A pixel detector with timing for LHCb Upgrade II

Vertex 2021

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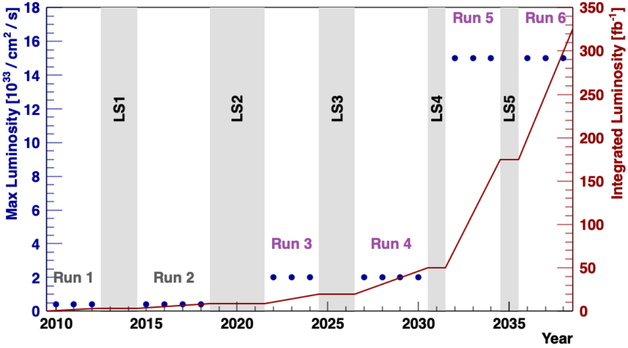
CERN

30 September 2021

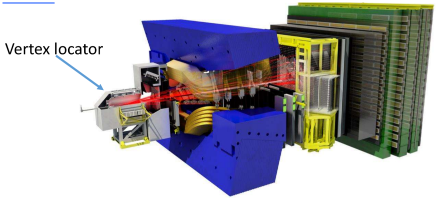
Timeline

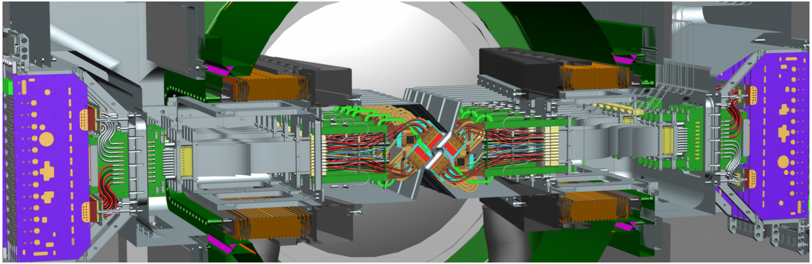


- Upgrade I is happening now. Presented Monday in Igor's talk
- Upgrade II to be installed in 2031, and will require significant improvements to maintain performance.
  - "Upstream Tracker" plans discussed yesterday in Yiming's talk

VErtex LOcator (VELO)

- LHCb detector is fully equipped in the forward region, optimised for studies of decays of *b* and *c* hadrons.
- VELO: Silicon tracker surrounding the interaction region, 5.1 mm from beam for Upgrade I





This is Upgrade I VELO, Upgrade II detector will likely look much different!

Motivation

- Details of physics case and our objectives are detailed here: Physics case for an LHCb Upgrade II (LHCb-PUB-2018-009)
- Upgrade II physics goals are centred on precision measurements
    - Require excellent control over systematic uncertainties
- Ability to precisely reconstruct primary vertices, secondary vertices, etc. crucial to the physics programme.

CERN/LHCC 2018-027
PUB-2018-019
27 August 2018

Physics Case for an LHCb Upgrade II

Opportunities in flavour physics, and beyond, in the HL-LHC era

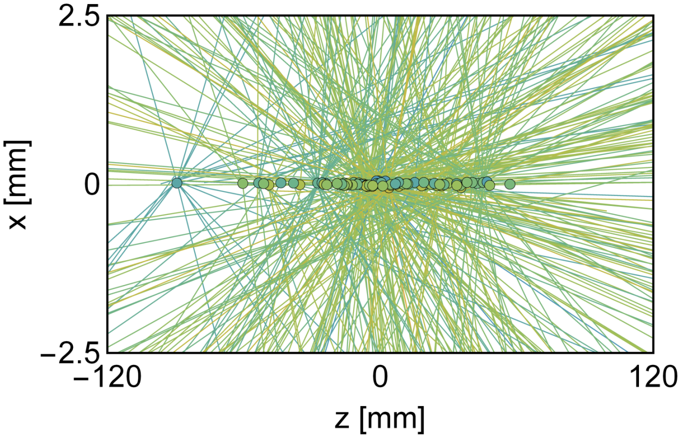
Upgrade II Environment

- What kind of environment will the detector be operating in?
- Increased luminosity comes from increase in pileup. and naturally will mean corresponding increases in fluence and readout rate.

	Run 1-2	Upgrade I	Upgrade II
Luminosity / year[fb^{-1}]	2	7	~ 50
Pileup	1.8	7	~ 50
Integ. Fluence [$\mathrm{MeV}\, n_{eq}/\mathrm{cm}^2$]	4.3×10^{14}	8×10^{15}	6×10^{16}
Readout rate [10^6 hits/s]		600	~ 4500

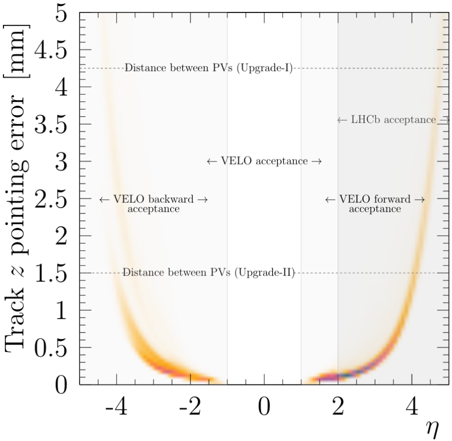
- To reach LHCb's physics goals: the precision and efficiency of the VELO Upgrade I detector must be maintained, and ideally improved upon.
  - Presents several challenges: dealing with high occupancy, radiation hardness of detector, data rates, and more...

Typical event



- Going to be difficult to (for example) measure B_s^0 oscillation frequency...

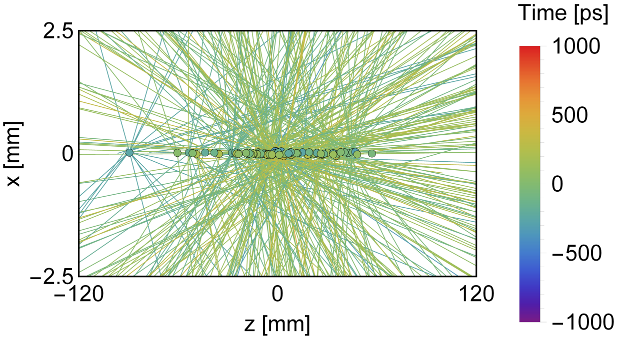
PV association



- At $\sim$ 50 interactions / bunch crossing, PV separation is comparable to the per-track pointing resolution to the beam axis

Timing!

- But, the proton bunches overlap for a finite time (RMS $\sim$ 180 ps). Can we resolve interactions within each crossing in time?



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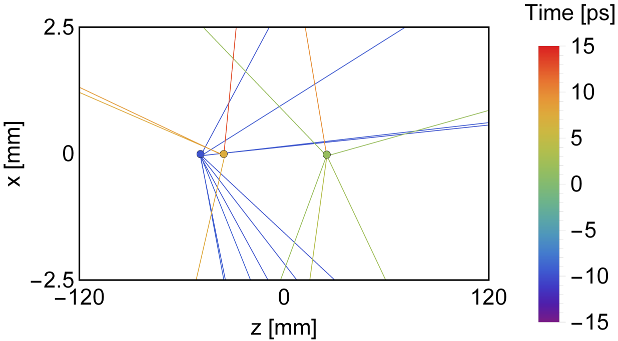
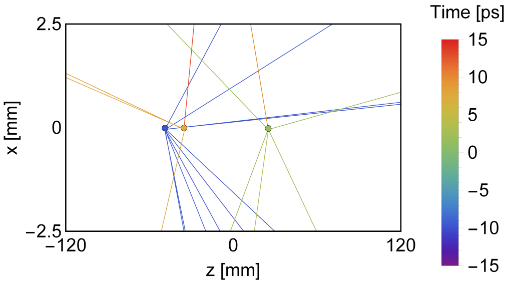


- In slices of 30 ps, only a few collisions and corresponding tracks to deal with.
- Becomes manageable in slices of time, but will need excellent temporal resolution.

Timing!

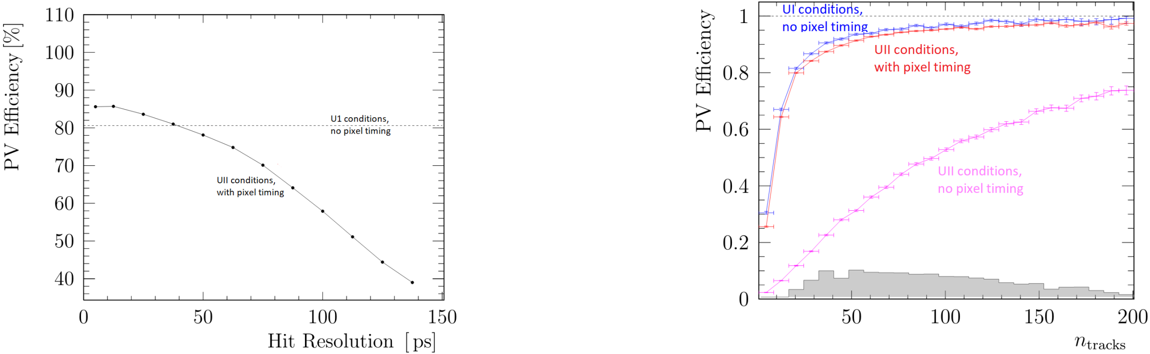
- Aim to achieve a track timestamp of 20 ps or better. Can be done by:

- Adding precise timing at every hit: Full 4D Tracking! Requires individual hit resolutions of 50 ps.
- Using dedicated timing planes. Single measurements need at least 25 ps resolution, multiple layers are required



Timing via 4D tracking

- Simulations show that we can almost completely recover the Upgrade-I vertex reconstruction efficiency with 50 ps hit resolution.

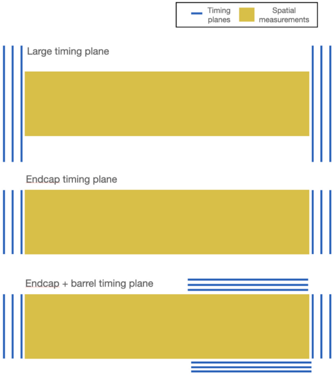


- If no timing information is added the efficiency collapses.

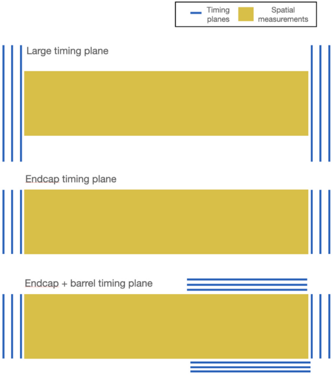
Timing via timing planes

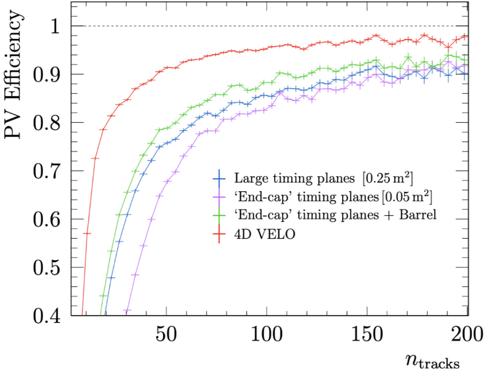
- Minimum of three segmented timing layers are required to be able to provide independent timestamps to the tracks and limit the combinatorics.

- Different configurations of the planes considered:
  - "Large": Covers the LHCb acceptance Requires 0.25 m^2 of silicon per layer
  - "Endcap": Partial LHCb coverage, but reduced area of 0.05 m^2
  - "Endcap + barrel": Recover missing coverage with a partial forward barrel layer.
- Surface area to be compared to rest of VELO : 0.10 m^2



Timing via timing planes



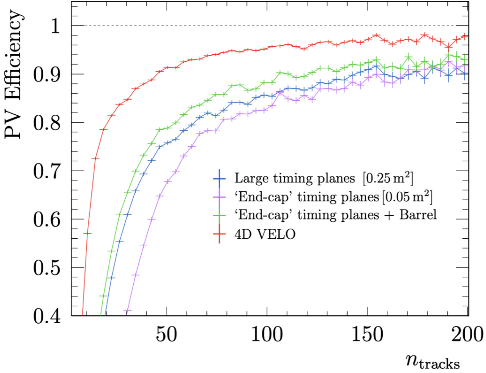


- Best timing layer performance comes from the "End cap + barrel" solution.
- Far from reaching the 4D tracking performance.
- At distance of planes from beam spot region, the time dispersion of low momentum particles leads to a bias in the extrapolated time at the beam axis.

Timing methods comparison

- Additional points to consider:

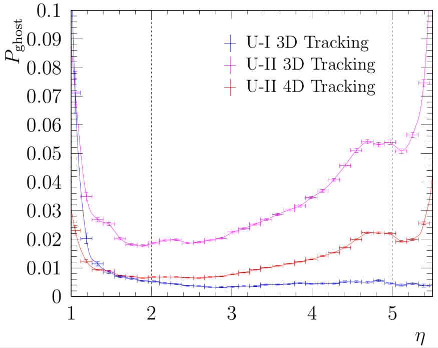
- Need to develop a second sensor and ASIC solution, implement it over a relatively large surface area.
- Planes lack the substantial benefits to track reconstruction.
- The impact of timing layers on the material budget must be carefully controlled.

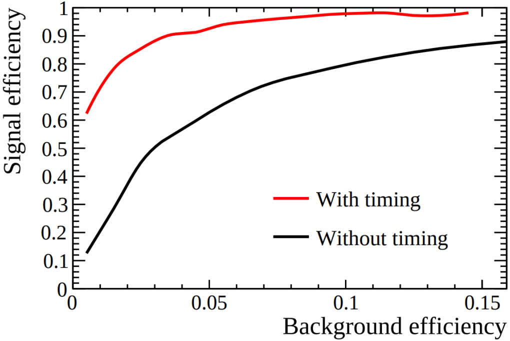


Full 4D tracking is strongly preferred.

Tracking

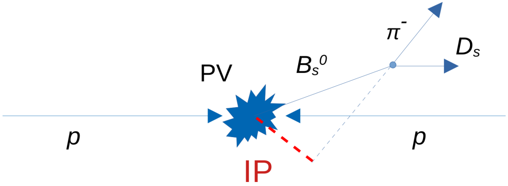
- Including timing in tracking extremely advantageous.
    - Improved efficiency and spatial uniformity.
    - Reduces rate of ghost tracks.
    - Reduces combinations of random tracks.
    - And more...





Impact parameter

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

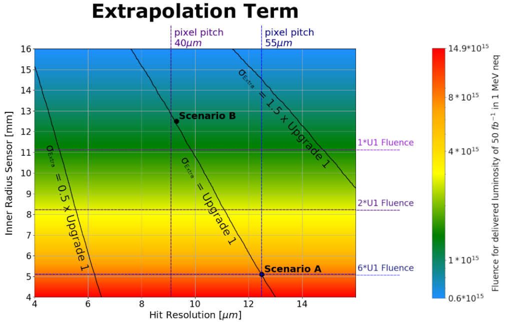


- Resolution can be parameterised as $\sigma_{\text{IP}} = \sigma_{\text{extrap}} \oplus \sigma_{\text{MSC}}/p_{\text{T}}$
- The goal is to keep comparable impact parameter resolution as in Upgrade I.
- Targeting $\sigma_{\text{IP}} = 12 \oplus 12/p_{\text{T}}$, which will yield typical resolutions of $26\mu m$

Sensor layout scenarios

- Innermost radius of the VELO is key driving parameter. Consider two scenarios, keeping impact parameter resolution at UI levels
  - Scenario A (S_A): Innermost radius is kept at 5.1 mm, sensor layout same as UI.
  - Scenario B (S_B): Radius relaxed to 12.5 mm, cluster occupancies match those of UI

- For S_B: Increased distance to the collision point requires significantly better hit resolution.
  - Reduce the pixel size to less than 42μm
- For S_A: ASIC needs to deal with a factor $\approx$ 7.5 times higher hit rate than the VELO Upgrade I ASIC (plus timing)



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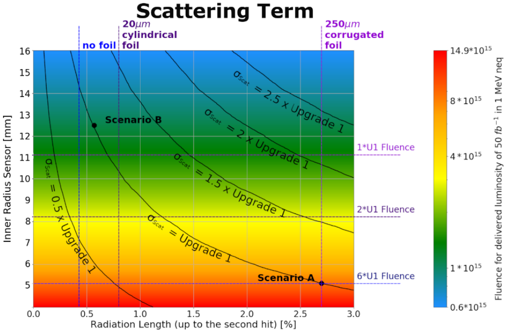
- For S_B: Material before the second hit needs to be dramatically reduced.
  - Requires lighter RF foil, but also improvements in sensor, ASIC and substrate materials, and would require major mechanical redesign.
- For S_A: Huge radiation dose means regular detector replacements likely needed.



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.

Requirement	scenario S_A	scenario S_B
Pixel pitch [µm]	≤ 55	≤ 42
Lifetime fluence [1×10^{16} 1 MeV $\mathrm{n_{eq}/cm^2}$]	> 6	> 1
TID lifetime [MGy]	> 28	> 5
Sensor Timestamp per hit [ps]	≤ 35	≤ 35
ASIC Timestamp per hit [ps]	≤ 35	≤ 35
Hit Efficiency [%]	≥ 99	≥ 99
Power per pixel [µW]	≤ 23	≤ 14
Pixel rate hottest pixel [kHz]	> 350	> 40
Max discharge time [ns]	< 29	< 250
Bandwidth per ASIC of 2 $\mathrm{cm^2}$ [Gb/s]	> 250	> 94

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- Determined by need to maintain Upgrade I IP resolution.
  - Assumes charge sharing, so is an upper limit.

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- For S_A, beyond the limit of what many radiation hard sensors can withstand
- Non-uniform nature of the radiation exposure leads to demanding requirements on the high voltage tolerance, guard-ring design.

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- Set to combine to 50 ps precision per hit.
- ASIC time resolution includes contributions from the analogue front-end, TDC and on-chip clock distributions.

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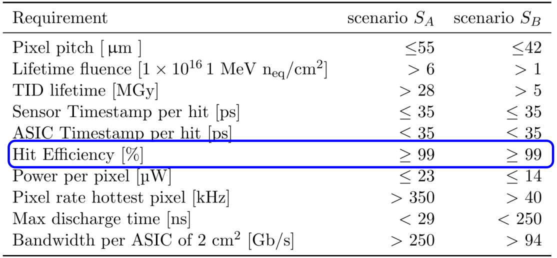

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- The target hit efficiency for VELO Upgrade II is 99% or better.
- Maximum allowed percentage of lost hits is 1%, including losses due to analogue pile-up, and buffer overflow in the readout.

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- Depends primarily on cooling capacity and thermal contact between ASIC and cooling substrate
- Assume power budget of at least 1.5W/$\mathrm{cm^2}$ (as for the VeloPix ASIC), split equally between the analog front-end and the digital components.
- Larger power budget likely needed to help meet the time resolution requirement.

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- The per pixel hit rate is derived from the track rate.
- For scenario S_A, a pixel hit rate of 350 kHz implies a mean time between hits of $\approx 2.9\mu s$.
- Discharge time should be $<$ 29 ns to keep pileup of hits $< 1\%$.

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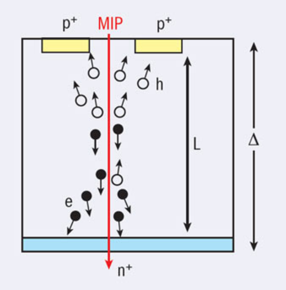
- Heavily depends on the region of the pixel matrix
- In scenario S_A (S_B), average track rate estimate of $\approx$ 64 (22) tracks per (colliding) bunch crossing for the ASIC closest to the interaction region, with hit rate of 3.8 (1.3) Ghits/s
- Assuming pixel packet size of 44 bits, plus a safety factor required bandwidth for scenario S_A (S_B) becomes 250 (94) Gb/s.

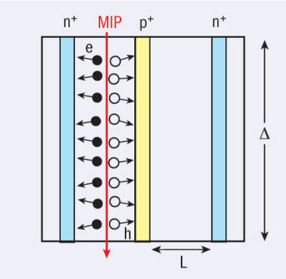
Sensor technologies

- No clear choice for the sensor technology. Several points to consider

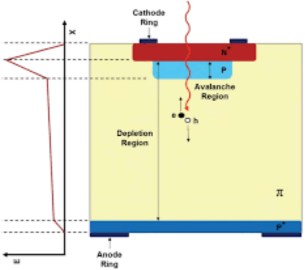
Planar



3D



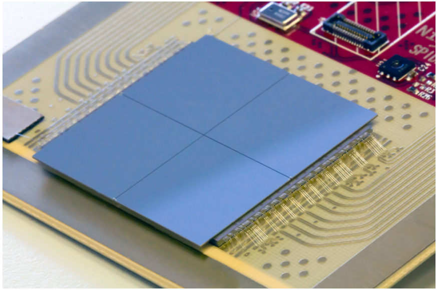
LGAD



- Planar: Not clear timing goals will be achievable while maintaining signal/noise.
- 3D: Good timing and radiation hardness, effect of insensitive volumes to be assessed.
- LGAD: Good timing resolution, spatial and radiation hardness requirements to be seen.

ASIC technologies

- Challenging requirements: good time resolution with small pixels, and hence limited power per pixel.



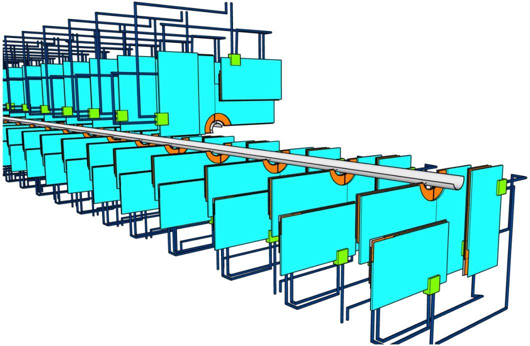
- VeloPix ASIC for Upgrade I developed in collaboration with the Medipix group.
- Next generation is Timepix4 chip, implemented in 65 nm technology with 55 μm pixels.

- TIMESPOT demonstrator chips (Timespot0 and Timespot1) implemented in 28 nm CMOS are also promising.
  - 55 μm pitch, optimised for 3D-trench sensors.

RF foil

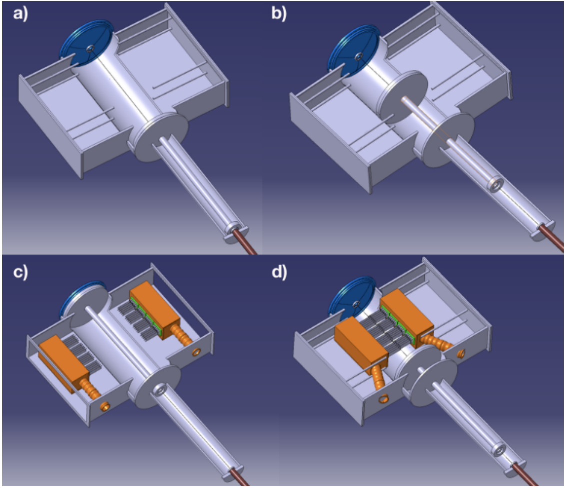
- Needed to: 1) guide beam mirror currents and avoid wakefields, 2) separate the high purity primary LHC vacuum from the secondary detector vacuum, 3) shield the detector electronics from RF pickup of the beams
- A thinner (or nonexistant) foil would significantly reduce the multiple scattering contribution to impact parameter resolution.

- Once concept: Support a very thin ($\sim 20\mu$m) foil using the modules themselves.



Vacuum tank

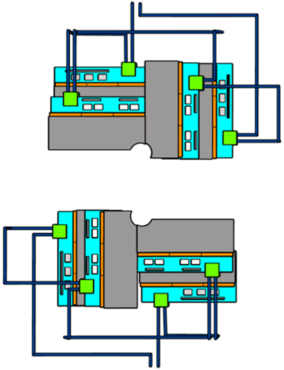
- Removal of RF box would increase constraints on the outgassing of the detector modules, and shielding properties would need careful investigation.
- Insertion and replacement of detector nontrivial!



Cooling

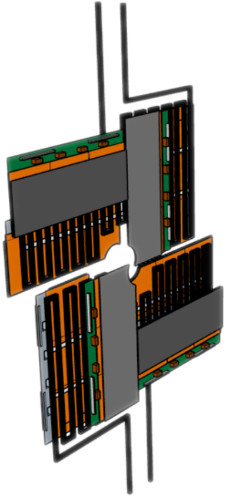
- Modules must be kept cold to prevent thermal runaway caused by leakage current after sensors are irradiated.

- In U1 used substrates with microchannels etched into silicon
- In UII aim to increase cooling performance while decreasing material budget.
- Can use smaller plates w.r.t. improve production yields, allow for creative designs to reduce material.
- Operating at even lower temperatures may be advantageous. Other coolants (such as Krypton) being considered.
- Larger scale of production (replacement) not trivial, careful consideration of fluidic connector.



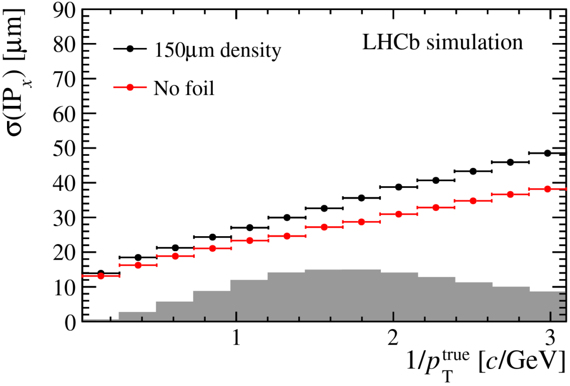
Cooling

- Alternative substrate solutions involve 3D-printed technologies
- Low cost and allow for quick prototyping and turn-around times.
- Were considered for Upgrade I, but performance didn't match silicon microchannel substrates
- Can also consider other materials such as Silicon Carbide.



Impact parameter resolution

- Dependent on the amount of material before second measured point
- Consider no foil to show potential in improvement from thinning foil.
- As expected, significant improvements to be made!



Summary

- Studies for second LHCb upgrade are underway, with the detector planned to be installed for Run 5 in 2031
- Many challenges being faced: high occupancy, high and non-uniform radiation, large data rates, more demanding cooling, mechanics, ...
- Currently in exploratory phase, but a few things are clear:
  - Precise timing will be essential. 4D tracking is preferable, but timing planes not excluded.
  - We should strive to reduce material budget where possible.
- Different sensor configurations being studied, no technologies excluded at this point.
- Work to be done on the ASIC design, but progress being made.

Stay tuned!