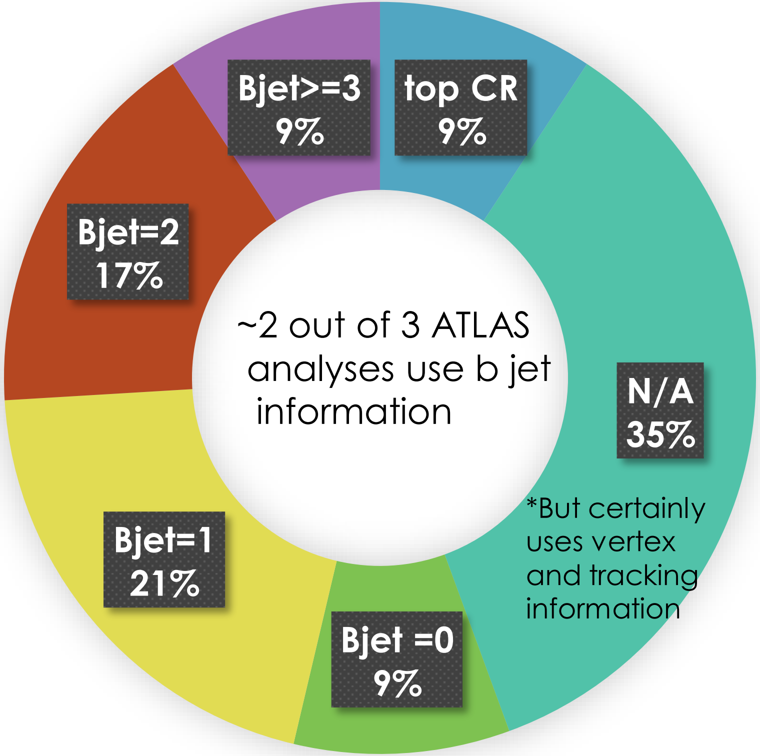
Past Present and Future of the Vertex Locator

Kazu Akiba on behalf of the LHCb VELO

A few words on why we do this

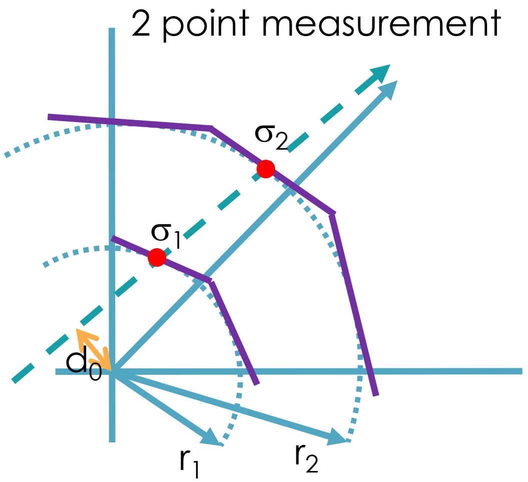
- Some particles "live" longer than others (b and c hadrons)
- The shorter they live the harder it is to separate them from the collision point.
- Precise measurements of the collision and ***displaced vertices***, allow a wide range of physics observations
  - *CP violation, rare decays*
  - *Higgs →bb, bb resonances*
  - *particle oscillations, lifetime measurements*
  - *New particles*



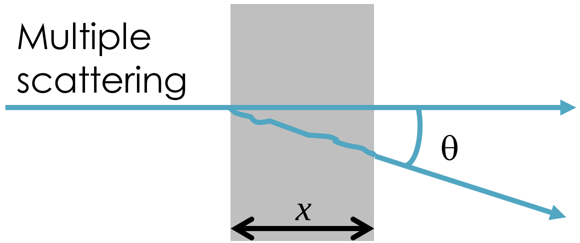
S. Tsuno (PIXEL2016)

How: IP Resolution

- Depends on 3 main parameters
  - Intrinsic ***hit resolution***
  - Distance to the ***first measured*** point and lever arm
  - Multiple scattering in ***detector material***, worse at low p_T



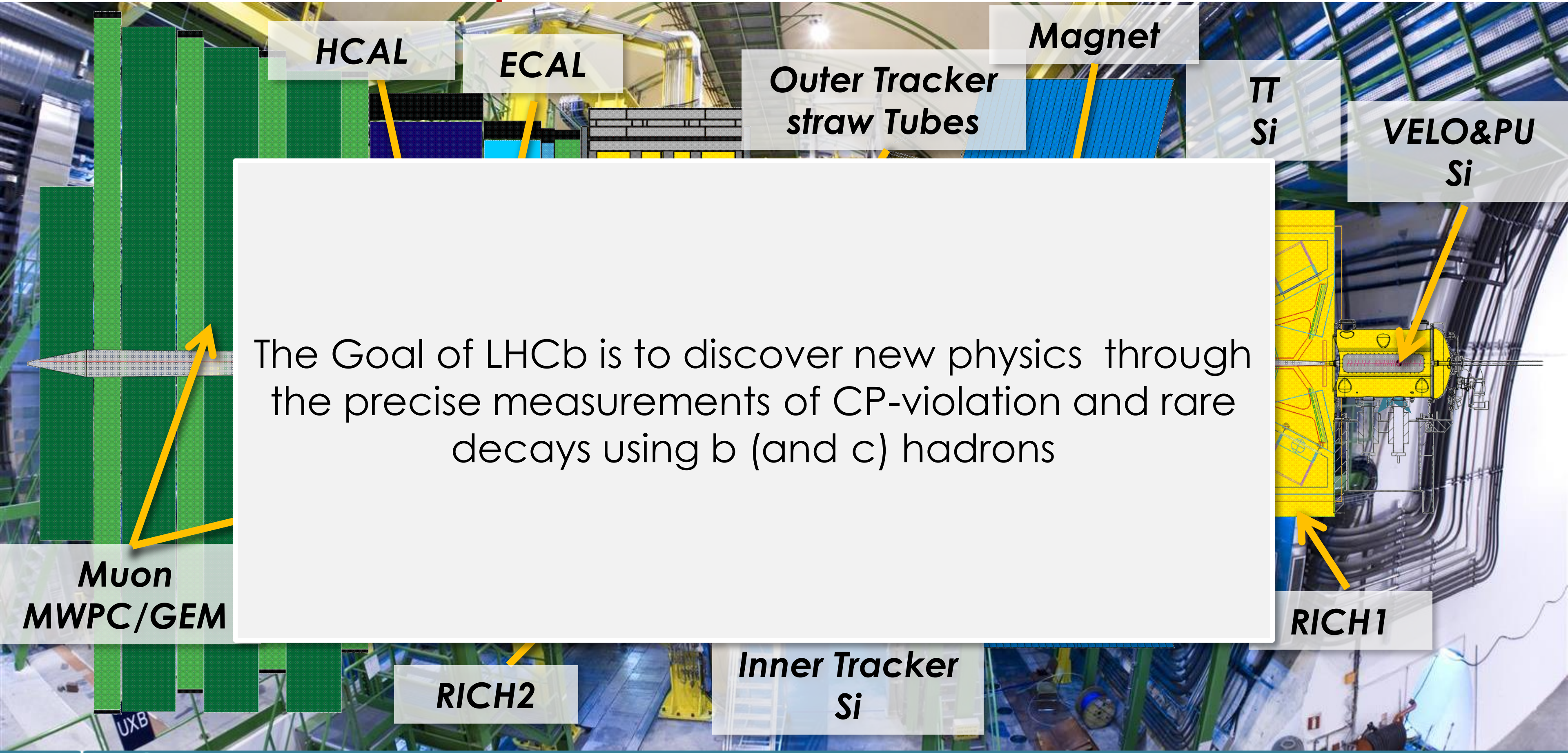
$$\sigma_{d_0} = \sqrt{\frac{r_2^2\sigma_1^2 + r_1^2\sigma_2^2}{(r_2 - r_1)^2}} \equiv \sigma_{geom}$$



$$\sigma_{d_0} = \frac{r}{p} 13.6\,MeV \sqrt{\frac{x}{X_0}}\left[1 + 0.038\log\left(\frac{x}{X_0}\right)\right]$$

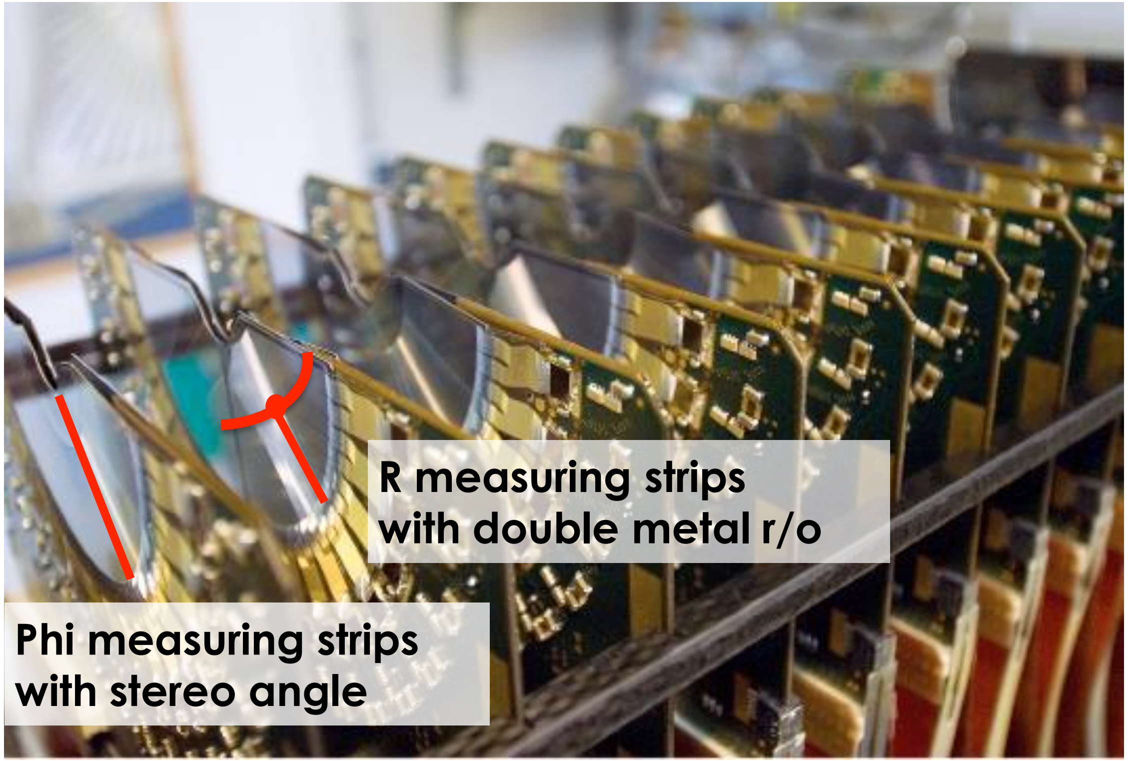
$$\sigma_{d_0}^2 \approx \sigma_{geom}^2 + \left(\frac{f(x/X_0)}{p_{T}\sqrt{\sin\theta}}\right)^2$$

The LHCb Experiment



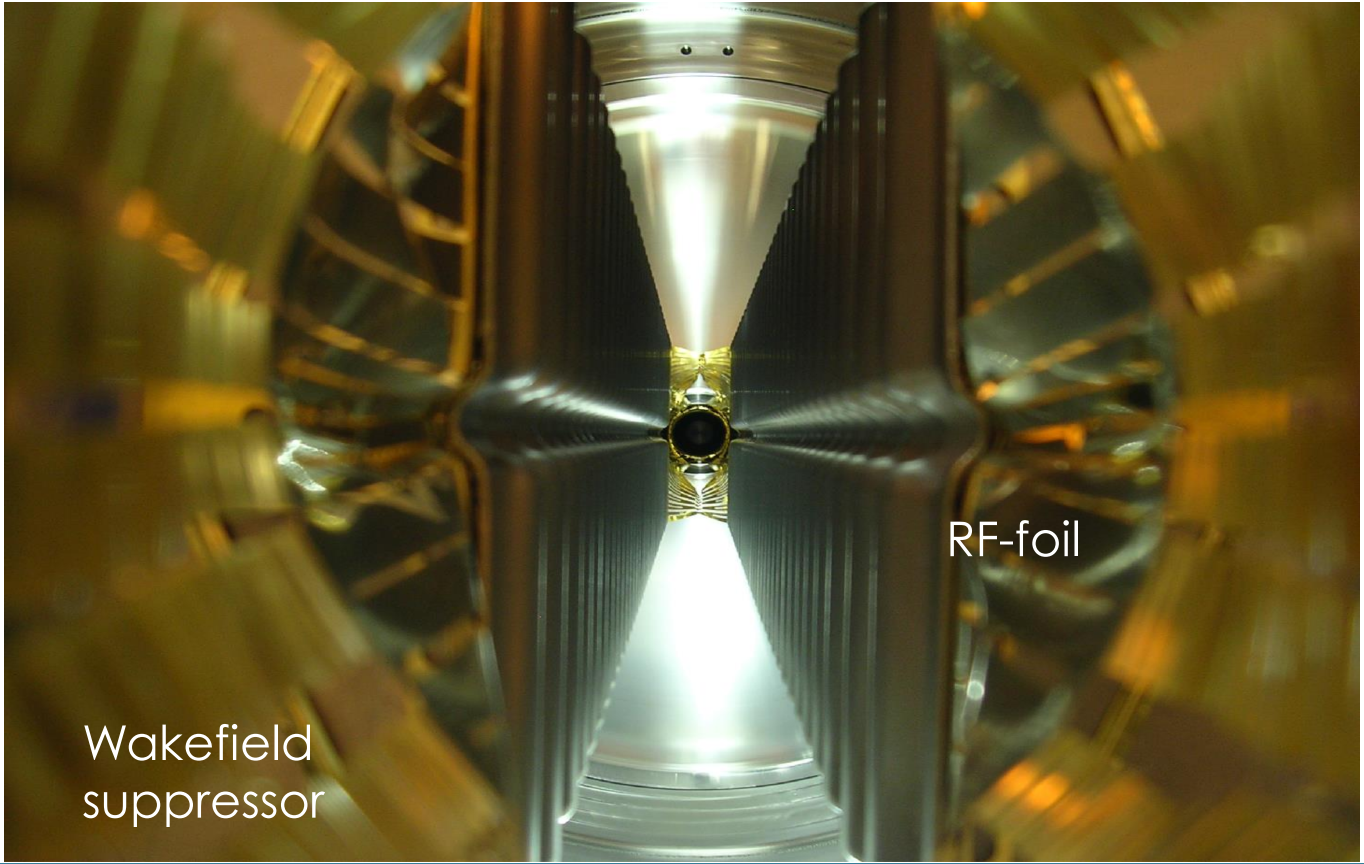
The Goal of LHCb is to discover new physics through the precise measurements of CP-violation and rare decays using b (and c) hadrons

The Past

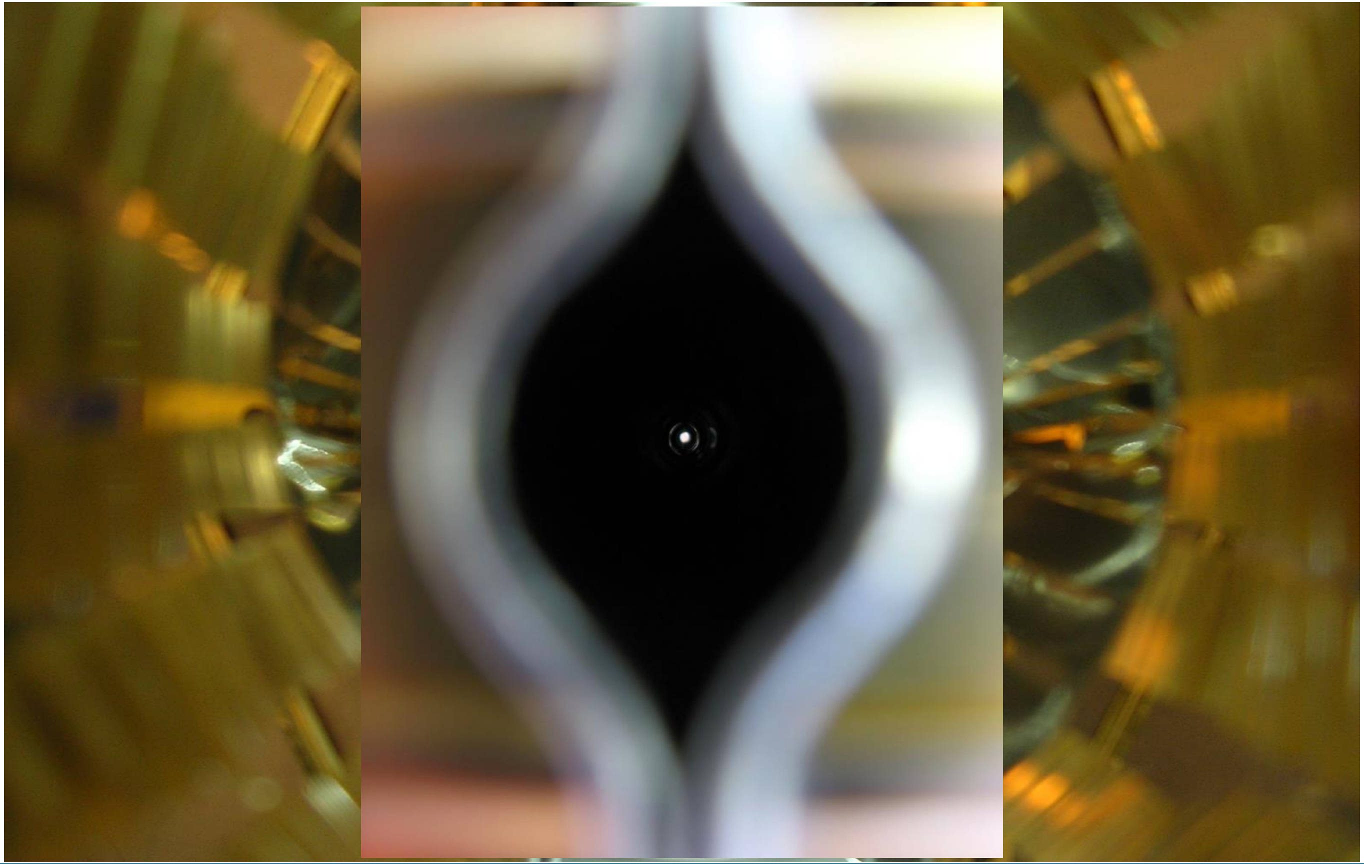

R measuring strips
with double metal r/o
Phi measuring strips
with stereo angle


CERNCOURIER
LHCb beholds more
than beauty
NUCLEAR
REACTORS

Proton view – injection



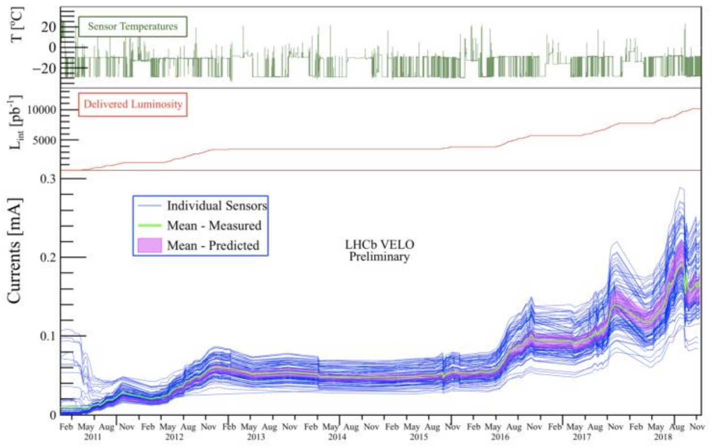
Proton view – stable beams

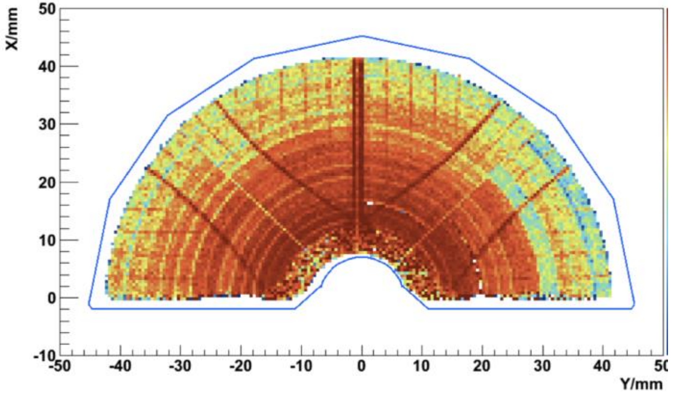


Proton view – stable beams

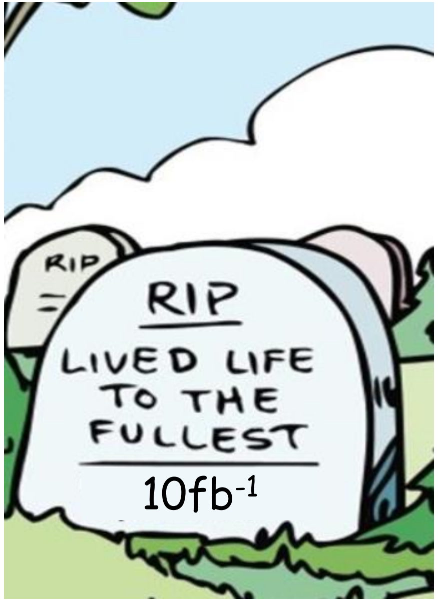
10 years of operation

- **Detector has accumulated fluence of approximately 7 x 10^{14} 1 MeV n_{eq}/cm^2**
- Leakage currents and depletion voltages have followed expectations
- Detector has been operated and maintained below -7°C; underwent **deliberate annealing warm up** at end of lifetime
- Charge loss experienced to double metal layer, but no degradation on IP resolution.
- Irradiation profile is very non uniform ~ $1/r^2$



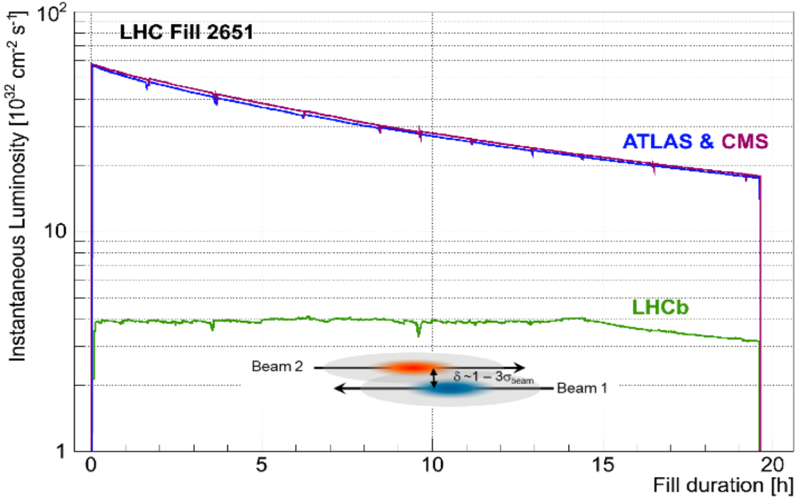


The original detector deinstallation

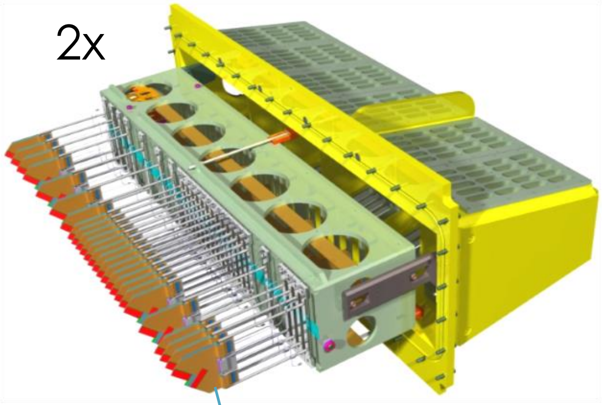


The Present – LHCb Upgrade I

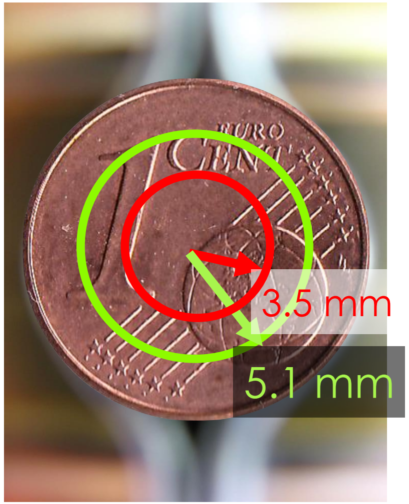
- LHCb upgrades to look for more **collisions/s** in order to select the most interesting ones.
- Smart trigger algorithms to increase the yield of **hadronic decays** and more luminosity for **rare decays.**
- The LHCb Upgrade increases the **luminosity (x5)** and the **readout rate (x40)**.
- This means more radiation damage, more occupancy, more data to transport.

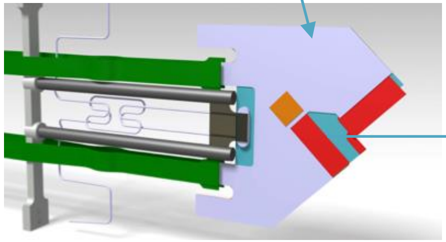


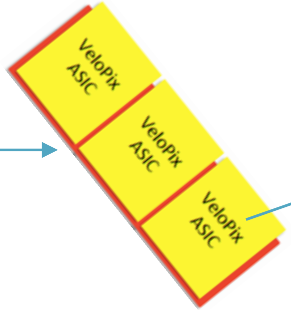
Overview of the Velo upgrade

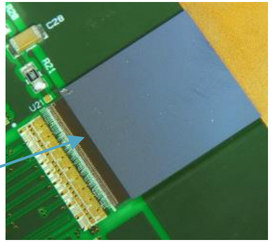


- 52 modules, 55 µm pitch sensors
- 40M pixels
- Data driven readout
- 5.1 mm sensitive distance to beam.
- Operate in Vacuum
- Innovative micro-channel cooling (-20 °C)
- Separated from the beam by an milled foil









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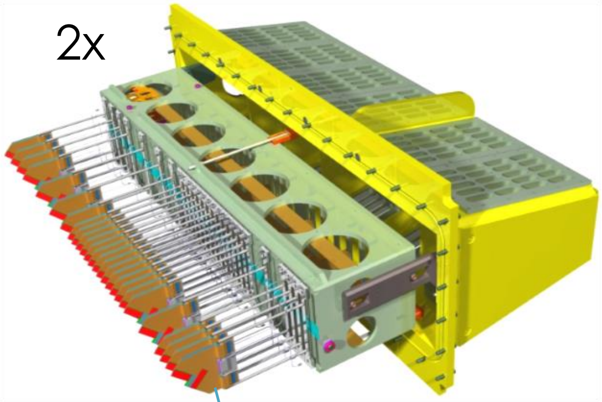

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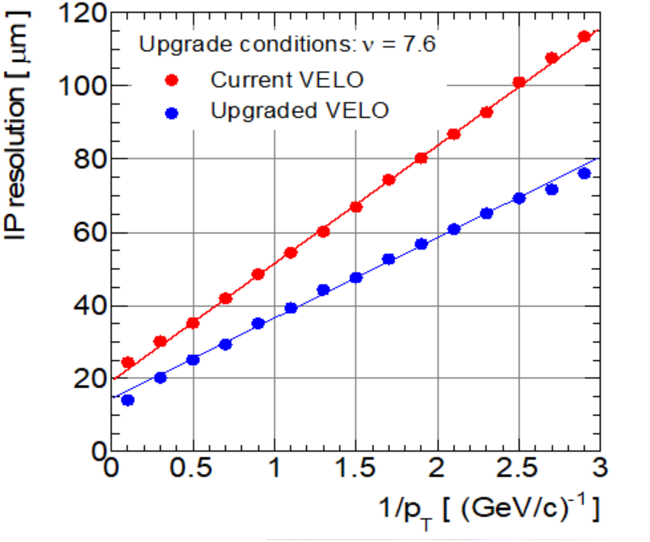
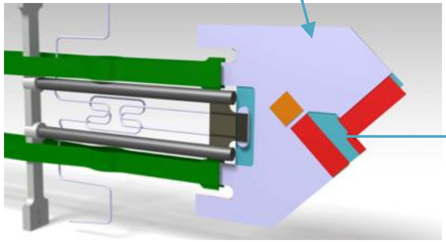
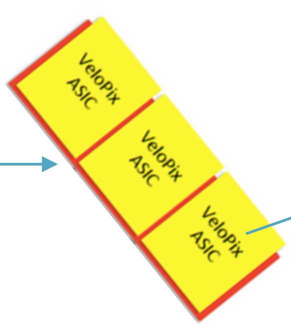
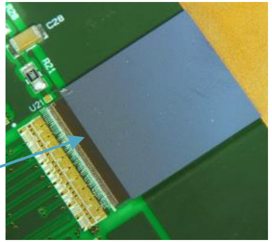






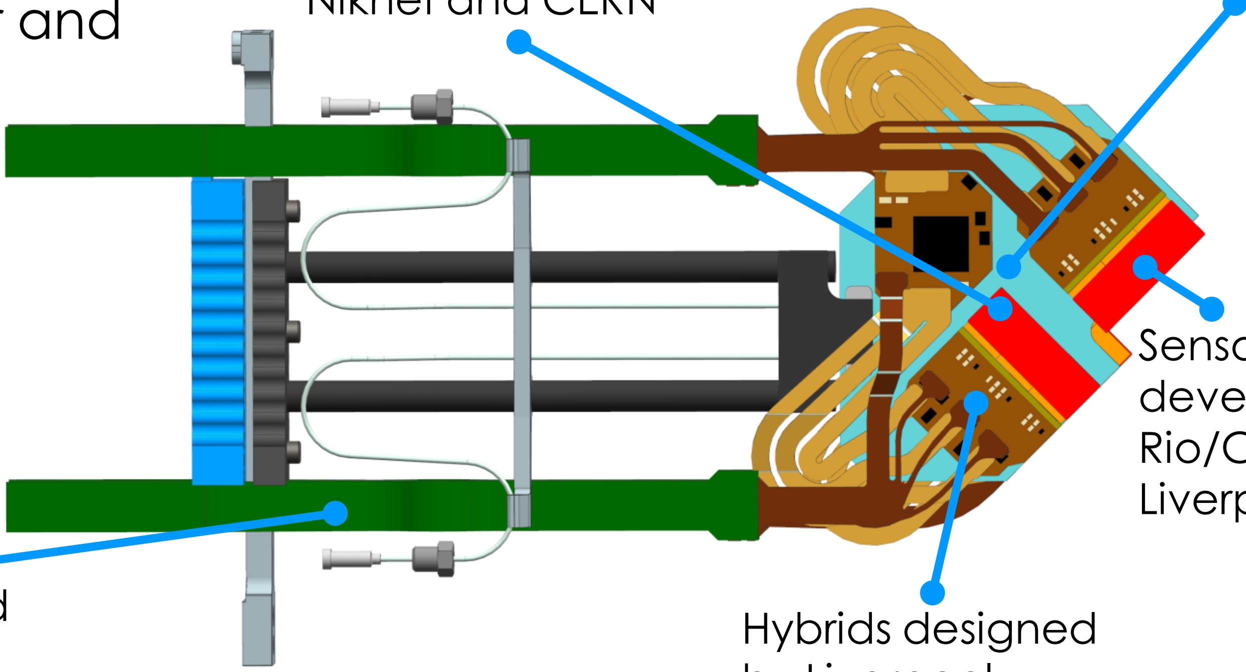


Modules

Modules to be built in Manchester and Nikhef

ASICs created by Nikhef and CERN

Microchannels developed by CERN and Oxford



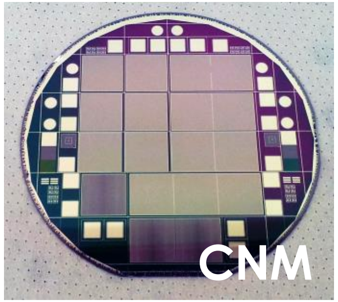
Sensors developed by Rio/CERN/USC Liverpool

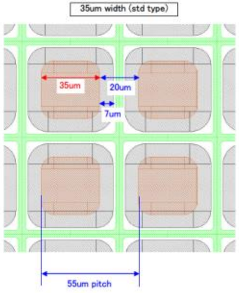
Ultra high speed copper links developed in Glasgow

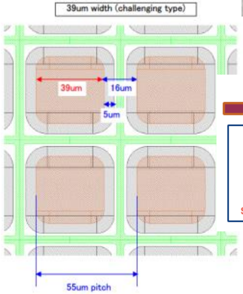
Hybrids designed by Liverpool

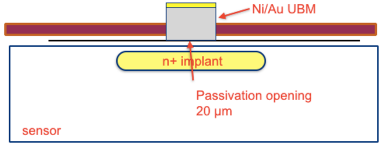
Sensor Prototypes

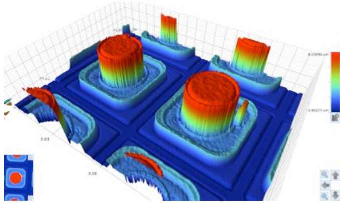
- Round 0 with CNM and VTT
- Round 1 quite some variants:
- Hamamatsu:
  - n-on-p 200 μm thick
  - 450 and 600 μm PTE
  - 35 and 39 μm implant
  - UBM
- Micron:
  - n-on-n and n-on-p
  - 36 μm implant
  - 150, 250 and 450 μm PTE

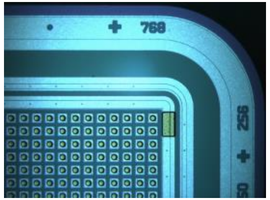


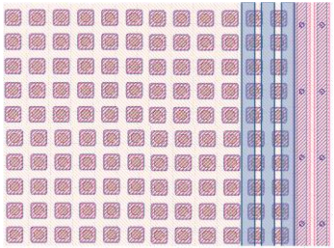


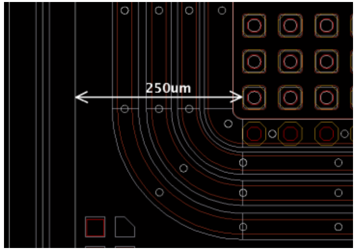


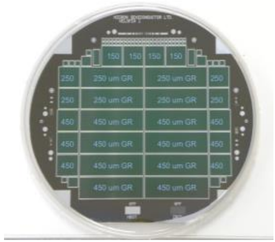












Testing programme

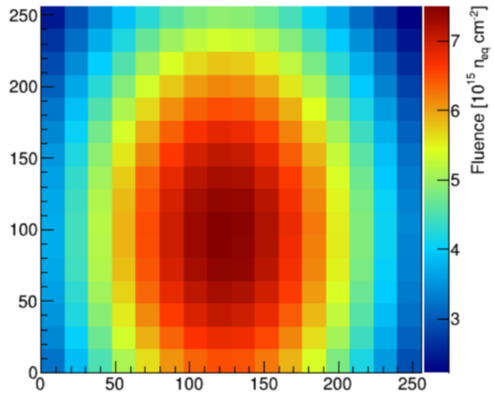
- Resolution, efficiency, charge collection: Measurements at the SPS using the Timepix3 telescope.
- The Velo sensors must collect ***6000 e^-/MIP – 99% eff*** at ***370 Mrad ~ 8 x 10^{15} 1 MeV n_{eq}/cm^2***.
  this is equivalent to 5 years of LHCB Upgrade ***50 fb^{-1}***
  - The ATLAS IBL – at 550 fb^{-1} – expects 3.3 x 10^{15} 1 MeV n_{eq}/cm^2 or 160 MRad.
- Prototypes used Timepix3 – TOT allows charge measurements.

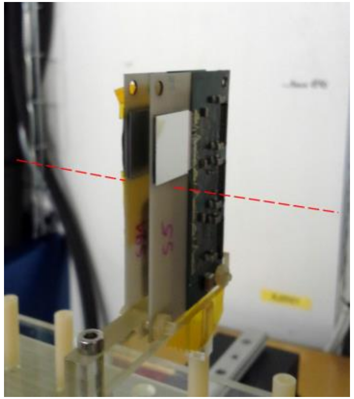
- Calibrations performed in the lab with test pulses, radioactive sources and synchrotron x-rays.
- HV tolerance to 1000 V.

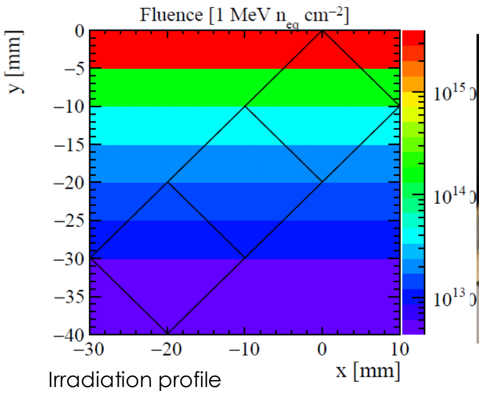
Irradiation

- Sensors were irradiated at
  - JSI/IST (n/reactor)
  - KIT (26 MeV p/beam),
  - IRRAD (24 GeV p/beam)
- collected charge > **6000 e⁻**.
- The sensors must withstand **1000 V** without breakdown after **non uniform** irradiation.
- Measure efficiency and resolution after irradiation.

IRRAD @ CERN
24 GeV protons

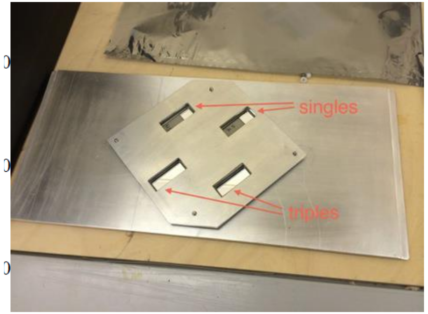






Irradiation profile

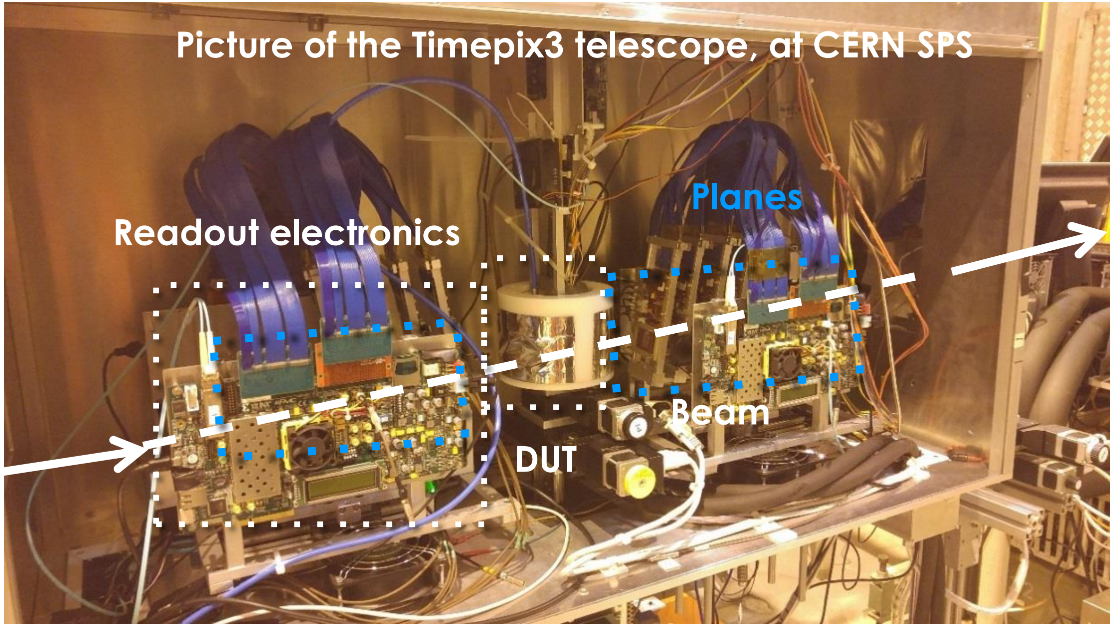
setup



KIT @ Karlsruhe 26 MeV p

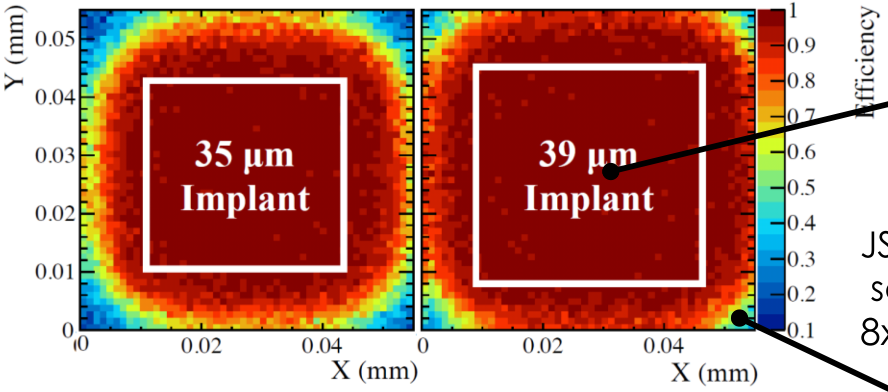
Testing prototypes with SPS beam

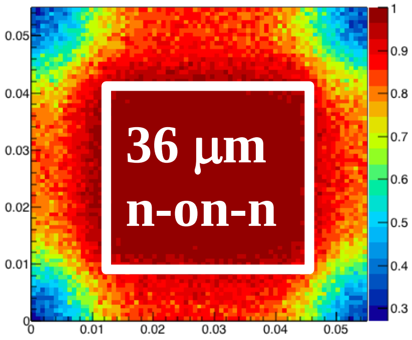
- Using **Timepix3** telescope
- 4 Timepix3 on 2 "arms"
- pointing resolution below **1.6 µm**
- Precise **time stamps (1.56 ns)** yield a clean Pat. Rec.
- 350 ps track time resolution
- **JINST 14 (2019) no.05, P05026**



Efficiencies

S22 S17 HPK 300V

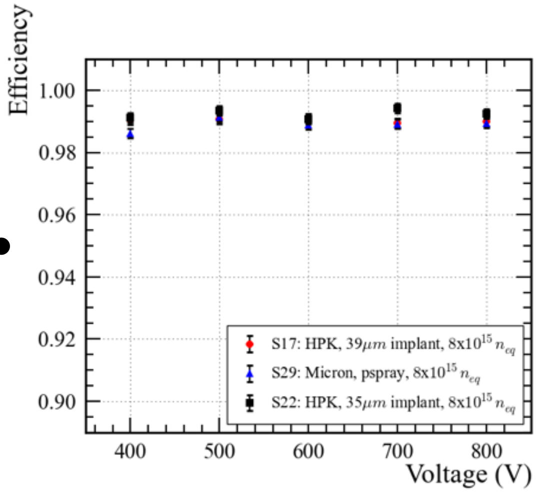


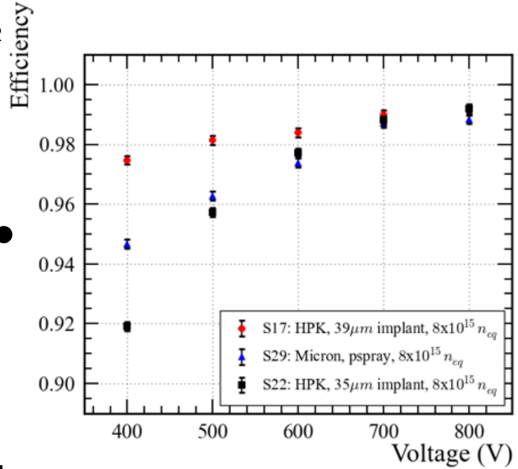


S27 Micron 300V

JSI irradiated sensors

$8x10^{15}$ 1MeV $n_{eq}.cm^{-2}$



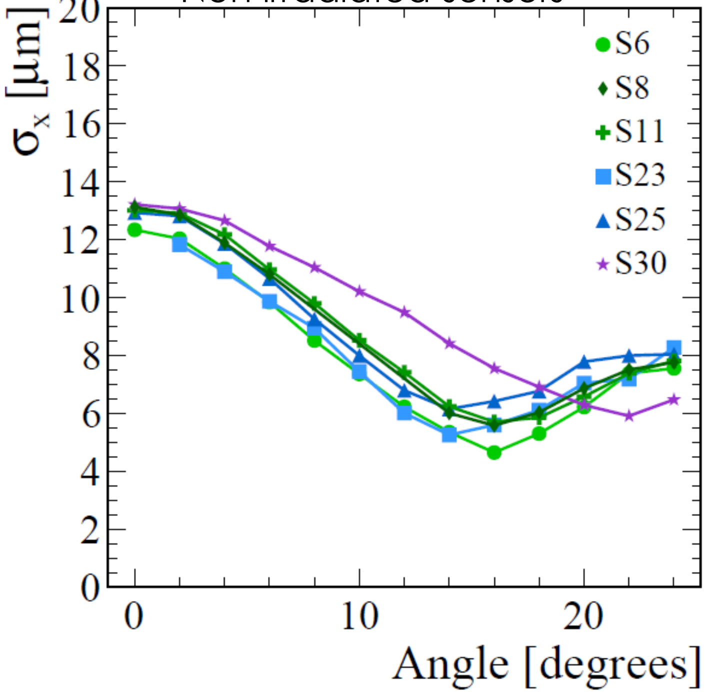


At 1000 V the corners are recovered.

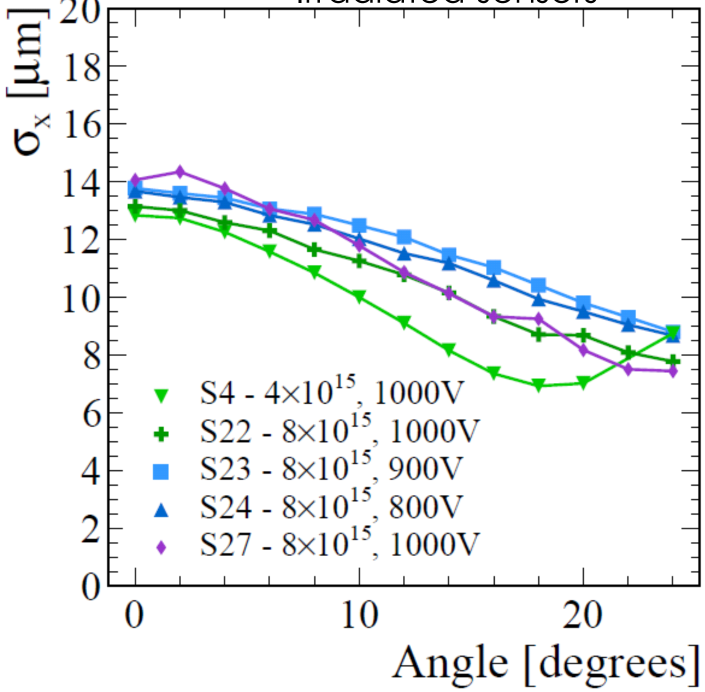
Hit resolution

HPK 200 μm n-on-p
Micron 200 μm n-on-p
Micron 150 μm n-on-n

Non irradiated sensors



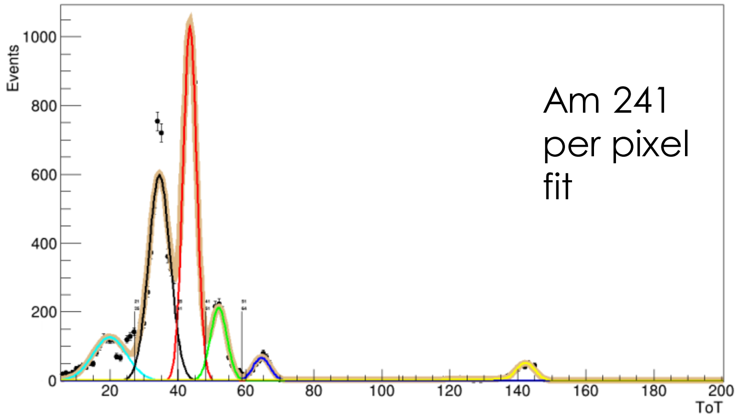
Irradiated sensors

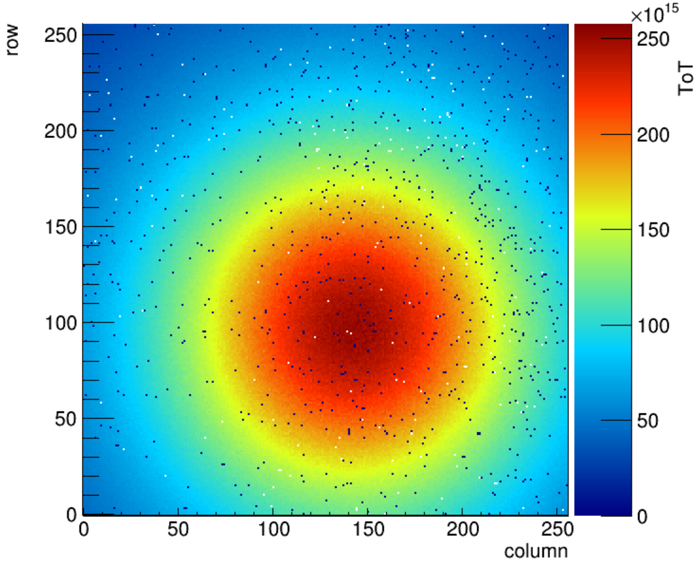


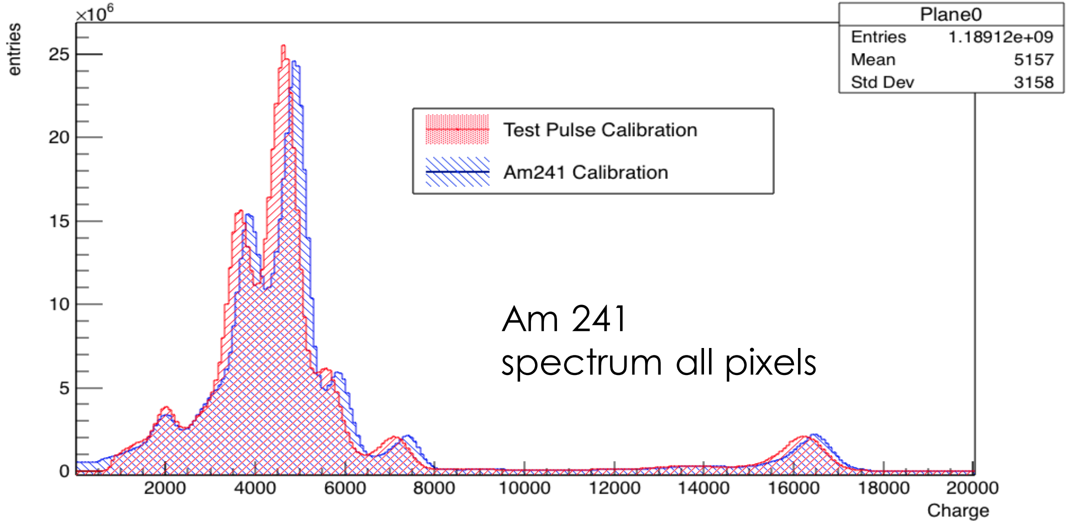
Best resolutions just below 5 μm.
Charge weighted – Non Binary data.

Charge calibration

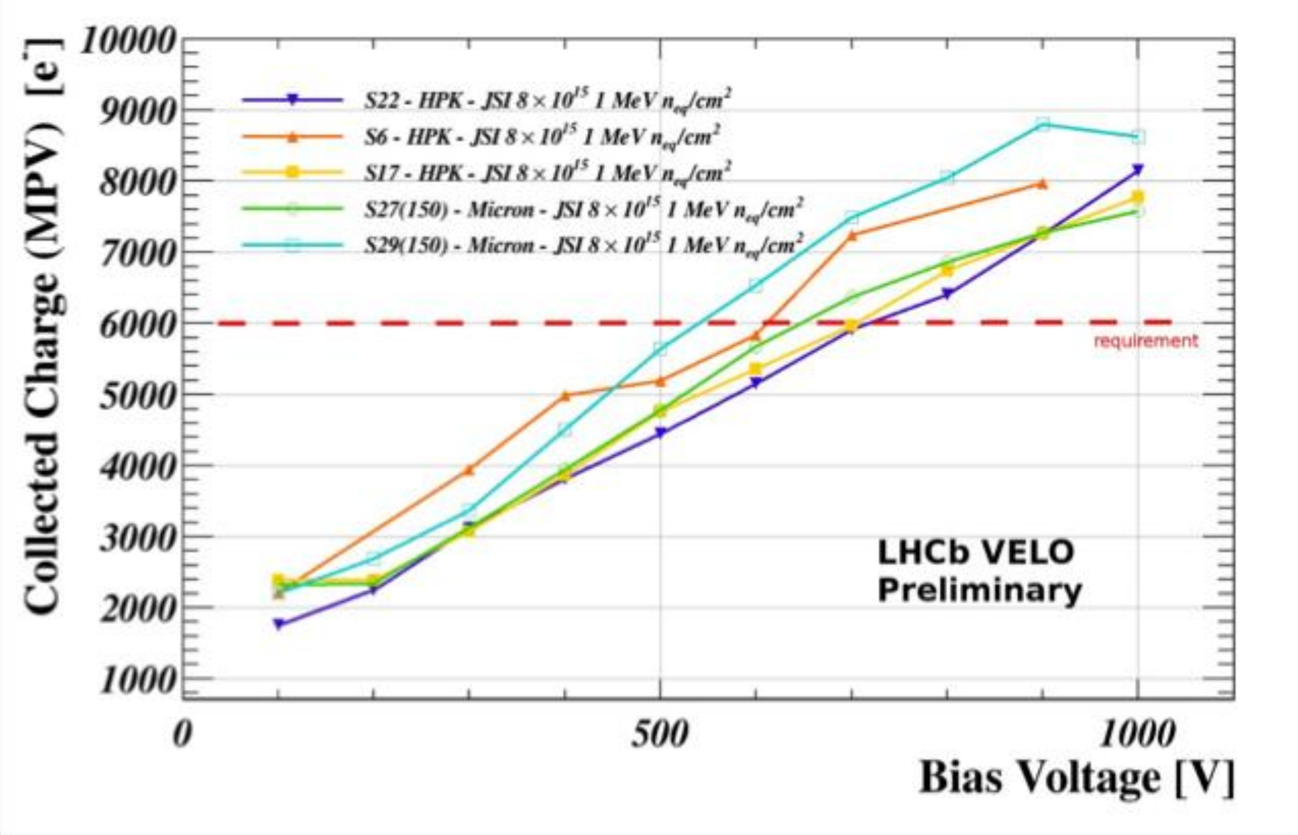
- Performed with radioactive sources, Synchrotron (LNLS) and test pulses.







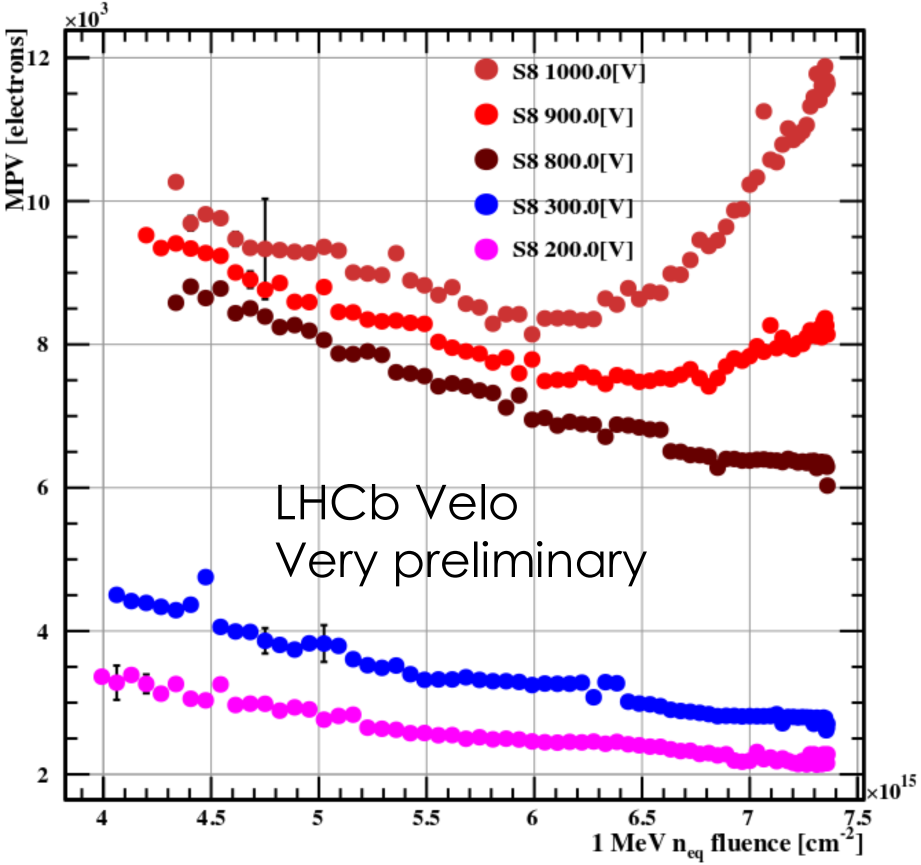
Collected Charge – neutron irradiated



- Even if the charge is shared up to 6 pixels the signal would cross the threshold.

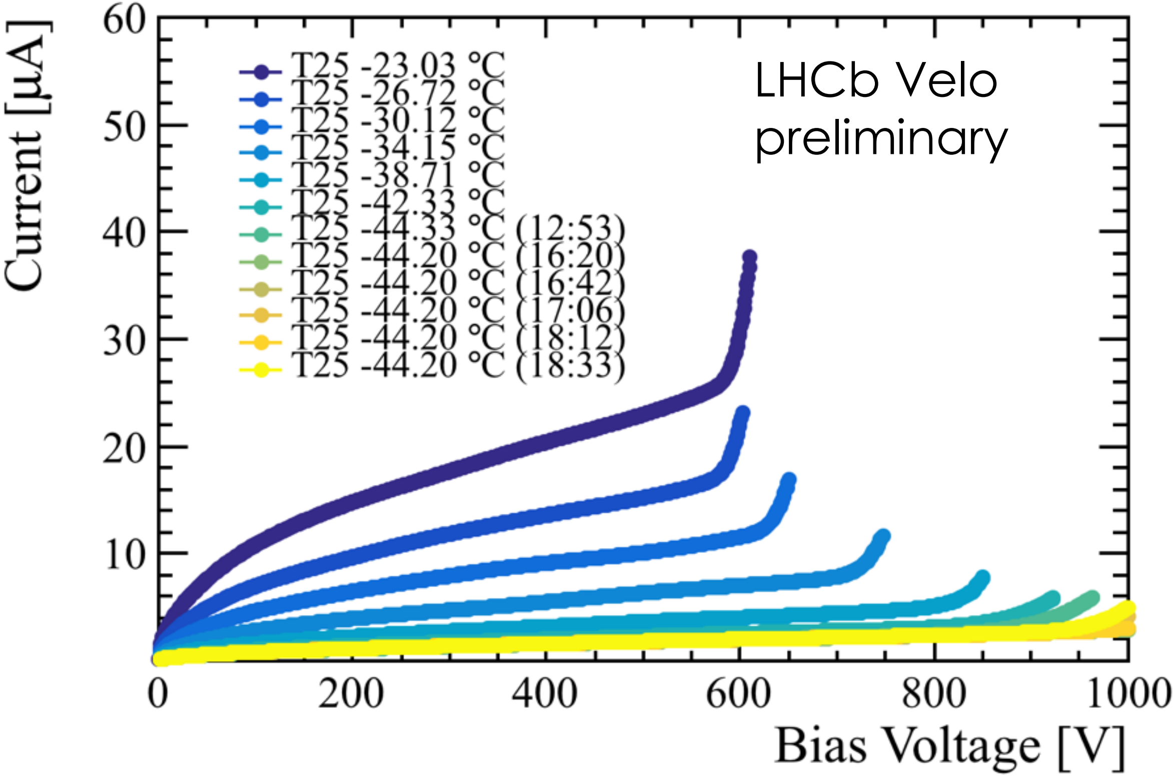
Charge Multiplication – IRRAD

- Heavily irradiated regions show higher charge collection at the same voltage.
- The effect increases with the voltage.
- Still under analysis



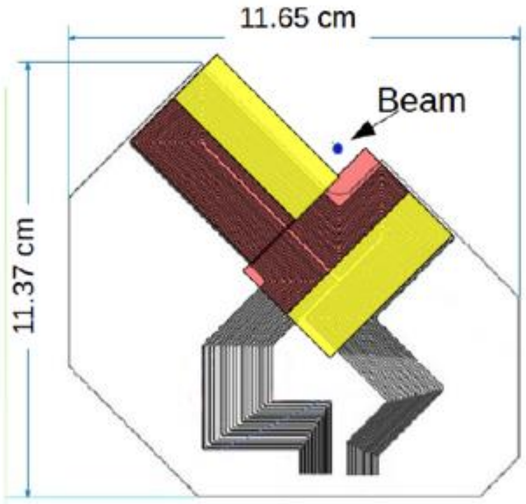
Temperature dependent Breakdown

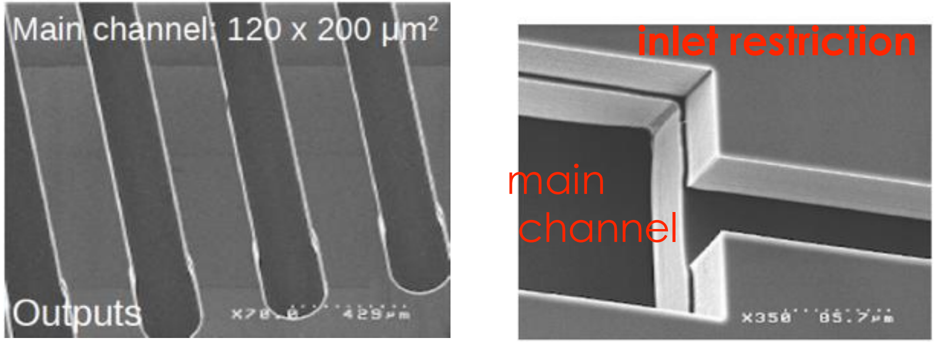
- Some sensors show early breakdown which is temperature dependent.
- This effect seems slightly mitigated after some time biased.
- Operate at lower temperatures to gain radiation hardness?



Microchannel cooling

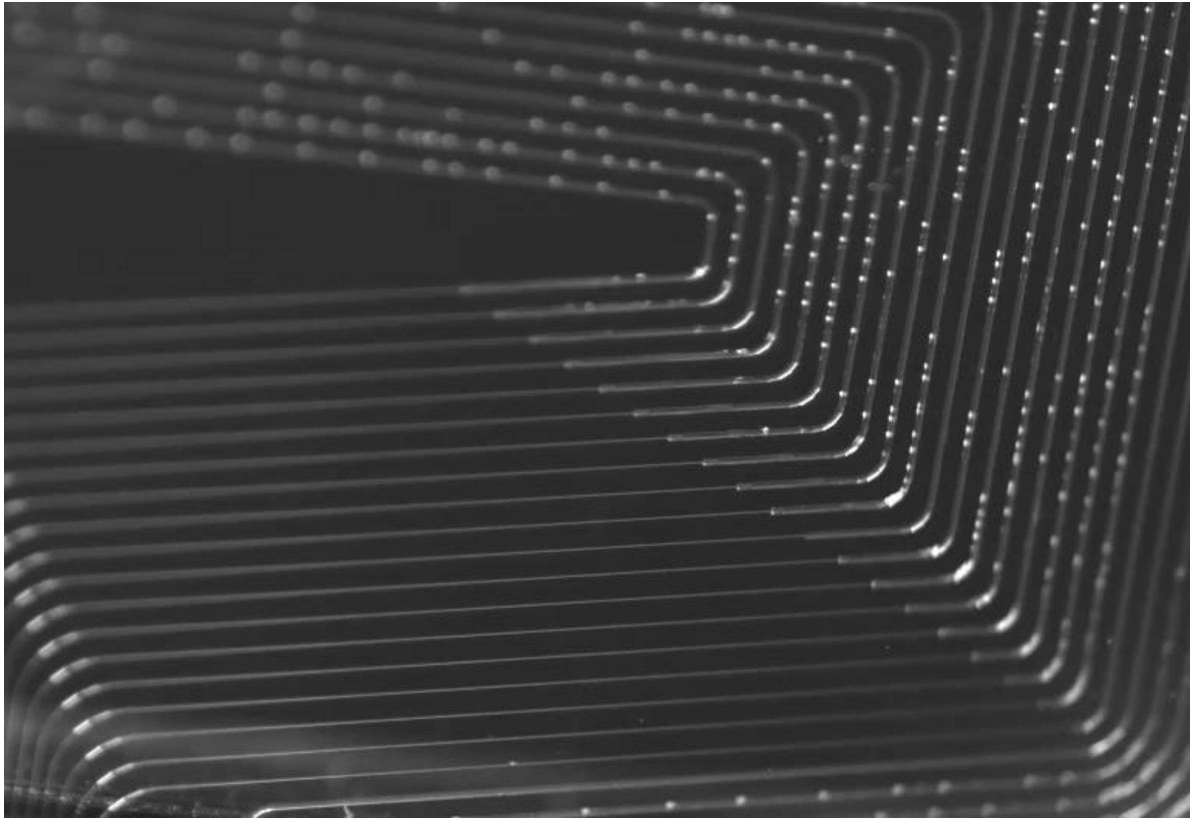
- Efficient cooling solution is required to maintain the sensors at < -20°C
- No CTE mismatch
- This is provided by the novel technique of evaporative CO_2 circulating in 120 μm x 200 μm channels within a silicon substrate.



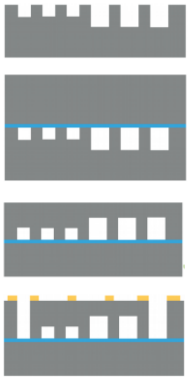


SEM images of etched wafer before bonding

Silicon on pyrex



Manufacturing and assembly

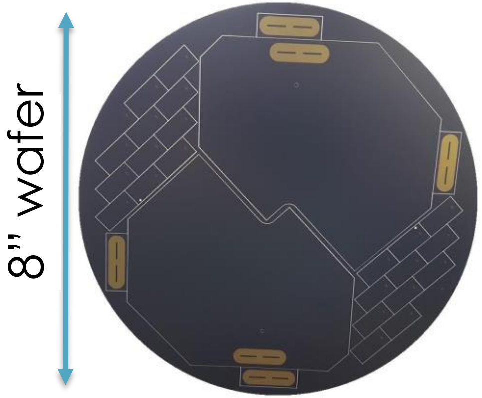


Channel etching

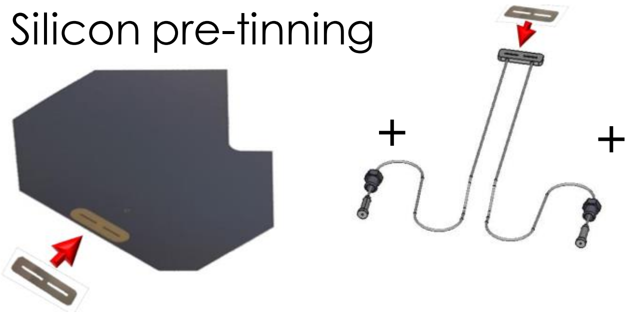
Cap wafer bonding

Thinning (both sides)

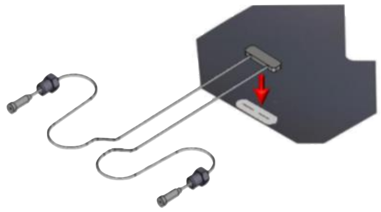
Inlet/Outlet etching



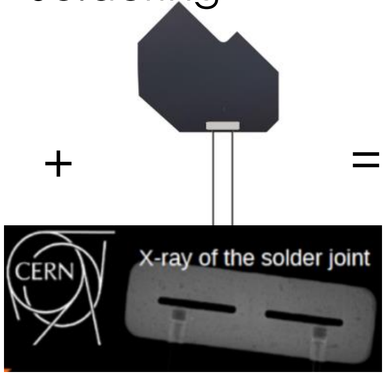
Silicon pre-tinning

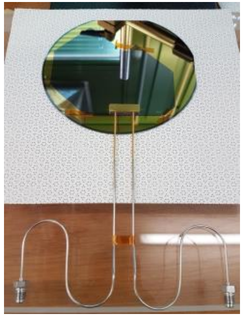


Alignment



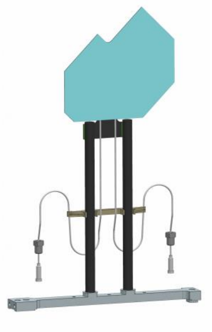
Soldering



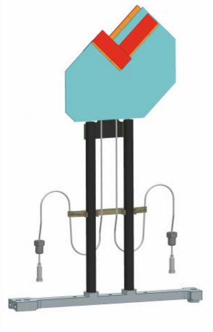


Final assembly can Withstand 200 bar

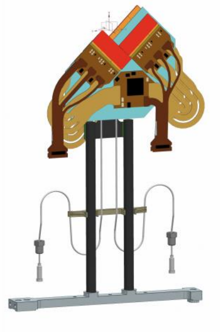
Module Production



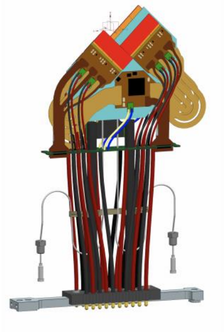
Mechanical construction



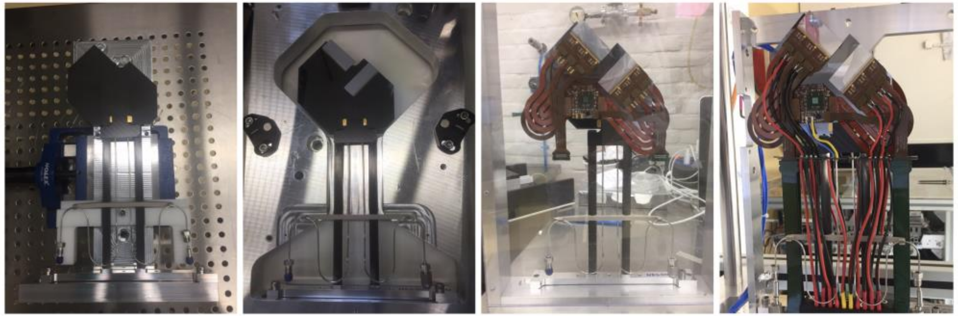
Precision tile placement to 10 μm



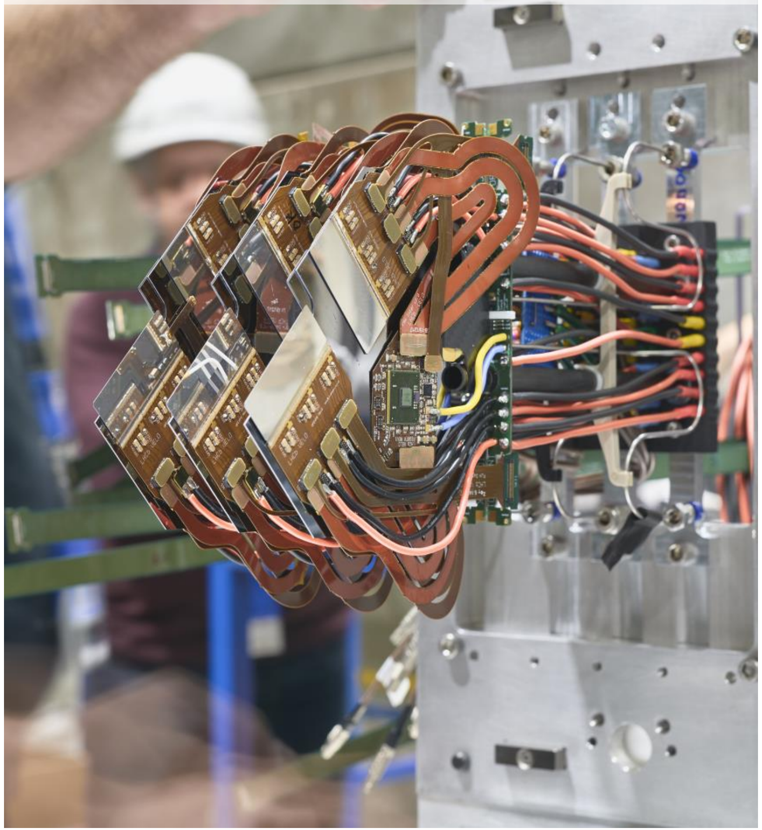
Flex circuit placement



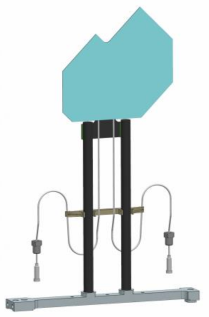
wire bonding and HV/LV/data cable attachment



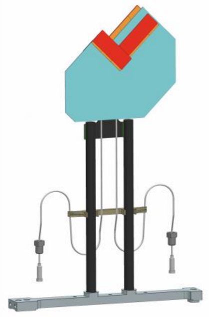
Three modules in SPS test beam



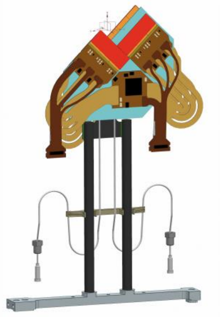
Module Production



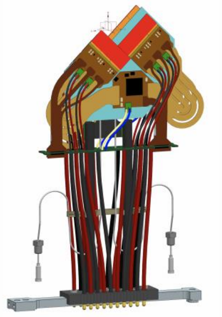
Mechanical construction



Precision tile placement to 10 µm



Flex circuit placement



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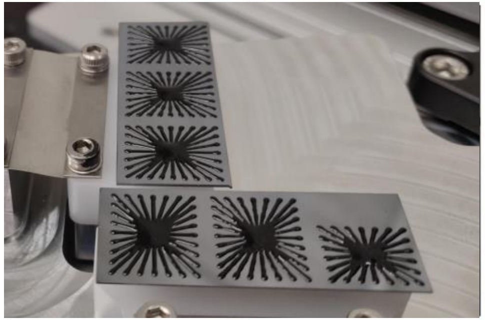

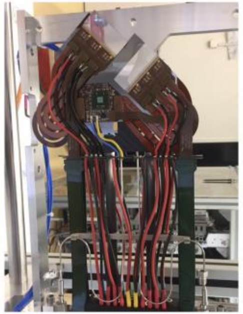

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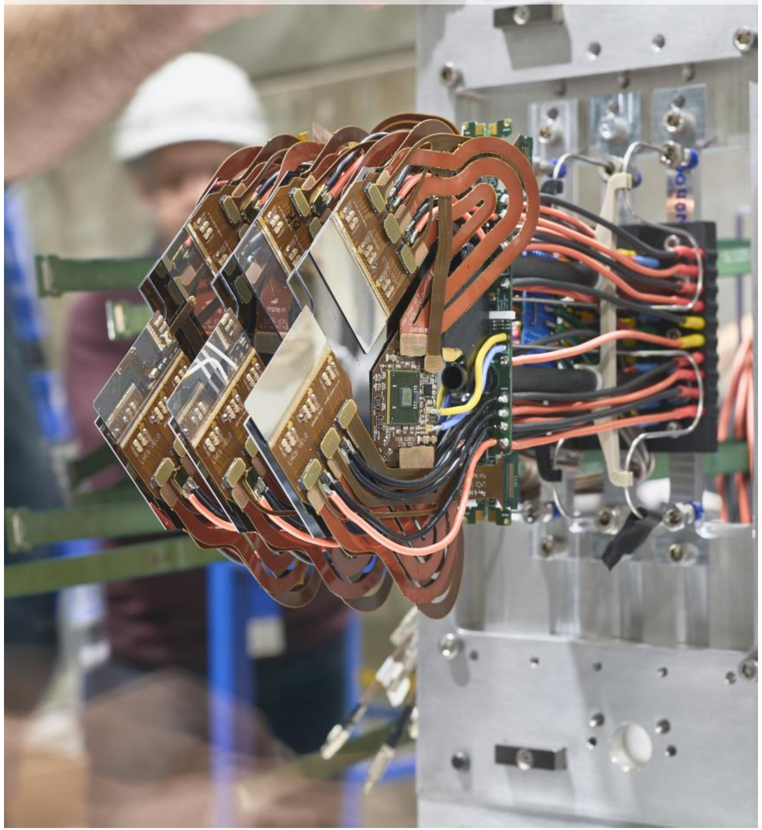
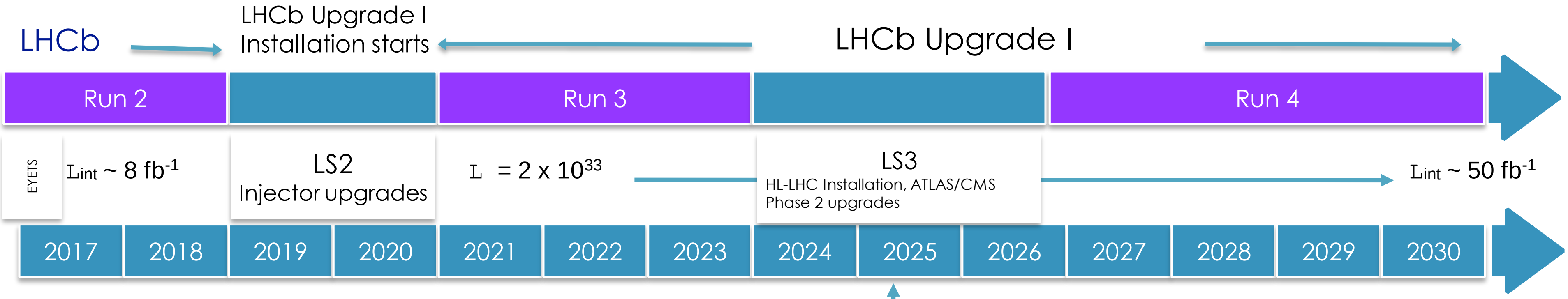
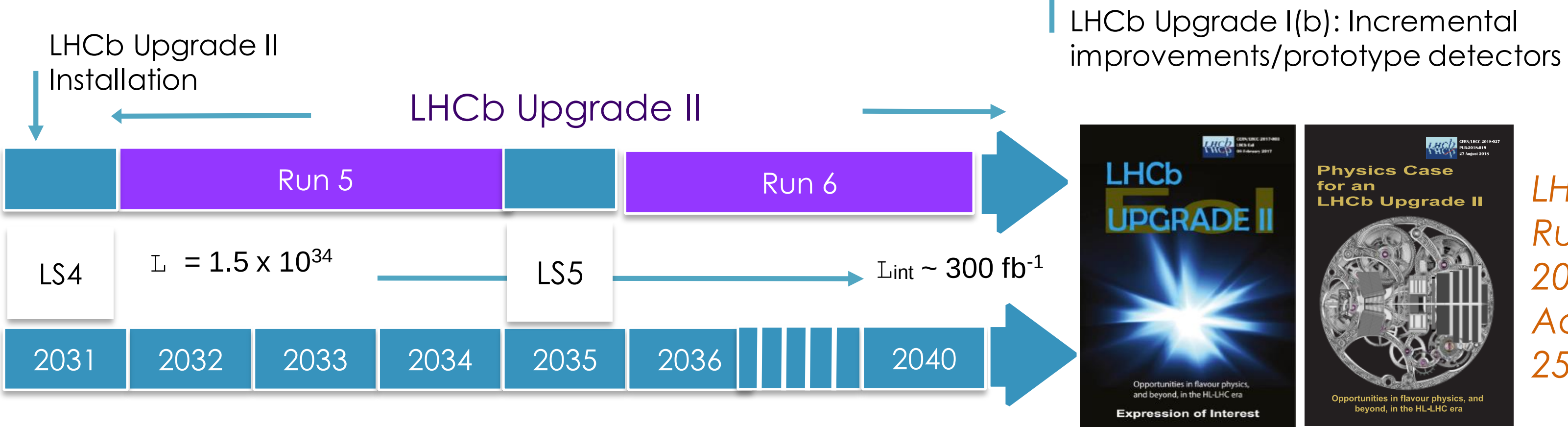


Upgrade I – Status

- Final items for the upgrade under production
- Modules being assembled
- Mechanical installation final planning
- Time to think of the next upgrade?

The Future





LHCb Upgrade II
Run 4 and Run 5
2030 ++
Accumulate
250-350 fb^{-1}

The Future

LHCb → LHCb Upgrade I Installation starts ← LHCb Upgrade I →

Run 2		Run 3		Run 4

EYETS

$L_{int} \sim 8\ fb^{-1}$

LS2
Injector upgrades

$L = 2 \times 10^{33}$

LS3
HL-LHC Installation, ATLAS/CMS Phase 2 upgrades

$L_{int} \sim 50\ fb^{-1}$

2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030

At least this time for R&D

LHCb Upgrade I(b): incremental improvements/prototype detectors

LHCb Upgrade II Installation

← LHCb Upgrade II →

	Run 5		Run 6

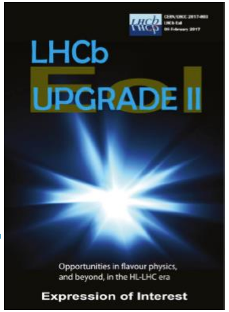
LS4

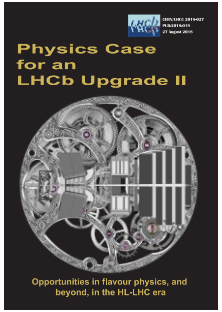
$L = 1.5 \times 10^{34}$

LS5

$L_{int} \sim 300\ fb^{-1}$

2031	2032	2033	2034	2035	2036		2040





LHCb Upgrade II
Run 4 and Run 5
2030 ++
Accumulate
250-350 fb^{-1}

LHC parameters for Upgrade II

$$\sigma_z^{RMS} \approx 44.7 \text{ mm}$$

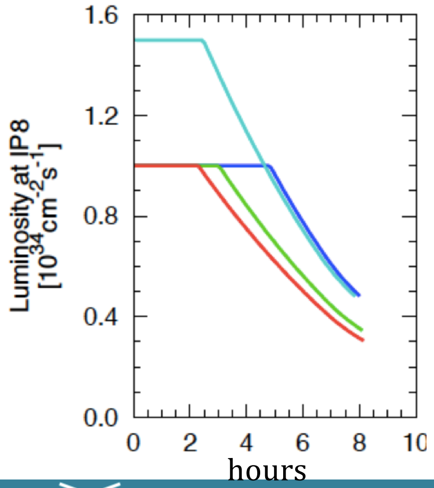
$$\sigma_t^{RMS} \approx 186 \text{ ps}$$

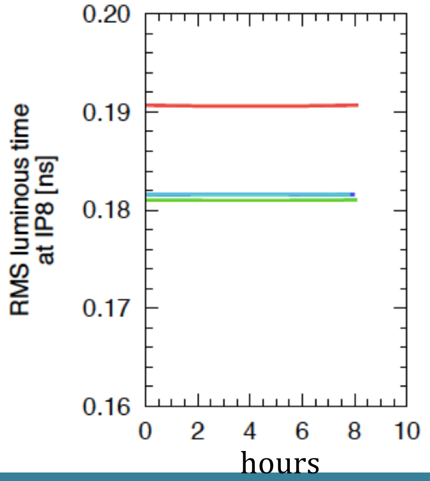
$$\sigma_{comb}^{RMS} \approx 240 \text{ ps}$$

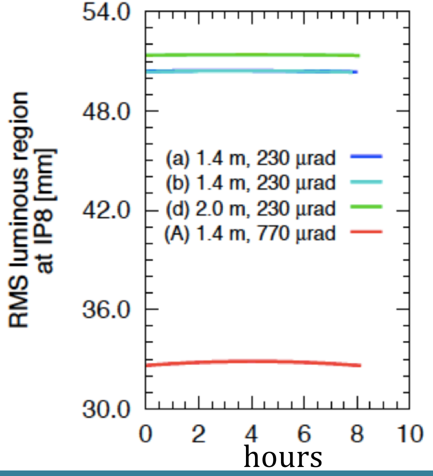
$$\text{Pile up} \approx 42$$

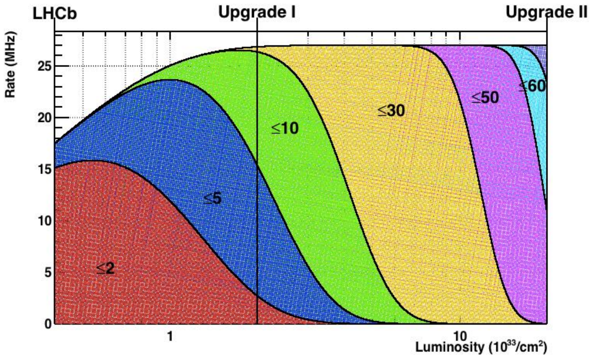
Baseline (nominal) beam parameters and levelling at IP1&5

- Range of potential solutions to operate LHCb Upgrade II at up to 1.5×10^{34} $cm^{-2}s^{-1}$
- Horizontal and vertical crossing angle scenarios under consideration
- Number of colliding bunches at IP8: 2572
- Levelling by parallel separation at IP8
- reduction of yearly integrated luminosity at IP1&IP5 - 1% - 2.5%









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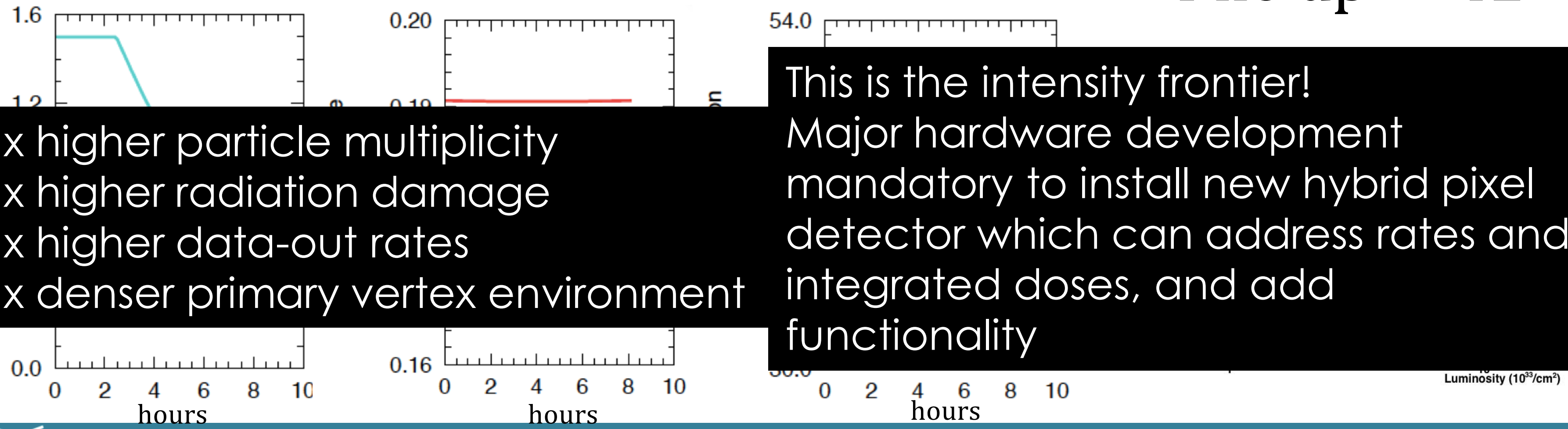


10 x higher particle multiplicity
10 x higher radiation damage
10 x higher data-out rates
10 x denser primary vertex environment

This is the intensity frontier!
Major hardware development mandatory to install new hybrid pixel detector which can address rates and integrated doses, and add functionality

Physics considerations

In an environment of ~50 PVs, how can we make B-tagging? How can we map the B to the right PV?

- The cross section of b-bar at 14 TeV is 150 μbarn
- At Upgrade I L = $2 \times 10^{33} cm^{-2} s^{-1}$
  - => 300k b-bar/second! 1 bbar every 100 bunch crossings.
  - At upgrade II this will be 10 times bigger
- High PT and High IP particles coming from many other PVs - can we really tag the B?
- Can we really find to which PV the reconstructed B points to?
- Can we do it fast enough?

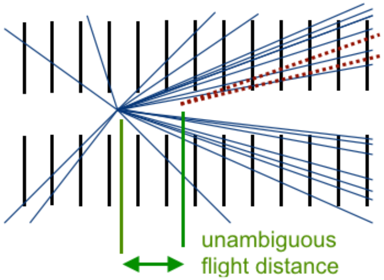
4D tracking and vertexing

Move towards **4D** tracker concept with addition of **hit timing**:

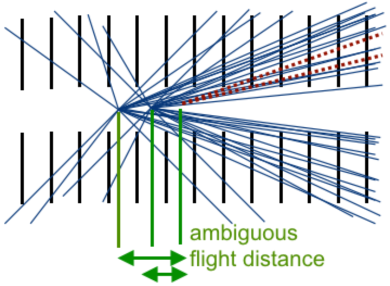
- Real time track reconstruction critical for Upgrade I and II: **Only High Level Trigger**

- Timing information will contribute to **Pattern Recognition** speed and efficiency
  - **Track time stamping** for PV association, PV timing, and combination with downstream detectors for beam gas and background control, calorimetry and time of flight

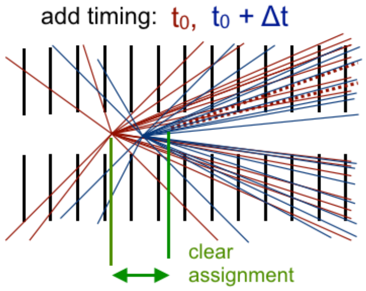
single primary vertex:



two primary vertices:



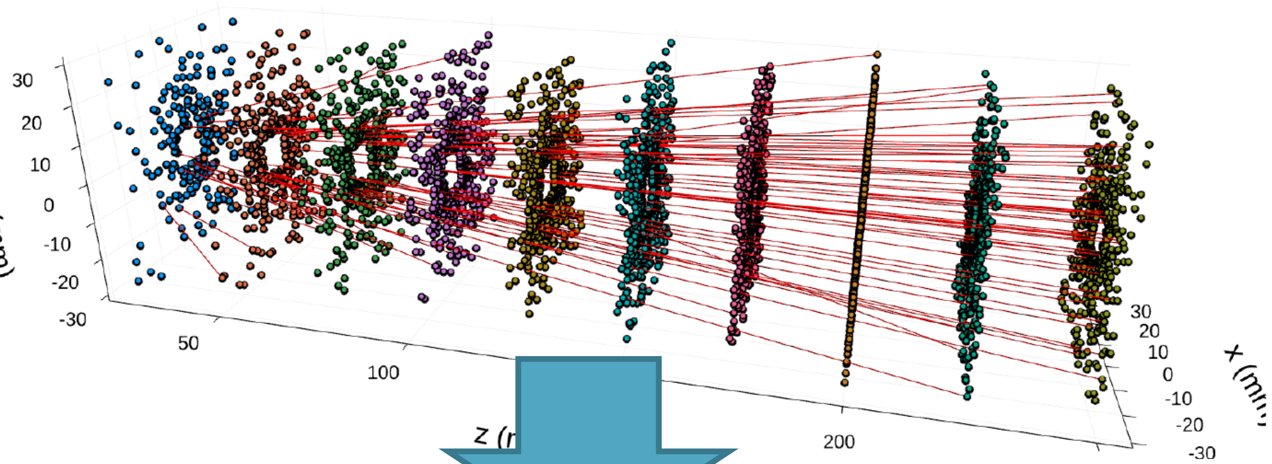
two primary vertices + time decoding $t_0, t_0 + \Delta t$



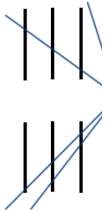
4D tr

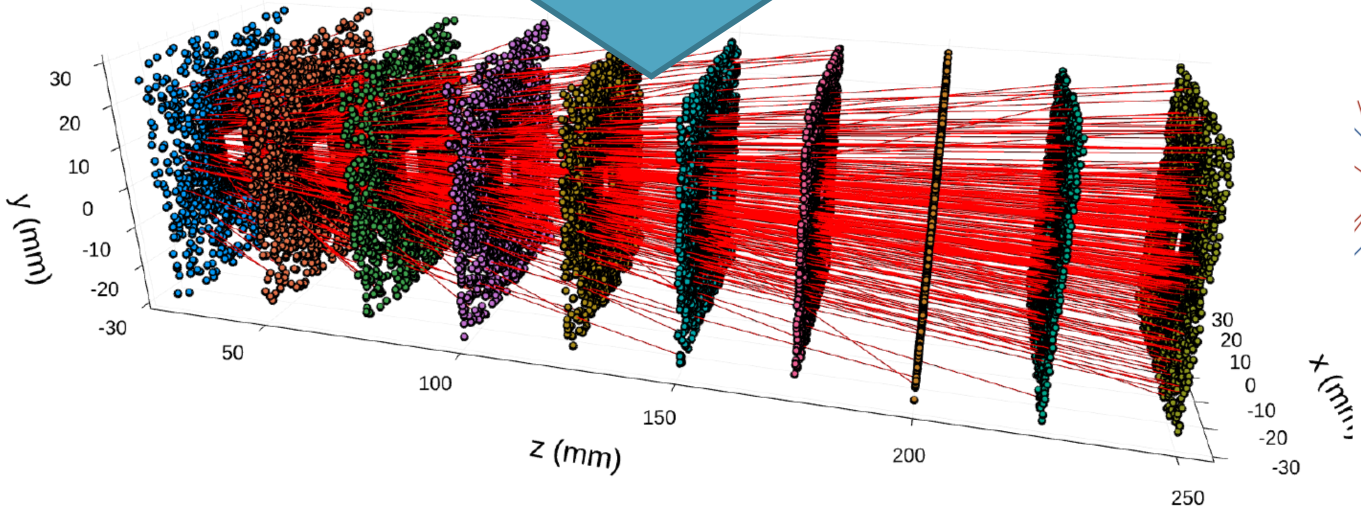
Move tow

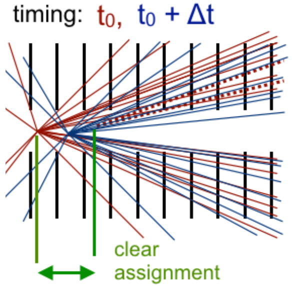
- Real tim r
- Timing info
  - **Track ti** ream detecto



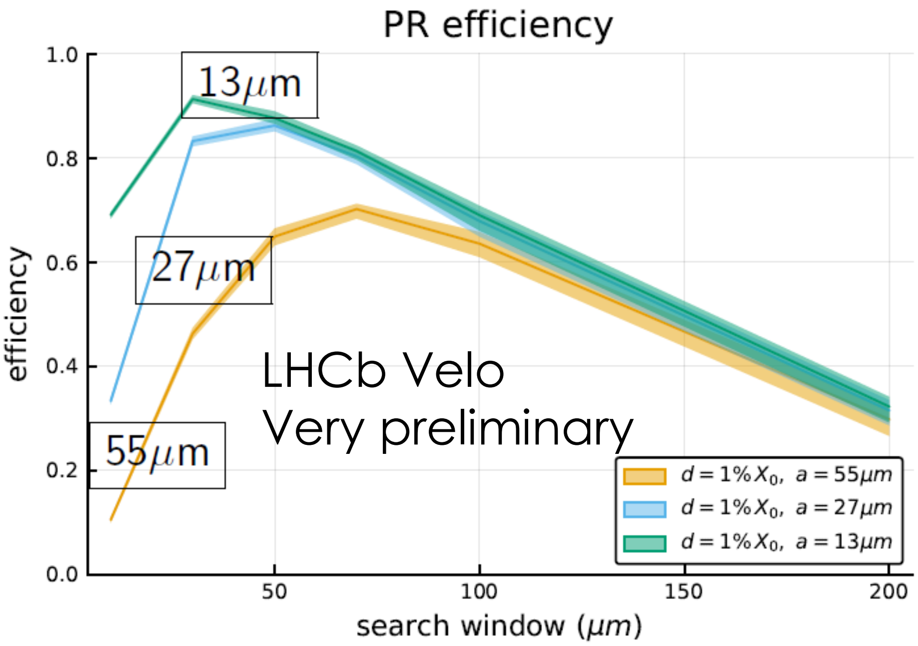
single primary vertex:

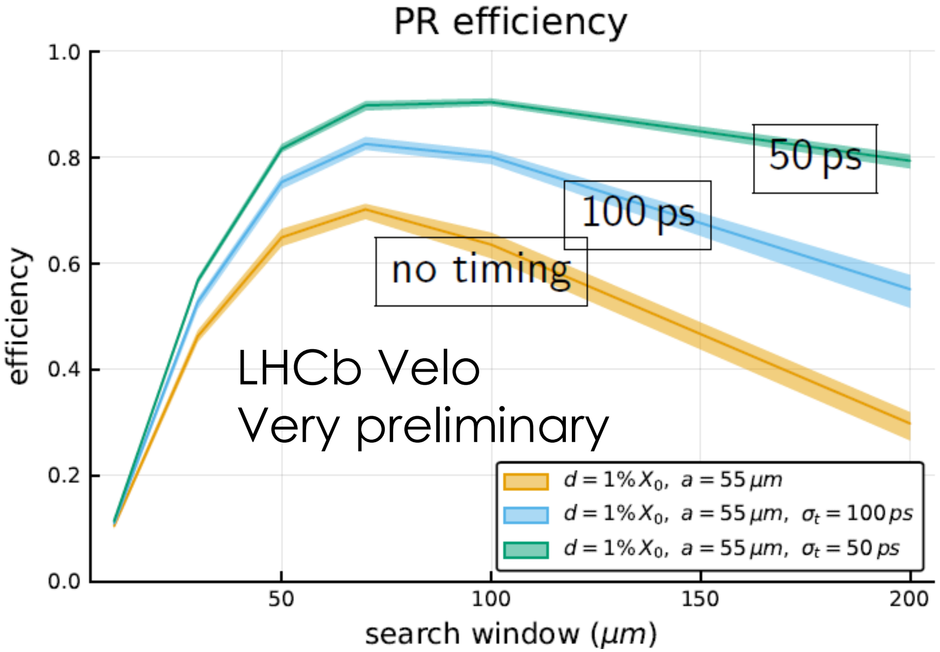




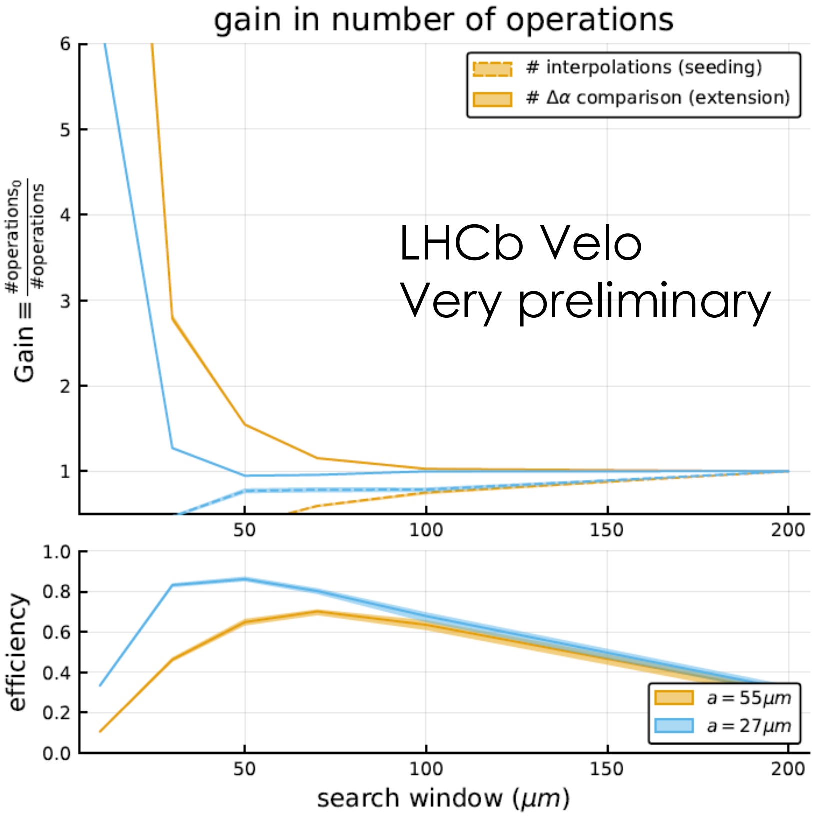


Pattern recognition improvement

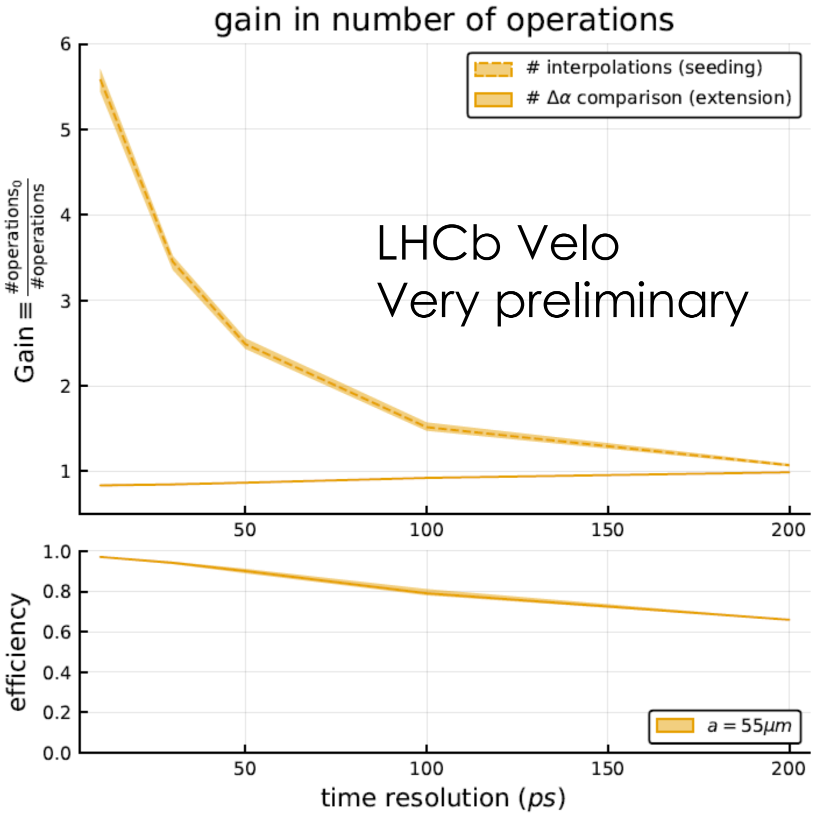




Timing gain



gain in number of operations
interpolations (seeding)
Δα comparison (extension)
LHCb Velo
Very preliminary
Gain ≡ #operations0 / #operations
efficiency
a = 55μm
a = 27μm
search window (μm)

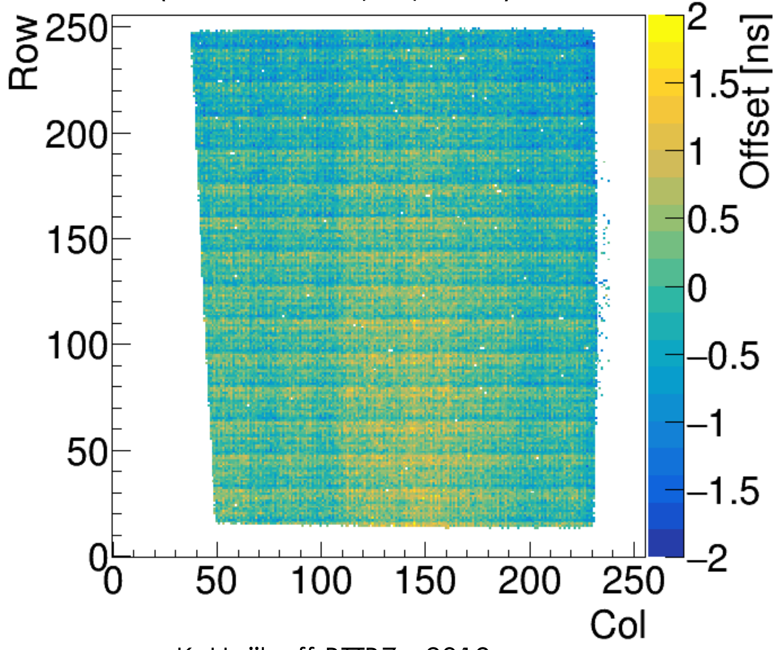


gain in number of operations
interpolations (seeding)
Δα comparison (extension)
LHCb Velo
Very preliminary
Gain ≡ #operations0 / #operations
efficiency
a = 55μm
time resolution (ps)

System wide implementation

- Pixel matrix variations affect the resolution.
- With better resolutions, per pixel corrections become more and more important.
- Telescope is based on 300 μm thick p-on-n sensors, which are not optimized for timing.

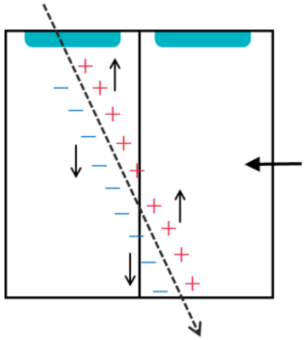
Mean time residual per pixel
(TPX3 telescope plane)

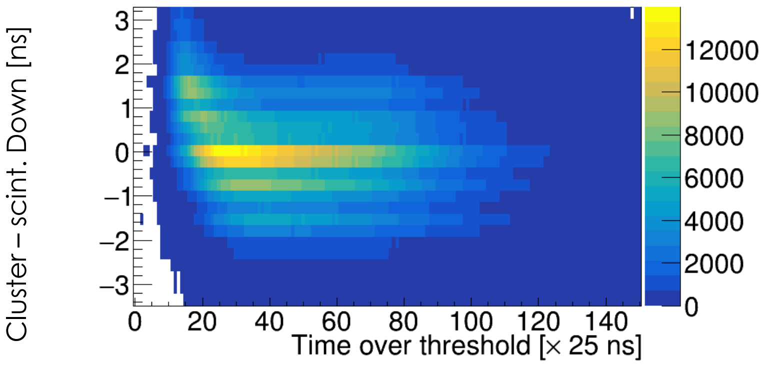


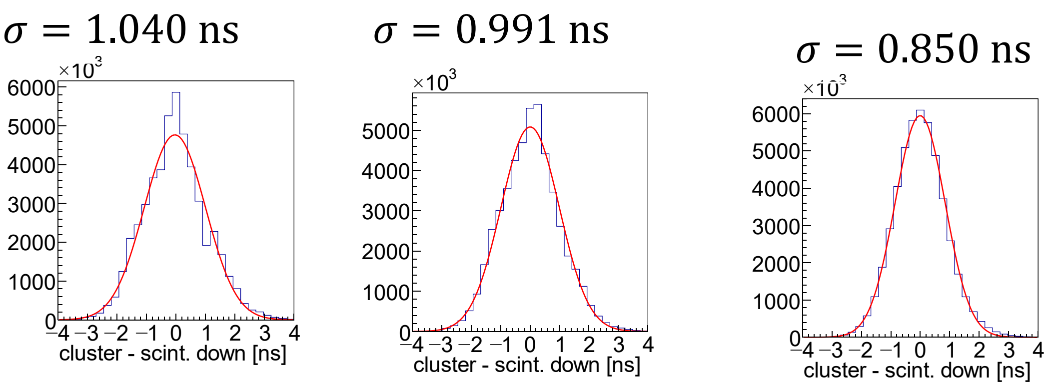
K. Heijhoff BTTB7 - 2019

Improving the timing

- Raw resolution
- Time walk compensation
- Pixel matrix systematics
- Track based drift time (coming soon)







K. Heijhoff Open Medipix meeting - may 2019

ASIC challenges

- Cope with increase in Radiation damage
- Analog front-end does not scale much -> about the same size as VeloPix/Timepix4 (25% of pixel)
- Cope with hit pile up:
  - @Upgrade I, MIP discharge time ~300 ns for 1% max pileup.
  - Upgrade II would need 10 times faster rate.
- Per pixel TDC with time resolution < 50 ps.
- More information in output and higher hit rate.
- Time-walk correction?
- Clock distribution effects?

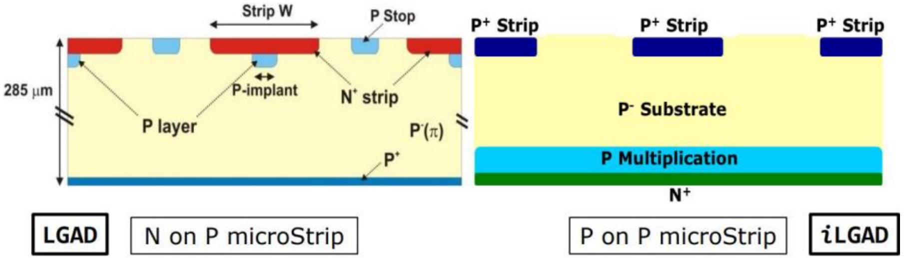
	VeloPix (2016)	Timepix4 (2019)	Velopix2 (202?)
technology	130 nm	65 nm	**28 nm**
Pixel size	55x55 μm^2	55x55 μm^2	**55x55 μm^2**
Sensitive area	2 cm^2	7 cm^2	**2 cm^2?**
Packet size	24 bit	64 bit	**64 bit?**
Max rate	400 Mhits/cm^2/s	180 Mhits/cm^2/s	**4000 Mhits/cm^2/s**
Time resolution	25 ns	200 ps	**20-50 ps?**
Output data rate	20 Gb/s	81 Gb/s	**500 Gb/s?**

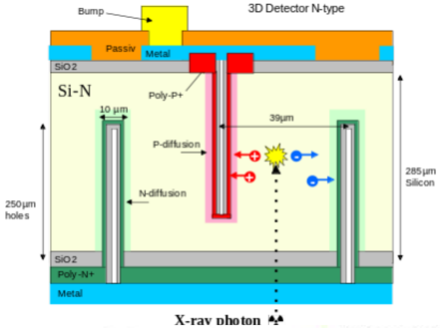
- Fruitful collaboration with the Medipix group has yielded the VeloPix ASIC for the LHCb Upgrade I.
- the Timepix4, with impressive fast timing capabilities is scheduled to appear soon.
- LHCb Upgrade II requirements more demanding still but could draw on similar concepts

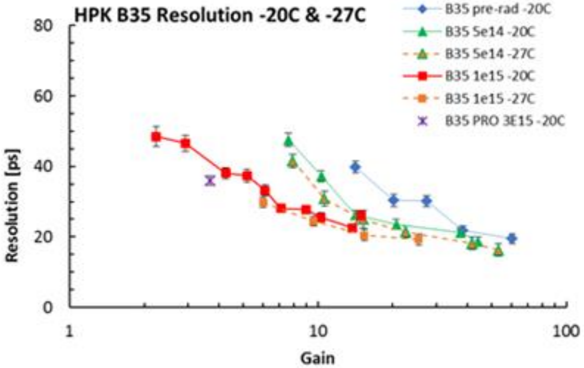
Sensors

- Sensor R&D considering:
  - Thin planar
  - LGAD and iLGAD
  - 3D concepts
- Starting an evaluation programme using Timepix4 as a prototype FE.

- Final temporal resolution under consideration between 20 and 200 ps per hit.
- Many manufacturers shown prototypes: CNM, FBK, HPK…



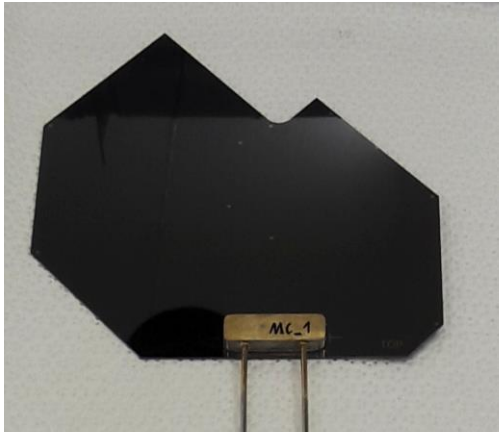




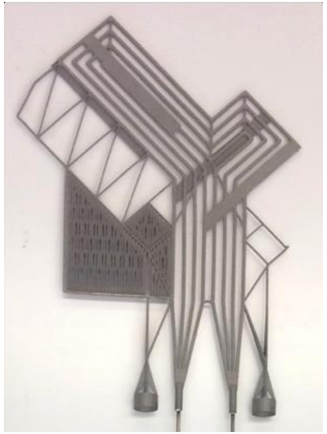
Cooling for next upgrade

- Operation in vacuum demands active cooling.
- Microchannel approach could be too complex if a replacement is planned.
- Studying the possibility to operate at lower temperatures < -30°C
  - Avoid runaway at high radiation damage
  - Mobility gets better at low temperatures
  - Requires the R&D of different cooling fluids…

General needs: lightweight, possibly partially replaceable modules and mechanics



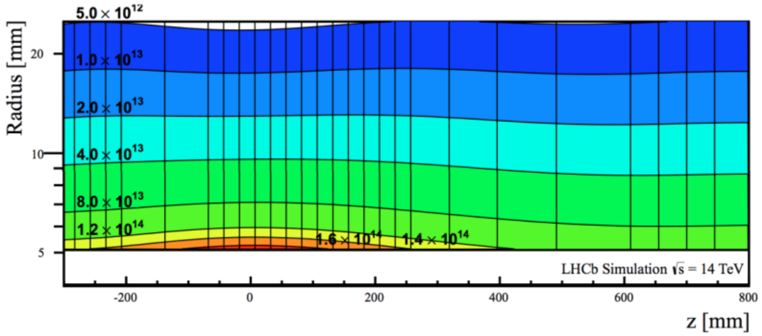
Micro channels could get cheaper

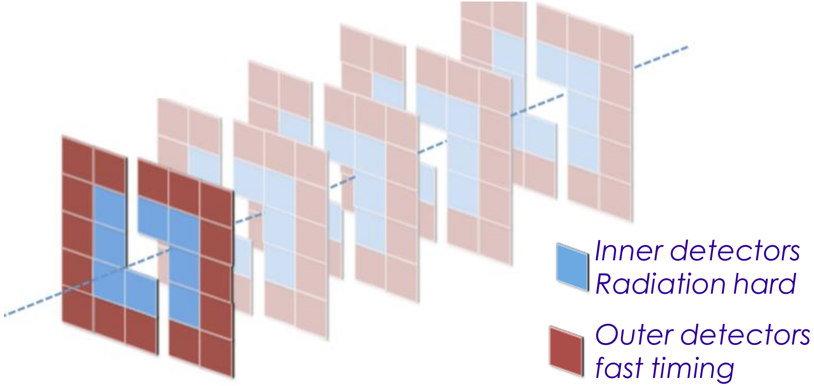


3d printed Titanium substrates, already prototyped for Upgrade I

Design considerations – Radiation

- At 5 mm, fluence translates to : 1.6×10^{14} 1MeV n_{eq}/fb. after 300/fb➔ $\sim 5 \times 10^{16}$ n_{eq}
- Very challenging constraint for fast timing devices.
- A dual technology system could combine radiation hardness at the inner part and timing resolution at the outer region.
- Planning for a replacement could allow a less resistant sensor technology.





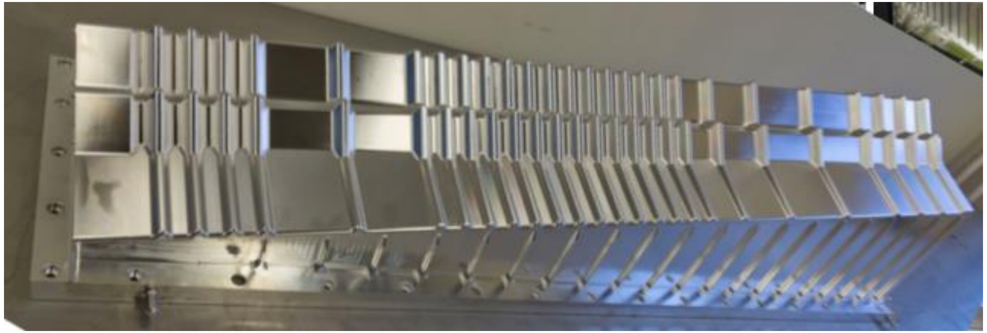
Possible design with 2 technologies: outer sensors with better timing but lower radiation resistance.

Considerations for the trigger

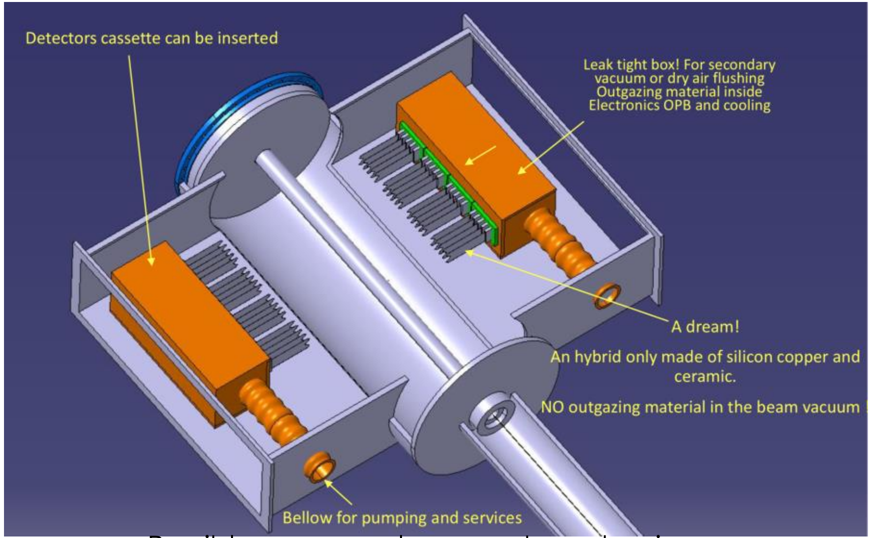
- VELO is an essential part of trigger decision.
  - Highest granularity, secondary vertices search, real time candidates.
  - Time measurement can provide input info (t_0) to other sub detectors
- VELO data must be processed **quickly**
  - Clustering might need to be done at the ASIC or in FPGAs.
  - Time ordering is needed in the further processing (time consuming).
- Could use time stamps to suppress tracks unrelated to the triggered candidate ➔ *clean up the event*.
  - Need to prove that association across subdetectors is possible.

Mechanics

- RF box construction is a very complex and demanding procedure.
- No foil would be ideal design.
- Issues:
  - Outgassing detectors.
  - Harmful wakefield
  - Beam mirror current.
- Construction without a foil also makes more difficult to replace detectors.



RF+Vacuum Box milled out from an Aluminium block.
Very complex and demanding procedure.



Possible sensor replacement mechanism

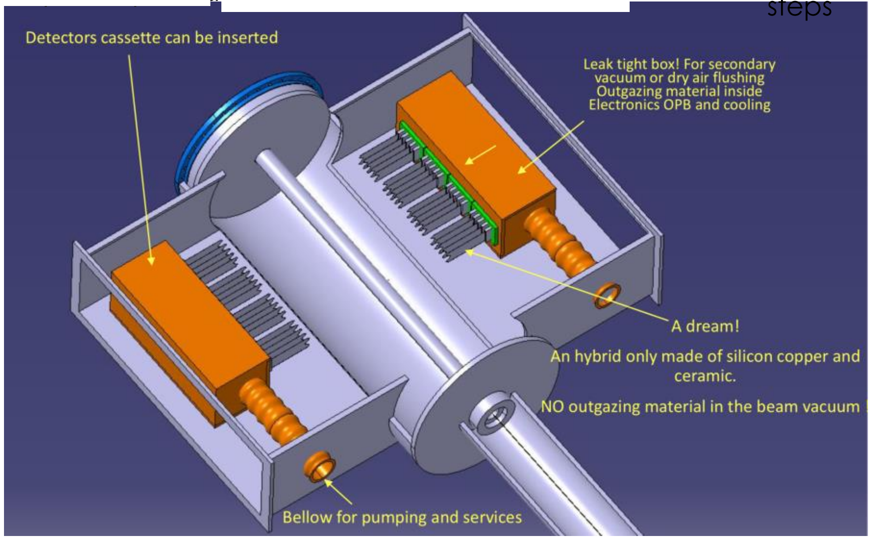
Mechanics

- RF box construction is a ve
  complex and demanding procedure.
- **No foil** would be the ideal design.
- Issues:
  - Outgassing detectors.
  - Harmful wakefield
  - Beam impedance.
- Construction without a foil also makes more difficult to replace detectors.

Initial solid forged Al alloy block

>98% of material removed

Internal mould support during machining steps



Possible sensor replacement mechanism

Summary

- LHCb is building and installing a whole new detector. NOW.
- We are also planning a next upgrade to run at up to **10 times higher** instantaneous luminosity.
- The high Primary Vertex density motivates a Vertex detector with **high resolution timing**.
- The **Secondary Vertex** reconstruction and **association** to its origin **PV** require precise Impact Parameter. Fast timing can allow this matching at the high pile up regime.
- Fast timing shows promising results in the **pattern recognition** as well.
- An ultra **high radiation** resistant **sensor** and **ASIC** technology is required to operate through the whole lifetime.
- Alternatively a suitable **replacement strategy** drives mechanical technology R&D.

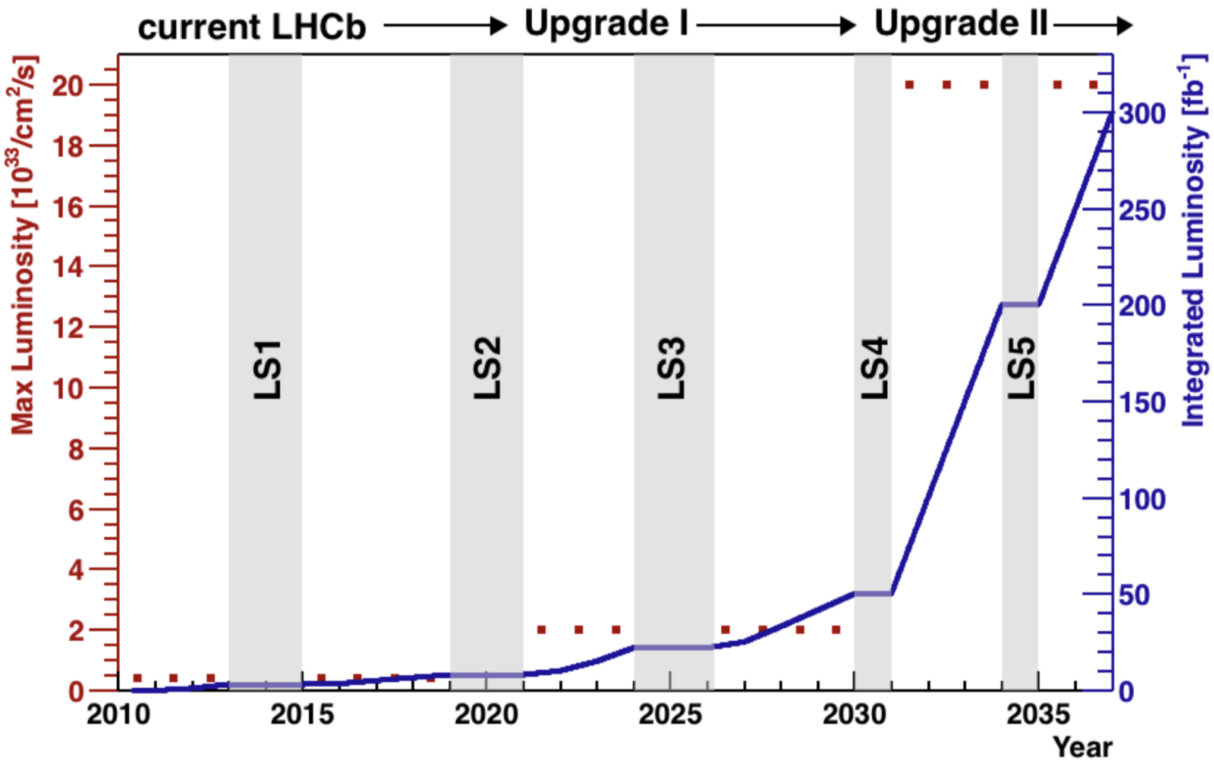
Thanks


LOOK AT THIS! THIS IS THE BIGGEST LUMINOSITY IN THE WORLD!
HA HA! I CAN'T WAIT TO TAKE DATA WITH IT!
HOW ABOUT THE RADIATION DAMAGE?
REALITY CONTINUES TO RUIN MY LIFE.
MAYBE YOU COULD PLACE YOUR DETECTOR A BIT FURTHER FROM IT

Back up

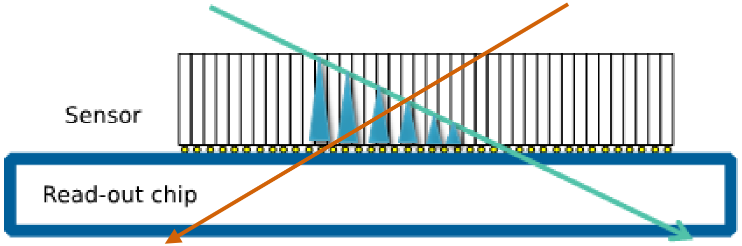
First test beam with final modules in 2006

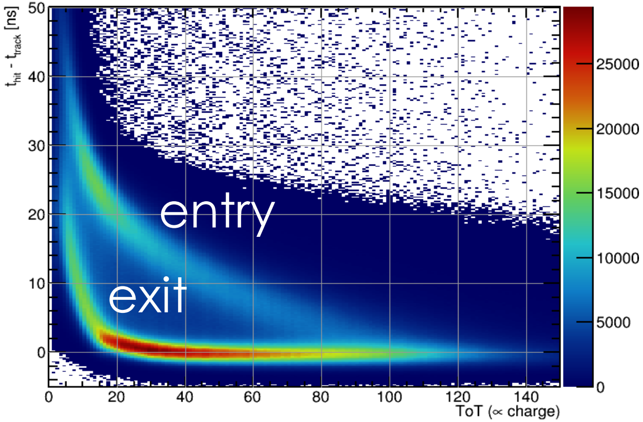
Luminosity ambitions Upgrade II



Timing experience: Timepix3

- Timepix3 telescope experience shows that "4D" tracking is the way forward.
- The telescope shows virtually no ghost track in the 10 ns window used in the reconstruction.
- Possible to calculate the slope inside the ASIC in a cluster: every cluster would be also a stub.

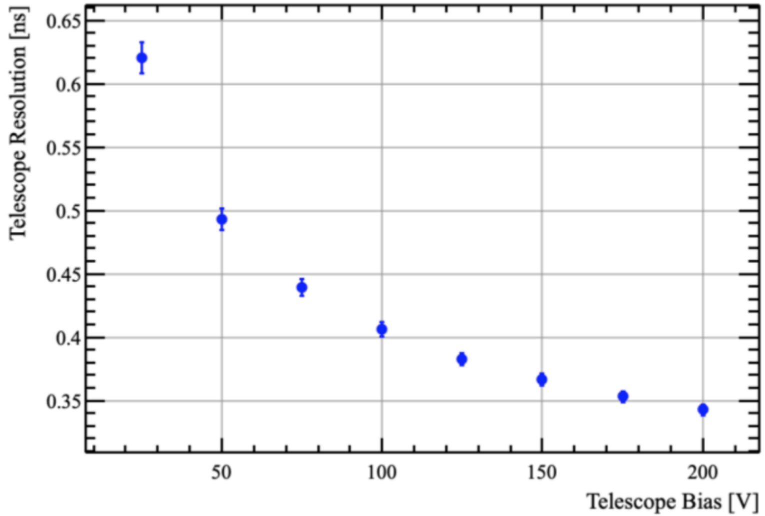




Timepix3 Telescope

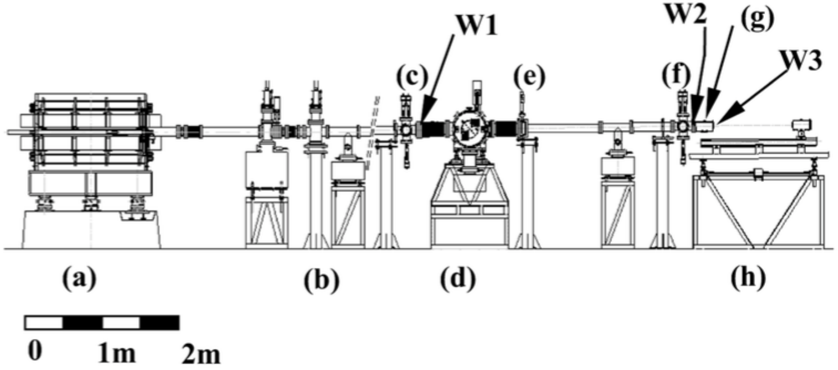
System-wide implementation

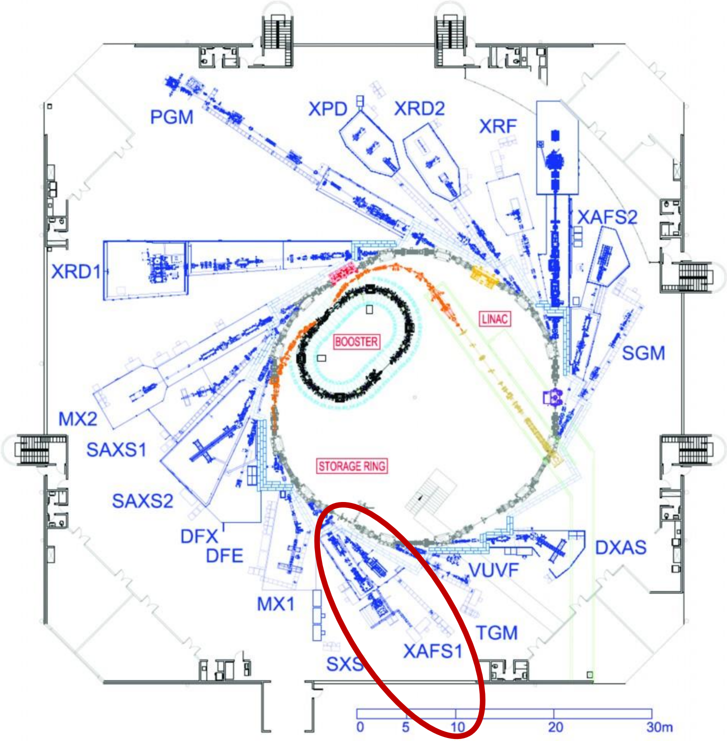
- Precise **hit timing** over several planes has been used in the **Timepix3 (1.56 ns TDC)** Telescope for pattern recognition and for **track time** measurement.
- Sensors were not optimized for time resolution ➔ results can still be improved.
- We are investigating new sensors for more precise timing.
- Track reconstruction is clean and **time resolution** from the combination of planes is compatible with combination of independent measurements.



Time resolution determined internally, only with the telescope planes and also with scintillators.

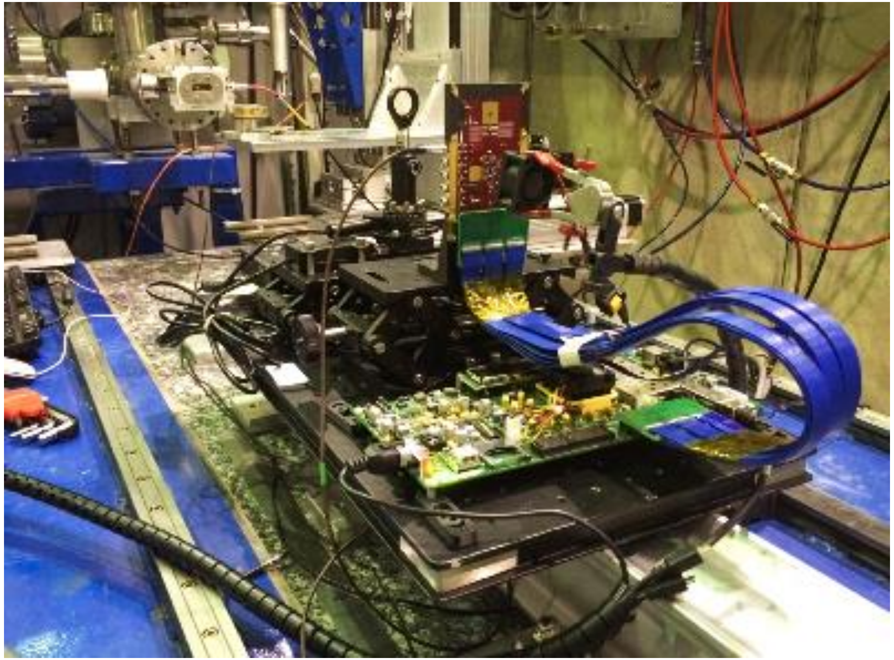
Charge calibration: LNLS*/Campinas

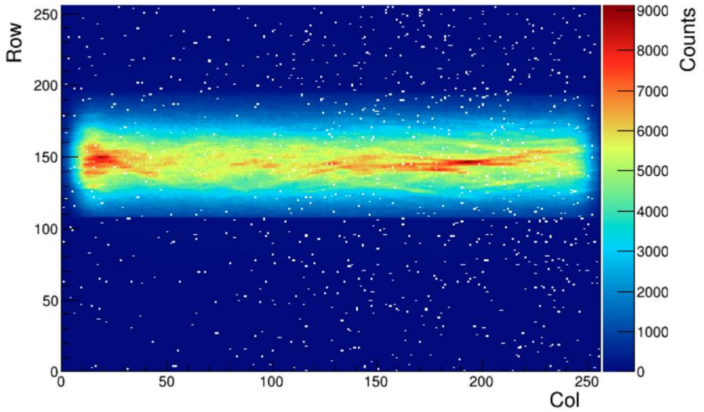


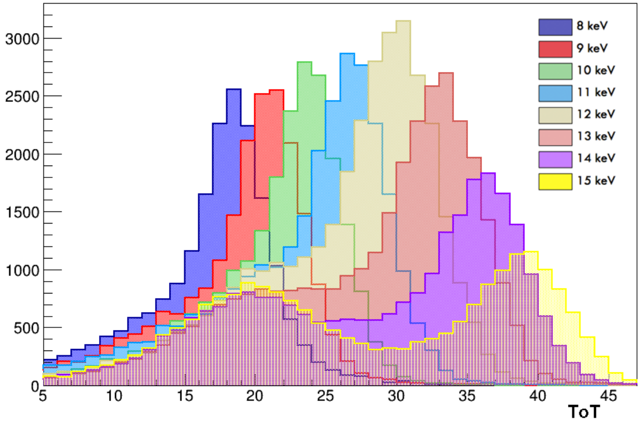


XAFS1 - X-ray Absorption and Fluorescence Spectroscopy
4 to 24 keV photons with $\sigma E/E \sim 0.01\%$.

Charge calibration: LNLS*/Campinas

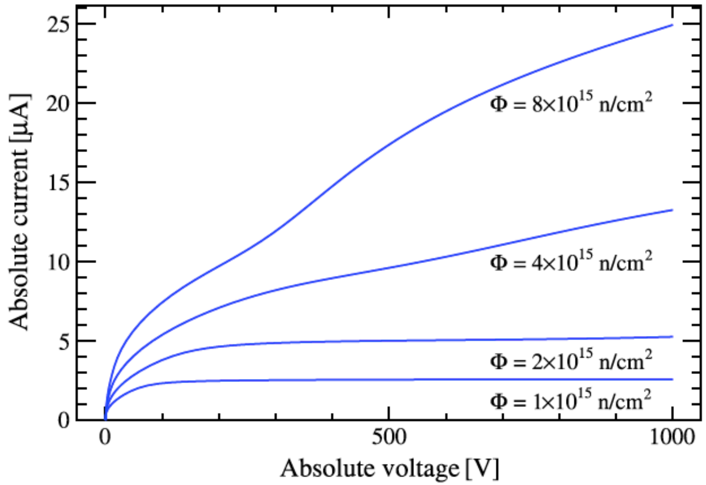


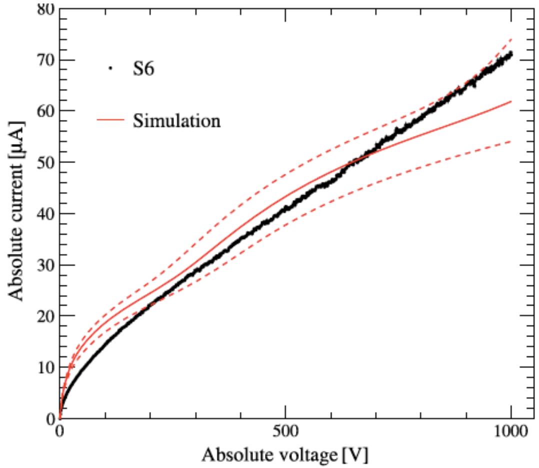




IV Model

- Current generated due to avalanche in the sensor.
- Avalanche is proportional to the radiation damage.
- (Shot noise increases with temperature and induces breakdown)*
- Related to the charge multiplication





Motivations for Upgrade II

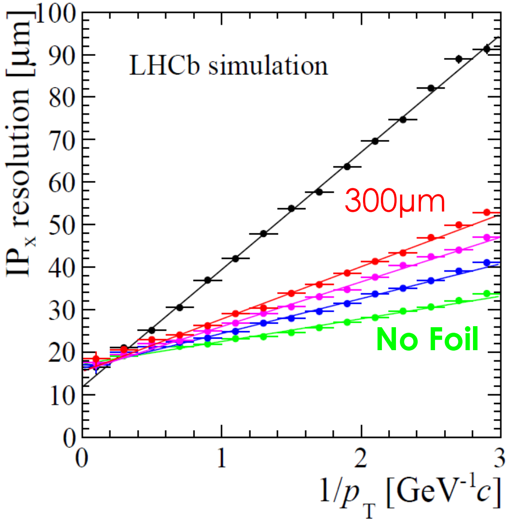
Many channels will still be statistically limited by the end of Runs 3 and 4.

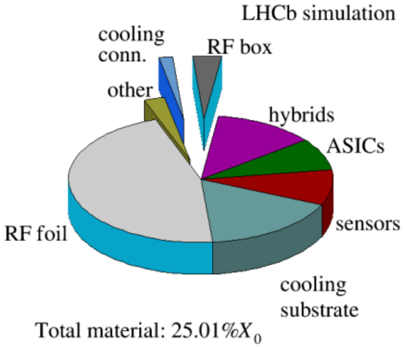
LHCb has no competitor in many decay channels.

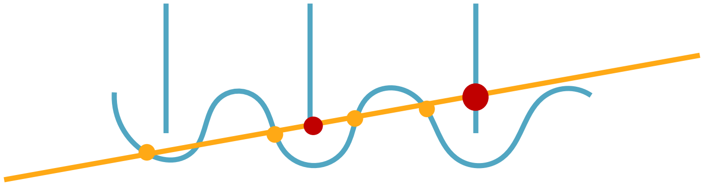
Observable	Current LHCb	LHCb 2025	Belle II	Upgrade II
EW Penguins				
R_K $(1 < q^2 < 6\,\mathrm{GeV}^2c^4)$	0.1 [274]	0.025	0.036	0.007
R_{K^*} $(1 < q^2 < 6\,\mathrm{GeV}^2c^4)$	0.1 [275]	0.031	0.032	0.008
R_ϕ, R_{pK}, R_π	–	0.08, 0.06, 0.18	–	0.02, 0.02, 0.05
CKM tests				
γ, with $B_s^0 \to D_s^+ K^-$	$(^{+17}_{-22})^\circ$ [136]	4°	–	1°
γ, all modes	$(^{+5.0}_{-5.8})^\circ$ [167]	1.5°	1.5°	0.35°
$\sin 2\beta$, with $B^0 \to J/\psi K_S^0$	0.04 [609]	0.011	0.005	0.003
ϕ_s, with $B_s^0 \to J/\psi\phi$	49 mrad [44]	14 mrad	–	4 mrad
ϕ_s, with $B_s^0 \to D_s^+ D_s^-$	170 mrad [49]	35 mrad	–	9 mrad
$\phi_s^{s\bar{s}s}$, with $B_s^0 \to \phi\phi$	154 mrad [94]	39 mrad	–	11 mrad
a_{sl}^s	33×10^{-4} [211]	10×10^{-4}	–	3×10^{-4}
$\lvert V_{ub}\rvert/\lvert V_{cb}\rvert$	6% [201]	3%	1%	1%
$\boldsymbol{B_s^0, B^0 \to \mu^+\mu^-}$				
$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	90% [264]	34%	–	10%
$\tau_{B_s^0 \to \mu^+\mu^-}$	22% [264]	8%	–	2%
$S_{\mu\mu}$	–	–	–	0.2
$\boldsymbol{b \to c\ell^-\bar{\nu}_l}$ **LUV studies**				
$R(D^*)$	0.026 [215, 217]	0.0072	0.005	0.002
$R(J/\psi)$	0.24 [220]	0.071	–	0.02

Foil

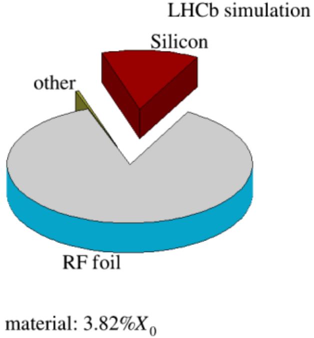
- Separation from primary LHC vacuum introduces material which degrades the IP performance
  - physics performance benefits from no foil.







Corrugations needed to minimize material.



Foil is the biggest contribution before second hit