Fast timing detector developments for a LHCb Upgrade-II

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On behalf of the LHCb Collaboration

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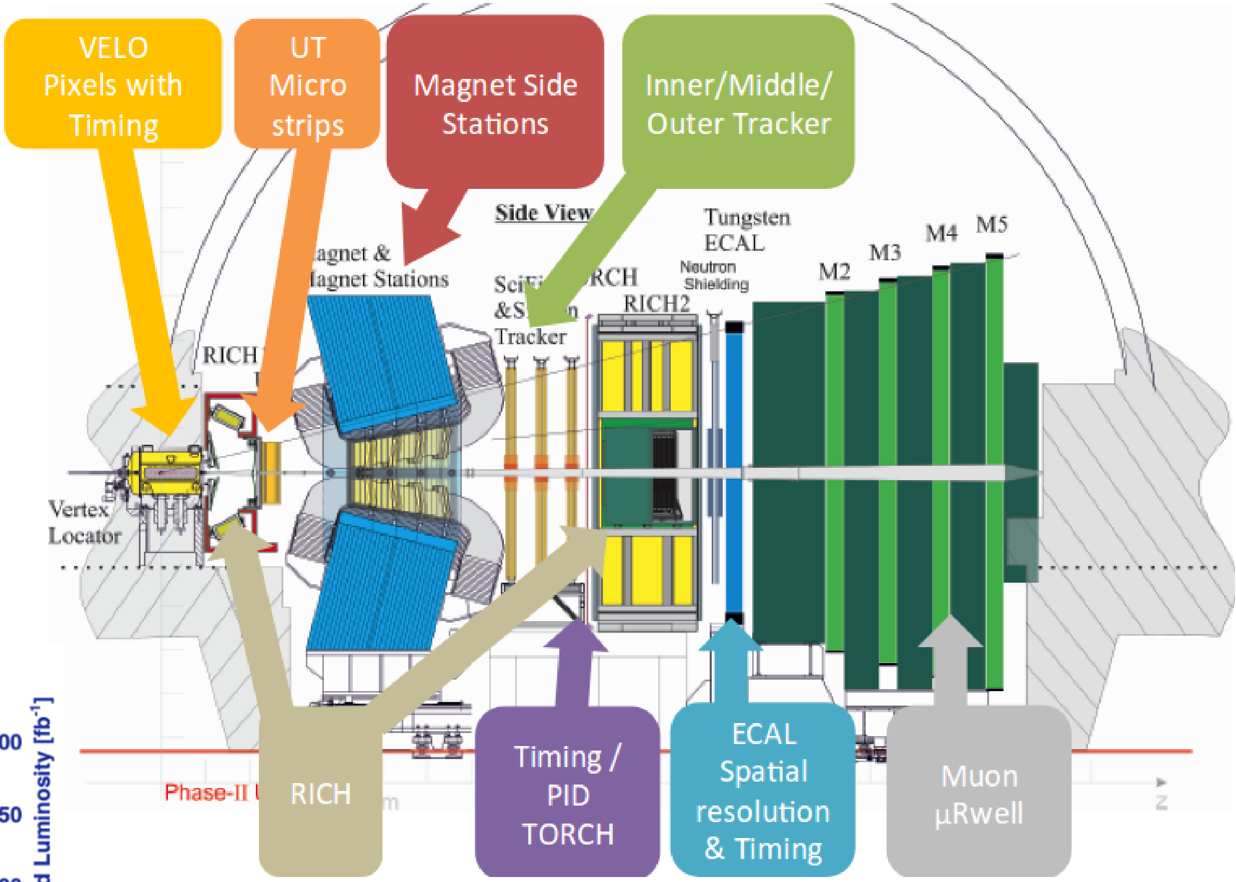
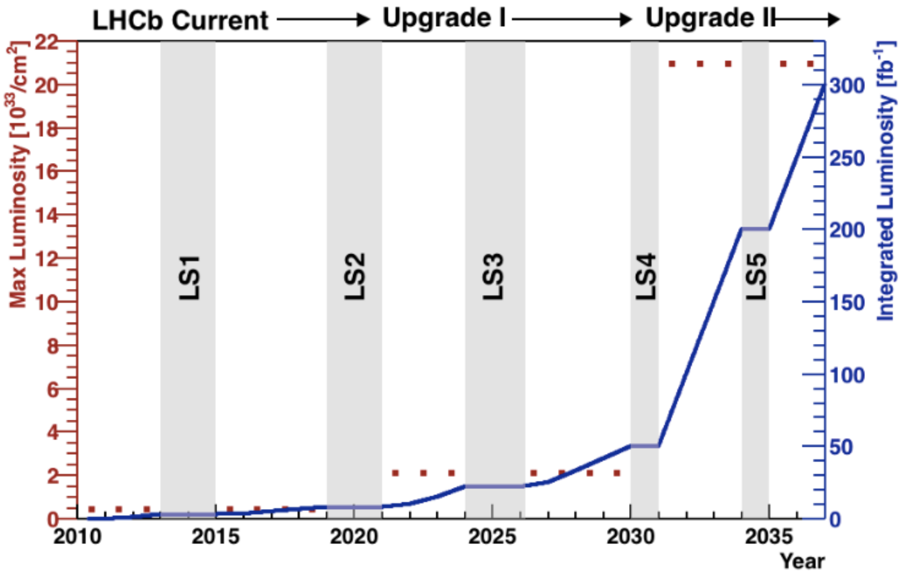
LHCb Upgrade II

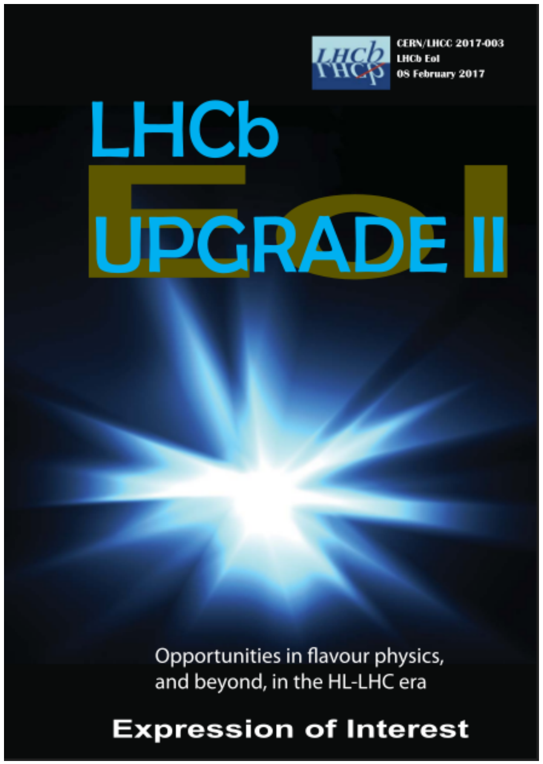
- **Major detector upgrade** during Long Shutdown 4 in 2030
- **Luminosity up to $2*10^{34}$ cm^{-2} s^{-1}**
  - 10x w.r.t to Upgrade I
  - ~50 visible interactions per crossing
- Aims at collecting > 300fb^{-1}

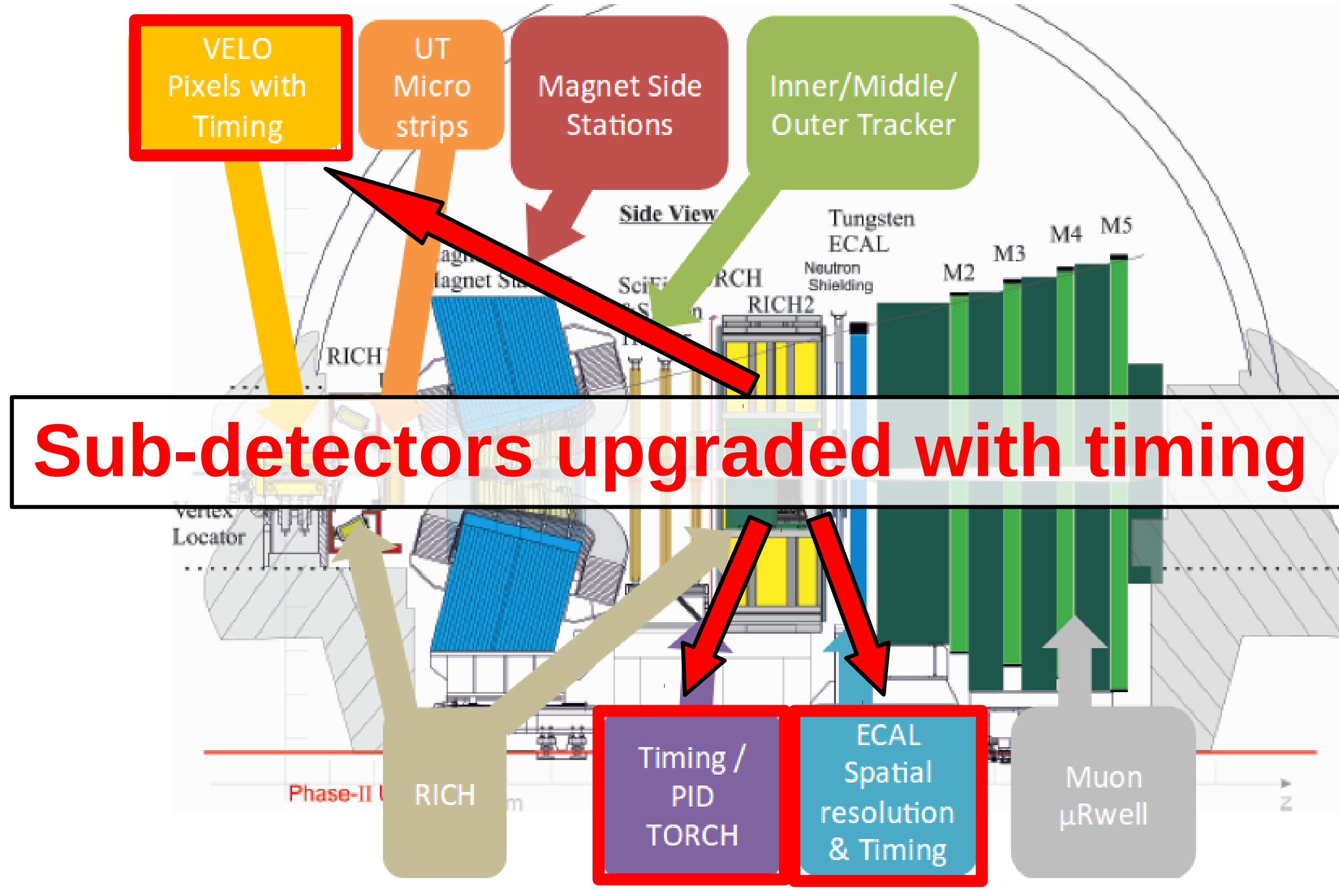




- **Big detector challenge:**
  - Tracking: 1500-3500 charged particles per bunch crossing
  - PID: higher occupancy, increase the momentum < 10GeV/c and > 100GeV/c
  - ECAL: sustain radiation dose ≲200 Mrad, energy resolution σ(E)/E~10%/√E⊕1-2%, reduce Moliere radius
  - Radiation damage: greater concern for certain sub-detectors

Timing detectors in LHCb Upgrade II

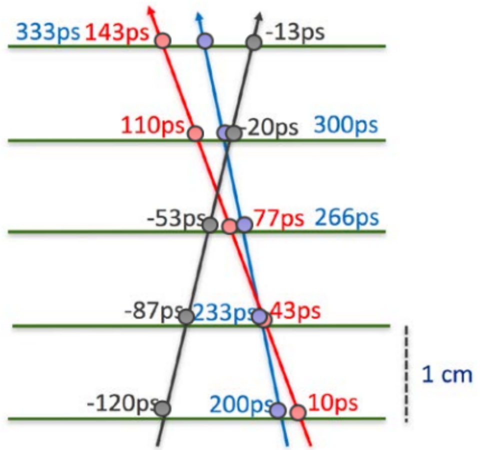




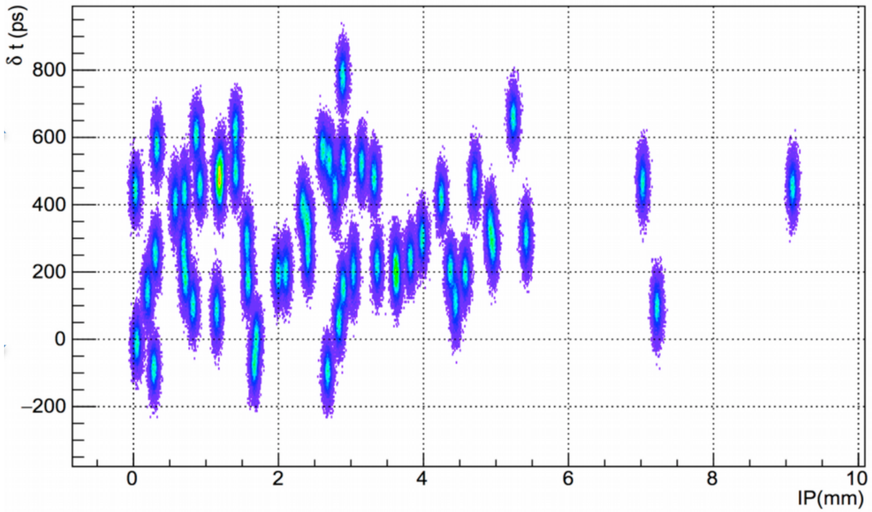
- *From the LHCb Upgrade II Expression of Interest:*
  - *"At very high pileup **fast-timing information becomes an essential attribute for suppressing combinatorics and enabling time-dependent CP -violation measurements**, and so this capability becomes a design feature for several detector components."*

Role of timing

- **Timing in track reconstruction:**
  - Hits distributed with in time with RMS ~ 170ps
  - Need ~30ps hit resolution to discriminate hits with similar positions, based on time
  - Use only compatible hits in the pattern recognition



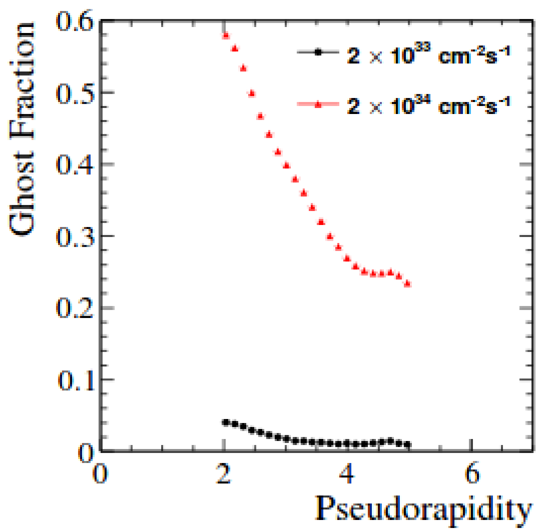
- **Timing in PV-association:**
  - Additional power to select the correct primary vertex
  - Hit time resolution needed: ~200ps
  - Enough to separate tracks with similar spatial parameters

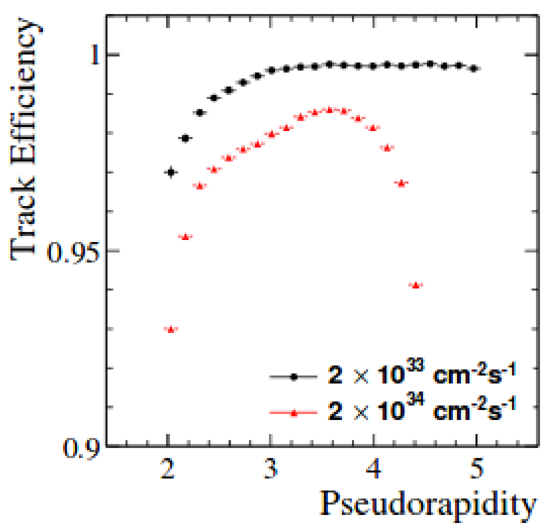


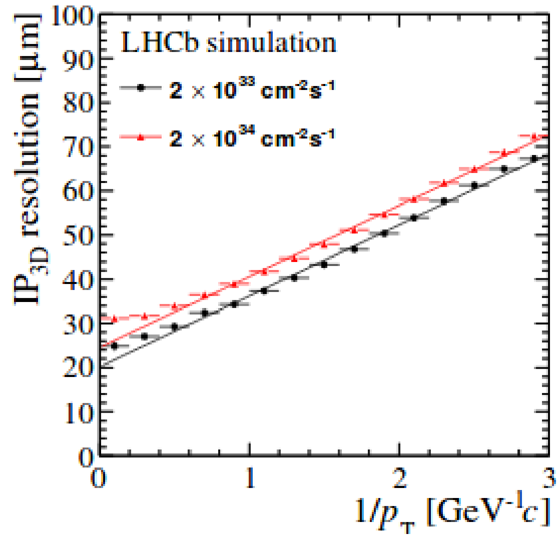
- **Others:**
  - Precise measurement of time of primary vertices
  - Track time stamping for better association of track upstream and downstream the magnet
  - Timing in PID and calorimetry

VELO tracking performance

- **VELO Upgrade-I detector** performance in **Upgrade-II conditions**



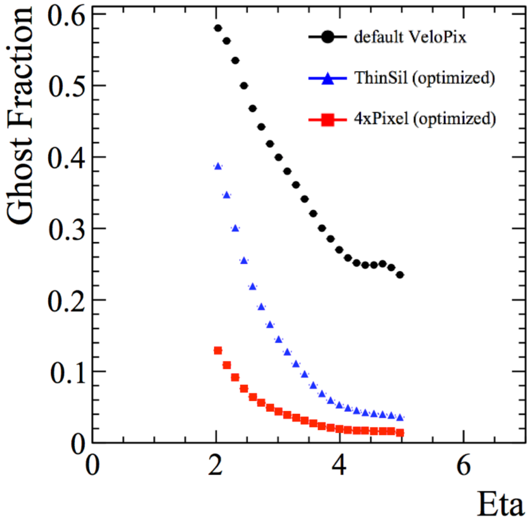




[CERN-LHCC-2017-003]

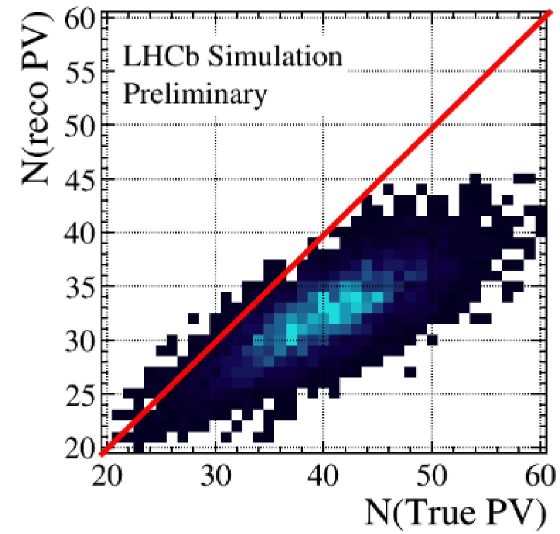
- **Upgrade-I** detector can't sustain the increased luminosity:
  - ~40% ghost rate
  - 96% tracking efficiency

- Tracking performance can be **partially recovered:**
  - Smaller pixels: 55x55μm^2 → 27.5x27.5μm^2
  - Re-optimized pattern recognition
  - Thinner silicon: 200μm → 100μm



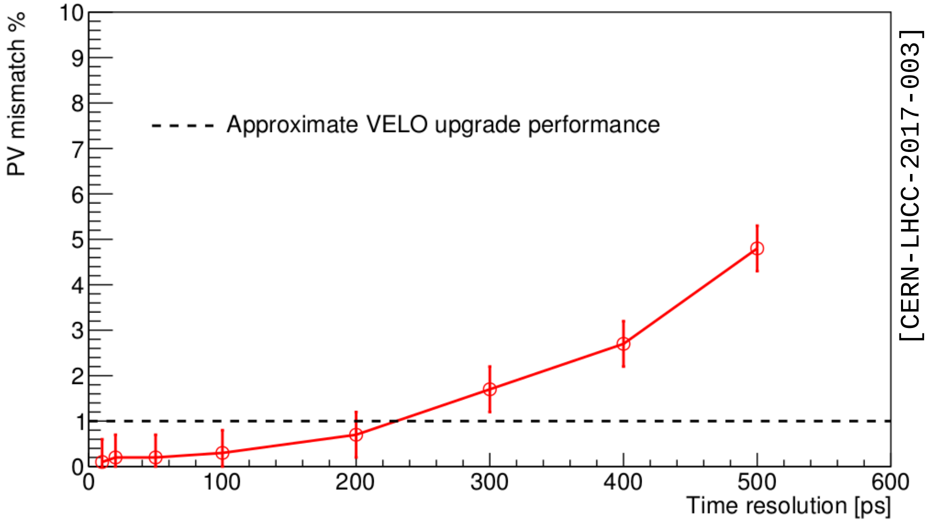
VELO tracking performance (2)

- **PV “merging” still present.**

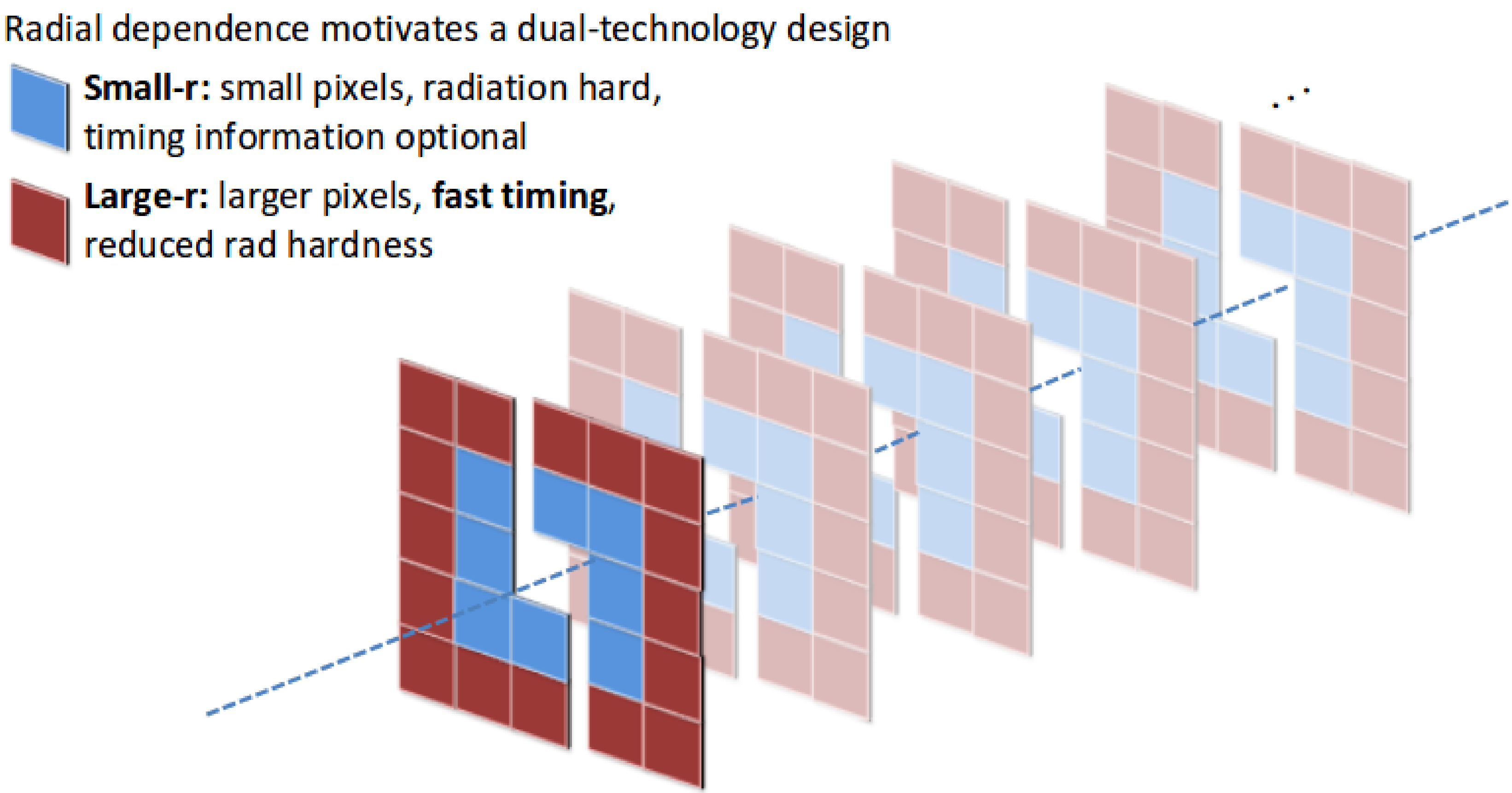


- **PV mis-association still present:**
  - 21% for long-lived particles
  - Degradation of decay time precisions

- **PV-association** would benefit from addition of timing information:
  - Modest time resolution needed **~200ps**
  - Restore the Upgrade-I VELO peformance
  - **Reduce the PV mismatch** back to acceptable level ~1%
- Assuming “perfect” pattern recognition
  - **200ps hit resolution not enough** to be useful **in track reconstruction**



SuperVELO case study



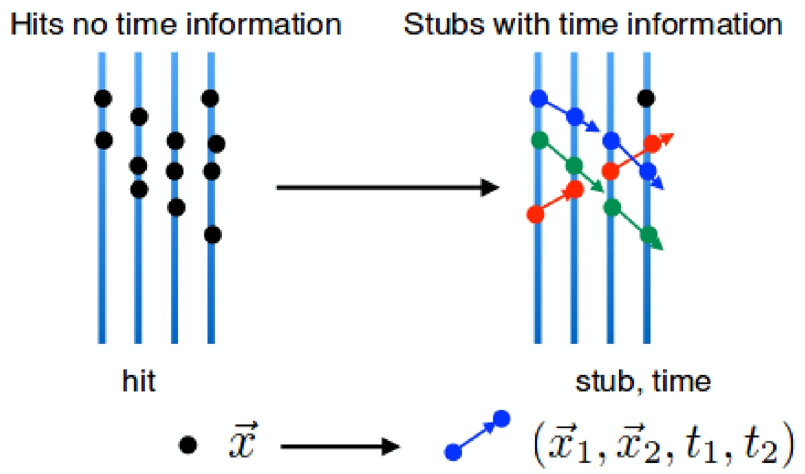
- **Dual technology** silicon pixel detectors:
  - **Timing information in the outer region** of each plane, reduced radiation hardness
  - Optional timing in the **inner region, smaller pixels**, more radiation hardness

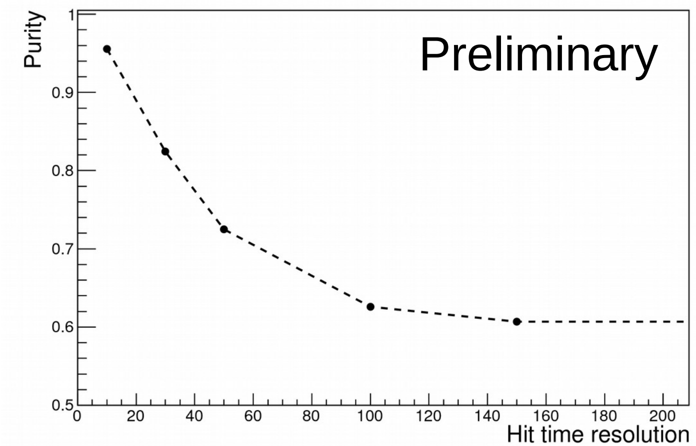
TIMESPOT R&D project

- **TIME** and **Sp**ace real-time **O**perating **T**racker
  - 1 M€ three years project (from 2018), funded by INFN
  - Development of a silicon and diamond 3D tracker with timing facilities
  - **Construction of a demonstrator** integrating sensors, electronics, real-time processors

- Implementing a **4D real-time reconstruction algorithm in FPGA**
  - Time information included in the pattern recognition and track reconstruction, ~30ps time resolution goal
  - Based on **early identification of hit couplets ("stubs")** and parallel track identification and fitting
  - Timing in pattern recognition allows significant ghost rate reduction in an Upgraded VELO-like case study

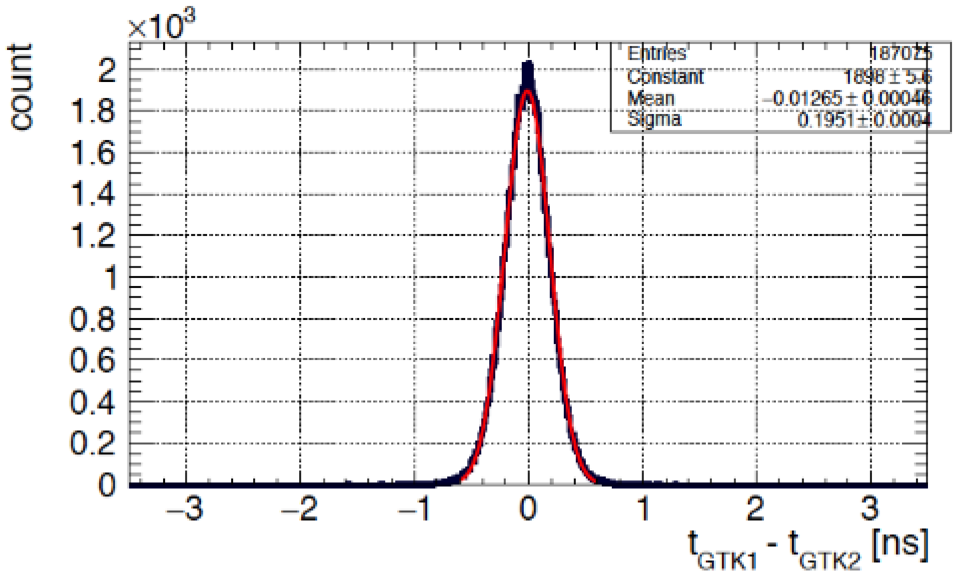
[N. Neri et al., JINST 11 (2016) no.11, C11040]





Silicon sensors with timing - NA62

- Examples of silicon pixel sensors already proved to work
- **NA62 GigaTracker** implements hybrid pixel sensors with 200ps time resolution
  - **Good timing** performance
  - **300x300µm^2 pixel size** → **“too big”** w.r.t. to VELOPIX 55x55µm^2 pixel size
- In 2017 data taking the GigaTracker system proved **~140ps single hit time resolution** and **74ps track time resolution** using three stations

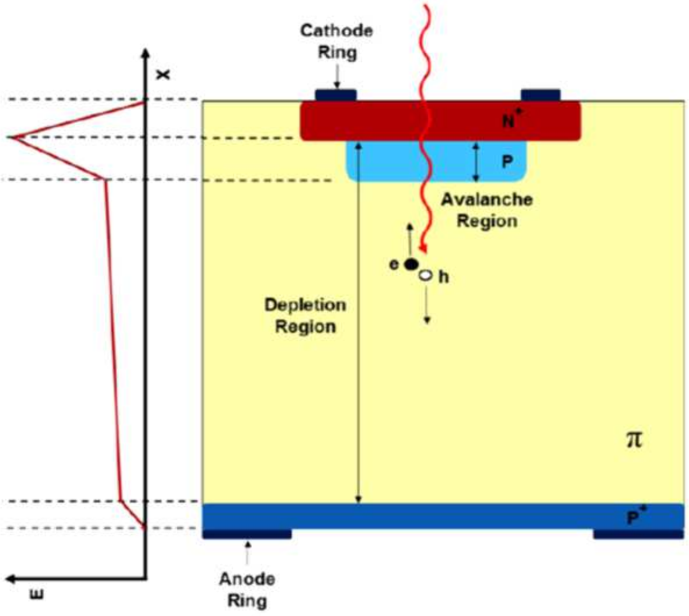


[https://goo.gl/erq2LQ]

σ_{GTK1}=139 ps	σ_{GTK2}=137 ps	σ_{GTK3}=142 ps

LGAD sensors

- **Low Gain Avalanche Detectors:**
  - Dedicated silicon design with extra doping layer to the readout side, providing an avalanche region to boost the signal.
  - Radiation hardness up to **4.5×10^{15} 1MeV n_{eq}/cm^2**
  - Excellent time resolution : **< 30ps per track**
  - “Big” pixel size: **~1x1mm^2**
- ATLAS High Granularity Timing Detector is going to use them in far (~3.5m) forward region
- In LHCb **“big pixels”** could be used to instrument the Inner Tracker with timing
- **UFSD project** aims at:
  - 90x90μm^2 pixel pitch
  - 50μm thickness
  - Time res. 30ps

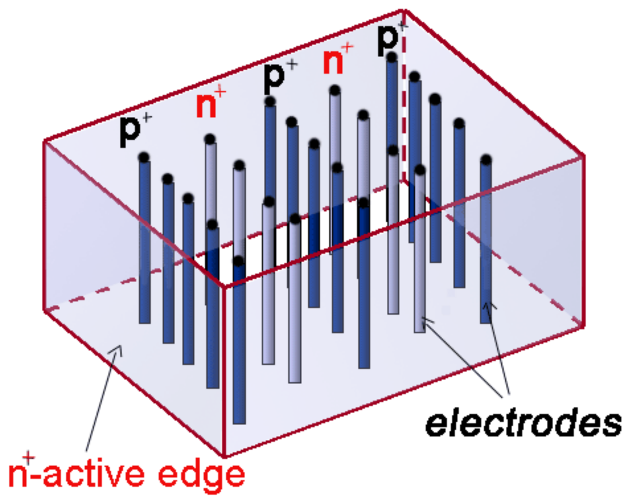


[https://goo.gl/6vmNUV]

Could utilize in VELO and tracker with precise timing info

3D silicon sensors

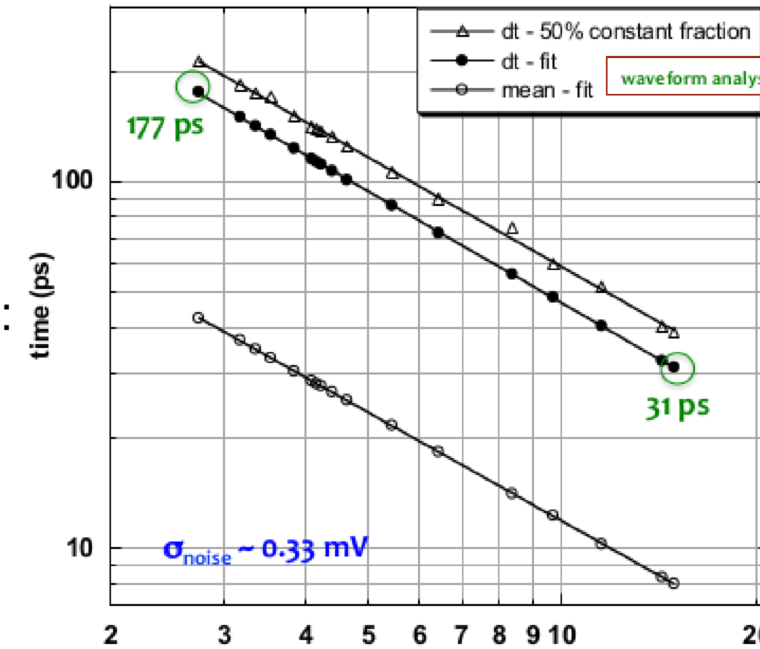
- **3D silicon pixel sensors:**
  - **Electrodes are “vertical”** w.r.t to an “horizontal” sensor
  - **Intrinsic potentiality for timing** applications
  - Small **pixel size : ~50µm**



[https://goo.gl/Py1AEk]

- Already in use in ATLAS IBL
  - **Timing capabilities not exploited**
  - Radiation hardness tested up to **$1*10^{16}$ 1MeV n_{eq}/cm^2**
  - 99% hit efficiency

- Timing functionalities, from waveform analysis off-line:
  - Timing resolution between **177ps and 31ps**

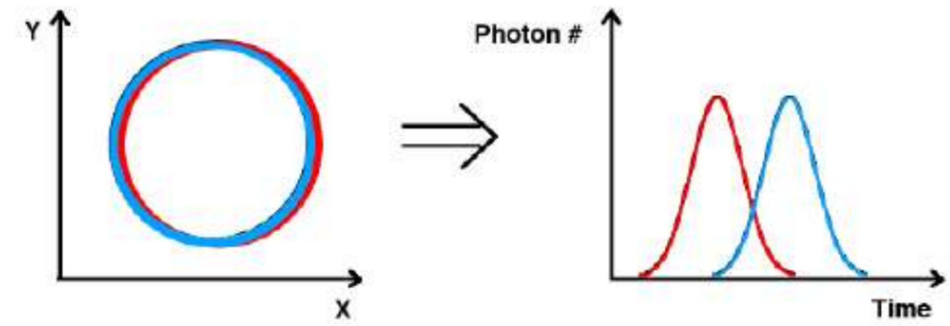


[S.Parker et al. IEEE TNS 58(2) (2011) 404]

Great potentiality for building a 4D tracker

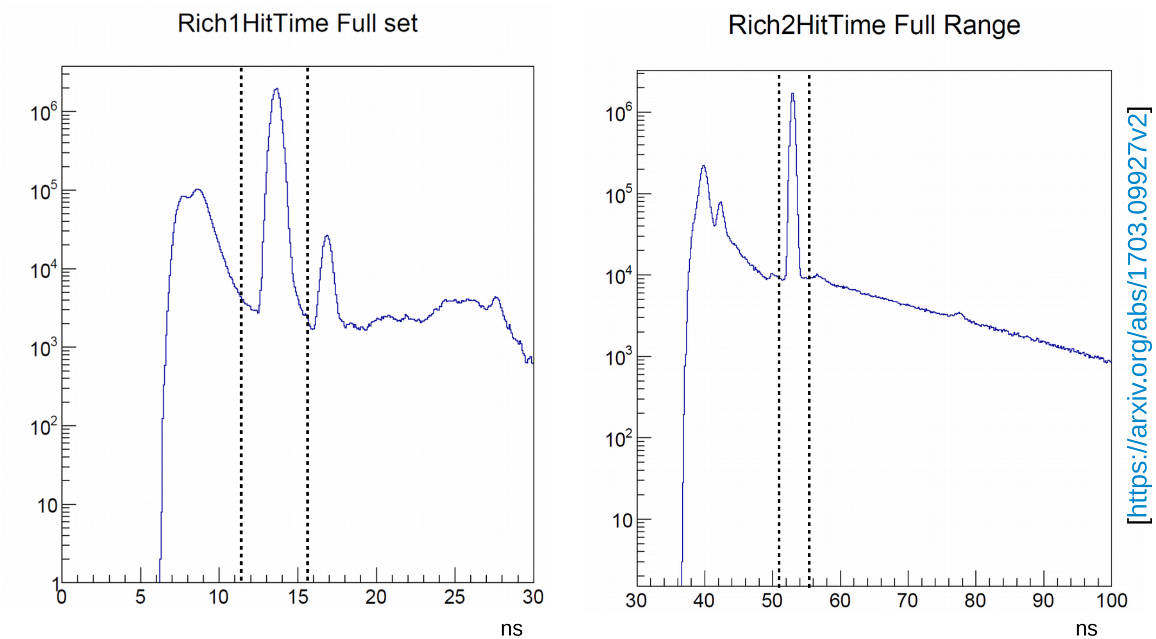
Timing in RICH

- In the **current RICH 1:**
  - **30% occupancy i**n the central region
- Same level occupancy can be kept with:
  - **Smaller pixel size** and larger focal length
  - **Precise timing** measurement



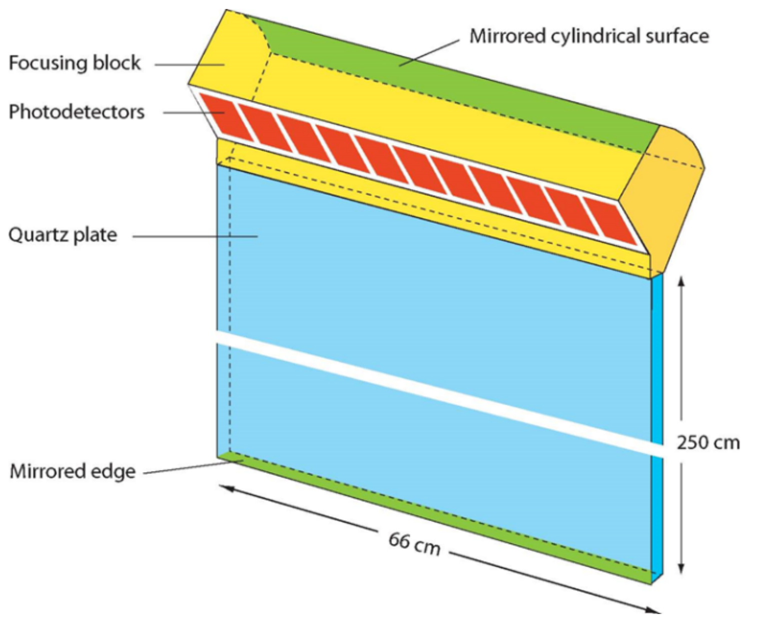
- **Separating the PVs** using the hit time would be desirable:
  - ***~0.2ns to 1ns** resolution on single photon,* **~50ps to ~150ps** resolution on track

- **Coarser resolution of ~1ns** enough to reject out-of-time photons
  - **Gate time window of 3ns** to reject background
  - Few percent in RICH1,
  - ~10% in RICH 2

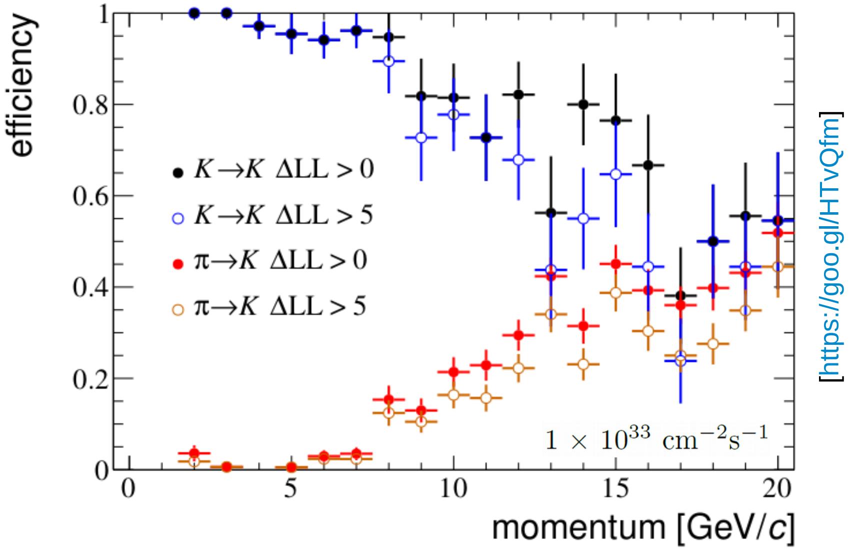


TORCH detector

- **Time Of internally Reflected CHerenkov light**
  - Possibly located in front of RICH 2 sub-detector
  - **Provides π/K PID** between 2 and 10 GeV/c momentum
  - Combines arrival times from multiple Cherenkov photons produced within a **10mm thick quartz plate**
  - Aims to achieve a timing resolution of **~70ps per photon**
    - **~15ps track time resolution,** given typically 30 photons
  - Based on **Micro Channel Plate PMTs**

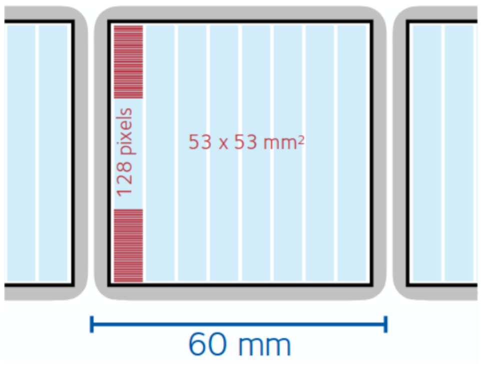


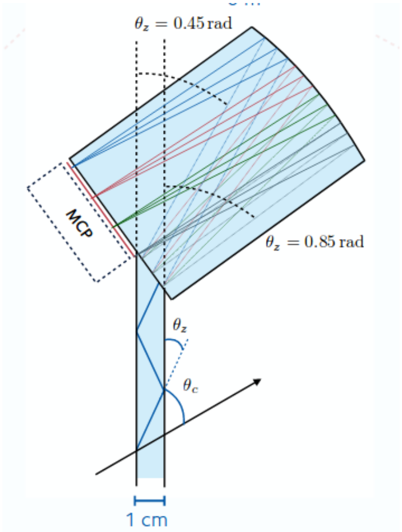
- Benefits of fast timing in the **downstream region:**
  - **Reduction of the association mismatch** between VELO+UT and T-tracks
  - **Downstream tracks timestamping** and better association with correct interaction
  - **Particle identification through Time-of-Flight below 10GeV/c.**
    Currently not possible with RICH 1 and RICH 2



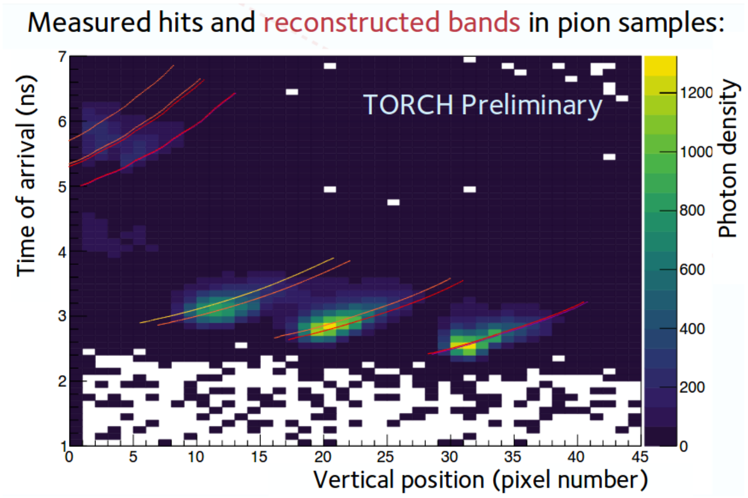
TORCH demonstrator test

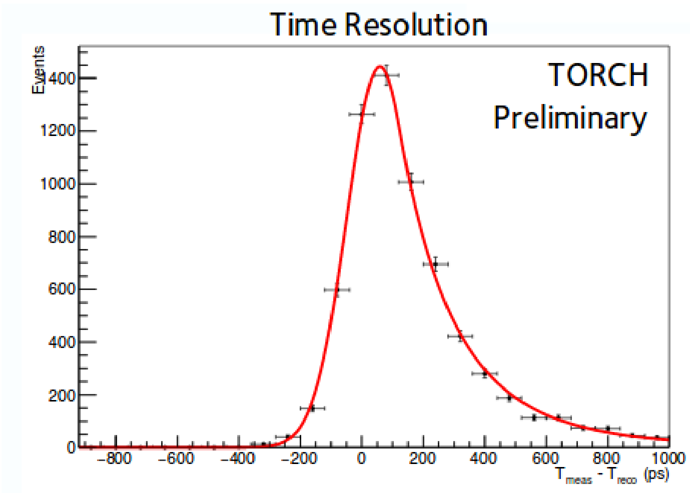
- MCP-PMTs developed in collaboration with Photek, to detect Cherenkov photons.
- Each detector needs **128x8 effective granularity over 53x53mm²**

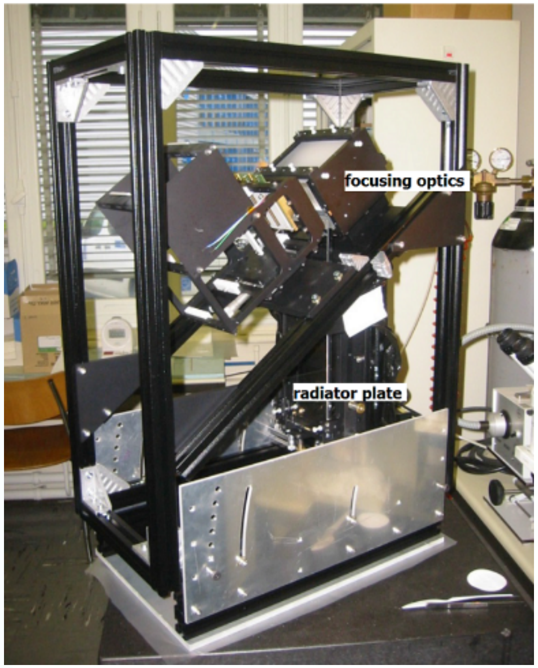




- A **small-scale TORCH demonstrator** tested in CERN PS 5 GeV pion-proton beam (Nov 2017) with a single MCP-PMT.
  - Patterns show characteristic reflections
  - Resolution of **~100 ps for single photon achieved**

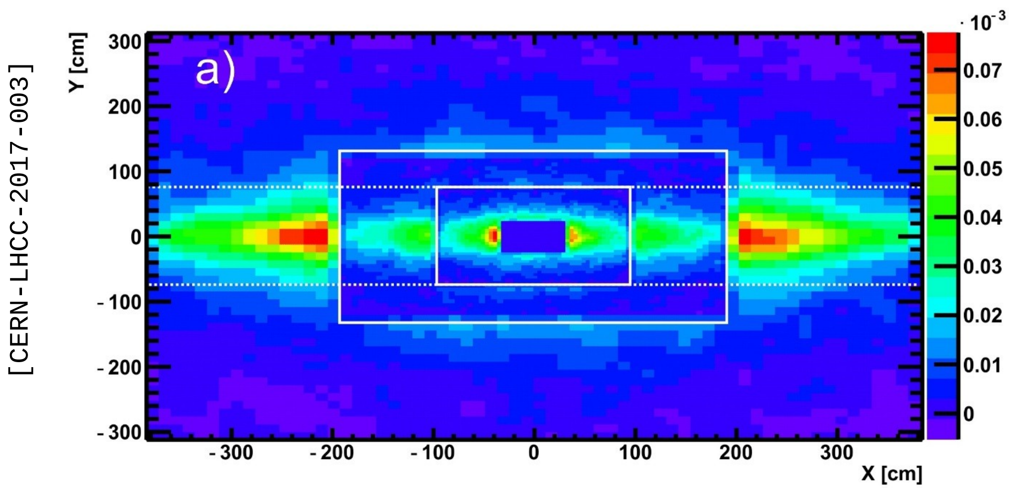




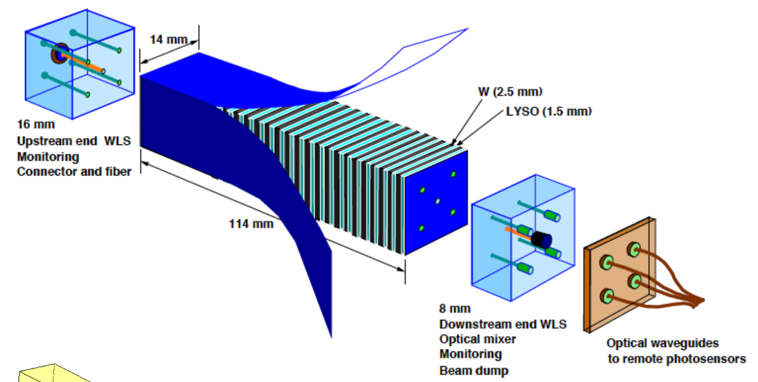


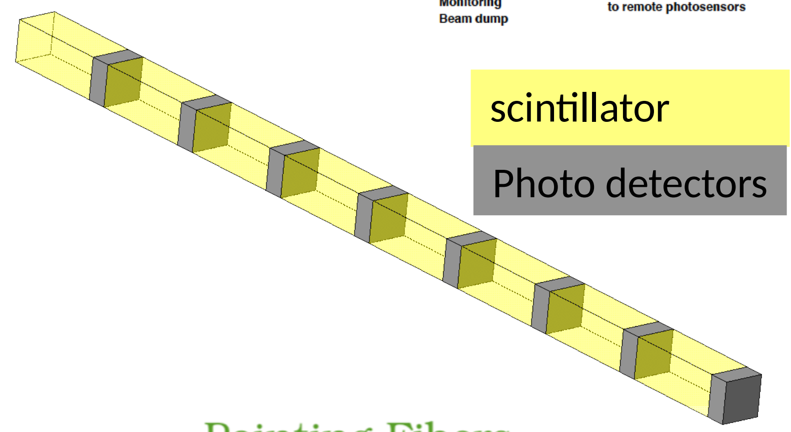
Timing in ECAL

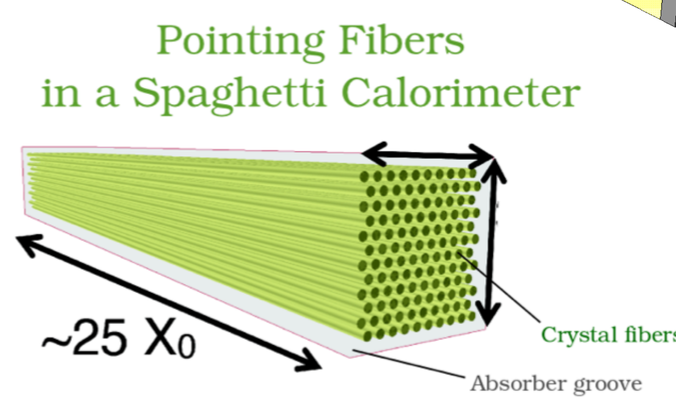
- **ECAL Upgrade-II** requirements:
  - Rebuilt ECAL in central high occupancy region
  - Reduced Moliere radius ~2-3cm and cell size $2x2cm^2$ in inner region ($12x12cm^2$ in outer region)
  - Rad-hard fast scintillator with **timing information for pile-up mitigation**



- Two different timing approaches:
  - Timing in **separate layer**, i.e. silicon timing layer
  - Timing **embedded in the ECAL**

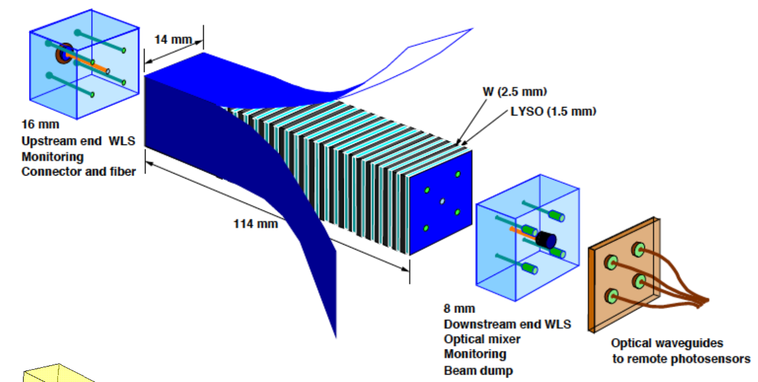


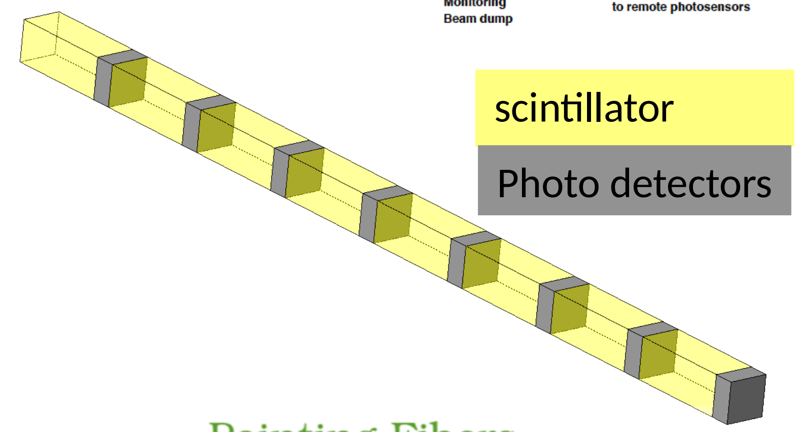


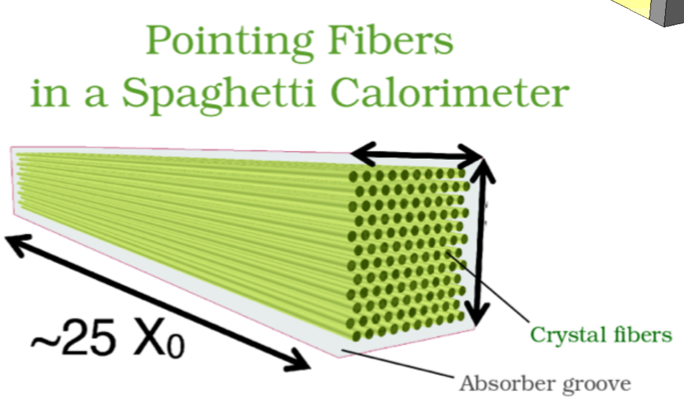


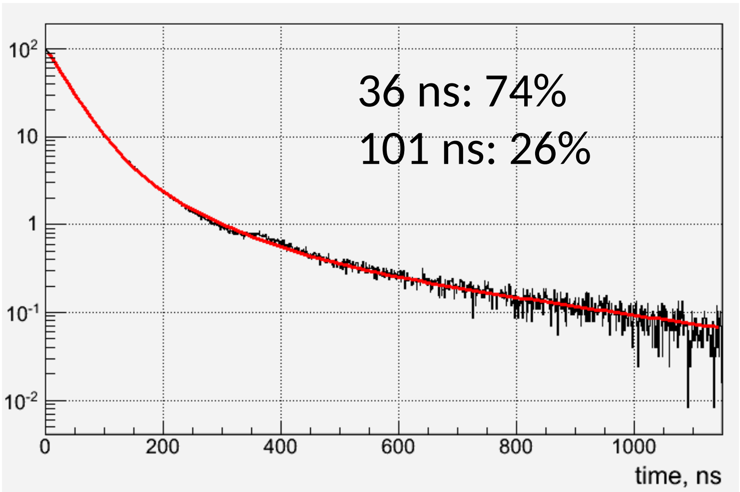
Timing in ECAL

- Possible design:
  - **“Shashlik”** : Tungsten + crystal layers, filled with WLS quartz capillaries. → Complex production
  - **Homogeneous calorimeter**: scintillators + photo detectors. → Difficult integration and need rad-hard photo detectors
  - **“Crystal SpaCal”**: pointing fibers in a “spaghetti” calorimeter.
- CMS $PbWO_4$ ECAL module proved **~20ps at testbeam**
- **LHCb** in investing in **GAGG crystals**
  - first samples tested at CERN PS





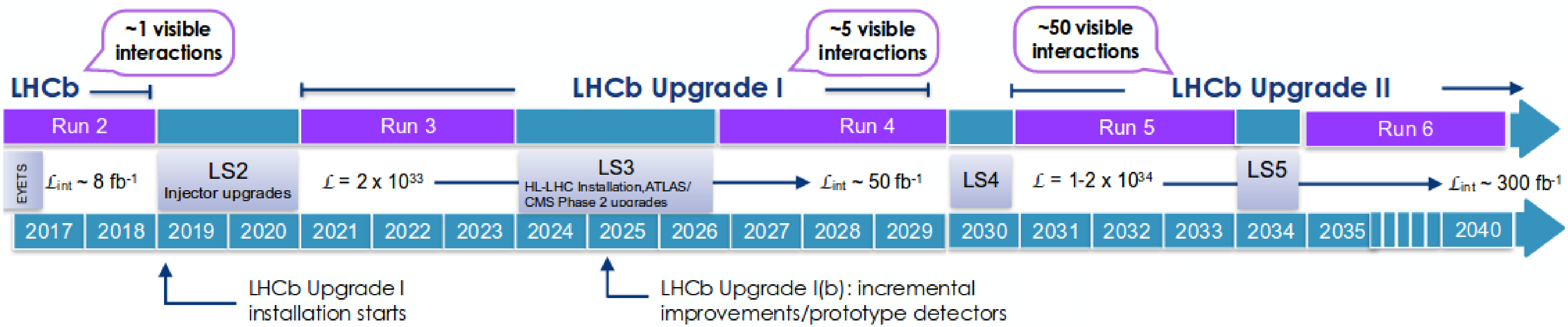




[https://goo.gl/yUAopW]

Conclusions

- Inclusion of timing detectors in LHCb Upgrade-II in 2030 is crucial
- With increased luminosity up to $2*10^{34} cm^{-2} s^{-1}$:
  - timing allows to mitigate pileup effects
  - Ghost rate suppression
  - Better association between tracks upstream and downstream the magnet



- Timing can be included in different sub-detectors already in Run4, i.e. in ECAL, RICH, TORCH
- Timing can be considered also in pattern recognition and track reconstruction
  - Not only for timestamping tracks
  - Promising UFSD and 3D silicon sensors R&Ds could allow ~30ps hit resolutions in Upgraded VELO