Tracking and vertexing in 4D for LHCb

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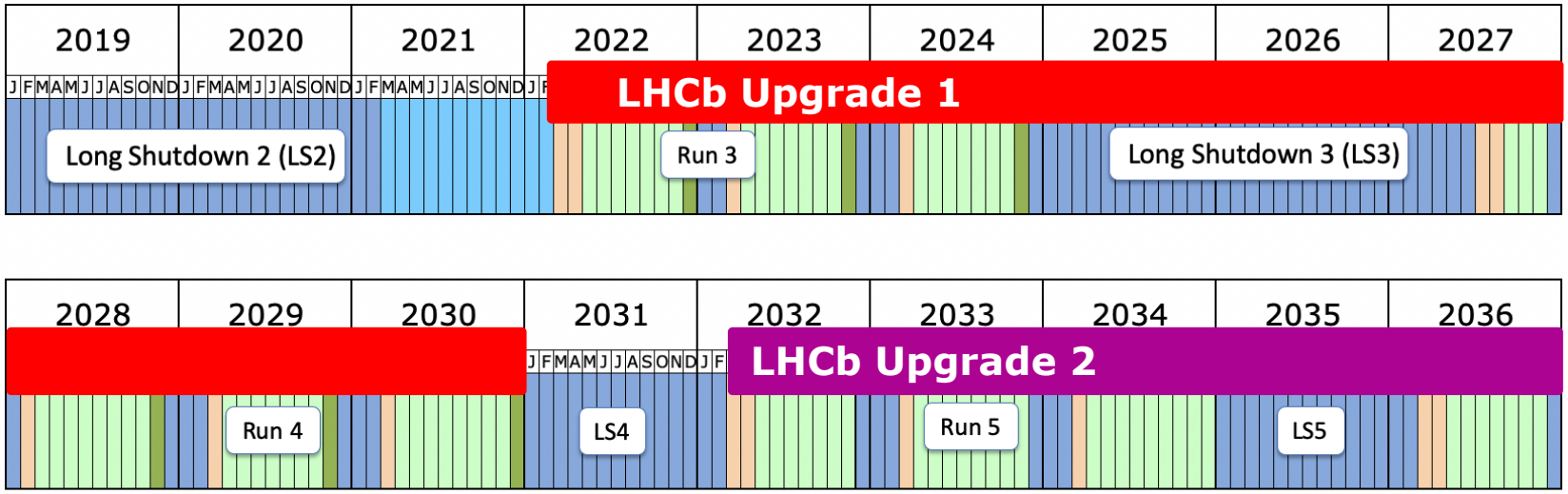
Dan Johnson (MIT)

Outline

Introduction



The challenge of upgrade 2 (cf upg1):

- maximum $\mathscr{L}$ increases by 7.5
- integrated radiation damage increases by 6

LHCb VELO requires timing with <50 ps resolution per hit

Outline

What we want

Maintain, with respect to Upgrade 1:

Track and vertex resolutions; signal efficiency and purity

Preserve, or improve, performance metrics:

- Resolve e.g. B_s^0 oscillations, vertex resolution $\sim 100\mu m$
- Avoid combinatorial bg: crucial for rare decays e.g. $B_s^0 \to \mu^+\mu^-$
- Improve σ_t (50 fs in R1-2) $\Rightarrow$ less dilution of CP observables
- Better vertexing $\Rightarrow$ prompt spectroscopy for lifetimes $< 100\,\mathrm{fs}$

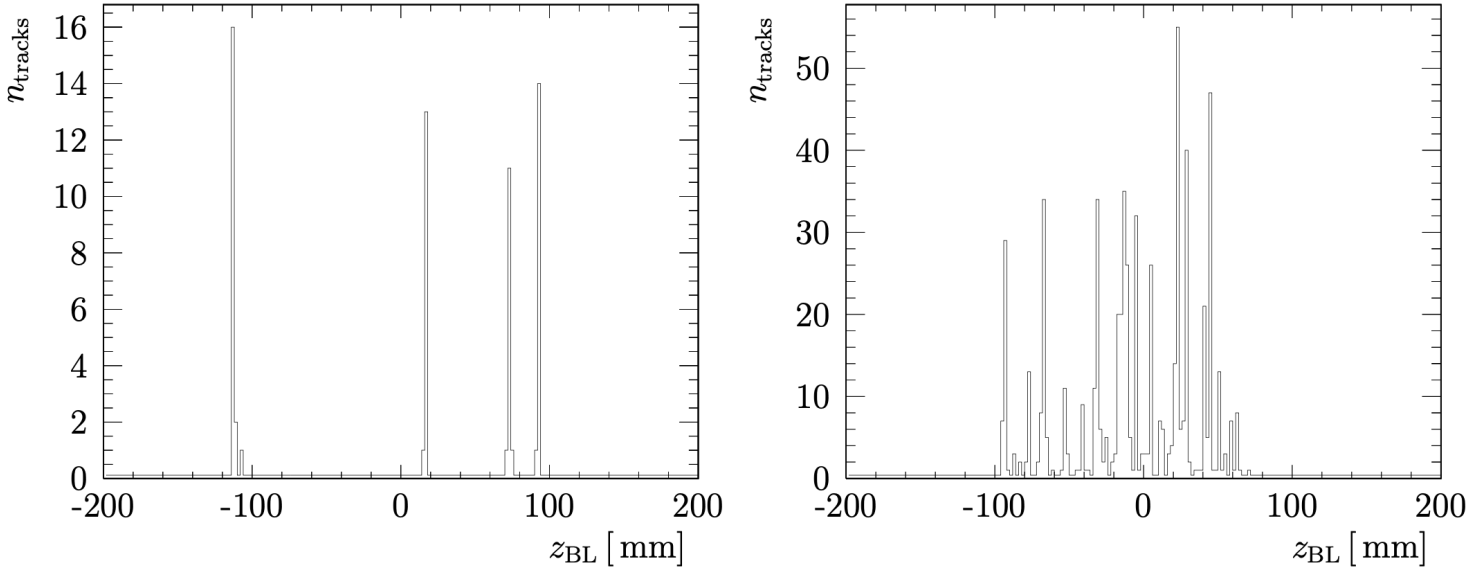
Preserve selection strategy:

- b- & c- fly $\sim 1\,\mathrm{ps}$: select on kinematics and topology
- No good measuring IP well if associated to the wrong PV

A very different reconstruction environment

7.5 x higher $\mathscr{L}$ a challenge: focus on event reconstruction

PVs start to overlap:

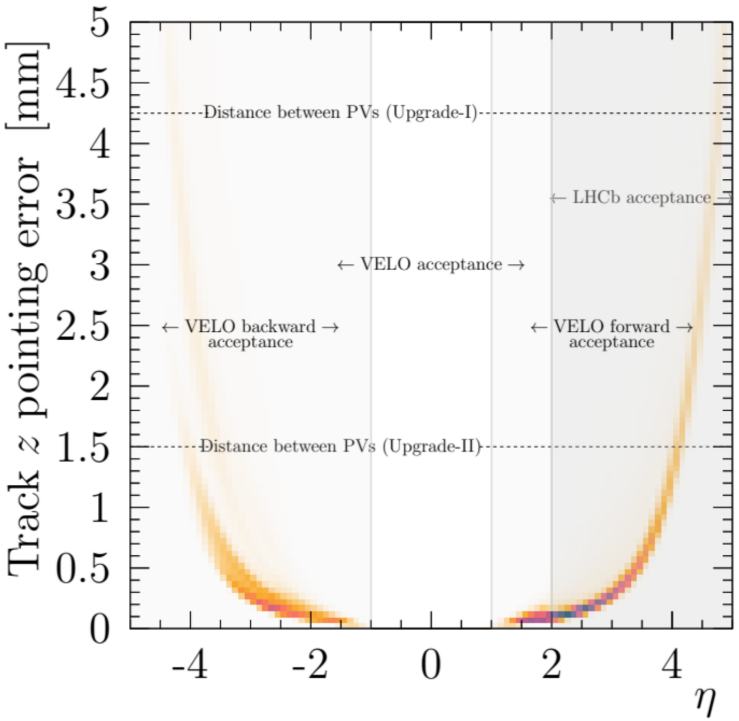


- 'minIP wrt any PV' falls down
- much more combinatorial background
- nearby PVs can fake displaced vertices

A very different reconstruction environment

7.5 x higher $\mathscr{L}$ a challenge: focus on event reconstruction

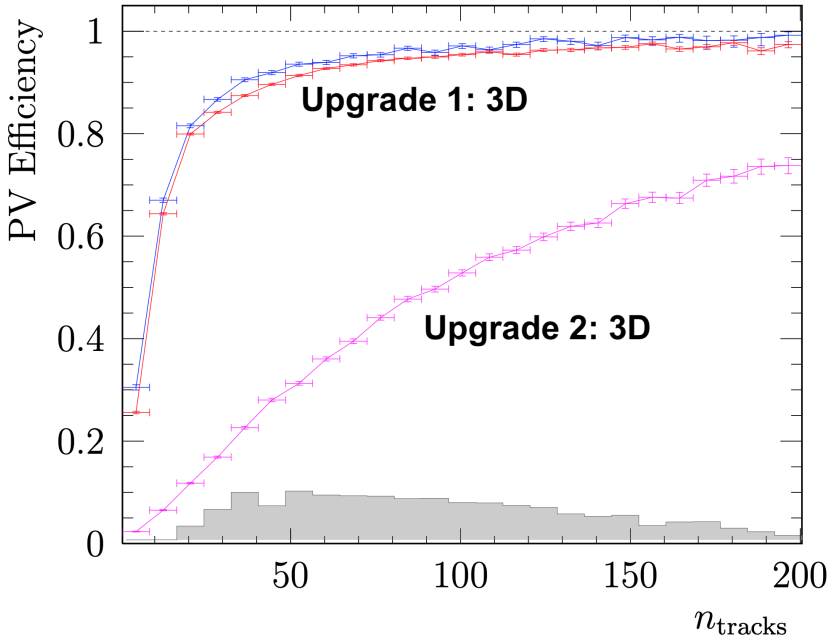
PVs start to overlap: (viewed another way)



Upgrade 2 PV separation and track-association break down

3D tracking for Upgrade 2?

Catastrophic fall in frac. of reconstructible PVs that are well-reconstructed:

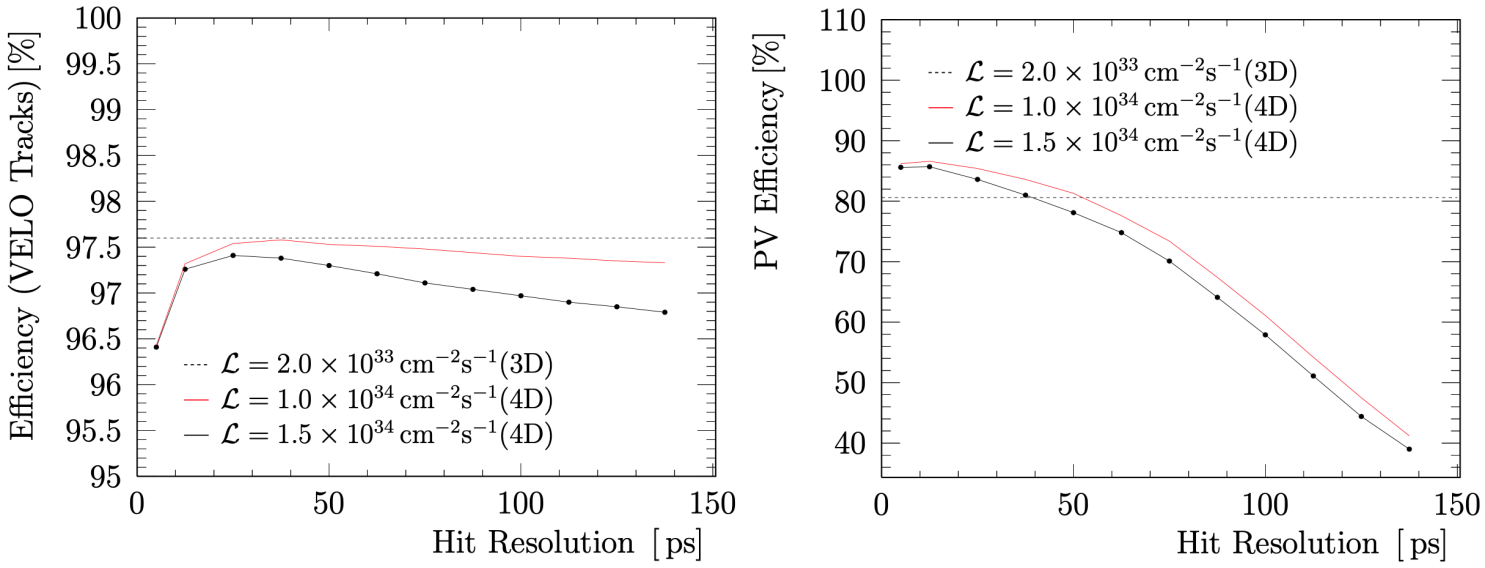


And secondary consequences:

- Ghost rate increases by a factor of 4
- Tracking efficiency drops by 2-2.5% *per track*
- Processing time scales at best linearly, 1μs/track

4D tracking: what time resolution do we need?

Tracking and PV-reco efficiencies for different hit resolutions:



- At low resolution: $v = c$ tracking assumption fails for soft tracks
- At high resolution: significant drop-off in ϵ_{PV} after 70 ps

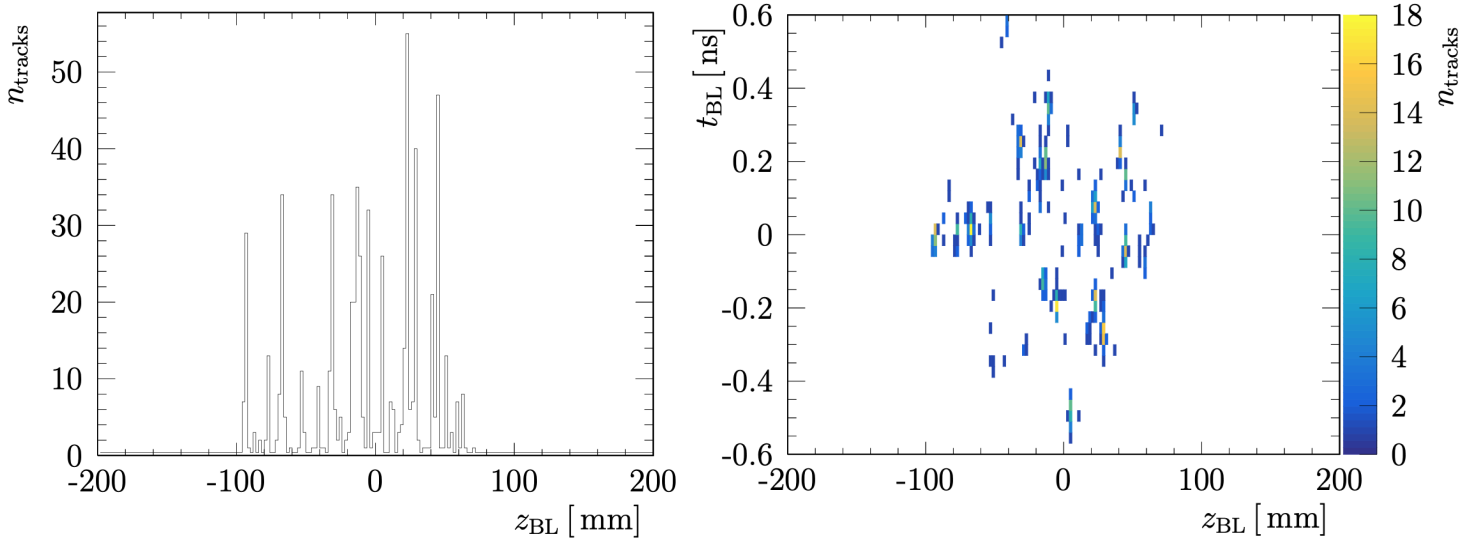
Compromise efficiency vs realism (on Run 5 timescale) at <50 ps

4D tracking: pattern recognition

1. Spatial requirements/polar-angle window relaxed
2. Compute t_{hit} - [expected time for track] ($v = c$)
3. Window size is 2.5 × uncertainty on difference
   - $\sim 180\,\mathrm{ps}$ for second hit, $\sim 150\,\mathrm{ps}$ for third hit, etc

4D tracking: PV reconstruction

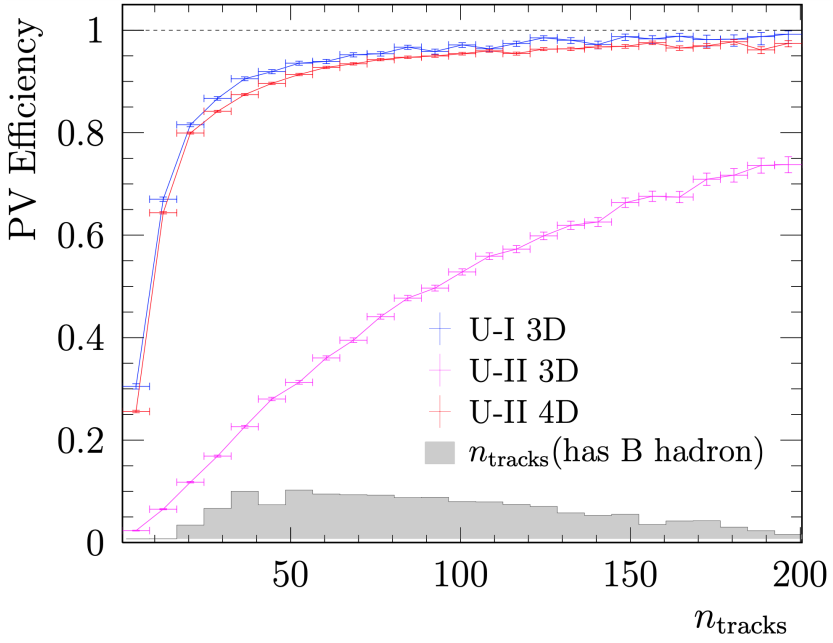
Extrapolate time of track to point of closest to beam-line



Associate tracks to closest local maximum and then 4D fit to the vertices iteratively adding tracks

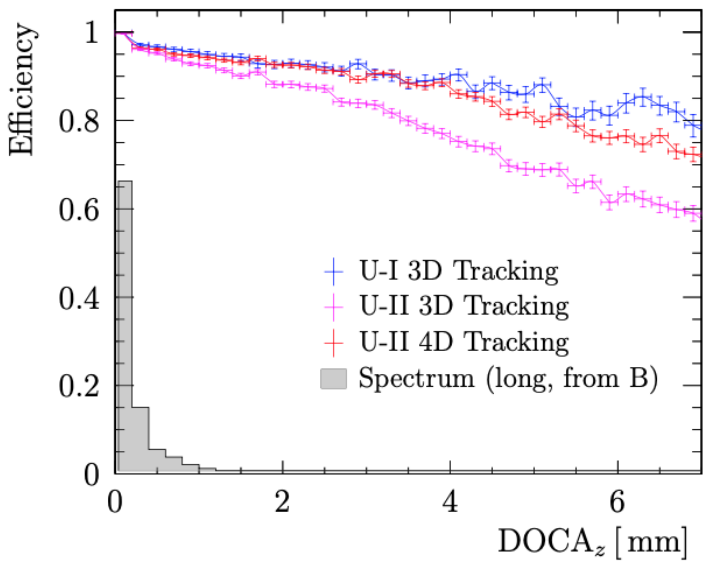
4D tracking: PV reconstruction

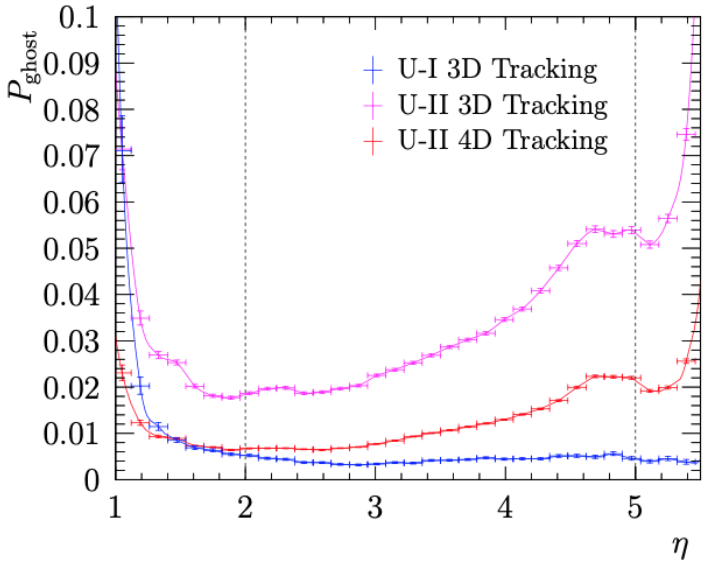
Near-complete recovery of PV reconstruction, despite early tuning



PV timing resolution a few ps for typical signal PV (> 50 tracks)

Adding timing: Tracking efficiency and ghost rates





- 3D tracking at U2 suffers particularly for displaced tracks; 4D largely recovers
- 4D significantly suppresses ghosts

Requirements for upgrade ASIC

Assuming Upgrade 1 design:

- ASIC experiences 8 Ghits/s. Hottest pixel 500 khits/s
- Data output > 30*Tb/s*, increasing if more information added

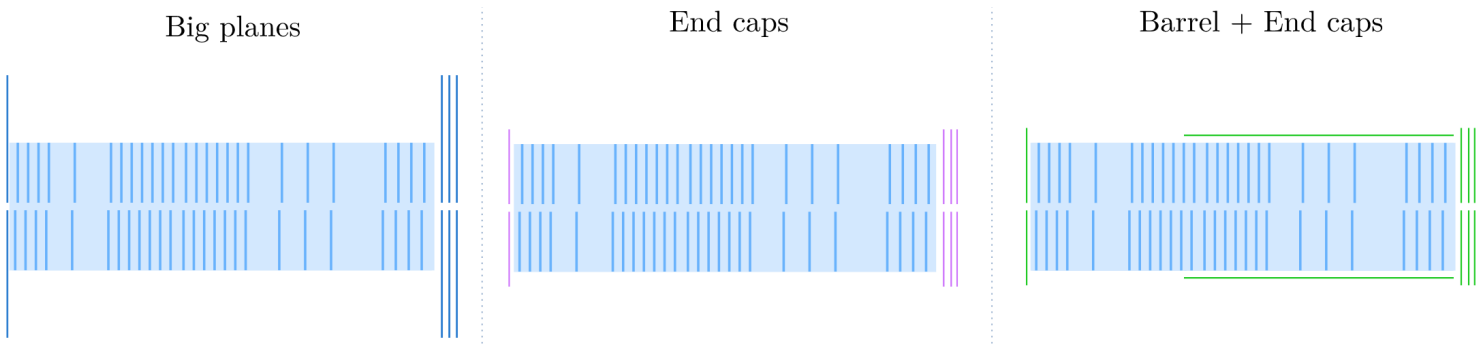
Wanted:

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

Do we really need per-hit timing?

Others are adding a timing layer:

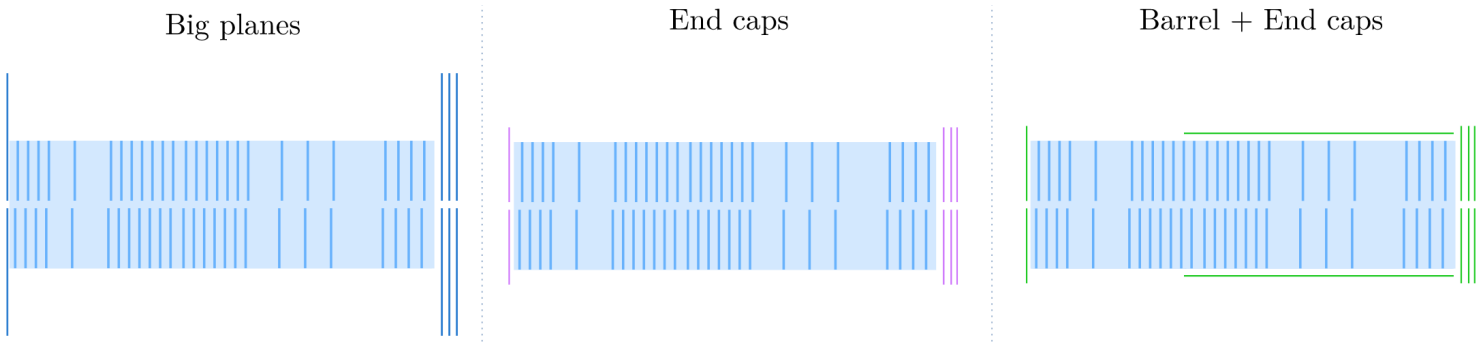
- further away ⇒ larger pitch
- can be less radiation hard



Why it won't work for us:

- None of the solutions out-performs the 4D VELO
- VELO price x2: 1m^2 sensitive material (cf 0.12m^2 for 4D VELO)

Do we really need per-hit timing?



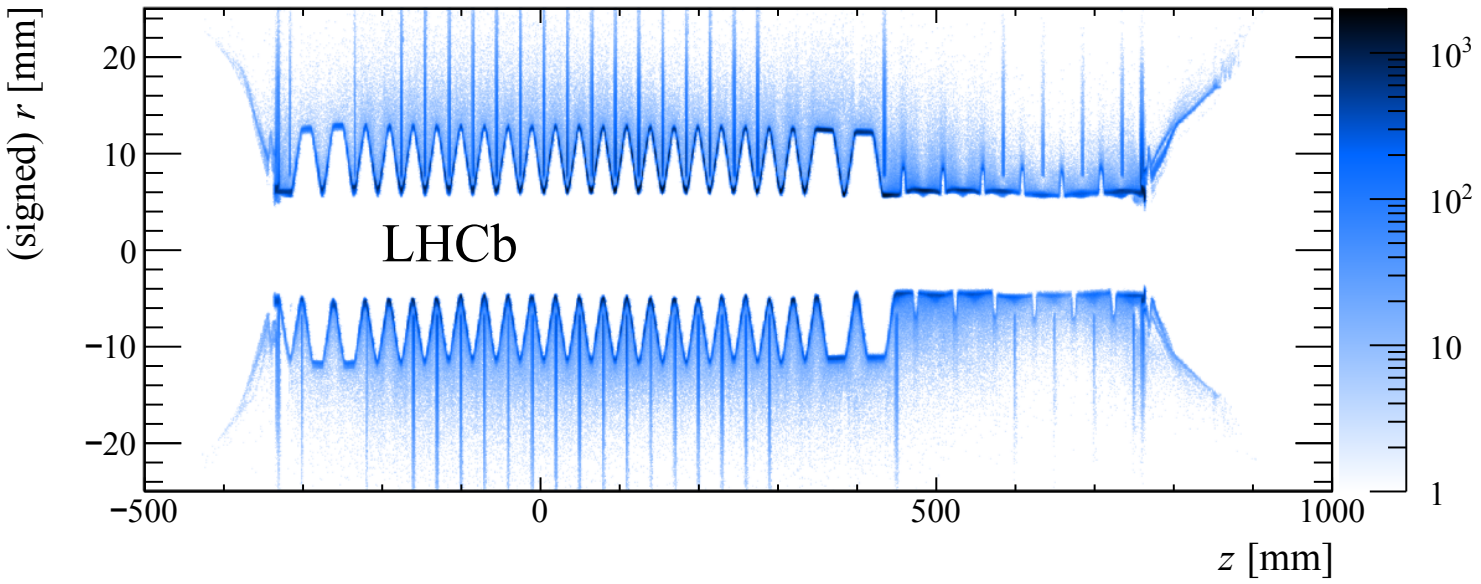
More reasons to avoid a VELO timing layer:

1. Hit efficiency, tracking, redundancy ⇒ 3 timing layers
2. Increased material budget
3. High forward occupancy + deadtime ⇒ pitch of 100μm
4. Far from collision ⇒ greater $v \neq c$ errors for low p_{T} tracks
5. Practical difficulty introducing different chip/mechanics for timing layer
6. Less precise timestamp (3 hits vs 20) for downstream detectors
7. More power-hungry

Outline

A thinner RF foil

- The foil contributes significant material budget
- Scattering degrades angular resolution, especially $p_{\mathrm{T}} < 1\,\mathrm{GeV}$
- Particularly important for electrons

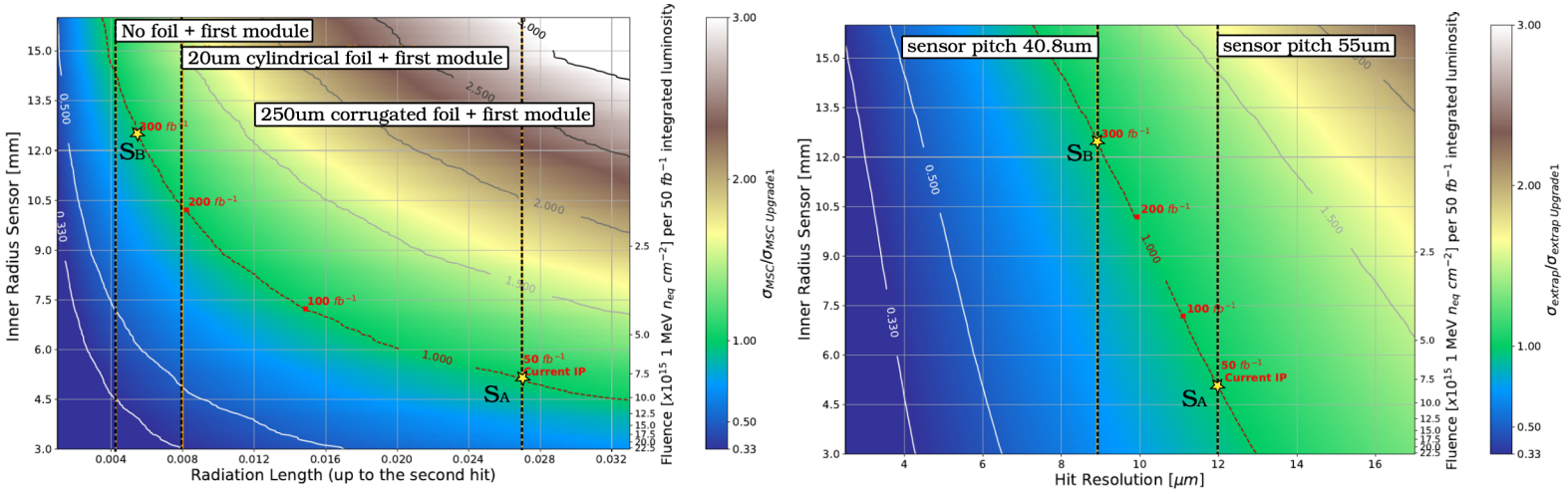


- Current geometry minimises material traversed by most tracks

A thinner RF foil

Removing, the foil:

- Improves track spatial resolution
- Allows to move the VELO further from the beam
  - Data rates
  - Radiation damage
  - VELO length

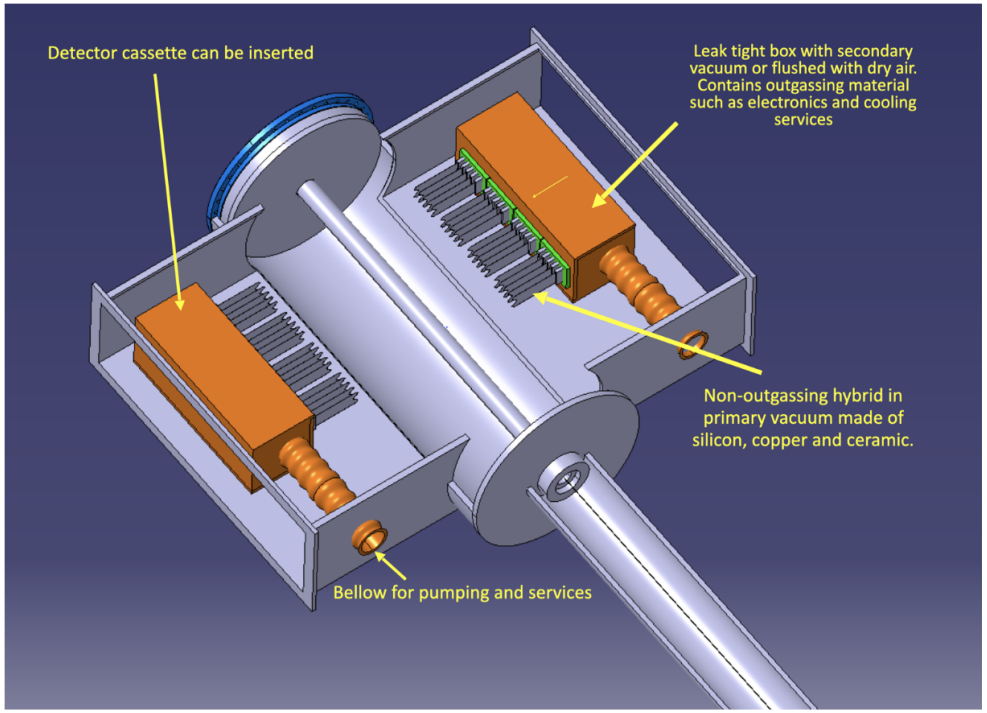


Larger inner radius and less radiation vs even smaller pitch

A thinner RF foil

Additional considerations:

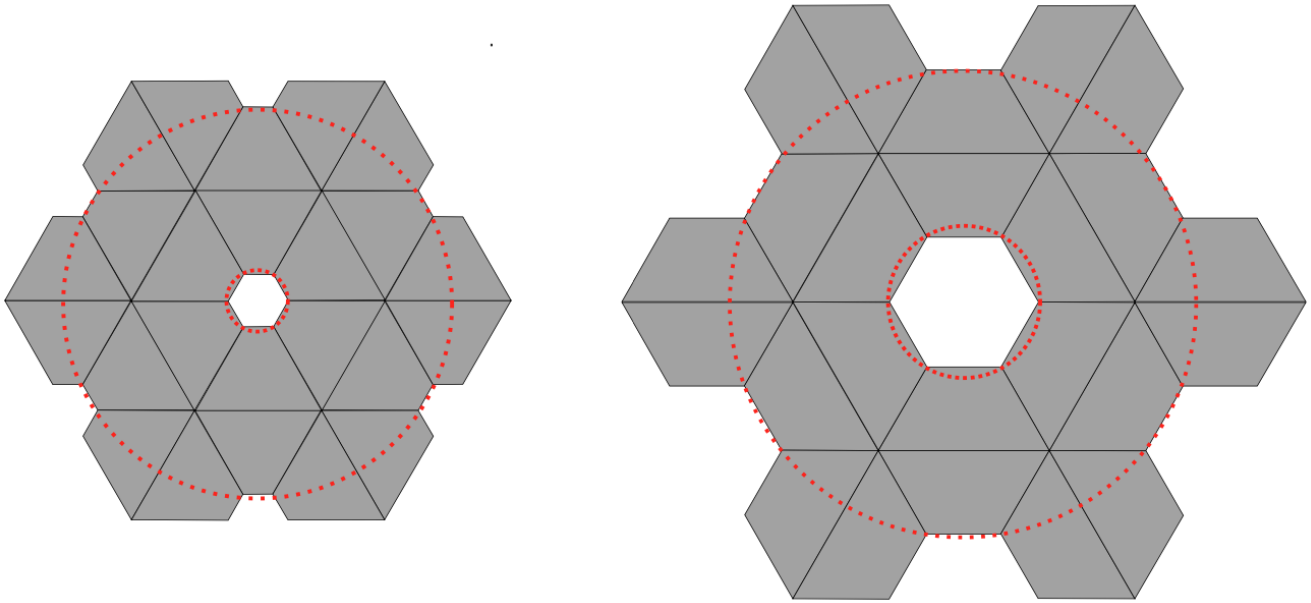
- Foil protects primary vacuum: no outgassing tolerated
- Must still handle wakefields and shield electronics
- Mechanical solution required to replace modules safely



A thinner RF foil

Additional considerations:

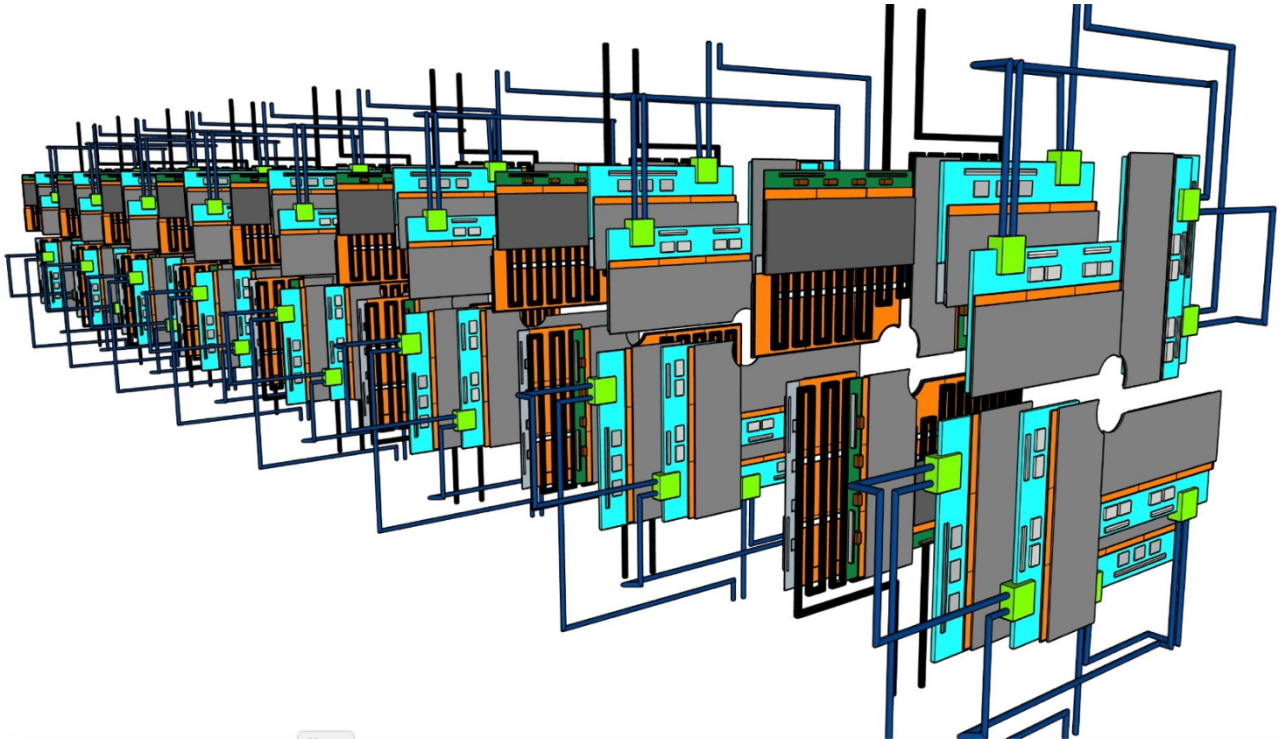
- Foil protects primary vacuum: no outgassing tolerated
- Must still handle wakefields and shield electronics
- Optimise sensor arrangement for more circular inner radius



Outline

Cooling

- Sensors must be operated cold (< 30°C) to control post-irradiation leakage-current
- Module production costs could be reduced through choice of substrate
- Running colder would require new cooling plant/coolant (Kr, N_2)



Outline

Conclusion

- Upgrade 2 presents a considerable challenge for the VELO
- Maintaining Upgrade 1 performance metrics is possible...
- ...<50 ps timing per hit is essential
- Bold detector reconfiguration is considered:
  - Rethinking LHCb's acceptance
  - Removing the RF foil
  - Reimagining the module arrangement
  - Revisiting cooling options
- Must connect design choices to high-level physics studies