# Beyond the SM searches with LHCb

**IGFAE Retreat 2021**

Instituto Galego de Física de Altas Enerxías (IGFAE)

Universidade de Santiago de Compostela (USC)

# The LHCb Collaboration

- About 1500 members from 89 institutes in 19 countries.
- **624 papers, 48243 citations (June 27, 2022).**
- Main focus on heavy quark flavour, but over the years LHCb has evolved to become almost a general purpose detector in the forward region.
- CKM & CPV, EW & QCD, semileptonic decays, rare decays, exotica searches, heavy ions and fixed target, spectroscopy…

**IGFAE/USC is a founder institution of the collaboration (1995). 43 members now.**

Responsibilities in the development, building and operation of the ***Silicon Tracker*** and the ***VELO*** detectors for the **LHCb and LHCb Upgrade I** experiments. Currently developing technologies for the **LHCb Upgrade II.**

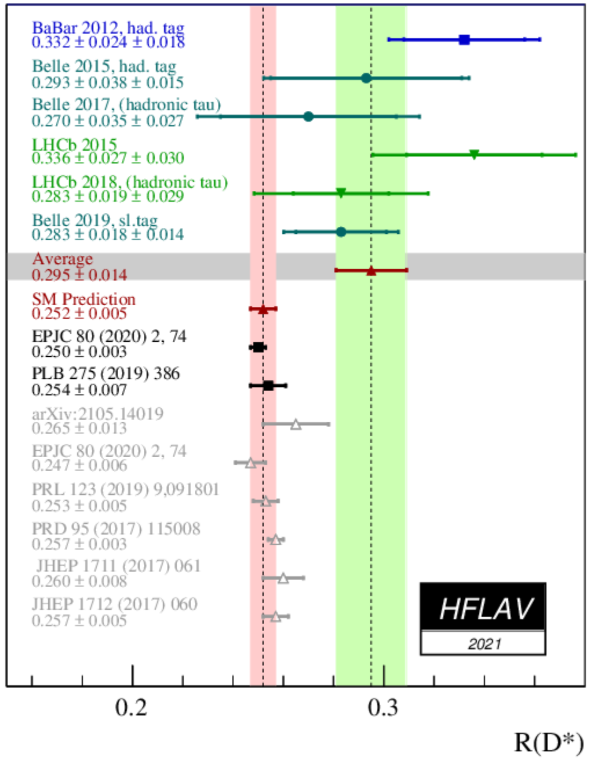
## Main research lines of the IGFAE group

- Lepton Flavour Universality in semileptonic decays of heavy mesons and hyperons
- Measurement of CP-violating observables in B meson decays
- Rare decays
- Exotica searches
- Proton-Lead collisions
- Reconstruction, Particle Identification and Real Time Analysis
- Beyond the Standard Model phenomenology
- Instrumentation for the LHCb Upgrades (and medical treatment)

# Lepton Flavour Universality (LFU) in semileptonic decays

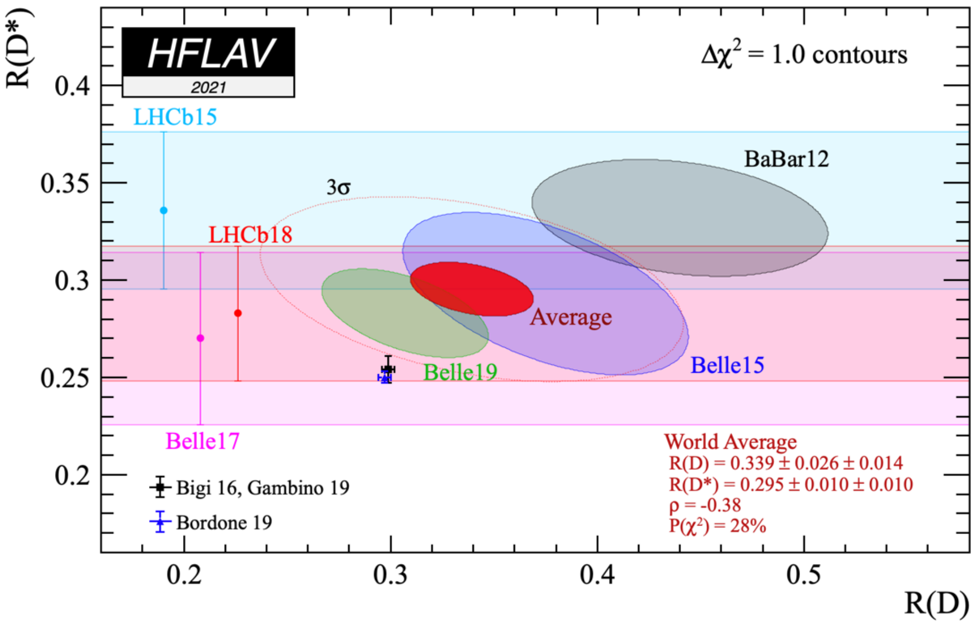
**Test of LFU at tree level.**
**Sensitive to charged Higgs bosons and leptoquarks**

$$R\left(D^{(*)+}\right) = \frac{\mathcal{B}\left(\bar{B}^0 \to D^{(*)+}\,\tau^-\,\bar{\nu}_\tau\right)}{\mathcal{B}\left(\bar{B}^0 \to D^{(*)+}\,\mu^-\,\bar{\nu}_\mu\right)}$$




Publications with contributions from IGFAE members:

- *Measurement of the ratio of the* $B^0 \to D^{*-}\tau^+\nu_\tau$ *and* $B^0 \to D^{*-}\mu^+\nu_\mu$ *branching fractions using three-prong tau-lepton decays,* ***Phys. Rev. Lett. 120, 17802 (2018).***
- *Test of lepton flavour universality by the measurement of the* $B^0 \to D^{*-}\tau^+\nu_\tau$ *branching fraction using three-prong decays,* ***Phys. Rev. D 97, 072013 (2018).***
- *Review of Lepton Universality tests in B decays*. ***J.Phys. G46 (2019) no.2, 023001.***



# Measurement of $R(D^{(*)0})$ using 3-prong hadronic tau decays

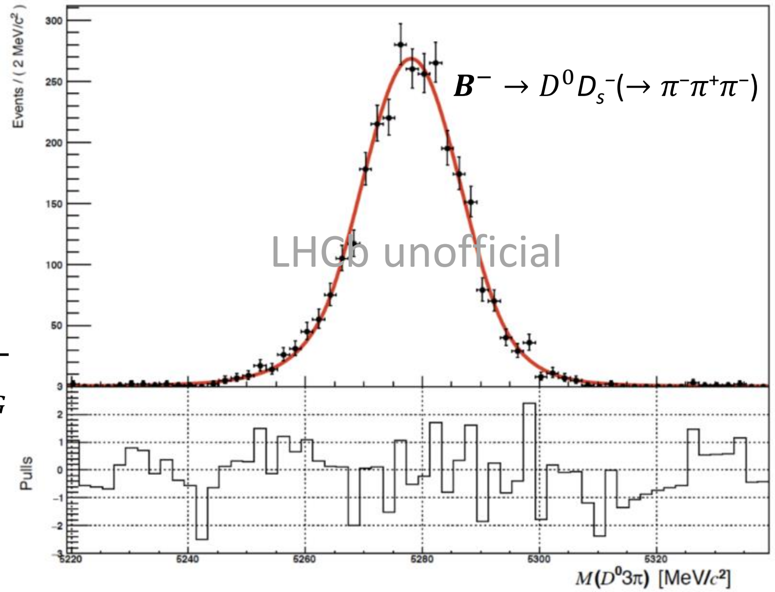
- Ongoing analysis: simultaneous measurement of

$$R(D^0) = \frac{\mathcal{B}(\boldsymbol{B^-} \to D^0\, \boldsymbol{\tau^-}\, \bar{\nu}_\tau)}{\mathcal{B}(\boldsymbol{B^-} \to D^0\, \boldsymbol{\mu^-}\, \bar{\nu}_\mu)} \qquad R(D^{*0}) = \frac{\mathcal{B}(\boldsymbol{B^-} \to D^{*0}\, \boldsymbol{\tau^-}\, \bar{\nu}_\tau)}{\mathcal{B}(\boldsymbol{B^-} \to D^{*0}\, \boldsymbol{\mu^-}\, \bar{\nu}_\mu)}$$

using 3-prong hadronic $\boldsymbol{\tau^- \to \pi^-\pi^+\pi^-\nu_\tau}$ decays.

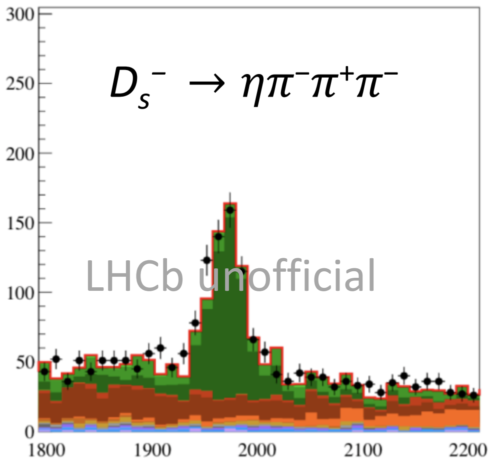
- Strategy:
  - Measurement of $\mathcal{B}(\boldsymbol{B^-} \to D^0\, \boldsymbol{\tau^-}\, \bar{\nu}_\tau)$ and $\mathcal{B}(\boldsymbol{B^-} \to D^{*0}\, \boldsymbol{\tau^-}\, \bar{\nu}_\tau)$ with respect to the normalisation mode $\mathcal{B}(\boldsymbol{B^-} \to D^0 D_s^-(\to \pi^-\pi^+\pi^-))$.
  - Use the best-known values of $\mathcal{B}(\boldsymbol{B^-} \to D^0 D_s^-)$ and $\mathcal{B}(\boldsymbol{B^-} \to D^{(*)0} \boldsymbol{\mu^-}\, \bar{\nu}_\mu)$ to obtain $\boldsymbol{R(D^0)}$ and $\boldsymbol{R(D^{*0})}$.

$$R(D^{(*)0}) = \left[\frac{\mathcal{B}(\boldsymbol{B^-} \to D^{(*)0}\, \boldsymbol{\tau^-}\, \bar{\nu}_\tau)}{\mathcal{B}(\boldsymbol{B^-} \to D^0 D_s^-)}\right]_{meas} \times \frac{\mathcal{B}(\boldsymbol{B^-} \to D^0 D_s^-)_{PDG}}{\mathcal{B}(\boldsymbol{B^-} \to D^{(*)0}\boldsymbol{\mu^-}\, \bar{\nu}_\mu)_{PDG}}$$

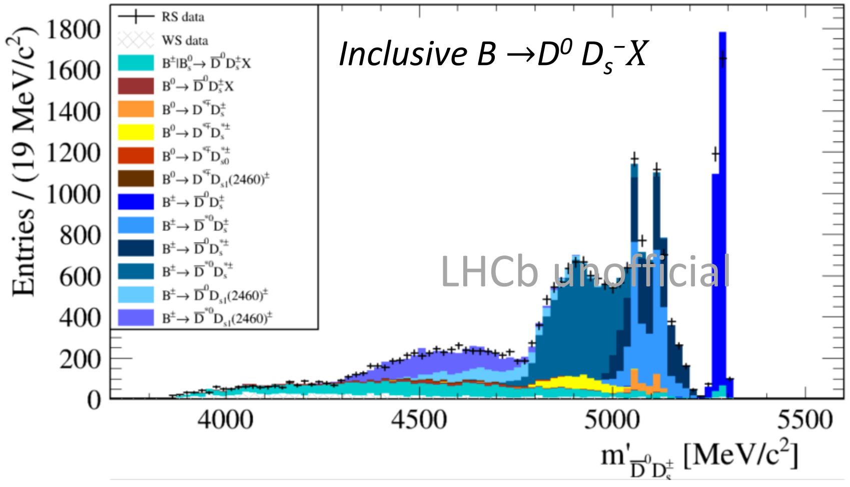


# Measurement of $R(D^{(*)0})$ using 3-prong hadronic tau decays

- Much progress since last year:
  - Large simulation samples have been produced. ✓
  - Events selection optimised. ✓
  - Data and simulation samples processed. ✓
  - Fit to the normalisation mode. ✓
  - New fit framework based on RooFit created and tested. ✓
  - Dedicated studies of backgrounds. ✓
  - Fit to signal data. ✓

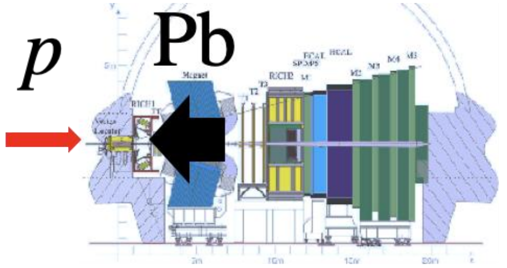



- Ongoing work:
  - Optimisation of background modelling.
  - Writing of analysis note.
- To be done:
  - Study of systematics.

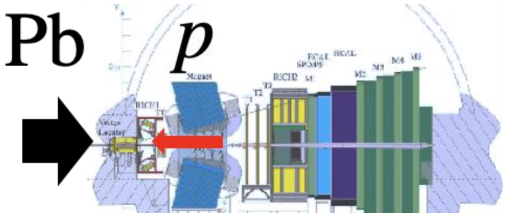


# Proton-Lead collisions

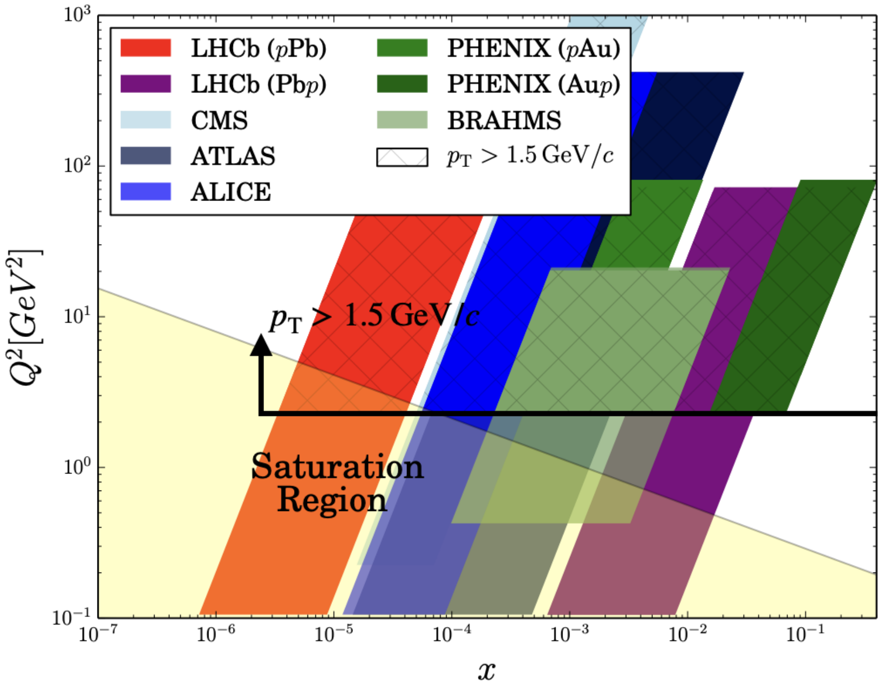
- Research line started in 2016
  - Unique acceptance of LHCb for proton-Ion collisions
    - Bjorken-*x* range in p-Pb 5 TeV collisions:
      - Forward $10^{-6}<x<10^{-4}$
      - Backward $10^{-3}<x<10^{-1}$
    - Access to saturation region in perturbative scale $p_T$>1.5 GeV/*c*
- First Goal:
  - Nuclear modification factor ($R_{pPb}$) in forward and backward regions:
    - Study of cold nuclear matter effects over a wide range of x.
    - Strong constrains to nuclear PDFs and saturation models at intermediate and very low x
  - Required result: determination of the proton-proton inelastic cross-section[LHCb Collaboration, JHEP06(2018)100 [arXiv:1803.10974] and Álvaro Dosil PhD thesis (also in hardware).




Forward $\eta > 0$



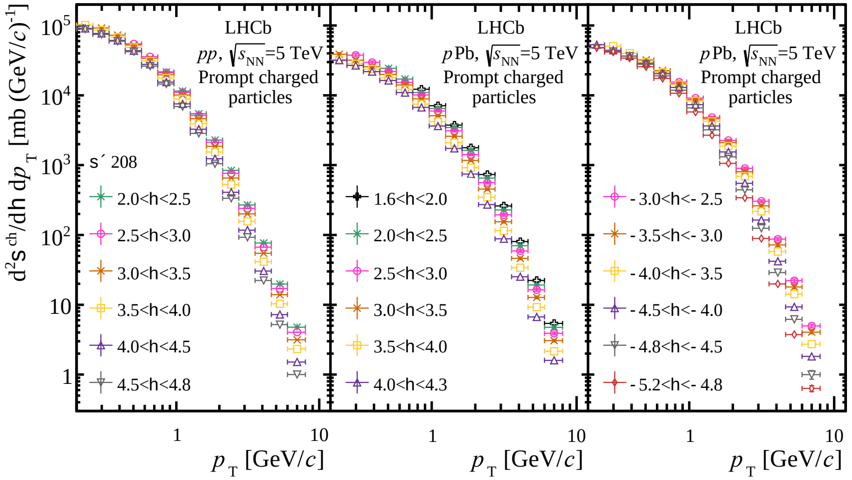

Backward $\eta < 0$

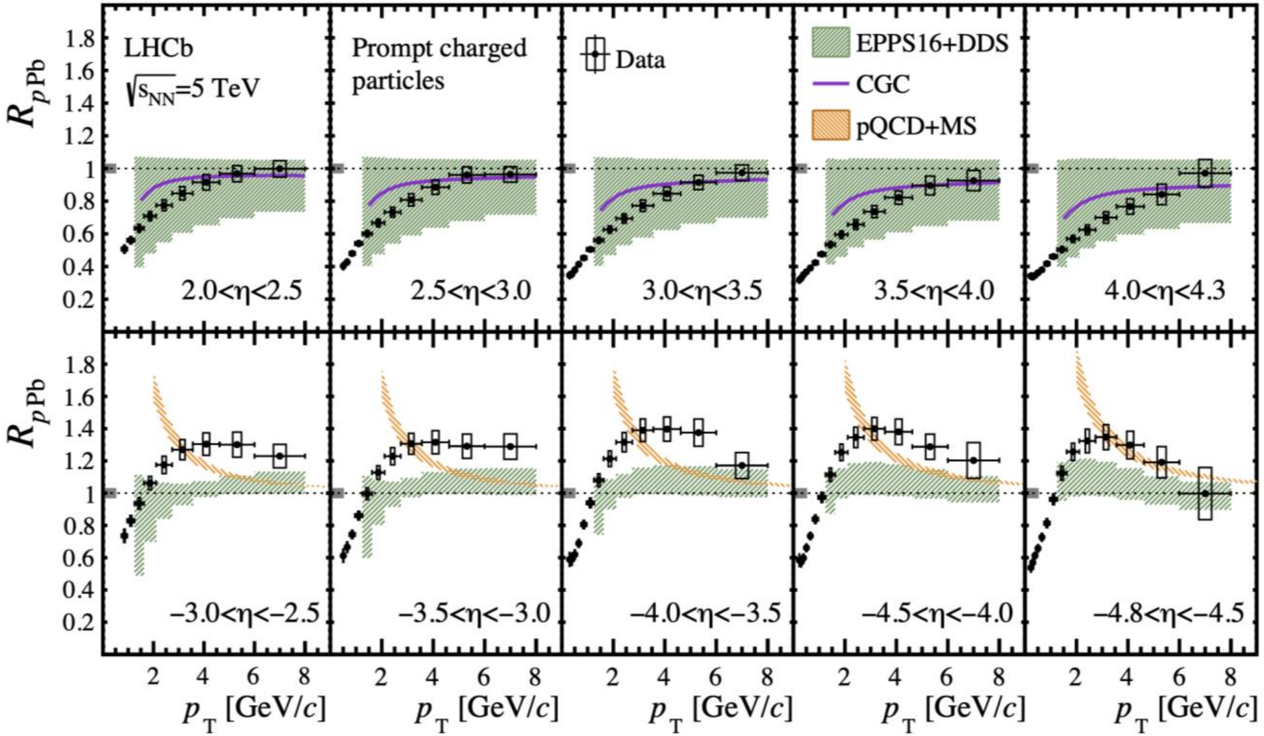


# First public heavy ion results



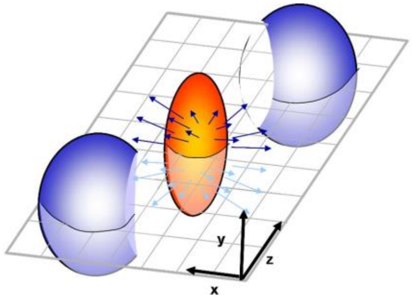
- LHCb Collaboration arXiv:2108.13115 Phys.Rev.Lett. 128 (2022), 142004
- Óscar Boente PhD thesis (09/09/2021)
- Determination of the double-differential cross-sections at 5 TeV
  - Unique input for Monte-Carlo generator tuning
- Measurement of $R_{p\text{Pb}}$ in the forward and backward regions
  - Comparison with nPDFs, pQCD and CGC predictions

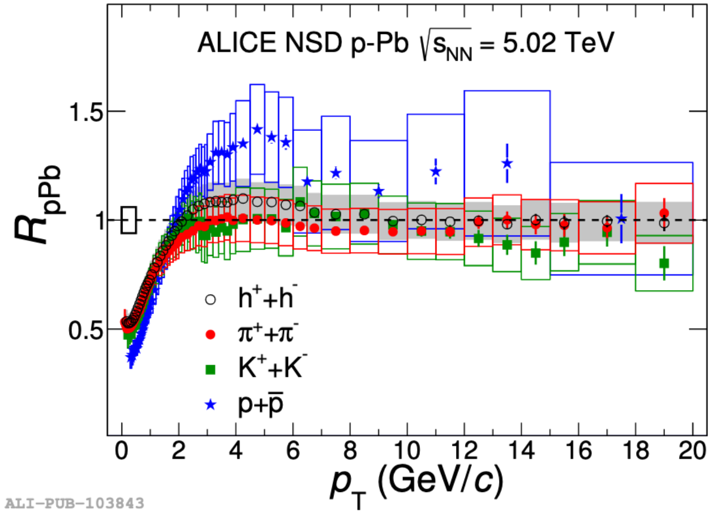


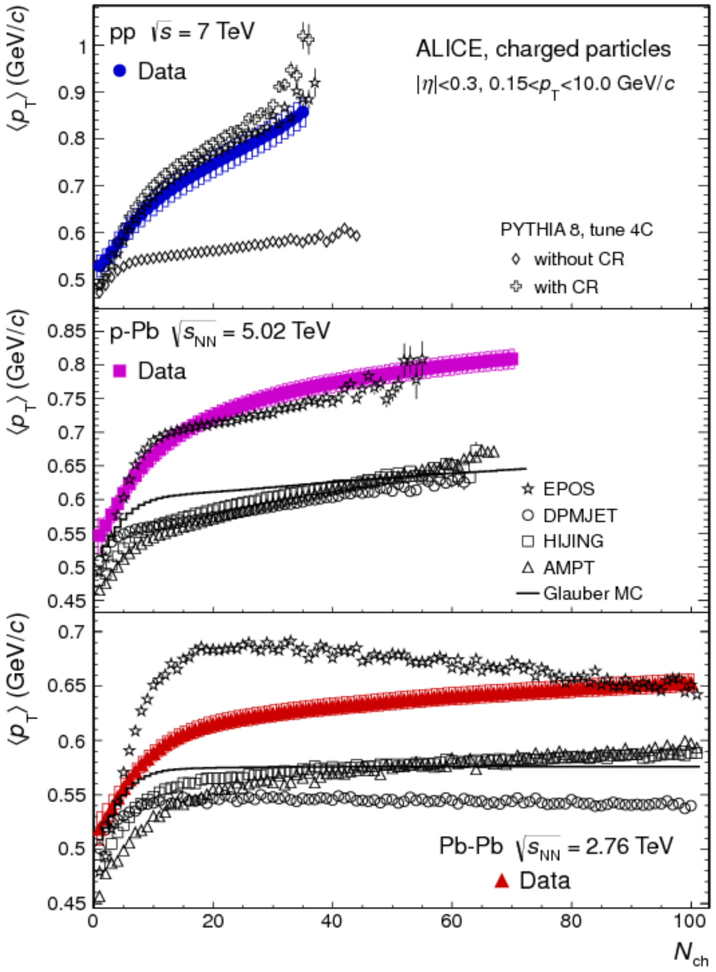



# Ongoing work and future prospects

- Ongoing
  - Determination of $R_{pPb}$ for pions, kaons and protons [Sara Sellam PhD]
    - Proton (baryon) $R_{pPb}$ particularly interesting
  - Measurement of the charged particle average $p_T$ with multiplicity in pPb and pp collisions [Imanol Corredoira PhD]
    - Information about particle production mechanism
    - Color re-connection required to explain tendency
  - Strangeness production in proton-lead and proton-proton collisions [Clara Landesa PhD]
- Possible future analyses
  - Particle flow with SMOG (fixed target) Heavy Ion collisions

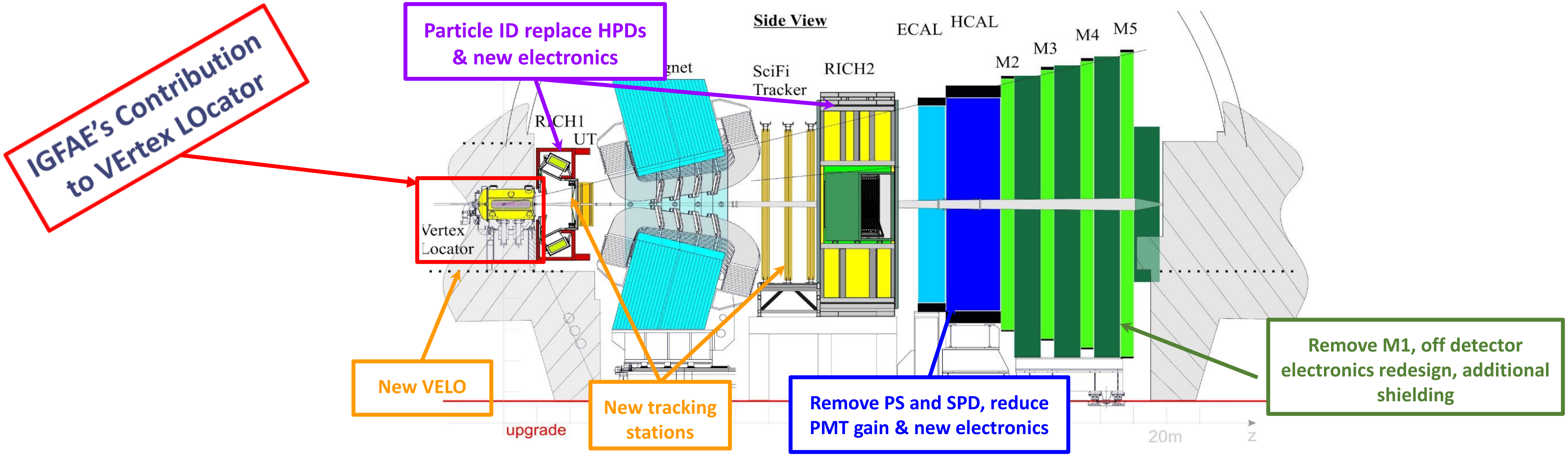


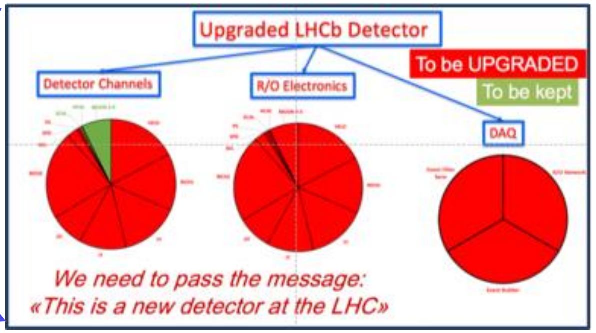



# LHCb Upgrade I

## 2019-2022



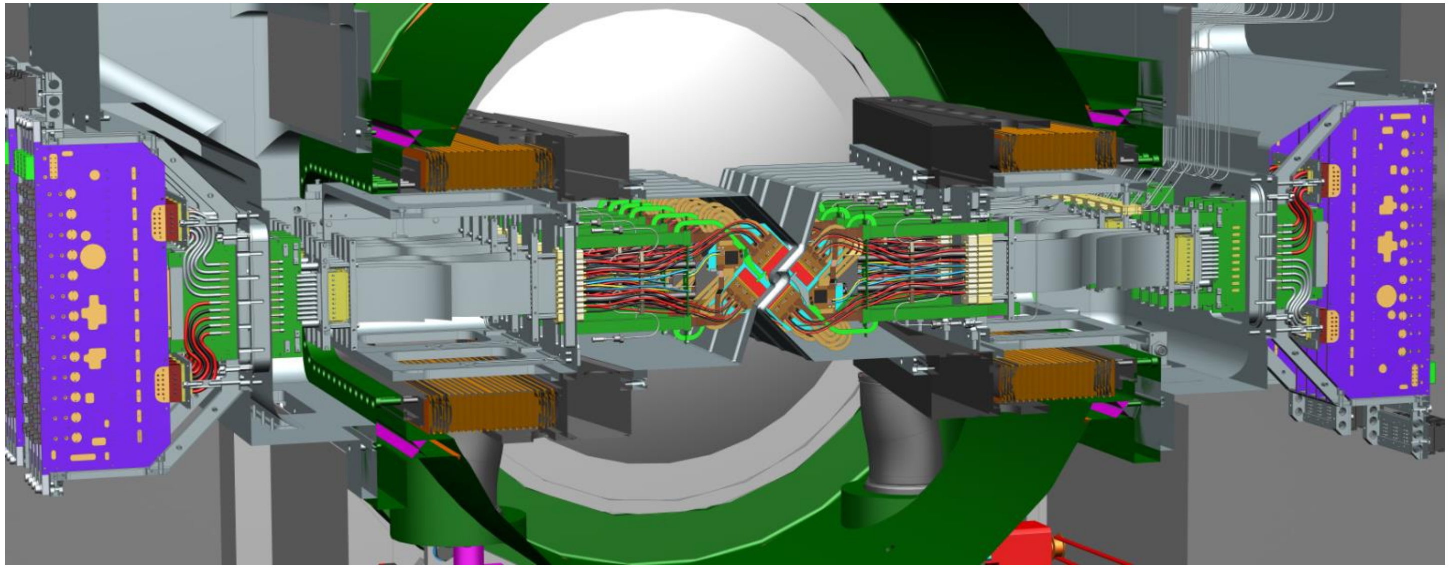

- Remove hardware trigger and read out the detector @ 40 MHz:
  - New front-end and back-end electronics
  - New vertexing and tracking systems
  - Fully software trigger
- Major upgrade of the apparatus



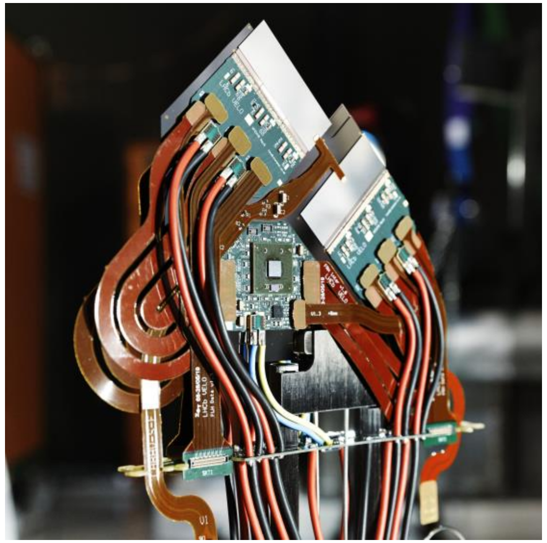
# LHCb VELO Upgrade I

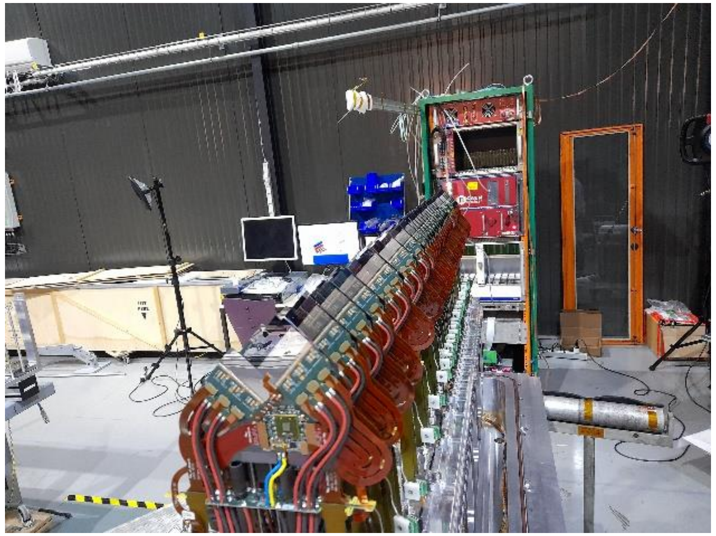
- **Primary tracking and vertexing detector** surrounding the collision region
  - In high vacuum (separated from the LHC vacuum by a RF foil)
- **Pixel** technology (formerly r/ϕ silicon microstrip)
  - **More robust track reconstruction performance**
  - Better resolution
  - **Closer to beam (8.1mm to 5.1mm).** Two retractable halves.
- **Faster readout (1MHz to 40MHz)**
- New ASIC VeloPix, based on TimePix family
- New micro-channel evaporative $CO_2$ cooling
- Some figures:
  - 52 modules, 624 VeloPix ASICs
  - Detector active area 0.12 $m^2$
  - **~41 M pixels** (**55x55 $\mu m^2$**)
  - HV tolerance of 1000V
  - **Trigger-less readout ~2.9 Tb/s**
  - Highly non-uniform radiation (4MGy)

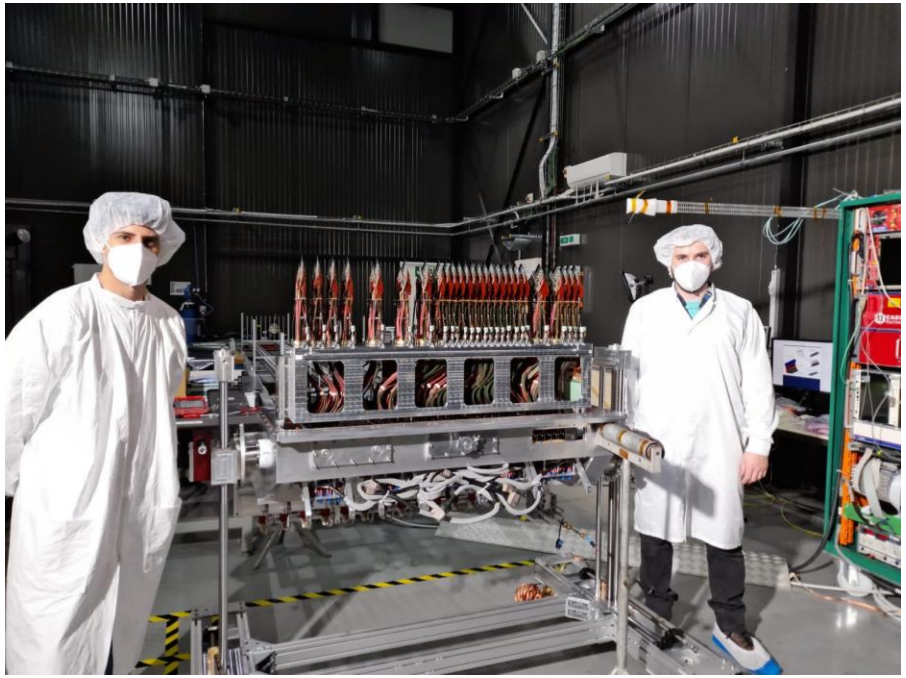
| Feature | Old VELO | upgraded VELO |
|---|---|---|
| Sensors | R & Φ silicon strips semicircular | Pixel sensors, L shape geometry |
| Maximum fluence | 4.3 $\times 10^{14}$ 1 MeV neq $cm^{-2}$ | 8 $\times 10^{15}$ 1 MeV neq $cm^{-2}$ |
| HV tolerance | 500 V | 1000 V |
| Readout rate | 1 MHz | 40 MHz |
| Total data rate | ~150 Gb/s | ~ 2.9 Tb/s |
| Power consumption | ~ 0.8 kW | ~ 1.6 kW |
| Operating Temp. | -8°C | -20°C |



# LHCb VELO Upgrade I installation

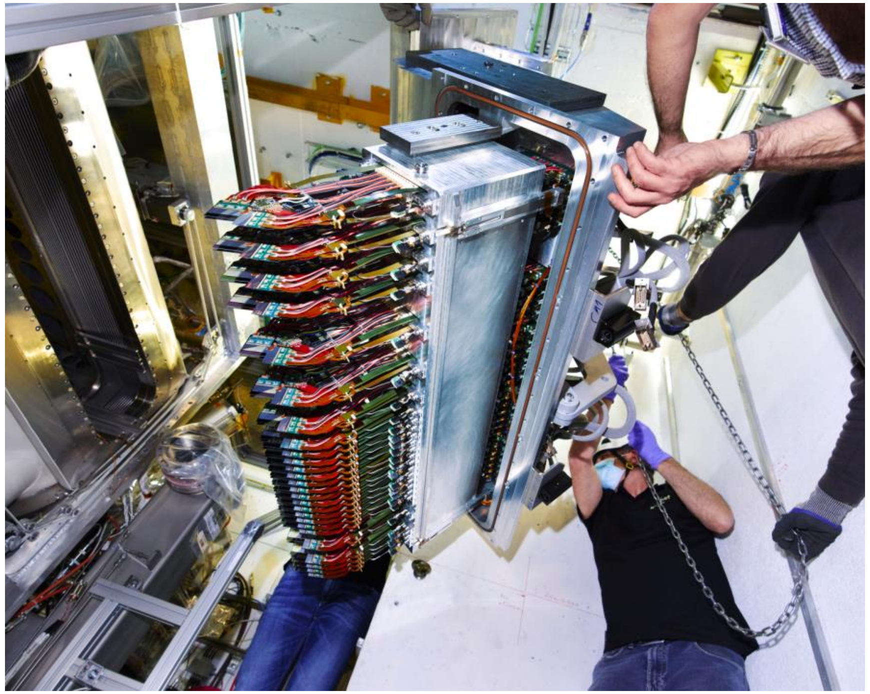


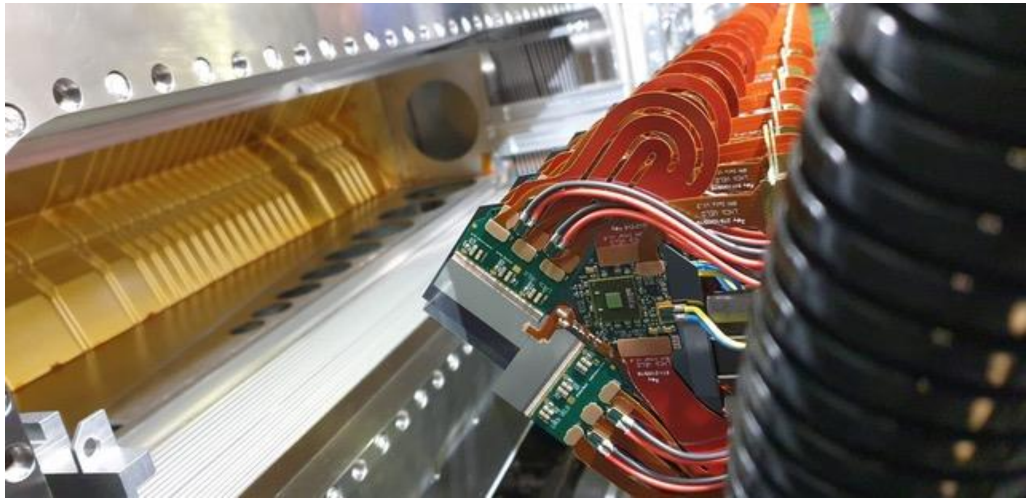




# LHCb VELO Upgrade I installation

- $1^{st}$ side of VELO installed on March $2^{nd}$.
- $2^{nd}$ side of VELO completed in May $11^{th}$ as foreseen at RRB.
- Commissioning of detector now proceeding well!!



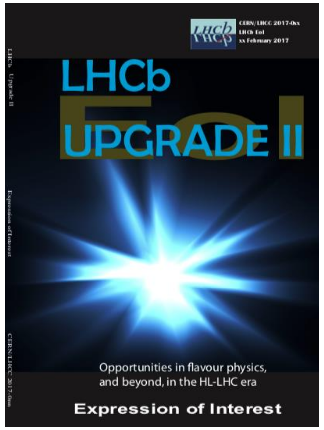


# LHCb Upgrades timeline

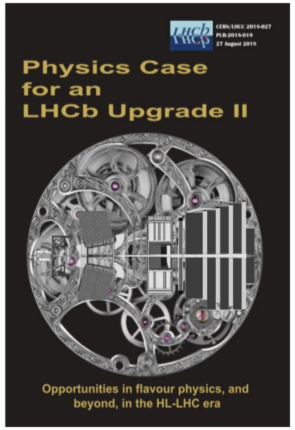
LHCb — LHCb Upgrade I — LHCb Upgrade II

| Run 1 - Run 2 | | Run 3 | | Run 4 | | Run 5 | | Run 6 |
|---|---|---|---|---|---|---|---|---|
| $L_{int}$ = 10 fb$^{-1}$<br>L = 4 x $10^{32}$ | LS2<br>Injector Upgrades<br>LHCb Upgrade I | L = 2 x $10^{33}$ | LS3<br>HL-LHC<br>ATLAS/CMS<br>Phase 2 Upgrades | $L_{int}$ ~ 50 fb$^{-1}$ | LS4<br>LHCb Upgrade II | L = 1-2 x $10^{34}$ | LS5 | $L_{int}$ ~ 300 fb$^{-1}$ |
| 2010 - 2018 | 2019 - 2022 | 2022 - 2025 | 2026 - 2028 | 2029 - 2032 | 2033 - 2034 | 2035 - 2038 | 2039 | 2040 – 20XX |

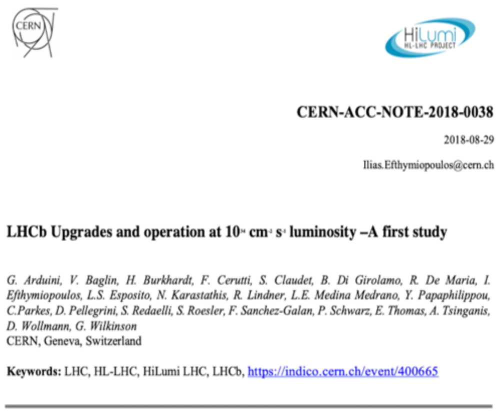
Belle II: 0,5 ab$^{-1}$ → 50 ab$^{-1}$




[LHCC-2017-003]




[LHCC-2018-027]


CERN-ACC-NOTE-2018-0038

2018-08-29

Ilias.Efthymiopoulos@cern.ch

**LHCb Upgrades and operation at $10^{34}$ cm$^{-2}$ s$^{-1}$ luminosity –A first study**

G. Arduini, V. Baglin, H. Burkhardt, F. Cerutti, S. Claudet, B. Di Girolamo, R. De Maria, I. Efthymiopoulos, L.S. Esposito, N. Karastathis, R. Lindner, L.E. Medina Medrano, Y. Papaphilippou, C.Parkes, D. Pellegrini, S. Redaelli, S. Roesler, F. Sanchez-Galan, P. Schwarz, E. Thomas, A. Tsinganis, D. Wollmann, G. Wilkinson
CERN, Geneva, Switzerland

Keywords: LHC, HL-LHC, HiLumi LHC, LHCb, https://indico.cern.ch/event/400665

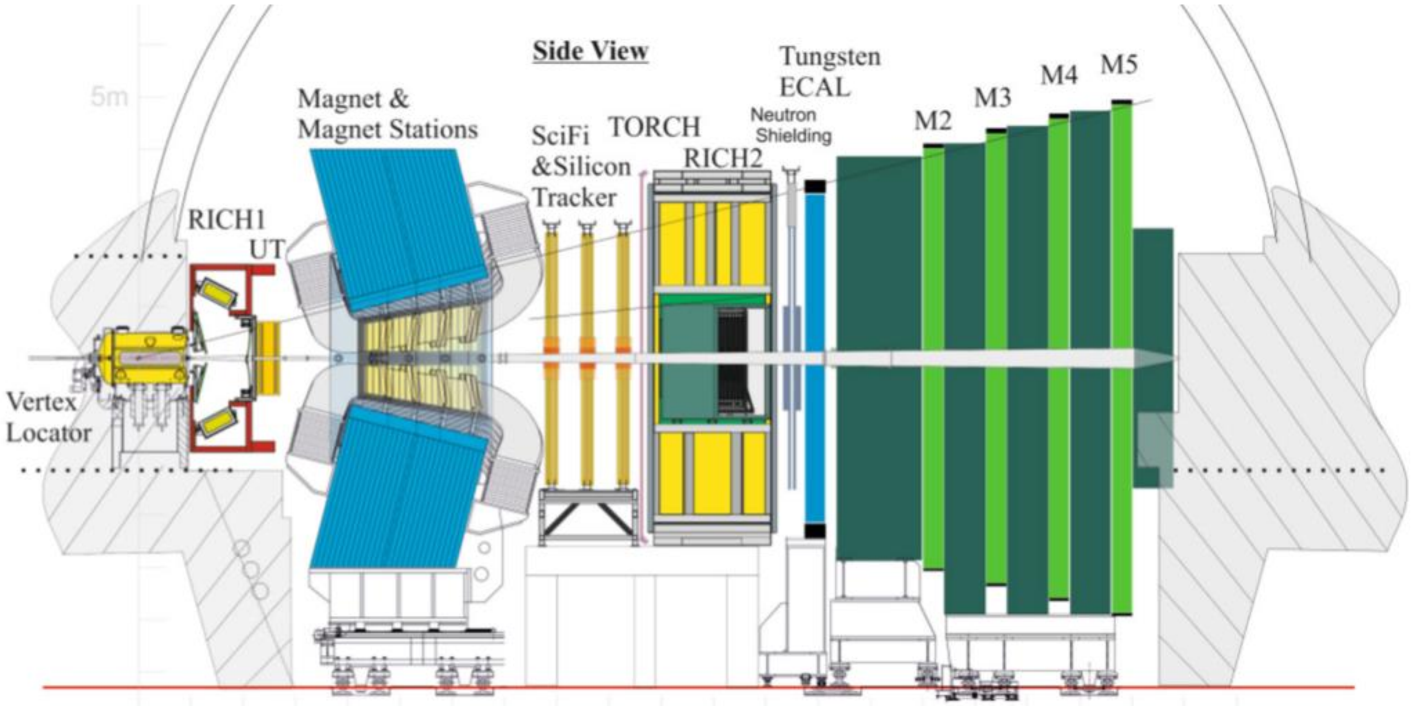
[CERN-ACC-2018-038]


[LHCC-2021-012]

**Approved in LHCC March 2022 !**
**R&D programme,**
**scoping document followed by sub-system TDRs 2022-2025**
**MoU ~2025**

***European Strategy Update 2020*** *"The full potential of the LHC and the HL-LHC, including the study of flavour physics, should be exploited"*

# LHCb Upgrade II




Same spectrometer footprint, innovative technology for detector and data processing

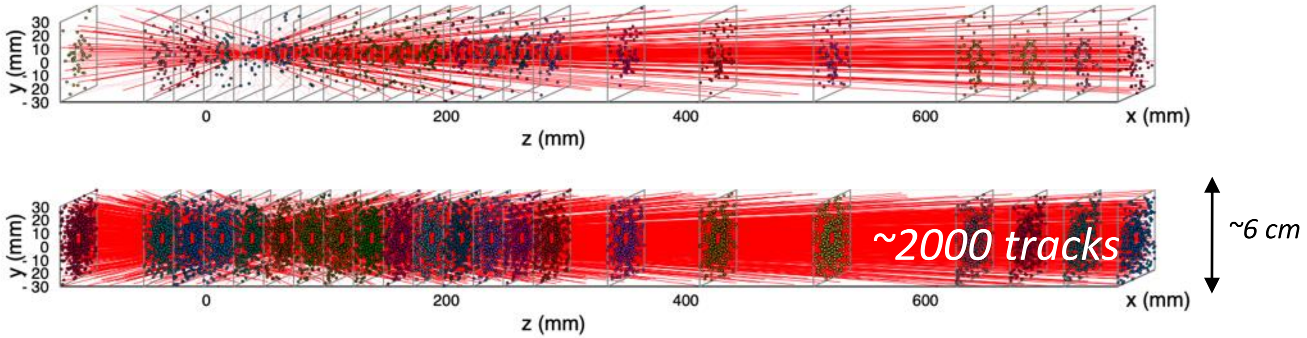
Key ingredients:

- granularity
- fast timing  (few tens of ps)
- radiation hardness

## *VErtex LOcator (VELO)*

*Run 3:  pile-up ~6*

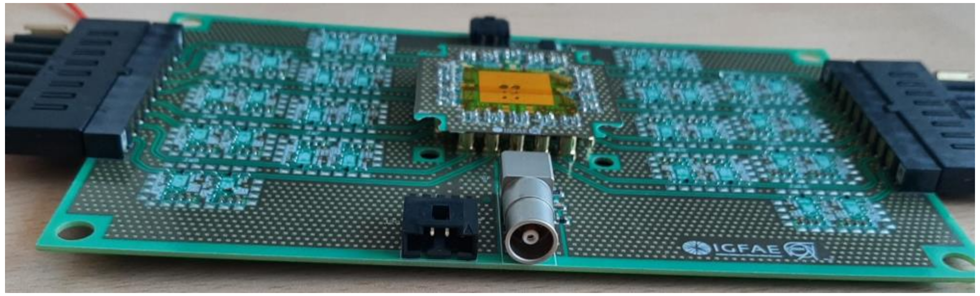
*Upgrade II:  pile-up ~42*




***Targeting same performance as in Run 3, but with pile-up ~40!***

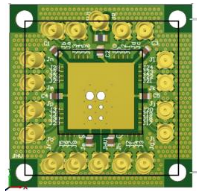
# VELO R&D for LHCb Upgrade II: 4D Vertexing

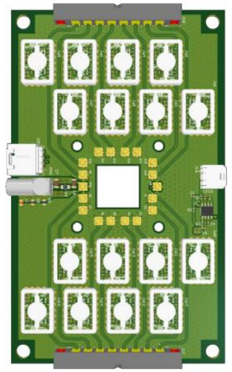
- High temporal resolution (tens of ps) and high granularity (small pixels ) at high rates:
  - Sensors (3D, iLGAD , thin planar…) production at CNM will finish Nov 2022.
  - Front-end and DAQ (TimePix4, and successors, most likely 28nm CMOs ).
- AIDAinnova — H2020-INFRAINNOV-2019-2020 (GA : 101004761 ) (2021-2025), RD50 …
- Test beam campaigns this summer 2022




- Multichannel timing board
  - 16 Channel readout board with first and second stage amplifiers integrated
  - Regulated input Voltage
  - 15 mm x 15 mm central opening
  - Use of miniaturized coaxial connectors. High life cycle
  - First and second stage SiGe Transistor
  - Sensor board
    - Quick sensor test around
    - Simplified probing and reduce sensor damage
    - Temperature monitoring
    - Low noise
    - Low material budget and easy alignment

| Infineon | BFR840L3RHESD |
|---|---|
| $G_{max}$ | 26.5 dB |
| $I_C$ max | 35.0 mA |
| NF | 0.5 dB |
| OIP3 | 17.0 dBm |
| OP1dB | 4.0 dBm |
| $V_{CEO}$ max | 2.25 V |
| Frq. Range | Up to 12 GHz |





# The Team

## 24 members

**5 senior staff:**
A. Gallas, A. Romero, J. Saborido, C. Santamarina, P. Vázquez.

**2 postdoc:**
S. Belin, A. Brossa

**5 engineers/technicians:**
E. Lemos, A. Fernández, A. Pazos, E. Pérez, M. Seco.

**9 PhD students:**
B. García, A. Gioventú, J. Lomba, I. Corredoira, S. Sellan, C. Eirea, C. Landesa, E. Rodriguez, J. Novoa.

**3 Master students:**
J. I. Cambón, L. Carcedo, C. J. Barbero

# Backup Slides

# Publications in instrumentation (2019-2022)

1) *The HEV Ventilator: at the interface between particle physics and biomedical engineering.* J. Buytaert et. al. https://royalsocietypublishing.org/doi/10.1098/rsos.211519

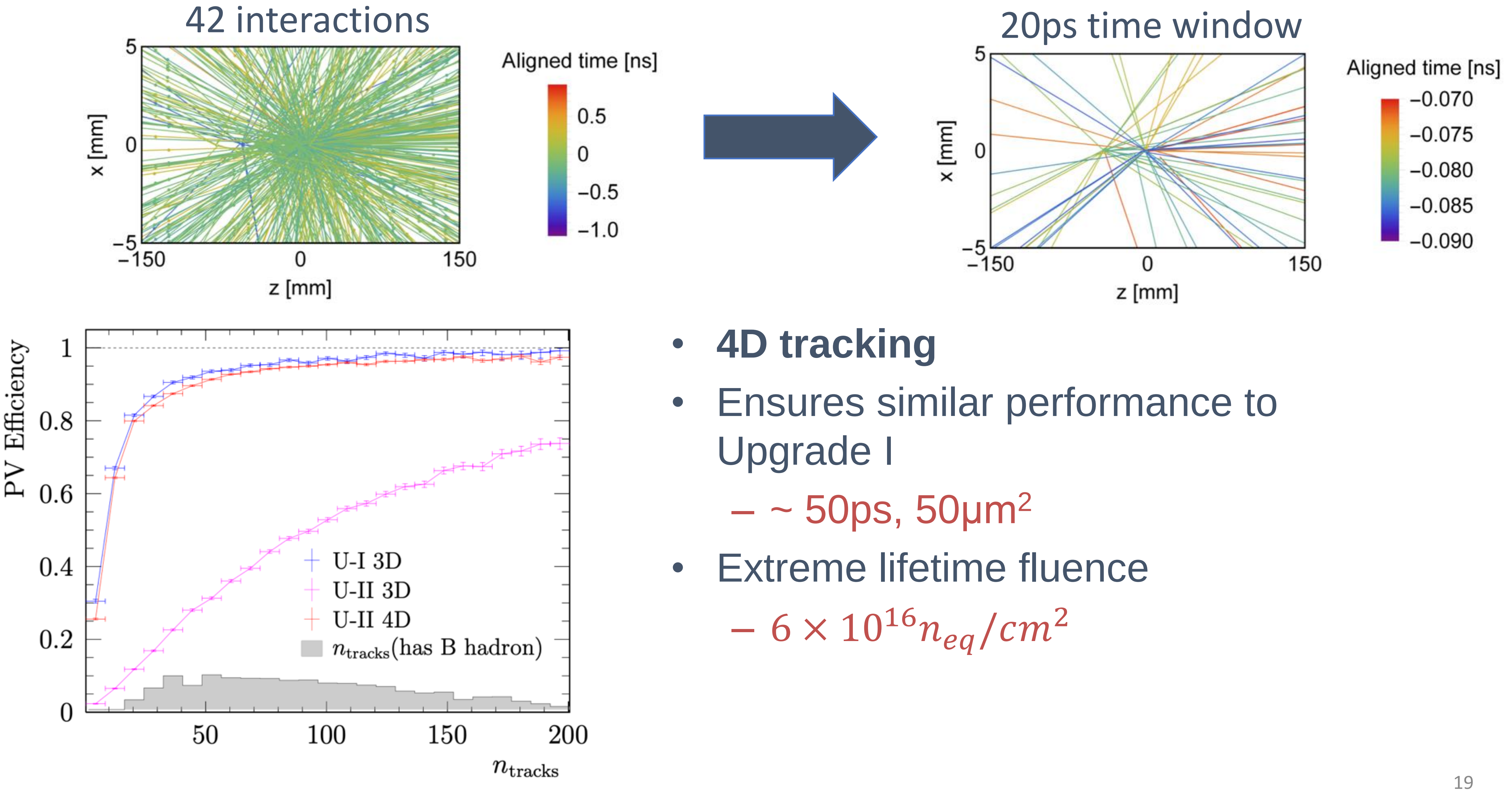
2) *PhD Thesis: Development of electronics for the VELO upgrade detector. Antonio Fernández Prieto. Supervisor: Pablo Vázquez. November the 24th 2020.*

3) *Readout Firmware of the Vertex Locator for LHCb Run 3 and Beyond. IEEE Transactions on Nuclear Science. (2021) DOI:10.1109/TNS.2021.3085018.*

4) *Phase I Upgrade of the Readout System of the Vertex Detector at the LHCb Experiment. IEEE Trans.Nucl.Sci. (2020) DOI: 10.1109/TNS.2020.2970534.*

5) *LHCb VELO Timepix3 telescope. 2019 JINST 14 P05026. DOI:10.1088/1748-0221/14/05/P05026.*

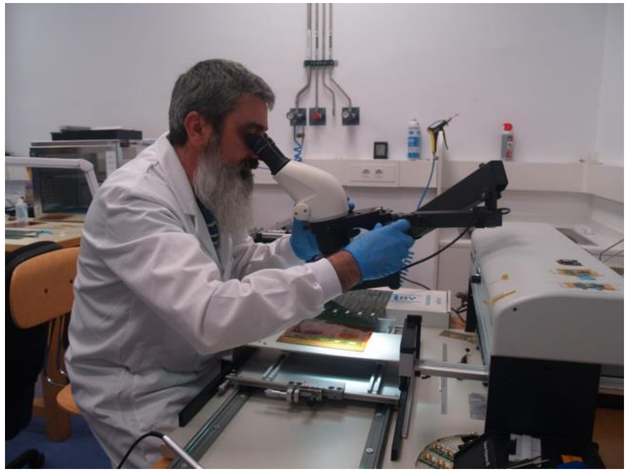
# 4D Vertexing

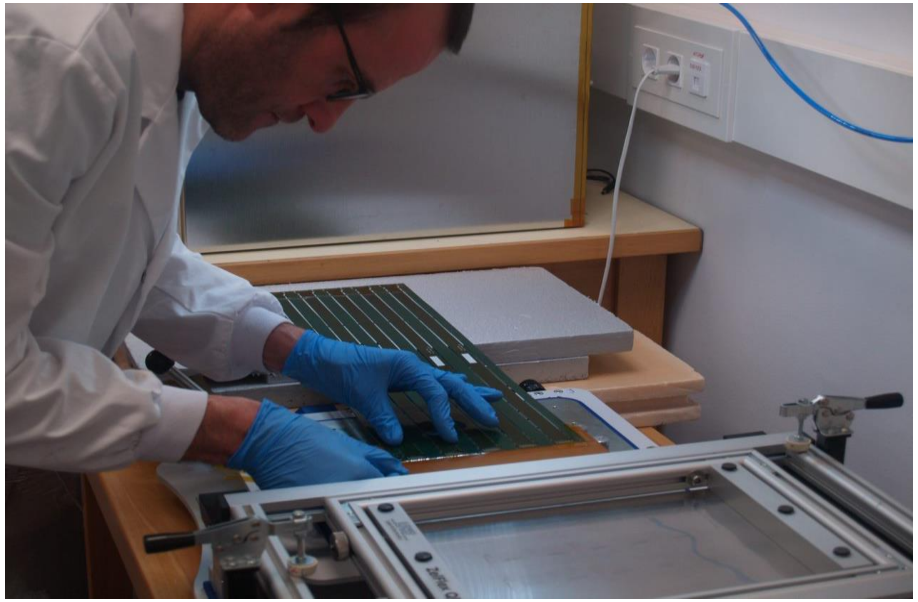


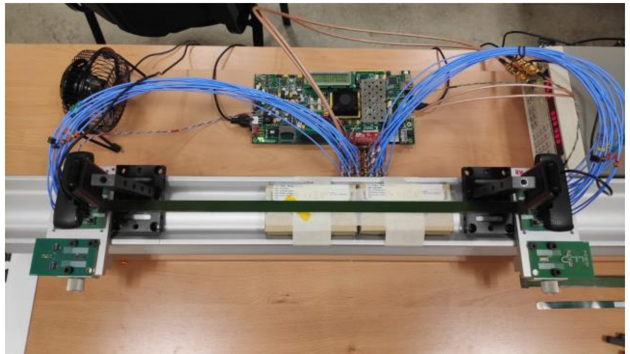

- **4D tracking**
- Ensures similar performance to Upgrade I
  - ~ 50ps, 50μm$^2$
- Extreme lifetime fluence
  - $6 \times 10^{16} n_{eq}/cm^2$

# LHCb VELO Upgrade I


- “Old” Inner Tracker (IT) dismantled at LHCb cavern
- VELO readout system developments:
  - DAQ, Control and Synch firmware
- VELO detector **D**esign, **C**onstruction and **QA**:
  - 320 High-speed data links (D,C,QA)
  - 190 High Voltage tapes (C,QA)
  - 52 Vacuum Feedthrough and Optical Power Boards (C,QA)

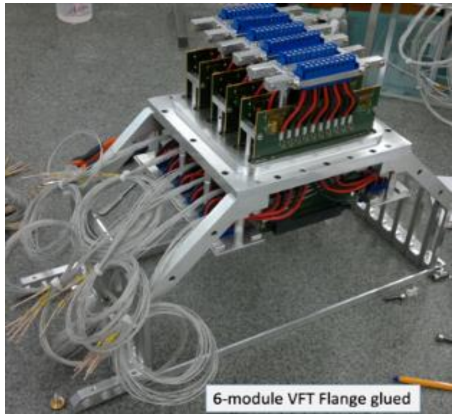






# LHCb VELO Upgrade I

- **Validation of a complete VELO slice :**
  - Microchannel cooling: operation and QA
  - Verification and optimization of on-detector electronics
  - LV and HV systems
  - Monitoring
- **VELO installation :**
  - 2 sides installed in March and May 2022
- **VELO commissioning and calibration:**
  - Monitoring and Control software for readout
  - FE ASICs calibration tools (software and firmware)



# PhD Thesis (2019-2022)

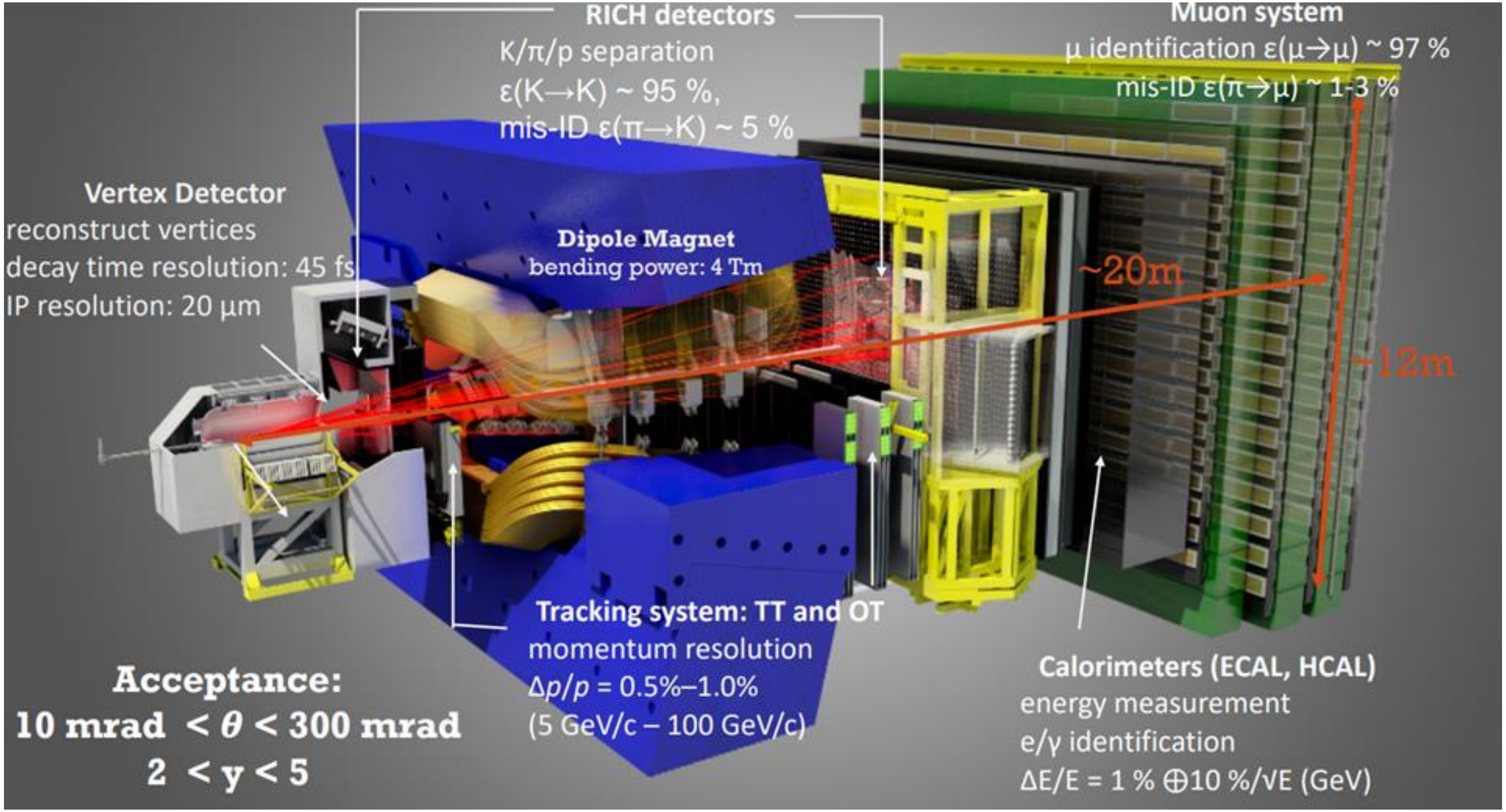
1) Analysis of the production of charged particles in proton-nucleus and proton-proton collisions in the LHCb experiment. Óscar Boente García. 09/09/2021.
2) Development of electronics for the VELO Upgrade Detector. Antonio Fernández Prieto. 24/11/2020.
3) Study of the $B^0 \rightarrow \rho K^*$ decay with an amplitude analysis of $B^0 \rightarrow (\pi\pi)(K\pi)$ decays. María Vieites Díaz. 27/03/2019.

# Funded Projects (2019-2021)

1) *PID2019-110378GB-100. Ministerio de Ciencia e Innovación. IPs: A. Romero, A. Gallas. Budget: 869.627,00 €. 2020-2023*
2) *2020-PG054. Consolidación 2020. Modalidad C. Xunta de Galicia. IP: A. Romero. Budget: 115.000,00 €. 2020-2024*
3) *RyC2018-024626-I. IP: A. Romero. Budget: 40.000,00 €. 2020-2024*
4) *ED431C 2018/15. Xunta de Galicia. IP: J. Saborido. Budget: 400.000,00 €. 2019-2021*
5) *AIDAinnova — H2020-INFRAINNOV-2019-2020 / H2020- INFRAINNOV-2020-2 (Grant Agreement number: 101004761 ).IP: A. Gallas, D. González. Budget: 75.000,00 €. 2021-2025*
6) *IGFAE/IGNITE. IP: E. Lemos, A. Pérez. Budget: 70.000,00 €. 2021-2022*

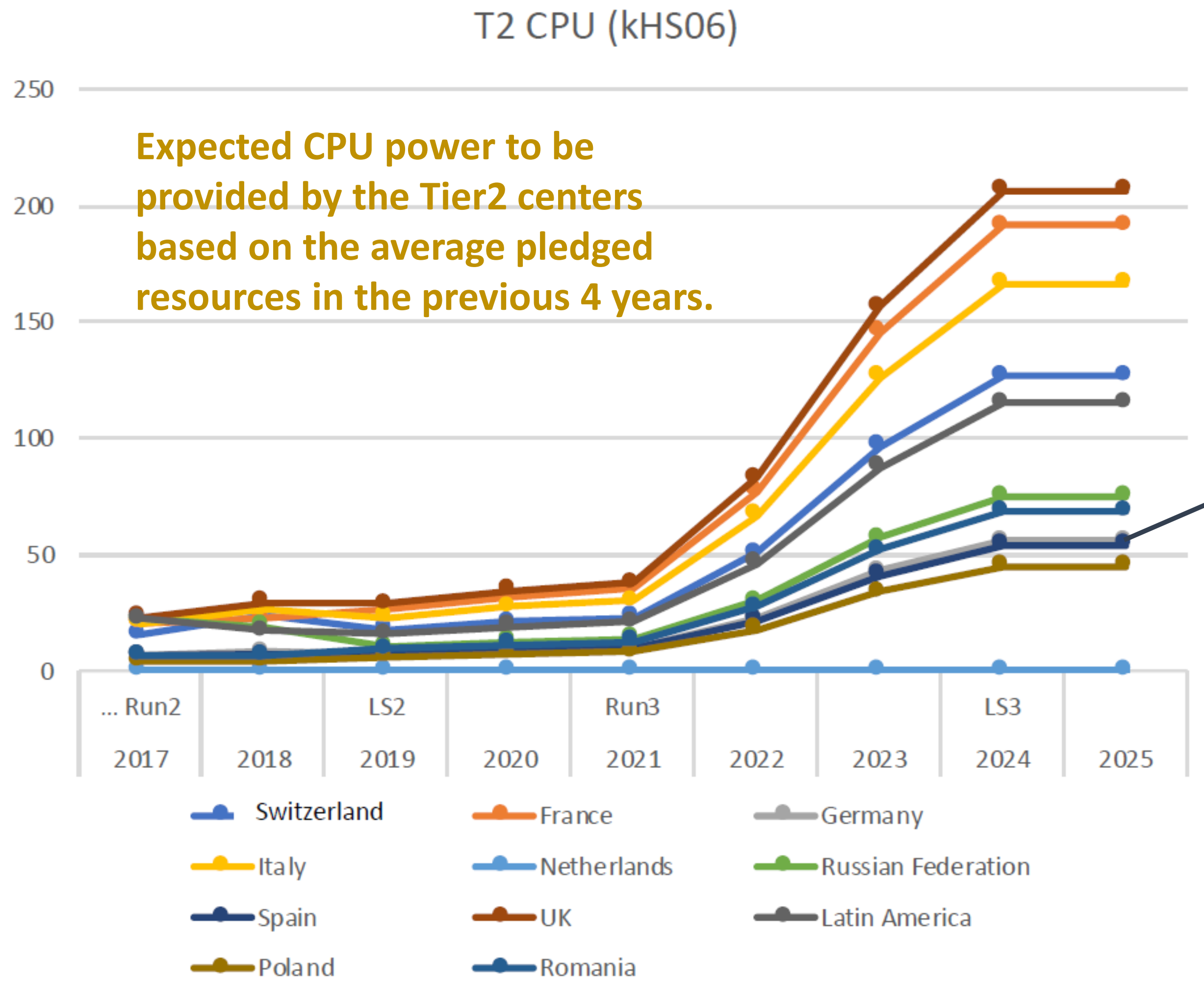
# The LHCb detector





# Tier2 GRID computing

- The Spanish LHCb Tier2 center runs now only at IGFAE. It has produced over the years about the 5% of the LHCb-Tier2 integrated resources.
- At present we have 74 working nodes: 148 physical (1016 logical) cores delivering 10 kHS06




**(1 HS06 = 10 €)**

**Core Cost**

**50 kHS06 = 500 k€**

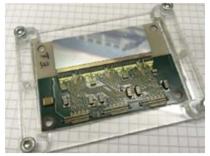
**Spain**

This is what ES-LHCb-T2 would need to have installed by the end of 2023

# Sensors & Electronics (IGFAE/USC)

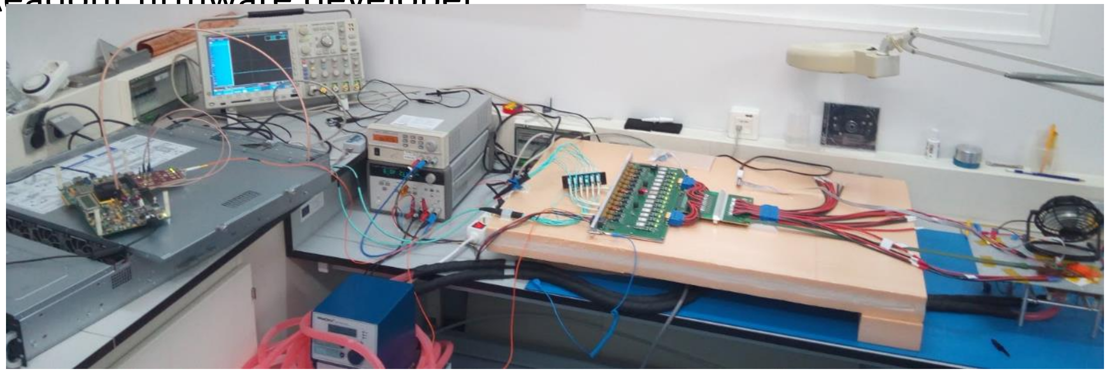
**IGFAE/USC contributions to** (already since 2008):


- **Sensors:**
  - Technology choice (strips vs pixels)
  - R&D, sensor design, prototype construction
  - Radiation resistance certification (neutron irradiations).



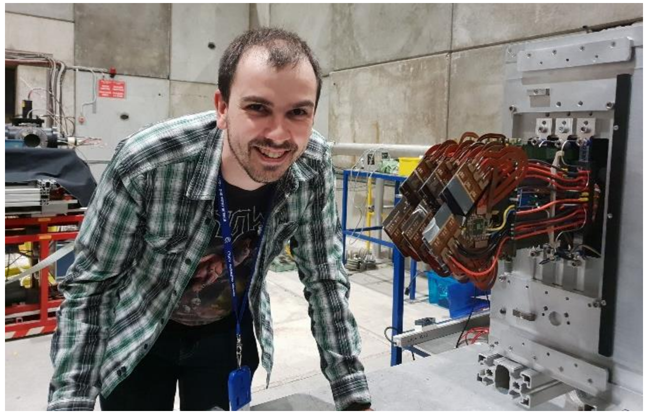
- **Front-end electronics qualification (VeloPix ASIC):**
  - Design and construction ASIC PCB carrier, Needle Probe Card
  - HV, High Speed Data Tapes and Vacuum Feed Through testing PCBs
  - Electronic Design Review (https://indico.cern.ch/event/725985/)
  - Radiation hardness:
    - Single Event Effects studies
    - Total Ionization Dose certification (up to 400 Mrad) in the USC X-ray facility.
  - Testing and quality assurance

- **Back-end electronics development:**
  - Workshop for the integration of VELO detector in the LHCb framework
  - 2 RO setups, based on Intel and Xilinx FPGAs, running at IGFAE/USC
  - Main Readout firmware developer

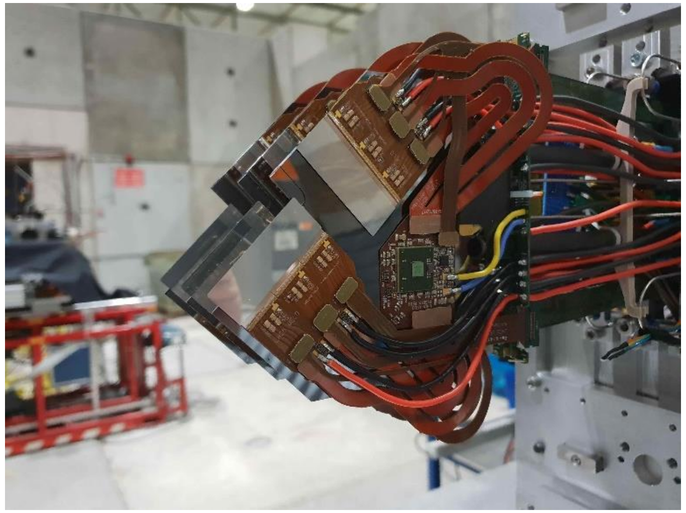


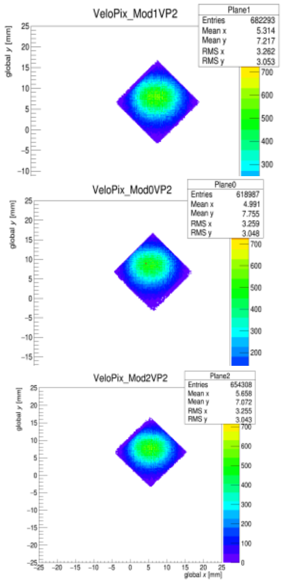
## *IGFAE Main contributor to the test-beam*

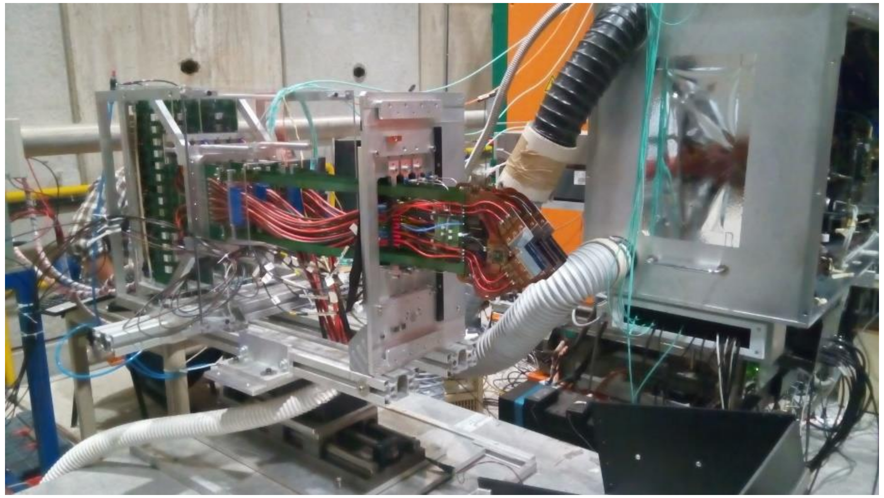
*Front-end electronics expert (IGFAE/USC)*
VELO *DAQ and firmware coordinator*



*Back-end electronics expert (IGFAE/USC)*
*Main firmware developer*



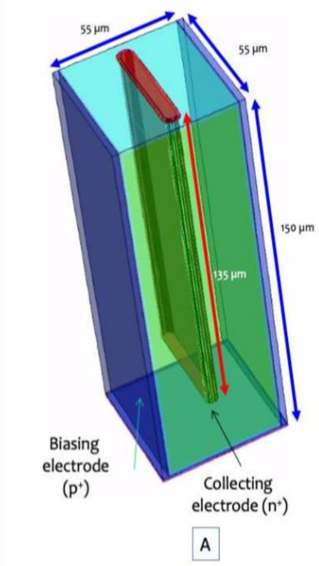


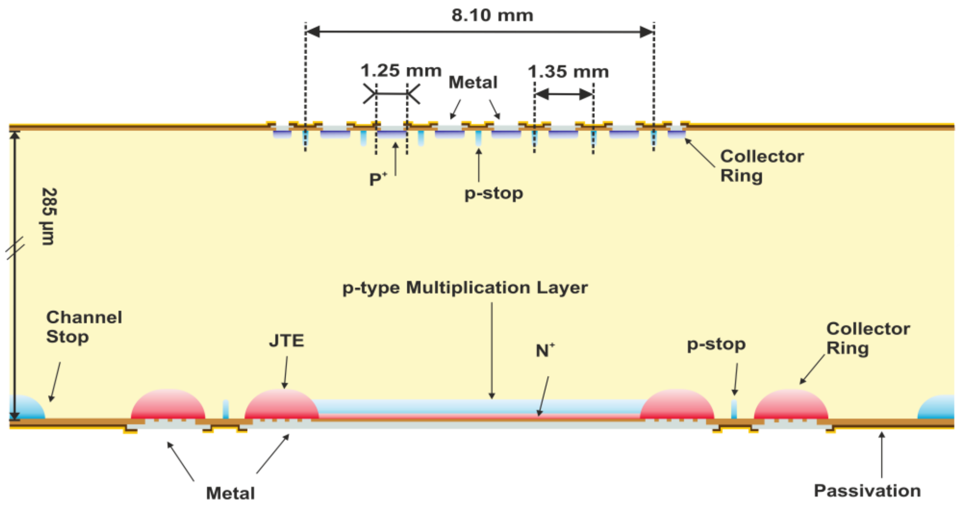



# Sensor R&D for LHCb Upgrade II

- High temporal resolution and high granularity (small pixels) at high rates Vertexing for LHCb phase-II upgrade :
  - Sensors (3D, pixelated iLGAD, 3D, thin planar…)
  - Front-end and DAQ (TimePix4,  and successors)
  - Test set-ups (Laser, X-ray, test-beam)
  - Radiation (Louvaine, Ljubljana, USC)
- R&D also done in collaboration with different partners from RD50, ATTRACT (EU program) outside LHCb

3D




Thick I-LGAD cross-section