The LHCb VELO Upgrade II

PIXEL Conference 2018

9th International workshop on Semiconductor Pixel Detectors for Particles and Imaging

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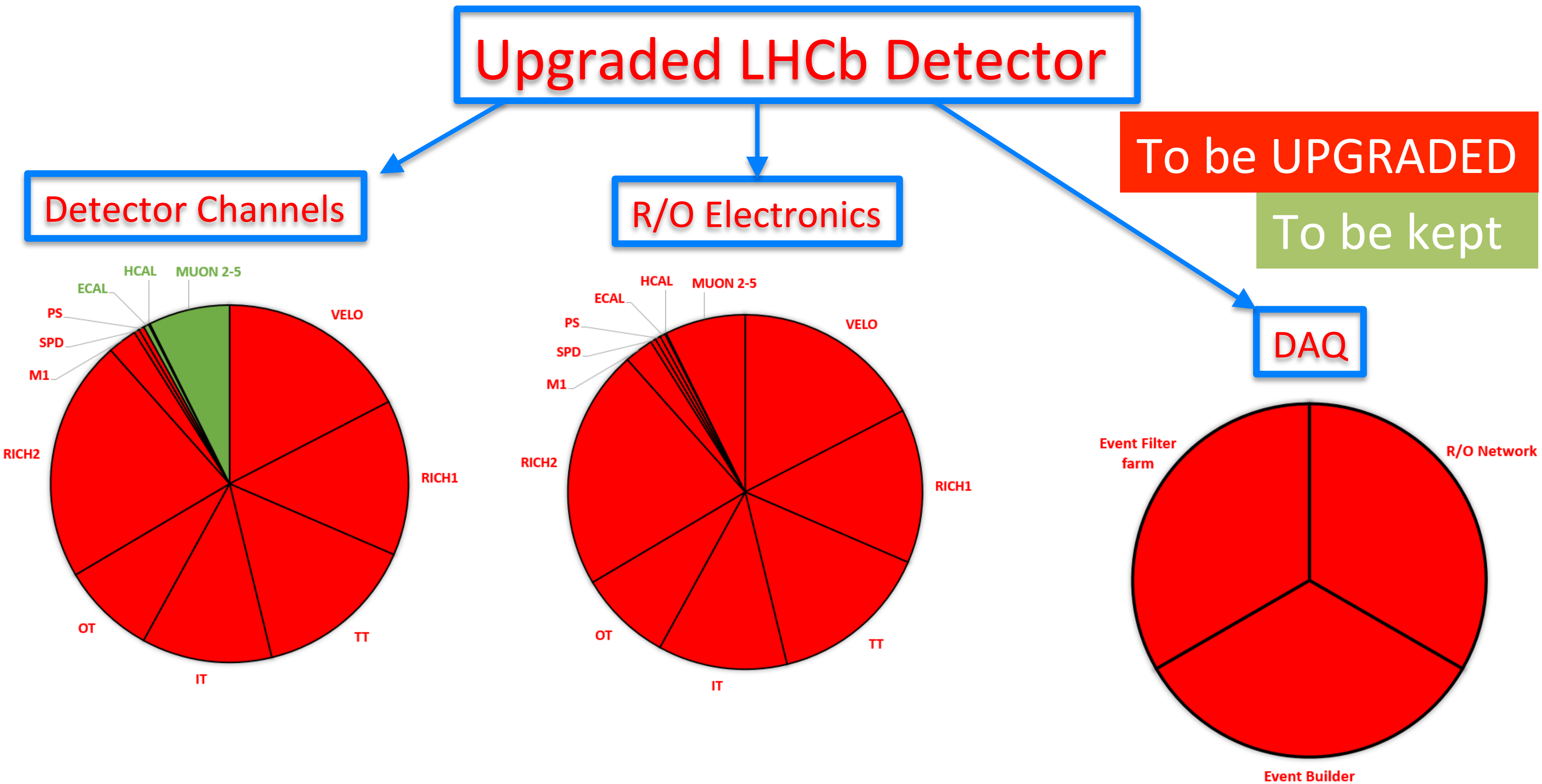
On behalf of the LHCb Collaboration

Taipei, 10-14 December 2018

The ~~king~~ LHCb detector is dead, long live the ~~king~~ Upgraded LHCb detector

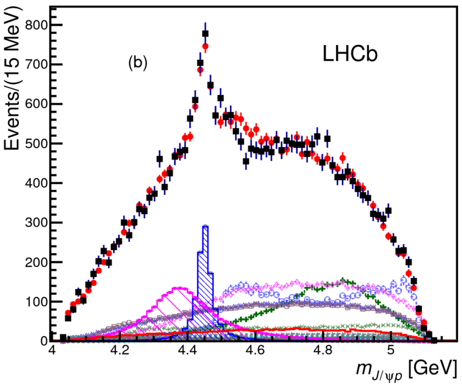
LHCb saw its final collisions on December 2nd

The detector as we know it will be ~completely replaced for Run 3 and beyond



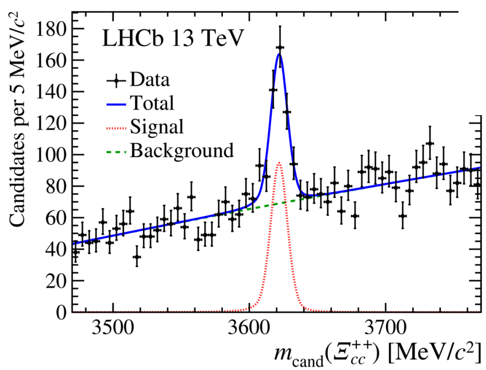
The ~~king~~ LHCb detector is dead, long live the ~~king~~ Upgraded LHCb detector

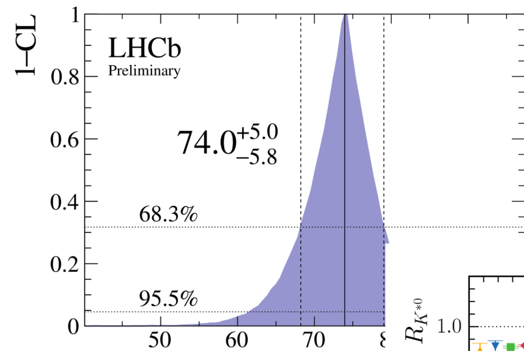
LHCb clearly shows the value of hadron colliders in flavour physics – addresses many open questions in HEP, and has brought some surprises!



Pentaquark(s)

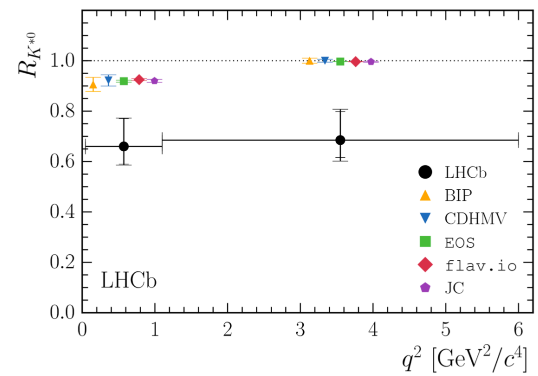
New baryons





CKM angle γ

Lepton universality?

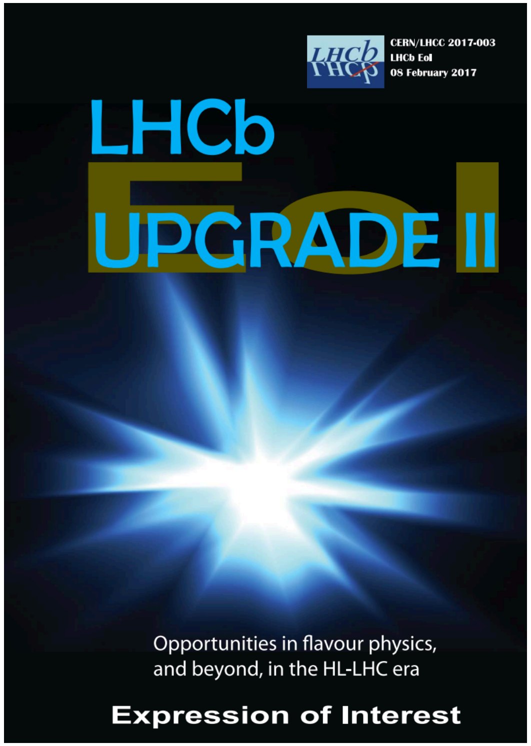


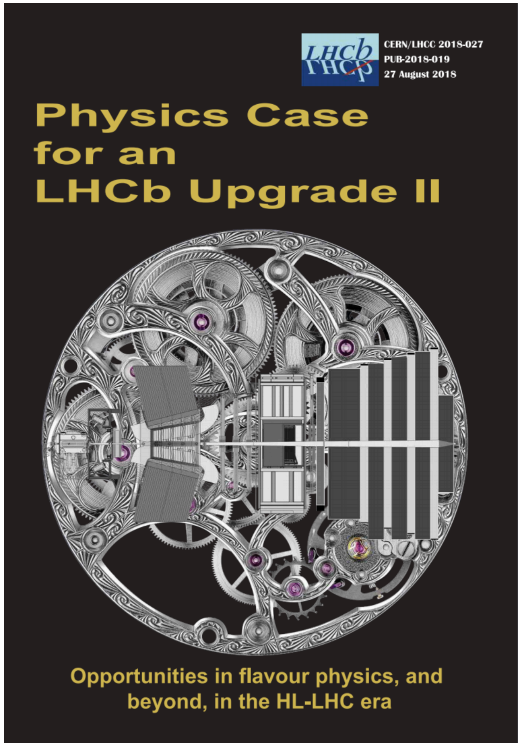
Expect a fruitful next decade with **LHCb Upgrade I** and **Belle II**

Beyond that, **LHCb Upgrade II** may be the only opportunity to pursue these kinds of measurements – strong physics motivation to make best use of the HL-LHC.

The ~~king~~ LHCb detector is dead, long live the ~~king~~ Upgraded LHCb detector

Physics case for Upgrade II, and preliminary investigation of potential detector systems presented in a couple of recent reports





https://cds.cern.ch/record/2244311/

https://cds.cern.ch/record/2320509

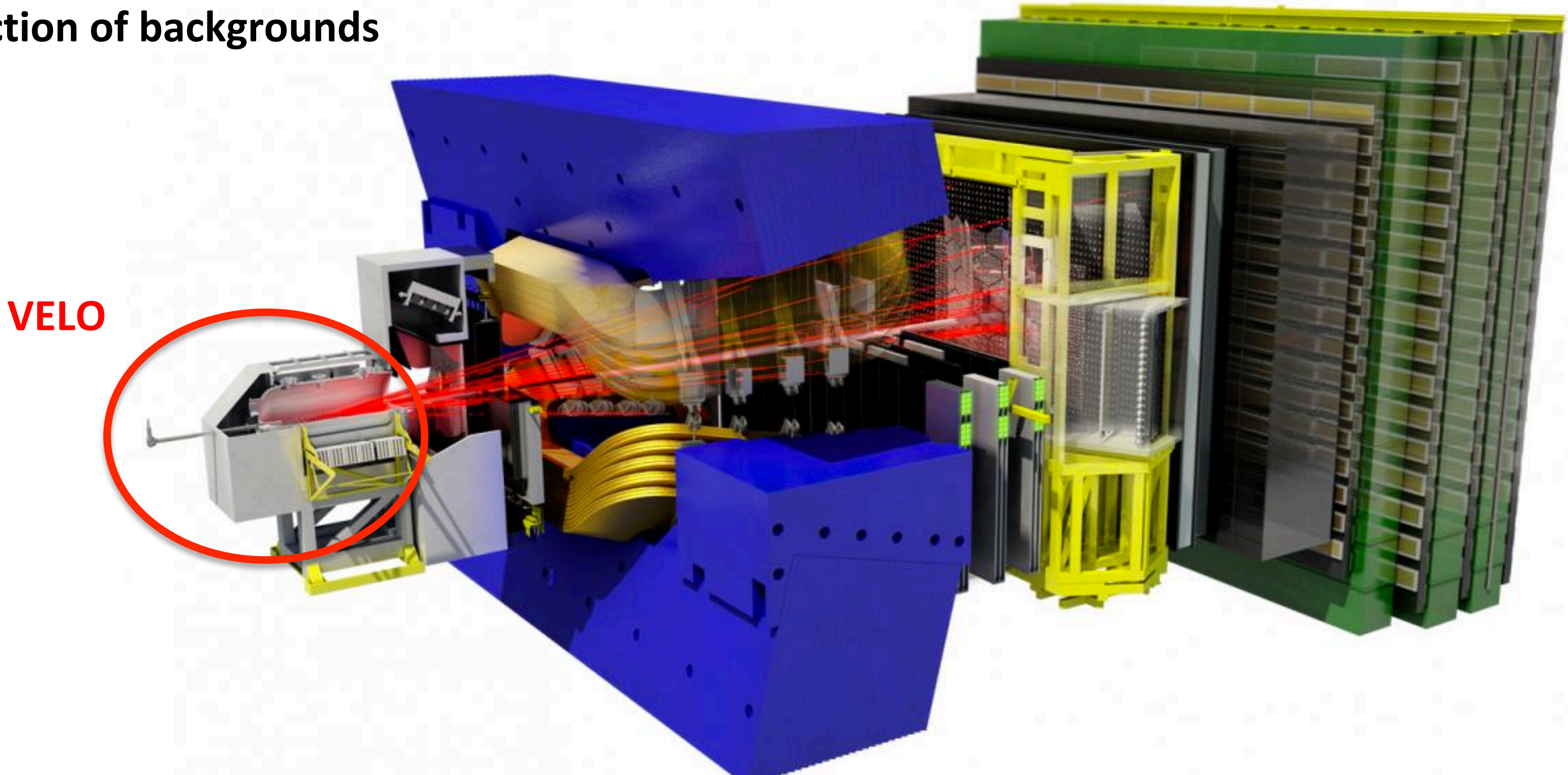
A Vertex Locator will be an essential component of any possible Upgrade II design

The LHCb Vertex Locator

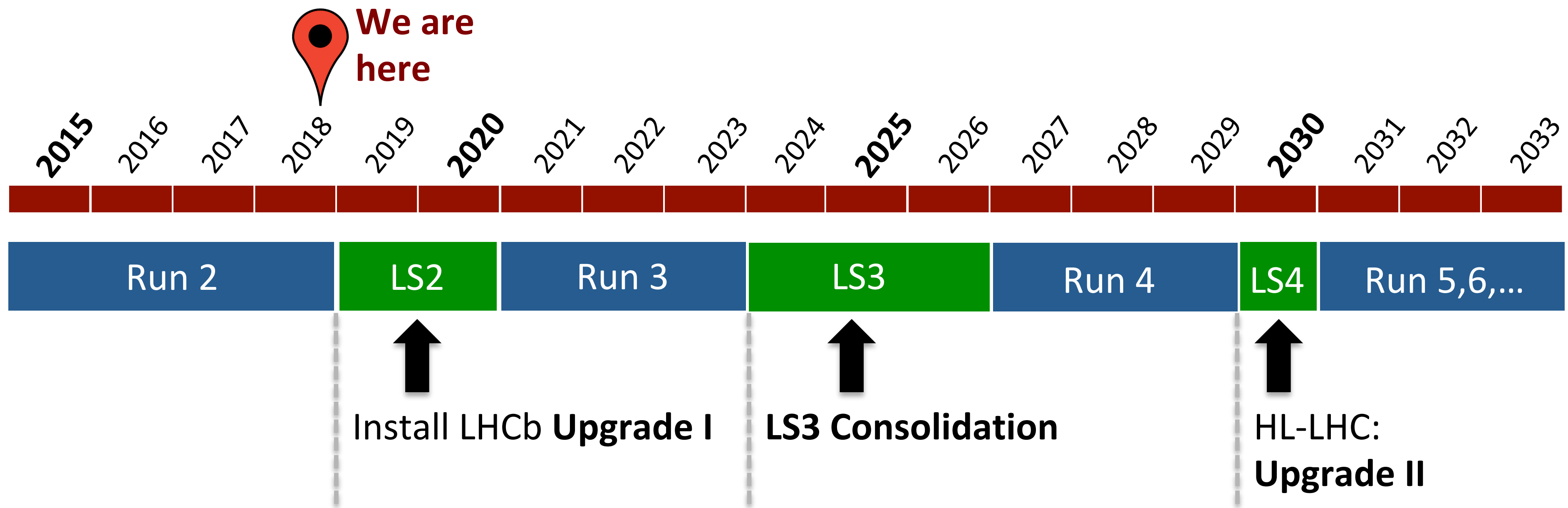
Vertex Locator (VELO) – a silicon strip detector surrounding the LHCb luminous region

Provides precise measurements of charged particle trajectories:

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



Timeline



We are here
2015
2016
2017
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2020
2021
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2023
2024
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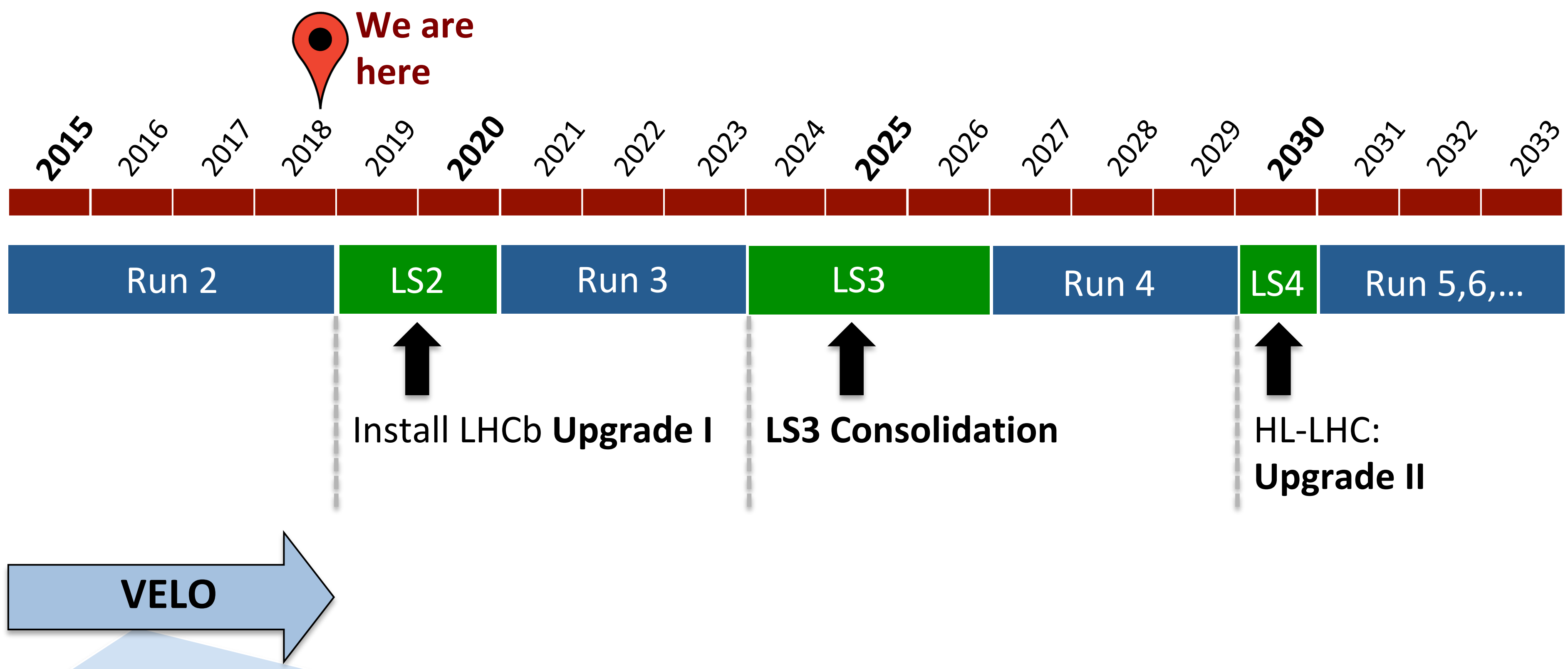
2026
2027
2028
2029
2030
2031
2032
2033
Run 2
LS2
Run 3
LS3
Run 4
LS4
Run 5,6,...
Install LHCb **Upgrade I**
LS3 Consolidation
HL-LHC:
Upgrade II

Timeline

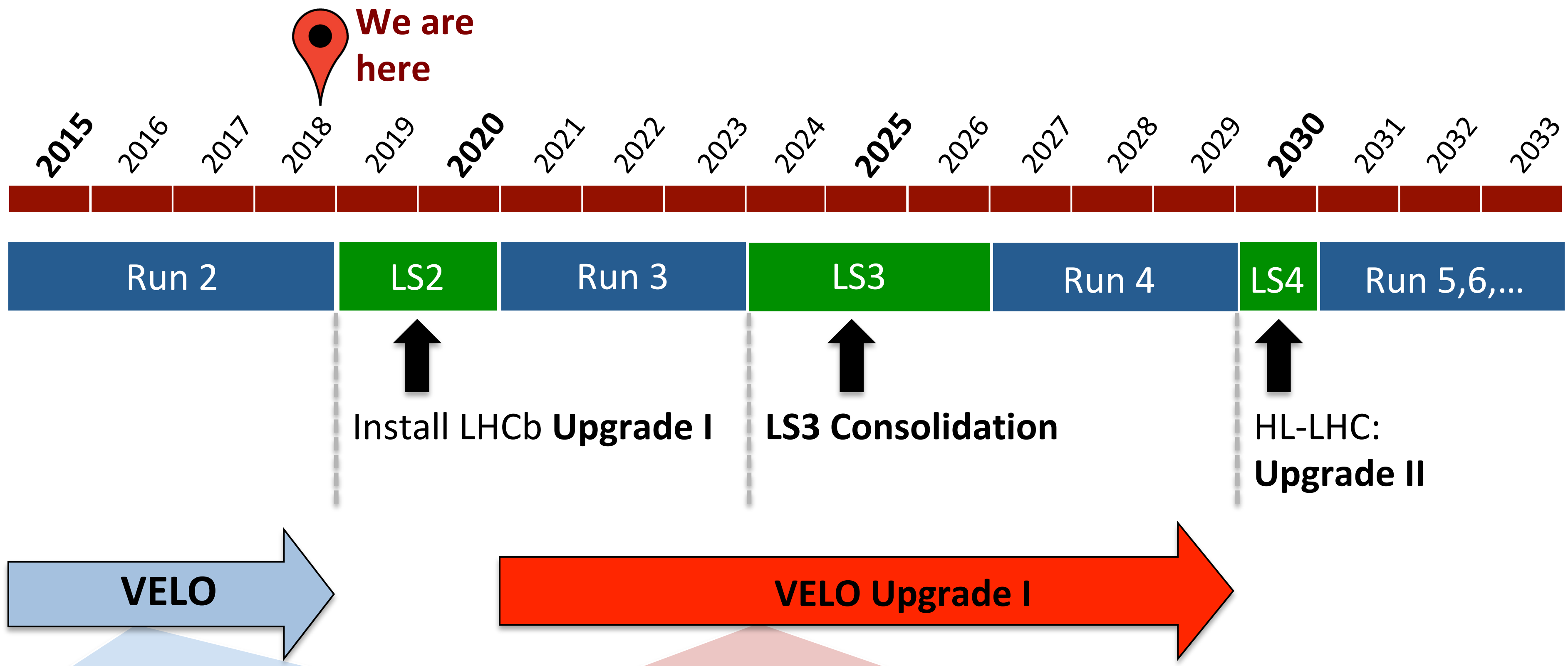


Silicon strip detector

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

1.1 visible interactions / crossing

Timeline



Silicon strip detector

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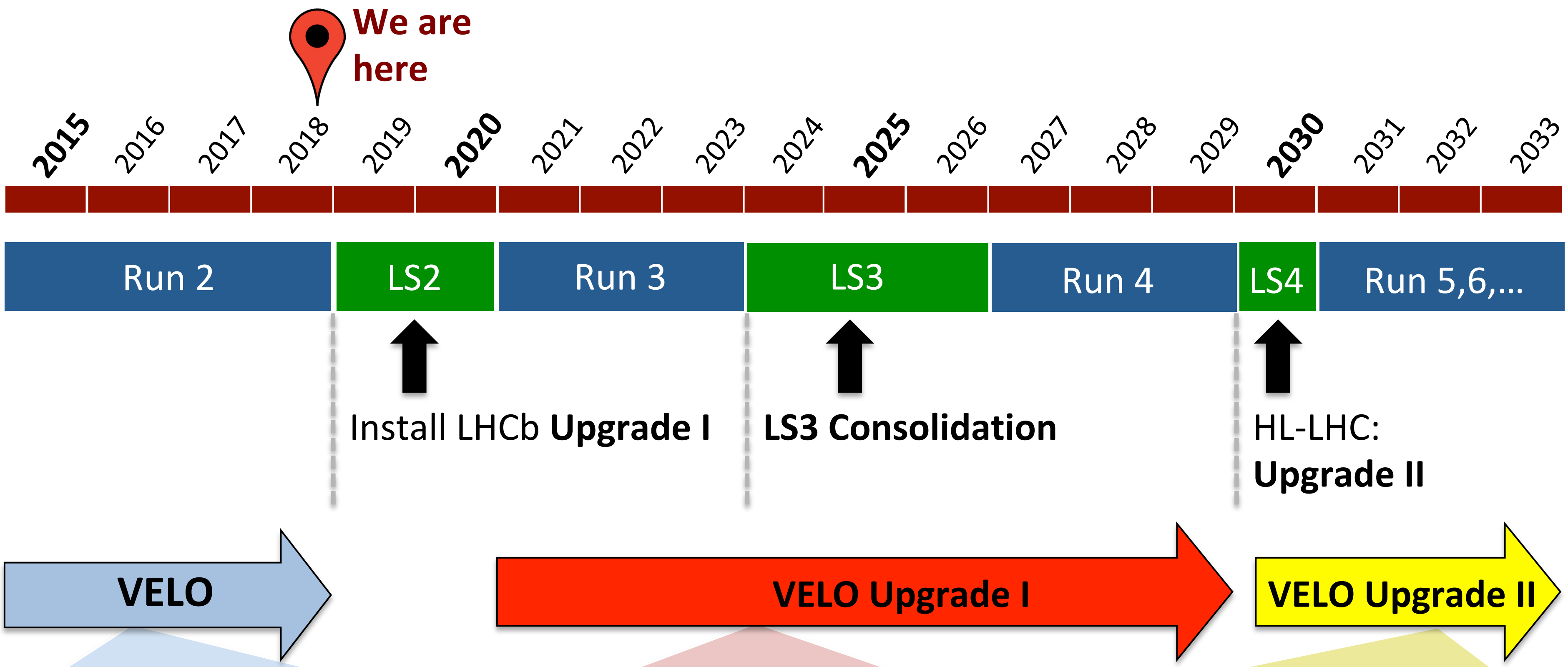
Silicon **pixel** detector

$\mathcal{L} = 2 \times 10^{33}\ \mathrm{cm^{-2}s^{-1}}$ **(5×)**

5.5 visible interactions / crossing

Timeline



VELO

Silicon strip detector

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1.1 visible interactions / crossing

VELO Upgrade I

Silicon **pixel** detector

$\mathcal{L} = 2 \times 10^{33}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$ **(5×)**

5.5 visible interactions / crossing

VELO Upgrade II

Pixel detector with **timing**

$\mathcal{L} = 1\text{-}2 \times 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$ **(5-10×)**

28-55 visible interactions / crossing

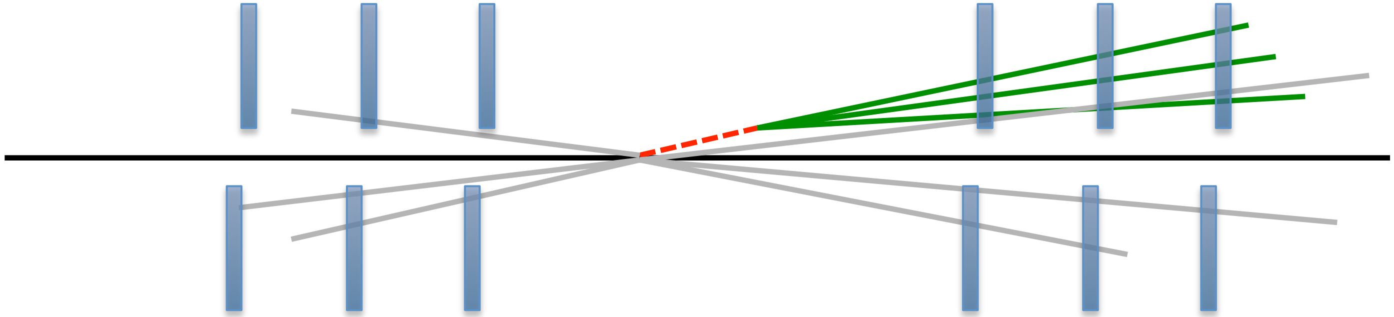
VELO Upgrade II?

We need:

Precision spatial measurements of charged particles

High track-finding efficiency

Low ghost/clone rate



VELO Upgrade II?

We need:

Precision spatial measurements of charged particles

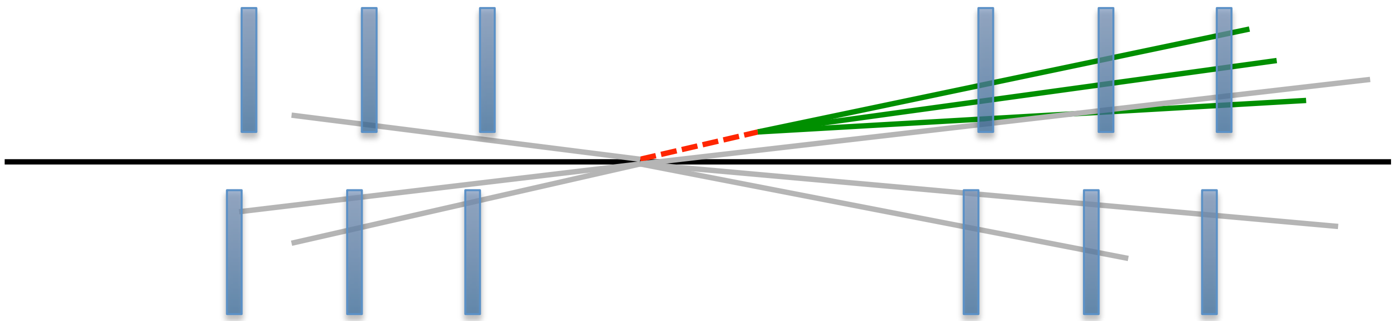
Low material

Close to beam line

Precise single-hit measurements

High track-finding efficiency

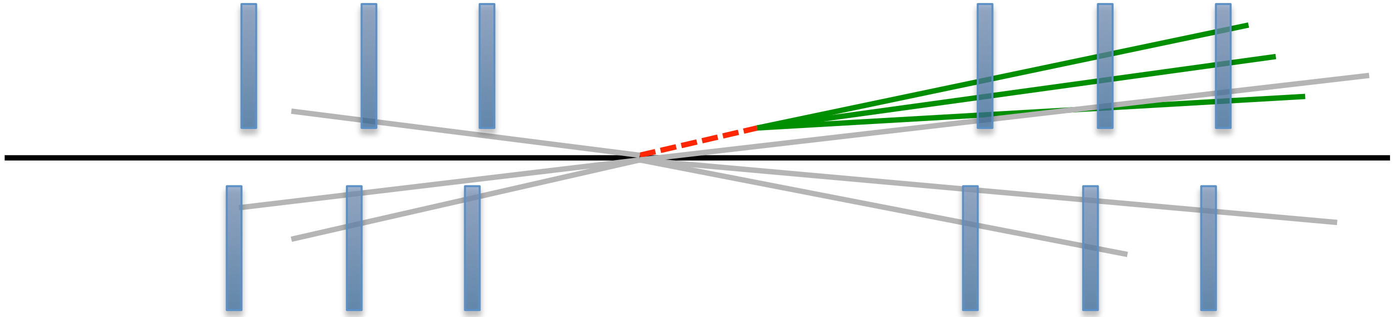
Low ghost/clone rate



VELO Upgrade II?

We need:

Precision spatial measurements of charged particles	**High track-finding efficiency** **Low ghost/clone rate**
Low material	Full coverage within acceptance
Close to beam line	High granularity
Precise single-hit measurements	Multiple O(10) hits per particle



VELO Upgrade II?

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+ Radiation hard

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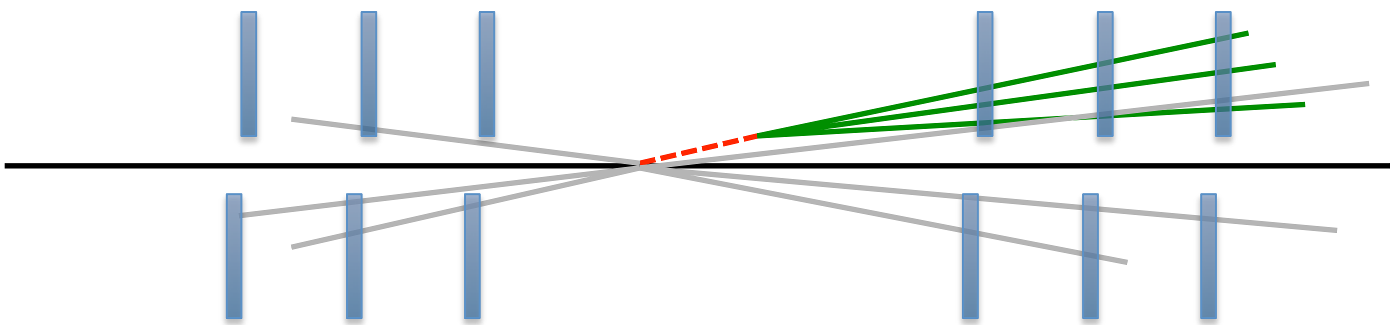

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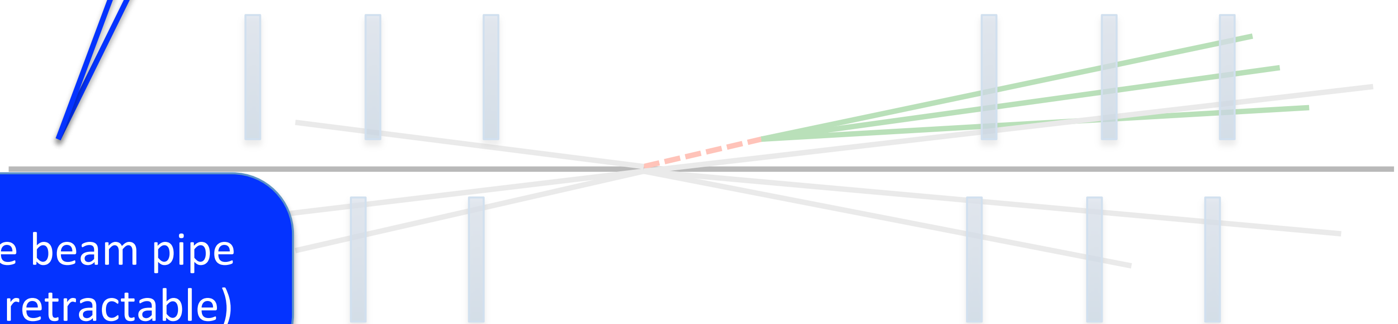

Inside beam pipe (and retractable)

VELO Upgrade II?

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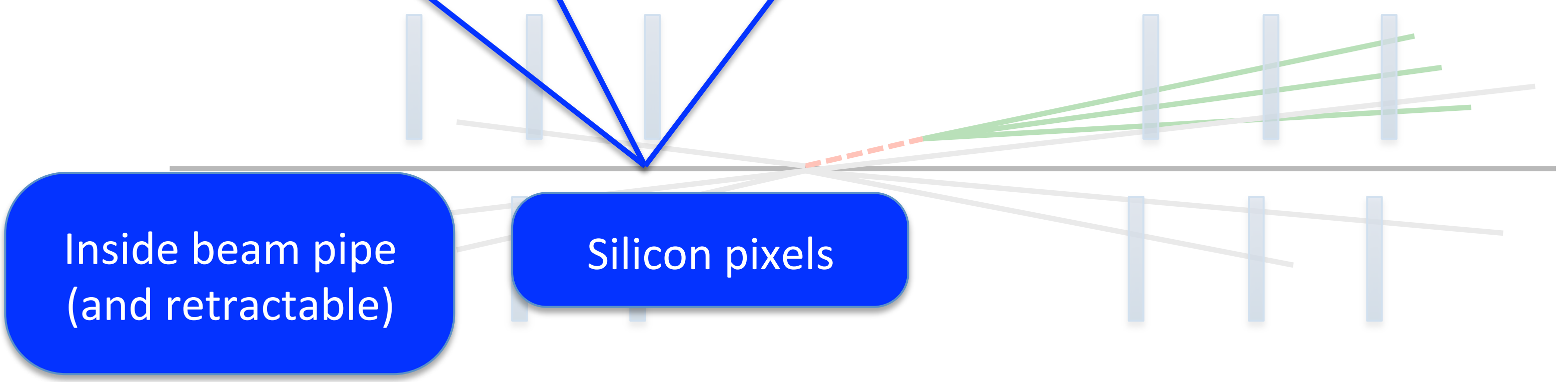

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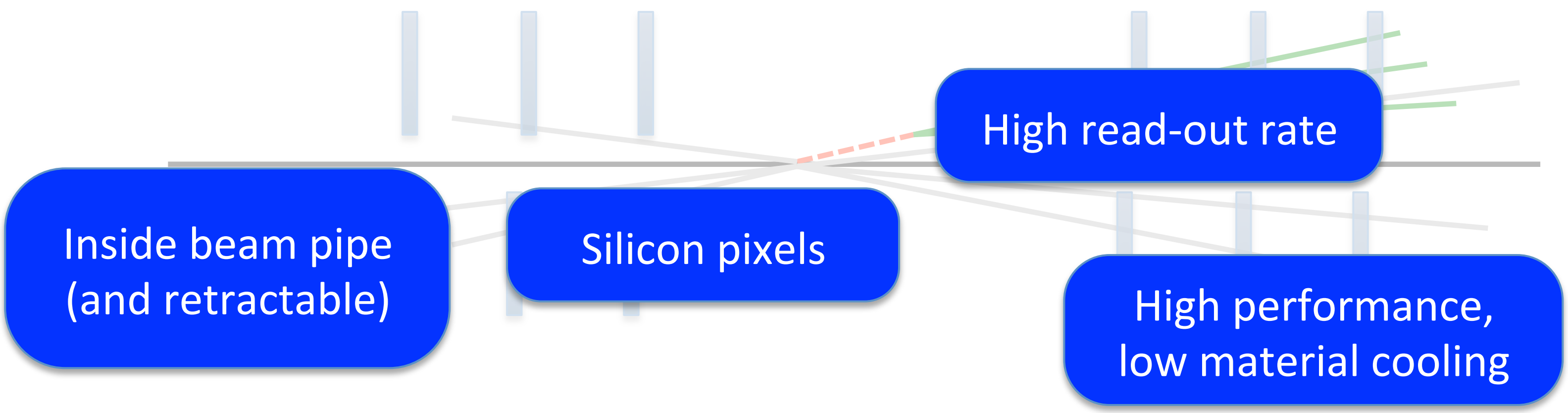
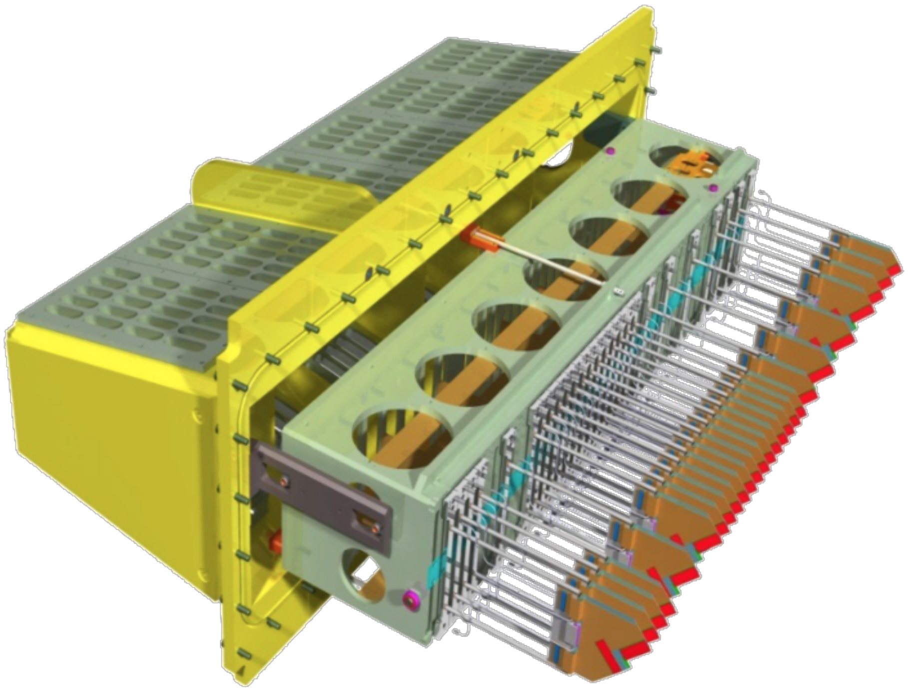
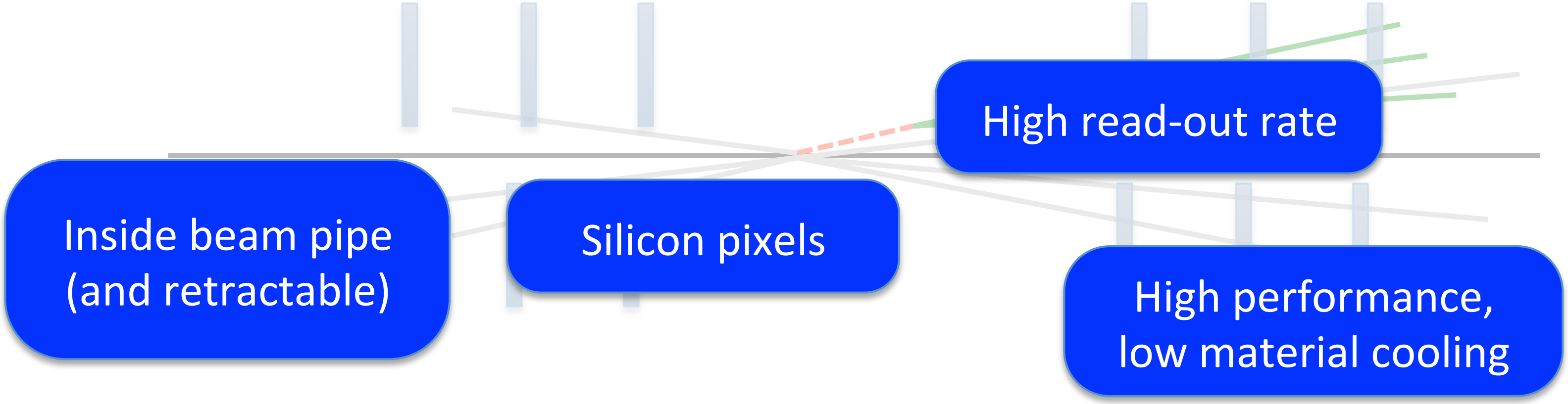


VELO Upgrade II?

Sound familiar?

VELO Upgrade I must fulfil same basic requirements





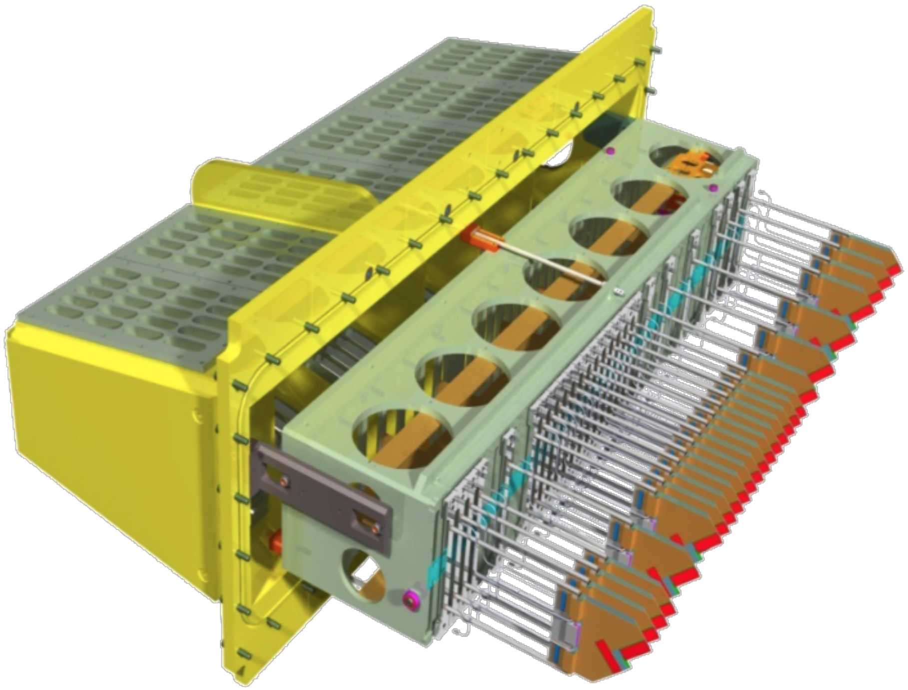
VELO Upgrade II?

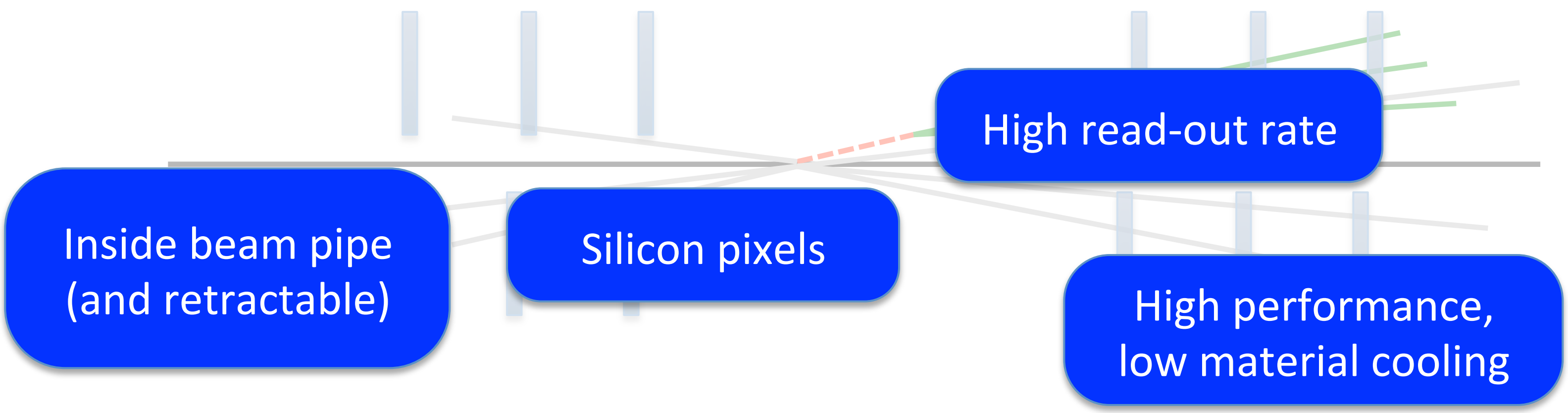
Sound familiar?

VELO Upgrade I must fulfil same basic requirements

Additional challenges:

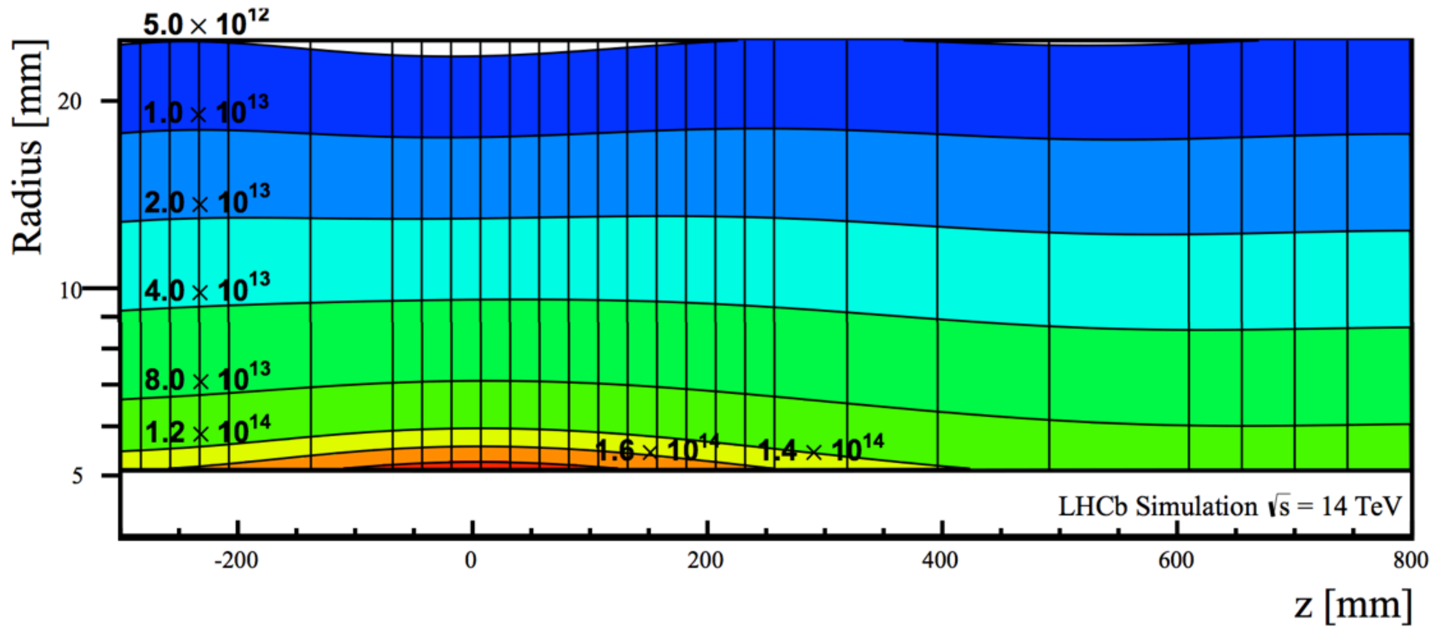
- 10x higher particle multiplicity
- 10x denser vertex environment
- 10x higher radiation damage





Upgrade II Challenge: 10x radiation dose

Radiation fluence (in 1 MeV n_{eq} / cm^2) in hottest region (r=5mm) reaches 1.6E14 per fb^{-1}



- Upgrade I VELO must survive fluence of **8×10^{15}** (50 fb^{-1})
- Upgrade II VELO must survive fluence of up to **5×10^{16}** (300 fb^{-1})

Highly non-uniform irradiation versus (r,z)

Upgrade II Challenge: Trigger and reconstruction

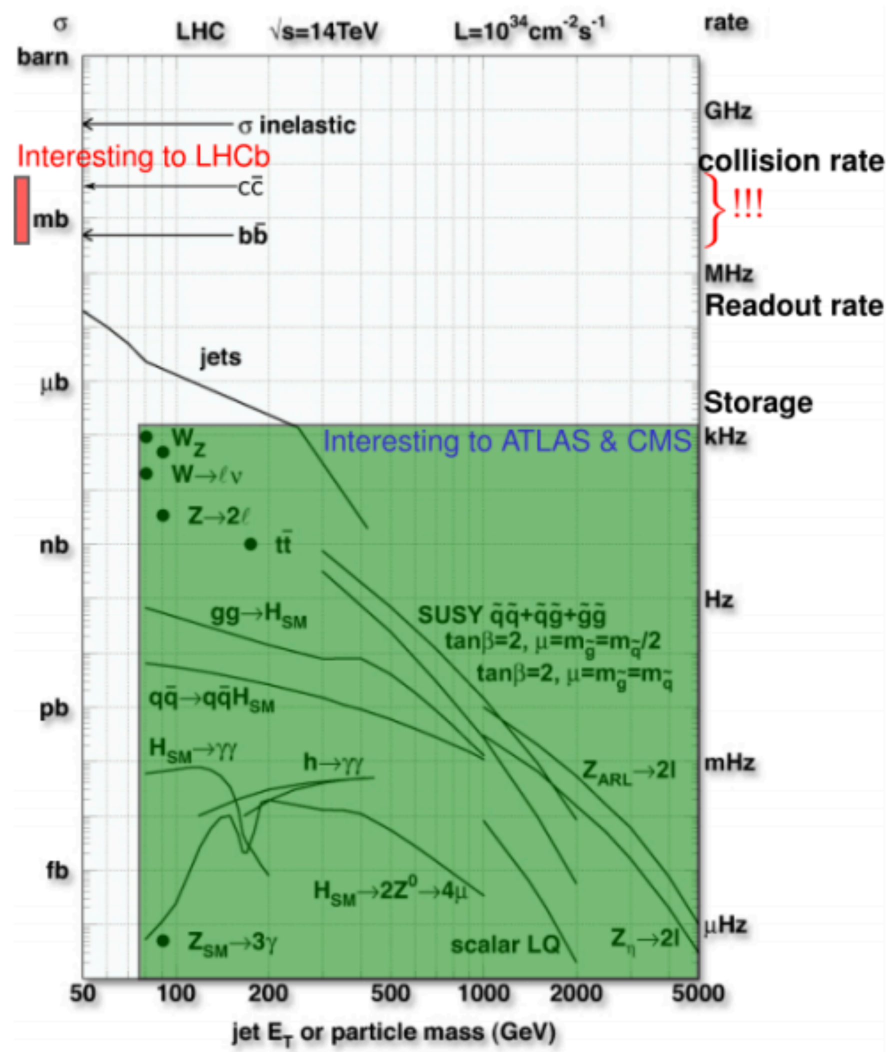
From Run 3, LHCb will operate without a hardware trigger

⇒ Every event must be fully read out by all detectors, and reconstructed with 'offline quality', before a software trigger decision is made

Already a huge challenge for Upgrade I – will be >10x harder for Upgrade II

With limited resources, will need to be creative, and make best use of commercial computing developments (FPGAs / GPUs) and efficient algorithms.

⇒ Will also influence the actual detector design, to ensure trigger is even feasible…



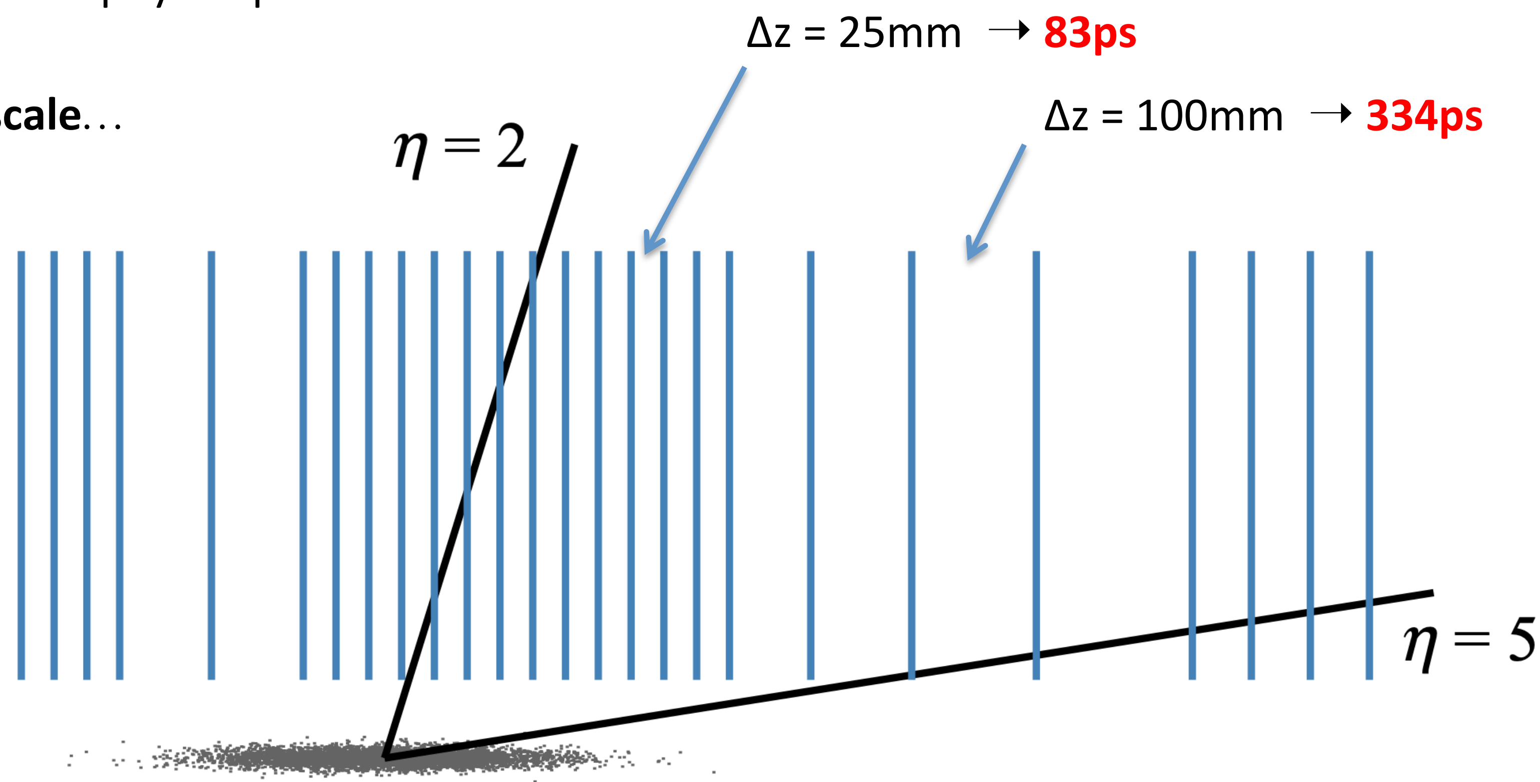
Upgrade II Challenge: Trigger and reconstruction

With **precise timing** on VELO hits upfront, can make best possible trigger decisions and reduce combinatorics for online track finding and reconstruction

⇒ Faster pattern recognition

⇒ Better physics performance

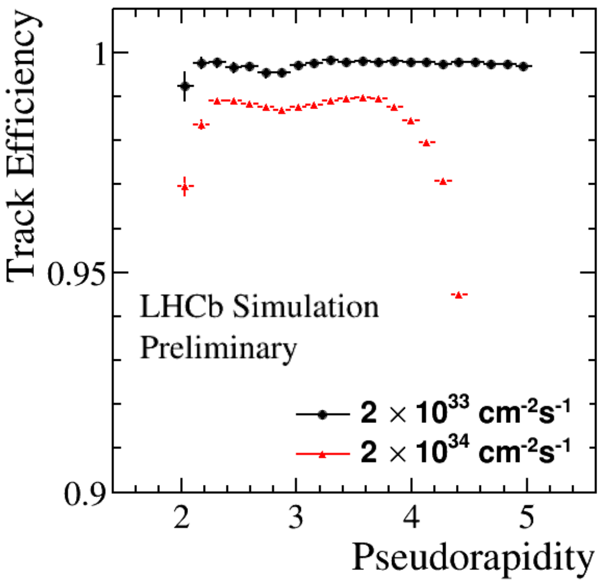
For scale…



In Upgrade-II: σ_t(PV) = 200ps σ_z(PV) = ~50mm (= 170ps @ v=c)

Upgrade II Challenge: 10x particle multiplicity

VELO Upgrade I performance degrades at HL-LHC luminosity ($L=2\times10^{34}\ cm^{-2}s^{-1}$)



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

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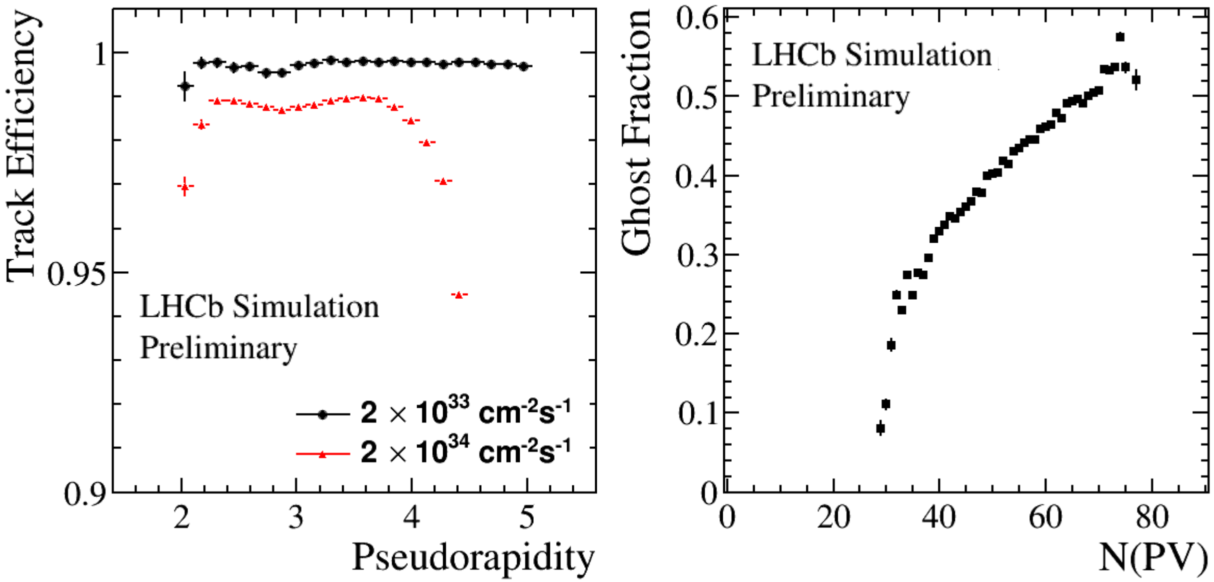

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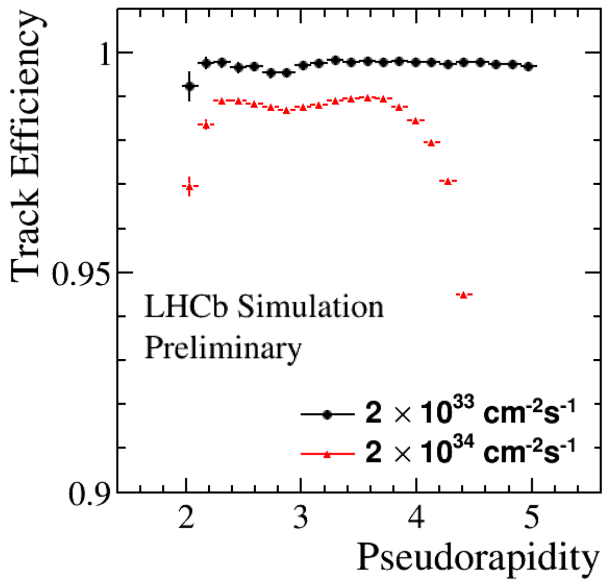

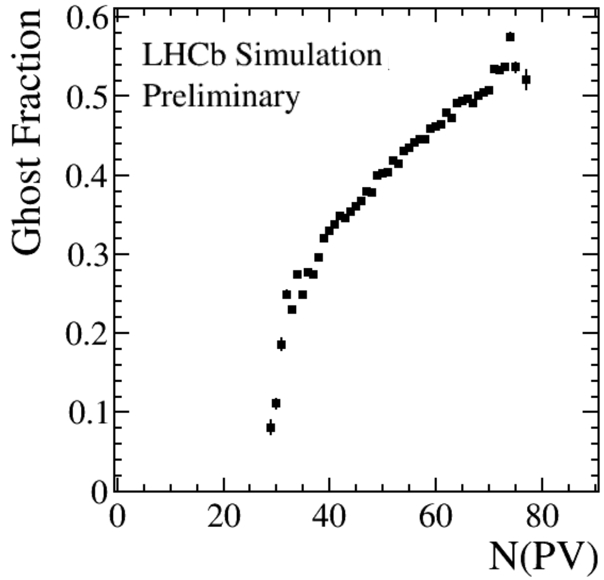

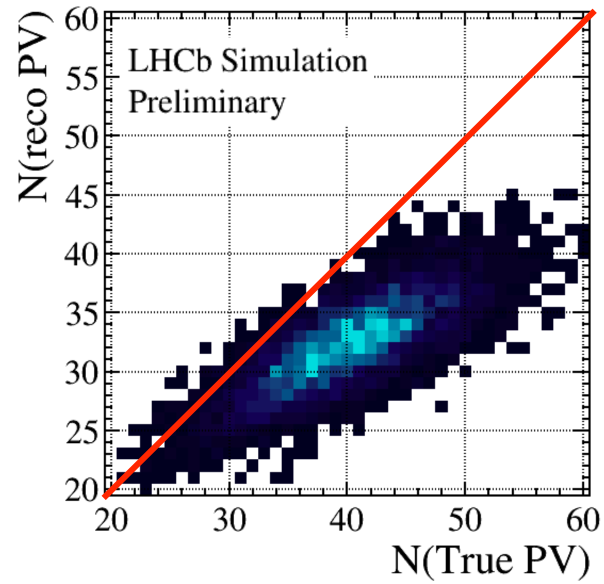

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To recover pattern recognition, need smaller pixels and/or precise timing on hits

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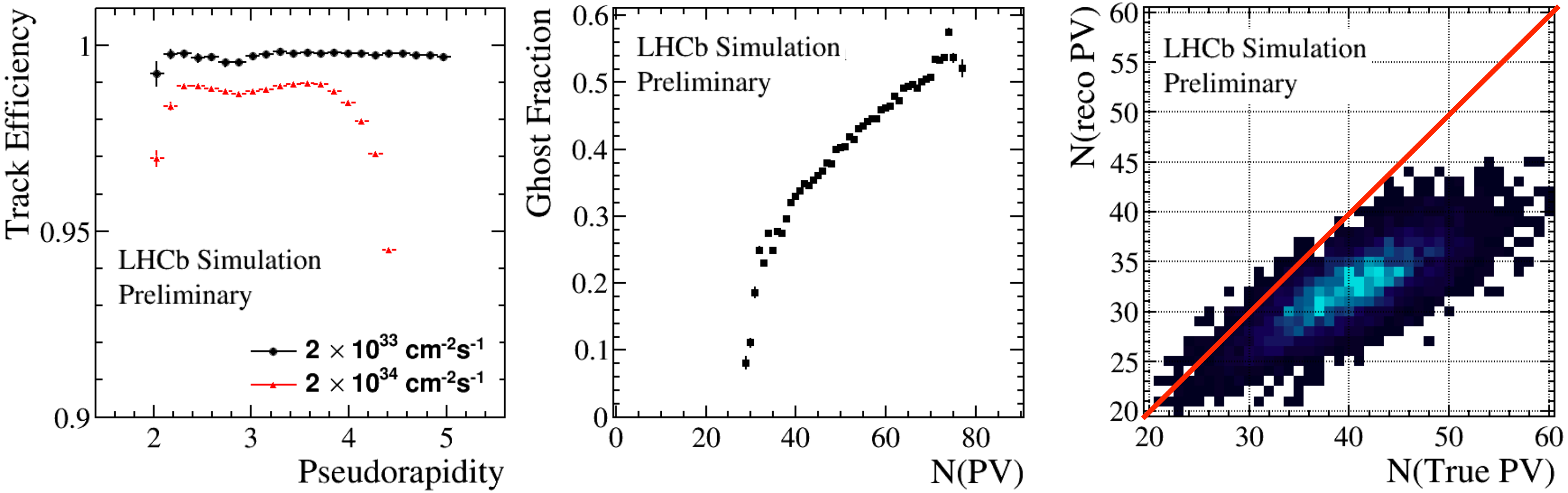

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To recover pattern recognition, need smaller pixels and/or precise timing on hits

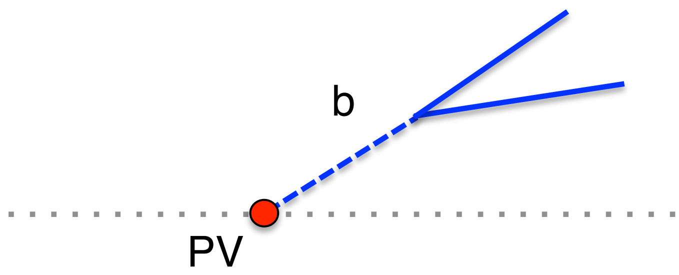
We also start to suffer from **PV mis-association**…

Upgrade II Challenge: PV association

LHCb relies on accurate association between long-lived particles and their origin vertex

⇒ allows **decay time** to be precisely measured

⇒ **key ingredient** for many analyses, e.g. time-dependent CP violation studies



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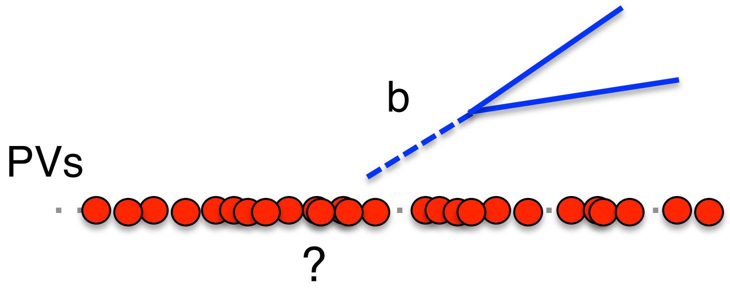

In HL-LHC environment, with ~50 PV per bunch crossing, this becomes a major challenge…

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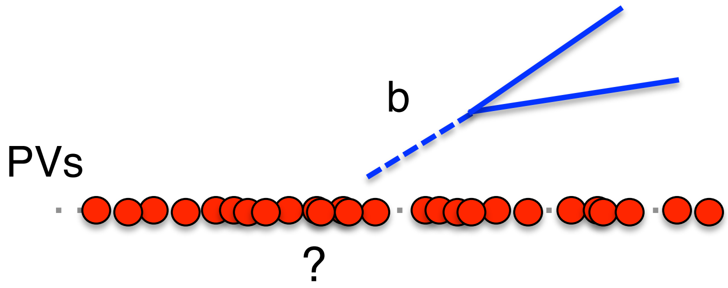
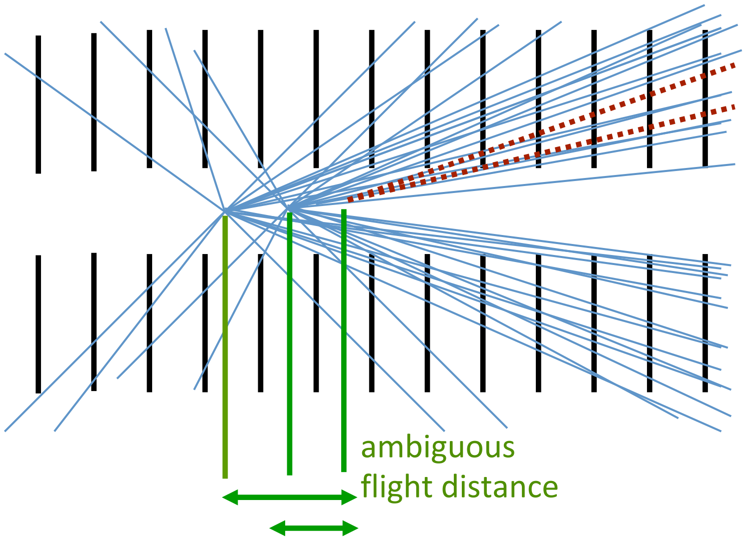


In HL-LHC environment, with ~50 PV per bunch crossing, this becomes a major challenge…

Especially difficult since LHCb has a forward acceptance $2 < \eta < 5$ ⇒ particles point back to collision region at acute angle



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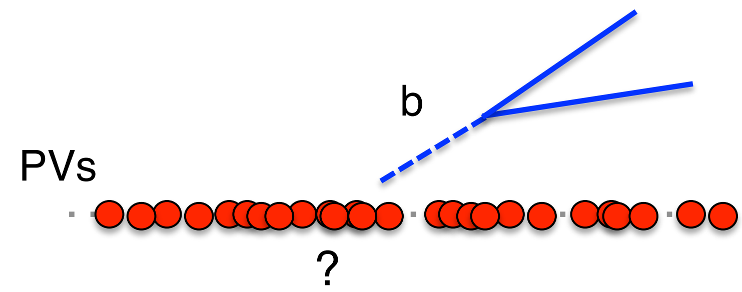

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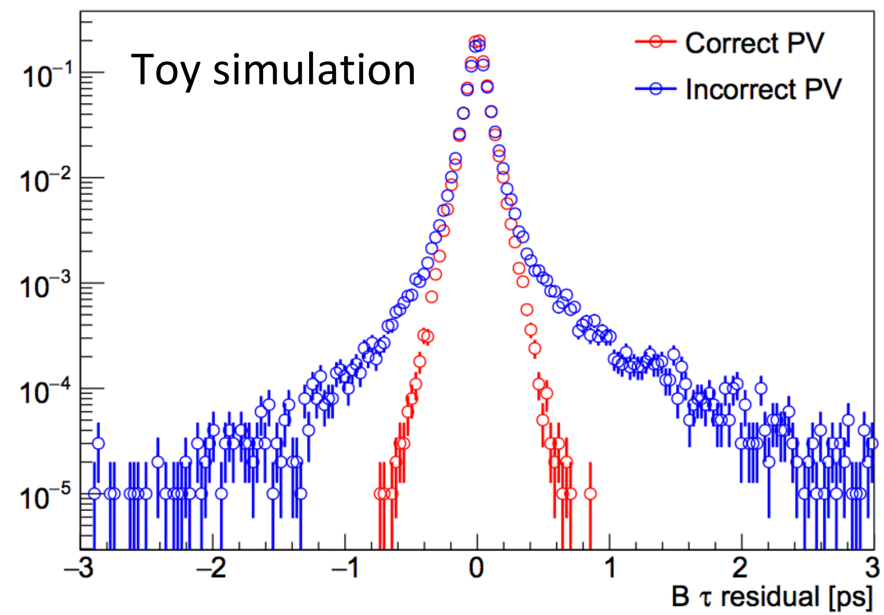
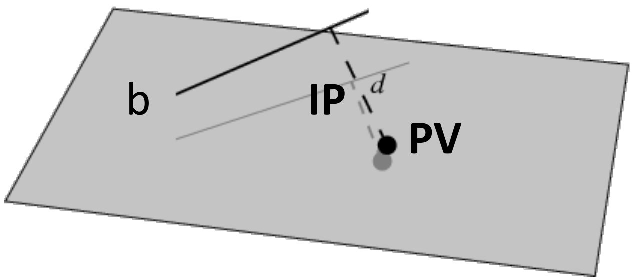
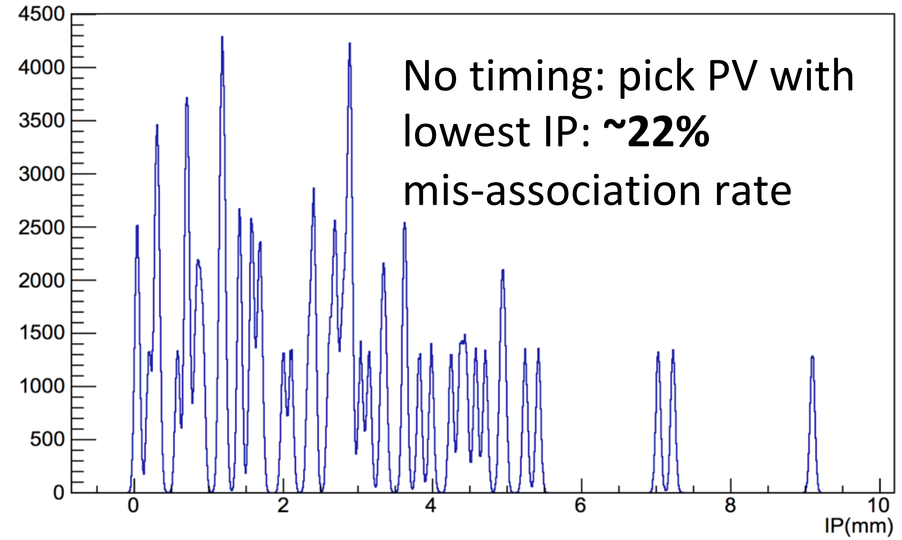


Leads to increased uncertainty on decay-time
⇒ Potentially limiting systematic effect for many measurements

Upgrade II Challenge: PV association

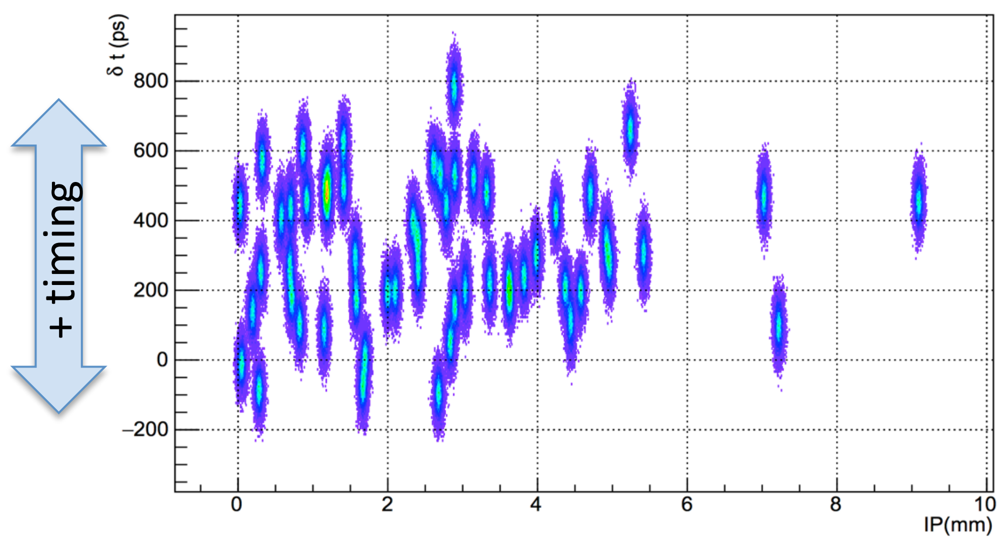
With addition of precise (~100ps) time information on VELO hits, the PV misassociation can be reduced significantly ⇒ recover required performance





No timing: pick PV with lowest IP: **~22%** mis-association rate

With timing: additional power to select correct PV using both IP and timing information: **4%** mis-association rate

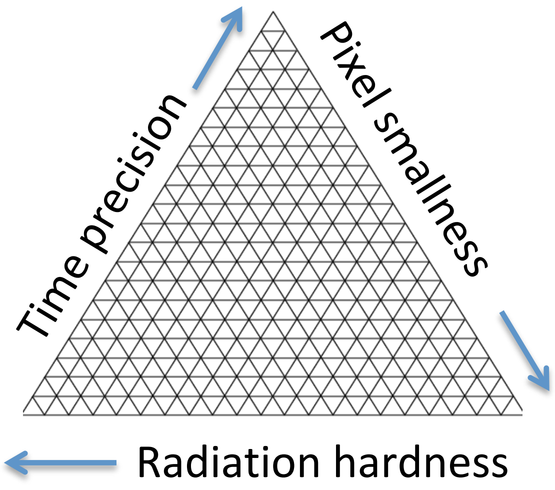


What does this mean for VELO Upgrade II?

We need a detector with:

- Small pixels (~**25→50μm**)
- Precise timing (~**100ps** per hit)
- Radiation hardness (detector must survive **5×10^{16}** 1 MeV neq /cm^2 over lifetime)

No technology can fulfil all these requirements simultaneously

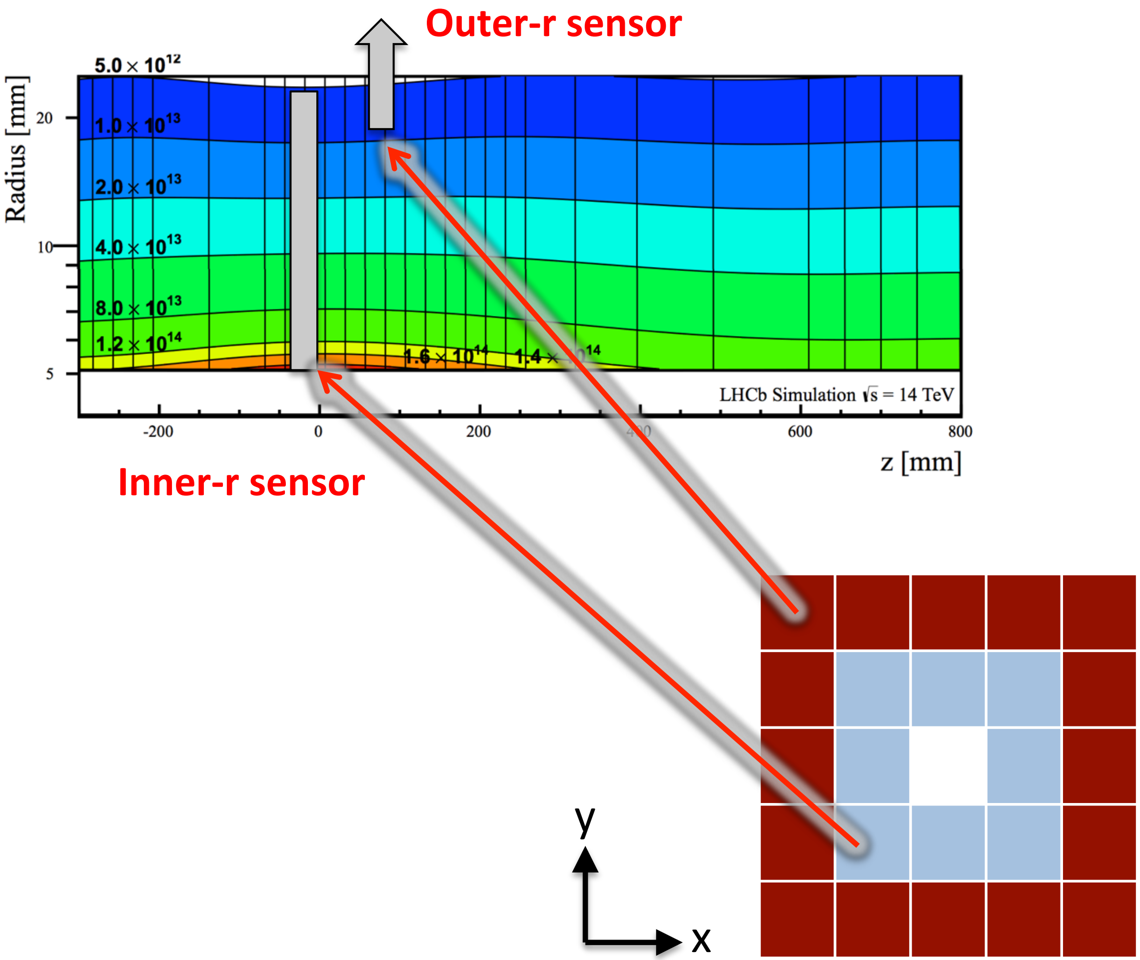


Solutions:

- Aggressive R&D to push technology performance?
- Clever designs to sidestep limitations?

Possible solution: Dual-technology approach

Limiting factors (radiation, occupancy) are highly dependent on radius



Approx. layout of Upgrade I ASICS in transverse plane

Possible solution: Dual-technology approach

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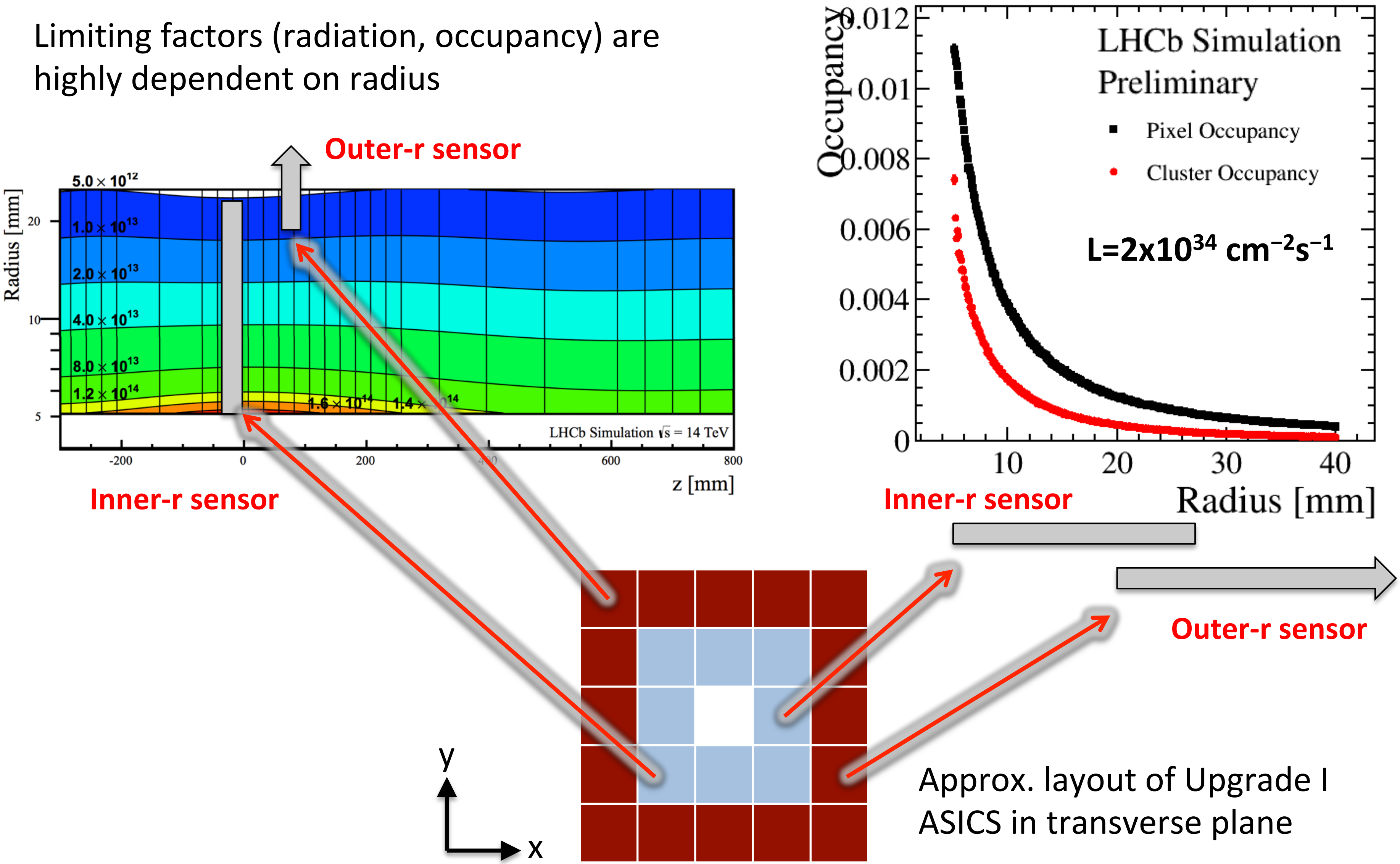
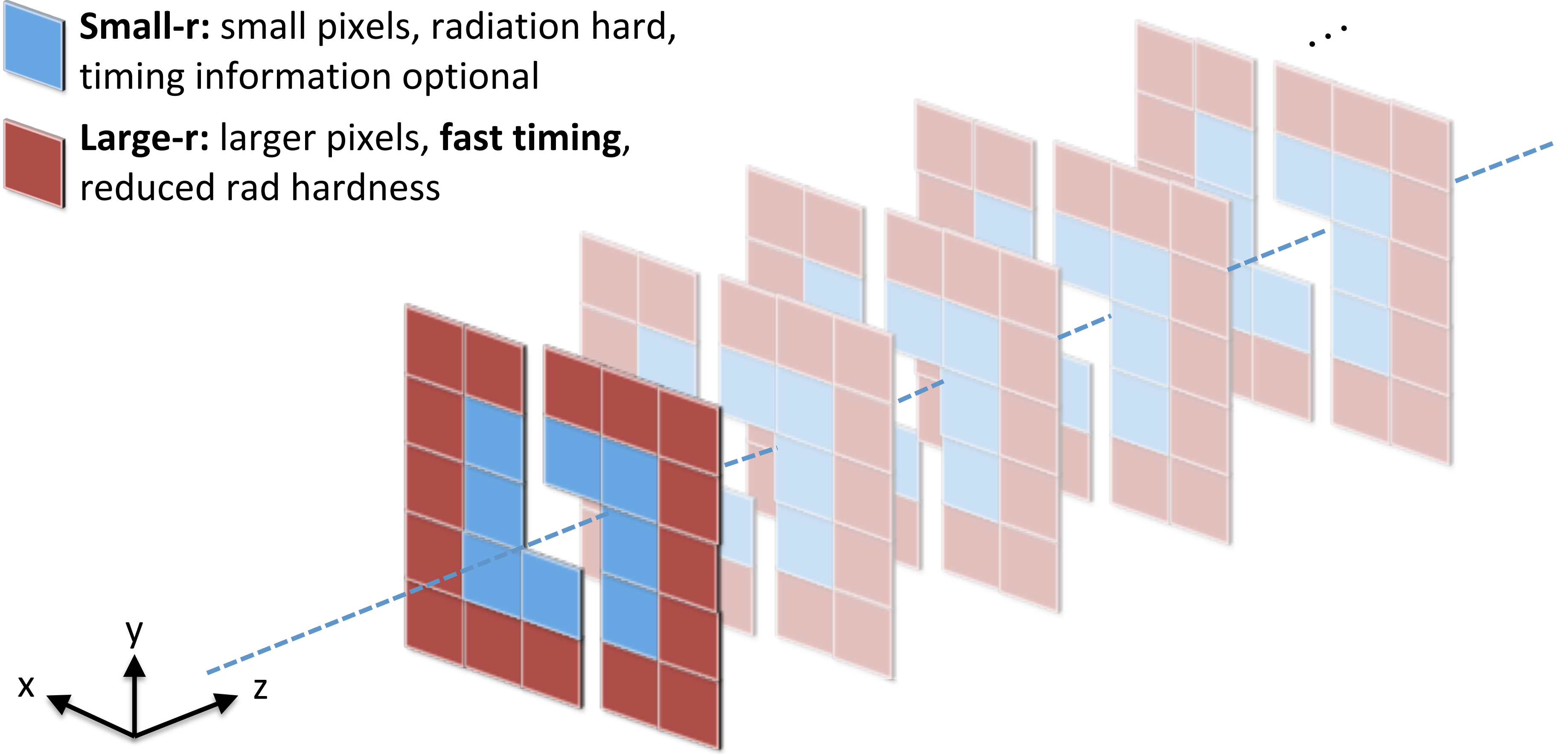


Approx. layout of Upgrade I ASICS in transverse plane

Possible solution: Dual-technology approach

Radial dependence motivates a dual-technology design

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



Possible solution: Dual-technology approach

Initial studies using simplified simulations

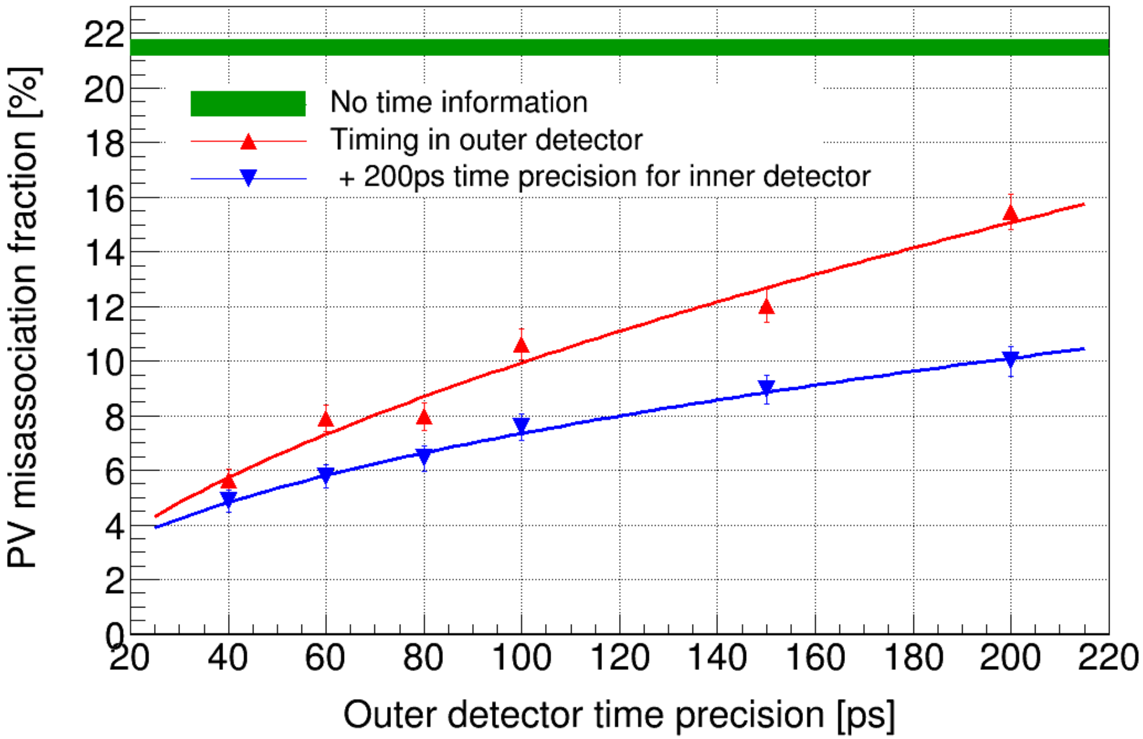
⇒ This approach can work for PV association at **$L = 2 \times 10^{34}$ /cm²/s**

⇒ Recover 5% PV misassociation with time precision of 200ps in inner region, and ~50ps in outer region

For this study: 50µm pixels throughout, but results similar for 200µm pixels for outer detector

Caveats:

- Preliminary detector geometry model
- Beam conditions not yet fixed – can influence results



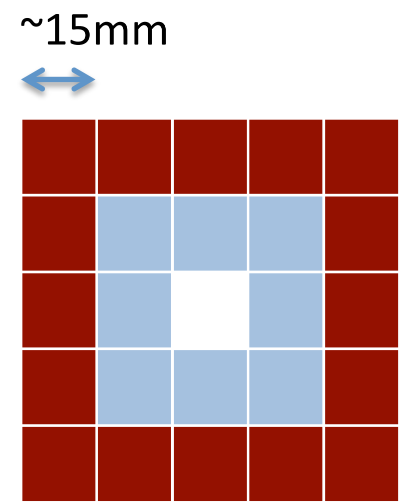
Possible solution: Dual-technology approach

Required technology performance now more realistic…

25-50µm pixels
200ps timing (optional)
Survive ~5 x 10^{16} 1 MeV n_{eq} cm^{-2} over lifetime

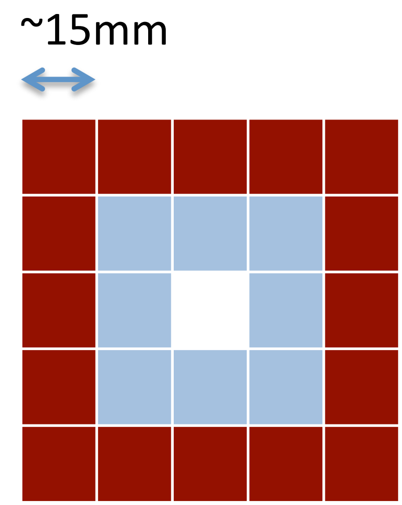
⇒ a more radiation hard version of our Upgrade I design, with incremental improvements in timing and pixel size

Possible technology: Hybrid pixel detector, VeloPix-II ASIC?



Possible solution: Dual-technology approach

Required technology performance now more realistic…



25-50µm pixels
200ps timing (optional)
Survive ~5 x 10^{16} 1 MeV n_{eq} cm^{-2} over lifetime

⇒ a more radiation hard version of our Upgrade I design, with incremental improvements in timing and pixel size

Possible technology: Hybrid pixel detector, VeloPix-II ASIC?

~200µm pixels
50ps timing
Survive ~3 x 10^{15} 1 MeV n_{eq} cm^{-2} over lifetime

⇒ Dedicated timing detector, with smaller pixels than currently available (e.g. $1x1mm^2$ pads for ATLAS and CMS timing planes) and improved rad hardness

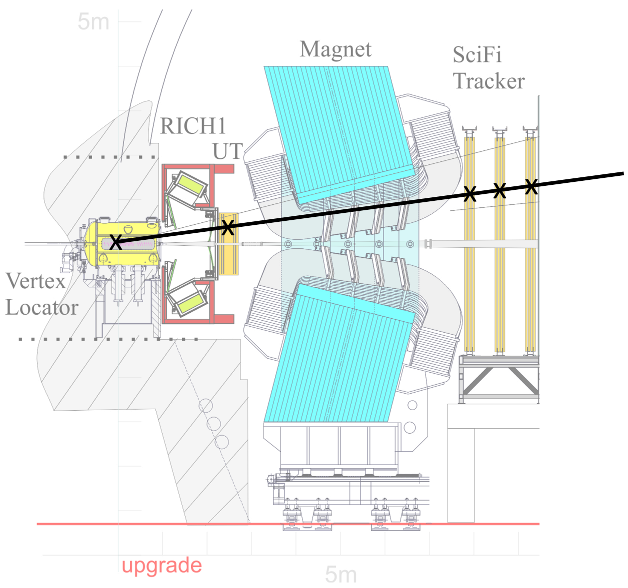
Possible technology: PixeLGAD? 3D silicon?

Other benefits of timing in the VELO

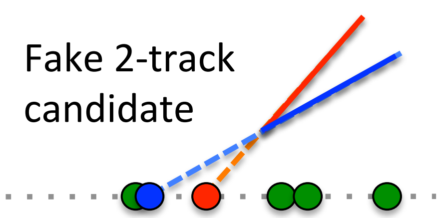
Fast timing could become a general theme in LHCb Upgrade II

- TORCH detector uses ToF from Cherenkov photons for Particle ID
- EM calorimeter may use timing to improve e/γ reconstruction

Timing VELO will improve **particle matching** between sub-detectors



High-level analysis tool: Use timing for **background rejection** – additional handle to remove fake track combinations

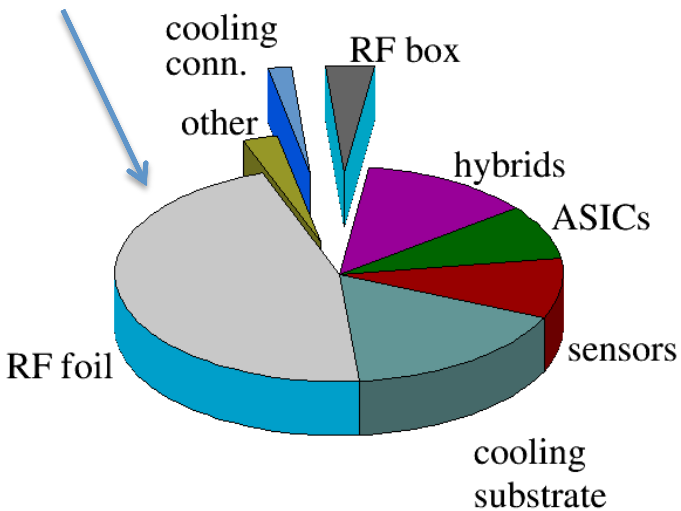


Upgrade II Opportunity: RF foil and material scattering

Track and vertex reconstruction performance limited by **material scattering**…

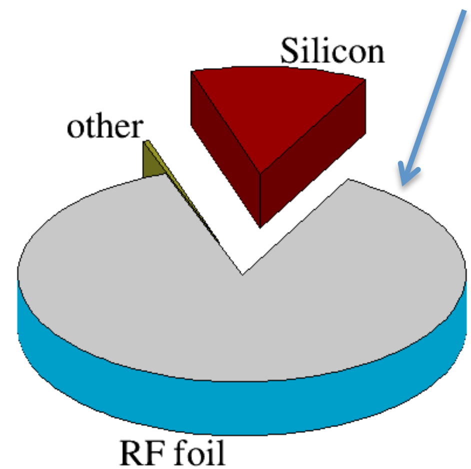
$$\begin{aligned}\sigma_{\rm IP}^2 &= \frac{r_1^2}{{p_{\rm T}}^2}\left(0.0136\ \ {\rm GeV}/c\ \sqrt{\frac{x}{X_0}}\left(1+0.038\ \ln\left(\frac{x}{X_0}\right)\right)\right)^2 + \frac{\Delta_{02}^2\sigma_1^2+\Delta_{01}^2\sigma_2^2}{\Delta_{12}^2}\\ &= \sigma_{\rm MS}^2 + \sigma_{\rm extrap}^2\ .\end{aligned}$$

Dominant source of material in Upgrade I detector is the RF foil



Total material: $25.01\% X_0$

(especially before 2nd hit)



Total material: $3.82\% X_0$

Upgrade II Opportunity: RF foil and material scattering

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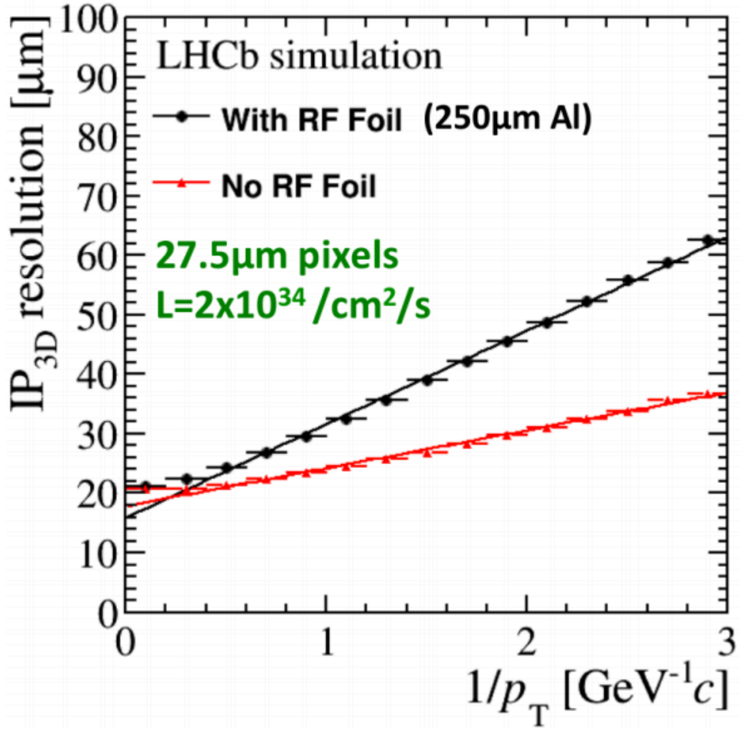
$$\sigma_{\mathrm{IP}}^2 = \frac{r_1^2}{{p_\mathrm{T}}^2}\left(0.0136\ \mathrm{GeV}/c\ \sqrt{\frac{x}{X_0}}\left(1+0.038\ \ln\left(\frac{x}{X_0}\right)\right)\right)^2 + \frac{\Delta_{02}^2\sigma_1^2+\Delta_{01}^2\sigma_2^2}{\Delta_{12}^2}$$

$$= \sigma_{\mathrm{MS}}^2 + \sigma_{\mathrm{extrap}}^2\ .$$

If the RF foil can be removed, IP resolution improves significantly

- ~50% improvement at low momenta
- IP and related variables crucial in background rejection
- For multibody final states, effect is even larger



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Track and vertex reconstruction performance limited by **material scattering**…

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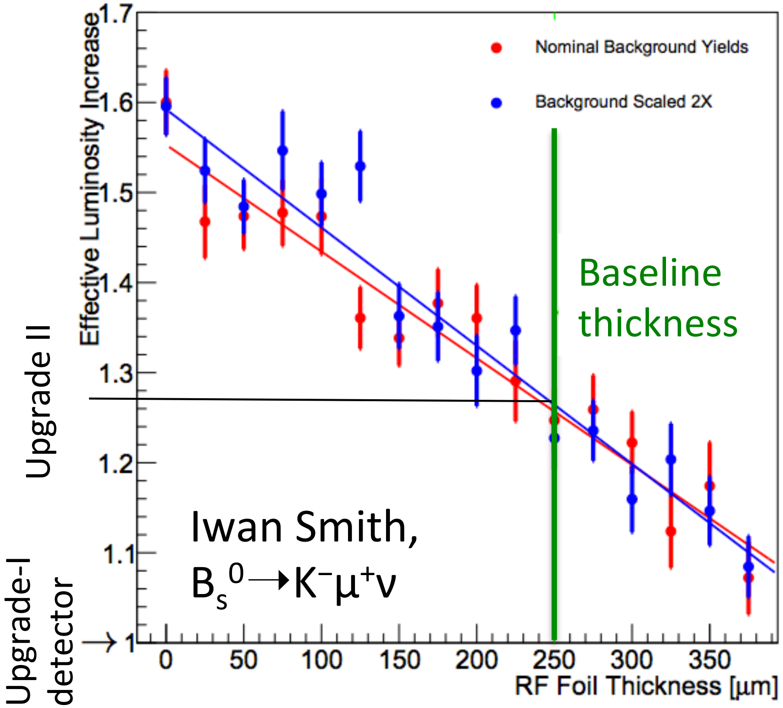
$$= \sigma_{\mathrm{MS}}^2 + \sigma_{\mathrm{extrap}}^2 .$$

Preliminary studies also show improved signal/background separation in semileptonic channels

⇒ Removing foil equivalent to increasing integrated luminosity by 25%

(luminosity is expensive!!)



Upgrade II Opportunity: RF foil and material scattering

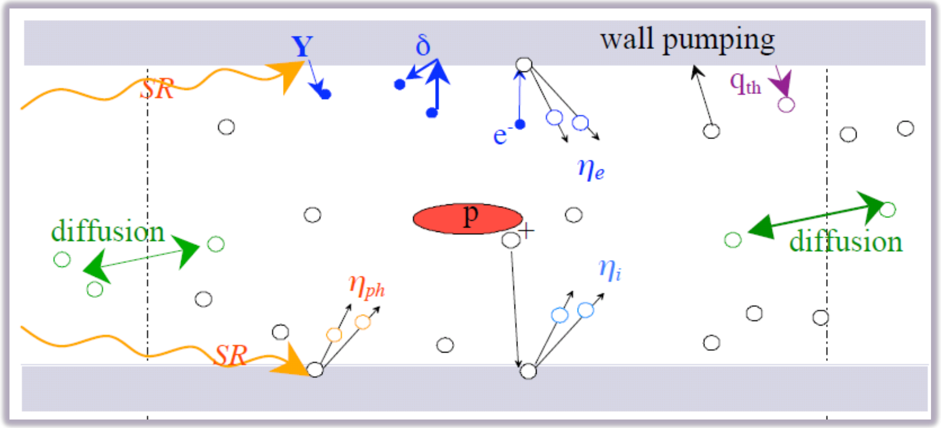
However… the RF foil is there for good reasons!

Separates VELO from primary beam enclosure:

- Protects VELO modules from **wake fields**
- Reduces machine **impedance** ⇒ essential for stable beams
- Protects primary **vacuum** from possible VELO outgassing

Replace with low-material (wire?) solution?

Confirm/improve leak-tightness of CO_2 microchannels

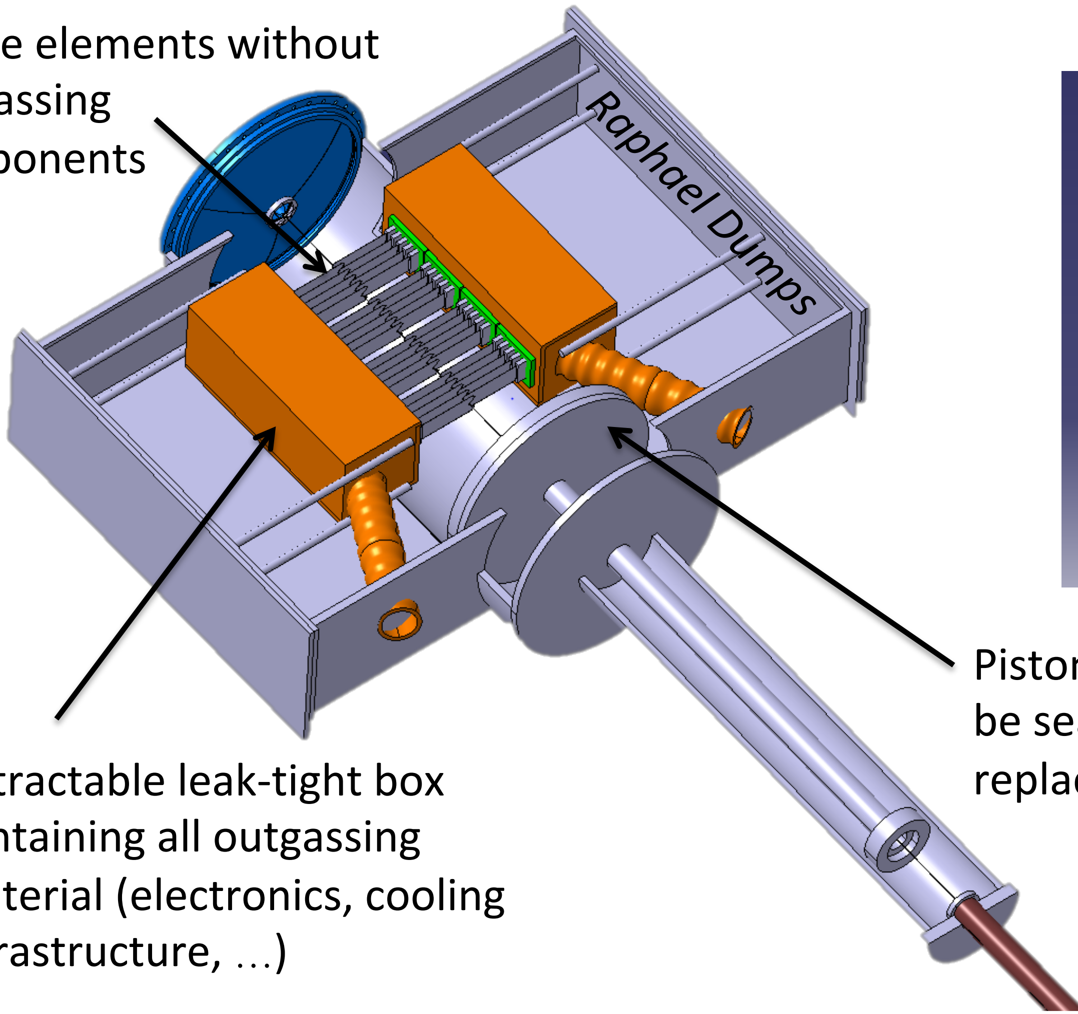


⇒ Many challenges to overcome, lots of scope for innovation and R&D

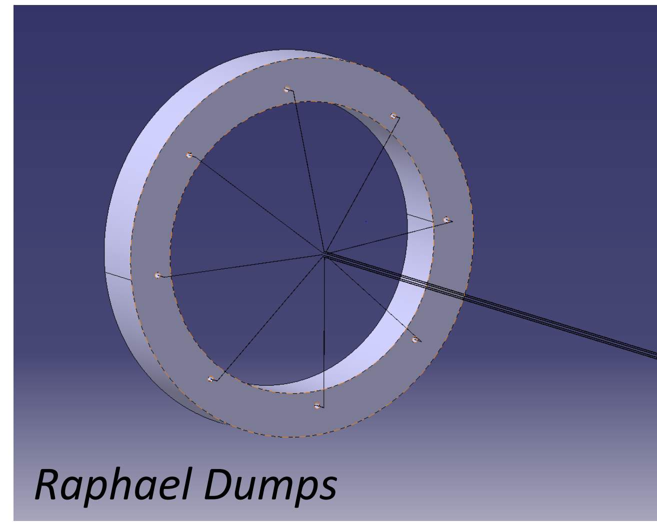
Upgrade II Opportunity: RF foil and material scattering

Ambitious concept for foil-less VELO:

Active elements without outgassing components



Wire-based RF guide with minimal material



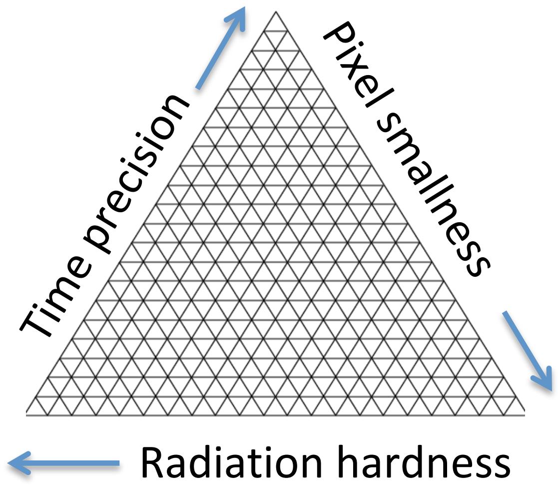
Piston allows entire VELO enclosure to be sealed from LHC to access (install / replace) the two VELO halves

Retractable leak-tight box containing all outgassing material (electronics, cooling infrastructure, …)

May also allow most irradiated components to be replaced during lifetime

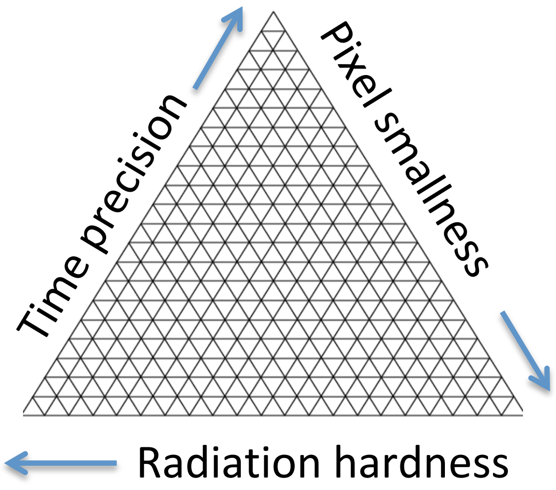
Status and Plans

- Very strong physics motivation to build LHCb Upgrade II
- Factor 50 increase in inst. lumi from current detector presents many challenges
- Upgrade II VELO in the concept stage – we can be ambitious and aim for the best possible performance
- Required technologies not yet available, but several candidates to be explored in coming years



Status and Plans

- Very strong physics motivation to build LHCb Upgrade II
- Factor 50 increase in inst. lumi from current detector presents many challenges
- Upgrade II VELO in the concept stage – we can be ambitious and aim for the best possible performance
- Required technologies not yet available, but several candidates to be explored in coming years
- Main challenges in sensor development, foil-less design, and radiation hardness
- Essential to also consider read-out / trigger / reconstruction **during the design process**



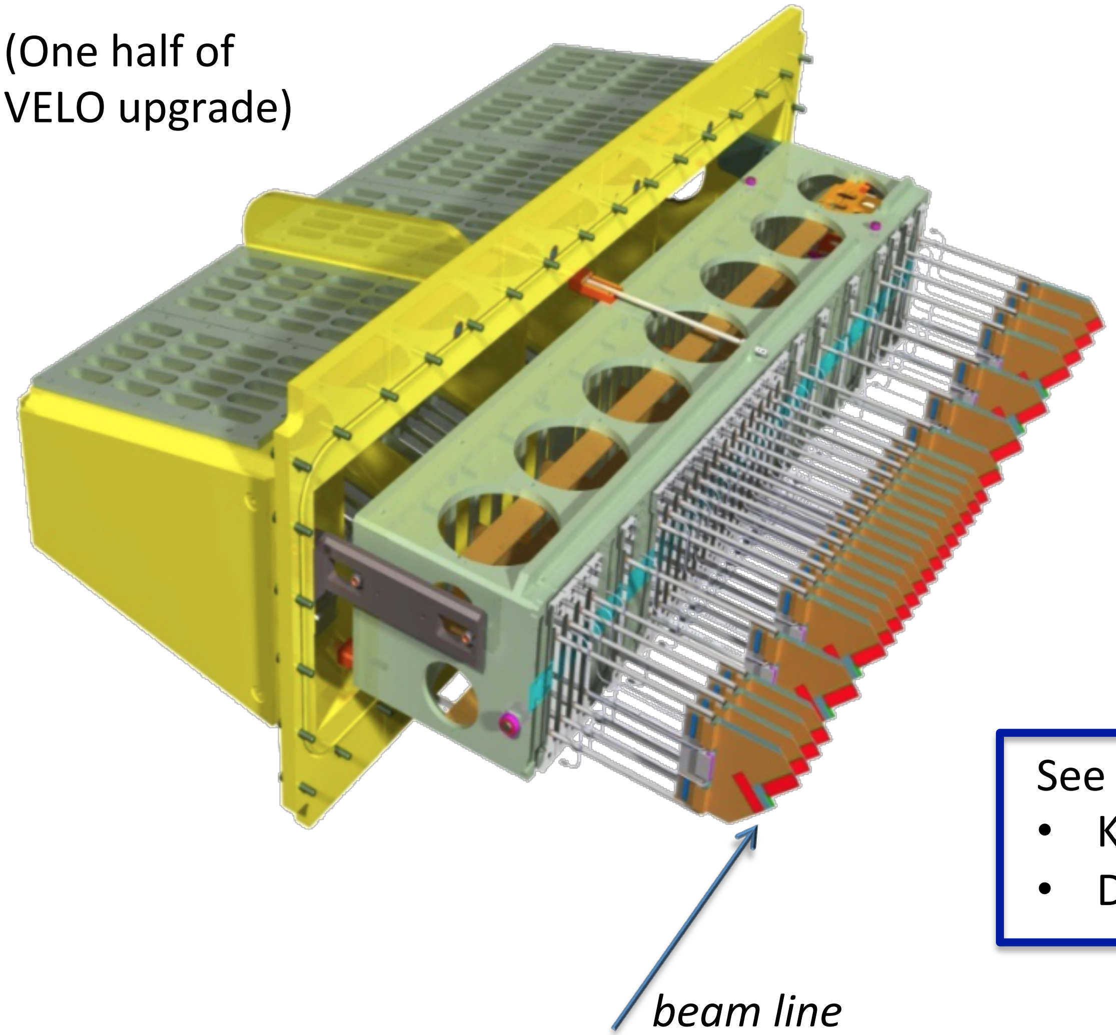
Upgrade I development, construction, and operation will be a valuable lesson!

If you are interested in collaborating on any R&D in these directions, please let us know!

Extra Slides

VELO Upgrade I

(One half of
VELO upgrade)



Major Changes:

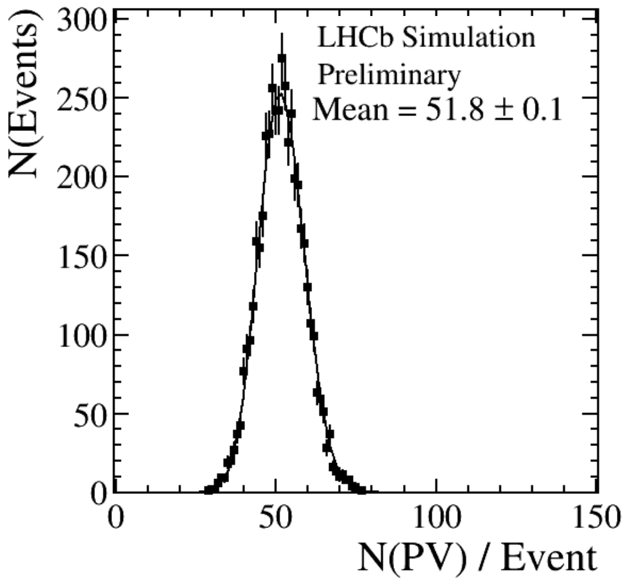
- **Pixels** (55μm) to handle higher particle multiplicity
- **Closer to beam** (5.1mm)
- Full **40 MHz read-out**

See talks by:

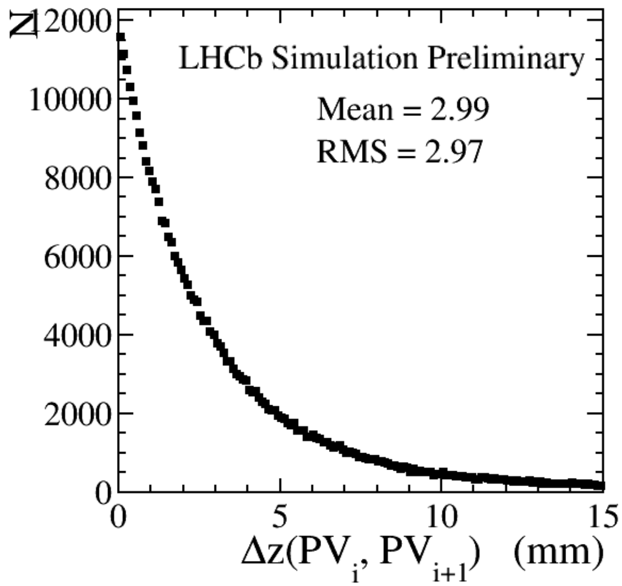
- Kristof De Bruyn (VeloPix)
- Donal Murray (VELO Upgrade I)

Upgrade II Challenge: 10x vertex multiplicity

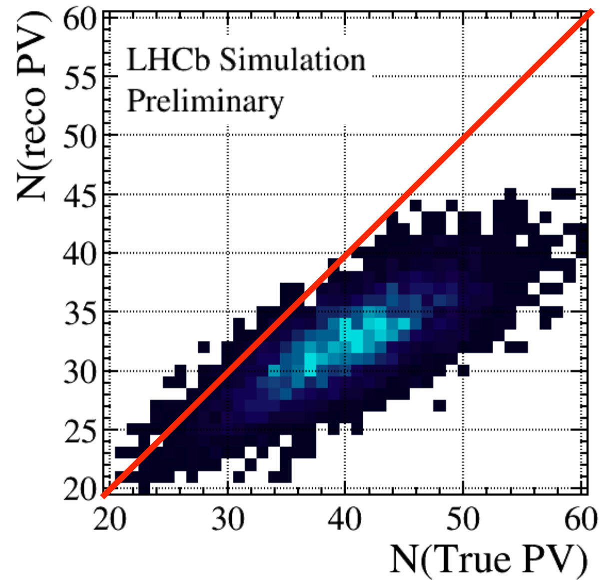
At Upgrade II luminosity, ~50 visible interactions / crossing



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



With Upgrade I detector, PVs start to merge



We also start to suffer from **PV mis-association**…