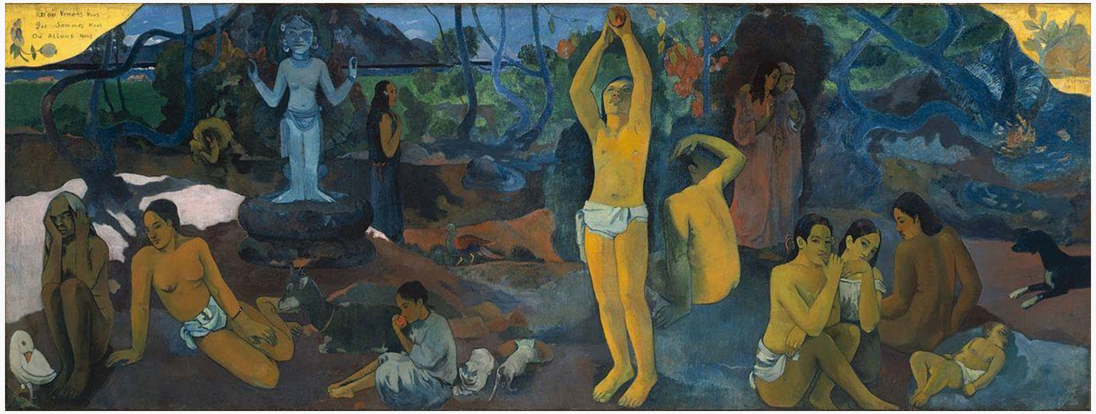


LHCb silicon detectors according to Gauguin

TOMASZ SZUMLAK

AGH-UST

JAGIELLONIAN UNIVERSITY SEMINAR ON PARTICLE PHYSICS PHENOMENOLOGY AND EXPERIMENTS

JAN 23, 2023

LHCb – short historical view…

LHCb before Run 1

LHCb after Run 2 (a lot of radiation damage too…)

Run 3 / 4 LHCb

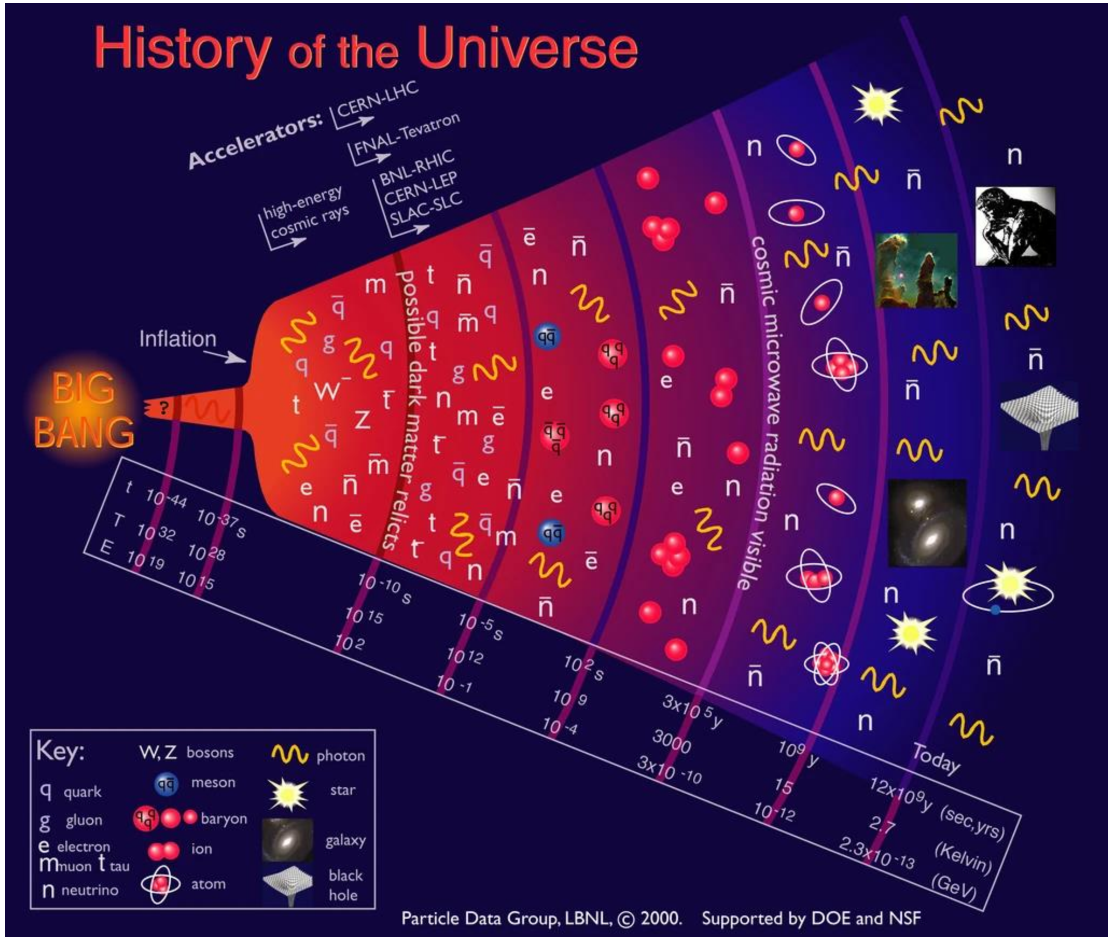
LHCb – short historical view…

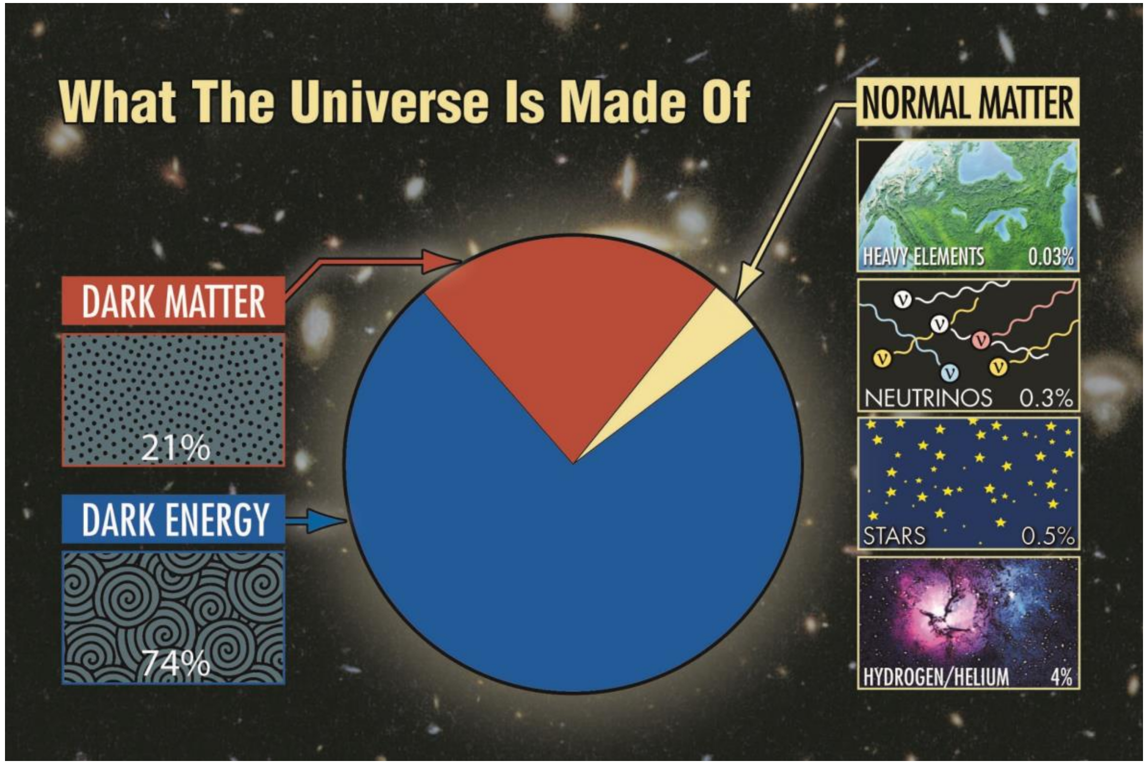
Upgrade I

Upgrade II

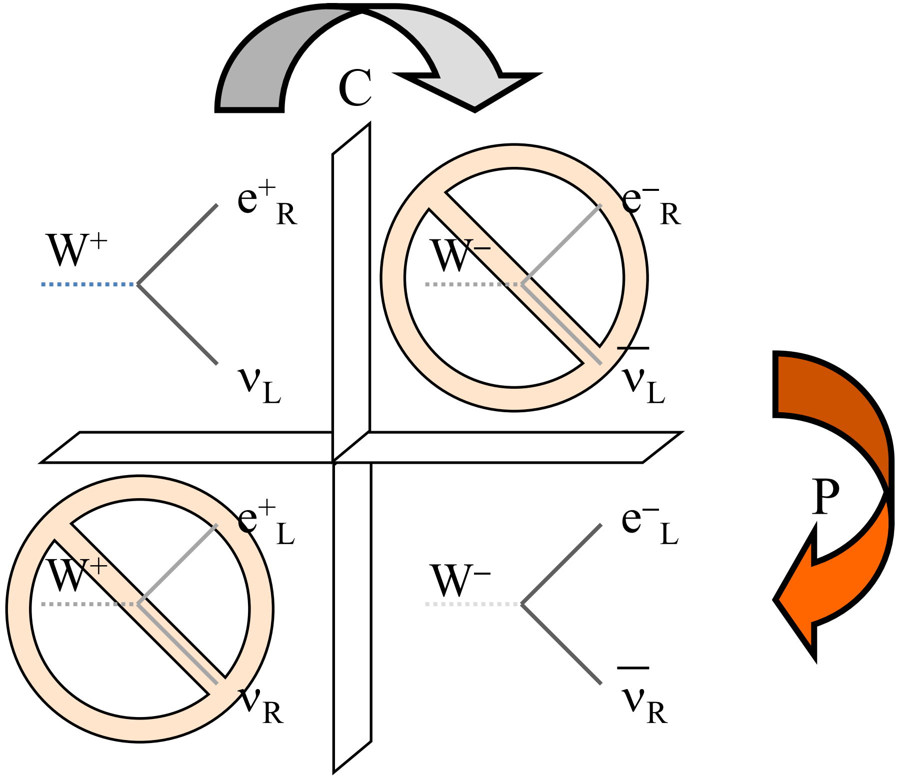
We started here…

Why we are here at all?





What's the matter with anti-matter...?

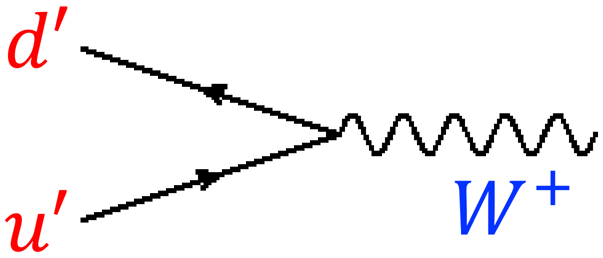


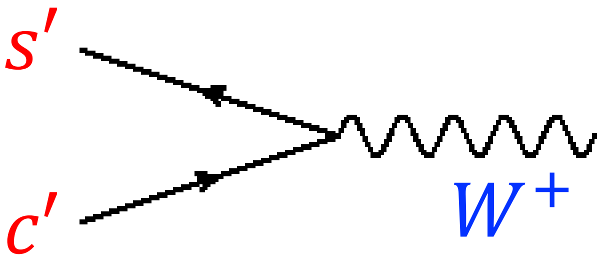
Weak interactions violate maximally space parity symmetry

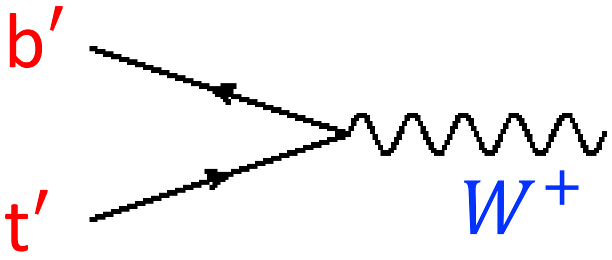
- $\boldsymbol{SU_L(2)}$ symmetry for massless quarks

$$\mathcal{L}_W = \frac{g}{\sqrt{2}} u'_L \, \gamma_\mu \, W^\mu \, d'_L \qquad \text{x3 !}$$

- Flavour universality – interactions do not depend on the family.
  - Cannot distinguish d' from s'

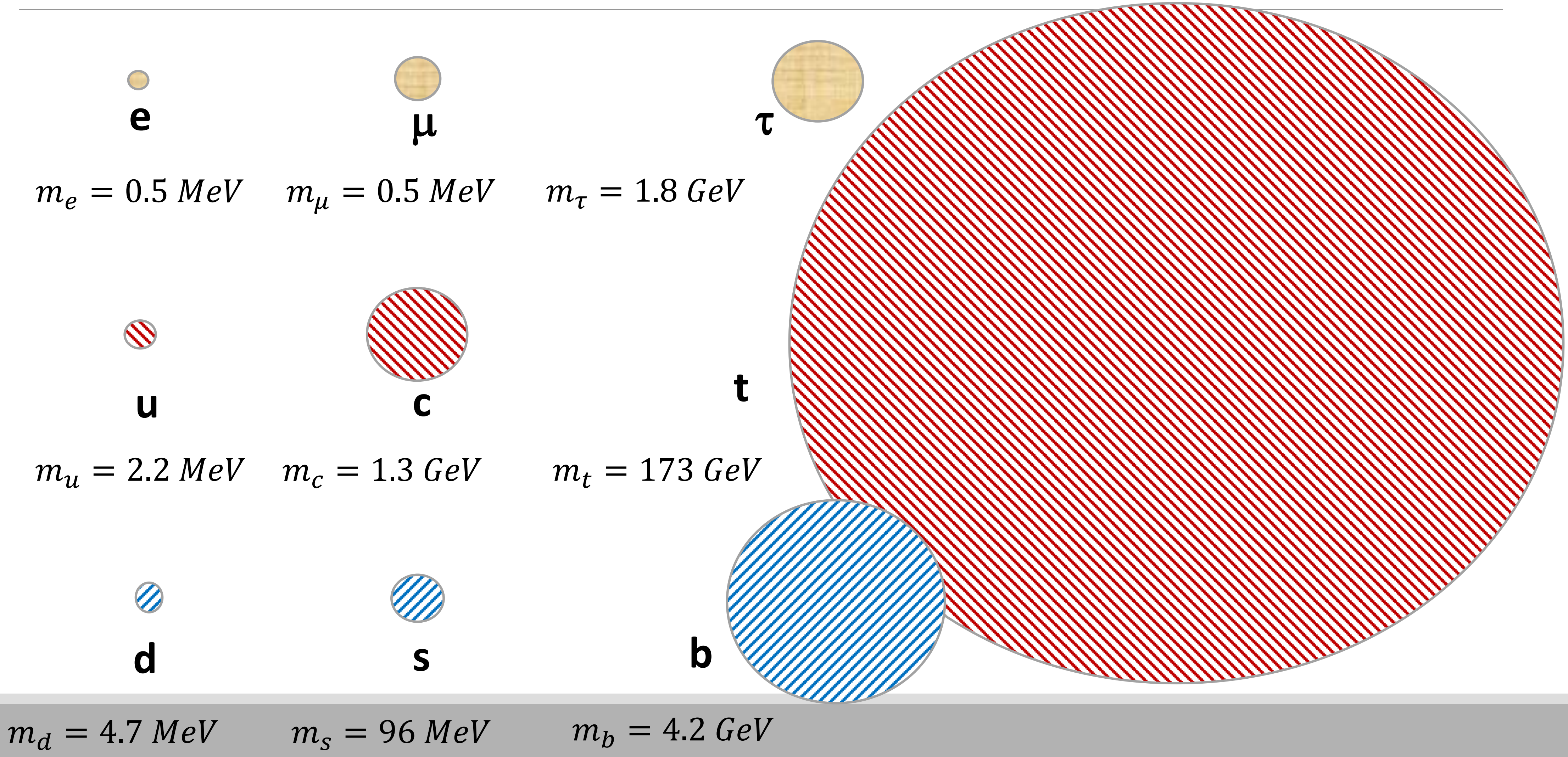






- No CP violation possible!!
  - Now we add the mass to the picture!

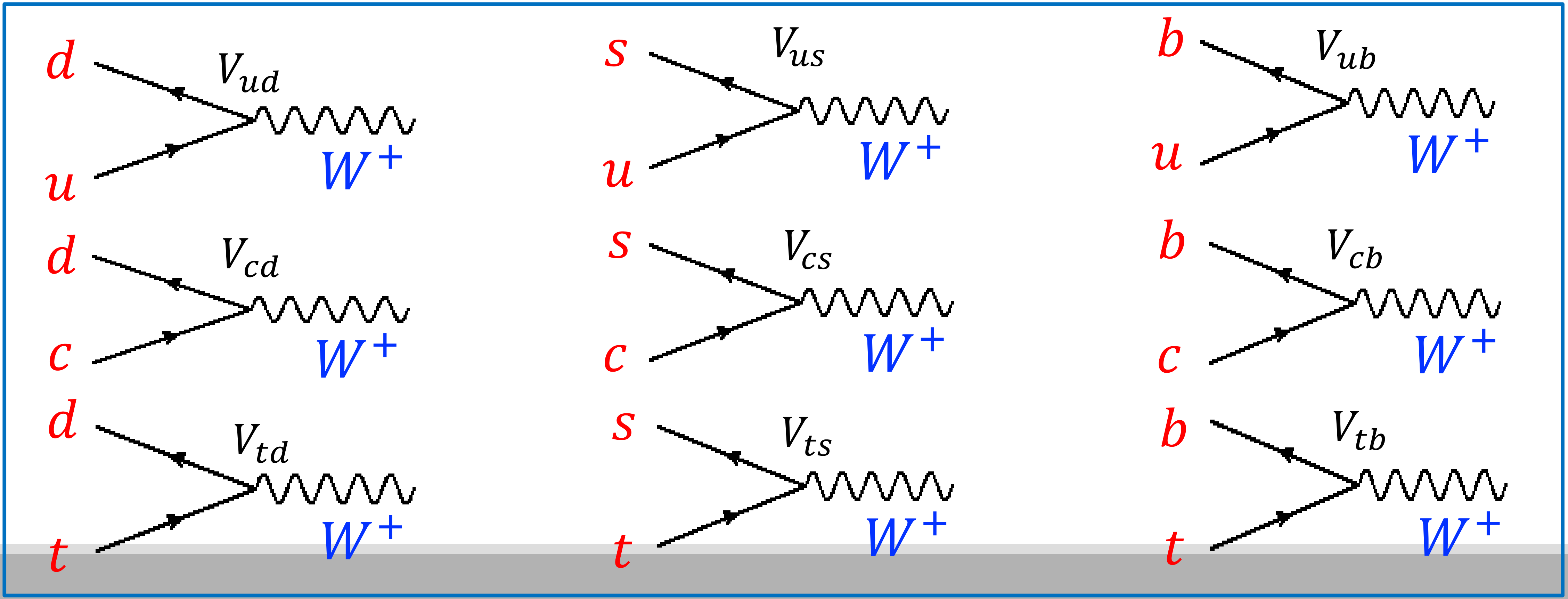
Mass hierarchy problem…



And we have 9 effective couplings

$$\mathcal{L}_W = \frac{g}{\sqrt{2}} u'_L \gamma_\mu W^\mu d'_L \longrightarrow \mathcal{L}_W = \frac{g}{\sqrt{2}} \boldsymbol{V_{CKM}} u_L \gamma_\mu W^\mu d_L$$

(Interaction base) (Mass base)

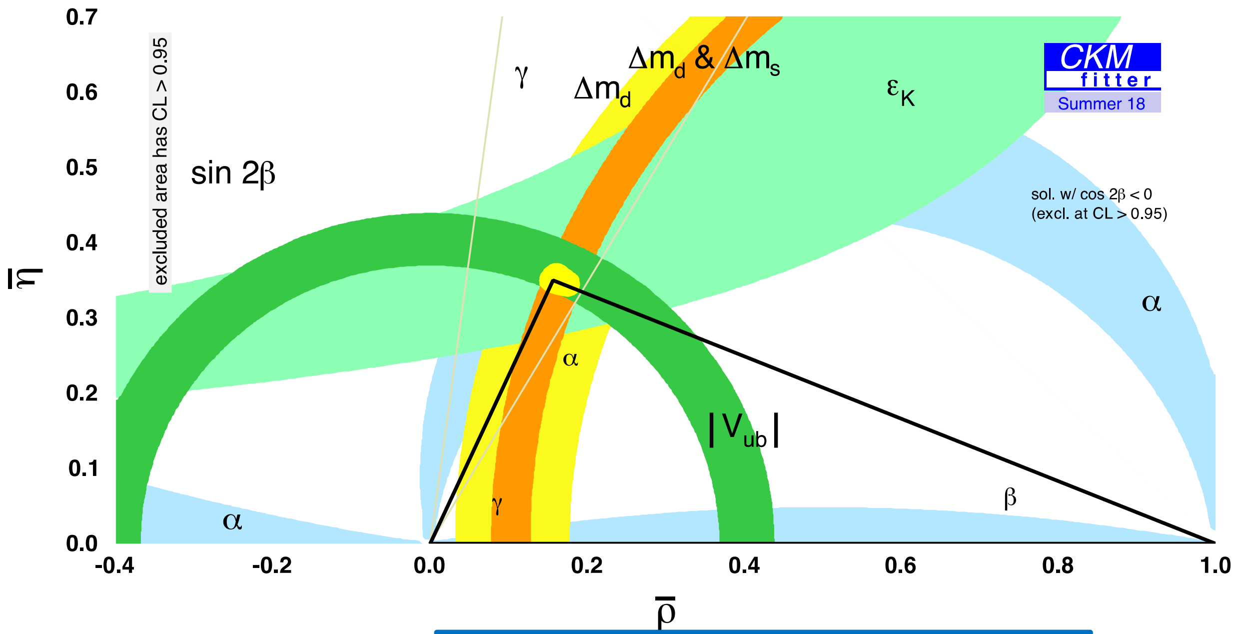


Need for 3 generations

Unitarity: $V_{CKM}V_{CKM}^{\dagger} = 1$

V_{CKM}:

	d	s	b
u	V_{ud}	V_{us}	V_{ub}
c	V_{cd}	V_{cs}	V_{cb}
t	V_{td}	V_{ts}	V_{tb}

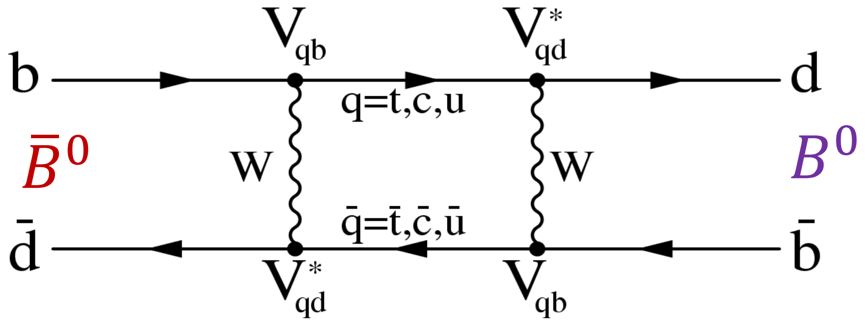


- Unitarity triangle view: V_{CKM} =

$$\begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}|e^{-i\gamma} \\ -|V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}|e^{-i\beta} & -|V_{ts}|e^{i\beta_s} & |V_{tb}| \end{pmatrix}$$

CP violation:
➔ Surface $\neq 0$
➔ Non-zero CP-phases.

Flavour oscillation – LHCb crucible



$$\bar{M}^0 - M^0$$

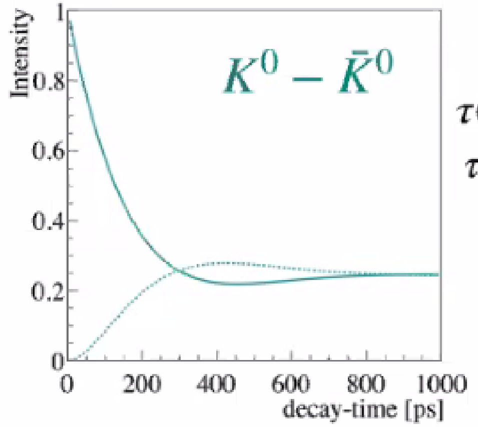
$$\Delta m = 2\,\Re\sqrt{\left(M_{12} - \frac{i}{2}\Gamma_{12}\right)\left(M^*_{12} - \frac{i}{2}\Gamma^*_{12}\right)}$$

$$\Delta\Gamma = 4\,\Im\sqrt{\left(M_{12} - \frac{i}{2}\Gamma_{12}\right)\left(M^*_{12} - \frac{i}{2}\Gamma^*_{12}\right)}$$

$$i\frac{\partial}{\partial t}\psi(t) = \begin{pmatrix} M - \frac{i}{2}\Gamma & M_{12} - \frac{i}{2}\Gamma_{12} \\ M^*_{12} - \frac{i}{2}\Gamma^*_{12} & M - \frac{i}{2}\Gamma \end{pmatrix}\psi(t)$$

B^0 : $\Delta\Gamma \approx 0$, $|q/p| = 1$
B^0_s : $\Delta\Gamma/\Delta m \ll 1$, $|q/p| = 1$
K^0 : $\Delta\Gamma/\Delta m \simeq 1$, $|q/p| - 1 \simeq 10^{-3}$

The same physics, different constants…

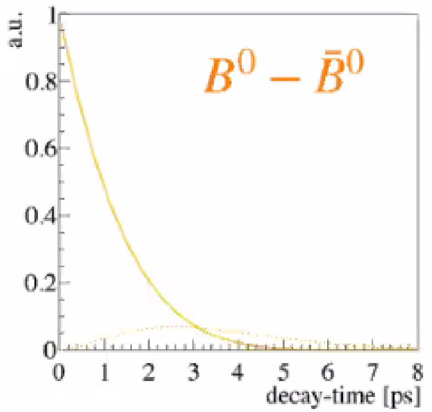


Very different lifetime:

$\tau(K_S^0) \sim 0.9 \times 10^{-10}$

$\tau(K_L^0) \sim 0.5 \times 10^{-7}$

the oscillation period longer than the K_S lifetime, but K_L^0 exceptionally long



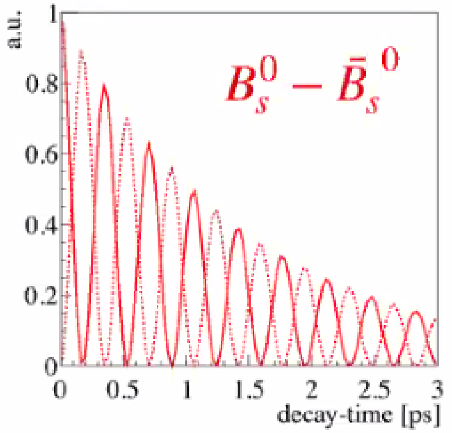
Oscillations

$\Delta m \sim 0.5\ ps^{-1}$

Lifetime

$\tau(B^0) \sim 1.5\ ps$

The same order of magnitudes

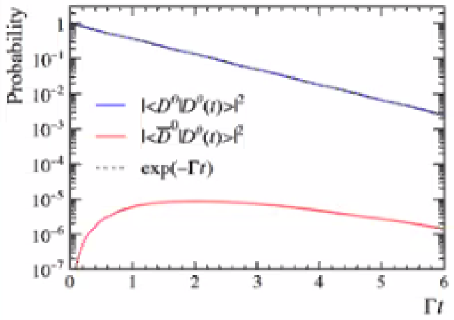


Very fast oscillations

$\Delta m_s > 15\ ps^{-1}$

$\tau(B_s^0) \sim 1.5\ ps$

Non-zero $\Delta\Gamma_s$



$D^0 - \bar{D}^0$

Very slow oscillations

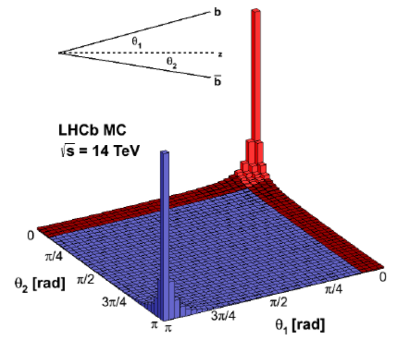
$\Delta m \sim 10^{-3}\ ps^{-1}$

Very short lifetime

$\tau(D^0) \sim 0.4\ ps$

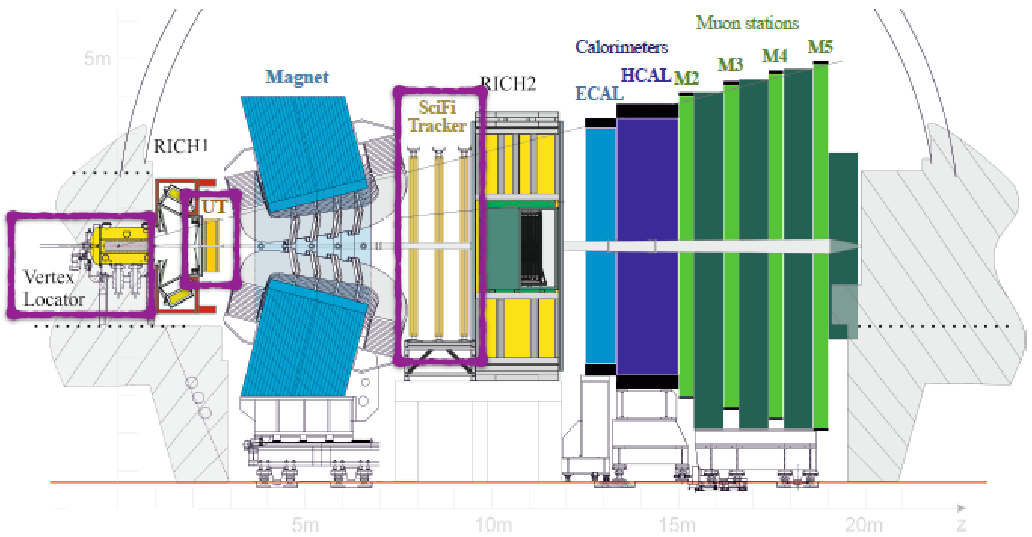
D^0 decays before has a chance to oscillate

Large Hadron Collider beauty



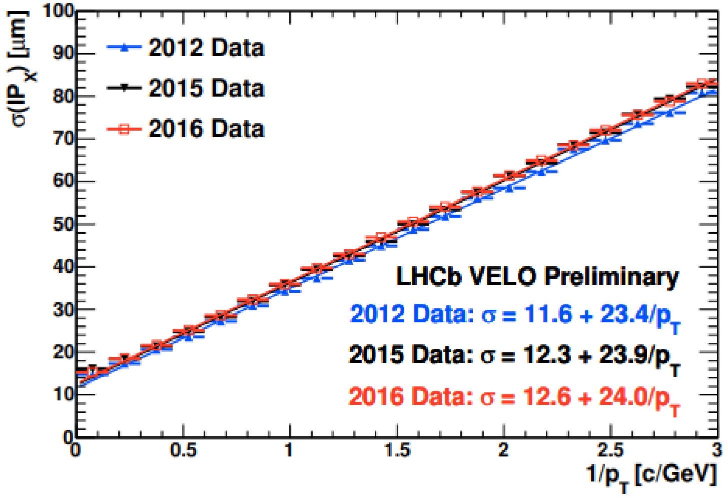
- After Run 1 and Run 2 LHCb proved to be the **General-Purpose Forward Detector**
  - a single arm spectrometer – not your typical geometry for a collider based experiment!
  - fully instrumented in the pseudo-rapidity range of $(2 < \eta < 5)$
  - can register up to 40% of all heavy quarks with only 4% of the solid angle coverage!
  - very precise measurements in beauty and charm sector and New Physics search
  - excellent performance in Run 1 and Run 2:
    - momentum resolution $\frac{\Delta p}{p} \sim \mathbf{0.5\%}$ **@20 [GeV]**
    - impact parameter resolution ~ $\mathbf{15 + \frac{29}{p_T}}$ $[\mu m]$
    - time resolution $\sigma_t \sim$ **45 [fs]** for $B_s \to J/\psi\varphi$
  - In time, the physics programme has been extended to cover exclusive processes, QCD studies, Electro-weak physics, direct NP searches and heavy ion physics

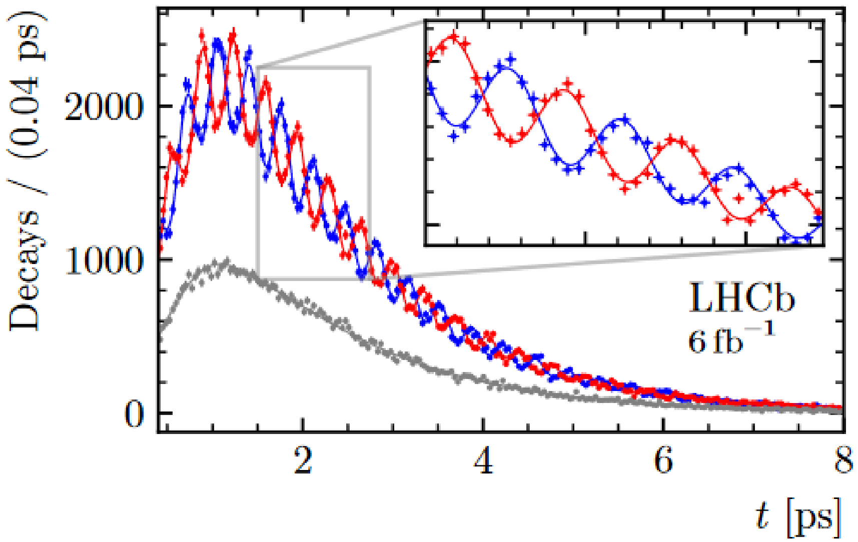
Int. J. Mod. Phys. A30 (2015) 1530022

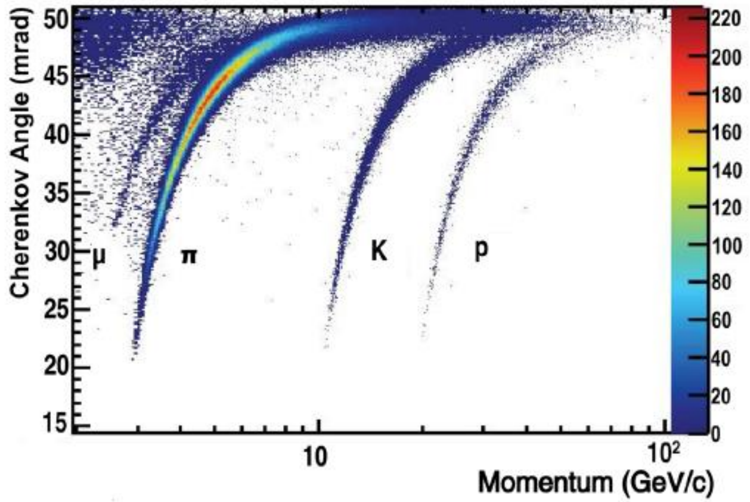


LHCb performance

Int. J. Mod. Phys. A 30, 1530022 (2015)
LHCb-PROC-2018-020
https://arxiv.org/abs/2104.04421 (2021)







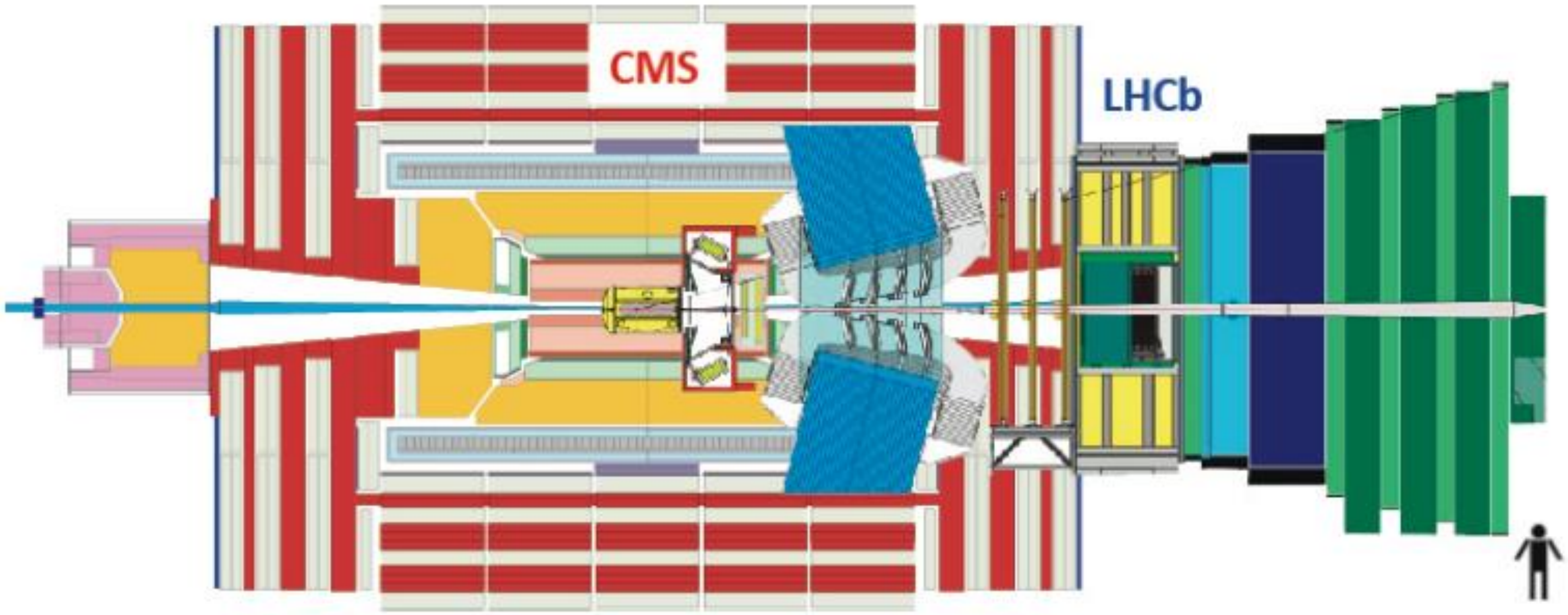
- ❑ Geometrical Impact parameter resolution
- ❑ **Separation of the primary and secondary vertices**

- ❑ Lifetime resolution
- ❑ **Can resolve fast $B_s - \bar{B}_s$ oscillations**

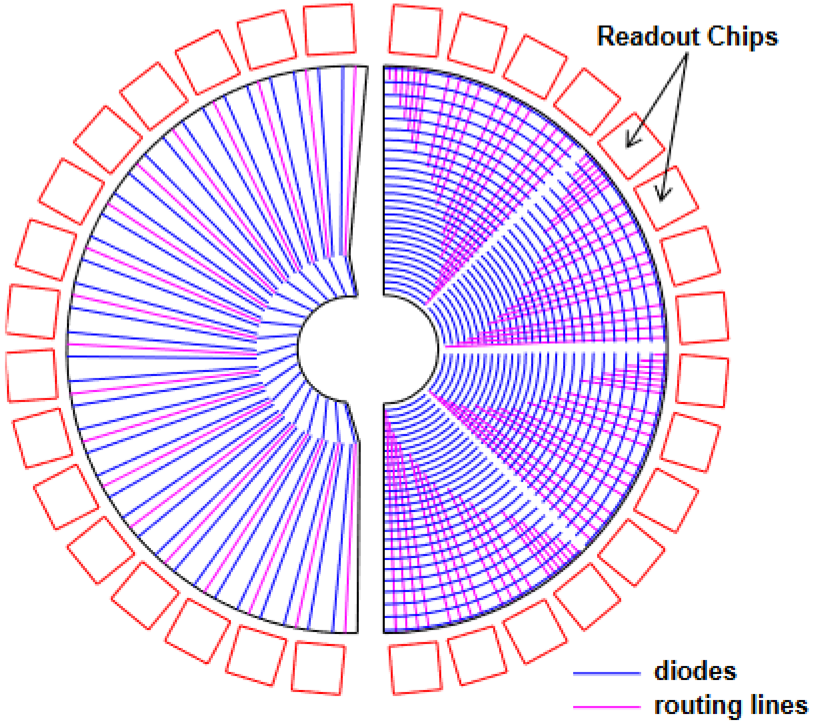
- ❑ Excellent particle identification
- ❑ **Separation between charged chadrons, $\gamma, e^{\pm}, \mu^{\pm}$**

LHCb detector

- Non typical geometry, but a typical composition…



Idea of „natural geometry” for LHCb vertex detector



- **Baseline design of sensors:**

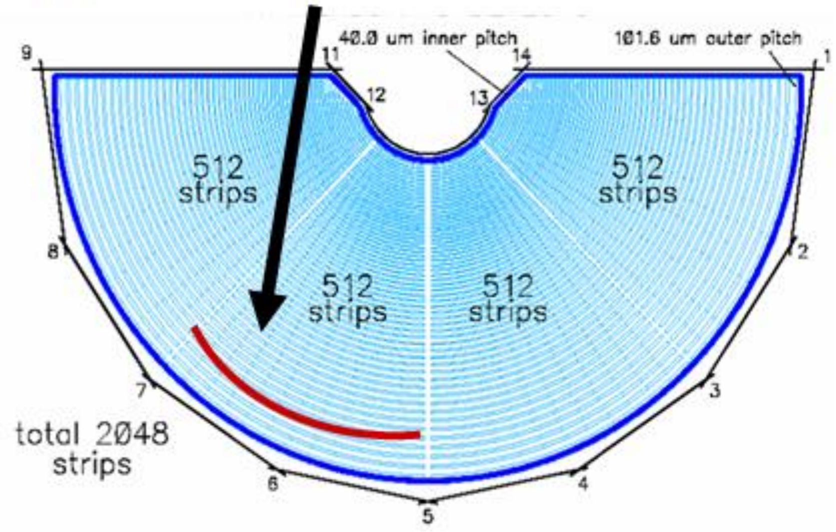
- Active area 8mm to 42 mm
- Smooth pitch variation from inner (40μm) to outer radii (100μm)
- 2nd metal layer to route signal to chips

- n^{+}-on-n DOFZ
- Analogue readout 40MHz

Sensors drawing

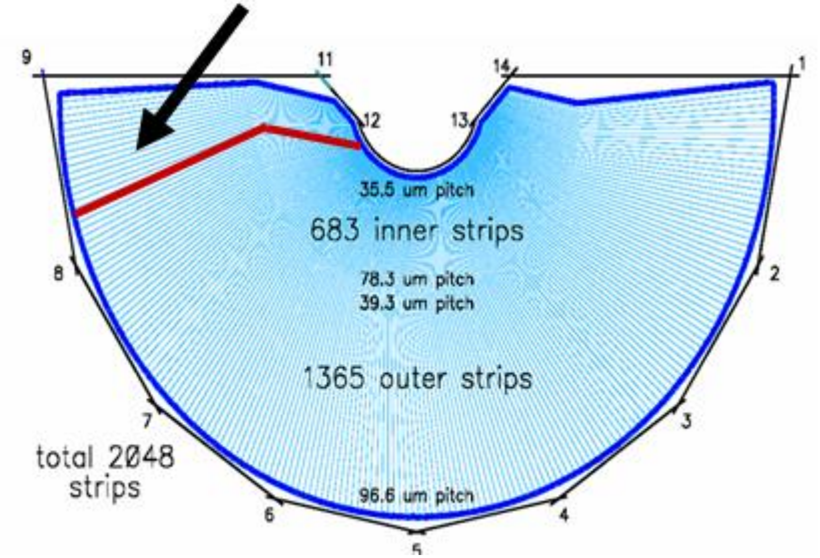
R-measuring sensor:

(concentric strips)

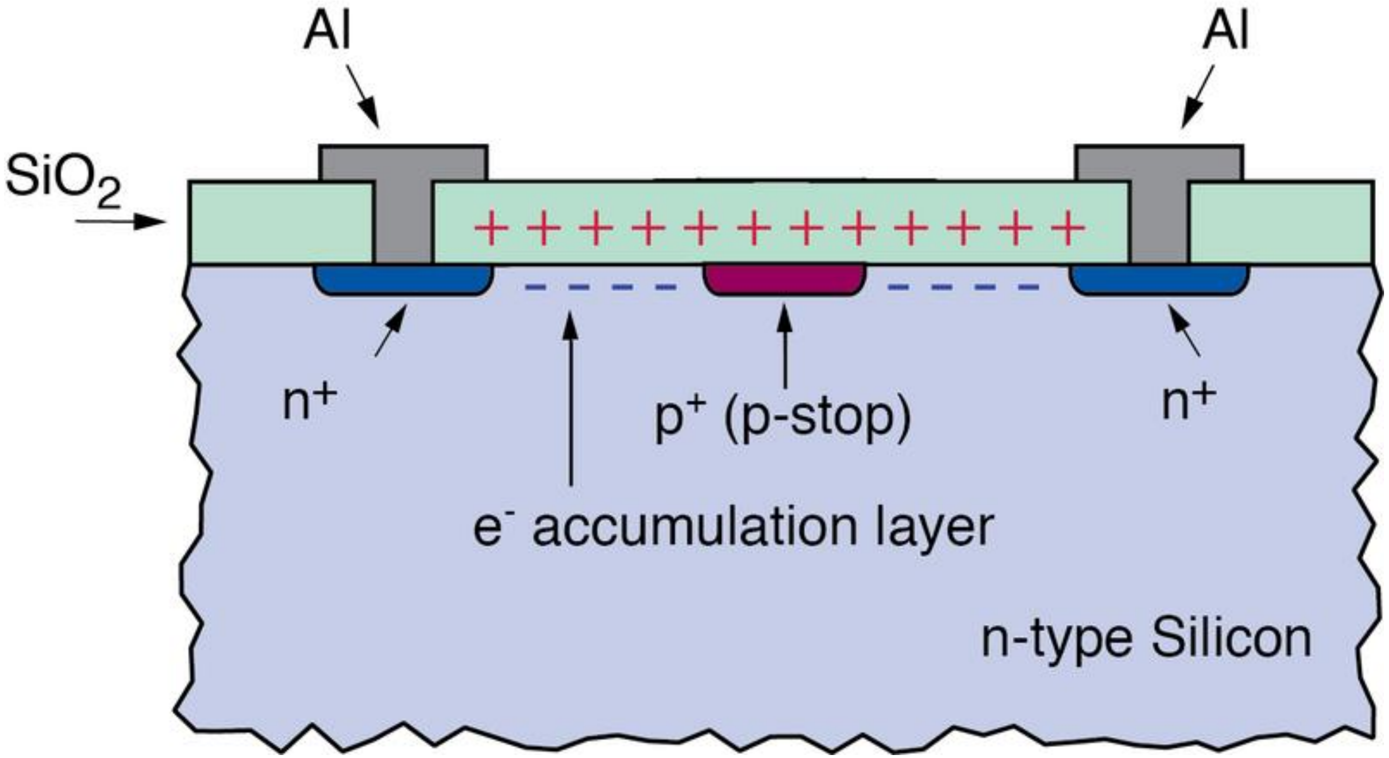


Φ–measuring sensor:

(Radial strips with a stereo angle)

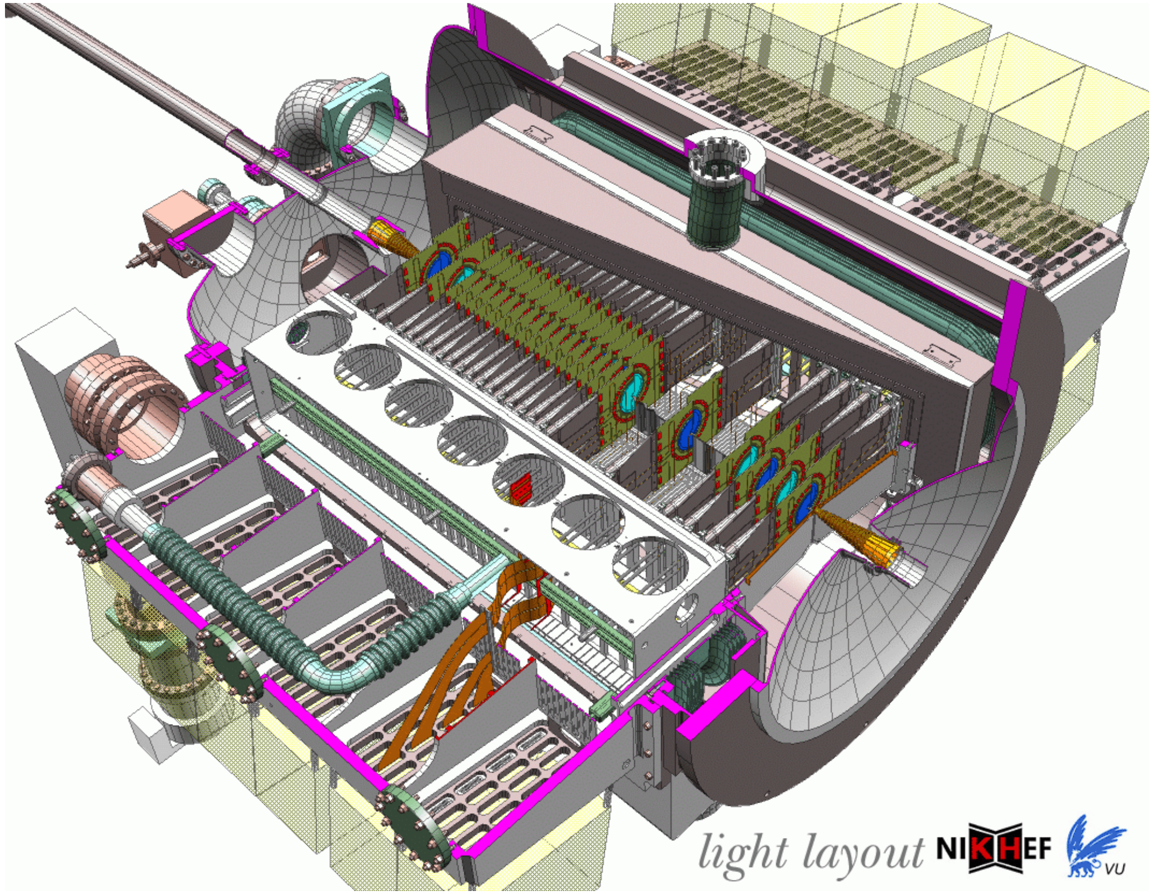


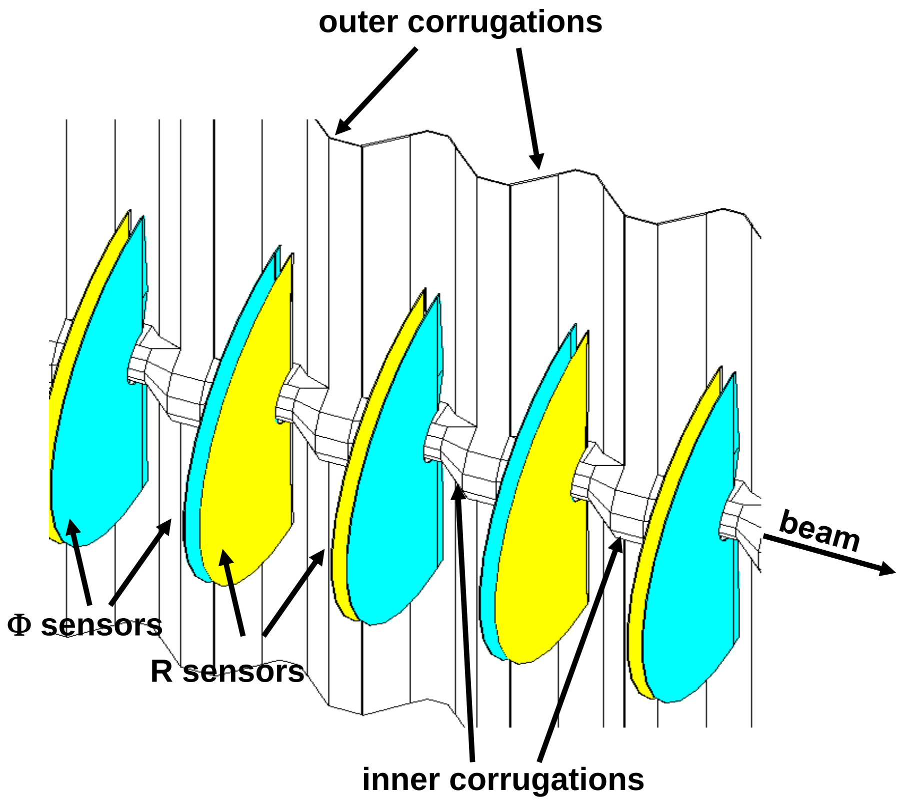
Cross section of a VELO sensor



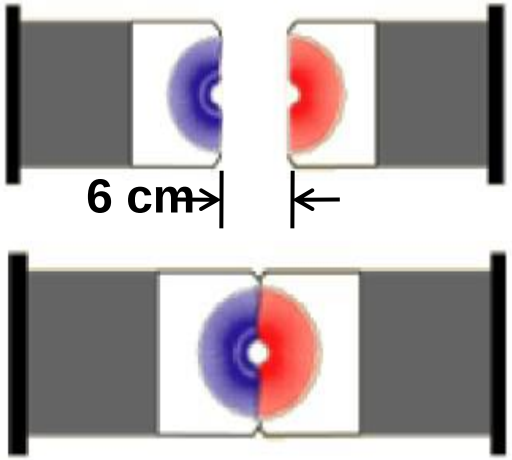
http://www.scholarpedia.org/article/File:Si_p-stops.png

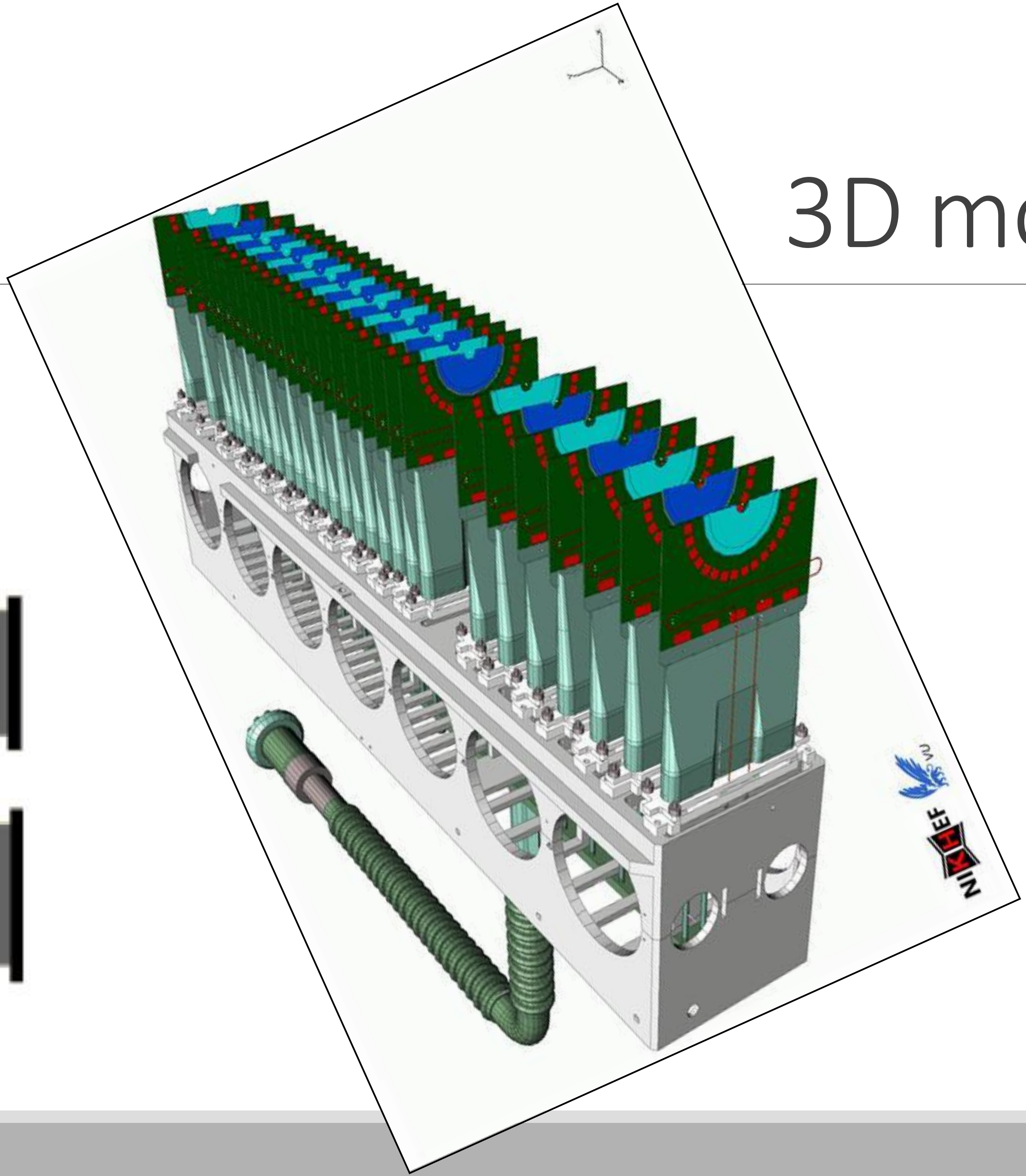
VELO strip in its glory





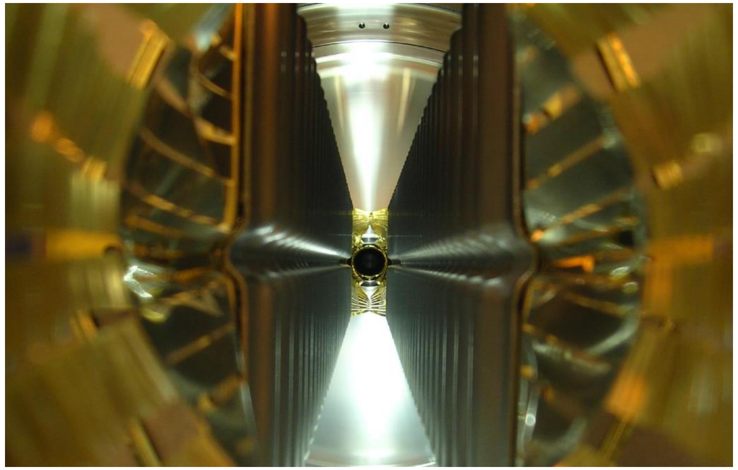
VELO half 3D model…



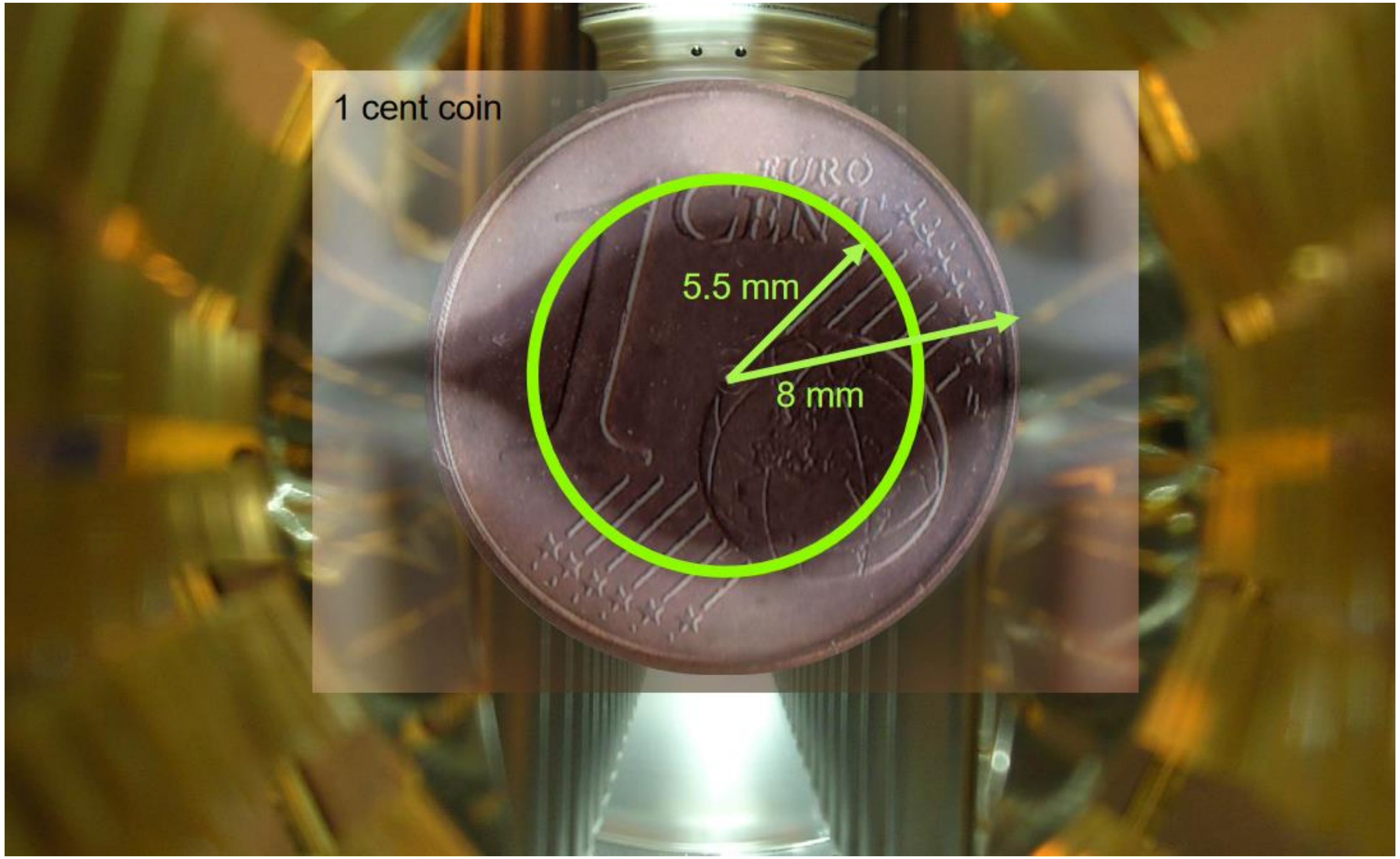


Corrugated foil

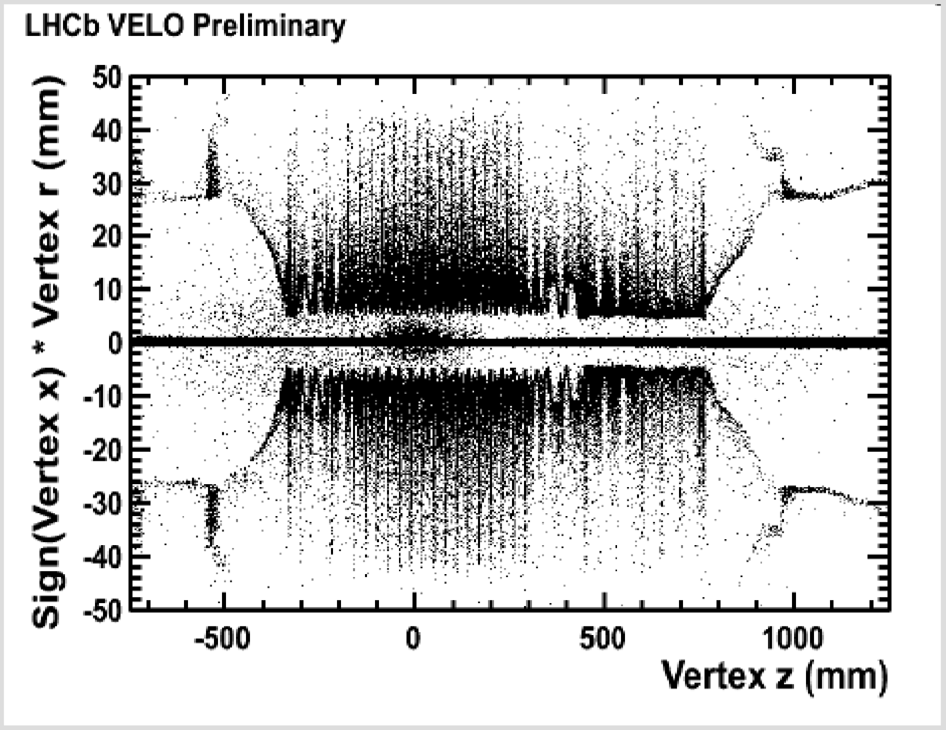
VELO half and the real deal

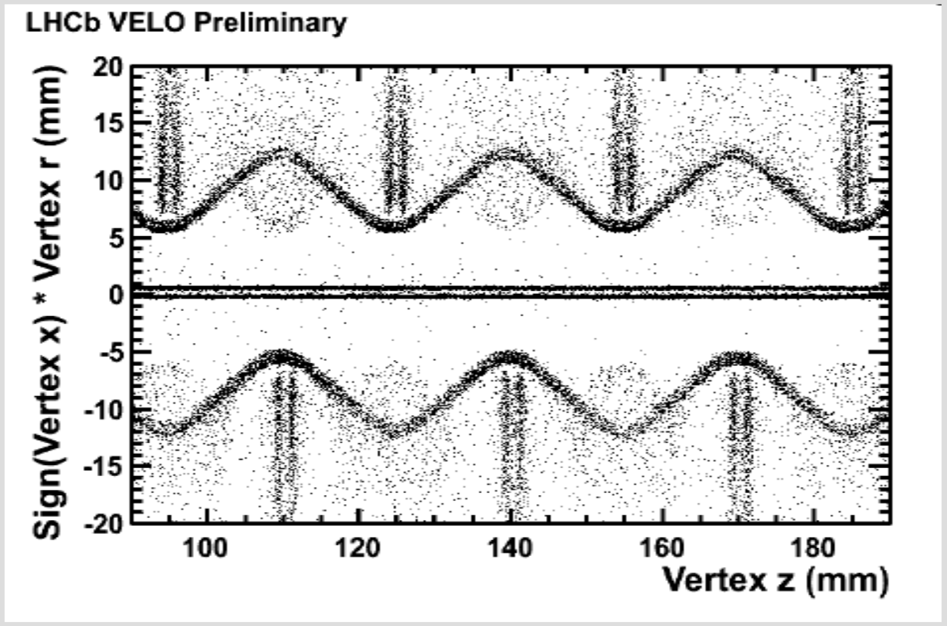


How close we get to the beam

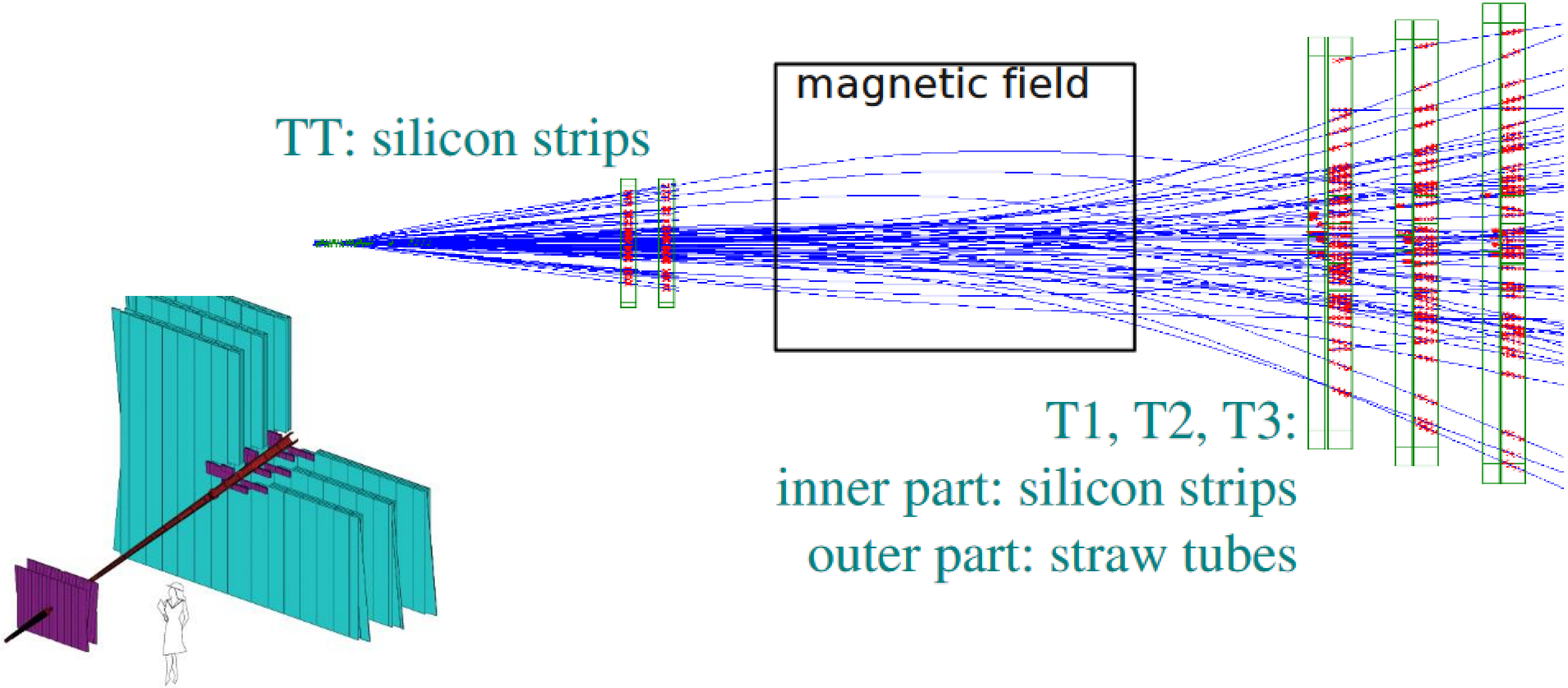


A whole story regarding physics or VELO foil tomography



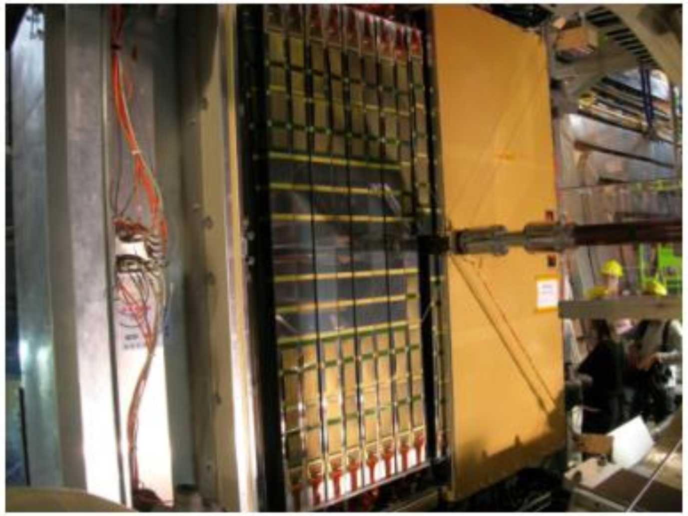


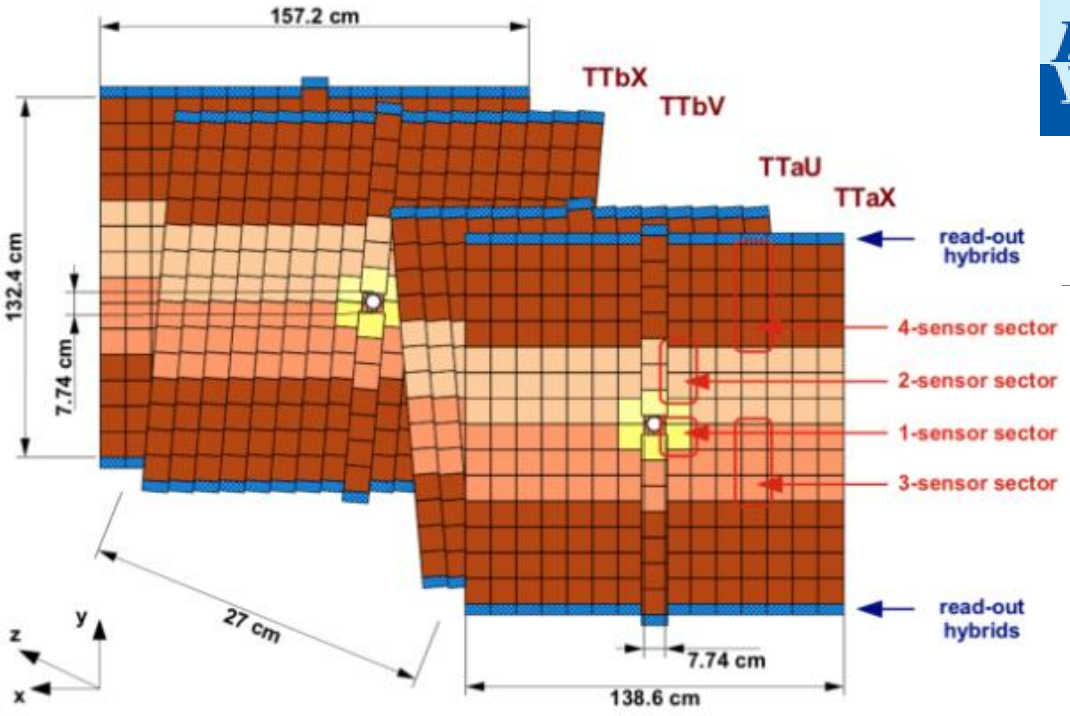
LHCb tracker

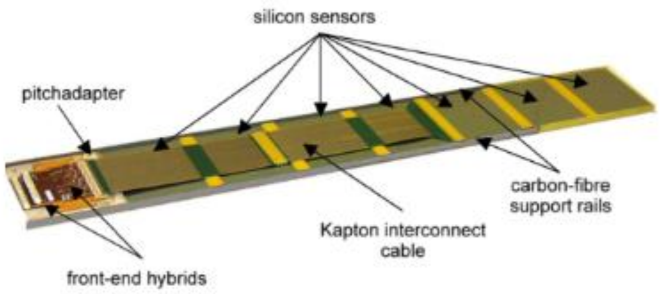


LHCb UT

- Silicon strip tracker upstream of the magnet with 4 detection layers
  - Inner layers tilted by a stereo angle (±5%)
- Single-sided p+-on-n sensors, with thickness of 500 μm
  - 9.44 cm x 9.46 cm
- Total active area of ~ 8m², ~144k readout channels
- Cooling operated at nominal temperature of 0°C, sensors at 8°C during data-taking

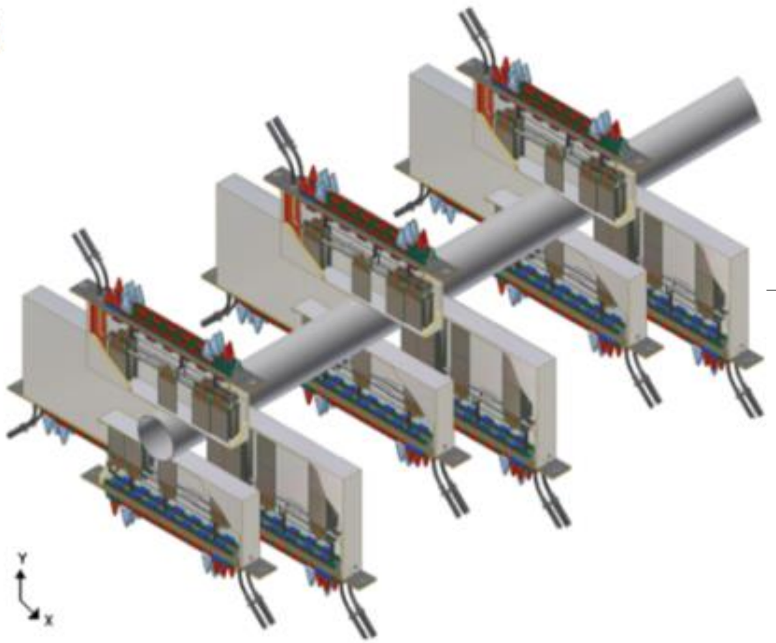


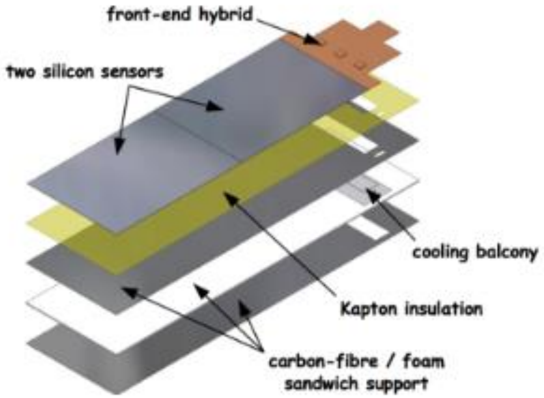




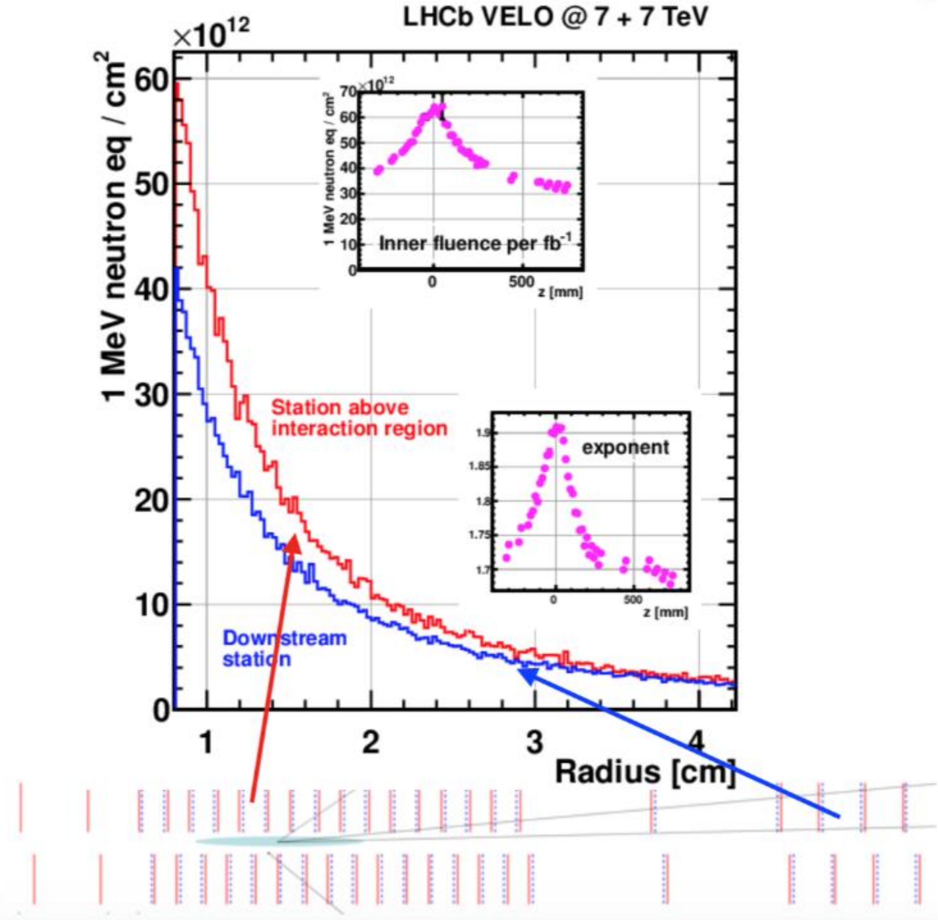
LHCb IT

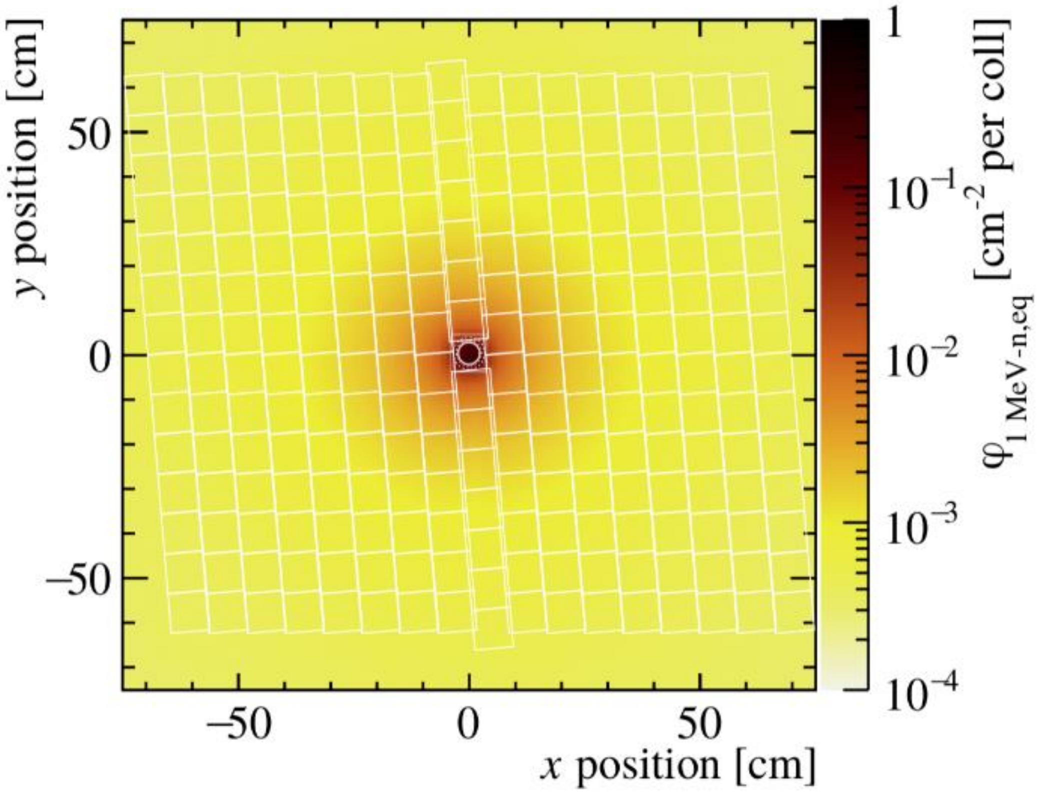
- Three stations, each with 4 detector boxes surrounding the beam pipe downstream of the magnet
  - 4 detection layers (7 modules each) per box, inner layers tilted by a stereo angle (±5%)
- Single-sided p+-on-n sensors, with thickness of 320 (410) μm
  - 7.6 cm x 11 cm
- Total active area of ~ 4m², ~130k readout channels
- Cooling operated at nominal temperature of 0°C, sensors at 8°C during data-taking





Radiation damage!!



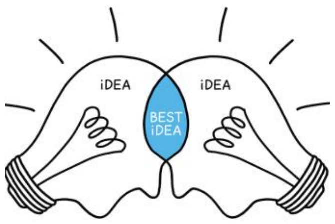


RD50 – going beyond

The R&D Collaboration: „Radiation hard semiconductor devices for high luminosity colliders” was proposed in 2001 and approved in 2002 as **RD 50**

RD50: 59 institutes (49 Europe, 1 Middle-East, 7 North America, 2 Asian)

354 members



Diverse expertise within the **RD 50 Collaboration**
- Solid state physics
- Interaction of radiation with matter
- Experimental high energy physics
- Electronics and ASIC design
- Sensor design

New semiconductor materials (studying and recommendation), relating microscopic radiation damage processes (provide deep understanding respective macroscopic effects), modelling the damage mechanisms

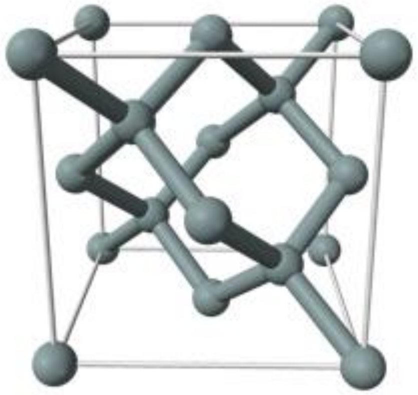
RD50 – going beyond

- p-type micro-strip and pixel technology
- 3D detectors (double column)
- LGAD (Low Gain Avalanche Detector) detectors for 4D tracking

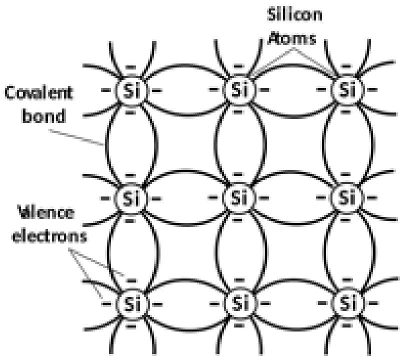
Understanding materials properties

- Modelling – provide models and their tunings (parameters) for the designers, also essential for upgrade planning (leakage current increase, charge collection efficiency, etc…)
- Using this knowledge to improve radiation hardness via defect engineering (not only in silicon but also in other semiconducting materials)
- Identification of defects that are responsible for degradation of detector properties

Micro to Macro – macroscopic parametrisation of radiation damage 

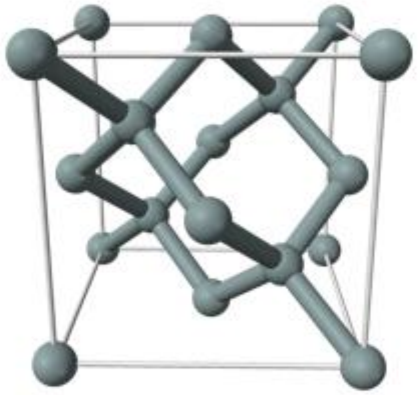


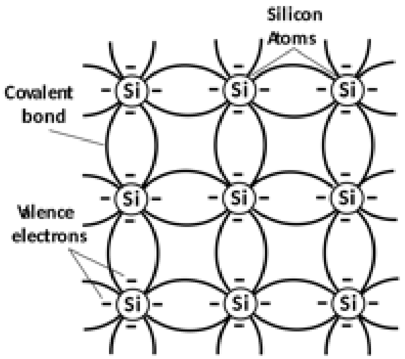
Silicon atoms in a monocrystalline substrate are arranged in a structure identical to a diamond cubic



- Strong covalent bonds form very strong structure
- However, there are defects that make this nice picture not so perfect anymore…

Micro to Macro – macroscopic parametrisation of radiation damage



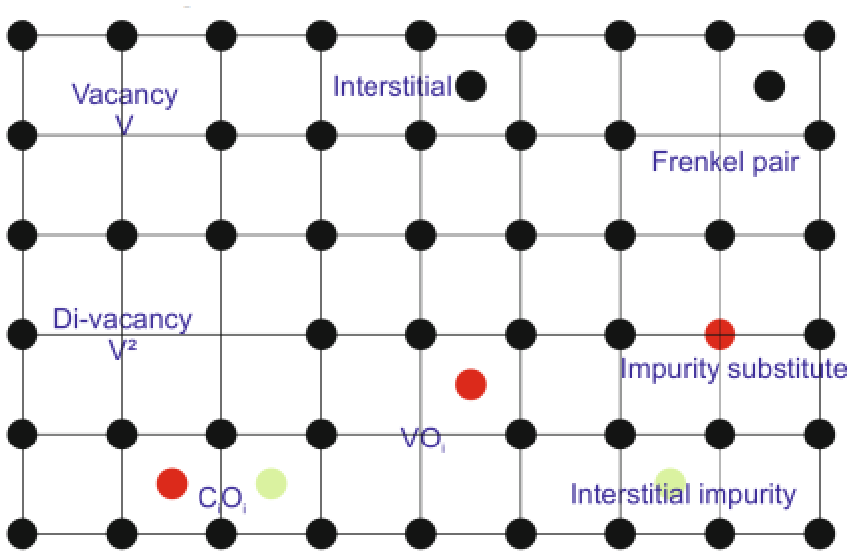


The silicon nice lattice may be „spoiled" in a number of ways

Not wanted **contamination** of the crystal

Deliberately introduced defects being a part of the property engineering through diffusion and ion implantation

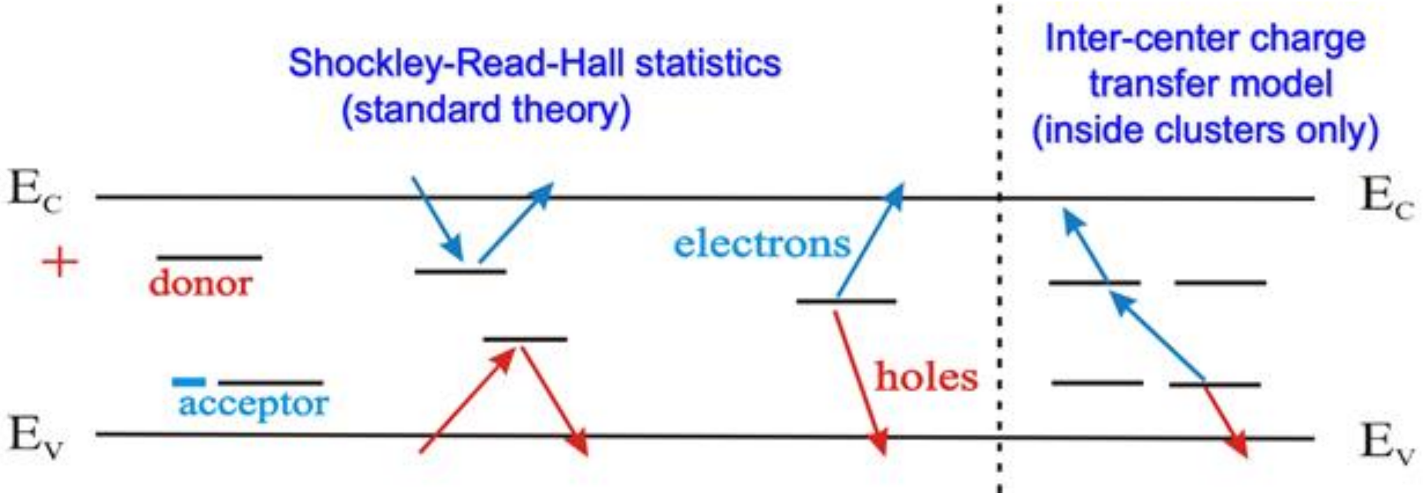
Devices build of silicon may be **exposed to hadronic radiation** that alters the material properties (large energy transfers)



Micro to Macro – macroscopic parametrisation of radiation damage

We can successfully explain evolution of semiconductor devices assuming that the **radiation introduces defects into the lattice**

- **Increase in leakage current** due to additional paths for generation
- **Change in depletion voltage** due to introduction of charged defects
- **Reduction of the collected charge** due to shallow trap stopping carriers for times comparable with integration times of read-out electronics



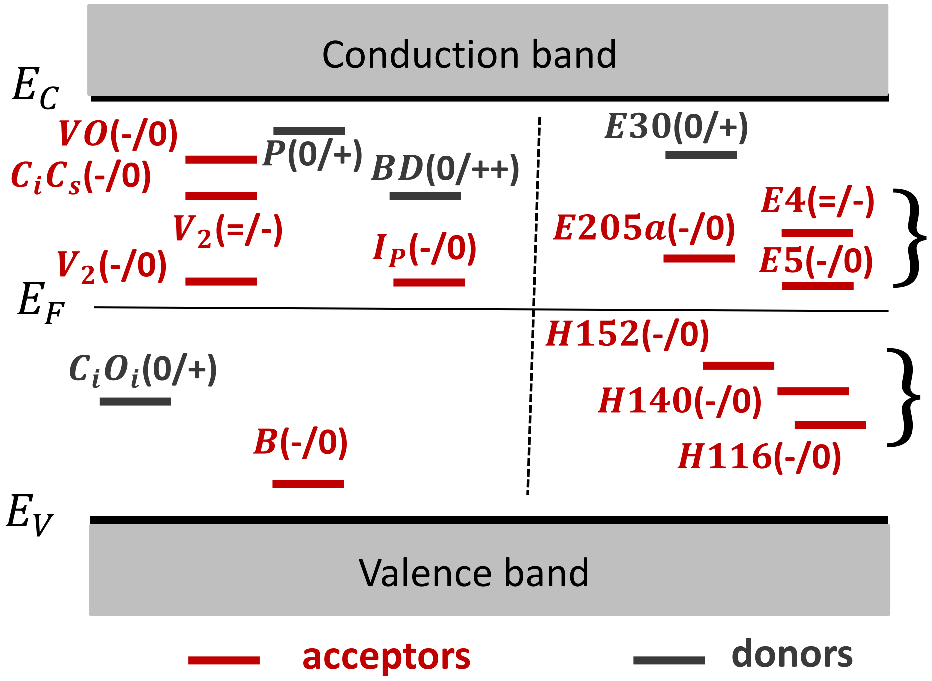
Charged defects N_{eff}, V_{FD} - donors in upper and acceptors in lower half of band gap ➨ Electrons and holes trapping CCE – both shallow and deep defects; in room temperature fast de-trapping ➨ **Leakage current generation** – most effective defects located close to the mid-gap region ➨ **Enhanced generation** of leakage current and space charge

Micro to Macro – macroscopic parametrisation of radiation damage

P(0/+) – Phosphorus shallow dopant (positive charge)

BD(0/++) – positive charge, depends on type of radiation and oxygen concentration

E30(0/+) – positive charge, depends on type of radiation



Leakage current generation

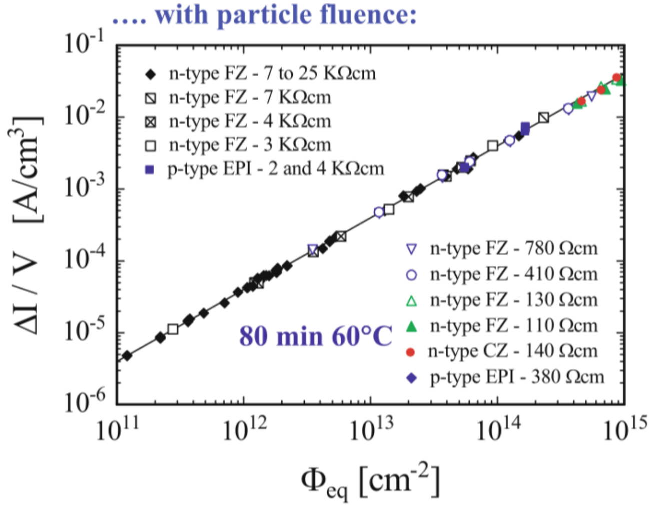
Reverse annealing effects

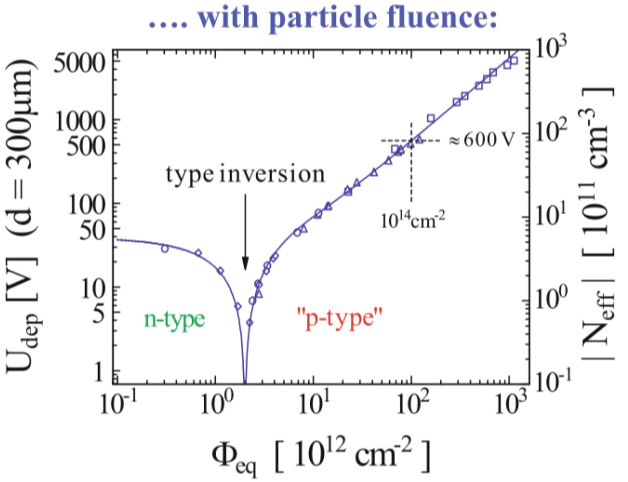
I_P(-/0) – leakage current and negative charge

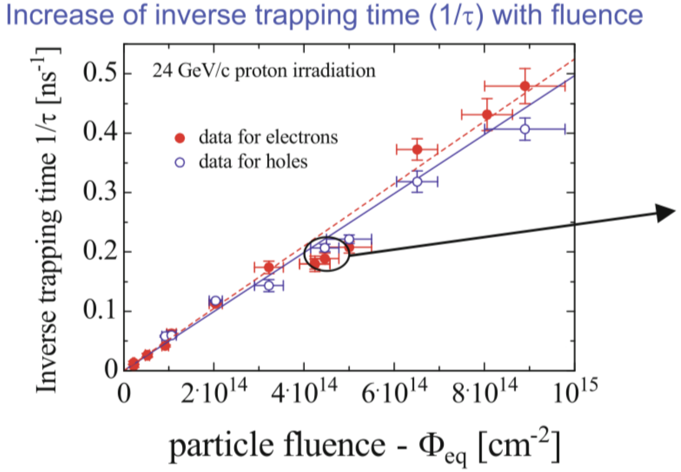
B(-/0) – boron shallow dopant (negative chargé)

For more extensive list and description see:
M. Moll „Displacement Damage in Silicon Detectors for High Energy Physics", IEEE Transactions on Nuclear Science 65, vol. 8

Micro to Macro – macroscopic parametrisation of radiation damage







Leakage Current

$$\frac{\Delta I}{V_{det}} = \alpha(t,T) \cdot \phi_{eq}$$

Depletion voltage

$$N_{eff} = N_{D,0} \cdot e^{-c_D \phi_{eq}}$$

$$-N_{A,0} e^{-c_A \phi_{eq}} - b\phi_{eq}$$

Decrease of CCE

$$N_i = g_i \phi_{eq} f_i(t) \rightarrow \frac{1}{\tau_{eff}} = \gamma \phi_{eq}$$

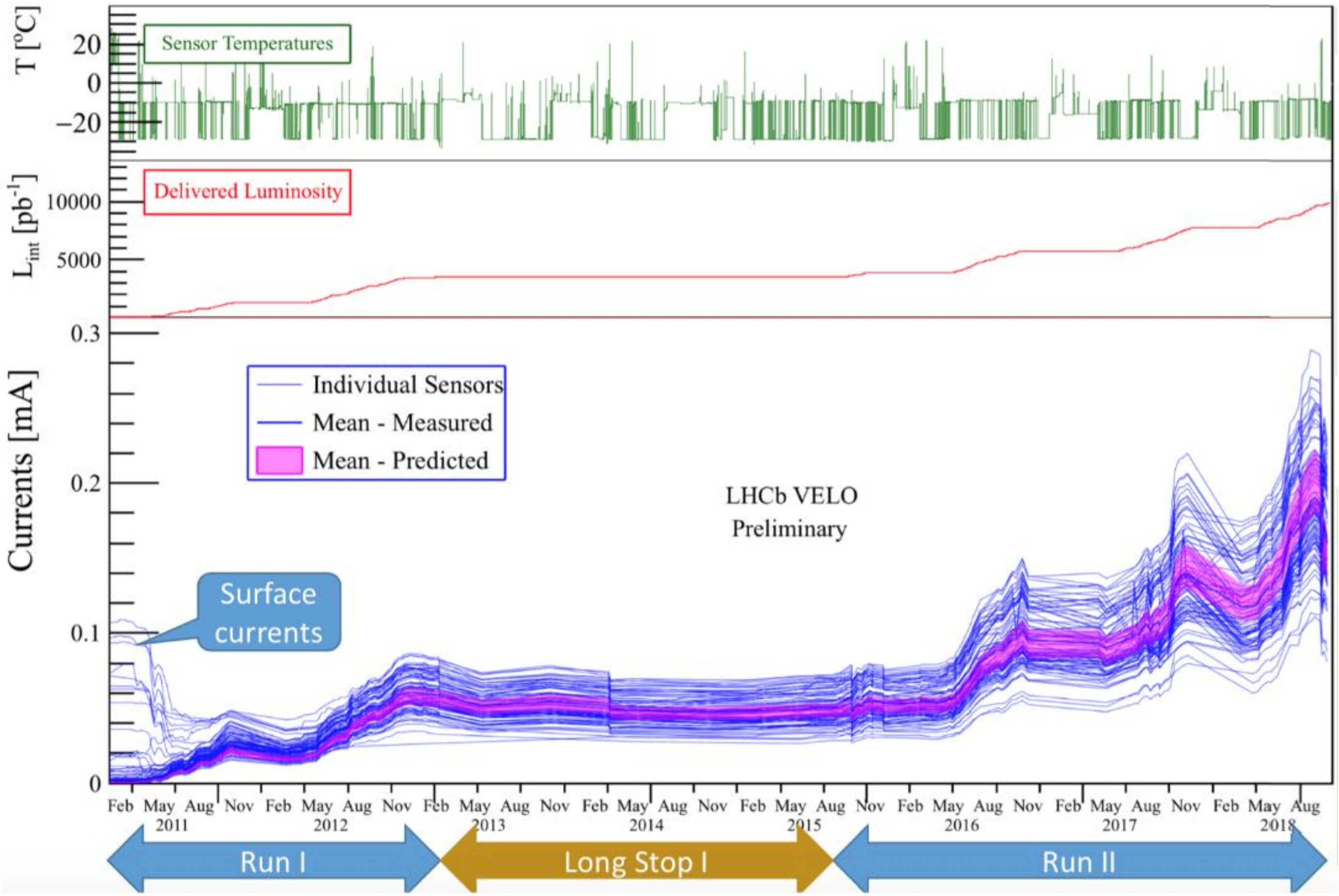
$$Q_{(e,h)} = Q_{0(e,h)} e^{-\frac{1}{\tau_{eff(e,h)}}}$$

$$\tau_{eff(e,h)} \propto N_{defects}$$

Wunstorf, R.: Radiation hardness of silicon detectors: current status. IEEE Trans. Nucl. Sci. 44(3), 806–814 (1997)

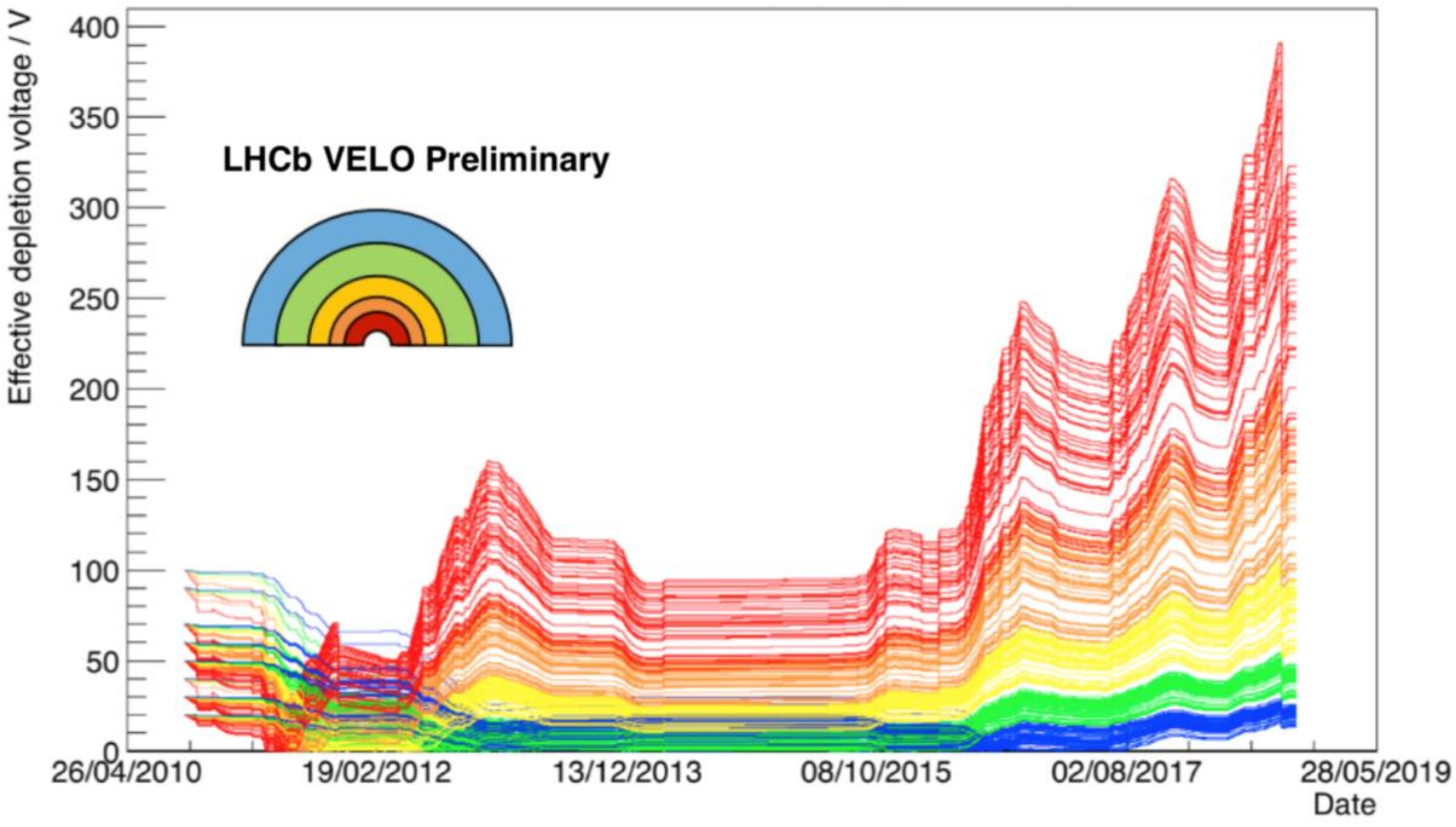
Radiation damage VELO case

Leakage currents time evolution



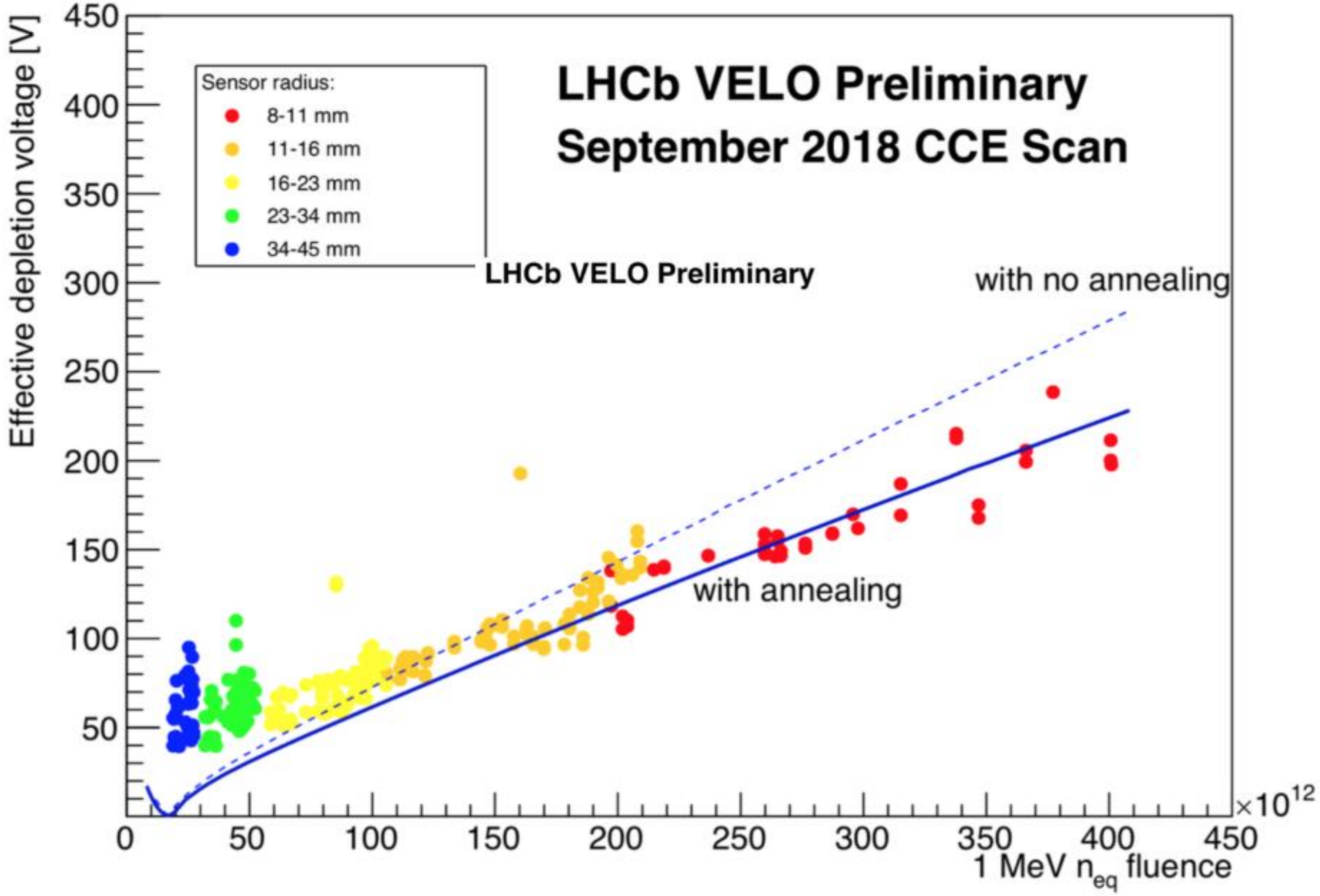
Radiation damage VELO case

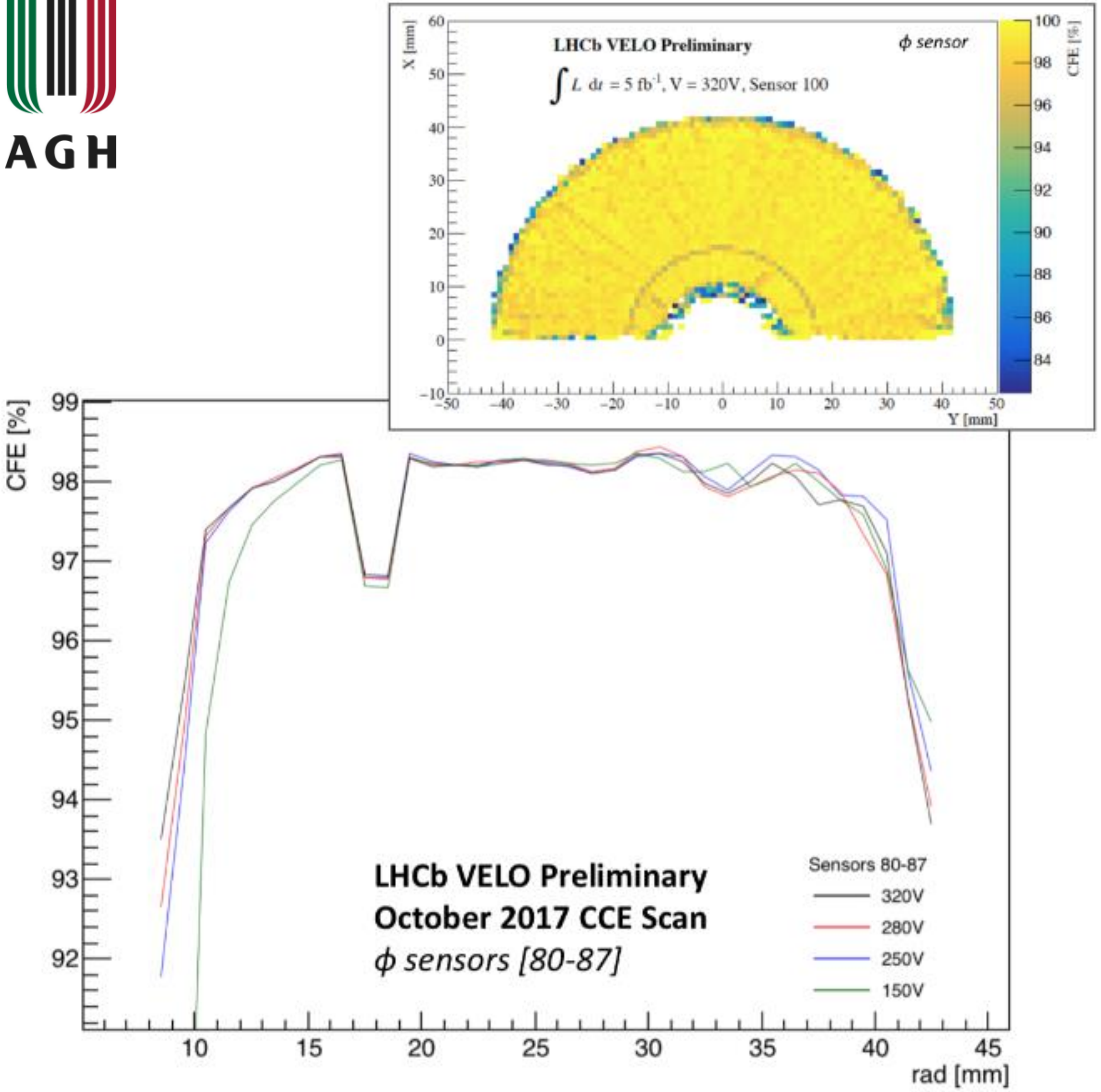
Depletion voltage evolution



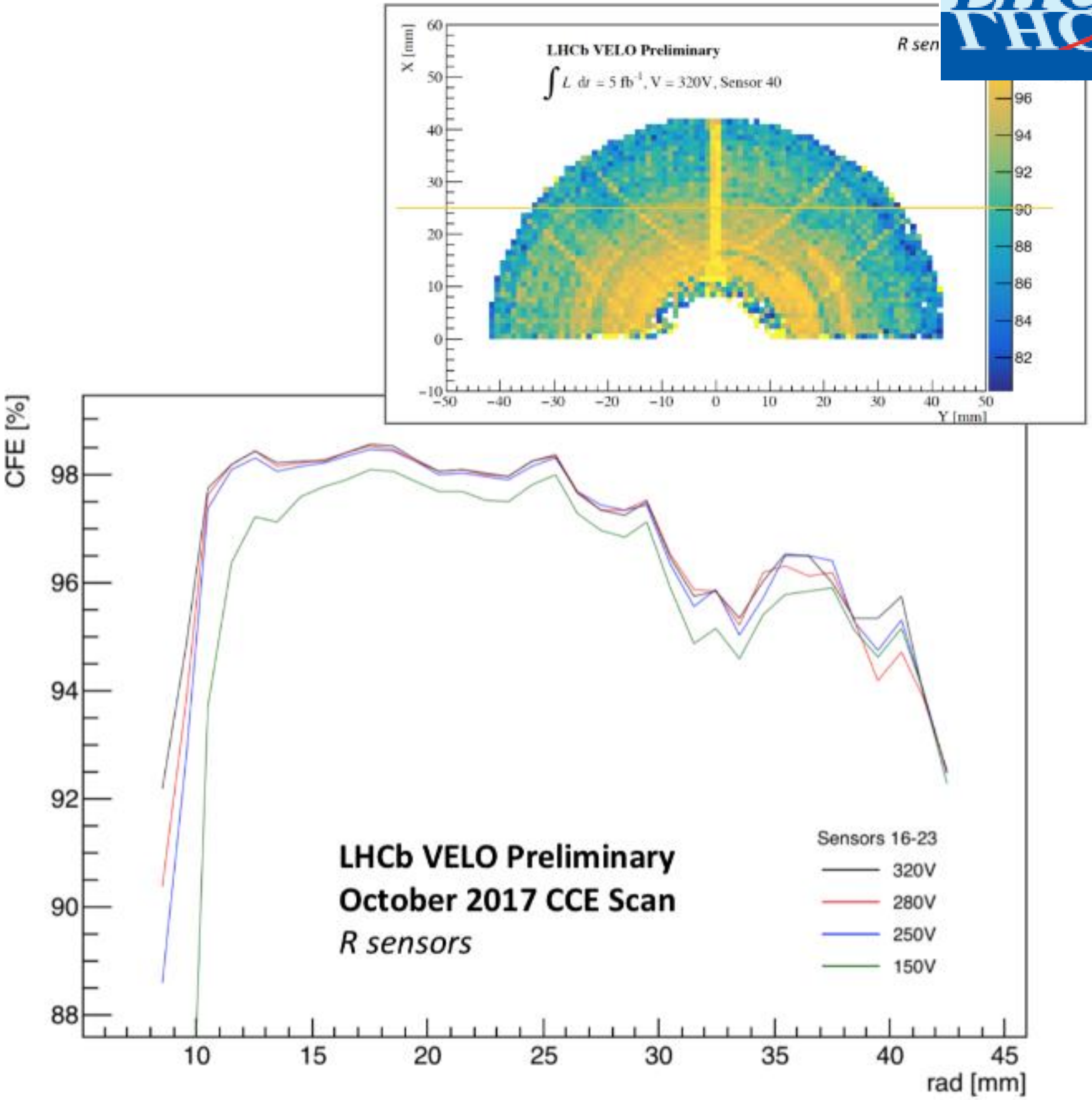
Radiation damage VELO case

Depletion voltage evolution



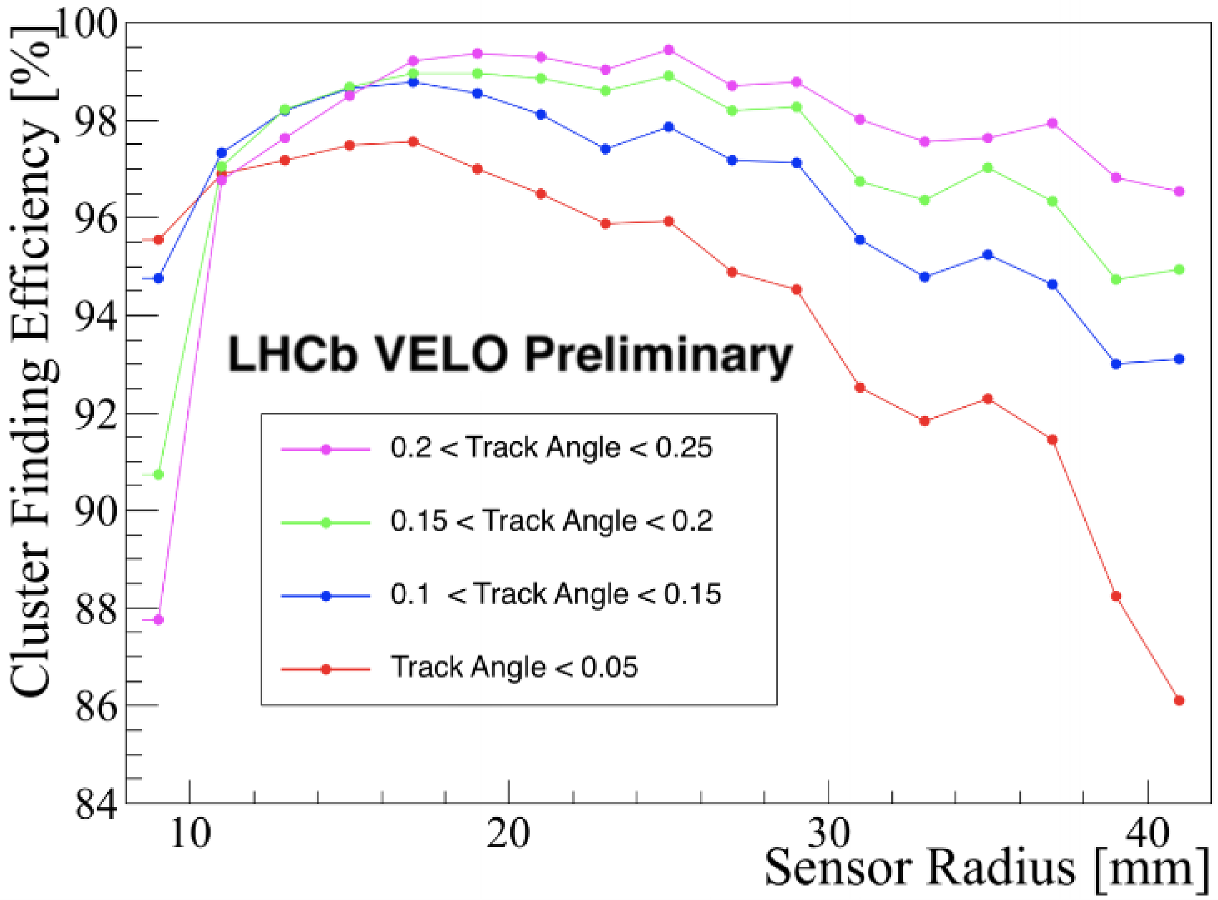


LHCb VELO Preliminary
ϕ sensor
∫L dt = 5 fb⁻¹, V = 320V, Sensor 100
X [mm]
Y [mm]
CFE [%]
CFE [%]
rad [mm]
LHCb VELO Preliminary
October 2017 CCE Scan
ϕ sensors [80-87]
Sensors 80-87
320V
280V
250V
150V



LHCb VELO Preliminary
∫L dt = 5 fb⁻¹, V = 320V, Sensor 40
X [mm]
Y [mm]
CFE [%]
rad [mm]
LHCb VELO Preliminary
October 2017 CCE Scan
R sensors
Sensors 16-23
320V
280V
250V
150V

Radiation damage VELO case

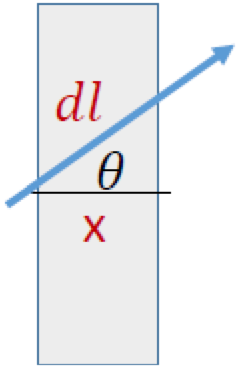


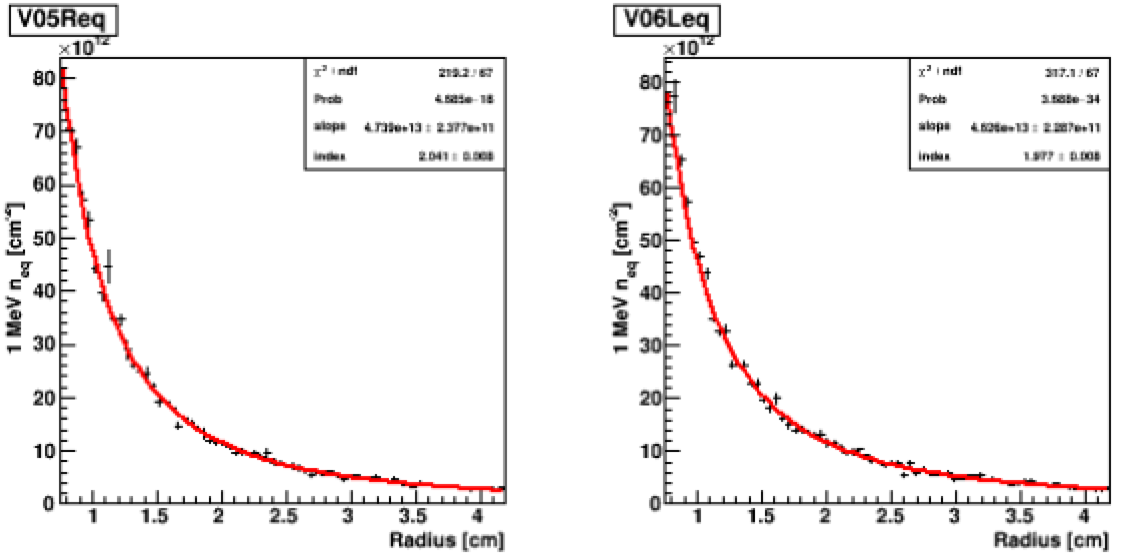
Fast hadron fluence – key quantity

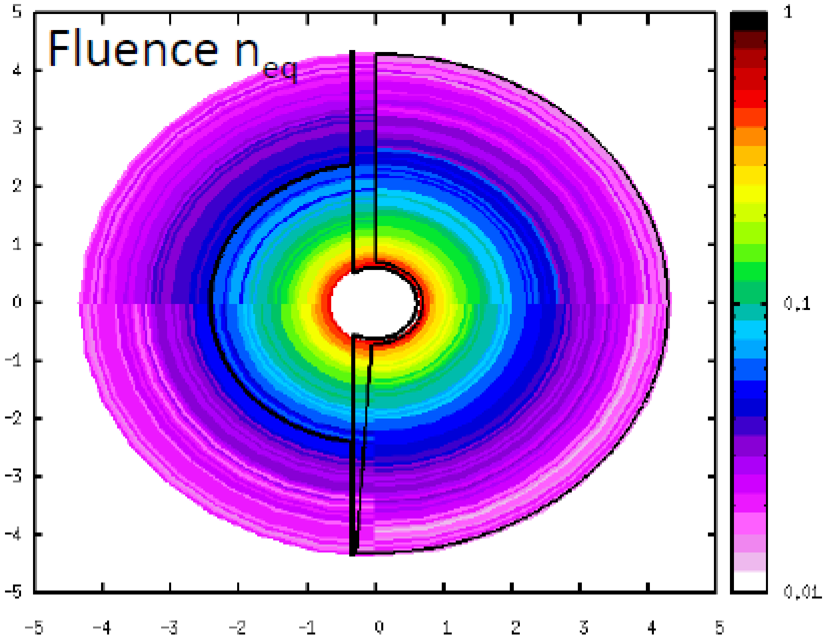
Fluence = track-length density.

$$\Phi[cm^{-2}] = \lim_{dV \to 0} \frac{\sum \frac{dx}{cos\theta}}{dV}$$

$$= Sdx$$



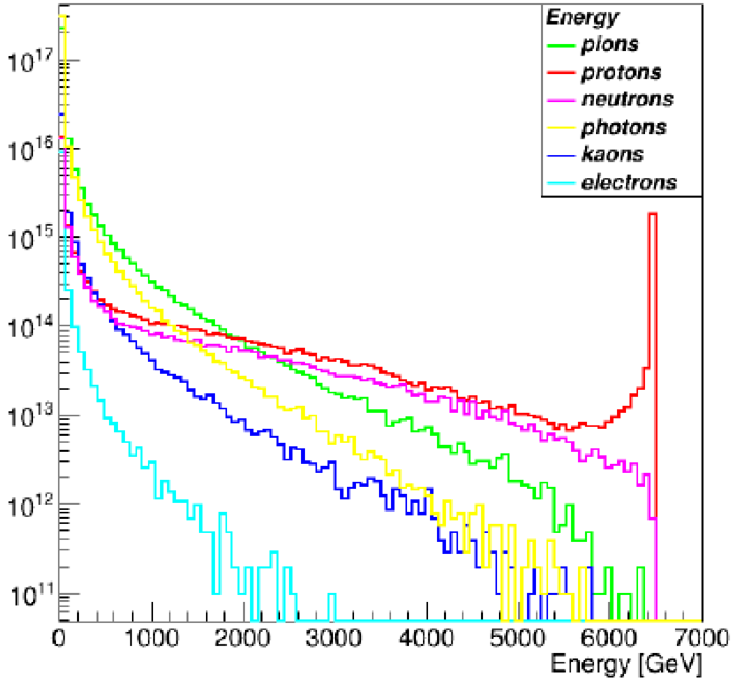




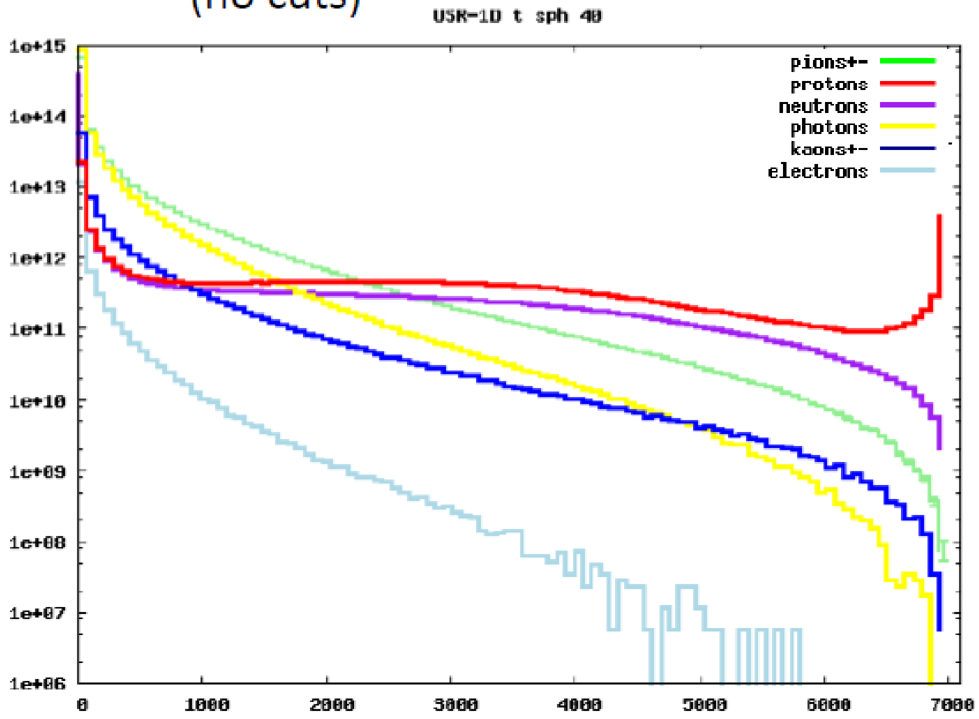
A. Obłąkowska-Mucha, Tomasz Szumlak, Eur.Phys.J.Plus 136 (2021) 10, 1036

Fast hadron fluence – key quantity

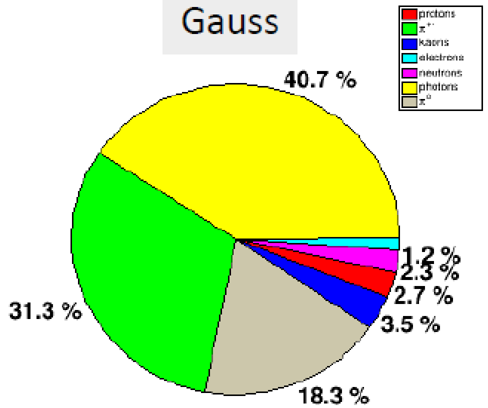
Gauss – 250 kevents of minimum bias (minimal cuts)



Fluka – 10^6 proton-proton collisions (no cuts)



Gauss



N_i/N_{prod} [%]	Gauss	Fluka
protons	3,3	2,91
neutrons	2,8	2,18
char pions	38,3	41,77
kaons	4,3	3,81
photons	49,8	48,6
electrons	1,4	0,63

A. Obłąkowska-Mucha, Tomasz Szumlak, Eur.Phys.J.Plus 136 (2021) 10, 1036

Motivation for LHCb upgrade(s) / 1

- No „smoking-gun" evidence for NP in direct searches yet… SM is still in control
- **Parameter space of most popular BSM is shrinking**! Still, taking into account „available" data till the end of HL-LHC **we just collected a tiny bit ($\sim 5\%$)**
- Some **intriguing hints of NP** in non-direct approach
  - **Flavour anomalies**: $b \to s l^+ l^-$ ($B_d^0 \to K^{*0} l^+ l^-$), $R(K)$ and $R(K^*)$
  - **Possible lepton flavour universality violation**: $B_d^0 \to D^* l^+ l^-$, $R(D^*)$
  - No „discovery significance" but the observed anomalies seem to indicate tension with the SM
- Clear need for more data! Many measurements are statistics limited – challenge theory
  - $\boldsymbol{BR(B_s \to \mu^+ \mu^-)}$ push down the precision to $\sim 10\%$ of the SM prediction
  - **CMK γ angle** down to $\sim 1^{\mathrm{o}}$
  - Probe **CPV in charm** sector below 10^{-4}

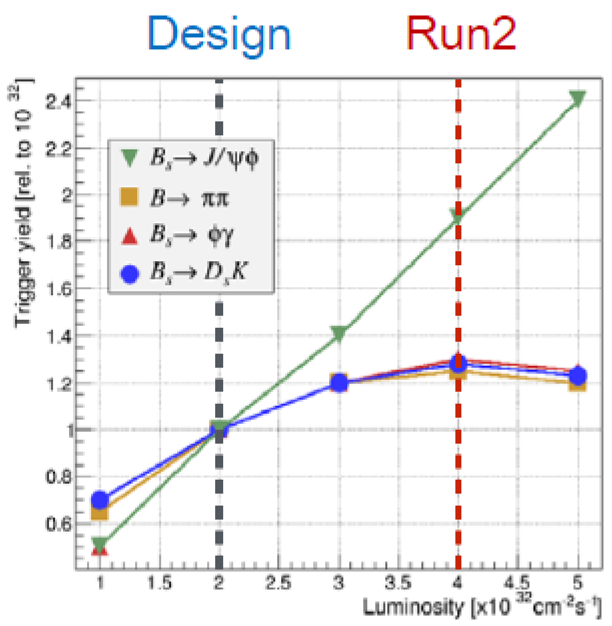
Motivation for LHCb upgrade(s) / 3

Observable	Current LHCb	LHCb 2025	Belle II	Upgrade II
EW Penguins				
R_K $(1 < q^2 < 6\,\mathrm{GeV}^2 c^4)$	0.1	0.025	0.036	0.007
R_{K^*} $(1 < q^2 < 6\,\mathrm{GeV}^2 c^4)$	0.1	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 $B_s^0 \to D_s^+ K^-$	$(^{+17}_{-22})^\circ$	4°	–	1°
γ, all modes	$(^{+5.0}_{-5.8})^\circ$	1.5°	1.5°	0.35°
$\sin 2\beta$, with $B^0 \to J/\psi K_S^0$	0.04	0.011	0.005	0.003
ϕ_s, with $B_s^0 \to J/\psi\phi$	49 mrad	14 mrad	–	4 mrad
ϕ_s, with $B_s^0 \to D_s^+ D_s^-$	170 mrad	35 mrad	–	9 mrad
$\phi_s^{s\bar{s}s}$, with $B_s^0 \to \phi\phi$	154 mrad	39 mrad	–	11 mrad
$a_{\rm sl}^s$	33×10^{-4}	10×10^{-4}	–	3×10^{-4}
$\lvert V_{ub}\rvert/\lvert V_{cb}\rvert$	6%	3%	1%	1%
B_s^0, $B^0 \to \mu^+\mu^-$				
$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	90%	34%	–	10%
$\tau_{B_s^0 \to \mu^+\mu^-}$	22%	8%	–	2%
$S_{\mu\mu}$	–	–	–	0.2
$b \to c\ell^-\bar{\nu}_l$ LUV studies				
$R(D^*)$	0.026	0.0072	0.005	0.002
$R(J/\psi)$	0.24	0.071	–	0.02
Charm				
$\Delta A_{CP}(KK - \pi\pi)$	8.5×10^{-4}	1.7×10^{-4}	5.4×10^{-4}	3.0×10^{-5}
A_Γ $(\approx x \sin\phi)$	2.8×10^{-4}	4.3×10^{-5}	3.5×10^{-4}	1.0×10^{-5}
$x \sin\phi$ from $D^0 \to K^+\pi^-$	13×10^{-4}	3.2×10^{-4}	4.6×10^{-4}	8.0×10^{-5}
$x \sin\phi$ from multibody decays	–	$(K3\pi)$ 4.0×10^{-5}	$(K_S^0\pi\pi)$ 1.2×10^{-4}	$(K3\pi)$ 8.0×10^{-6}

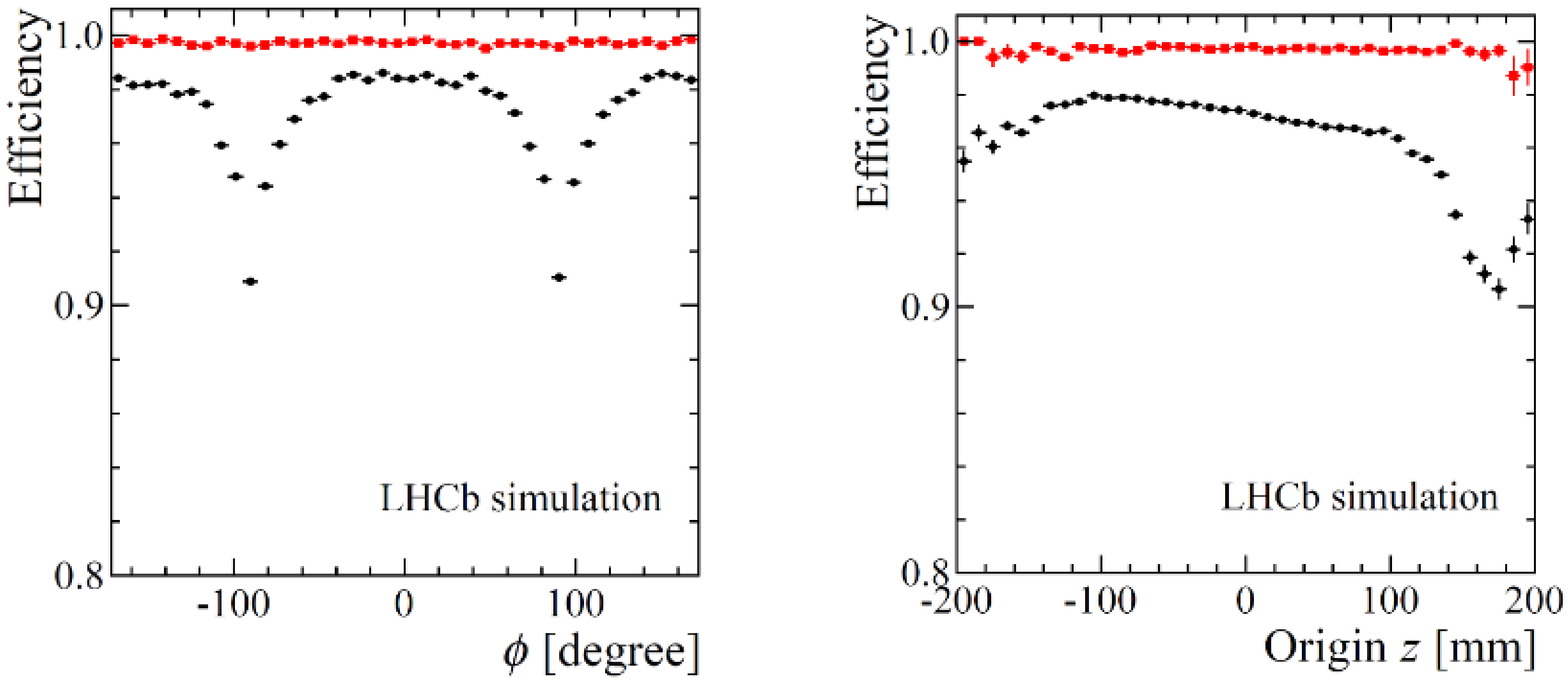
arXiv:1808.08865

Motivation for LHCb upgrade(s) / 2

- The old detector was **severely limited by its hardware trigger** layer (a.k.a. L0)
  - The **maximum available rate** of events is 1.1 MHz
- To keep up with evolution of other LHC experiments need to go up with the luminosity
  - Old system would just saturate
  - Harder cuts on both E_T (transverse Energy - calorimeter) and p_T (transverse momentum – tracking)
  - Serious loses for hadronic channels
- **Much higher pile-up** (up to ~ 5 primary vertices per bunch crossing, $\mathcal{L} = 2 \times 10^{33}\ [\mathrm{cm}^{-2}\mathrm{s}^{-1}]$)
  - Tracking super difficult with the Run 1/2 design
  - Radiation damage not manageable for Run 1/2 technologies

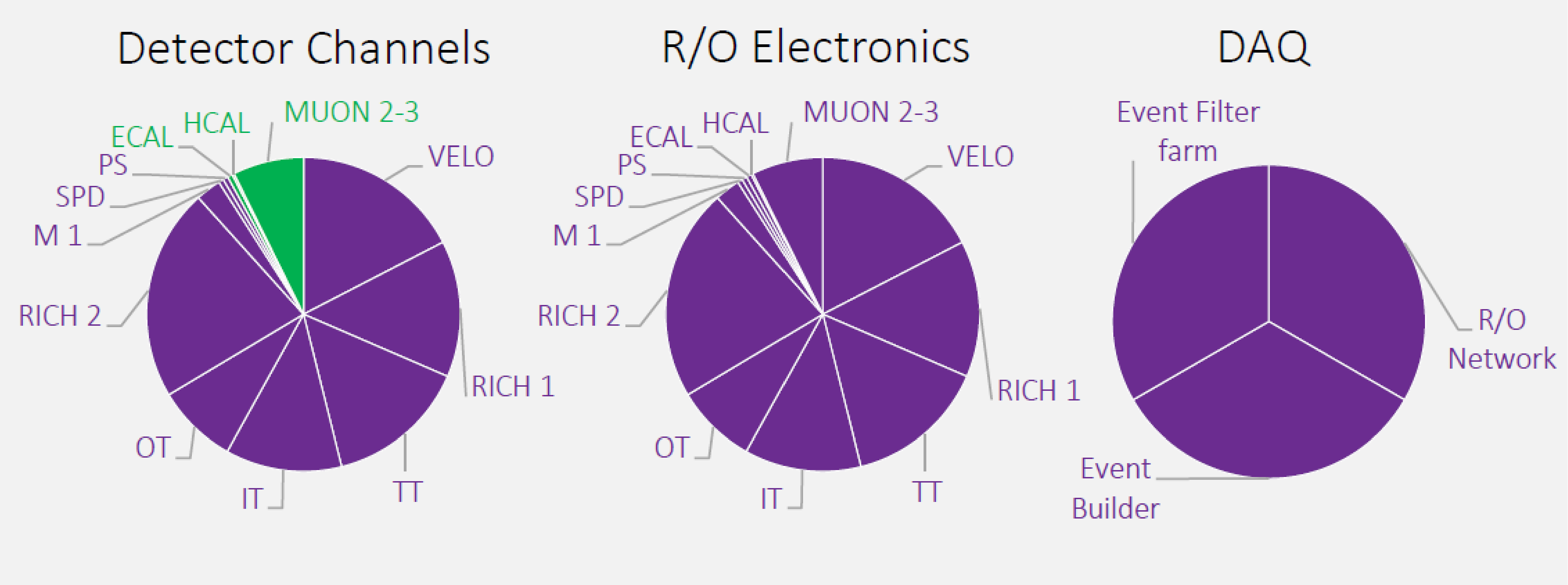


Run 3 conditions with old VELO



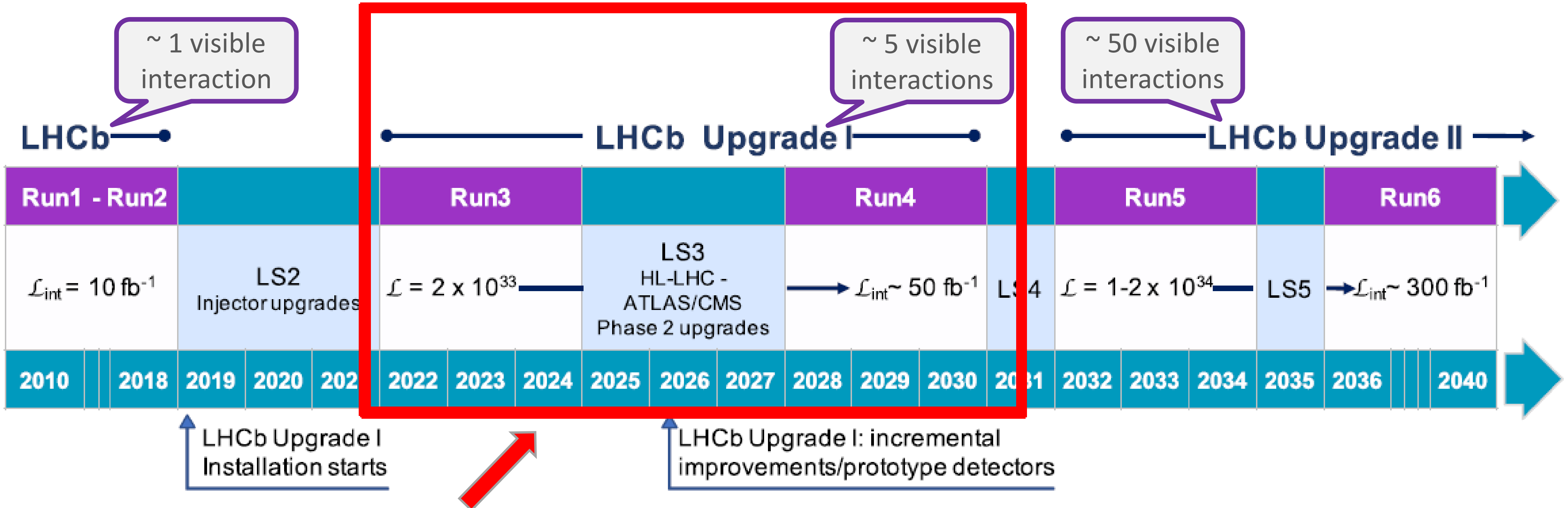
Upgrade scope and timeline / 1

CERN-LHCC-2012-007



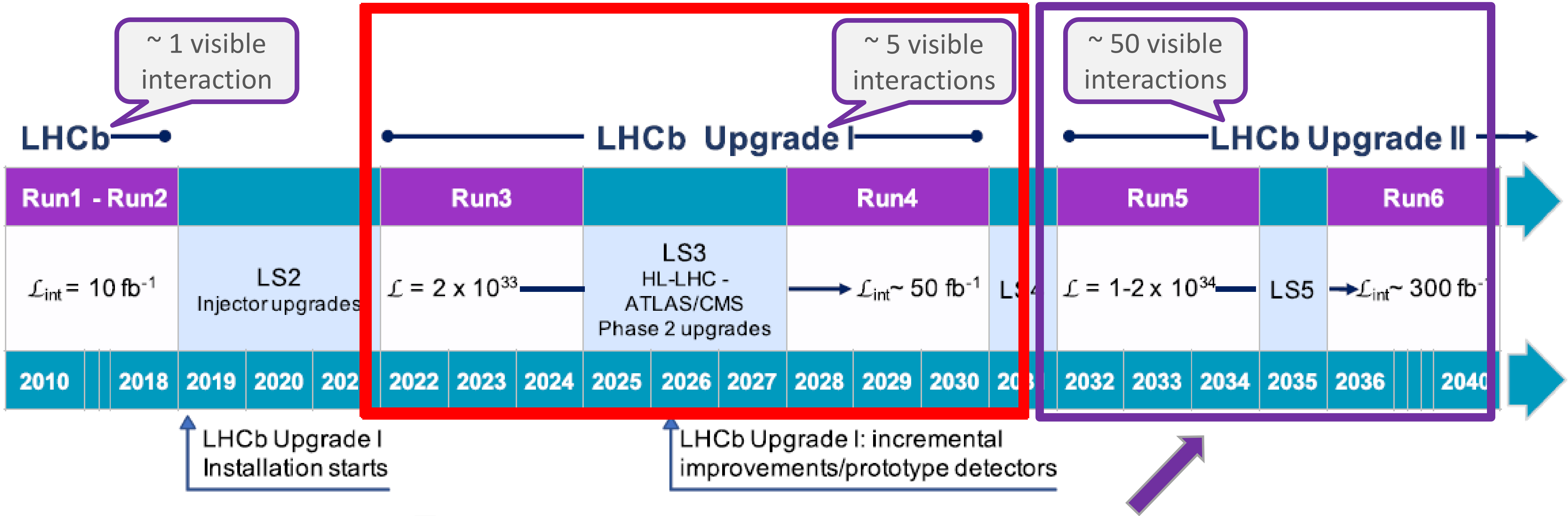
What to keep and what to upgrade… Major upgrade!

Upgrade scope and timeline / 2



- LHCb **Phase-I/Ib** upgrade for LHC Run 3 and Run 4
  - Full software trigger and readout at the LHC clock speed of 40 MHz
  - Replace tracking system and PID
  - Consolidate PID, tracking and ECAL during LS3

Upgrade scope and timeline / 3



- LHCb **Phase-II** upgrade, installation in LS4, operation beyond Run 4
  - New radiation hard technologies for tracking
  - Add timing to cope with $\mathcal{L} \sim 1.5 \times 10^{34}\ [\mathrm{cm}^{-2}\mathrm{s}^{-1}]$

Upgrade scope and timeline / 4

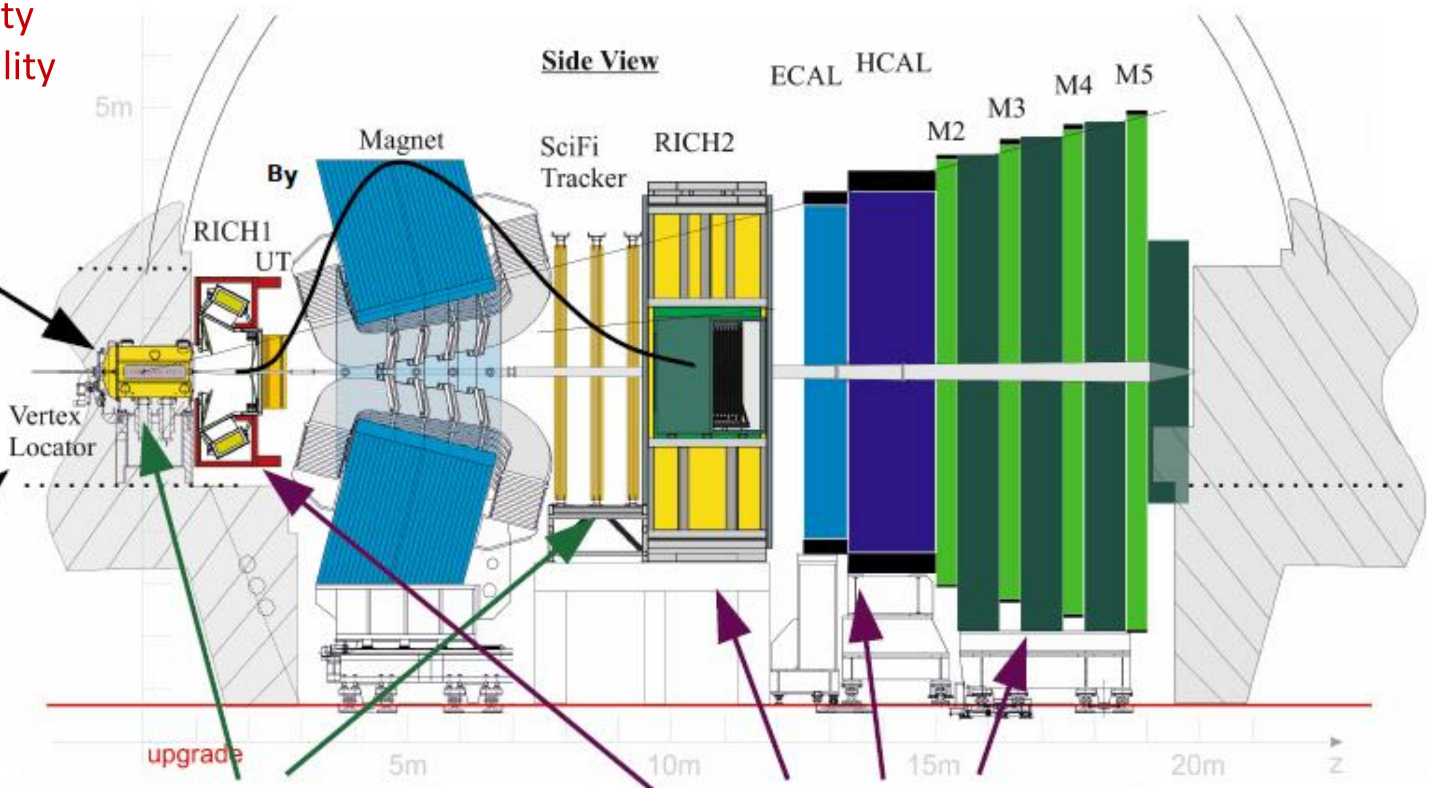
Kaon ID ~ 95 % for ~ 5 % π→K mis-id probability
Muon ID ~ 97 % for 1-3 % π→μ mis-id probability

Precise vertex measurements

Impact parameter resolution:
(15 +29/pT[GeV]) μm

Decay time resolution: ~45 fs

Excellent decay time resolution

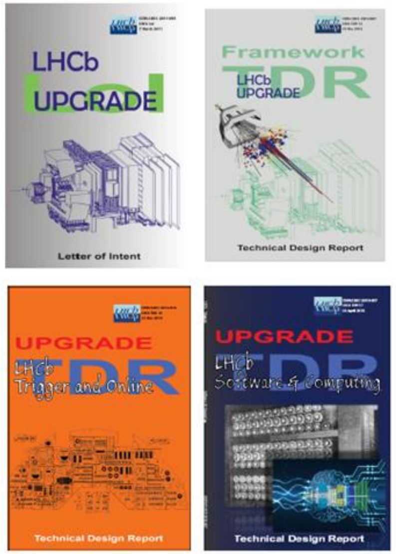


Δ p / p = 0.5 % at low momentum to 1.0% at 200 GeV/c

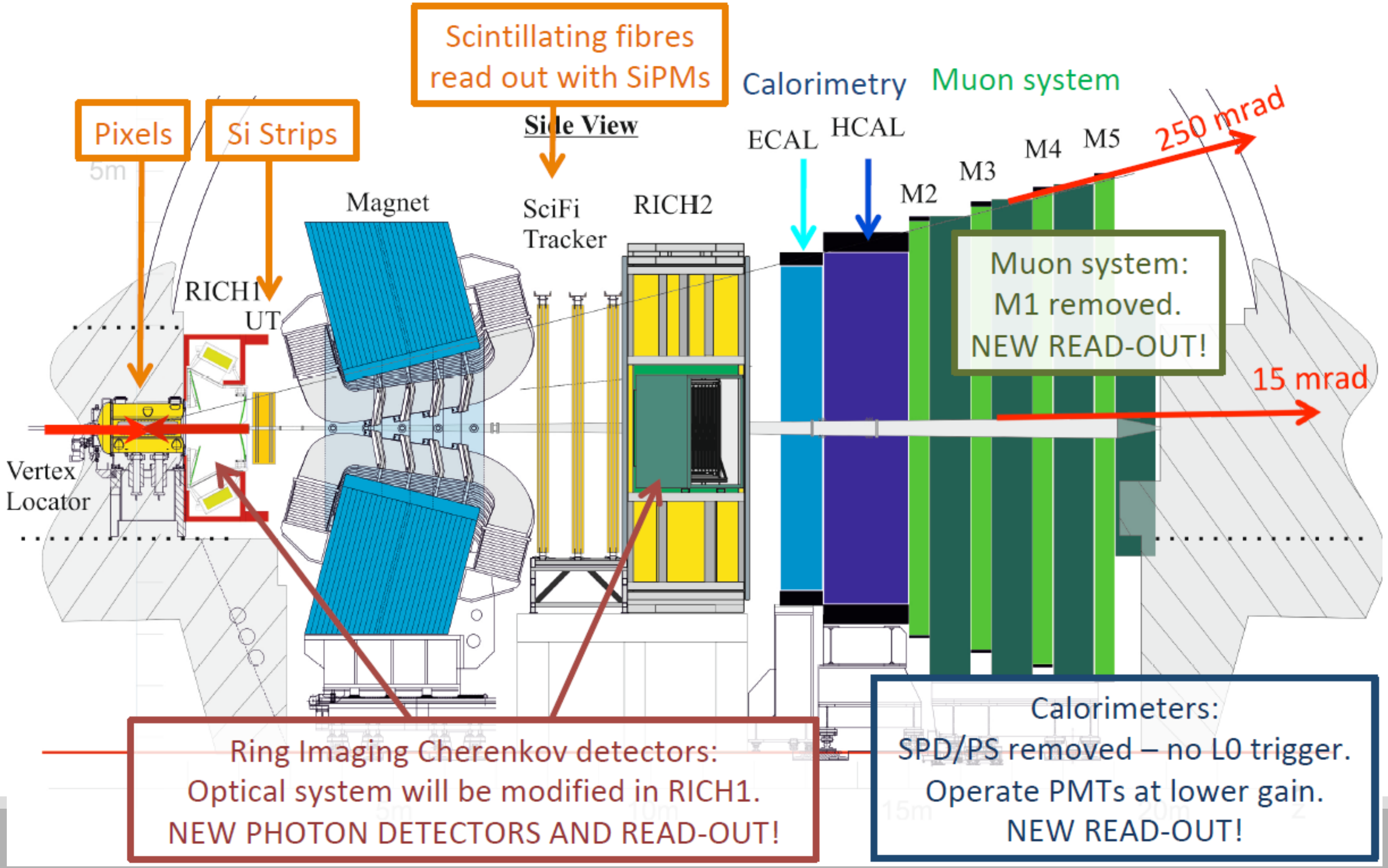
Excellent momentum resolution

Excellent particle identification

Upgrade scope and timeline / 5



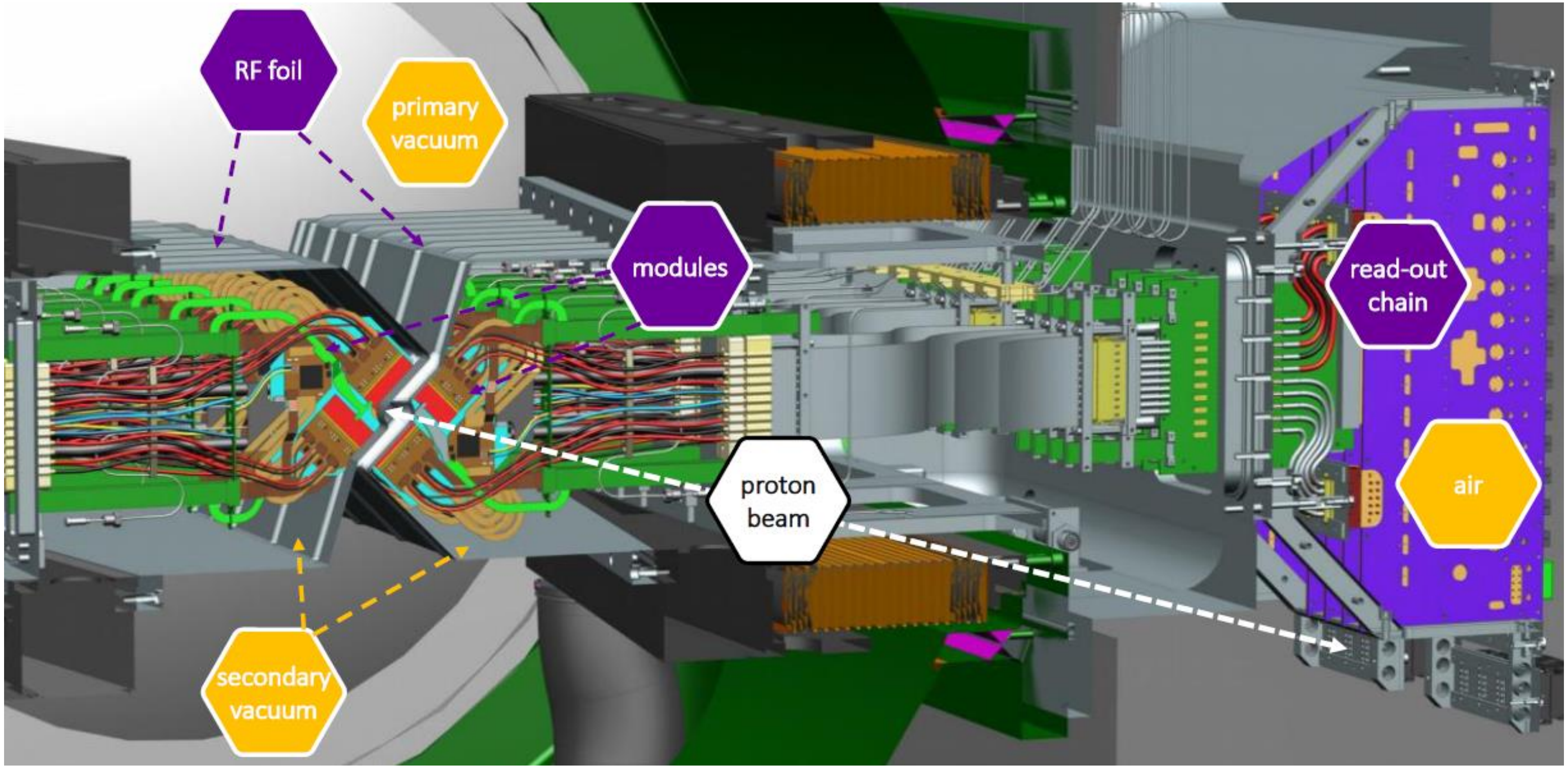
CERN-LHCC-2011-001
CERN-LHCC-2012-007
CERN-LHCC-2014-016
CERN-LHCC-2018-007



CERN-LHCC-2013-021
CERN-LHCC-2013-022
CERN-LHCC-2018-014
CERN-LHCC-2014-001

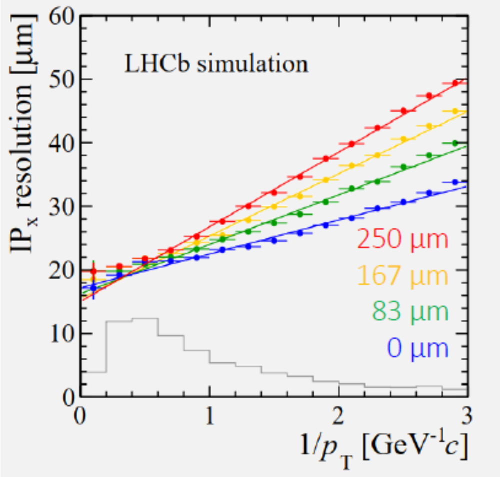
Pixel Vertex Locator (VELO) / 1

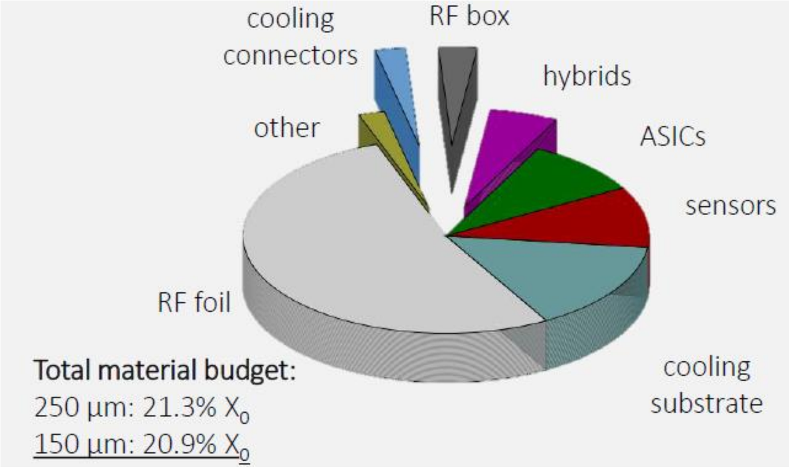
~50 cm



Pixel Vertex Locator (VELO) / 2

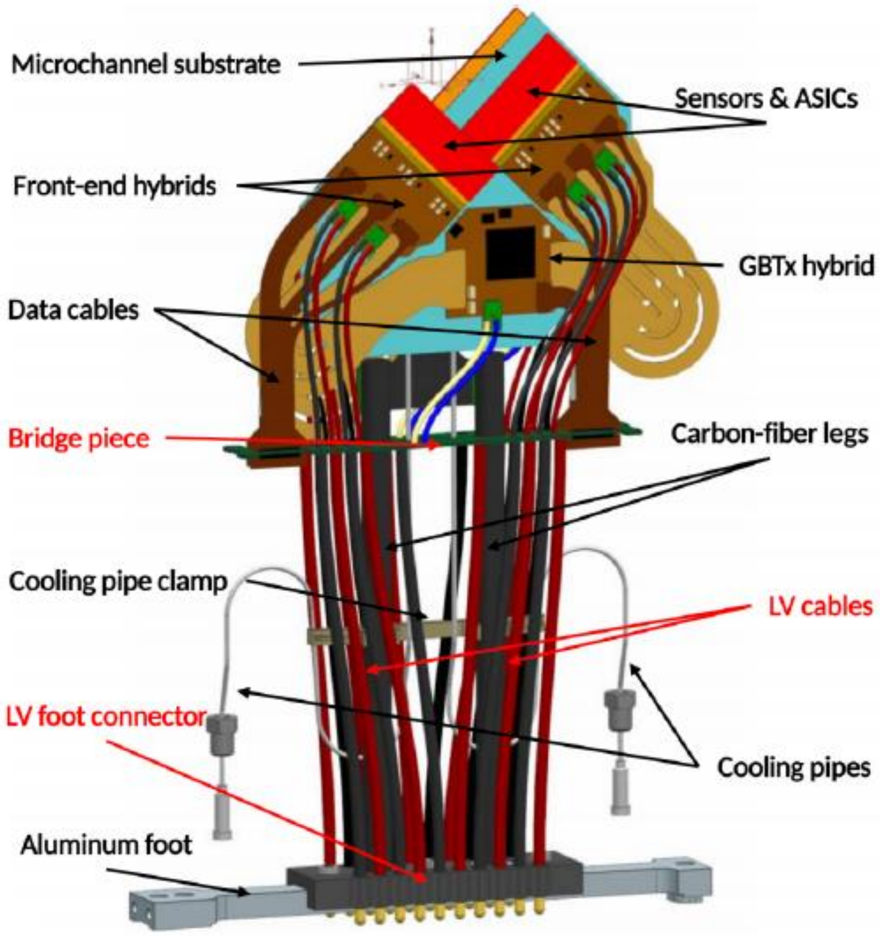
- Built with **two retractable halves**
- Closest to the proton beam @LHC just 3.5 mm when stable beams
- **First active pixels @5.1 mm**
- Secondary vacuum tank
  - Aluminium R.F. foil made for each half to separate it from the machine vacuum
  - Milled from one block to 250 μm then etched down by another 100!
- The whole detector made of **52 hybrid-pixel modules**
  - **~ 41 Mpixels covering $\sim 0.12\ \mathrm{m}^2$**

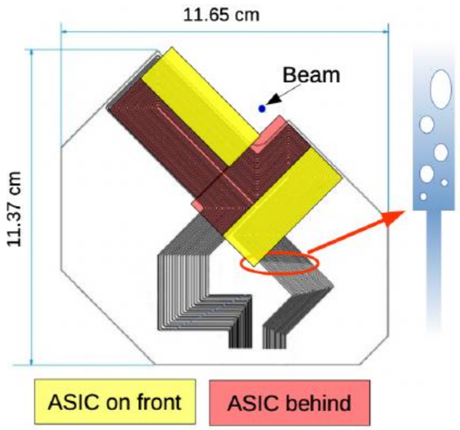


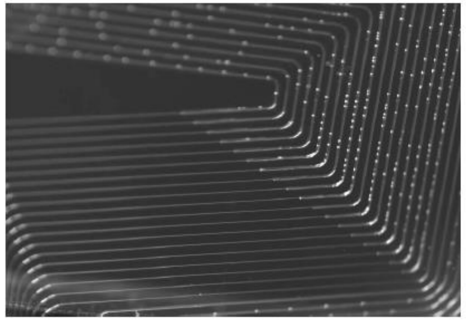


Pixel Vertex Locator (VELO) / 3

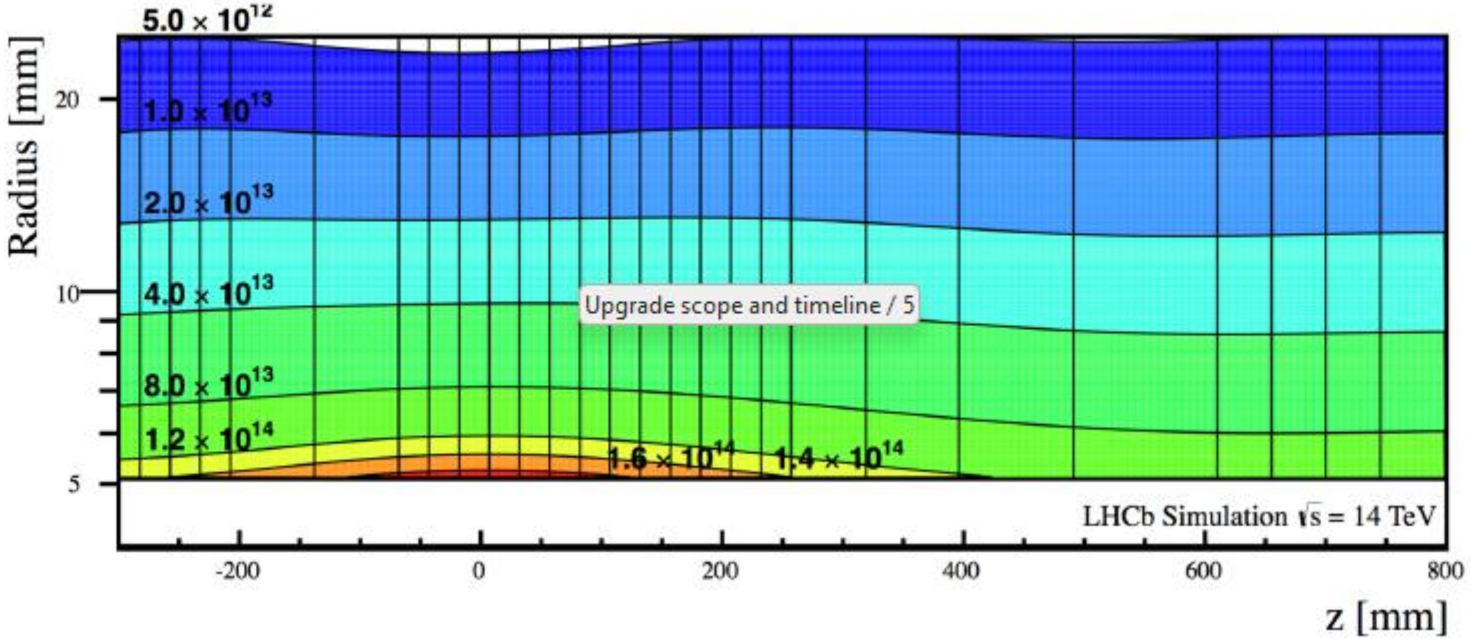
- Hybrid pixel detector with **n-on-p 200 μm thick silicon sensors**
- **New readout ASIC** (VeloPix)
  - Based on TimePix3 design
  - 256×256 array with square pixels 55×55 μm
- State-of-the-art **microchannel cooling** with evaporative CO_2
  - Down to $\sim -20^{o}C$
- Data rate ~2.8 Tbit/s with the hottest ASICs @20 Gbit/s
- Highly un-uniform irradiation







Fluence, again…



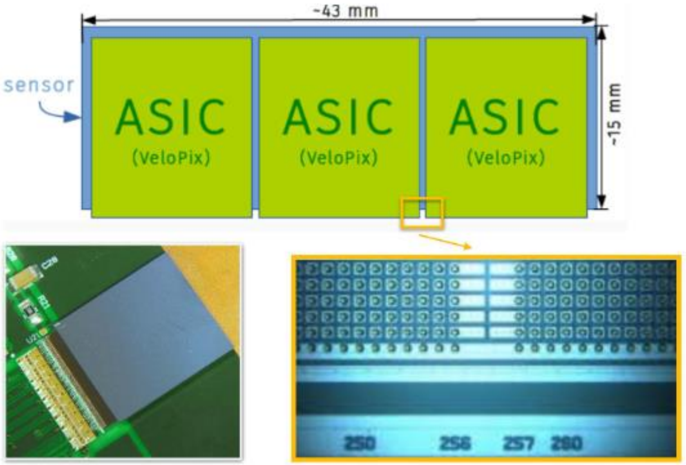
- 10 x higher than for Run 1 and 2
- 1 year @Run3 conditions equal entire Run 1 and 2 radiation damage!!!

Old and new…

Feature	VELO	Upgrade
Sensors	R & φ strips 0.22 m^2 172,032 strips electron collecting 300 μm thick 40-100 μm pitch	Pixels 0.12 m^2 **41 M pixels** electron collecting **200 μm thick** 55 μm pitch
# of modules	42	52
Max fluence	4.3×10^{14} MeV n_{eq} cm^{-2}	**8×10^{15}** 1 MeV n_{eq} cm^{-2}
HV tolerance	500 V	**1000 V**
ASIC readout rate	1 MHz	40 MHz
Total data rate	analog (eq. to 150 Gb/s)	2.8 Tb/s
Total Power consumption	1 kW	**1.6 kW** (30 W/module)

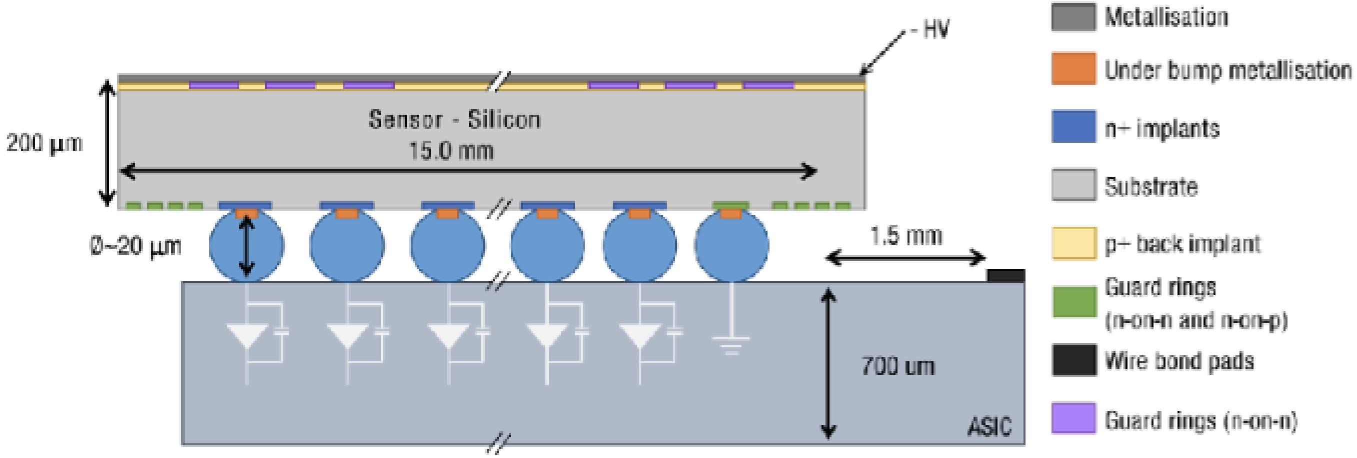
New sensor and new chip

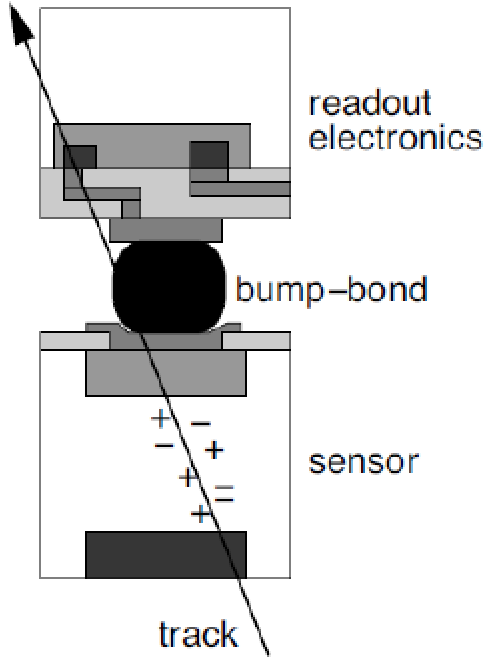
- ❑ Silicon sensor 200 μm thick
- ❑ P-type, 8×10^{15} 1 MeV n_{eq}/cm^2 lifetime fluence
- ❑ 768×256 pixels, each 55×55 μm^2



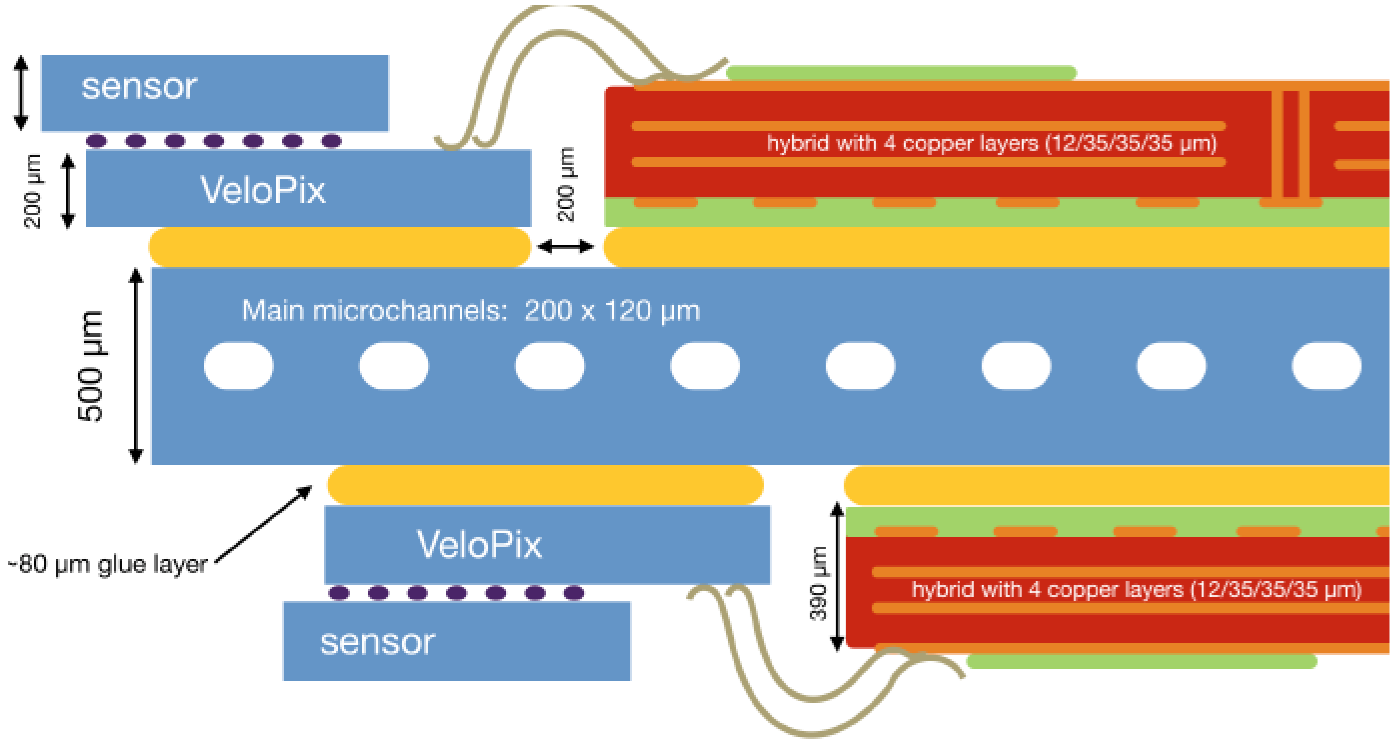
- ❑ Each sensor has three ASICs
- ❑ Each bump-bonded to 256×256 pixels
- ❑ Readout of every hit: up to 50 khits/s/pixel
- ❑ Power consumption < 2 W

New sensor and new chip



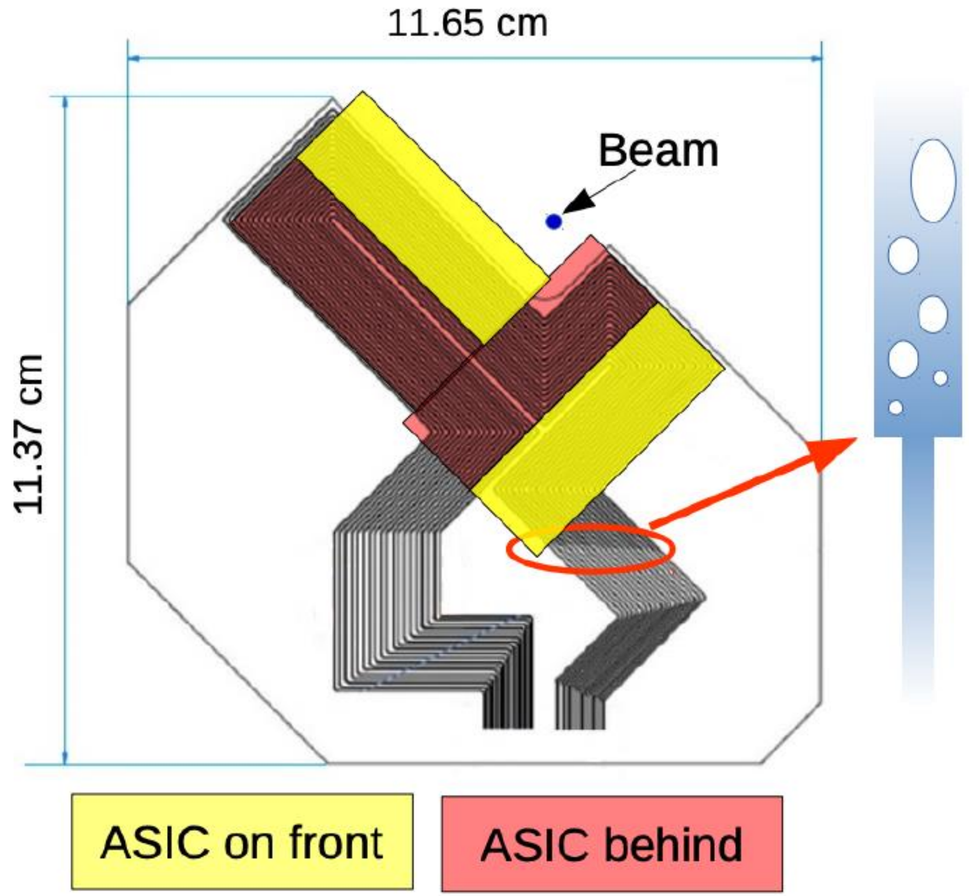


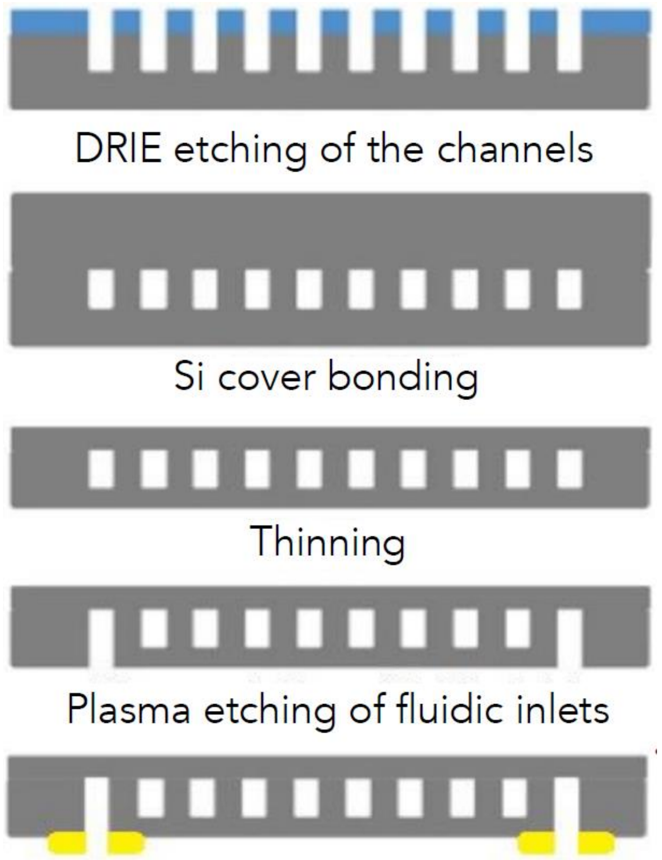
VELO Module cross-section



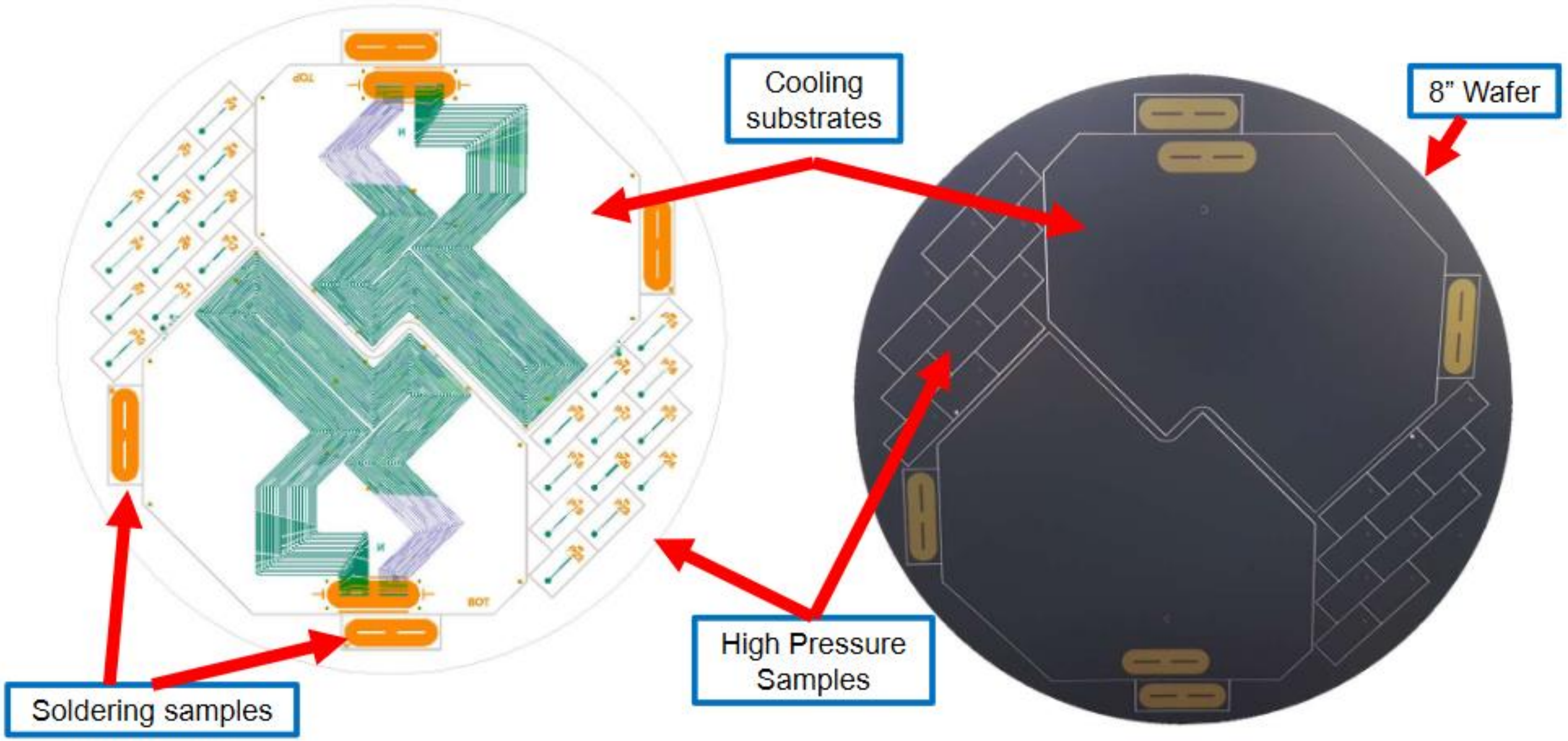
https://cds.cern.ch/record/2770574/files/TIPP_2021%20Vinicius%2027.05.pdf

μ-channel cooling



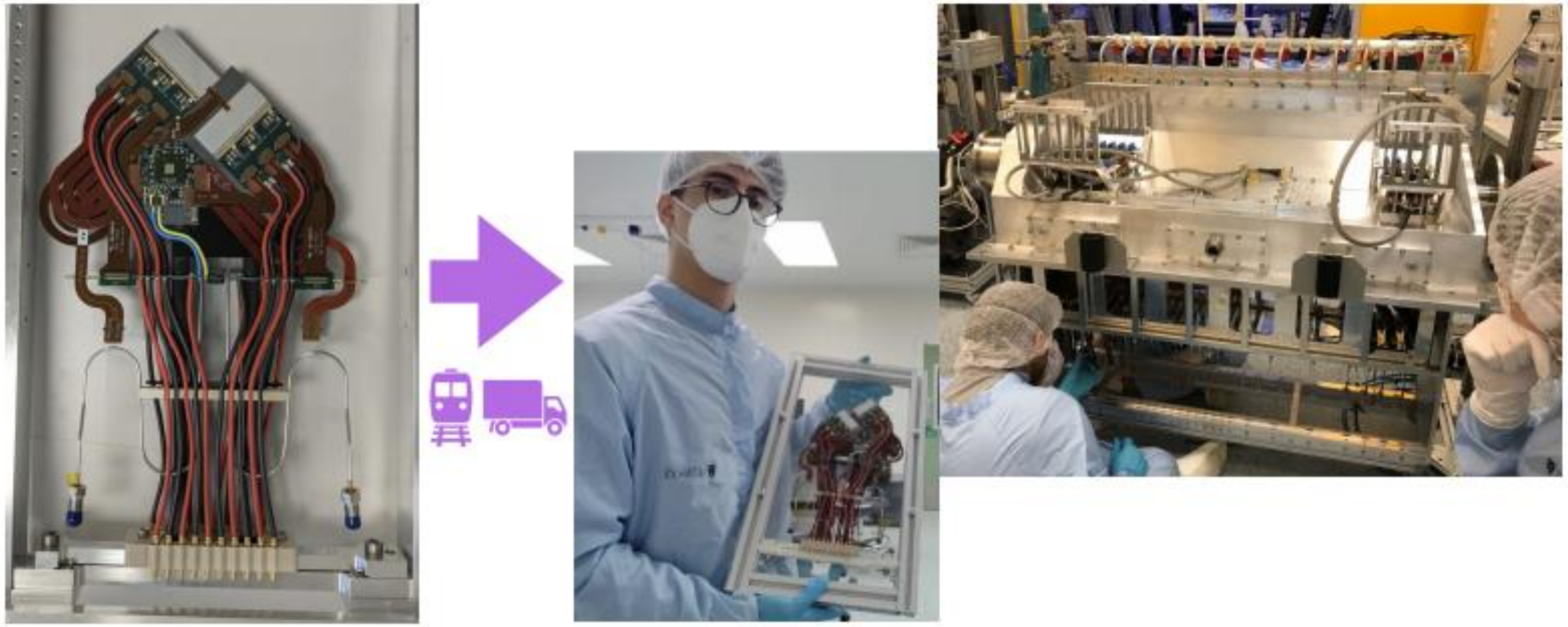


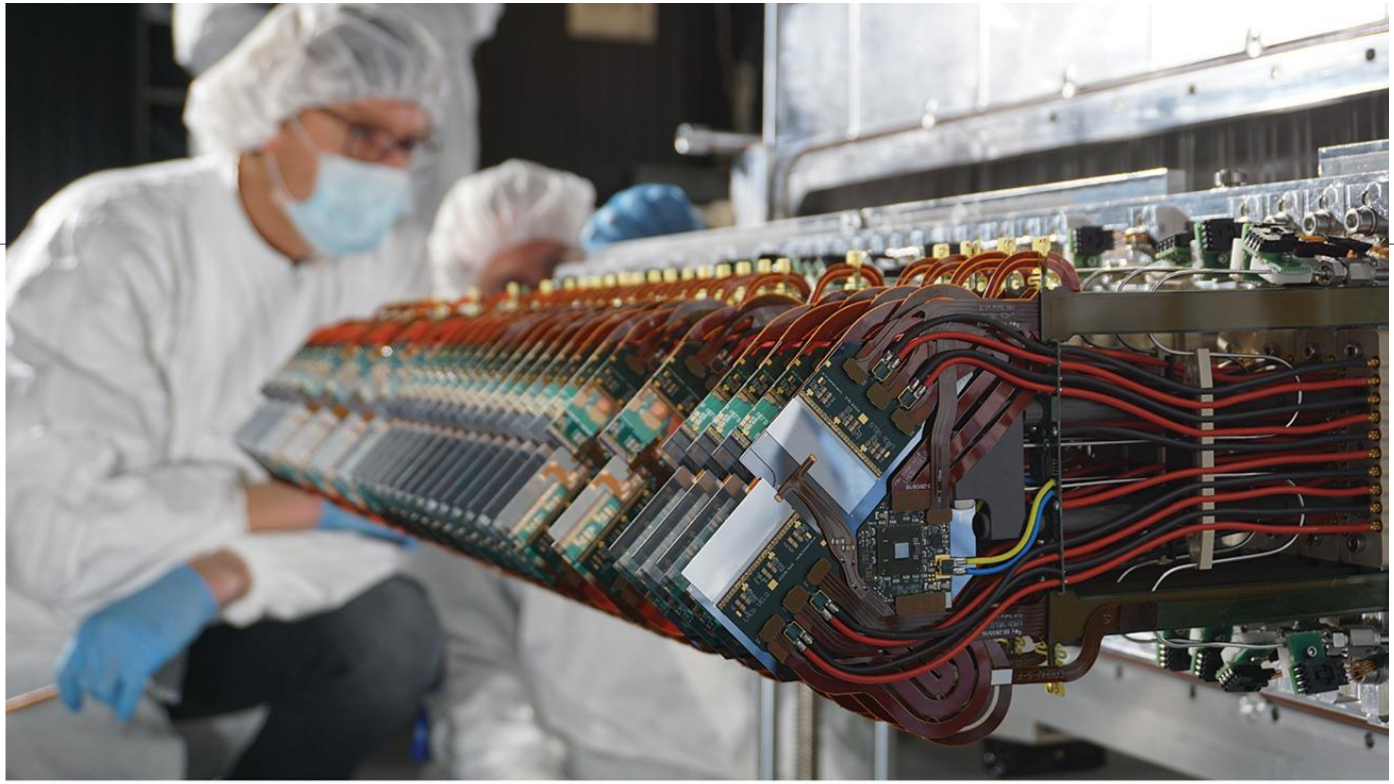
μ-channel cooling - wafers

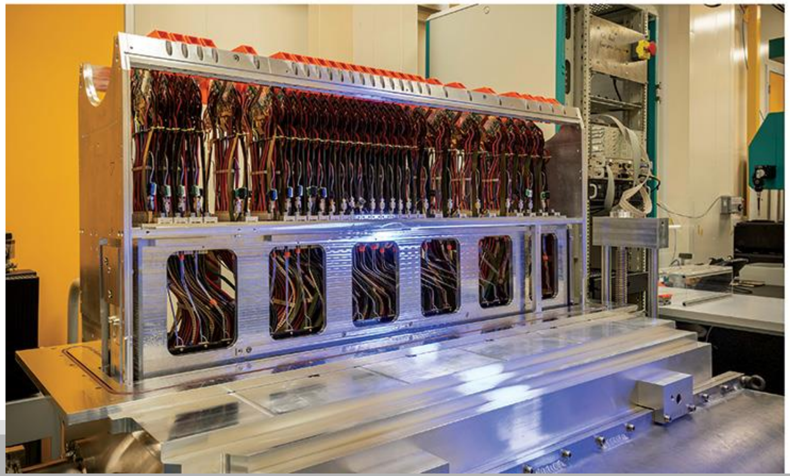


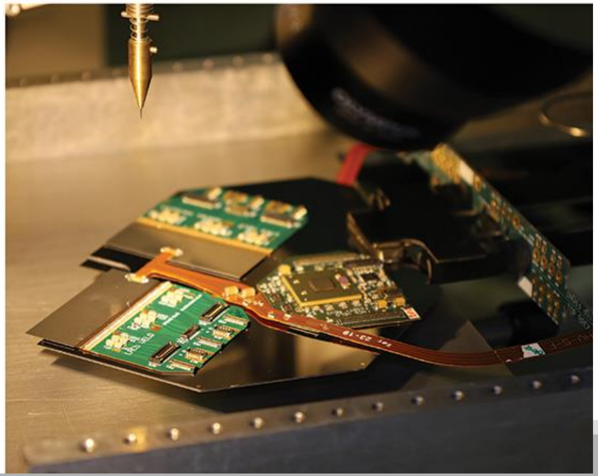
VELO pixel – real life

VELO module... ...VELO assembly site...



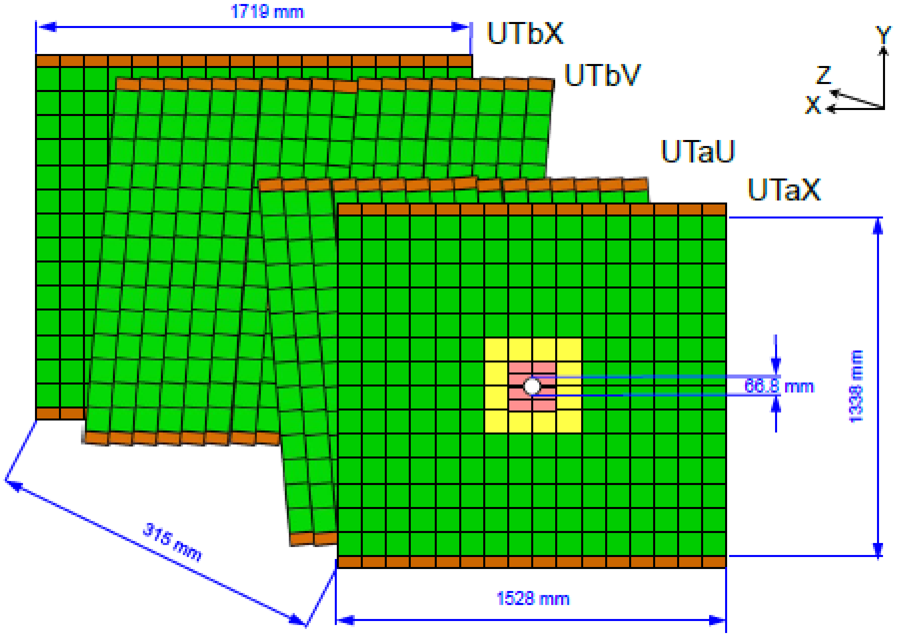


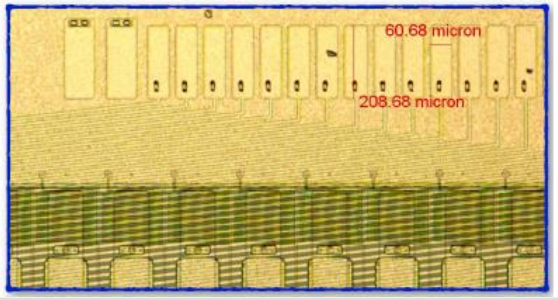




Upstream Tracker (UT) / 1

- Placed upstream to the VELO detector before the warm dipole magnet
- **4 layers of silicon micro-strip sensors** with the geometry similar to Run 1/2 tracker
  - Each vertical plane has a stereo counter part that provides second coordinate
- **40 MHz readout thanks to new SALT ASIC** capable of sophisticated on-detector data processing
- Finer granularity with fine pitch close to the beam, sensors featuring embedded pitch adapters
- Larger coverage thanks to the sensors with **round cut-outs** („touching" the beam pipe)

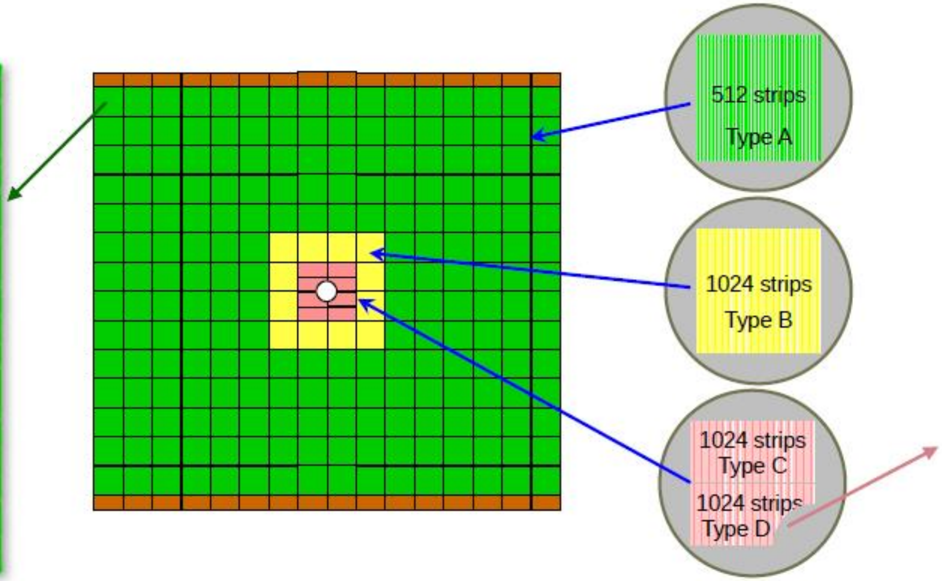


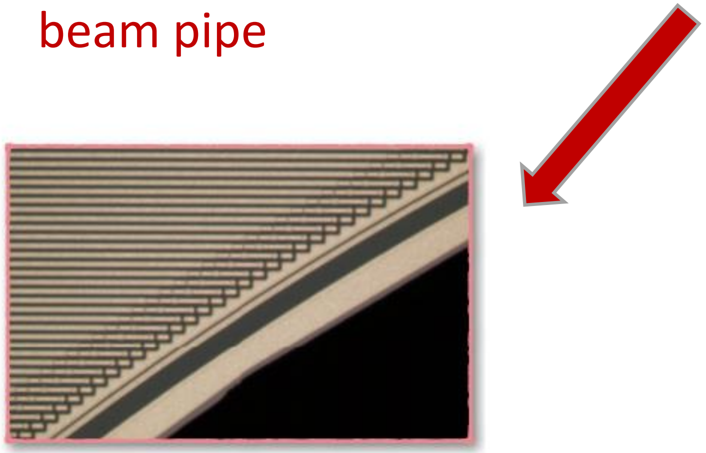


Upstream Tracker (UT) / 2

Sensor	Type	Pitch	Length	Strips	# sensors
A	p-in-n	187.5 μm	99.5 mm	512	888
B	n-in-p	93.5 μm	99.5 mm	1024	48
C	n-in-p	93.5 μm	50 mm	1024	16
D	n-in-p	93.5 μm	50 mm	1024	16

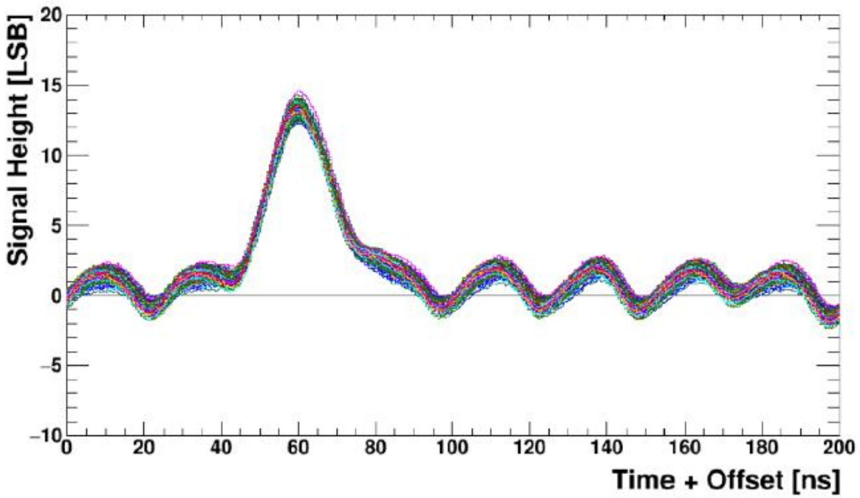
- 4 types of silicon sensors with different granularities (cost optimisation)
  - **Outer region with p-in-n sensors** with 187.5 μm pitch
  - **Inner region with n-in-p sensors** (more radiation hard) with 93.5 μm pitch
  - Complex readout scheme
- Circular cut-out for sensors closest to the beam pipe

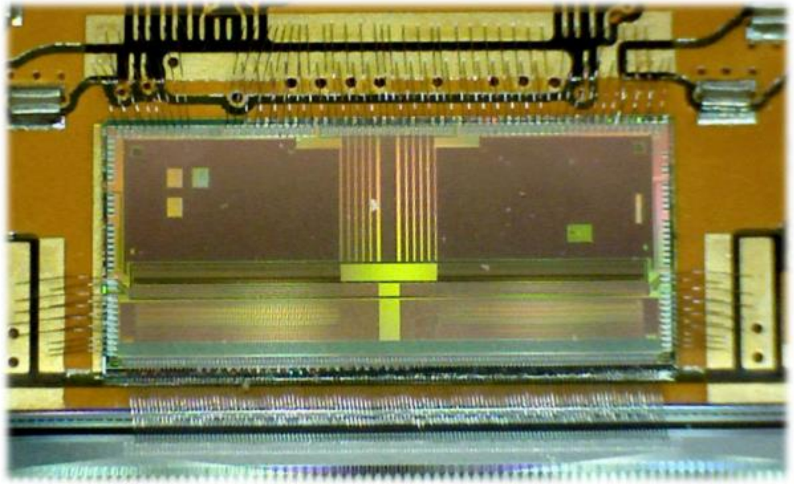




Readout chip – SALT. Designed @AGH

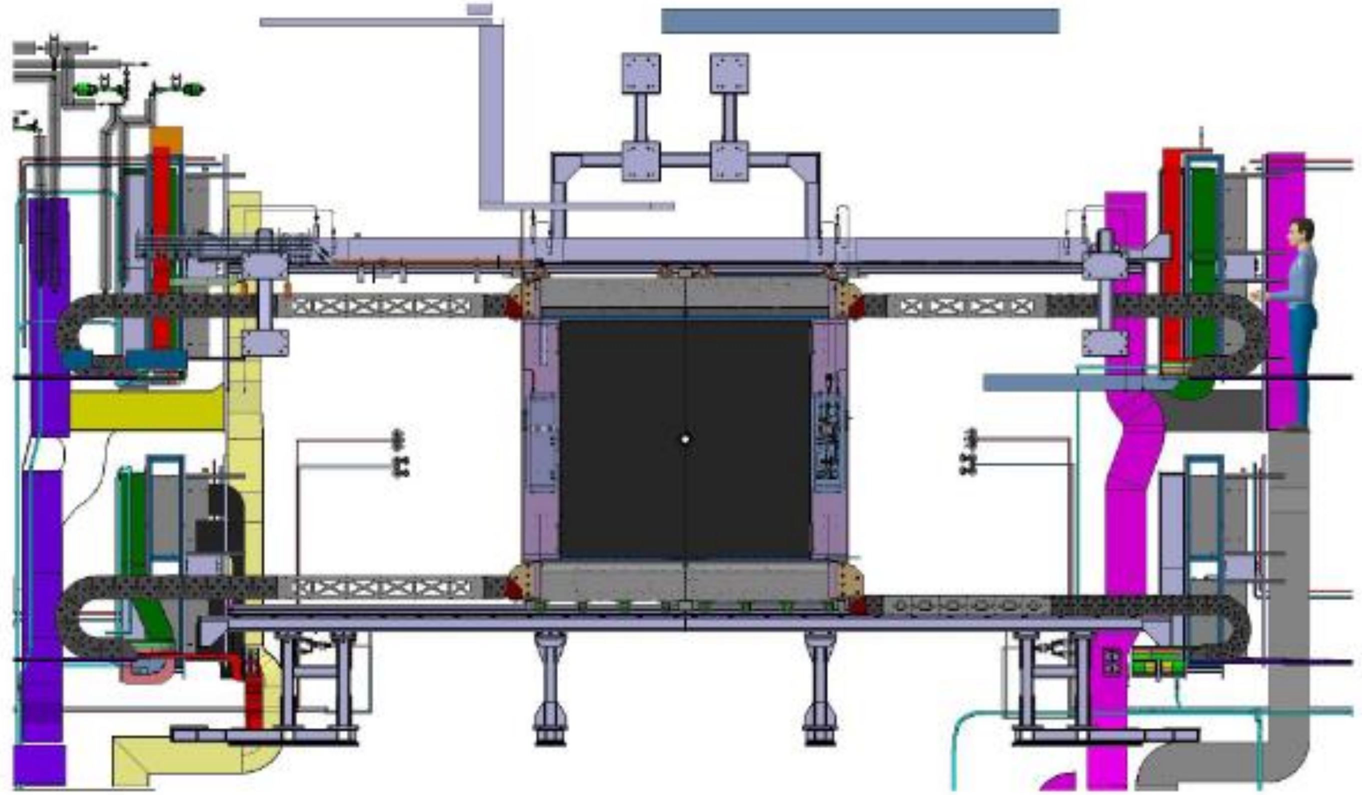
- ❑ 4192 ASICs with 128 channels each
- ❑ 130 nm-TSMC with 30 MRad radiation tolerance
- ❑ Wire-bonded to sensors
- ❑ Input pitch 80µm
- ❑ Allow for 40 MHz readout of UT
- ❑ Up to 5 SLVS e-links @ 320 Mbps



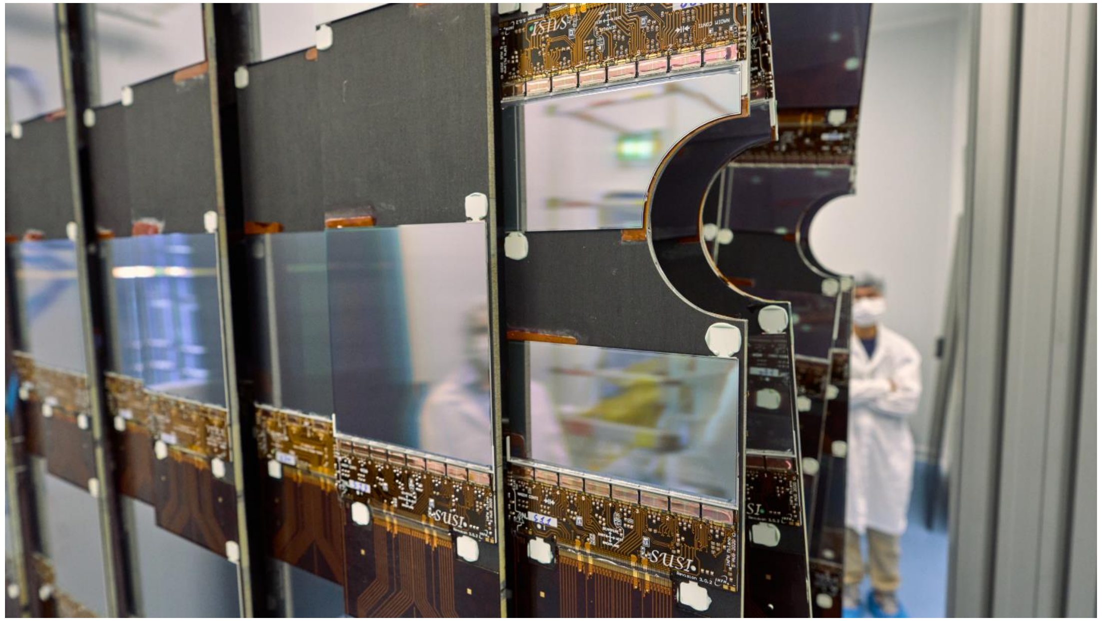


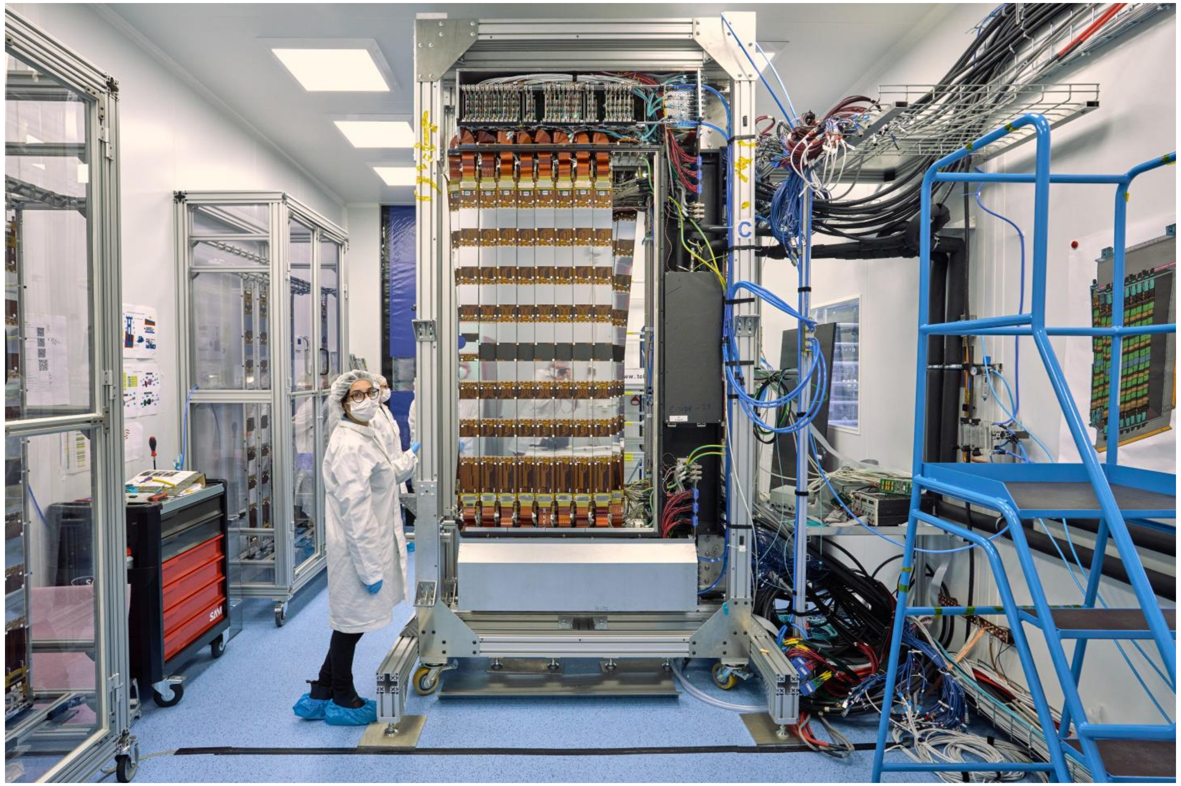
- ❑ Fast shaping
- ❑ 6-bit ADC
- ❑ On-chip memory

Upstream Tracker – model

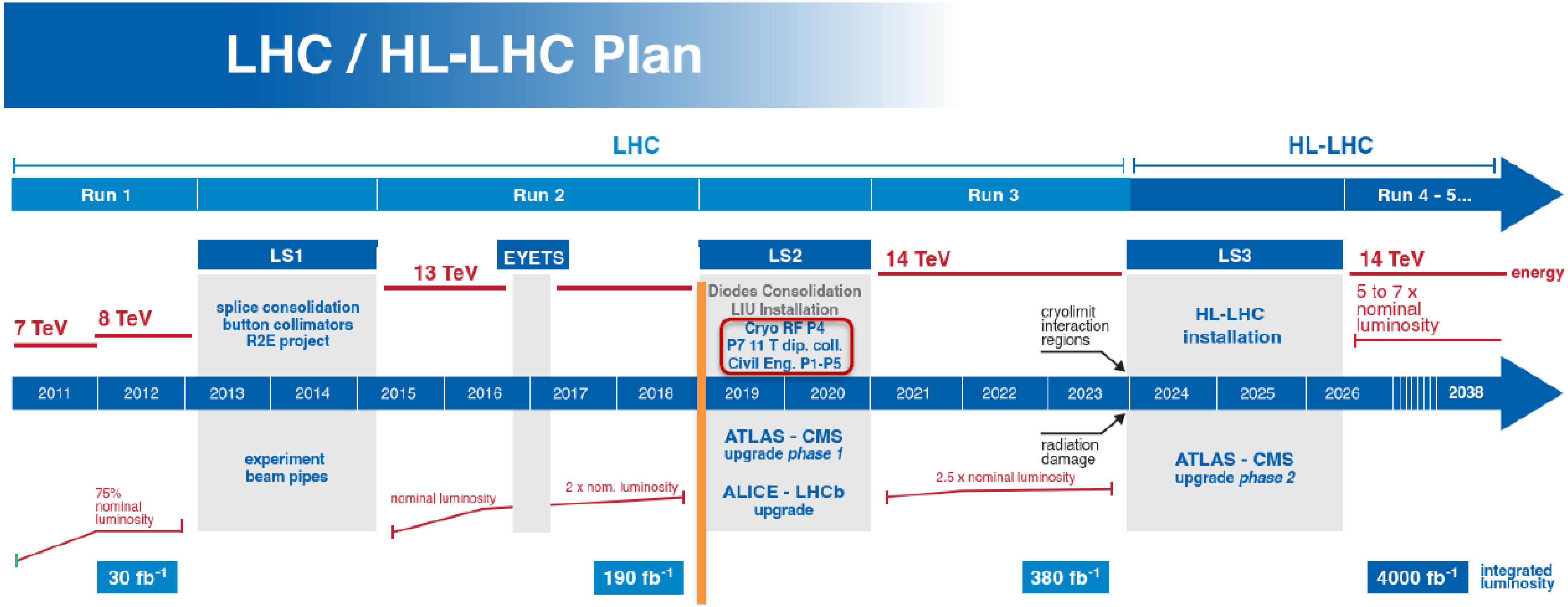


Upstream Tracker – and real detector





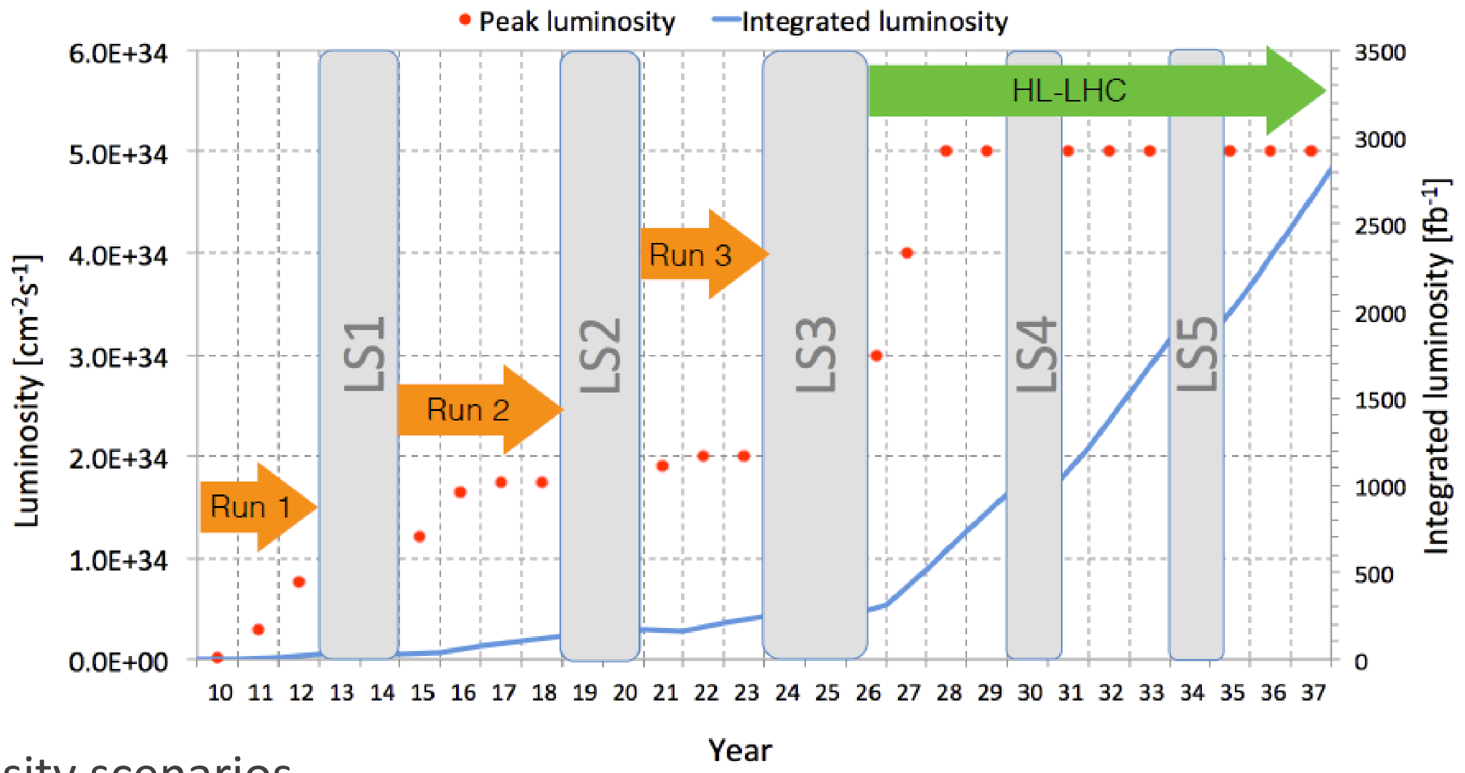
Let’s switch gears – High Lumi LHC (HL-LHC)



HL-LHC = LHC on steroids (well not only that): new service tunnels, new superconducting links near ATLAS and CMS, „CRAB” cavities for ATLAS and CMS, new focusing magnets, collimators and bending magnets

L. Rossi, Project status, 8th HL-LHC collaboration meeting

Let's switch gears – High Lumi LHC (HL-LHC)



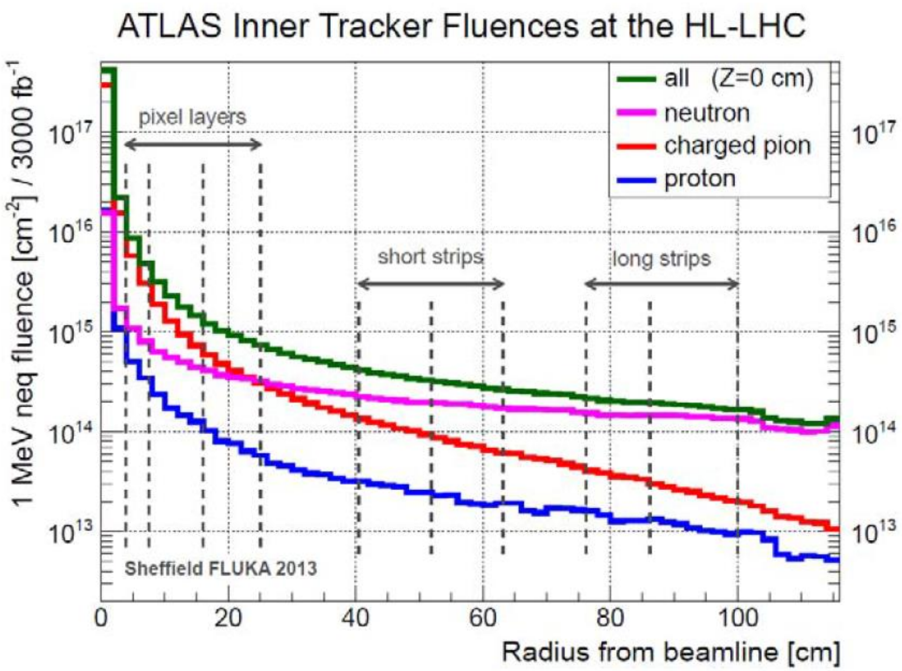
Two luminosity scenarios

- Nominal: $5 \times 10^{34} Hz/cm^2$ - 140 proton – proton interactions per one crossing (in the picture)
- Ultimate: $7.5 \times 10^{34} Hz/cm^2$ - up to 200 interactions per one crossing

HL-LHC: new limits of extreme fluences

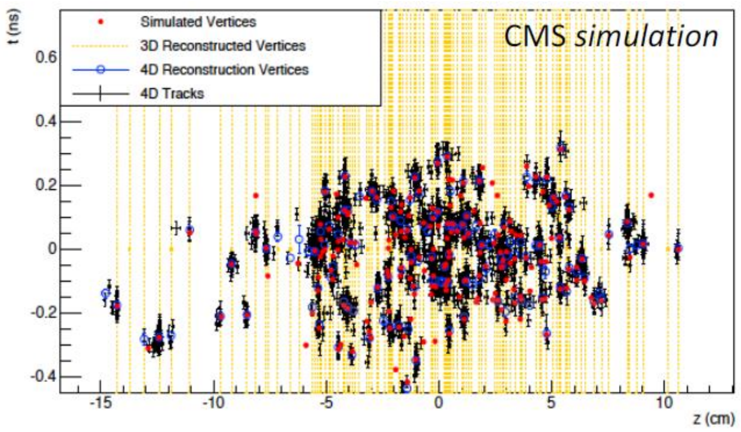
Silicon detectors to be exposed to particle fluences up to $\sim 2 \cdot 10^{16} \frac{n_{eq}}{cm^2}$

Critical role of RD50 Collaboration: mandate to develop semiconductor sensor and characterisation techniques for extreme fluences (here we mean HL-LHC)



„New Machine" – new challenges

- In order to be able to use the physics potential @HL-LHC it is necessary to increase granularity, lower the material budget (critical for LHCb to keep its flavour strength)
- Precise timing essential for coping with large pile-up (up to 200 interactions)
  - ATLAS, LHCb and CMS considering high granularity LGAD detectors
- Thinning essential for radiation hardness (200 μm or 150 μm options considered) Alternative technologies for expensive bump bonding



Timing information (aka 4D tracking) with precision better than 50 ps is essential for high efficiency of primary vertices reconstruction and track association

Upgrades I and II (HL-LHC)

2019 – 2020: LHCb Upgrade I and ALICE (LS2)

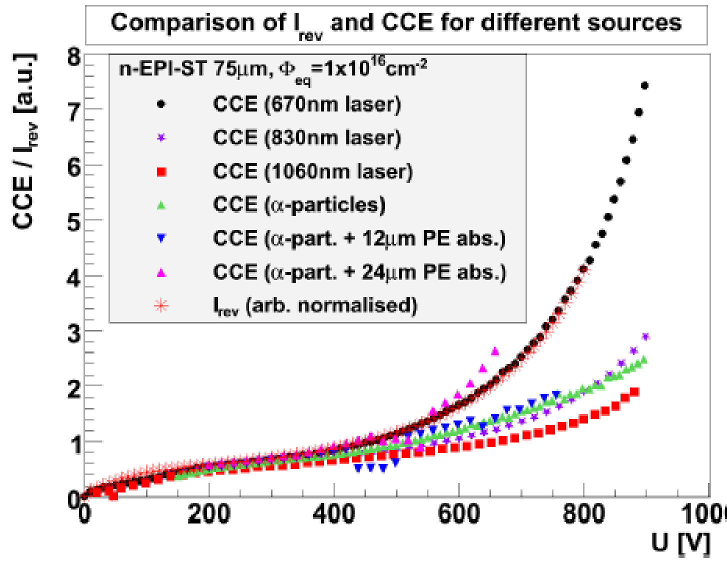
- 55x55 μm hybrid pixel detectors and higher granularity strip detector (n-in-p technology in the innermost region), fibre tracker is going to use silicon PM
- New inner tracker featuring 30x30 μm monolithic active pixels

2024 – 2026: ATLAS and CMS (LS3) and LHCb Upgrade II

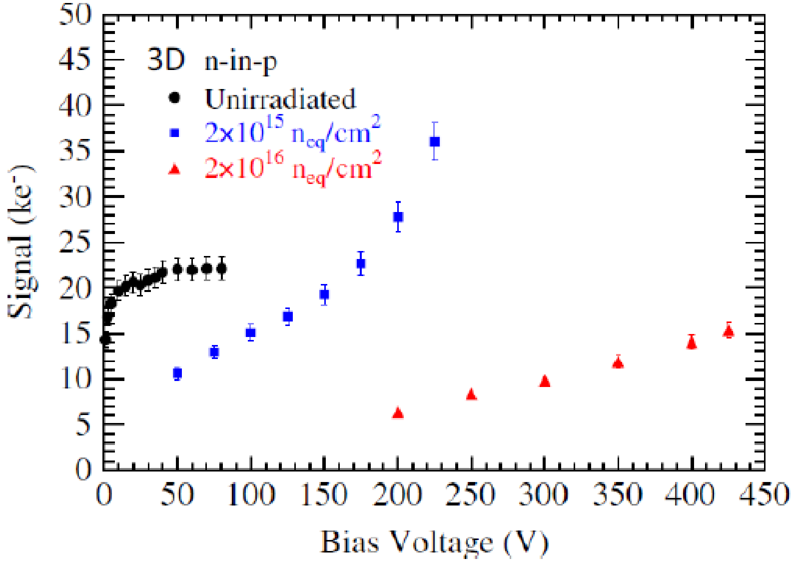
- Going from n-in-n technologies to far more radiation hard n-in-p (hybrid pixels)
- Both 3D pixel and HV/HR-CMOS technologies considered baseline
- CMS replacing the hadronic and electromagnetic calorimeters with high granularity silicon pad detectors
- Timing essential – LGAD/iLGAD and 3D pixel detectors

Charge multiplication:

- signal larger than expected from conventional silicon devices observed after irradiation 2-5·10^{15} $n_{eq}cm^{-2}$,
- irradiation causes negative space charge in detector bulk that increases the electric filed (>15 V/μm), impact the ionisation which manifests through charge multiplication,
- observed in different types of devices (diode, strip, 3D), at very high bias voltages, heavy irradiated,
- could be beneficial for sensors and give extra signal – usable for HL-LHC.



J.Langeet al, 16thRD50 Workshop, Barcelona



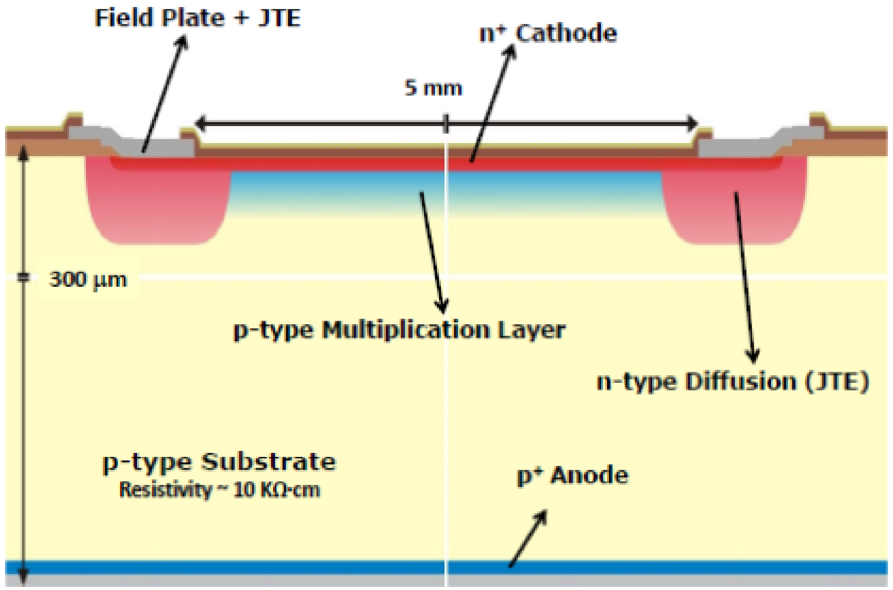
M. Kohler, NIM A, 659 (2011), 272–281

RD50 project: exploit charge multiplication detectors:
- 1 cm x 1 cm, n-in-p FZ strip detectors,
- LGAD sensors (first segmental sensors on thin substrates).

Aims:
- exploit the charge multiplication effect,
- fabricate, test and irradiate sensors,
- simulate and predict (TCAD),
- measure with TCT setup.

LGAD – Low Gain Avalanche Detector

The Low Gain Avalanche Detector (LGAD): a new concept of silicon radiation detector with intrinsic multiplication of the charge.



Advantages:

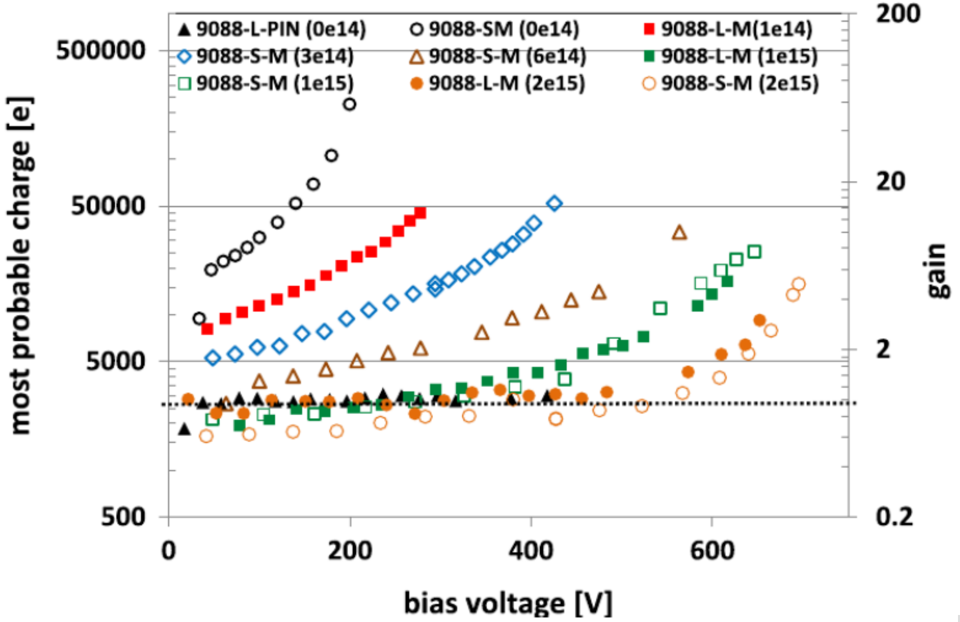
- higher charge collection efficiency,
- short drift time,
- signal shorter and steeper while retaining a large amplitude due to the multiplication mechanism.

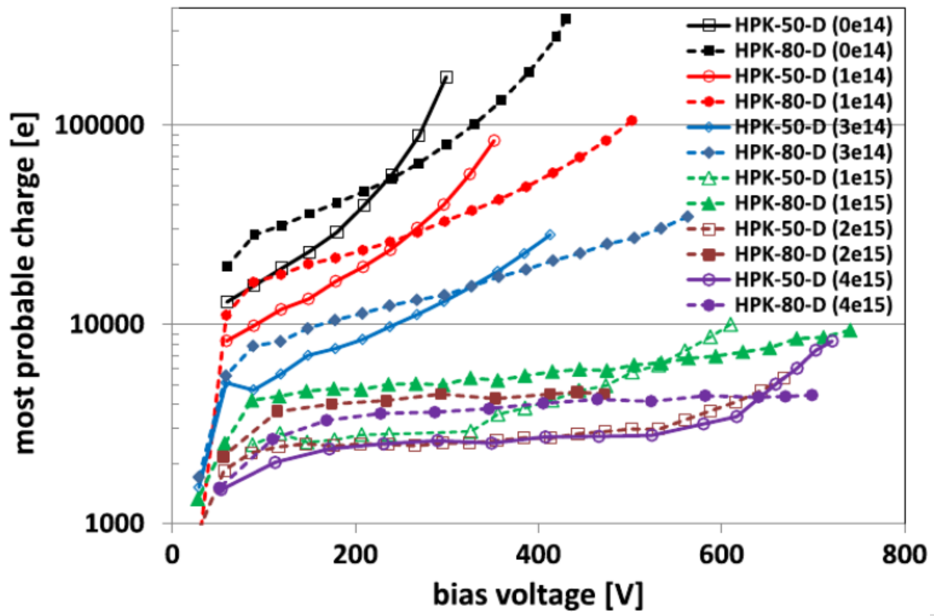
After irradiation (reactor neutrons and 800 MeV protons):

- decrease of charge collection,
- decrease of multiplication (before irradiation it was 3 times higher than standard diode), after irradiation with fluence $2 \cdot 10^{15}\ n_{eq}cm^{-2}$ the gain was lost.

LGAD – Low Gain Avalanche Detector

Thin (50 μm) LGAD detectors
- CMS Endcap Timing Layer
- ATLAS High Granularity Timing Detector
- Need to understand strong acceptor removal (drop in gain with particle fluence)
  - p-doping layer with Gallium instead of Boron or carbon co-implantation?

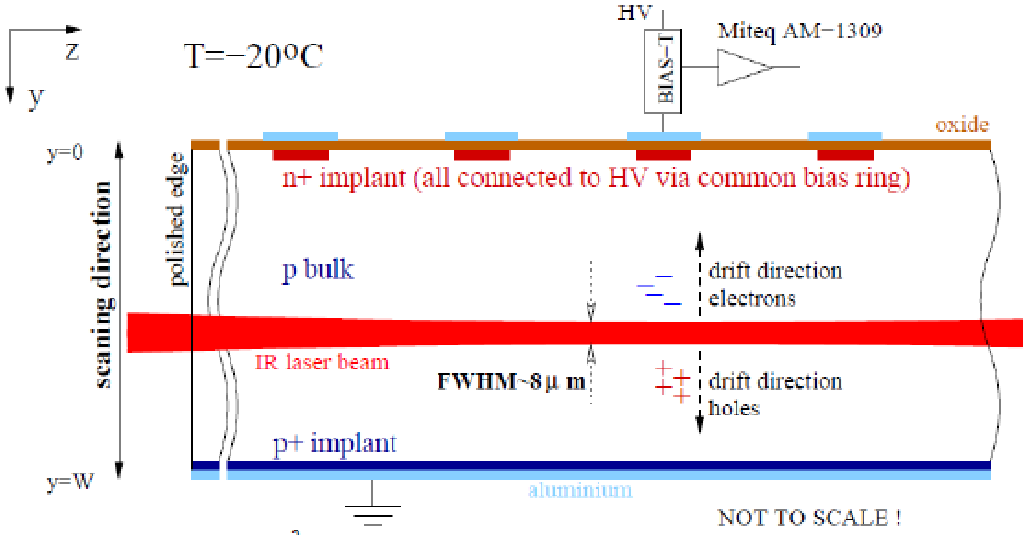


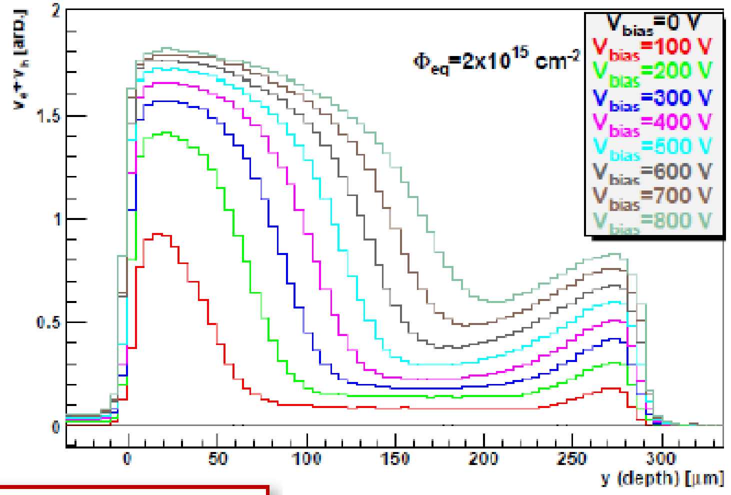


Edge Transient Charge Technique:

Method of reconstruction of electric field pioneered by Ljubljana group and promoted by RD50.

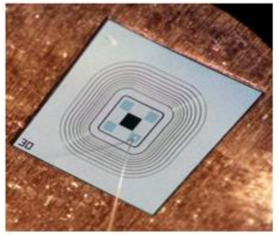
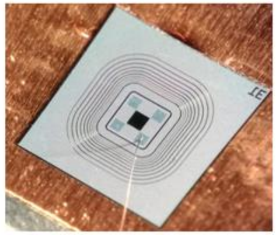
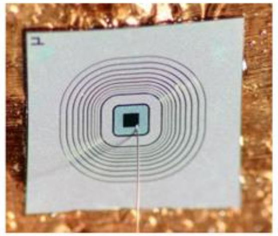
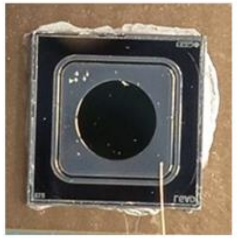
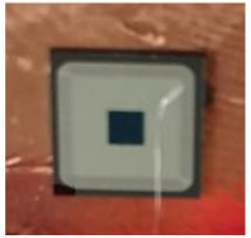
- photon pulses from an infrared laser are directed towards the detector edge, perpendicular to the strips and focused to the region below the readout strip, electron-hole pairs are produced,
- scans across the detector thickness enables relative measurement of the induced current at given depth, extrapolate rise time, drift velocity and charge collection profiles,
- finally, the electric field can be reconstructed by determination of drift velocity.

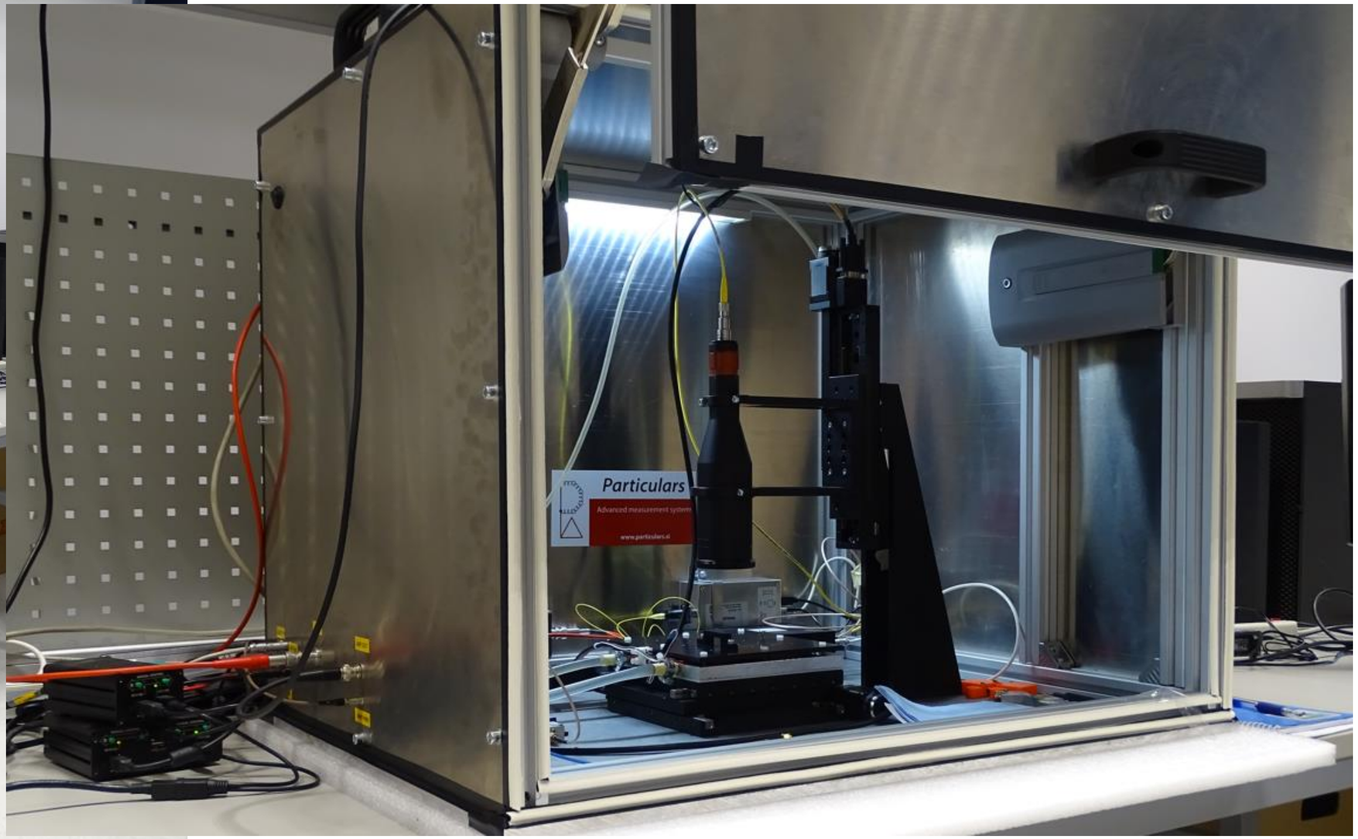




Edge-TCT is widely used ideal tool to study substrate properties!

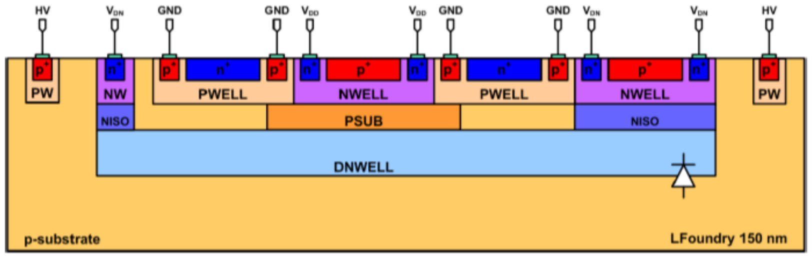
TCT@AGH

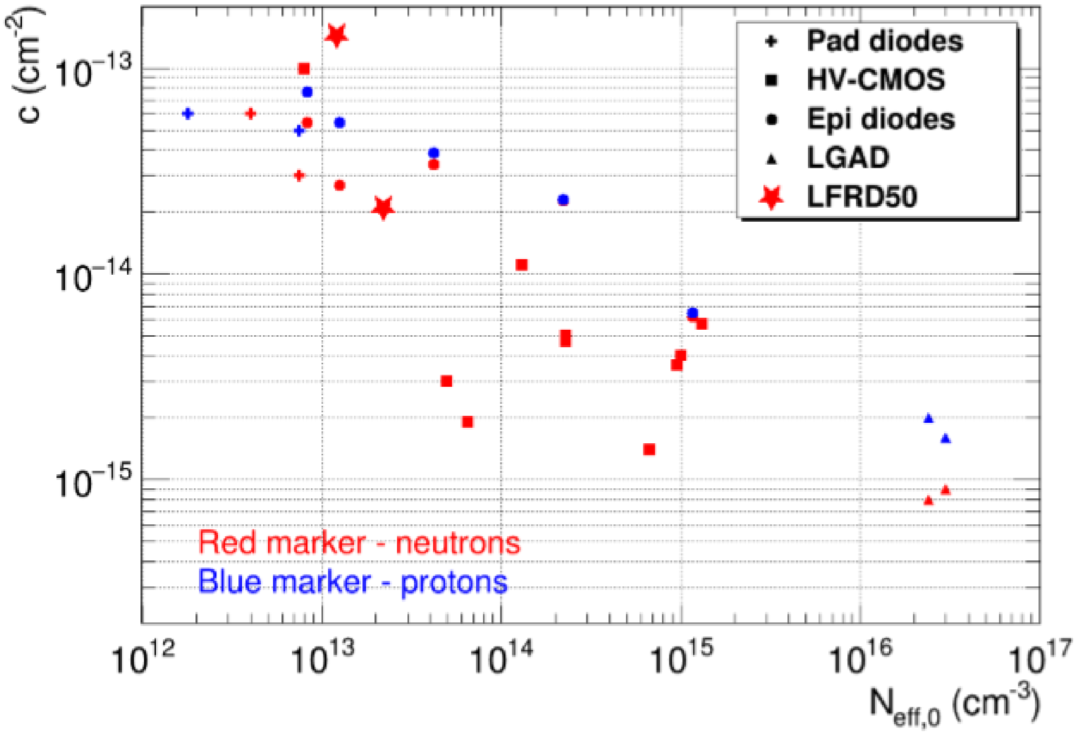








Upgrades I and II (HL-LHC)

HV-CMOS – common fabrication of RD50 – MPW1 (150 nm LFoundry proces)





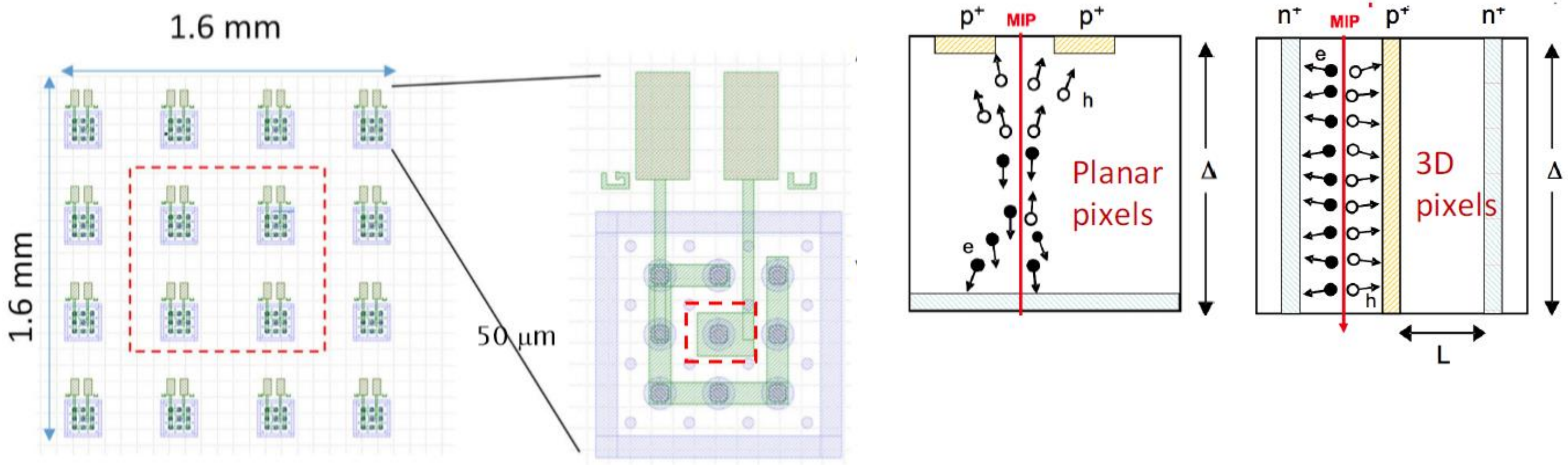
- Analysed irradiated pixel detectors
- Used E-TCT to measure N_{eff} as a function of particle fluence
- Acceptor removal parameter c has been estimated
- Acceptor removal constant higher for substrates with lower initial resistivity

Upgrades I and II (HL-LHC)

LGAD are the favourite timing detectors for HL-LHC, but this come at a cost – radiation hardness and fill factor may be a problem

What about using 3D well established technology?

Tested small cel 3D silicon detectors

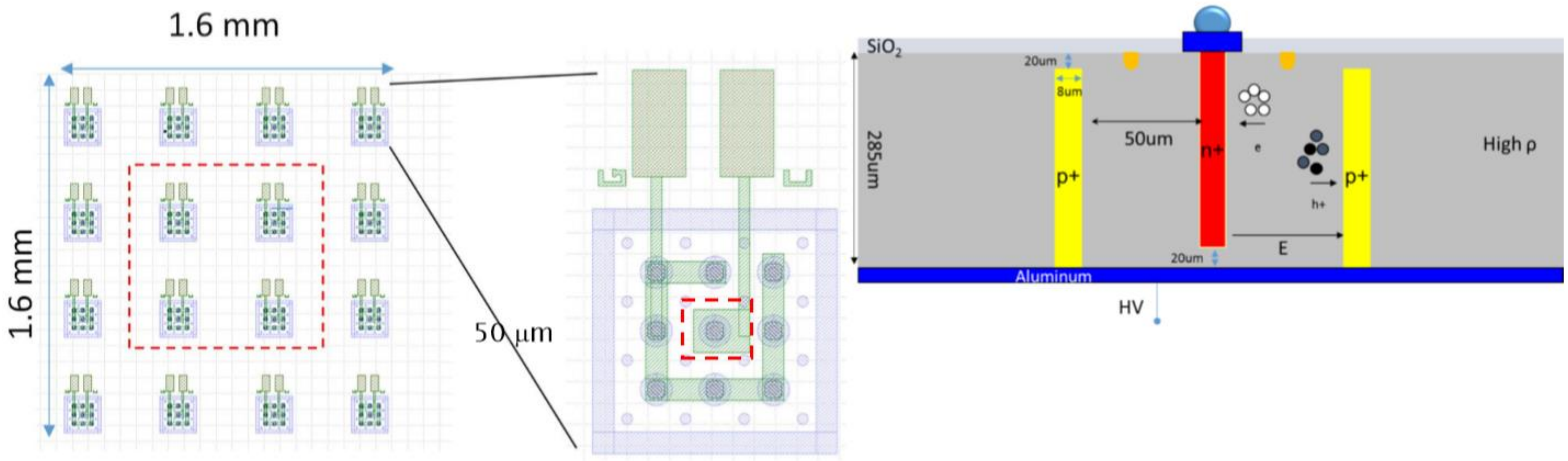


Upgrades I and II (HL-LHC)

LGAD are the favourite timing detectors for HL-LHC, but this come at a cost – radiation hardness and fill factor may be a problem

What about using 3D well established technology?

Tested small cel 3D silicon detectors – new generation 3D devices



Upgrades I and II (HL-LHC)

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- What about using 3D well established technology?
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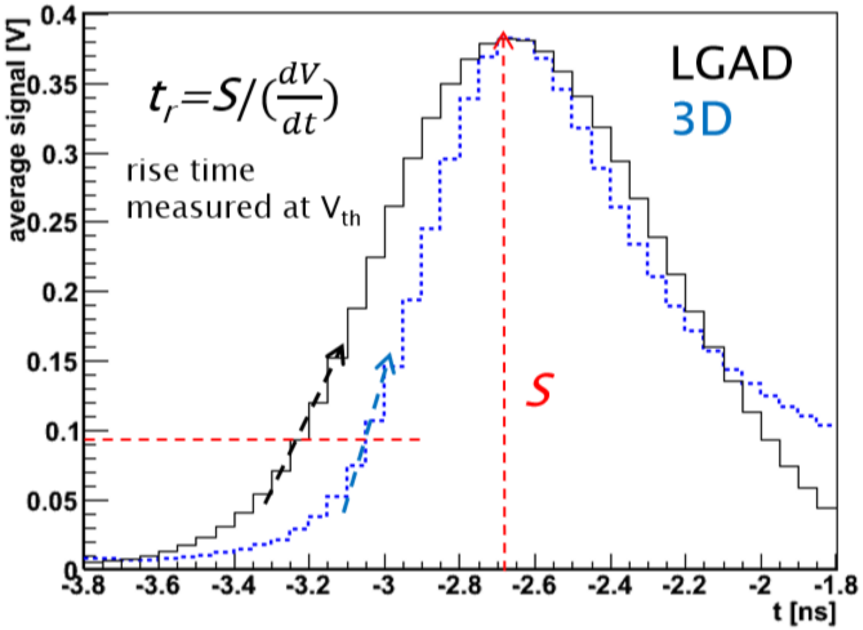
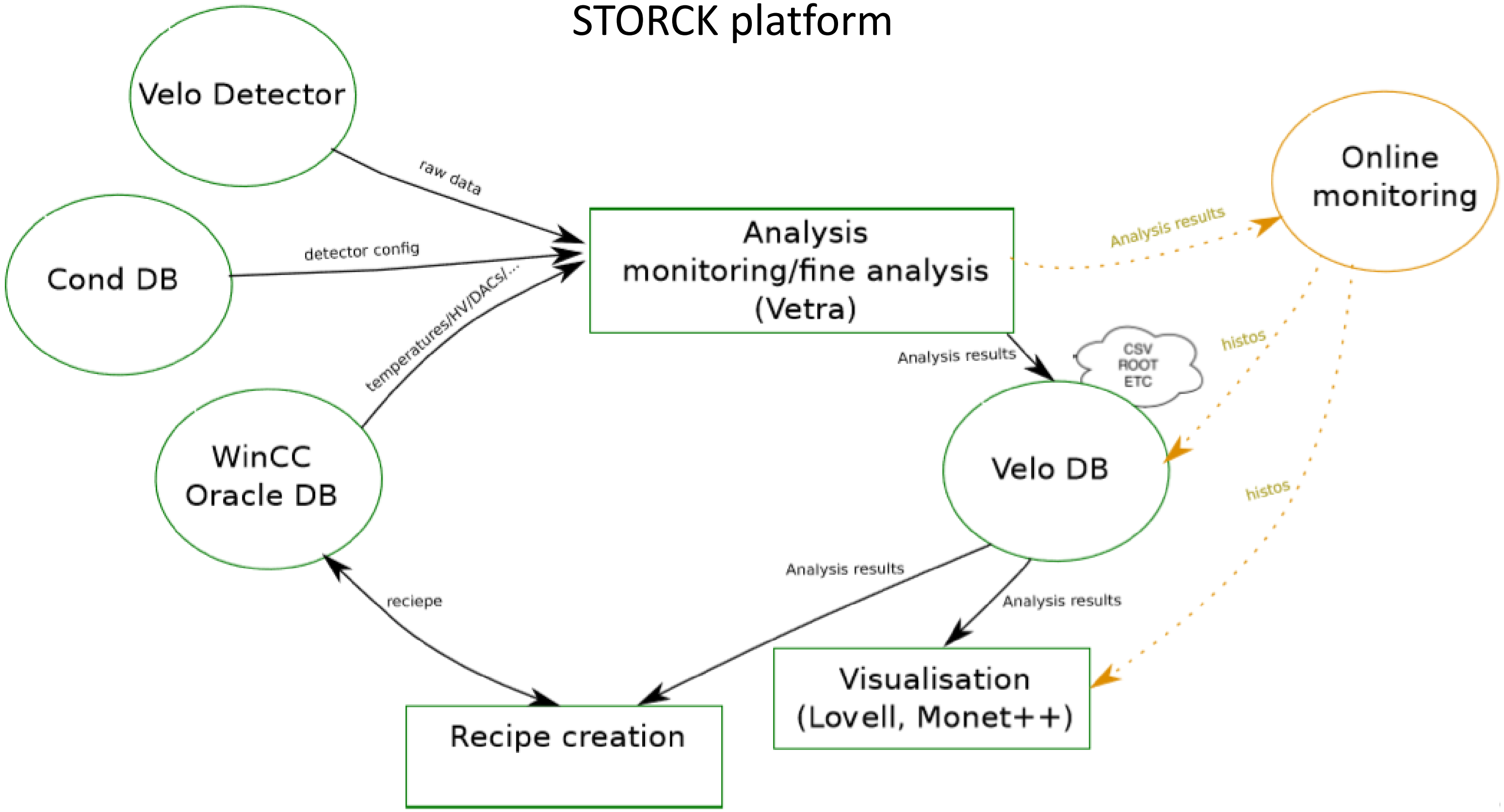


- Timing in small cell 50x50 μm^2 3D detectors was measured and simulated
- Timing resolution comparable with LGAD type sensor performance
- Can be considered as a backup solution for LGAD detectors (especially in the places with the harshest radiation)

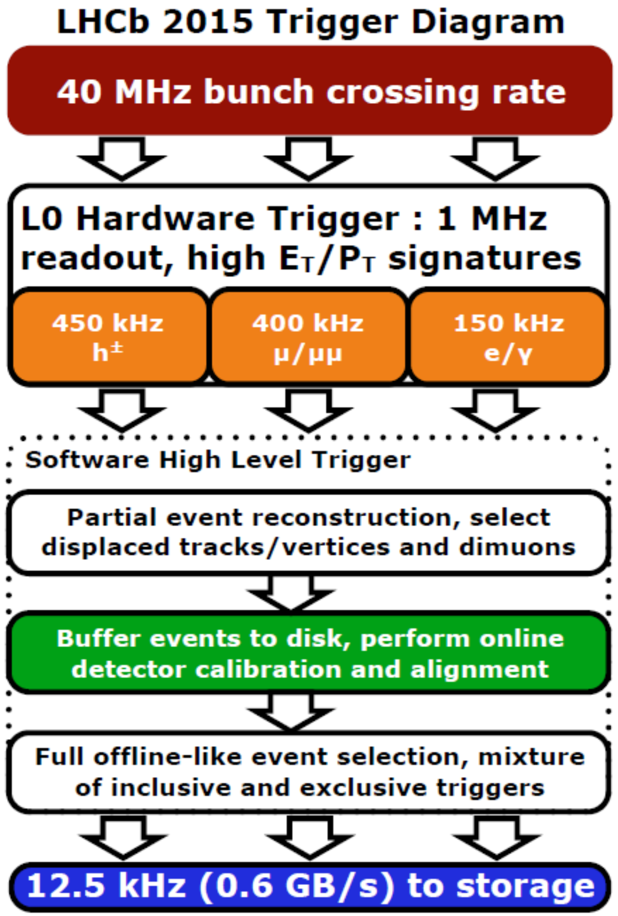
END

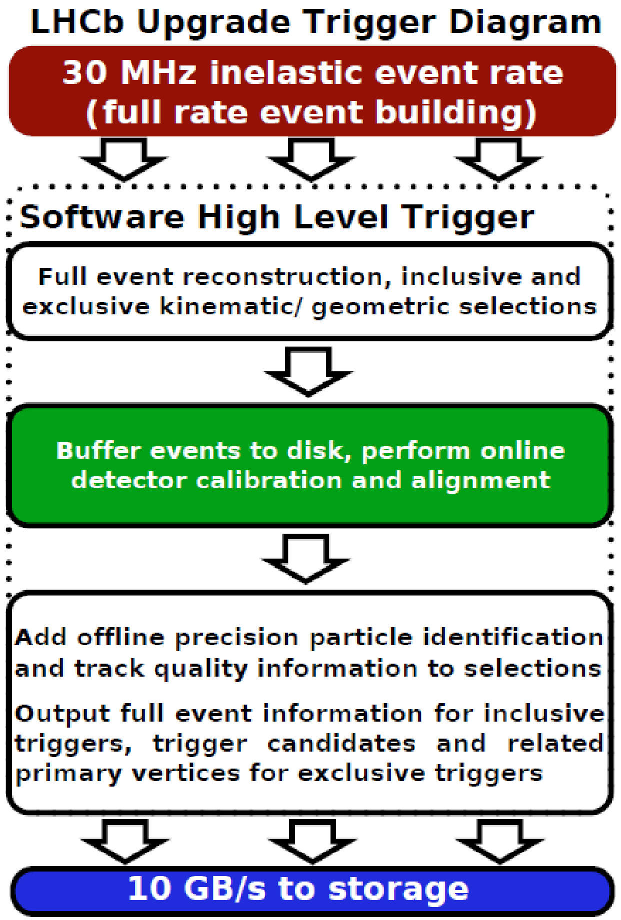
Robust software for silicon detectors

STORCK platform



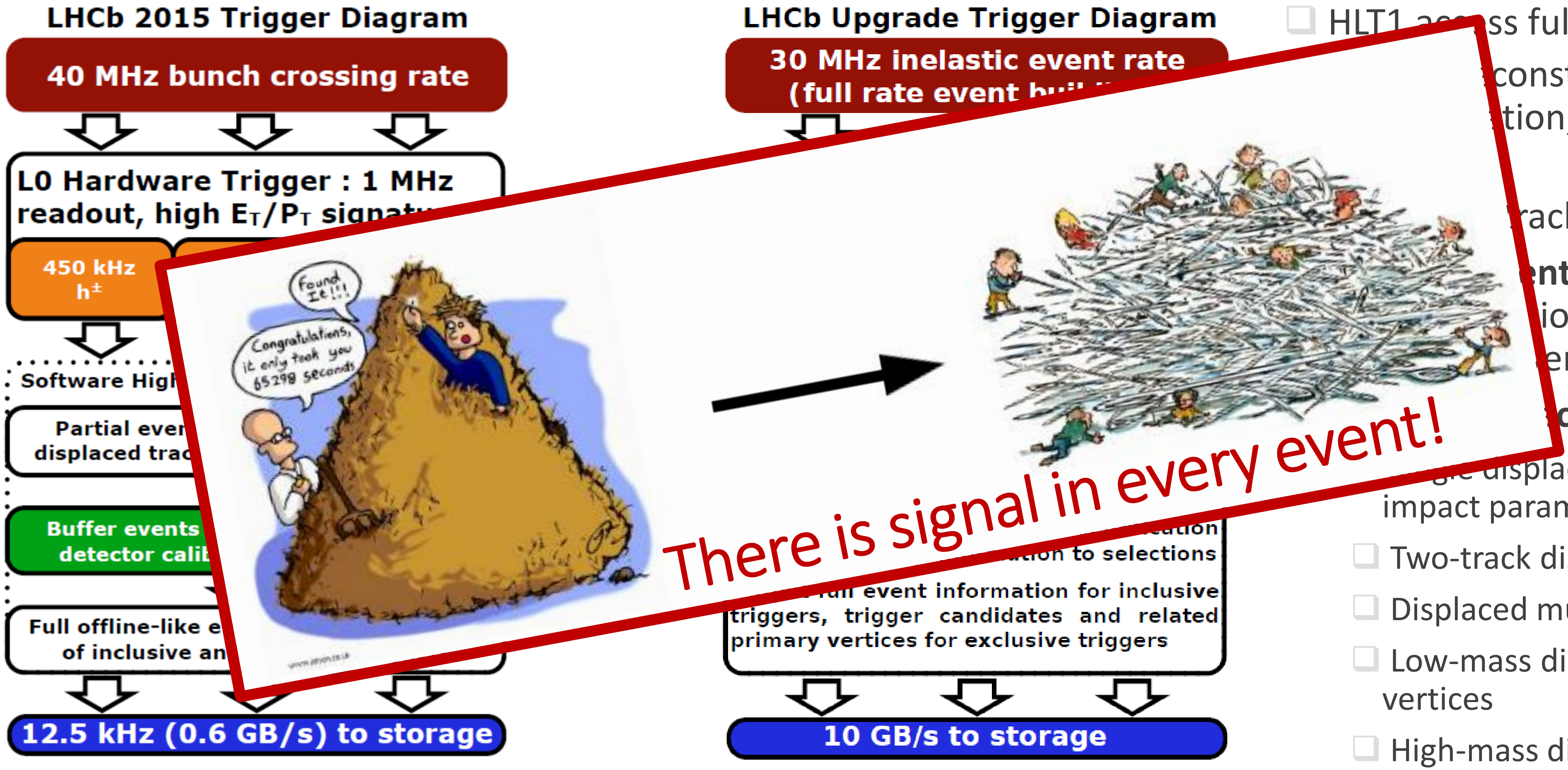
Software trigger (HLT) Run 2 → Run 3 / 1





- HLT1 access full detector information
  - **VELO** reconstruction with clusterisation, tracking and vertex fitting
  - **UT & FT** track reconstruction
  - **Global event reconstruction** with Full bidirectional Kalman filter and secondary vertices
  - **Physics selections**
    - Single displaced (in terms of large impact parameter) tracks
    - Two-track displaced vertices
    - Displaced muons
    - Low-mass displaced two-muon vertices
    - High-mass dimuons

Software trigger (HLT) Run 2 → Run 3



- HLT1 a… ss full detector information
  - …construction with …tion, tracking and vertex
  - …rack reconstruction
  - …**ent reconstruction** with …ional Kalman filter and …ertices
  - …**ctions**
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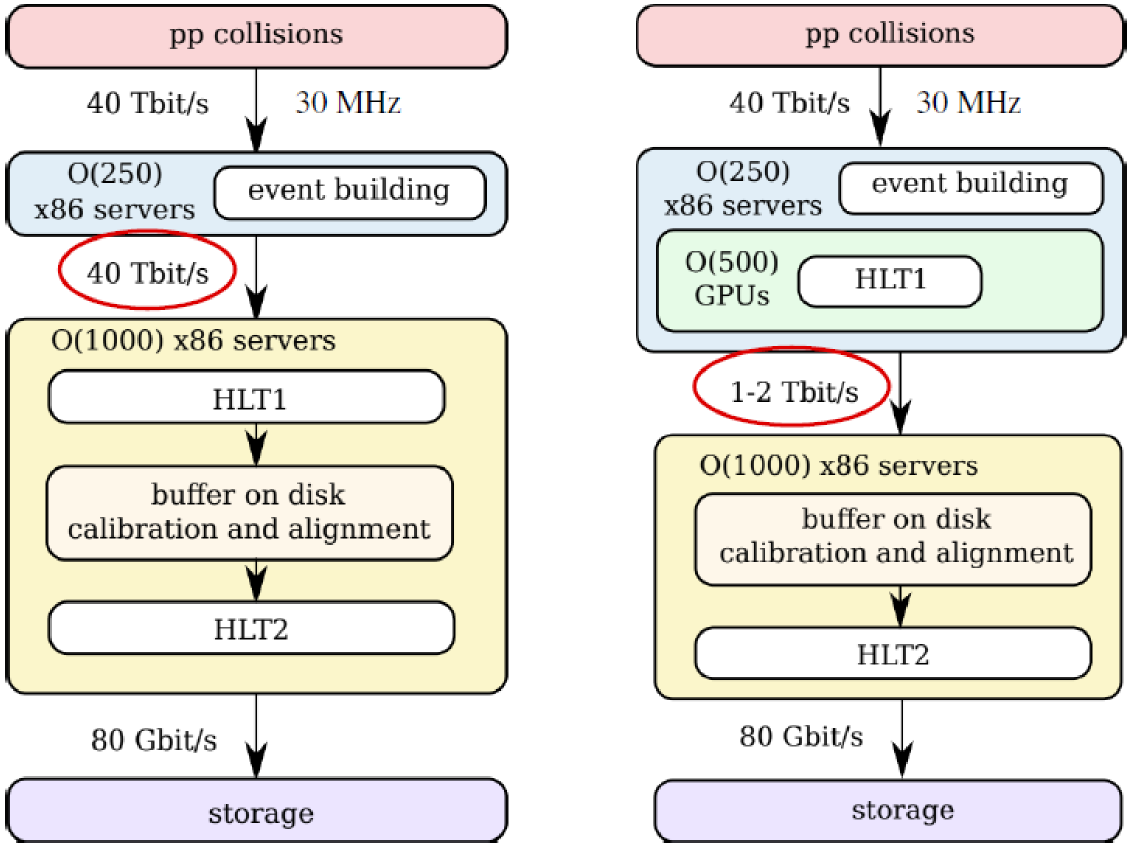
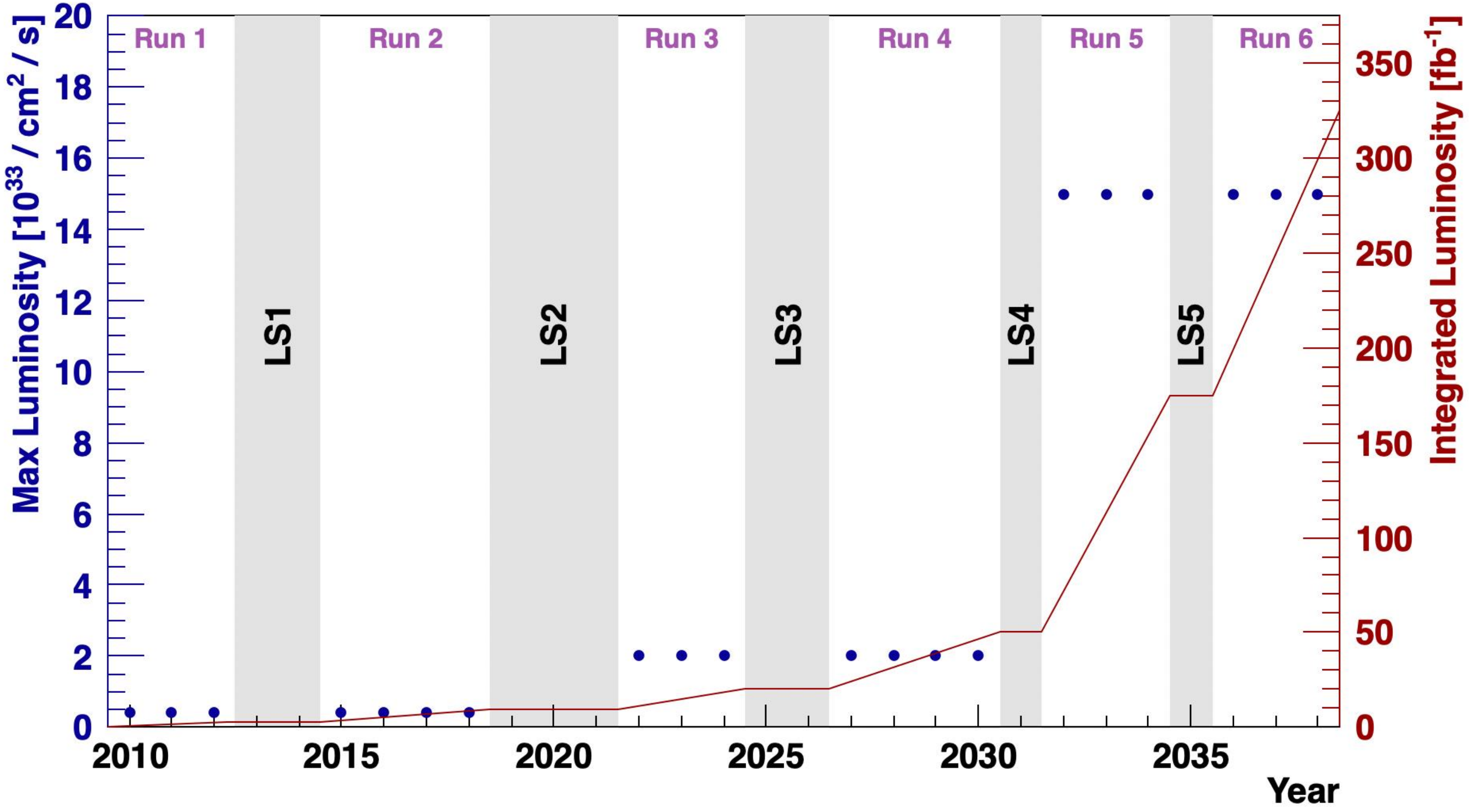
LHCb Software trigger goes GPU



- Trigger event selection exibits **„natural" data parallelism** – could be exploited using massively parallel GP-GPUs
- LHCb RAW event size about 100 kB
- GPU used for producing selection decision
- The HLT1 data stream can be processed using **~500 top-shelf GP-GPU cards**
- Physics performance with simulated data **exceeds by far the TDR proposal regarding full CPU trigger**

Run 3/4/5/6 luminosities for LHCb



Magnet stations / Upgrade Ib