10th International Workshop on Pixel Detectors for Particles and Imaging
Santa Fe, New Mexico
12 December 2022

VELO Upgrade II
The LHCb 4D pixel detector

Tommaso Pajero
on behalf of the VELO group

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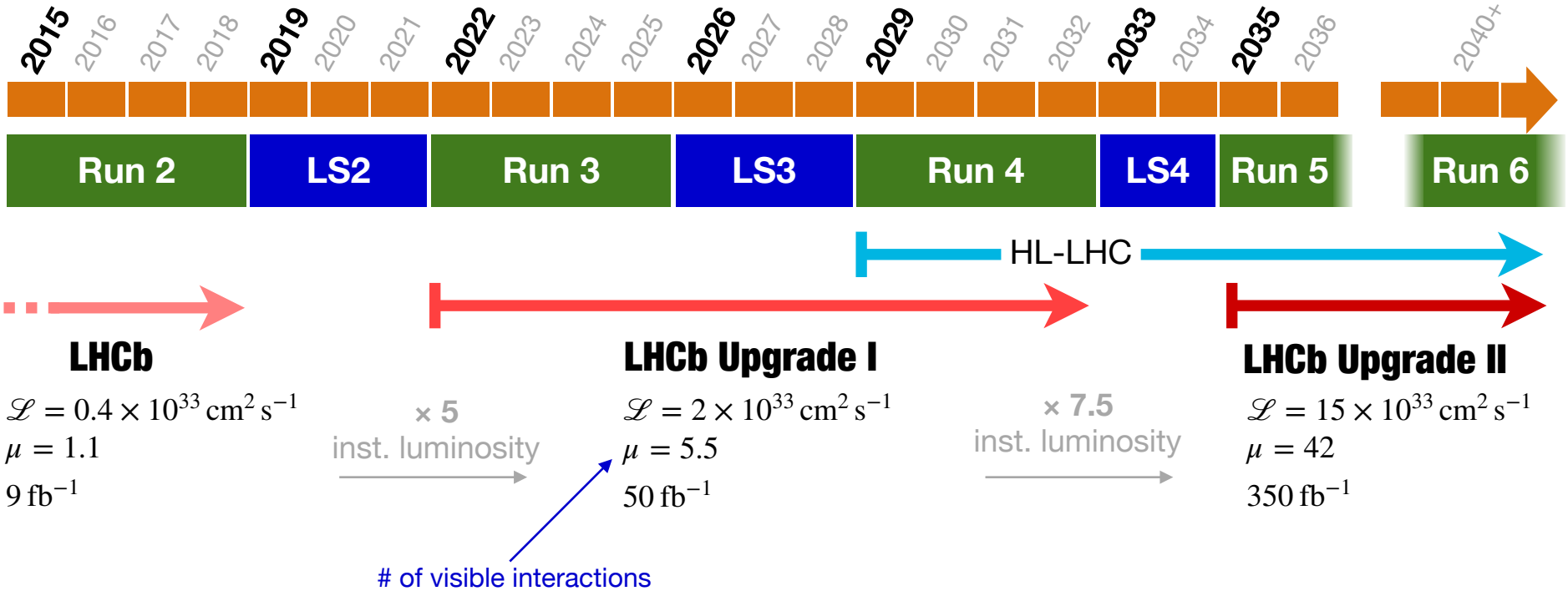
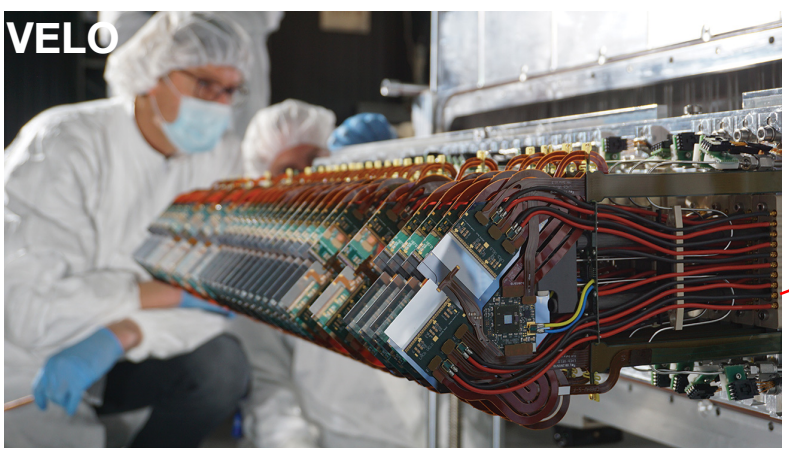
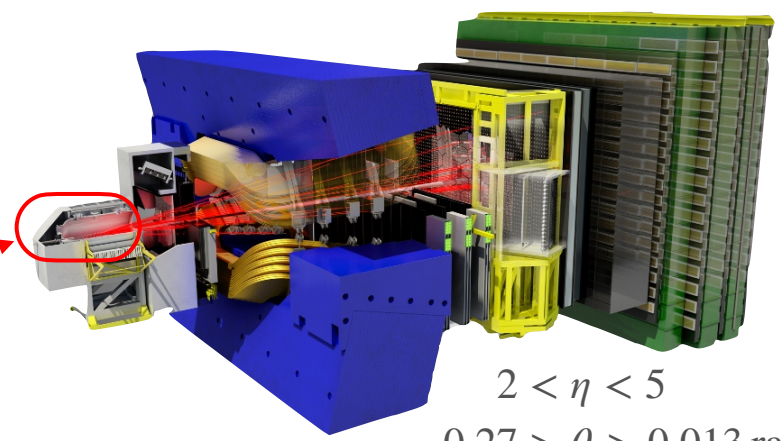
LHCb timeline



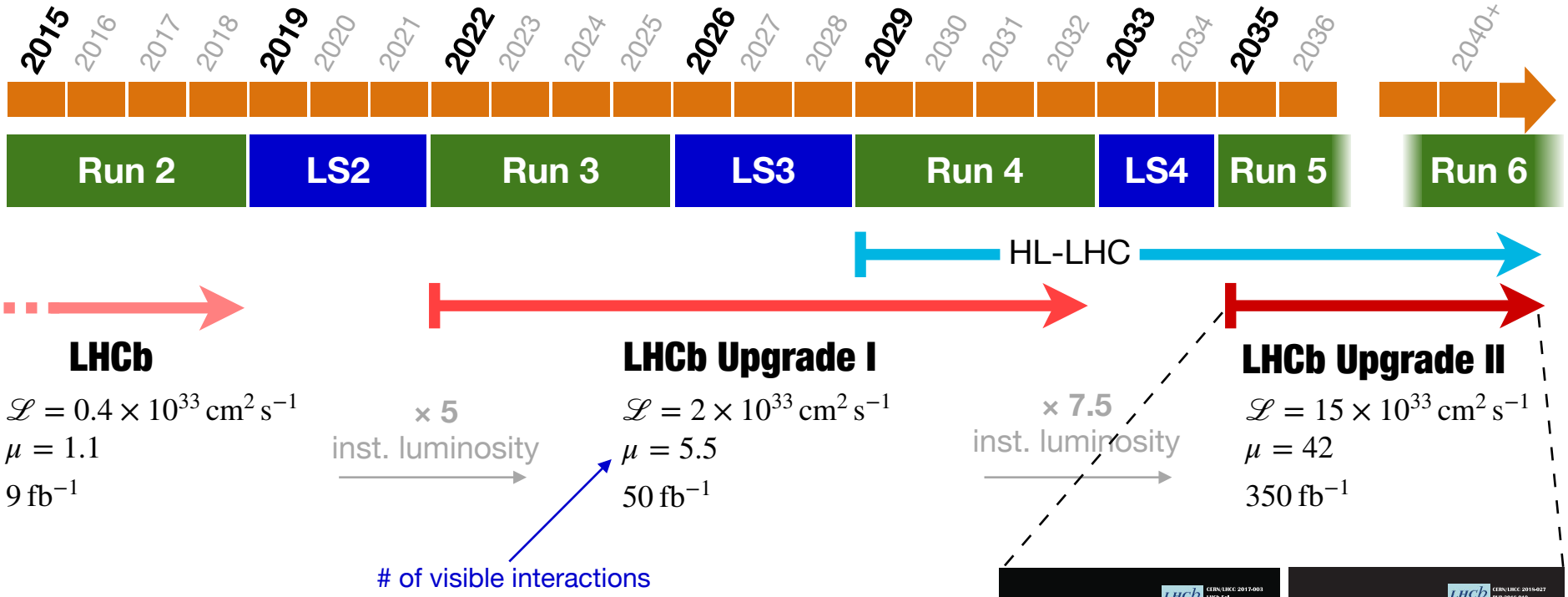




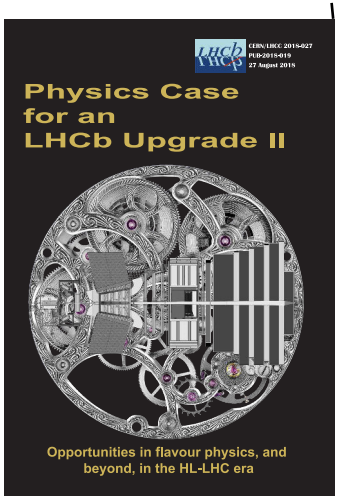
$2 < \eta < 5$

$0.27 > \theta > 0.013$ rad

LHCb timeline



CERN-LHCC-2017-003

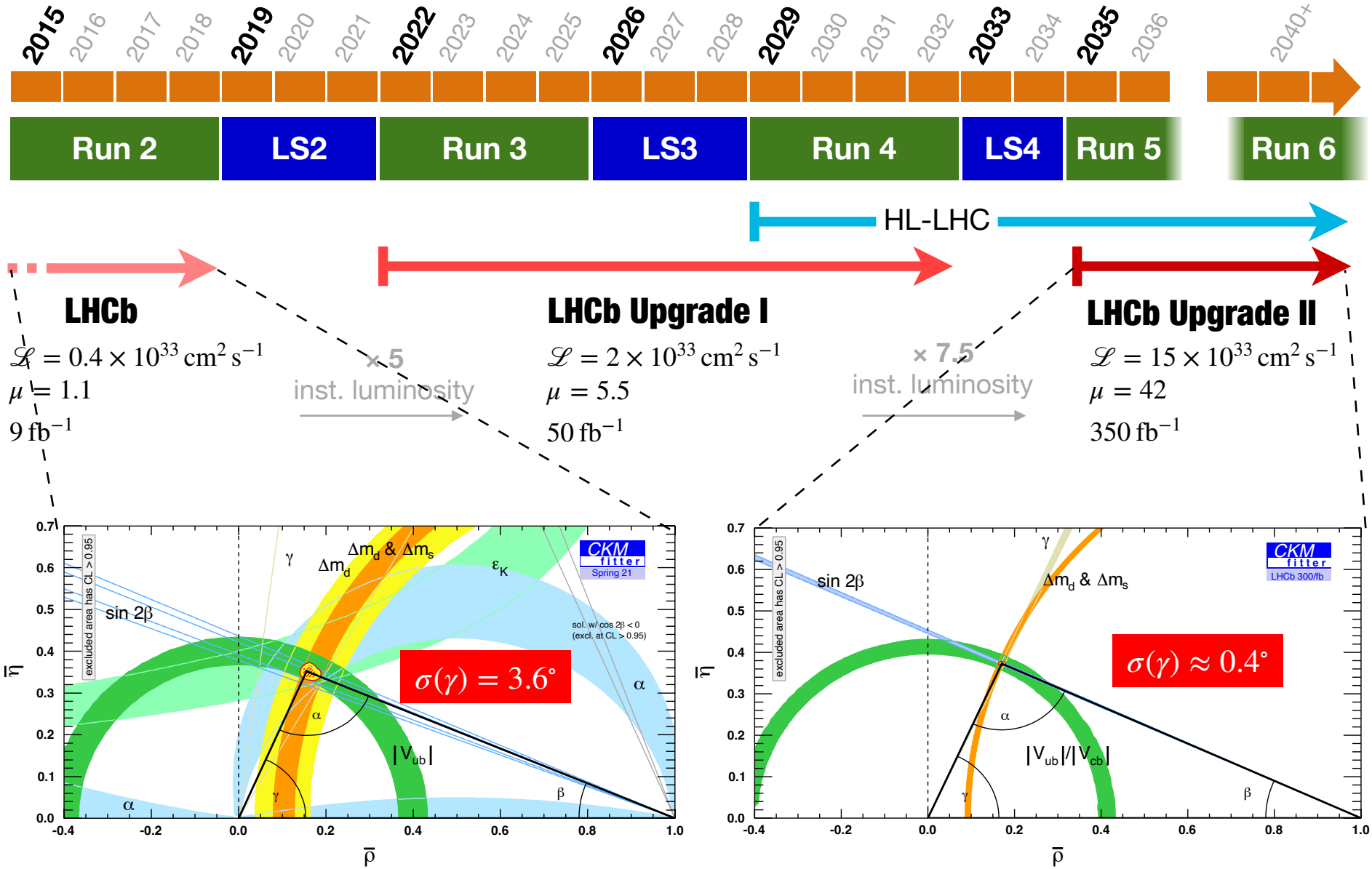


CERN-LHCC-2018-027

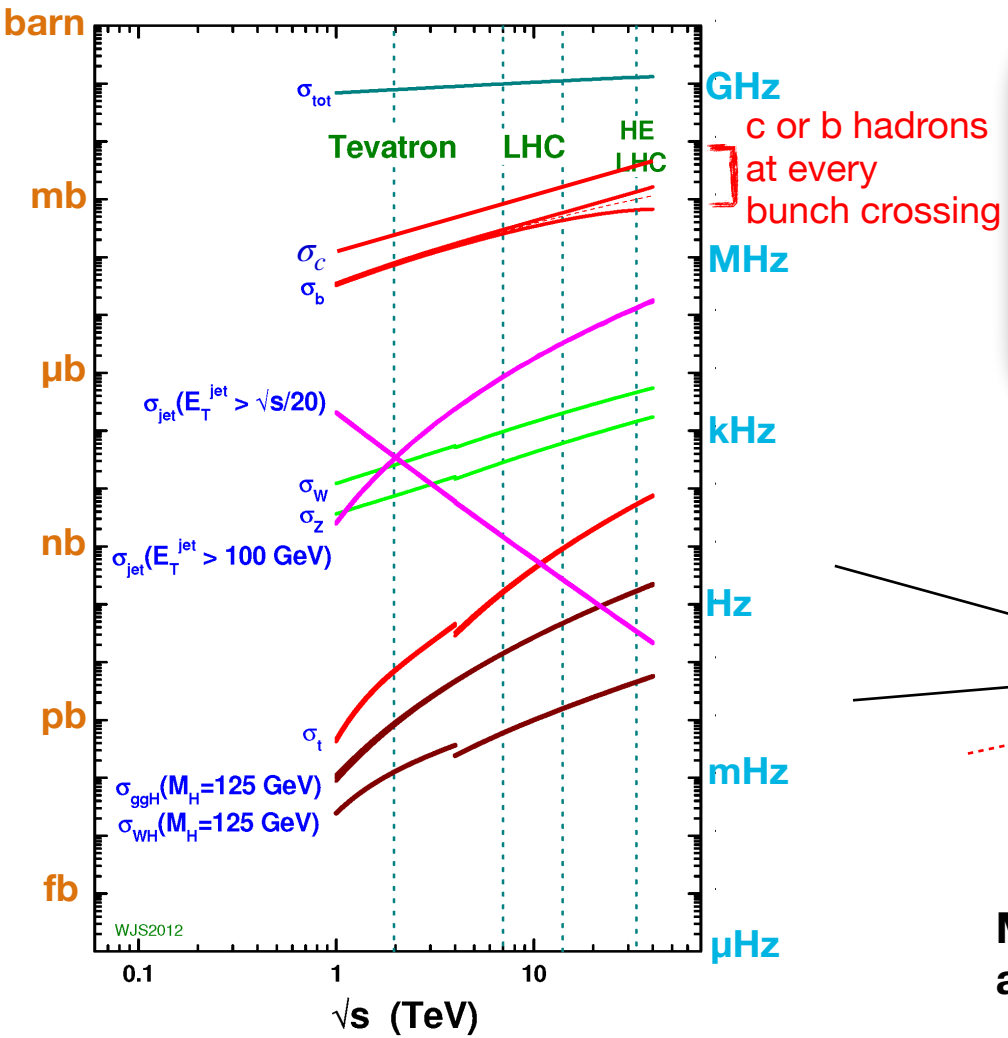
Goal: equivalent or better performance than in Upgrade I **at much higher rate**

- efficiency (trigger)
- resolutions and PID
- sys. uncs. should remain smaller than the stat. ones

LHCb timeline

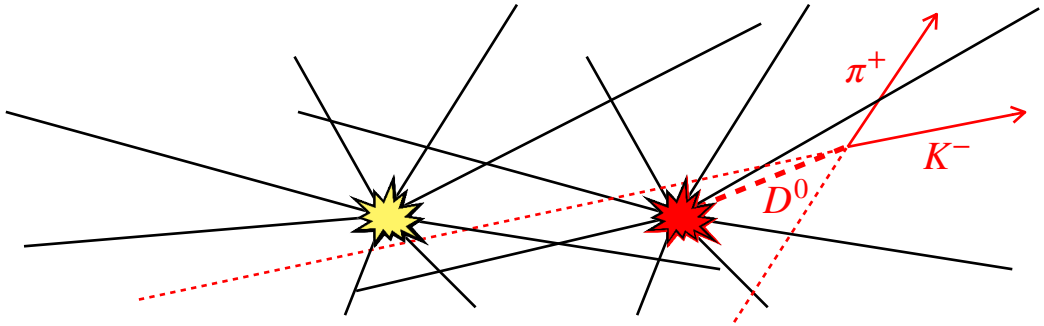


VErtex LOcator role



c or b hadrons at every bunch crossing

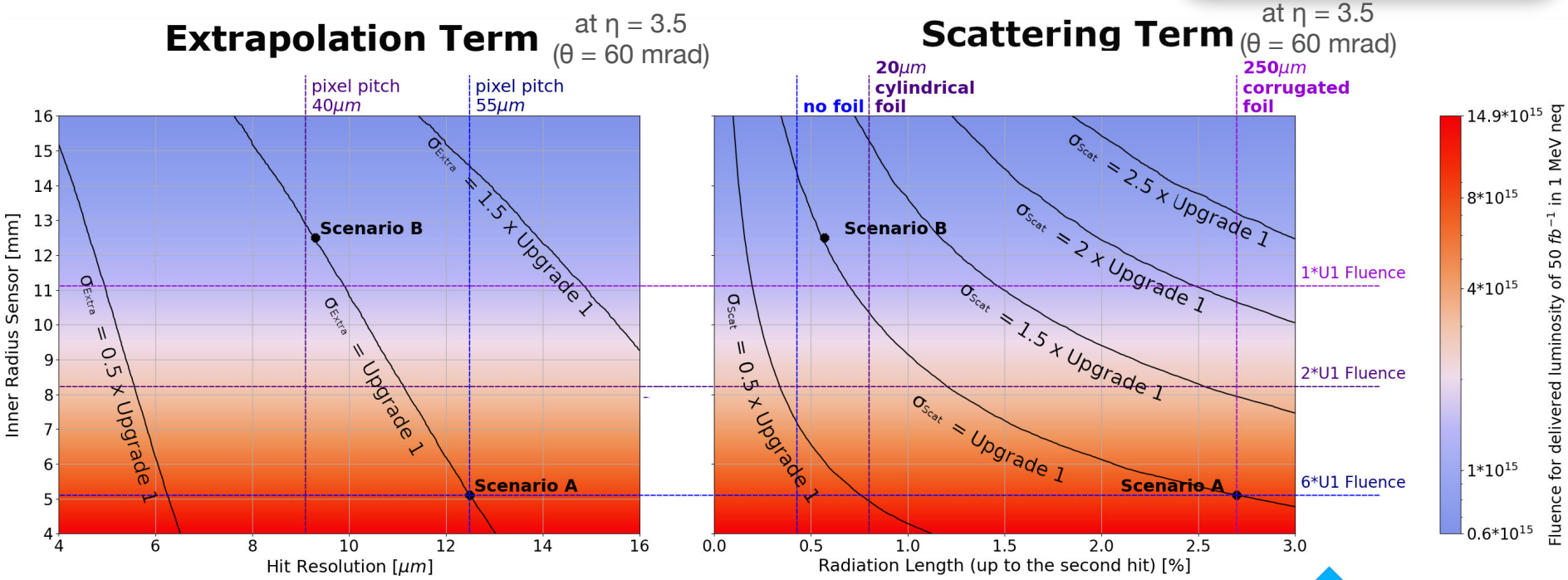
- Hardware trigger inefficient
- Reconstruct all tracks and primary vertices (PVs) in near real time. Look for displaced vertices
  - track-to-PV association crucial to measure decay times



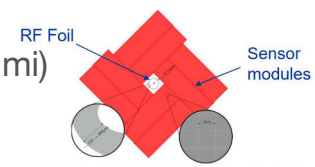
Maintain at least the same acceptance and spatial resolution as in Upgrade I (U1)

How far from the beam?

$$\sigma_{IP} = \sigma_{extra} \oplus \frac{\sigma_{scat}}{p_T}$$

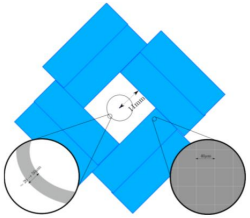


Scenario A (S_A) (same as in UI, at 7.5× lumi)



- 5.1 mm inner radius
- 55 × 55 μm pixels
- 6 × 10^{16} 1 MeV n_{eq} cm^{-2} maximum fluence, 3 Grad ionising dose
  - highly non homogeneous
  - radiation harder sensors or regular replacement
- >250 Gb/s ASIC bandwith (900 Mtracks/cm^2/s)

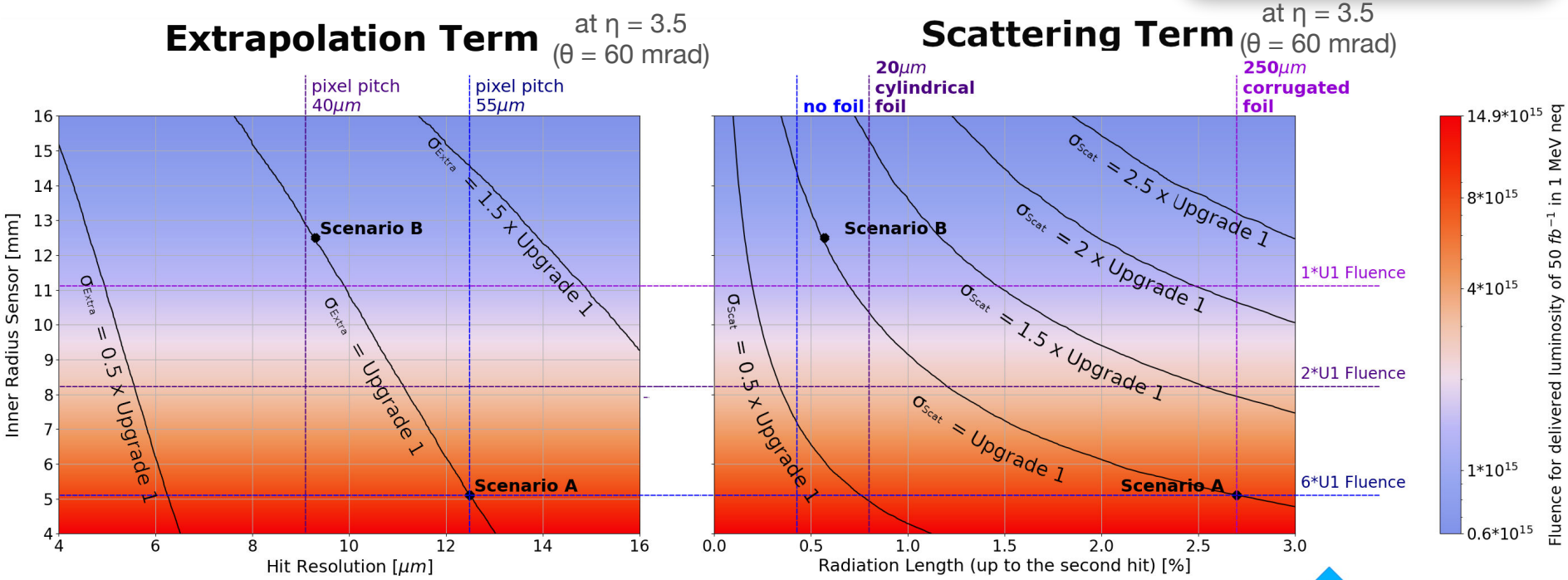
Scenario B (S_B)



- 12.5 mm inner radius
- 42 × 42 μm pixels
- 5× reduction of material budget before 2nd hit
  - much thinner RF foil or substitution with wires
- 8 × 10^{15} 1 MeV n_{eq} cm^{-2} maximum fluence, 400 Mrad ionising dose
- >94 Gb/s ASIC bandwith

How far from the beam?

$$\sigma_{IP} = \sigma_{extra} \oplus \frac{\sigma_{scat}}{p_T}$$



Scenario A (S_A) (same as in UI, at 7.5× lumi)

- 5.1 mm inner radius
- 55 × 55 μm pixels
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  3 Grad ionising dose
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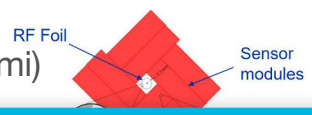
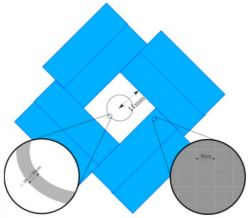


Scenario B (S_B)



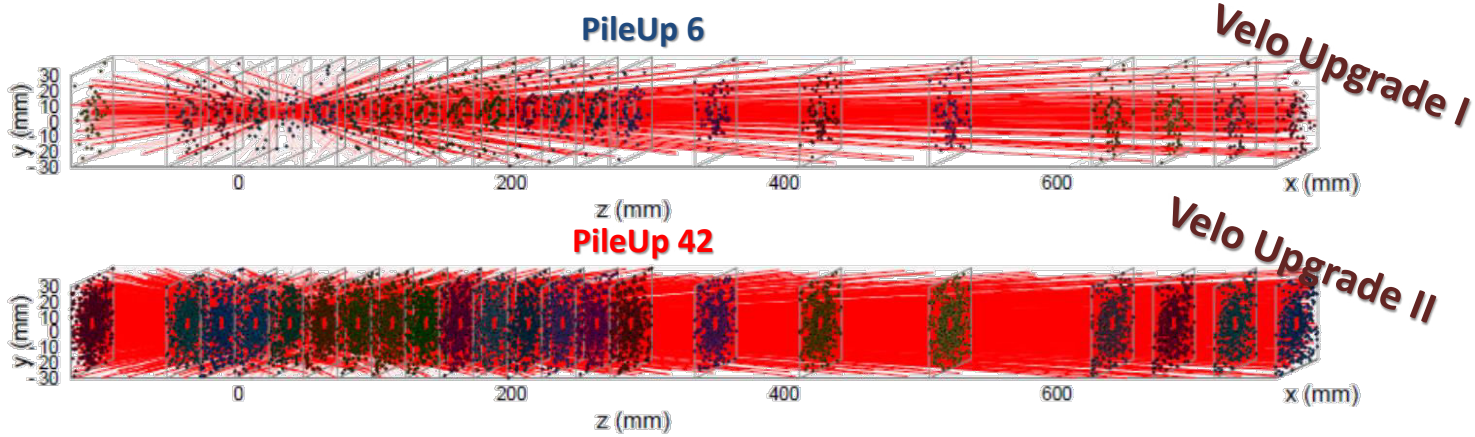
l budget before 2nd hit
l or substitution with
wires

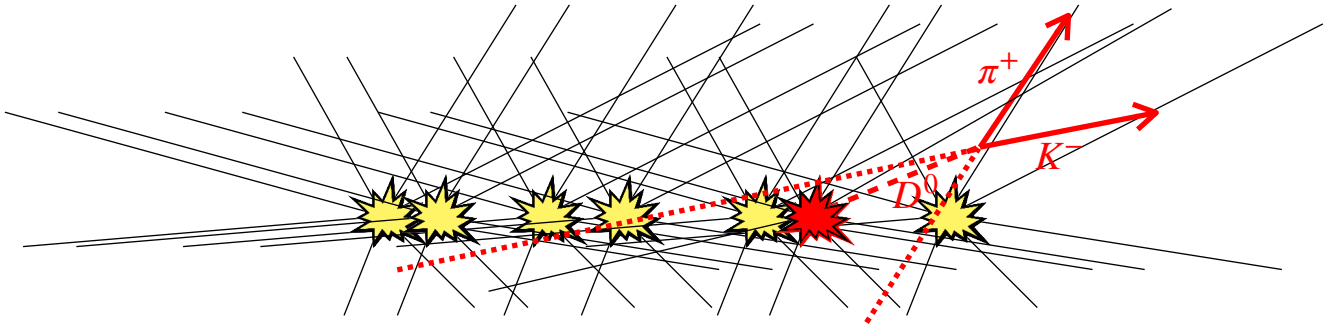
- 8 × 10^{15} 1 MeV n_{eq} cm^{-2} maximum fluence, 400 Mrad ionising dose
- >94 Gb/s ASIC bandwith

DISCLAIMER

S_A and S_B are just extreme scenarios considered to guide detector R&D

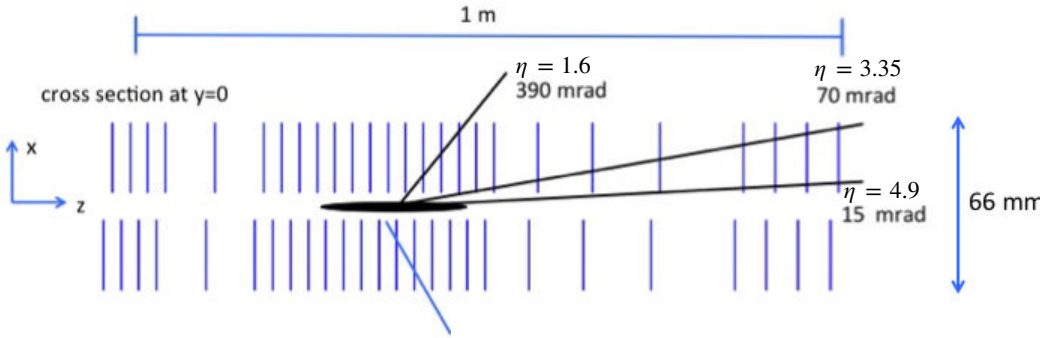
Pileup challenge





- **Lower triggering efficiency**
  - sheer chance that a displaced track points to an unrelated PV increases
  - higher chance of misreconstructing/merging PVs (1.5 mm^{-1} avg. linear density along z)
    - degraded time resolution (longer tails)
- **Higher combinatorial background and ghost rate**
- **More computing power for reconstruction**

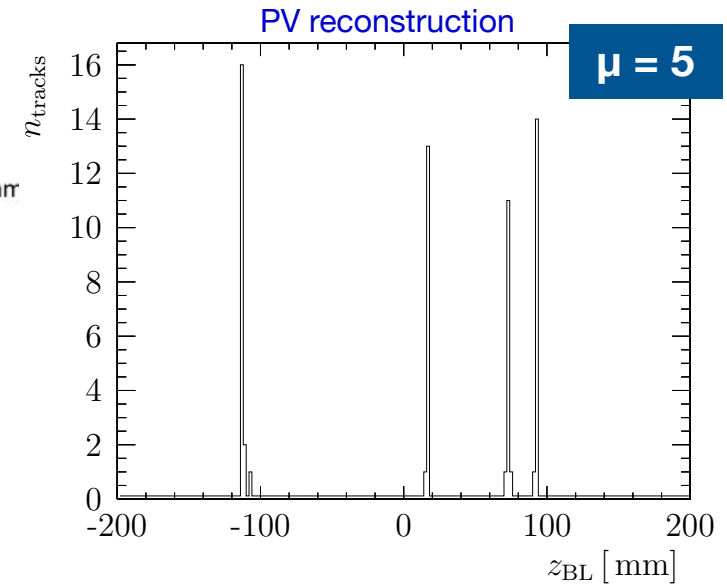
Mitigation strategy: add timing



interaction region (constraints from LHC)

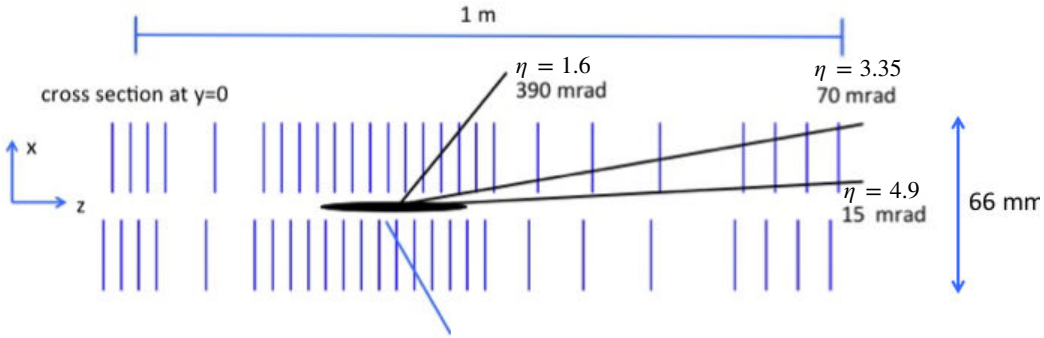
$\sigma_t \approx 186\,\mathrm{ps}$

$\sigma_z \approx 45\,\mathrm{mm}$



track z extrapolated position at the beam line

Mitigation strategy: add timing



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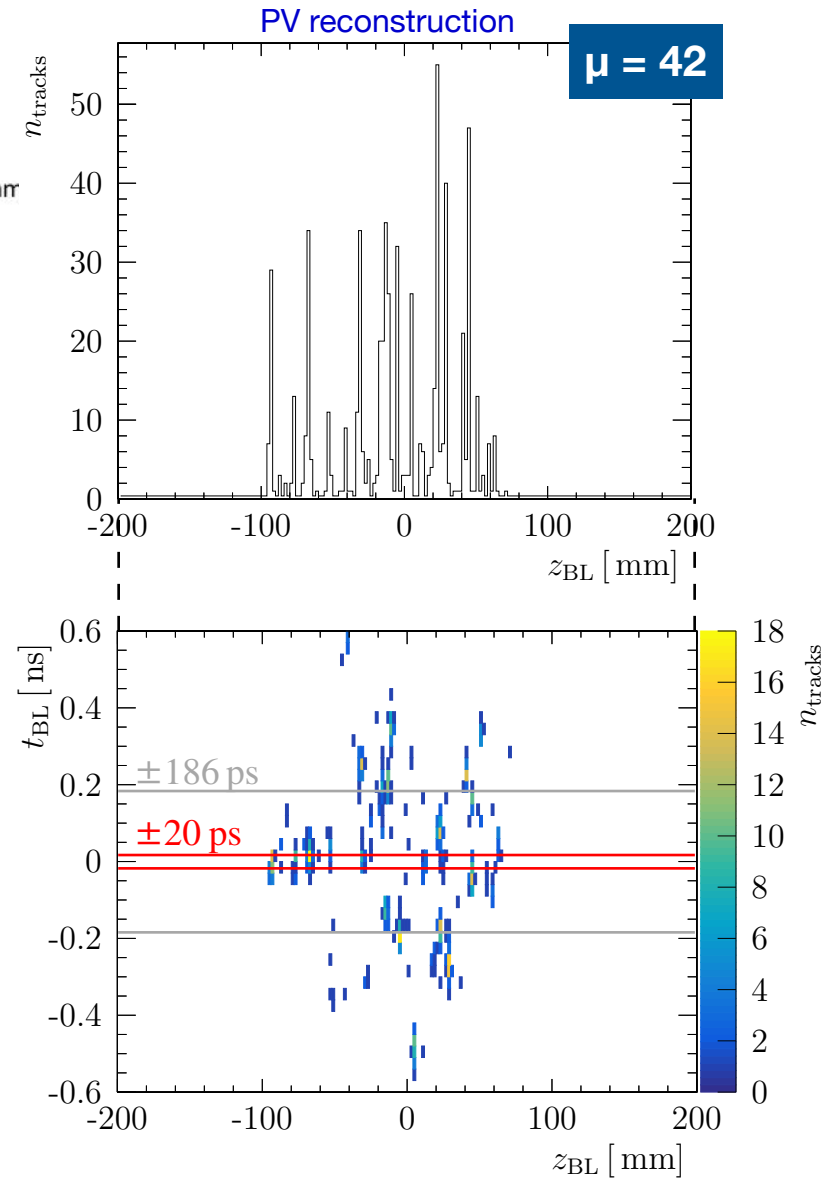
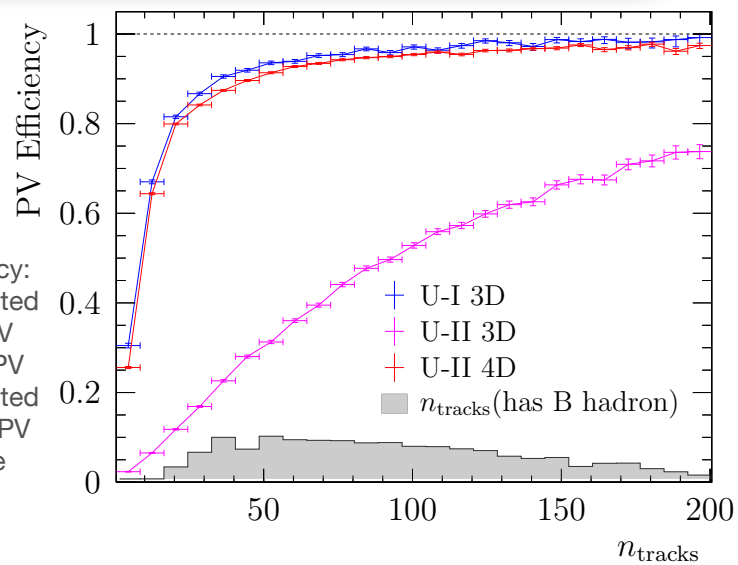


20 ps per-track (50 ps per hit) time resolution restores the performance to U1 level



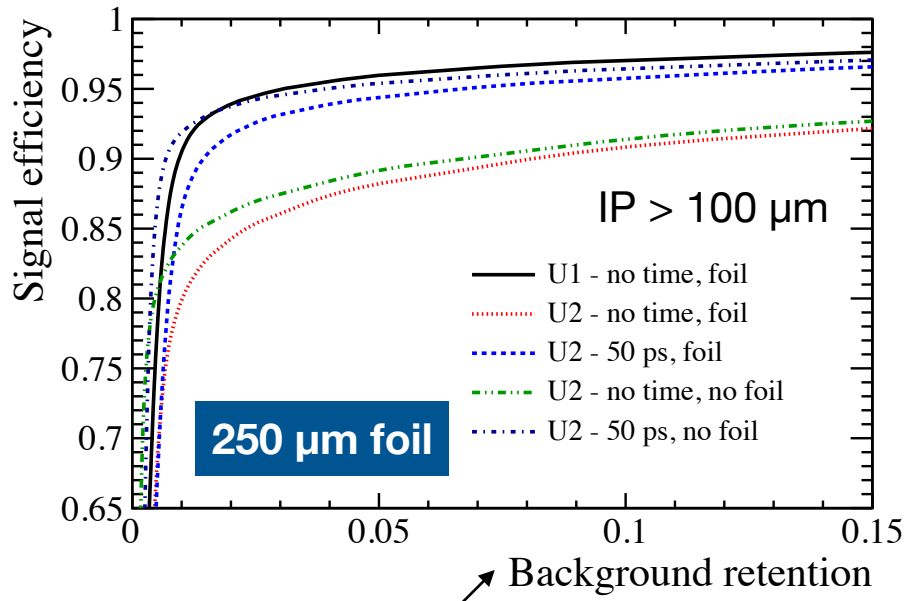
"Good PV" for efficiency:

- > 75% of reconstructed tracks forming the PV come from the true PV
- > 75% of reconstructed tracks from the true PV are associated to the reconstructed PV

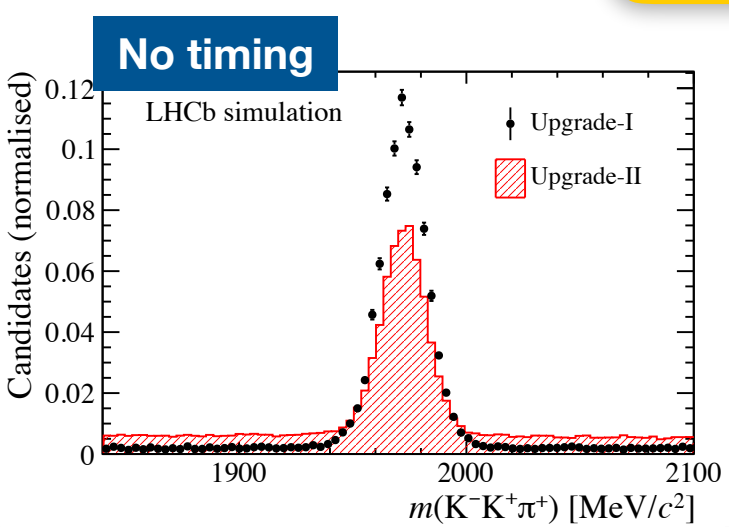
Physics example: $B_s^0 \to D_s^- \pi^+$

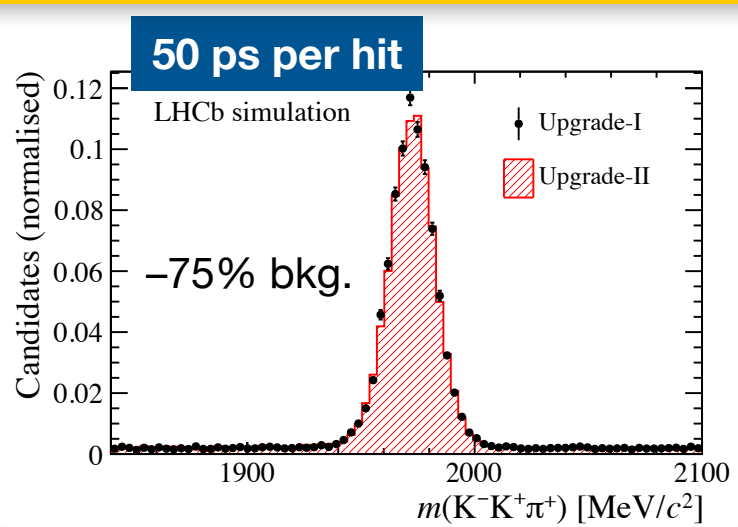
Every simulated event contains one signal decay

Trigger efficiency and S/N ratio nearly recovered thanks to timing.

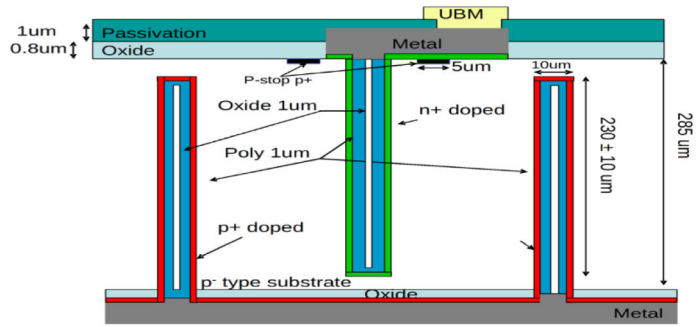


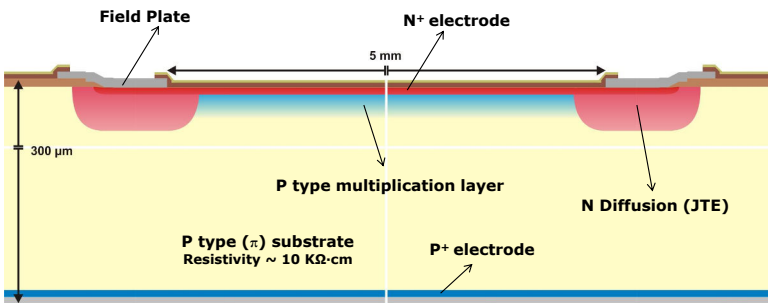
Keep in mind: x% of U2 background >> x% of U1 background





Sensor technologies





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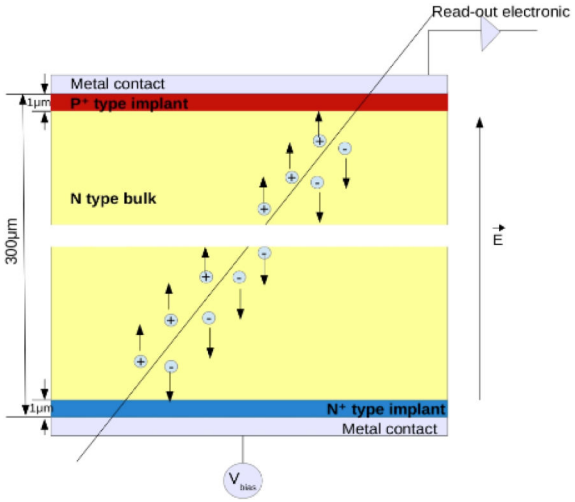
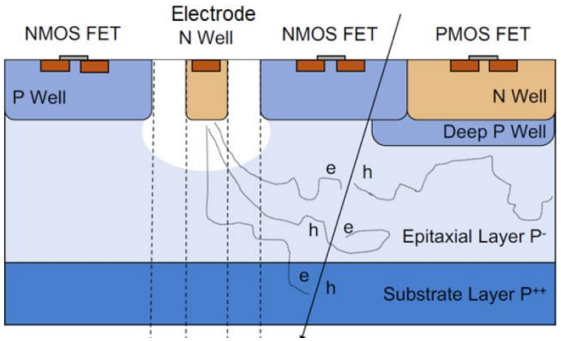


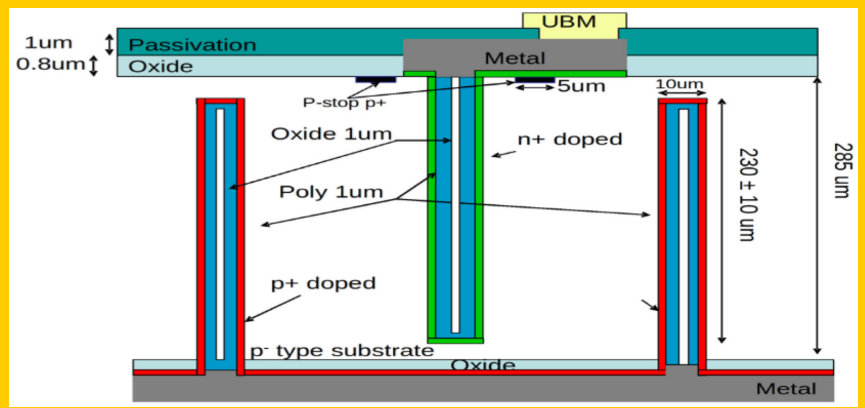


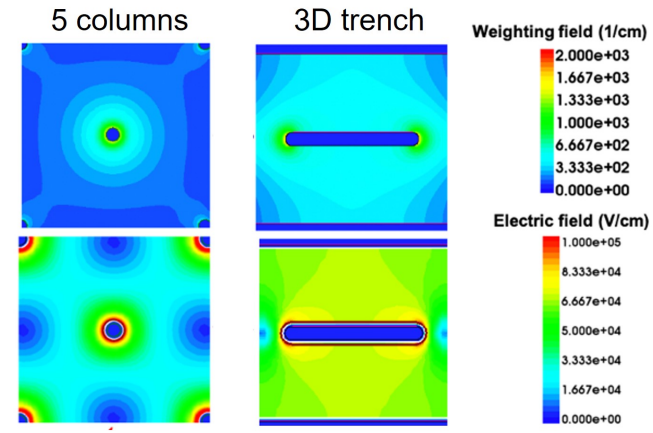
$$\sigma_t^2 = \sigma_{landau}^2 + \sigma_{timewalk}^2 + \sigma_{Distortion}^2 + \sigma_{jitter}^2 + \sigma_{TDC}^2$$

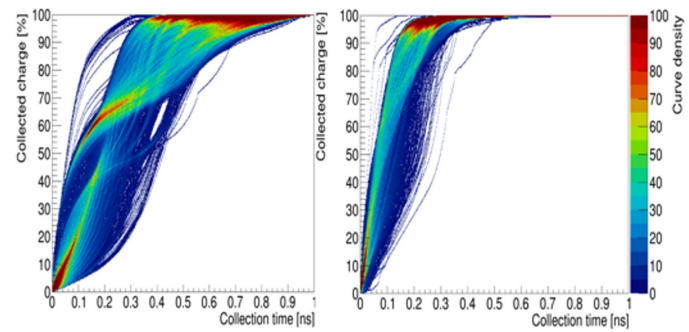
3D sensors

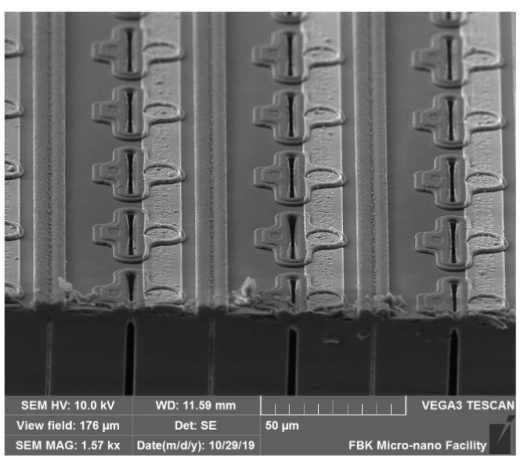
see Adriano Lai's talk

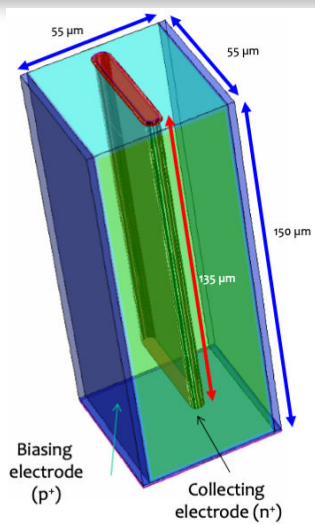
- Decouple charge-carrier drift distance from sensor thickness
- **Intrinsically fast** (small Landau contribution)
- **radiation hard** up to few 10^{16} 1 MeV n_{eq} cm^{-2}
- non-uniform field, dead regions at the electrodes
- expensive and relatively large capacitance





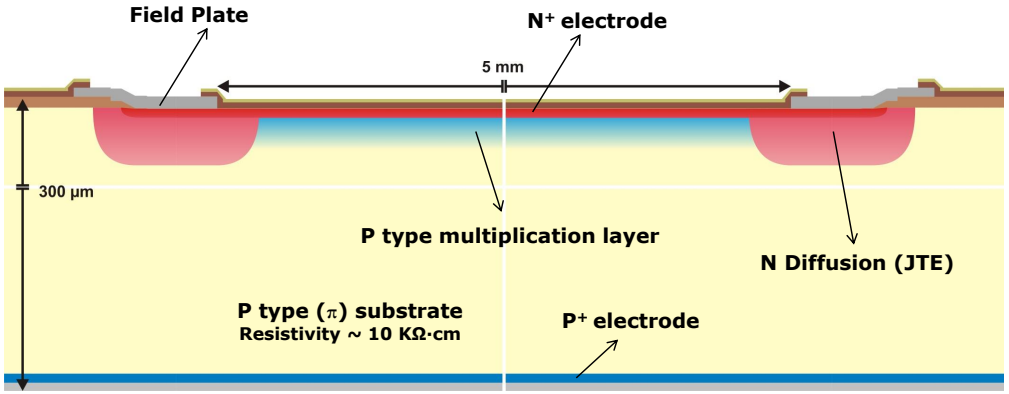






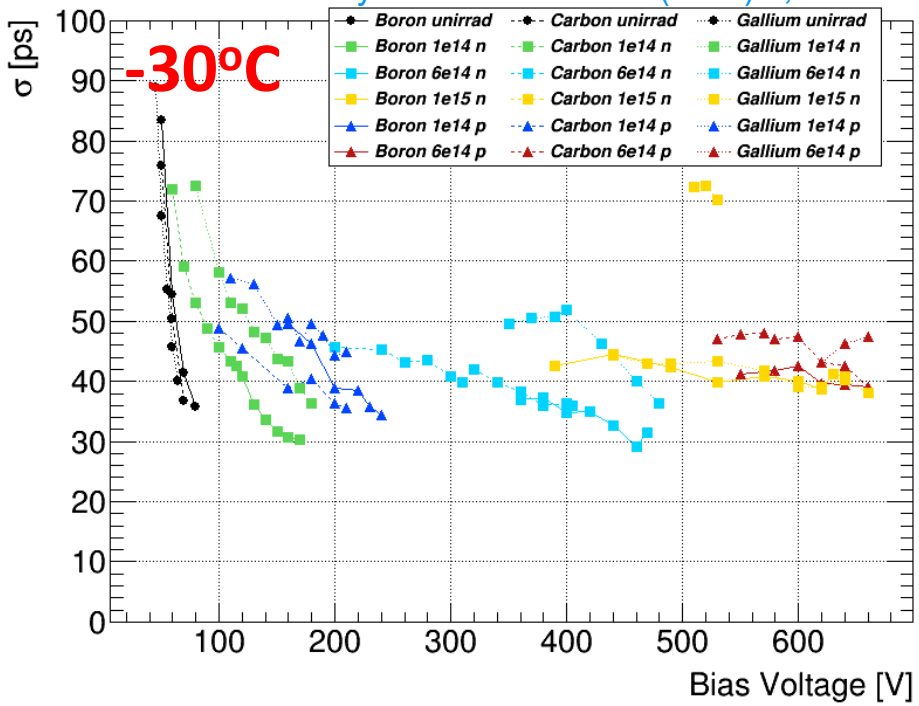
- **Trench** geometry guarantees more homogeneous field and charge collection w.r.t. columnar designs
- but also larger capacitance (110 fF) and hence noise
- inefficiency close to electrodes could be mitigated by 20° tilt
- **~10 ps** resolution for single pixel
- effect of 110 fF capacitance to be measured on full-sized readout ASIC

LGADs



- **40 ps time resolution for 10x gain** (low jitter) and high SNR
- Spatial inefficiency under study (I-LGAD, TI-LGAD)
- **Not radiation hard** (3–4 10^{15} 1 MeV n_{eq}) (gain decreases due to acceptor removal)
  - B and B+C implantation improve performance after irradiation by 20%

J. Phys. Conf. Ser. 2374 (2022) 1, 012175



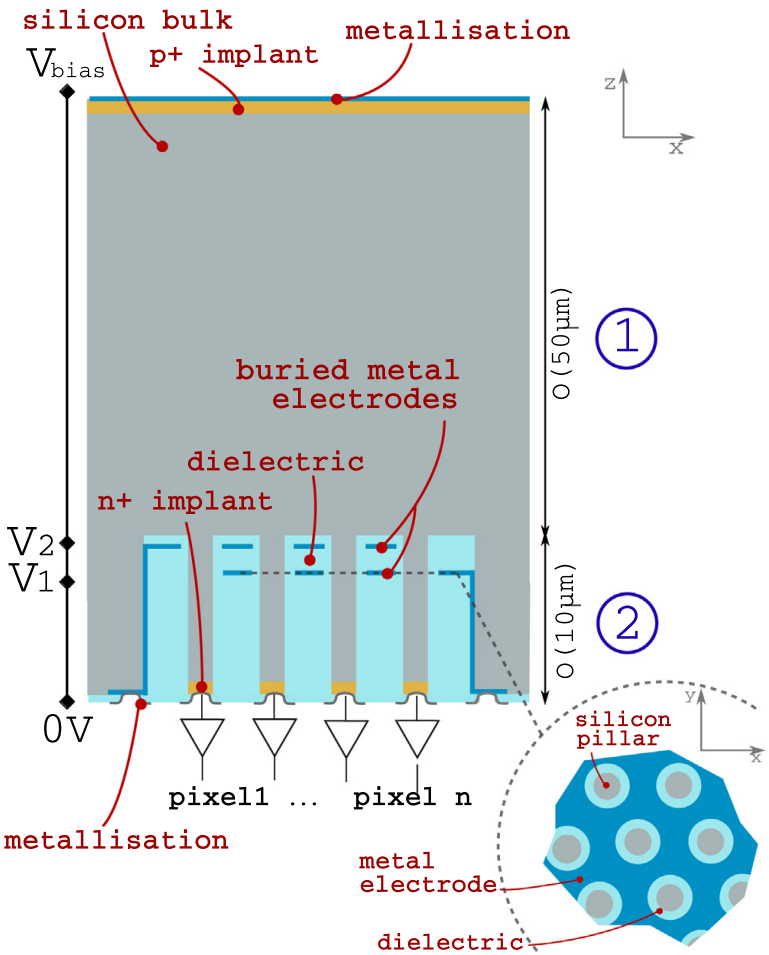
- B+Li coimplantation shows better neutron radiation hardness
- studies ongoing to replace Li with In

- Could be a candidate for S_B if radiation hardness could be improved by at least 2×

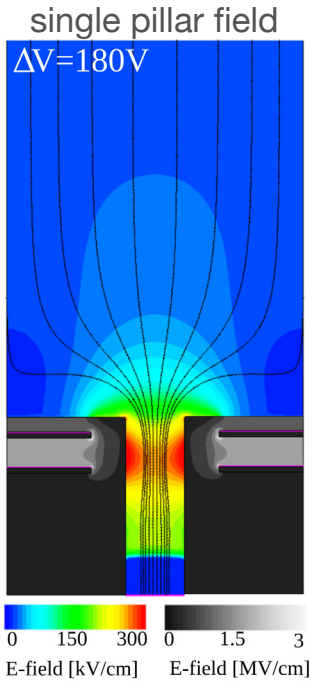
JINST 15 (2020) 04, C04027
Gkougkousis at Trento workshop 2021
Ramos at 50RD workshop 2022

Silicon electron multiplier sensor (SiEM)

NIM A 1041 (2022) 167325



- Amplification <u>without doping</u> takes place in silicon pillars ②
  - two electrodes buried in between the pillars and separated by a dielectric create large $\vec{E}$
- Fast timing (**15–40 ps**) from O(10) gain + low drift time in thin depleted region ①
- Pitch can be as low as 10 μm
- Expected rad. hardness up to 10^{16} 1 MeV n_{eq} cm^{-2}



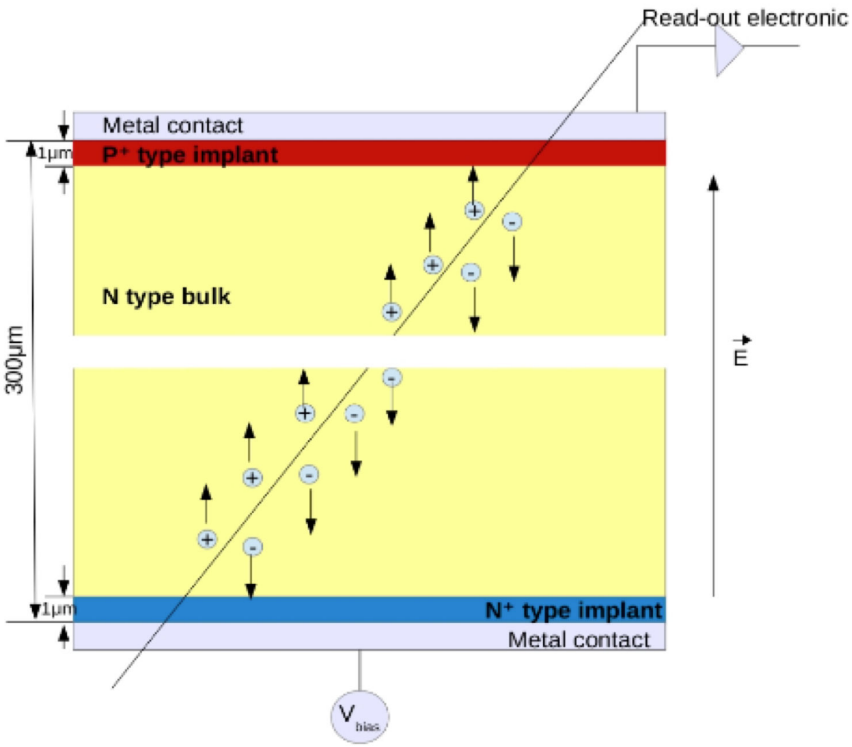
- Optimisation of geometry and bias voltages ongoing
- Fabrication through Deep Reactive Ion Etching (DRIE)

Planar sensors

Good time resolution requires:

- thin sensor
- time-over-threshold for time walk correction
  JINST 16 (2021) 07, P07035

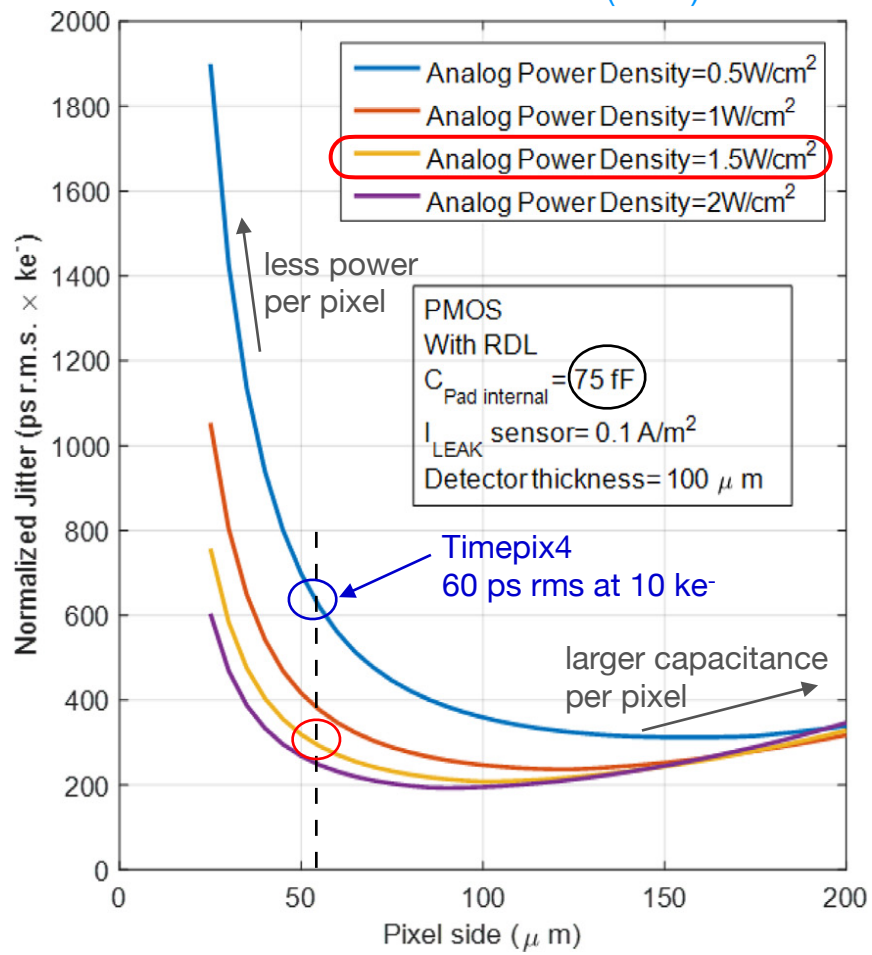
Radiation hard up to 10^{16} 1 MeV n_{eq} cm^{-2}
(with high V_{bias} and power dissipation).
At some point charge multiplication kicks in
JINST 16 (2021) 02, P02029
JINST 17 (2022) 06, P06038

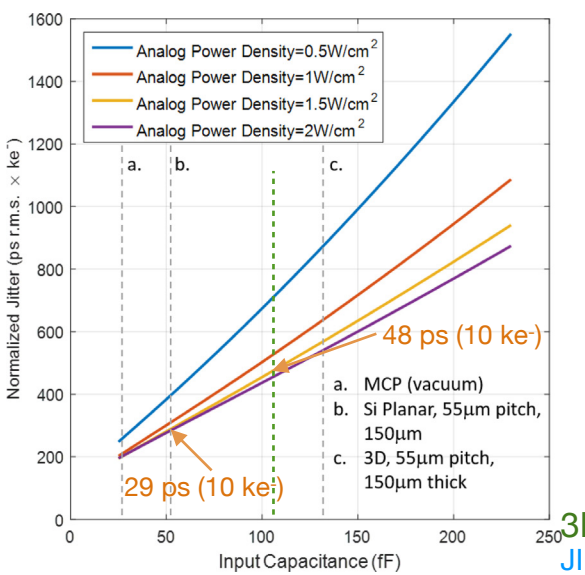


ASIC requirements

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

NIM A 1045 (2023) 167489





3D trench: 110 fF

JINST 15 (2020) 09, P09029

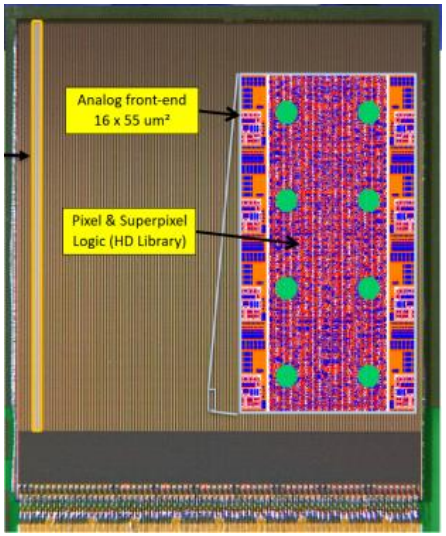
ASIC developments

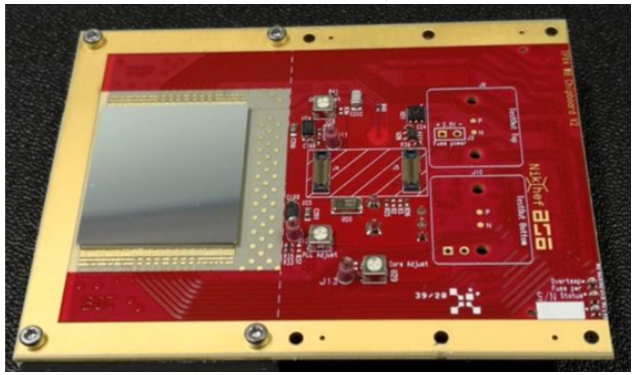
+ TimeSpot ASIC
see Adriano Lai's talk

JINST 12 (2017) 01, C01070 JINST 15 (2020) 09, P09035

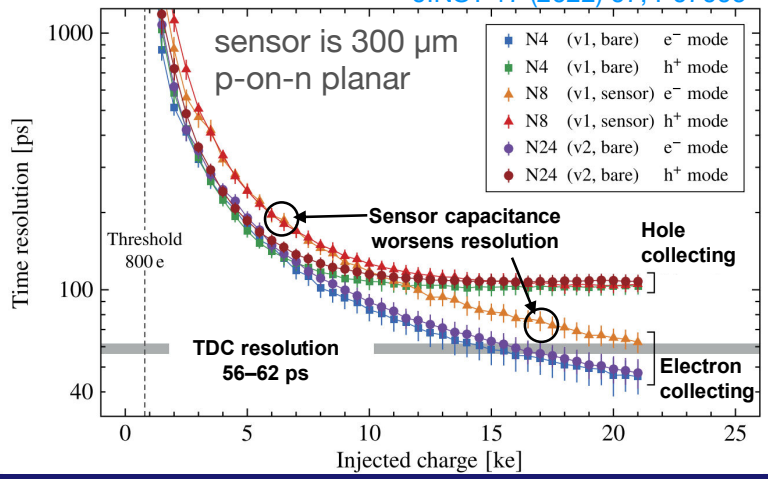
	VeloPix	Timepix4	PicoPix
Technology	130 nm	65 nm	28 nm
Time resolution	25 ns	58 ps from TDC binning ~70 ps from analog front end	< 30 ps
Pixel pitch (μm)	55 x 55	55 x 55	55 x 55/42 x 42
Bandwidth (Gb/s/cm²)	10.4	23	>125
Power density (W/cm²)	< 1.5	< 0.5	< 1.5

First prototype with a view to VeloPix II





JINST 17 (2022) 07, P07006

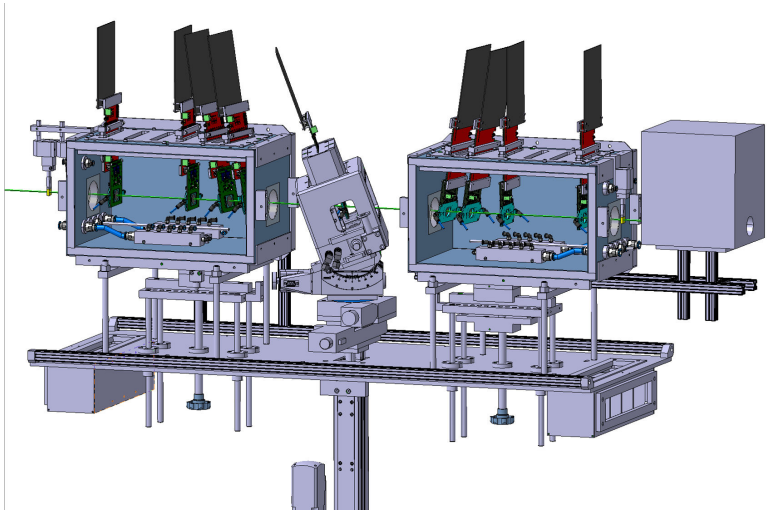


K. Heijhoff at Vertex 2022

Timepix4 telescope

New facility at SPS (180 GeV mixed hadron beam) to test

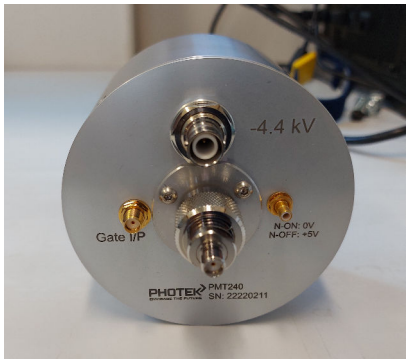
- sensor + ASIC assemblies (**temporal and spatial resolution vs. track incidence angle and intercept within pixel**)
- clock distribution ($\approx 1/\sqrt{N_{\text{hits}}}$ **scaling** of track time resolution, cf. JINST 15 (2020) 09, P09035)

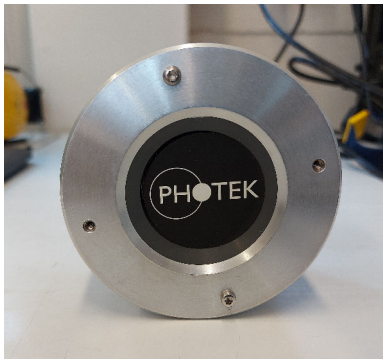


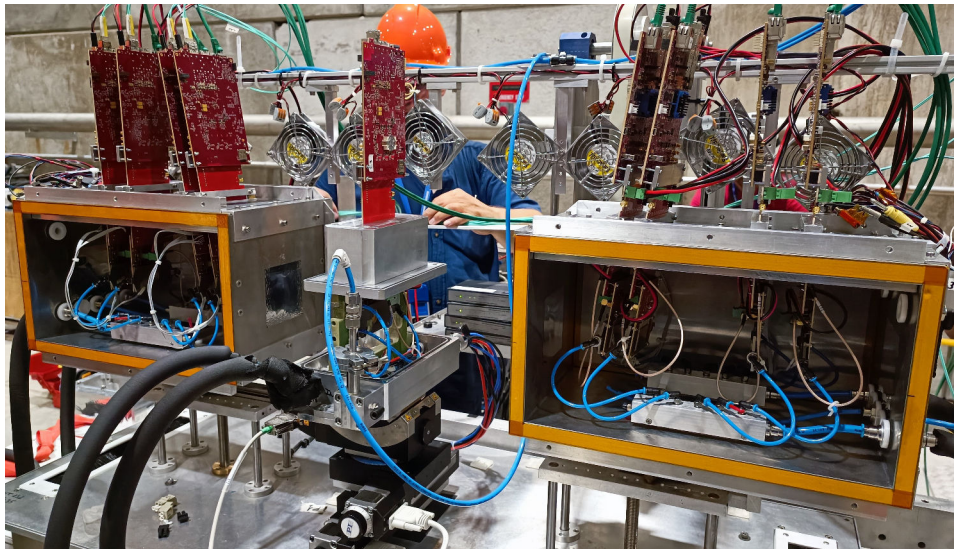
Two arms of four planes each
Central space for device under test

Design specifications

- **2 μm** pointing resolution
- **20–30 ps** track time resolution (MCP-PMT)
- operation at **1-10 Mtracks/s**



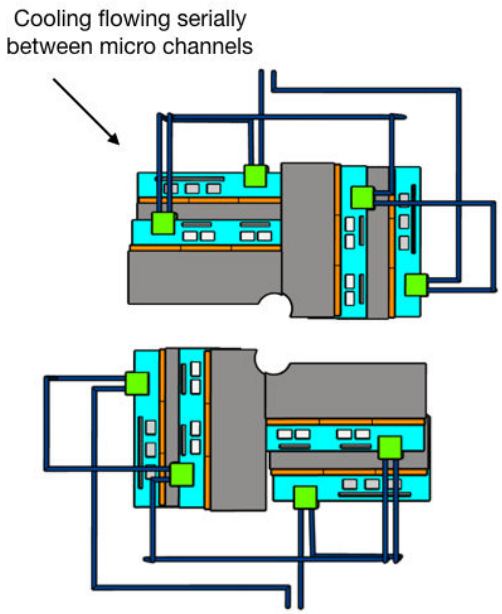




- First results from Oct 2021 (4 planes) in arXiv:2210.01442
- New data taking with full telescope last Oct

Active cooling

- Reduce radiation damage from reverse annealing
- control leakage current and avoid thermal runaway
- power budget (in vacuum!): 1.5 W / cm^2

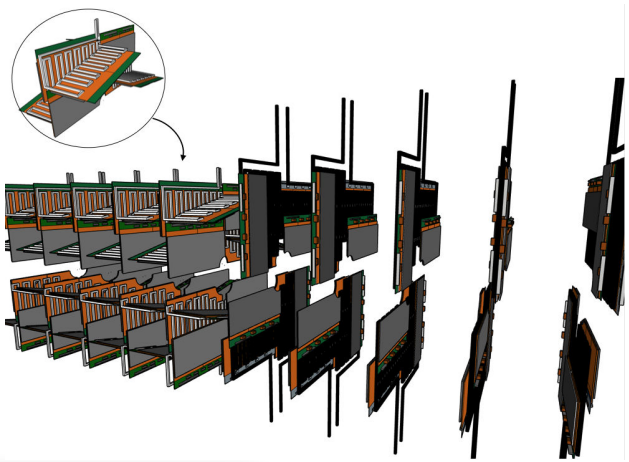


Microchannel substrate cooling NIM A 1039 (2022) 166874

- better cooling performance (1.5–3.5 K cm^2 W^{-1})
- R&D for laser etching or anodic bonding to glass to lower production cost

3D printed metal (Ti/Al) or silicon carbide

- cheaper
- more flexible design (metal)
- experience in industry
- easier to integrate with cooling plant
- more material

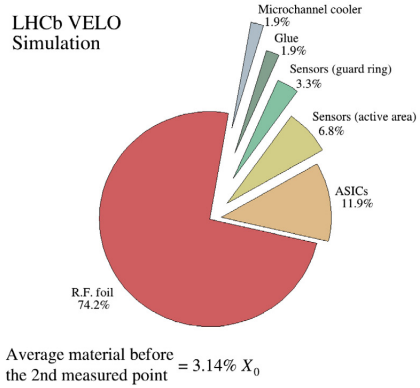


Biphasic Kr cooling for operation at < –40° under consideration
(CO_2 triple point: –56°)

RF shielding

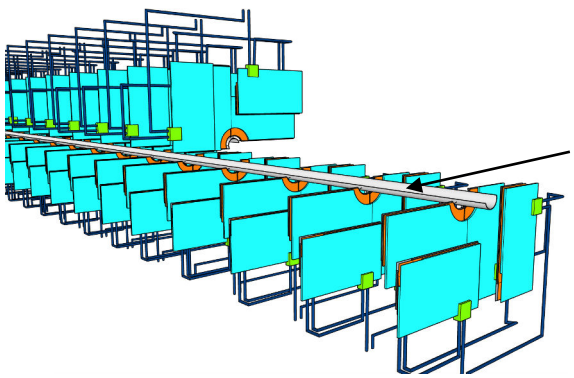
Needed to protect the sensors from the beam-induced field

- S_B → reduce X_0 before 2nd hit by 80%
- current 185 μm Al foil accounts for 75% of the material



Tensioned 20 μm Al cylindrical shield

- 1.4 skin depths
- NEG coating significantly contributes to X_0 (Ti, V, …)
- 0.4 μm amorphous carbon coating investigated



Testing the RF performance in the lab

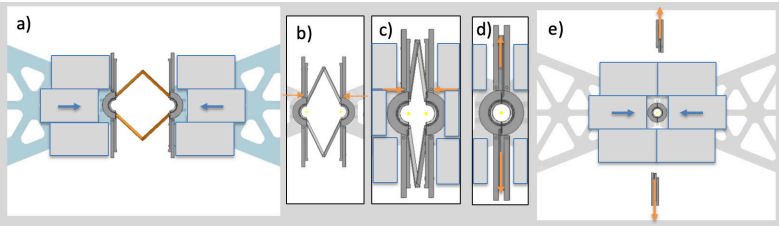
Wire mesh

- see next slide

60 μm carbon composite

- equivalent to 20 μm Al
- self-supporting
- convenient for small thicknesses and complex shapes

Additional shielding when RF foil in open position

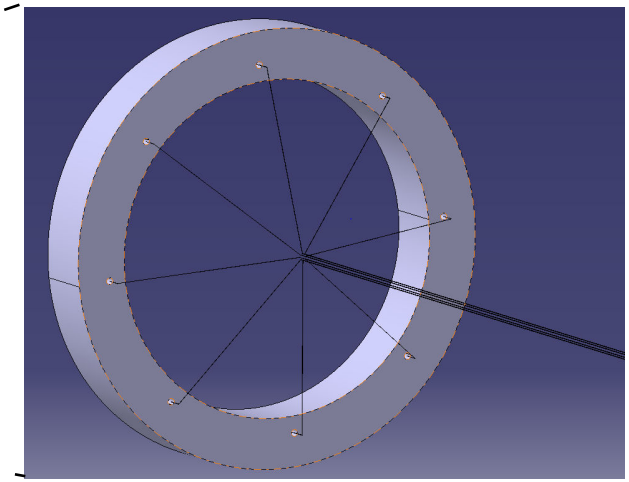


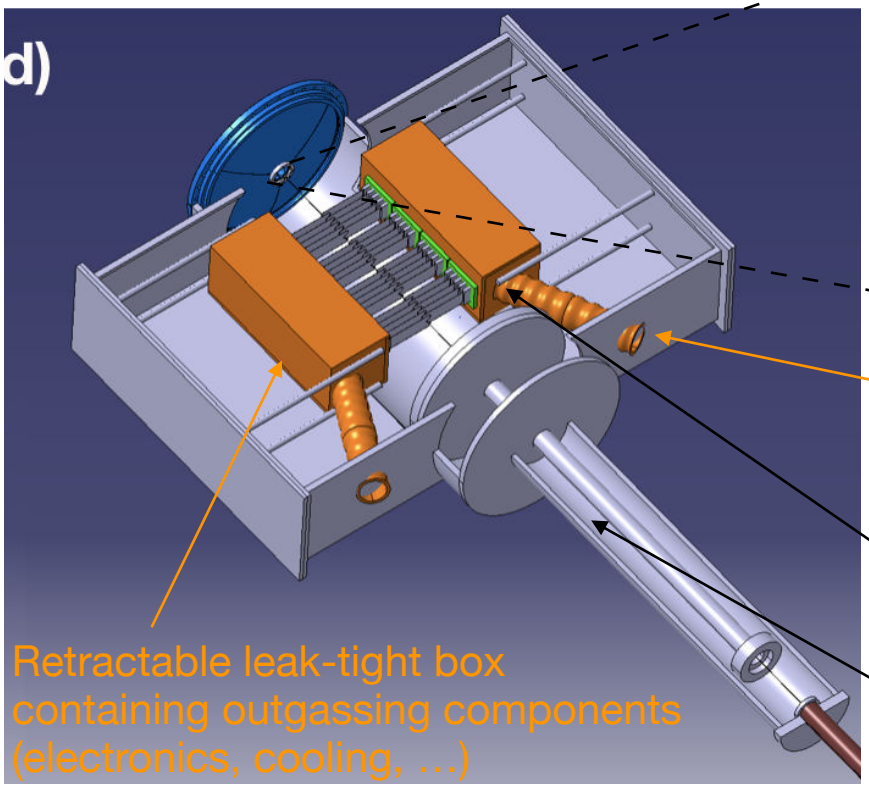
Piston and wires concept

LHC/VELO vacuum separation cannot be to maintained with thin/no RF foil. Vacuum tank must allow reasonably easy module replacements

Wire mesh

- 70 μm ⌀, 200 μm pitch
- equivalent to 20 μm cylinder
- tungsten-rhenium gold plated





Bellow for pumping and services

Active elements without outgassing components (Si, ceramics, Cu)

Piston allows to seal VELO tank from LHC vacuum to install/replace modules

Piston and wires concept

LHC/VELO vacuum separation cannot be to maintained with thin/no RF foil. Vacuum tank must allow reasonably easy module replacements

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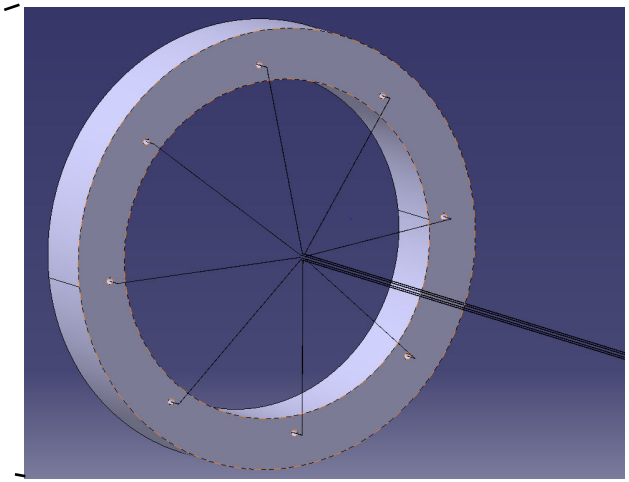
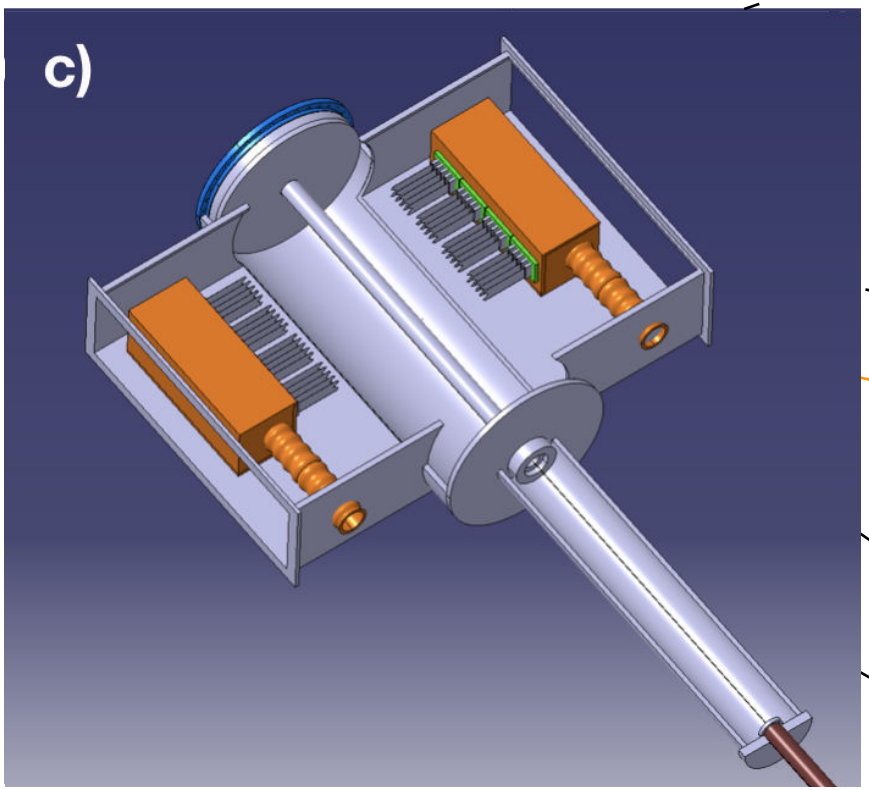




Bellow for pumping and services

Active elements without outgassing components (Si, ceramics, Cu)

Piston allows to seal VELO tank from LHC vacuum to install/replace modules

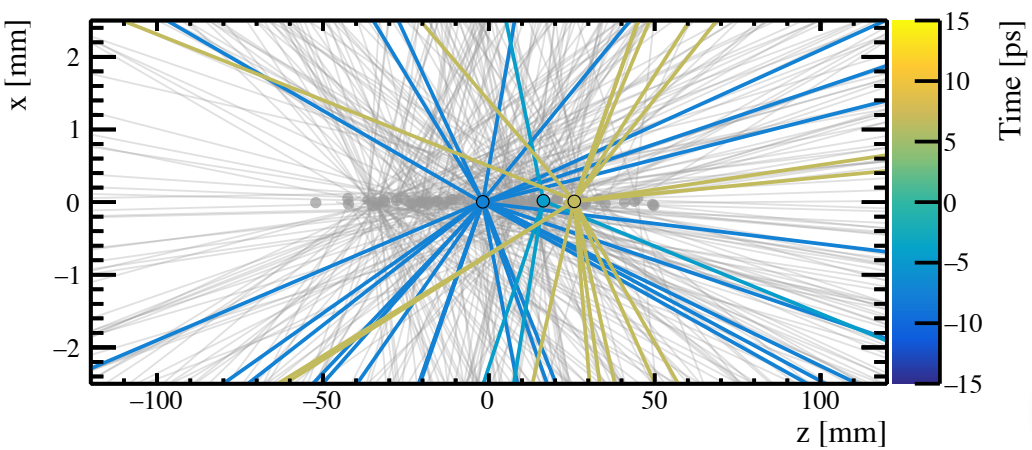
Summary

The first fully 4D tracking detector!

Operation at $\mathscr{L} = 1.5 \times 10^{34}\,\mathrm{cm}^2\,\mathrm{s}^{-1}$ (7.5× w.r.t. U1) requires developments in many different and possibly competing directions:

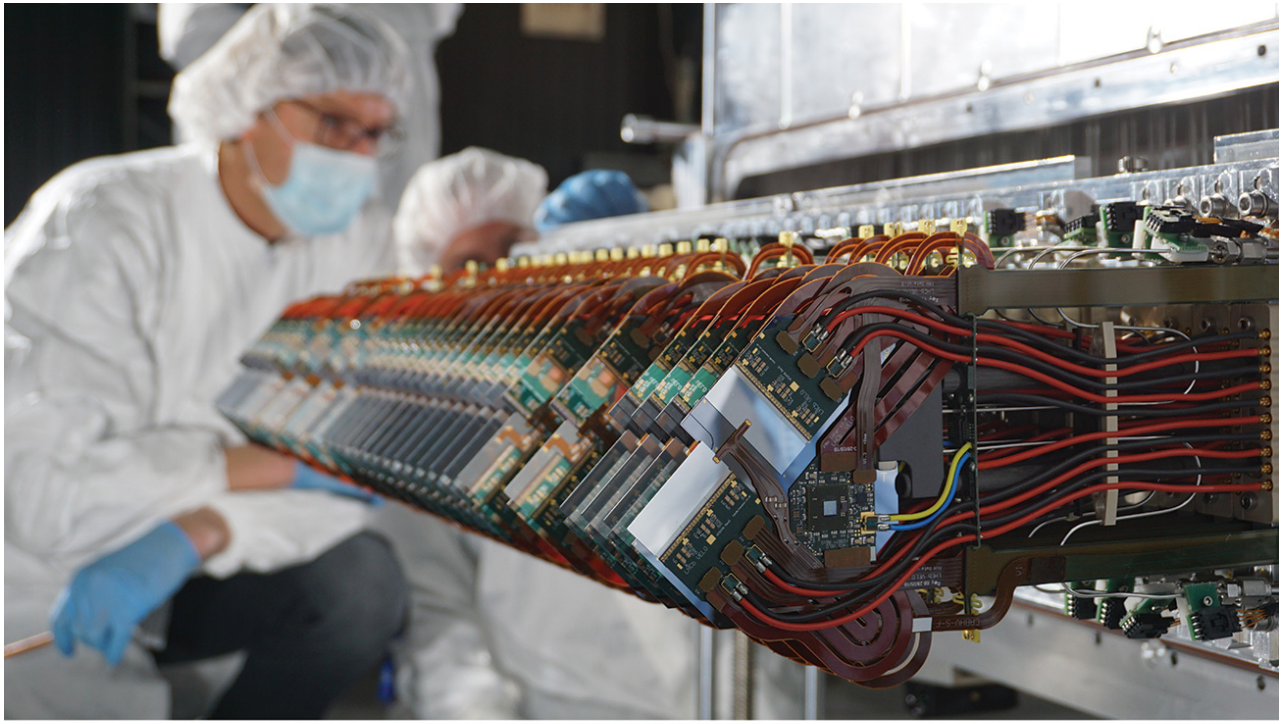
- **50 ps per-hit** resolution
- plus (at least) one of the following
  - S_A: **radiation tolerance to 6 × 10^{16} 1 MeV n_{eq} cm^{-2}** (or regular replacement of some modules); ability to deal with extreme rates (**350 kHz/pixel**, **250 Gb/s per ASIC**)
  - S_A: **80% X_0 reduction before 2nd hit** (implies **operation in the LHC vacuum**) and **9 μm hit resolution**

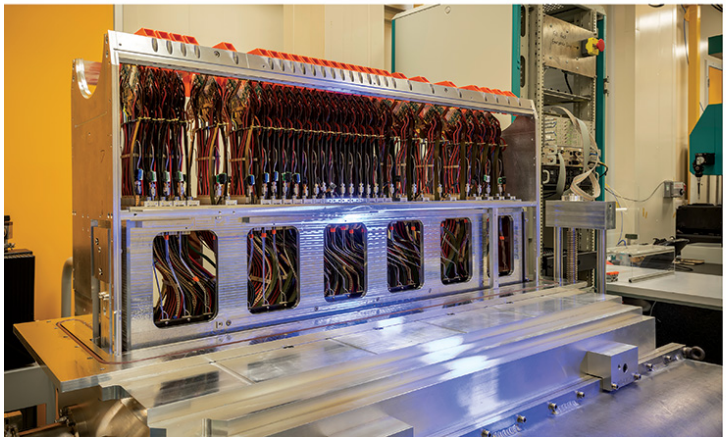
Next 2 years will be crucial to assess feasibility of necessary technologies

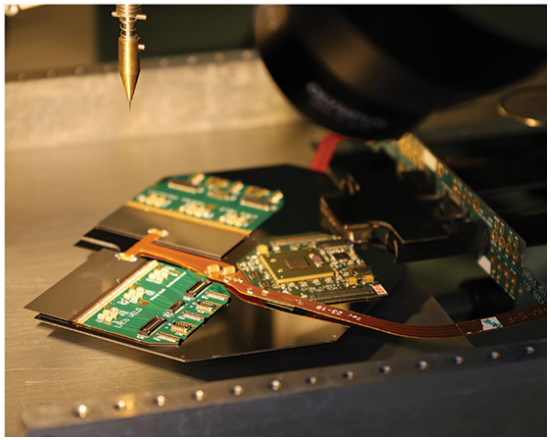


Many more details in LHCb-PUB-2022-001

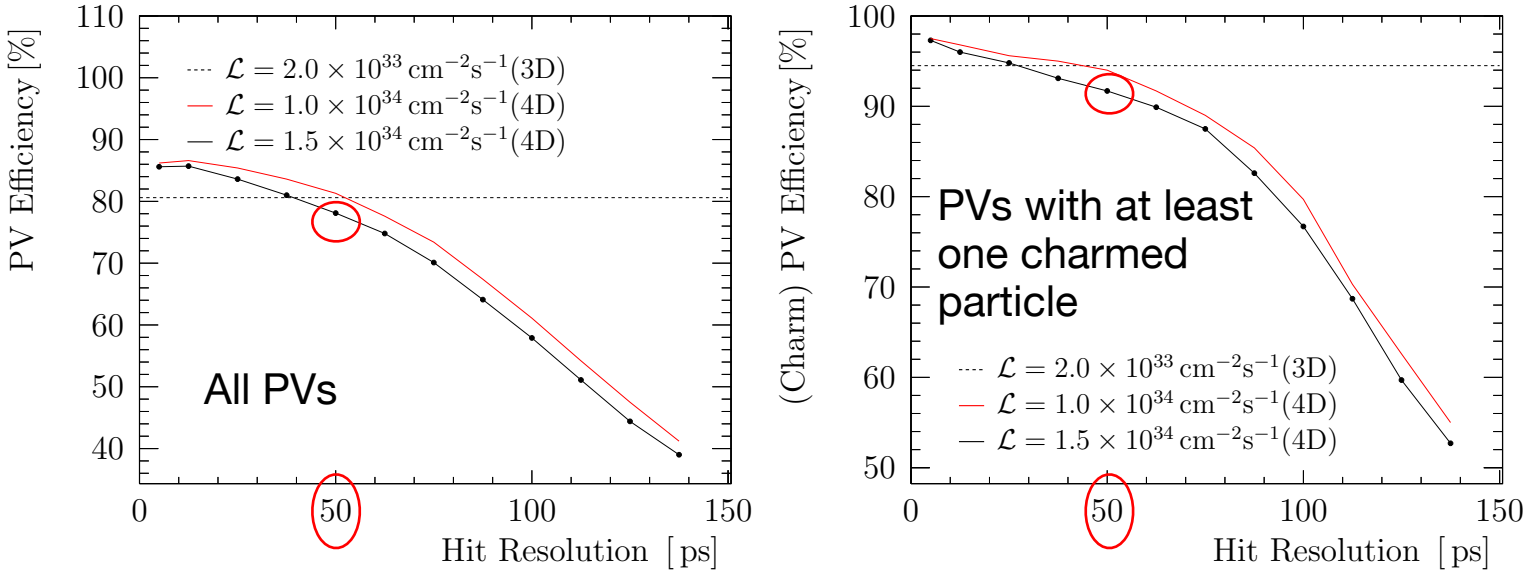
Additional slides



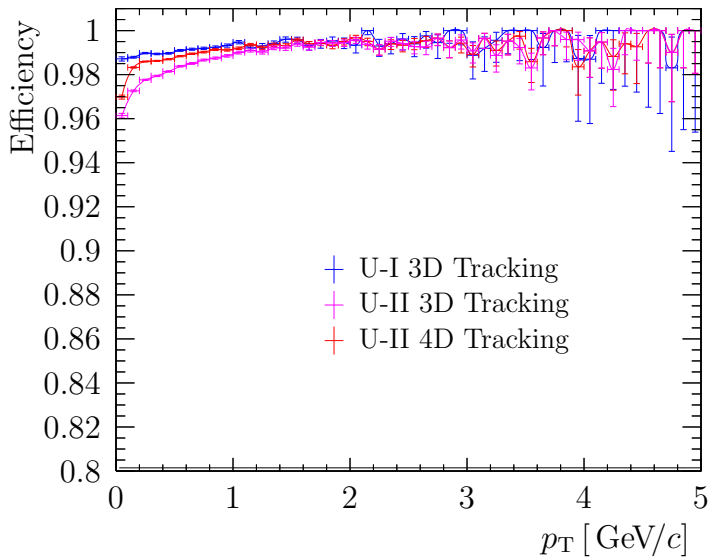


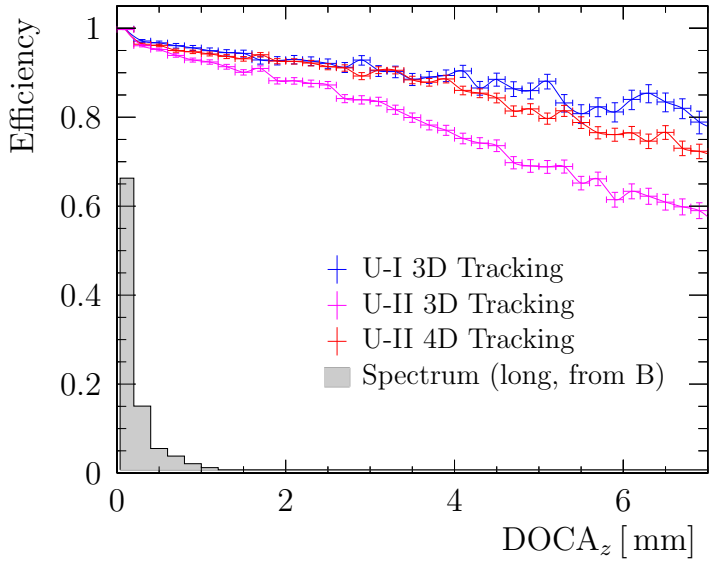


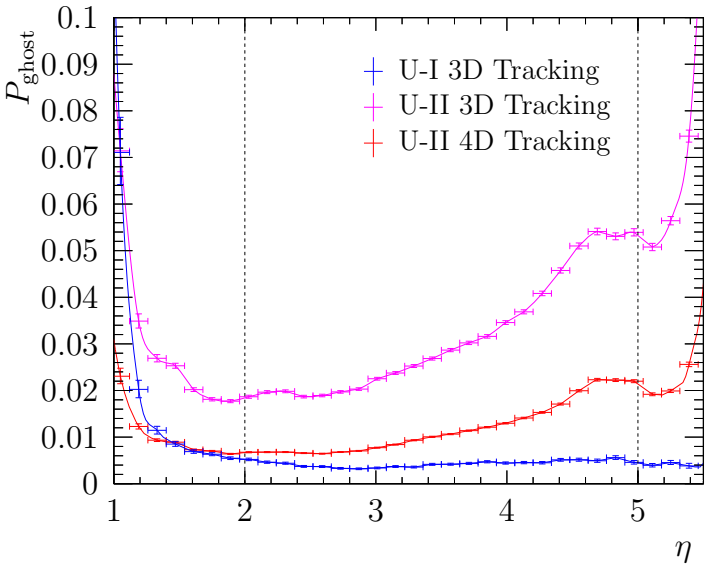
PV reconstruction efficiency vs. time resolution



Tracking efficiency

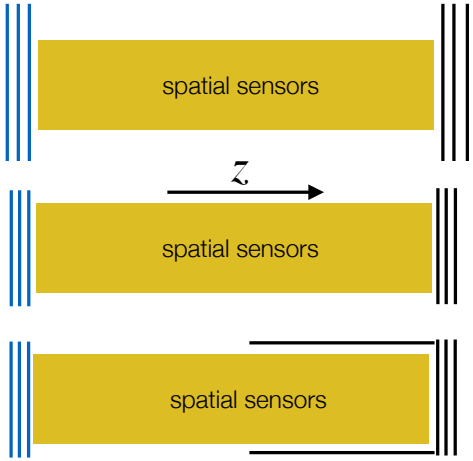






	Configuration	$\varepsilon_{\text{velo}}$ [%]	$\varepsilon_{\text{long}}$ [%]	P_{ghost} [%]
U1-like	Loose 3D	96.6	98.1	3.2
	4D	97.2	98.7	1.1
U1-like no RF foil	Loose 3D	97.8	98.9	2.3
	4D	98.0	99.2	1.0

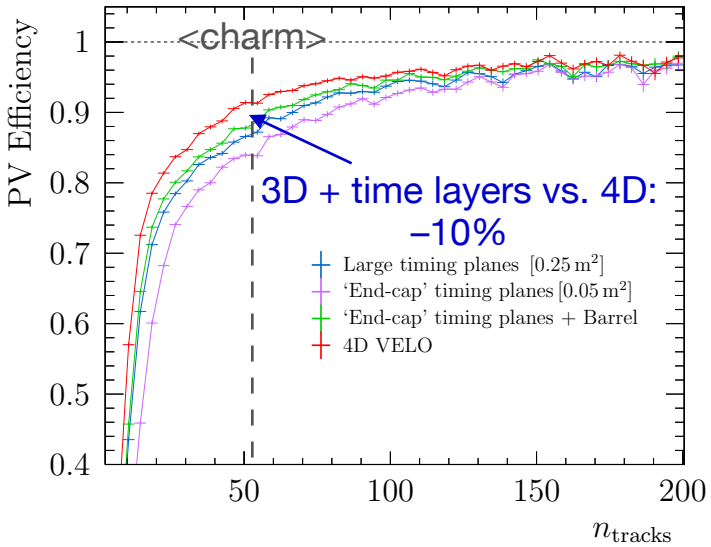
Why not just timing layers?

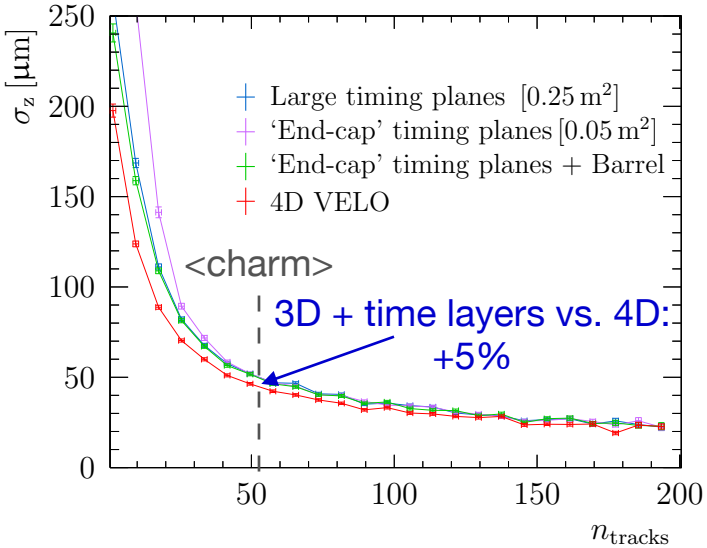


3D VELO + timing layers

- at least 3 layers for efficiency and and combinatorics removal
- larger pitch (100 μm)
- 25 ps per layer
- lower radiation tolerance acceptable
- very large area required compared to VELO ($$$)

	VELO *(à la U1)*	Large endcaps	Endcaps	Endcaps + barrel
Covered range	2 < η < 5	2 < η < 5	2.8 < η < 5	2 < η < 5
Area [m²]	**0.15**	**1**	**0.3**	**1.35**

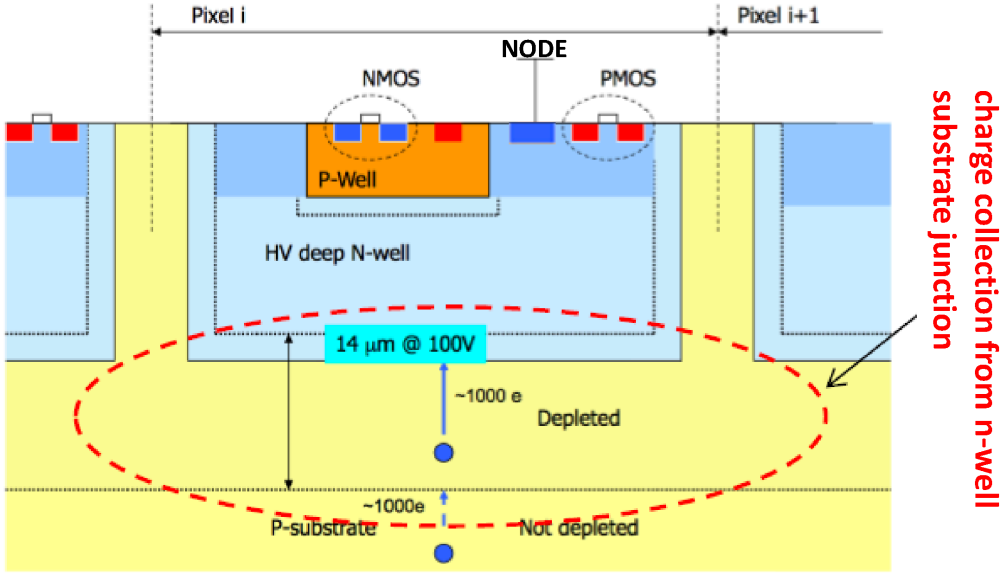




4D VELO

- 50 ps single-hit resolution
- better performance (efficiency, ghost rate)
- lower cost
  - single sensor technology and ASIC
  - easier event reconstruction

HV-CMOS MAPS



- Integrated electronics, lower cost
- Low capacitance & noise → 50 ps res.
- Low signal (thin depletion layer)
- Radiation hardness proven only to 10^{15} 1 MeV n_{eq} cm^{-2}
- Low material (but VELO functionality will require the combination with an ASIC…)
- Might have problems in coping with the rate

Timepix4 ASIC

JINST 17 (2022) 01, C01044
Xavi Llopart's CERN seminar

			Timepix3 (2013)	Timepix4 (2019)	
Technology			130nm – 8 metal	65nm – 10 metal	
Pixel Size			55 x 55 µm	55 x 55 µm	
Pixel arrangement			3-side buttable 256 x 256	4-side buttable 512 x 448	
Sensitive area			1.98 cm^2	6.94 cm^2	3.5x
Readout Modes	Data driven (Tracking)	Mode	TOT and TOA		
		Event Packet	48-bit	64-bit	33%
		Max rate	0.43×10^6 hits/mm^2/s	**3.58×10^6 hits/mm^2/s**	8x
		Max Pix rate	1.3 KHz/pixel	**10.8 KHz/pixel**	
	Frame based (Imaging)	Mode	PC (10-bit) and iTOT (14-bit)	CRW: PC (8 or 16-bit)	
		Frame	Zero-suppressed (with pixel addr)	Full Frame (without pixel addr)	
		Max count rate	~0.82×10^9 hits/mm^2/s	~5×10^9 hits/mm^2/s	
TOT energy resolution			< 2KeV	**< 1Kev**	2x
TOA binning resolution			1.56ns	**195ps**	8x
TOA dynamic range			409.6 µs (14-bits @ 40MHz)	**1.6384 ms** (16-bits @ 40MHz)	4x
Readout bandwidth			≤5.12Gb (8x SLVS@640 Mbps)	**≤163.84 Gbps (16x @10.24 Gbps)**	32x
Target global minimum threshold			<500 e^-	<500 e^-	

28.2 x 25.6 mm^2

TOT = Time Over Threshold
TOA = Time Of Arrival