LHCb Upgrade II: Adding Precise Timing to the Vertex Locator

Upgrade I

Workshop on the physics of HL-LHC, and perspectives at HE-LHC

CERN

1 Nov 2017

Mark Williams

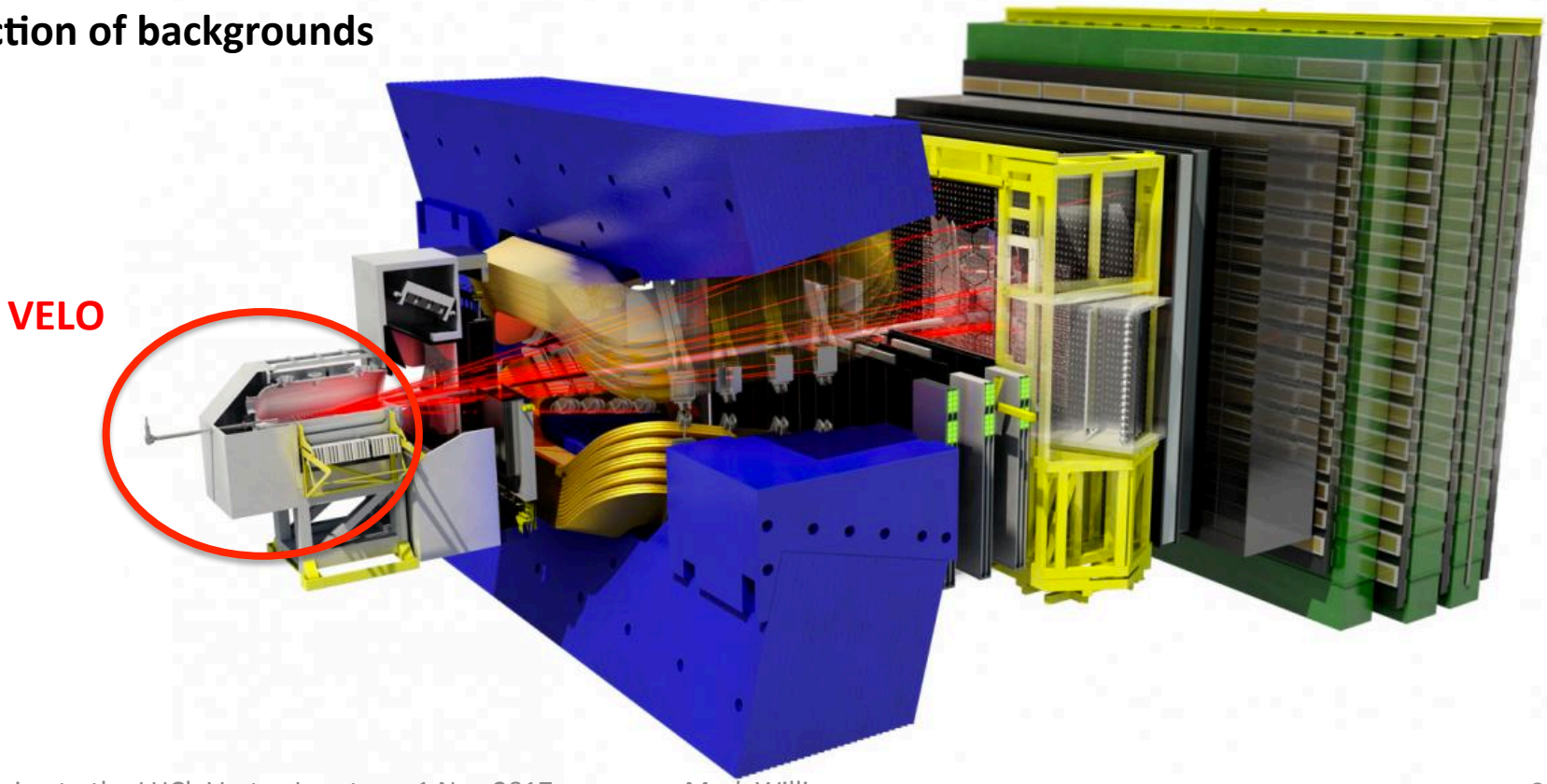
The University of Manchester

Introduction: The LHCb Vertex Locator

Vertex Locator (VELO) – a silicon strip detector surrounding the LHCb luminous region

Provides precise measurements of charged particle trajectories:

- Primary and secondary **vertex reconstruction**
- Precise **lifetime measurements**
- **Rejection of backgrounds**



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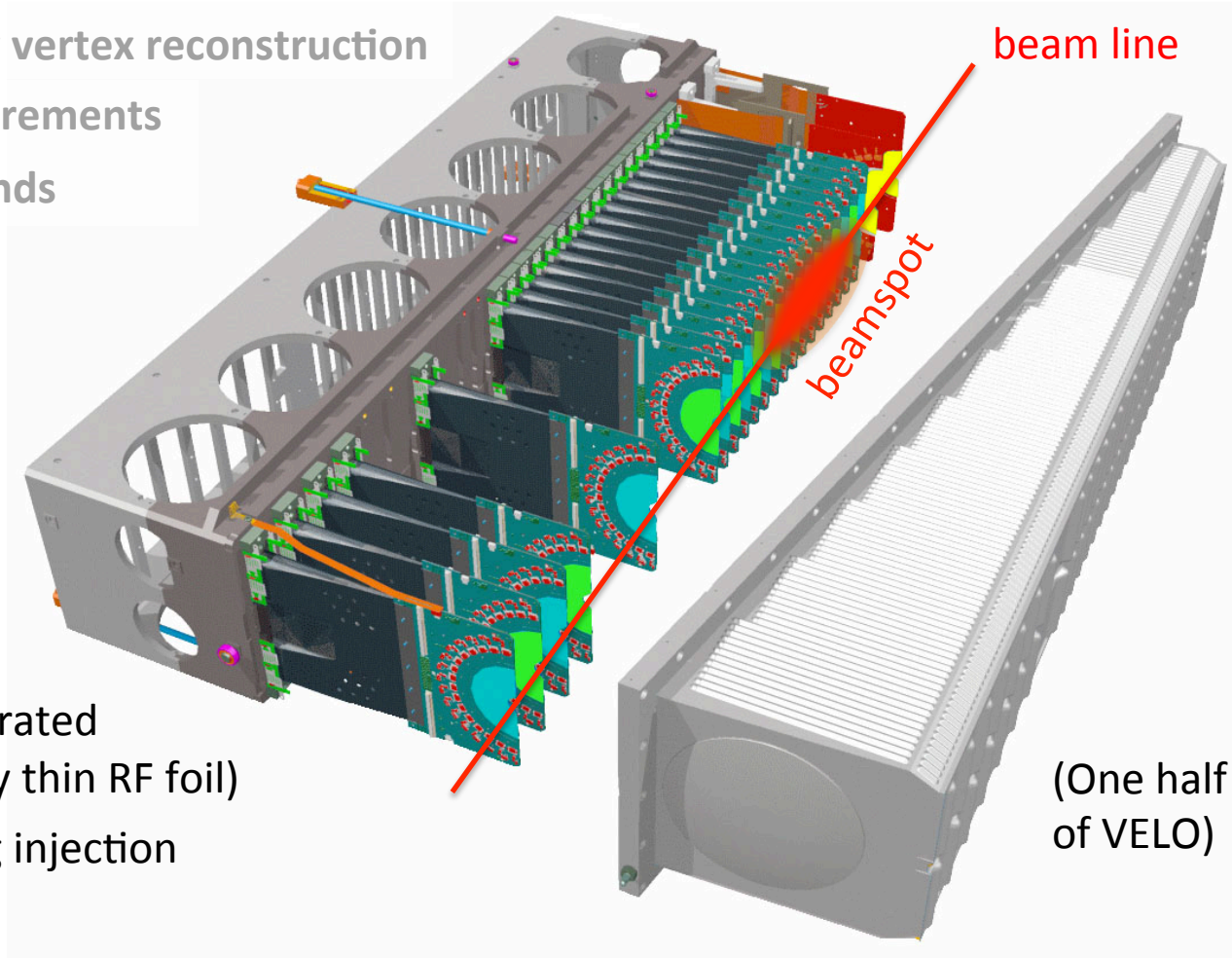
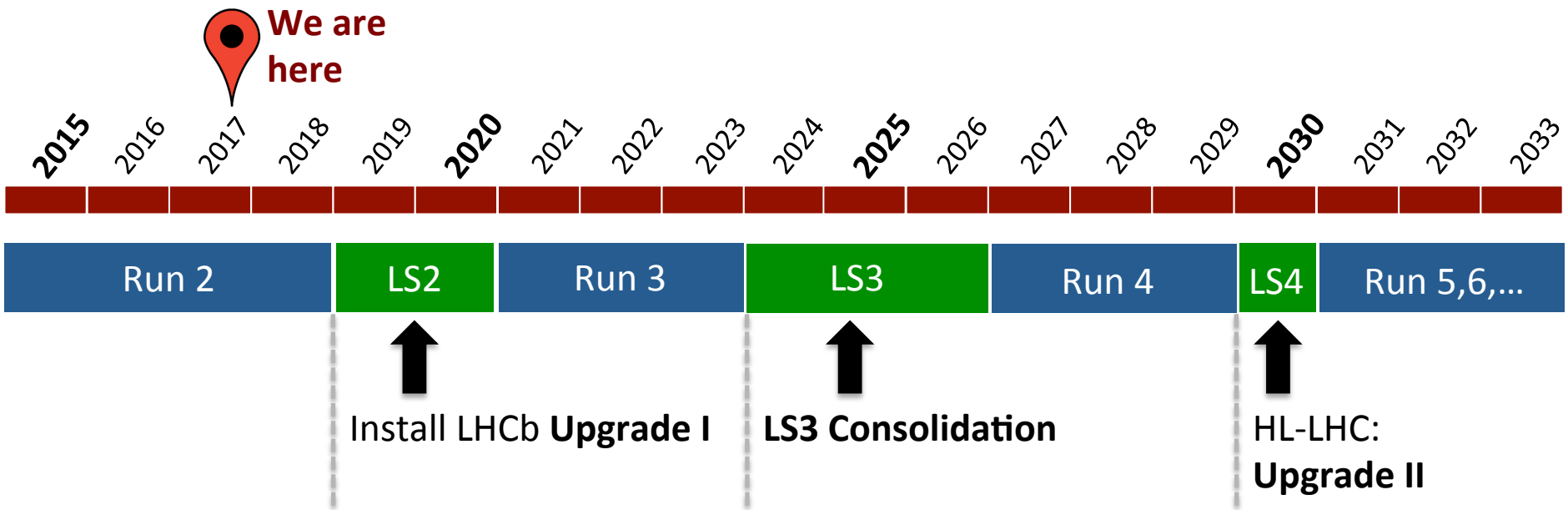


(One half of VELO)

Special Features:

- Within beam pipe (separated from primary vacuum by thin RF foil)
- Detector retracts during injection

Timeline


We are here
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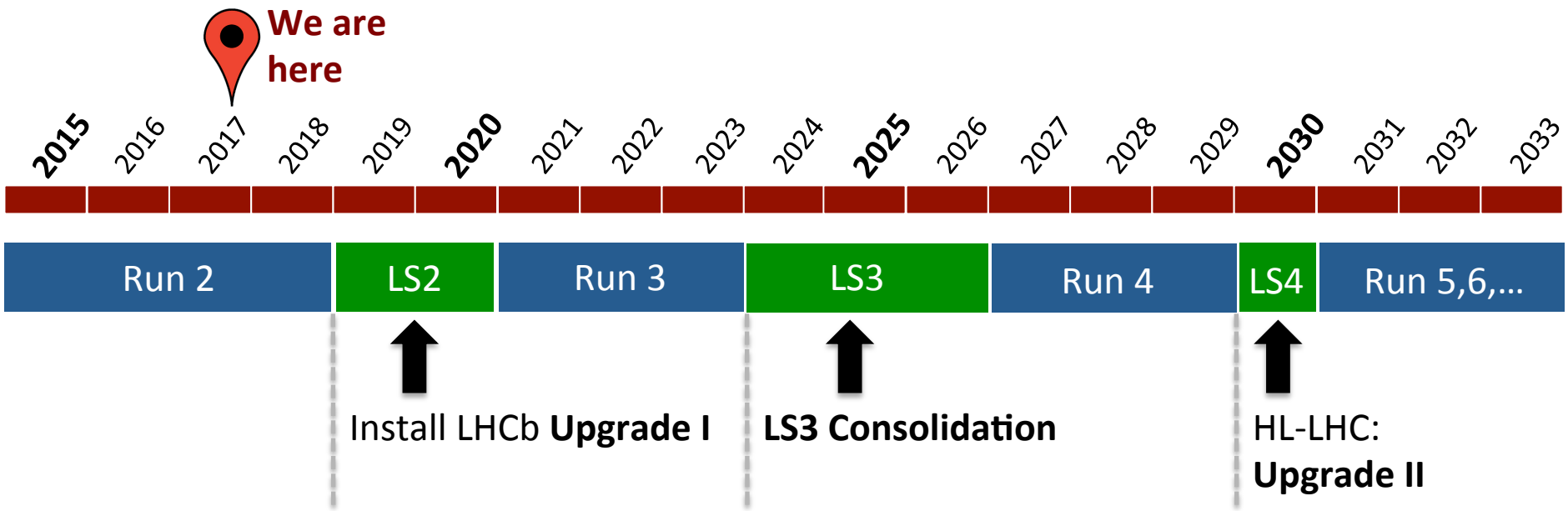
2032
2033
Run 2
LS2
Run 3
LS3
Run 4
LS4
Run 5,6,...
Install LHCb Upgrade I
LS3 Consolidation
HL-LHC:
Upgrade II

Timeline



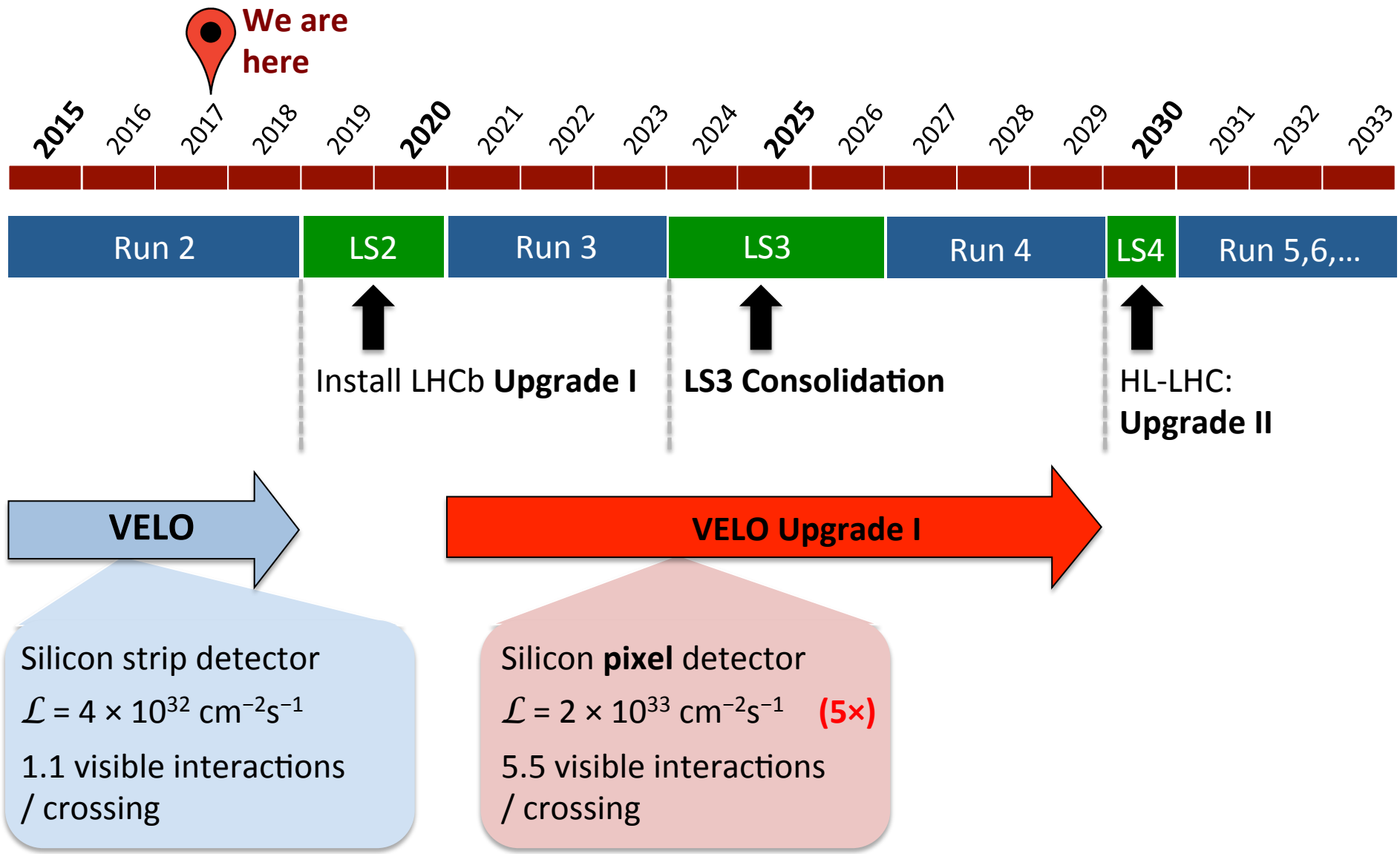
VELO

Silicon strip detector

$\mathcal{L} = 4 \times 10^{32}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$

1.1 visible interactions / crossing

Timeline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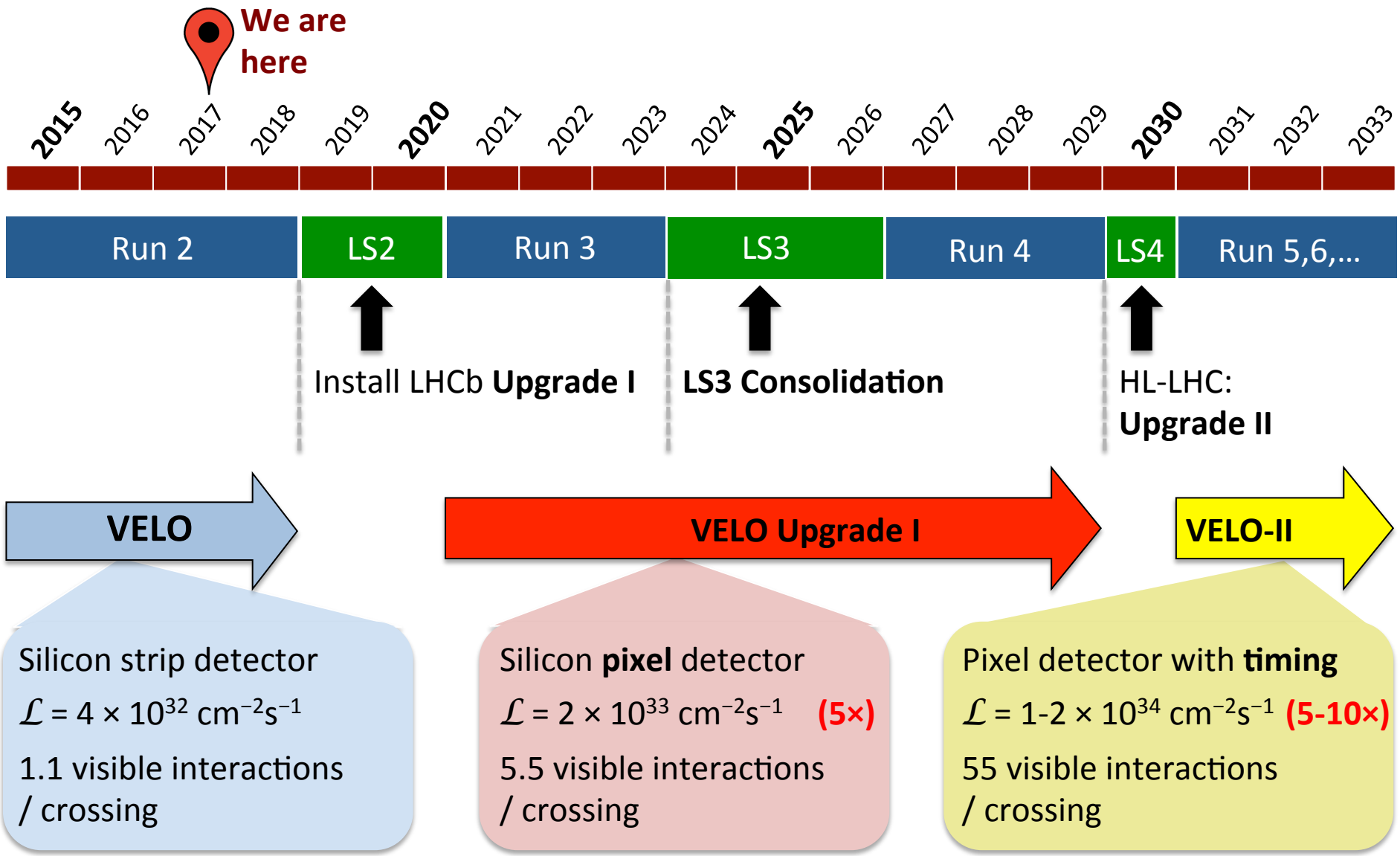
VELO
VELO Upgrade I
Silicon strip detector
$\mathcal{L} = 4 \times 10^{32}$ cm^{-2}s^{-1}
1.1 visible interactions / crossing
Silicon pixel detector
$\mathcal{L} = 2 \times 10^{33}$ cm^{-2}s^{-1} (5×)
5.5 visible interactions / crossing

Timeline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VELO-II
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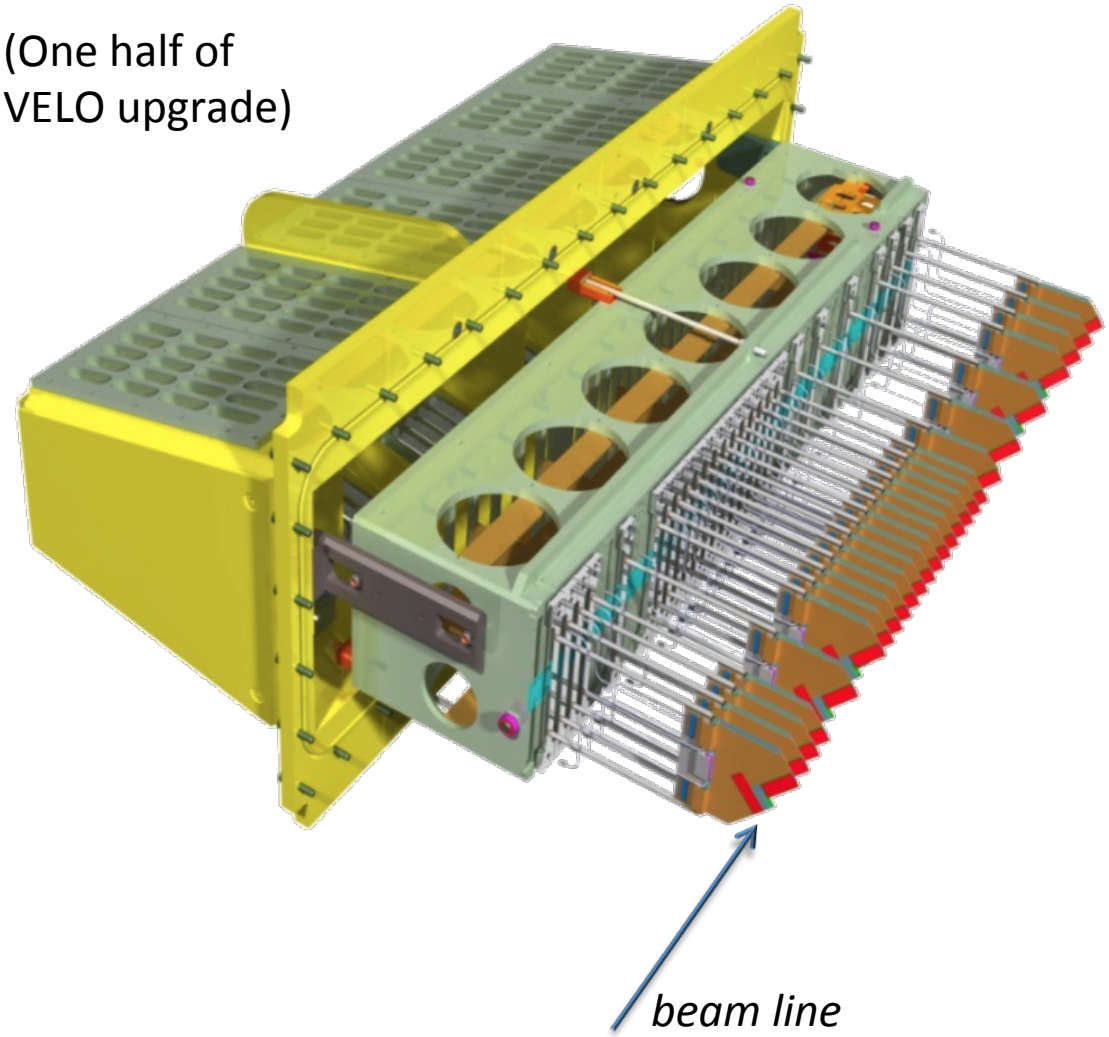
Pixel detector with timing
$\mathcal{L} = 1\text{-}2 \times 10^{34}$ cm^{-2}s^{-1} (5-10×)
55 visible interactions / crossing

VELO Upgrade I

(One half of VELO upgrade)



Major Changes:

- **Pixels** (55µm) to handle higher particle multiplicity
- **Closer to beam** (5.1mm)
- Full **40 MHz read-out**

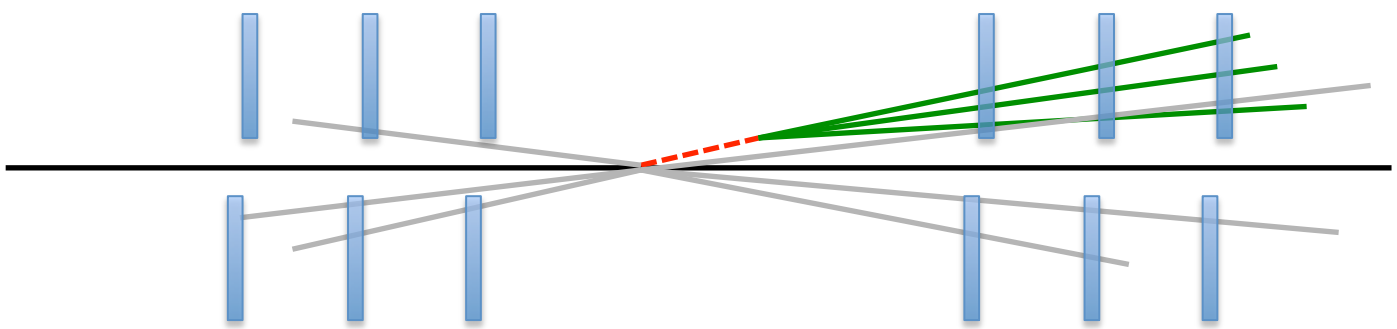
VELO Upgrade II?

We need:

Precision spatial measurements of charged particles

High track-finding efficiency

Low ghost/ clone rate



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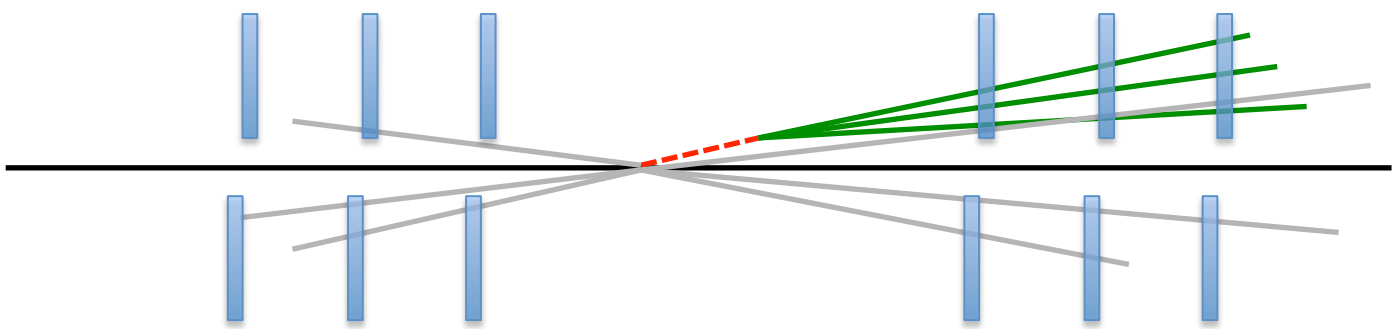
Low ghost/ clone rate

Low material

Close to beam line

Precise single-hit measurements



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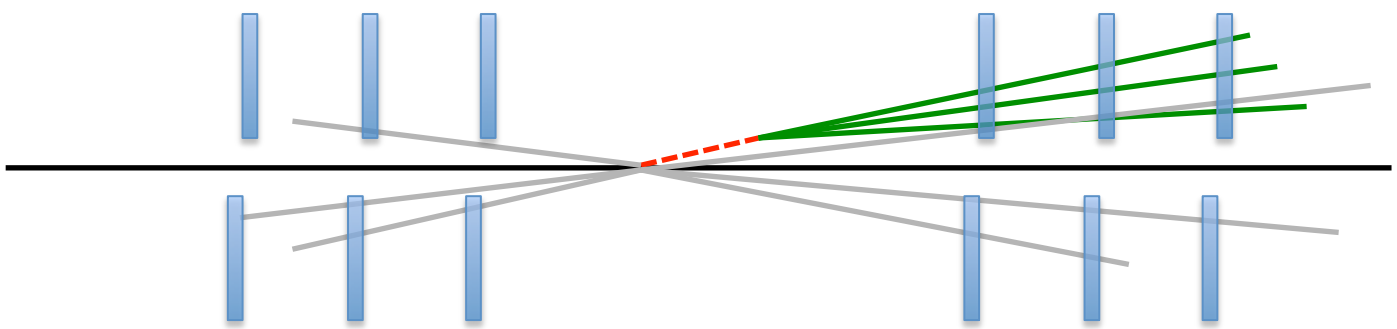
Full coverage within acceptance

High granularity

Multiple O(10) hits per particle



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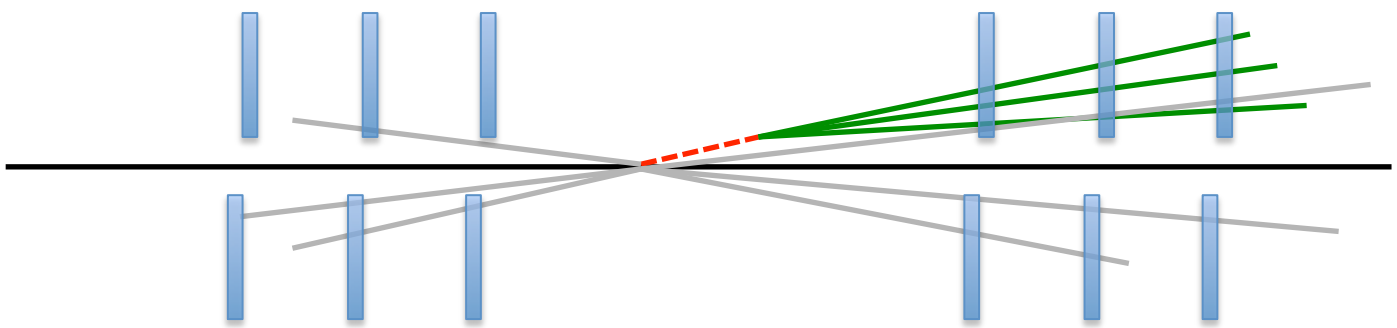

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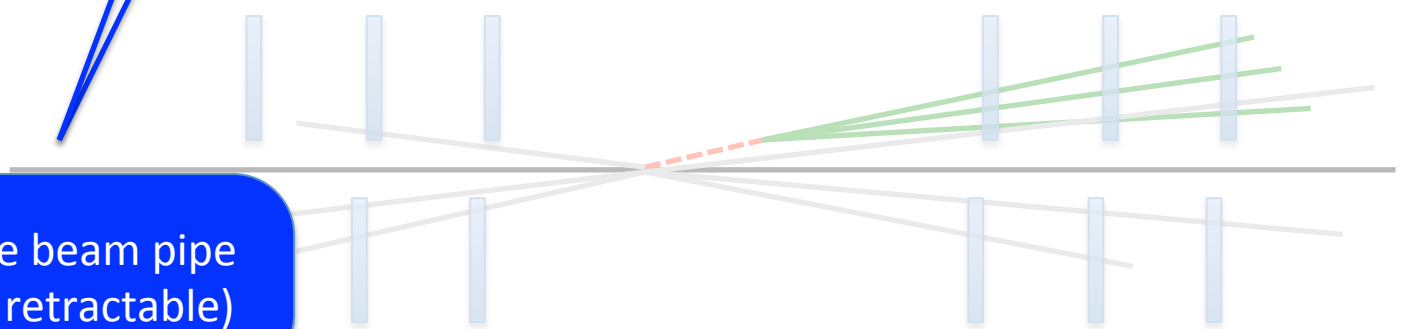

Inside beam pipe (and retractable)

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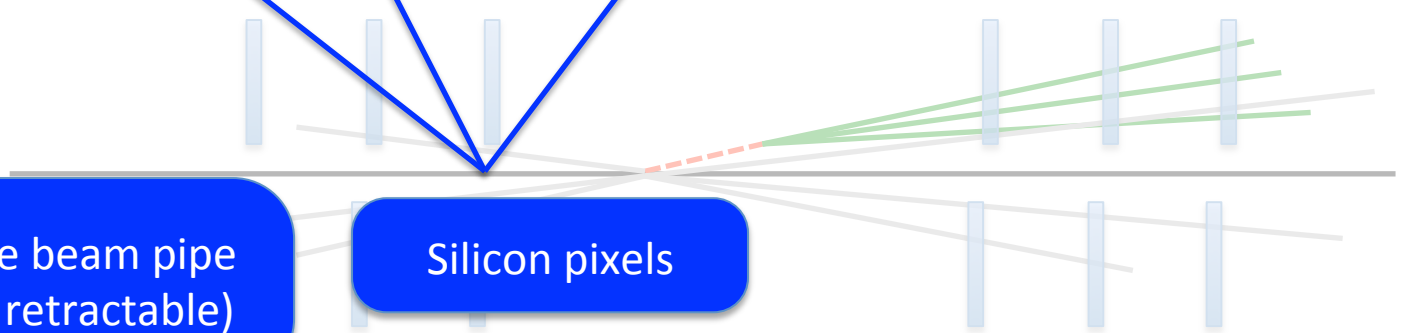

Inside beam pipe (and retractable)

Silicon pixels

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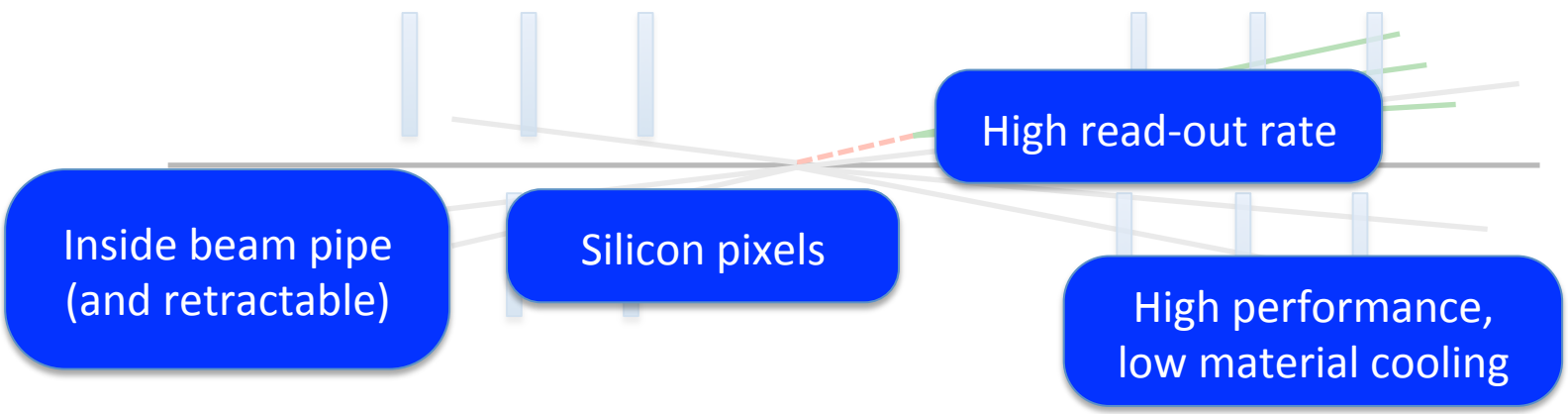
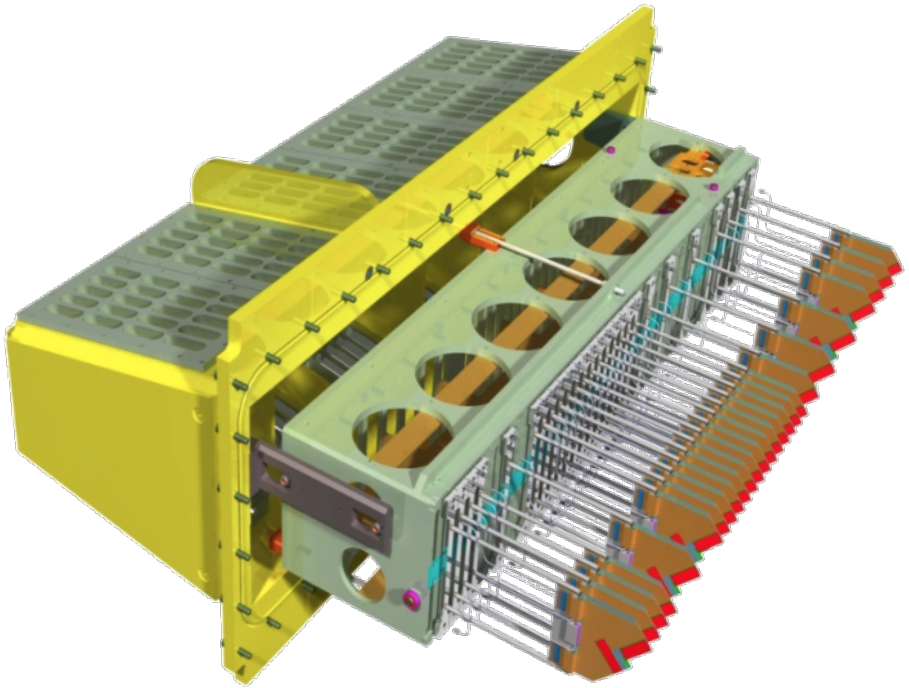
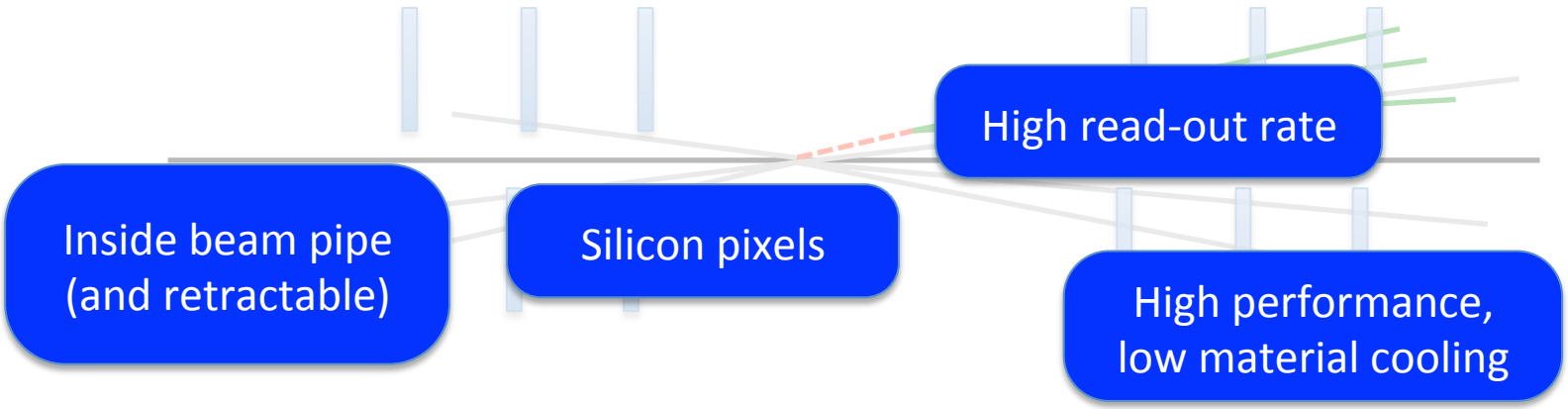


VELO Upgrade II?

Sound familiar?

VELO Upgrade-I must fulfil same basic requirements





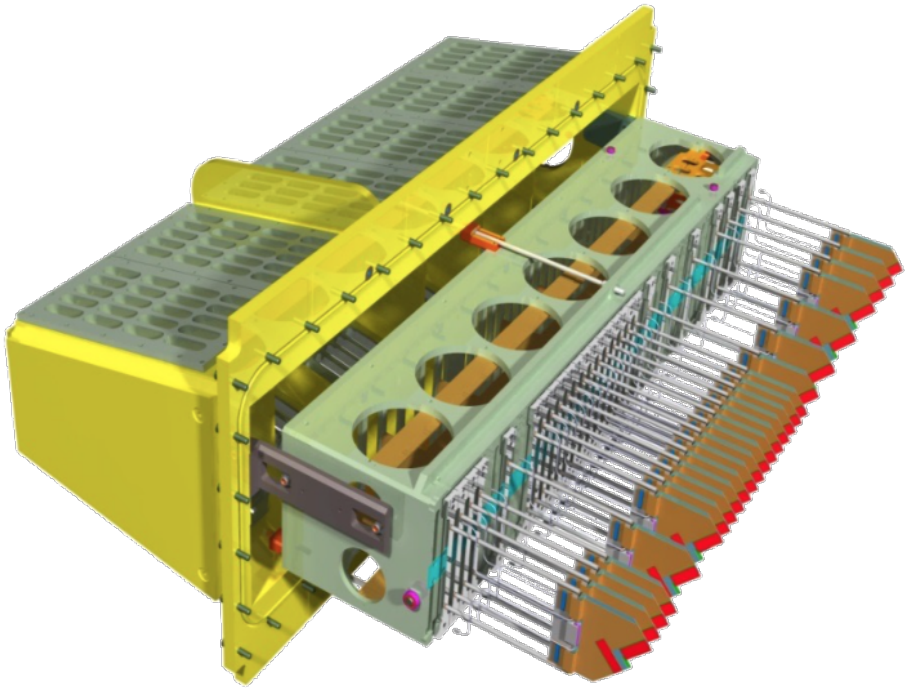
VELO Upgrade II?

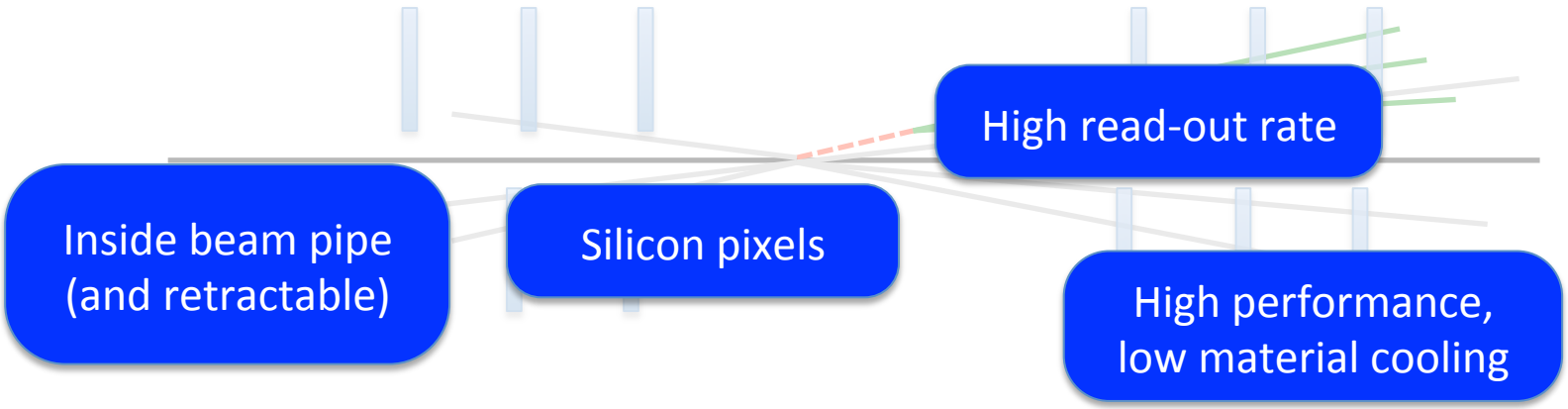
Sound familiar?

VELO Upgrade-I must fulfil same basic requirements

Additional challenges:

- 10x higher particle multiplicity
- 10x denser vertex environment
- 10x higher radiation damage





How can Timing Help

Adding timing information to the pixel hits can potentially recover / gain performance:

- Improved pattern recognition − reduces **hit** combinatorics in tracking
- Improved background rejection − reduces **track** combinatorics when reconstructing decay chains
- Improved PV association − reduced **vertex** combinatorics

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- **Improved PV association – reduced vertex combinatorics**

The main topic of this talk:
using timing to reduce PV mis-association
for long-lived particles

How can Timing Help

Adding timing information to the pixel hits can potentially recover / gain performance:

- Improved pattern recognition – reduces **hit** combinatorics in tracking
- Improved background rejection – reduces **track** combinatorics when reconstructing decay chains
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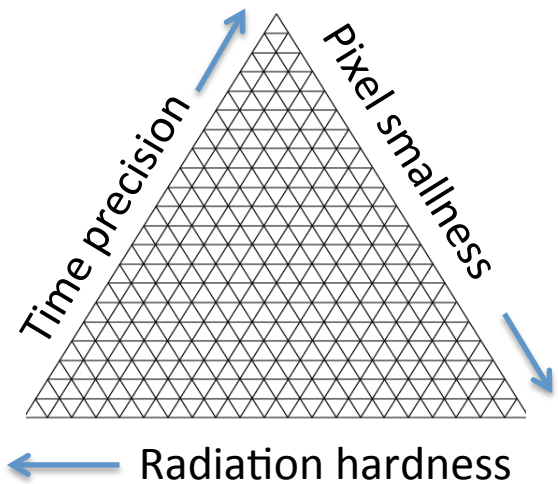
However, must consider impact on (1) pixel size, and (2) radiation hardness

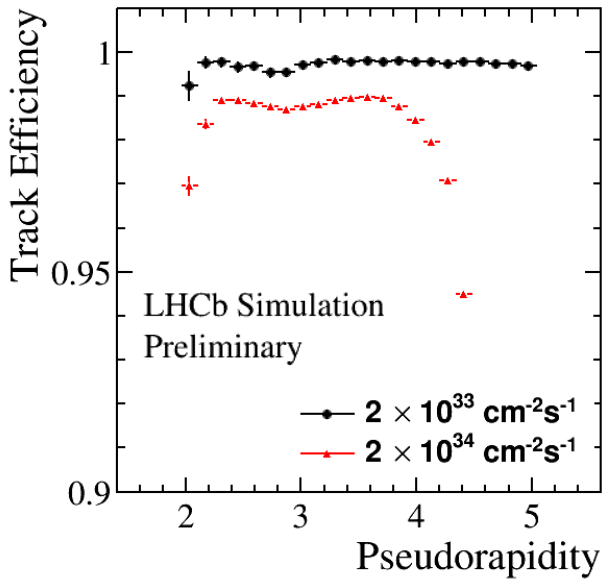
(non-linear scales! – illustration only)



+ extra time information increases required bandwidth

Upgrade II Challenge: 10x particle multiplicity

VELO Upgrade-I performance breaks down at HL-LHC luminosity ($L=2x10^{34}$ $cm^{-2}s^{-1}$)



Tracking efficiency reduced to 96% (not so bad)
+ less flat

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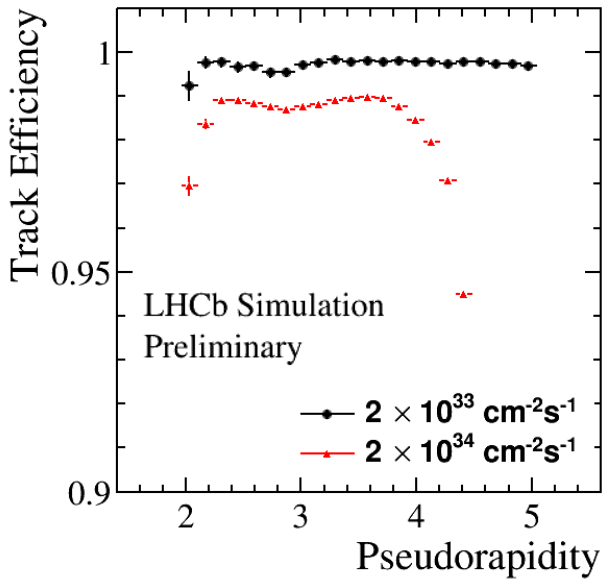

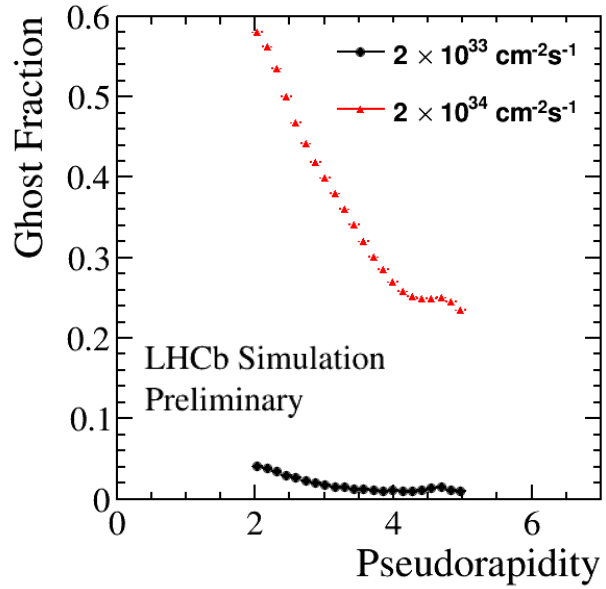

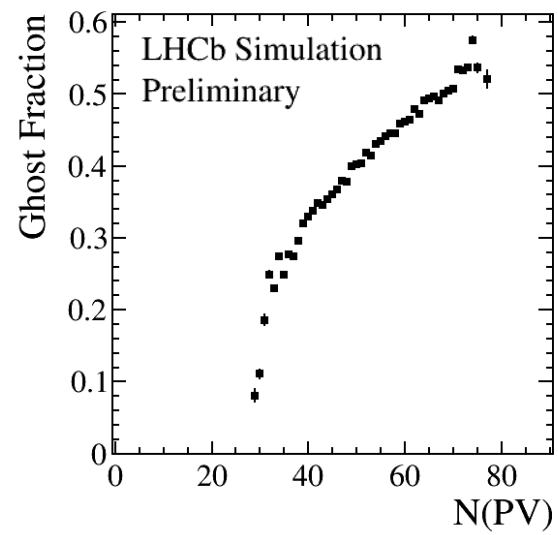

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Ghost rate explodes (~2% → 40%)

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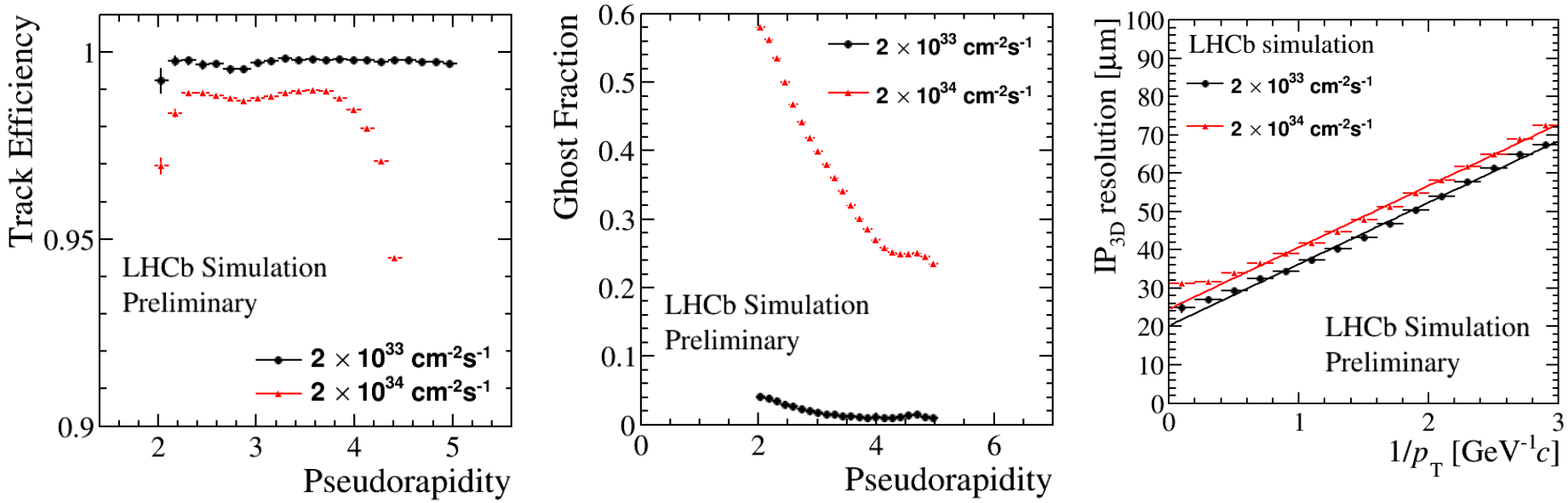

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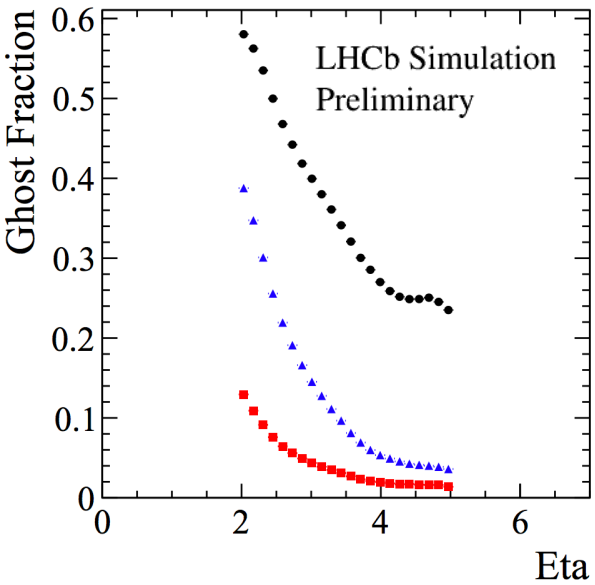
Ghost rate explodes (~2% → 40%)

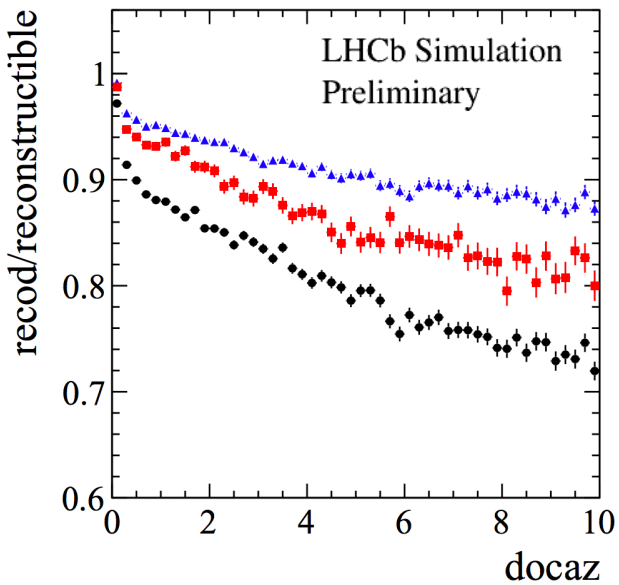
Spatial resolution degrades due to reduced track-finding performance

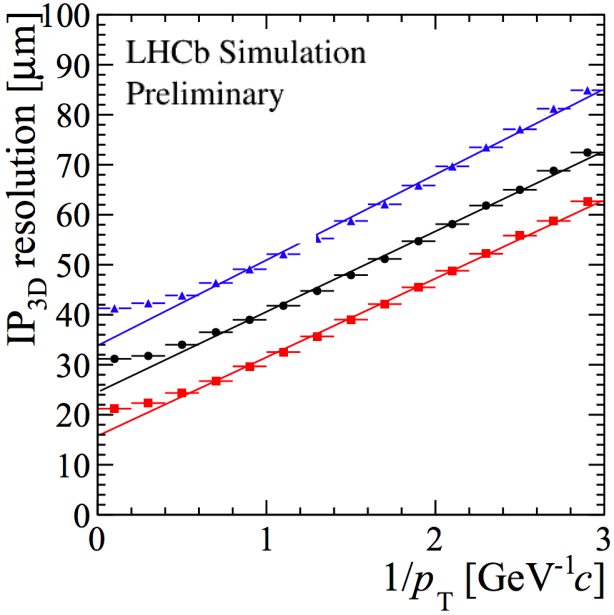
Upgrade II Challenge: 10x particle multiplicity

Can recover most performance with modest improvements: ✔

- Smaller pixels (55µm → 27.5µm)
- Thinner silicon (200µm → 100µm)
- Re-optimised pattern recognition







Only simple re-optimisation for this study – likely significantly more gains to be made

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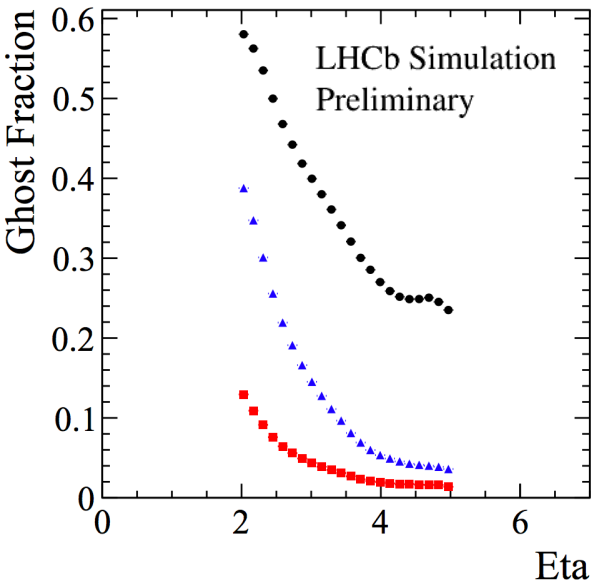
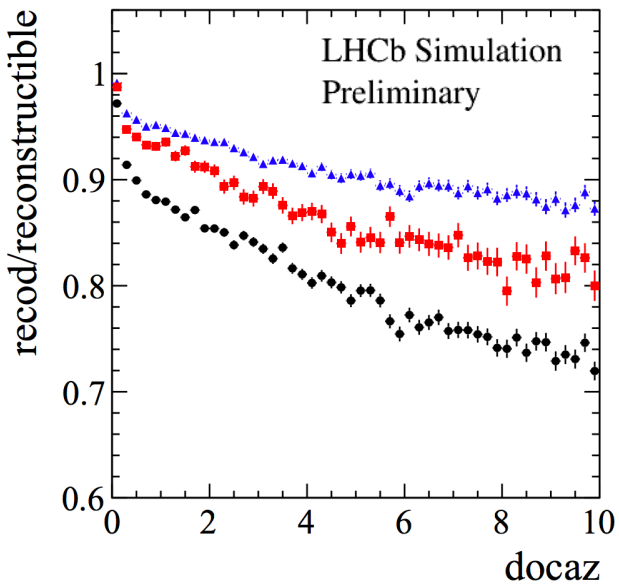
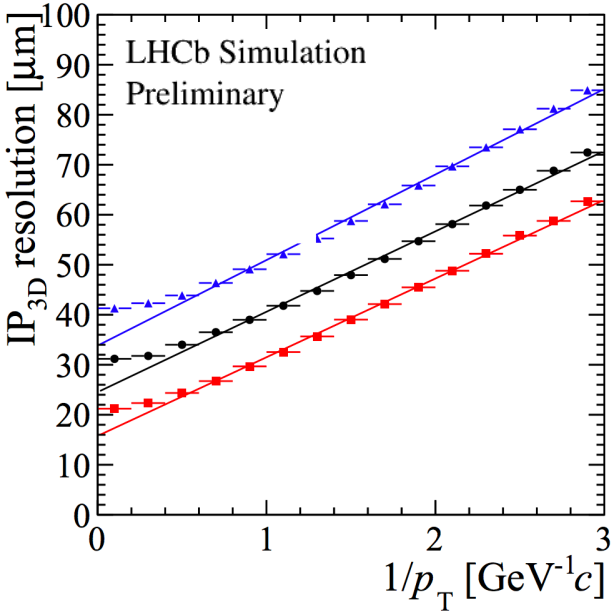






Does this mean that we can live without precise timing?

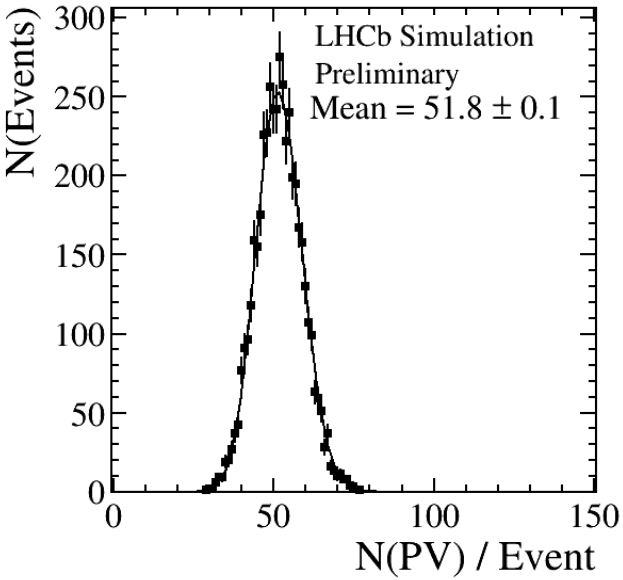
No!

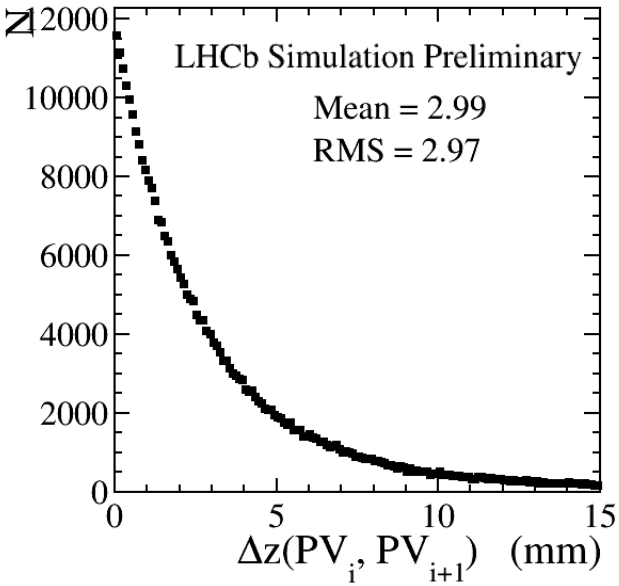
Upgrade II Challenge: 10x vertex multiplicity

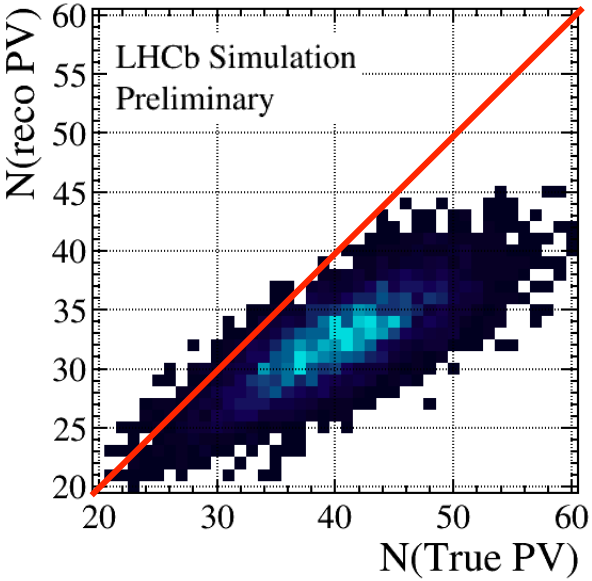
At Upgrade-II luminosity, ~50 visible interactions / crossing

PV separation ~3mm on average, but peaks at very small values (<500µm)

With Upgrade-I detector, PVs start to merge







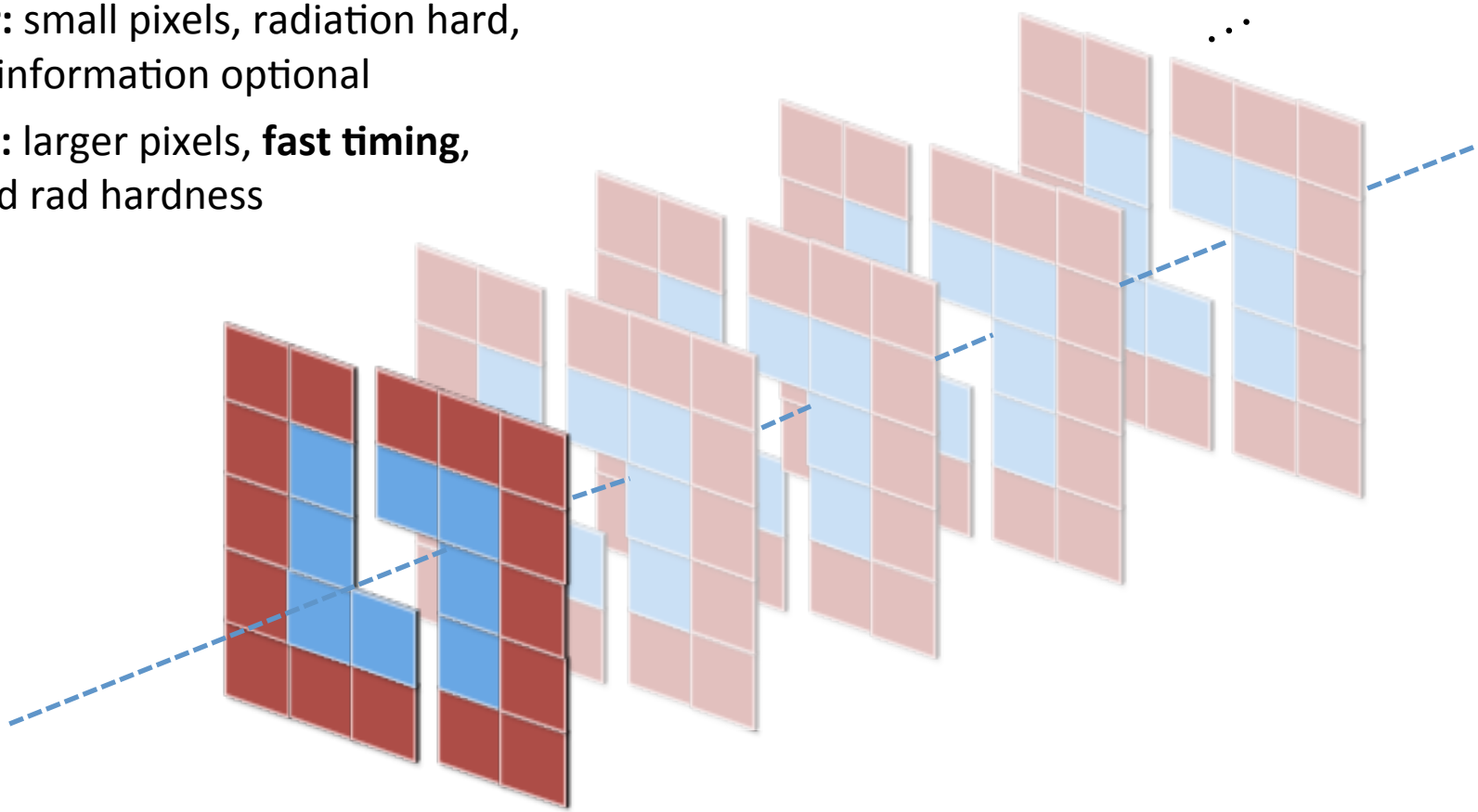
PV **reconstruction** recovered with smaller pixels

BUT we start to suffer from PV-track **mis-association**…

A Possible Upgrade-II VELO: Dual Technologies

Main modules have two technologies:

- **Small-r:** small pixels, radiation hard, timing information optional
- **Large-r:** larger pixels, **fast timing**, reduced rad hardness

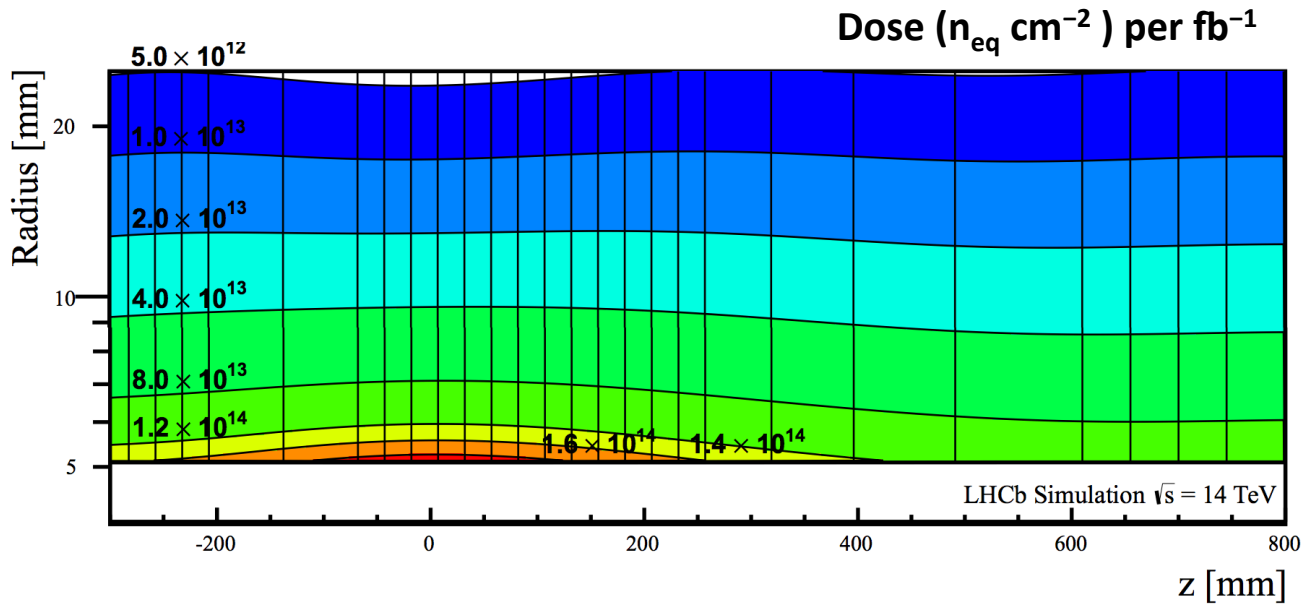


Starting point: use same z-layout as Upgrade-I
Use similar-sized sensor units (15x15mm^2 per square)

Upgrade II Challenge: 10x radiation damage

Highly non-linear radiation dose

Upgrade I:
Maximum dose of
8 x 10^{15} 1 MeV n_{eq} cm^{-2}
after 50fb^{-1}



Upgrade II will see **5-8 x 10^{16} 1 MeV n_{eq} cm^{-2}**
over course of lifetime

This is beyond the limits of current silicon technology – very important to find a solution

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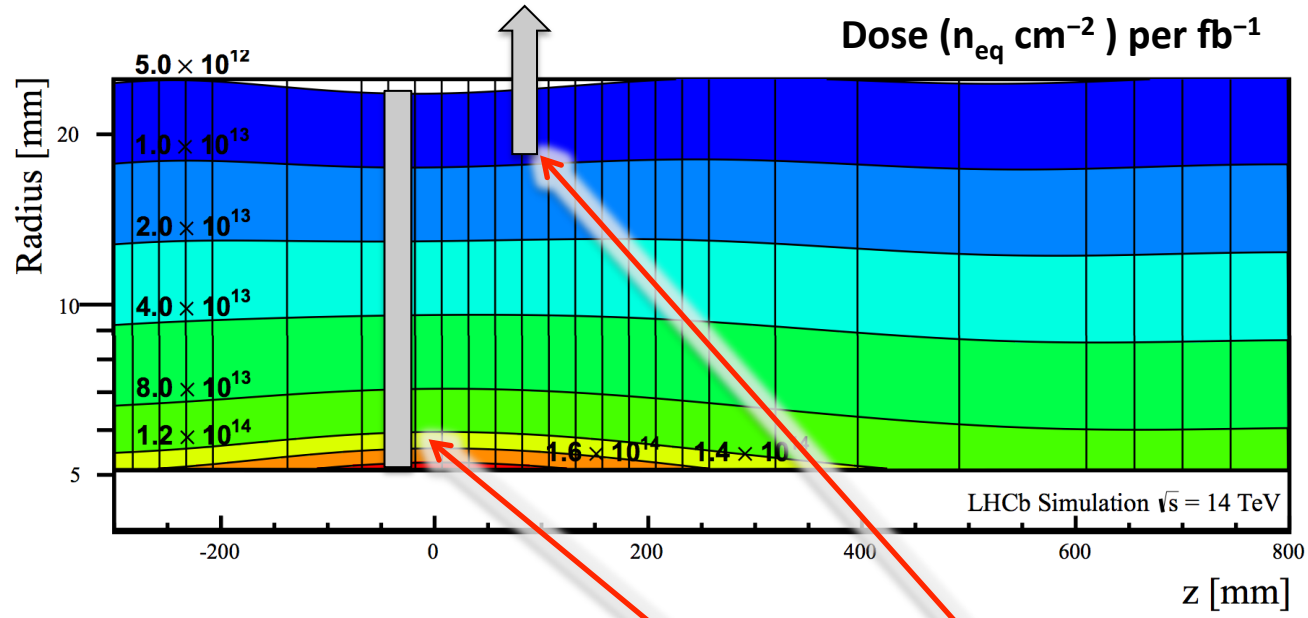
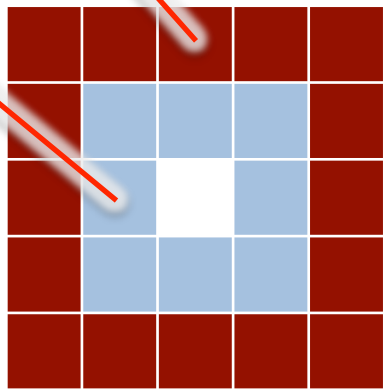


Inner-r hybrids

Outer-r hybrids



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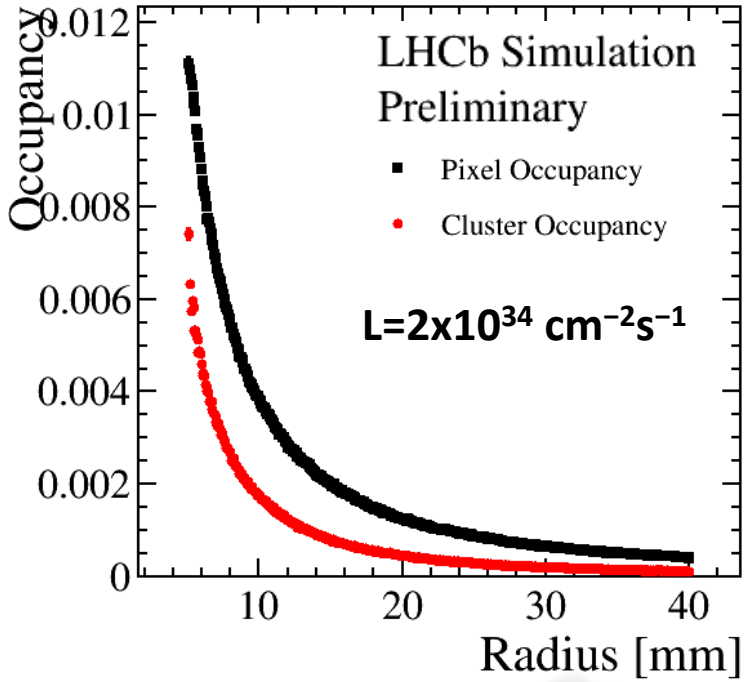
Upgrade II Challenge: Hit Occupancy



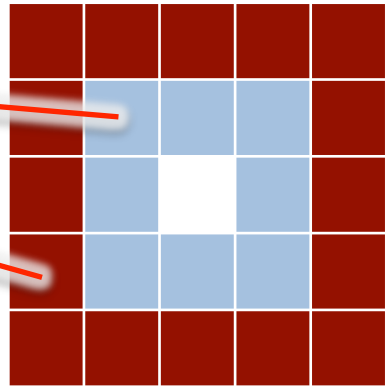
Occupancy also falls with $1/r^2$

Two-technology approach allows us to loosen requirements on

- pixel size
- radiation hardness

for precision timing planes

Inner-r hybrids



Outer-r hybrids

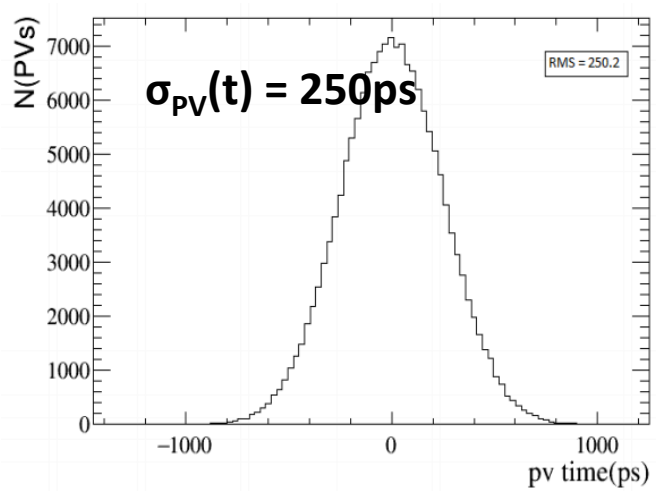
IP resolution dominated by first 2 hits

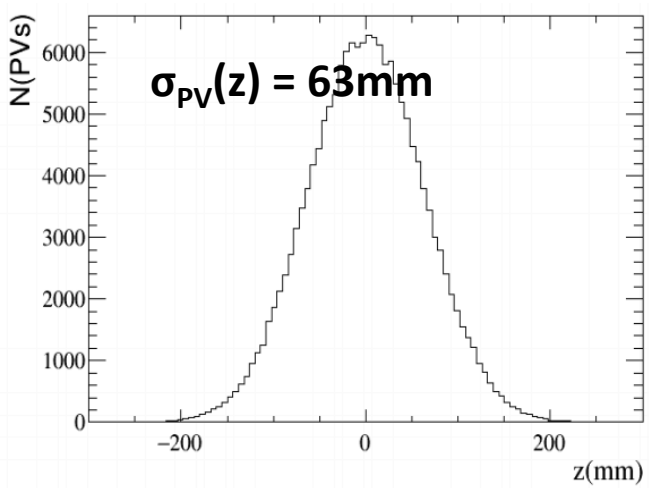
⇒ **Spatial hit resolution less important at large-r**

PV mis-association study

Run toy simulation that models the two-technology geometry, and assess PV mis-association rate under different time-hit resolutions.
Use reasonable inputs from full simulation / data / upgrade-II projections

Step 1: Generate pp collisions according to expected **(x, y, z, t, N_{PV})** distributions

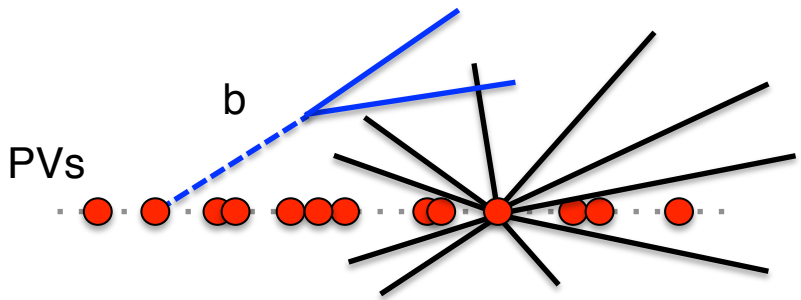


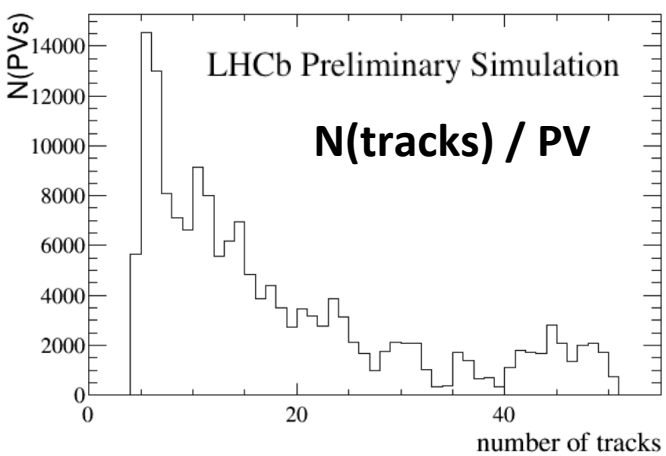


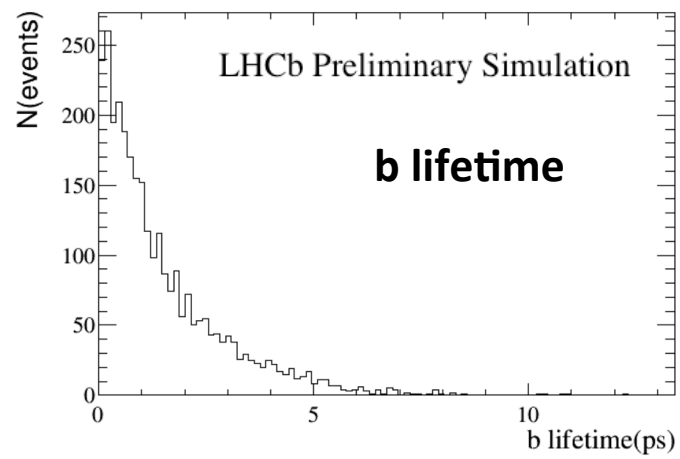
In progress…
Working with LHC beam experts to identify realistic collision conditions

PV mis-association study

Step 2: Generate charged particles from each PV, and one b hadron (2-body decay)

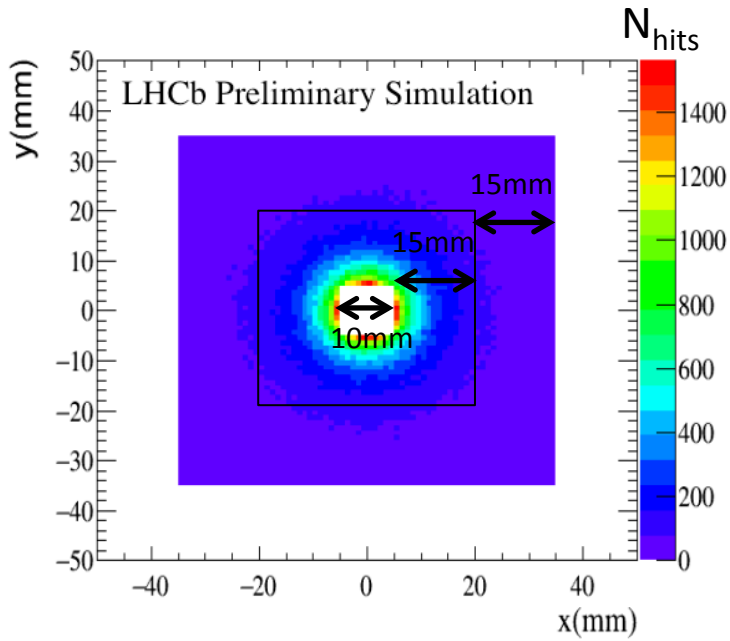


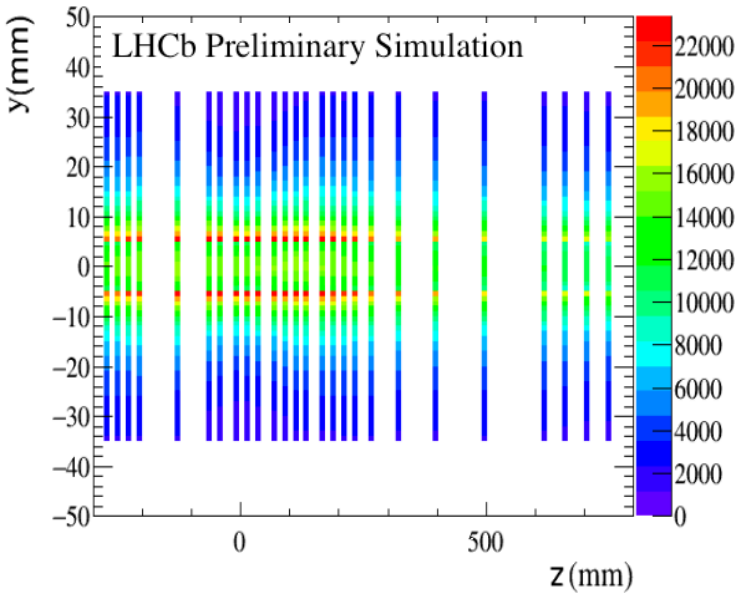




PV mis-association study

Step 3: Propagate tracks through detector model, picking-up hits in both types of sensor





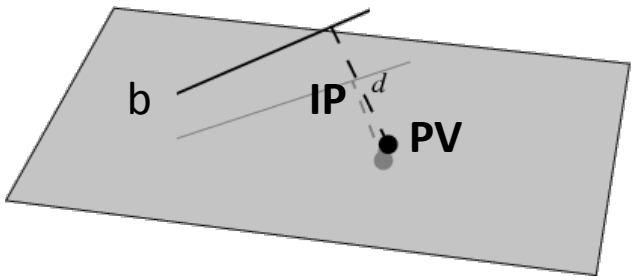
- Use time information on hits to assign **t(track)**, and then **t(vertex)**
- Use spatial information to assign **b-hadron trajectory**

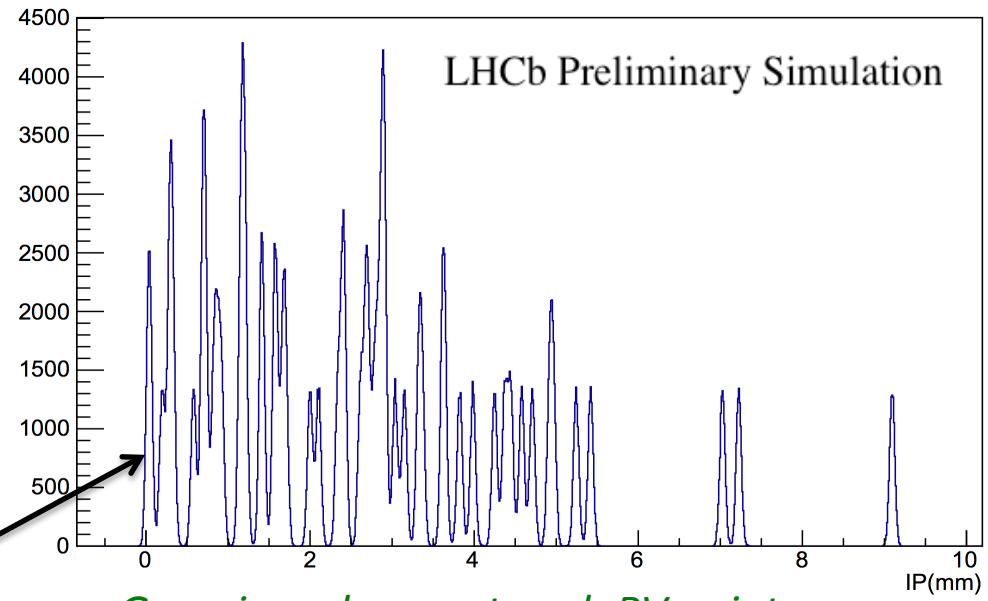
PV mis-association study

Step 4: Assign PV to B hadron using/excluding time information, and compare results

Just using IP:

- Select PV with lowest B hadron Impact parameter





Gaussians drawn at each PV point to show significance

Example for single event:
In this case, wrong PV was assigned using IP method

PV mis-association study

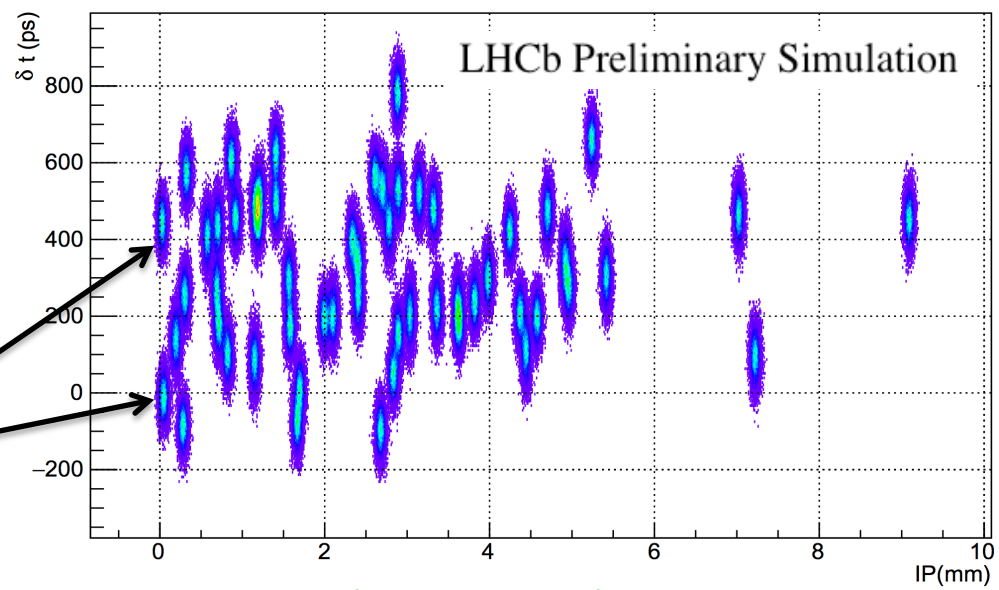
Step 4: Assign PV to B hadron using/excluding time information, and compare results

Using IP and timing:

- Select PV with lowest:

$$\sqrt{\frac{(IP)^2}{\sigma_{IP}^2} + \frac{(\delta t)^2}{\sigma_t^2}}$$

For same event, correct PV is now selected [close to (0,0)]

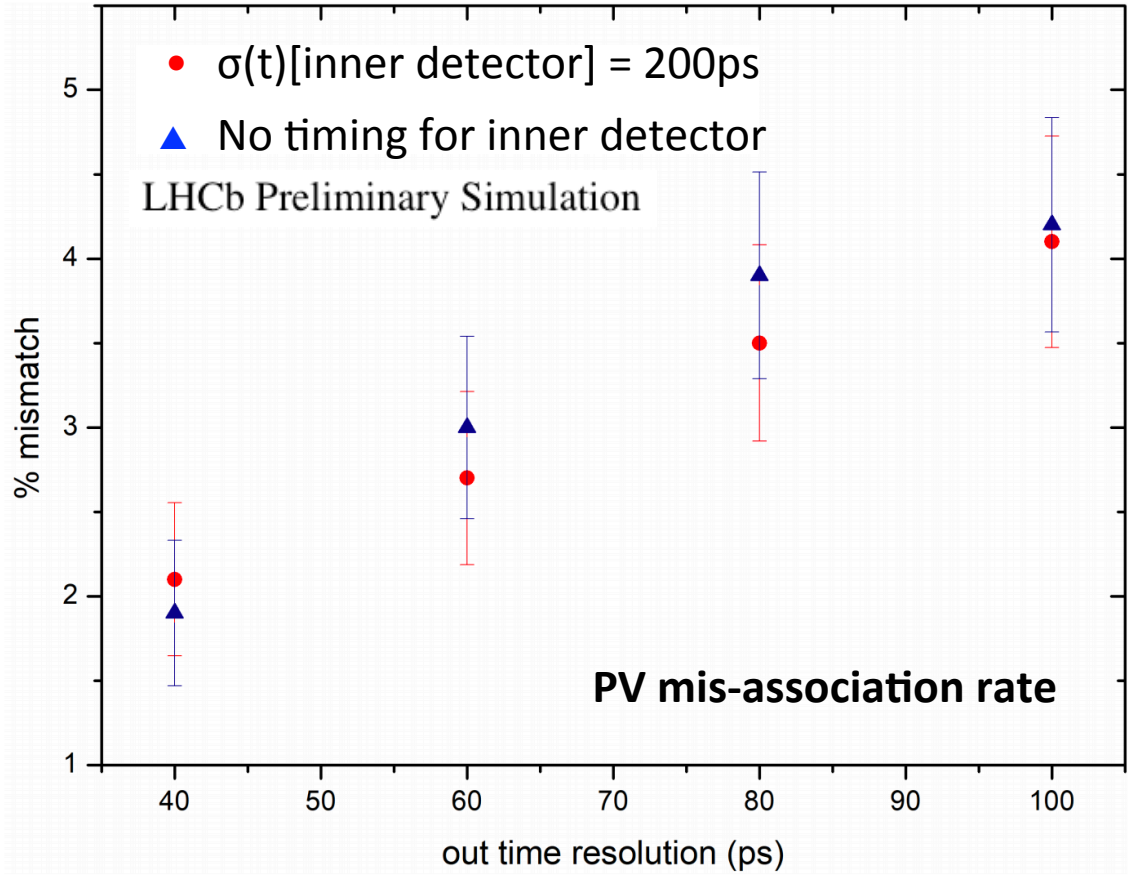


Gaussians drawn at each PV point to show significance

PV mis-association study

With no time information: PV mis-association rate = **15%** **(c.f. Upgrade I: ~1%)**

With timing:



Two different scenarios for the time precision of inner detector:

(1) No timing

(2) 200ps timing (timepix4?)

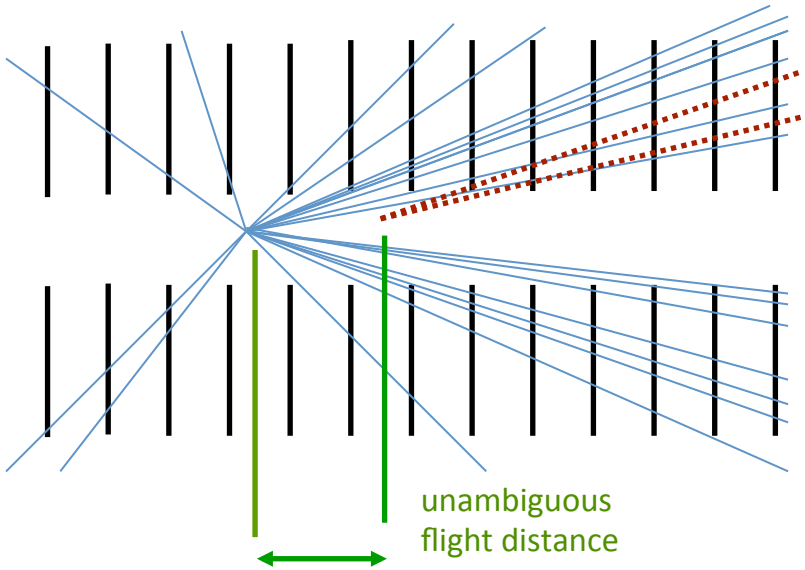
Implies having timing in inner detector is not vital

Can get to ~2% mis-association rate with 40ps timing for outer detector

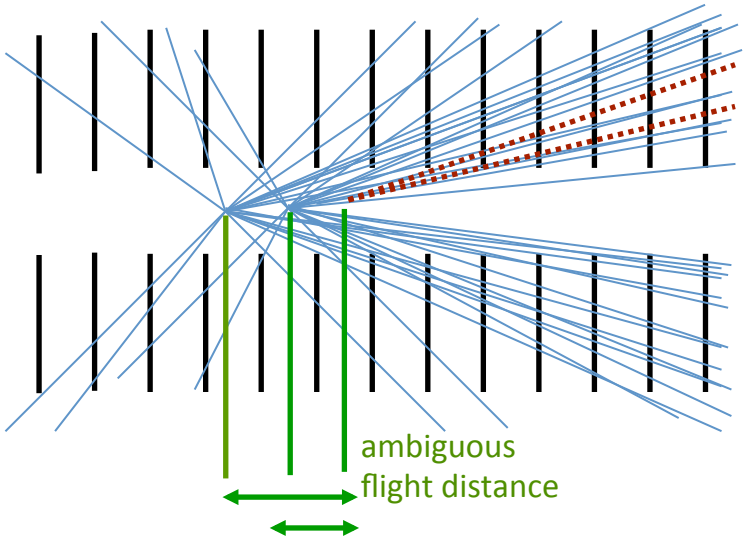
Impact on decay time precision

Incorrect PV association ⇒ incorrect decay time measurement

One primary vertex:

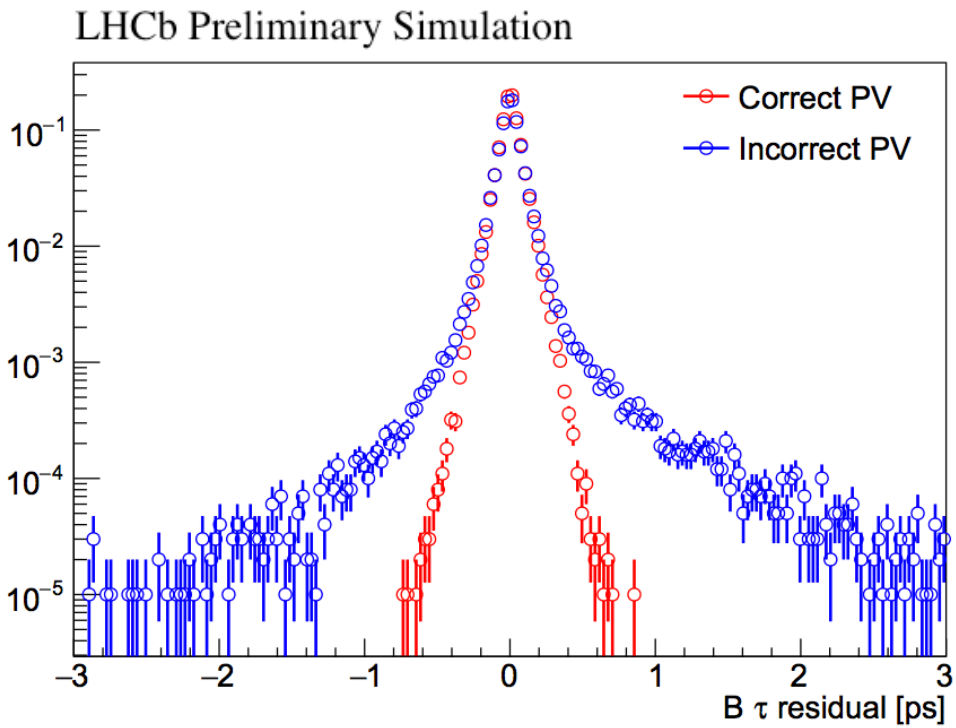


Two primary vertices:



Impact on decay time precision

Incorrect PV association ⇒ incorrect decay time measurement



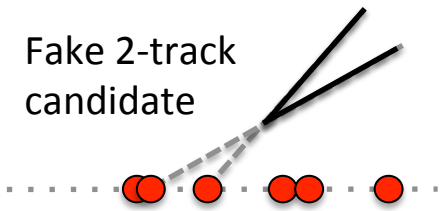
Important for much of core LHCb programme:

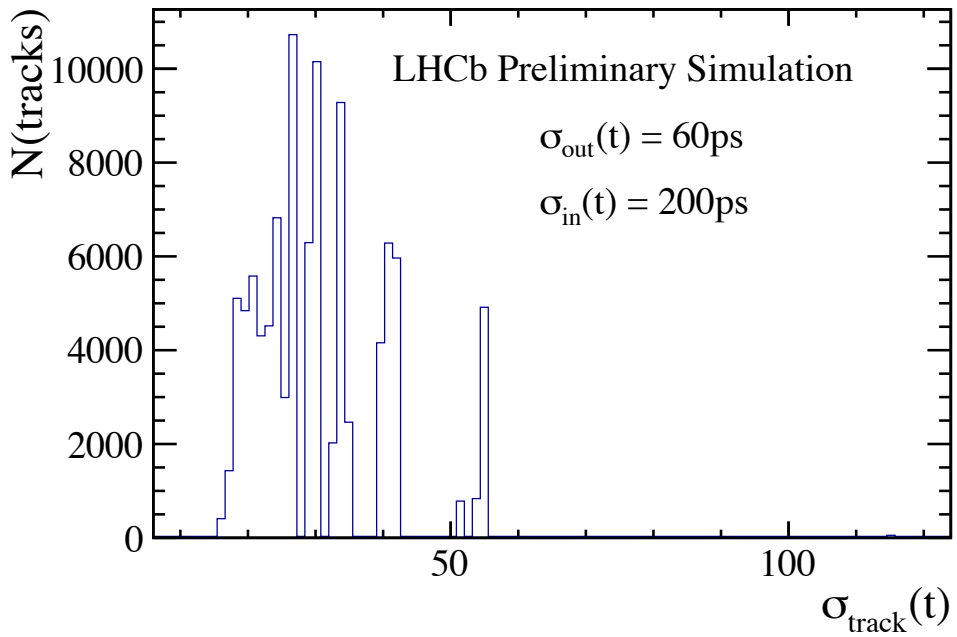
- Lifetime measurements
- Precision mixing analyses
- Time-dependent CP violation

Effect will be even stronger for partially-reconstructed decays (e.g. semileptonics) where spatial pointing is distorted, but time is not

Further Studies: Timing for background rejection

With 50x track multiplicity, many more spurious combinations of tracks
⇒ larger contributions from combinatorial backgrounds





With modest per-hit timing, can cleanly reject combinations of tracks from different PVs

e.g.
200ps inner region, 60ps outer region

⇒ **30ps mean track time resolution**

Will provide significant suppression of backgrounds, and boost sensitivity of many analyses (notably **Rare Decays**)

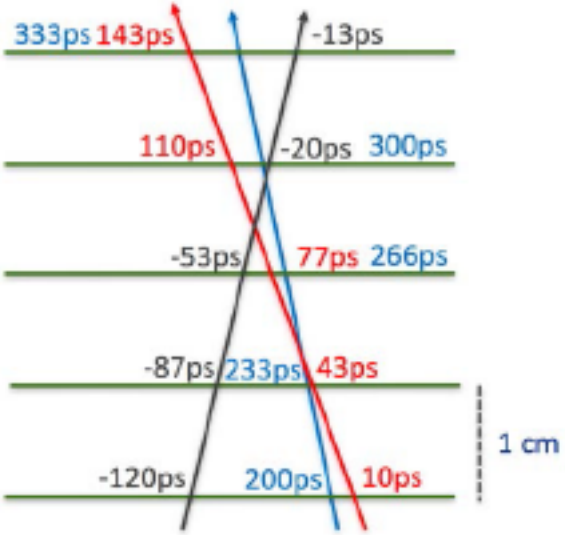
Full study to be done

Further Studies: Timing for reconstruction

Hit times will be spread over ~few 100 ps

Adding hit time as an extra dimension in the pattern recognition (4D tracking) can improve tracking performance

- **Reduced ghost rate**
- **Faster reconstruction** (very important given LHCb's 'offline quality' trigger approach)
- **Higher efficiency** – can loosen some spatial requirements without increasing ghost rate



Same arguments hold for PV reconstruction – can recover merged / missing PVs and improve spatial resolution.

Full study to be done

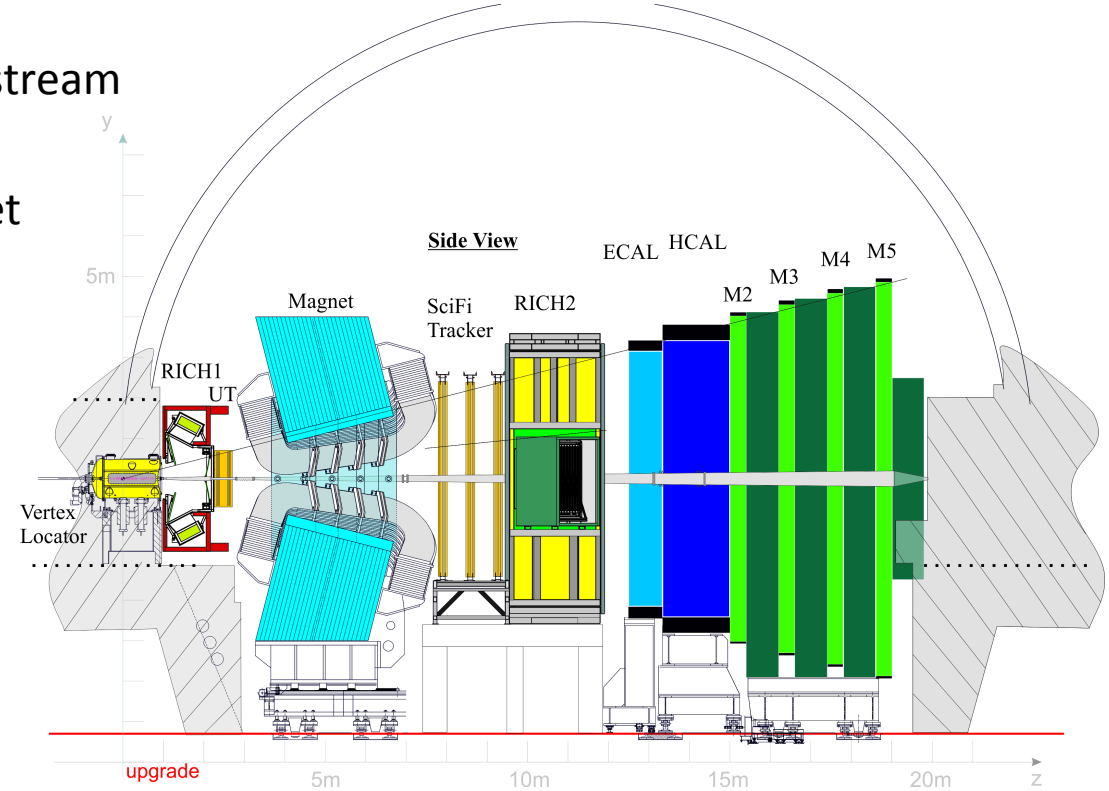
Further Studies: Timing for extrapolation

Tracking stations upstream / downstream of magnet are separated by ~5m

Extrapolating tracks through magnet could be problematic in HL-LHC era

- High ghost rates

Adding timing plane in downstream tracker could help



Further Studies: Timing for extrapolation

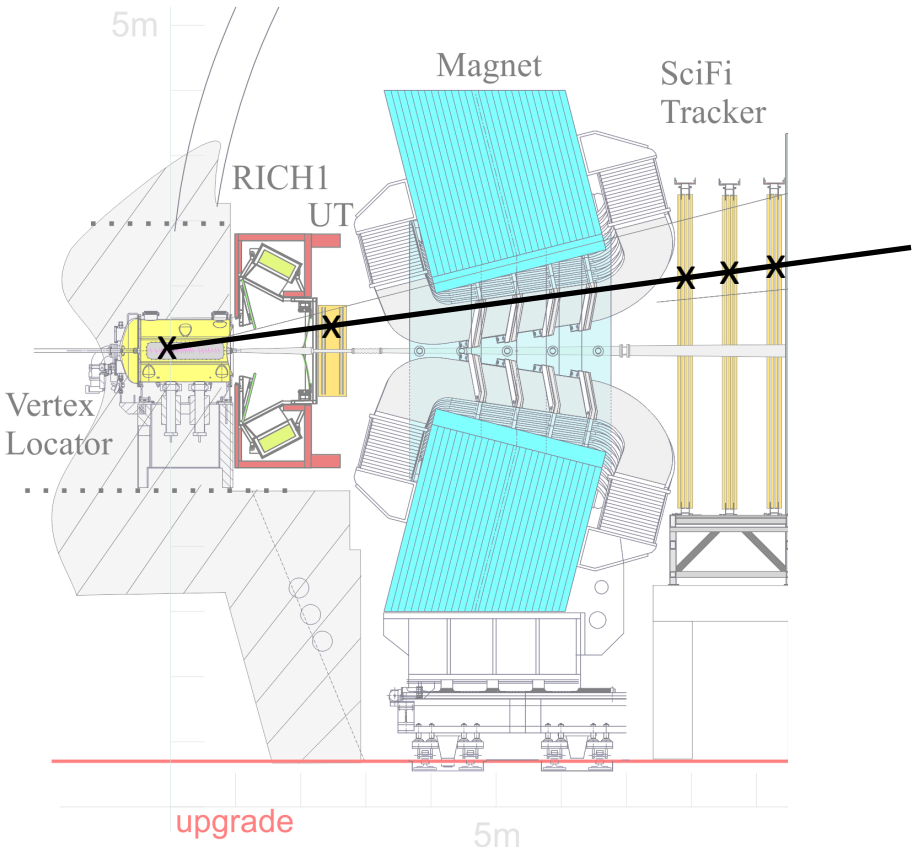
Tracking stations upstream / downstream of magnet are separated by ~5m

Extrapolating tracks through magnet could be problematic in HL-LHC era

- High ghost rates

Adding timing plane in downstream tracker could help

c.f. ideas proposed by Atlas / CMS to place timing layers in their trackers (e.g. HGTD based on LGAD detectors)



Could also significantly speed-up reconstruction

Full study to be done

Summary and Future Work

HL-LHC: huge **opportunity** for LHCb to search for new physics in precision measurements

Also significant **challenges** – particularly for the VELO

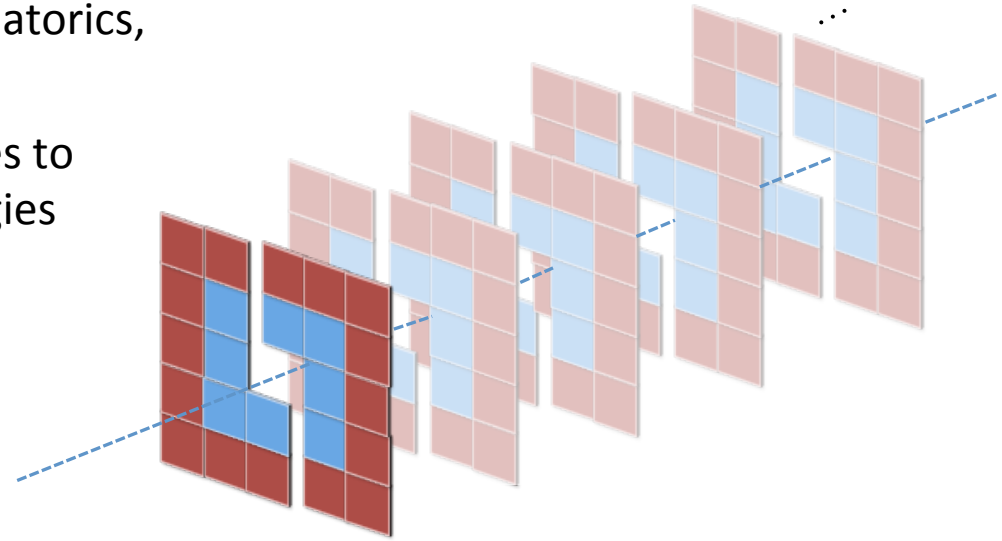
- High track multiplicity, high radiation dose, high pile-up

Two-technology solution ⇒ reduced requirements on pixel size and radiation hardness for **timing technologies** for the outer radial region of the VELO

Even with timing only in the outer region, can reduce PV **mis-association** rate from **15% to ~2%**.

Will also significantly reduce track combinatorics, and hence backgrounds

Now starting to plan research programmes to **identify** and **develop** candidate technologies for both the inner and outer detector.



Possible Technologies: ASICs

Upgrade I will use **VeloPix** technology – based on **Timepix** family of ASICs

- **55µm pixels**
- **130 nm technology**
- **1 ns timing precision**

Timepix3

+ Radiation hard
+ 800 Mhit/s readout
(10x Timepix3)

VeloPix

Under validation – all looks good!

- **Same 55µm pixels**
- **65 nm technology**
- **~200 ps timing precision**
- **4-sided buttable design**

Timepix4

Now in design phase

SuperVeloPix ?

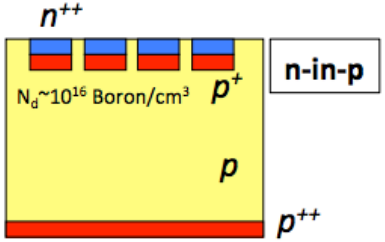
??

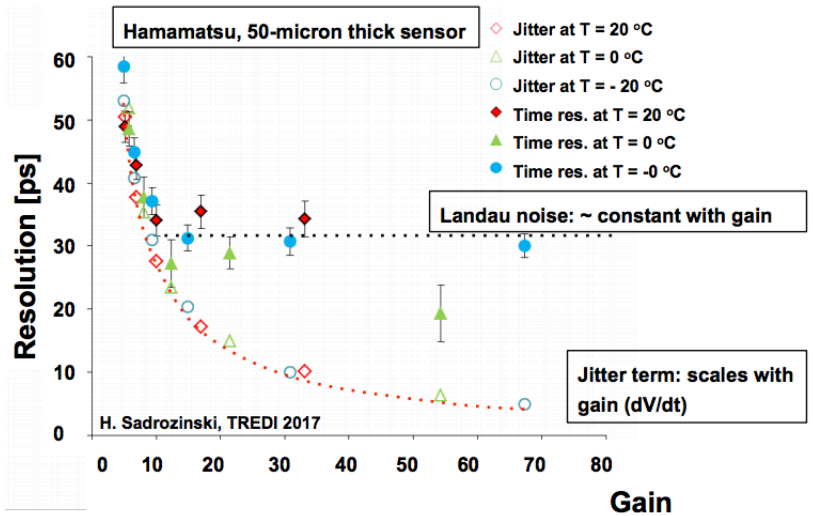
Small pixels, timing, high rate, radiation hard, …

- **Reduced pixel size?**
- **Improved timing precision?**

Possible Technologies: Sensors

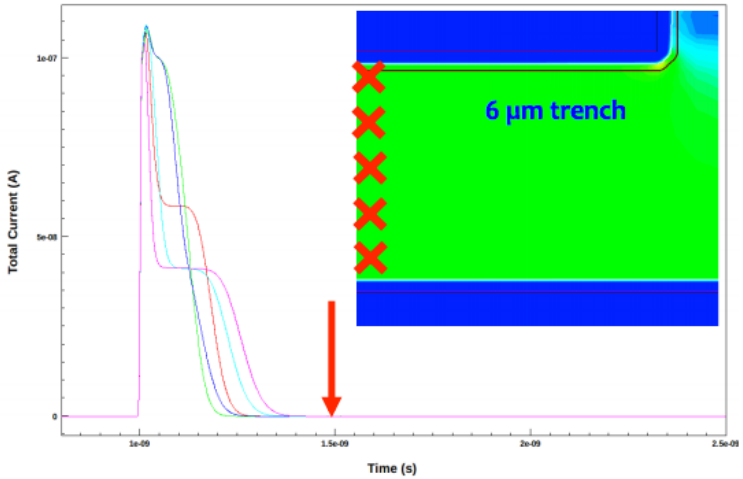
Low Gain Avalanche Detectors (LGAD)





σ(t) ≈ 35ps, degrades with radiation (current prototypes ~1mm pads)

3D Silicon detectors



New 3DSi trench topologies give more uniform fields – so uniform charge collection rates
⇒ potential to reach <100ps timing
Good radiation hardness
Scalable to smaller pixels (<50µm)