.
   (using a Markov chain)