A Silicon Vertex Detector with Timing for the Upgrade II of LHCb

15th Pisa Meeting on Advanced Detectors

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on behalf of the LHCb VELO group

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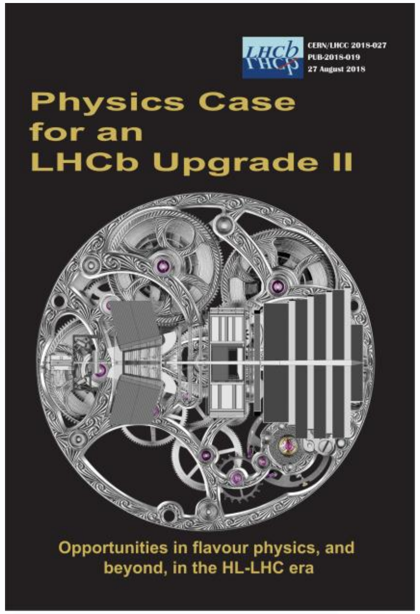
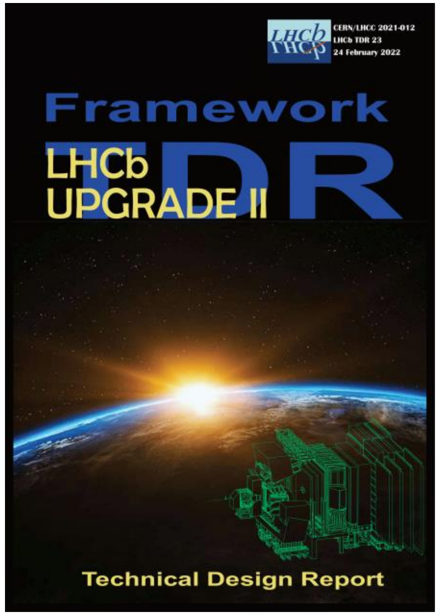
Motivations

LHCb: dedicated heavy flavour experiment at LHC

Why the upgrade:

- Need much more data to further test theoretical predictions
- Extended physics case in flavour physics and beyond (https://cds.cern.ch/record/2636441)
- Run at higher luminosity (300 fb^{-1} for Run 5) →Hence need for new/improved detector



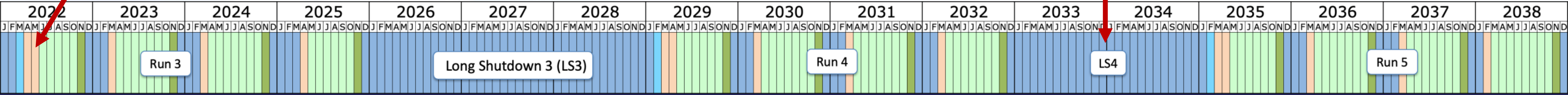


Upgrade I installation has just finished

Ramping up developments for Upgrade II

- To be installed in LS4 (~2033)

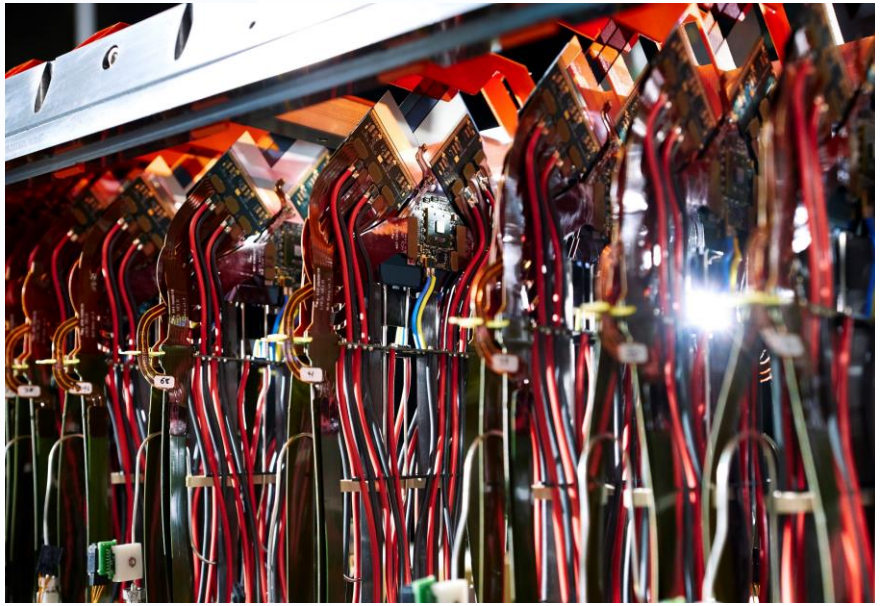
Upgrade I installation finished



More information in Gianluca poster: "The Upgrade of LHCb VELO"

VErtex LOcator (VELO) Upgrade I

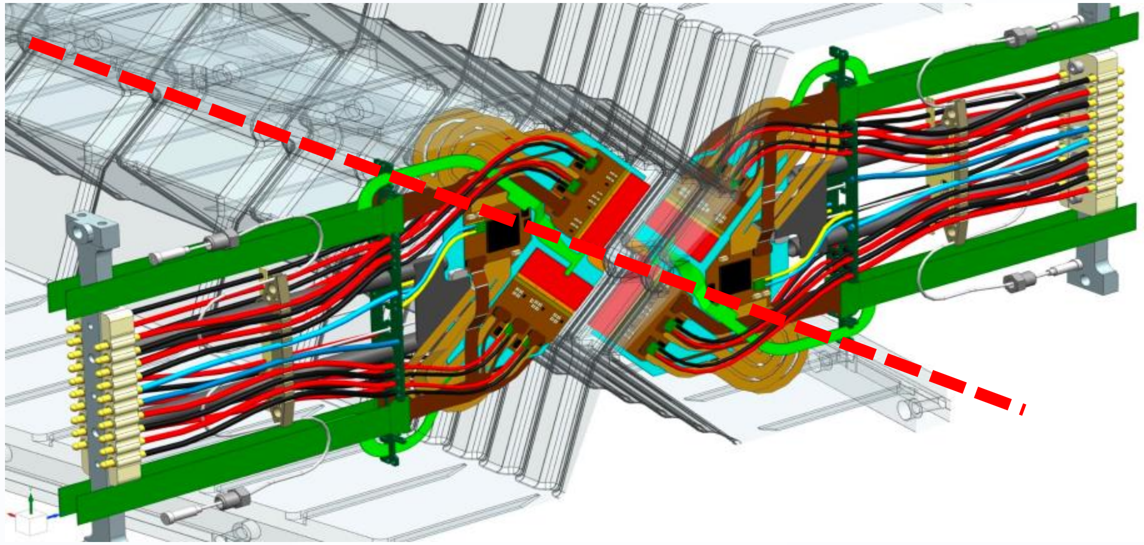
LHCb detector is fully equipped in the forward region, optimised for studies of decays of *b* and *c* hadrons



Picture of half of the VELO detector, now installed in LHCb

The **VELO** is a silicon tracker surrounding the interaction region:

- Capable of **discern** between **primary and secondary vertices**
- **5.1 mm from beam** in secondary vacuum
- 52 modules with 4 sensors each
  - 768x256 pixels of 55x55 μm^2



Upgrade II conditions

Increased pileup and luminosity :
increased fluence and readout rates

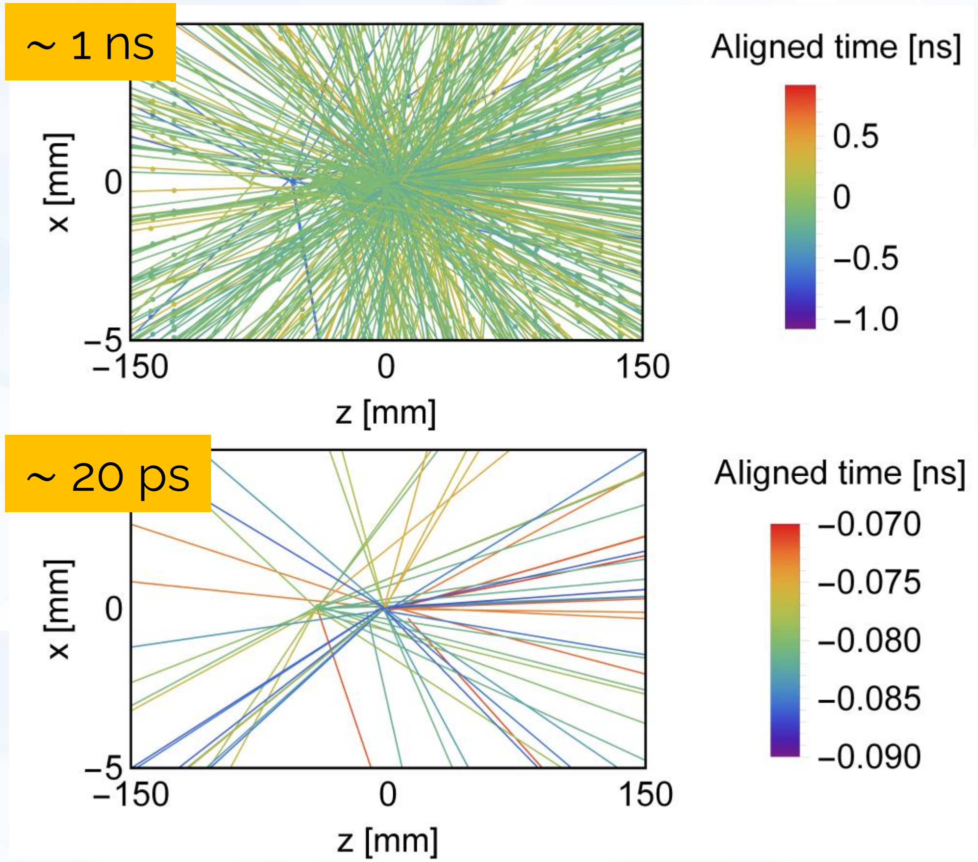
Maintain precision of VELO Upgrade I to reach LHCb's physics goals

	Run1-2	Upgrade I	Upgrade II
Inst. Luminosity [$cm^{-2}s^{-1}$]	~4×10^{32}	~2×10^{33}	~1.5×10^{34}
Luminosity / year [fb^{-1}]	2	7	~ 50
Visible Pileup	1.8	7	~ 50
Integ. Fluence [$MeVn_{eq}$ /cm^2]	4.3×10^{14}	8×10^{15}	6×10^{16}
Readout rate /ASIC [10^6 hits/s]		600	~ 4500

Several challenges: high occupancy, radiation hardness needs and non-uniform irradiation damage, material budget, higher data rates, etc

Several studies need to be done:
- **Importance of timing**
- Different **layout scenarios**
- **Sensor and ASIC technologies** under study
- Material budget: **RF foil**; **vacuum tank** and **cooling**

Importance of timing



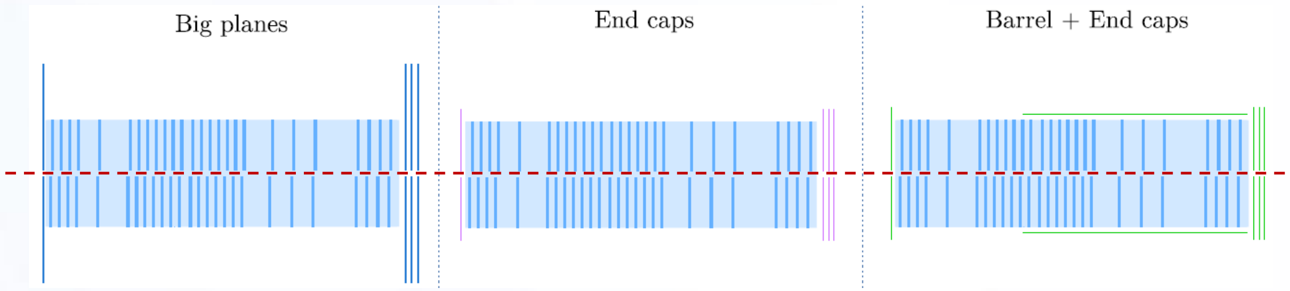
Higher pileup implies **primary vertex separation** from Upgrade I reduced to a much smaller value of **1.5 mm** at Upgrade II

Proton bunches overlap for a finite time (RMS ~ **180 ps**) with this, in 1 ns we have many collisions overlapped

Increasing the resolution to **20 ps** only a few collisions and corresponding tracks remain

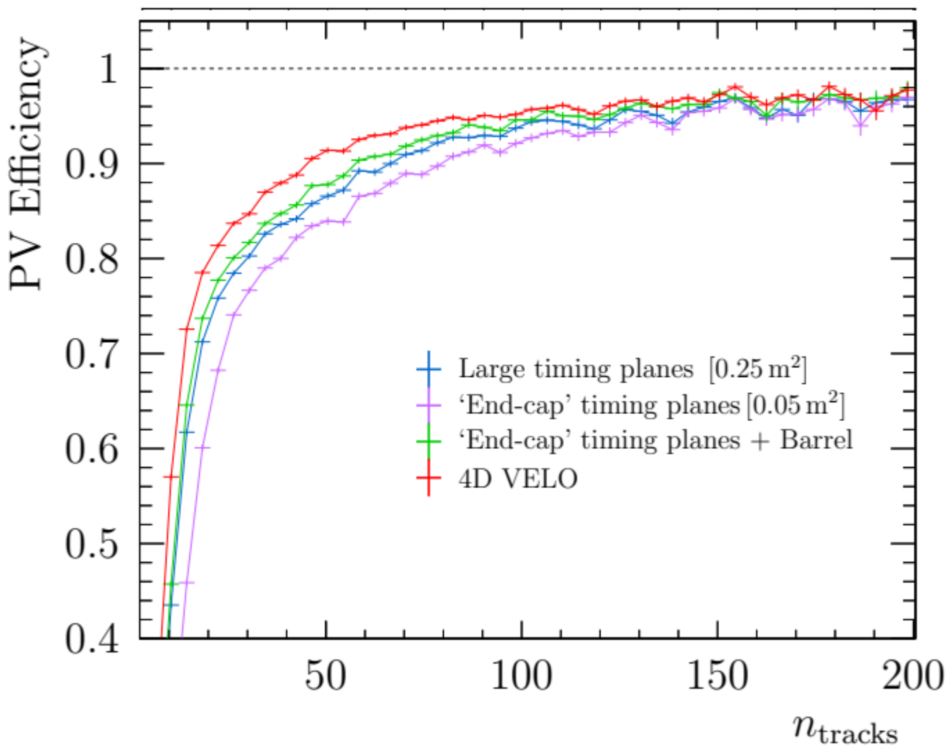
Thus, it is necessary good temporal resolution!

Temporal resolution options



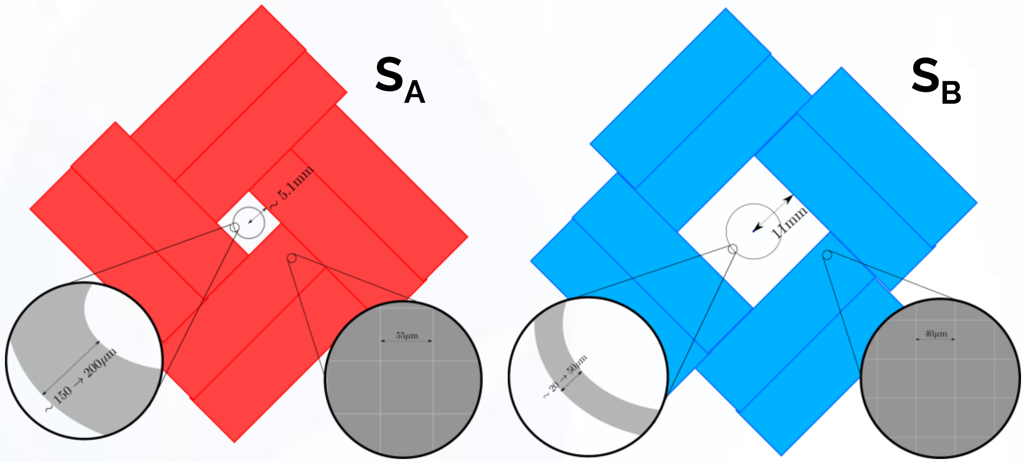
Dedicated timing planes

- Greater distance to luminous region -> less radiation hardness
- Three segmented timing layers required to provide independent timestamps
- Single measurements need at least 25 ps resolution
- Much higher detector area, restrains in material budget and higher price



Full 4D Tracking: Precise timing at every hit

- Requires individual hit resolutions of 50 ps
- Better efficiency in pattern recognition and vertex reconstruction
- Reduction of ghost track rate



Sensor layout scenarios

Innermost radius of the VELO is a key driving parameter. Consider two limit scenarios (anything in between is an option), keeping impact parameter resolution at Upgrade I levels

Scenario A (S_A):

- **Innermost radius** is kept at **5.1 mm**, sensor layout same as Upgrade I
- ASIC needs to deal with a factor **~7.5 times higher hit rate** than the VELO Upgrade I ASIC (plus timing)
- Huge radiation dose means regular **detector replacements** likely needed

Scenario B (S_B):

- **Radius** relaxed to **12.5 mm**, cluster occupancies match those of Upgrade I
- Increased distance to the collision point requires significantly **better hit resolution**
  - Reduce the pixel size to less than 42µm
- **Material** before the second hit needs to be dramatically reduced
  - Requires lighter RF foil, but also improvements in sensor, ASIC and substrate materials, and would require major mechanical redesign.

Sensor and ASIC requirements

Sensor R&D is closely matched to the ASIC development

These will govern scenario choices and be important input to decision of inner radius

Pixel pitch and matrix size dependant on innermost radius in order to **maintain spatial resolution** from Upgrade I

For S_A the **dose** is **beyond** the **limit** of what many radiation hard sensors can withstand -> **need of replacements**

Requirement	scenario S_A	scenario S_B
Pixel pitch [µm]	≤55	≤42
Matrix size	256×256	335×335
Time resolution RMS [ps]	≤ 30	≤ 30
Loss of hits [%]	≤ 1	≤ 1
TID lifetime [MGy]	> 24	> 3
ToT resolution/range [bits]	6	8
Max latency, BXID range [bits]	9	9
Power budget [W/cm^2]	1.5	1.5
Power per pixel [µW]	23	14
Threshold level [e$^-$]	≤ 500	≤ 500
Pixel rate hottest pixel [kHz]	> 350	> 40
Max discharge time [ns]	< 29	< 250
Bandwidth per ASIC of 2 cm^2 [Gb/s]	> 250	> 94

Sensor and ASIC requirements

For scenario S_A a maximum **pixel hit rate** of **350 kHz** implies a mean time between hits of ≈30 µs.

To keep the **pileup of hits < 1 %** the discharge time should be < 29 ns

In scenario S_A, average track rate estimate of ≈64 tracks per bunch crossing for the ASIC closest to the interaction region, with **hit rate of 3.8 Ghits/s**

Assuming pixel packet size of 44 bits, plus a safety factor, **required bandwidth** for scenario S_A becomes **250 Gb/s per ASIC**

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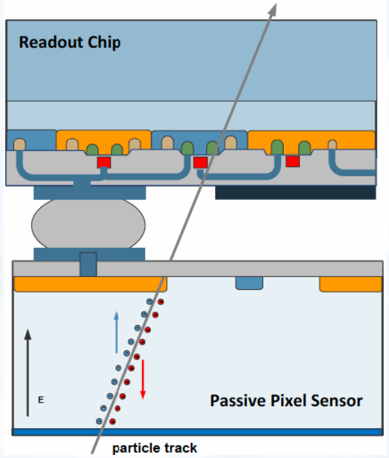
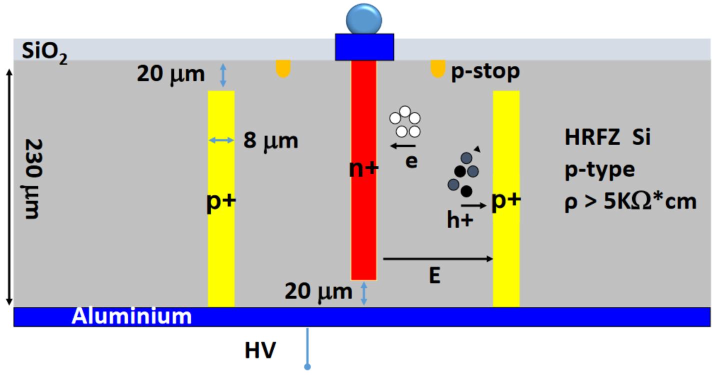
Sensor technologies

More information on 3D sensors in my poster:
"Tracking the Time: Single cell 3D pixel time resolution and Landau contribution evaluation via test-beam and laboratory measurements"



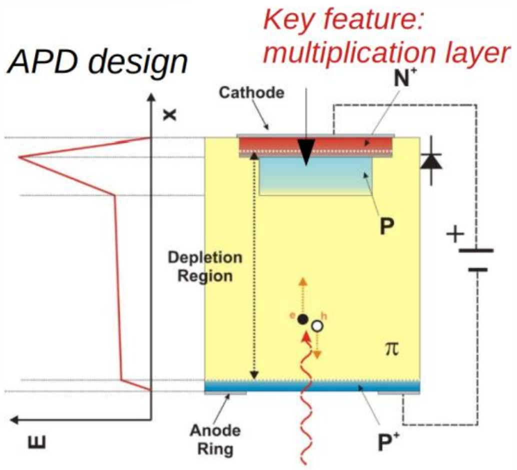
Planar sensors: (Used in Upgrade I)

- Time resolution achievable with low thickness
- Low thickness → more uniform weighting field
- High fluence resistance → low collected charge
- Signal proportional to thickness: Faster → thinner → less signal → FE challenge
- Not clear timing goals achievable while maintaining signal/noise



3D sensors:

- Good radiation resistance
- 3D geometry also benefits timing performance (small column to column distance)
- Signal proportional to thickness
- Time resolutions range of 20 ps
- Inefficient volumes at the columns (challenge high geometrical efficiency at small pitch)



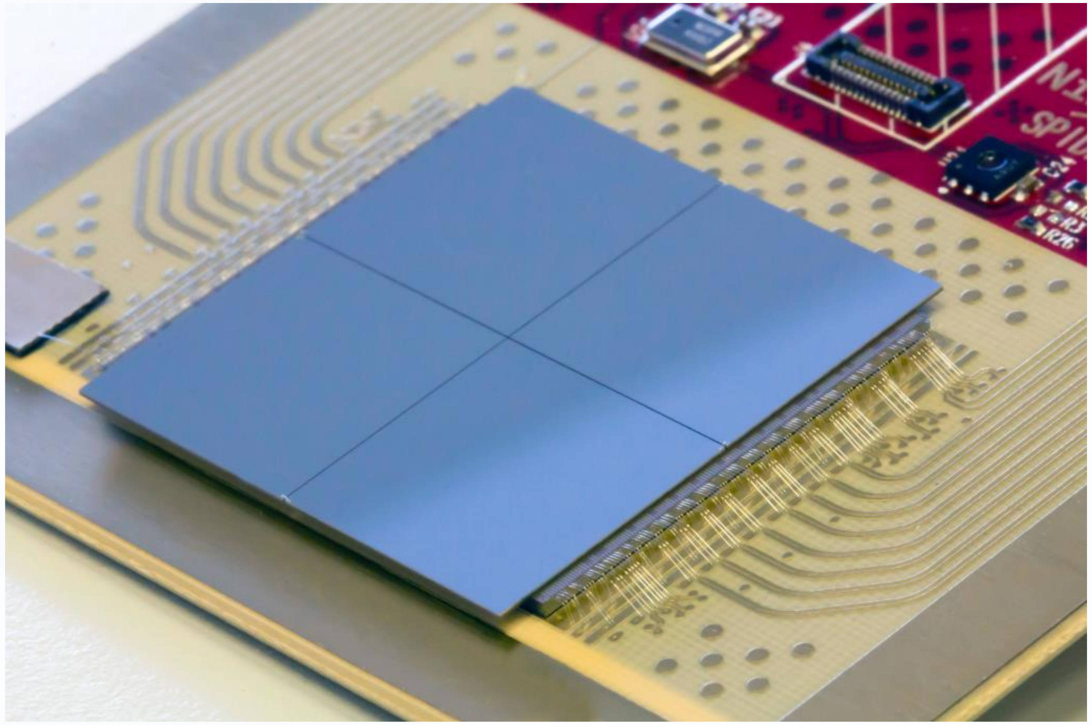
Low Gain Avalanche Detector (LGAD):

- Thin high field layer → Excellent timing performance
- Gain structure is placed in the sensor itself →Good gain at small thickness
- Time resolutions range from 20 to 40 ps
- Gain drop as function of fluence (acceptor removal)
- non-uniform irradiation → difficult tune sensor gain

ASIC technologies

VeloPix ASIC for Upgrade I developed in collaboration with the Medipix group (130 nm)

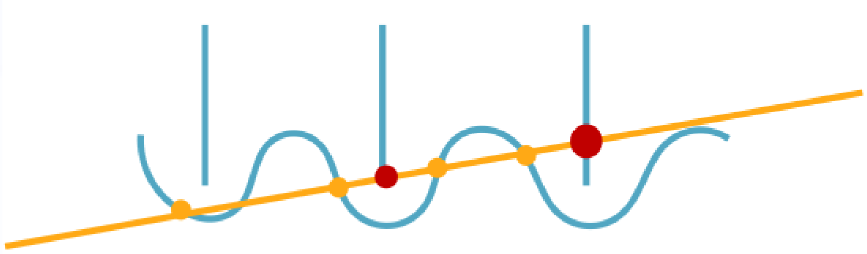
- The next generation of this ASIC, the **VeloPix-II**, would be implemented in 28 nm technology with 55μm pixels
- **TIMESPOT** demonstrator chips (Timespot0 and Timespot1) implemented in 28 nm CMOS are also promising:
  - 55 μm pitch, optimised for 3D-trench sensors

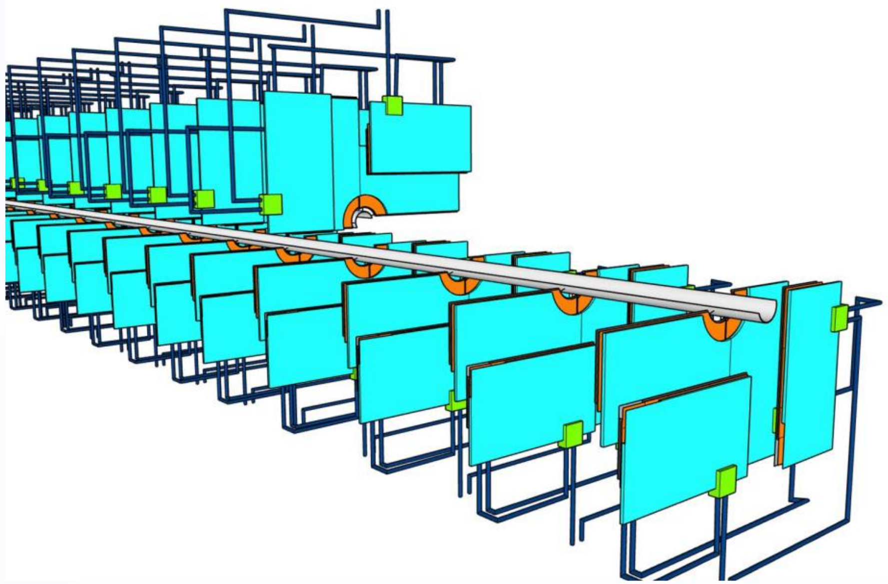


Timepix4 (65nm, Medipix4 collaboration, 2019)

Material budget: RF foil

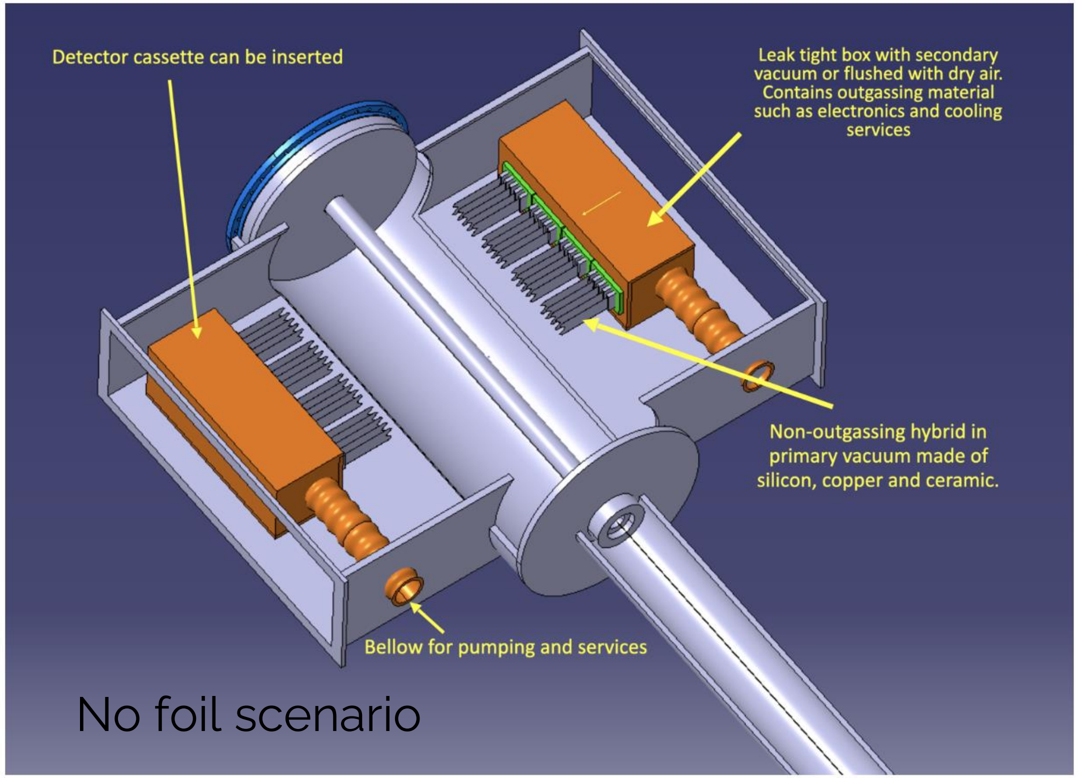
- **Guides beam mirror current** to avoid wakefield excitation
- **Shield** the detector electronics from **RF pickup** of the beams
- **Separate** the high purity primary LHC vacuum from the **secondary detector vacuum** (need to tolerate 10 mbar pressure difference)
- Lower the constraints on material outgassing
- **Corrugated foil** helps to tolerate pressure difference**.** Benefits also on reducing amount of material before first measured point





A **thinner foil**, or even the **complete removal** of the foil could potentially reduce significantly the multiple scattering term of the impact parameter resolution

Vacuum tank

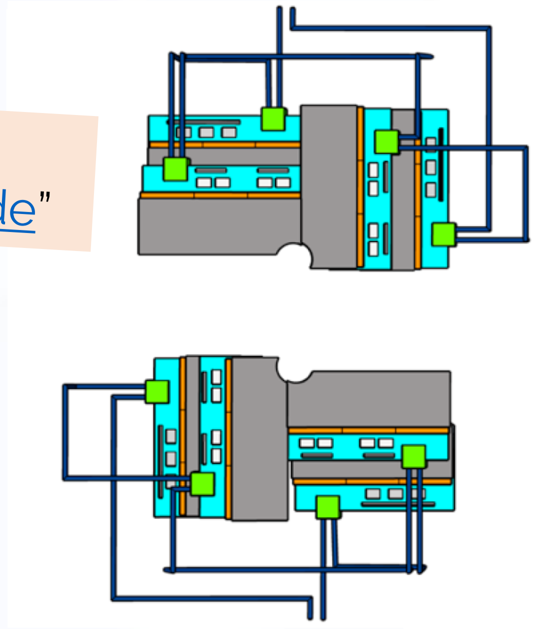


Possible mechanical redesign of vacuum tank:

- **Detector modules** can be **swapped** during technical stops due to high irradiation (luminosity ~50 fb^{-1}/year)
- Different designs for **different RF foil approaches** (no foil or different positions/shapes) implies better vacuum and bakeout resistance
- Space for **VELO modules movement** to approach beam line
- Allocation of new cooling system

Cooling

More information in Oscar's talk:
"Microchannel cooling for the VELO Upgrade"



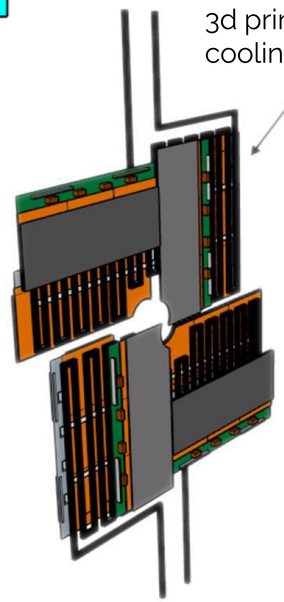
Modules must be **kept cold** to **prevent thermal runaway** caused by leakage current after sensors are irradiated.

In the **VELO Upgrade I**: CO_2 cooling via Silicon micro channel plates

Upgrade II modules will **dissipate more power**: need of lower temperatures, other coolants (such as Krypton) being considered

- Other factors to consider such as **large scale production** for replacement (careful consideration of fluidic connector)

Alternative substrate solutions involve **3D-printed technologies** such as titanium



Summary

Studies for LHCb Upgrade II are underway, with the detector planned to be installed during LS4

- **2 layout scenarios**:
  - S_A very close to the beam line, requires extreme radiation tolerance and high data transmission
  - S_B requires higher precision hit resolution and a reduction of material budget
- Precise timing: needed **resolution** of **20 ps**
- **4D tracking** performance better than separate timing planes, with lower overall cost
- R&D is underway for sensors and electronics**: Fast timing sensors** show promising results, could satisfy **spatial and temporal resolution**
- **Material budget** is an important challenge, several RF foil scenarios considered
- New **vacuum tank and cooling system** must be designed to reach Upgrade II needs

Thank you for your attention!

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Backup

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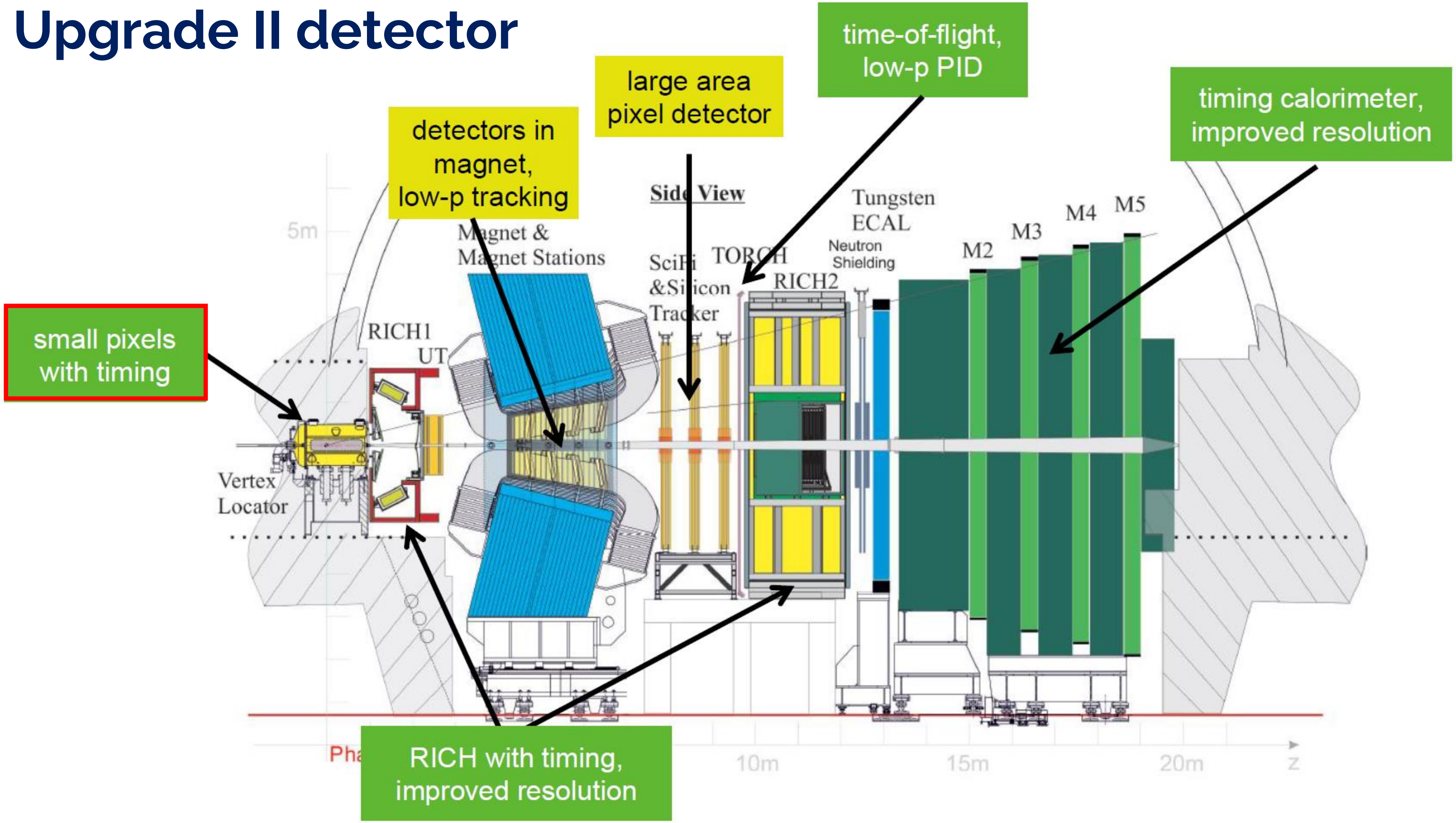
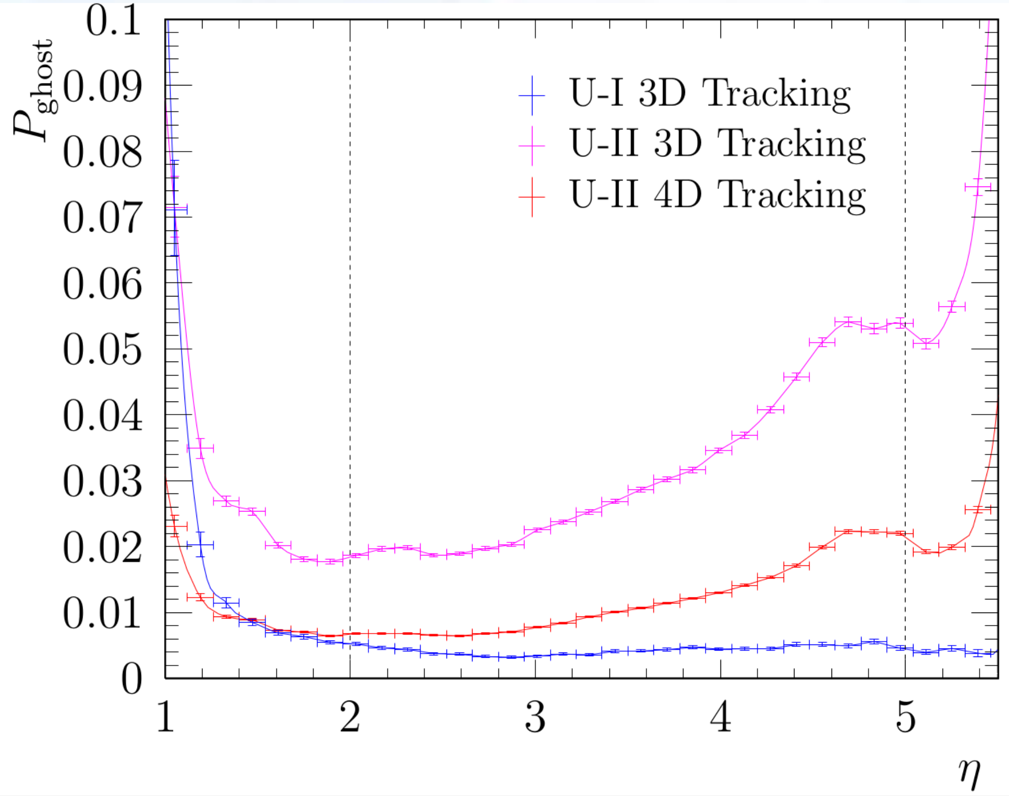
Upgrade II detector



Tracking



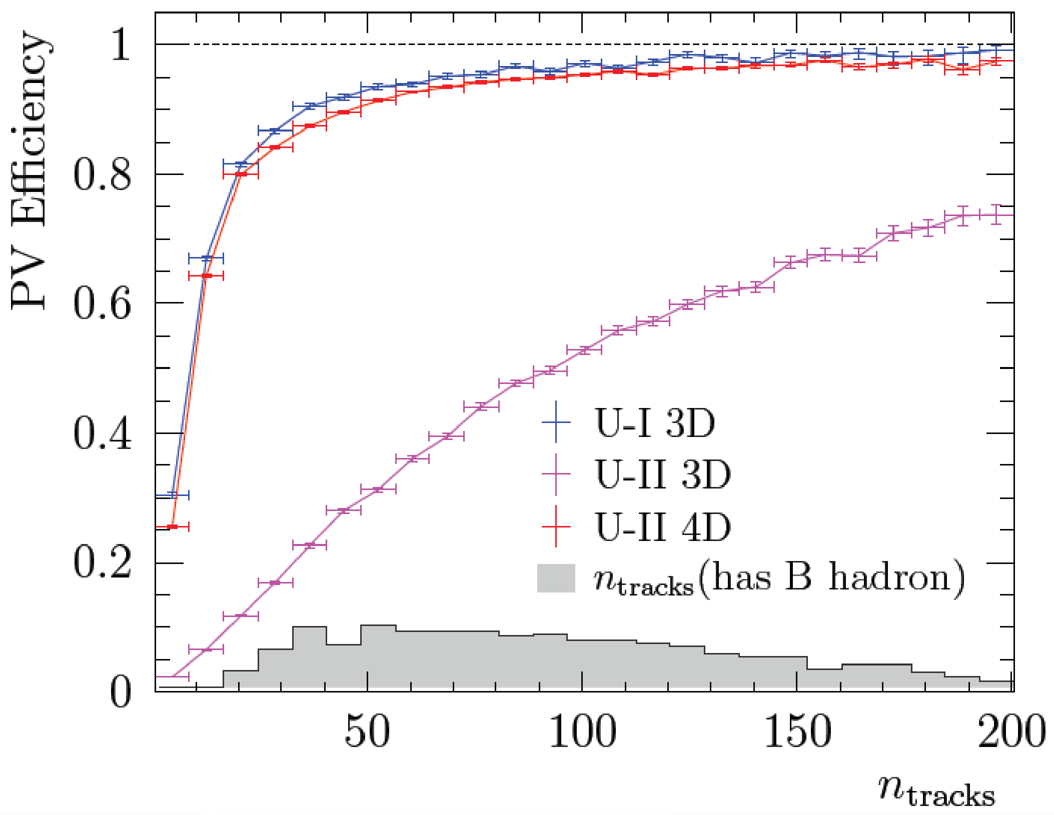
Including timing in tracking extremely advantageous

- Improved efficiency and spatial uniformity
- Reduces rate of ghost tracks
- Reduces combinations of random tracks

And more…

Temporal resolution options

- 4D tracking shows higher efficiency in primary vertex reconstruction
- Timing planes needs to develop a second sensor and ASIC solution, implement it over a relatively large surface area
- The impact of timing layers on the material budget must be carefully controlled
- Higher pattern recognition efficiency in 4D tracking



Dedicated timing planes

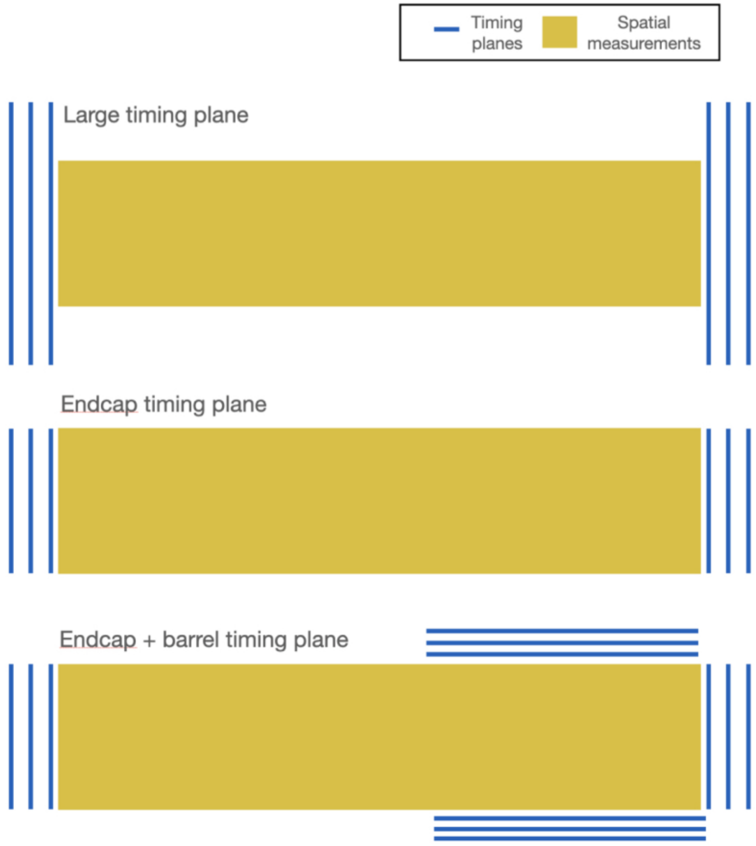
At least three segmented timing layers are required to be able to provide independent timestamps

Different configurations of the planes considered:

- “Large”: Covers the LHCb acceptance requires 0.25 m2 of silicon per layer
- “Endcap”: Partial LHCb coverage, but reduced area of 0.05 m2
- “Endcap + barrel”: Recover missing coverage with a partial forward barrel layer

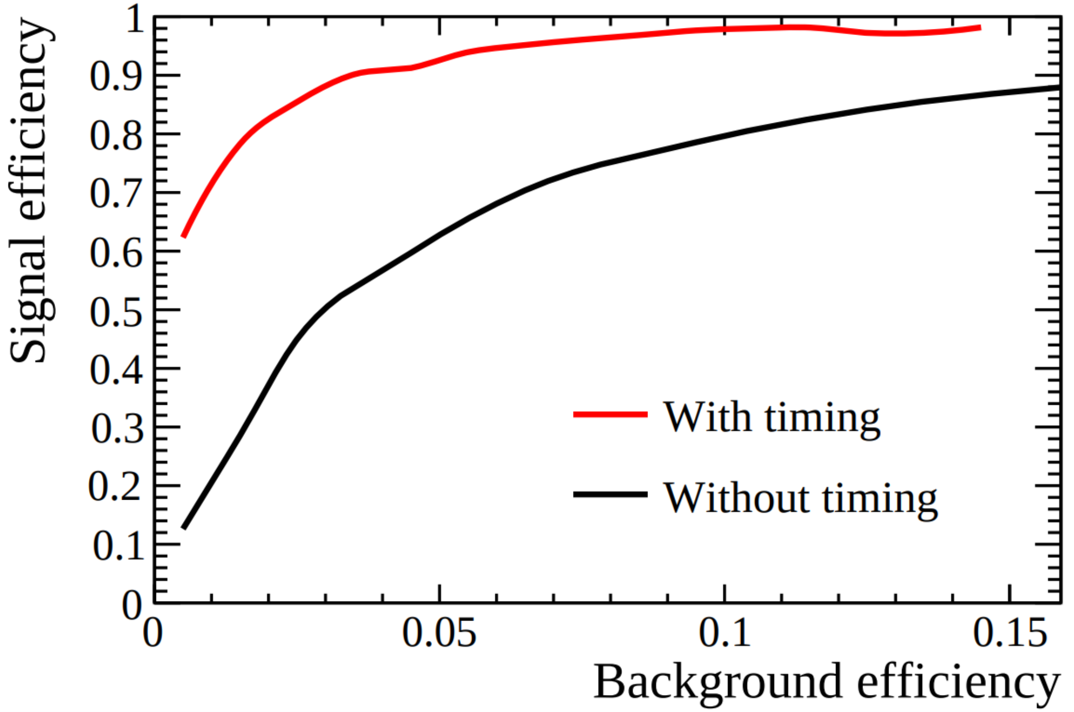
Some benefits:

- Greater distance to luminous region -> less radiation hardness



Physics signal reconstruction efficiency

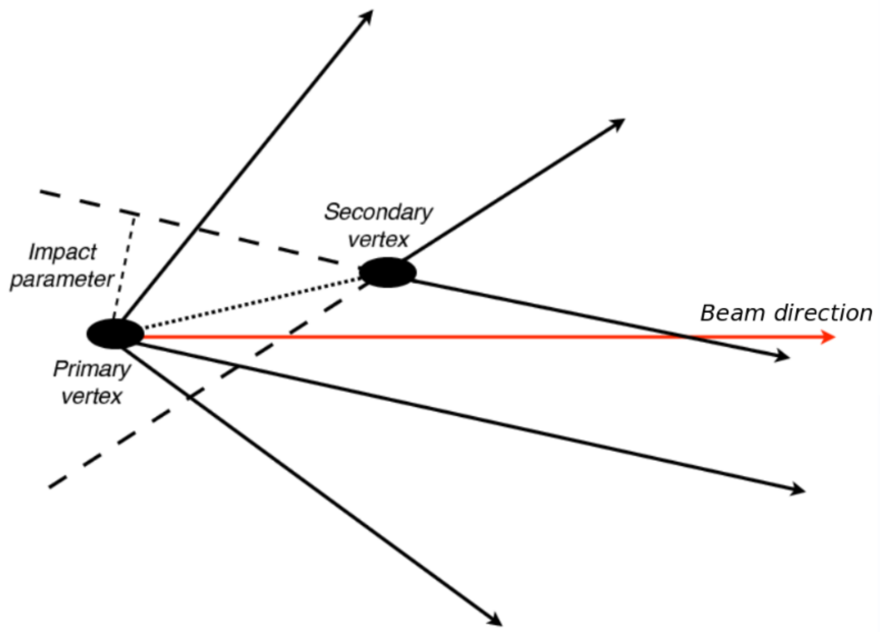
Including timing in tracking extremely advantageous



Impact parameter

Critical quantity for signal selection is **impact parameter** (IP): distance of closest approach between the reconstructed track and primary vertices

Importance to reconstruct **correlated secondary and primary vertices** for heavy flavour physics. Spatial and time resolution needs are deeply affected by this



The goal is to keep comparable impact parameter resolution as in Upgrade I, this is highly dependent on:

- The minimal **distance to the beam** line
- The amount of **material**
- The **hit resolution**

Sensor layout scenarios