31st International Workshop on VERTEX Detectors

Tateyama Japan, 24 – 28 October 2022

An LHCb Vertex Locater (VELO) for 2030s

Evangelos – Leonidas Gkougkousis (CERN)

ON BEHALF OF THE LHCb COLLABORATION

Tateyama Resort Hotel – October 27th, 2022

•Overview

Introduction

- ✓ The LHCb Experiment @ LHC
- ✓ HL-LHC timescale and planning
- ✓ Physics at Run 4 and beyond
- ✓ Run 4 Conditions

Velo @ Run 5

- ✓ Timing Options
- ✓ Towards a 4D tracker
- ✓ X_0, Φ_{eq} and σ_{HIT} – A delicate balance

Sensor R & D

- ✓ Silicon Technologies
- ✓ Timing with LGADs and 3Ds

ASIC Development

- ✓ Requirements & Limits
- ✓ ASIC Generations

RF Shield

- ✓ Wake field suppression manifold

Cooling

- ✓ 3D and microchannel implementations

Vacuum tank

- ✓ Vacuum separation considerations

Conclusions

- ✓ R&D and timeline

• Related Talks

LHCb Upgrade I & II, ASICs

LHCb Upgrade I

- ➢ Valeriia Lukashenko – Monday October 24th

  “The Vertex Locator at LHCb Upgrade I”

  https://indico.cern.ch/event/1140707/contributions/5036353/

- ➢ Dimitra Andreou – Monday October 24th
  “Status of the Upstream Tracker”
  https://indico.cern.ch/event/1140707/contributions/5052643/

VELO Upgrade II workshop
6 - 8 February 2023

LHCb Upgrade II

- ➢ Ryunosuke O'Neil – Tuesday October 25th

  “HV-MAPS for the LHCb Upgrade II Mighty Tracker”

  https://indico.cern.ch/event/1140707/contributions/5086206/

ASICs

- ➢ Adriano Lai – Thursday October 27th

  “TimeSPOT results on sensors and electronics and future perspectives”

  https://indico.cern.ch/event/1140707/contributions/5031145/

- ➢ Kevin Heijhoff – Thursday October 27th

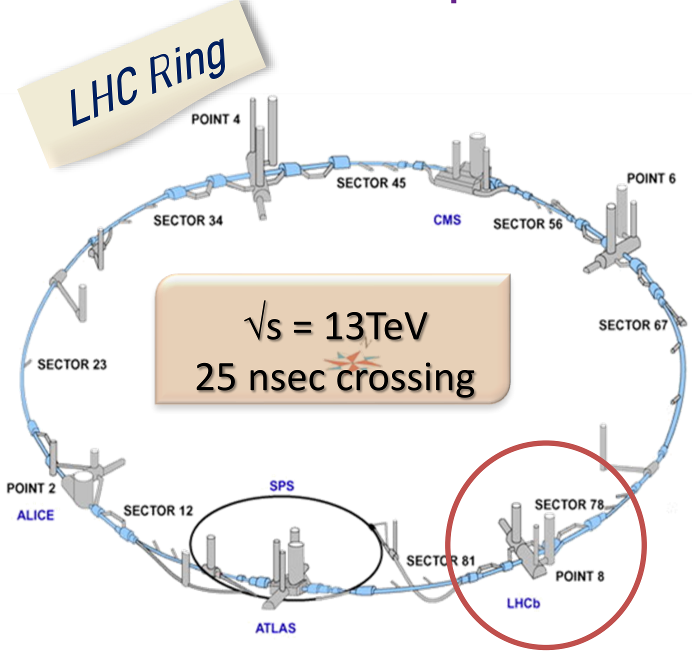
  “Timepix4 timing performance and first beam test results”

  https://indico.cern.ch/event/1140707/contributions/5041530/

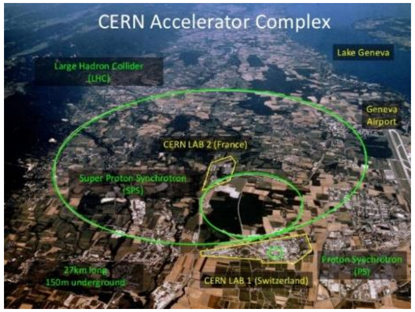
• Introduction

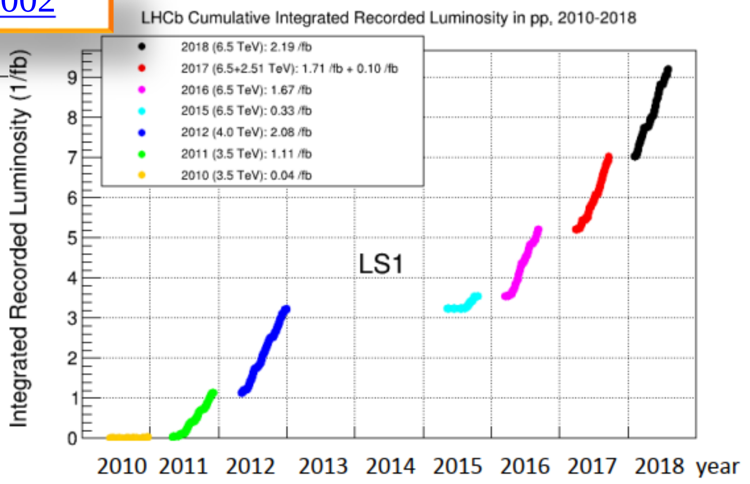
Pub. Note: [LHCb-DP-2014-002]

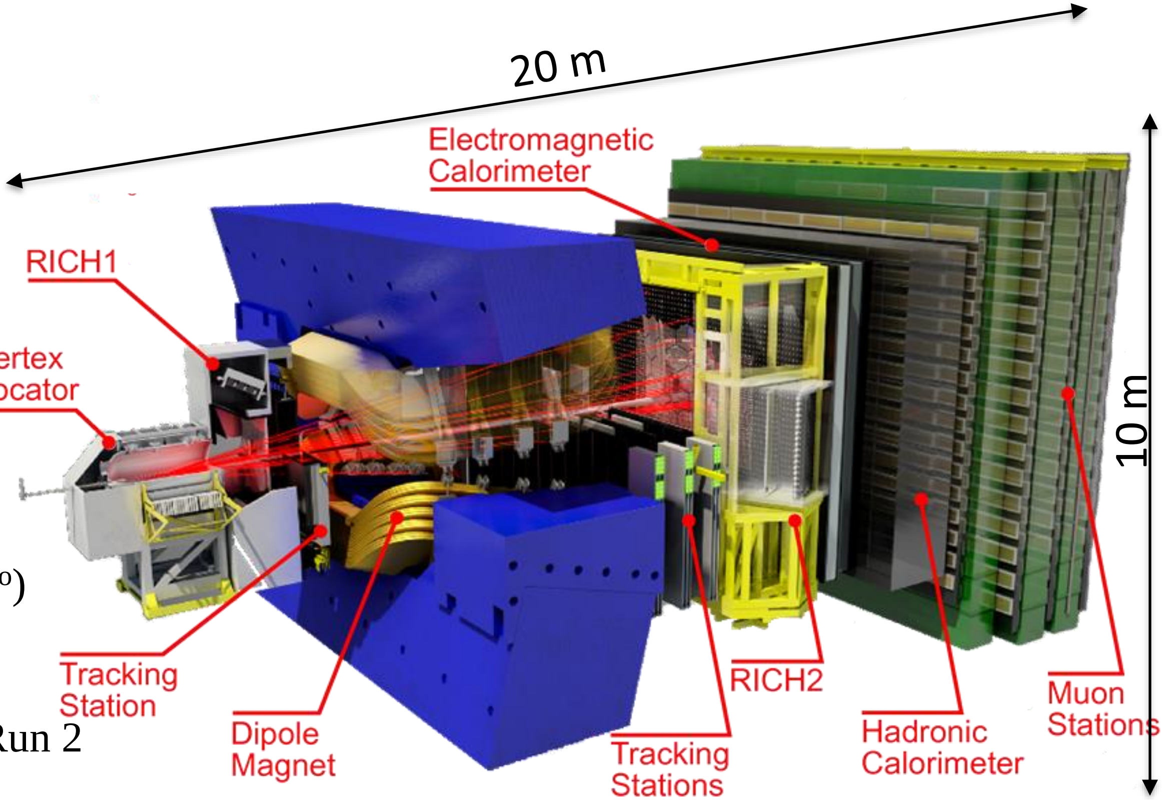
The LHCb Experiment



√s = 13TeV
25 nsec crossing







LHC beauty

General purpose forward spectrometer optimized for high precision heavy flavor

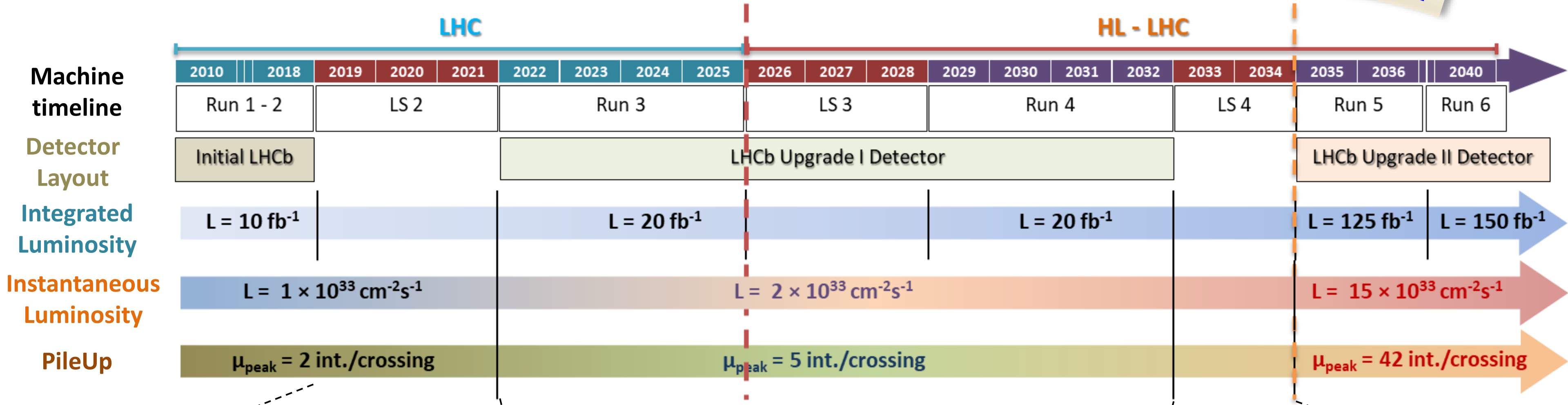
- Coverage: $2 < \eta < 5$ (0.86° – 17.2°)
- 1.05 T – 10 m dipole magnet
- $\Delta p/p = 0.5\ \%$ @ < 20 GeV

✓ ~ 10 fb^{-1} integrated luminosity end of Run 2

• Introduction

Towards HL-LHC

COVID Revised,
LHC schedule link



LHC
HL - LHC

Machine timeline
2010 | 2018 | 2019 | 2020 | 2021 | 2022 | 2023 | 2024 | 2025 | 2026 | 2027 | 2028 | 2029 | 2030 | 2031 | 2032 | 2033 | 2034 | 2035 | 2036 | 2040
Run 1 - 2 | LS 2 | Run 3 | LS 3 | Run 4 | LS 4 | Run 5 | Run 6

Detector Layout
Initial LHCb | LHCb Upgrade I Detector | LHCb Upgrade II Detector

Integrated Luminosity
L = 10 fb^{-1} | L = 20 fb^{-1} | L = 20 fb^{-1} | L = 125 fb^{-1} | L = 150 fb^{-1}

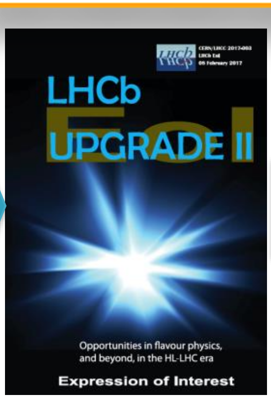
Instantaneous Luminosity
L = 1 × 10^{33} cm^{-2}s^{-1} | L = 2 × 10^{33} cm^{-2}s^{-1} | L = 15 × 10^{33} cm^{-2}s^{-1}

PileUp
μ_{peak} = 2 int./crossing | μ_{peak} = 5 int./crossing | μ_{peak} = 42 int./crossing

Phase I upgrades

- ✓ Pixelated VELO at 5.1 mm from beam line, microplate CO$_2$ cooled
- ✓ Full 40 MHz software trigger and readout
- ✓ New silicon microstrip upstream tracker (UT)
- ✓ SciFi – Scintillating fiber tracker, 12 layers (4 stations)
- ✓ Upgraded RICH 1 & 2 stations

EoI: CERN-LHCC-2017-003



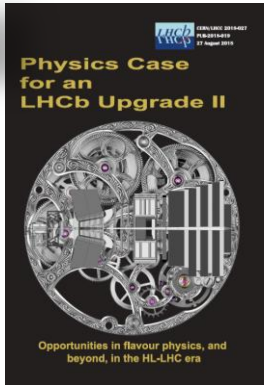
Framework TDR:
CERN-LHCC-2021-012

Phase II upgrades

- ✓ Fully 4D VELO with ~ 50 ps hit resolution
- ✓ HV-CMOS based MAPS sensors for UT
- ✓ Timing in both RICH and TORCH stations (70 ps)
- ✓ Timing @ECAL with increase special resolution

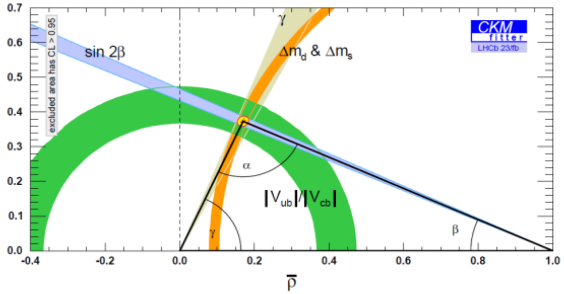
• Introduction

Pub Note: CERN-LHCC-2018-027

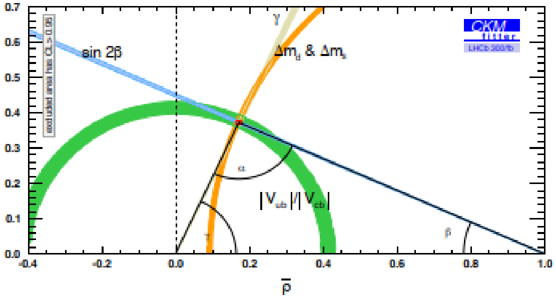


Physics Case

Current measurement



End of Run 6 (300 fb⁻¹)



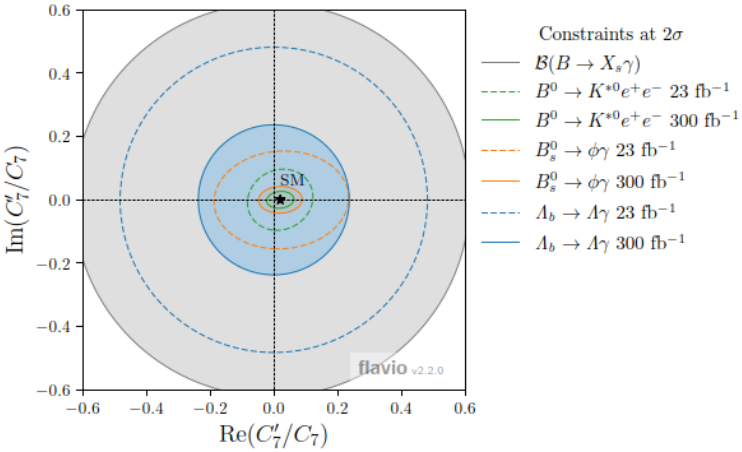
SM benchmarks – Unitarity triangle

- ✓ Precise benchmark of SM through apex of CKM unitarity triangle
- ✓ Allows tree level processes to be assessed against loop contributions
- ✓ Angle γ can be estimated with minimal theory uncertainties and tree level processes
- ✓ End of upgrade I precision (50 fb^{-1}) → 1°
  End of upgrade II precision (300 fb^{-1}) → 0.35°

Article: arXiv:2108.09283

Rare Decays

- ✓ Flavor changing transitions anomalies show hits of new physics (B anomalies – 1.5 σ SM deviation)
- ✓ Greater statistics allows precision measurement of branching rations and angular distributions

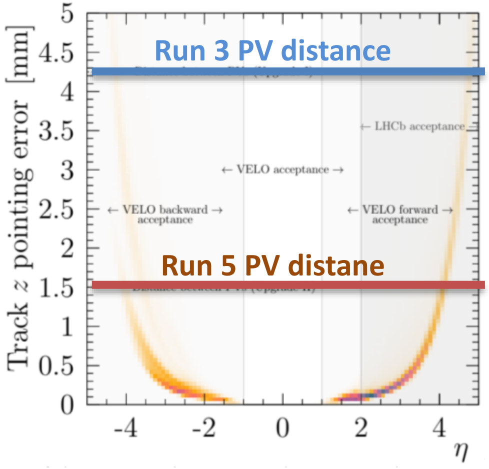


Observable	LHCb 2025	Upgrade II
$\frac{B_s^0, B^0 \to \mu^+\mu^-}{B(B^0 \to \mu^+\mu^-)/(B_s^0 \to \mu^+\mu^-)}$	34 %	10 %

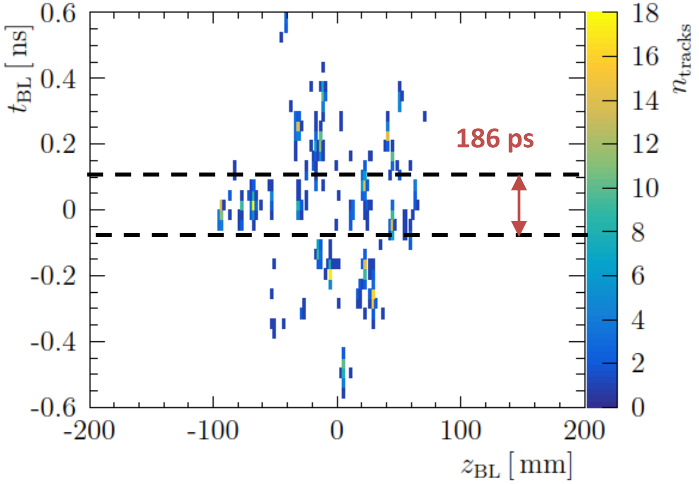
• Introduction

Run 4 Conditions I

VELO spatial Resolution

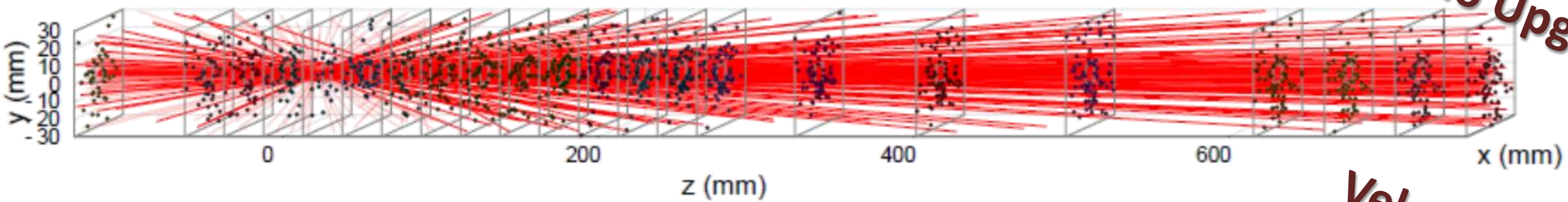


VELO PV Distribution (Run5)



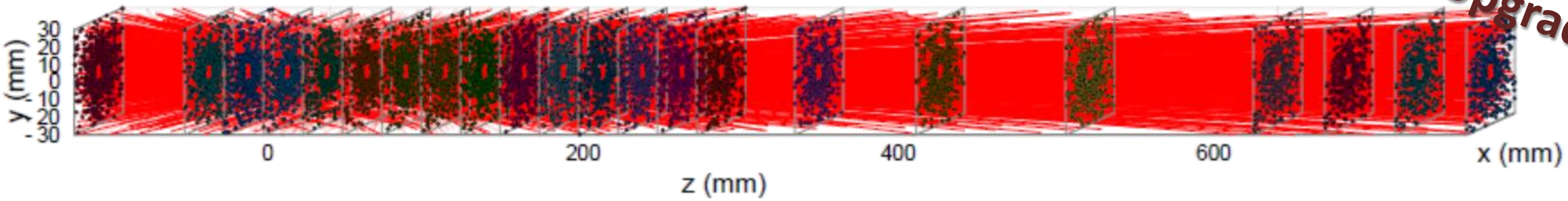
- ✓ High PileUp induces PV spatial separation of the same order as detector resolution → **PV unresolvable**
- ✓ PV RMS time distribution in the order of 186 ps (Gaussian)
- ✓ Using time information, PV reconstruction efficiency can be recovered
- ✓ Track reconstruction highly benefits from timing
- ✓ 20 ps track binning sufficient for recovering efficiency

PileUp 6



Velo Upgrade I

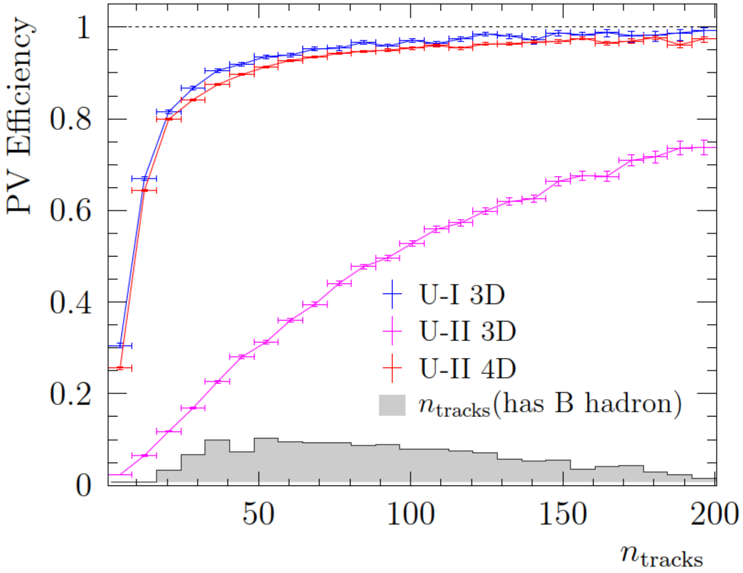
PileUp 42



Velo Upgrade II

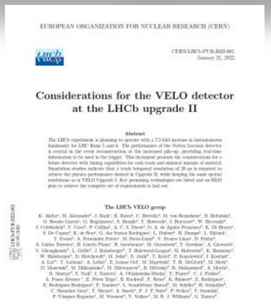
• Introduction

Run 4 Conditions II



- ✓ Timing essential to maintaining practically identical reconstruction efficiency as upgrade I at Run 5 conditions
- ✓ Needed for mitigating ghost track rejection
- ✓ Important for b-related analysis for the identification of the displace vertex
- ✓ Separate b-decays from primary vertices

Pub Note: CERN-LHCb-PUB-2022-01

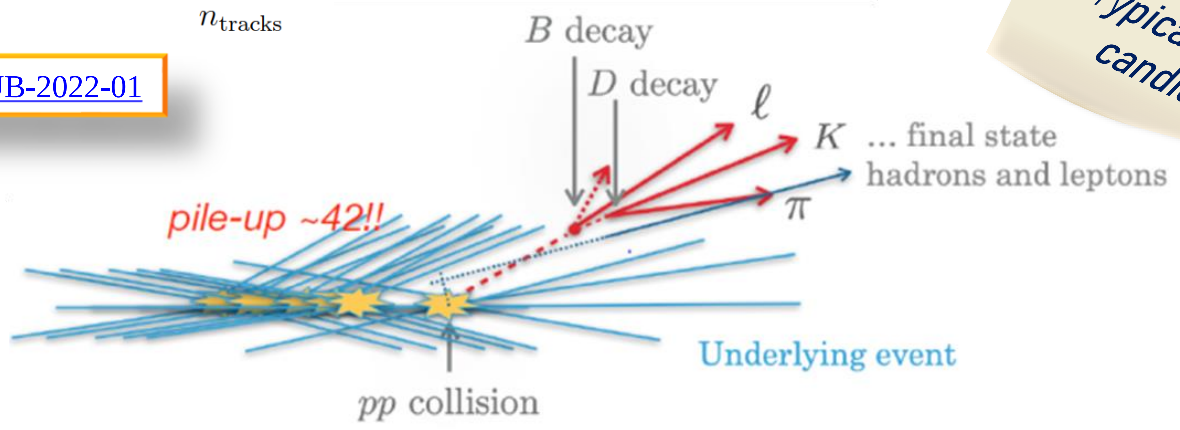


EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

CERN-LHCb-PUB-2022-001
January 21, 2022

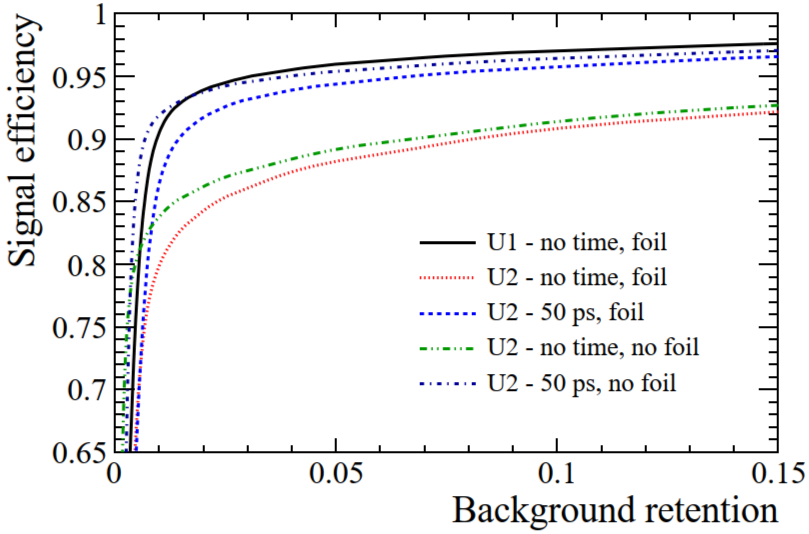
Considerations for the VELO detector at the LHCb upgrade II

Typical Event candidate



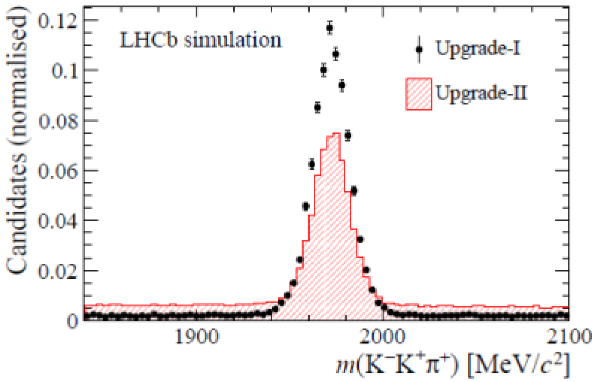
• Introduction

Run 4 Conditions

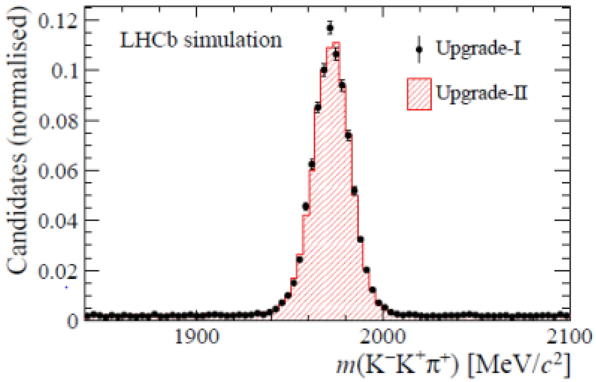


- ✓ LHCb is essentially a trigger experiment (on-line trigger lines for interesting decays)
- ✓ If events not recognized as belonging to one of the trigger lines, they are rejected with no recourse
- ✓ Very important to ensure trigger efficiency at high PileUp conditions
- ✓ Simulated studies using a simplified Kalman filter approach at $B_s^0 \to D_s^- \pi^+$ events
- ✓ Efficiency is recovered to 90% for an IP > 0.1 mm with the addition of timing

no time information

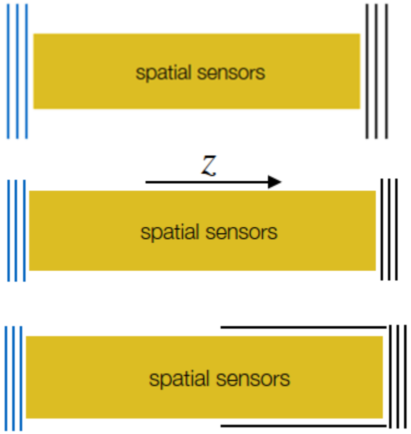


20 ps timing



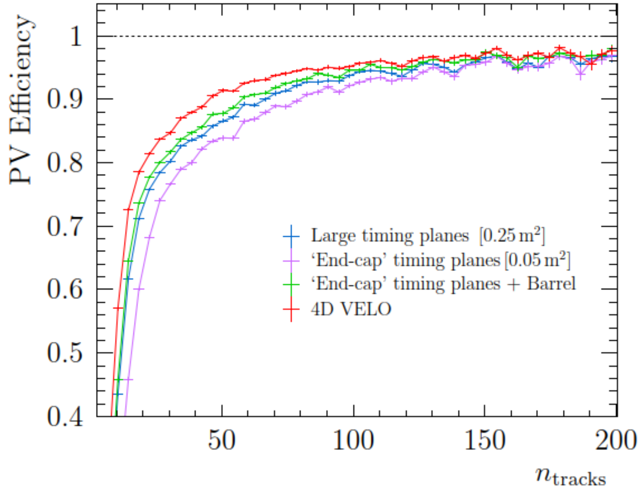
• Velo @ Run 5

Evaluated Options

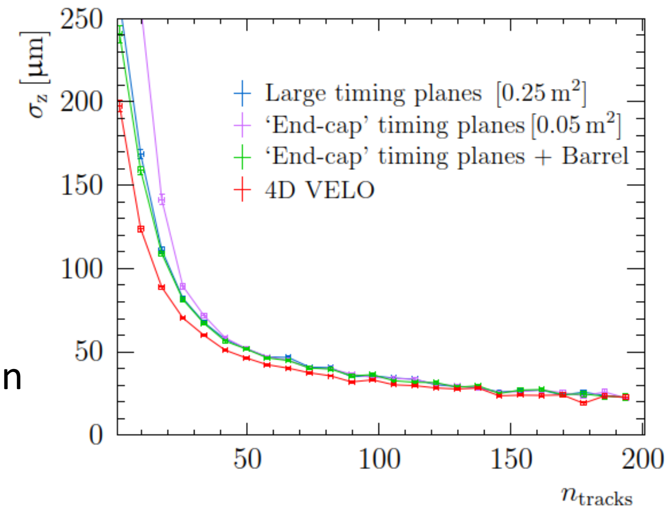


Timing planes + tracking option

- At least three layers required for outlier rejection & combinatorics
- Single hit resolution requirement at 25 ps
- Dispersion due to different particle momenta
- 100 µm pixel to maintain occupancy



	Upgrade I	Large Planes	Endcaps	Endcaps + Barrel
Covered range	2 ≤ η ≤ 5	2 ≤ η ≤ 5	2.8 ≤ η ≤ 5	2 ≤ η ≤ 5
Additional area [m^2]	0.1	0.25	0.05	0.4

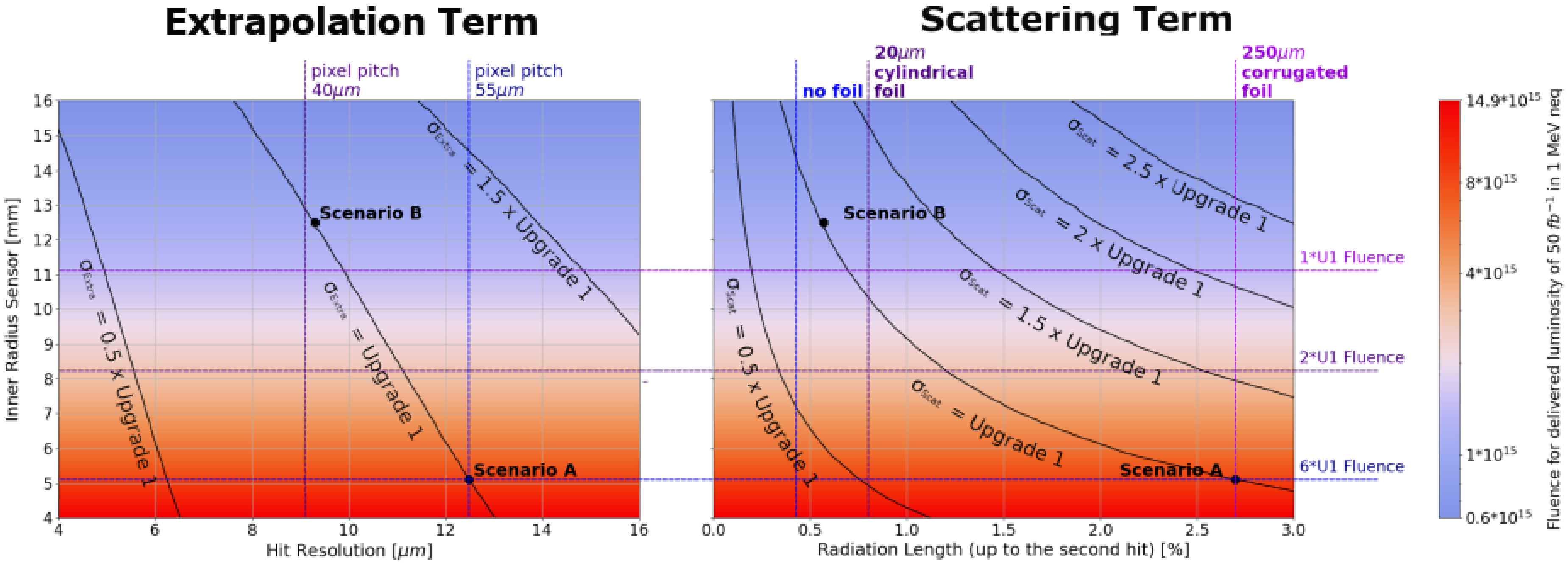


Full 4D VELO option

- Single hit resolution at 50 ps
- Better efficiency in pattern recognition and vertex reconstruction
- Lower cost with respect to discrete timing solution:
  - Single sensor technology and ASIC
  - Less computing power due to higher efficiency in PV reconstruction

• Velo @ Run 5

X_0, Φ_{eq} and σ_{HIT} – A delicate balance



Extrapolation Term

Scattering Term

- IP resolution: $\sigma_{\text{IP}} = \sigma_{\text{extrap.}} \times \sigma_{\text{scatter}}$
- Calculation for tracks of |η|=3.5
- To keep radiation hardness to moderate levels (Scenario B):
  - Increase binary pixel resolution → **decrease quadratically electronics footprint**
  - Decrease material budget by a factor of ~5

It's a game of balance to find the "right" operational point

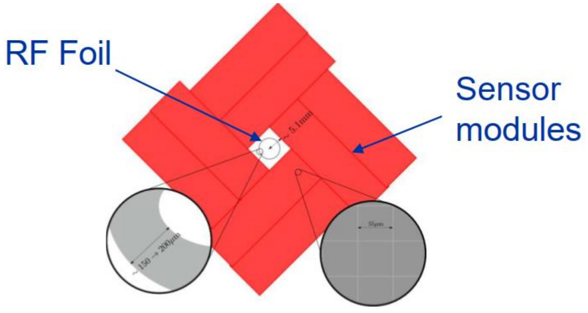
• Velo @ Run 5

Full-on trimming VELO

Two different layout scenarios as baseline for optimization:

Scenario A (S_A)

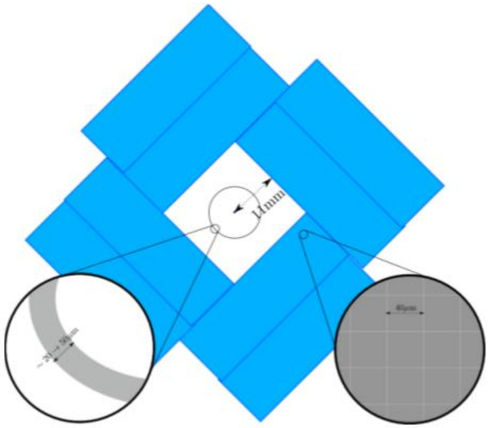
- Closest pixel to beamline: 5.1 mm
- ~ 9 × Upgrade I Hit Rate (350 kHz)
- Pixel size can remain at 55 × 55 μm^2
- Highly Radiation hard Silicon (sensors/ASIC) and/or frequent replacement
- 5 × radiation damage with respect to UI (6×10^{16} n_{eq}/cm^2)



Sketch of a Scenario A using the current sensor modules

Scenario B (S_B)

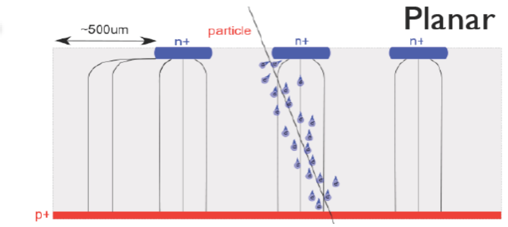
- Closest pixel to beamline: 12.5 mm
- Same Hit Rate as Upgrade I (40 kHz)
- Pixel size < 42 × 42 µm
- Same radiation damage with respect to UI (8×10^{15} n_{eq}/cm^2)
- Material budget to be reduced by a factor of ~5 before second hit (no RF foil?)

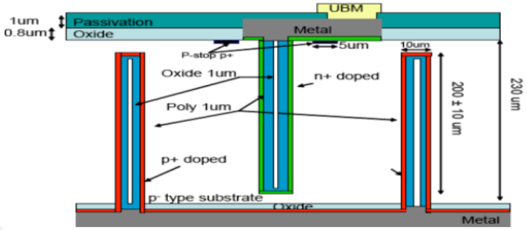


• Sensor R&D

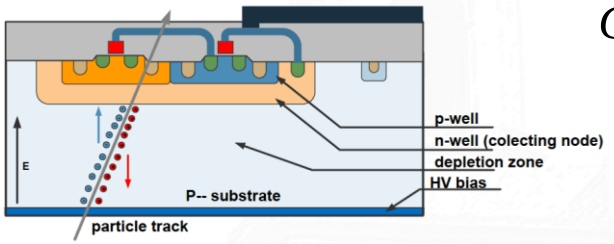
Silicon Technologies

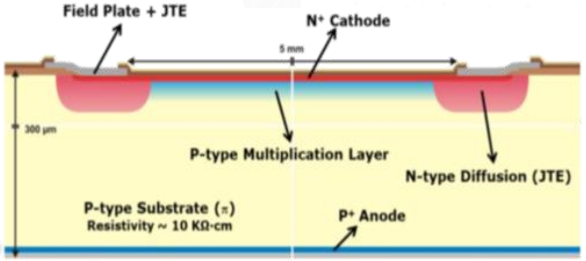
No charge amplification





Charge amplification





Planar Pixels

- ✓ Uniform weighting field → low sensor induced jitter
- ✓ Charge generation & collection time propositional to thickness
- ✓ Low SNR, high power dissipation at $\Phi > 10^{16}\ n_{eq}/cm^2$

3D pixels

- ✓ Decoupled charge generation and drift volumes
- ✓ Proven radiation hardness at $\Phi < 10^{16}\ n_{eq}/cm^2$
- ✓ Highly non-uniform field (+ gain, - jitter) with dead regions
- ✓ Higher capacitance and expensive process

CMOS Sensors

- ✓ Integrated electronics, lower production cost (industrial process)
- ✓ Low capacitance → resolutions of ~50 ps (noise scales ~ C)
- ✓ Typically, thin depletion layers → lower signal
- ✓ Moderate radiation hardness, proven up to $\sim 10^{15} n_{eq}/cm^2$

Low Gain Avalanche Diodes (LGAD)

- ✓ Signal amplification with intrinsic gain (double junction)
- ✓ High SNR and lower capacitance with 50 μm substrate
- ✓ Carbon and deep-implanted LGADs radiation hard up to ~ $3 - 4 \times 10^{15}\ n_{eq}/cm^2$
- ✓ Segmentation under investigation, Ti-LGADs & iLGADs

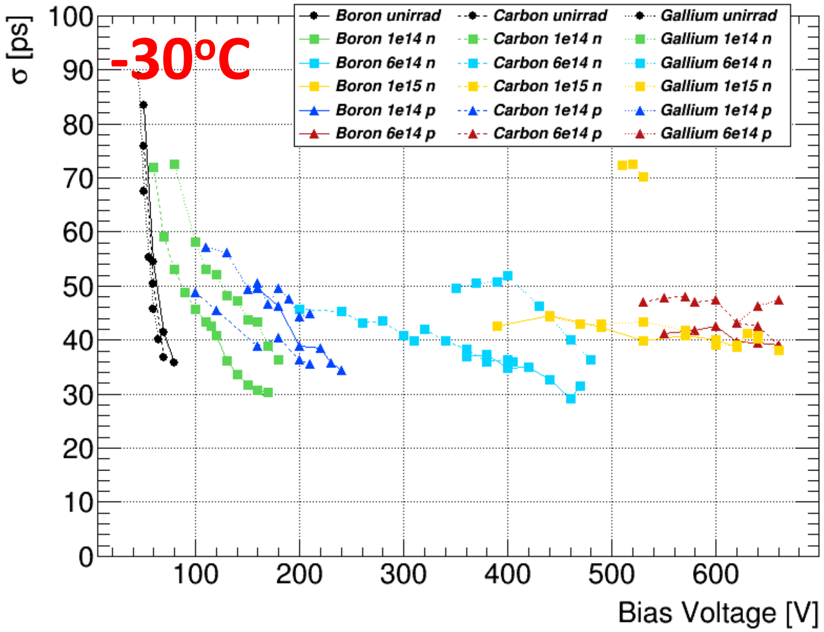
• Sensor R&D

Presentation: 16th Trento workshop

LGADs

Article: arXiv:2111.06731

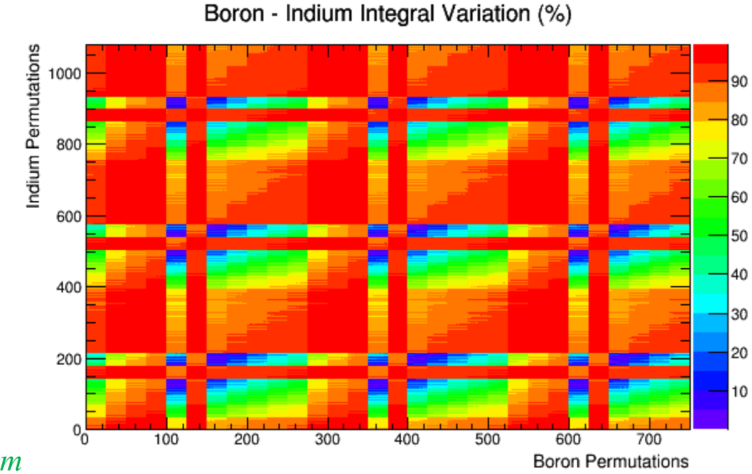
- ✓ Investigated different dopants to increase radiation hardness
- ✓ Ga, B gain layer and B + deep carbon implant studies under neutron and proton irradiation
- ✓ 20% improvement with deep carbon, 20% degradation with Ga devices



Time Resolution:

$$\sigma_{tot}^2 = \underbrace{\sigma_{timewalk}^2}_{\sigma_{Dist.}^2 + \sigma_{Landau}^2} + \underbrace{\sigma_{jitter}^2}_{\left(\frac{t_{rise}}{S/N}\right)^2} + \underbrace{\sigma_{conversion}^2}_{\left(\frac{TDC_{bin}}{\sqrt{12}}\right)^2} + \underbrace{\sigma_{Clock}^2}_{\text{Fixed Term} \sim 5\text{-}7\ psec}$$

- ✓ Radiation damage lead to acceptor removal though defect kinematics
- ✓ Modify gain layer implants to generate beneficial defects for gain (**gain regulation**):
  - **Lithium co-implantation:**
    - Boron with Lithium co-implantation demonstrates better neutron radiation hardness
  - **Replace Boron with Indium**
    - Indium higher mass and lower reaction cross-section expected to generated less O_i defect clusters
- ✓ Implantation energy and doping profiles already optimized via TCAD simulations

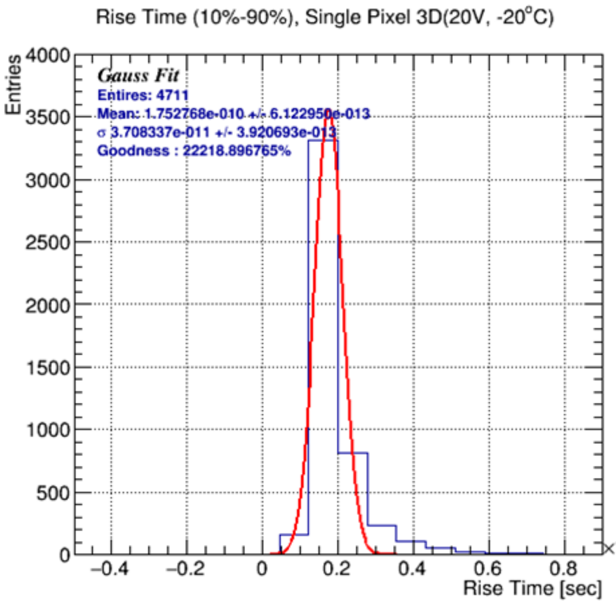


• Sensor R&D

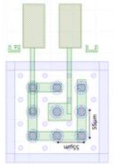
3D Pixel (Columns - Trenches)

Column design

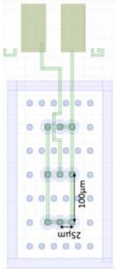
- ✓ Extremely sharp signals with very fast rise time (< 180 ps)
- ✓ Several geometries with 25 μm and 50 μm electrode distance
- ✓ Studies ongoing with pion beam at n/p irradiation fluences up to 1 × 10^{17} n_{eq}/cm^2
- ✓ Single- and double-sided processes



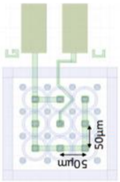
55 x 55 µm double



25 x 100 µm single



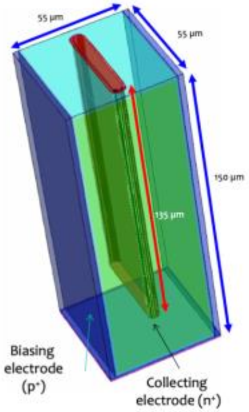
50 x 50 µm single



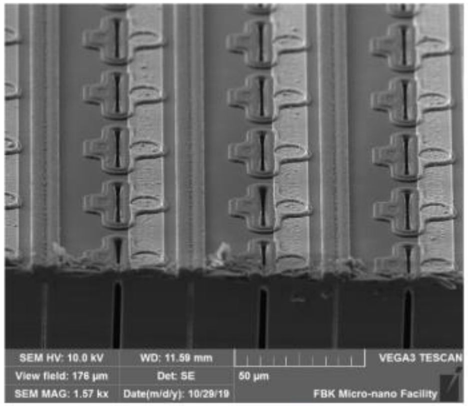
Trench design (TimeSpot)

- ✓ More uniform field than standard 3D
- ✓ Lower distortion term in σ_{tot}
- ✓ Intransigently higher capacitance and larger inefficient regions due to tranches
- ✓ New process under development with very promising results
- ✓ Radiation studies to be performed, expecting similar results as for standard 3Ds

Presentation: [TimeSpot]



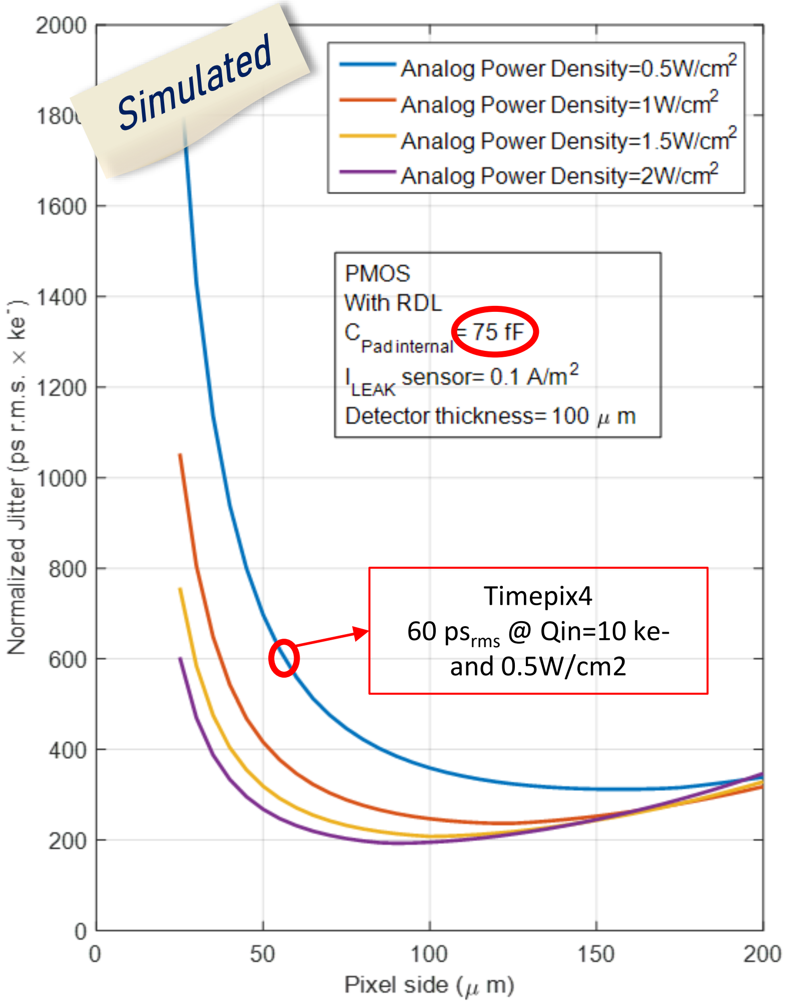
A



B

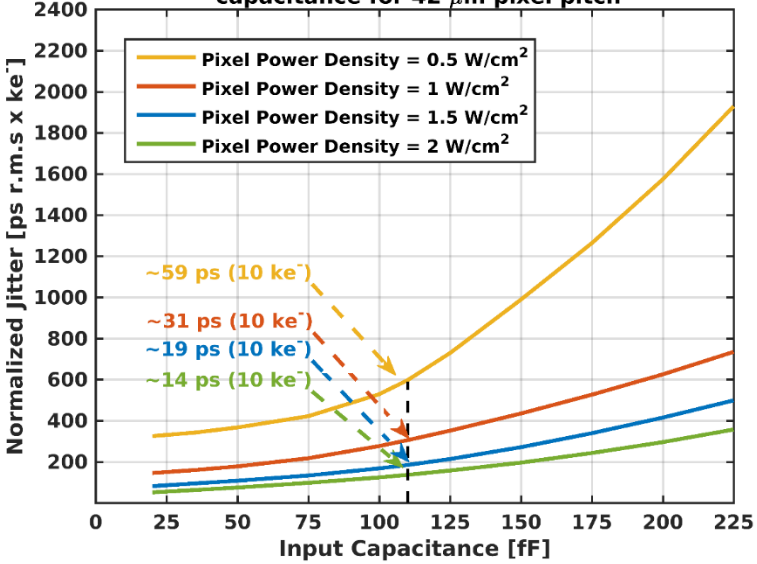
• ASIC Development

Requirements & Limits



Requirement	scenario S_A	scenario S_B
Pixel pitch [μm]	≤55	≤42
Matrix size	256×256	335×335
Time resolution RMS [ps]	≤ 30	≤ 30
Loss of hits [%]	≤ 1	≤ 1
TID lifetime [MGy]	> 24	> 3
ToT resolution/range [bits]	6	8
Max latency, BXID range [bits]	9	9
Power budget [W/cm^2]	1.5	1.5
Power per pixel [μW]	23	14
Threshold level [e$^-$]	≤ 500	≤ 500
Pixel rate hottest pixel [kHz]	> 350	> 40
Max discharge time [ns]	< 29	< 250
Bandwidth per ASIC of 2 cm^2 [Gb/s]	> 250	> 94

Simulated jitter at the front-end ouput versus input capacitance for 42 μm pixel pitch



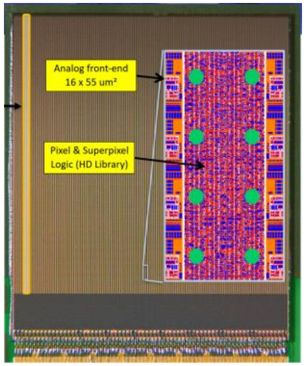
• ASIC Development

Generations & Performance

- ✓ **UI ASIC**: VeloPix, Developed in collaboration with MediPix collaboration
- ✓ **UII small scale prototype**: PicoPix (estimated 1st iteration submission ~ 18 month)

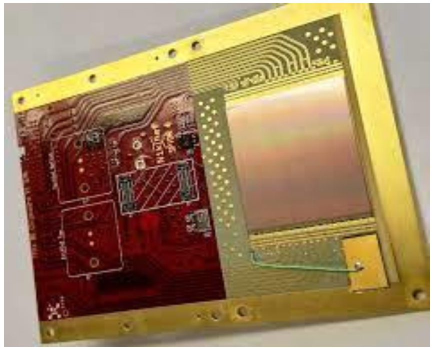
VeloPix:

- ✓ TSMC **130 nm** technology
- ✓ Rate: **10.44 Gbps/cm²**
- ✓ Total time resolution **25 ns**
- ✓ Power: **< 1.5 W/cm²**



TimePix4:

- ➢ **65 nm** technology
- ➢ Rate: **23 Gbps/cm²**
- ➢ TDC: ~**62 ps** resolution
- ➢ AFE**:** ~ **70 ps** resolution
- ➢ Power: < **0.5 W/cm²**



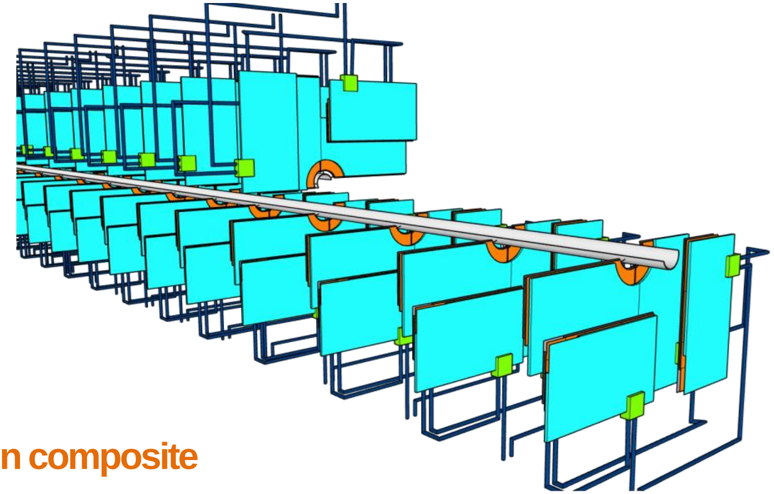
PicoPix (In development)

- ✓ **28 nm** technology
- ✓ Rate: **> 125 Gbps/cm²**
- ✓ Minimum pixel size 42- 55 μm
- ✓ Total time resolution **< 30 ps**
- ✓ Power: **< 1.5 W/cm²**
- ✓ 1st small scale prototype towards Upgrade II ASIC

• RF shield

Wake field suppression manifold

- ✓ A wake field guide required to protect sensors and ensure a smooth transition of the beam's field
- ✓ It can be a large part of X_0
- ✓ Three options under investigation:



Cylindrical foil

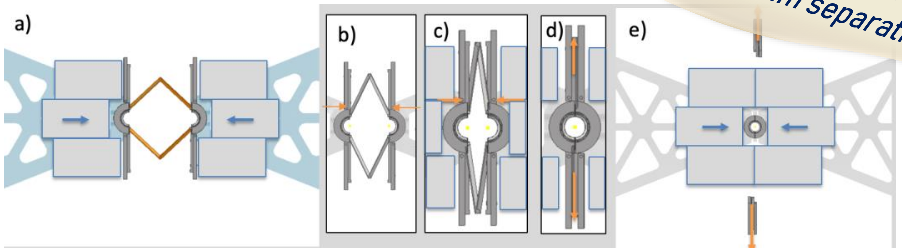
- 20 μm Al foil
- Tensioned shield for mechanical stability
- NEG coating can be big part of X_0 – contains Vanadium, Titanium etc.
- Amorphous carbon coating is investigated (0.4 μm)

Wire mesh

- Wires at 200 μm pitch
- Equivalent to a 19 μm thick cylindrical foil
- 70 μm diameter should be more than sufficient for the equivalent current

Carbon composite

- 1.5 × Al X_0 but self supporting
- Can serve as mechanical support for modules
- Convenient for small thicknesses and complex shapes



Proposal for no vacuum separation

• Cooling

Pub Note: [AIDA-2020-NOTE-2020-003]

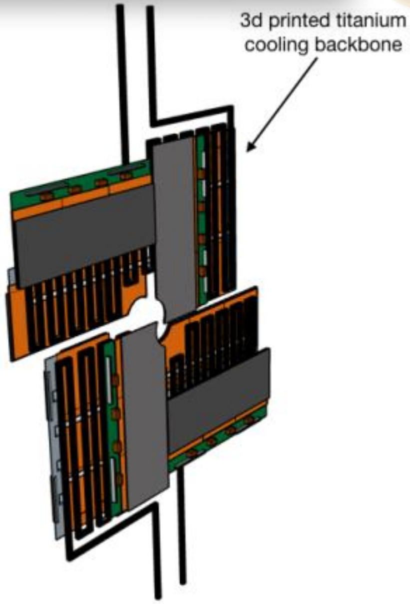
3D & Microchannel solution

- ✓ Active cooling required to control thermal runaway due to electronics power dissipation and avoid annealing of irradiated sensors
- ✓ Power budget expected to remain at > 1.5 W/cm^2
- ✓ Current option consists of CO_2 cooling via microchannel plates in direct contact with modules

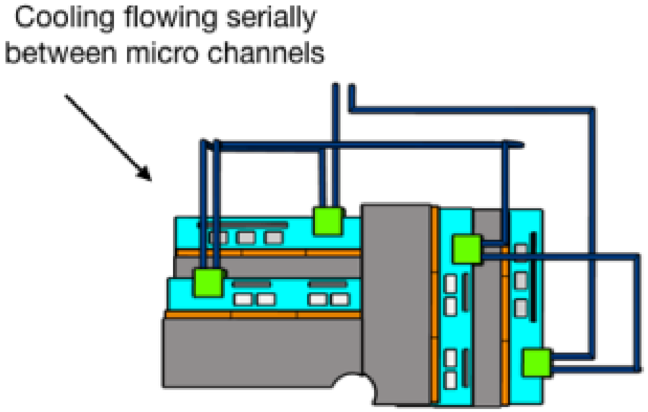
Two options evaluated for upgrade 2:

1. Microchannel plate cooling (150 W/mK)
2. 3D printed Titanium / Si-Carbide (16 W/mK)
    1. Strong and easy to handle
    2. Lower cost and experience in industry

Bi-phasic Krypton cooling for operation at < -40 ^{0}C under consideration

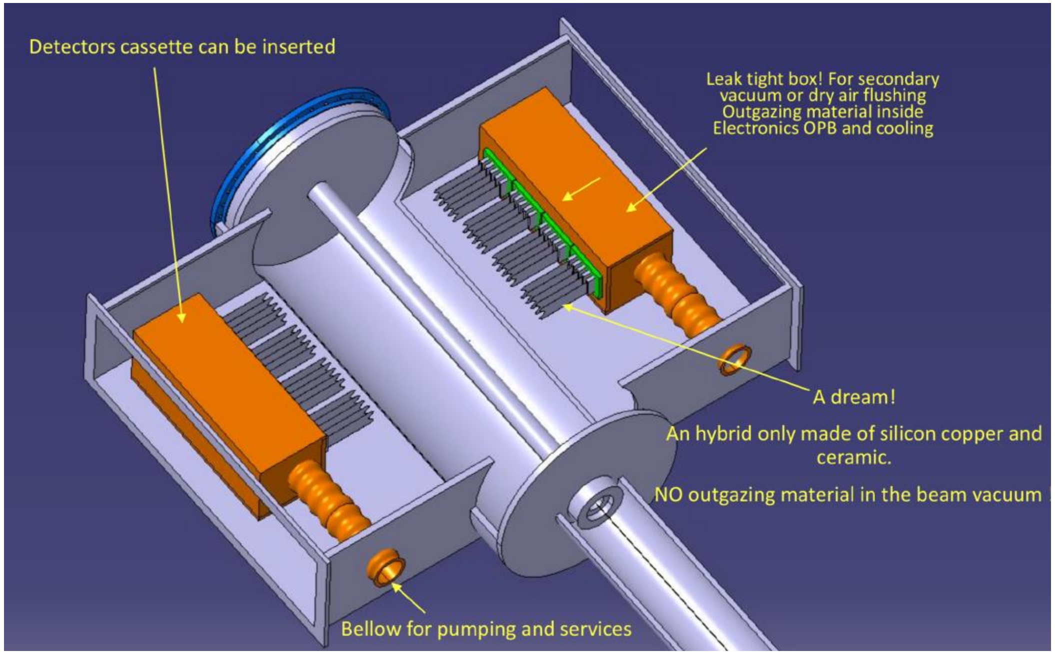



3D printed prototype



• Vacuum tank

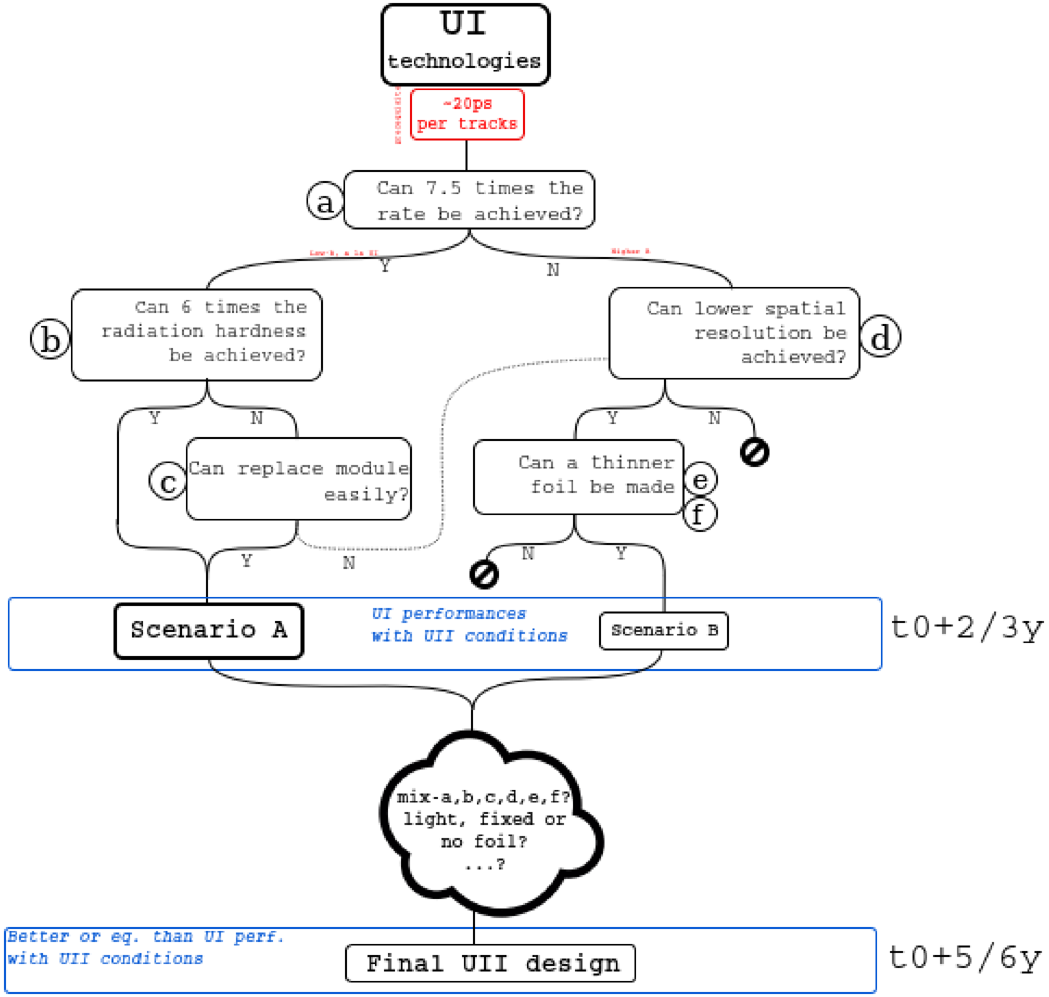
Vacuum separation considerations



- ✓ **Secondary - primary vacuum separation**
  - ✓ Difficult to keep in scenario B while reducing material budget
  - ✓ Impractical in scenario A if frequent replacement required
  - ✓ If removed required materials that do not outgas to the primary vacuum
- ✓ **Module replacement**
  - ✓ Mechanical design must be radically optimized towards flexibility in scenario A
  - ✓ Fast replacement of modules during technical stops
  - ✓ Material choice to control outgassing

• R&D Path Towards Velo Upgrade II

Timeline



Necessary R&D

- ✓ IC digital / analog design allowing for high rate and high bandwidth
- ✓ IC and sensor technology to withstand radiation hardness requirements
- ✓ Easy to make modules allowing replacement
- ✓ Lower special resolution (charge sharing or pixel pitch)
- ✓ Ability to make thin foil (cylindrical, wires)
- ✓ Ability to make thin foil openable

• Conclusions

Summary and outlook

So far….

Two Scenarios considered as a starting point

- S_A: High data rate and radiation tolerance at $> 6 \times 10^{16}$ n_{eq}/cm^2
- S_B: Higher hit resolution and reduction of material budget

Full 4D Velo Tracker

- 20 ps per track timing to recover Run 3 efficiency
- Timing plane options rejected due to more complicated construction

R&D Paths

- Next 2 years crucial to develop necessary technologies:
  - Fast and radiation hard sensors and ASIC
  - Reduced material budget RF shield option
  - New cooling solution
  - Vacuum tank that satisfies the requirements