Super VELO studies: Status and plans

Elba Workshop:
Beyond the LHCb Phase-1 Upgrade

30 May 2016

Mark Williams

The University of Manchester

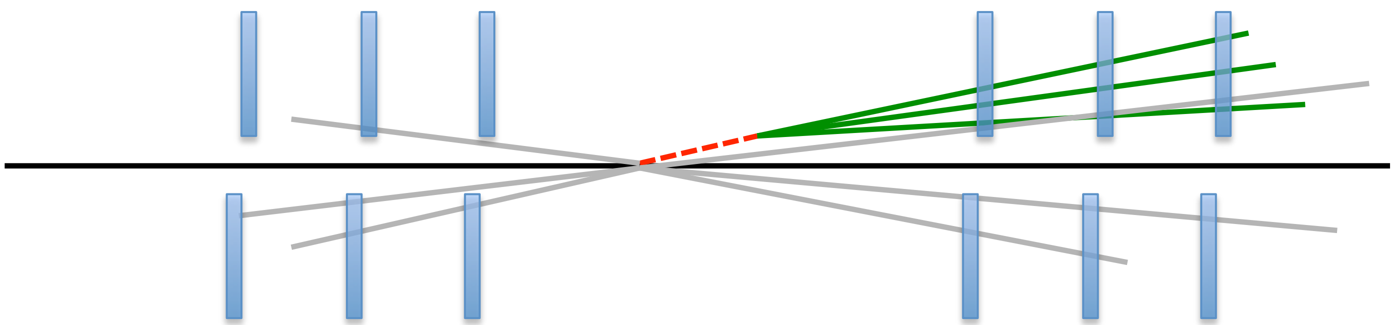
The Basics

We need:

Precision spatial measurements of charged particles

High track-finding efficiency

Low ghost/ clone rate



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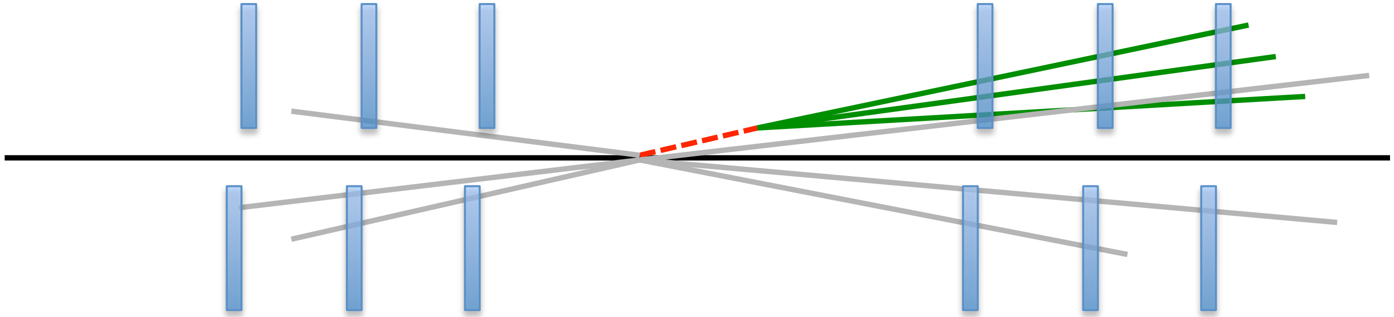
Close to beam line

Precise single-hit measurements



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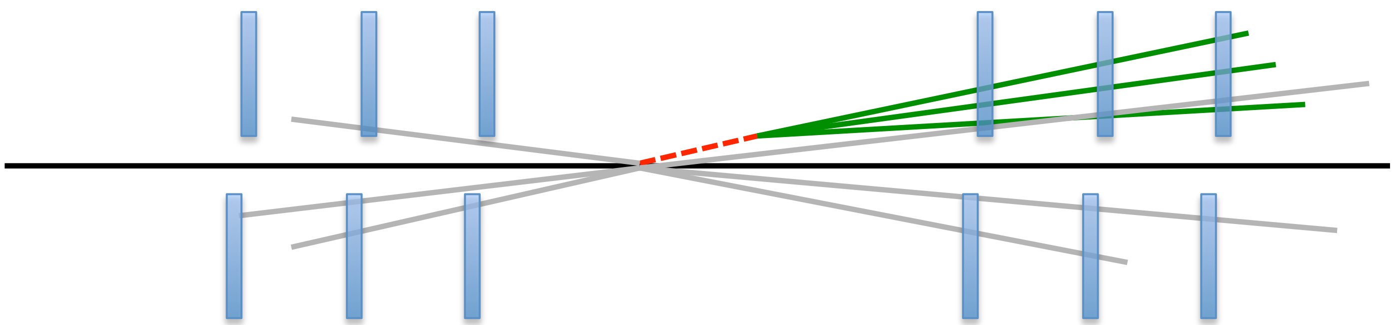
Low material	Full coverage within acceptance
Close to beam line	High granularity
Precise single-hit measurements	Multiple O(10) hits per particle



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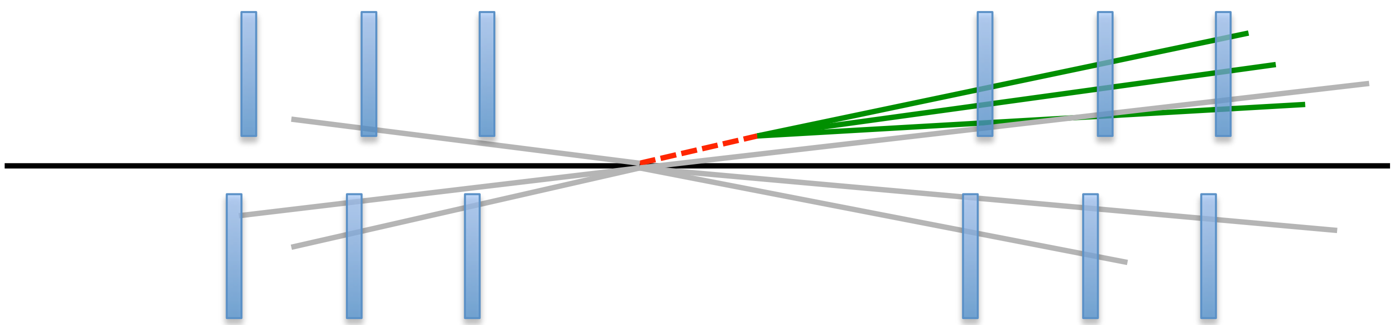

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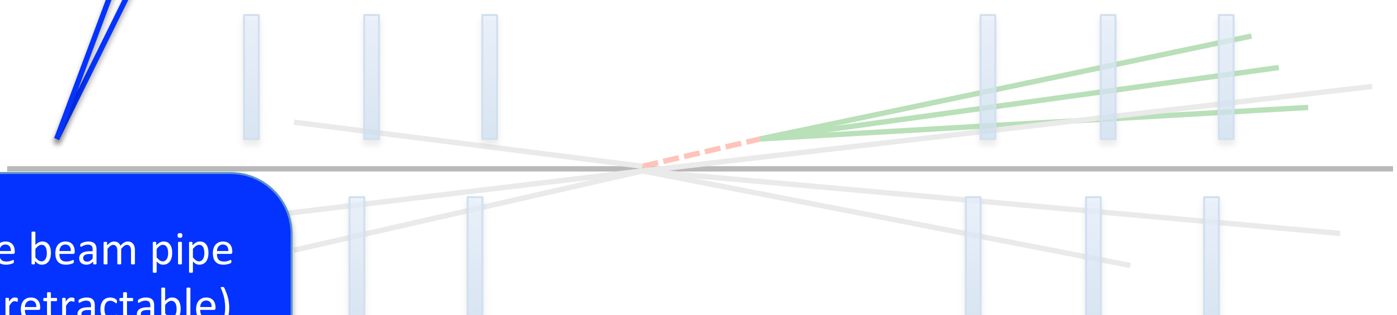

Inside beam pipe (and retractable)

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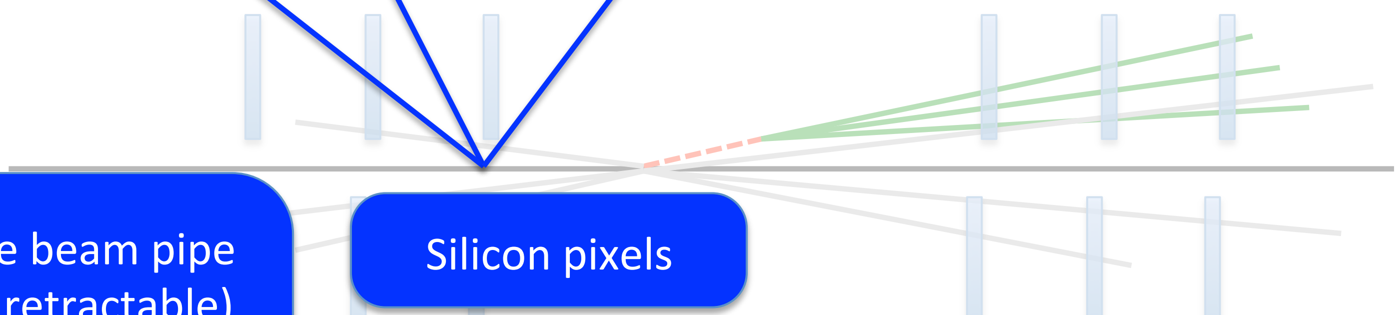

Inside beam pipe (and retractable)

Silicon pixels

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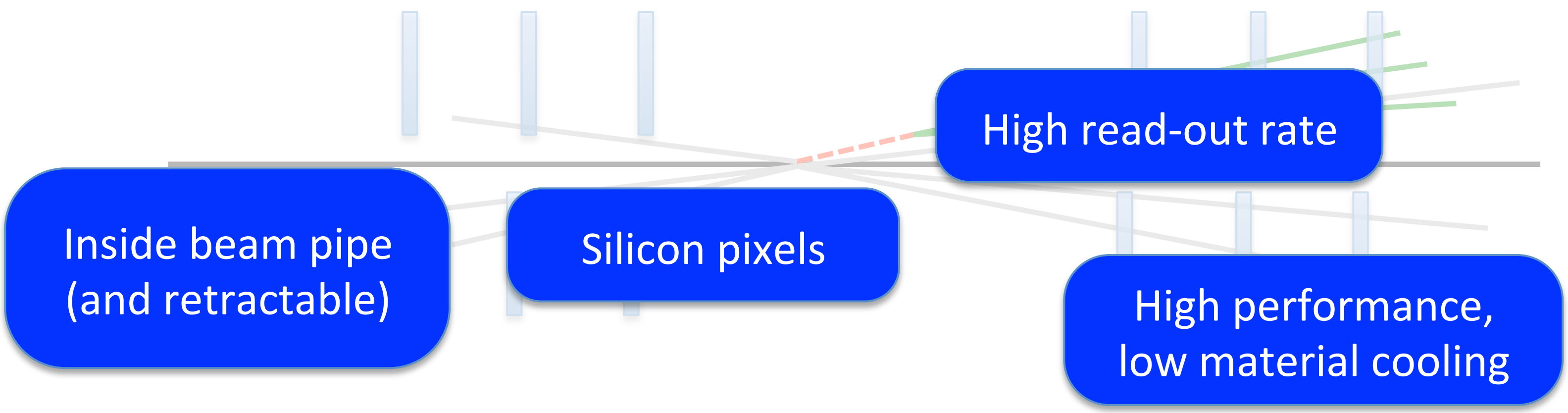

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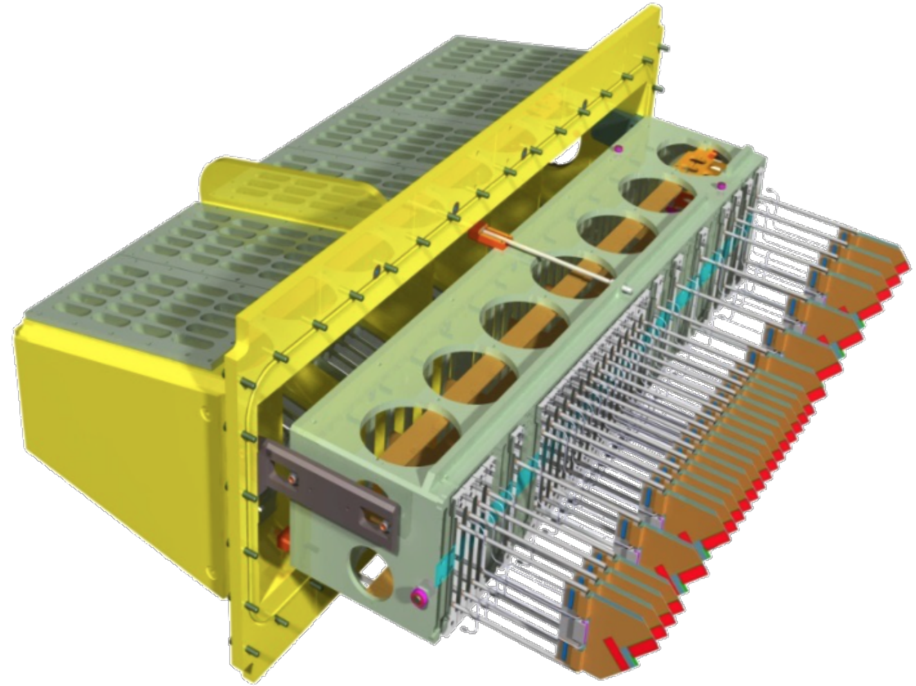
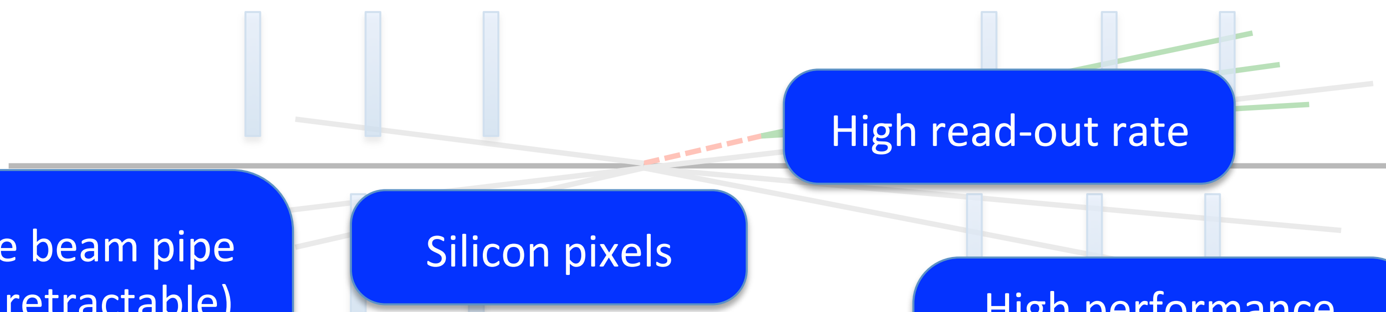


Sound familiar?

Phase-I upgrade VELO must fulfil same basic requirements



High read-out rate

Inside beam pipe (and retractable)

Silicon pixels

High performance, low material cooling

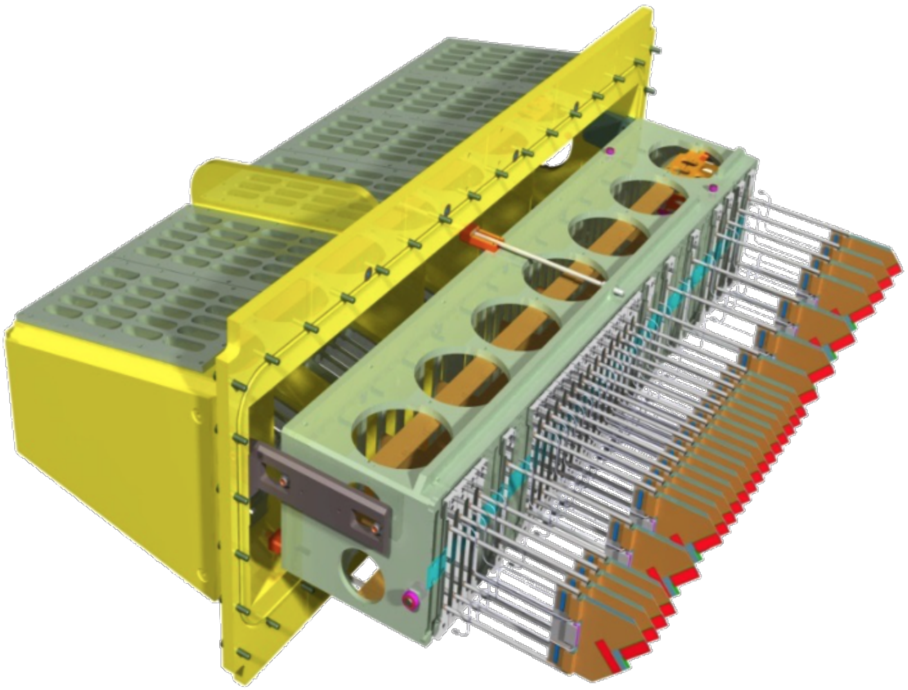
The Basics

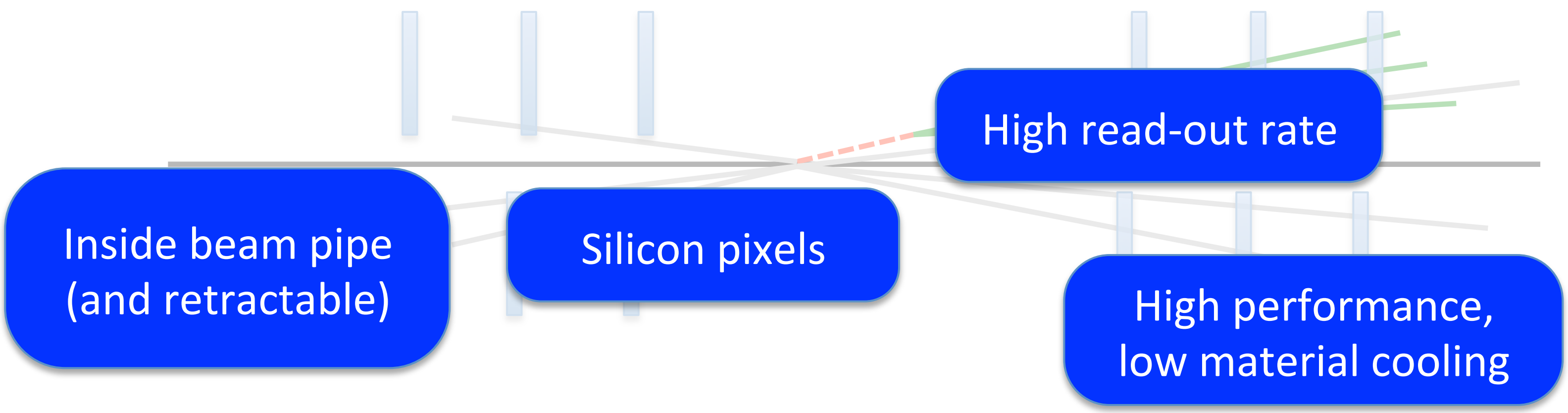
Sound familiar?

Phase-I upgrade VELO must fulfil same basic requirements

Additional challenges:

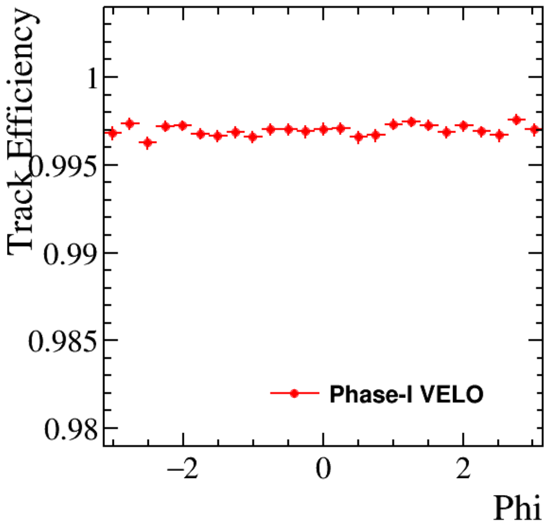
- 10x higher particle multiplicity
- 10x denser vertex environment
- 10x higher radiation damage



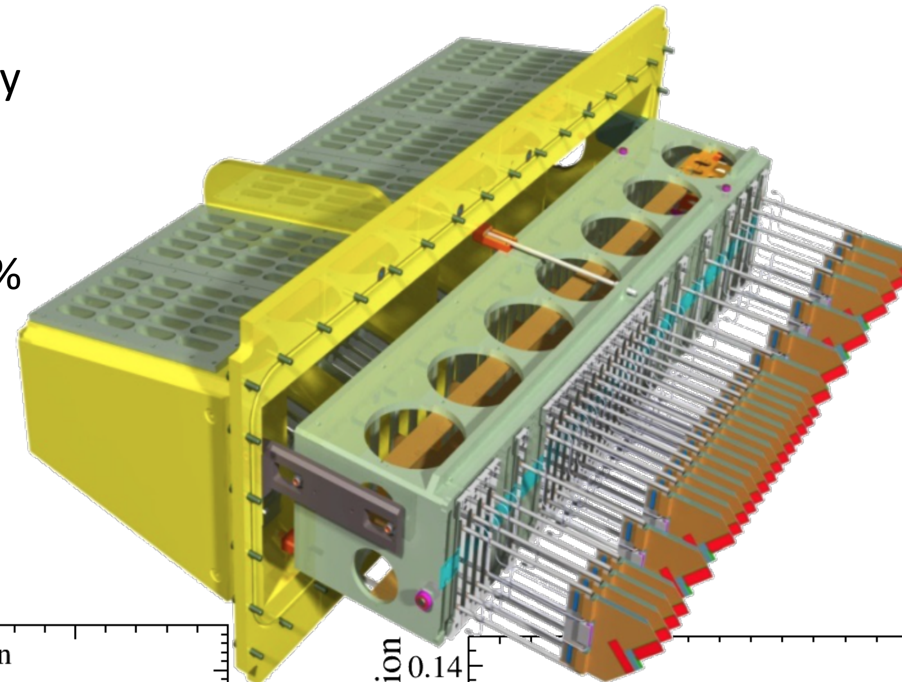


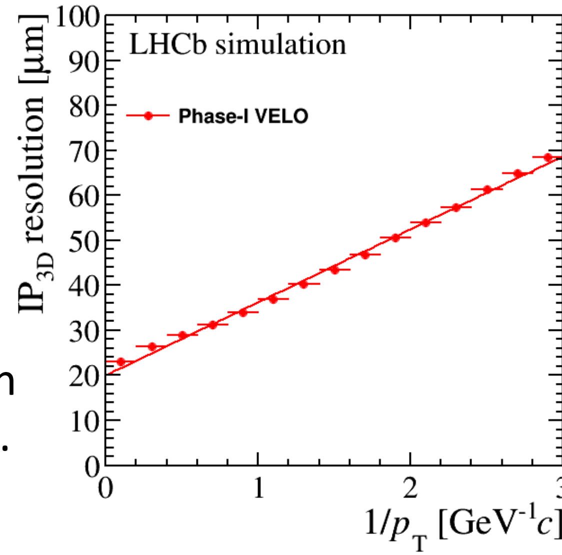
Phase-I VELO

Very high performance at Run 3-4 luminosity

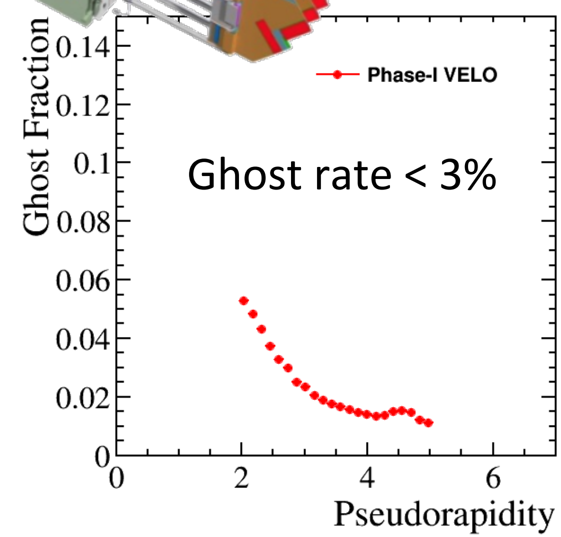


Tracking efficiency > 99.5% for long tracks





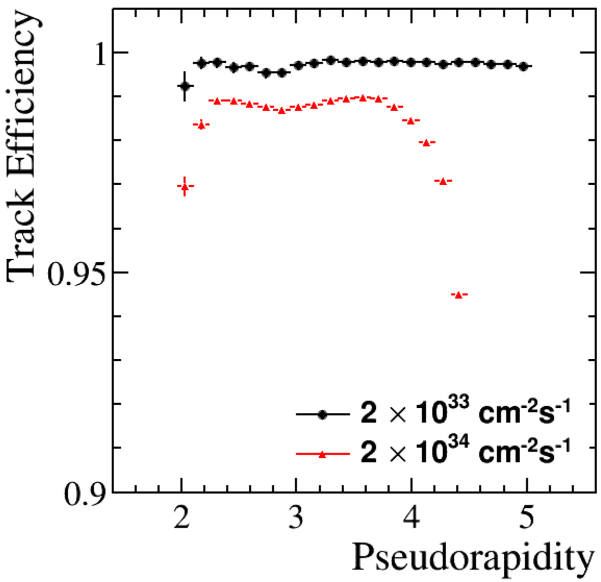
Impact parameter resolution ~20 (60) μm at high (low) p_T.



Ghost rate < 3%

Phase-II Challenge A: 10x particle multiplicity

Phase-I VELO performance breaks down at Phase-II luminosity ($L=2x10^{34}$)



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

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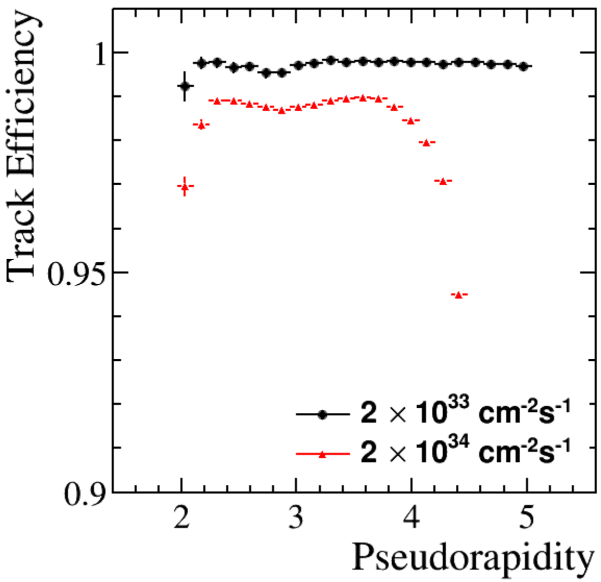

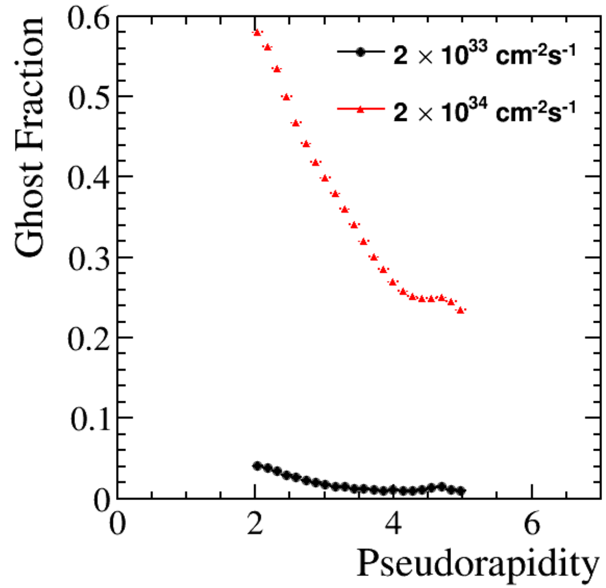

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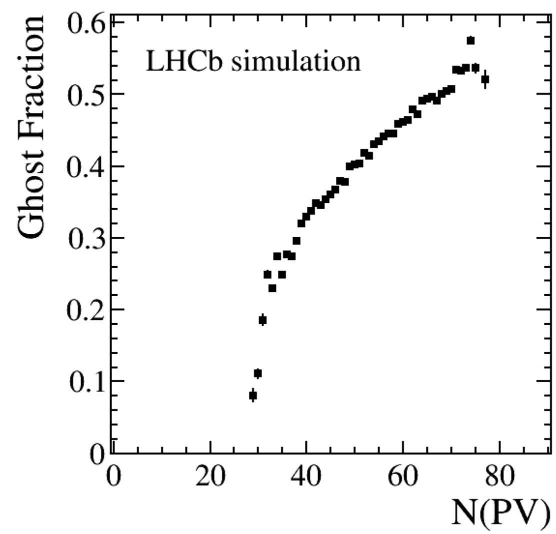
Ghost rate explodes (~2% → 40%)



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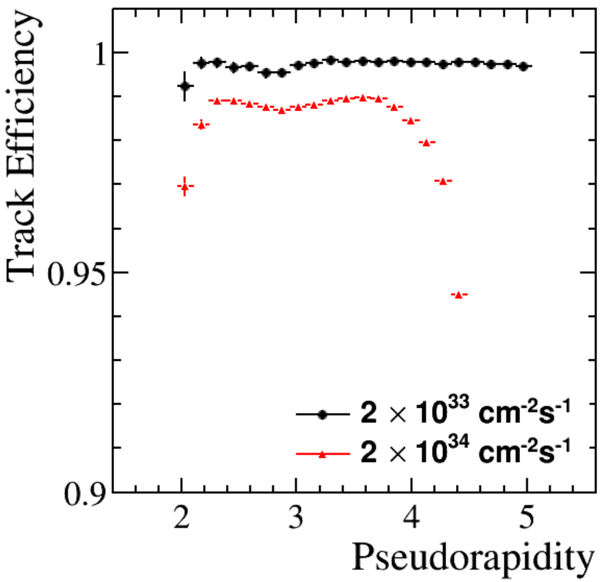

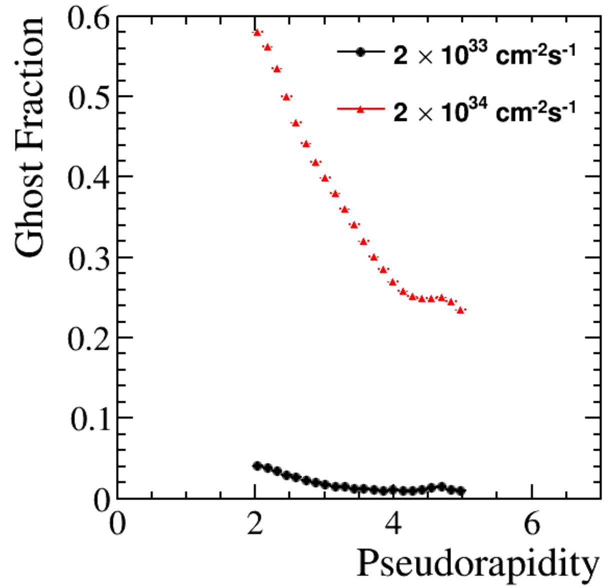

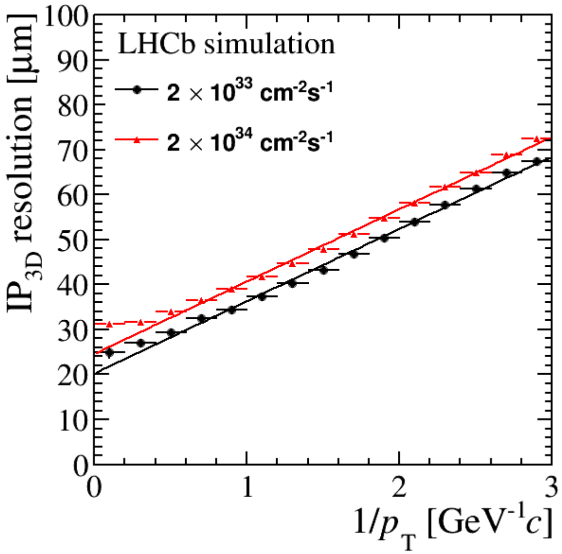

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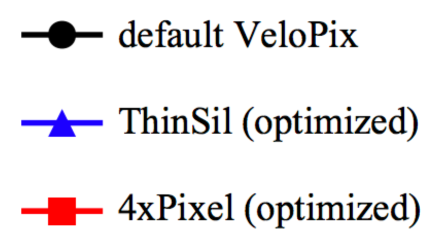
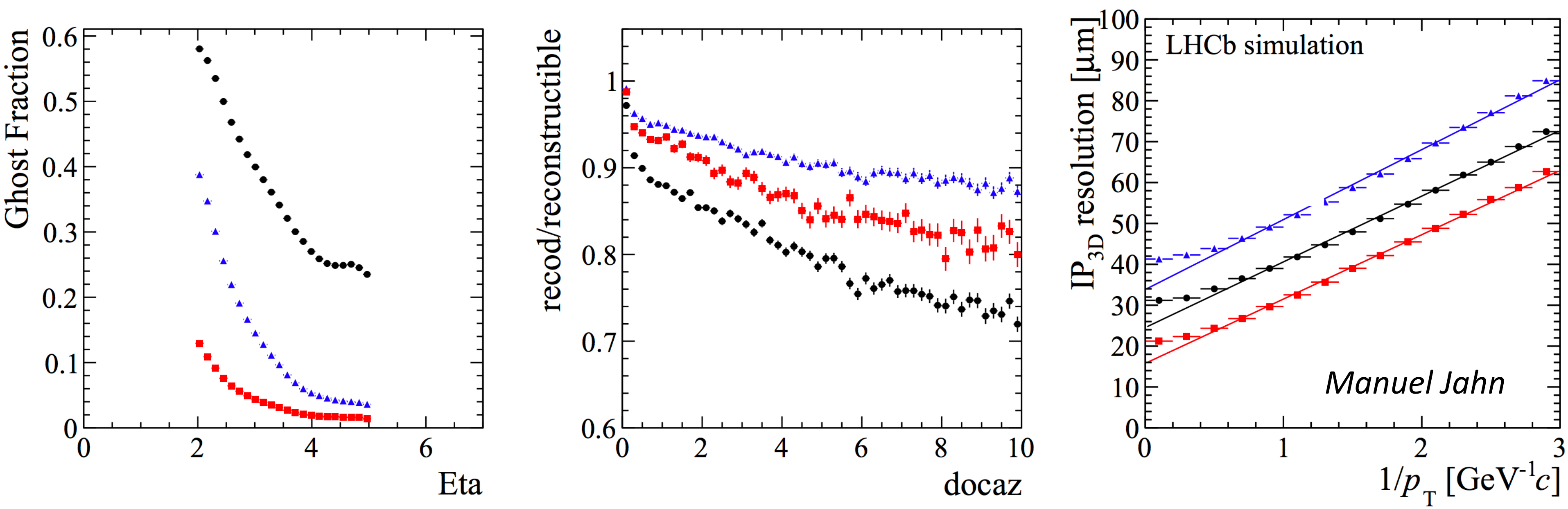
Spatial resolution degrades due to reduced track-finding performance

Phase-II Challenge A: 10x particle multiplicity

Can recover most performance with modest improvements: ✔

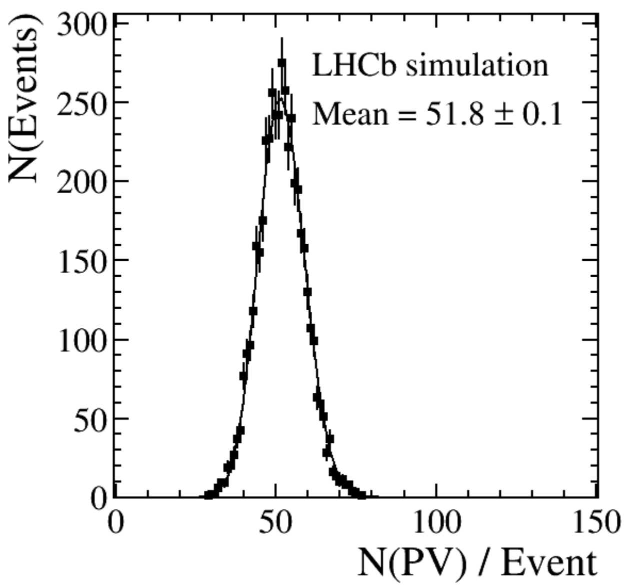
- Smaller pixels (55µm → 27.5µm)
- Thinner silicon (200µm → 100µm)
- Re-optimised pattern recognition



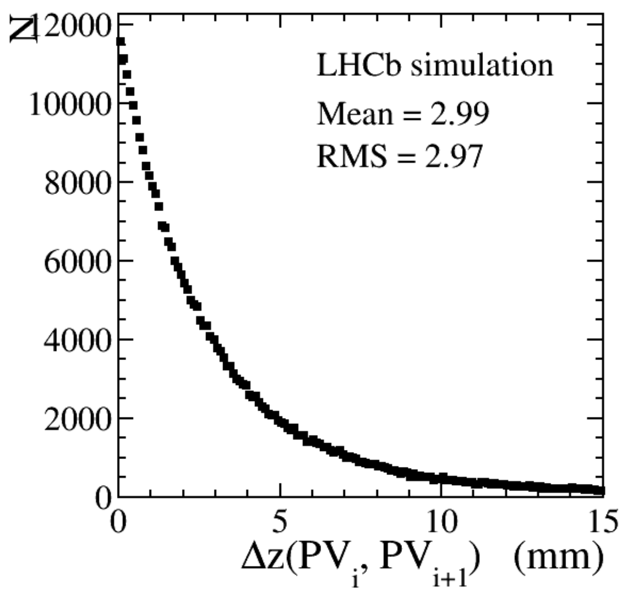


Phase-II Challenge B: 10x vertex multiplicity

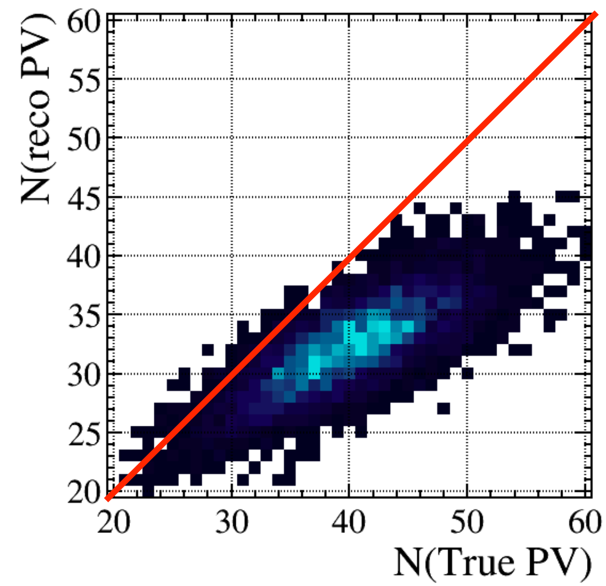
At Phase-II luminosity, ~50 visible interactions / crossing



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



With phase-I detector, PVs start to merge



PV **reconstruction** recovered with smaller pixels

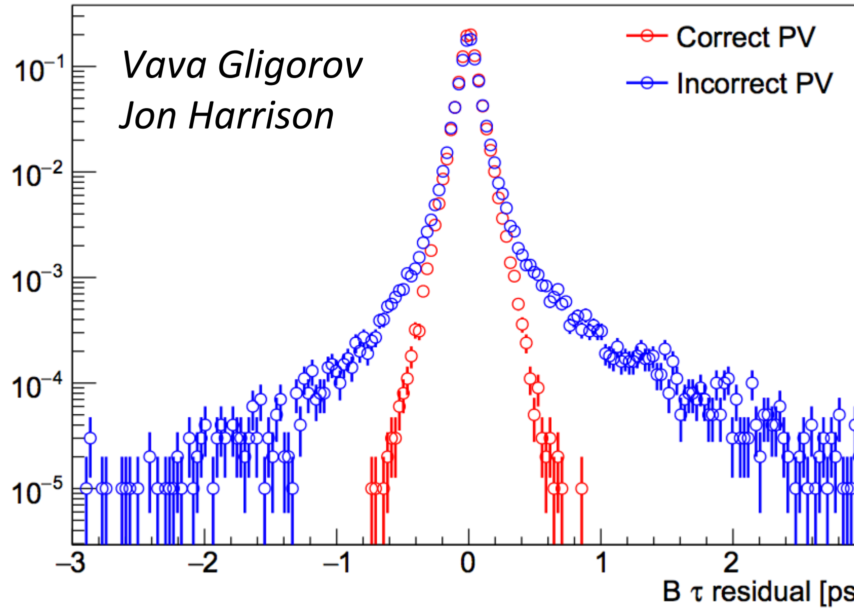
BUT we start to suffer from PV-track **mis-association**…

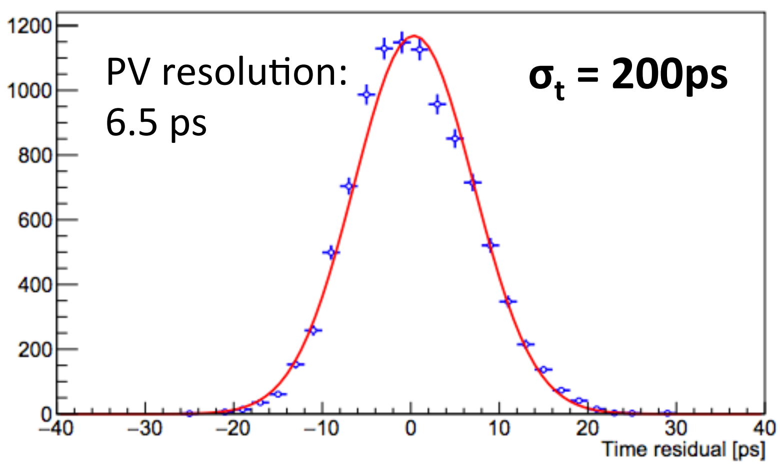
Phase-II Challenge B: 10x vertex multiplicity

Assigning incorrect PV to track → poorly measured lifetime

Becomes a dominant systematic for time-dependent analyses

Can be recovered by adding timing information to tracks ✔





Preliminary study with time information added to all VELO hits

e.g. 200ps per-hit resolution → 6.5ps PV resolution (8.5ps for 2-body SV)

Phase-II Challenge B: 10x vertex multiplicity

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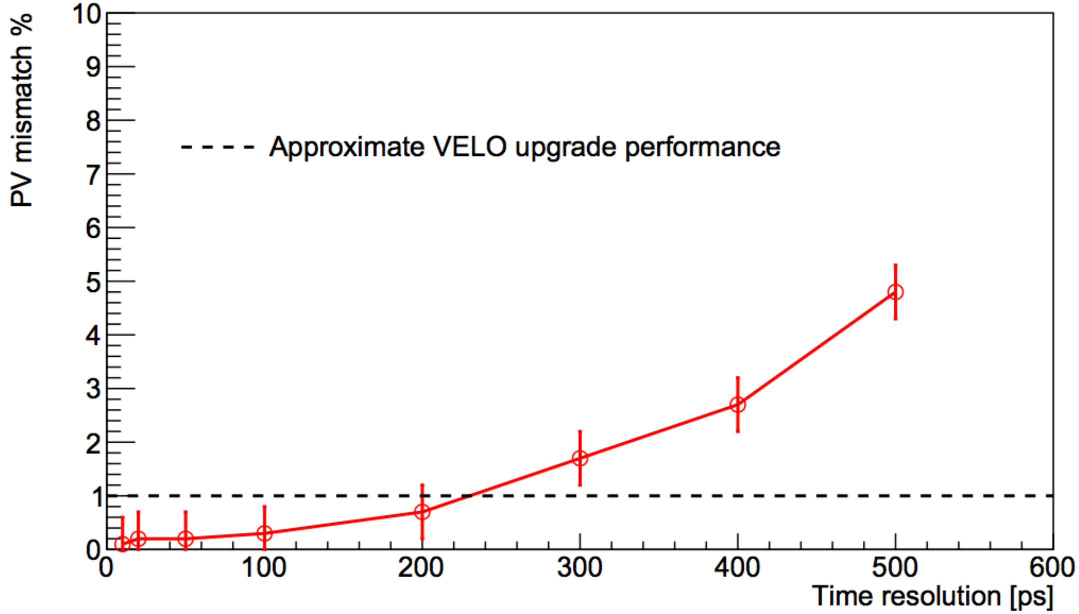
With no timing information, **14%** mis-association rate

With 200ps resolution (per-hit), PV mis-association rate reduces **below 1%** (Phase-I upgrade expectation).

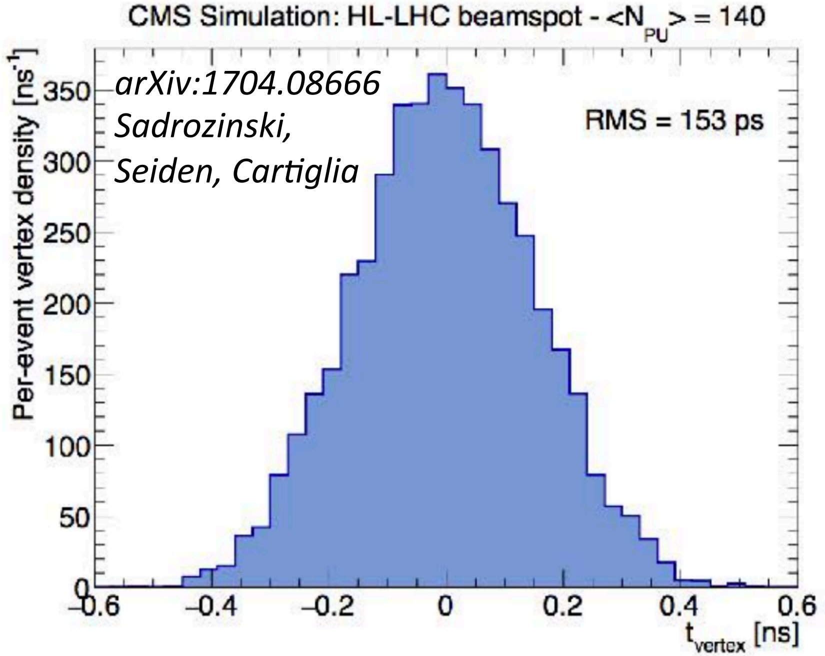


Pixels with timing

See dedicated talk (next) by Margherita Obertino

How precise?

- PV distribution has RMS ~150ps
- For 4D pattern recognition, need **single hit resolution** sufficient to separate hits from ~50 different interactions : O(10-30ps).
    - Simulation shows we can achieve decent tracking performance with spatial hit information alone (but need small pixels)
    - 4D tracking would give larger gains – worth investigating



- For PV association, **track resolution** must be O(10ps) – can combine information from multiple hits, and don't need time information from all hits

Pixels with timing

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Some general comments:

- Difficult to achieve precise timing information with small pixels
- Fast timing detectors more susceptible to radiation damage

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Suggests separate technologies for spatial and time information

Dedicated timing planes and/or timing sensors at larger radius

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Timepix4 aiming for 200ps timing information − could potentially get time/space information simultaneously

Still challenges to extend this functionality to potential 'SuperVeloPix' chip:

- Need to qualify **radiation hardness**
- Need to push **hit rate** (e.g. Velopix has 10x output rate of timepix3, but sacrifices information to achieve this)
- Will **Pixel size** be small enough? (we need <30μm, larger if we have 4D)

SuperVeloPix ?

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

Timepix3

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

VeloPix

Under validation
– all looks good!

- Reduced pixel size
- 65 nm technology
- ~200 ps timing precision
- 4-sided buttable design

Timepix4

Now in design phase

SuperVeloPix ?

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

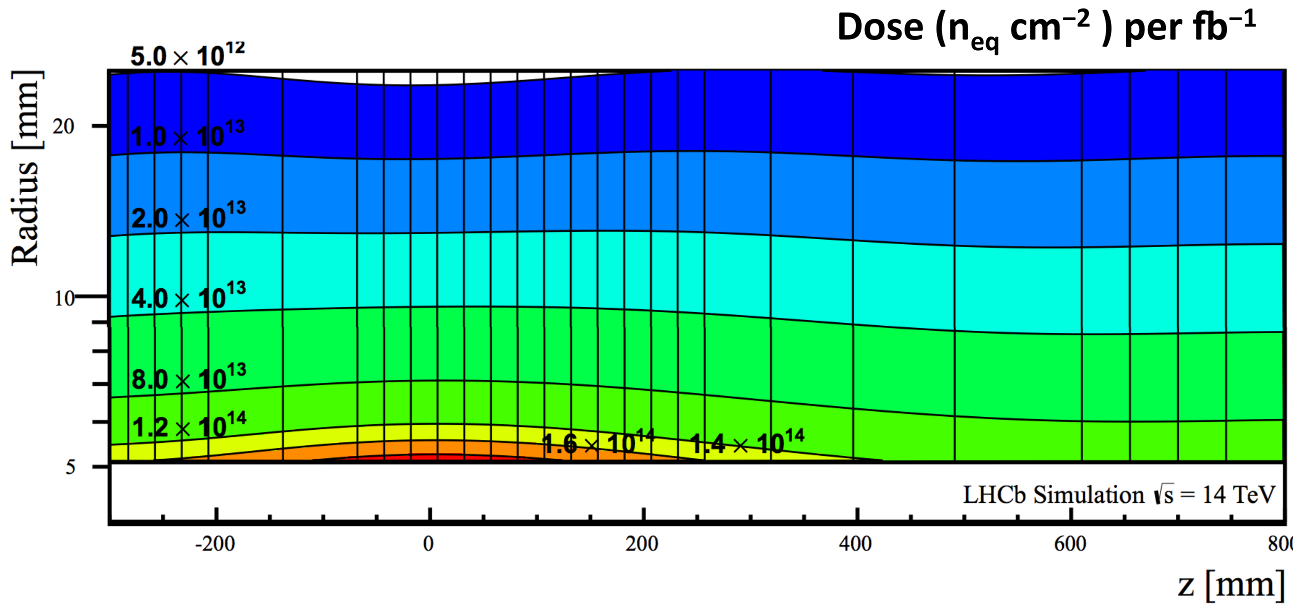
- Even better timing precision?

??

Phase-II Challenge C: 10x radiation damage

Highly non-linear radiation dose

Phase-I upgrade:
Maximum dose of
8×10^{15} 1 MeV n_{eq} cm^{-2}
after $50fb^{-1}$
(closest active area **5.1mm** from beam).



Phase-II will see **$5\text{-}8 \times 10^{16}$ 1 MeV n_{eq} cm^{-2}** over course of lifetime

This is beyond the limits of current silicon technology –
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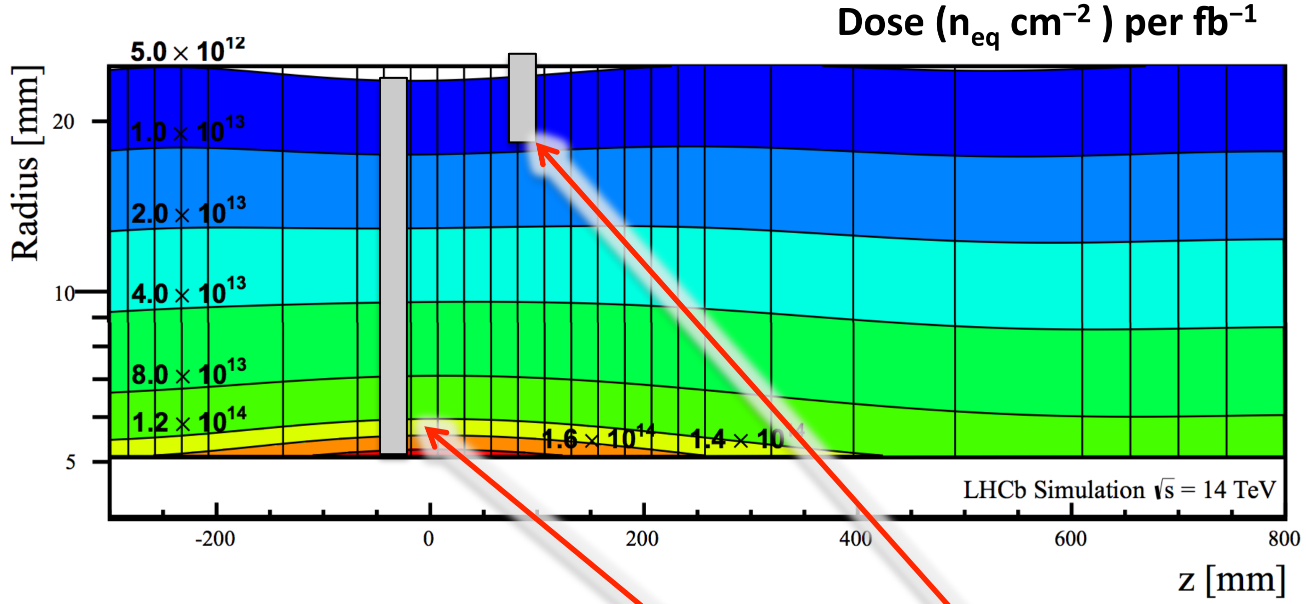

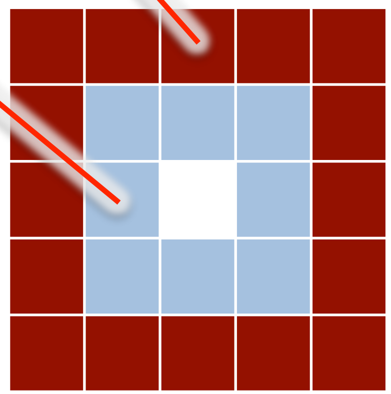

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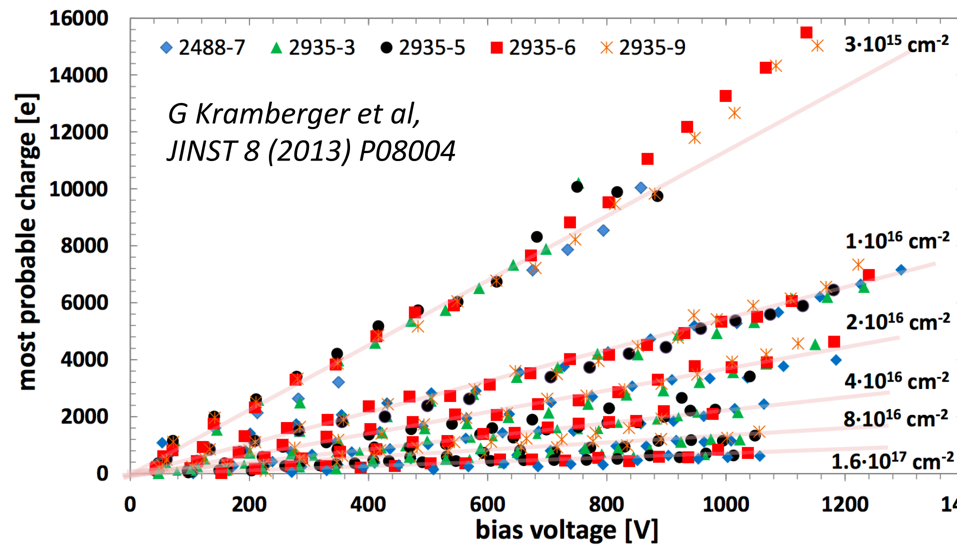
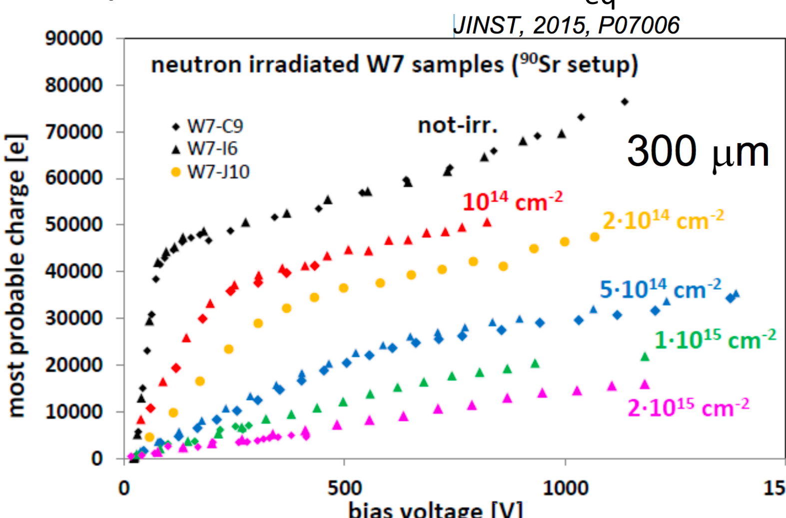
Phase-II Challenge C: 10x radiation damage

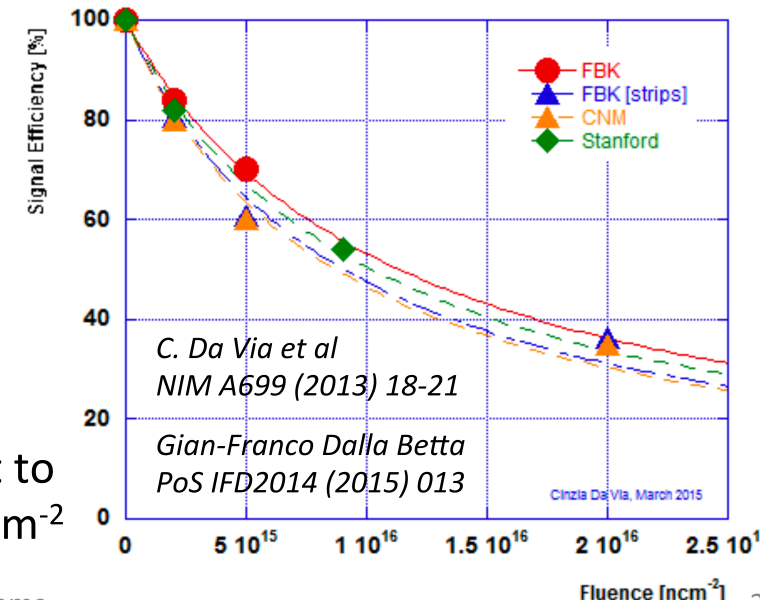
Planar silicon retains acceptable charge collection efficiency up to **10^{16} 1 MeV n_{eq} cm^{-2}**
(plot from 2013, 300μm Si)



45μm LGAD detectors lose gain beyond a few 10^{14} 1 MeV n_{eq} cm^{-2}



3D pixels efficient to ~10^{16} 1 MeV n_{eq} cm^{-2}



Phase-II Challenge C: 10x radiation damage

Options to survive Phase-II dose:

1. **Move sensors further from the beam**

   Pro: Can use existing technology

   Con: Major degradation in physics performance (factor 2-3 in IP resolution)

   Not very ambitious

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   Not very ambitious

2. **Develop sensors that can tolerate full dose of 8 x 10^{16} 1 MeV n_{eq} cm^{-2}**
   Pro: Can use traditional construction/operation methods
   Retain high performance
   Con: Requires significant progress in rad hardness, with no commercial pressure, and no obvious roadmap
   Even more challenging for fast timing detectors

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   Even more challenging for fast timing detectors
3. **Replace modules as required over lifetime of detector**
   Pro: Doesn't rely on developing rad hard sensors
   Retain high performance
   Con: Mechanically challenging (depending on strategy)
   May increase cost (depending on £/module)

Phase-II Challenge C: 10x radiation damage

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1. ~~Move sensors further from the beam~~
2. Develop sensors that can tolerate full dose of 8×10^{16} 1 MeV n_{eq} cm^{-2}
3. Replace modules as required over lifetime of detector

Most likely some combination of these two approaches

Dream scenario:

- Develop sensors that can survive for a full ~4 year run (~4×10^{16} 1 MeV n_{eq} cm^{-2})
- Replace hottest modules during long shutdown

More likely:

- Develop sensors which can survive for ~2 years
- Replace in situ when required (automated cassette loading?)

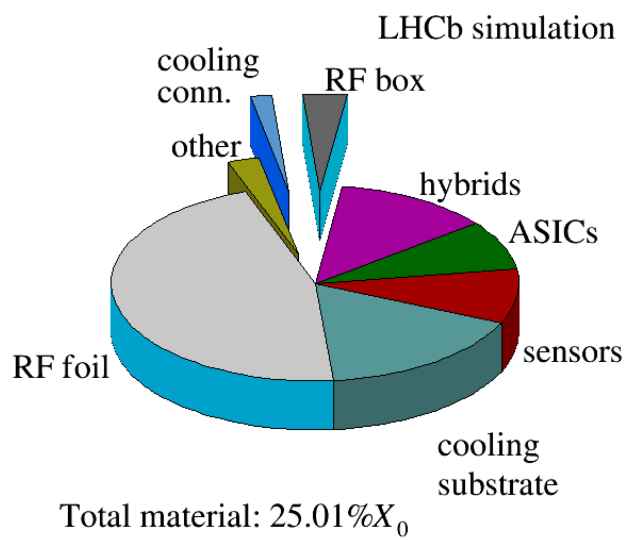
Reaching Further: Removing RF Foil

Radius of 1st hit — Material before 2nd hit — Hit resolutions

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

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

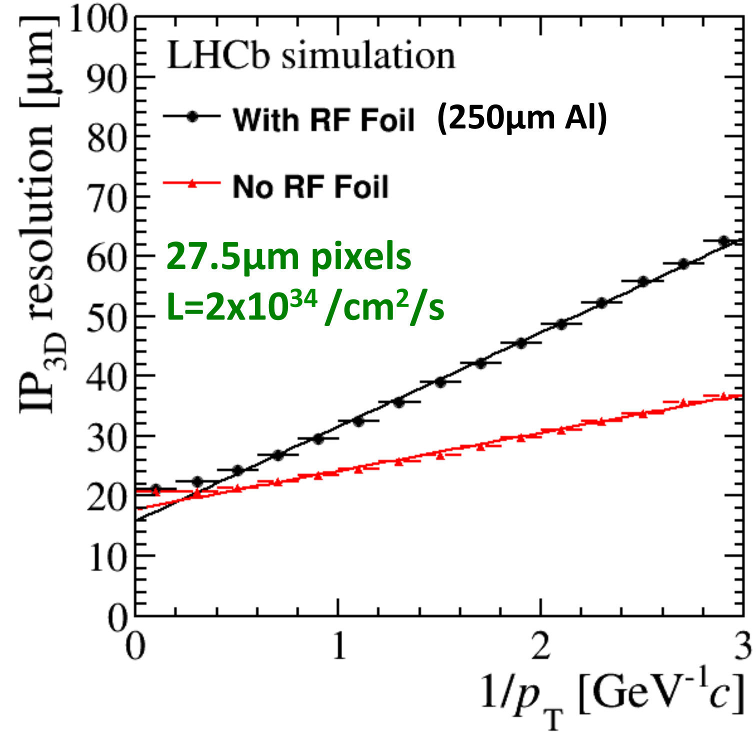
- Multiple scattering dominates IP resolution at low p_T
- Proportional to material traversed before 2nd hit
- RF foil is by far the largest material contributor



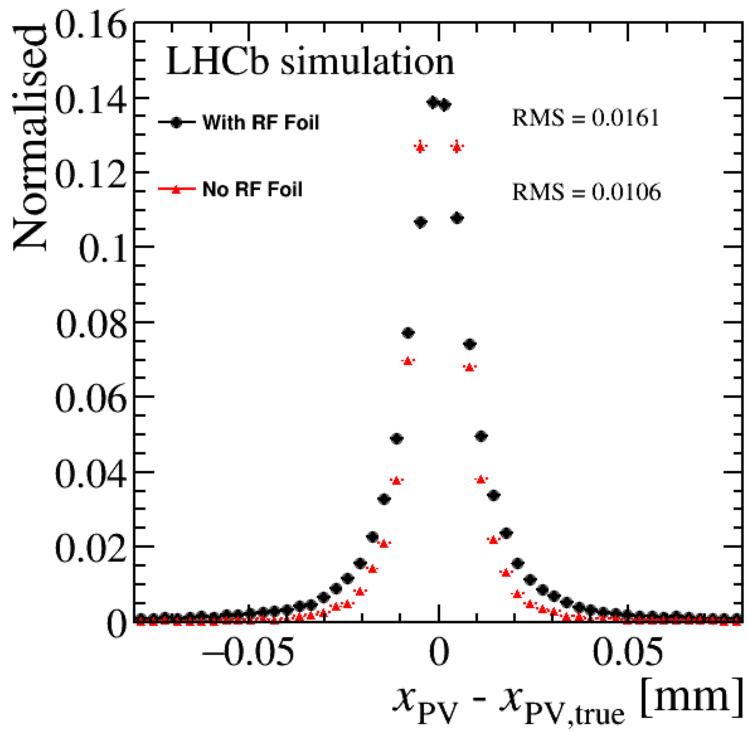
Reaching Further: Removing RF Foil

Significant and immediate physics gain from removing the RF foil

Also consider alternative designs with less material. Smaller gains but fewer obstacles



Factor 2 gain in IP resolution at low p_T



35% improved PV resolution
→ Factor 2 reduction in uncertainties for SL channels (see talk by Patrick O.)

Reaching Further: Removing RF Foil

Significant and immediate physics gain from removing the RF foil

Can we do this?

Two main questions (need YES to both):

- **Q:** Can we ensure a leak-tight VELO and qualify to a level which meets the **machine vacuum** criteria?

  A: Depends on machine requirements. Significant expertise from Phase-I VELO R&D.

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- **Q:** Can we guide the **wake fields** with an alternative method, without harming VELO operations (e.g. wires)?

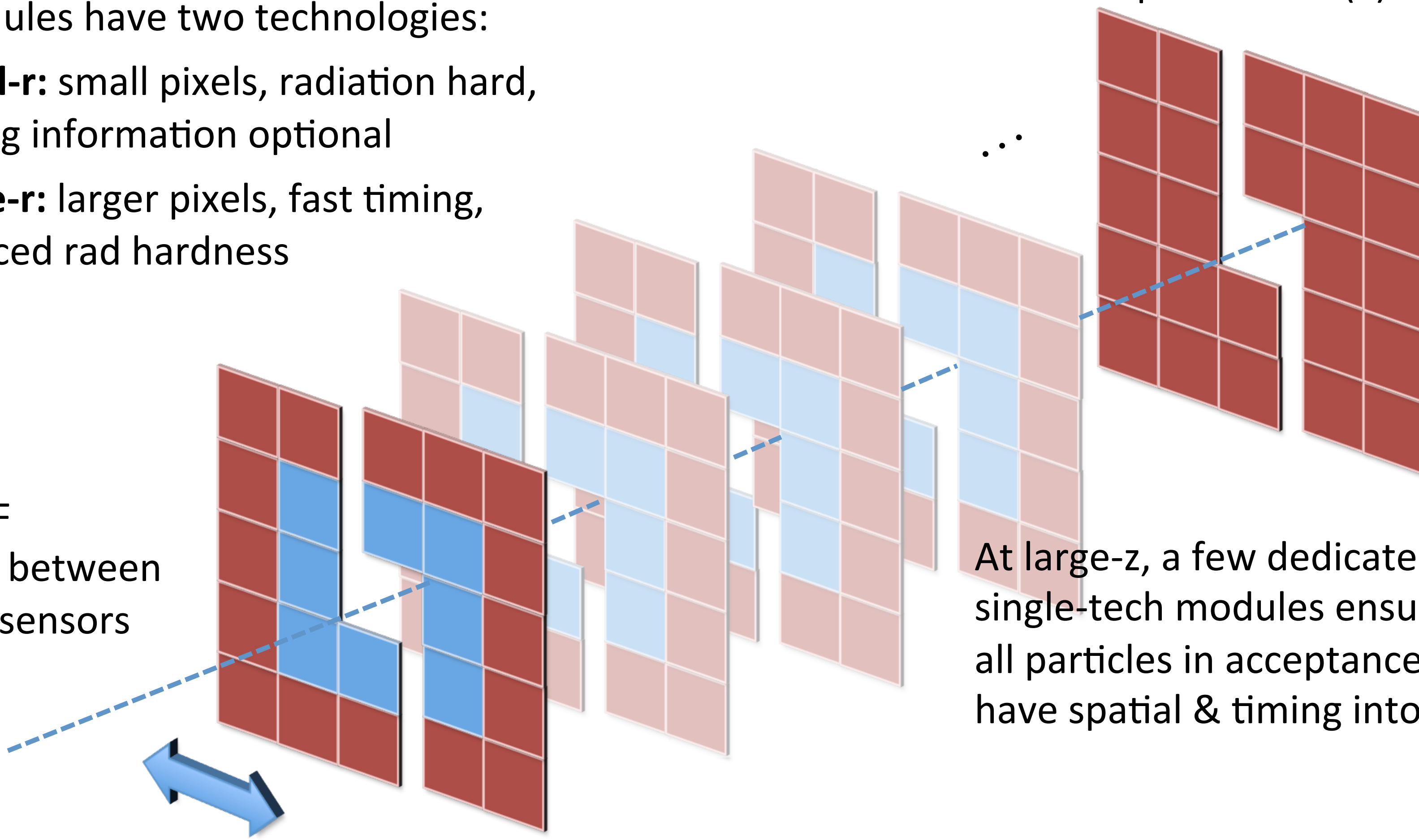
  A: For machine considerations, see talk by Nicolo Biancacci.
  For VELO operation, open question: need to test.

A Possible Phase-II VELO

Main modules have two technologies:

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

Automated 'cassette replacement' (?)



Minimal RF protection between beam and sensors

At large-z, a few dedicated single-tech modules ensure all particles in acceptance have spatial & timing into

Retractable modules as in current/phase-I VELO

Cooling from evaporative CO_2 in microchannels? (benefit from phase-I experience)

Summary: next steps

Four main streams:

Develop silicon detectors with **small pixel size** (~30µm), high data rates, and as radiation hard as possible (aim for >4 x 10^{16} 1 MeV n_{eq} cm^{-2})

Possible technologies: hybrid detectors (e.g. SuperVeloPix), 3D sensors, HV-CMOS? (see talk from ***Themis***)

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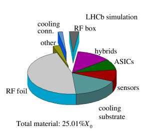


Study effect of **removing/redesigning RF foil**, from vacuum and impedance perspectives. Requires collaboration with machine experts (talk from ***Nicolo***)

Summary: next steps

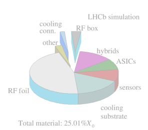
Four main streams:

Develop silicon detectors with **small pixel size** (~30µm), high data rates, and as radiation hard as possible (aim for >4 x 10^{16} 1 MeV n_{eq} cm^{-2})

Possible technologies: hybrid detectors (e.g. SuperVeloPix), 3D sensors, HV-CMOS? (see talk from ***Themis***)

Develop pixel detector with **fast timing** (~30ps?), high data-rate and with radiation hardness to survive large-r/large-z region

Possible technologies: LGAD (see talk from ***Margherita***)



Study effect of **removing/redesigning RF foil**, from vacuum and impedance perspectives. Requires collaboration with machine experts (talk from ***Nicolo***)

Investigate options for **replaceable modules**. Needs engineering R&D – exploit experience from current/phase-I VELO mechanics.